Astro 500

Techniques of Modern Observational Astrophysics

Matthew Bershady
University 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
  - II: Fabry-Perot interferometry
  - III: Spatial heterodyne spectroscopy

Approaches

Examples of available instruments

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

Grating-dispersed spectrographs

basic spectrograph design

- **Grating equation**

* $m \lambda = \sigma (\sin \beta \pm \sin \alpha)$
(reflection or transmission)

σ is groove separation (nm)

§ m is grating order (integer)

- **Angular dispersion**

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

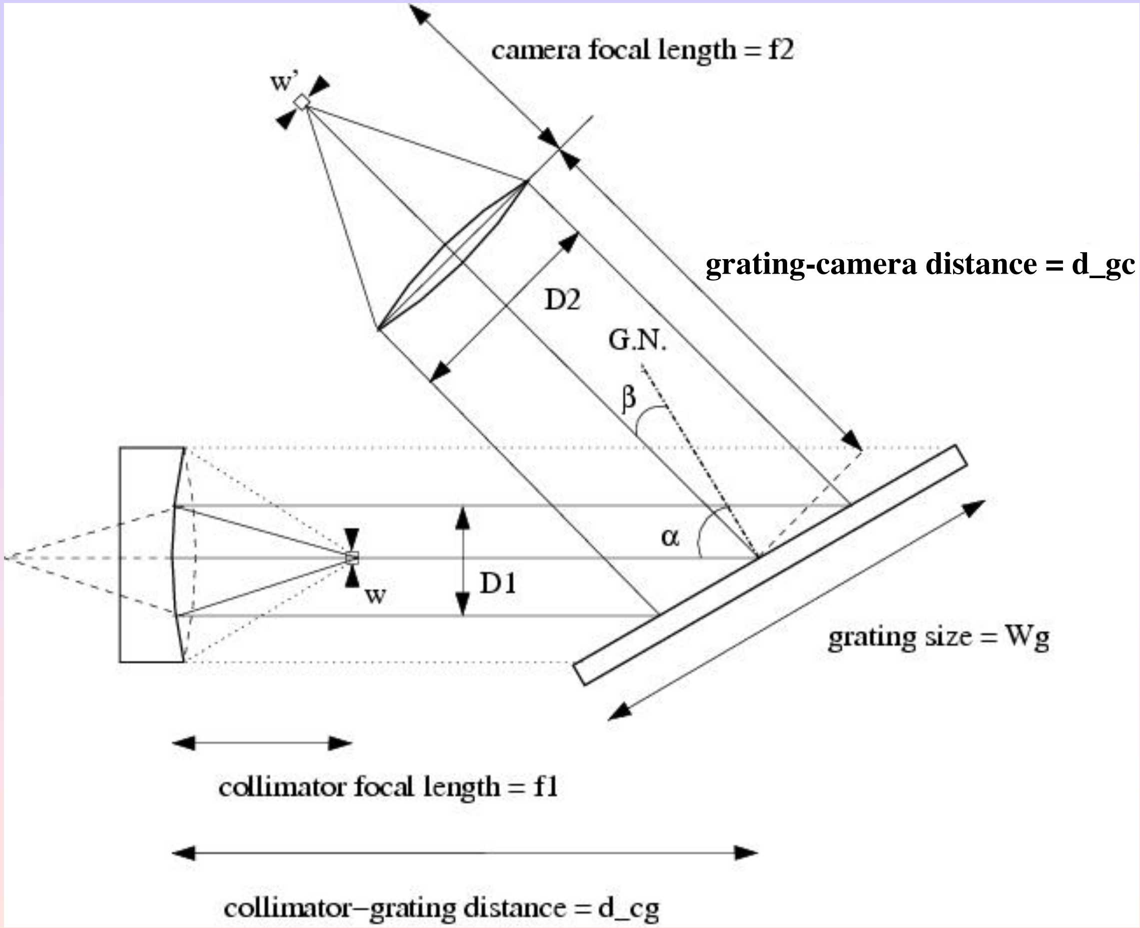
$= (\sin \beta \pm \sin \alpha) / \lambda \cos \beta$

- **Linear dispersion**

$dl/d\lambda = f_2 \gamma$

§ $-\infty < m < \infty$

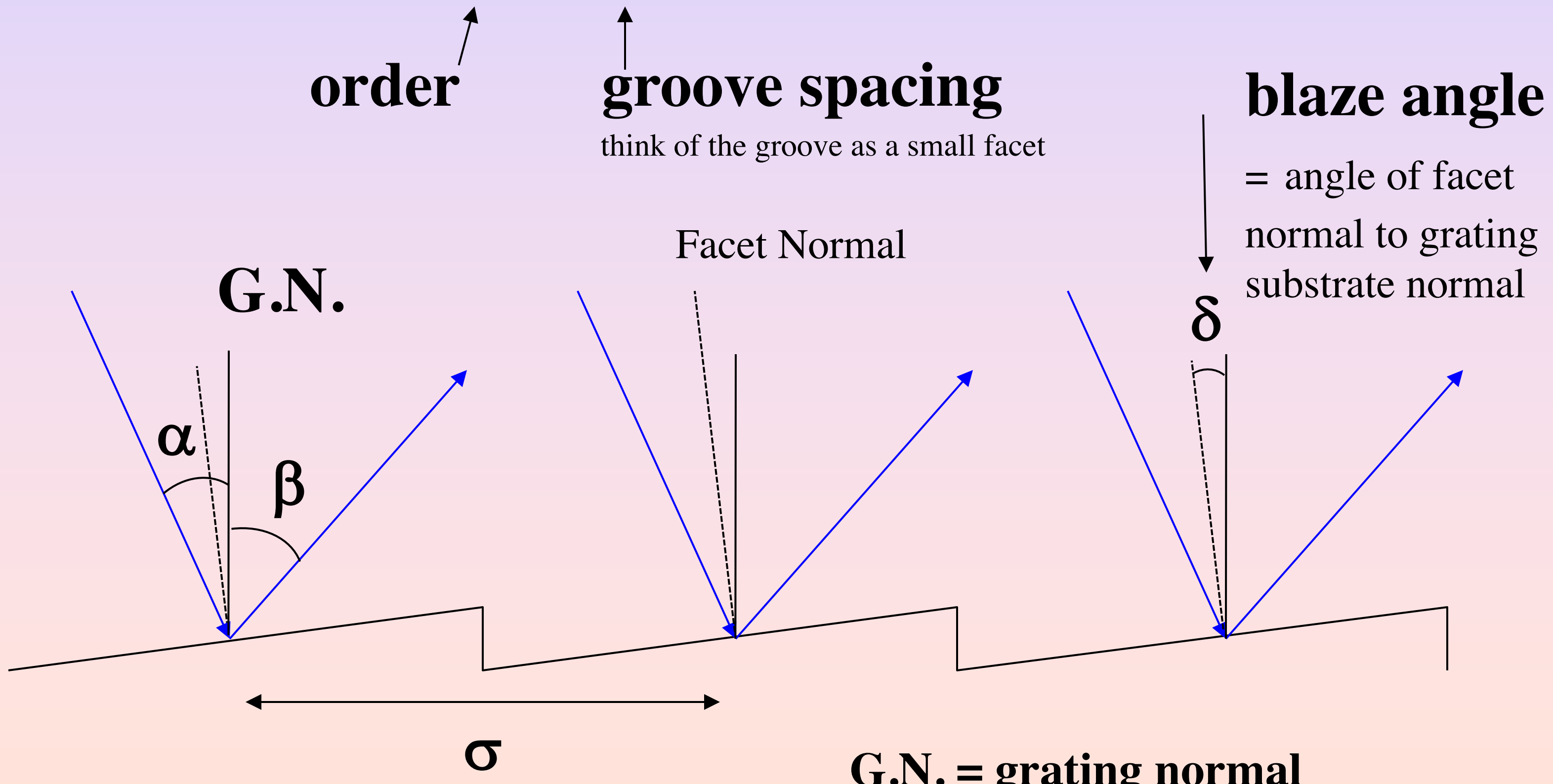
* Sign convention:
+ for reflection
– for transmission



🡐 more on signs in a few slides

Diffraction Gratings

- Most common is probably the *reflecting diffraction grating*.
- Grating equation: $m\lambda = \sigma\,[\sin(\alpha) + \sin(\beta)]$



Grating dispersion

- Think of the Young Double-slit experiment with many slits very closely spaced together (100 - 10,000+ lines/mm) and for non-monochromatic light - same constructive/destructive interference phenomenon from *path-length differences*.
- Note: ruling gratings is not easy! Spacing tolerance is ~1nm. Richardson has a machine in a room kept a constant temperature to 0.01˚C

Deriving the grating dispersion

- Differentiate the grating equation w.r.t. outgoing angle (β) and take the inverse to get the *angular dispersion:*

$$\frac{d\beta}{d\lambda} = \frac{m}{\sigma \cos(\beta)}$$

- The inverse of the *linear dispersion* is (for a length *l*):

$$\frac{d\lambda}{dl} = \frac{d\lambda}{d\beta}\frac{d\beta}{dl} = \frac{\sigma \cos(\beta)}{\mathrm{m}\, f_2}$$

in camera focal plane

order

Å/mm $\propto$ σ/m

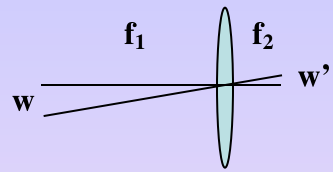
lines/mm

$$f_2 = \frac{dl}{d\beta} \equiv \text{camera focal length}$$

Grating-dispersed spectrographs

basic spectrograph design

Spectrograph magnification



Spatial magnification

w = physical slit width

w' = reimaged slit width

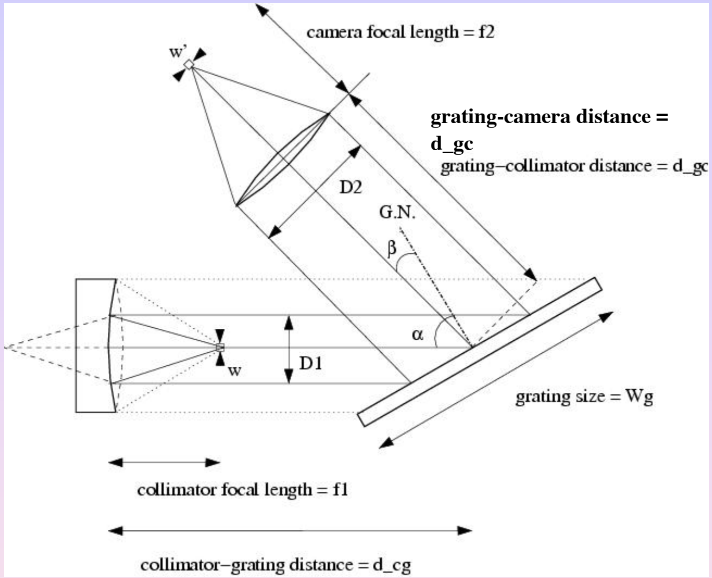
w_θ' = reimaged spatial width = $(f_2/f_1)\, w$

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**: see next slide



- ***r<1 yields demagnification*** gives more resolution elements per mm (good!)
- requires large camera optics to avoid vignetting beam (expensive)
- ***r*** = 1 for littrow configurations: $\alpha = \beta = \delta$, δ is blaze angle

Grating-dispersed spectrographs
basic spectrograph design

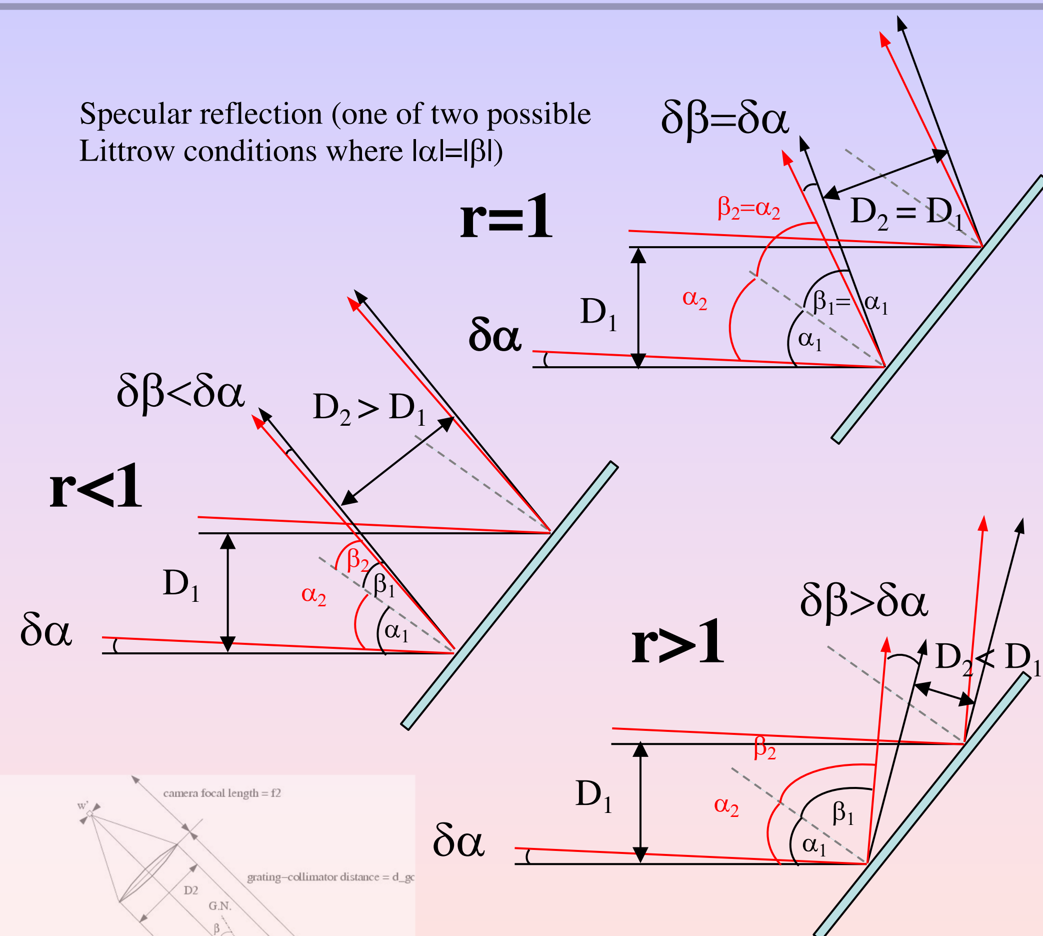
Anamorphic (de)magnification

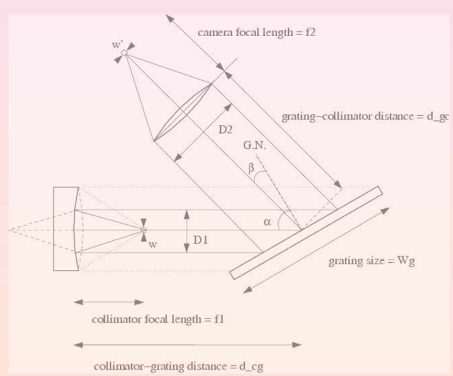
r is the **anamorphic factor**:

$r = |d\beta/d\alpha| = \cos\alpha / \cos\beta = D_1 / D_2$

> for a give **δα** (angular slit width) what is **δβ** such that δλ = 0? (differentiate grating equation and set to 0)

- "AΩ" is conserved
  - bigger beam : smaller angle
- β/α > 1 magnification;
- β/α < 1 demagnification: 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

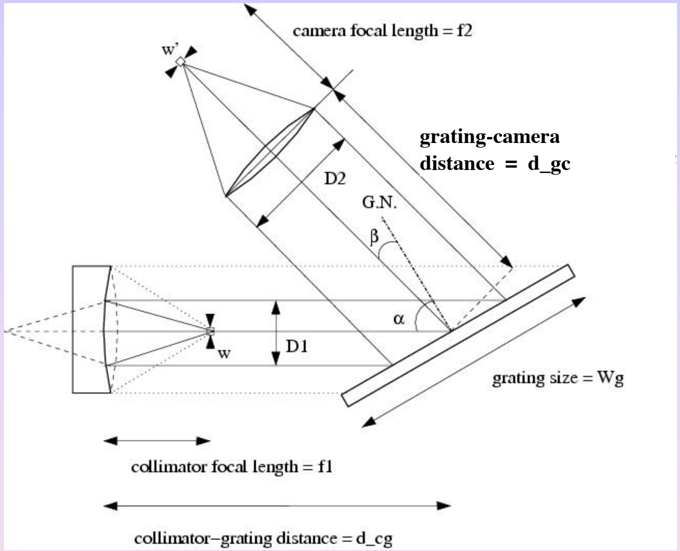
Spectral resolution

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

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:

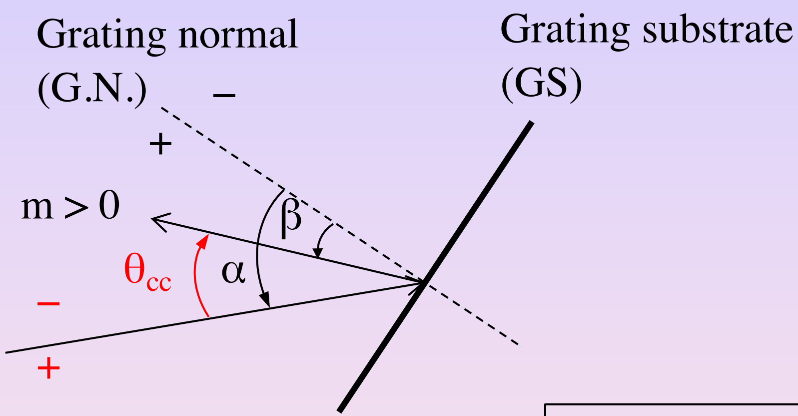
$$R = (f_1/w)\, 2 \tan\alpha$$

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

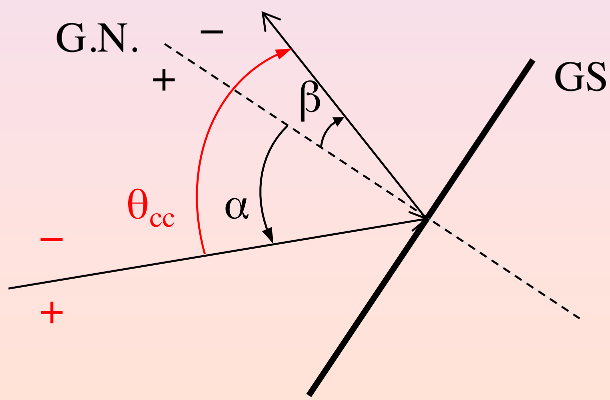
Gratings: sign conventions

REFLECTION

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

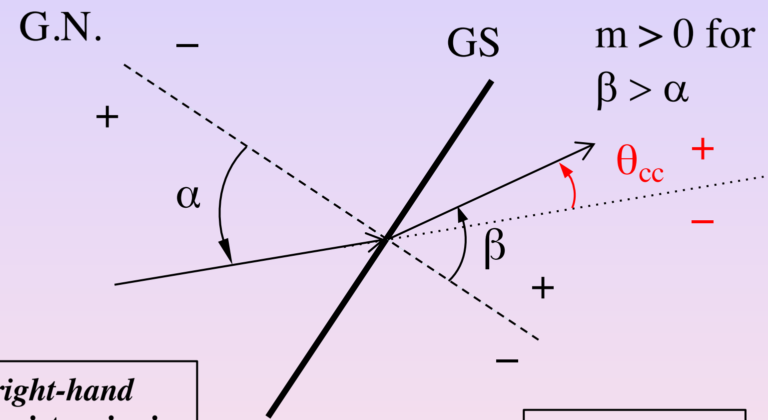


$$\theta_{cc} = \beta - \alpha$$



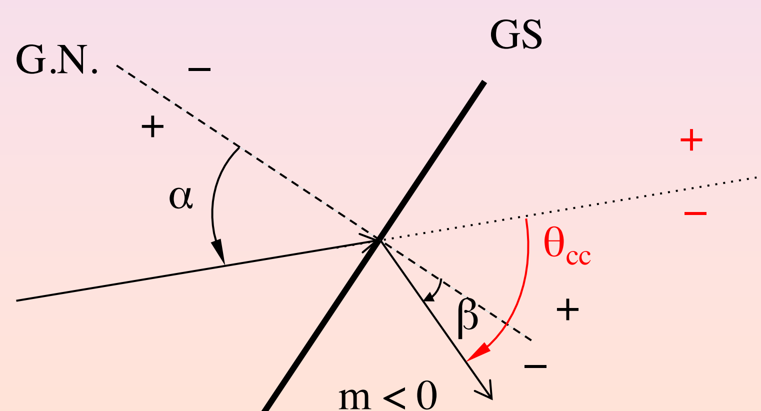
TRANSMISSION

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



Sign convention adopts *right-hand rule*, but note many inconsistencies in literature, vendors, and in practice

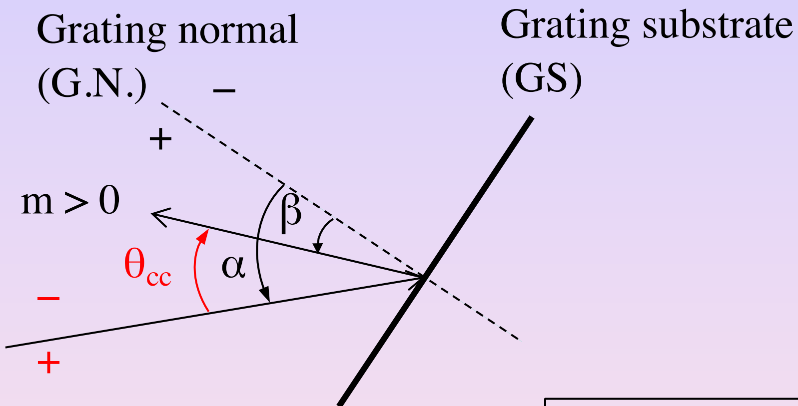
$$\theta_{cc} = \beta - \alpha$$



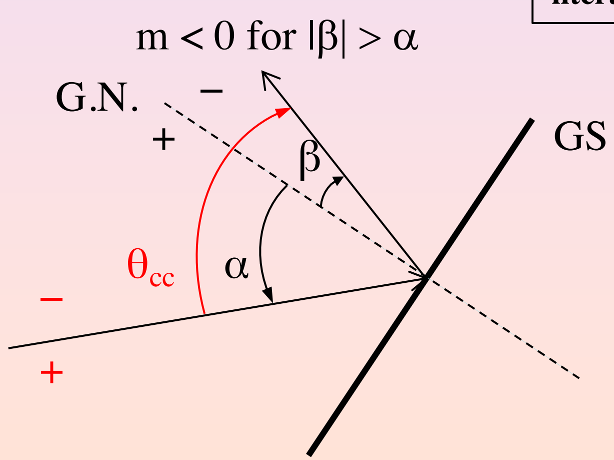
Gratings: sign conventions

REFLECTION

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

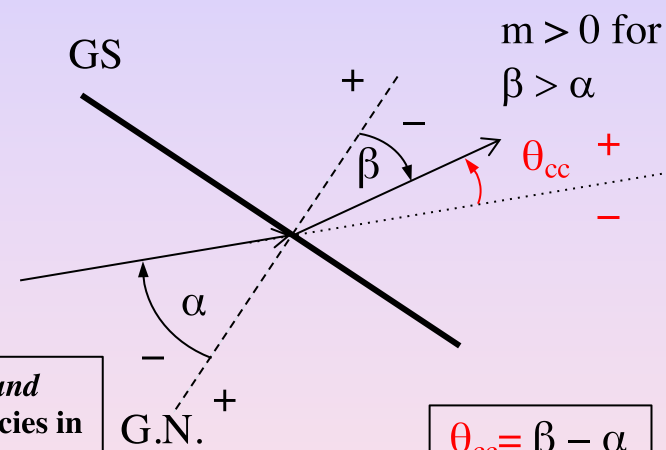


$\theta_{cc} = \beta - \alpha$

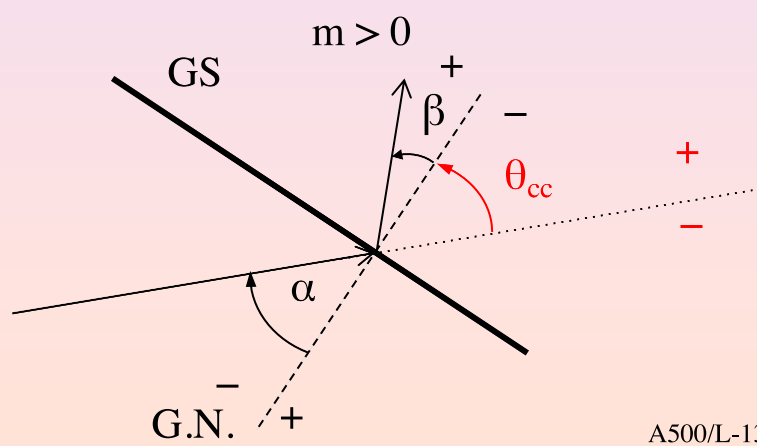


TRANSMISSION

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



$\theta_{cc} = \beta - \alpha$

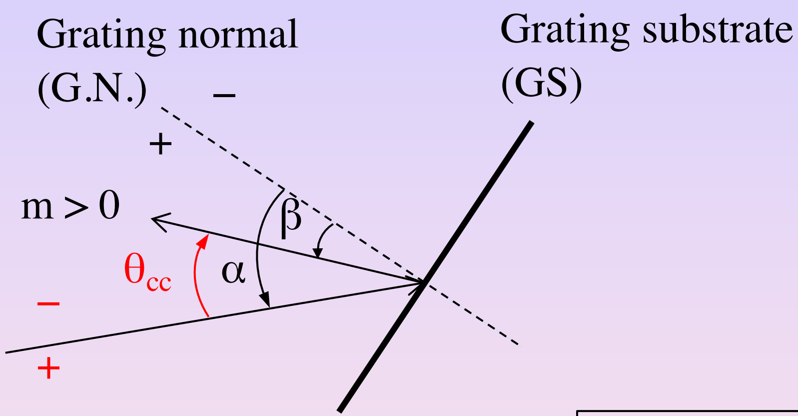


Sign convention adopts *right-hand rule*, but note many inconsistencies in literature, vendors, and in practice

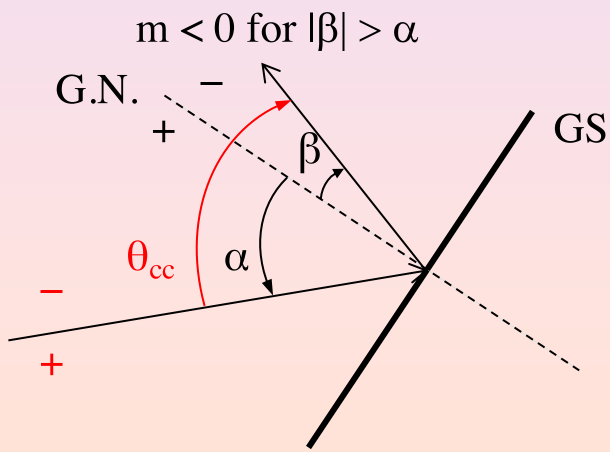
Gratings: sign conventions

REFLECTION

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



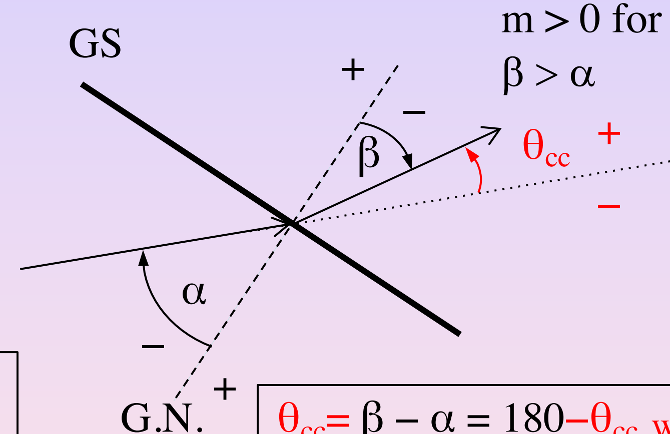
$$\theta_{cc} = \beta - \alpha = -\theta_{cc,\,WBS}$$



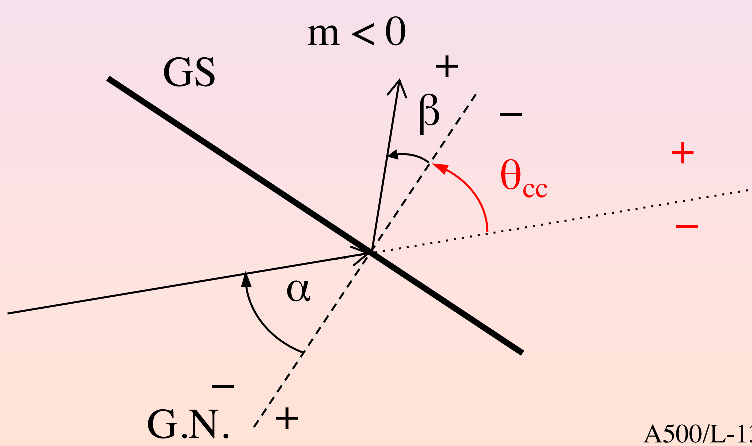
Examples of inconsistencies:
WIYN Bench Spectrograph

TRANSMISSION

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



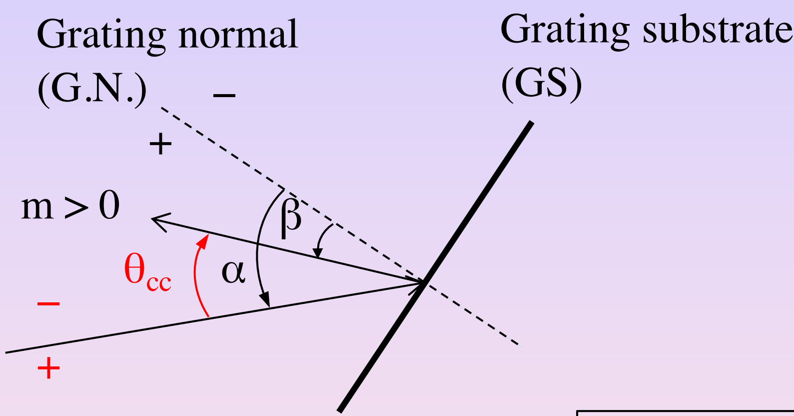
$$\theta_{cc} = \beta - \alpha = 180 - \theta_{cc,\,WBS}$$



Gratings: sign conventions

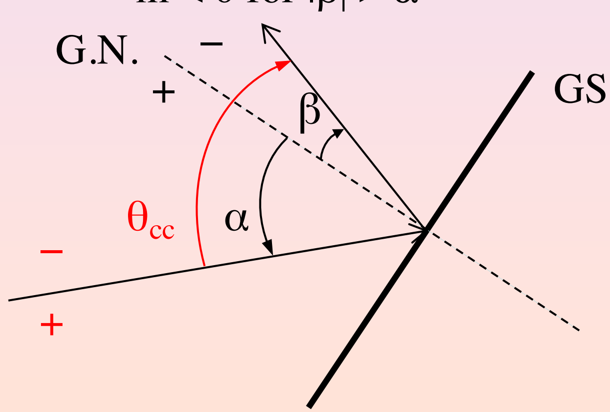
REFLECTION

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



$\theta_{cc} = \beta - \alpha = -\theta_{cc,\,WBS}$

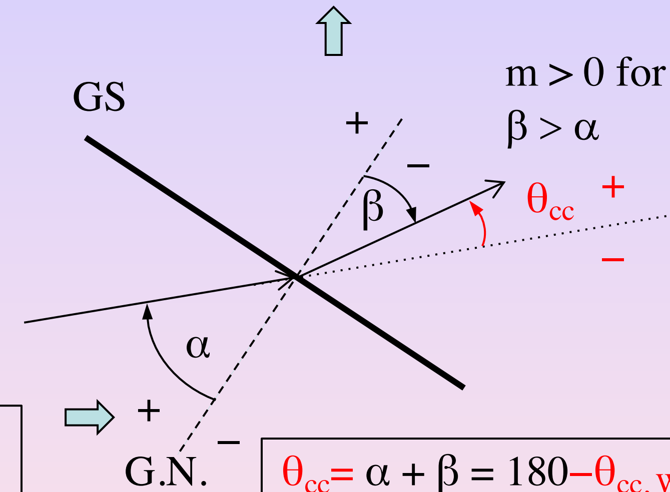
m < 0 for |β| > α



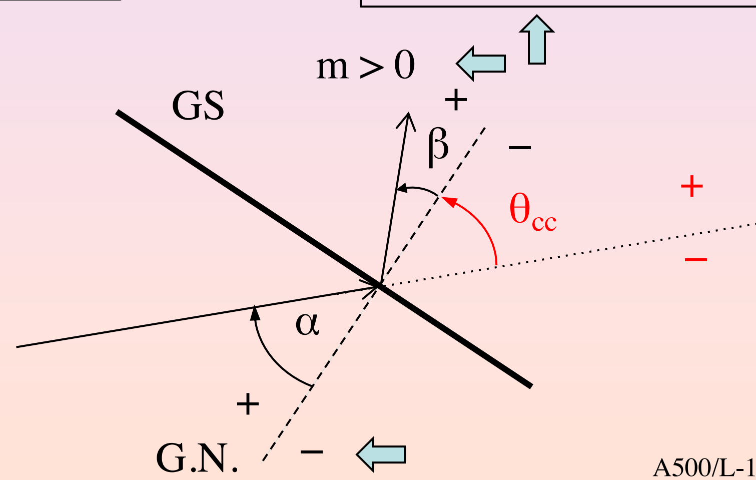
Examples of inconsistencies:
VPH transmission

VPH TRANSMISSION

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

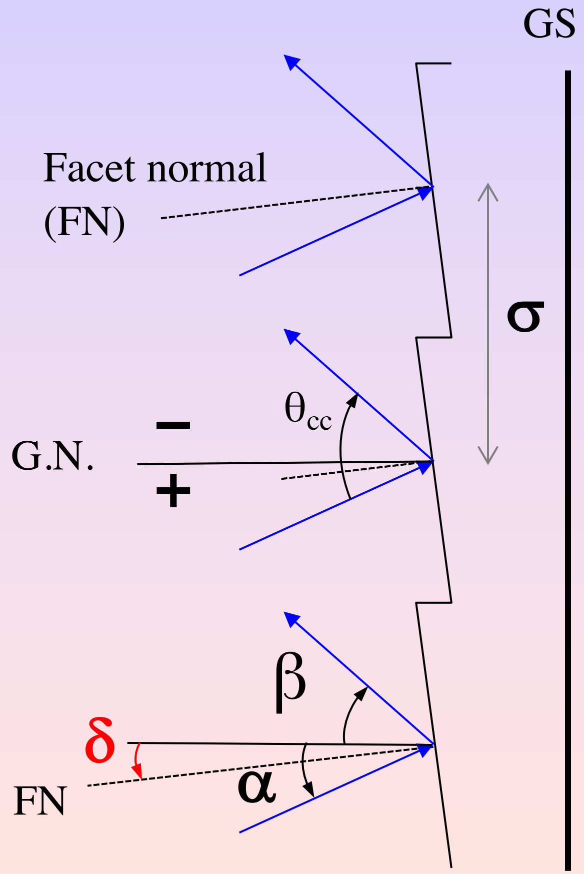


$\theta_{cc} = \alpha + \beta = 180 - \theta_{cc,\,WBS}$



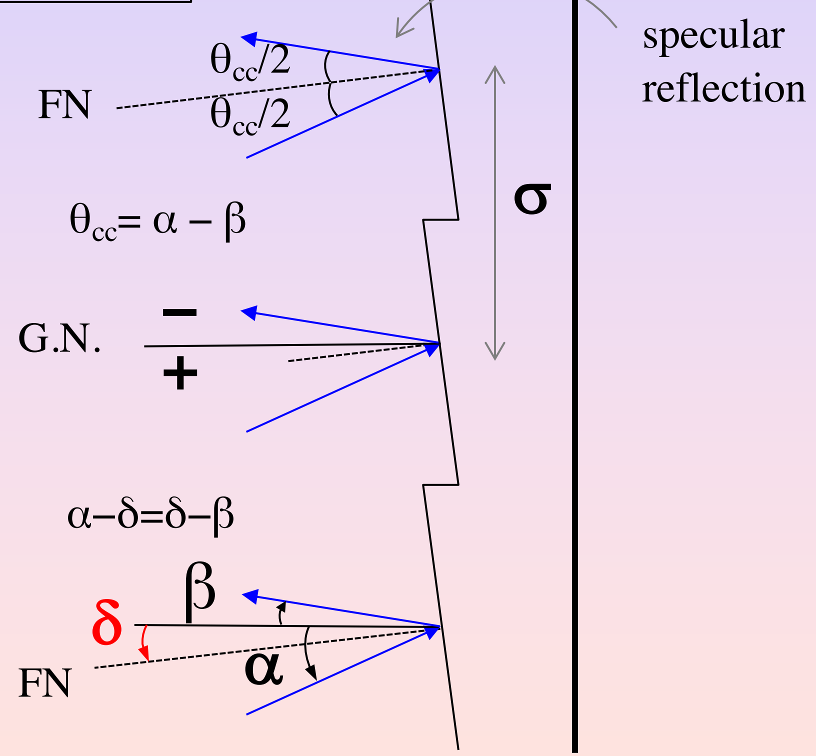
Blaze condition

OFF blaze



ON blaze also satisfies

$$\alpha+\beta=2\delta$$



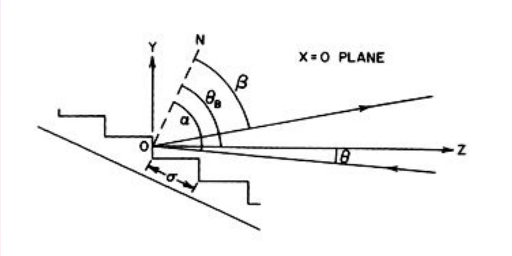
All cases obey grating equation:
$m\lambda = \sigma (\sin \beta + \sin \alpha)$
for right-hand rule.

δ is the blaze angle, equivalent to the angle of the ruled facet, or groove

σ is the groove spacing, sometimes called the facet spacing

Grating-dispersed spectrographs
dispersive elements

- **Reflection and transmission gratings: pros and cons**
- **Reflection gratings**:
  - ➢ Ruled surface-relief (SR) gratings
    - \+ Control of groove shape, blaze, and density for good efficiency in higher orders (e.g., echelle) and at high dispersion
    - \+ Existing sample of masters with replicas giving up to 70% efficiency
    - o 50-60% efficiency typical, 40% if coatings not well-maintained
    - \- Scattered light, ruling errors, can be significant
    - \- Existing masters limited in type and size; not possible to make larger masters with high quality
  - ➢ Holographically etched SR gratings
    - \+ Low scattered light
    - \+ High line-density (hence high dispersion)
    - \+ Large size
    - \- Low efficiency (<50%) because symmetric grooves put equal power in +/- orders.



  - ➢ Volume-phase holographic (VPH) reflection gratings: not yet developed.
  - ➢ *Reflection gratings do not yield compact spectrograph geometries:* ***vignetting.***
    - o Especially important for echelles (large angles), even more so if they are cross-dispersed.
    - o This can be ameliorated using field lenses or white pupil designs.

Grating-dispersed spectrographs
dispersive elements

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

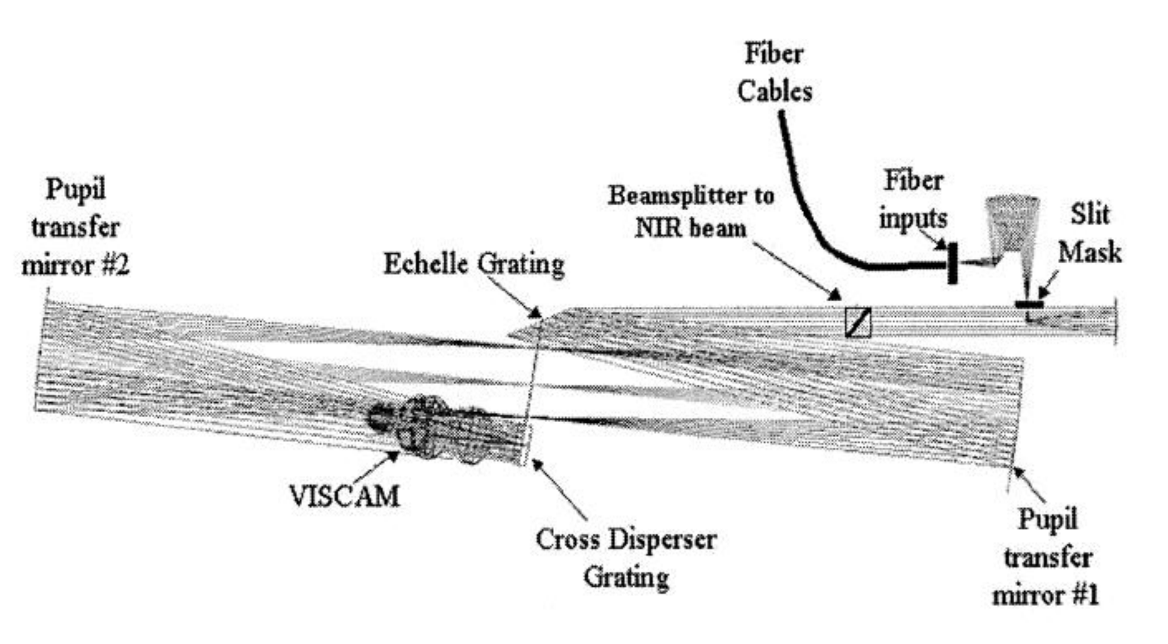
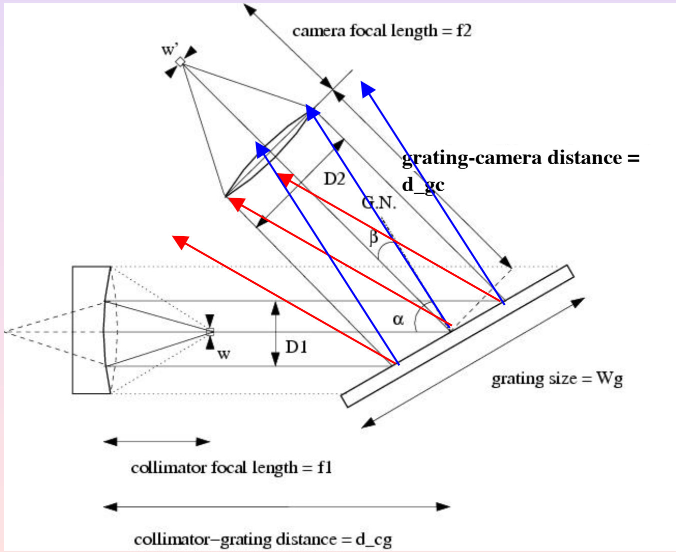


Figure 6: MRS Visible beam optical layout

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



Ramsey '03

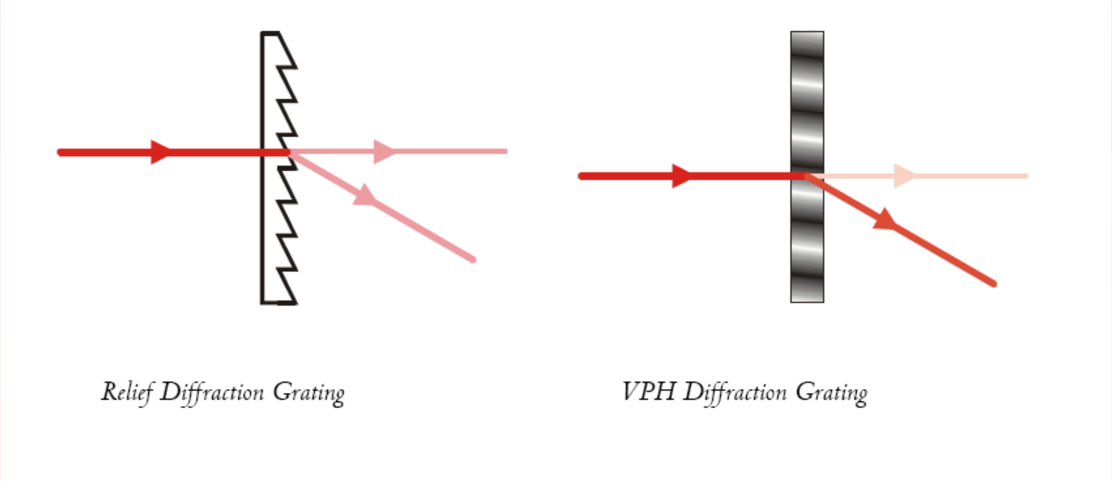
Grating-dispersed spectrographs

dispersive elements

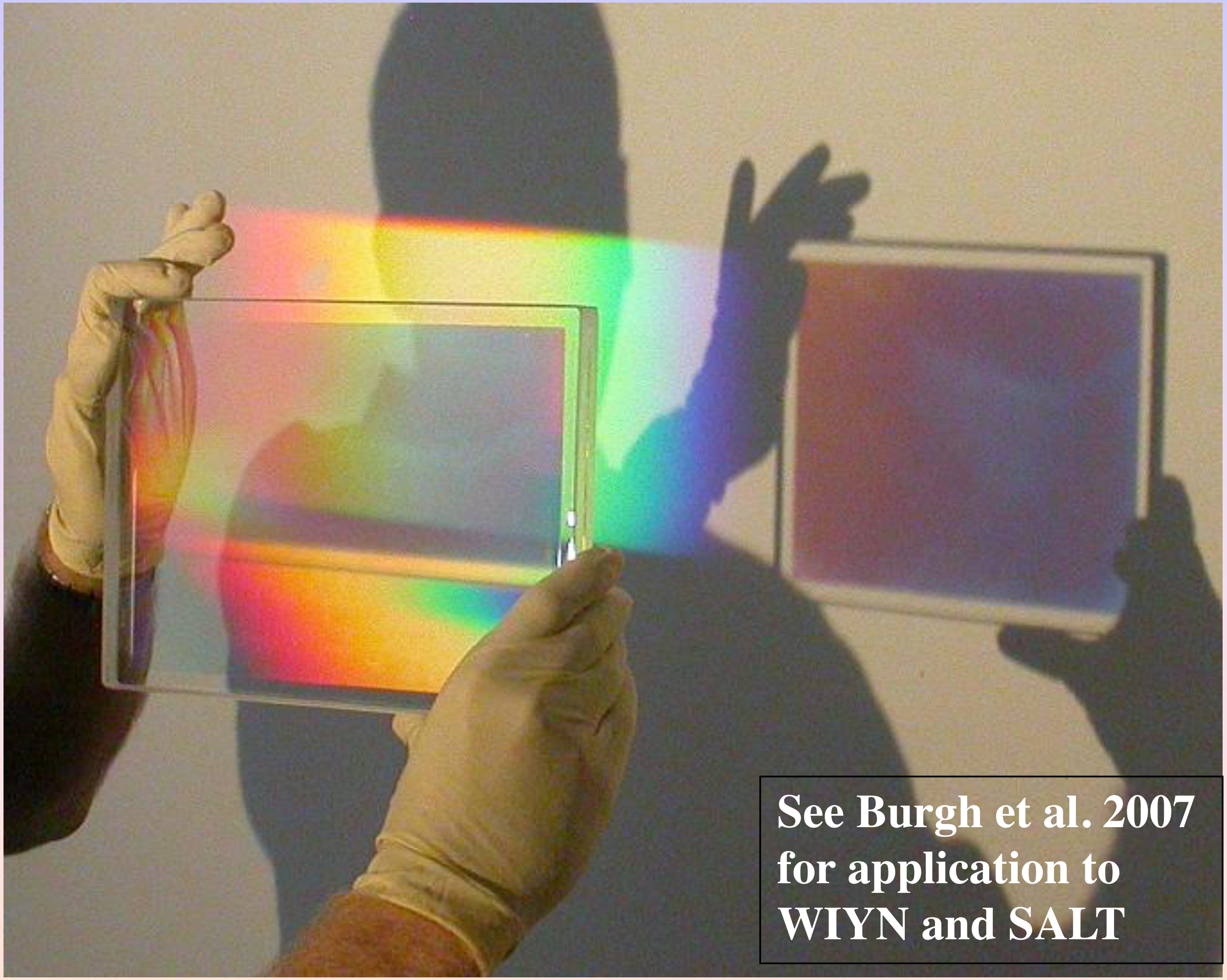
- **Transmission gratings**:
  - SR transmission gratings and grisms
    - + Efficient at small angles and low line-densities (good for low-resolution spectroscopy)
    - - Inefficient at large angles and high line-densities (although transmission echelles do exist, but have 30% efficiency)
  - VPH gratings and grisms
    - + Efficient over a broad range of line-densities and angles
    - + Individual gratings efficient over broad range of angles (the superblaze)
    - + Peak efficiencies as high as 90%
    - + Inexpensive to make
    - + Inexpensive to customize
    - + Can be very large (as large as your substrate and recording beam)
    - - Gratings used at Littrow (hard to get significant anamorphic factors)
    - - Uniformity may still be an issue for manufacturing.
  - *Transmission gratings yield compact, efficient spectrograph designs*

Transmission gratings

- There are also different versions of transmission gratings.
  - Transmission grating
  - *Grisms* - add a prism for *zero-deviation* transmission dispersion
  - *Volume Phase Holographic Gratings*: VPH - use modulations of the index of refraction rather than surface structures to produce dispersion. High efficiency.



Volume Phase Holographic gratings

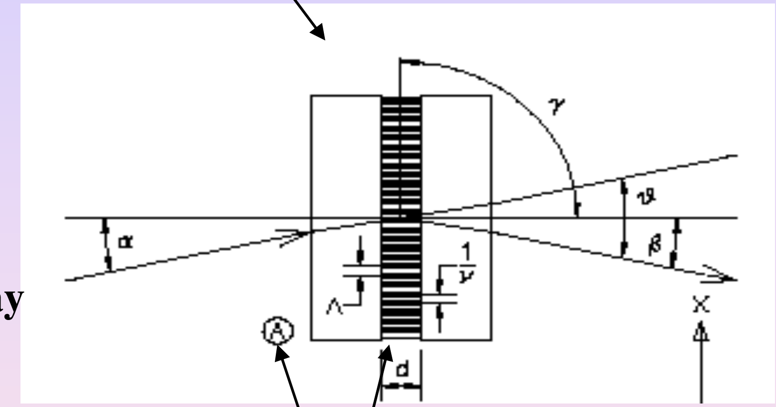


Volume Phase Holographic gratings

Dichromated gelatin layer (exposed to laser hologram)

Fringes are changes, Δn, in mean gelatin index, n.

Incident ray



diffracted ray

Barden et al. '00

Optically flat fused silica
or BK7 glass (can AR coat)

Thickness (d) is > than depth of groove in surface-relief grating.
Implies efficiency profile governed by Bragg diffraction.

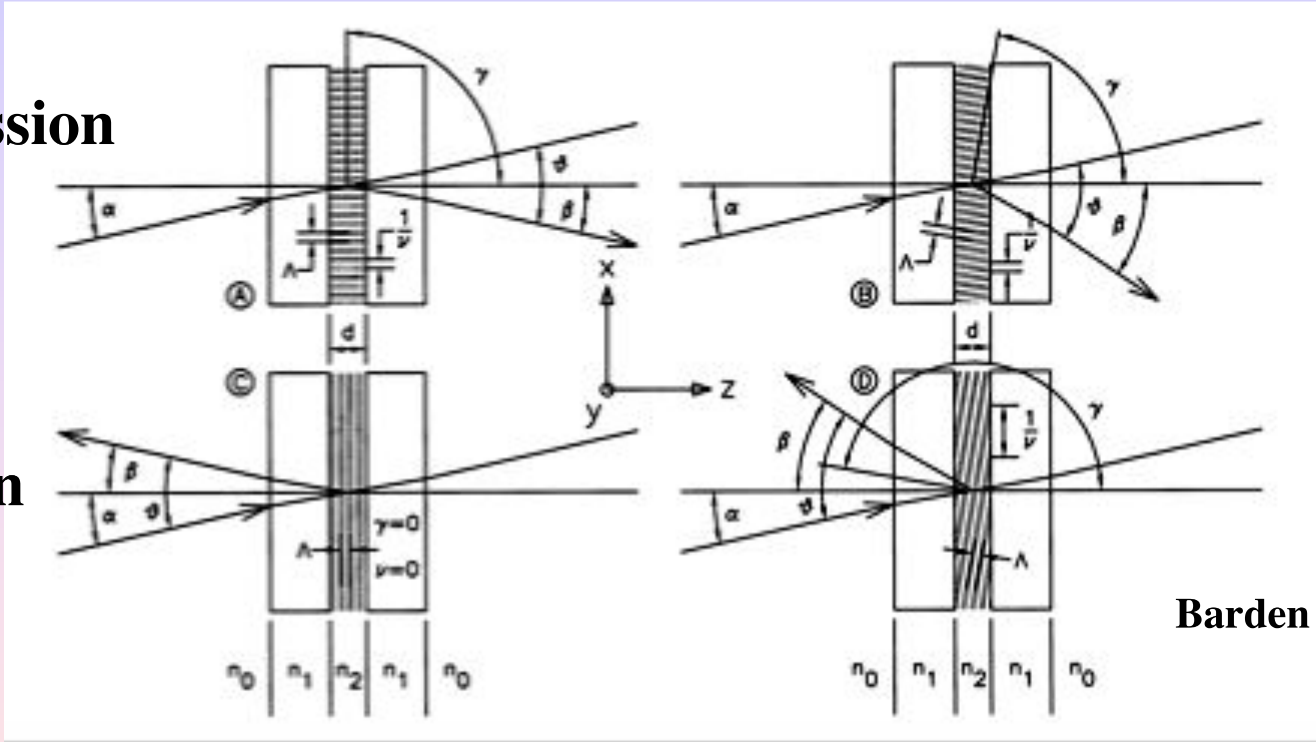
Work at the Bragg condition: α = β

Volume Phase Holographic gratings

unblazed **blazed**

transmission

reflection



Barden et al. ‘00

- Issues remain on perfecting grating development and uniformity
    - typical exposure beams are gaussian; gelatin can have non-uniform hydroscopic properties; high index modulation can cause milkiness; mean index indeterminate.
- Tilted (blazed) fringes may sag during development

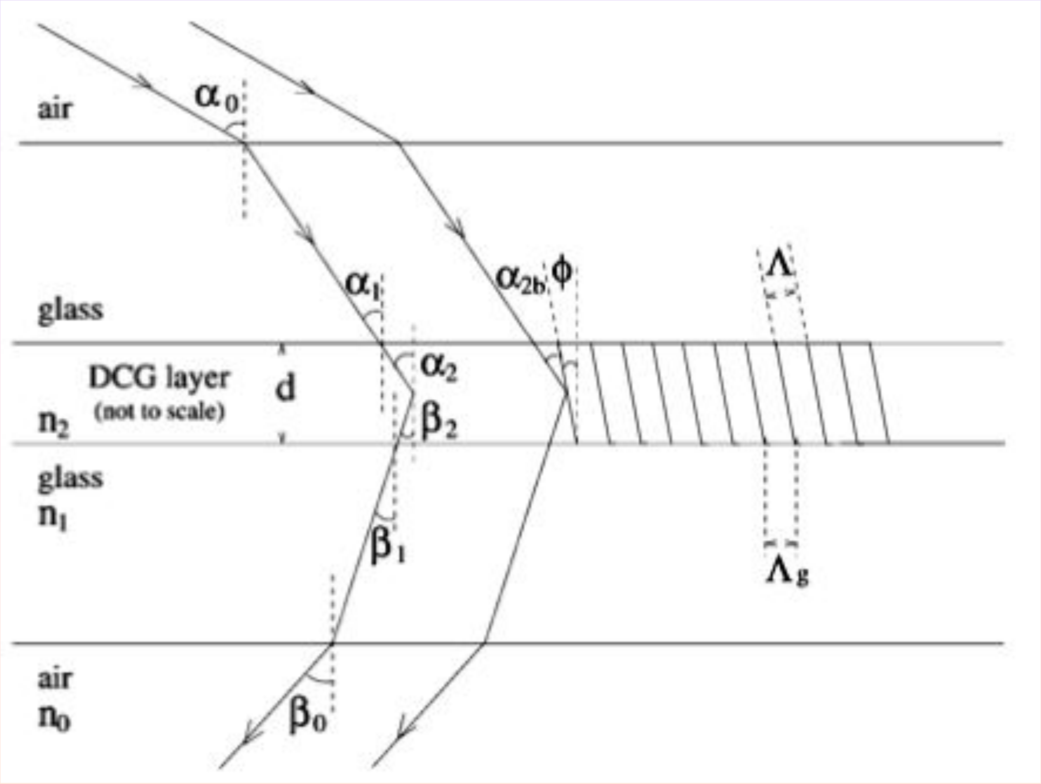
Volume Phase Holographic gratings

- 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:*
    - 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
    - Thinner d yields larger band-width but required larger Δn_2 which is difficult in practice

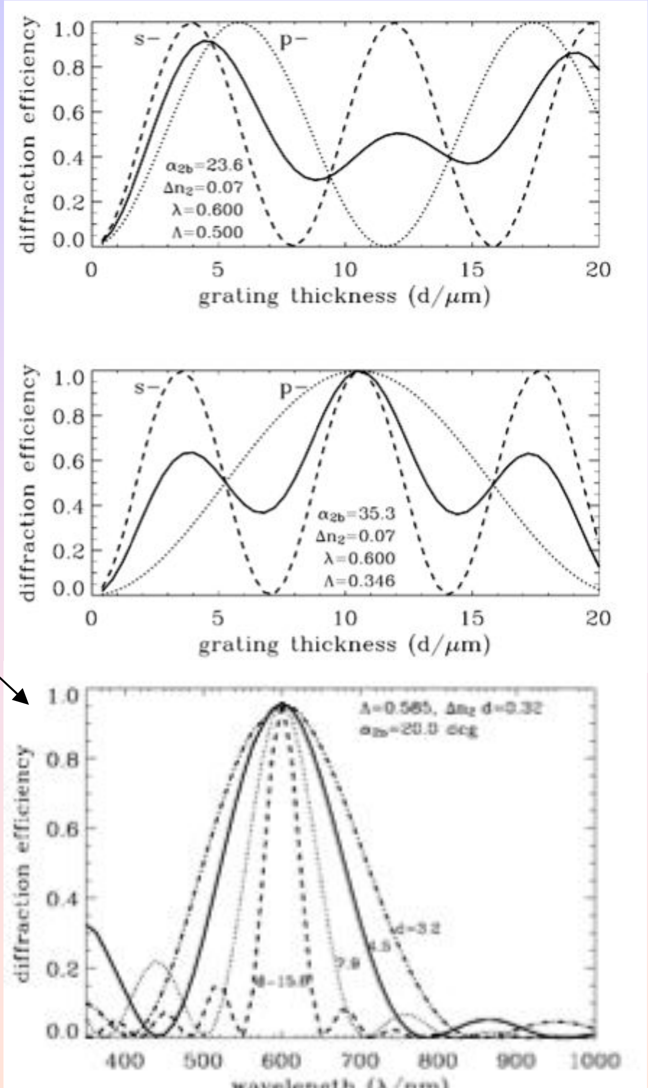
*Kogelnik limit

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

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

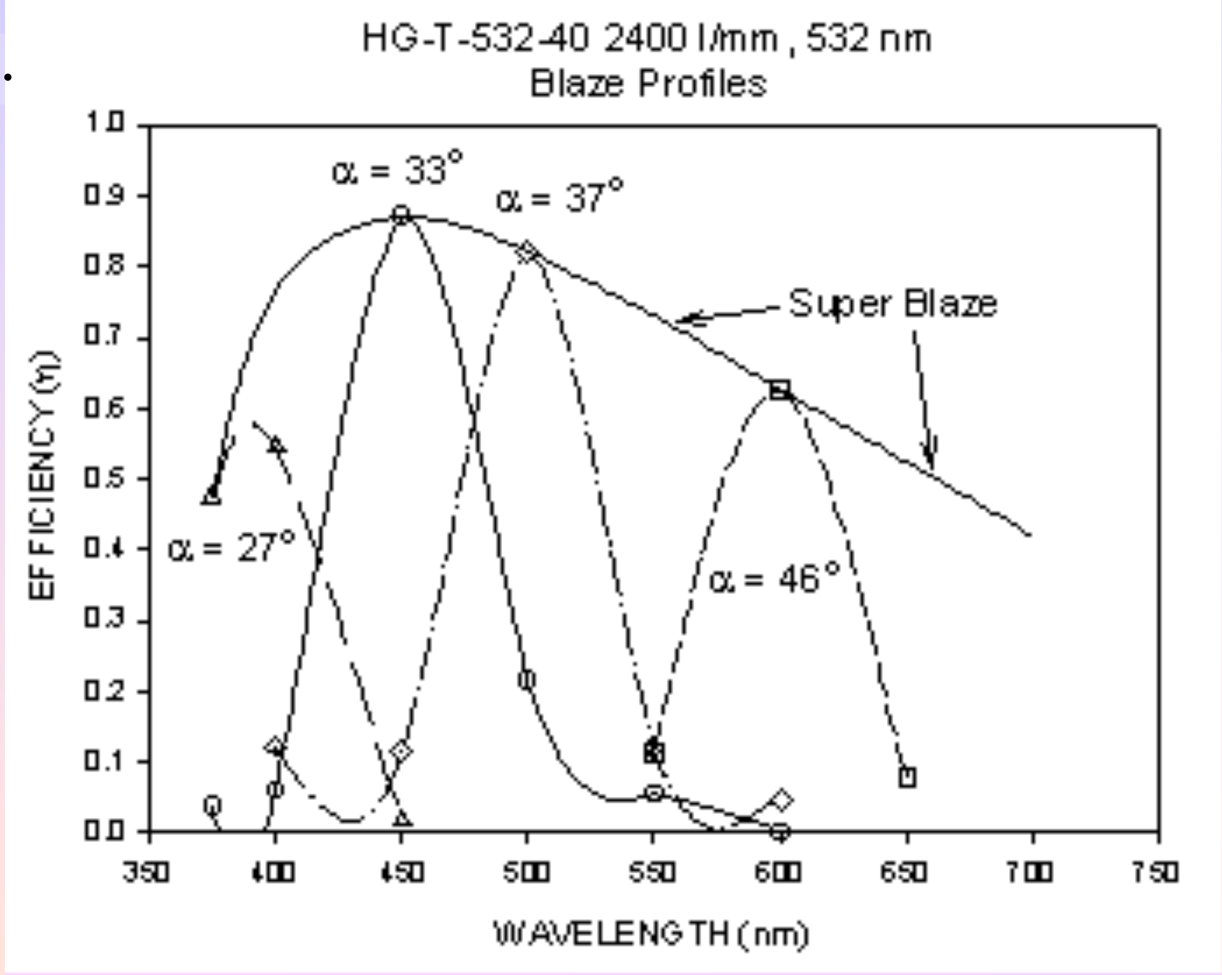
$$\eta = \frac{1}{2}\sin^2\left(\frac{\pi \Delta n_2 d}{\lambda \cos \alpha_{2b}}\right) + \frac{1}{2}\sin^2\left[\frac{\pi \Delta n_2 d}{\lambda \cos \alpha_{2b}} \cos\left(2\alpha_{2b}\right)\right],$$

TE **TM**



Tuneability of VPH gratings

The good news….

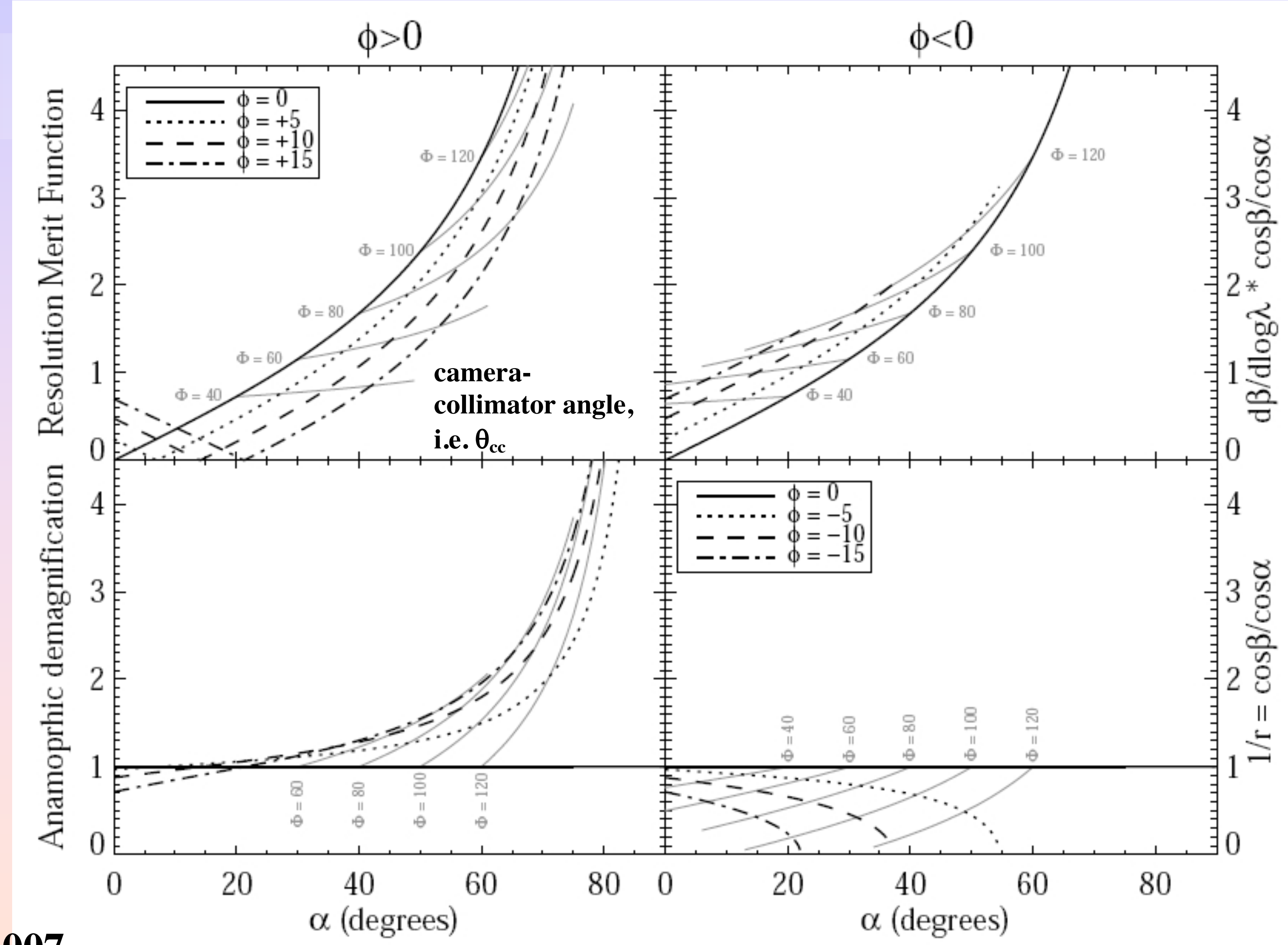


Anamorphic factors with VPH gratings

postive fringe tilts **negative fringe tilts**

…which could be even better

demagnification



Burgh et al. 2007

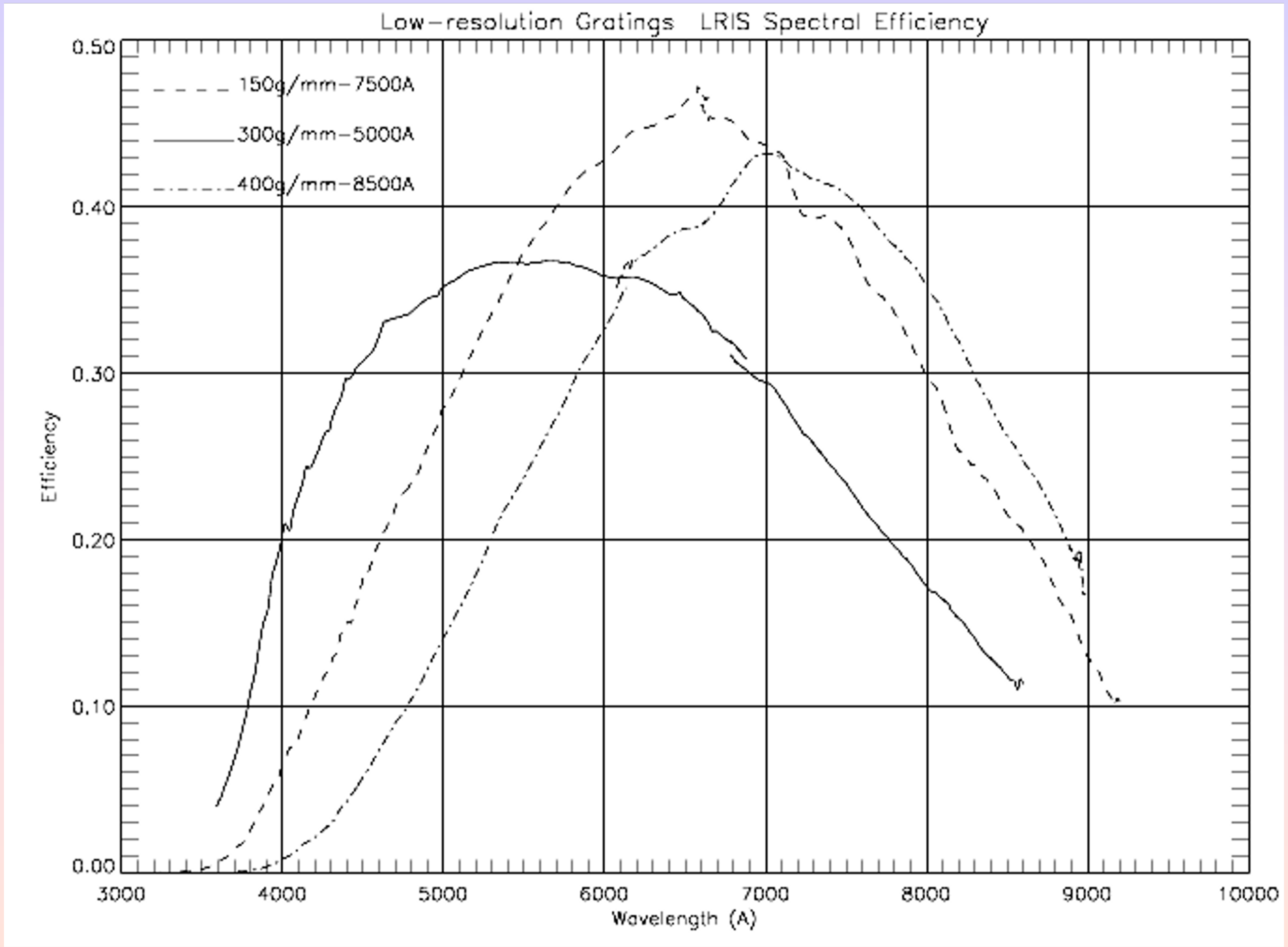
Anamorphic factors with VPH gratings

- **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



Grating Efficiencies