Spectroscopy

X. How to design a Spectrograph

Goals of a Spectrograph

A goal of a spectrograph is to answer **scientific questions**. The nature of those questions will drive the design of the spectrograph. A spectrograph can be described by the **resolution**, **wavelength coverage**, **efficiency,** and **cost**.

resolution

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

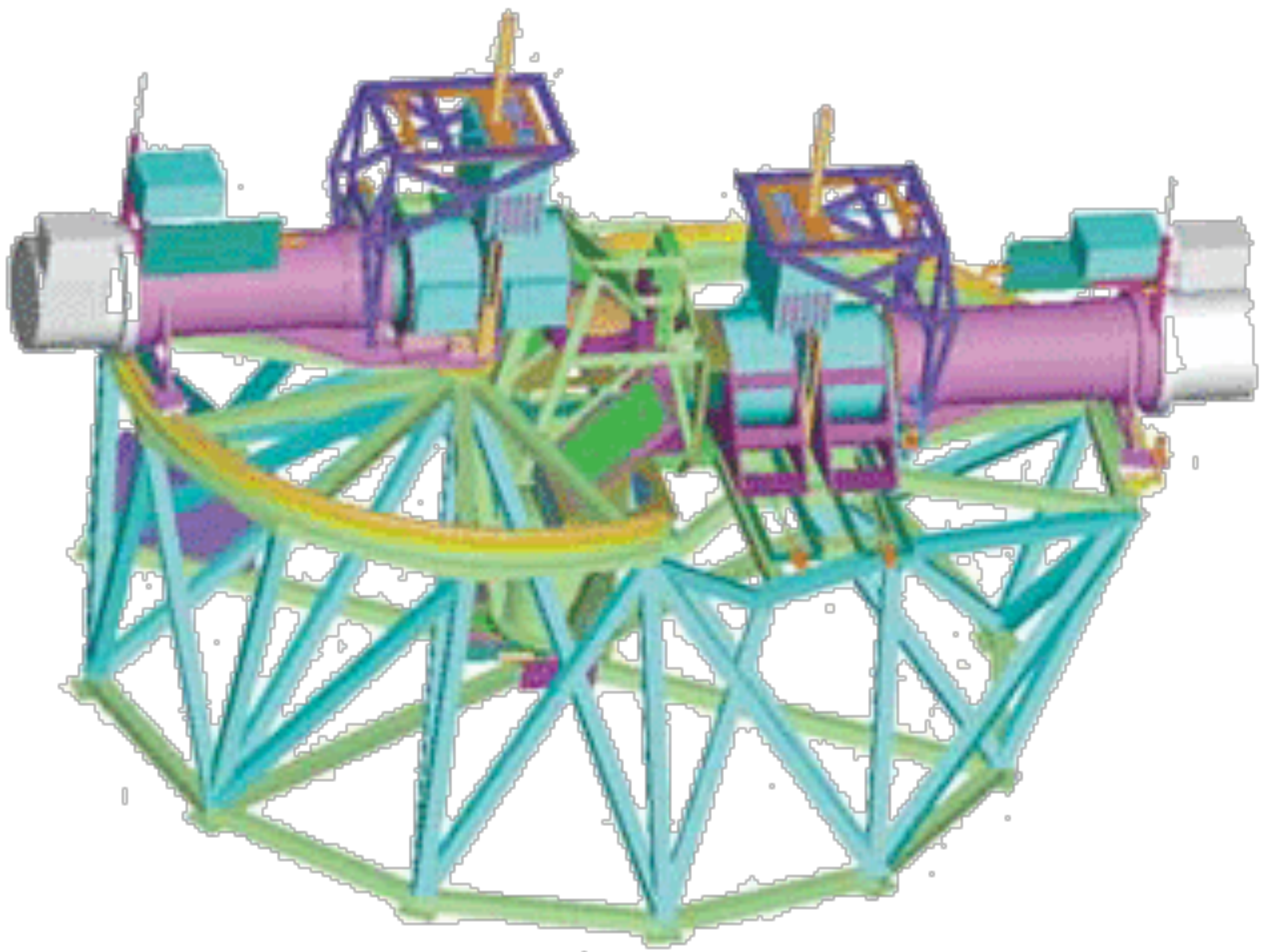
wavelength coverage

$$\lambda_{red}, \lambda_{blue}$$

efficiency

throughput limiting magnitude, etendue, grasp, power

The Robert Stobie Spectrograph



Scientific Case

- Newly emergent objects in star forming clusters
- Faint Cataclysmic Variables
- Radial velocities of stars in globular clusters
- Stellar studies in the Magellenic cloud
- Velocity structures in Magellenic cloud supernova remnants
- compact objects in the Magellenic clouds
- Chemical abundances in nearby and high-z galaxies
- Dynamics of nearby and high-z galaxies
- Star forming galaxies in intermediate redshift galaxy clusters
- Identification of faint x-ray sources

Design Requirements

These are only some of the scientific requirements for grating spectroscopy. RSS can be used in multiple other modes, but we are just going to focus on the simplest. The scientific requirements result in the following design requirements:

- medium to high spectral resolution
- Large wavelength coverage
- High UV sensitivity
- Multi-object capability
- Compact, light-weight design

Design Basics

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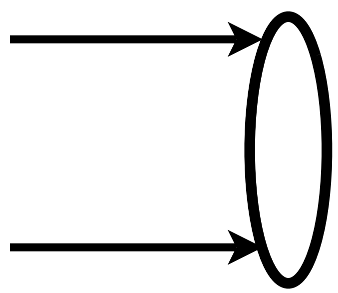
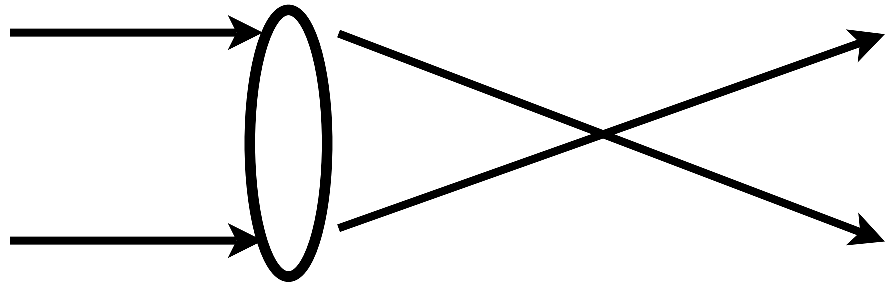


Telescope

Design Basics



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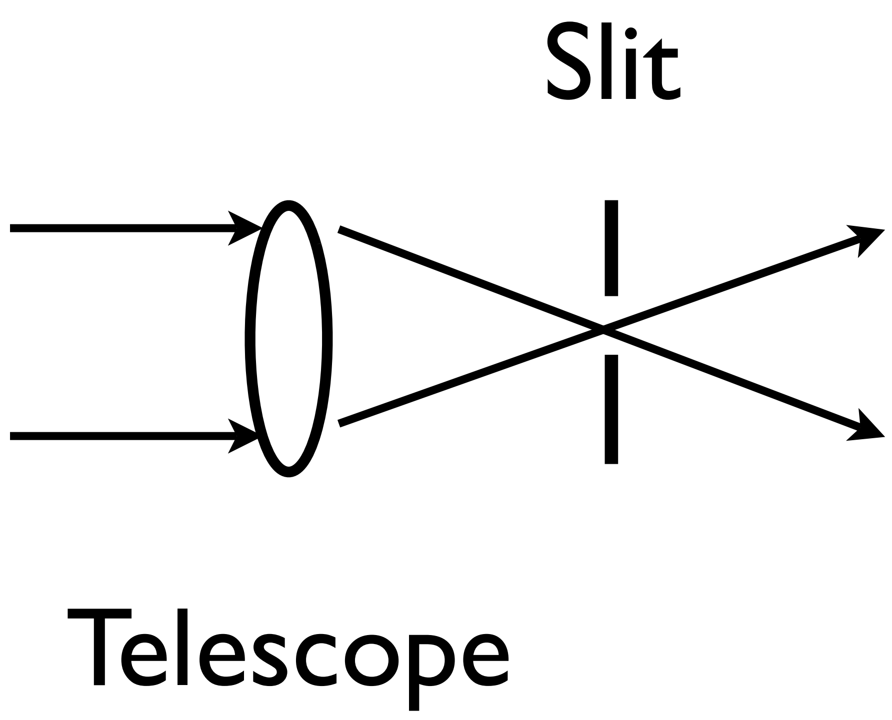

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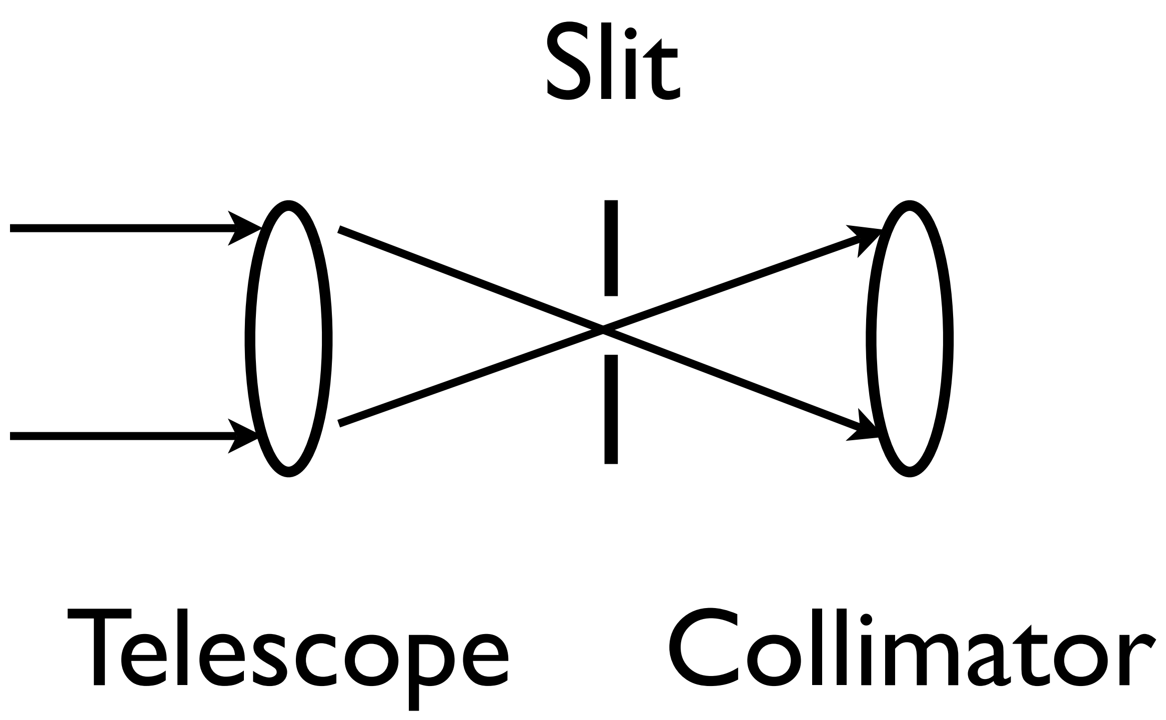

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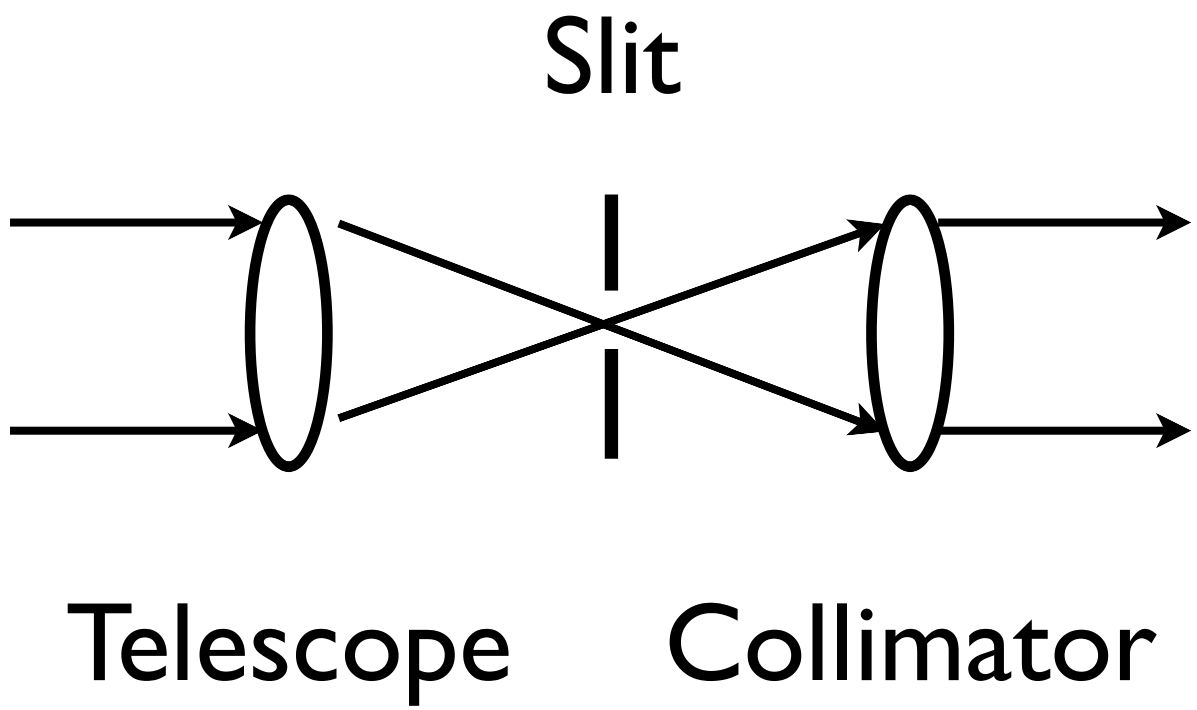

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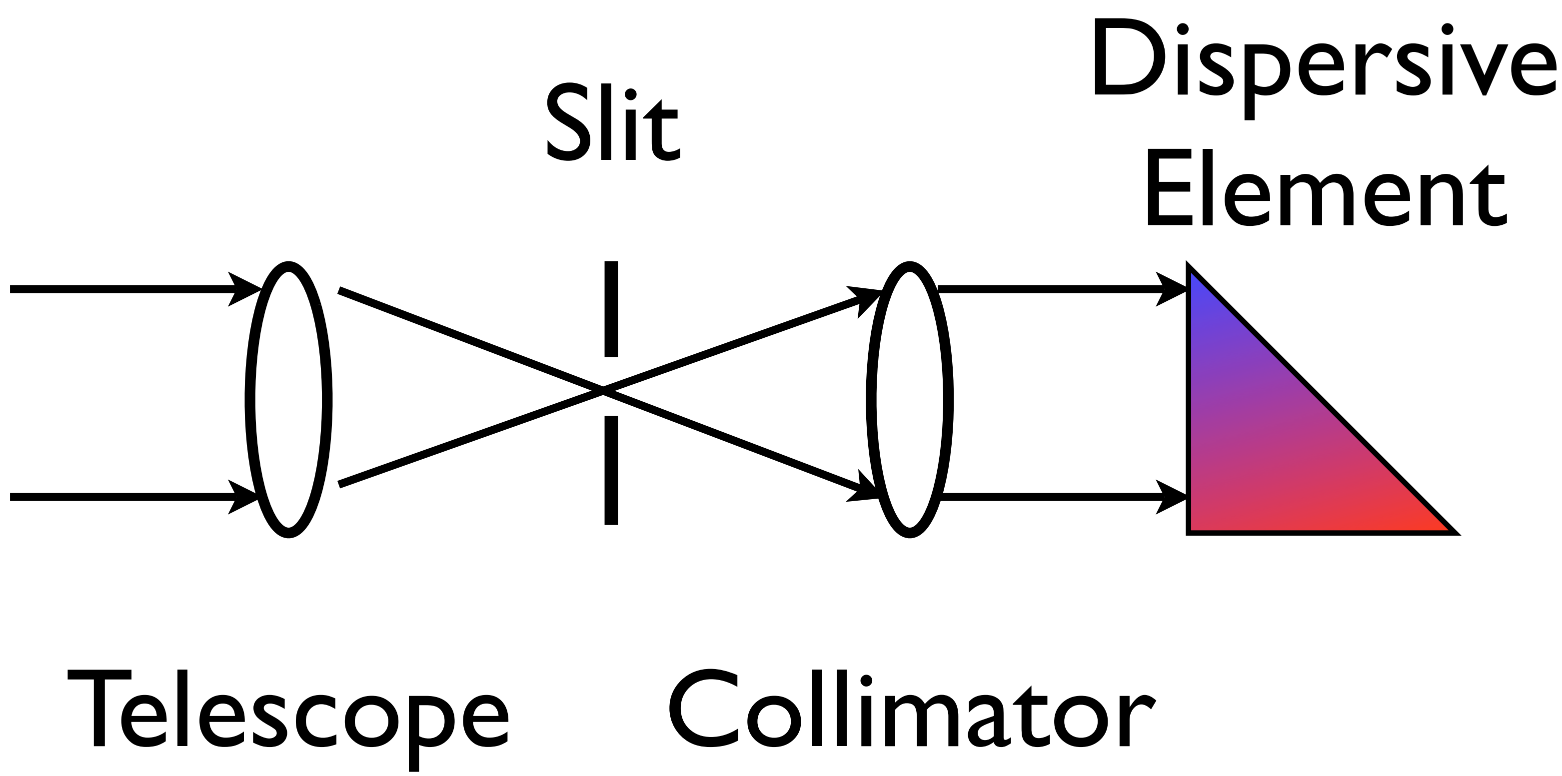

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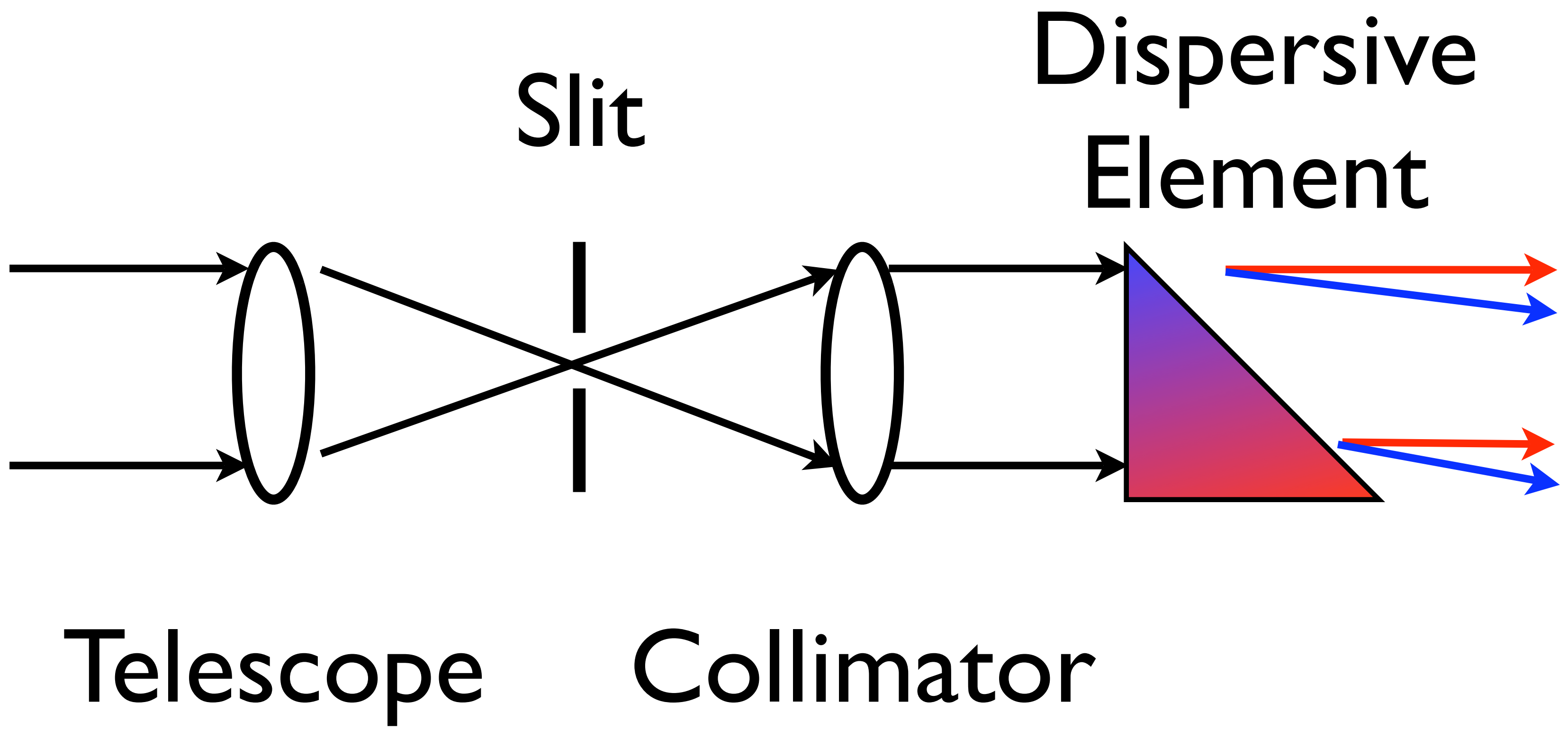

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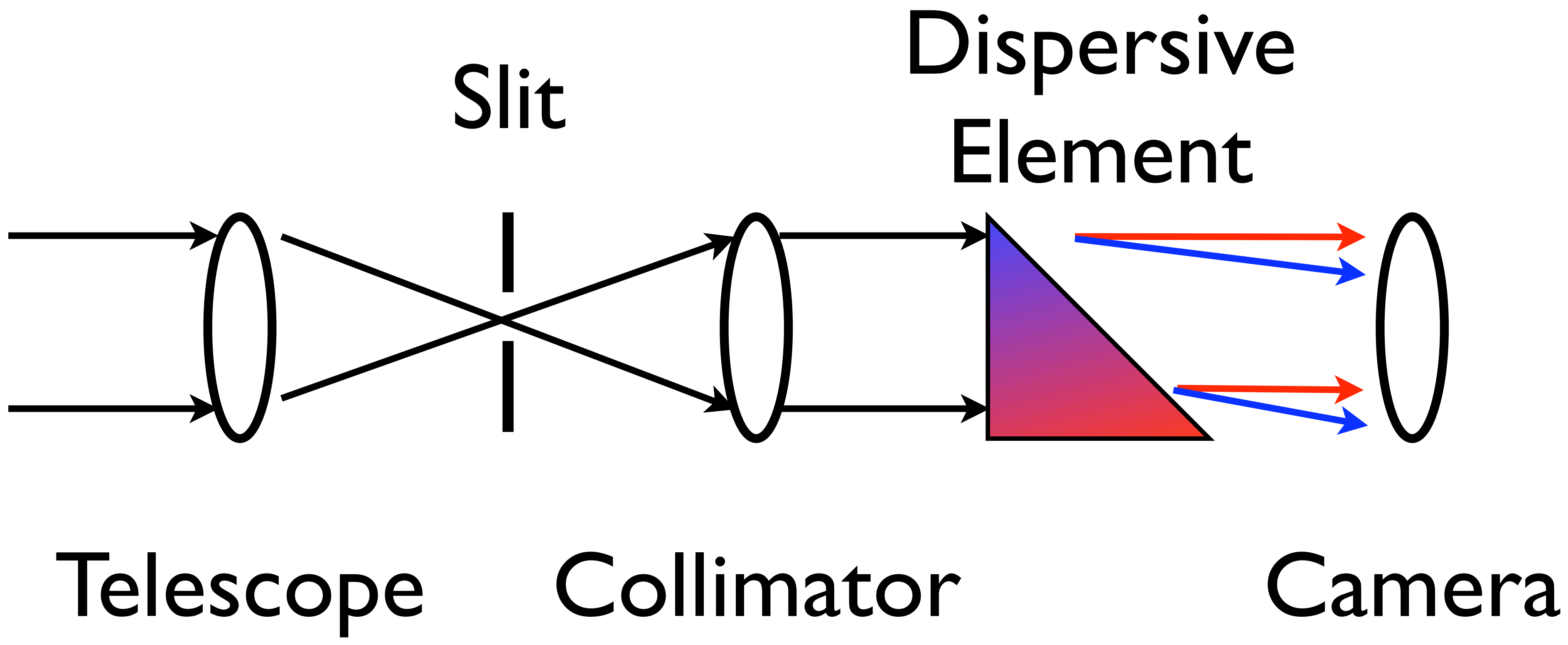

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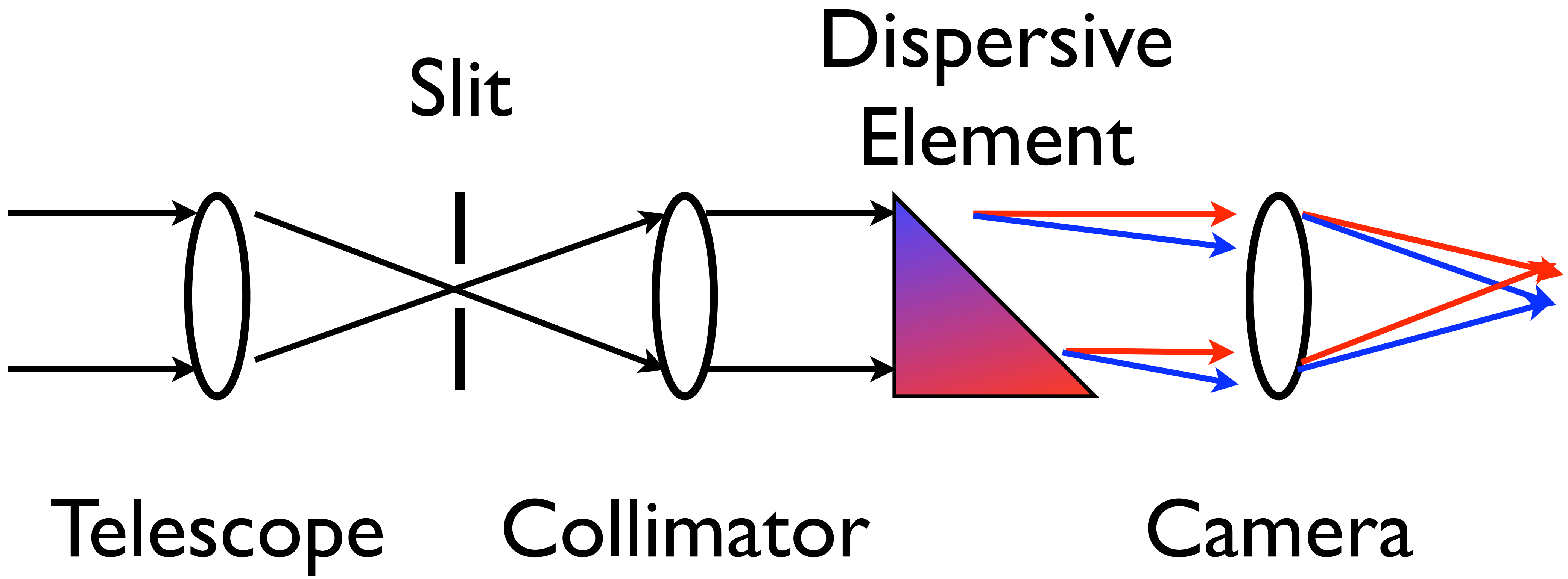

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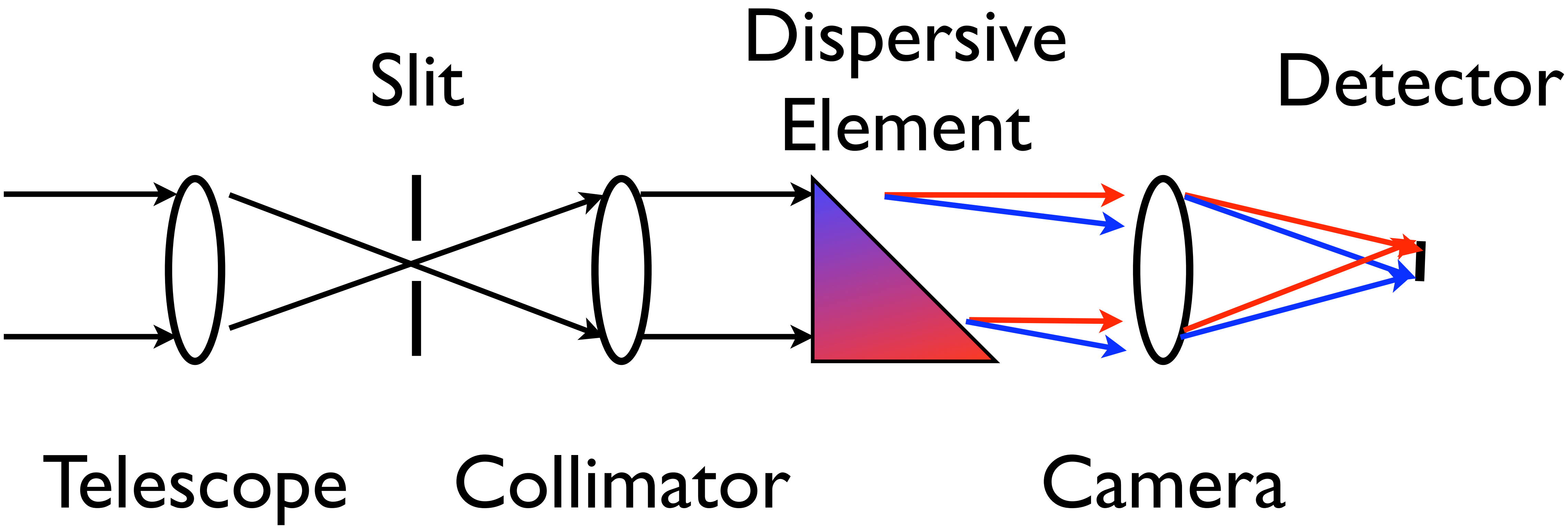

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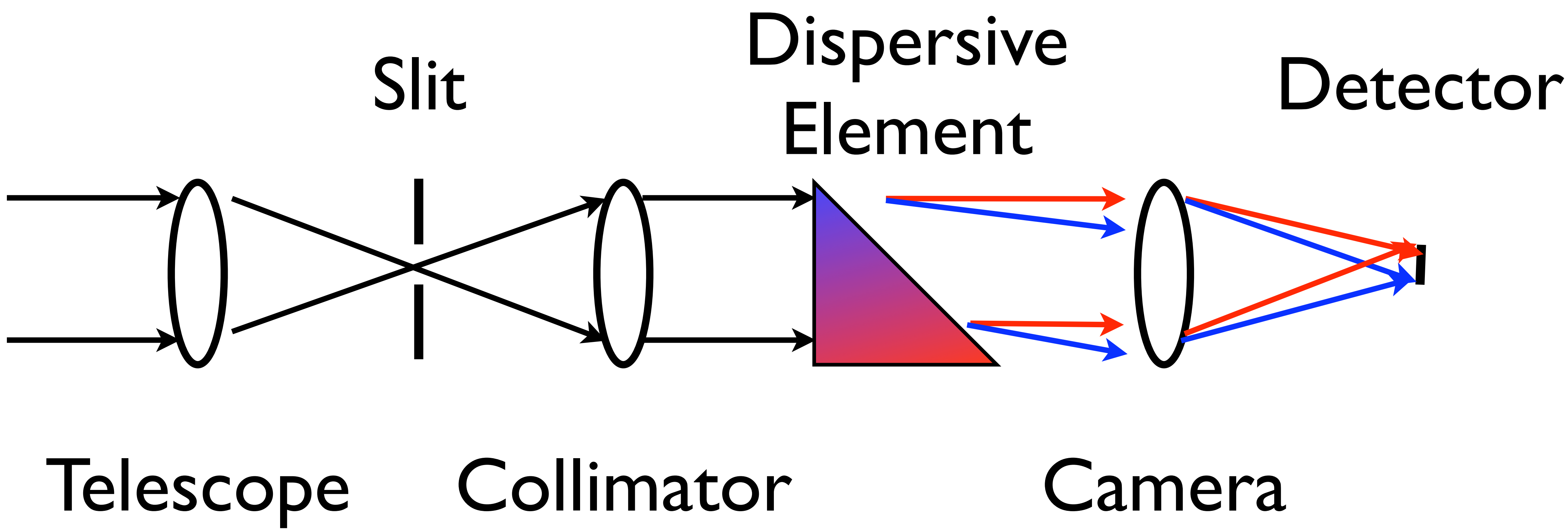
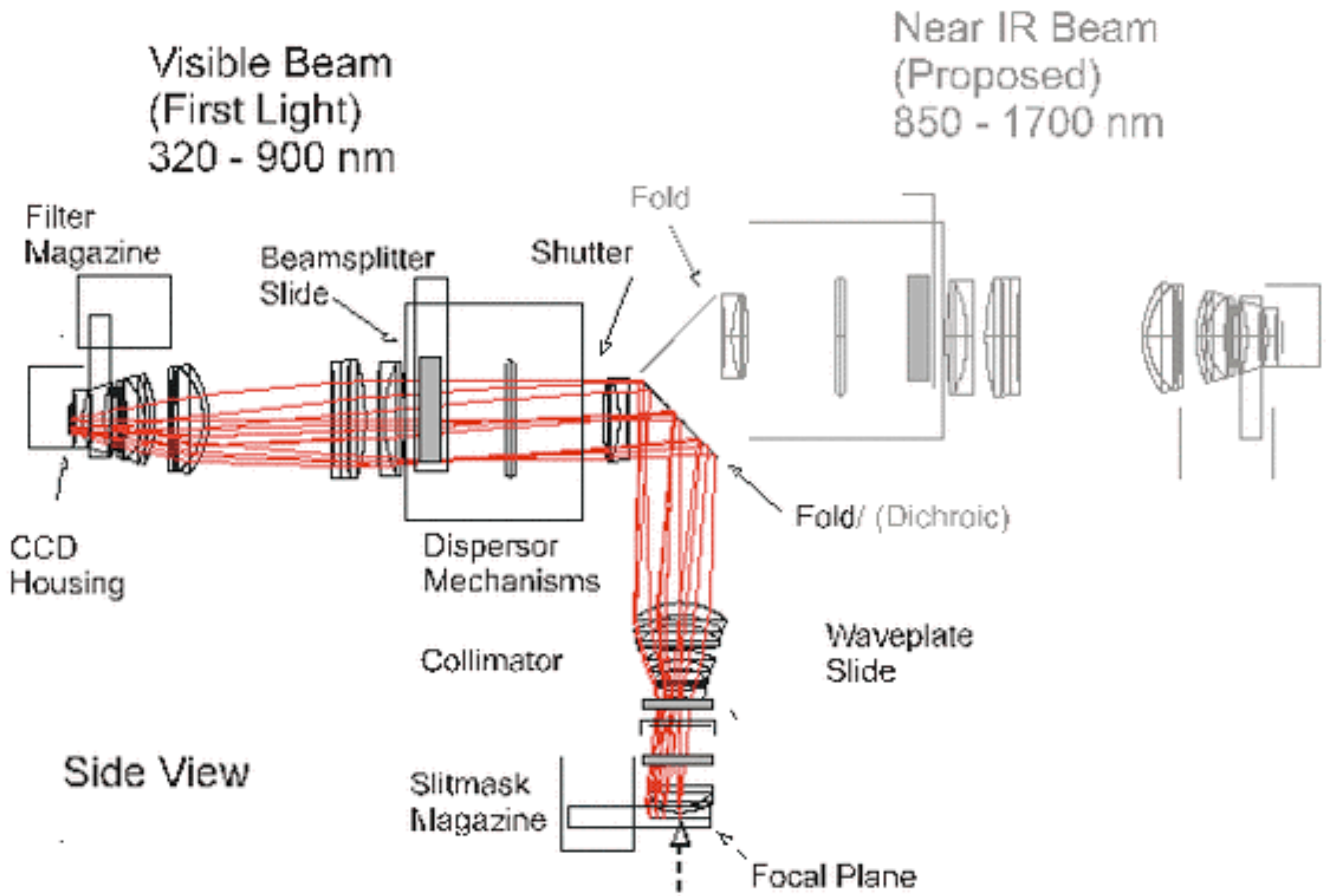


NB: From geometrical arguments, $f_{tel}/d_{tel}=f_{col}/d_{col}$.

Design Basics

Element	**What we need to know**
Telescope	Focal Length, Diameter, Effective Area, reflective
Slit	Slit width, slit position, number of slits
Collimator	Focal Length, Diameter, Transmission
Dispersive Element	type, angular dispersion
Camera	Focal Length, Diameter, Transmission
Detector	Size, pixel scale

RSS Model



Visible Beam
(First Light)
320 - 900 nm
Near IR Beam
(Proposed)
850 - 1700 nm
Fold
Filter
Magazine
Beamsplitter
Slide
Shutter
CCD
Housing
Dispersor
Mechanisms
Fold/ (Dichroic)
Collimator
Waveplate
Slide
Side View
Slitmask
Magazine
Focal Plane

Resolution

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Slitwidth in mm corrected for spatial and spectral magnitication effects

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Slitwidth in mm corrected for spatial and spectral magnitication effects

Linear dispersion in [Å/mm]

The Slit

Spectrograph slits come in a variety of formats including:

- no slit
- a single, long slit
- multi-slit
- fibers
- slitlits
- lens

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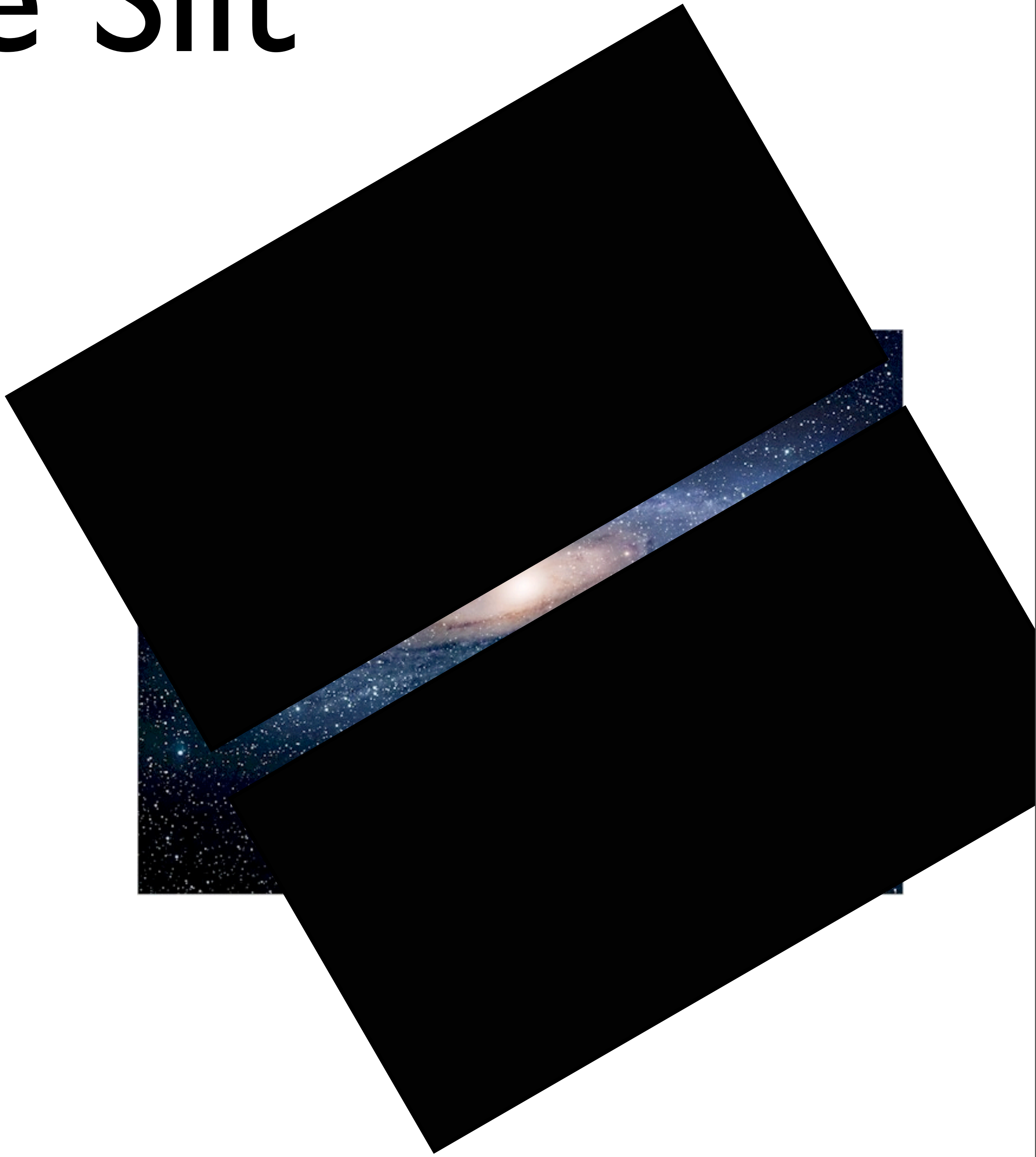

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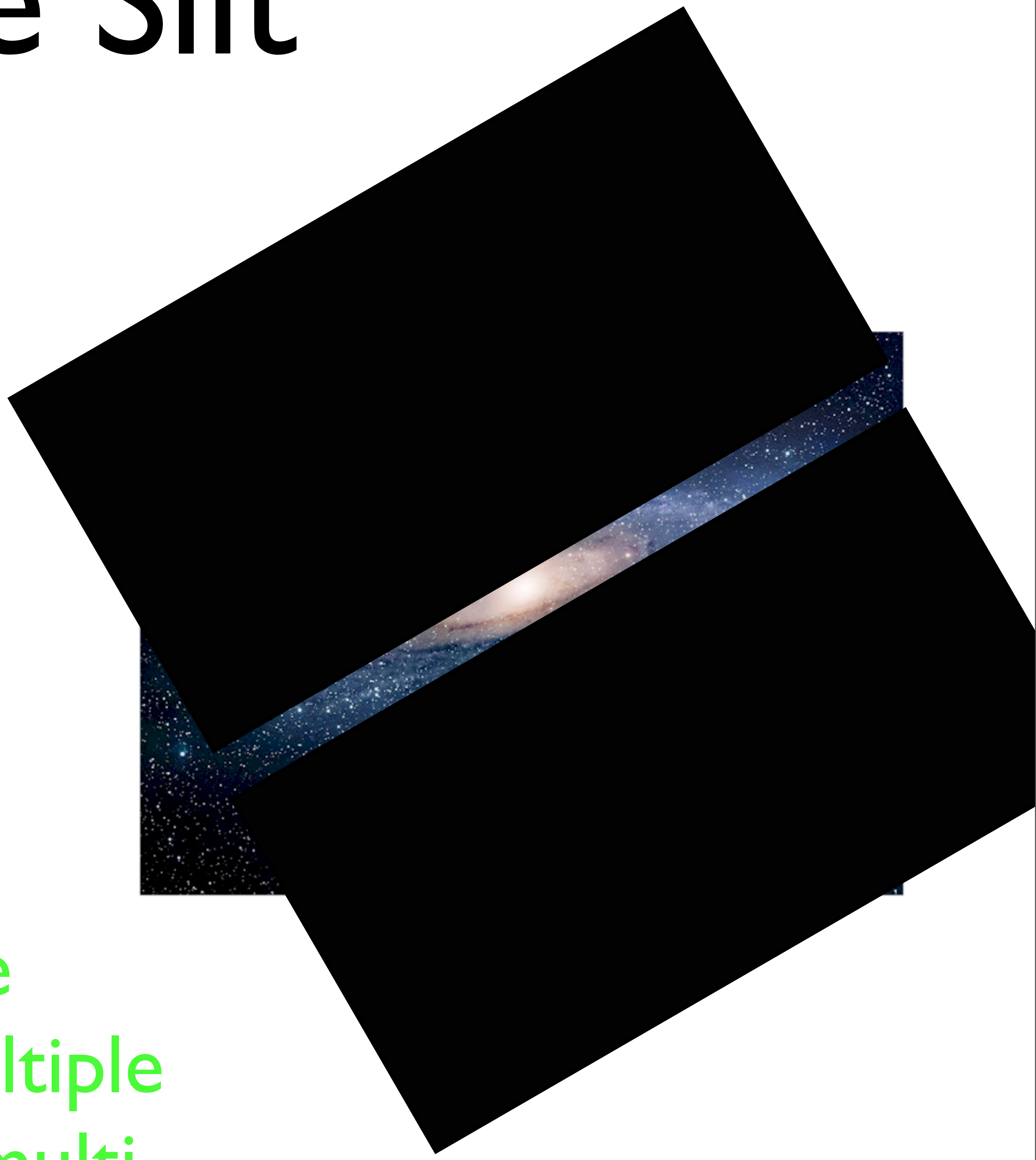

For RSS, we have the requirement of doing multiple objects. This requires a multi-slit coniguration

The Slit

Spectrograph slits are usually given by their on-sky size, which is related to their physical size by:

$$\phi = w / f_{tel}$$

where f_{tel} is the focal length of the telescope and w is the size of the slit (in mm). Phi is then given in radians.

However, if the size of the object is smaller than the slit, than the appropriate size is the size of the object. If the object is larger than the slit, light will be lost. This is where seeing can play an important role in spectroscopic observations.

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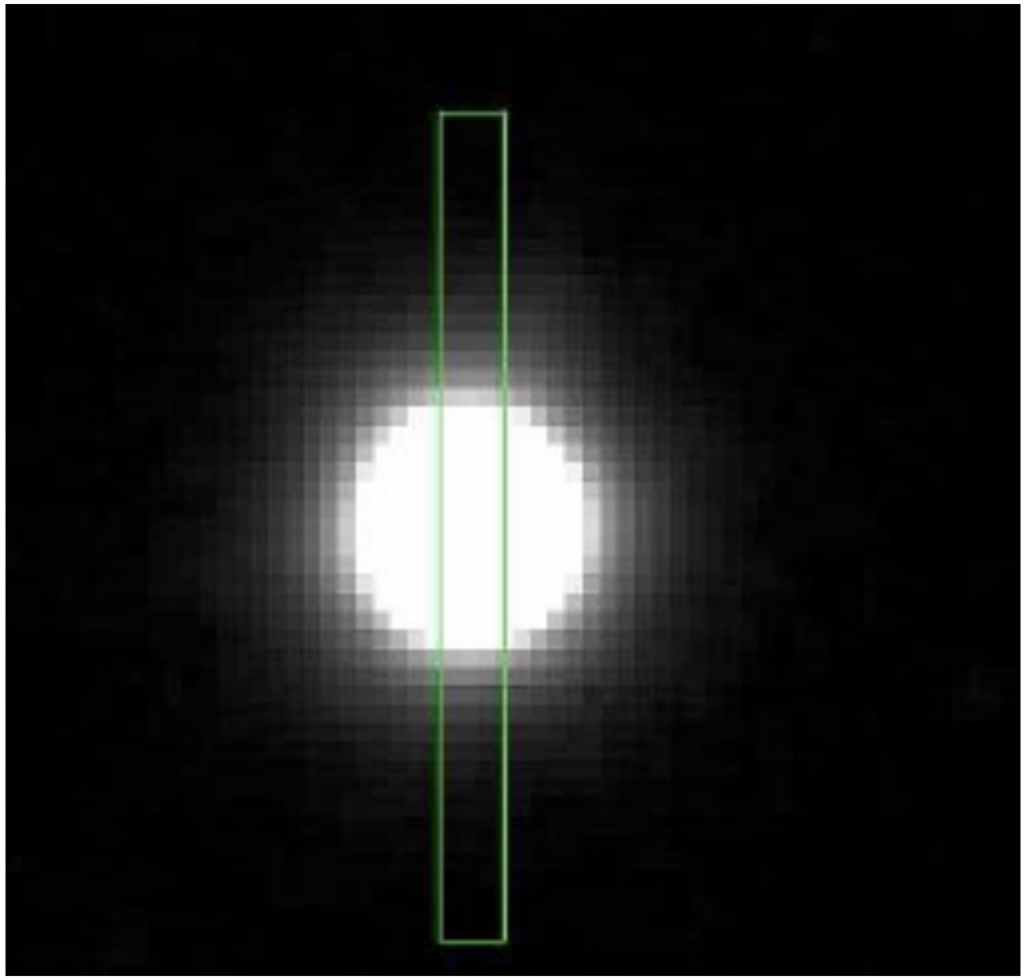

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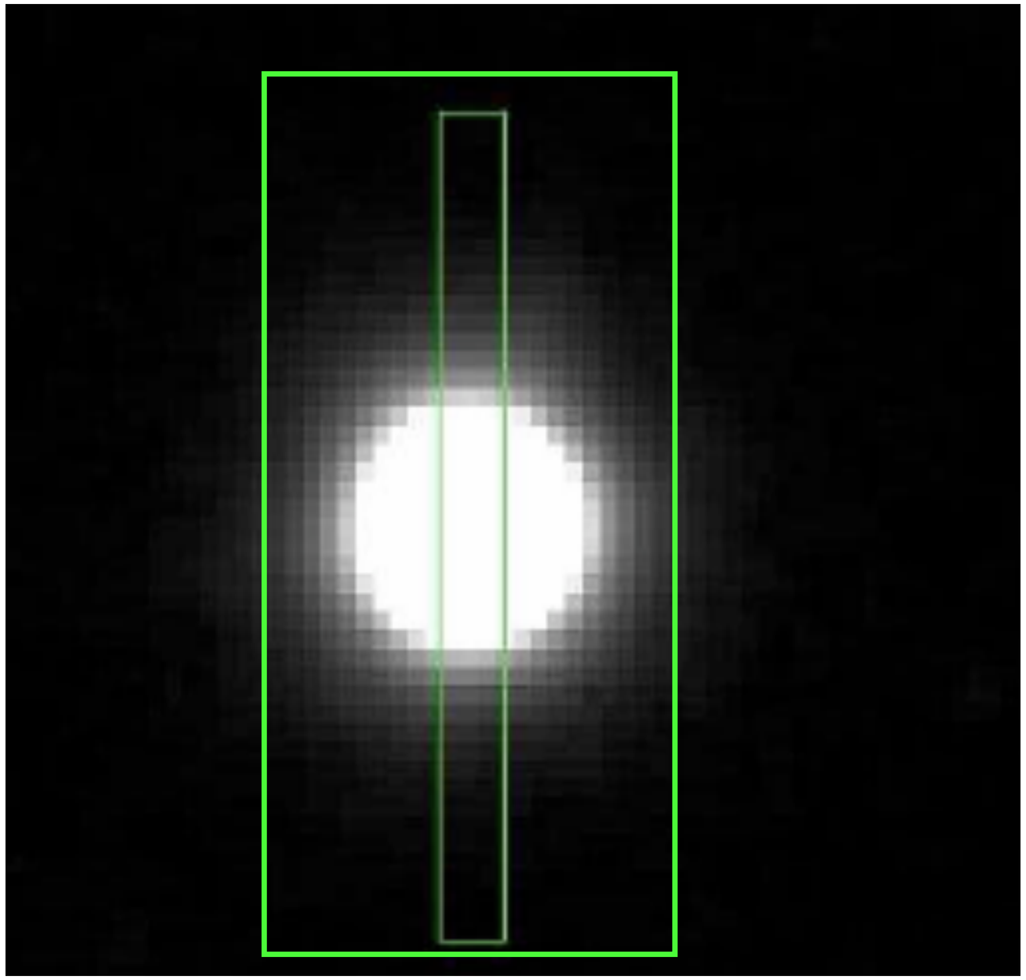

Slit Magnification

The slit will suffer from two types of magnification: spatial and spectral. So in the end, the size that the detector sees for the slit is given by:

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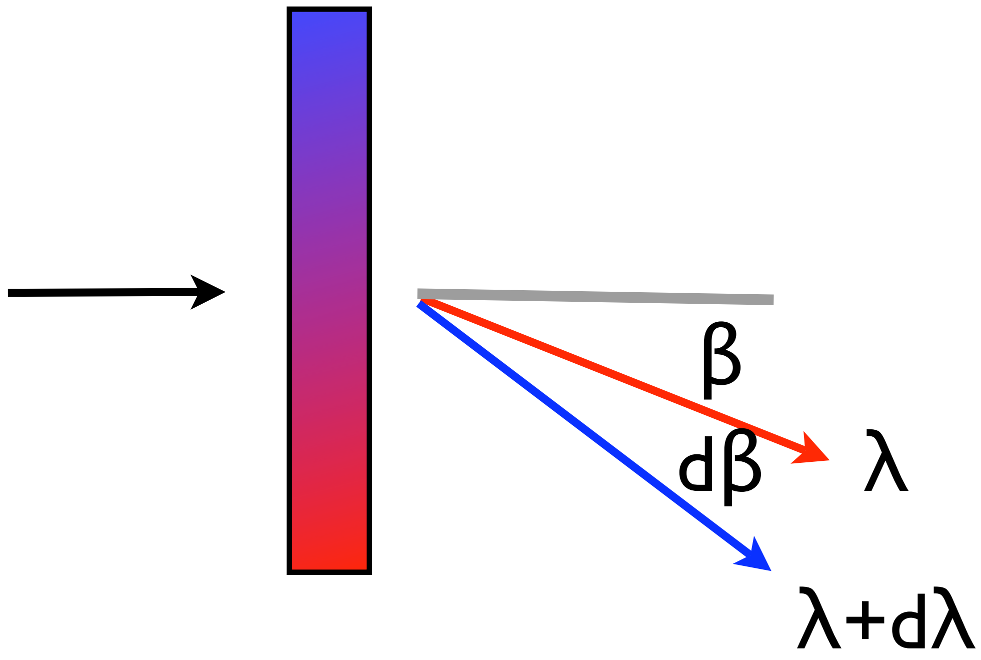
Dispersion



The angular dispersion for an element is given by:

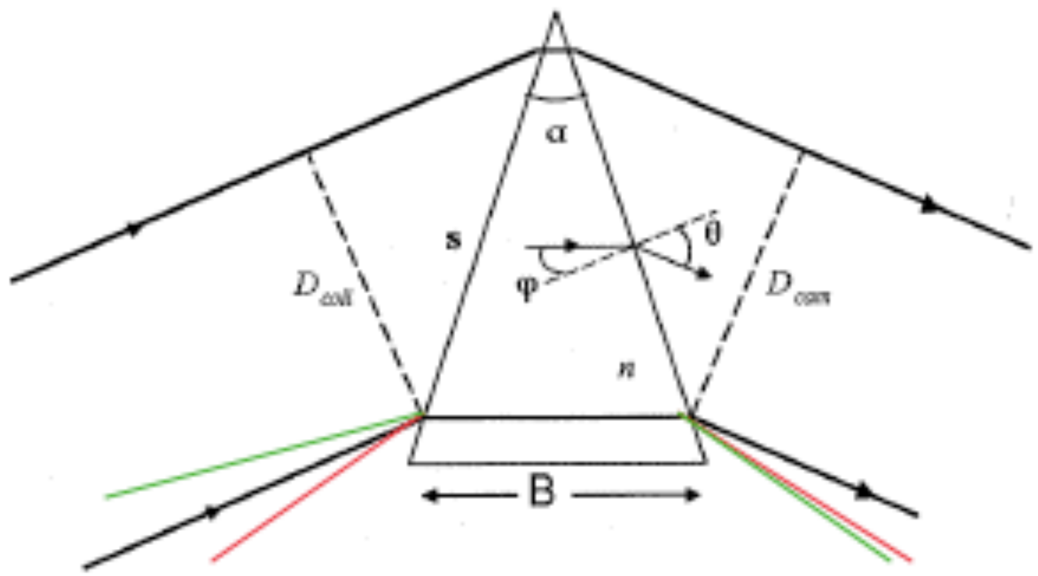
$$A = \frac{d\beta}{d\lambda}$$

For collimated light, the linear dispersion is then given by:

$$\frac{dl}{d\lambda} = f_{cam} A$$

Prisms

Prisms are typically used at near minimum deviation such that rays inside the prism are parallel to the base. The input and output beams are the same size, so that r=1. The angular dispersion for a prism is given by:



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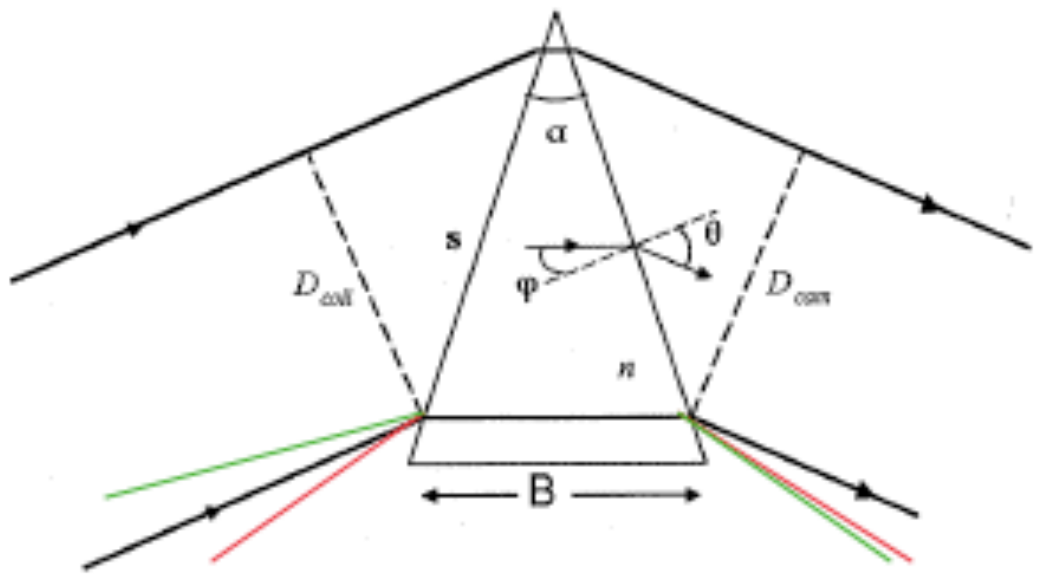

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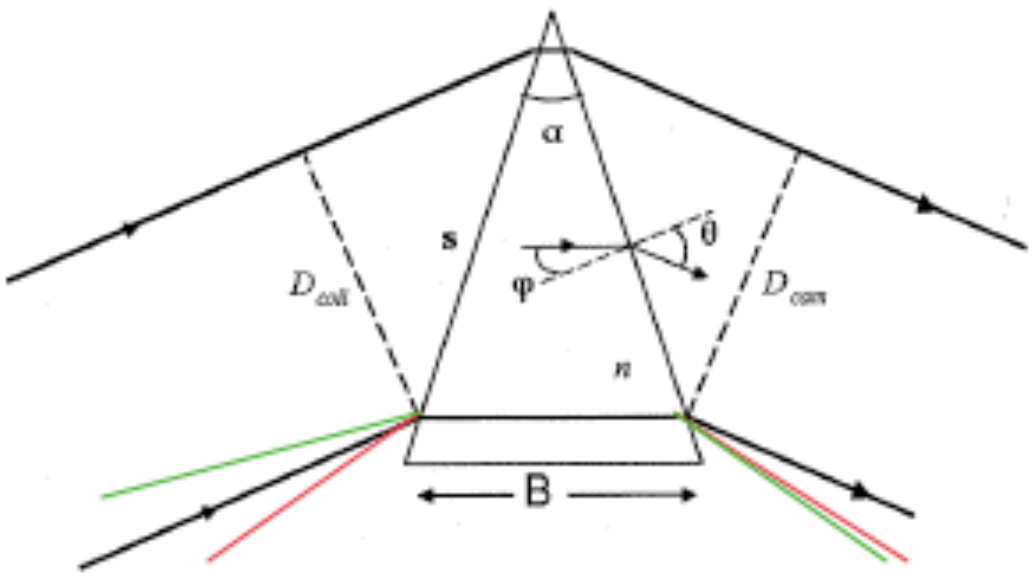

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NBI: The angular dispersion depends on the wavelength!

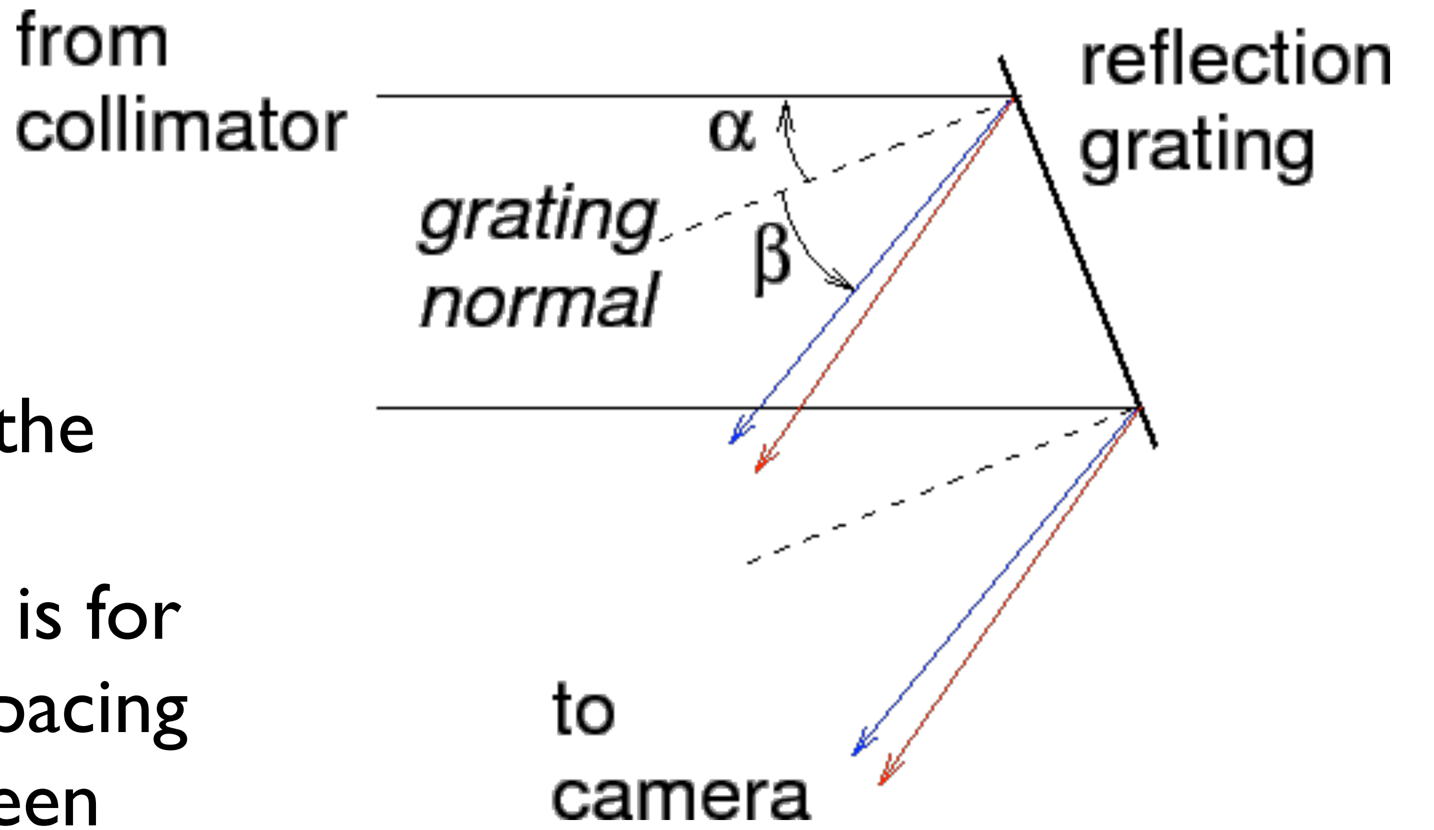
NBII: For k identical prisms in a row, the dispersion increases by a factor of k.

Gratings

Analysis of grating spectrographs, stars with the grating equation:

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

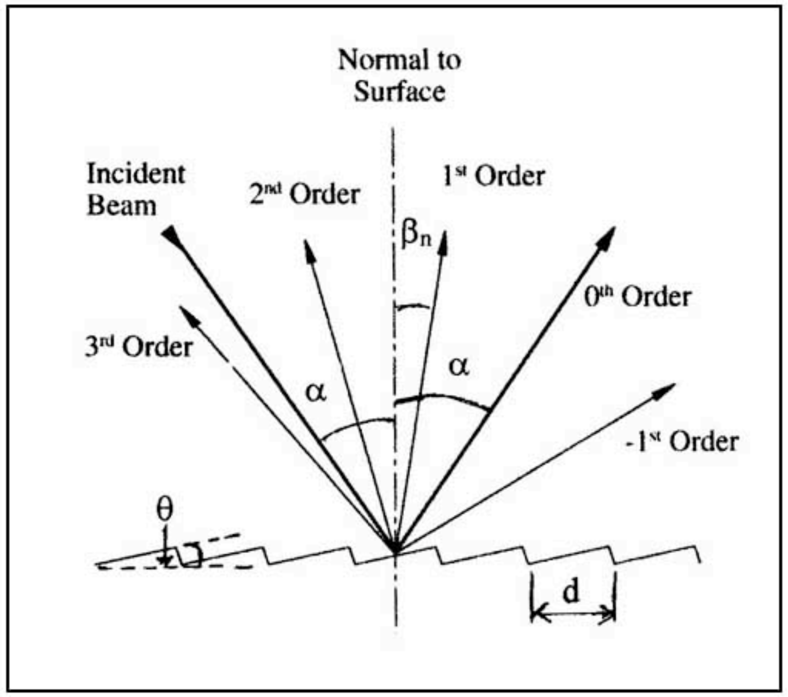
Where m is the order and sigma is the groove spacing. The plus sign is for reflection gratings and the negative is for transmission gratings. The groove spacing is typically the number of mm between each line and is the inverse of the lines/mm.



Differentiating this equation gives the angular dispersion:

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

Higher Orders



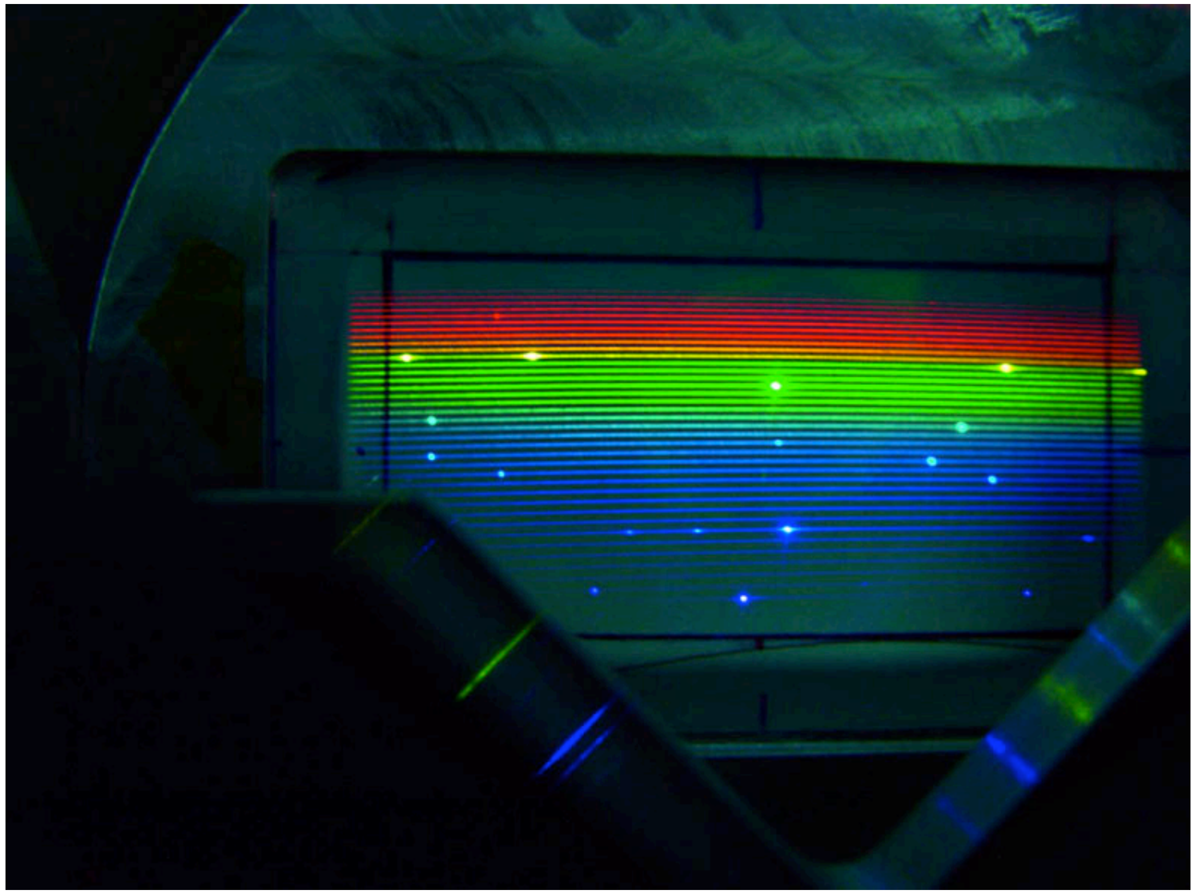
Reflection Grating Diffracted Orders

The free spectral range of a spectrograph is given by

$$\lambda' - \lambda = \lambda/m$$

$$m\lambda' = (m+1)\lambda$$

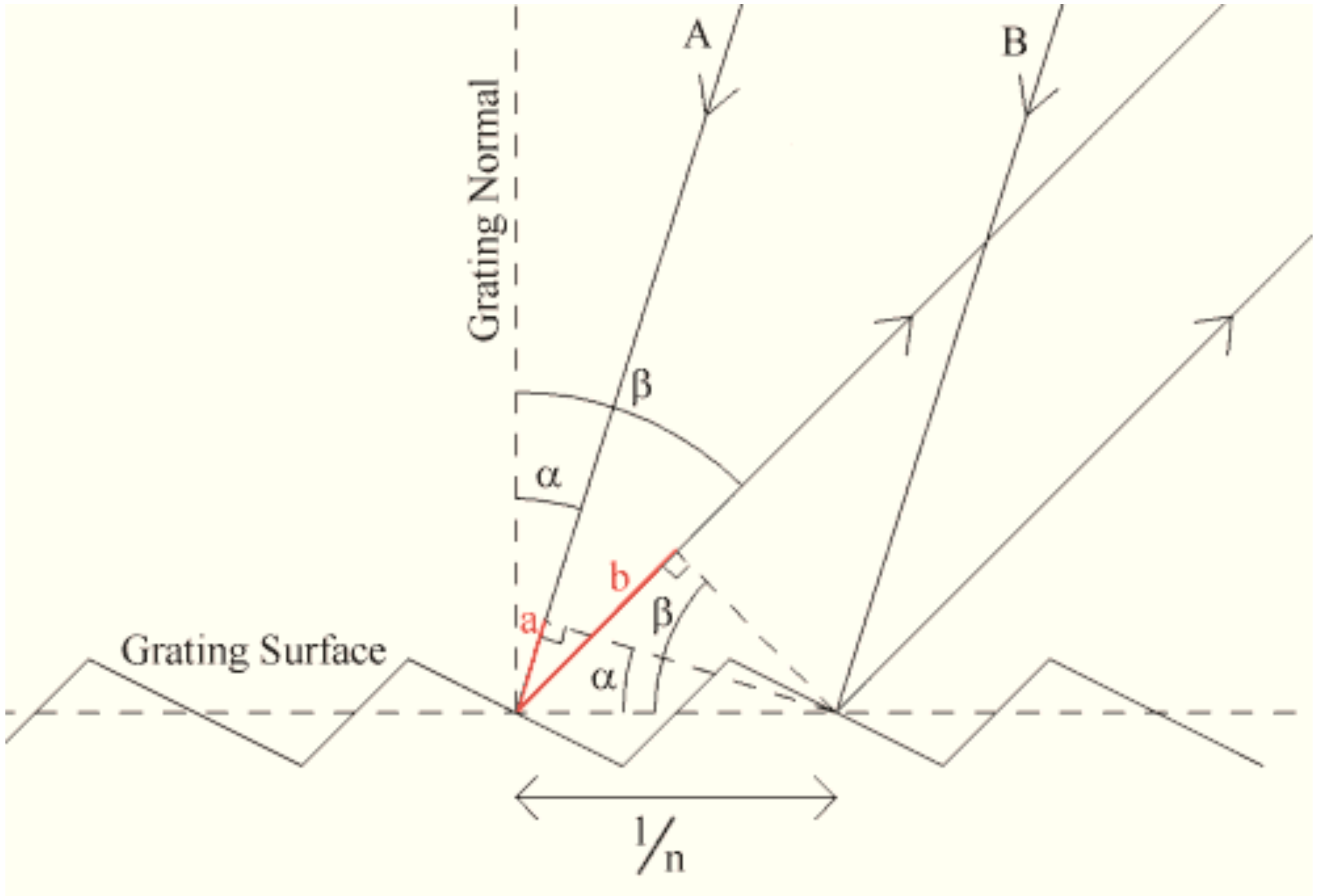
Higher order dispersion from the grating will result in overlapping spectra. These higher order spectra can be removed by using order blocking spectra. Or we can use a cross-dispersion element to see all of these different orders. This is what is typically done in echelle spectrographs.



OHP

Blaze Angle

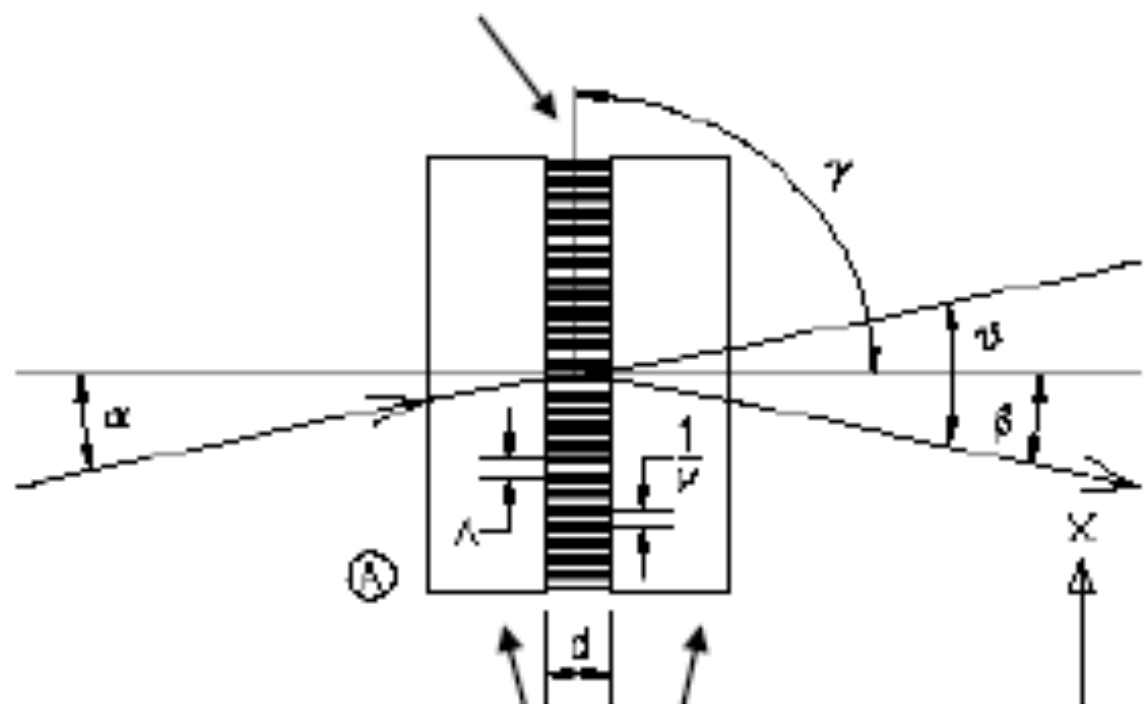
As can be seen, higher resolution can be reached by accessing higher orders. The efficiency at higher orders can be boosted by adjusting the grating so that the grooves are angled. The angle of the grooves is called the blaze angle, δ.



Typically, one wants to work at blaze, which implies working very close to **littrow**. This is the condition where $\alpha=\beta=\delta$ and the central wavelength is at the peak of the blaze function

VPH gratings

In RSS, Volume Holographic Gratings are the dominate dispersal element. VPH gratings are transmission gratings that have very high efficiencies. The blaze peak for these gratings can be tuned by rotating the grating.



For more information on VPH gratings, see Barden et al. 1998

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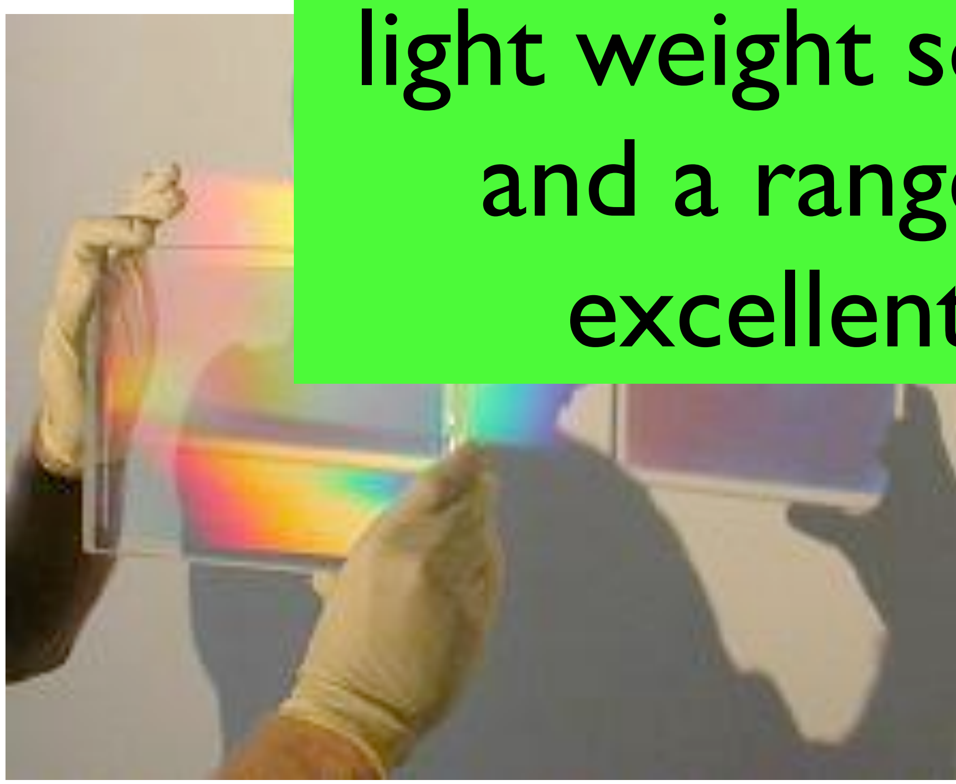
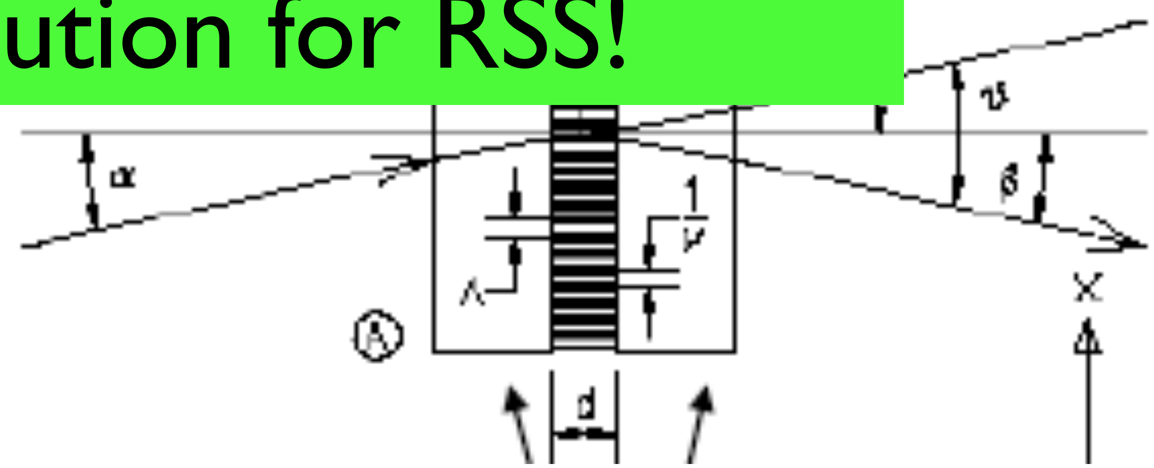
VPH Gratings provide a compact, light weight solution, high efficiency,, and a range of resolutions. An excellent solution for RSS!





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Resolution

Once again, the resolution and resolution element are given by:

$$R = \frac{\lambda}{\Delta\lambda} \qquad \Delta\lambda = w'\frac{d\lambda}{dl}$$

But we now have expressions for the linear disperion and slit width such that:

$$w' = rw\frac{f_{cam}}{f_{col}} = r\phi f_{tel}\frac{f_{cam}}{f_{col}} \qquad \frac{dl}{d\lambda} = f_{cam}A$$

This gives the following equation for the resolution of a telescope:

$$R = \frac{\lambda A f_{col}}{rw} = \frac{m\lambda}{\sigma cos\alpha}\frac{d_{col}}{\phi d_{tel}}$$

How to increase the resolution?

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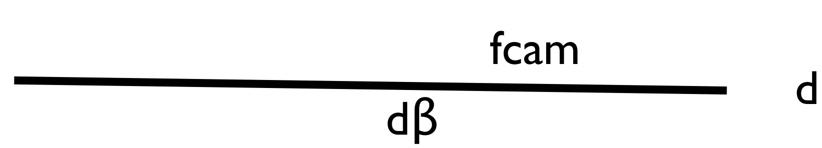
- High order,
- higher wavelength
- more lines per mm (smaller separation)
- Smaller slit
  - Physically smaller
  - image slicing
- Different technology
  - Fabry-Perot
  - Fourier Transform

Wavelength Coverage

Since the littrow condition typically gives the peak of the throughput for a grating, most spectrographs are operated with $\alpha=\beta$ for the central wavelength. In this case the central wavelength is given by:

$$\lambda = \frac{2\sigma sin\alpha}{m}$$

If the resolution element does not depend on wavelength (which for gratings it does not), then the wavelength coverage can just be estimated from the central wavelength, the size of the detector. Otherwise the wavelength coverage has to be calculated using the grating equation, the camera focal length, and the size of the detector.



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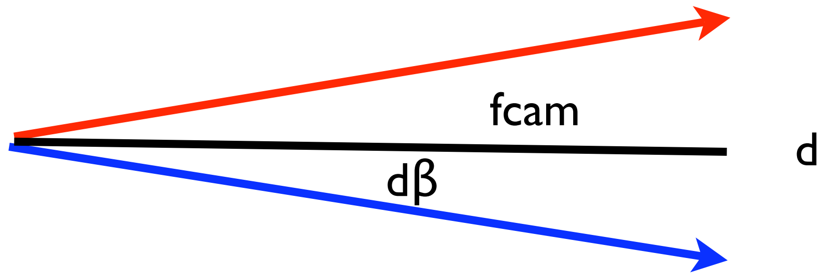

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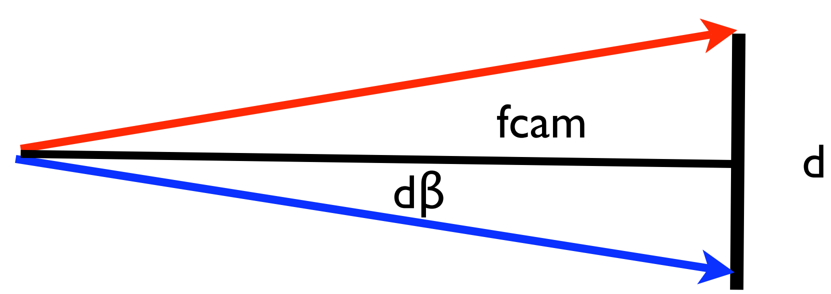

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Detector

One more issue for design of a spectrograph and the detector is the sampling of the spectra. At a minimum, the smallest resolution element for the spectrograph should be sampled at the minimum of the Nyquist Frequency, which corresponds to 2 pixels per resolution element.

A useful metric is the spectral dispersion per pixel which is given by:

$$\mu \frac{d\lambda}{dl}$$

where μ is the pixel size [mm].

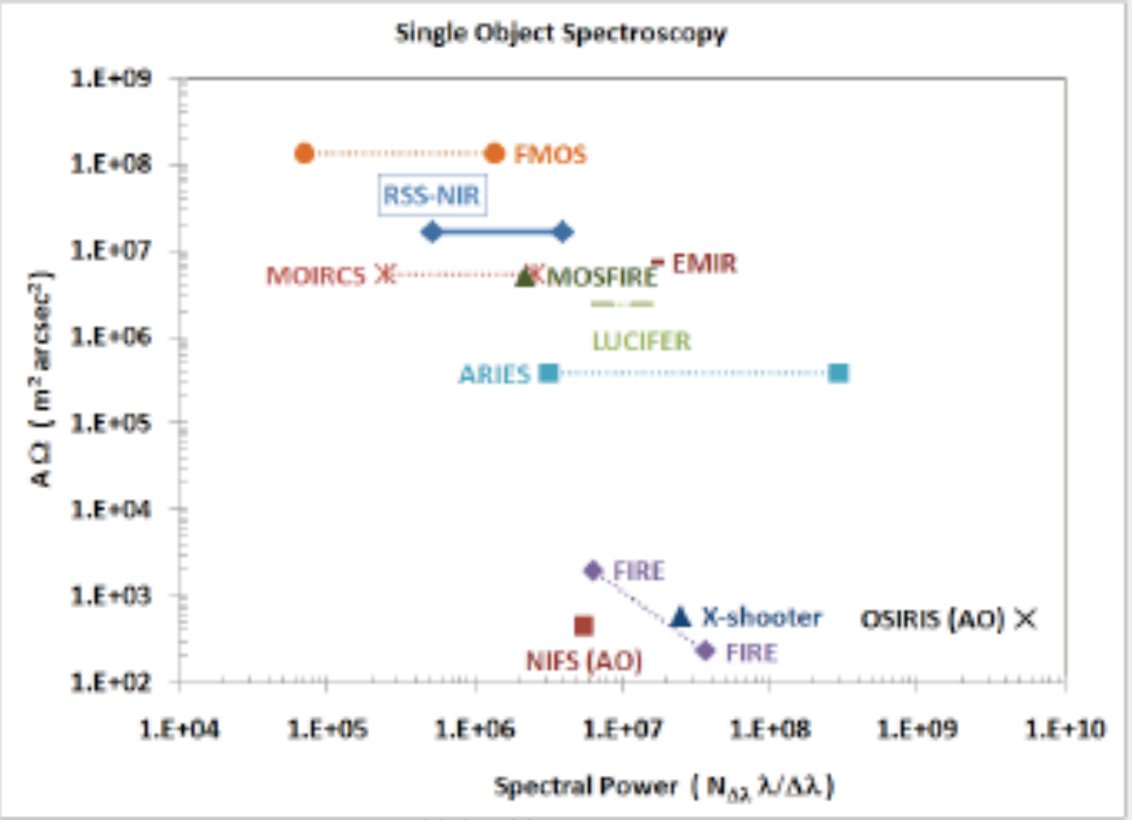
Efficiency

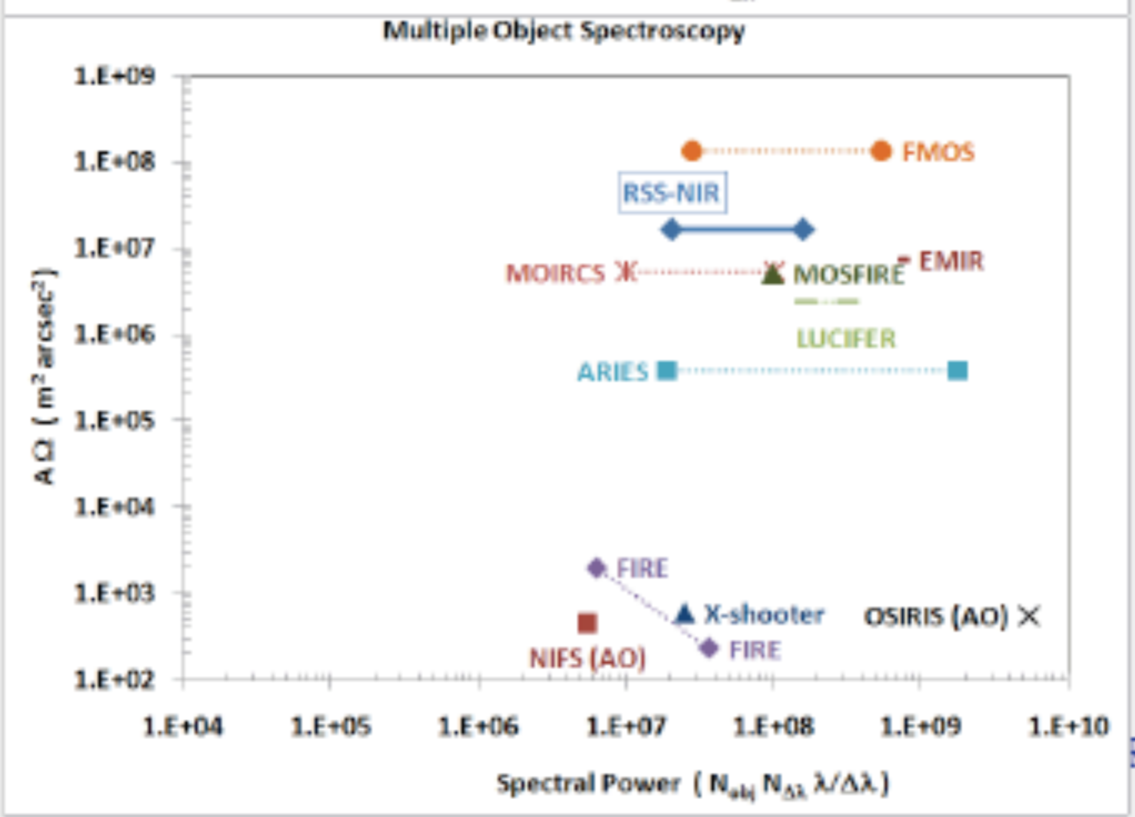
Efficiency can be determined in a number of different manners.

Throughput	τ	How much light makes it from the source to the detector.
Limiting Magnitude	M_{lim}	What is the faintest object that can be observed?
Etendue	$A\Omega$	Pupil Area x solid angle
Luminosity-Resolution	LR	$(\tau\ \pi/4)(D\Phi')(\lambda A d_{cam})$
Spectral Power	P	$N_{obj}\ N_{\Delta\lambda}\ R$

A number of other different parameters can be defined as well depending on what type of spectrograph is being built and what comparisons are being made such as $\tau\, A\Omega$.

COMPARISON TO OTHER INSTRUMENTS





Telescope	Instrument	Resolution	A Ω	$N_{\Delta\lambda}\ \lambda/\Delta\lambda$	$N_{obj}\ N_{\Delta\lambda}\ \lambda/\Delta\lambda$
SALT	RSS-NIR	4000	4.41E+04	1.12E+06	4.50E+07
	RSS-NIR	7000	4.41E+04	3.95E+06	1.58E+08
Keck	MOSFIRE	3270	5.09E+06	2.21E+06	9.92E+07
Subaru	MOIRCS	500	5.32E+06	2.50E+05	1.00E+07
	MOIRCS	1600	5.32E+06	2.56E+06	1.02E+08
Subaru	FMOS	500	1.34E+08	7.03E+04	2.81E+07
	FMOS	2200	1.34E+08	1.36E+06	5.45E+08
VLT	X-shooter	5000	5.90E+02	2.50E+07	2.50E+07
GTC	EMIR	4000	7.34E+06	1.60E+07	7.20E+08
LBT	LUCIFER	10000	2.39E+06	1.38E+07	3.16E+08
	LUCIFER	5000	2.39E+06	7.19E+06	1.65E+08
Magellan	FIRE	6000	2.32E+02	3.65E+07	3.65E+07
	FIRE	2500	1.99E+03	6.33E+06	6.33E+06
MMT	ARIES	2000	3.80E+05	3.15E+06	1.89E+07
	ARIES	30000	3.80E+05	2.98E+08	1.79E+09

COMPARISON TO OTHER INSTRUMENTS

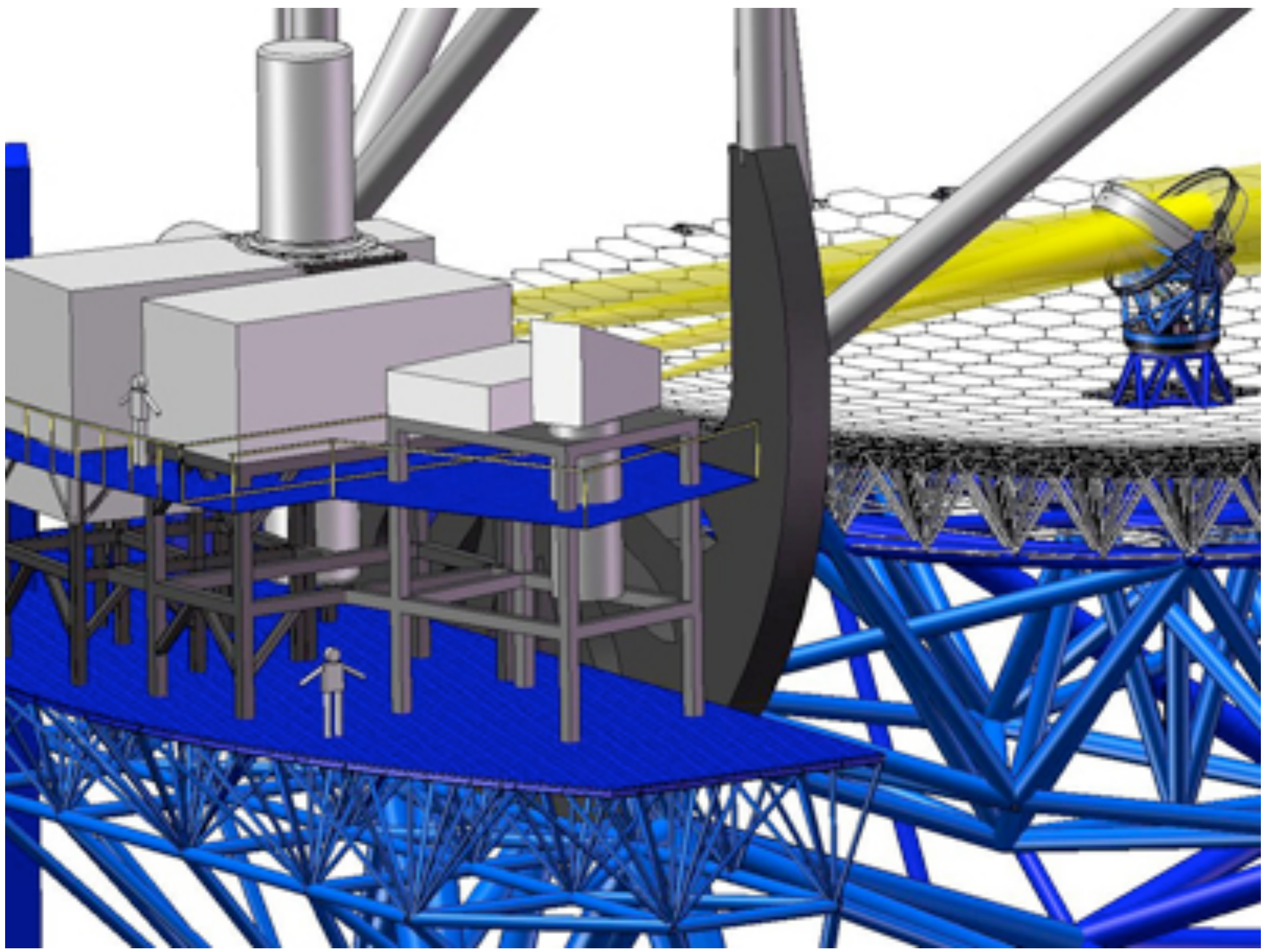
$$P = \frac{R\left(\frac{\lambda_2}{\lambda_1}\right)}{t}$$

R = spectral resolution
λ_2 = longest wavelength in FSR
λ_1 = shortest wavelength in FSR
t = time to S/N=10 $Å^{-1}$ for H_{AB} = 19.5

Telescope	Instrument	Resolution	Time (s)	P (single)	P (MOS)
SALT	RSS-NIR	4000	652.17	6.58	263.21
	RSS-NIR	7000	1125.45	6.74	269.67
Keck	MOSFIRE	3270	127.52	31.36	1411.25
Subaru	MOIRCS	1600	21493.27	0.21	8.27
VLT	X-shooter	5000	4586.19	6.90	6.90
GTC	EMIR	4000	524.93	21.17	952.50
Magellan	FIRE	6000	6698.35	2.53	2.53
MMT	ARIES	2000	7219.09	0.58	3.48
	ARIES	30000	1846.29	23.14	138.83

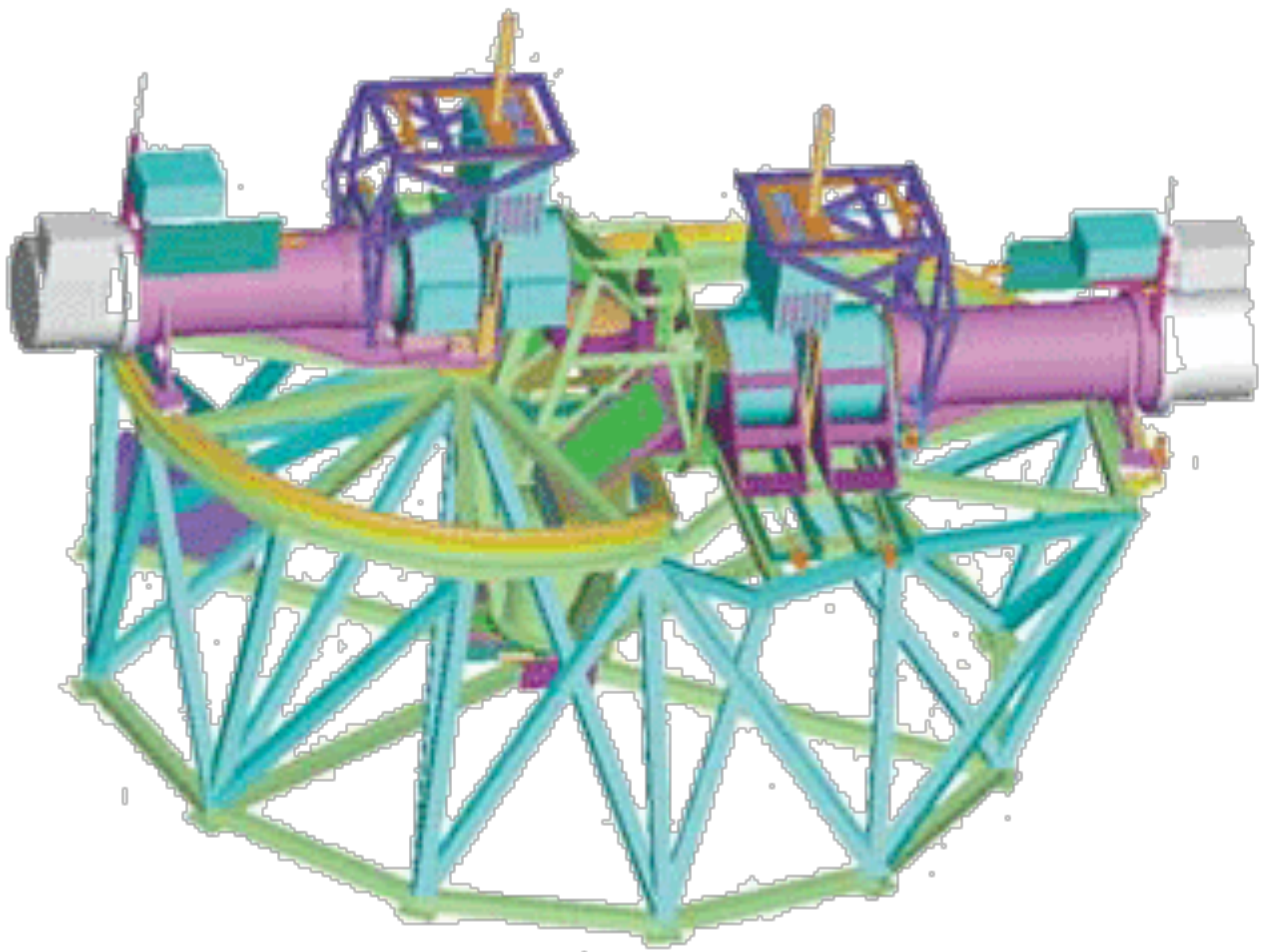
Cost

Obviously an important driver for the design and building an instrument is cost of the instrument. On a 10m telescope, base instruments will run ~$5M dollars. The cost typically scale with aperture (HRS costs more than GIRAFFE) and complexity (RSS costs more than HRS).

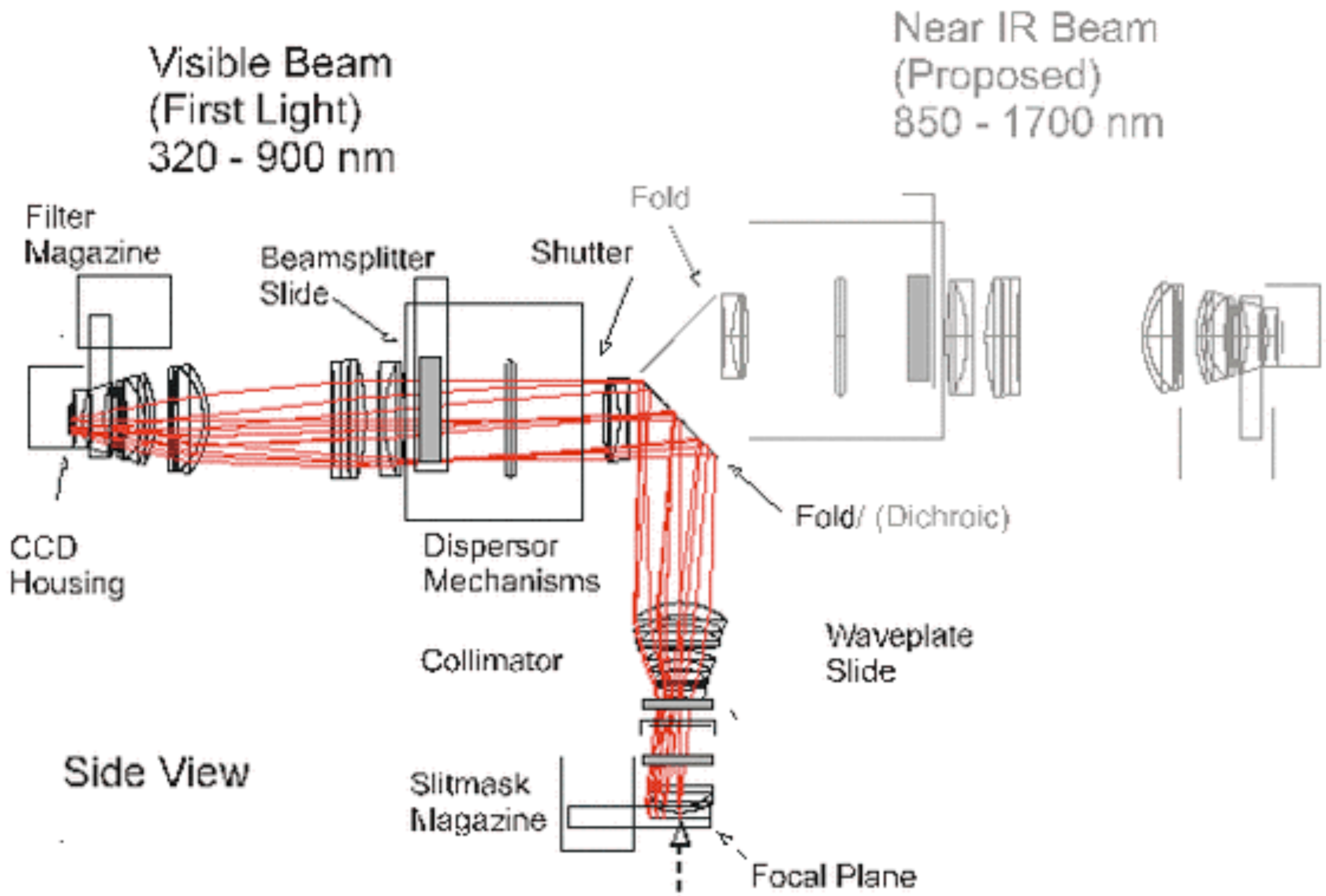


So for a thirty meter telescope...

The Robert Stobie Spectrograph



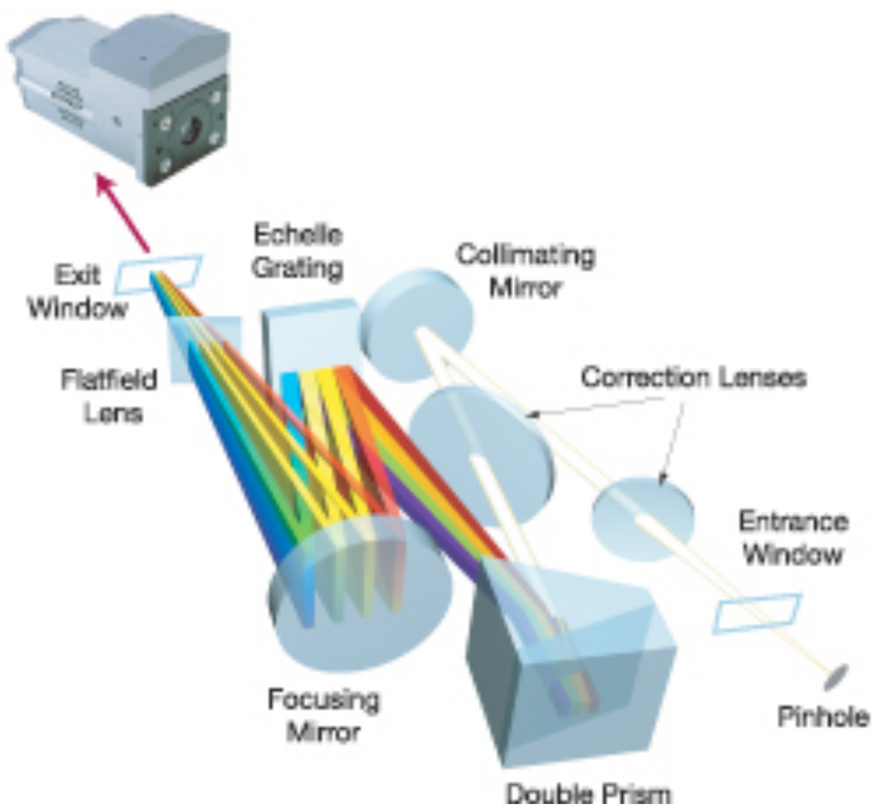
RSS Model

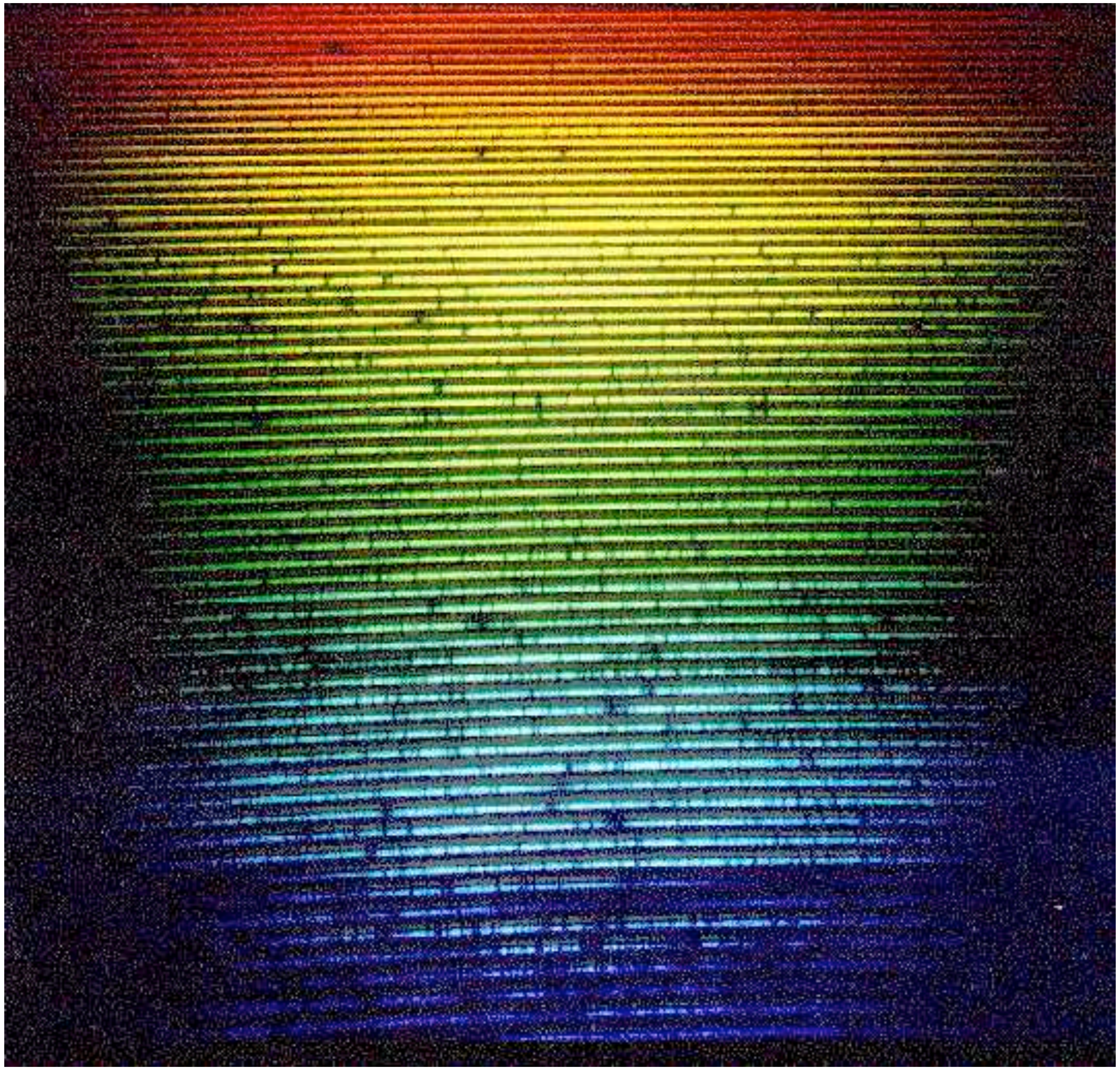


Visible Beam
(First Light)
320 - 900 nm
Near IR Beam
(Proposed)
850 - 1700 nm
Fold
Filter
Magazine
Beamsplitter
Slide
Shutter
CCD
Housing
Dispersor
Mechanisms
Fold/ (Dichroic)
Collimator
Waveplate
Slide
Side View
Slitmask
Magazine
Focal Plane

Echelle Spectrograph

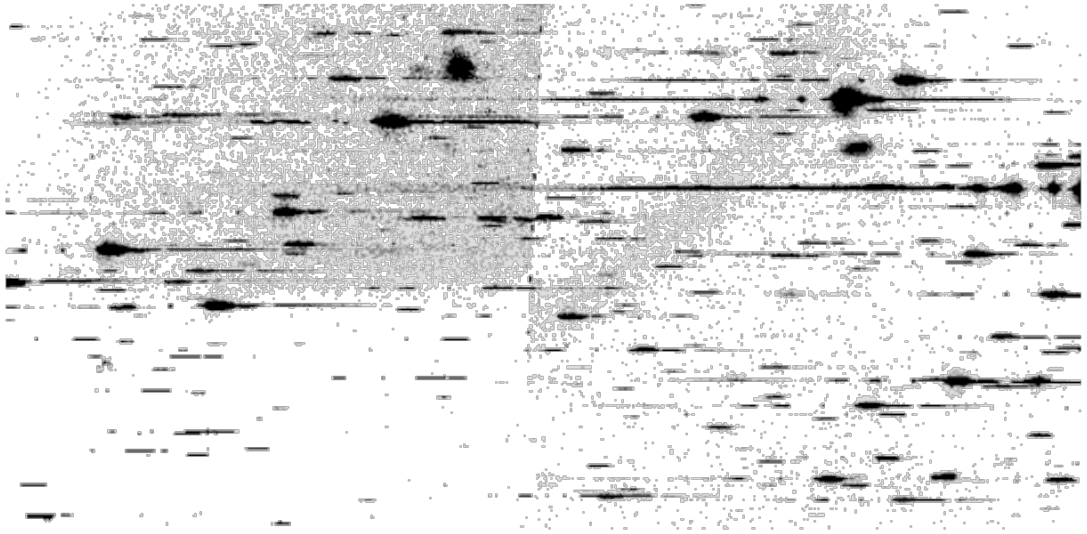
Echelle Spectrographs work at high blaze angle and will use a second grating to cross disperse the spectra to see multiple orders





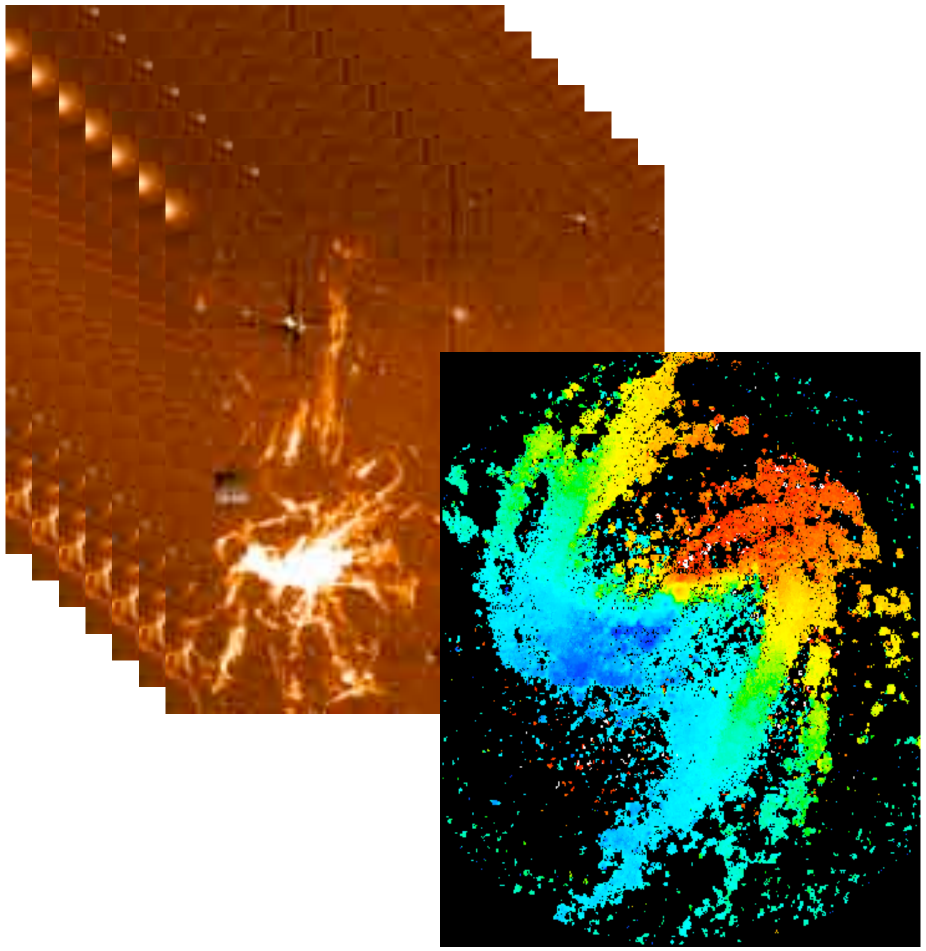
Other Designs

- Slitless
- Without a collimator
- Without a dispersive element
  - Imaging
  - Fabry-Perot
  - Calorimeters



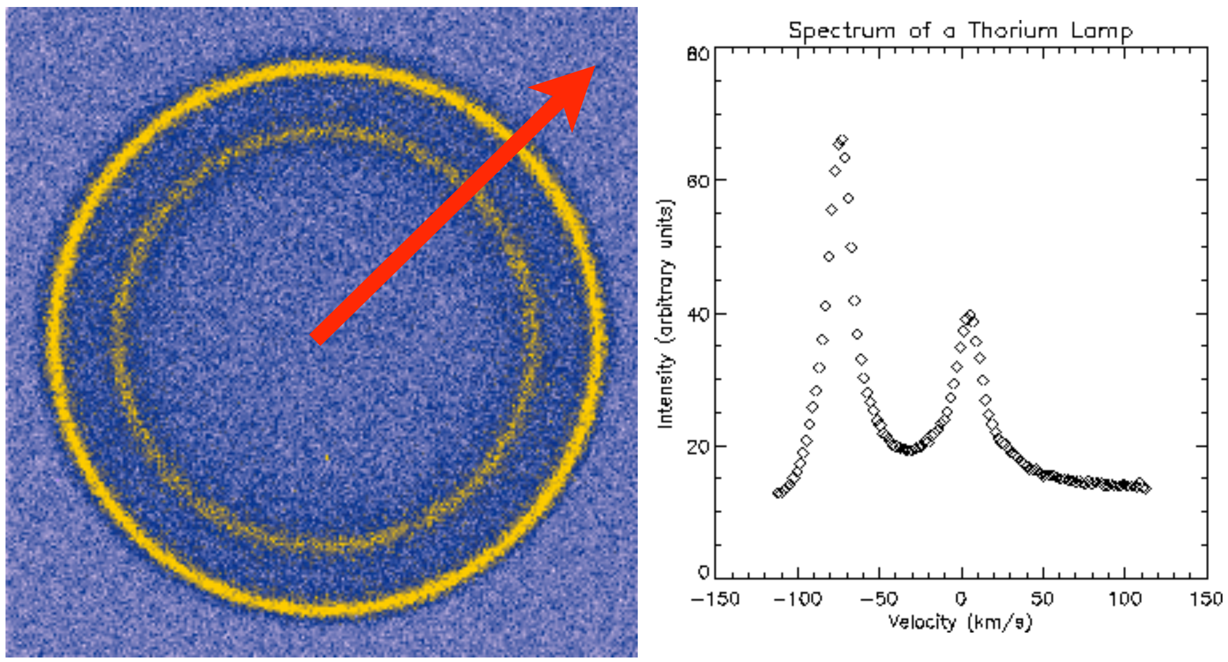
Fabry-Perot

Imaging Mode:
Build up a data cube



Sanchez (RU)

Spectroscopic Mode:
High R and $A\Omega$



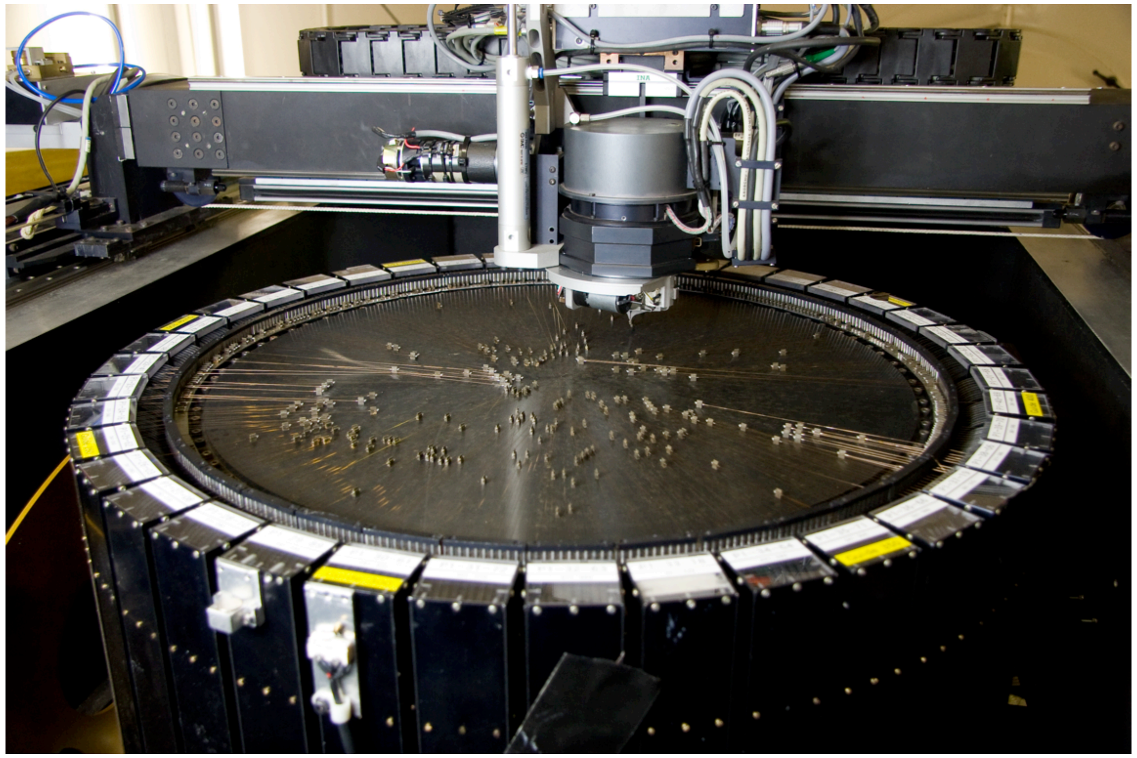
Haffner

Wavelength changes as a function of radial position

Fiber-Fed Spectrographs

Instead of using a slit, the light is fed down a fiber in the image plane. This allows the spectrograph to be located somewhere else, decoupled from the telescope structure. Very common for large Field of View (FOV) Multi-object spectrographs (SDSS, AOmega) and high stability, high resolution spectrographs (HRS).

SDSS

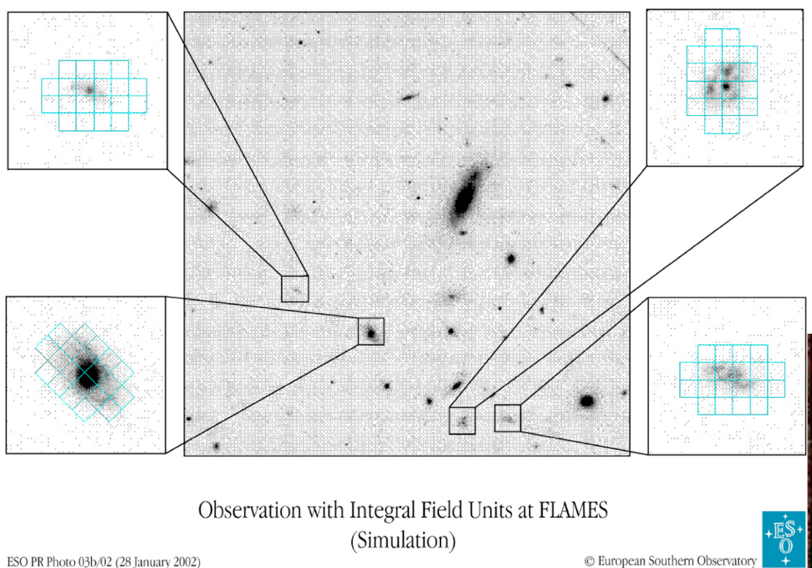


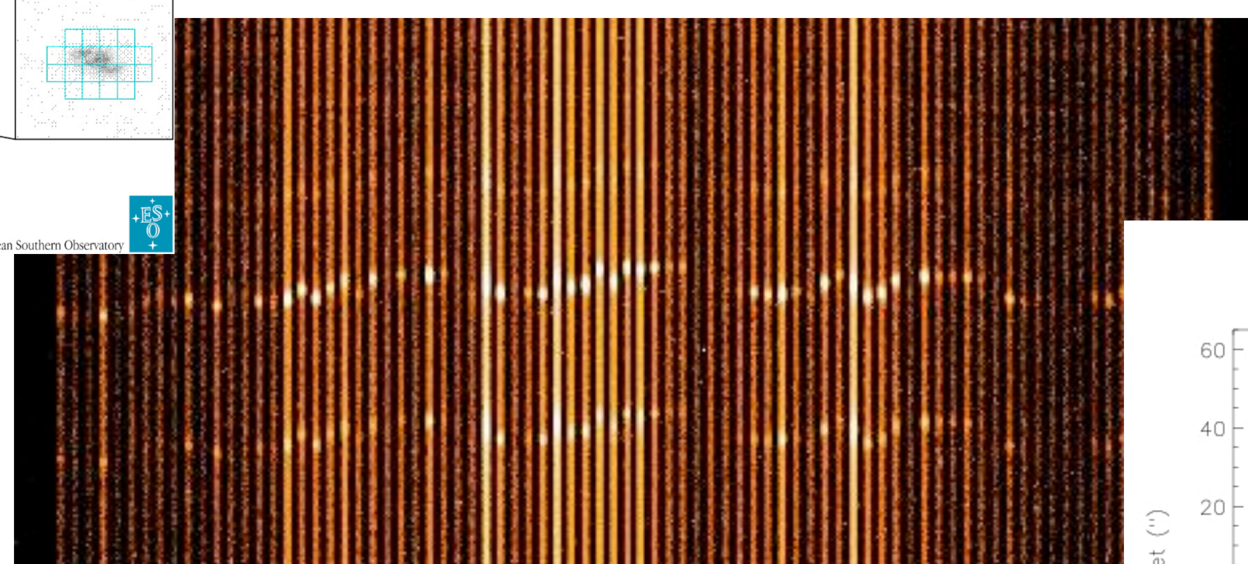
AAO

Richmond

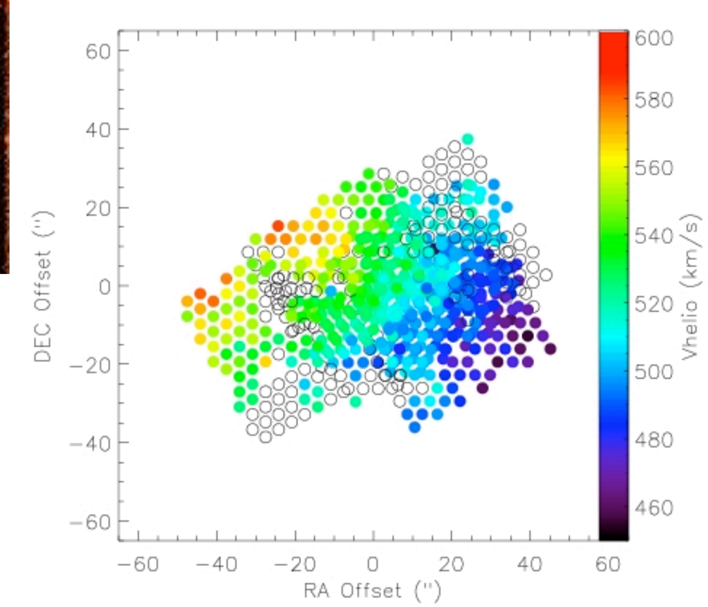
IFU

The fibers can also be placed in a bundle to gather spatial information along with the spectral information.



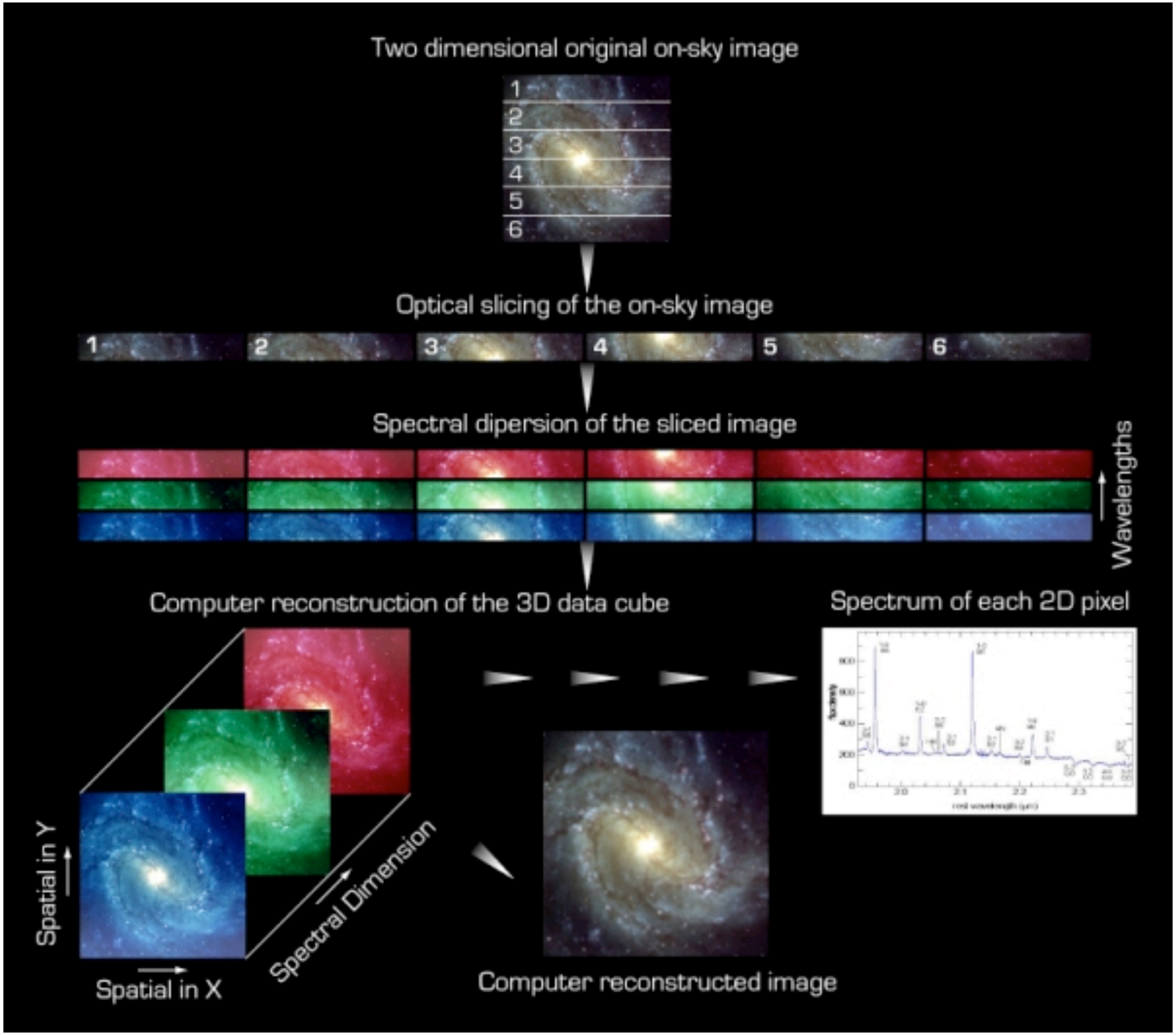


Bershady



Sanchez (RU)

Kuzio de Naray



Two dimensional original on-sky image
1
2
3
4
5
6
Optical slicing of the on-sky image
1
2
3
4
5
6
Spectral dipersion of the sliced image
Wavelengths
Computer reconstruction of the 3D data cube
Spectrum of each 2D pixel
Spatial in Y
Spatial in X
Spectral Dimension
Computer reconstructed image

Wegner

Reducing Spectroscopic Data

Reducing Spectroscopic Data

Observer the Data

Reducing Spectroscopic Data

Observer the Data

Reducing Spectroscopic Data

Observer the Data

Basic CCD Reductions

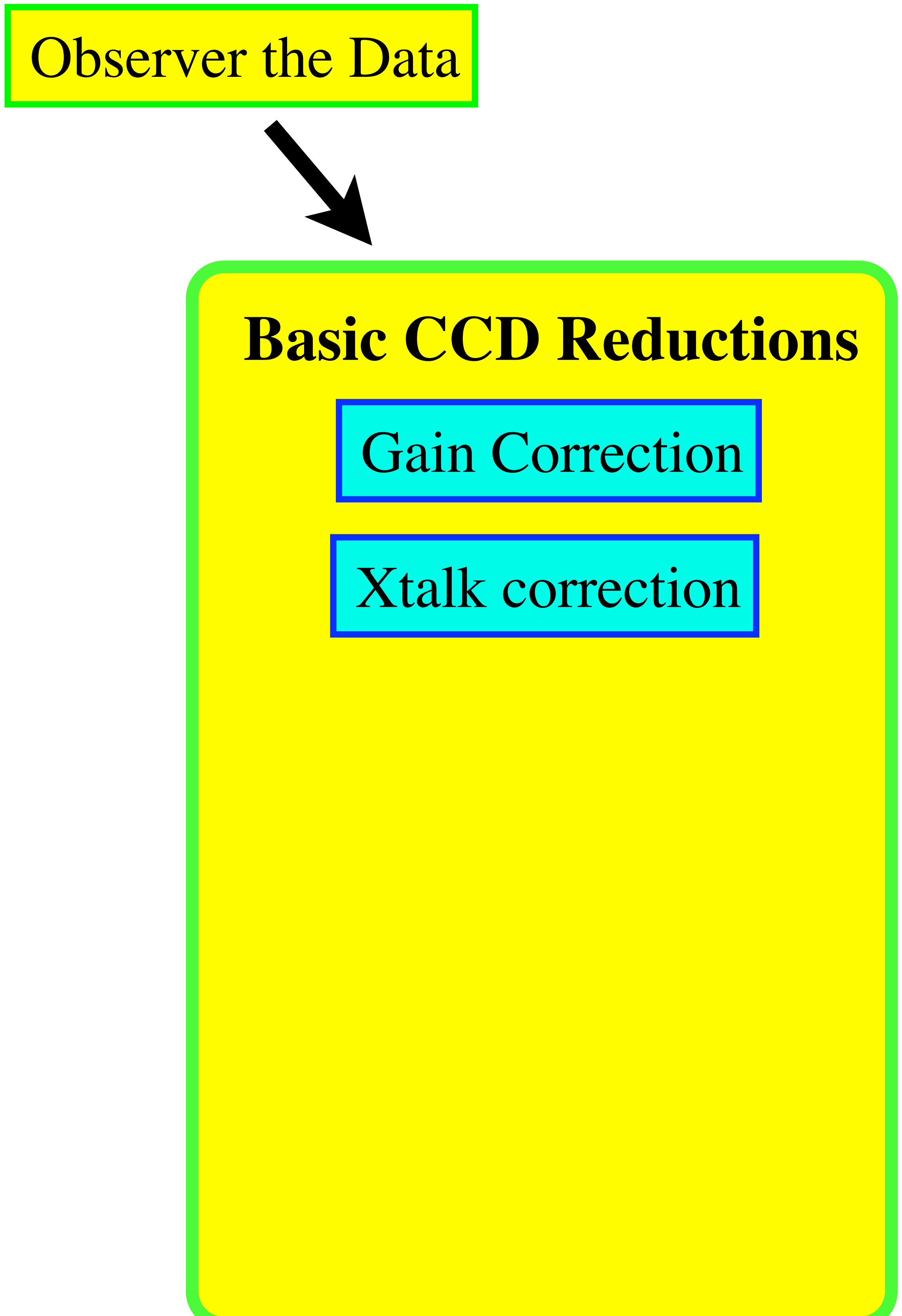
Reducing Spectroscopic Data

Observer the Data

Basic CCD Reductions

Gain Correction

Reducing Spectroscopic Data



Reducing Spectroscopic Data

Observer the Data

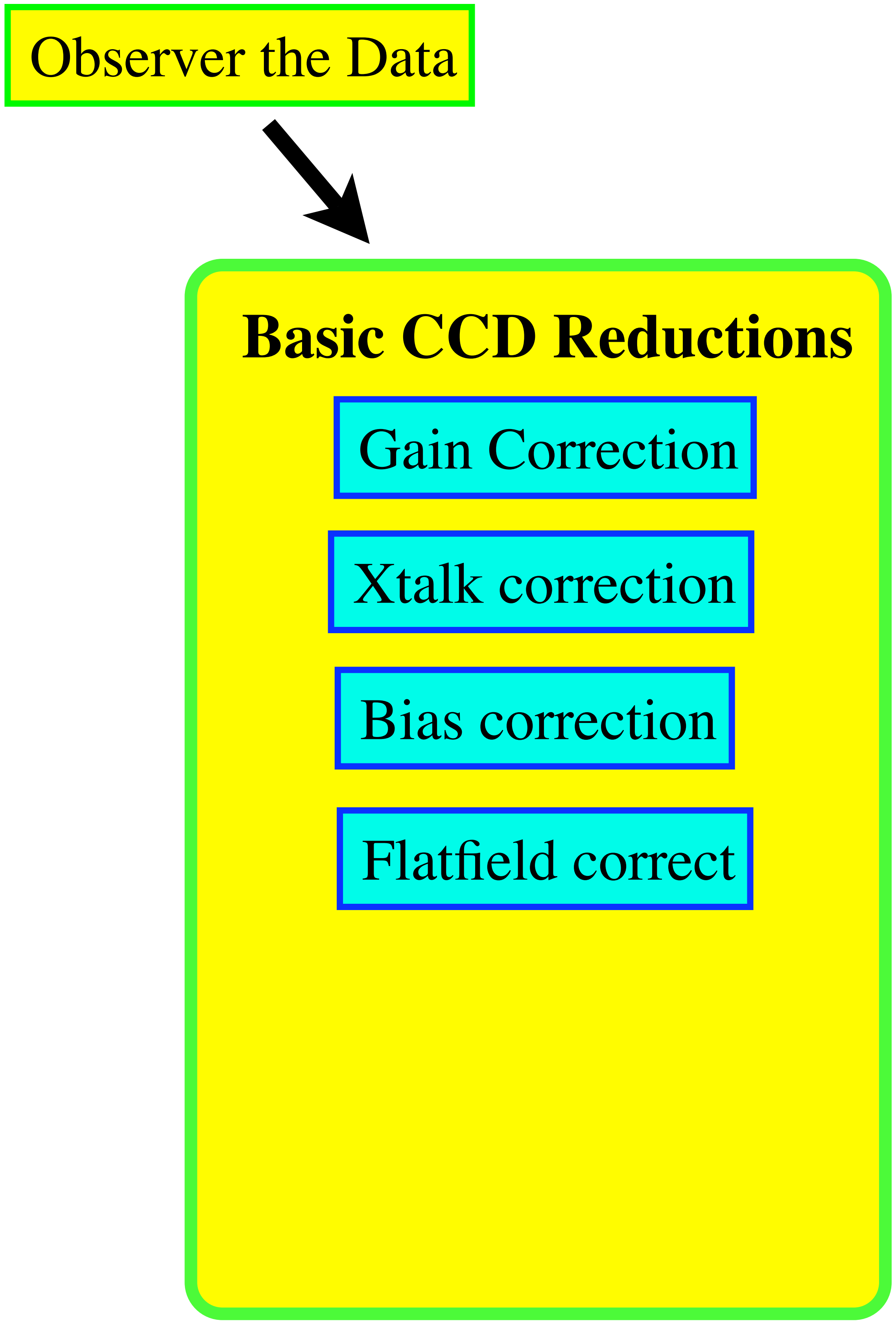
Basic CCD Reductions

Gain Correction

Xtalk correction

Bias correction

Reducing Spectroscopic Data



Reducing Spectroscopic Data

Observer the Data

Basic CCD Reductions

Gain Correction

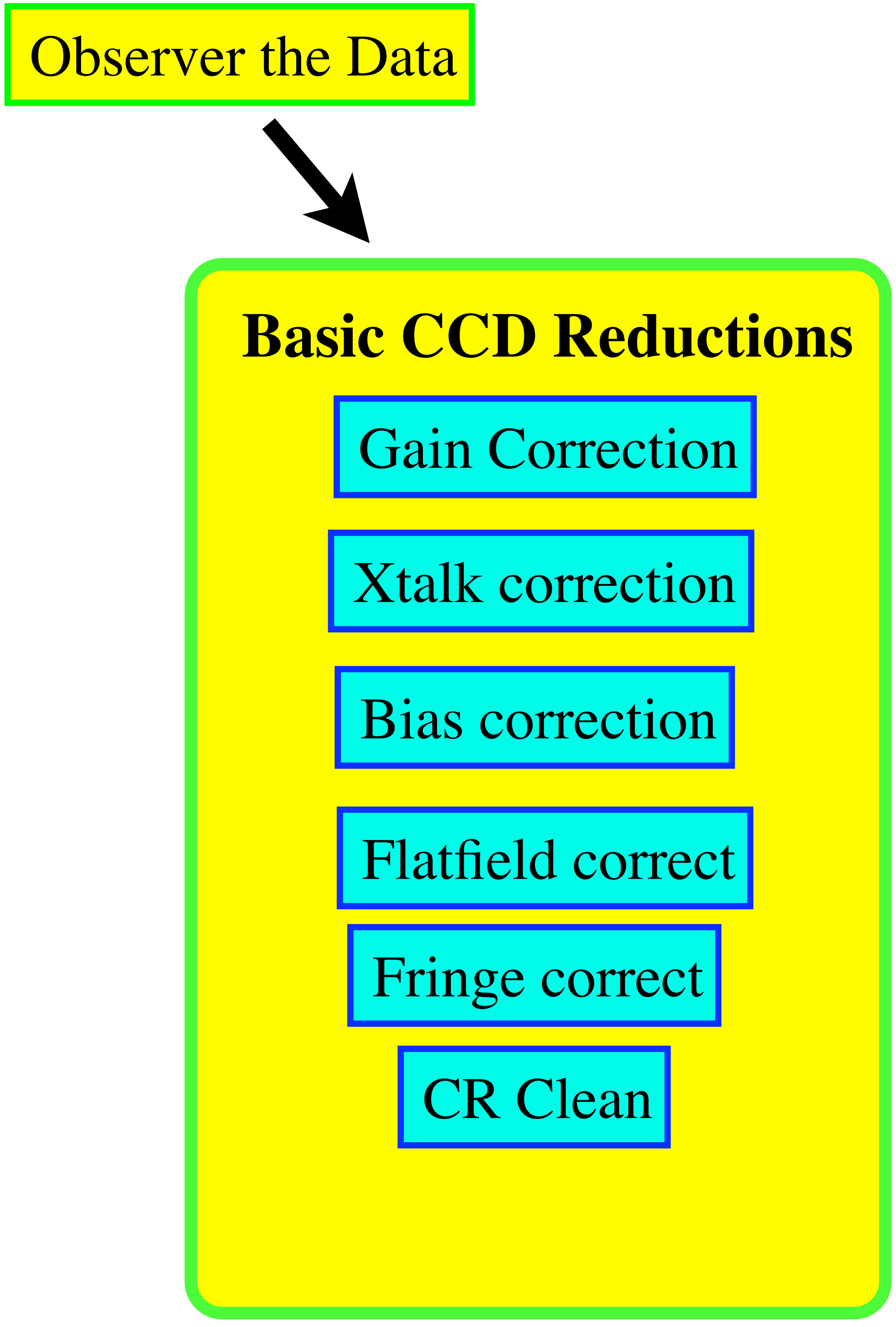
Xtalk correction

Bias correction

Flatfield correct

Fringe correct

Reducing Spectroscopic Data



Reducing Spectroscopic Data

Observer the Data

Basic CCD Reductions

Gain Correction

Xtalk correction

Bias correction

Flatfield correct

Fringe correct

CR Clean

Mosaic images

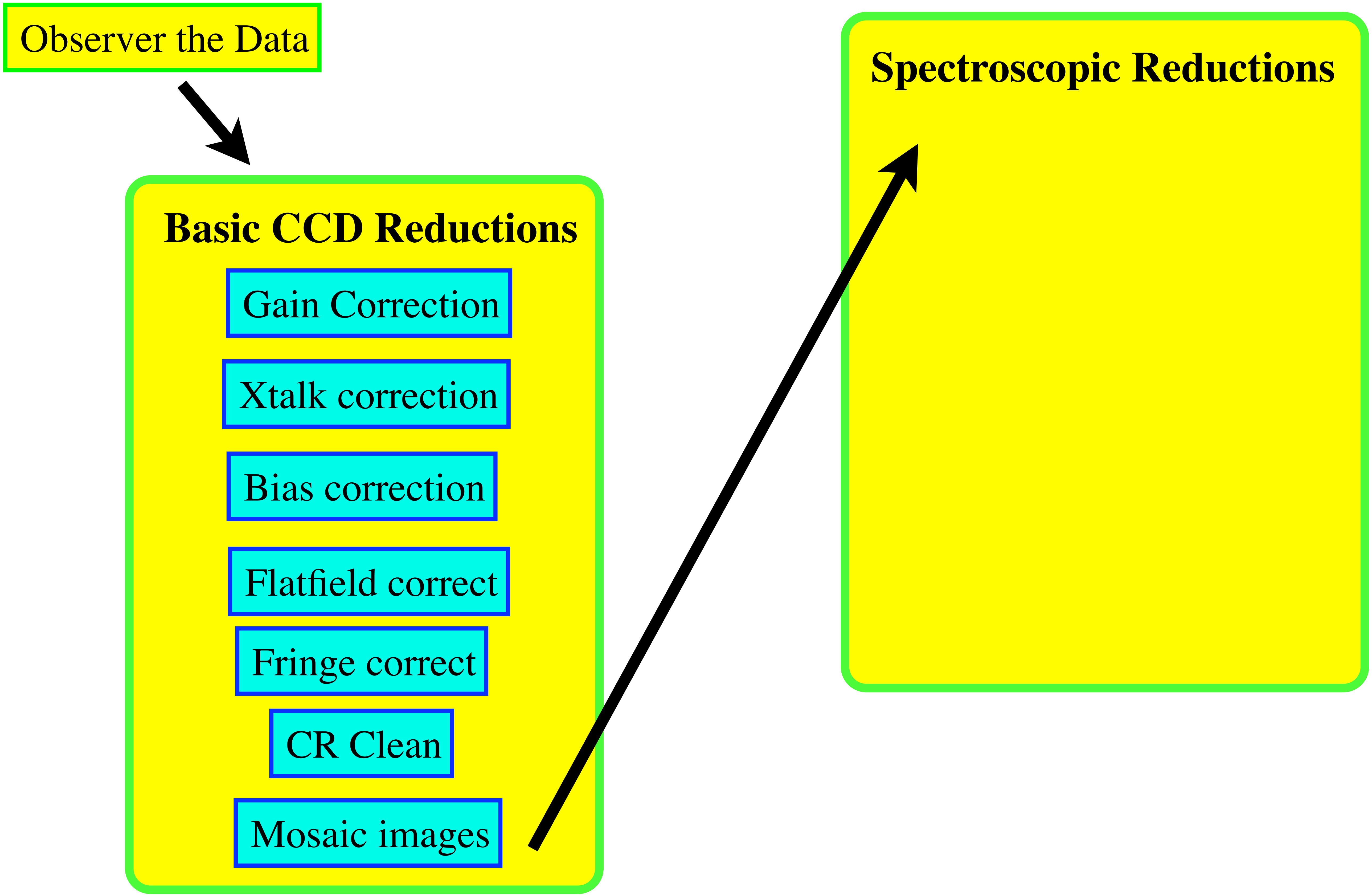
Reducing Spectroscopic Data

Observer the Data

Basic CCD Reductions

- Gain Correction
- Xtalk correction
- Bias correction
- Flatfield correct
- Fringe correct
- CR Clean
- Mosaic images

Reducing Spectroscopic Data



Reducing Spectroscopic Data

Observer the Data

Basic CCD Reductions

Gain Correction

Xtalk correction

Bias correction

Flatfield correct

Fringe correct

CR Clean

Mosaic images

Spectroscopic Reductions

Identify Slit(s)

Reducing Spectroscopic Data

Observer the Data

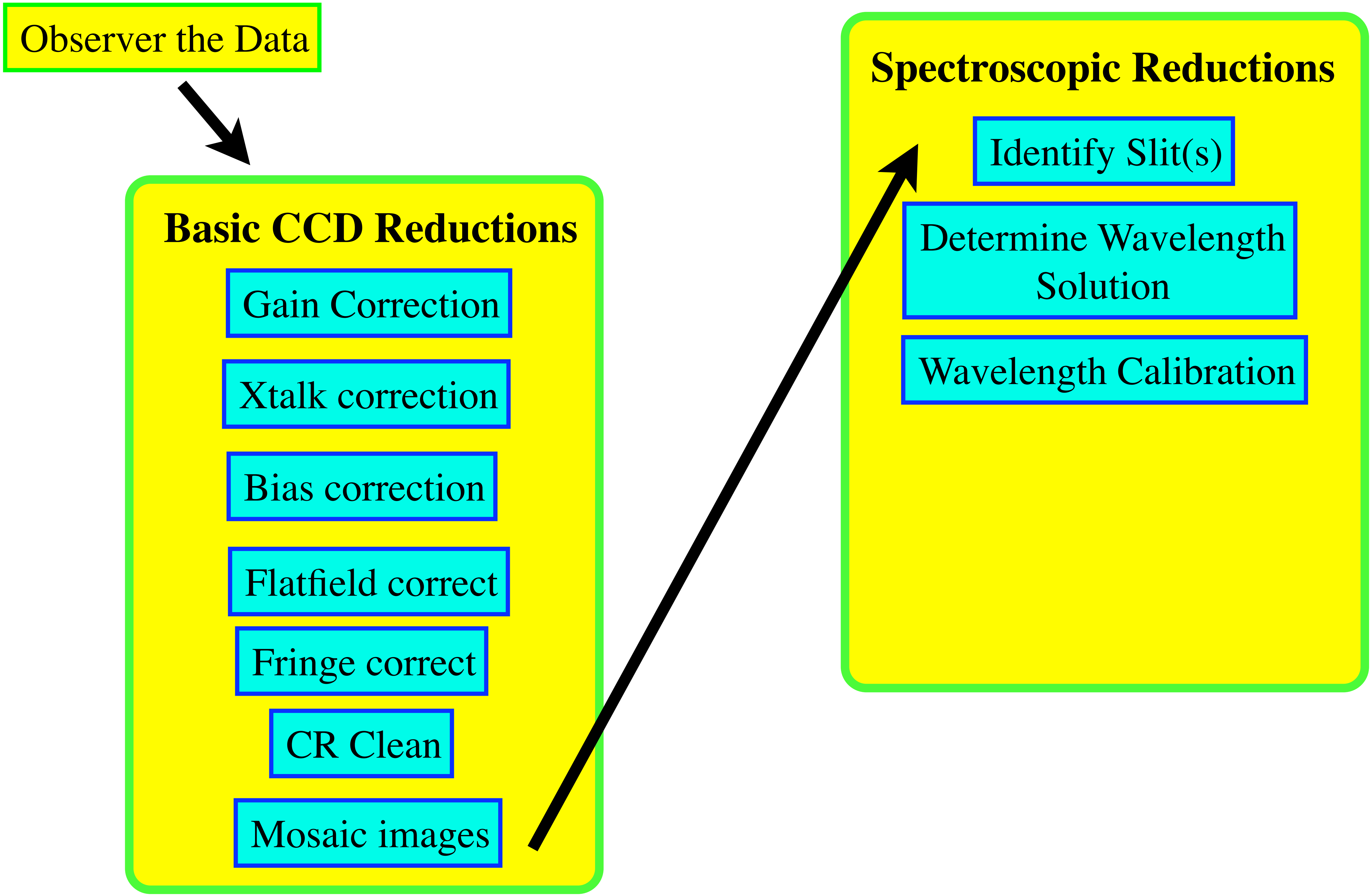
Basic CCD Reductions

- Gain Correction
- Xtalk correction
- Bias correction
- Flatfield correct
- Fringe correct
- CR Clean
- Mosaic images

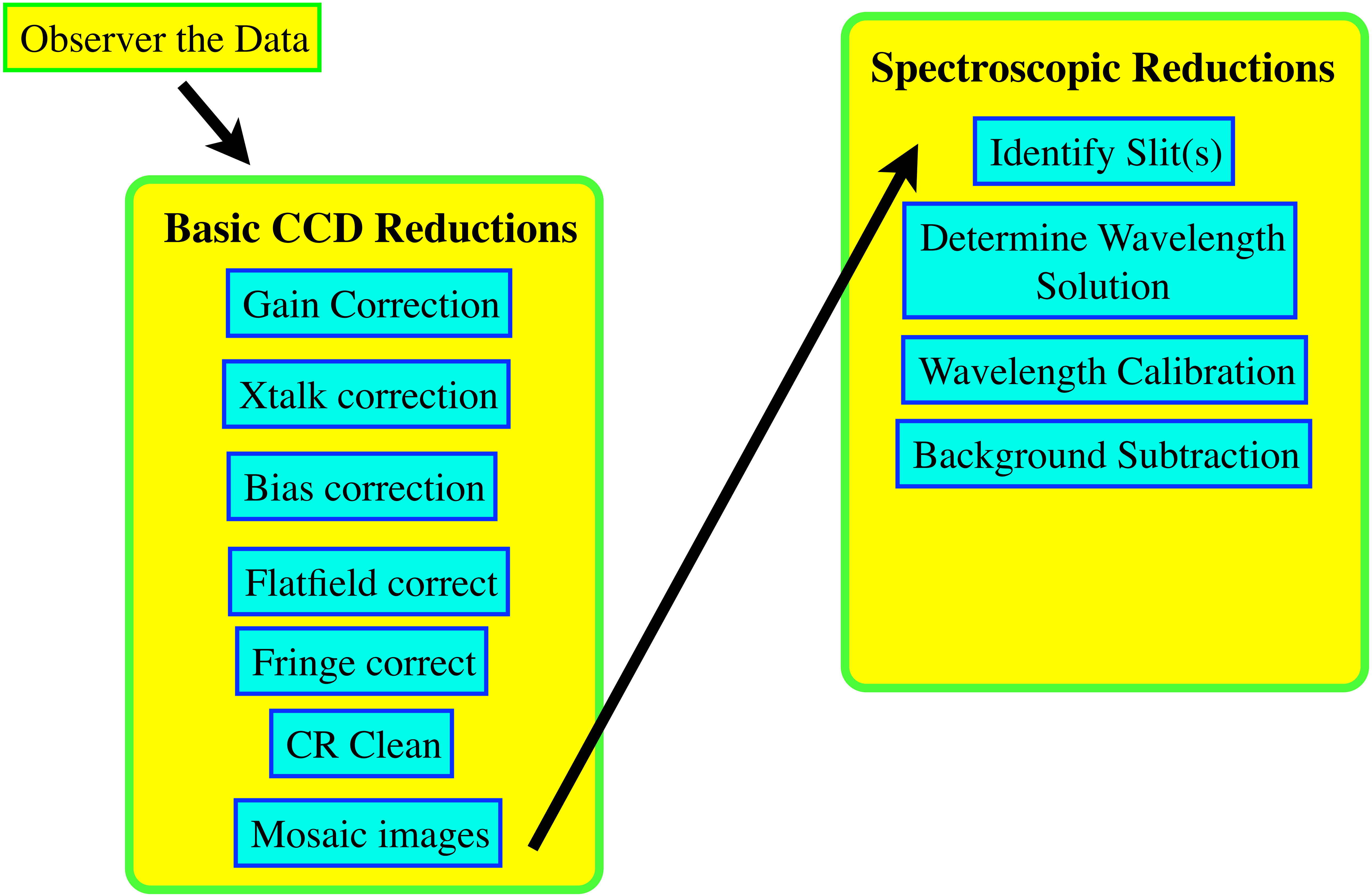
Spectroscopic Reductions

- Identify Slit(s)
- Determine Wavelength Solution

Reducing Spectroscopic Data



Reducing Spectroscopic Data



Reducing Spectroscopic Data

Observer the Data

Basic CCD Reductions

- Gain Correction
- Xtalk correction
- Bias correction
- Flatfield correct
- Fringe correct
- CR Clean
- Mosaic images

Spectroscopic Reductions

- Identify Slit(s)
- Determine Wavelength Solution
- Wavelength Calibration
- Background Subtraction
- Flux Calibration

Reducing Spectroscopic Data

Observer the Data

Basic CCD Reductions

- Gain Correction
- Xtalk correction
- Bias correction
- Flatfield correct
- Fringe correct
- CR Clean
- Mosaic images

Spectroscopic Reductions

- Identify Slit(s)
- Determine Wavelength Solution
- Wavelength Calibration
- Background Subtraction
- Flux Calibration
- Aperture Extraction