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
    - o 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

Finish this off: VPH gratings

Grating-dispersed spectrographs
basic spectrograph design

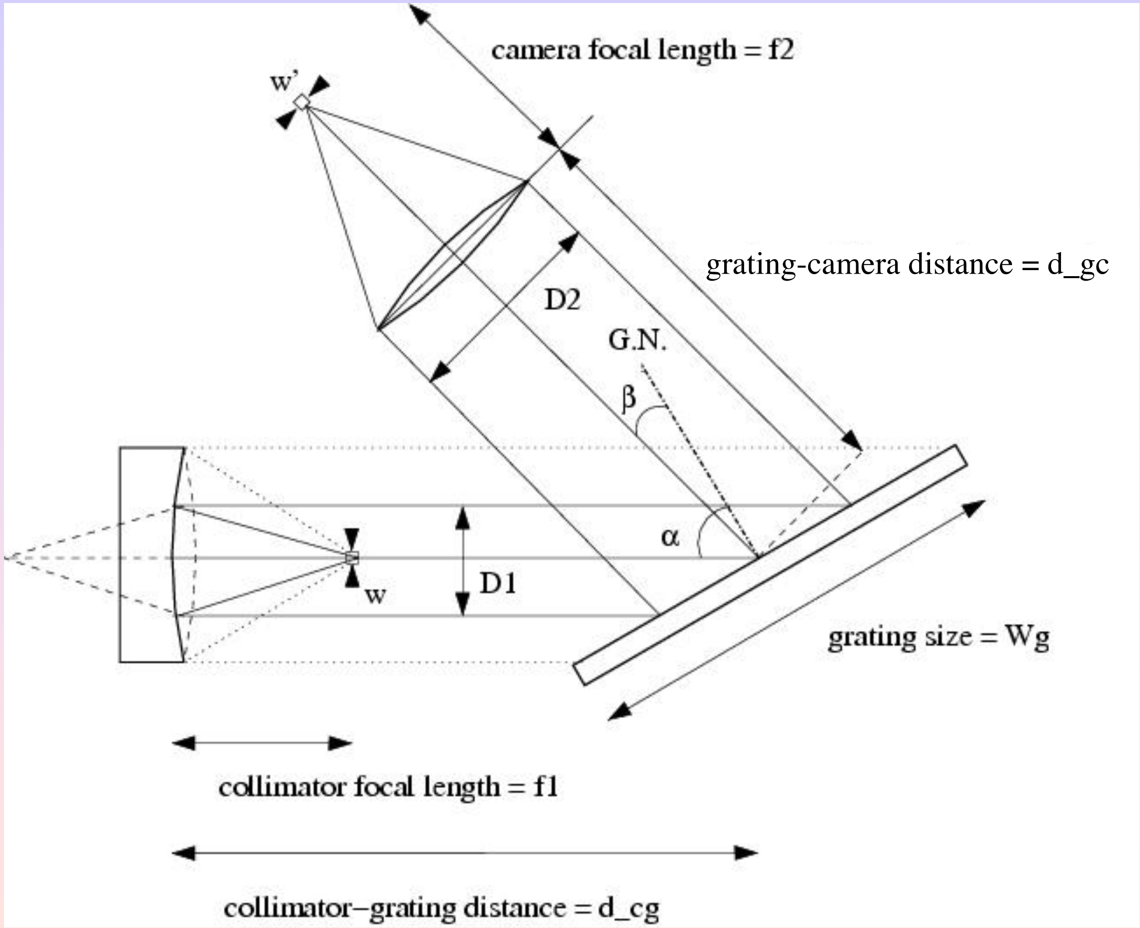
- **Grating equation**

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

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

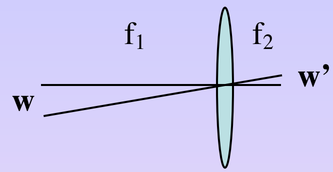
  $\gamma = d\beta/d\lambda = m / \sigma \cos\beta$
  $= (\sin\beta + \sin\alpha) / \lambda \cos\beta$
- **Linear dispersion**

  $dl/d\lambda = f_2\,\gamma$

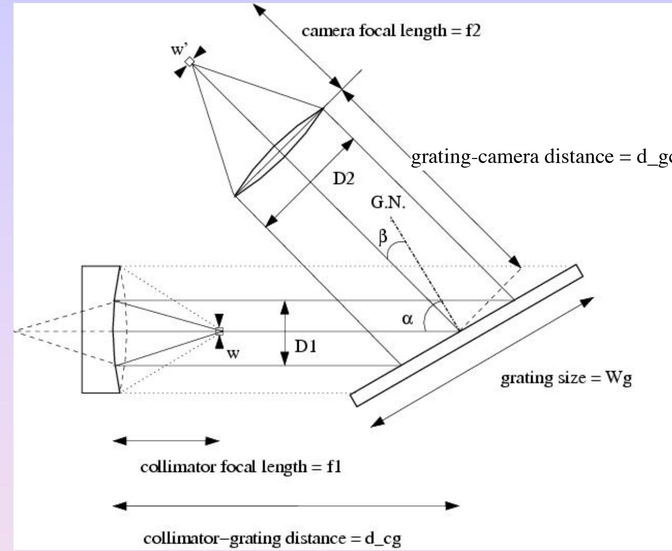


Grating-dispersed spectrographs

basic spectrograph design



Spatial magnification



Spectrograph magnification

- w = physical slit width
- w' = reimaged slit width
- w_θ' = reimaged spatial width = (f_2/f_1) w
- w_λ' = reimaged spectral width
  - $= \boldsymbol{r}\, (f_2/f_1)\, w = \boldsymbol{r}\; w_\theta'$
- $\boldsymbol{r} = |d\beta/d\alpha| = \cos\alpha / \cos\beta = D_1 / D_2$
- ***r*** is the **anamorphic factor**: for a give dα (angular slit width) what is dβ such that dλ = 0? (differentiate grating equation and set to 0)

- "AΩ" is conserved
  - bigger beam : smaller angle
  - β/α > 1 magnification; β/α < 1 demagnification
- ***demagnification*** gives more resolution elements per mm (good!)
- requires large camera optics to avoid vignetting beam
- ***r*** = 1 for littrow configurations: α = β = δ, δ is blaze angle

Grating-dispersed spectrographs
basic spectrograph design

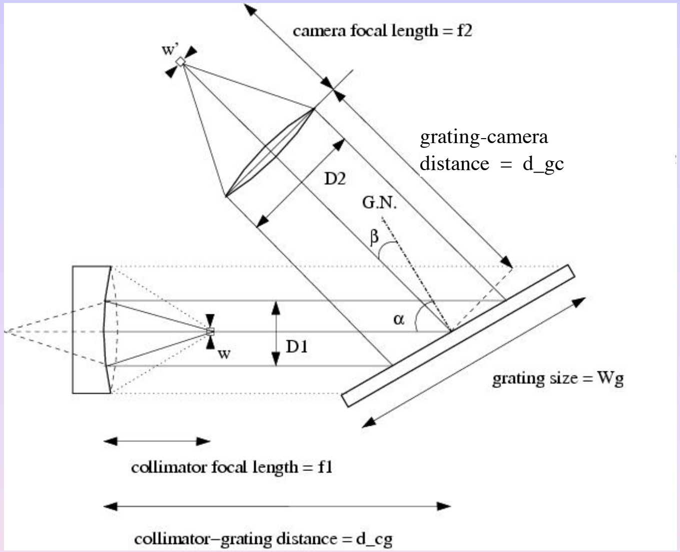
Spectral resolution

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

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:

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

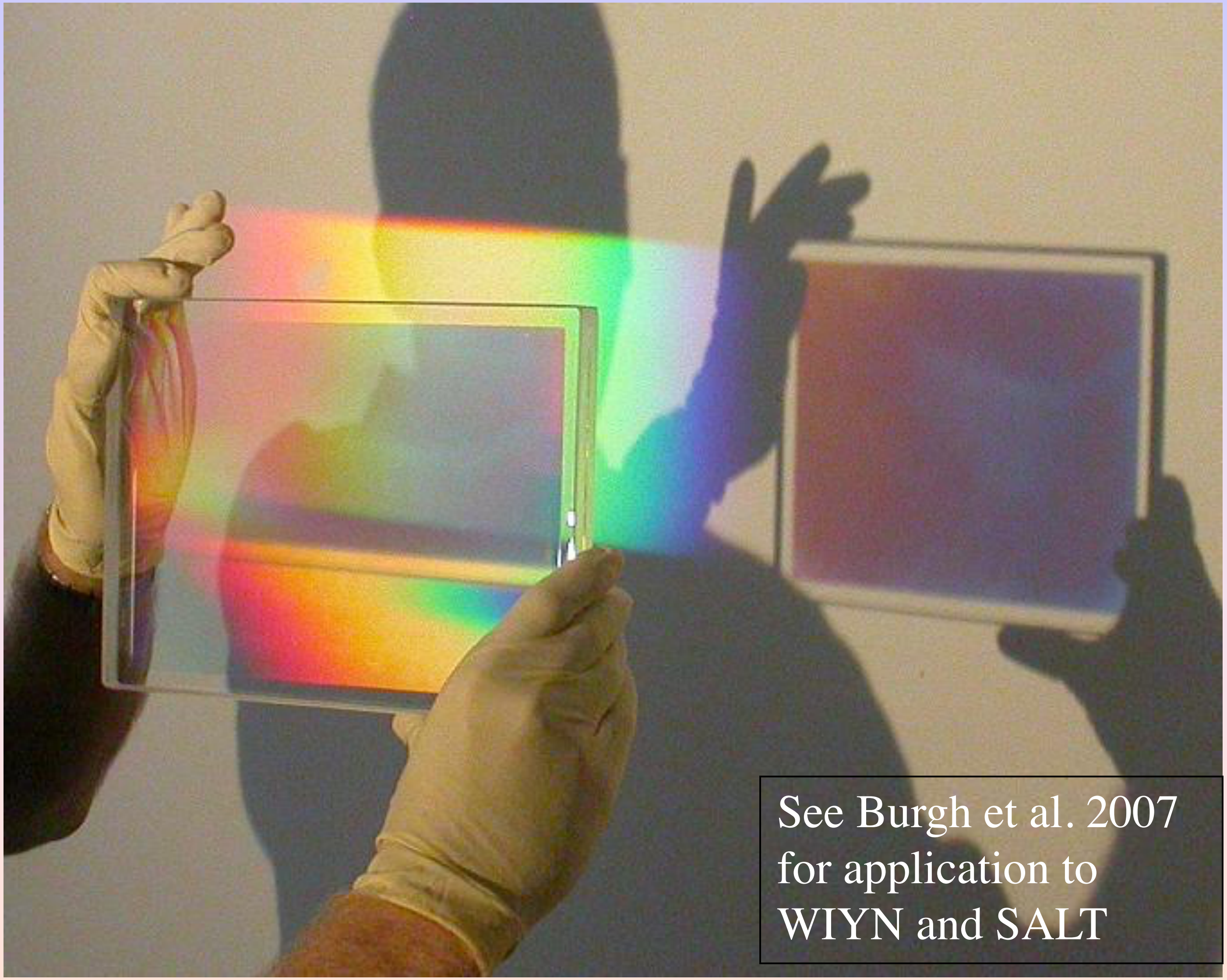
θ = angle of slit on sky
$d\lambda = w_\lambda' / (dl/d\lambda)$
$w = f_T\,\theta$
$f_1/d_1 = f / D_T$

which becomes in Littrow:

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

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

Volume Phase Holographic gratings



See Burgh et al. 2007 for application to WIYN and SALT

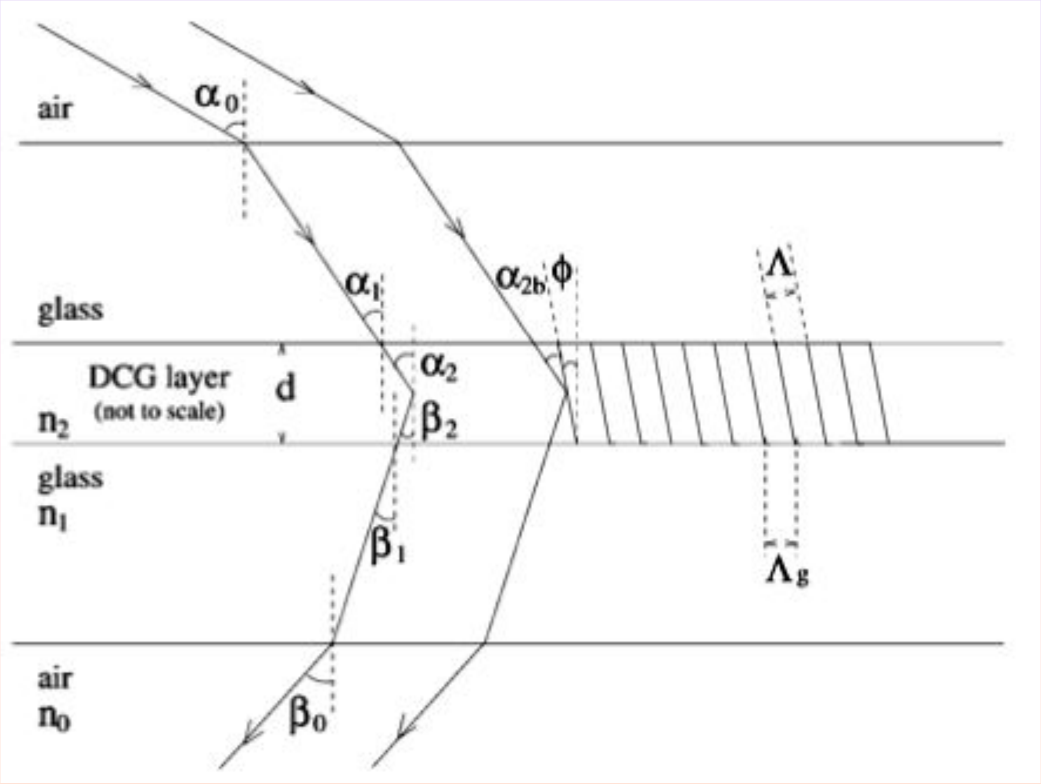
Volume Phase Holographic gratings

- Bragg condition for un-tilted fringes

$$m\lambda / n_i = 2\ \Lambda_g \sin \alpha_i$$

- Generalized Bragg condition for tilted fringes

$$m\lambda / n_2 = 2\ \Lambda \sin \alpha_{2b}$$

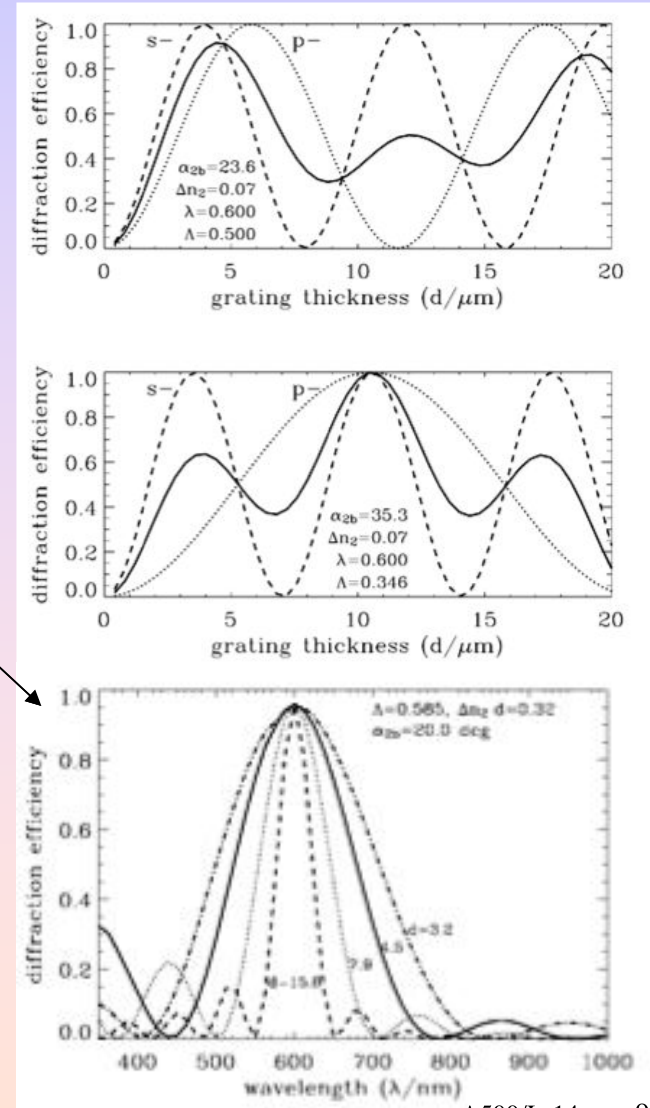


Baldry et al. ‘04

Volume Phase Holographic gratings

Baldry et al. '04

- **Tuning TE and TM polarizations**
  - Possible to visualize in Kogelnik limit:*
    - o Tune $\Delta n_2 \, d \,/\, n_2 \, \Lambda$
  - $n_2 \, \Lambda$ sets relationship between λ and α_{2b}
  - Δn_2 and d adjusted for band-width
    - o Thinner d yields larger band-width but required larger Δn_2 which is difficult in practice



*Kogelnik limit

$$\rho = \frac{\lambda^2}{\Lambda^2 n_2 \Delta n_2} > \rho_{\rm limit},$$

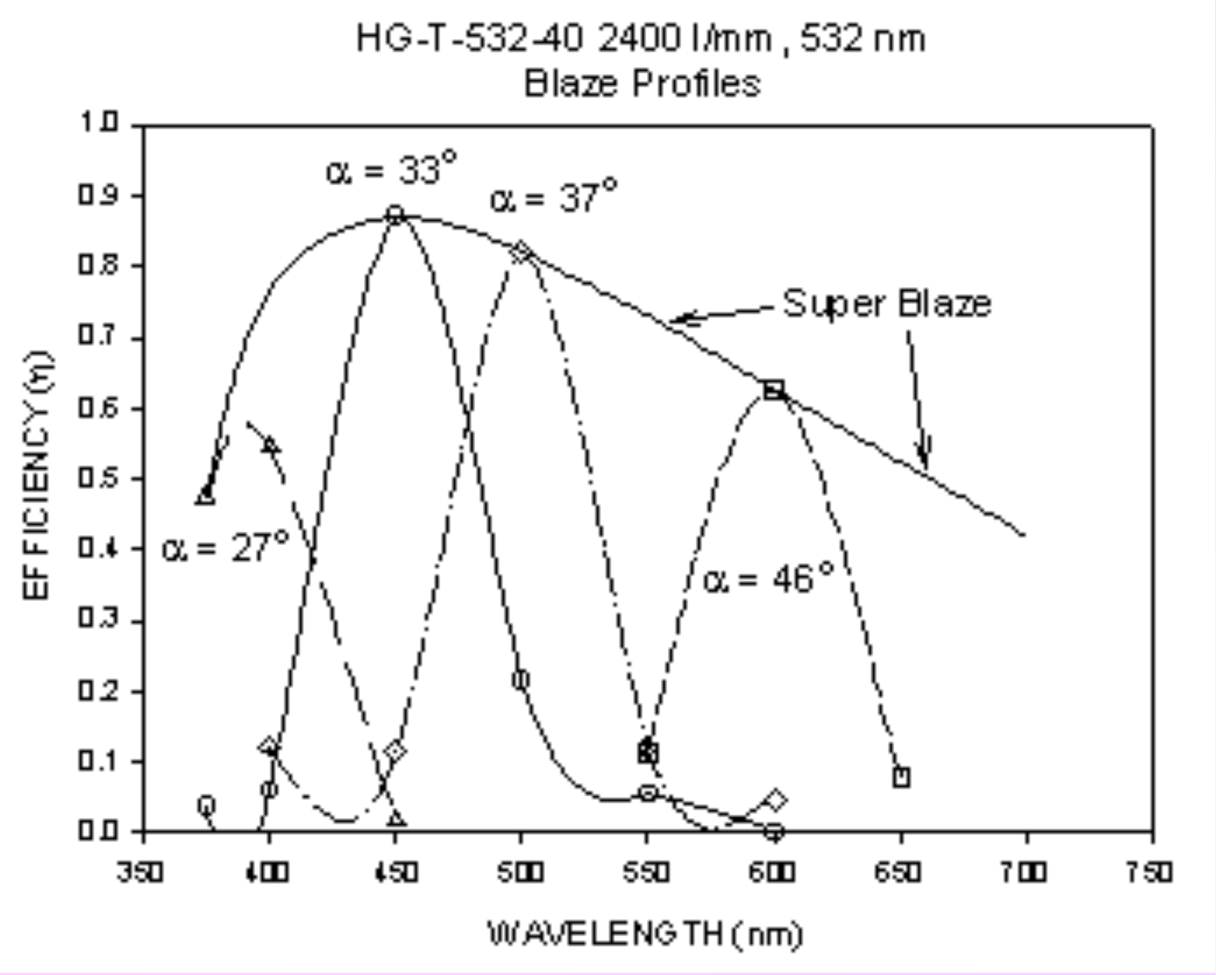
$\rho_{limit} \sim 10$: $\lambda > \Lambda$

$$\eta = \frac{1}{2}\sin^2\left(\frac{\pi \Delta n_2 d}{\lambda \cos \alpha_{2b}}\right) + \frac{1}{2}\sin^2\left[\frac{\pi \Delta n_2 d}{\lambda \cos \alpha_{2b}} \cos(2\alpha_{2b})\right],$$

TE TM

Tuneability of VPH gratings

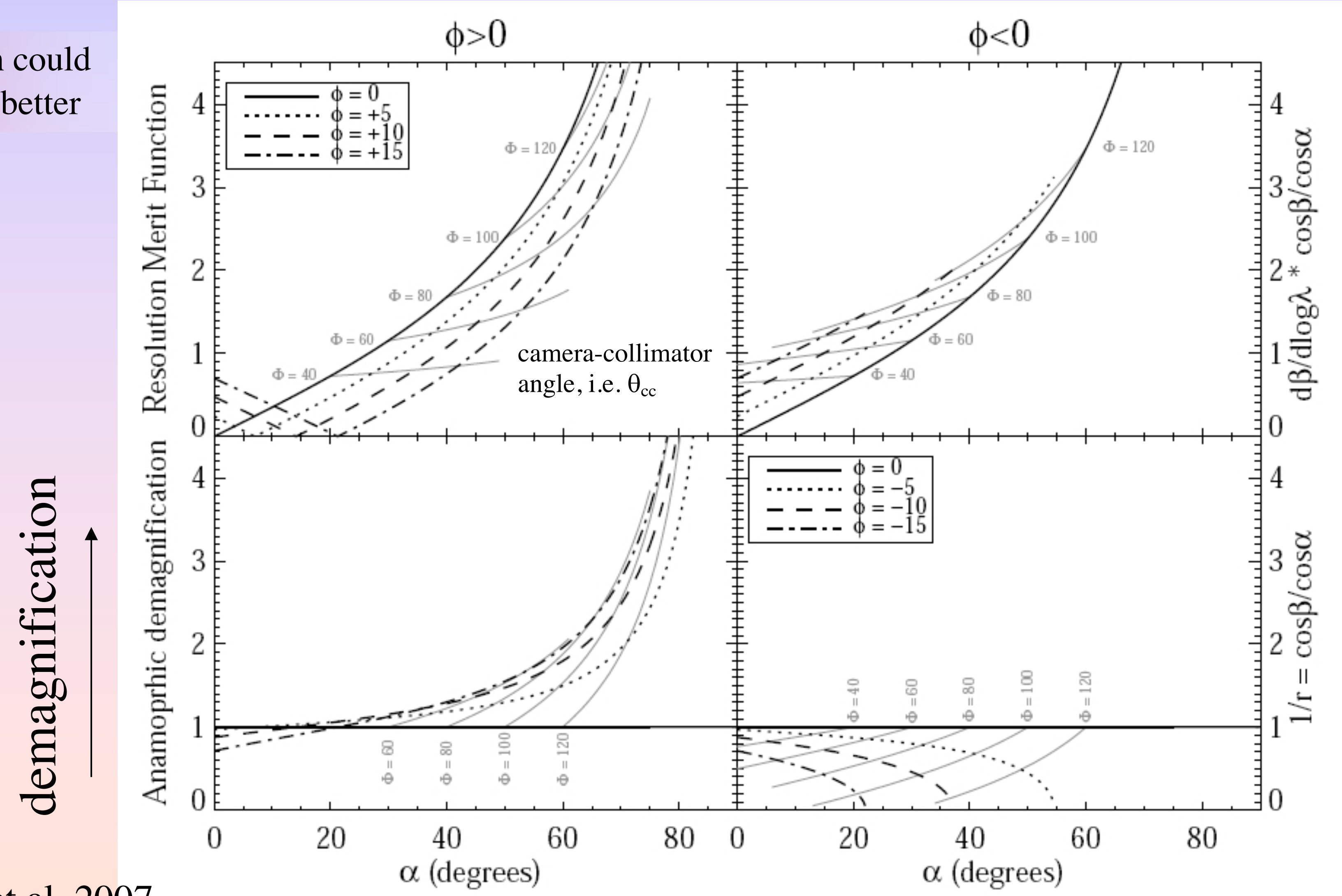
The good news….



Anamorphic factors with VPH gratings

postive fringe tilts negative fringe tilts

…which could be even better



Burgh et al. 2007

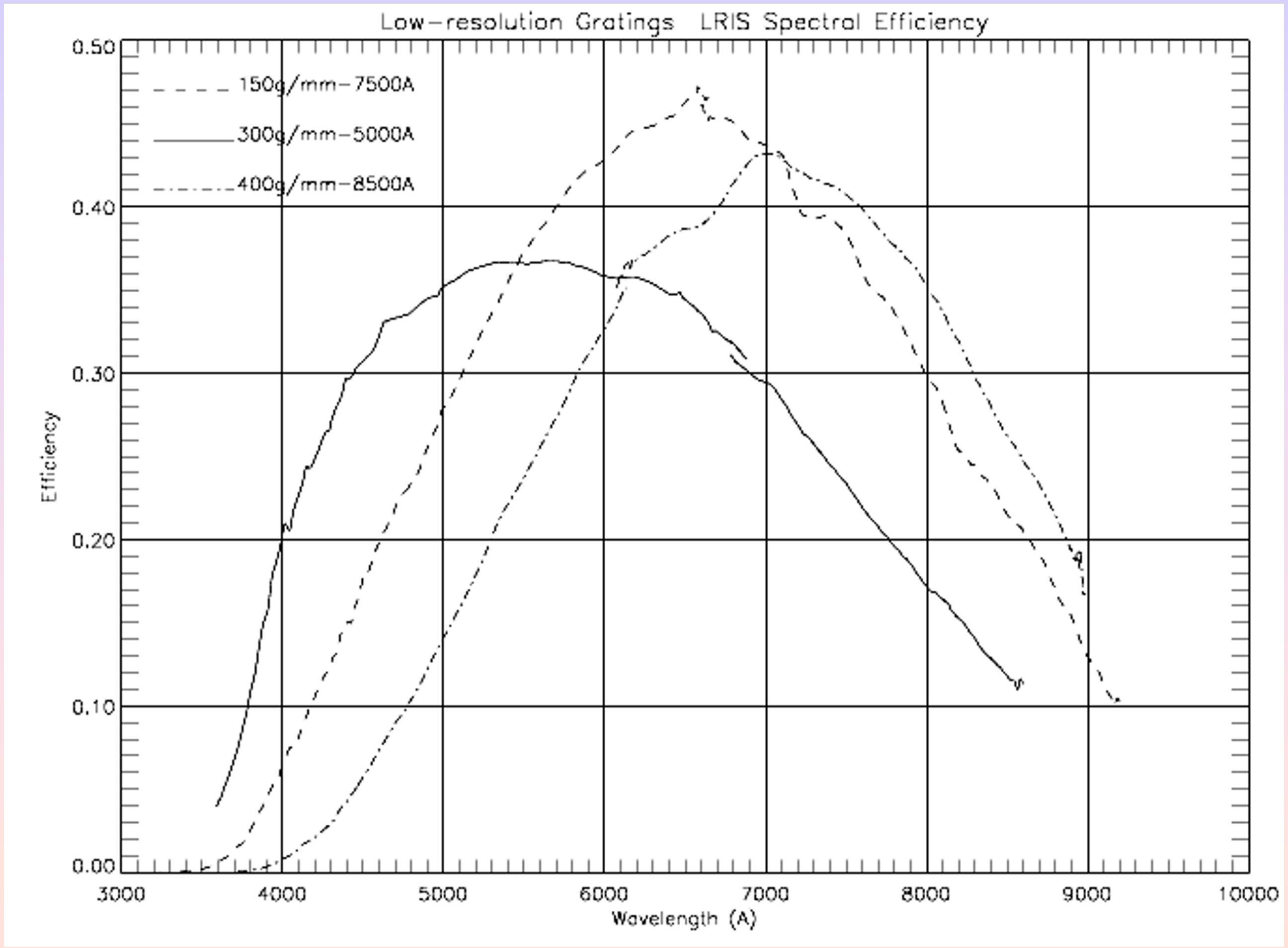
Anamorphic factors with VPH gratings

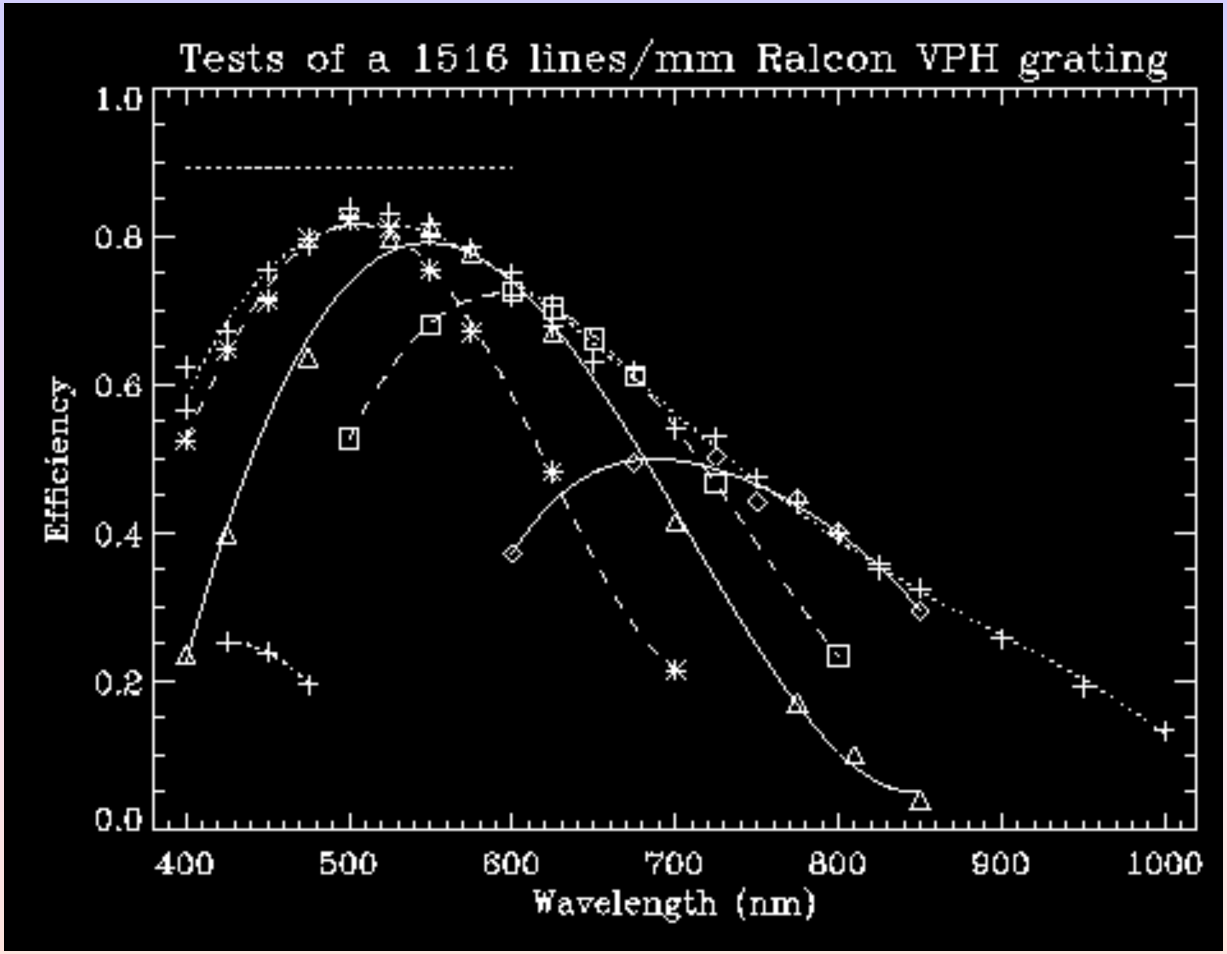
• Negative fringe tilts give increased resolution by virtue of increased dispersion (anamorphic factor is decreased).

• Positive tilts give increased anamorphic factor but decreased resolution.

Burgh et al. 2007

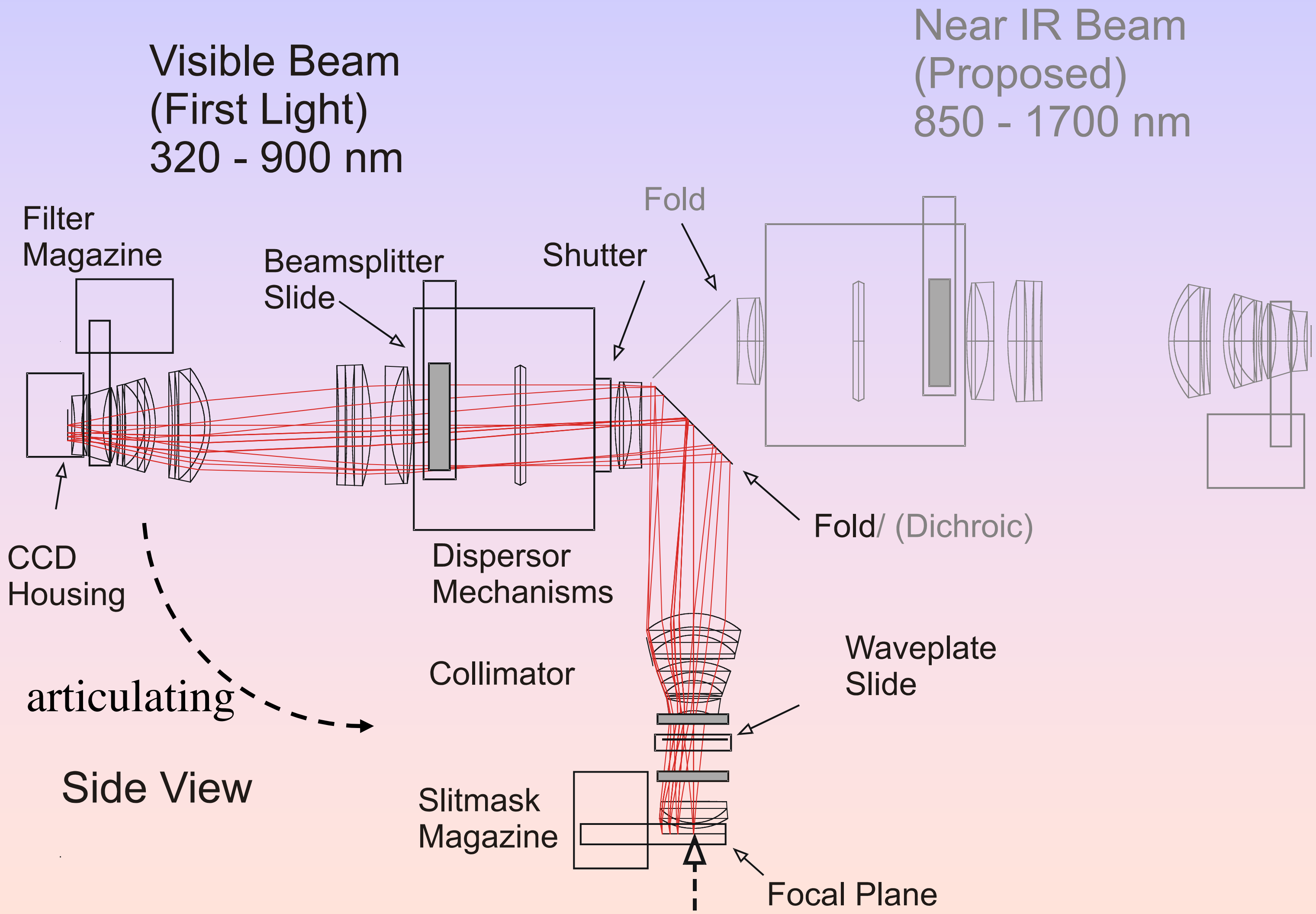
Grating Efficiencies



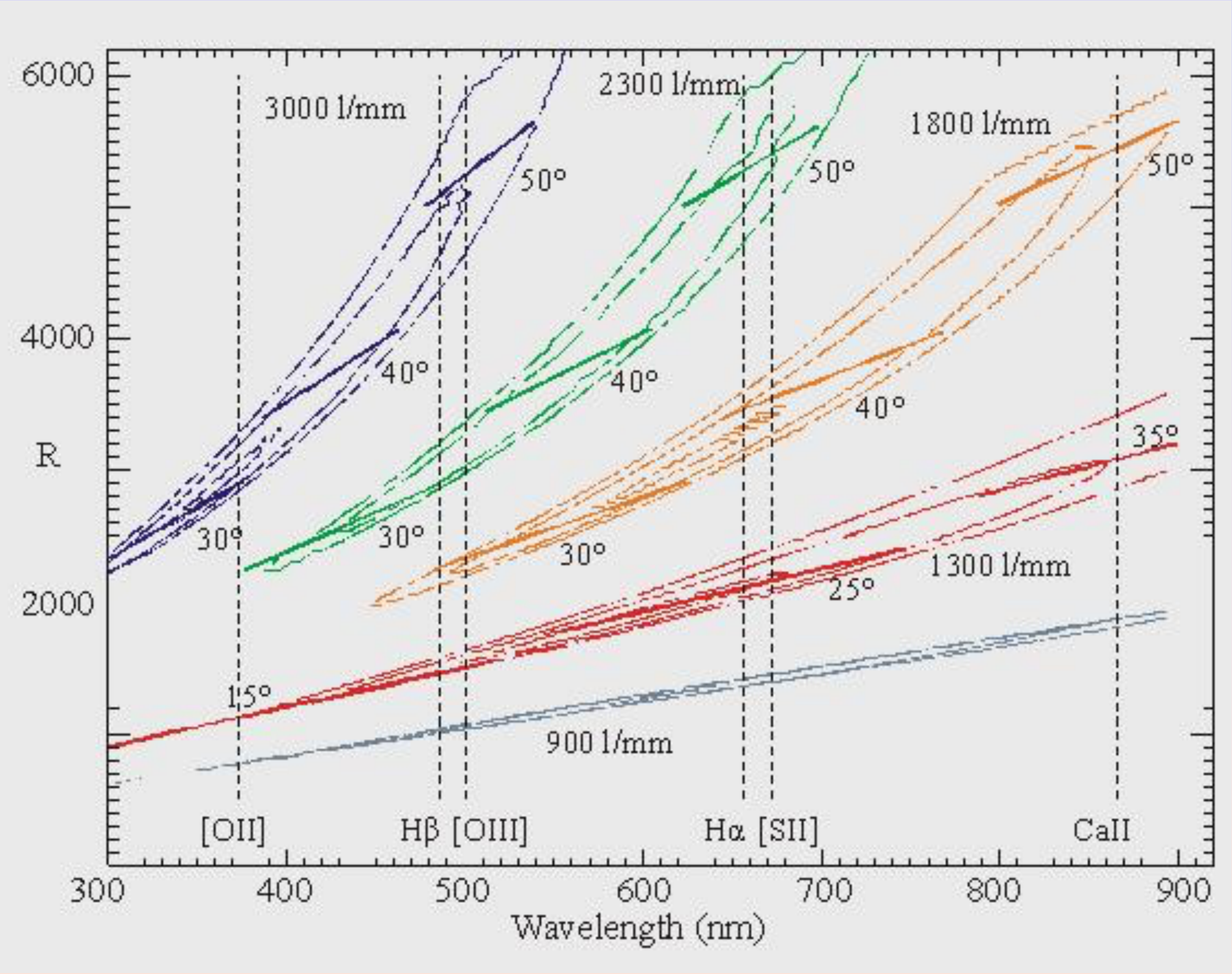

Tests of a 1516 lines/mm Ralcon VPH grating
Efficiency
0.0
0.2
0.4
0.6
0.8
1.0
400
500
600
700
800
900
1000
Wavelength (nm)

An example of a VPH spectrograph:

Southern African Large Telescope (SALT) Robert Stobie Spectrograph (RSS) layout:

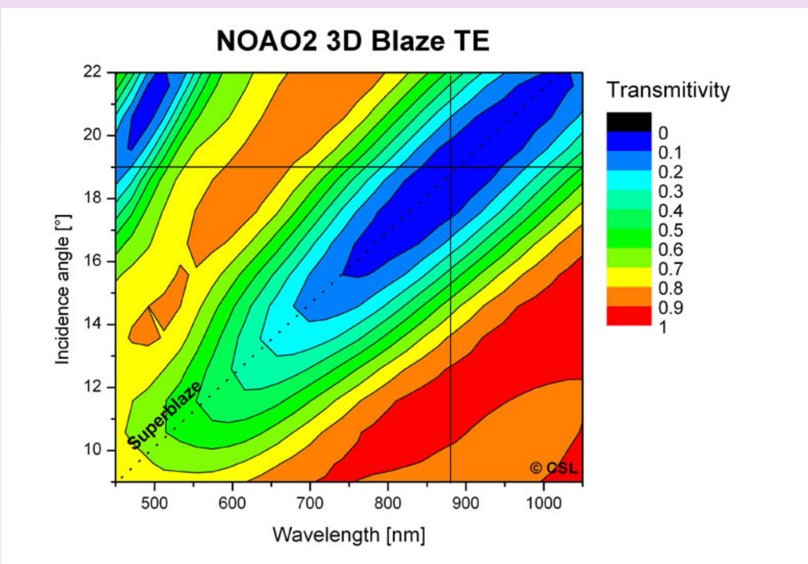


RSS complement of VPH gratings

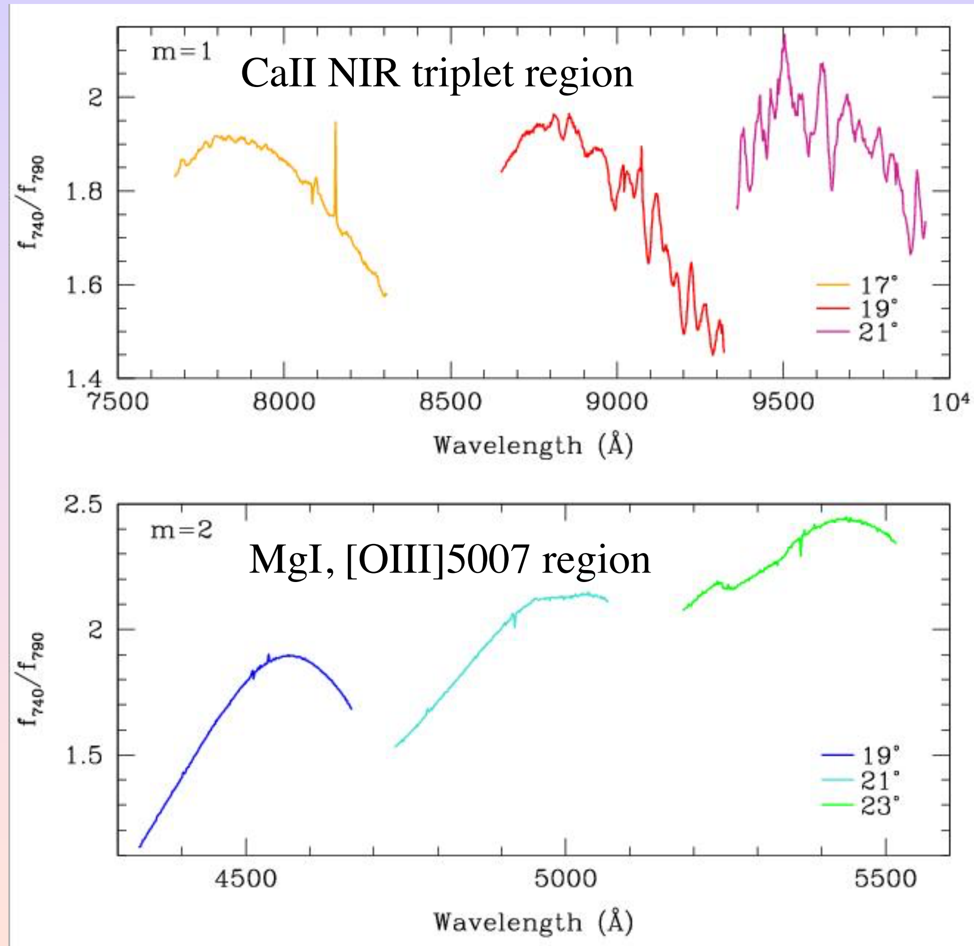


An example of a VPH spectrograph:
WIYN 3.5m upgraded Bench Spectrograph

- 740 l/mm: delivered and in use
- R ~ 2500
- 2x the diffraction efficiency of a comparable SR grating measured "head-to-head."



Measured transmisivity



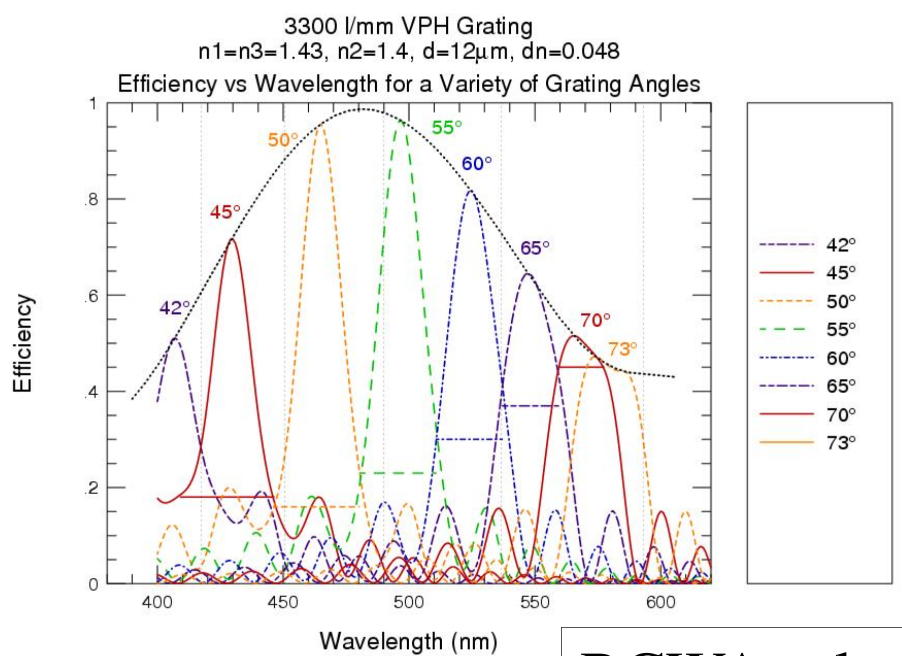
An example of a VPH spectrograph:
WIYN 3.5m upgraded Bench Spectrograph

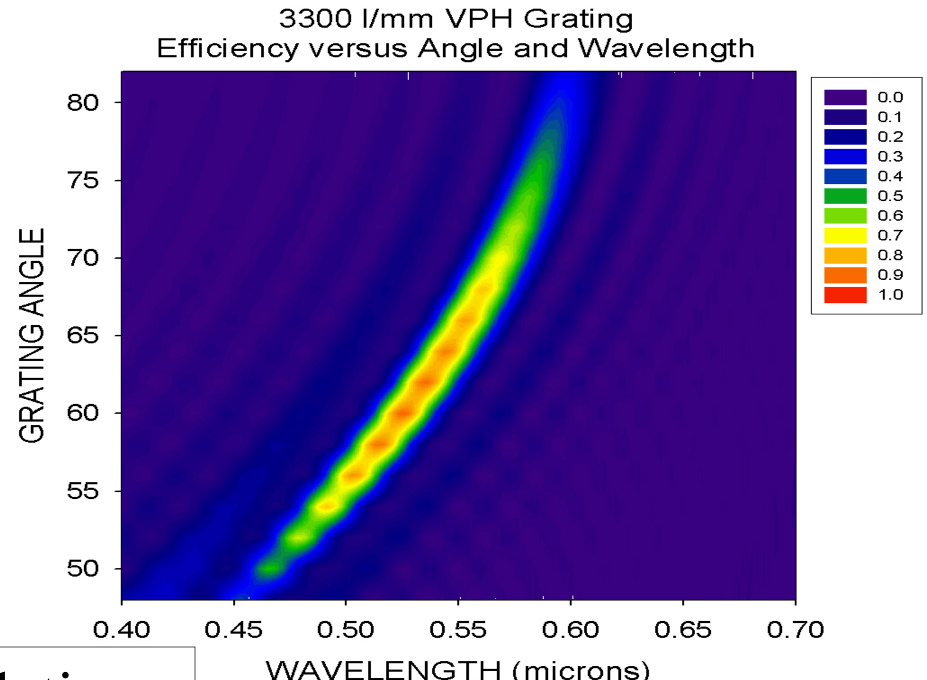
Challenging angles!
Coatings an issue

- 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
55^0	6	2.5	2	< 1
60^0		3.5	2.5	
65^0	11	5.5	4.5	< 2
70^0		9.5	7.5	
75^0	24	17	15.5	< 7

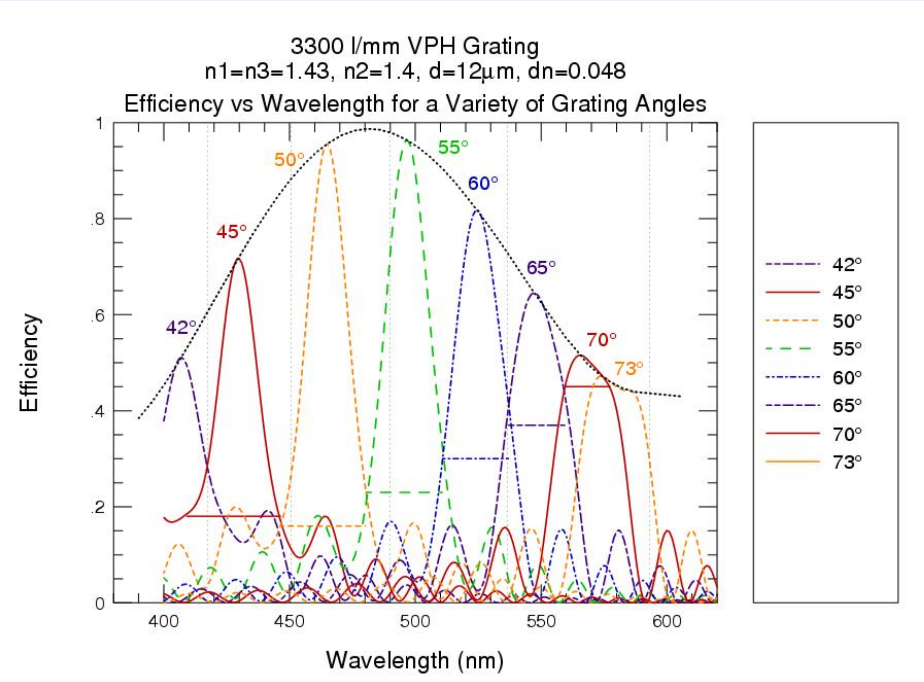


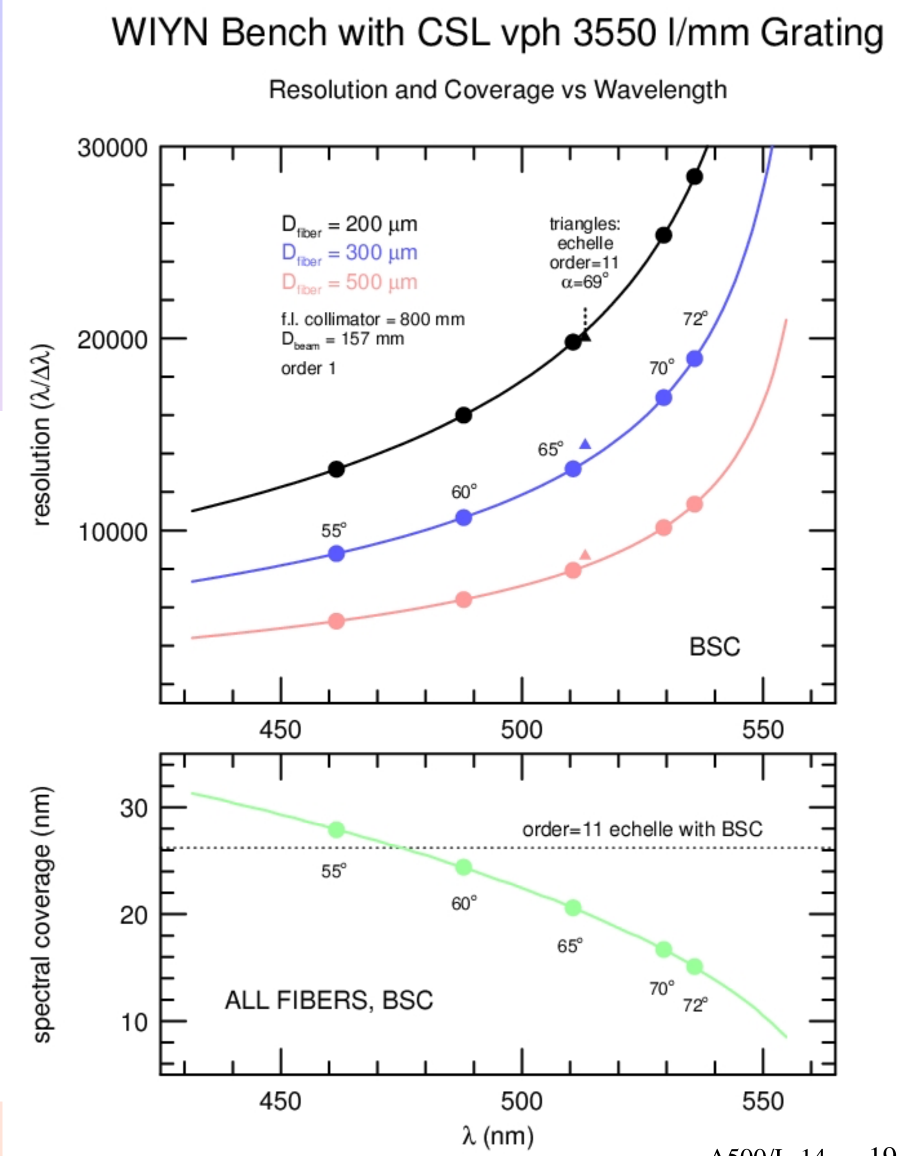


RCWA calculations

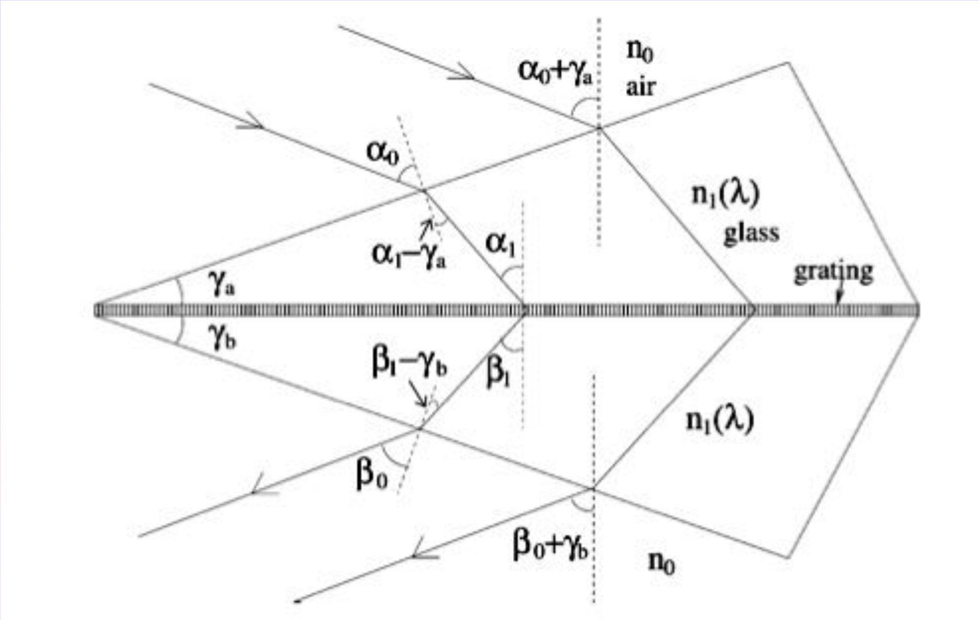
An example of a VPH spectrograph:
WIYN 3.5m upgraded Bench Spectrograph

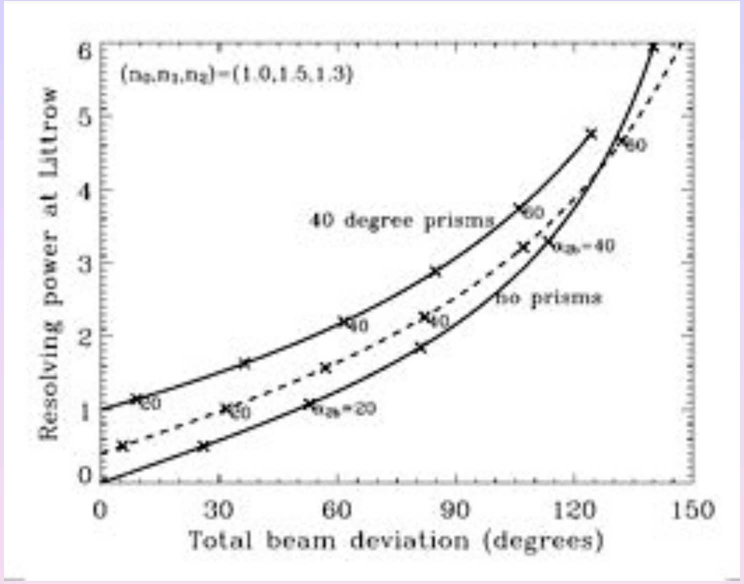
- 3300 l/mm: *in use*
- 0.5m in size*!*
- R ~ 7000-20,000
- expect 2x diffraction efficiency of existing echelle.





Volume Phase Holographic gratings
other possibilties: grisms

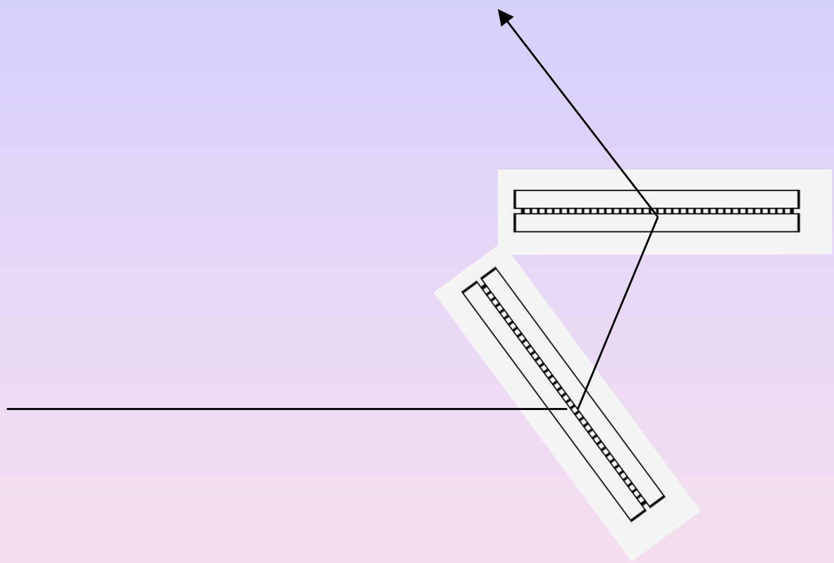




Baldry et al. '04

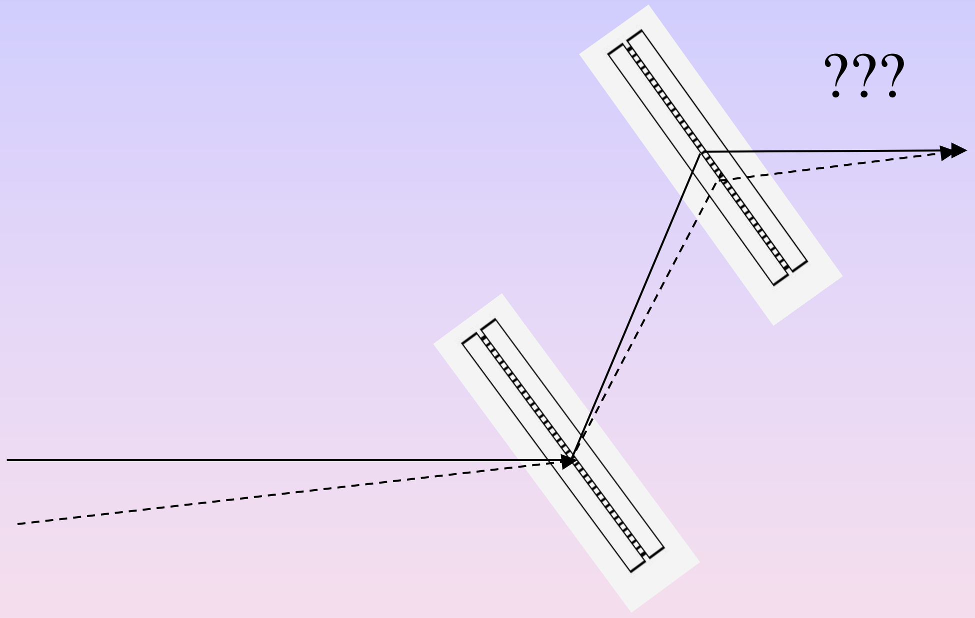
- Prismatic wedge boosts Littrow resolving power for given total beam deviation (as with SR gratings; e.g., Wynne '91)
  See Hill et al. '04 for example of NIR VPH grism.

Volume Phase Holographic gratings
other possibilities: double modes



- Because diffraction efficiencies are high, double-grating configurations are reasonable to consider
  - We are implementing this on the WIYN Bench spectrograph
- Dispersion is roughly the sum of the two individual grating dispersions.

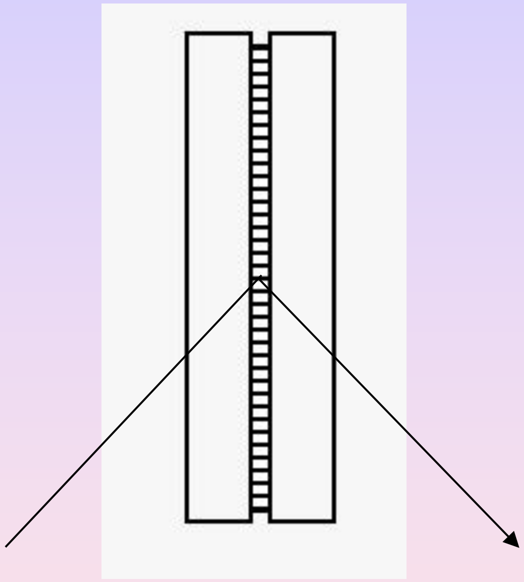
Volume Phase Holographic gratings
other possibilities: double modes

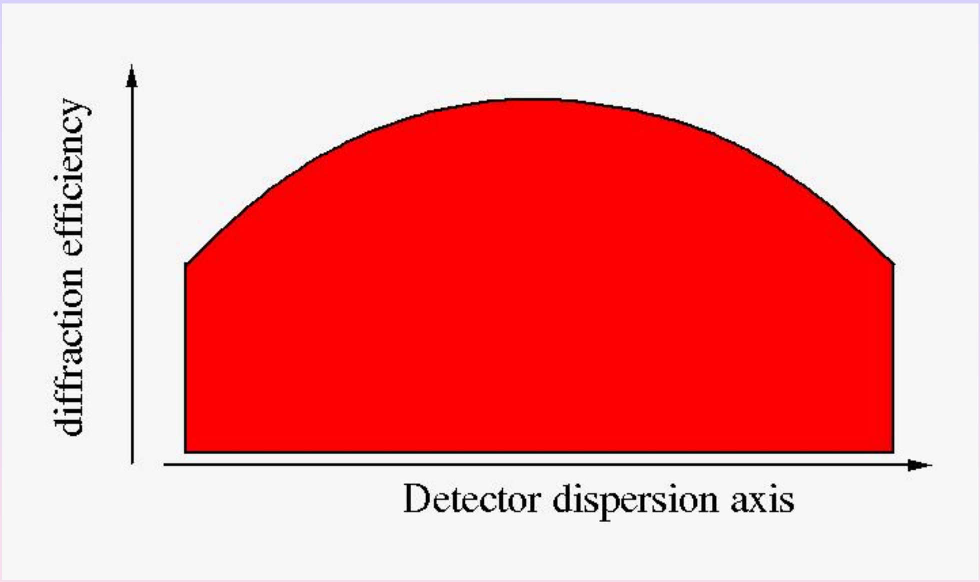


- Narrow-band filter
- What happens off-axis (in the dispersion dimension)?

  ➢ Narrow-band filter with field-dependent band-pass given by Bragg condition.

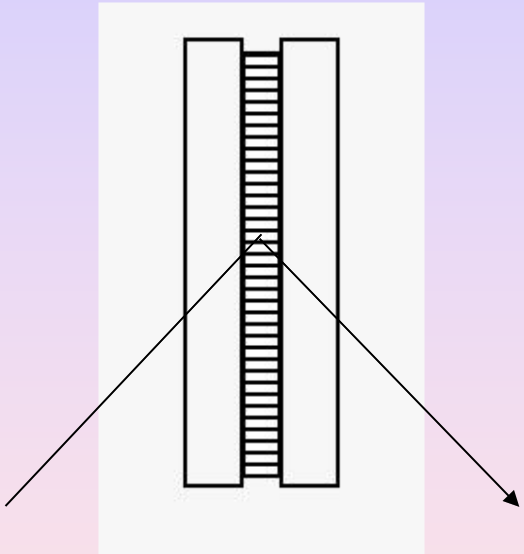
Volume Phase Holographic gratings
other possibilities: notch modes

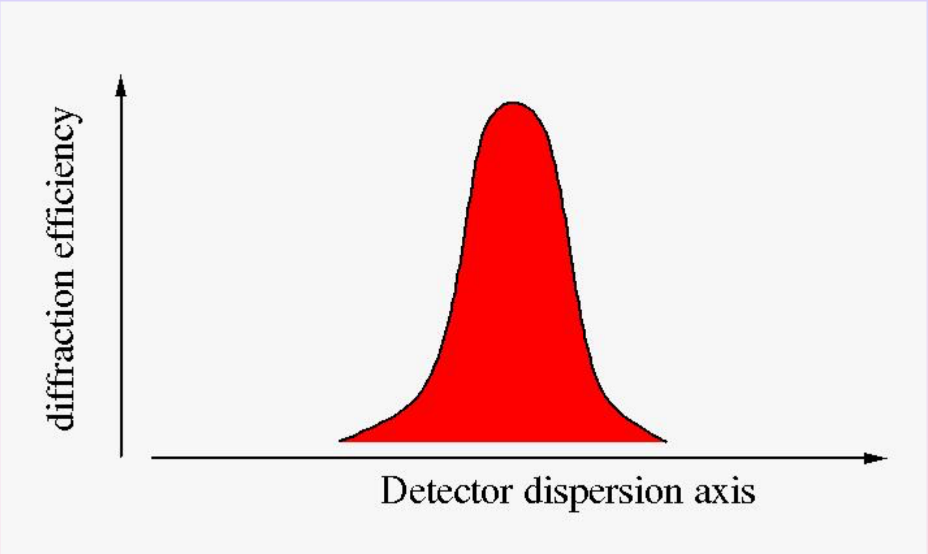




- Start with a thin, single gelatin layer for large band-pass at high angle and dispersion.
- Unslanted fringes center band-pass on detector in Littrow configuration.

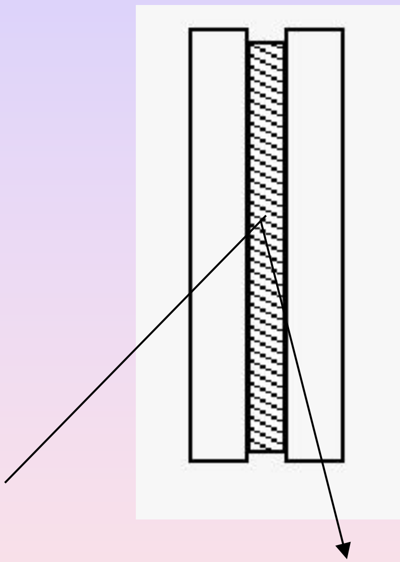
Volume Phase Holographic gratings
other possibilities: notch modes

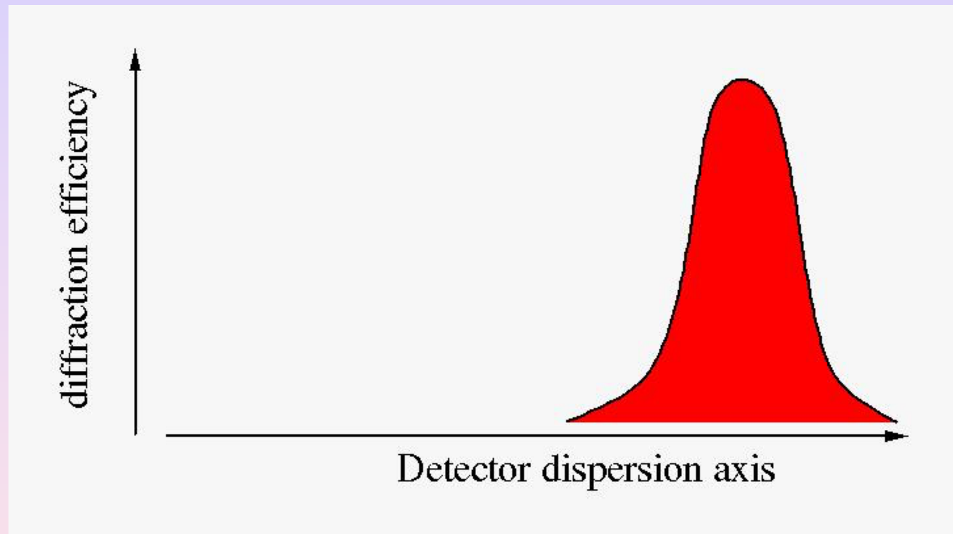




- Broaden the gelatin layer to optimize for a smaller band-pass.
- Band-pass is still centered on detector in Littrow configuration.

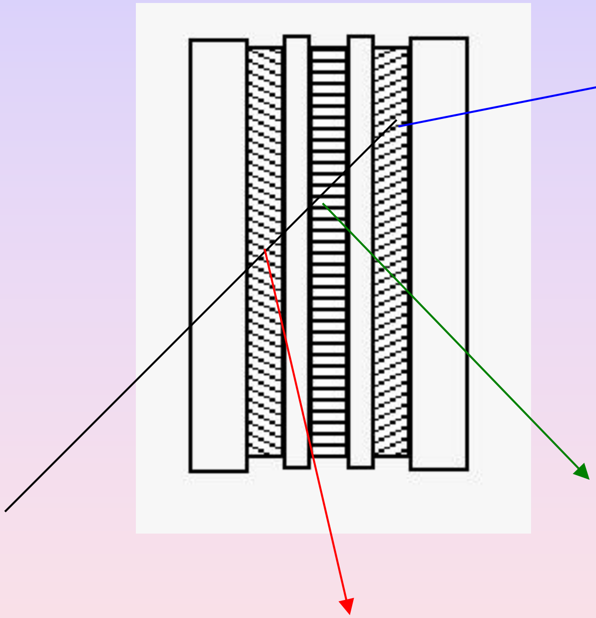
Volume Phase Holographic gratings
other possibilities: notch modes

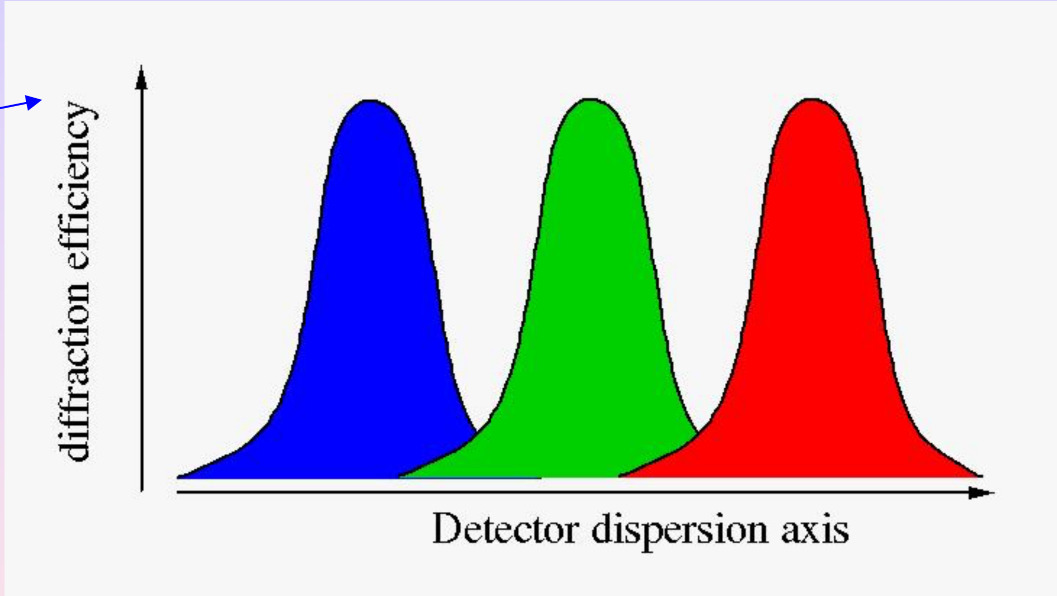




- Tilt fringes in same thick gelatin layer.
- Band-pass not shited to one edge of detector in Littrow configuration.

Volume Phase Holographic gratings
other possibilities: notch modes





- Now add multi-layers of gelatin, each with their own fringe tilt and line density (for different wavelength regions, e.g.,
  [OII]3727, Hβ+[OIII]5007, Hα
- Notch grating!