Physics 1901

Experimental Astronomy – Graduate Course
Autumn (Apr-May 2014)

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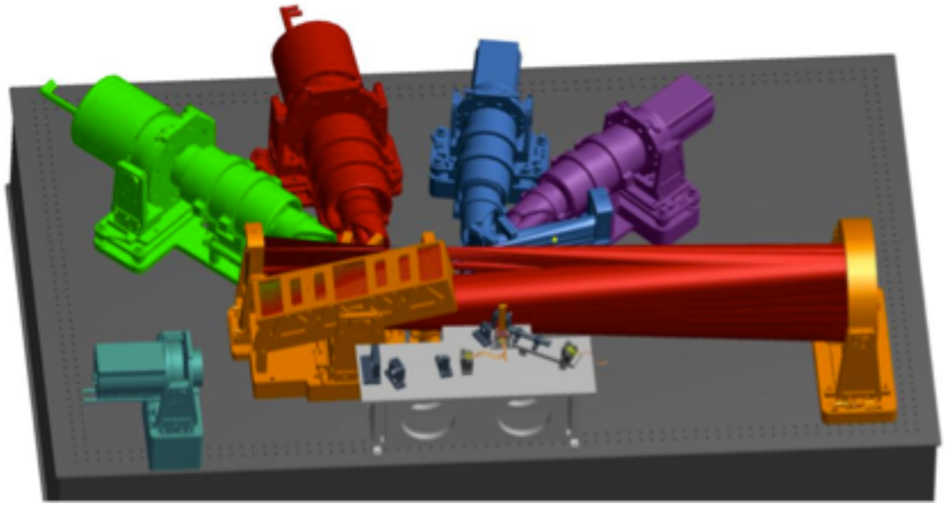
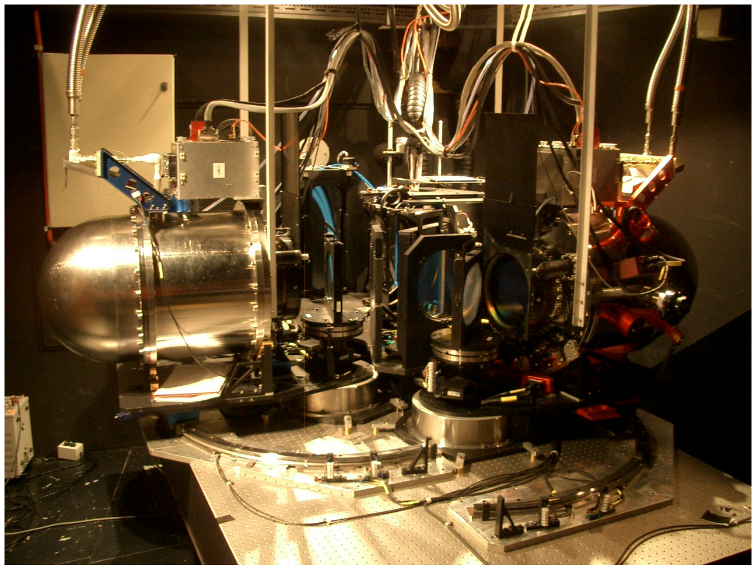
Some questions:
(which you should be able to answer at the end of the course)

- What are the parts of a spectrograph
- Why are spectrographs so big?
- What sets the sensitivity?
- How do I estimate the exposure time?

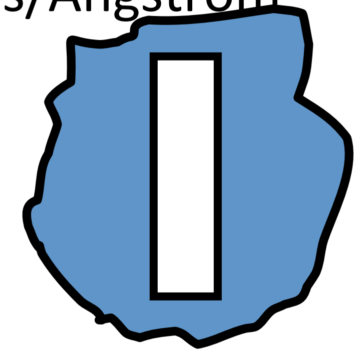




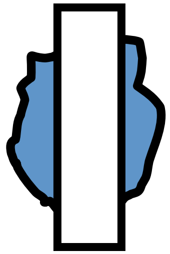
Spectrograph Speed

Speed=# of counts/s/Angstrom

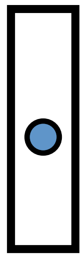
I. Slit-limited



II. Intermediate



III. Image-limited



Bowen, I.S., “Spectrographs,” in Astronomical Techniques, ed. by W.A. Hiltner, (U. of Chicago Press, 1962), pp. 34-62.

Spectrograph Speed

Schroeder 12.2e, Ira Bowen (1962)

I. Slit-limited

$$Speed \propto D_{Tel}^{0} \bullet W_{grating}^{2}$$

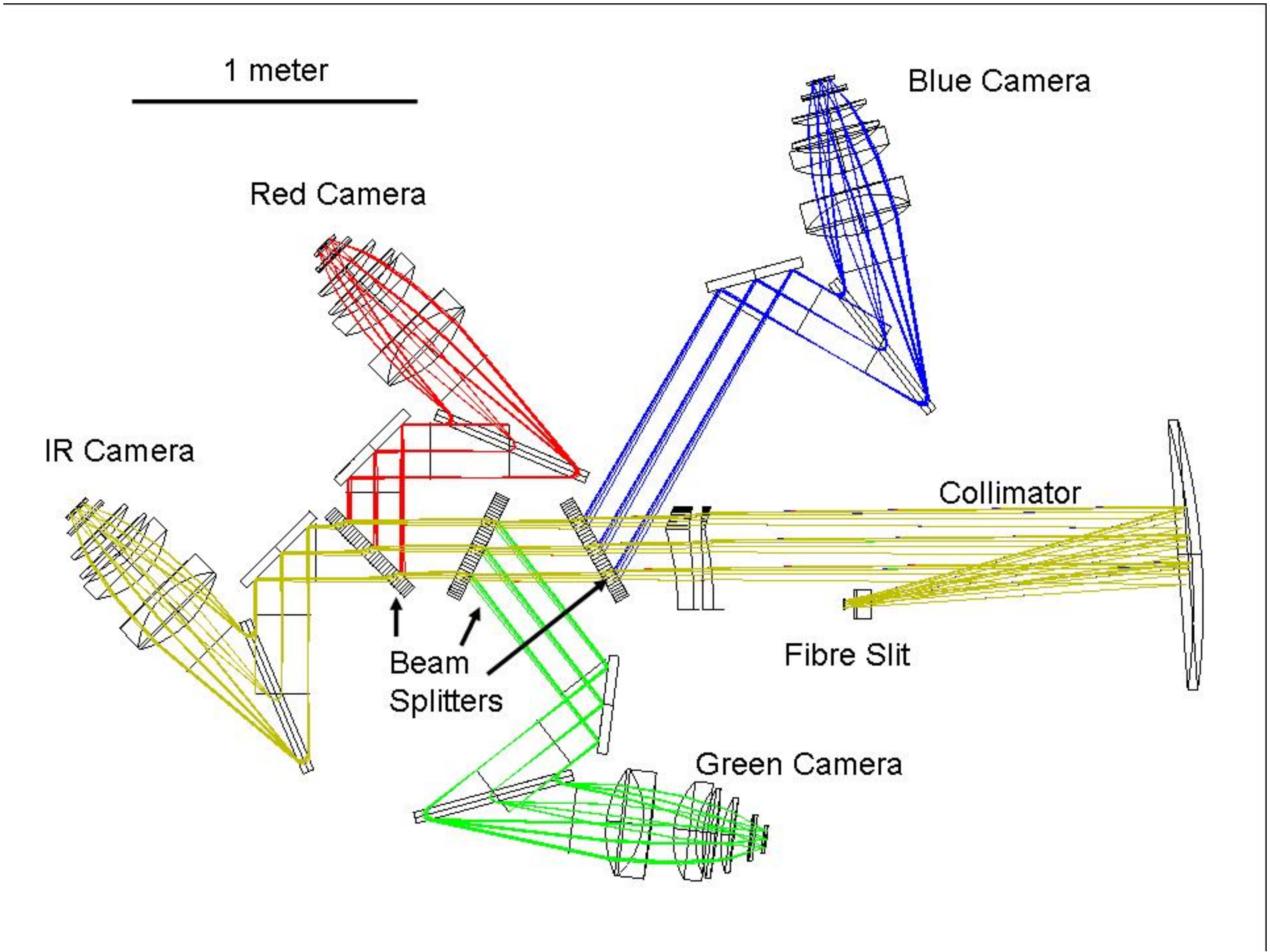
II. Intermediate

$$Speed \propto D_{Tel}^{1} \bullet W_{grating}^{1}$$

III. Image-limited

$$Speed \propto D_{Tel}^{2} \bullet W_{grating}^{0}$$

Speed=# of counts/s/Angstrom, W= illuminated grating length


1 meter
Blue Camera
Red Camera
IR Camera
Collimator
Beam
Splitters
Fibre Slit
Green Camera

Some questions:
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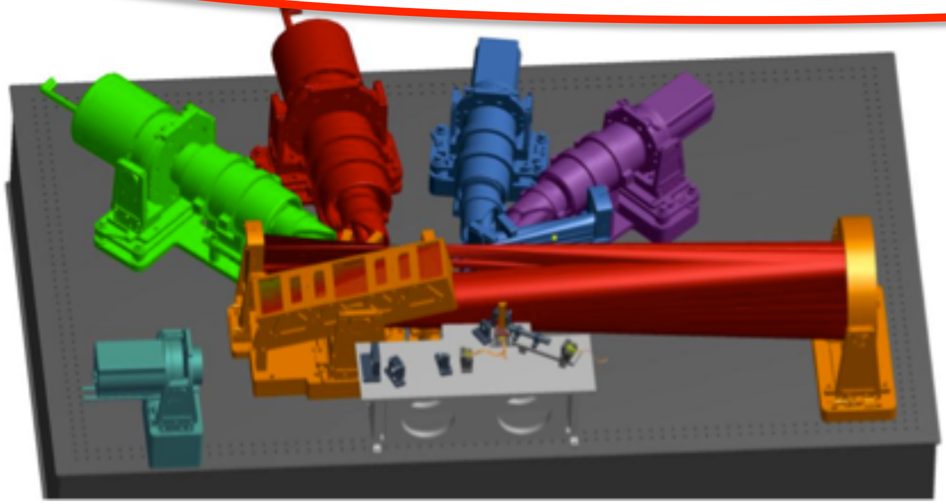

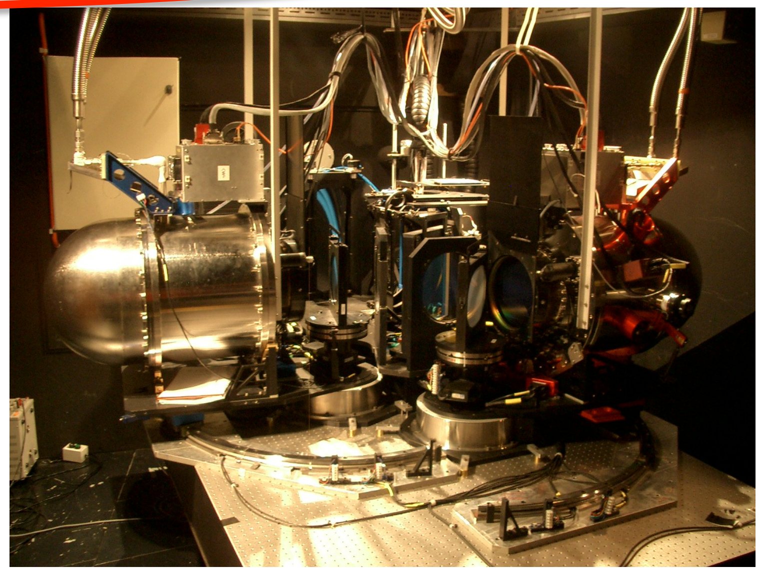

S/N for object measured in aperture with radius r: n_{pix}=# of pixels in the aperture= πr^2

$$SNR = \frac{R_* t}{\left[\sum noise^2\right]^{\frac{1}{2}}}$$

How do I calculate the number of photo electrons/s on my detector?

- Resolved source
  - We are measuring surface brightness
  - $E=A\Omega I_\nu$
- For an extended object in the IR that is easy: You just need the temperature of the source, the system losses (absorption, QE etc), resolution and etendu of a pixel. No telescope aperture or F/#, no slit size, no optical train!
- For an extended object in the visible: You just need the surface brightness of the source, the system losses (absorption, QE etc), resolution and etendu of a pixel. No telescope aperture or F/#, no slit size, no optical train!
- Point source
  - we are measuring flux
  - $E=Af_\nu dt$
- For an unresolved object, you need the source magnitude, telescope aperture, system losses and resolution.

- Noise Sources:

$\sqrt{R_* \cdot t}$ $\Rightarrow$ shot noise from source

$\sqrt{R_{sky} \cdot t \cdot \pi r^2}$ $\Rightarrow$ shot noise from sky in aperture

$\sqrt{RN^2 \cdot \pi r^2}$ $\Rightarrow$ readout noise in aperture

$\sqrt{\left[RN^2 + (0.5 \times \text{gain})^2\right]} \cdot \sqrt{\pi r^2}$ $\Rightarrow$ more general RN

$\sqrt{\text{Dark} \cdot t \cdot \pi r^2}$ $\Rightarrow$ shot noise in dark current in aperture

$R_* = \text{e}^-/\text{sec}$ from the source

$R_{sky} = \text{e}^-/\text{sec/pixel}$ from the sky

$RN =$ read noise (as if RN^2 e^- had been detected)

Dark = e^- /second/pixel

Sources of Background noise

- Relic Radiation from Big Bang
- Integrated light from unresolved extended sources
- Thermal emission from dust
- Starlight scattered from dust
- Solar light scattered from dust (ZL)
- Line emission from galactic Nebulae
- Line emission from upper atmosphere (Airglow)
- Thermal from atmosphere
- Sun/moonlight scattered by atmosphere
- Manmade light scattered into the beam
- Thermal or scatter from the telescope/dome/instrument

Putting it all together:

S/N for object measured in aperture with radius r: n_{pix}=# of pixels in the aperture= πr^2

Noise from the dark current in aperture

Signal

$$\frac{R_* t}{\left[R_* \cdot t + R_{sky} \cdot t \cdot n_{pix} + \left((RN)^2 + \left(\frac{\text{gain}}{2}\right)^2\right) \cdot n_{pix} + \text{Dark} \cdot t \cdot n_{pix}\right]^{\frac{1}{2}}}$$

Noise

$$\sqrt{(R_* \cdot t)^2}$$

Readnoise in aperture

Noise from sky *e*- in aperture

All the noise terms added in quadrature
Note: always calculate in *e*-

S/N - some limiting cases. Let's assume CCD with Dark=0, well sampled read noise.

$$\frac{R_* t}{\left[R_* \cdot t + R_{\mathrm{sky}} \cdot t \cdot n_{\mathrm{pix}} + (RN)^2 \cdot n_{pix}\right]^{\frac{1}{2}}}$$

<u>Bright Sources:</u>

$(R_* t)^{1/2}$ dominates noise term

$$\mathrm{S/N} \approx \frac{\mathrm{R_* t}}{\sqrt{\mathrm{R_* t}}} = \sqrt{\mathrm{R_* t}} \propto \mathrm{t}^{\frac{1}{2}}$$

<u>Read-noise</u> Limited

$$(3\sqrt{\mathrm{R_{sky} t}} < \mathrm{RN}):\ \mathrm{S/N} \propto \frac{\mathrm{R_* t}}{\sqrt{\mathrm{n_{pix} RN^2}}} \propto t$$

<u>Sky Limited</u>

$$(\sqrt{\mathrm{R_{sky} t}} > 3 \times \mathrm{RN}):\ \mathrm{S/N} \propto \frac{\mathrm{R_* t}}{\sqrt{\mathrm{n_{pix} R_{sky} t}}} \propto \sqrt{\mathrm{t}}$$

Note: seeing comes in with n_{pix} term

Some questions:

- What are the parts of a spectrograph
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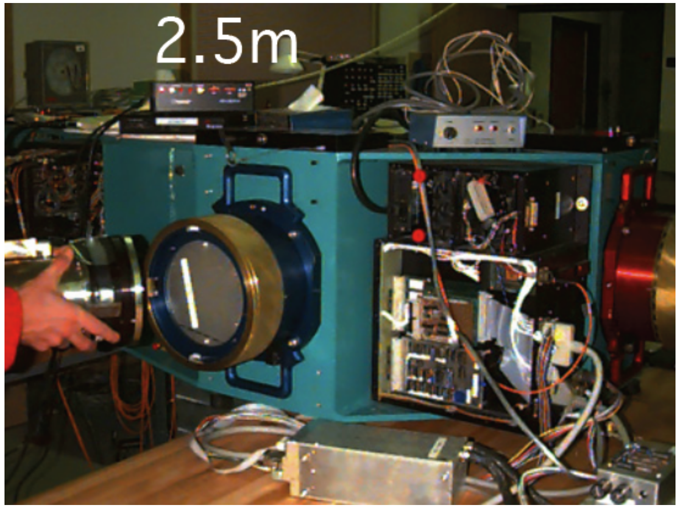
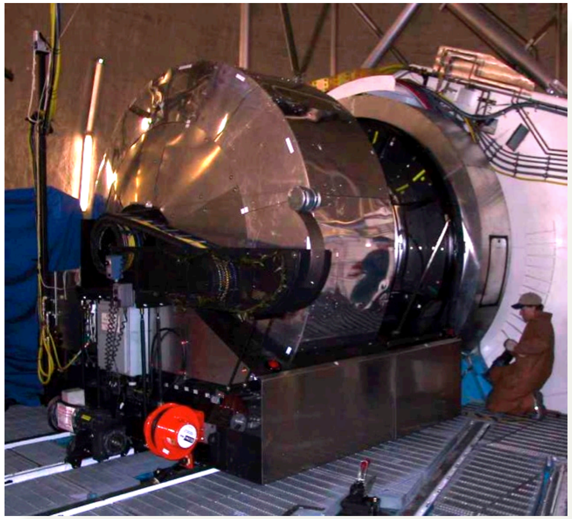
Three Spectrographs of similar field and resolution

- Why do they look so different?

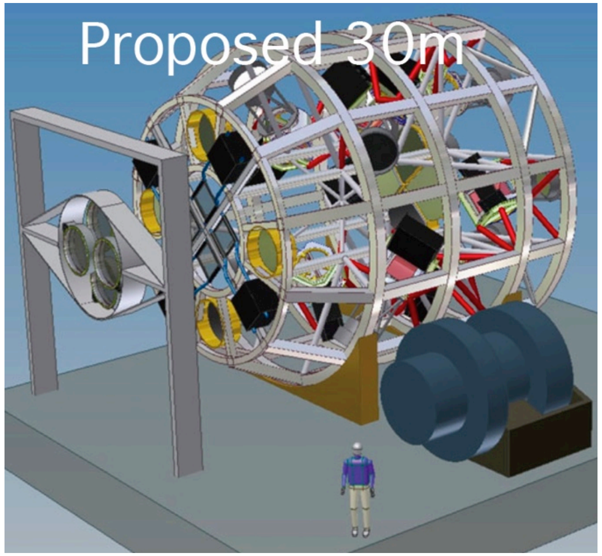
SDSS 2.5M



Nasmyth Focus at Keck 10M



TMT 30M



What causes dispersion

- The number of grooves in the grating
- Optical path difference in the interfering beam,
- Or
- Optical time delay in the interfering beam

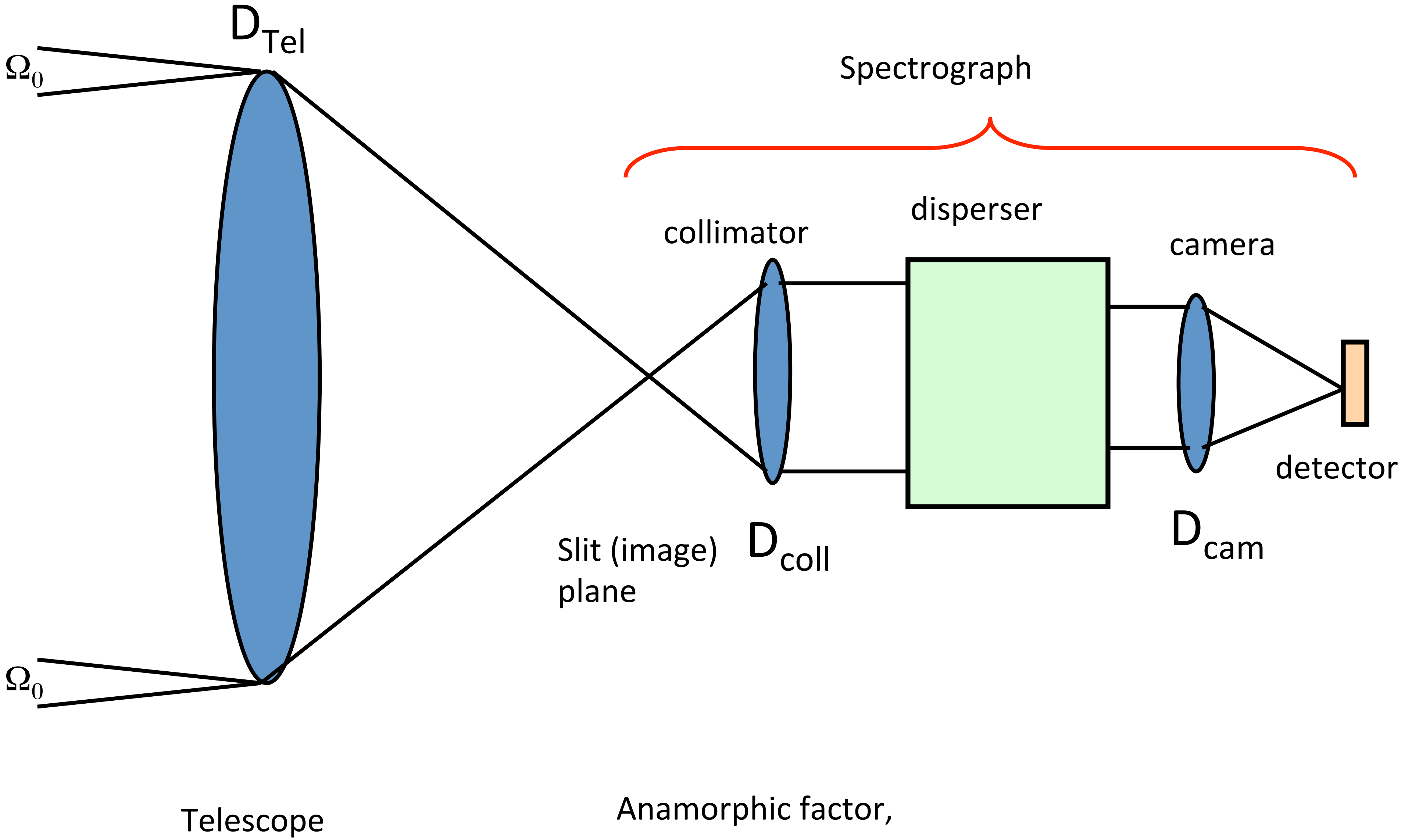
Thought experiment 1:

How Big an aperture do you need to achieve R=100,000 in the diff-limited case on a 10-meter telescope at 1 μm?

a) 2.5 meters
b) 250 mm
c) 25 mm
d) 2.5 mm

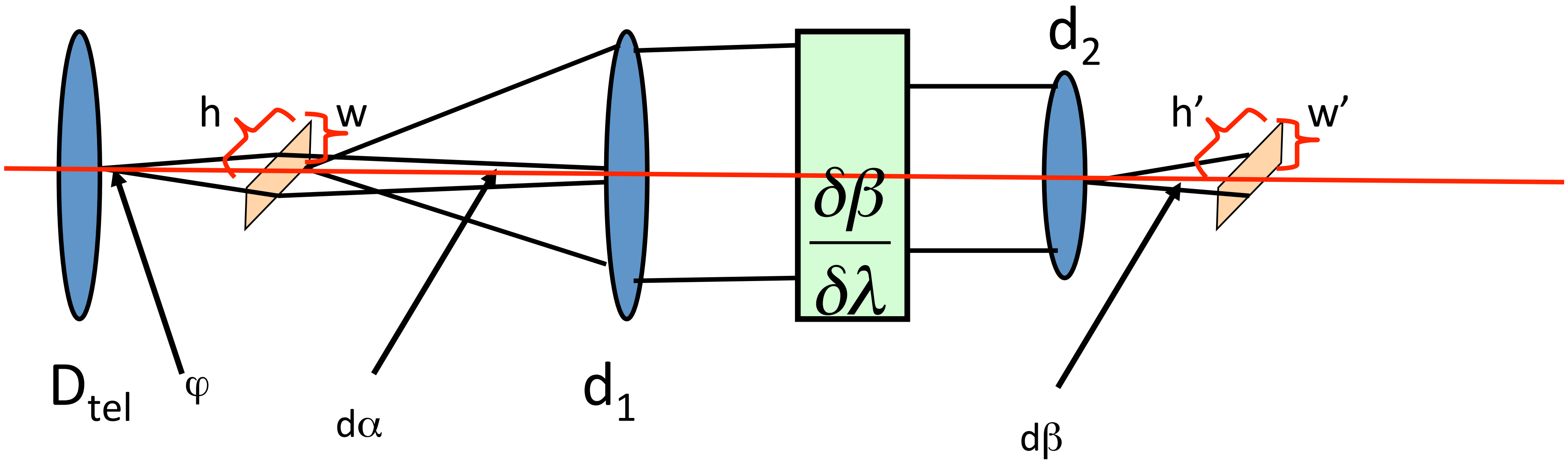
Slit Spectrograph analysis

- Follows Schroeder CH12



Anamorphic factor,

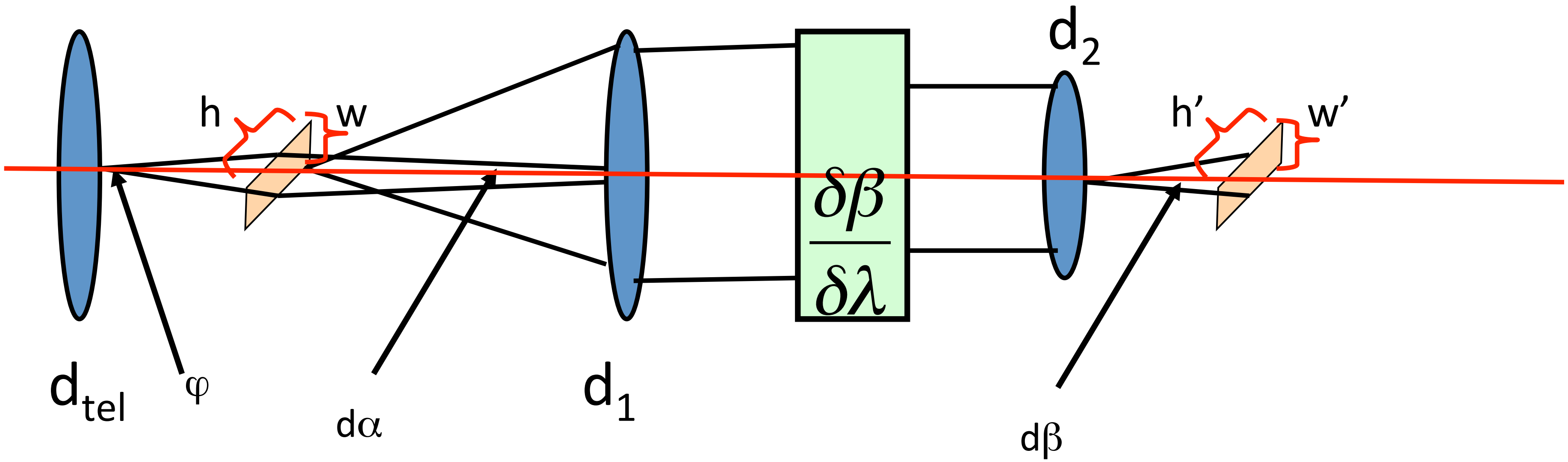
$$r = D_{coll}/ D_{cam}$$



Etendu: $$\phi D_{tel} = d\alpha\ d_1 = d\beta\ d_2$$

Anamorphism: $$r = \frac{d_1}{d_2}$$

$$\Rightarrow d\beta = \frac{\phi D_{tel}}{d_2} = \frac{\phi\, r\, D_{tel}}{d_1}$$

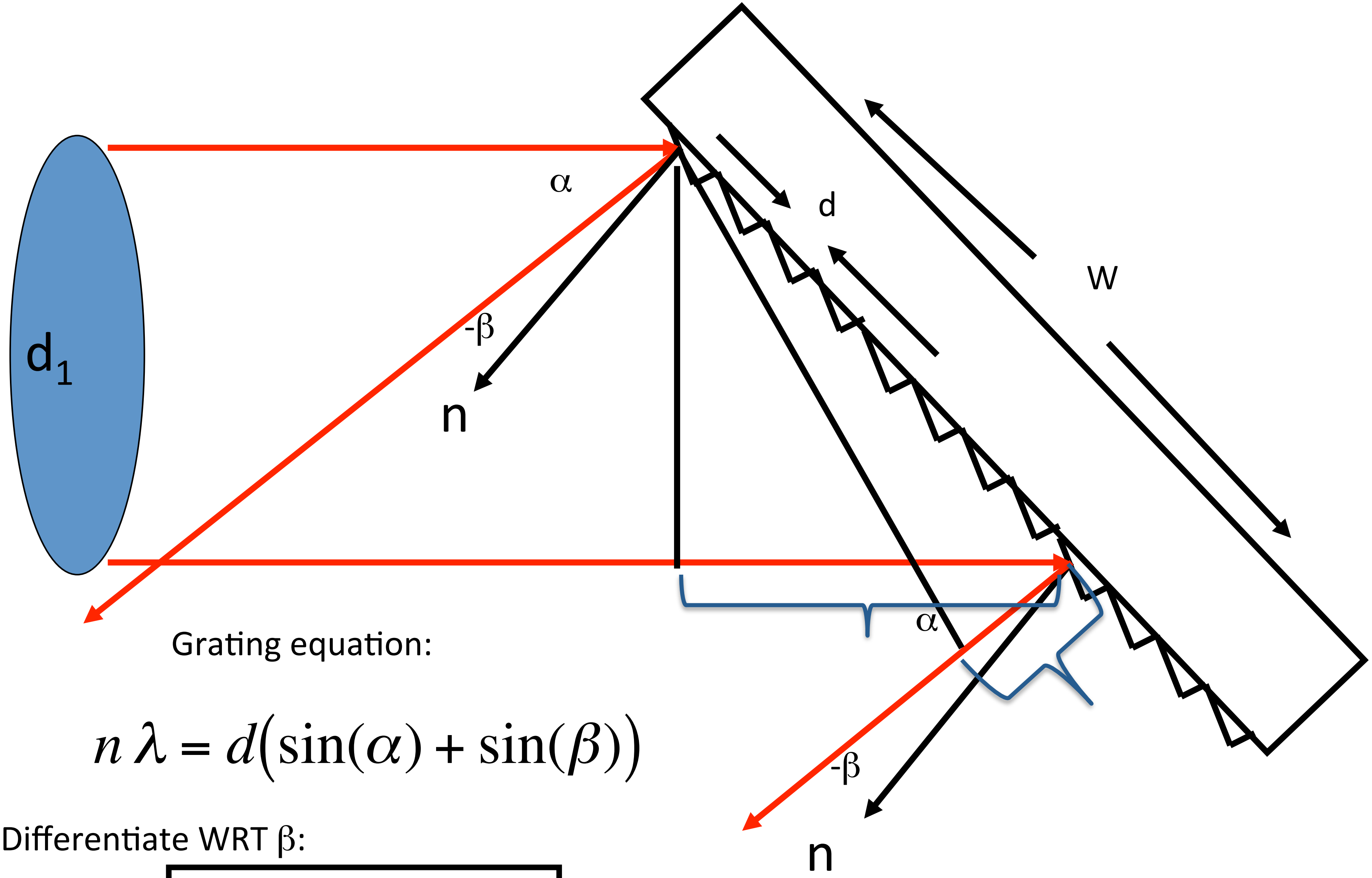


$$d\lambda = \lambda_2 - \lambda_1 = \frac{\delta\lambda}{\delta\beta} \bullet d\beta = \frac{\delta\lambda}{\delta\beta} \bullet \frac{\phi\, r\, D_{tel}}{d_1}$$

$$\phi\, R = \phi \frac{\lambda}{d\lambda} = \frac{\delta\beta}{\delta\lambda} \bullet \frac{\lambda\, d_1}{r D_{tel}}$$

$$\phi R = \phi \frac{\lambda}{d\lambda} = \frac{\delta\beta}{\delta\lambda} \bullet \frac{\lambda d_1}{r D_{tel}}$$

- The spectrograph “knows” about the telescope.
- The larger the telescope the larger the spectrograph at fixed slit width and resolution
- Move a spectrograph to a larger telescope, reduce R or ϕ or both!



Grating equation:

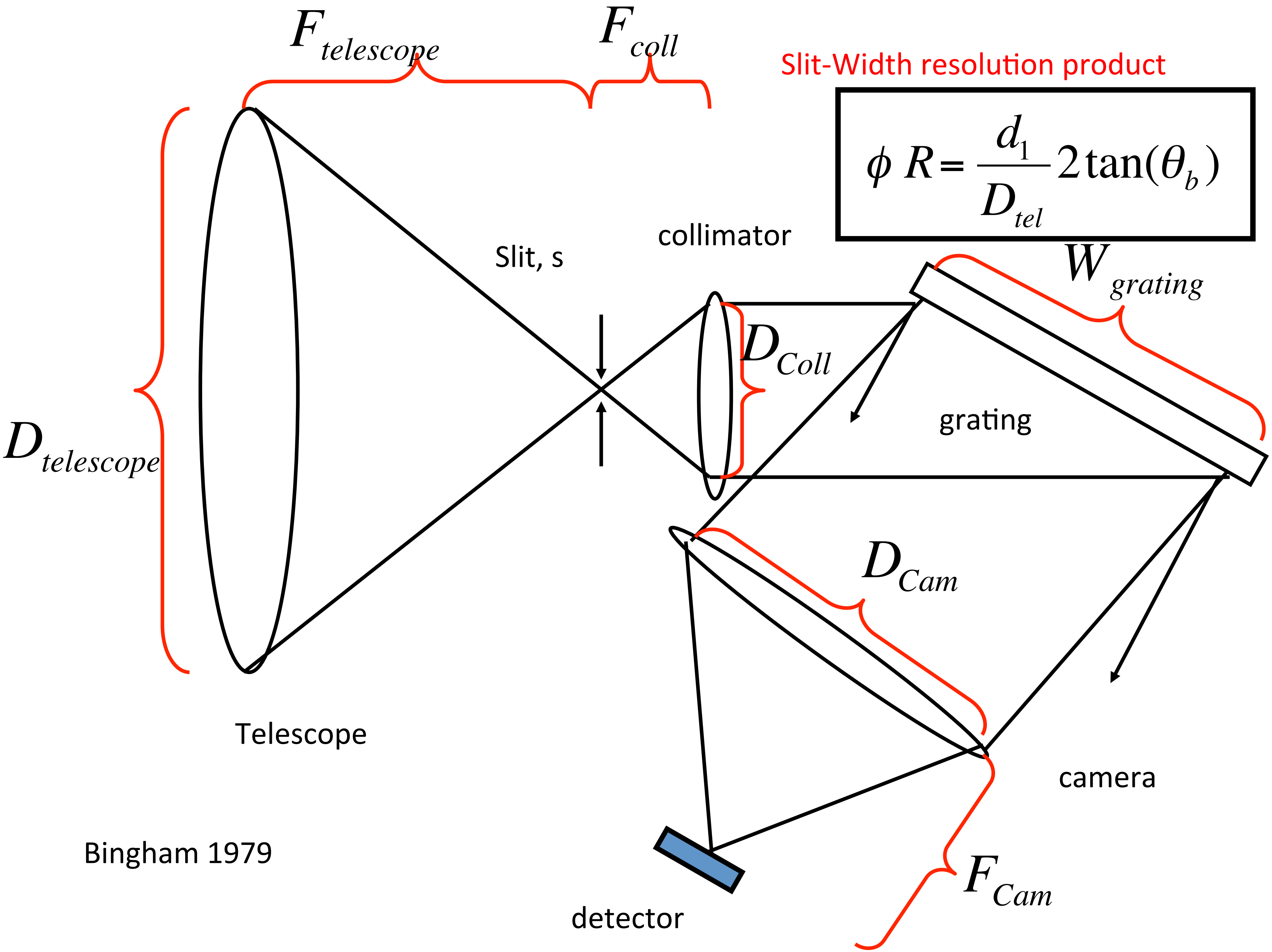
$$n\lambda = d\left(\sin(\alpha) + \sin(\beta)\right)$$

Differentiate WRT β:

$$\boxed{\frac{\delta\lambda}{\delta\beta} = \frac{d\cos(\beta)}{n}}$$

Slit-Width resolution product

$$\phi R = \frac{d_1}{D_{tel}} 2\tan(\theta_b)$$



Bingham 1979

OPD available for interference in the *coherent* beam !

Diff-limited

$$\phi = \frac{\lambda}{D_{tel}} \quad \Rightarrow \quad R = \frac{d_1}{\lambda} 2\tan(\theta_b)$$

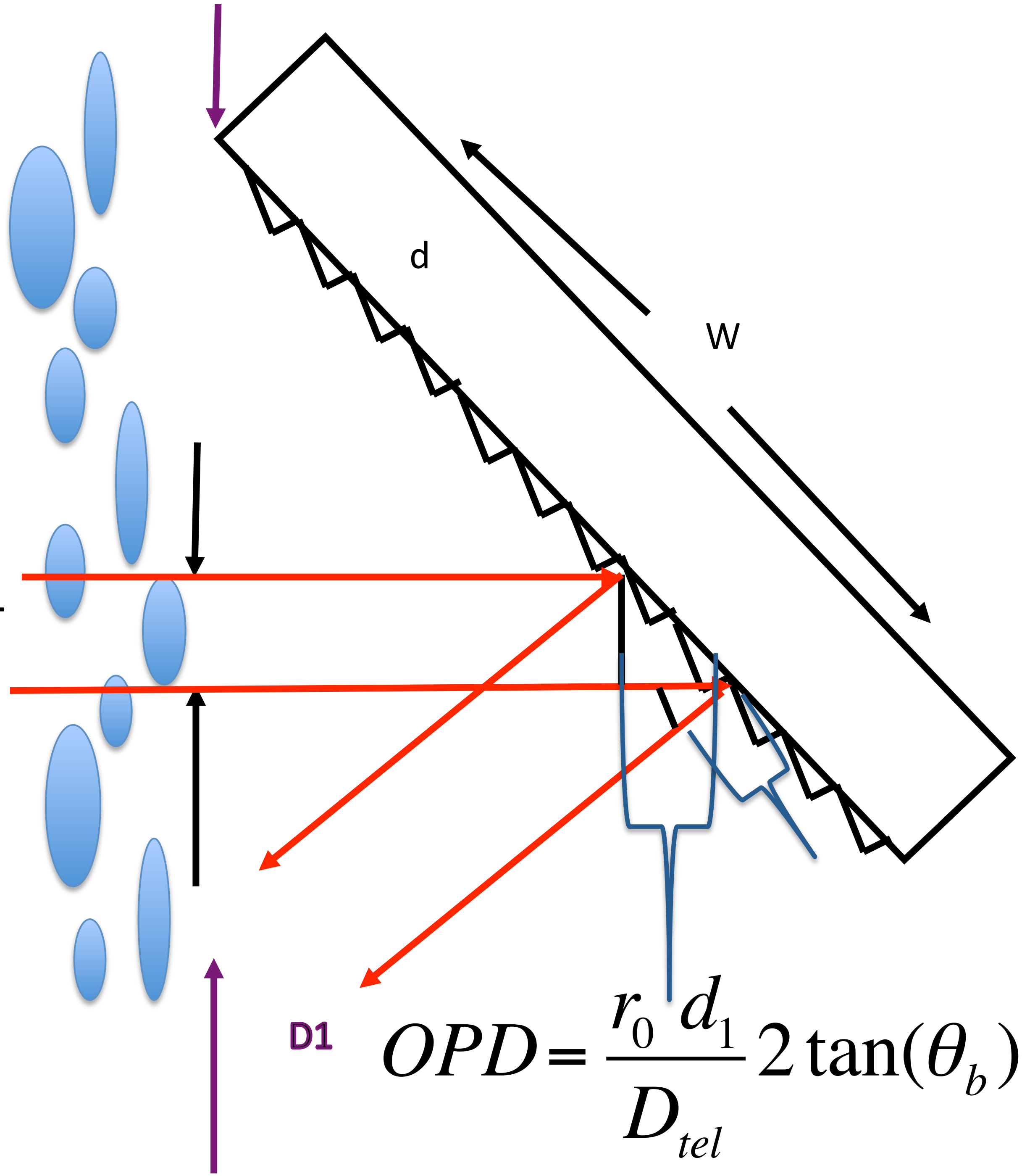
seeing-limited

$$\phi = \frac{\lambda}{r_0} \quad \Rightarrow \quad R = \frac{r_0 \, d_1}{D_{tel}\lambda} 2\tan(\theta_b)$$

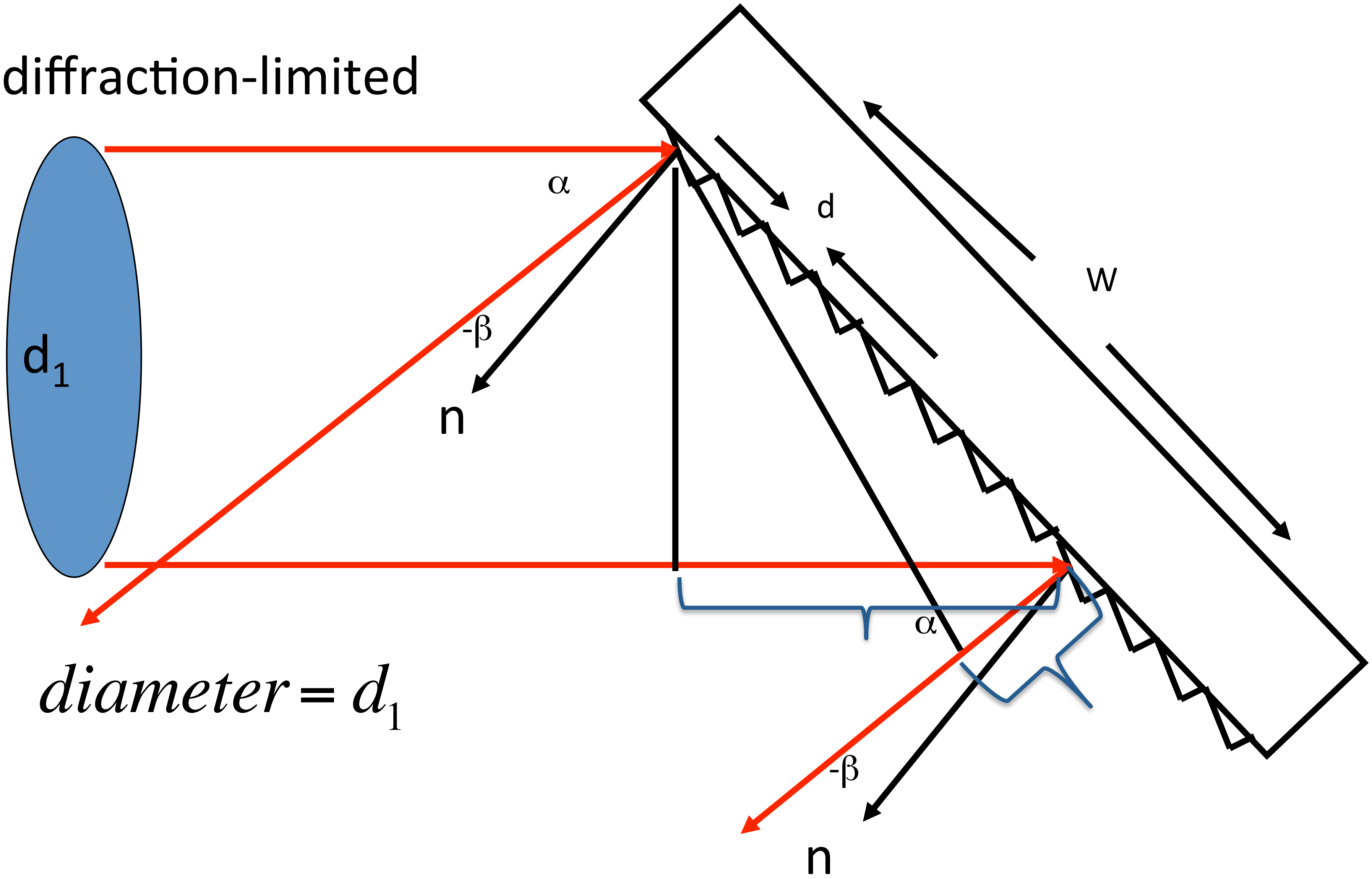
* Not just for Littrow: n*grooves * nλ = OPD

seeing-limited

$$diameter = \frac{r_0 \, d_1}{D_{tel}}$$



$$OPD = \frac{r_0 \, d_1}{D_{tel}} 2\tan(\theta_b)$$



$$OPD = d_1\left(\sin(\alpha)+\sin(\beta)\right) = d_1 2\tan(\theta_b)$$

- One way to think about this: Spectrograph resolution is NOT a function of the spectrograph or the optics!
- R ~ OPD or optical time delay available for interference in the *coherent* beam (works for prisms and other dispersing elements too)
- The job of the telescope/spectrograph/AO system is to create as much OPD as possible then collect that information!

Some numbers:
Consider collimator diameter for an R2 ($\tan\theta=2$) spectrograph with R=50,000 at λ=1 micron

- 2.5-meter aperture > 150mm D_{col}
- 10-meter aperture > 0.61-meter D_{col}
- 30-meter aperture > 1.84-meter D_{col}

- Diffraction-limited > 12.8-mm D_{col}!

How do you get a long time delay

- Long grating (echelle)
- High index (immersion grating
- Big beam
- All of the above

What are Echelles/echellettes?

- Course, precisely-ruled gratings (few grooves/mm)
- Used at high-angles= high R; R= $\tan(\theta_b)$
- θ_b is BIG, θ_b = 63 degrees to 78 degrees
- Used at high orders
- N=100-600 (echelle)
- N=10-100 (echellette)

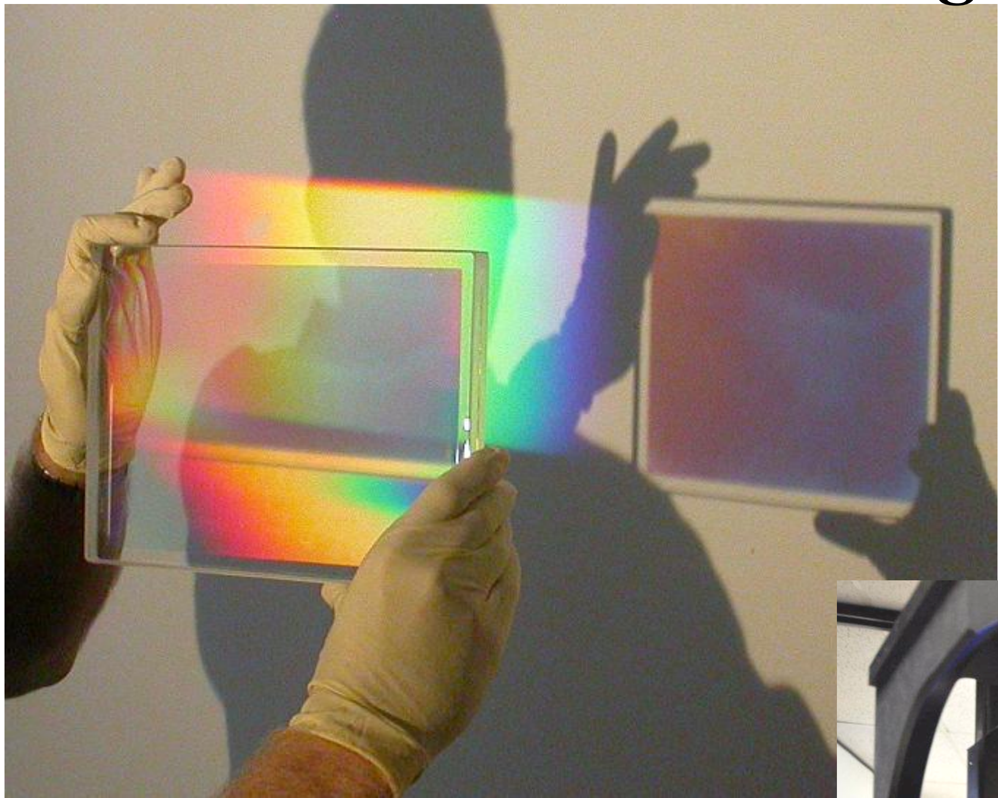
Echelles/echellettes important features

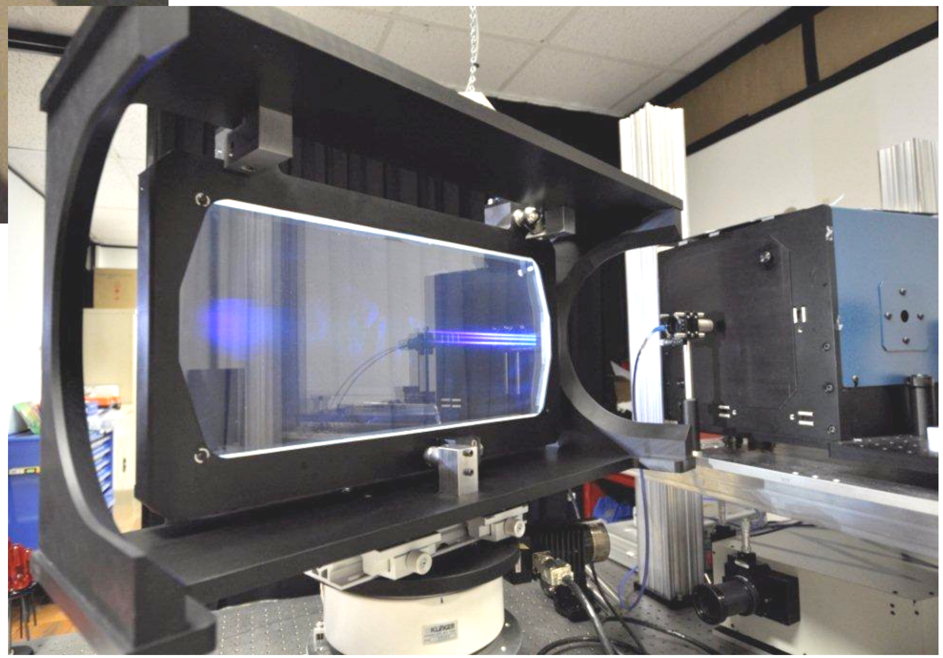
- High dispersion in compact package
- High R-value (high $\tan\theta_b$) High throughput
- High blaze efficiency over wide wavelength range
- Nearly free of polarization effects

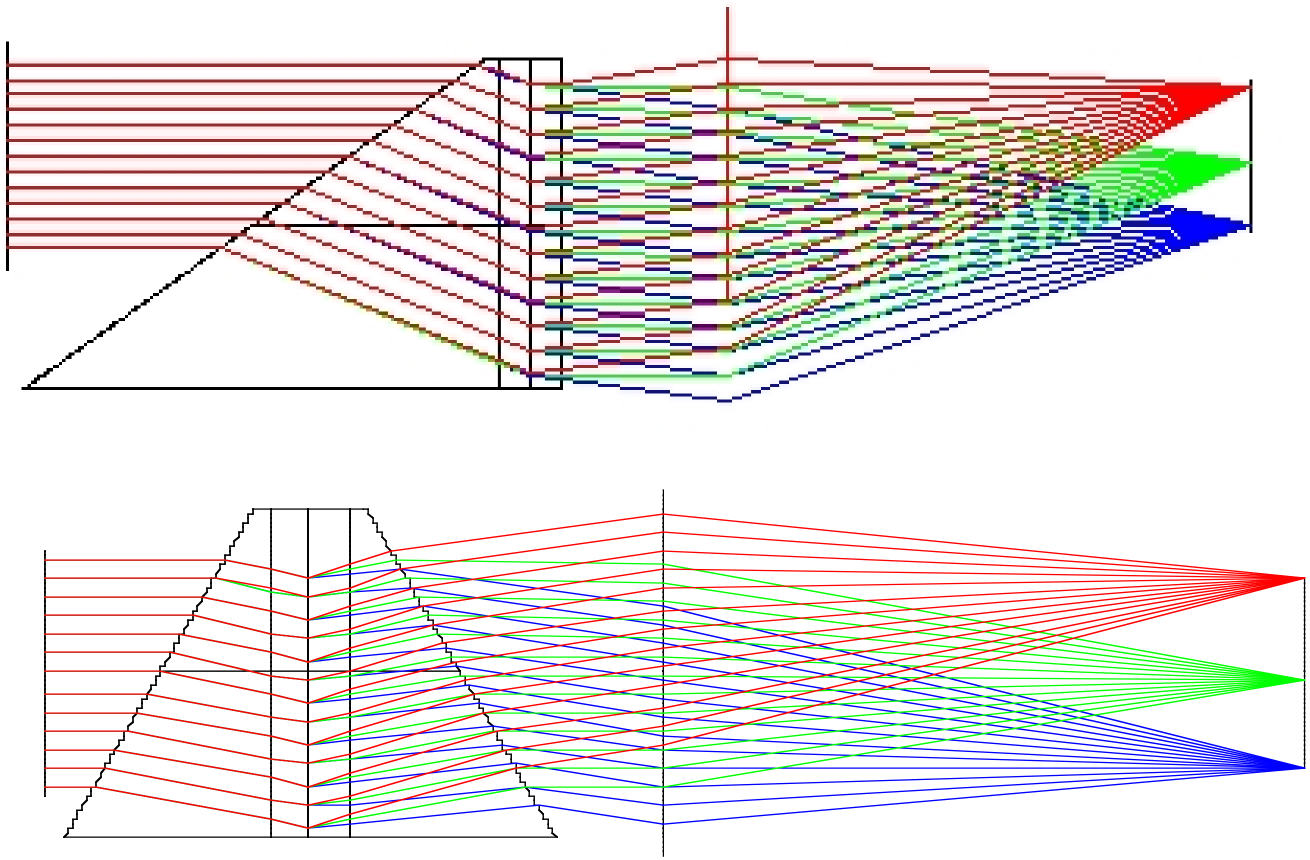
Echelles/echellettes disadvantages

- Hard to manufacture
- Orders overlap
- Need order-blocking filters or
- Cross-dispersion (becomes an advantage with a 2-D detector)

Volume Phase Holographic Gratings

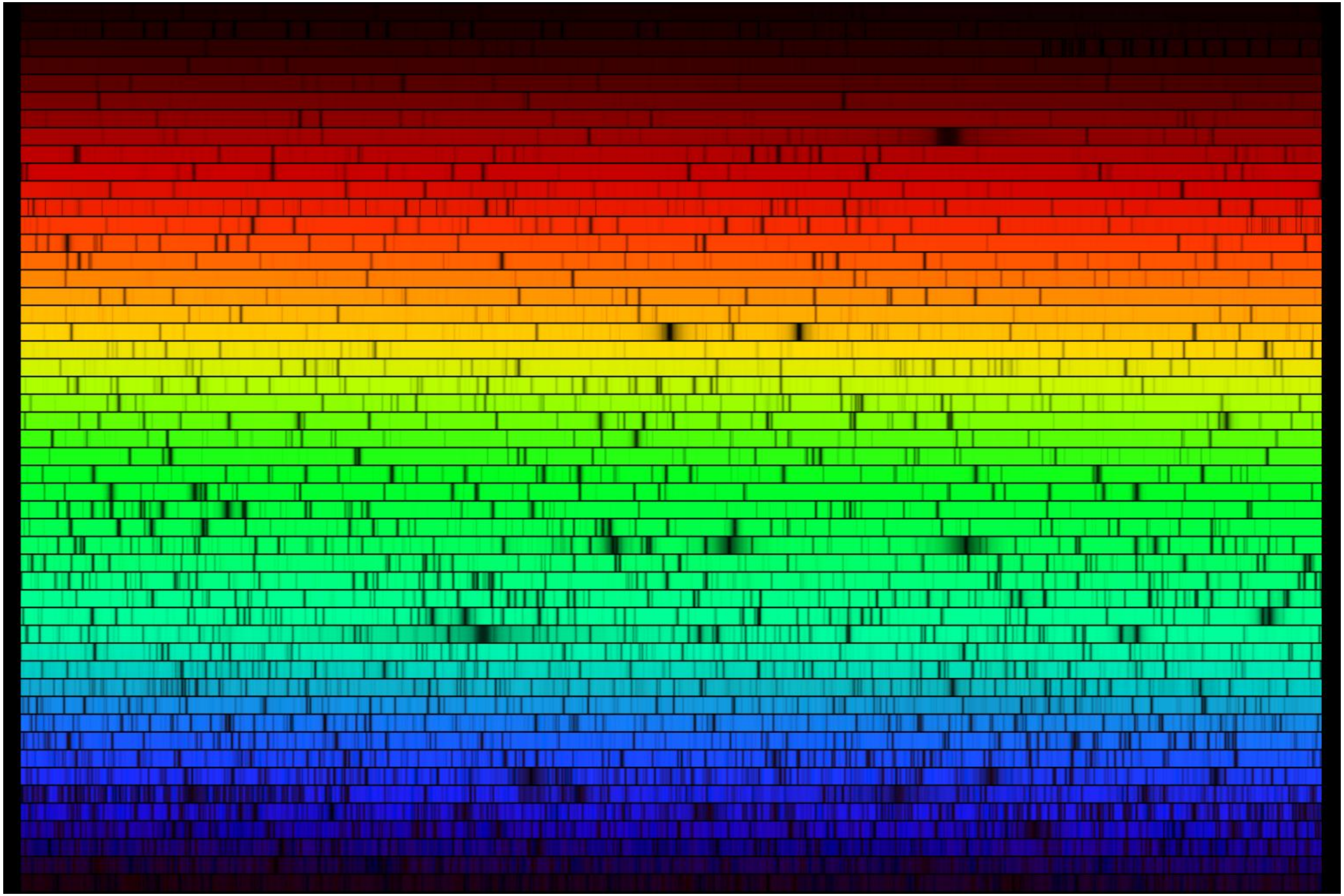


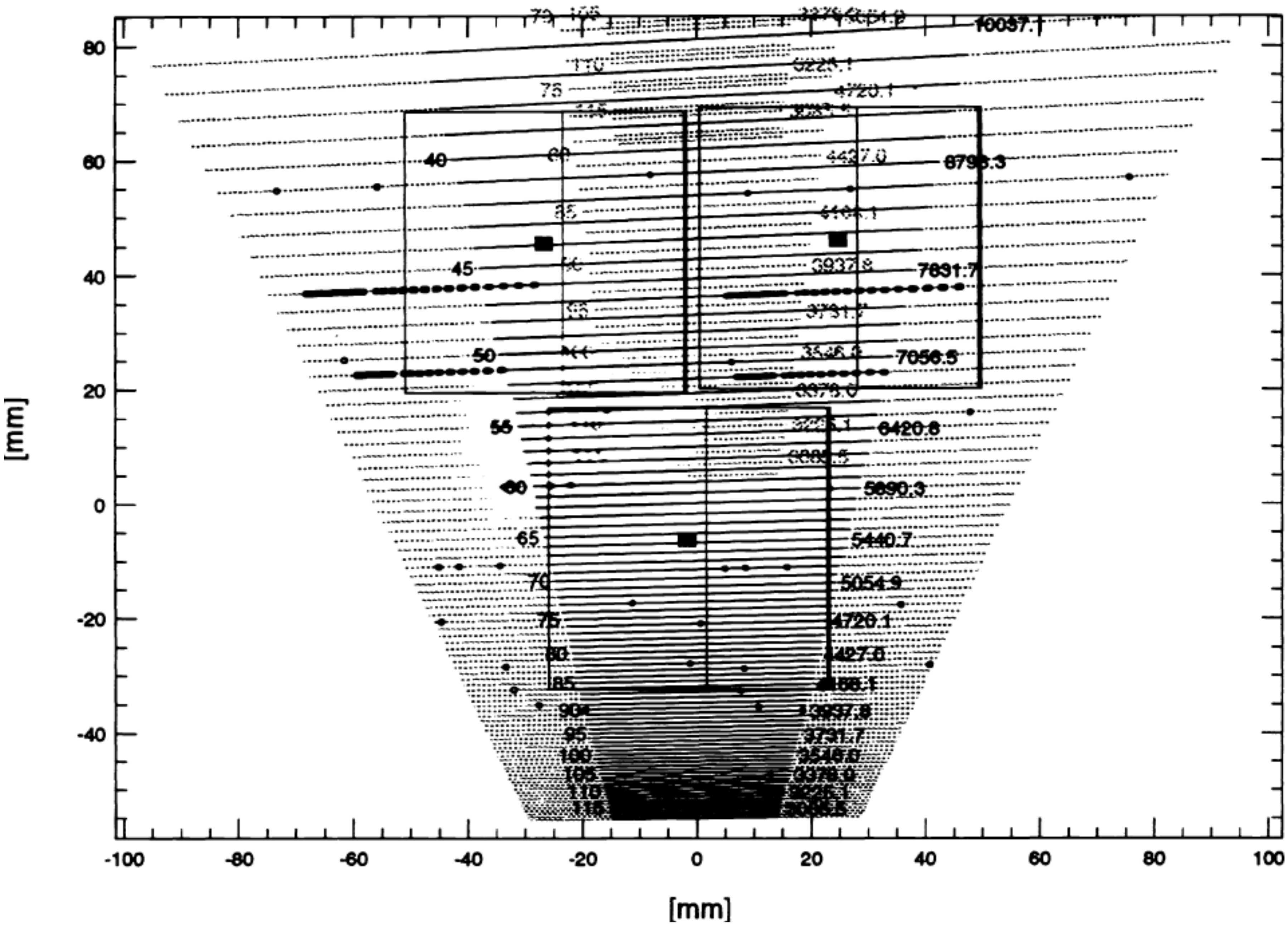




Examples of VPH grisms with tilted fringes (above, 1a), and fringes at Littrow (below, 1b). Both gratings are 930 l/mm blazed at 600 nm. For reference, the size of the beam, paraxial camera and focal surface are the same.

* Hill, Wolf, Tufts, Smith, 2003, SPIE, 4842,





[mm]
80
60
40
20
0
-20
-40
-100
-80
-60
-40
-20
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20
40
60
80
100
[mm]
10037.1
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45
50
55
65
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7631.7
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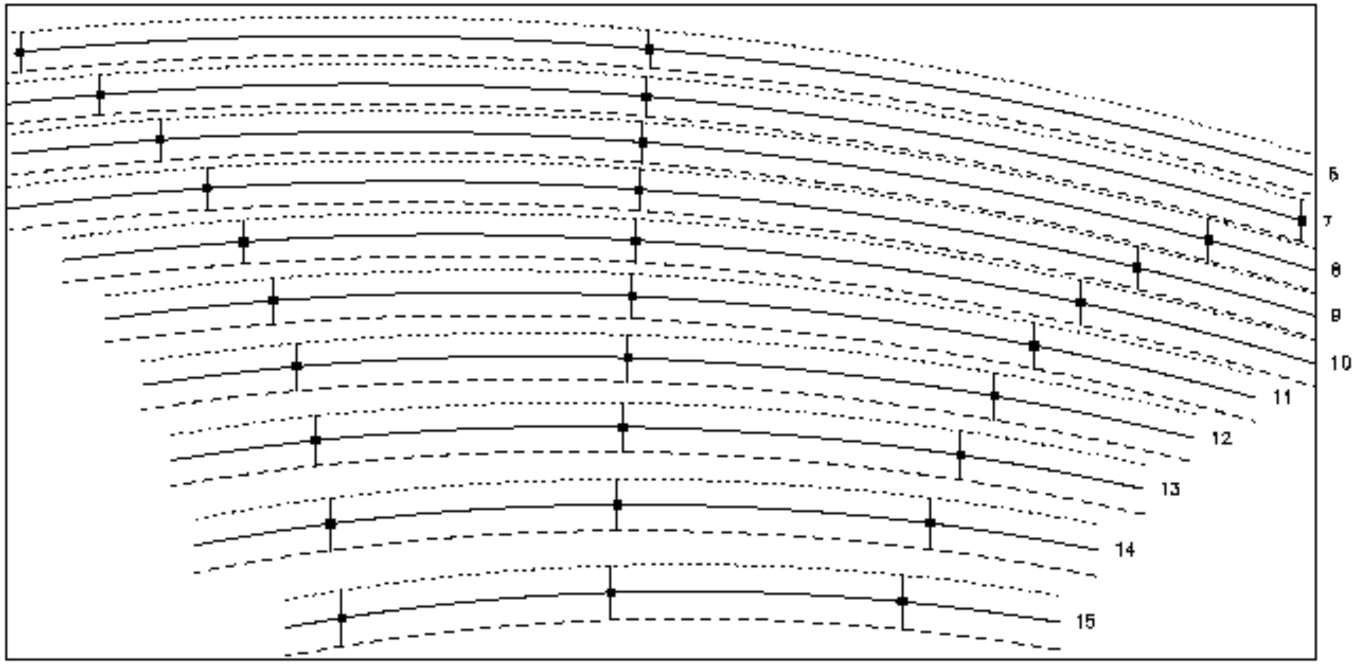
6420.8
5440.7
5054.9
4720.1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End lecture 4