



Astro 500



Techniques of Modern Observational Astrophysics

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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

Grating-dispersed spectrographs

basic spectrograph design

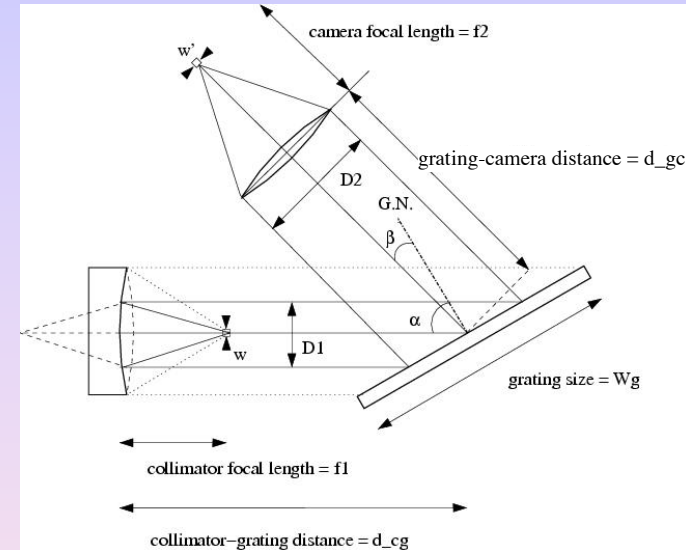
Spectral resolution

$$\begin{aligned}
 R &= \lambda / d\lambda \\
 &= \lambda (\gamma/r) (f_1/w) \\
 &= \lambda (\gamma/r) (D_1/\theta D_T)
 \end{aligned}$$

Want *large* collimator and even *larger* camera

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.



Using grating equation:

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

$$\begin{aligned}
 \theta &= \text{angle of slit on sky} \\
 d\lambda &= w_\lambda' / (dl/d\lambda) \\
 w &= f_T \theta \\
 f_1/d_1 &= f / D_T
 \end{aligned}$$

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 = $\tan \delta$
- 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**

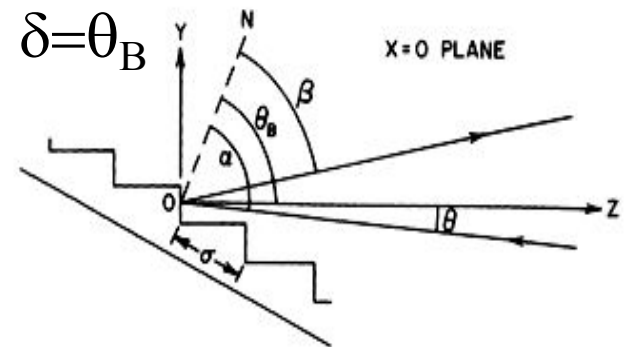
$$\gamma = d\beta/d\lambda = m / \sigma \cos \beta$$

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

- **Anamorphism**

$$r = |d\beta/d\alpha| = \cos \alpha / \cos \beta$$

- **Blaze angle: δ**

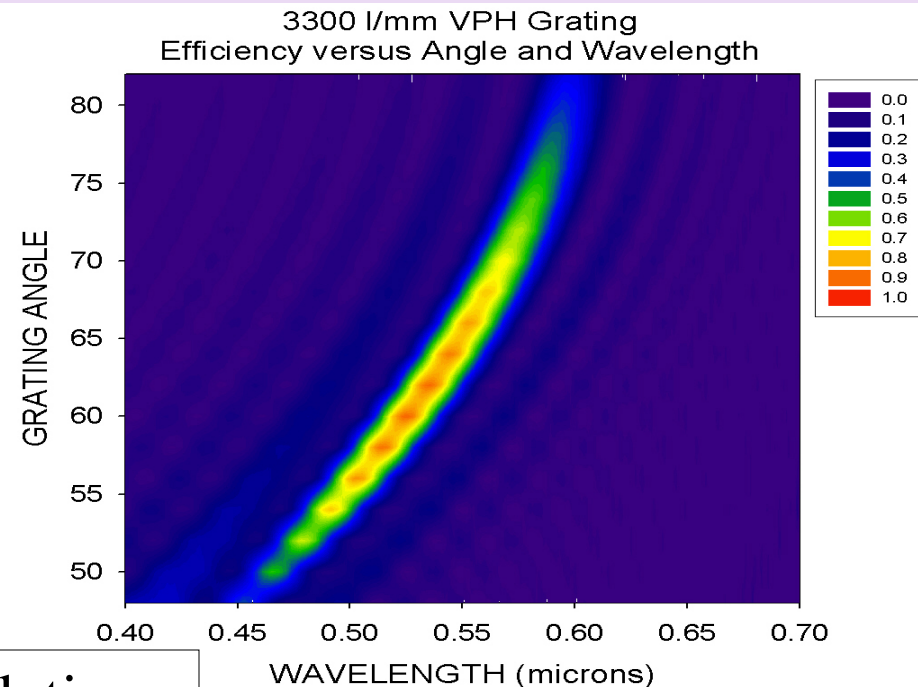
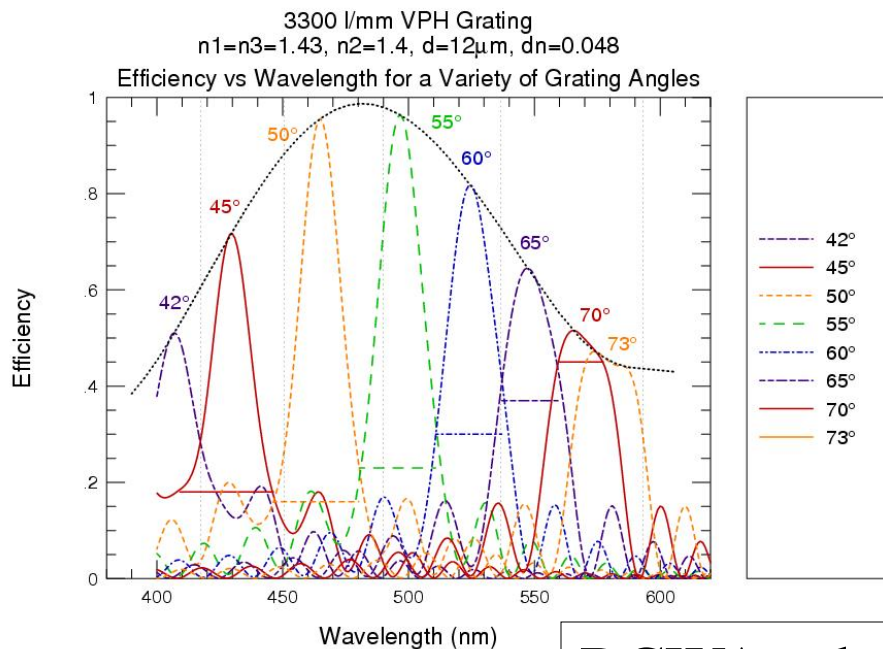


An example of a VPH spectrograph: WIYN 3.5m upgraded Bench Spectrograph

Challenging angles!
Coatings an issue

- 3300 l/mm: *in use*
- 0.5m in size!
- $R \sim 7000\text{-}20,000$
- expect 2x diffraction efficiency of existing echelle.

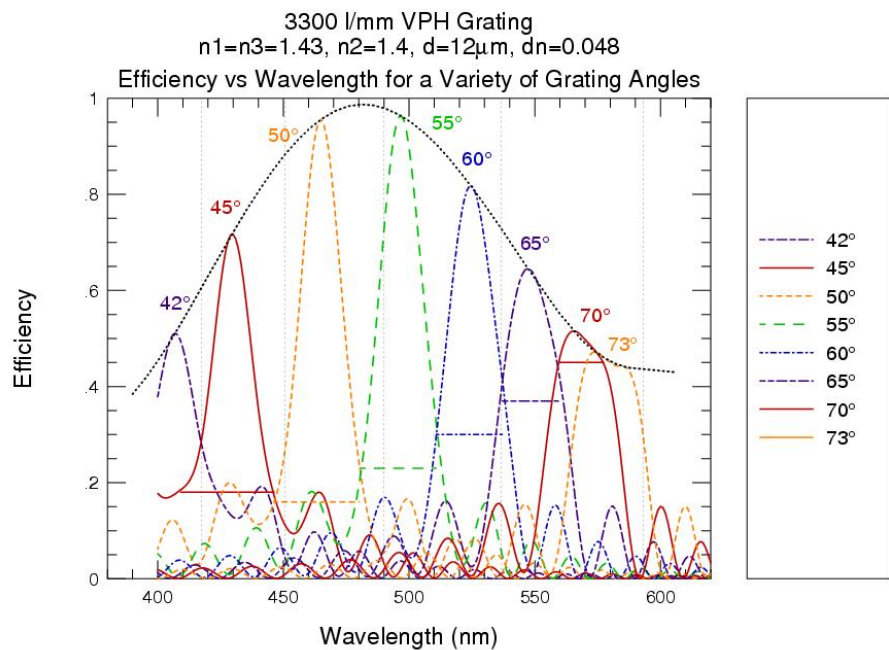
Air-Glass % Reflection Losses Per Surface				
		Uncoated	Newport Thin Film	Spectrum Thin Film
Angle			400-500nm	500-550nm 450-550nm
55°	6	2.5	2	< 1
60°		3.5	2.5	
65°	11	5.5	4.5	< 2
70°		9.5	7.5	
75°	24	17	15.5	< 7



RCWA calculations

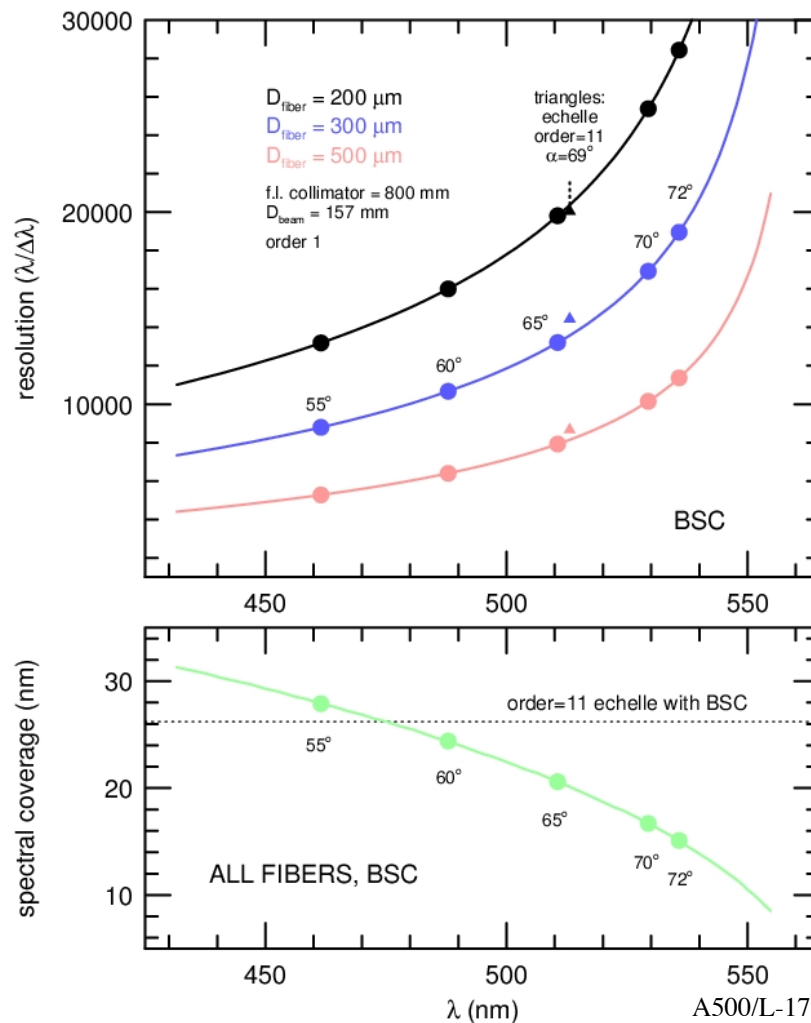
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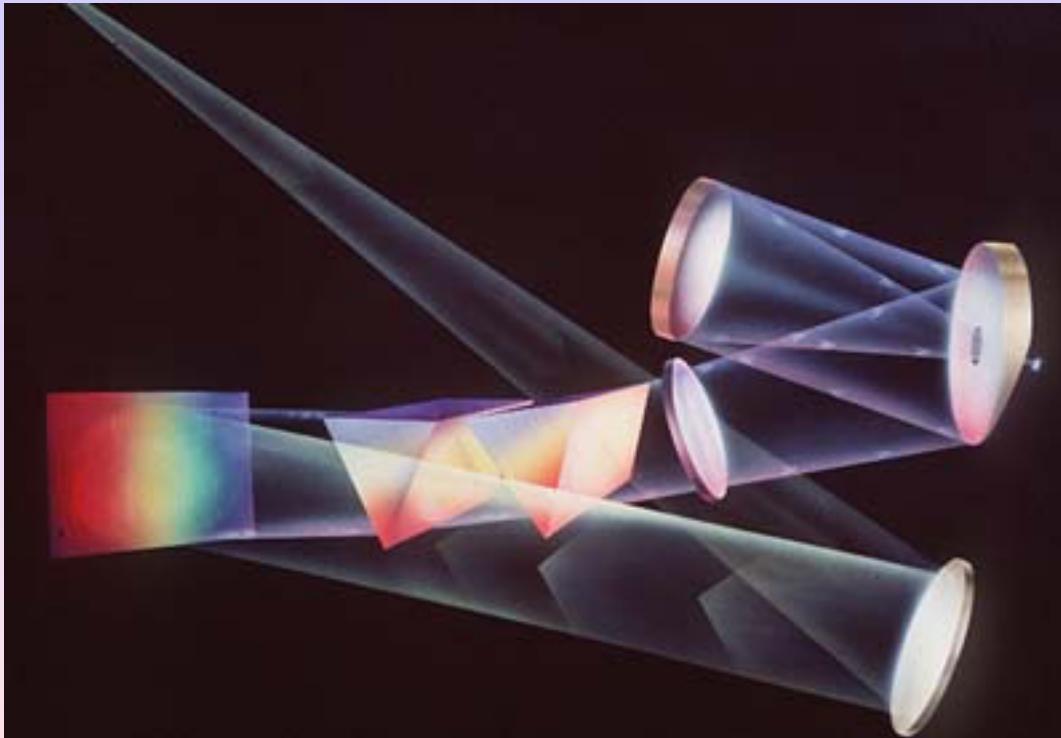


WIYN Bench with CSL vph 3550 l/mm Grating

Resolution and Coverage vs Wavelength



Echelle Spectrometers

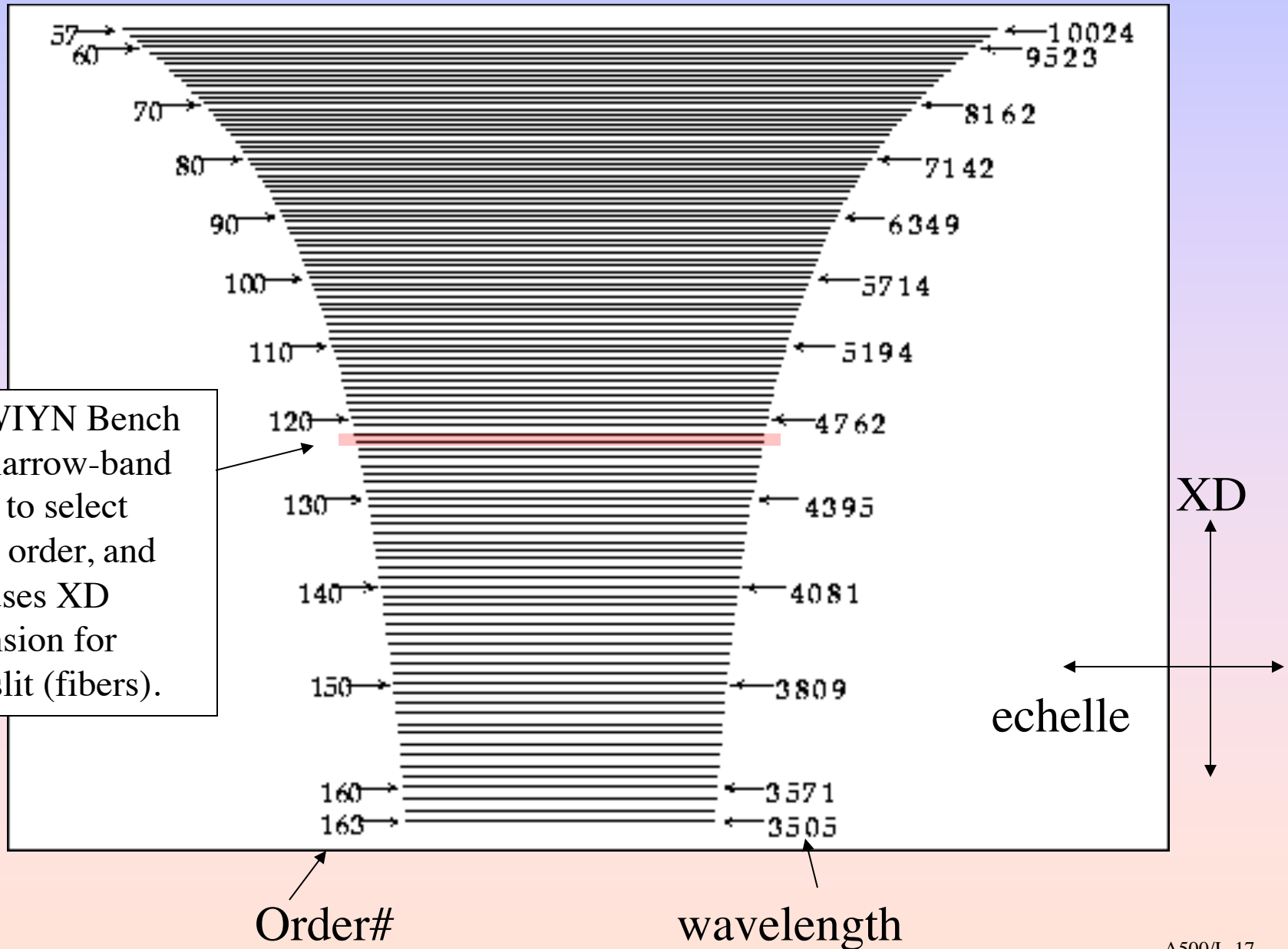


- Fine examples are the Lick Hamilton Spectrometer and Keck HIRES

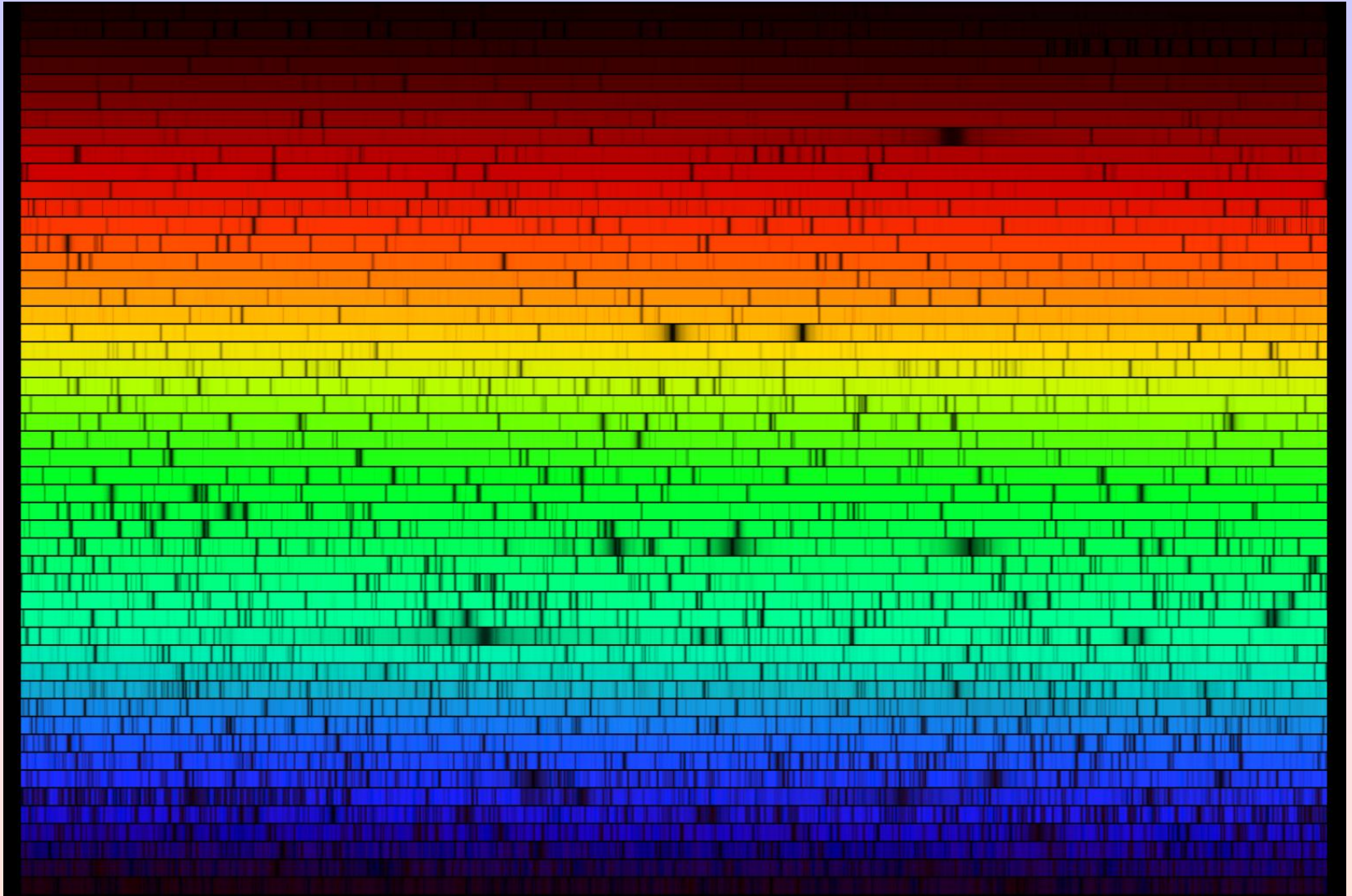
- The WIYN Bench Spectrograph also has an echelle mode but it is not cross-dispersed.

- 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



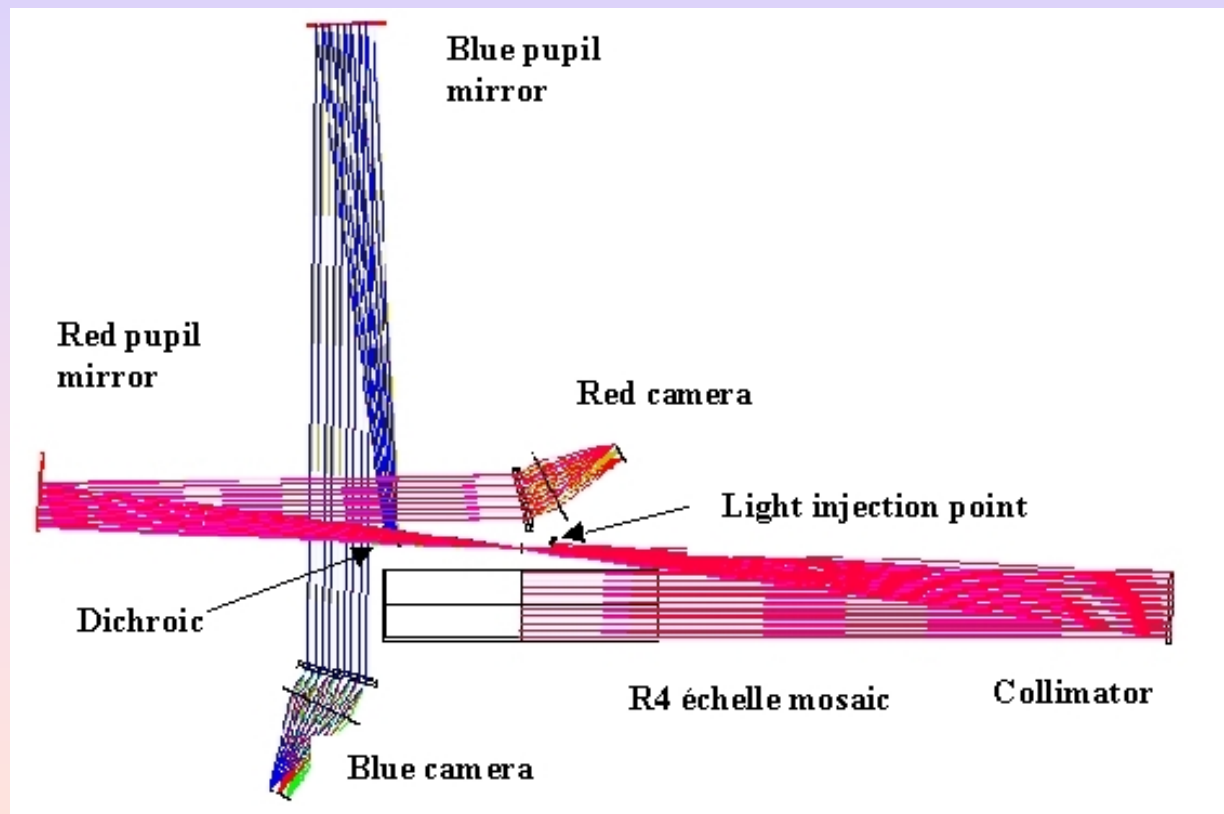
Solar Spectrum (echellogram)



SALT HRS: High-Resolution Spectrograph

PI: Ray Sharples, Durham UK

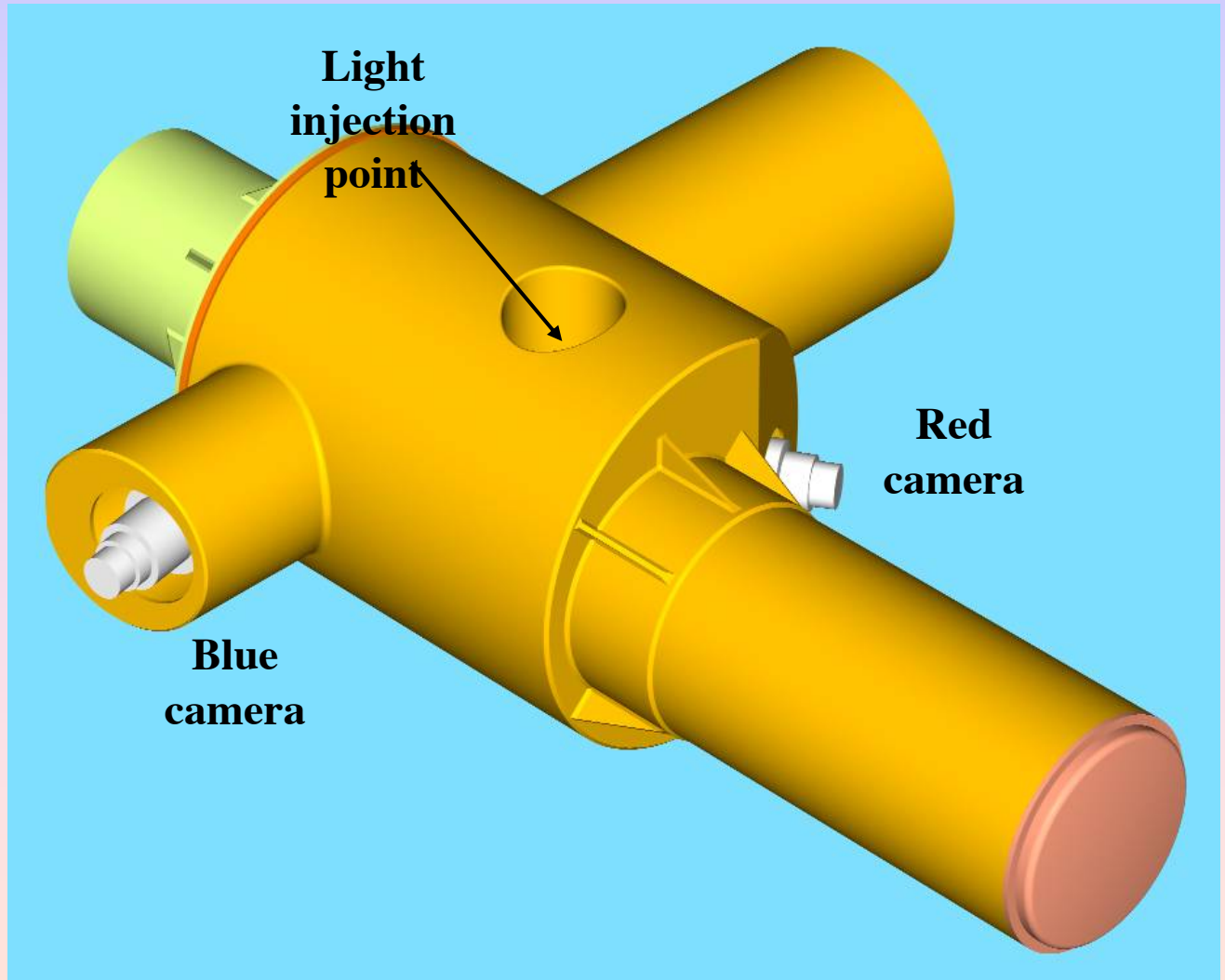
- Dual beam white-pupil R_4 duplex echelle, with VPH grating cross-dispersion.
- $R = 17,000$ to $70,000$
 - image slicers
- Simultaneous wavelength coverage from 370-950 nm.
- Single object spectroscopy with sky subtraction and nod/shuffle.
- Precision radial velocities (few m/s):
 - vacuum tank.



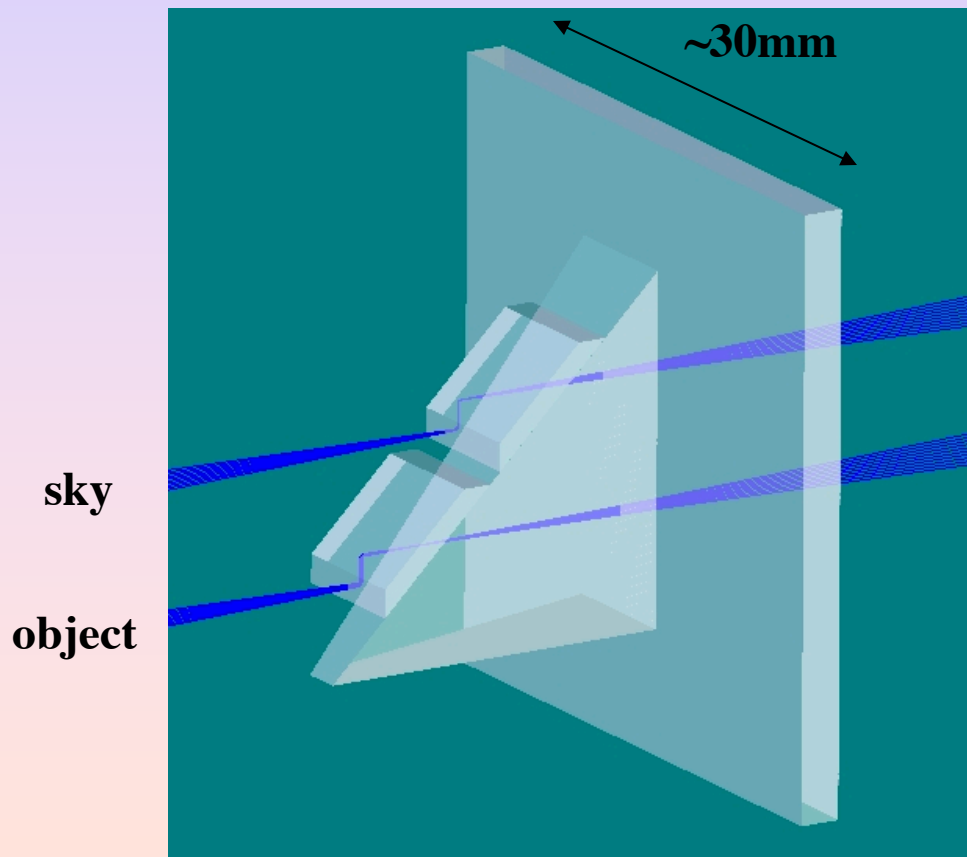
HRS Vacuum tank - for stability

Notes:

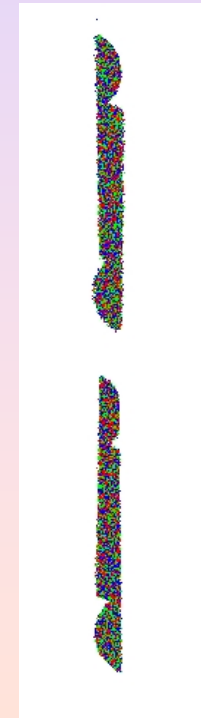
- 1. cameras are outside vacuum
- 2. Fiber selector inside cylinder at top



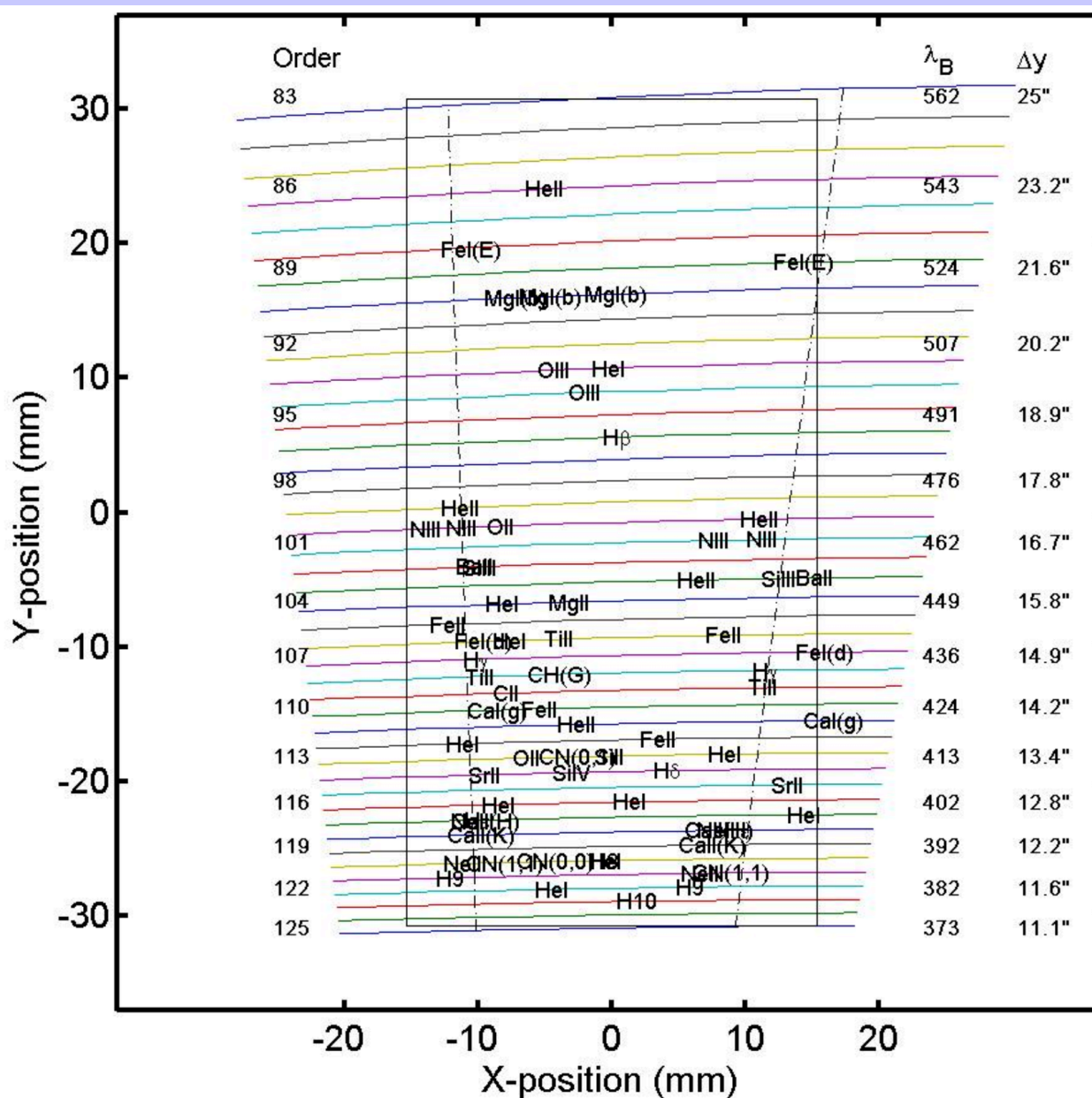
HRS: Bowen-Walraven-type image slicers



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

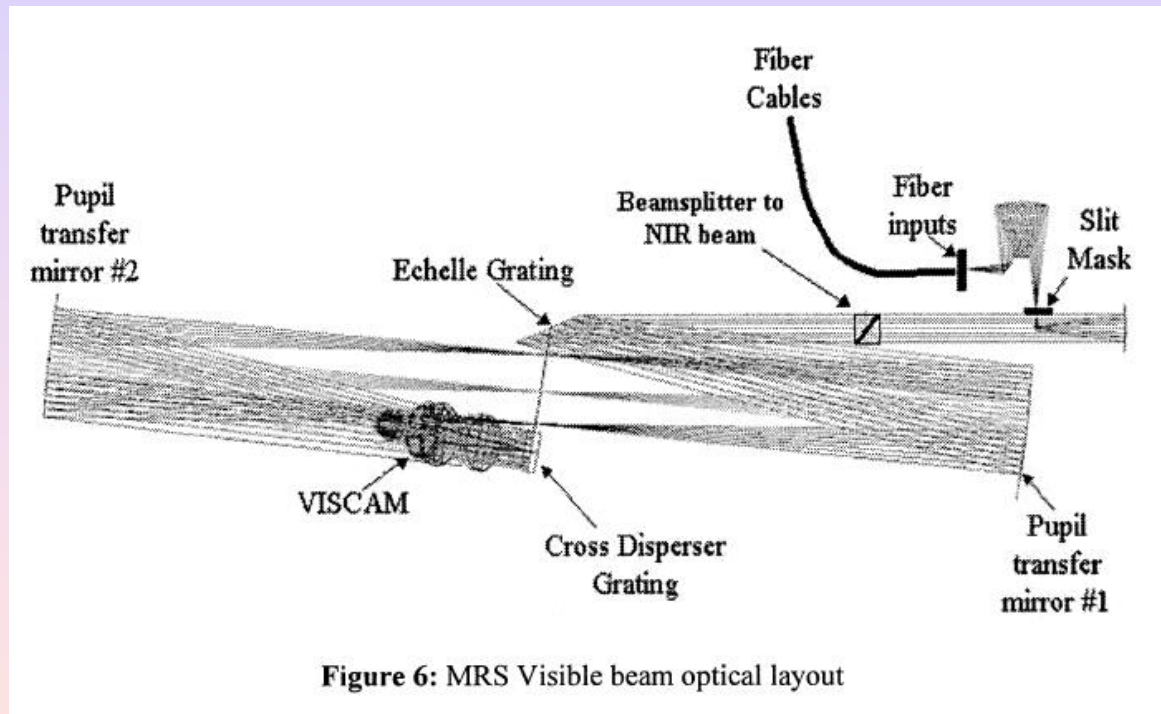


HRS: blue arm spectral format

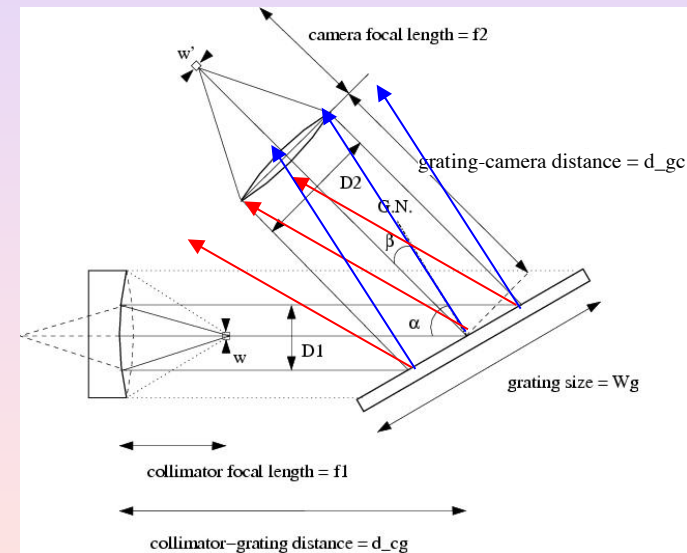


Grating-dispersed spectrographs dispersive elements

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



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



Ramsey '03