

# ASTR 400/700: Stellar Astrophysics

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# **Exams and homework**

- **The mid-terms and final exams are closed book and held in class. I will provide an equation sheet.**
- **Mid-term will cover everything up to and including Lecture 11. Final will cover everything!**
- **Graduate students will present a ~20 minute seminar on a stellar astrophysics related topic during last week of class. Proposed topic must be submitted by the mid-term exam. PDFs of presentations must be submitted to me (via email) by December 2.**

# Upcoming schedule

- **Sep 29: Solar evolution effect on climate (Zan Stine)**
- **Oct 6: Mid-term**
- **Oct 13: NO CLASS!**
- **Nov 29: Brown Dwarf atmospheres (Jonathan Fortney)**
- **Dec 1: Summary**
- **Dec 6/8: A700 presentations**
- **Dec 13: NO CLASS!**

# Instrumentation

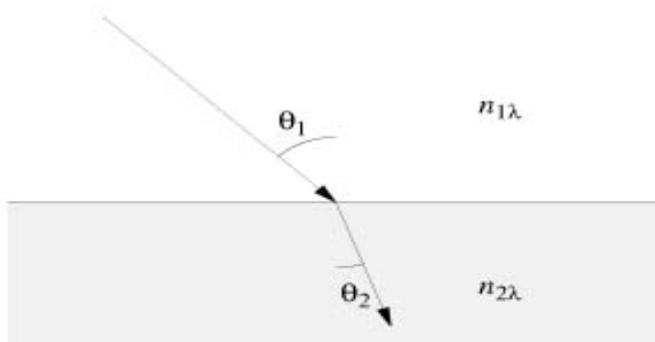
## Chapter 6

# Telescopes

- Light gathering power and resolution
- Telescopes designed for different wavelengths
- Limitations of Earth's atmosphere and satellite missions.
- Instruments (prism spectrographs and diffraction gratings), detection devices (CCDs), and methods (photometry and spectroscopy)

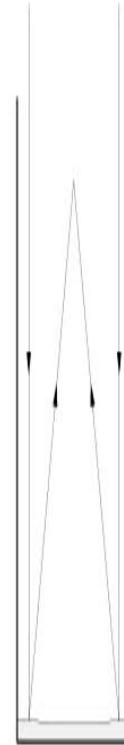
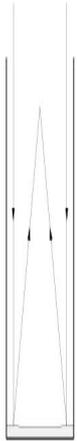
**Telescopes with lenses work because of refraction:** at the interface between two transparent media the light path changes because the *speed* of light depends on the medium that it is passing through.

Snell's Law :  $n_{1\lambda} \sin \theta_1 = n_{2\lambda} \sin \theta_2$



# Why a BIG Telescope? - Light Gathering Power

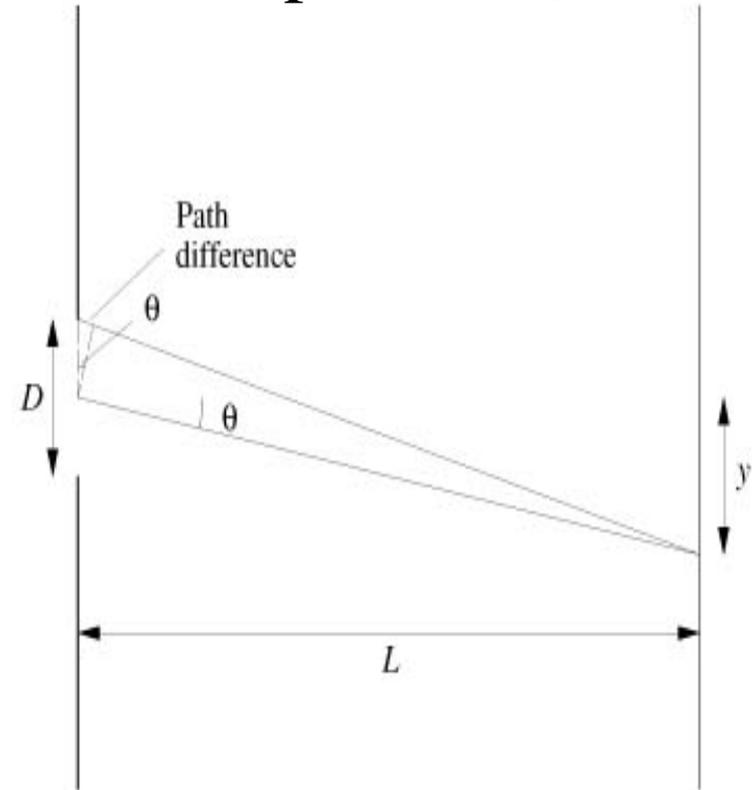
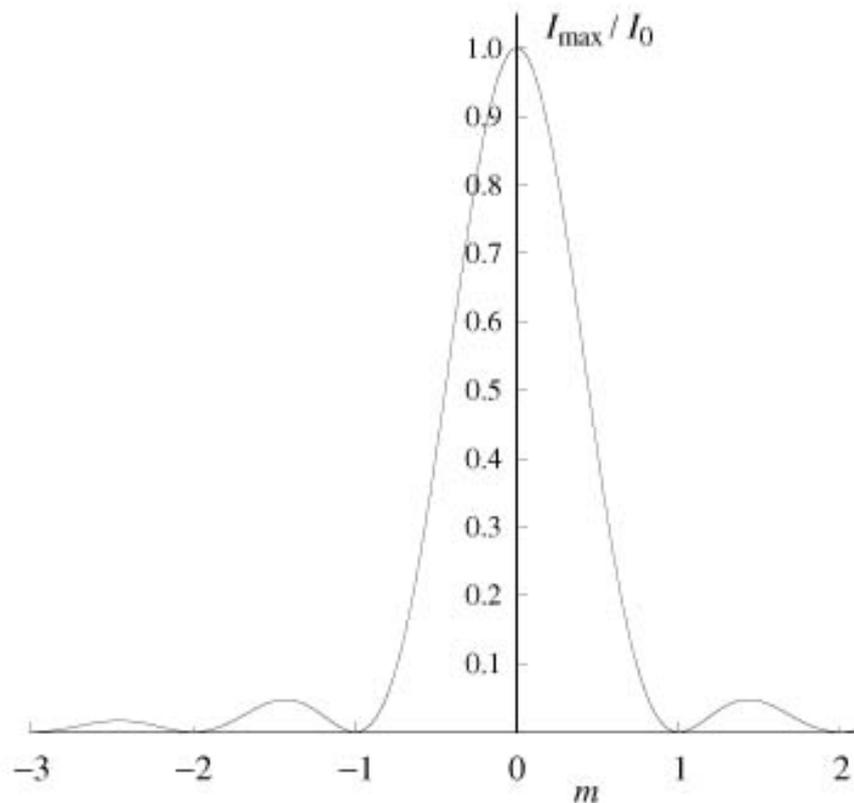
Think of a telescope as a bucket sitting in a rain of photons: increasing the aperture (diameter) of a telescope its **light gathering power** (it can capture more photons in the same amount of time because it is bigger). i.e.



$$LGP \propto E^2$$

# Resolution and the Diffraction Limit

Light from the same object incident on different portions of the telescope's mirror can interfere constructively and destructively to form a pattern of light and dark **Airy rings** (similar to the double slit experiment).





Airy rings around a single star.



The interference pattern produced as the Airy rings of two stars overlap each other.

No image can be smaller than the innermost Airy ring, and this sets the **diffraction limit** of a telescope to be

$$\theta_{\min} = 1.22(206,265) \frac{\lambda}{D}$$

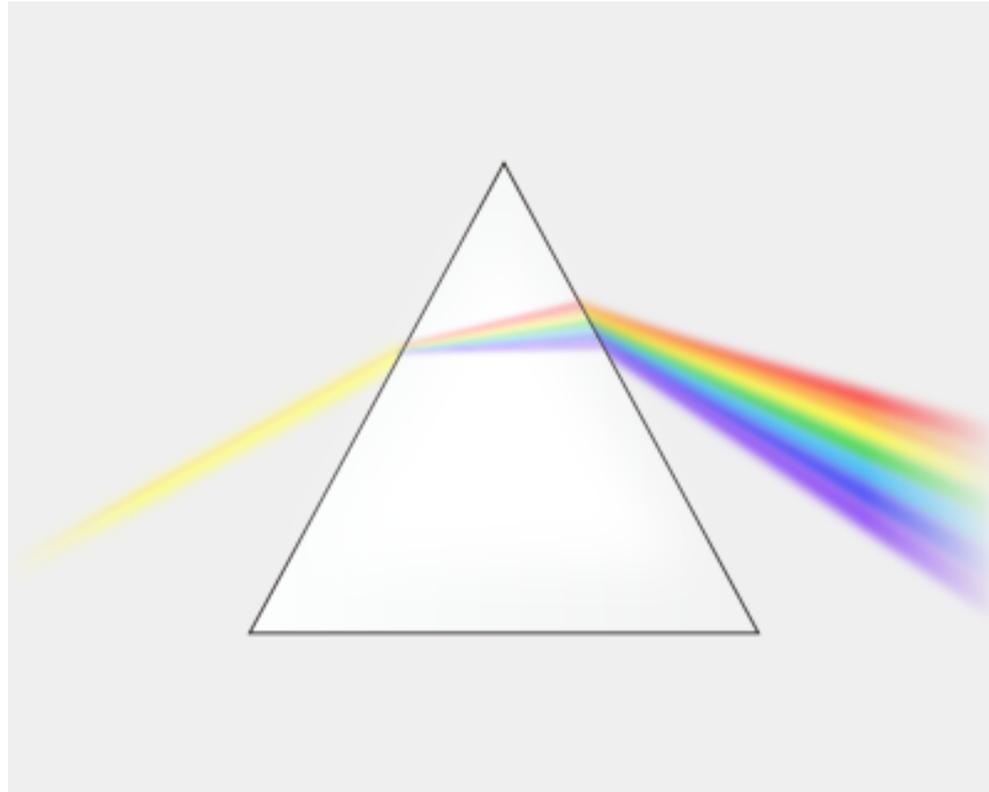
where  $D$  is the telescope's **aperture**

= diameter of the telescope's mirror

(in same units used to measure the wavelength).

$\theta_{\min}$  (the above expression gives the answer in arcseconds) sets a limit to the **resolution** of the image.

# Spectroscopy & Spectrographs



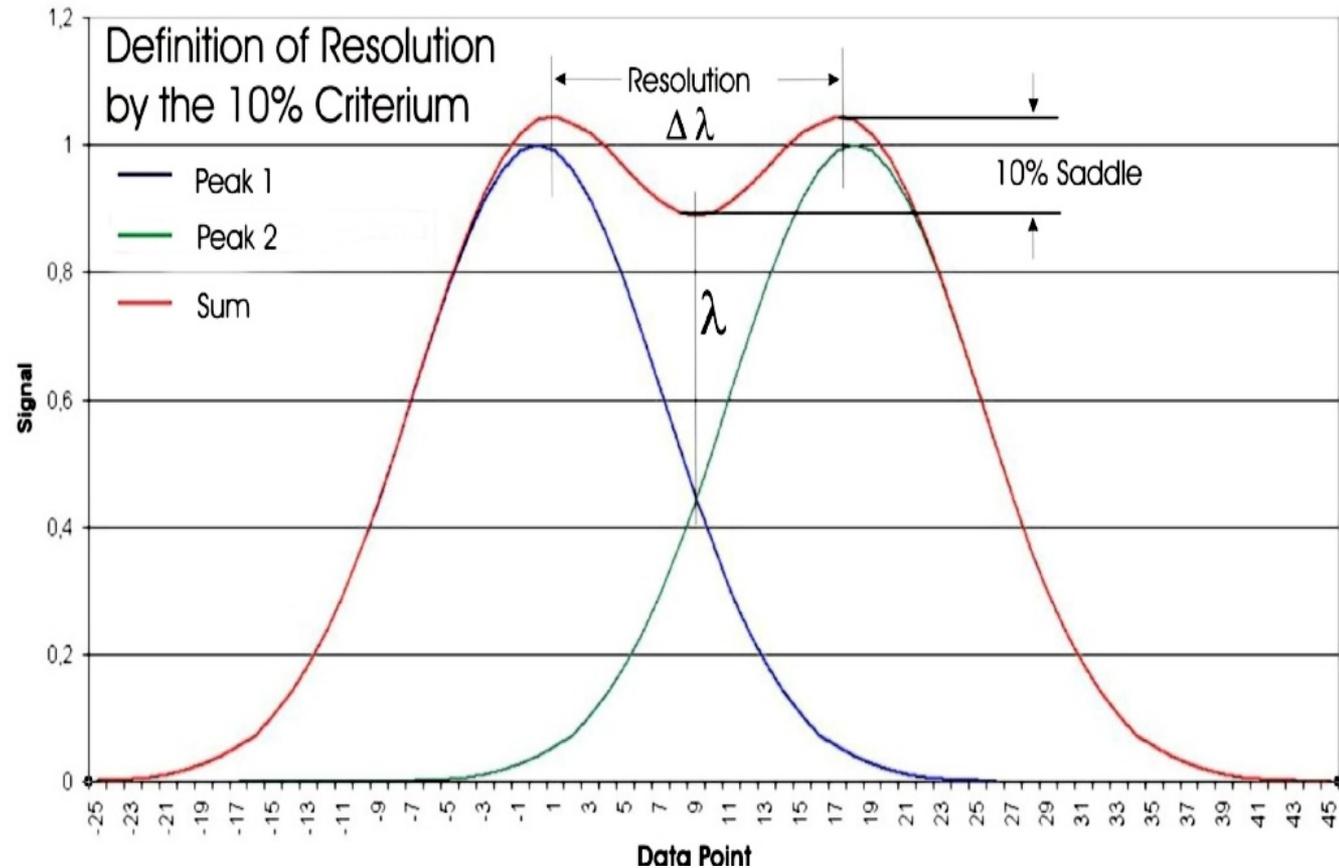
# Overview

- Spectrum, spectral resolution
- Dispersion (prism, grating)
- Spectrographs
  - longslit
  - echelle
  - fourier transform
- Multiple Object Spectroscopy

# Spectral resolution

- Smallest separation in wavelength that can still be distinguished by instrument, usually given as fraction of wavelength and denoted by  $R$ :

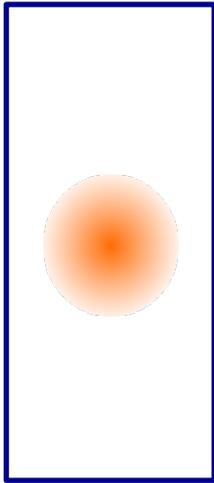
$$R = \frac{\Delta\lambda}{\lambda}$$



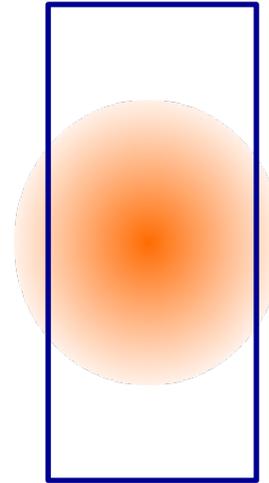
**useful, though somewhat arbitrary working definition**

# Seeing vs. spectral resolution

- If the slit is wide, then it is the seeing that determines the spectral resolution:



Good seeing  
conditions:  
high spectral  
resolution



Bad seeing  
conditions:  
low spectral  
resolution

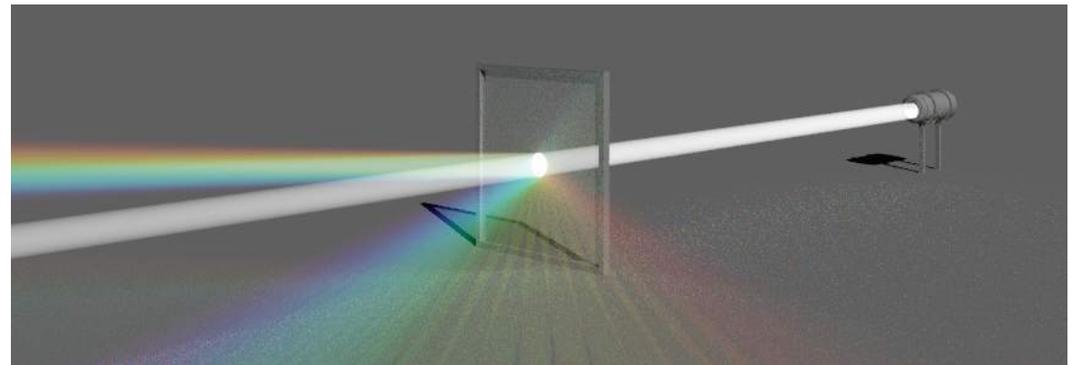
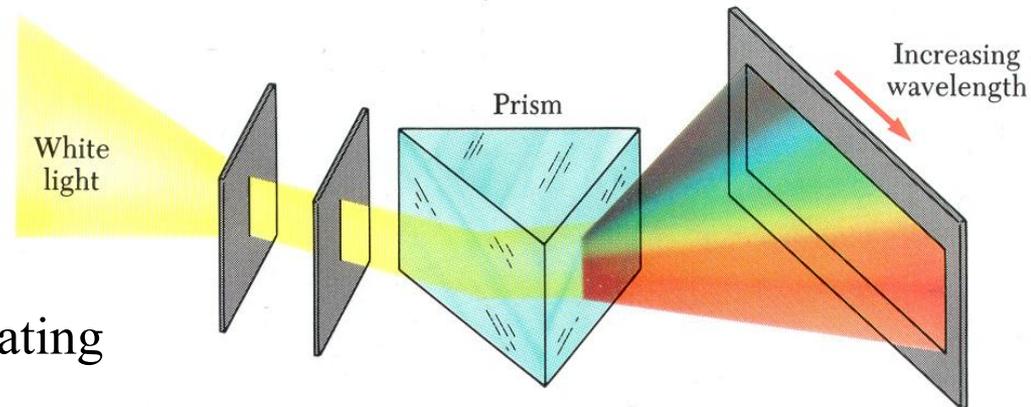
# Basic spectrograph layout

- a means to isolate light from the source in the focal plane, usually a slit
- “collimator” to make parallel beams on the dispersive element
- dispersive element, e.g. a prism or grating. Reflection gratings much more frequently used than transmission gratings
- “Camera”: imaging lens to focus beams in the (detector) focal plane + detector to record the signal

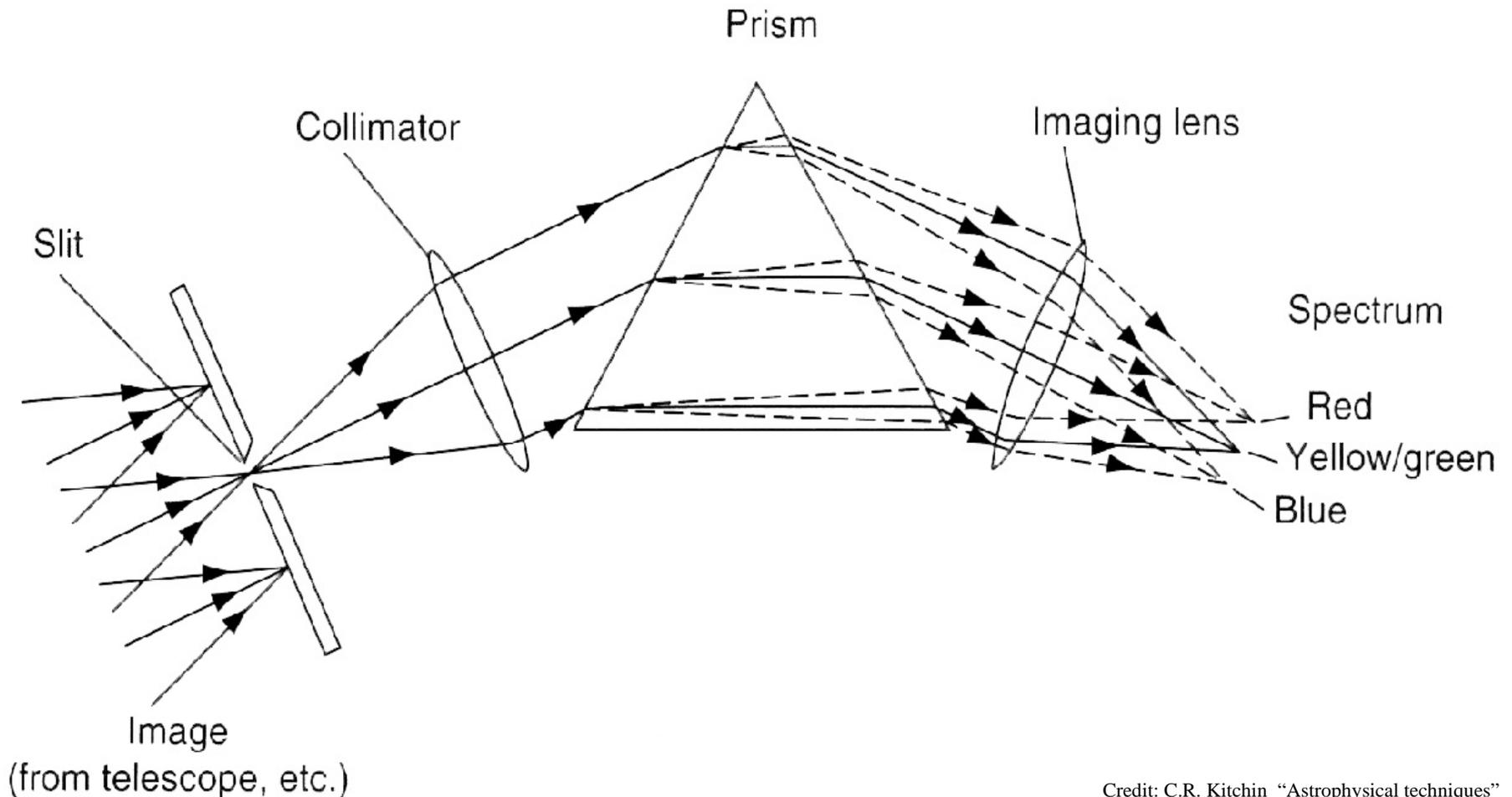
# Dispersion

Splitting up light in its spectral components achieved by one of two ways:

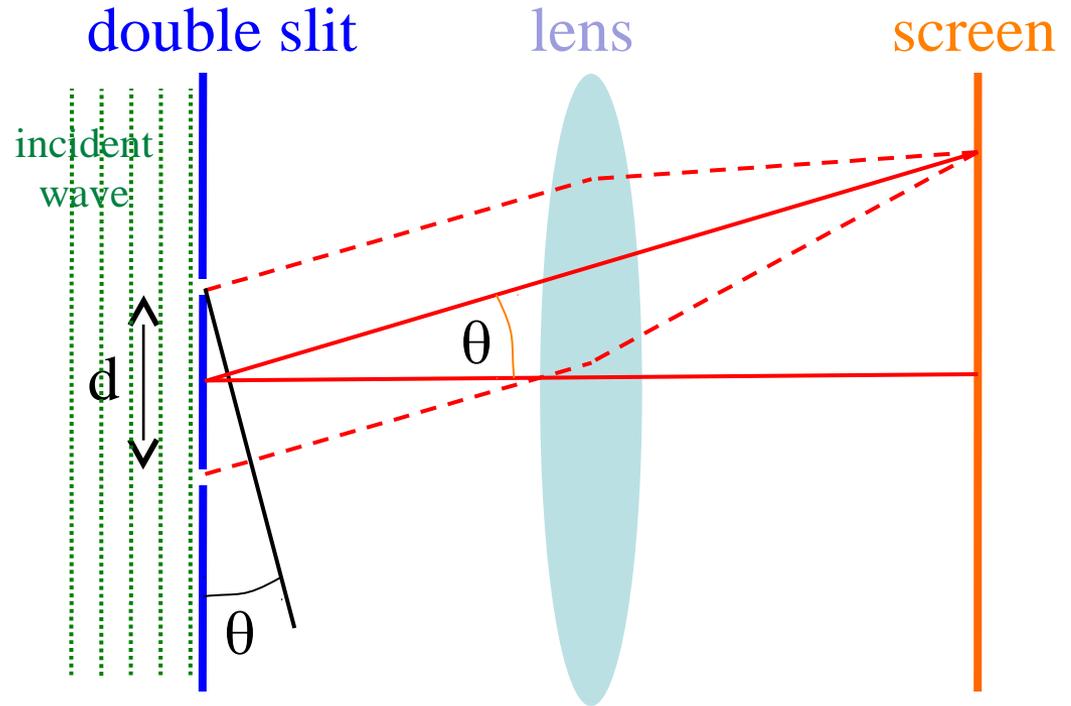
- differential refraction
  - prism
- interference
  - reflection/transmission grating
  - fourier transform
  - (Fabry-Perot)



# Prism spectrograph layout



# Young's double slit experiment



# Young's double slit experiment

Optical path difference:

$$\Delta P = d \sin \theta$$

Phase difference:

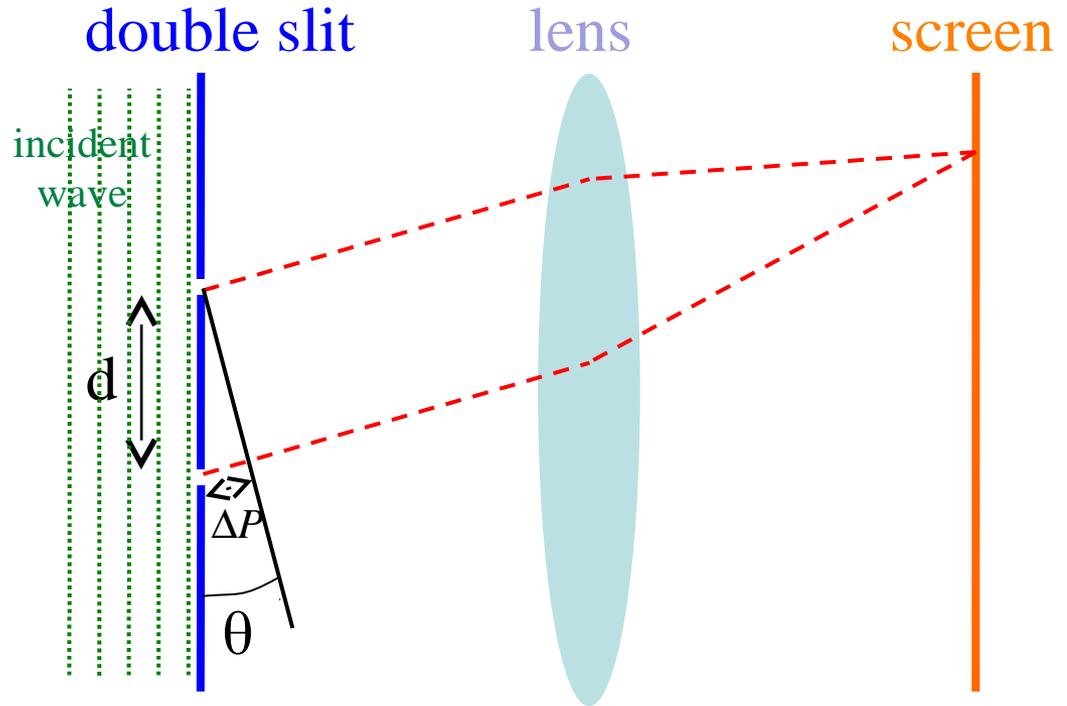
$$\Delta \phi = 2\pi \frac{\Delta P}{\lambda}$$

Add the two waves:

$$E(t) = E_1 (e^{i\omega t} + e^{i(\omega t + \Delta \phi)}) = E_1 e^{i\omega t} (1 + e^{i\Delta \phi})$$

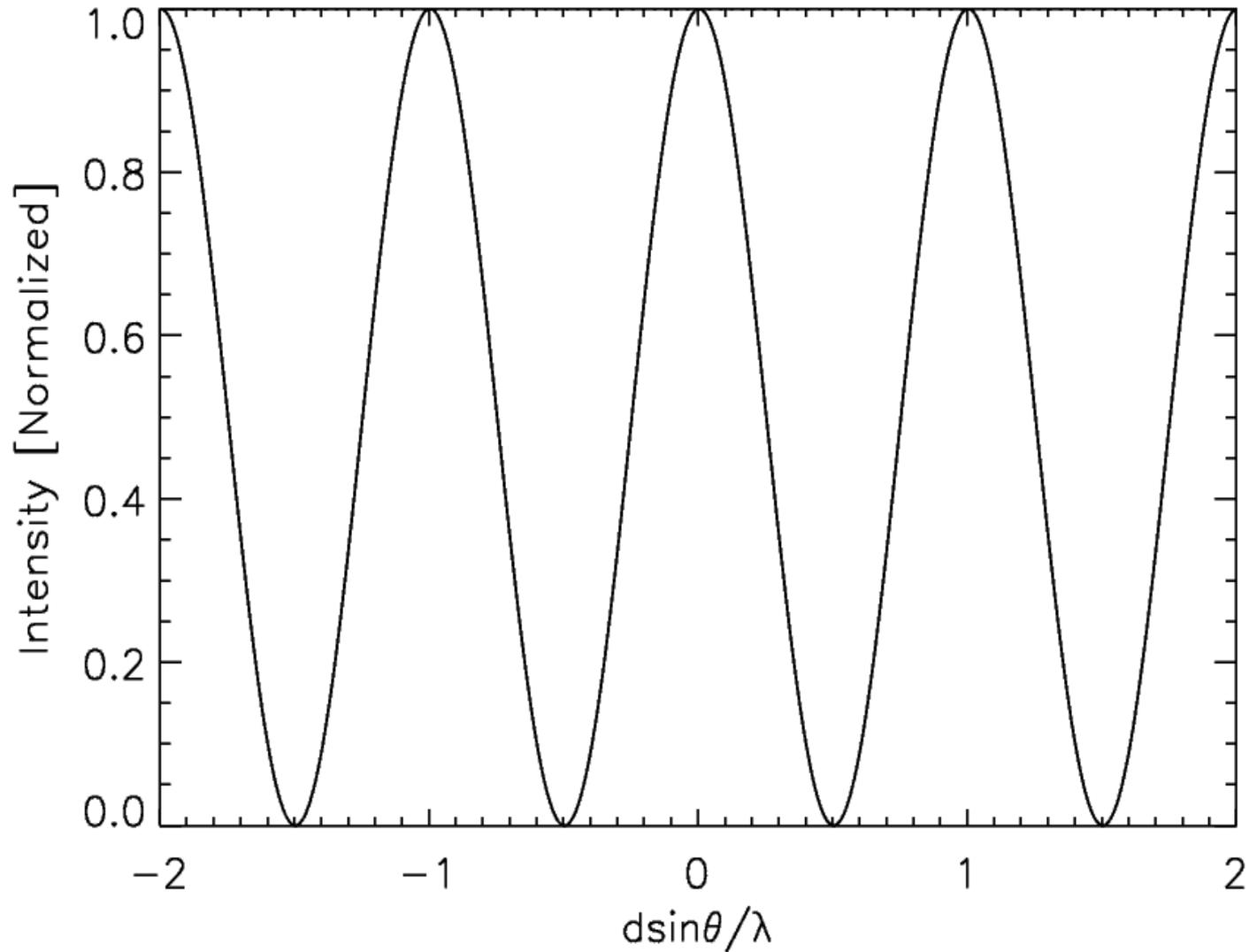
Intensity is amplitude-squared:

$$\begin{aligned} I &= E_1^2 (1 + e^{i\Delta \phi})(1 + e^{-i\Delta \phi}) = E_1^2 (2 + 2\cos \Delta \phi) \\ &= 4E_1^2 \cos^2(\Delta \phi) = 4E_1^2 \cos^2\left(\frac{2\pi d \sin \theta}{\lambda}\right) \end{aligned}$$



# Young's double slit experiment

$N=2$



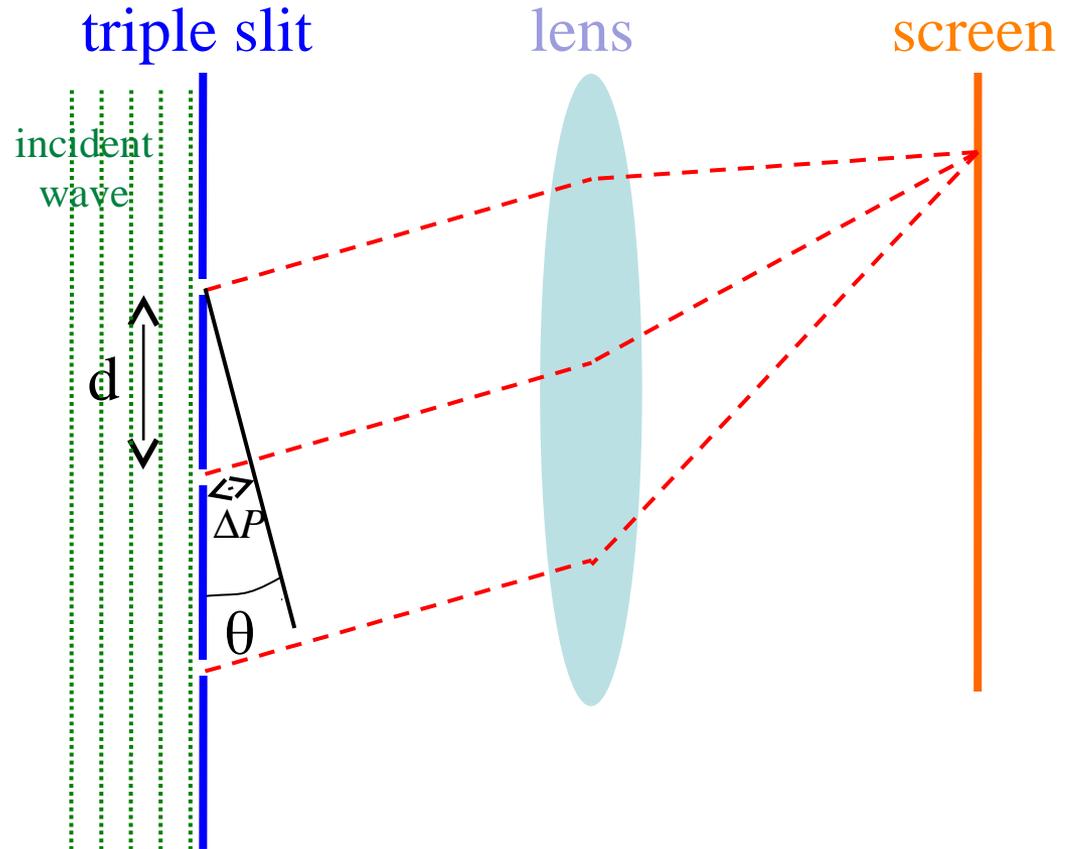
# Now a triple slit experiment...

Optical path difference:

$$\Delta P = d \sin \theta$$

Phase difference:

$$\Delta \phi = 2\pi \frac{\Delta P}{\lambda}$$

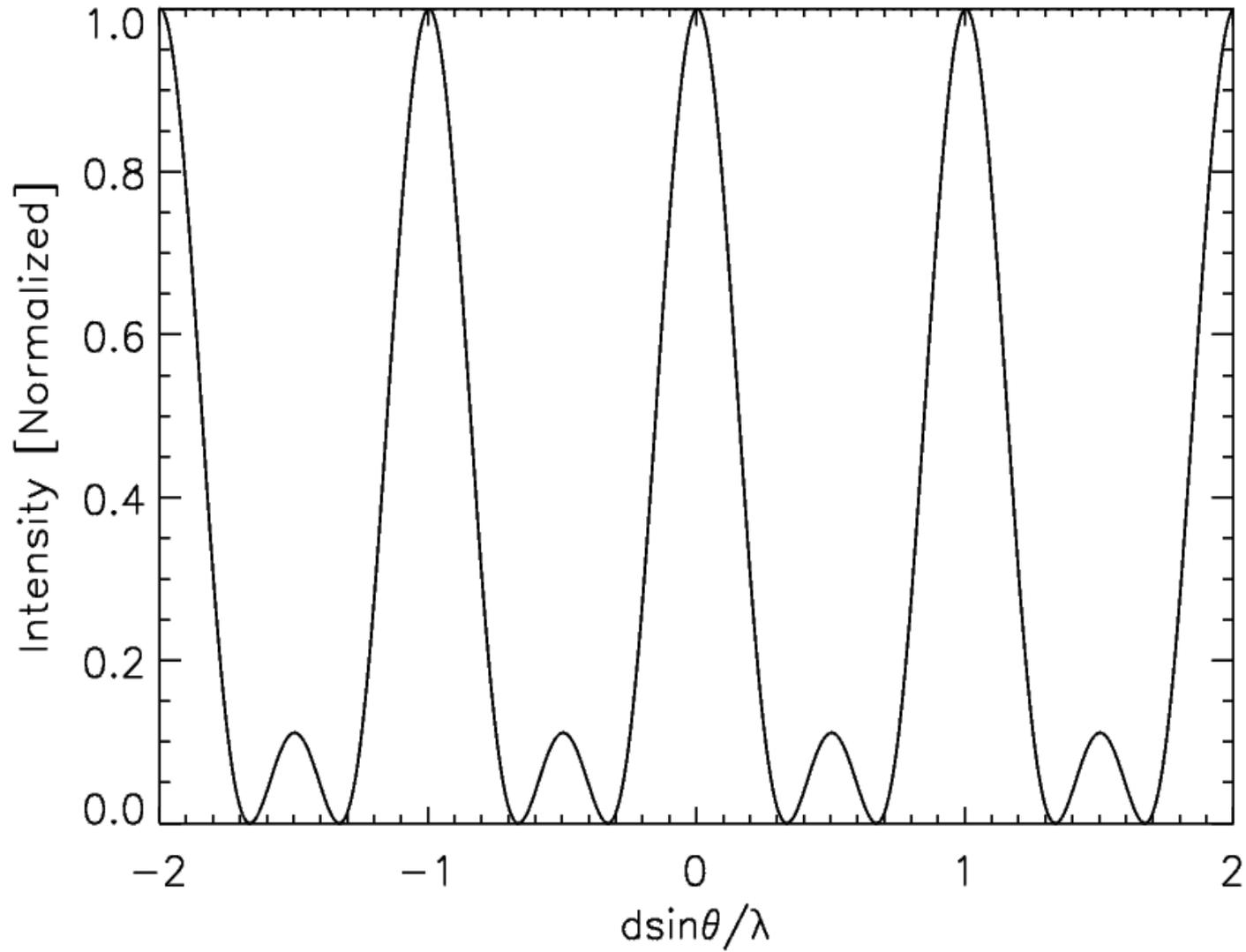


Add the three waves, and take the norm:

$$I = \left| E_1 \left( e^{i\phi} + e^{2i\phi} \right) \right|^2$$

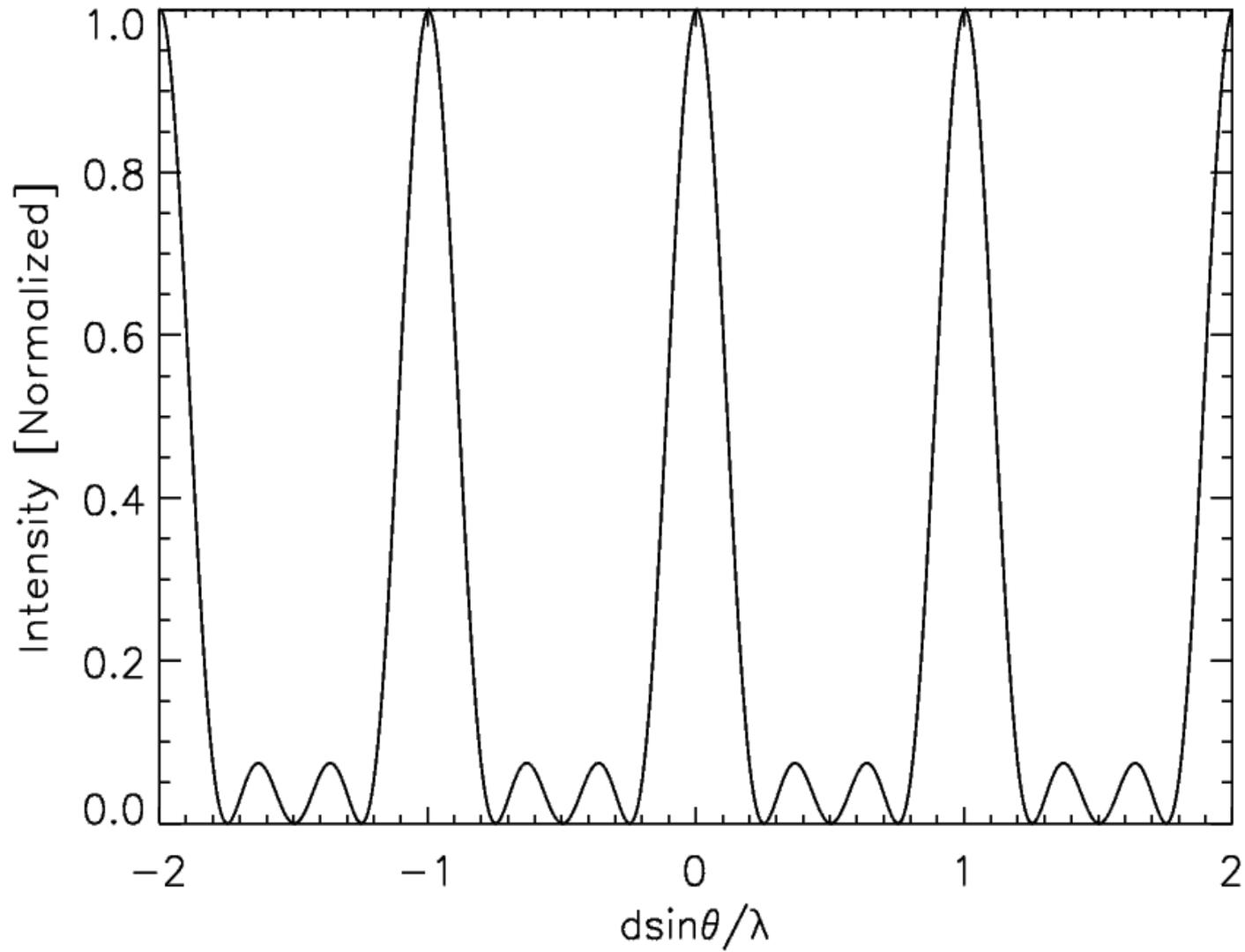
# Now a triple slit experiment...

$N=3$



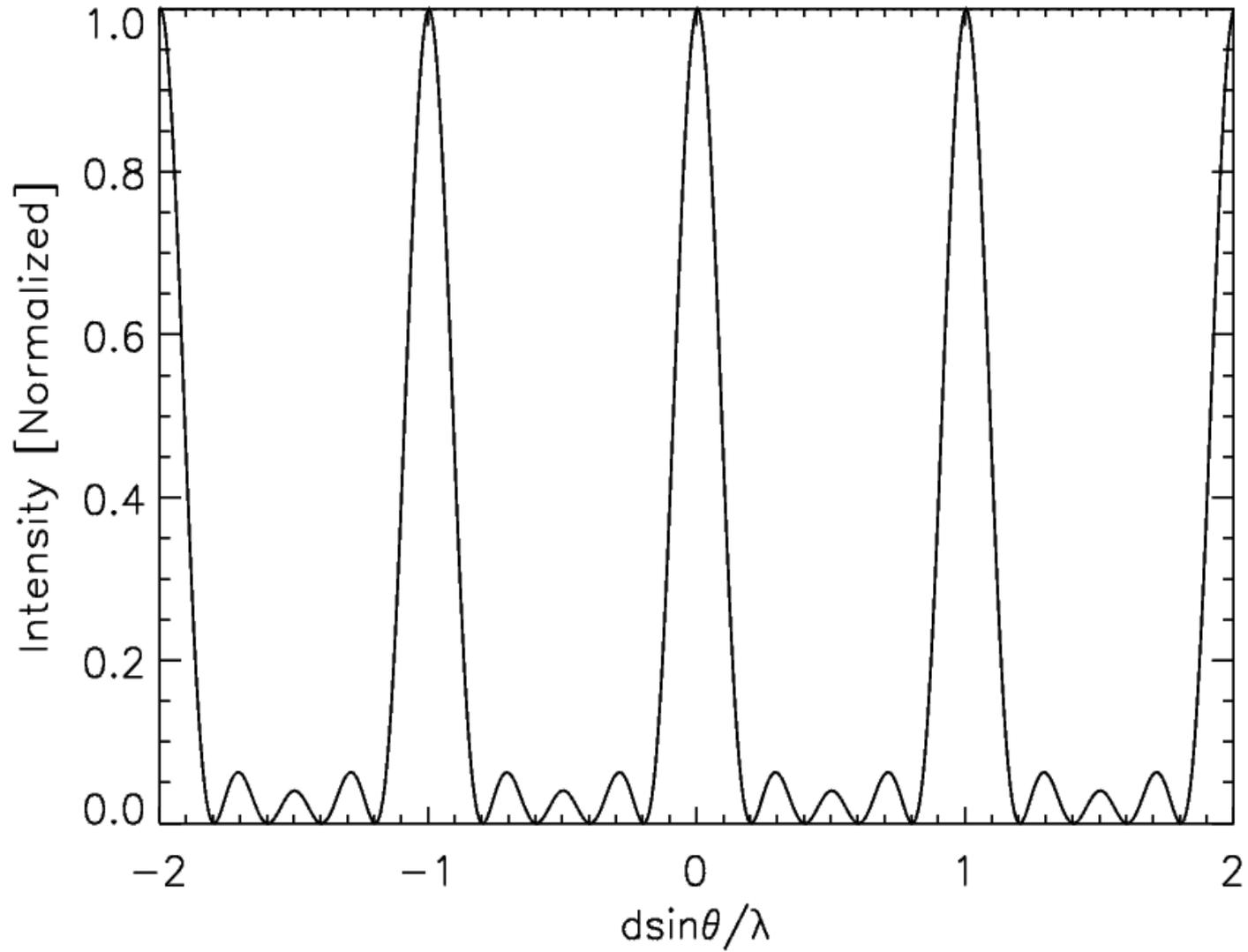
# Adding more slits...

$N=4$



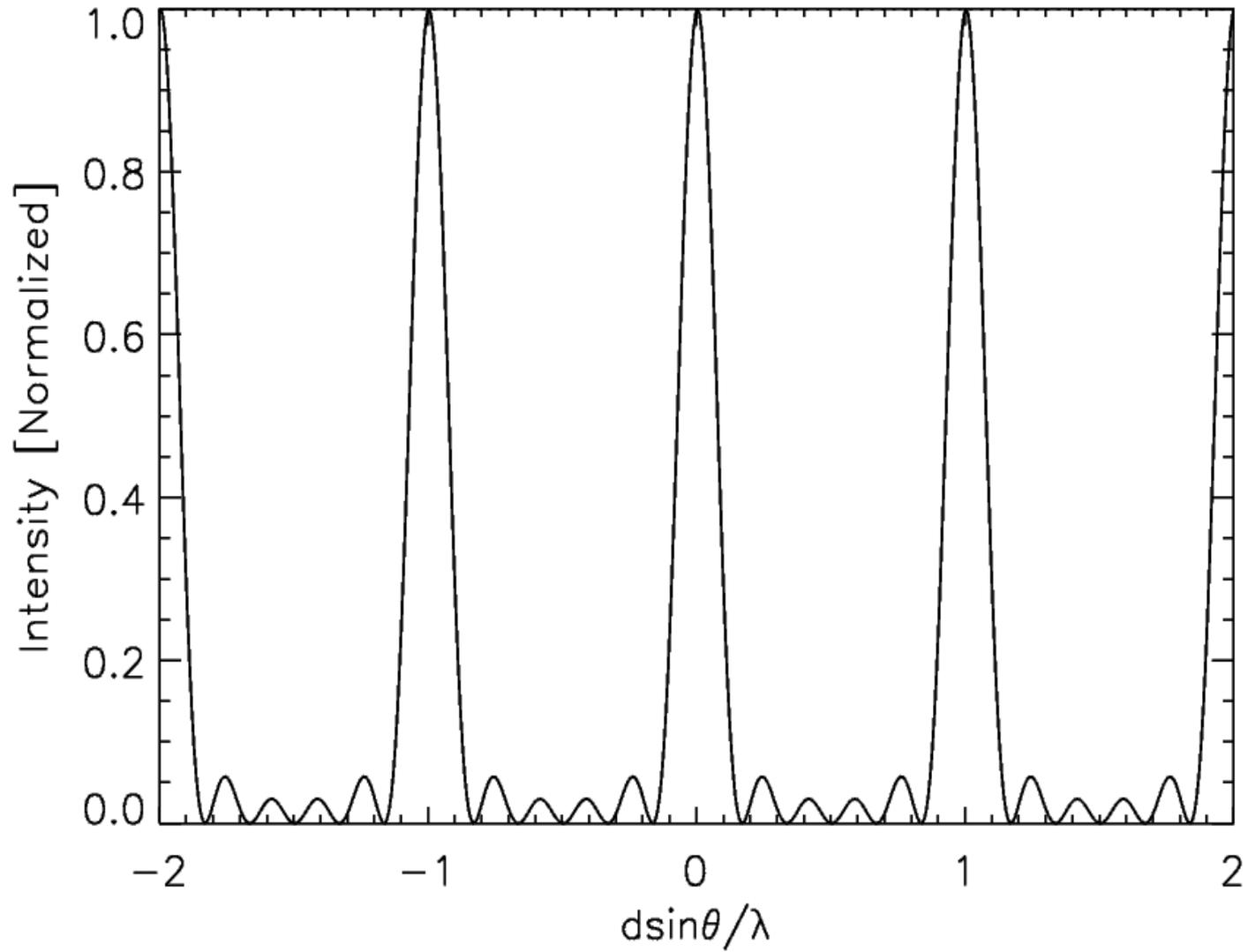
# Adding more slits...

$N=5$



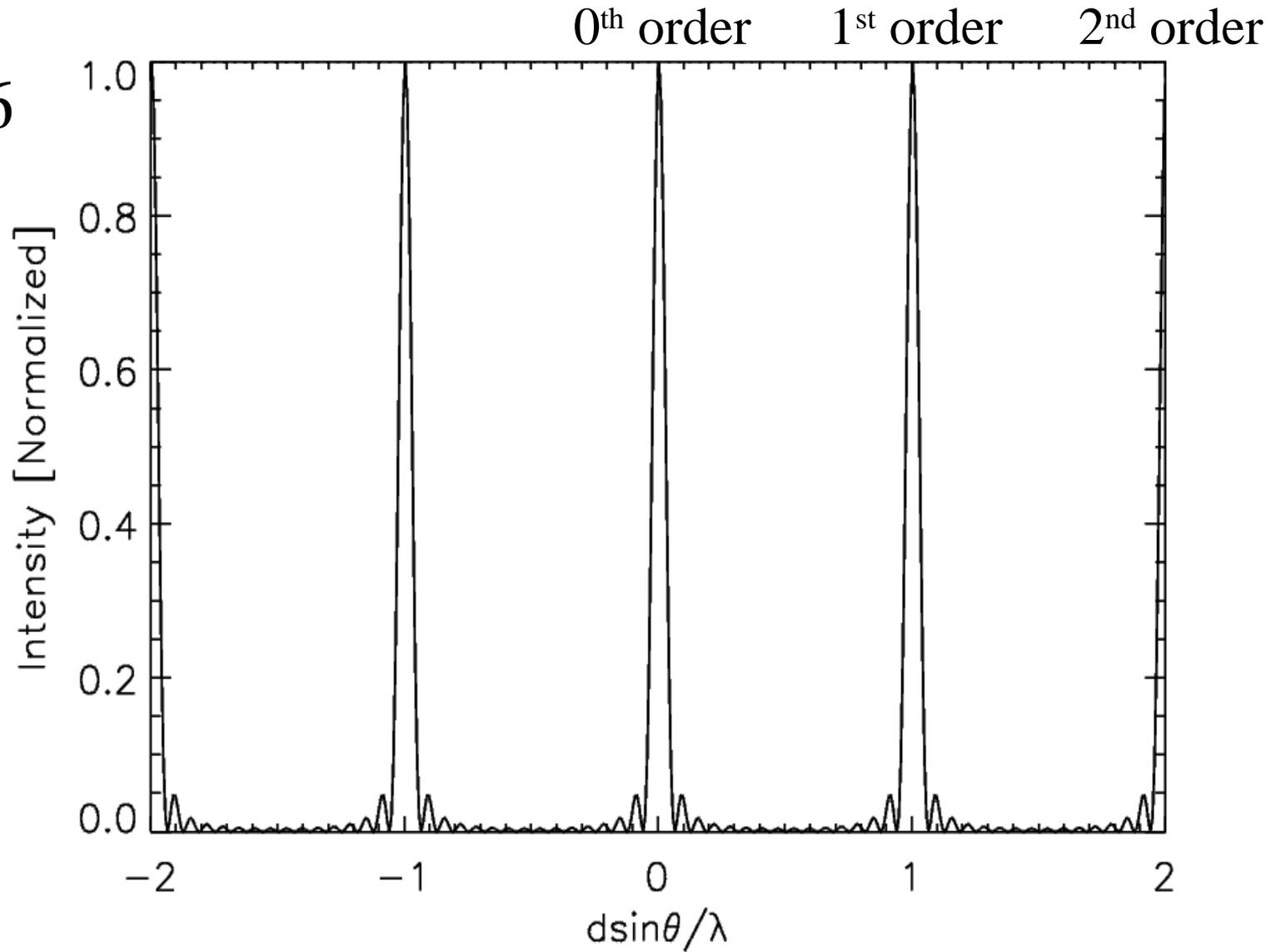
# Adding more slits...

$N=6$



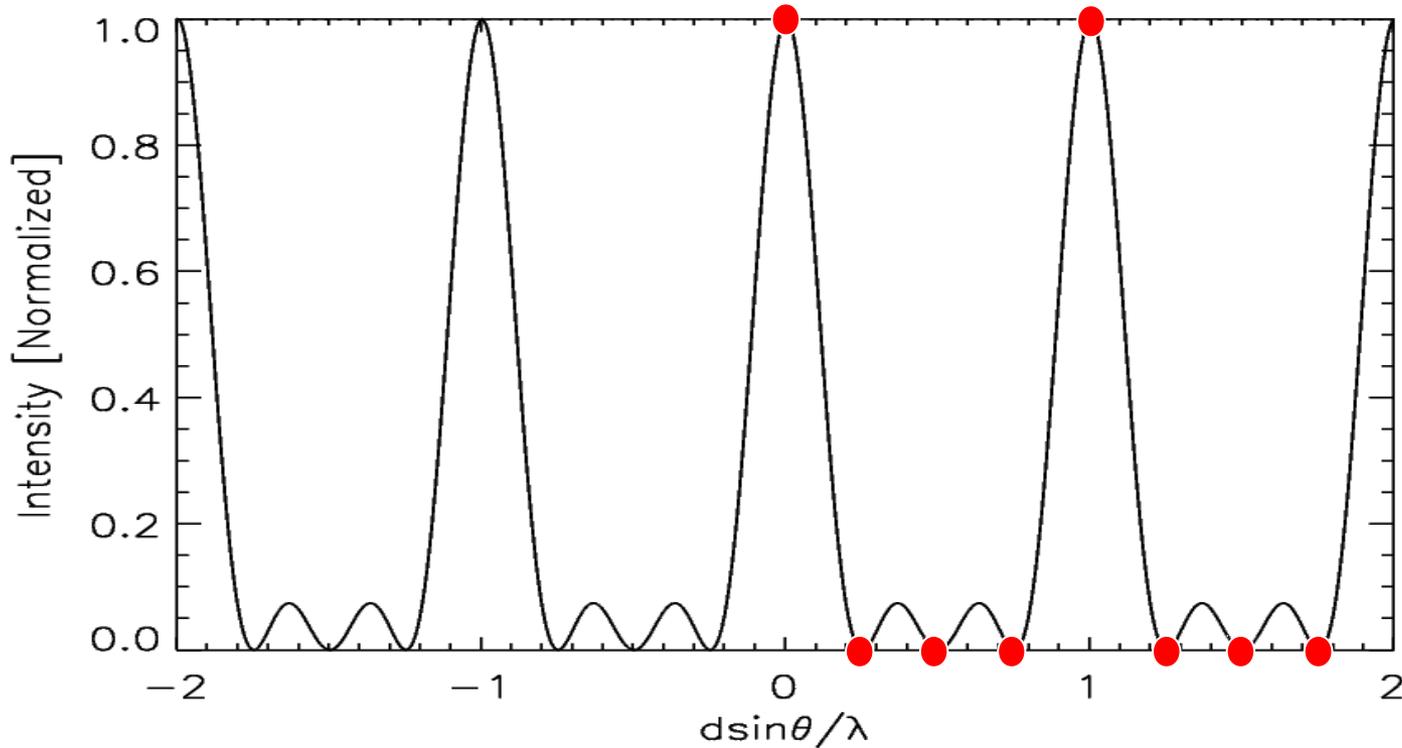
# Adding more slits...

$N=16$



# Width of the peaks

$N=4$



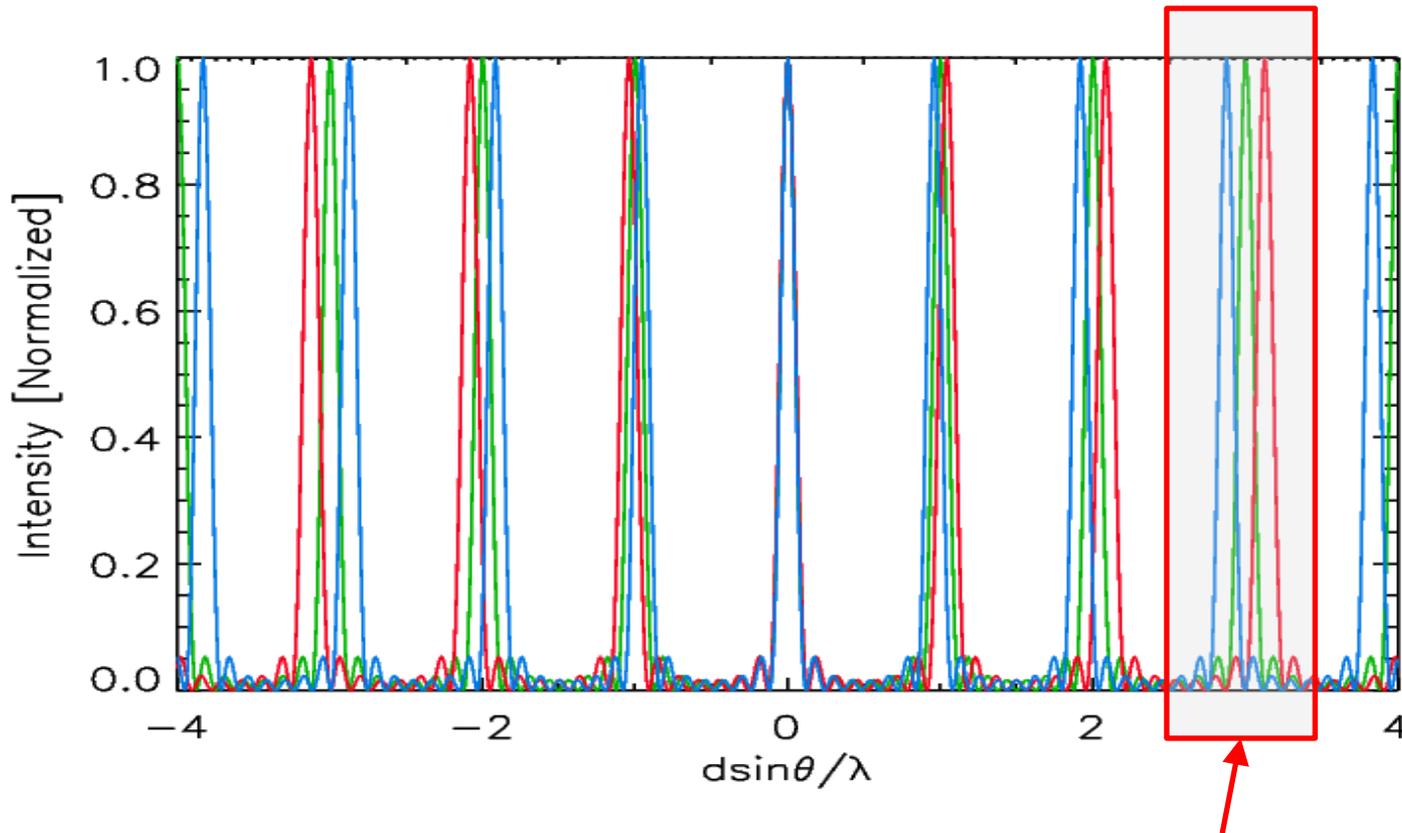
Peak width is therefore:

For  $\frac{d\sin\theta}{\lambda} = \frac{n}{N}$  with  $\mathbf{k} \neq \mathbf{0}$

$$\Delta\sin\theta = \frac{\lambda}{Nd}$$

one has  $\mathbf{k} \neq \mathbf{0}$

# Moving to higher orders



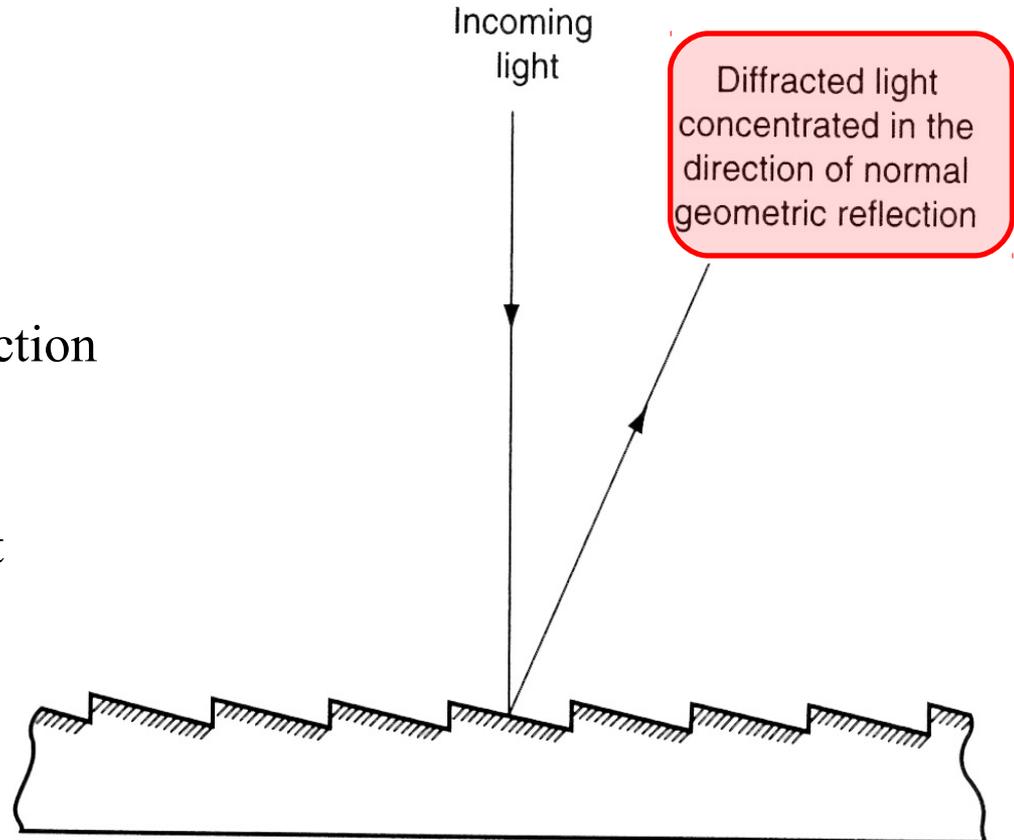
Place a CCD chip here

Make sure to have small enough pixel size to resolve the individual peaks.

# Grating

- many parallel “slits” called “grooves”
- Transmission gratings and reflection gratings
- width of principal maximum (distance between peak and first zeros on either side):

$$\Delta\theta = \frac{\lambda}{Nd \cos\theta}$$

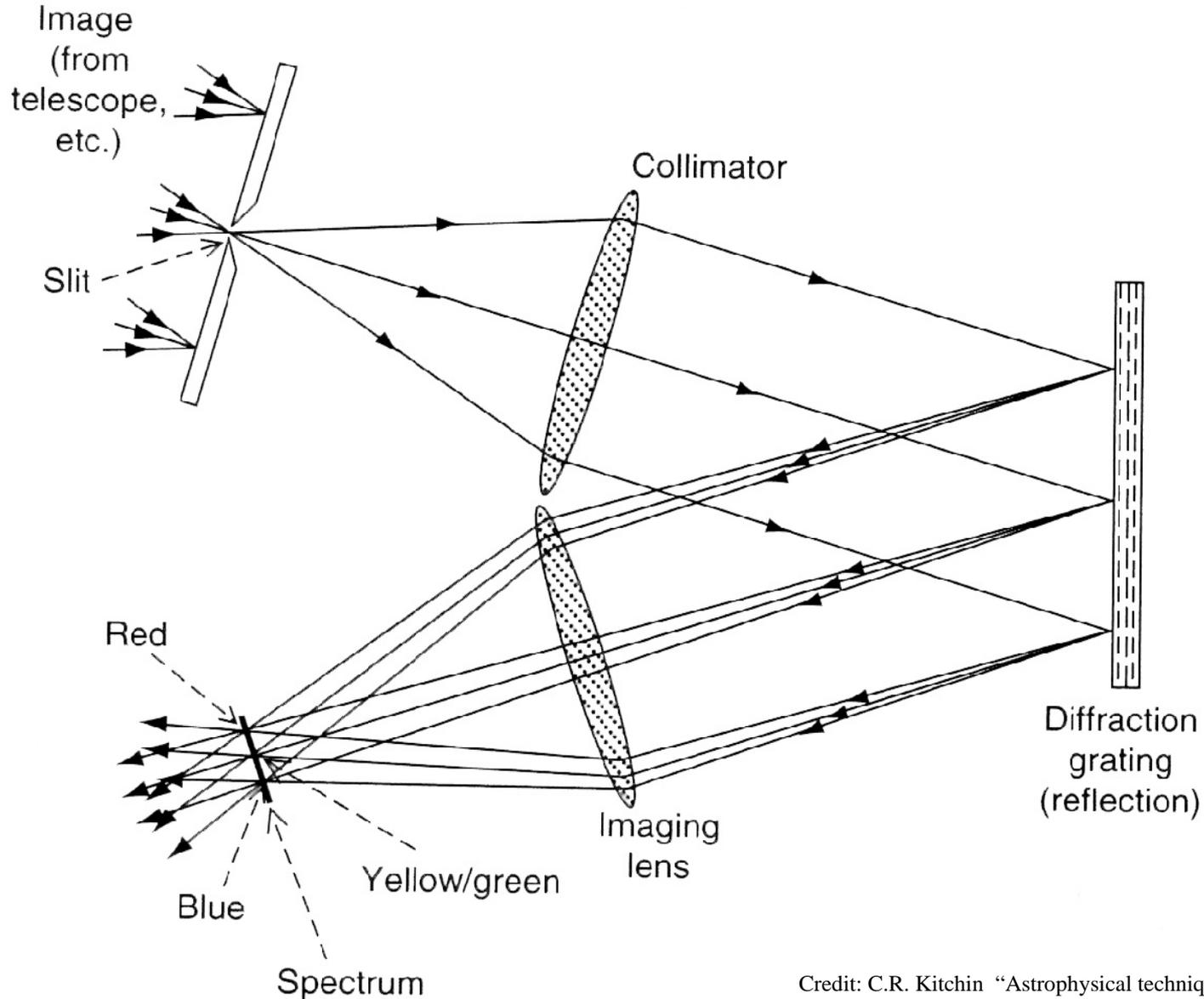


Credit: C.R. Kitchin "Astrophysical techniques"  
CRC Press, ISBN 13: 978-1-4200-8243-2

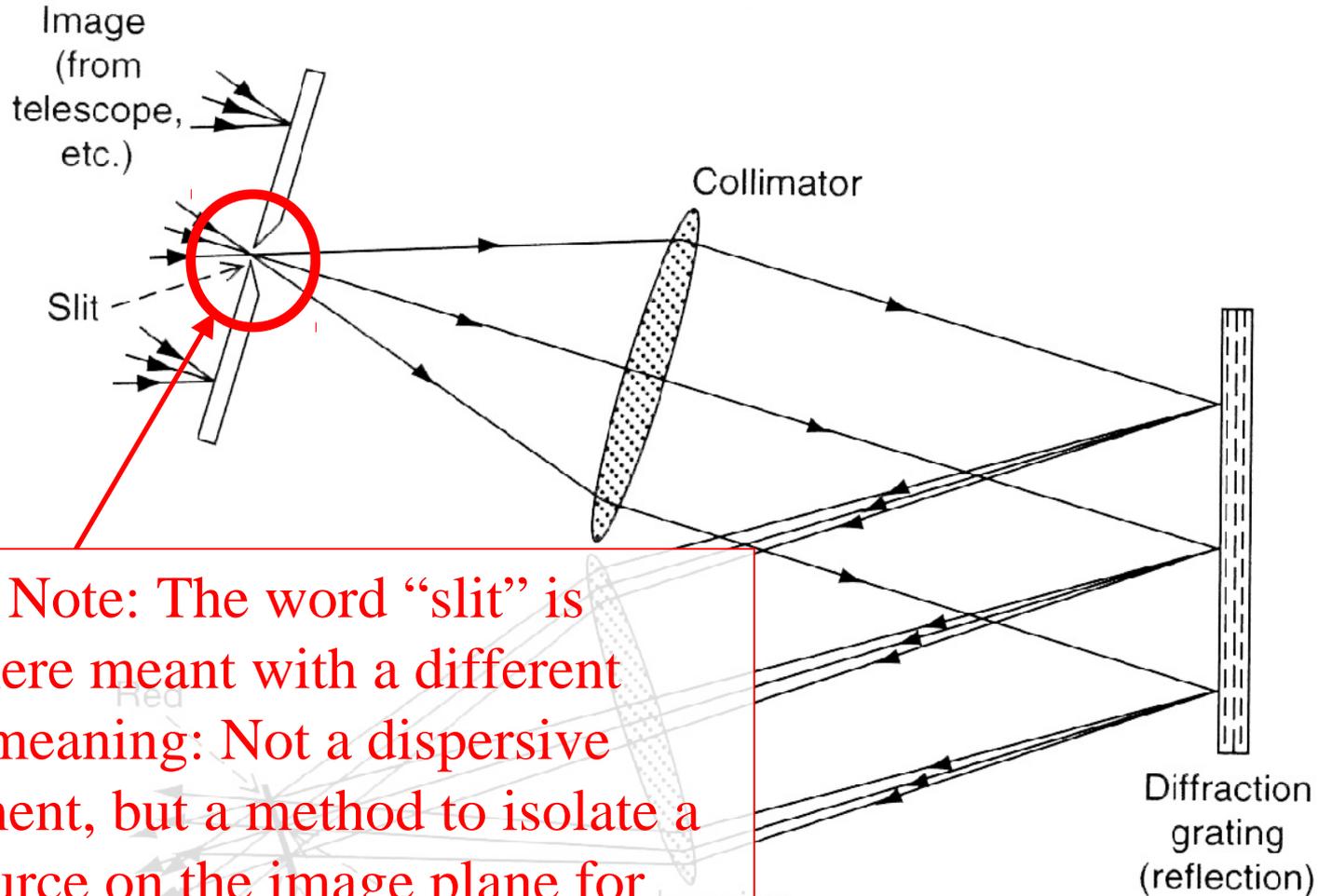
blazed reflection grating

- “Blazing”: tilt groove surfaces to concentrate light towards certain direction

# Basic grating spectrograph layout



# Basic grating spectrograph layout



Note: The word “slit” is here meant with a different meaning: Not a dispersive element, but a method to isolate a source on the image plane for spectroscopy. From here onward, “slit” will have this meaning.  
Dispersive slit = groove on a grating.

# Some applications of spectroscopy

- Stellar spectroscopy: temperature, composition, surface gravity, rotation, micro-turbulence
- Temperatures of interstellar medium, intergalactic medium
- radial velocities, mass and internal structure of stars, exoplanets
- Dynamics & masses of milky way and other galaxies (dark matter)
- Cosmology / redshifts
- spectro-astrometry (direct spatial information on scales, relative between continuum emission and spectral lines)
- composition of dust around young & evolved stars, ISM

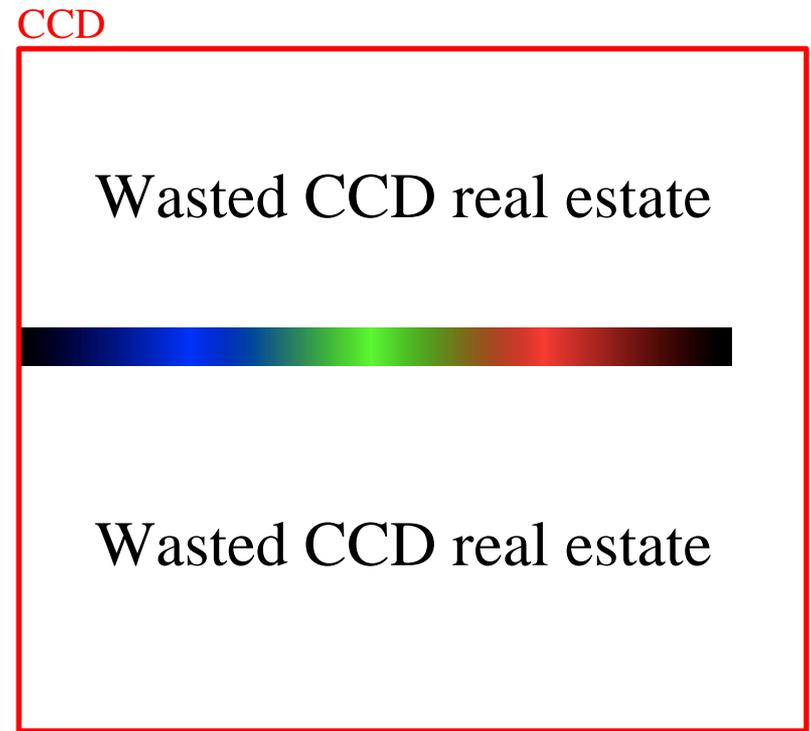
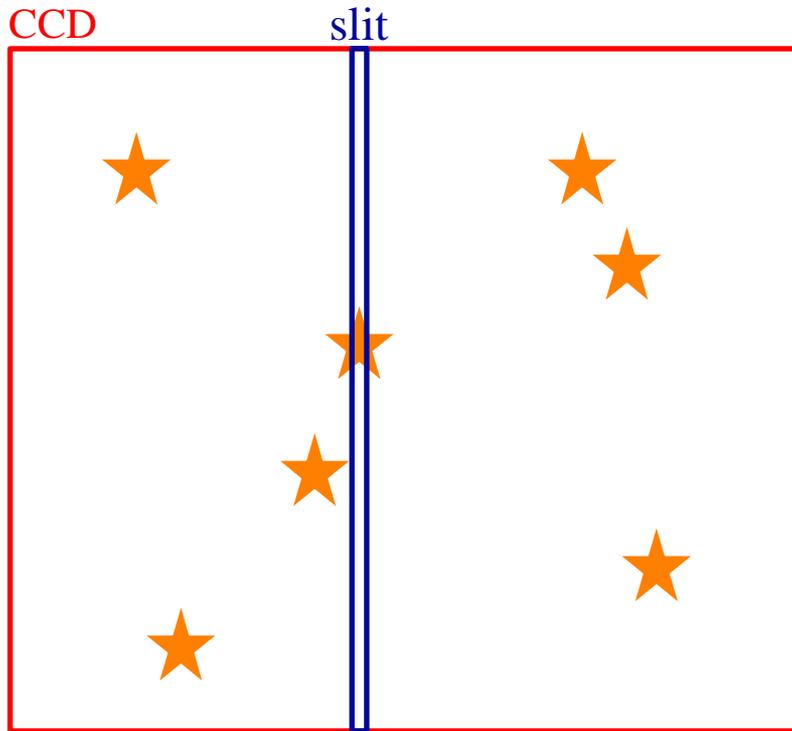
# Different Resolution for Different Scientific Applications

- Active galaxies, quasars, high-redshift objects:  $R \approx 500 - 1,000$
- Nearby galaxies (velocities 30...300 km/s):  $R \approx 3,000 - 10,000$
- Supernovae (expansion velocity  $\approx 3,000$  km/s):  $R > 100$
- Stellar abundances:
  - Hot stars:  $R \approx 30,000$
  - Cool stars:  $R \approx 60,000 - 100,000$
- Exoplanet radial velocity measurements. E.g.  $R \approx 115,000$  (HARPS). Best accuracy currently reached  $\sim 1$  m/s, “effective”  $R \approx 300,000,000$ . How: centroid of a single line measured to much higher precision than spectral resolution + use many lines, precision scales like  $1/\sqrt{N_{\text{lines}}}$

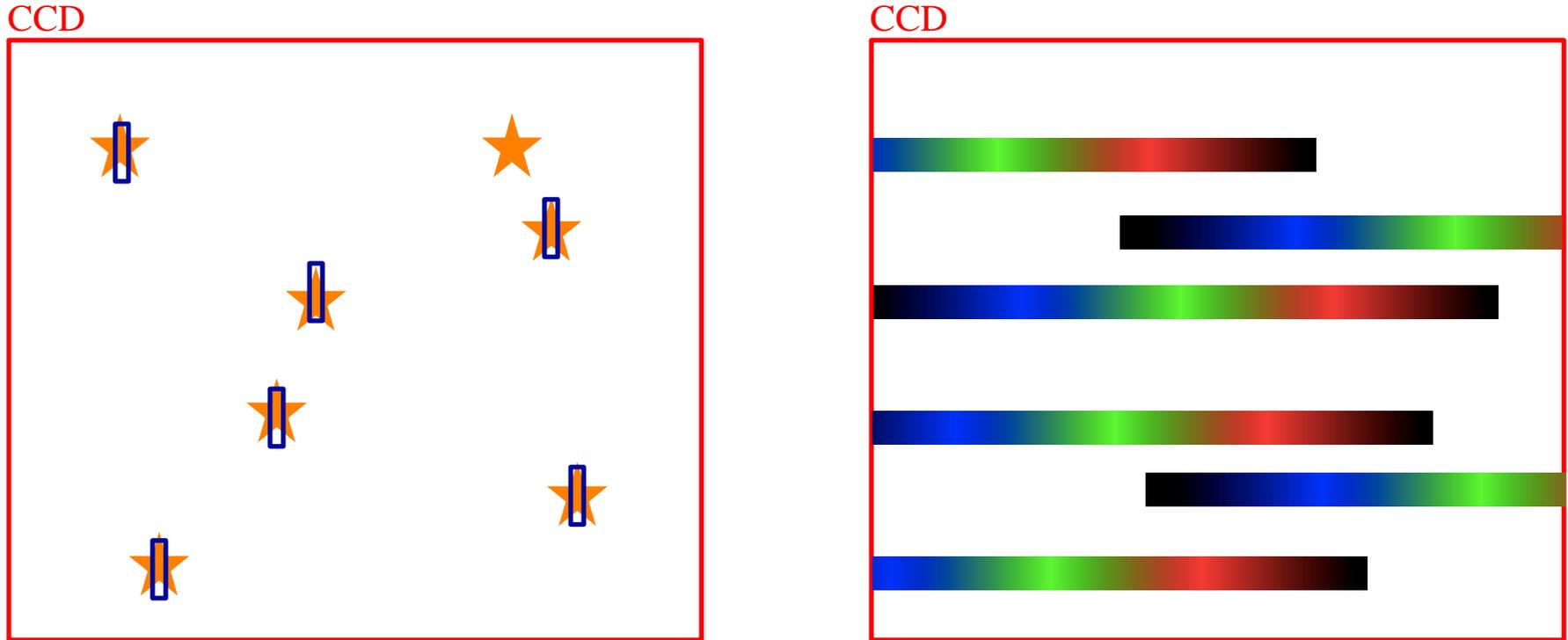
# Multiple object spectroscopy

- Often you want spectra of many objects in the same region on the sky
- Doing them with a single slit is very time consuming
- When putting a slit on a source in the focal plane, the photons from all other sources are blocked and thus “wasted”
- Wish to take spectra of many sources simultaneously!
- Solution: “multiple object spectrograph”. Constructed to guide the light of  $\gg 1$  objects through the dispersive optics and onto the detector(s), using:
  - a small slit over each source (“slitlets”)
  - a glass fiber positioned on each source
  - “integral field unit”

# Multi-object spectroscopy with slitlets



# Multi-object spectroscopy with slitlets



- First do pre-imaging to find the stars/objects of interest + reference object
- Create mask using computer program (mask is then cut in metal plate with laser)
  - Go back to telescope, do acquisition to center slits on objects
  - Do spectroscopic integration

# Very high $R$ work: peculiarities

- For accurate calibration, need to take Earth motion into account (orbital motion up to  $\sim 30$  km/s corresponding to  $R = 10^4$ , daily rotation up to  $\sim 460$  m/s corresponding to  $R = 6.5 \times 10^5$ )
- In the infrared, at high resolution the atmospheric opacity breaks up into *very* many narrow absorption lines. A specific spectral line you wish to measure may coincide with a **telluric line** and not be measurable at some instant, but due to the Earth's orbital motion it may have red- or blue shifted out of the telluric absorption line later in the year. "Best time of year" depends on position of source w.r.t. ecliptic and the source radial velocity.
- When wavelength calibration must be extremely good (e.g. for exoplanet radial velocity measurements) we cannot use separate wavelength calibration frames, calibration must be done simultaneously with science observation. Use gas absorption cell or telluric lines .