

PHY 517 / AST 443: Observational Techniques in Astronomy

Lecture 3:
CCDs /
FITS files /
Spectroscopy

StarAlt

you have to pay attention to the format of your coordinates!

The screenshot shows the StarAlt software interface. Under the 'Mode' section, 'Staralt' is selected. In the 'Night' section, the date is set to 06 September 2017. The 'Observatory' section contains a dropdown menu with 'Roque de los Muchachos Observatory (La Palma, Spain)' selected, and a text input field for custom site specification. A red circle highlights the text input field and the dropdown menu. Below the input field, there is an example of coordinate format: 'Ex.: 289.2767 -30.2283 2725 -4'. The entire 'Observatory' section is circled in red.

How are Mt. Stony Brook's coordinates correctly specified?

- A) 41 73
- B) 73 40
- C) -41 73
- D) 287 41

Coordinates: 40.914224°N 73.11623°W

Stony Brook University



Finding Charts

HW asked for chart orientation “as if you were looking at the sky with the naked eye”

WHAT NORTH-SOUTH ORIENTATION WOULD YOU LIKE? *

North Up North Down

WHAT EAST-WEST ORIENTATION WOULD YOU LIKE? *

East Left East Right

Which of these is correct?

- A) North Up, East Left
- B) North Up, East Right
- C) North Down, East Left
- D) North Down, East Right

Significant digits

Code output with way
too many digits:

$$99.123456789 \\ \pm 0.004556789$$

Round the error to
one (or two) digits:

$$0.00455679 \rightarrow 0.005$$

The location of this
digit tells you the
location of the last
significant digit:

$$99.123 \\ \pm 0.005$$

Voila:

$$99.123 \pm 0.005$$

a python tutorial will follow this lecture

tutorial notebooks can be found on the class wiki
("python" tab or "schedule" tab)

Note on Astro Computing cluster

- you will probably want to do at least some of the analysis steps on the cluster
- your data should go into `/astrolab/Fall_2018/username`
- scripts and go into `/home/username`
- both are accessible from any machine in the cluster
- neither is backed up - *make sure to back up your data!*
- remember to change your password

Github

GitHub: version tracking + so much more!

excellent tool for collaborative work on code and documents, standard IT tool

course webpage is on github; please sign up even if you do not want to use the github features

announcements, bug reports, “issue” discussions will take place on github - you will only be notified if you are “watching” the class repository

[Code](#)[Issues 1](#)[Pull requests 0](#)[Wiki](#)[Pulse](#)[Graphs](#)[Settings](#)

J2000.0 coordinates from <http://exoplanet.eu/catalog/> #1

[Edit](#)[New issue](#)[Open](#)

NamHoNguyen opened this issue 16 minutes ago · 1 comment



NamHoNguyen commented 16 minutes ago



The RA and Dec coordinates of the host stars obtained from the catalog were recorded for the epoch J2000.0, which is at noon of January 1, 2000. We're observing the stars 16 years after this epoch so there must be some deviation in the coordinates. Is this difference negligible, and does it depend on the position of the chosen star?

"Right ascension for "fixed stars" near the ecliptic and equator increases by about 3.3 seconds per year on average, or 5.5 minutes per century, but for fixed stars further from the ecliptic the rate of change can be anything from negative infinity to positive infinity. The right ascension of Polaris is increasing quickly. The North Ecliptic Pole in Draco and the South Ecliptic Pole in Dorado are always at right ascension 18h and 6h respectively." from

https://en.wikipedia.org/wiki/Right_ascension

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Schedule

anjavdl edited this page 22 seconds ago · 1 revision

Date	Topics	Slides	Tutorials	Homework
Aug 27	Intro, Coordinate Systems, Time	Lecture 0 , Lecture 1		HW1, due Aug 29
Aug 29	Magnitudes, Atmosphere, Telescopes	Lecture 2	Tu1	HW2, due Sept. 5
Sep 5	CCDs, FITS files, spectroscopy	Lecture 3	Python1 , Python2	
Sep 10	Statistics 1	Lecture 4		HW3, due Sep 19

[Pages 25](#)

General Information

- [Schedule](#)
- [Grading](#)
- [Academic Policies](#)

Labs and Write-Ups

- [Guidelines](#)
- [How to write a decent lab report](#)

Mt. Stony Brook observing calendar - linked from wiki

Secure | https://calendar.google.com/calendar/embed?src=57n4gvtda95480oabi8v2tb528%40group.calendar.google.com&ctz=America/New_York

Mt Stony Brook Observing Calendar

Today September 2018

Print Week Month Agenda

Mon	Tue	Wed	Thu	Fri	Sat	Sun
27 6pm Lecture 1	28 6pm Lecture 2	29 6pm Lecture 3	30	31	Sep 1	2
3 Labor day - no class	4 4pm Lab 0 Biermann, Bishop, Yu 7pm Lab 0 Lee-Hand, Mertes, Ye	5	6	7	8 New Moon	9
10 6pm Lecture 4	11 3pm Lab 0 Campana, Filament	12	13	14	15	16
17	18	19	20	21	22	23
24 Full Moon	25	26	27	28	29	30

Events shown in time zone: Eastern Time - New York

+ Google Calendar

CCDs

CCDs

- CCD: “charge-coupled device”
- CCDs are the detectors of choice over much of the electromagnetic spectrum (X-rays to infrared)
- replaced photographic plates
- similar to detectors found in digital cameras

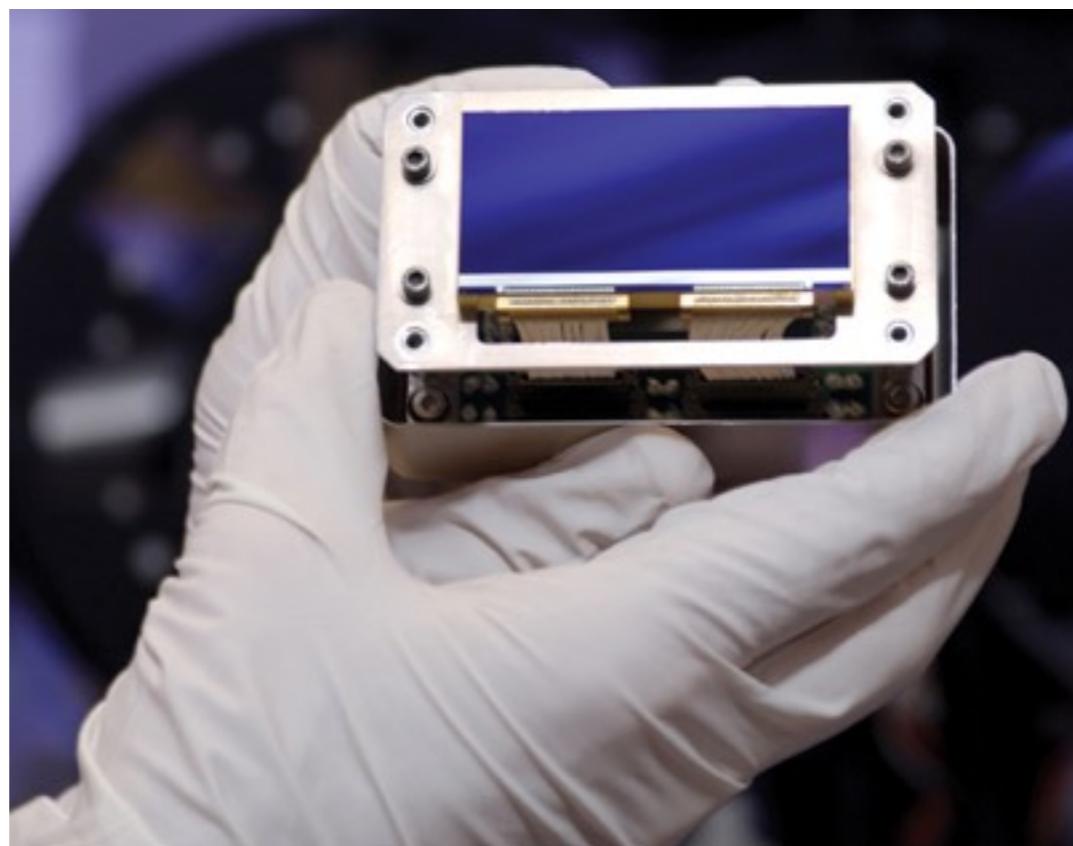


Figure 3. Kepler CCD in handling jig.

CCDs - Advantages

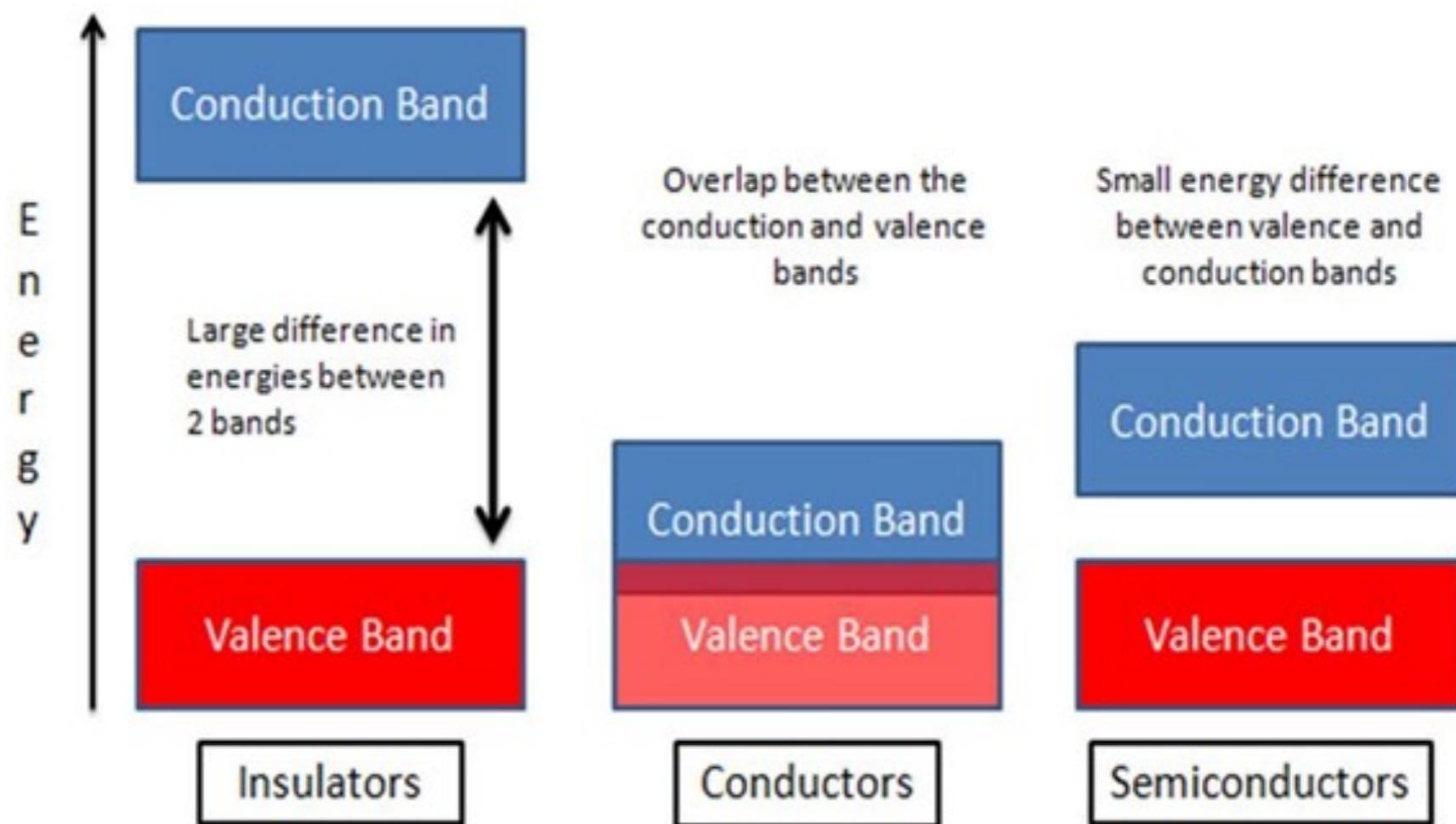
- (nearly) linear response $N_{\text{electrons}} \propto N_{\text{photons}}$
- high sensitivity
- low noise (especially when cooled)
- built-in digitization



CFHT MegaPrime

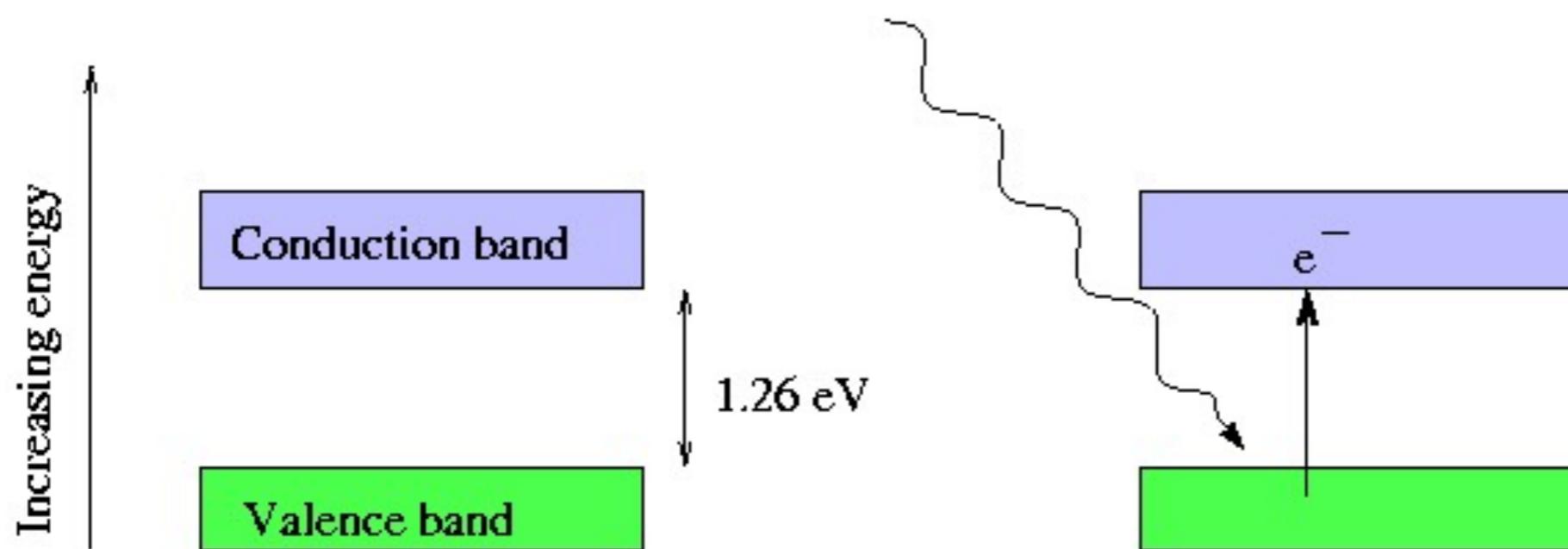
Semi-Conductors

- CCDs are made of semi-conducting silicon wafers
- key feature: small energy gap between “valence band” (energy levels of outermost bound electrons) and “conduction band” (energy levels of free electrons)



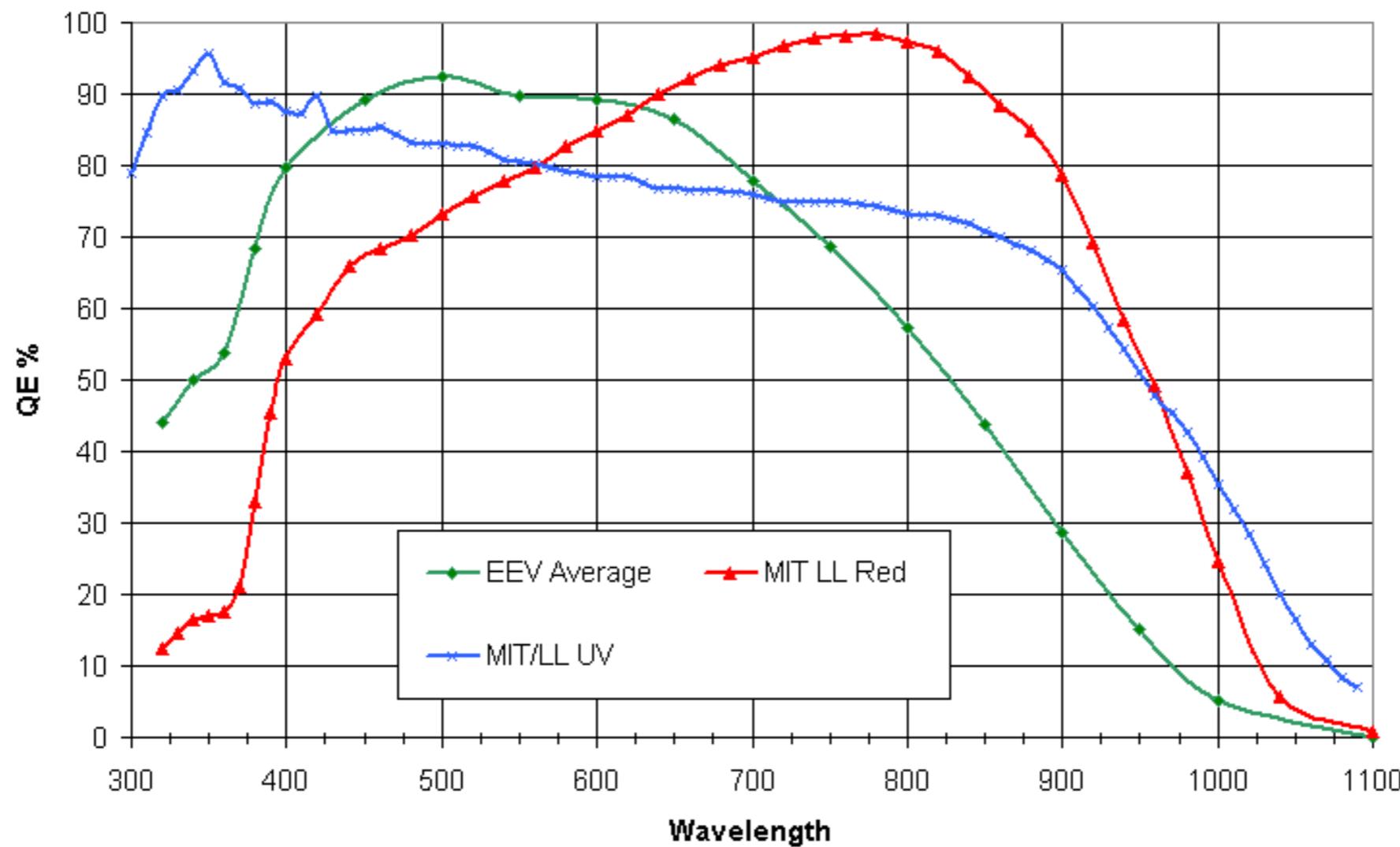
Photoelectric effect

- light is quantized, “photons” $E = h\nu$
- when a photon is absorbed, the energy is transferred to an electron \rightarrow “jumps” into conduction band



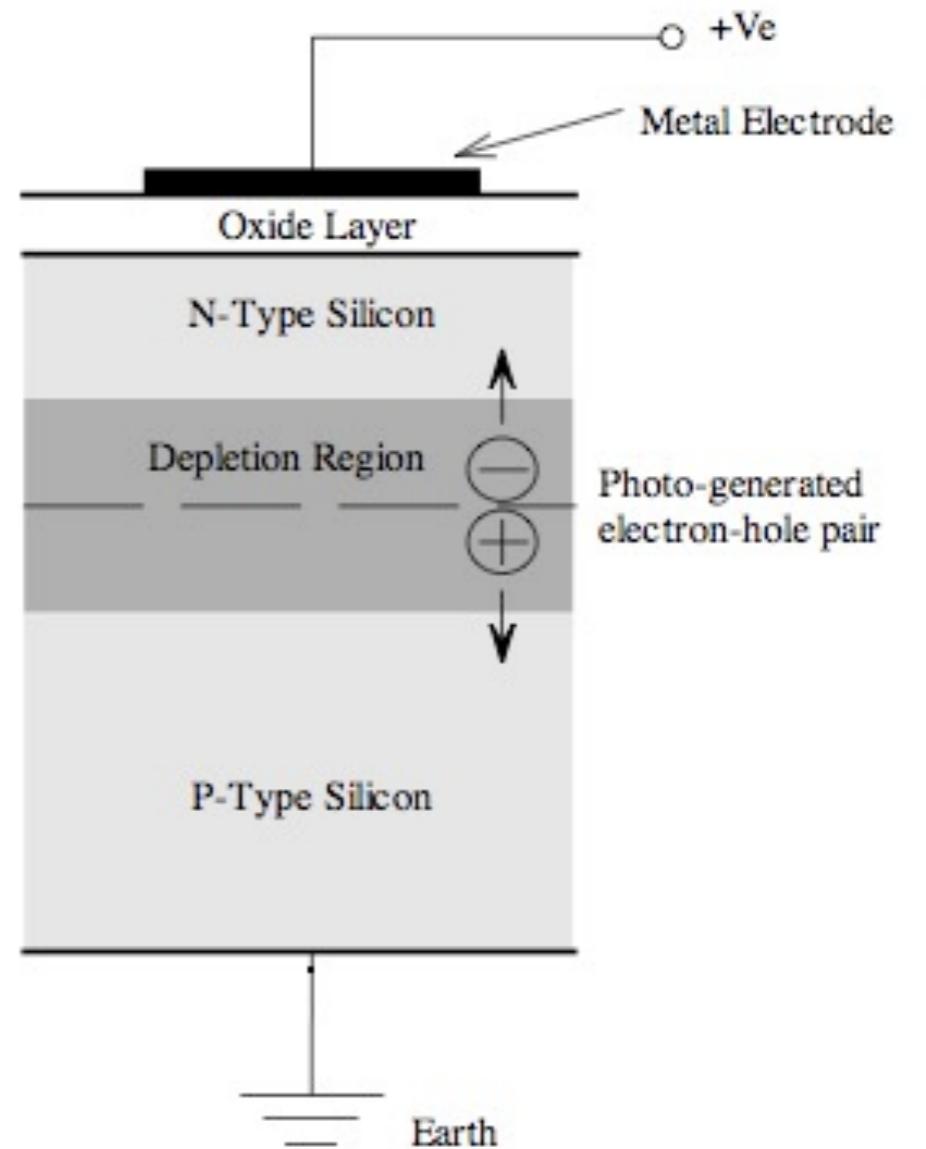
CCD Quantum Efficiency (QE)

- fraction of photons that are detected
- depends on wavelength
- different technologies lead to red vs. blue optimized CCDs



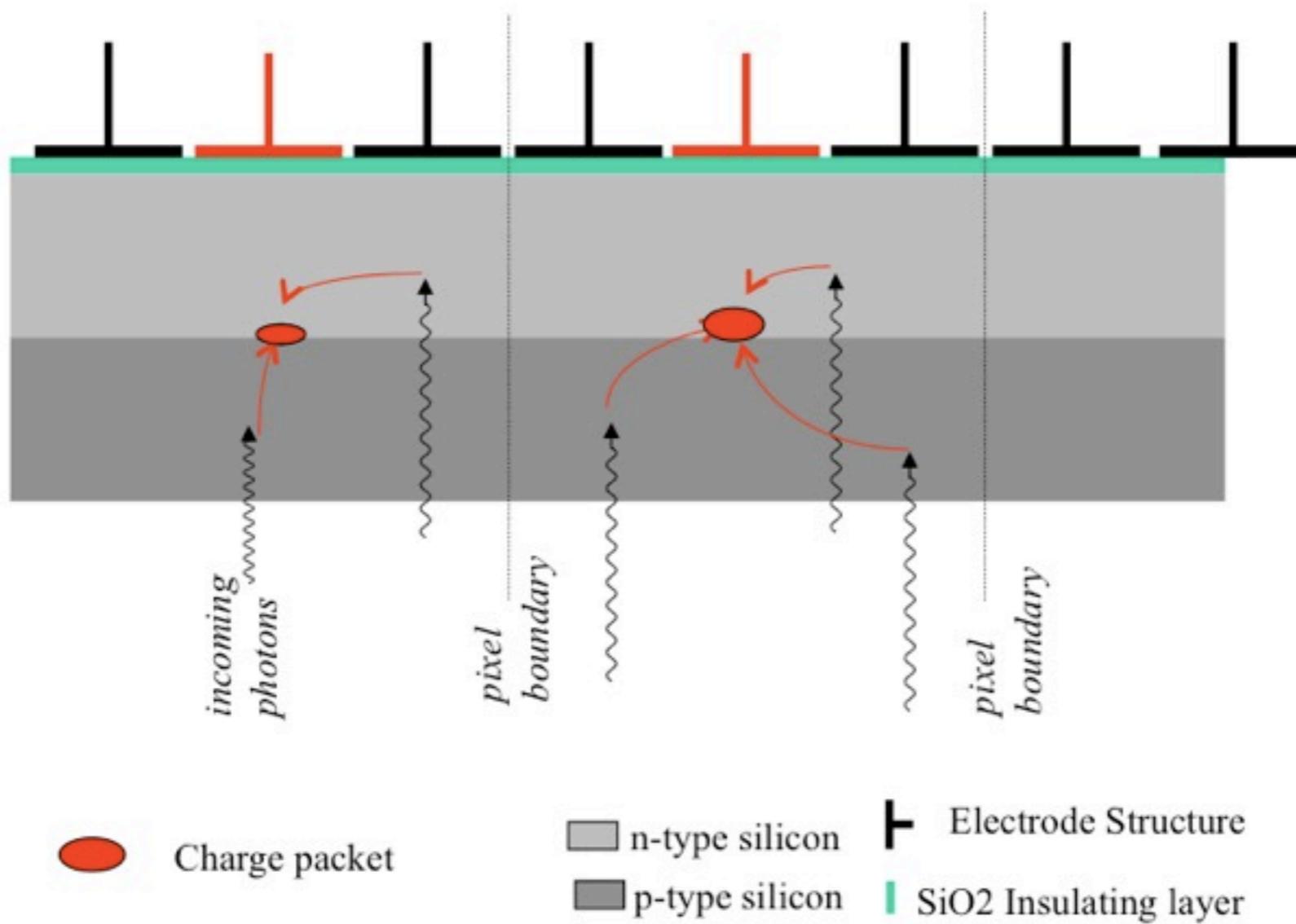
One pixel

- apply an electric field to keep electrons / holes separated



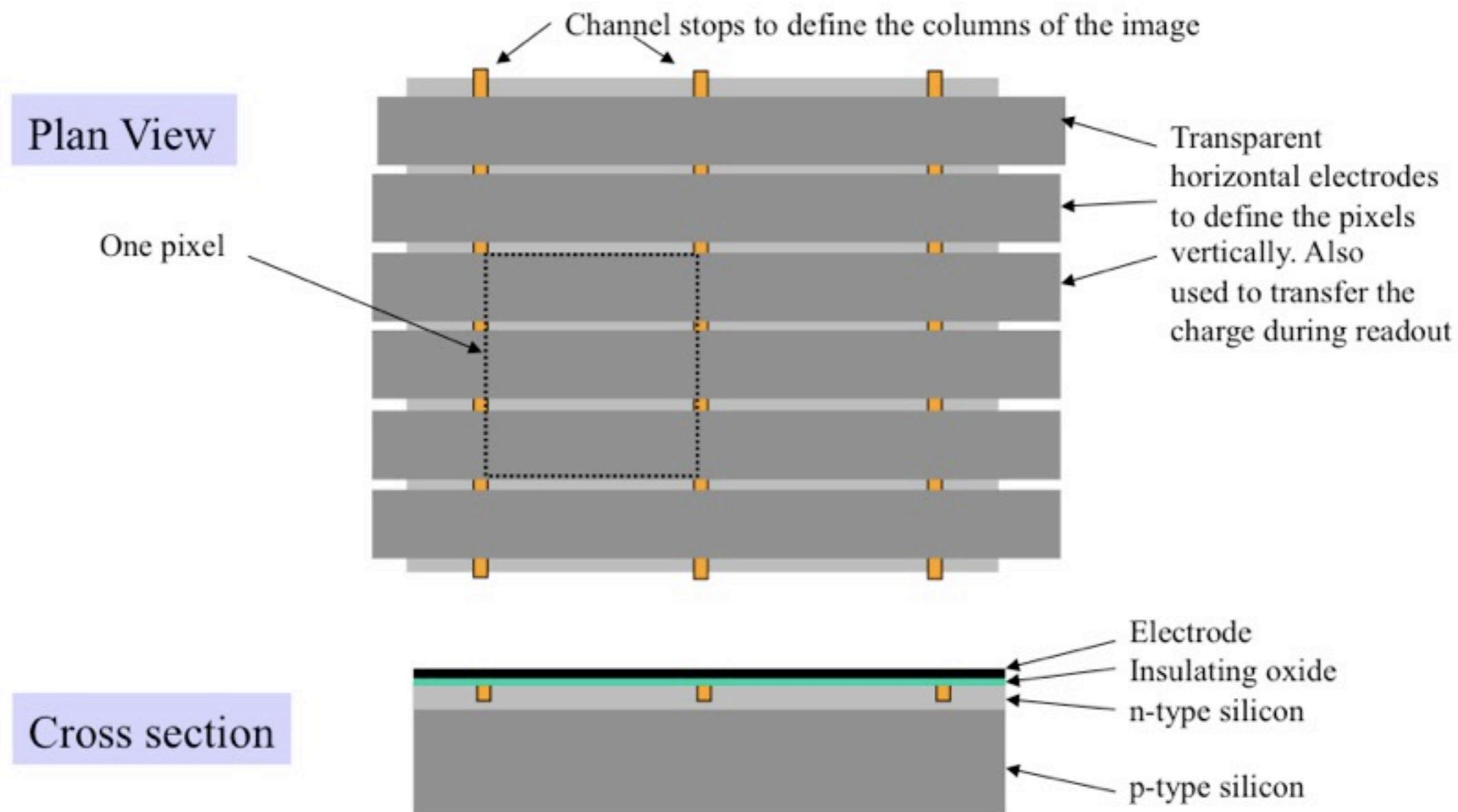
Many pixels

- pixels are defined by the electric field generated by the applied electrodes



Many pixels

- ... and by insulator strips between columns



Reading out CCDs

- “rainbuckets on conveyor belts” analogy
- 1 conveyor belt = 1 CCD column
- in practice: modulate the electric fields to move pixel charges

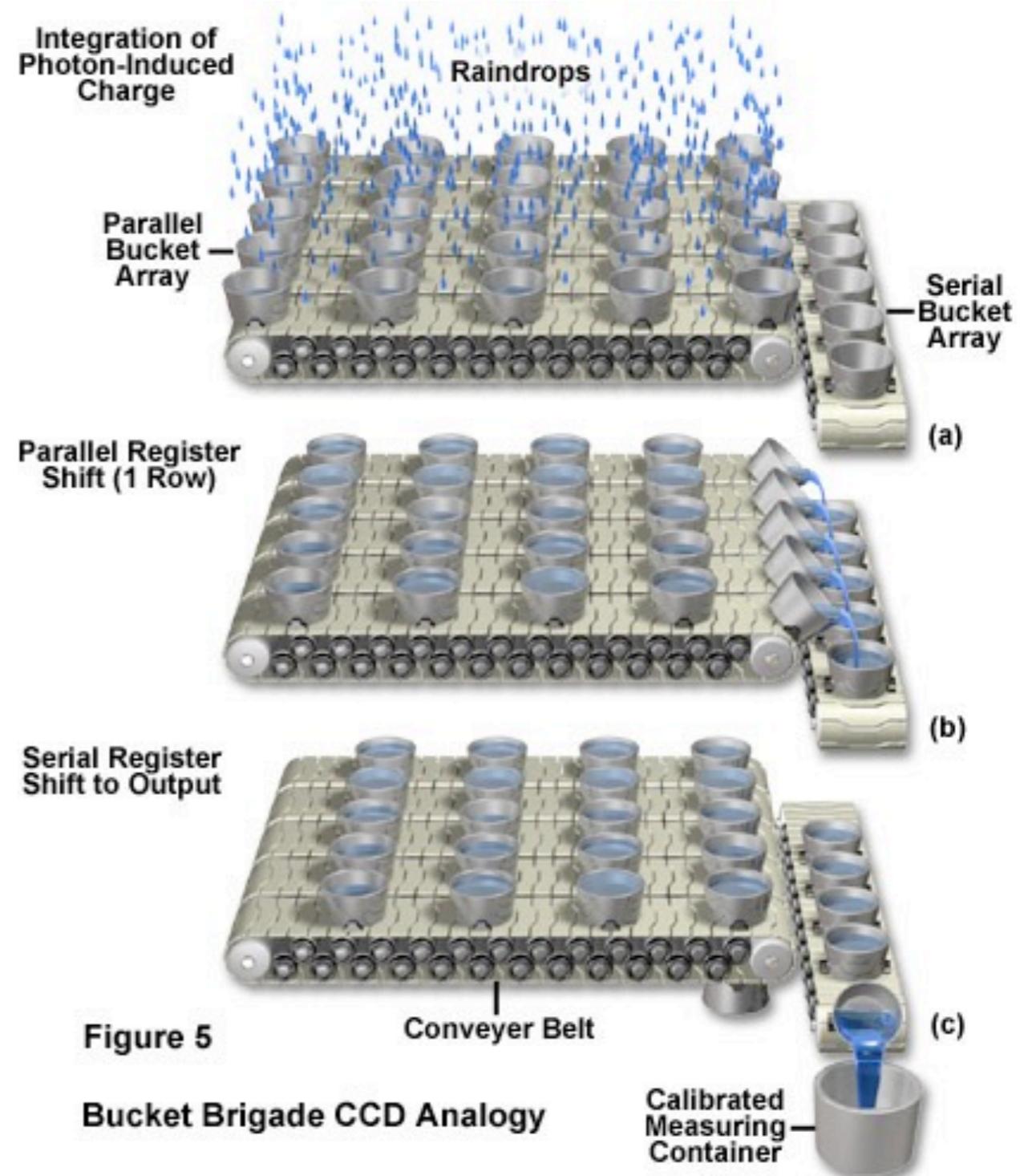
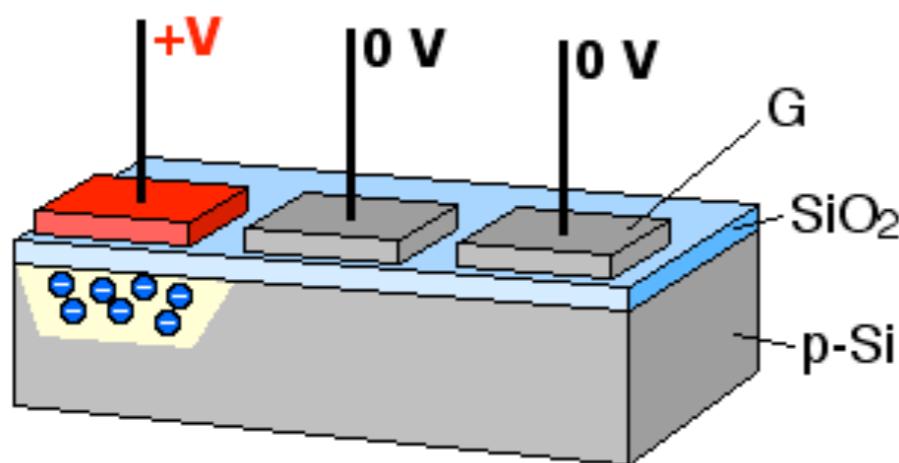
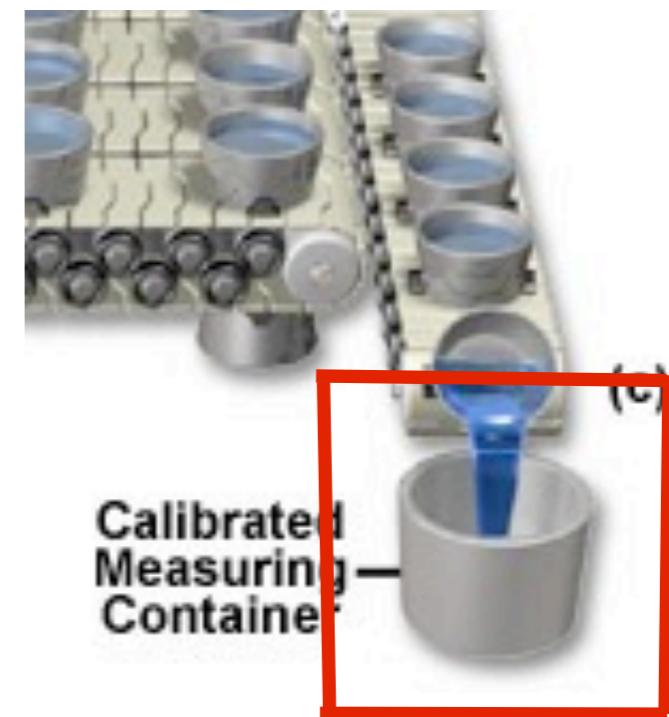


Figure 5

Bucket Brigade CCD Analogy

Assembling the Image

- each charge collection is passed to an amplifier and analog-to-digital converter (ADC)
- final output: “counts” or ADUs (analog-to-digital units) → *integer value*
- can apply rescaling: “gain”



$$\text{gain } G = \frac{N_{\text{electrons}}}{N_{\text{counts}}}$$

Full Well Capacity

- each pixel can only hold a limited charge → *full well capacity*, of the order of 100 000 e⁻
- ADCs have a maximum output value, e.g. 16-bit = 2^{16} = 65536 counts
- gain should be chosen roughly so that ADC maximum ~ full well
- typically, gain ~ 2-4

Bias level

- **bias level**: an electronically induced offset which ensures that the ADC always gets a positive input
- the bias needs to be subtracted so that the counts are proportional to the signal
- note: the bias level is not a “counting process”, i.e. the standard deviation of the bias values is NOT $\text{sqrt}(N_{\text{cts}}[\text{bias}])$

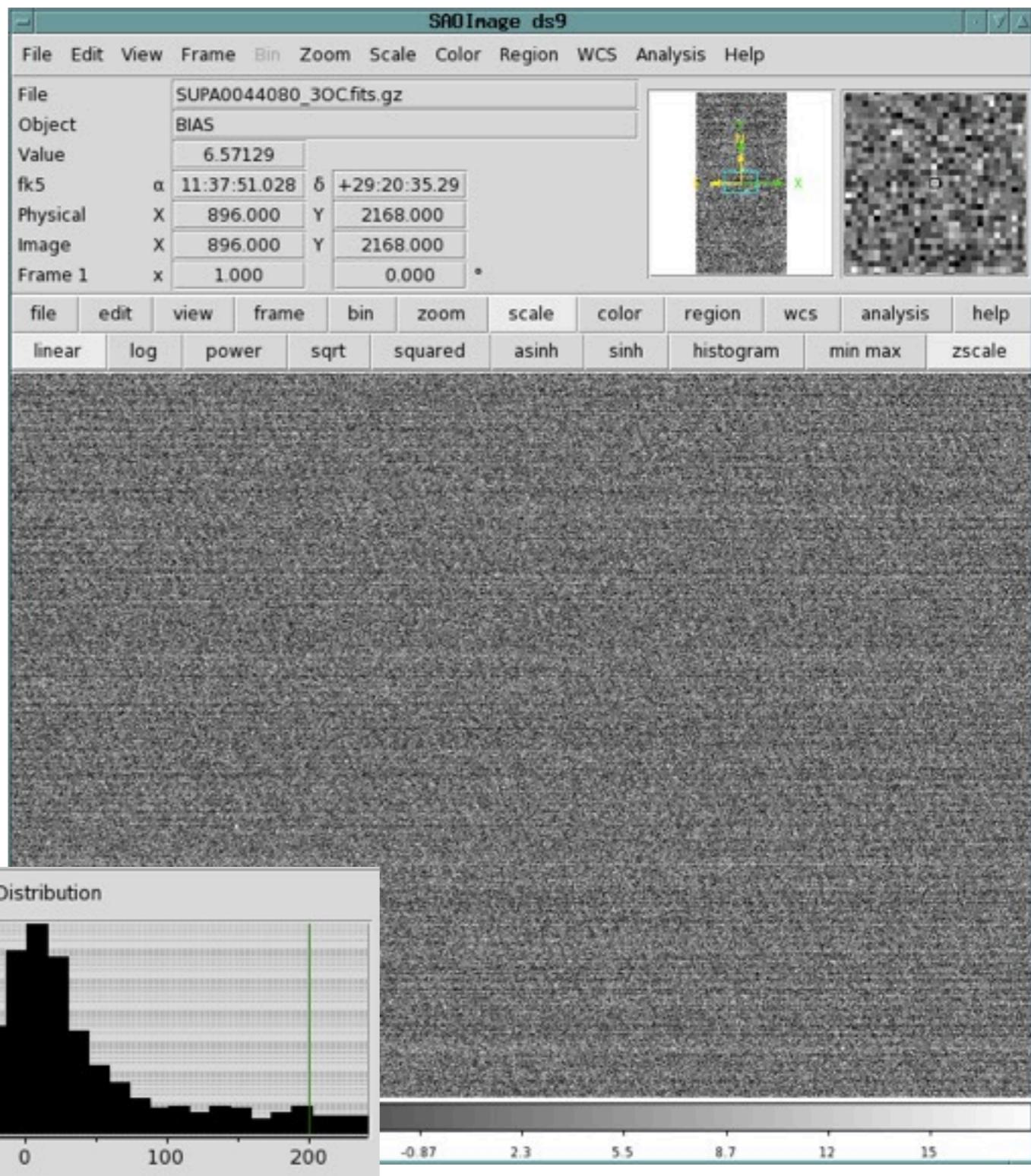
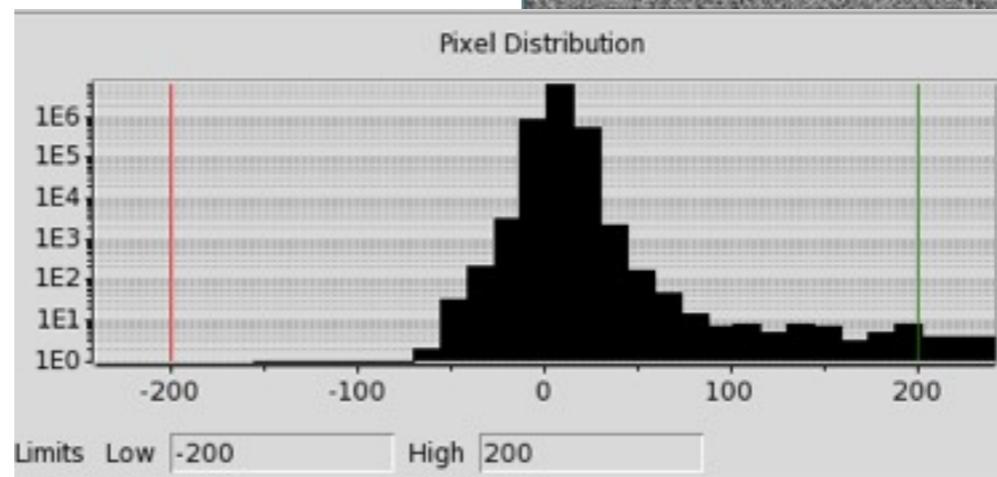
Read-out noise

- **read-out noise:** noise produced by various electronics during read-out, e.g. the amplifiers
- the slower the read-out, the lower the read-out noise

Bias images

- images with 0s exposure time
- single bias frame: pixel values scatter around the bias level, width of this distribution is the read-noise
- master bias frame (median or average of many bias frames): read-noise is averaged out, remaining structure is due to electronics

$$\sigma \sim 5e^-$$



Overscan region

- problem: the bias level may not be stable
- images on large astronomical cameras come with an overscan region
- each row is clocked out more often than there are physical pixels
- can be used as an in-situ estimate of the bias level
- use the extra pixels to estimate the bias level of each row; subtract it from entire row
- the overscan is subtracted from all images (including bias frames)

Dark current

- the energy gap in the semi-conductor is small → thermal noise leads to extra charge accumulation
- proportional to the exposure time
- cooling the CCDs significantly mitigates dark current
- professional astronomical CCDs cooled to -100°C → almost no dark current
- **dark frame:** images taken with closed shutter, same exposure time, same temperature as science frames
- similar to bias frames; need to be subtracted
- (subtracting non-bias corrected darks subtracts the bias, too)

Flat-field

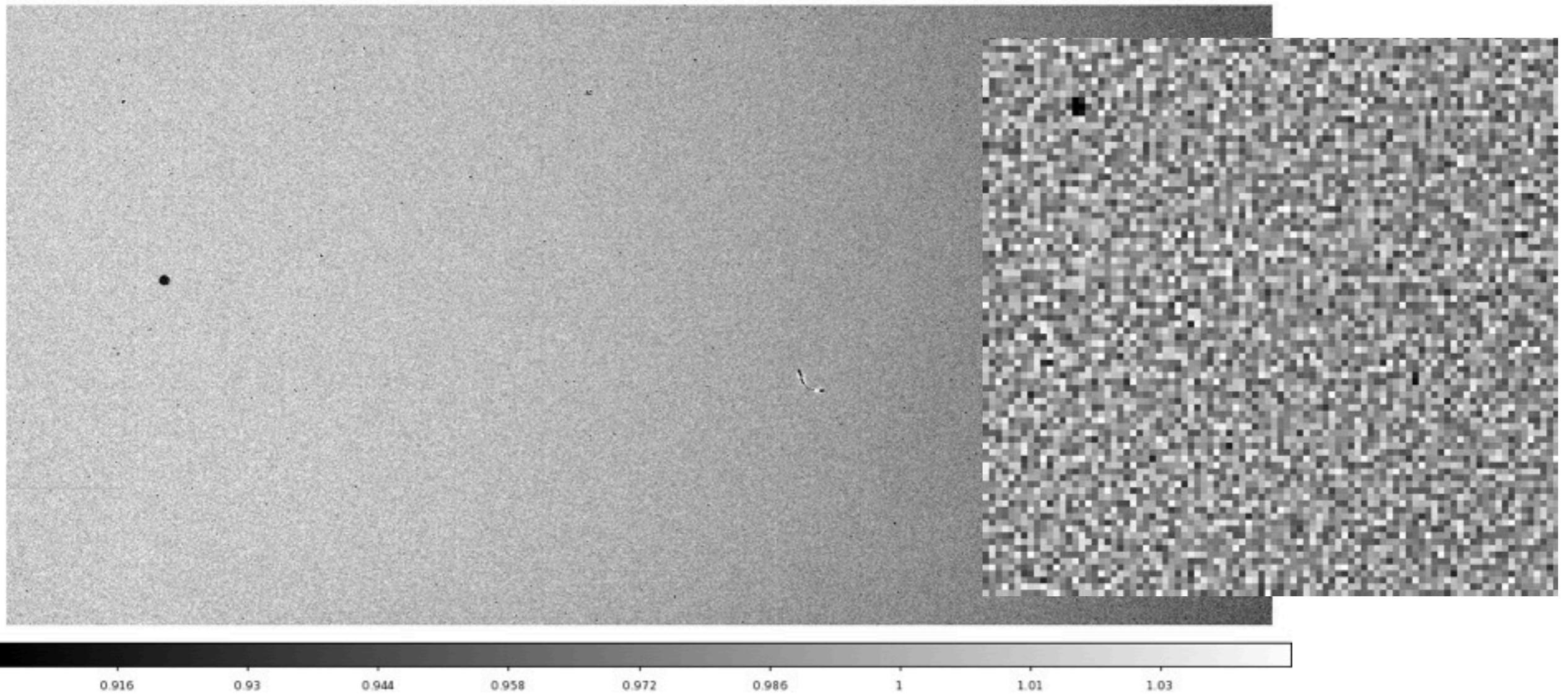
- the pixels in a CCD do *not* have uniform sensitivity
- due to variations in silicon crystal, electric field, pixel size, illumination (vignetting)

$$N_{\text{electrons}} = A_{ij} N_{\text{photons}}$$

- A_{ij} different for each pixel
- need to correct for differences for meaningful measurements

Flat-field

- flat-field: take an image of a spatially uniform source of light (e.g. the twilight sky, or a screen in the dome)
- input signal (N_{photons}) is the same for each pixel; variations in N_{counts} are due to different sensitivities



Flat-field

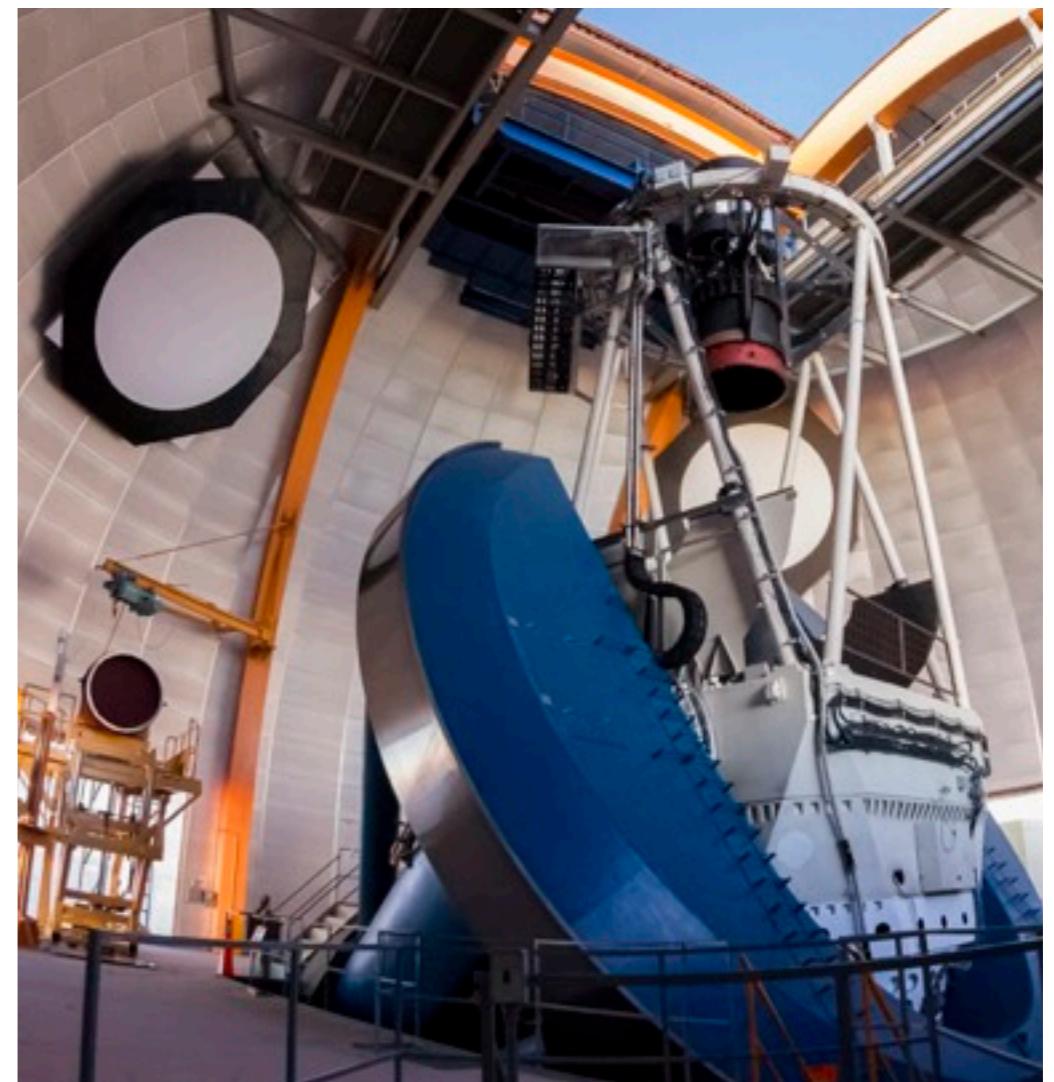
- flat-field is a *multiplicative* correction (unlike bias / dark)
- in practice: take a series of flat-field images
- correct each flat image by the bias image (overscan if available)
- average the flat-field images (reduces counting noise)
→ master flat-field
- each science image needs to be corrected by the master bias (or dark) and the master flat-field:

$$\frac{\text{science image} - \text{master bias}}{\text{master flat}}$$

Types of flat fields

dome flats:

- ✓ easy
- ✓ constant conditions
 - not entirely uniform
 - different spectrum than astronomical objects



Types of flat fields

twilight flats:

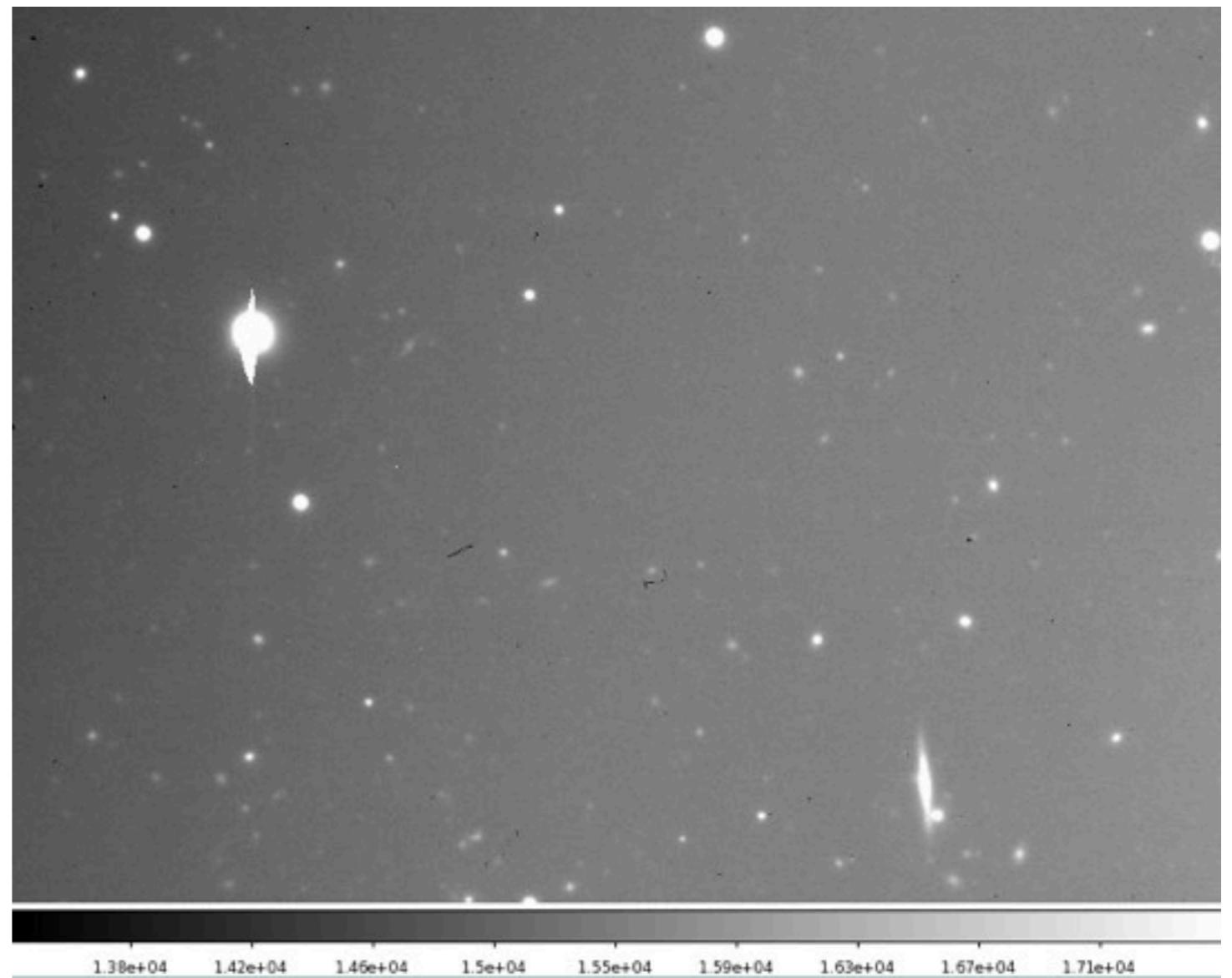
- ✓ same “source”
- ✓ almost uniform
- variable
- difficult



Types of flat fields

night-sky flats: if observations of several different targets are taken in one night, can average these images into flat-fields assembled from the sky background (best to mask out detected objects)

- ✓ most similar to data
- ✓ uniform
- need “empty” fields
- need a lot of images

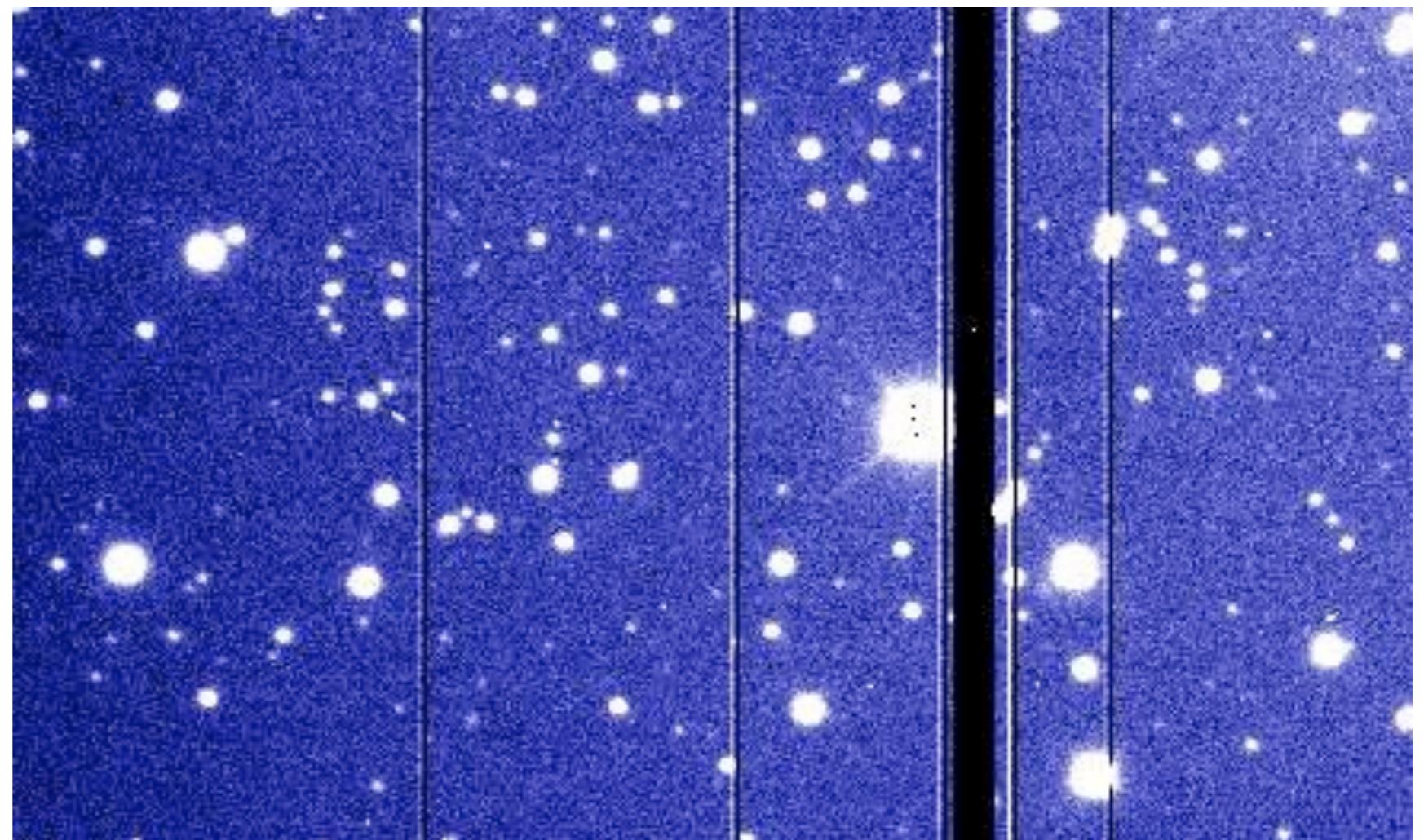


Artifacts

dead pixels / columns / rows: no (or little) response

hot pixels / columns / rows: very high noise

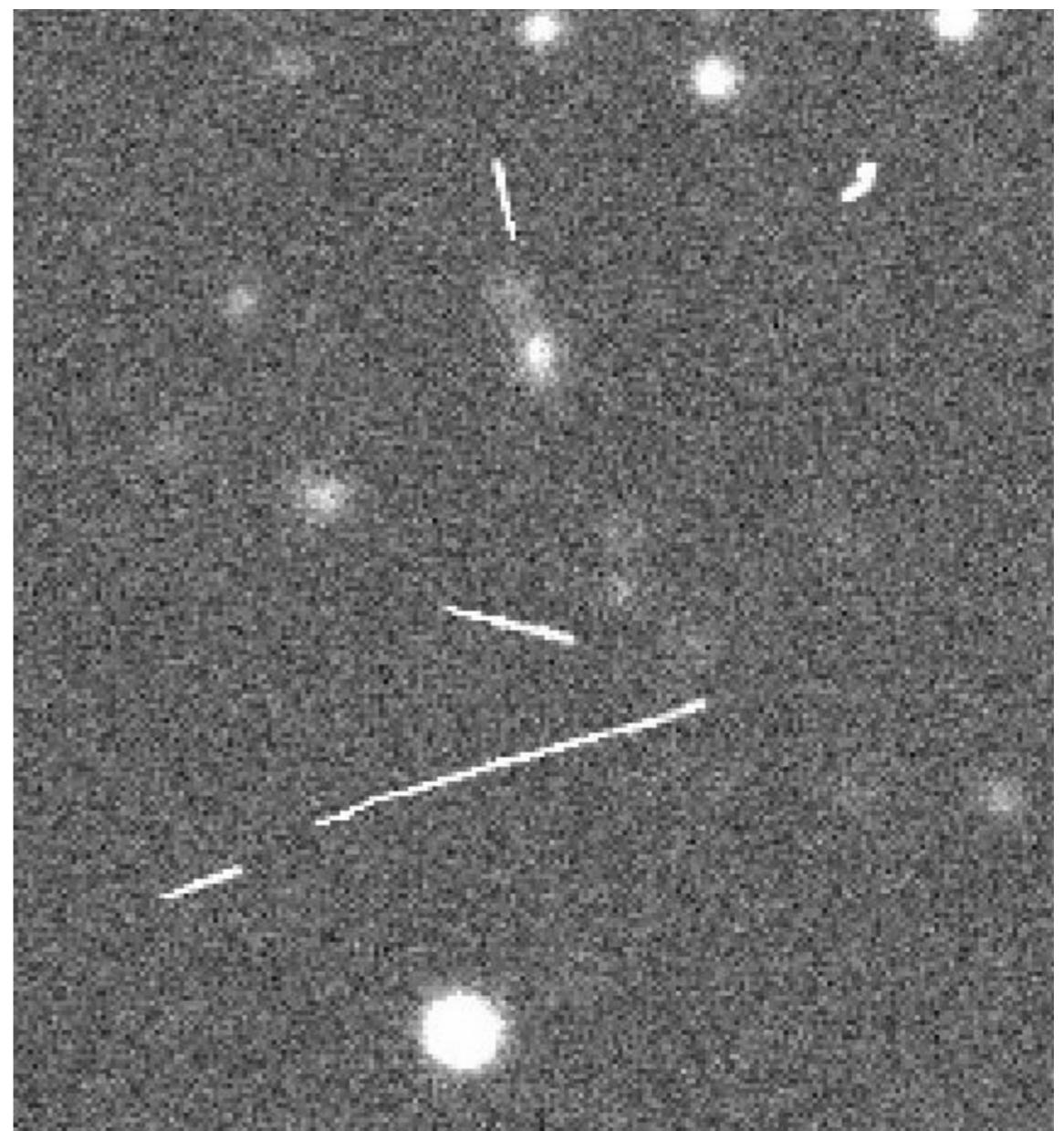
*signal is not
recoverable;
pixels need to
be masked in all
exposures*



Artefacts

cosmic rays: charged
particles hit the CCD

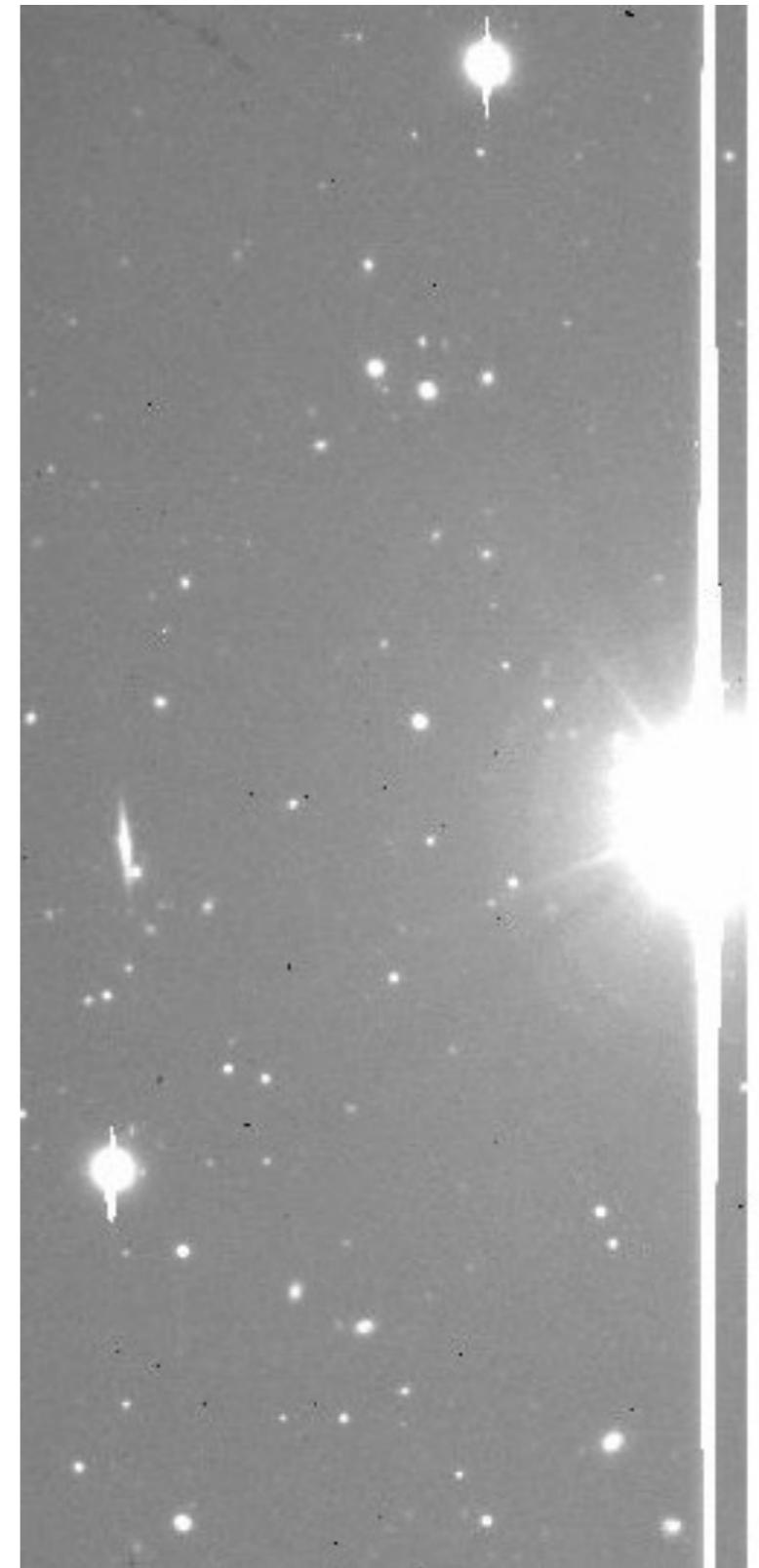
*need to be masked -
single exposure*



Artifacts

saturation spikes: when full well capacity is reached, electrons spill over into neighboring pixels

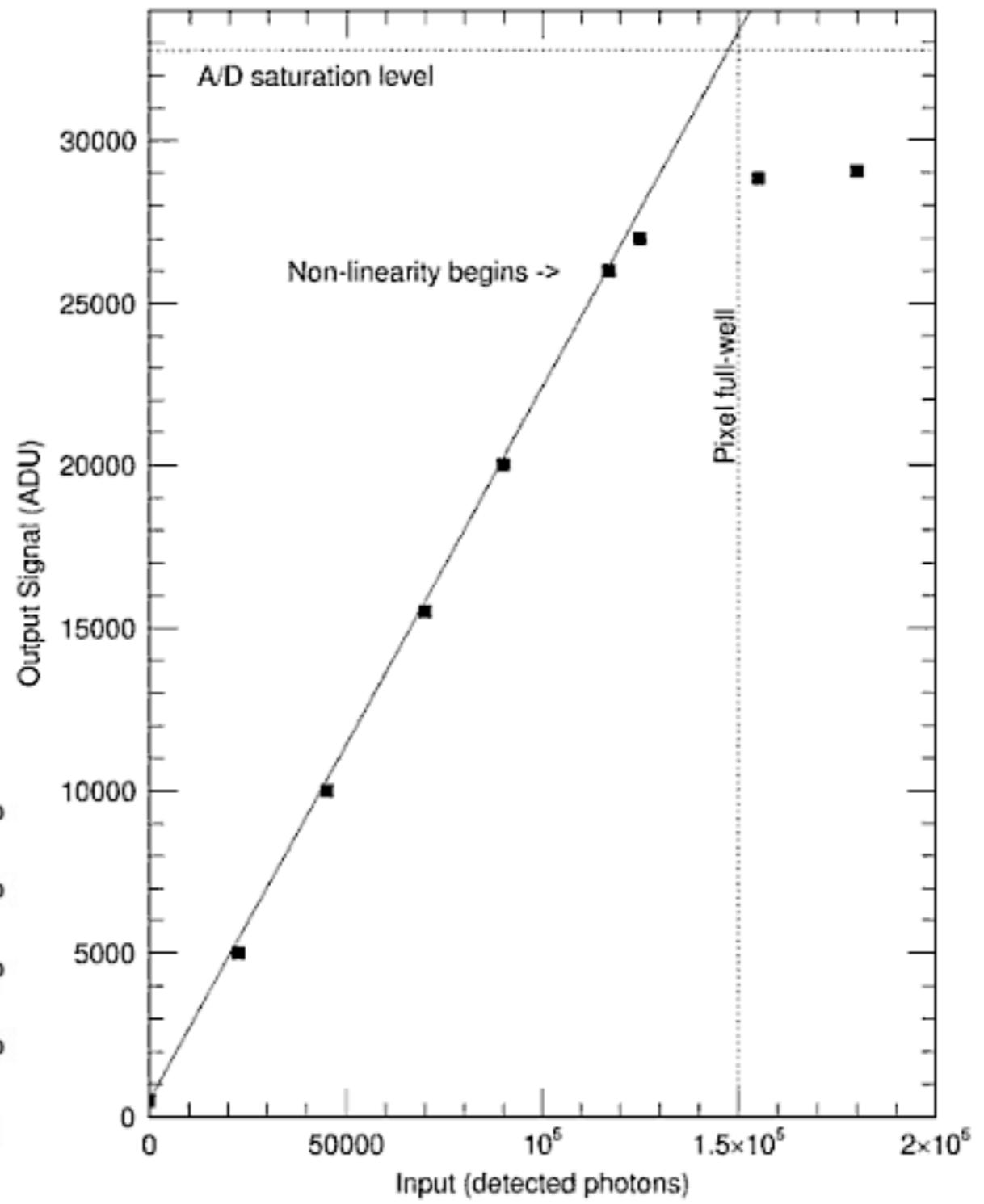
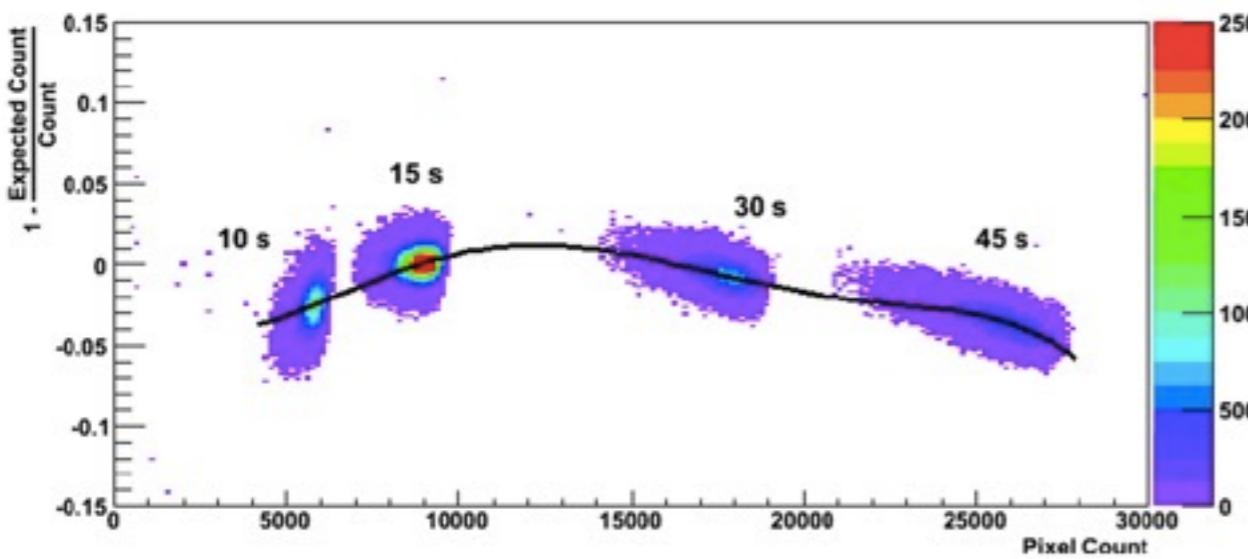
*need to be masked -
single exposure*



Artifacts

non-linearity: even before saturation level is reached, response becomes non-linear

can be measured from dome-flats



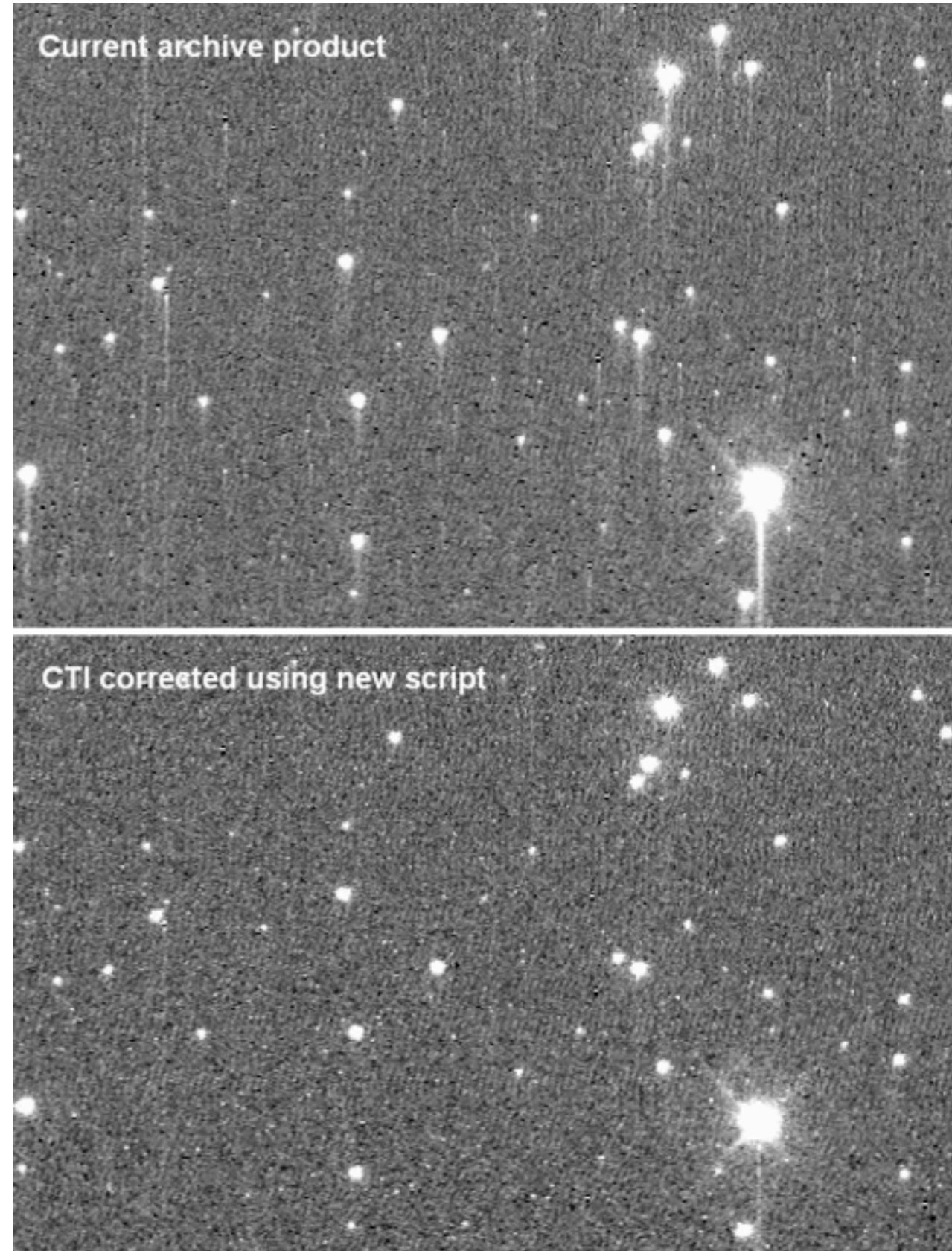
Artifacts

Charge Transfer Inefficiency (CTI): not all electrons are transferred from one pixel to the next during read-out

Charge Transfer Efficiency (CTE): fraction of photons that is transferred

CTI is a significant problem for Hubble's cameras because of radiation damage

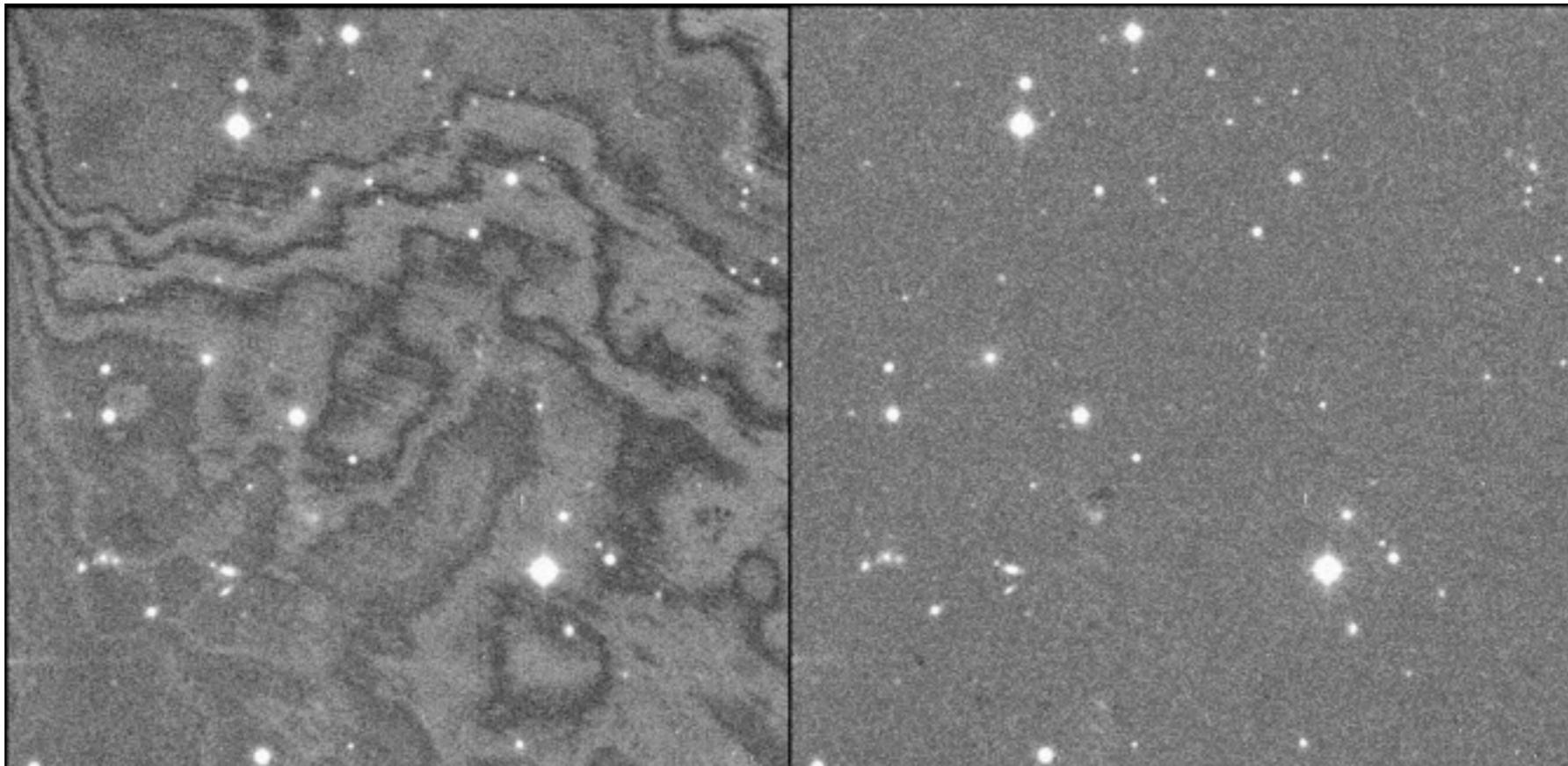
correction based on re-distributing charge



Artifacts

fringing: some light is reflected within the CCDs → leads to interference with incident light

fringing increases with wavelength, and decreases with thickness of CCDs



needs to be modeled; e.g. by subtracting a heavily smoothed image

FITS files

So you took all those images, now what?

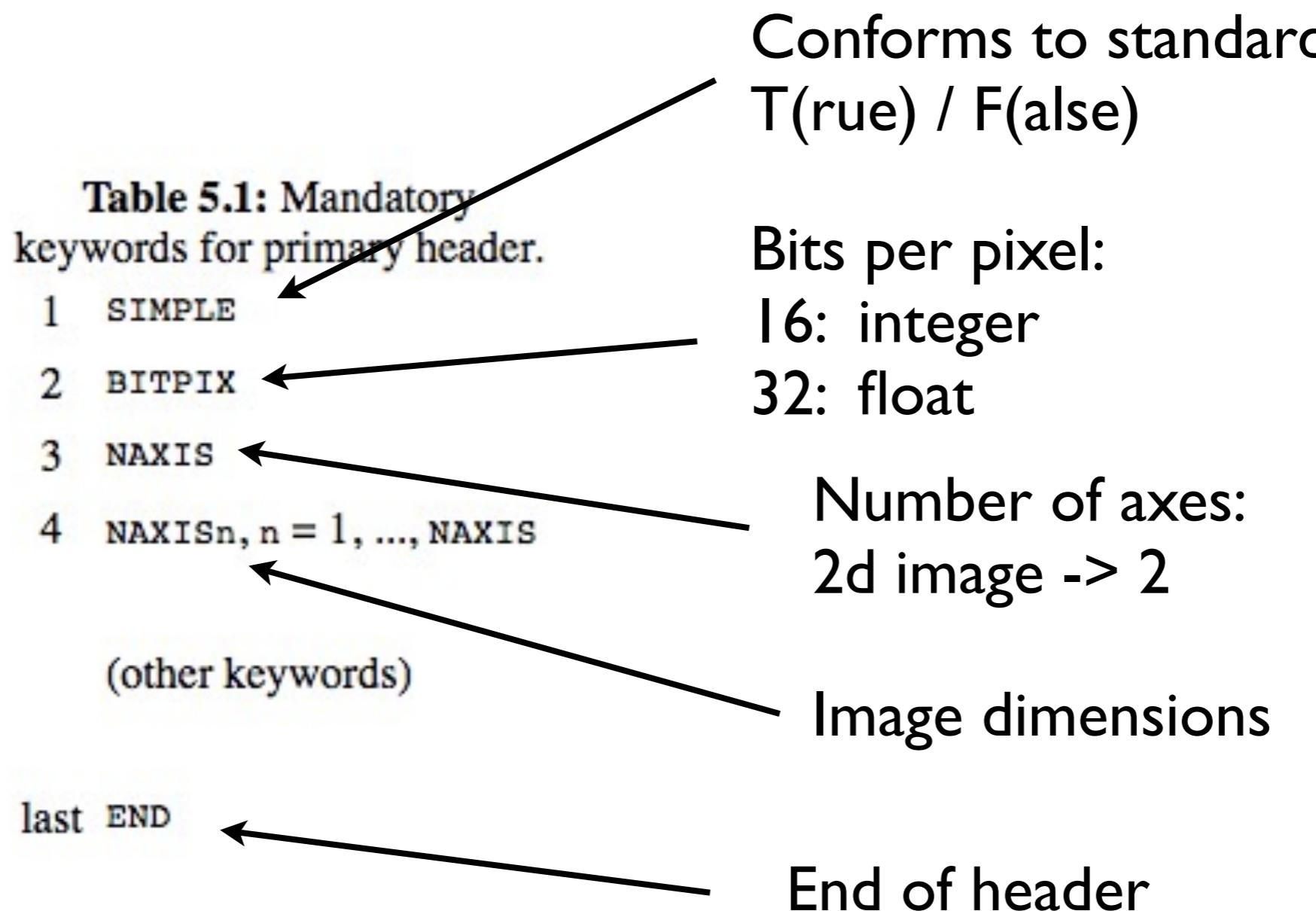
Images

FITS: Flexible Image Transport System

- open standard for astronomical images
- (at least) two parts:
 - image (binary format, integer or float)
 - ASCII *header*
- can have multiple extensions (images)

Header Keywords

Mandatory Structure:



Example

Images from our CCD camera:

```
====> file m13.00000077.FIT (main) <====  
SIMPLE = T/CCDSOFT-SOFTWARE BISQUE 3  
BITPIX = 16  
NAXIS = 2  
NAXIS1 = 1024  
NAXIS2 = 1024  
BSCALE = +1.00000000000E+000  
BZERO = +3.27680000000E+004  
BIAS = 100  
FOCALLEN= +3.55600000000E+003  
OPTDREF = +0.00000000000E+000
```

How big is the image (pixels by pixels)?

Example

Images from our CCD camera:

```
HFTHREH = +0.00000000000E+000
APTDIA = +3.560000000000E+002
TELESCOP= 'Meade LX200'
UBSERVER= 'T. Cohen, B. Schultz, X. Liu, B. Baserdem'
DATE-OBS= '2016-08-30T03:11:28.477'
TIME-OBS= '03:11:28.477'
SWCREATE= 'CCDSoft Version 5.00.210'
SET-TEMP= -5.00000000000E+000
COLORCCD= 0
DISPCOLR= 1
IMAGETYP= 'Light Frame'
CCDFPFT = 1

UBSERVER= SBIGLEXI version 1.0
FILTER = 'Visual'
EXPTIME = +1.00000000000E+001
EXPOSURE= +1.00000000000E+001
LW-SPLIT= 200
CCD-TEMP= -5.232156845990E+000
TEMPERAT= -5.232156845990E+000
INSTRUME= 'SBIG STL-1001 3 CCD Camera'
EGAIN = +2.06000000000E+000
F-GATN = +2.06000000000F+000
ICK = 342
TE = 447
```

Specifying coordinates

The astrometric information in FITS images (also referred to as the WCS) is stored in the header using a standard set of keywords. The reference location is defined by the following keywords:

- CRVAL1: defines the right (α) ascension of the reference pixel
- CRVAL2: defines the declination (δ) of the reference pixel
- CRPIX1: the x location of the reference pixel
- CRPIX2: the y location of the reference pixel

The plate scale and rotation of the image is contained in the CD MATRIX (CD?_? keywords).

- CD1_1 is the partial of first axis coordinate w.r.t. x
- CD1_2 is the partial of first axis coordinate w.r.t. y
- CD2_1 is the partial of second axis coordinate w.r.t. x
- CD2_2 is the partial of second axis coordinate w.r.t. y

$$\begin{pmatrix} CD1_1 & CD1_2 \\ CD2_1 & CD2_2 \end{pmatrix} = scale * \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix}$$

Specifying coordinates

$$\begin{pmatrix} CD1_1 & CD1_2 \\ CD2_1 & CD2_2 \end{pmatrix} = scale * \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix}$$

Thus, to go from image coordinates (x,y) to sky coordinates (α, δ):

$$\begin{pmatrix} \alpha - CRVAL1 \\ \delta - CRVAL2 \end{pmatrix} = \begin{pmatrix} CD1_1 & CD1_2 \\ CD2_1 & CD2_2 \end{pmatrix} \begin{pmatrix} x - CRPIX1 \\ y - CRPIX2 \end{pmatrix}$$

Specifying coordinates

```
CTYPE1 = 'RA---TAN-SIP' / TAN (gnomic) projection + SIP distortions
CTYPE2 = 'DEC--TAN-SIP' / TAN (gnomic) projection + SIP distortions
EQUINOX = 2000.0 / Equatorial coordinates definition (yr)
LONPOLE = 180.0 / no comment
LATPOLE = 0.0 / no comment
CRVAL1 = 250.418630769 / RA of reference point
CRVAL2 = 36.5118440685 / DEC of reference point
CRPIX1 = 351.470682144 / X reference pixel
CRPIX2 = 386.277894974 / Y reference pixel
CUNIT1 = 'deg' / X pixel scale units
CUNIT2 = 'deg' / Y pixel scale units
CD1_1 = -3.33986320359E-05 / Transformation matrix
CD1_2 = 0.000411933007076 / no comment
CD2_1 = -0.000411849476697 / no comment
CD2_2 = -3.33825508905E-05 / no comment
```

Viewing FITS images

best done with specialized software

e.g. ds9 (by
Smithsonian
Observatory)

<http://ds9.si.edu>

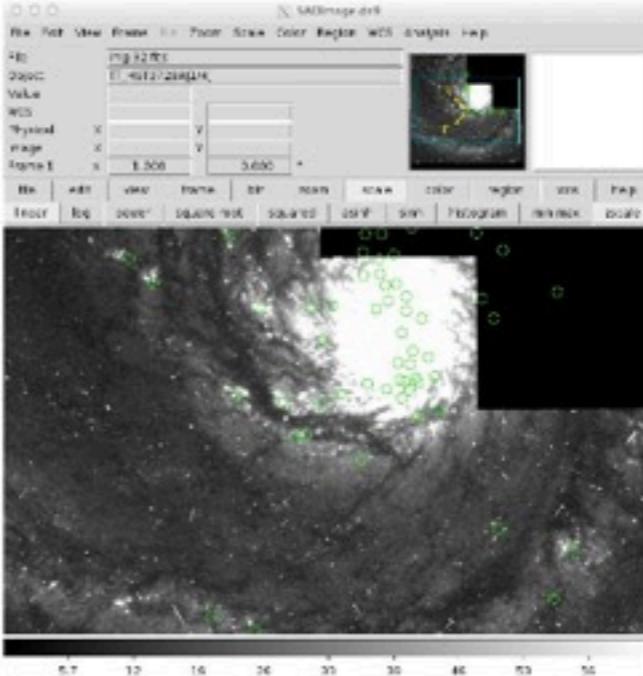
SAOImage DS9

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SAOImage DS9 Version 7.4

DS9 version 7.4 is now available on the [Download](#) page. New to version 7.4 is image blocking and reordering of data cube axes. Please see the [What's New](#) page for more details. *News Flash-- Version 7.5b4 is now available*



SAOImage DS9 development has been made possible by funding from the Chandra X-ray Science Center (CXC) and the High Energy Astrophysics Science Archive Center (HEASARC). Additional funding was provided by the JWST Mission office at Space Telescope Science Institute to improve capabilities for 3-D data visualization.

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Tweets by @SAOImageDS9

 **SAOImage DS9**
@SAOImageDS9

SAOImage DS9 version 7.5b4 is now available for download at ds9.si.edu/site/Beta.html

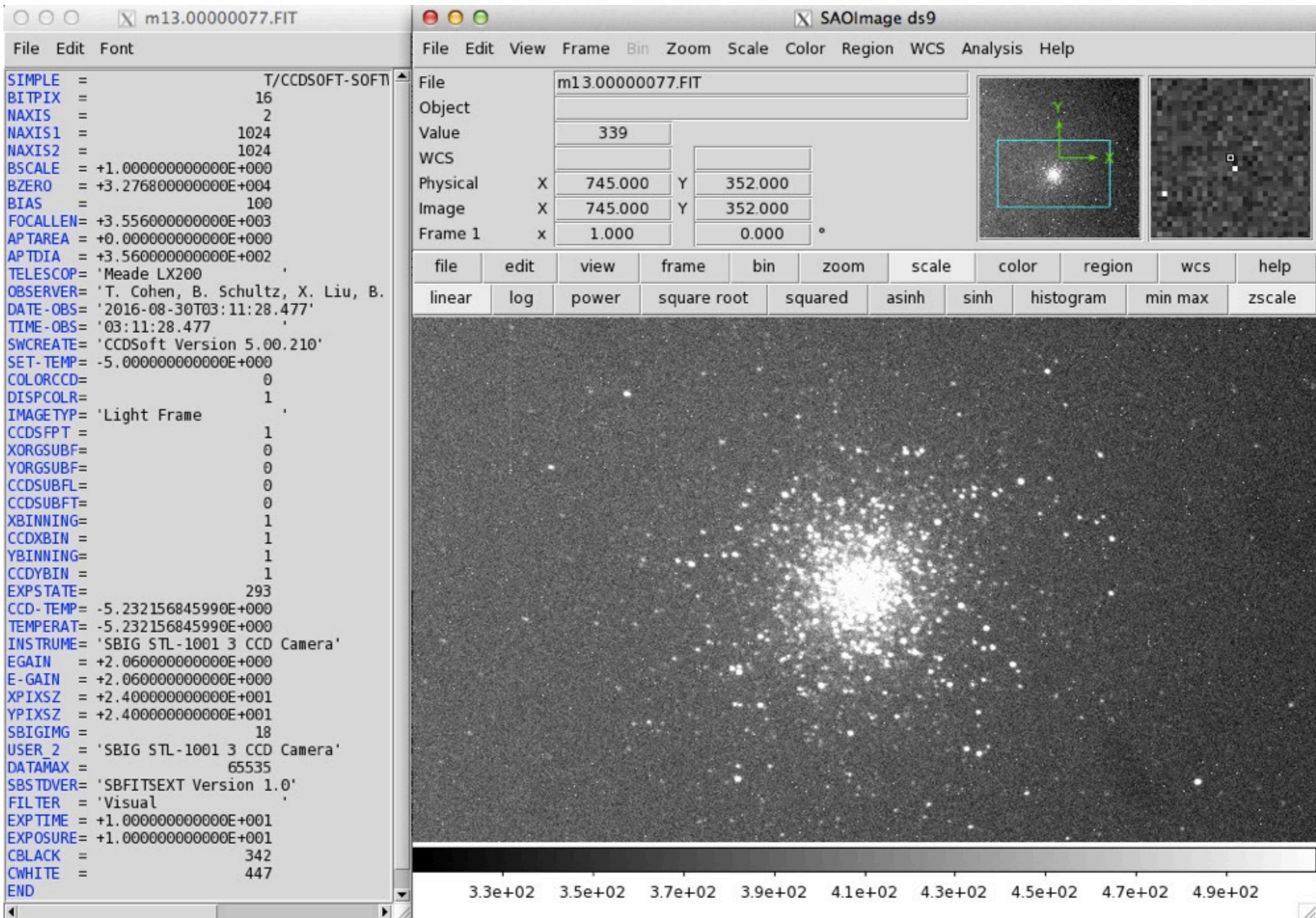
 **SAOImage DS9**
@SAOImageDS9

SAOImage DS9 version 7.5b3 is now available for download at ds9.si.edu/site/Beta.html. New support for Simple Image Access protocol

 **Eric Mandel**
@astrosoftware



SMITHSONIAN ASTROPHYSICAL OBSERVATORY | 60 GARDEN STREET | CAMBRIDGE, MA 02138



Viewing FITS headers

- ds9 (File -> Display Header)
- python (see tutorial)
- command-line tools: dfits and fitsort

```
[anja@ki-ls08 test_data]$ dfits 00000001.BIAS.FIT | more
====> file 00000001.BIAS.FIT (main) <====
SIMPLE = T/CCDSOFT-SOFTWARE BISQUE 3
BITPIX = 16
NAXIS = 2
NAXIS1 = 1024
NAXIS2 = 1024
PCRSIZE = +1.00000000000E+000
```

```
[anja@ki-ls08 test_data]$ dfits *.DARK.FIT | fitsort EXPTIME CCD-TEMP
FILE          EXPTIME          CCD-TEMP
00000011.DARK.FIT +1.00000000000E+001 -5.232156845990E+000
00000012.DARK.FIT +2.00000000000E+001 -5.232156845990E+000
00000013.DARK.FIT +4.00000000000E+001 -4.817803680962E+000
00000014.DARK.FIT +8.00000000000E+001 -4.817803680962E+000
00000015.DARK.FIT +1.00000000000E+002 -4.817803680962E+000
```

Viewing FITS headers

- if dfits and fitsort not available: use “fold” command

```
[anja@ki-1s08 test_data]$ fold 00000001.BIAS.FIT | more
SIMPLE = T/CCDSOFT-SOFTWARE BISQUE 3
BITPIX = 16
NAXIS = 2
NAXIS1 = 1024
NAXIS2 = 1024
-----
```

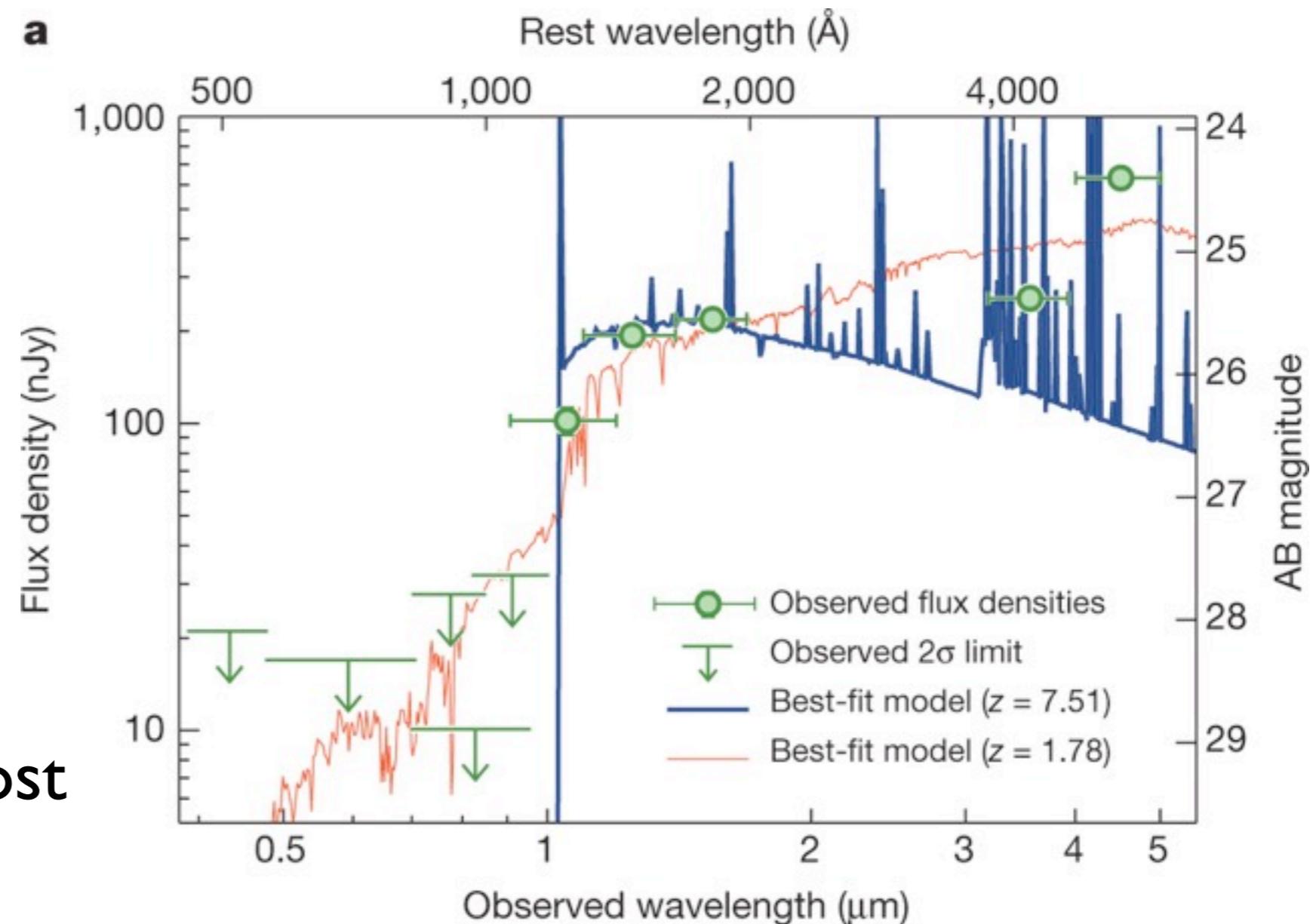
Spectroscopy

Motivation

photometry (measuring flux from images) only measures integrated flux

gives some information about the object properties, but (usually) not enough

e.g.: finding the most distant galaxies

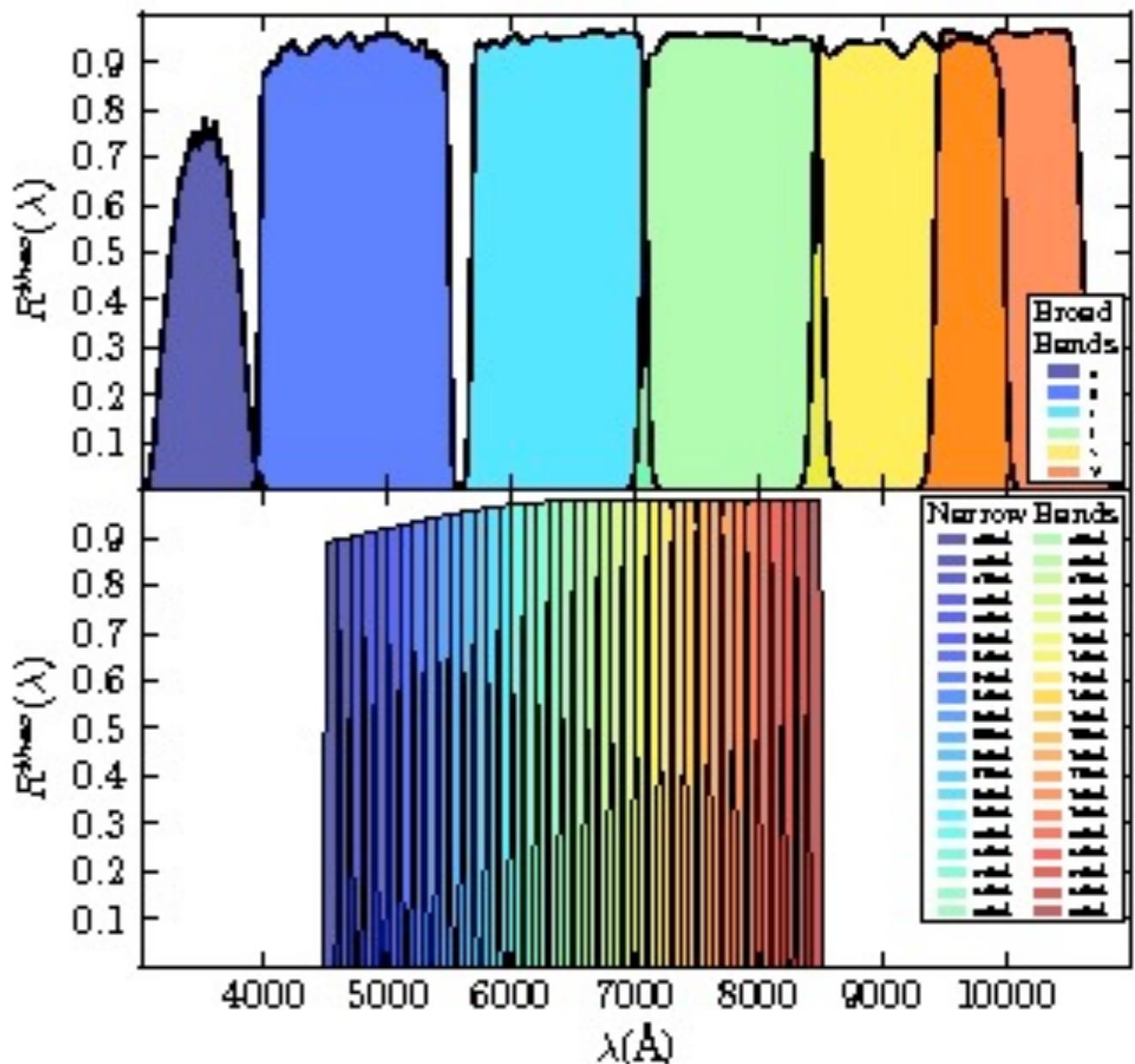


Narrow-band imaging

can determine spectrum of object with images in many narrow-band filters

advantage: can determine spectra of all objects in the same FOV

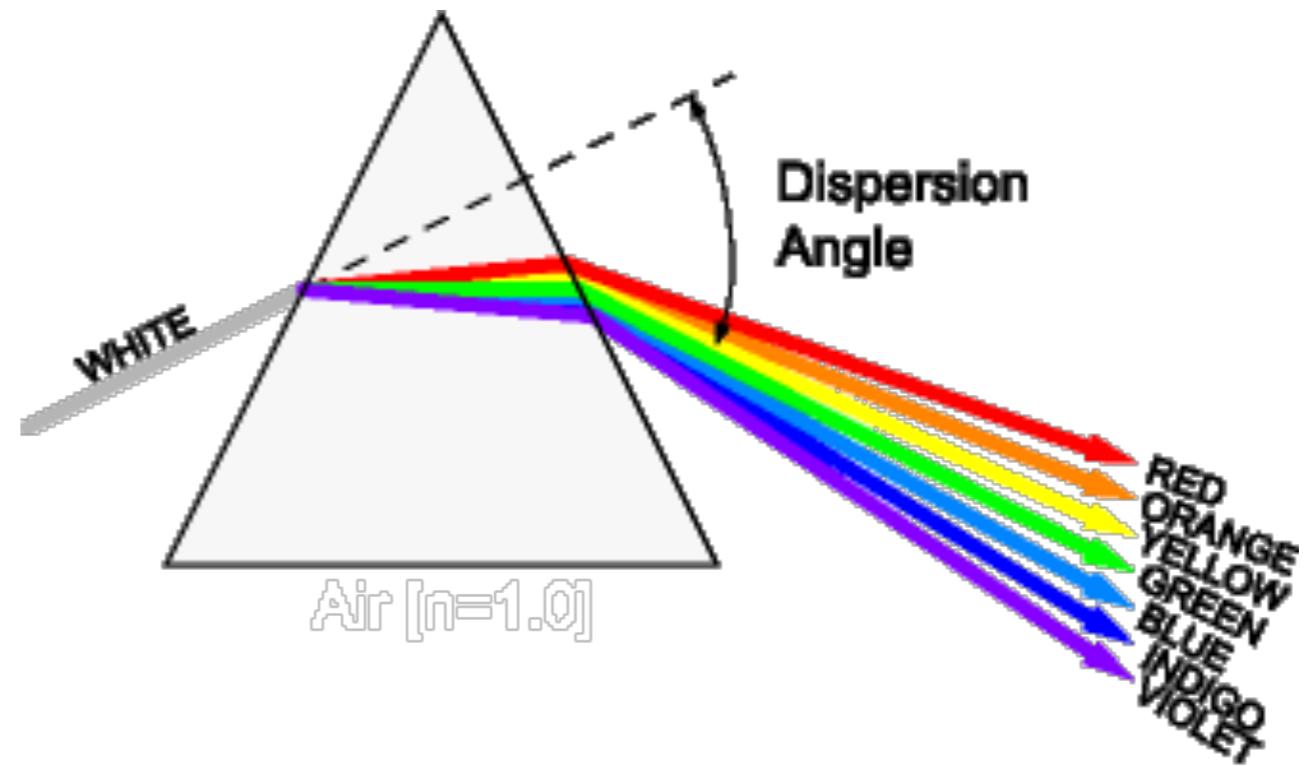
disadvantage: have to take a lot of images!



Spectroscopy

add a dispersing element
to split up the light from
an object: measure the
spectrum directly

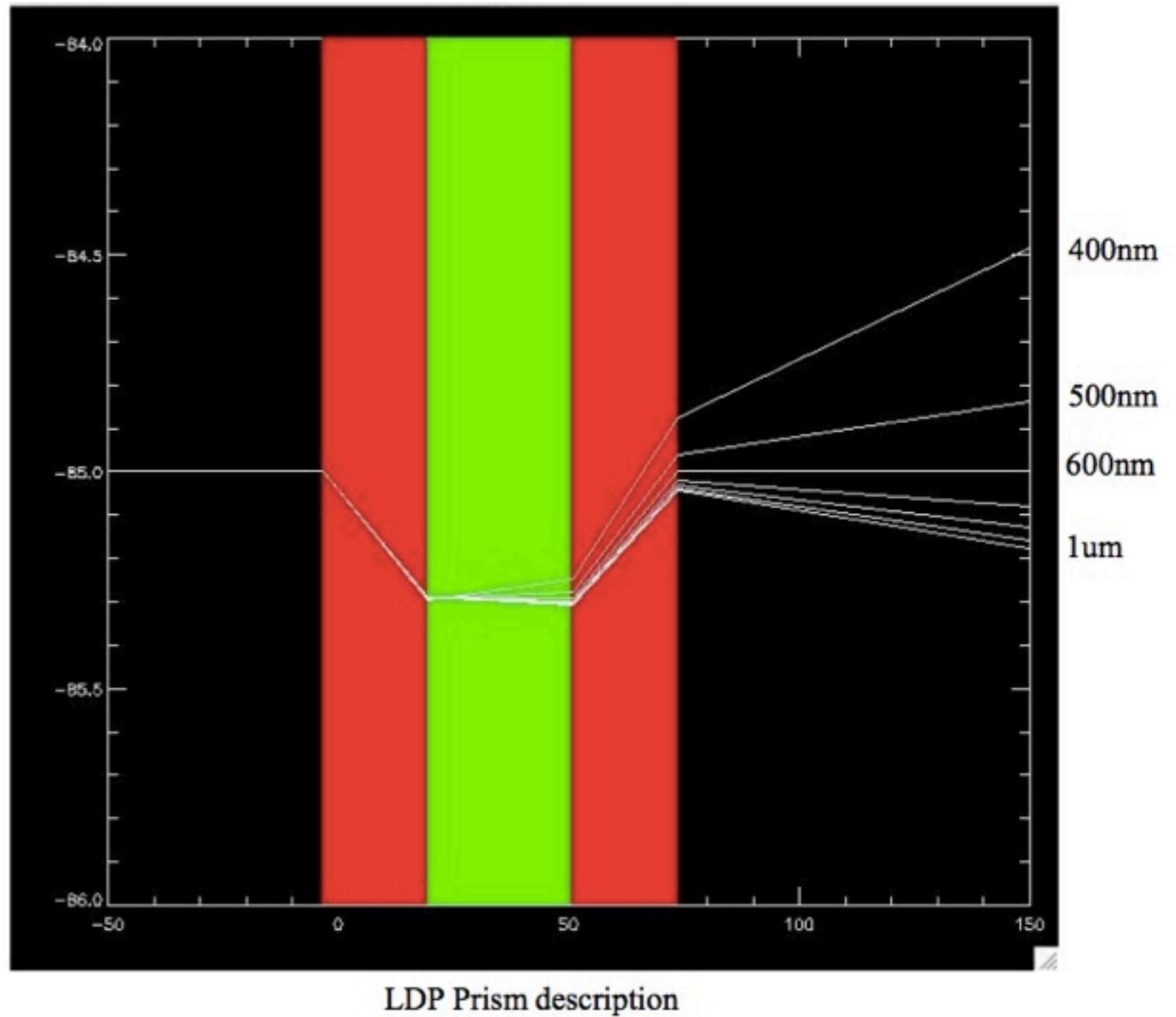
e.g. a prism:



Prism Spectroscopy

only few
astronomical
spectrographs
use prisms

- low dispersion (resolution)
- dispersion varies with wavelength



“low dispersion prism” for IMACS spectrograph on Magellan 6-m telescope; uses 3 prisms

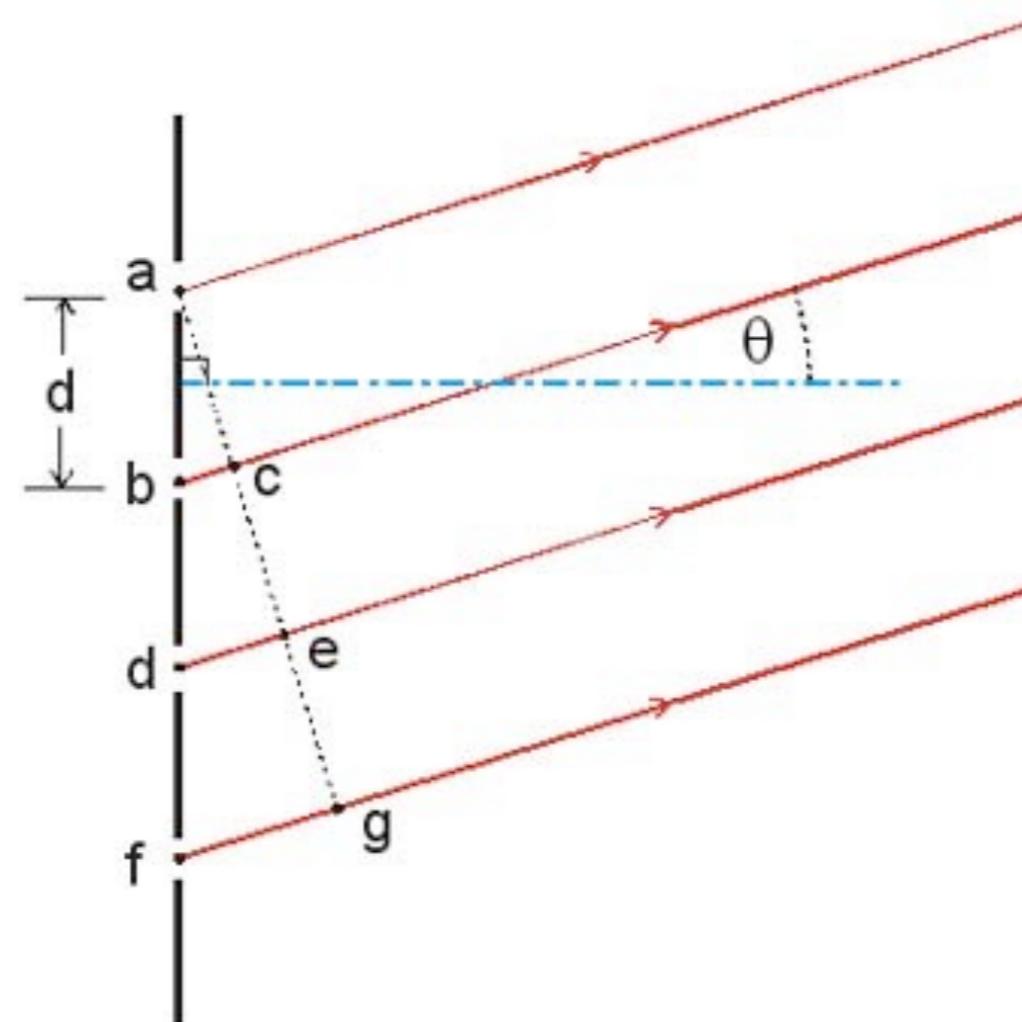
Diffraction gratings

make use of wave properties of light:
interference

grating: many parallel lines ($\sim 500/\text{mm}$)

similar to single-slit and double-slit experiments

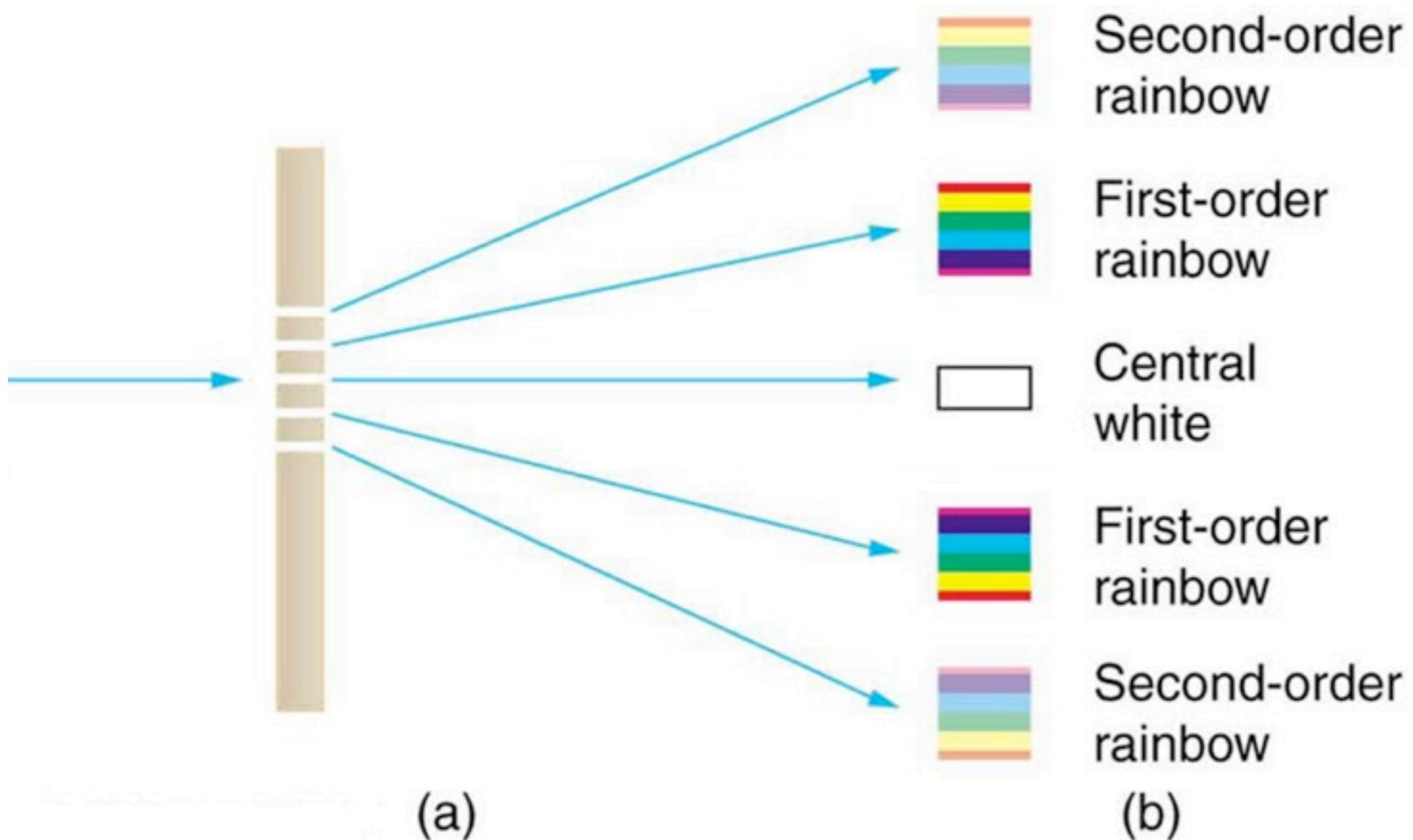
position of n th order:



if $b-c = \lambda$: maximum at θ
and $d-e = 2\lambda$, etc.

$$n\lambda = d \sin \theta$$

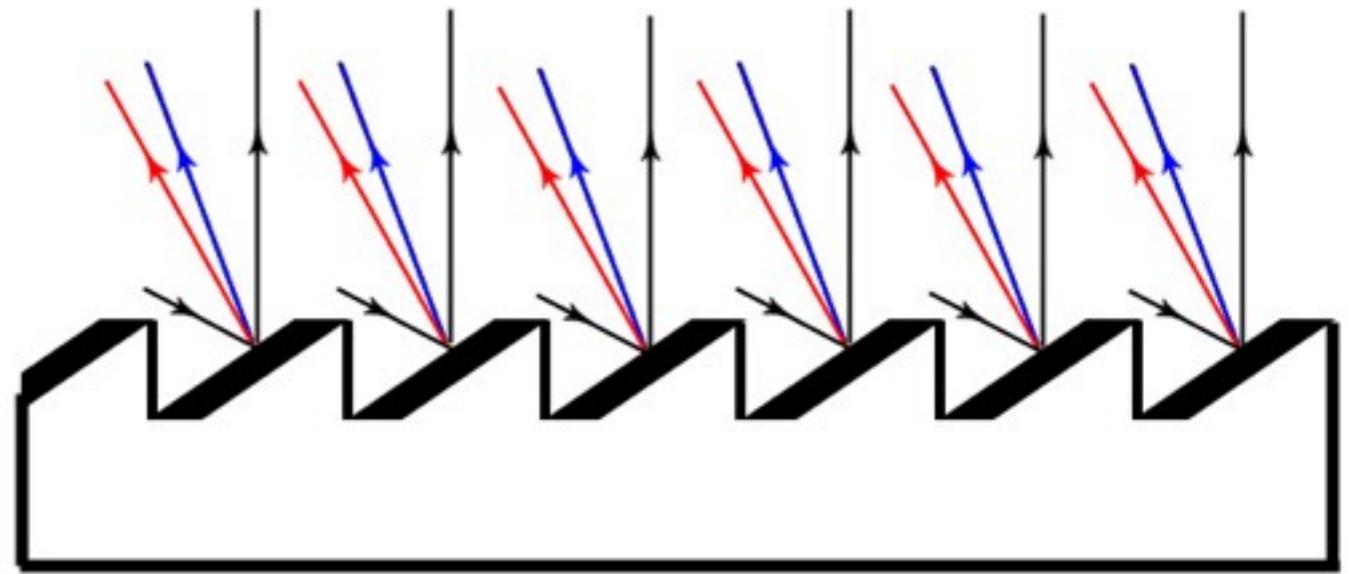
Diffraction gratings



Diffraction gratings

can be transmission gratings
or reflection gratings

most astronomical
spectrographs use reflection
gratings

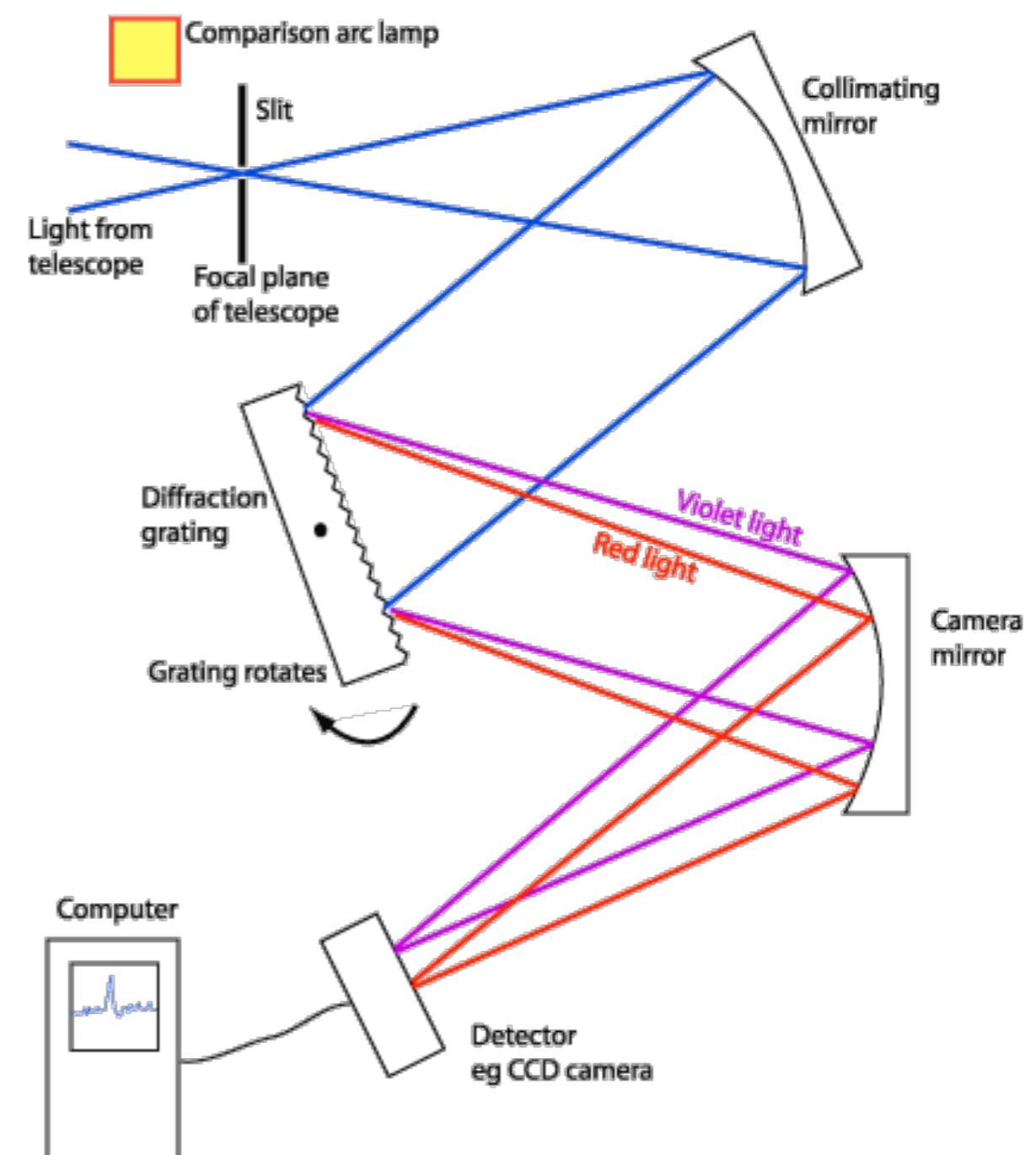
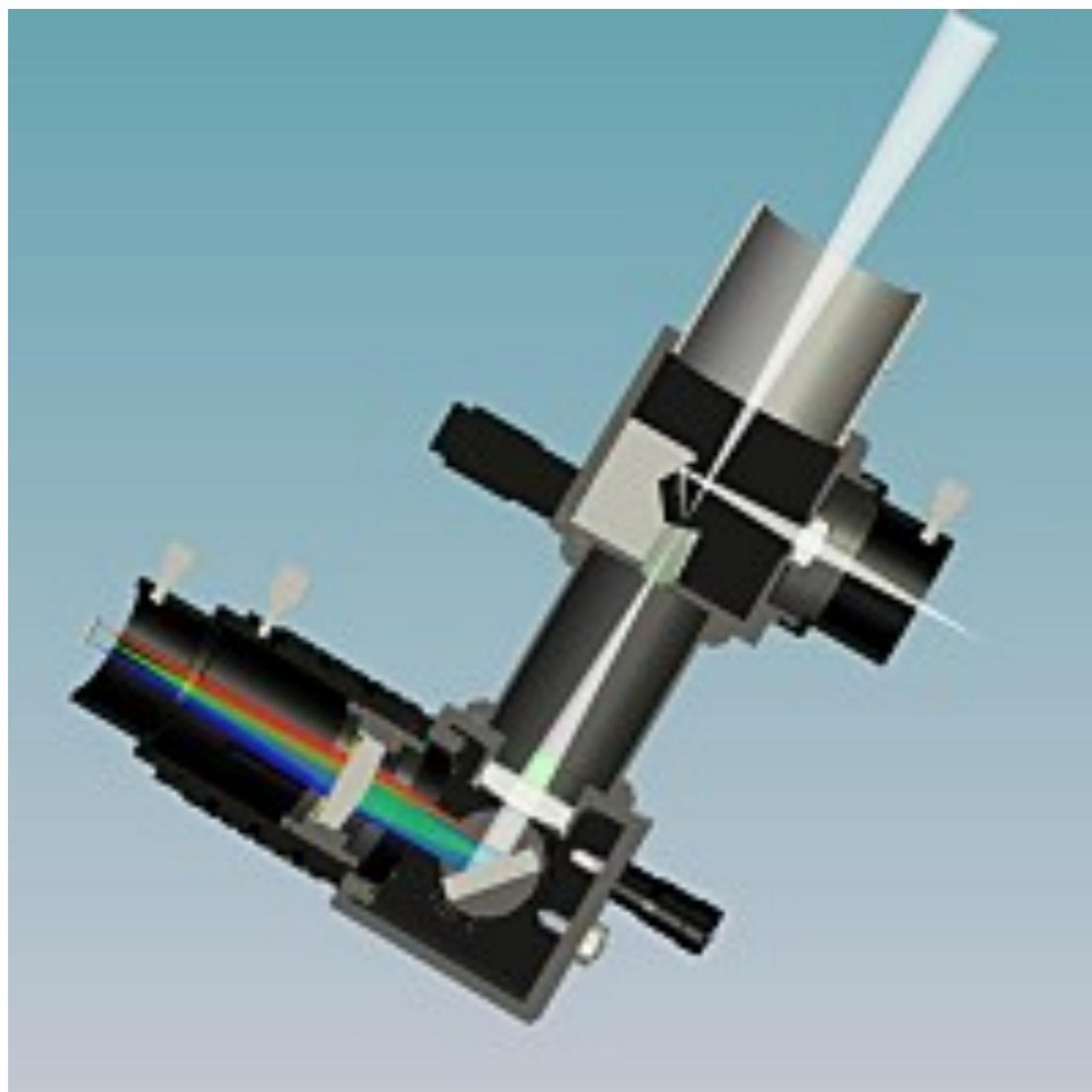


blaze wavelength: wavelength for direction of reflection coincides with desired spectral order
→ maximal efficiency

Typical spectrograph

entrance: usually a slit, similar to seeing size

collimator: converts a diverging beam to a parallel beam



A Schematic Diagram of a Slit Spectrograph

Spectral Resolution

defined by smallest wavelength difference $\Delta\lambda$ that can be distinguished at wavelength λ

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

determined by:

- grating (line density)
- width of entrance slit
- seeing

resolution: R or $\Delta\lambda$

dispersion: length $\Delta\lambda'$ of spectrum over single pixel, [$\text{\AA}/\text{px}$]

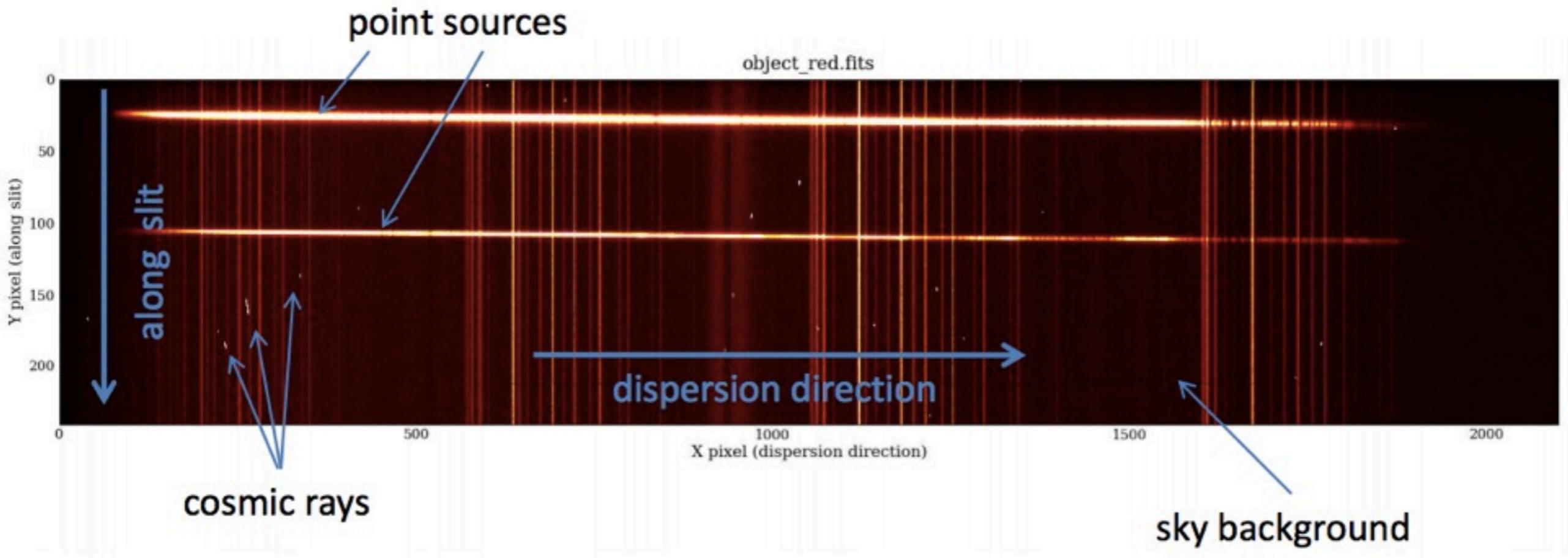
to properly sample the spectrum:

$$\Delta\lambda \sim 2 - 3 \Delta\lambda'$$

Spectral Resolution

$R < 1000$	low-resolution	e.g. our “low-resolution” spectrograph
$1000 < R < 10,000$	medium-resolution	e.g. our “high-resolution” spectrograph
$R < 10,000$	high-resolution	Echelle spectrographs

A long-slit observation



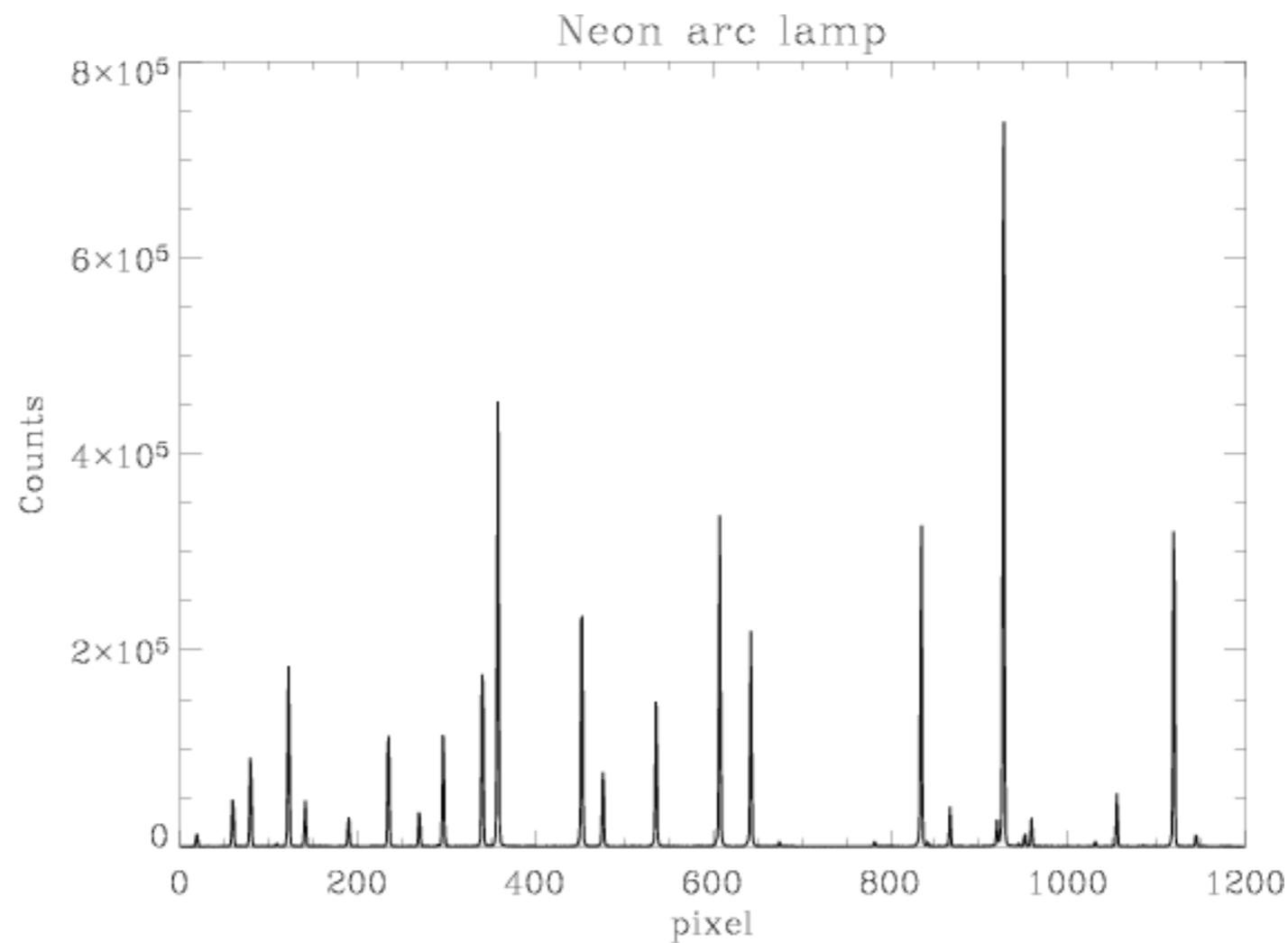
- long axis of CCD used to sample spectrum
- spatial information along slit still available: two objects, lots of sky
- sky background has a lot of emission lines!

Spectroscopic Calibration

- dark frames!
- flat field: use bright continuum source
 - small-scale pixel sensitivity variation
 - variations in slit width
- wavelength calibration: which position on the CCD corresponds to which wavelength?
 - use “arc” lamps with discrete emission lines
 - can also use sky emission lines
- flux calibration:
 - “spectrophotometric” standard stars: stars with known spectral shapes, smooth continua

Spectroscopic Calibration

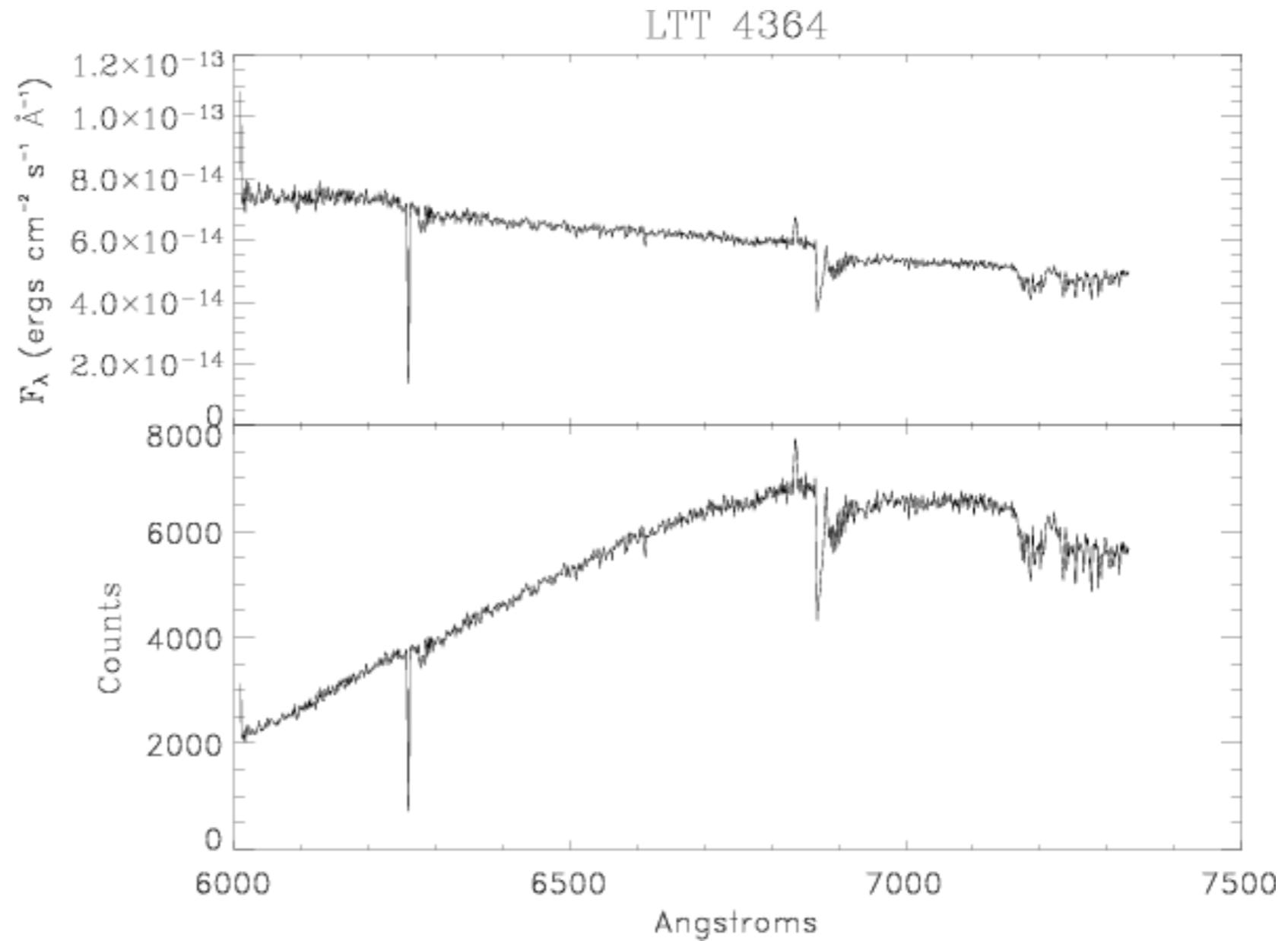
wavelength calibration: map pixel position to emission lines



Spectroscopic Calibration

flux calibration:
observe
spectrophotometric
standard star

compare observed
spectrum (counts)
to known spectrum



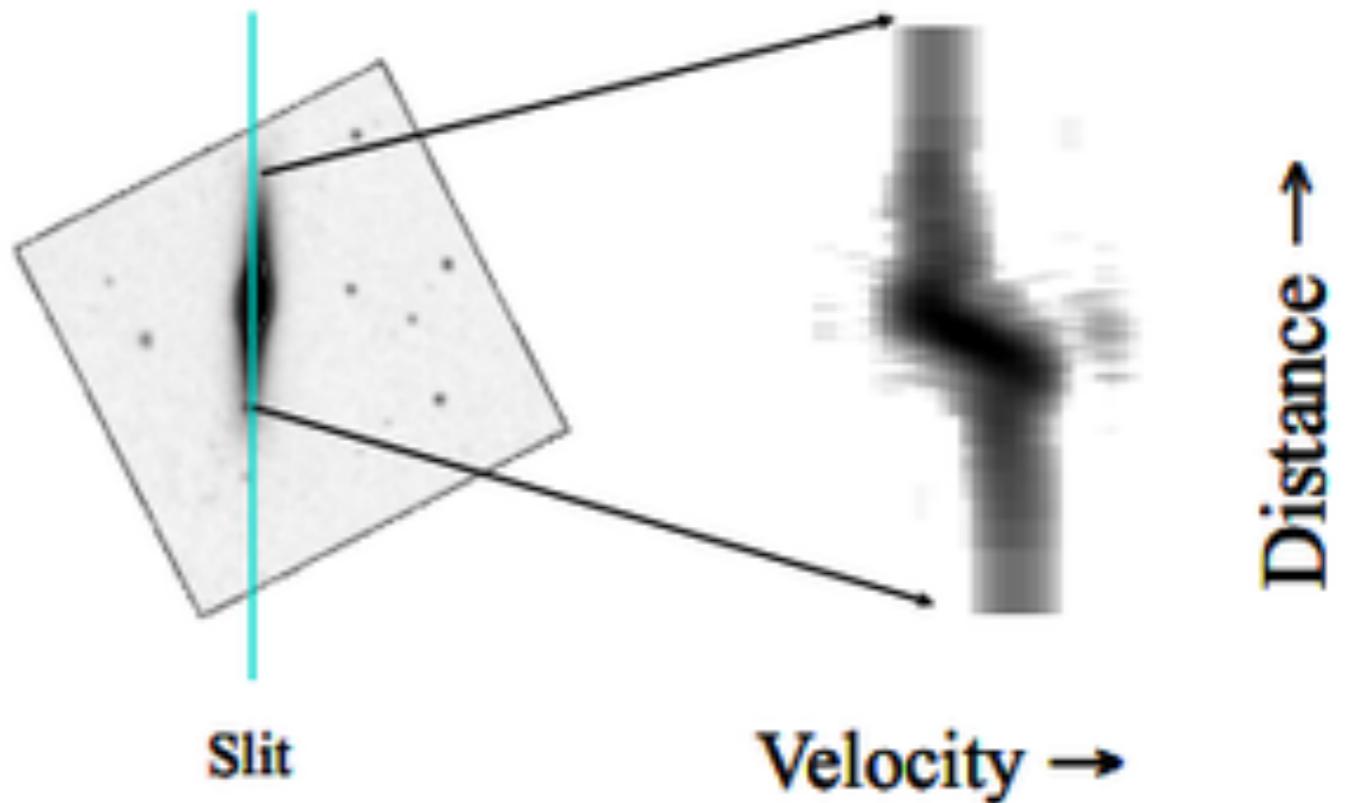
Long-slit spectrographs

most common spectrograph

can only target one (or a few) objects

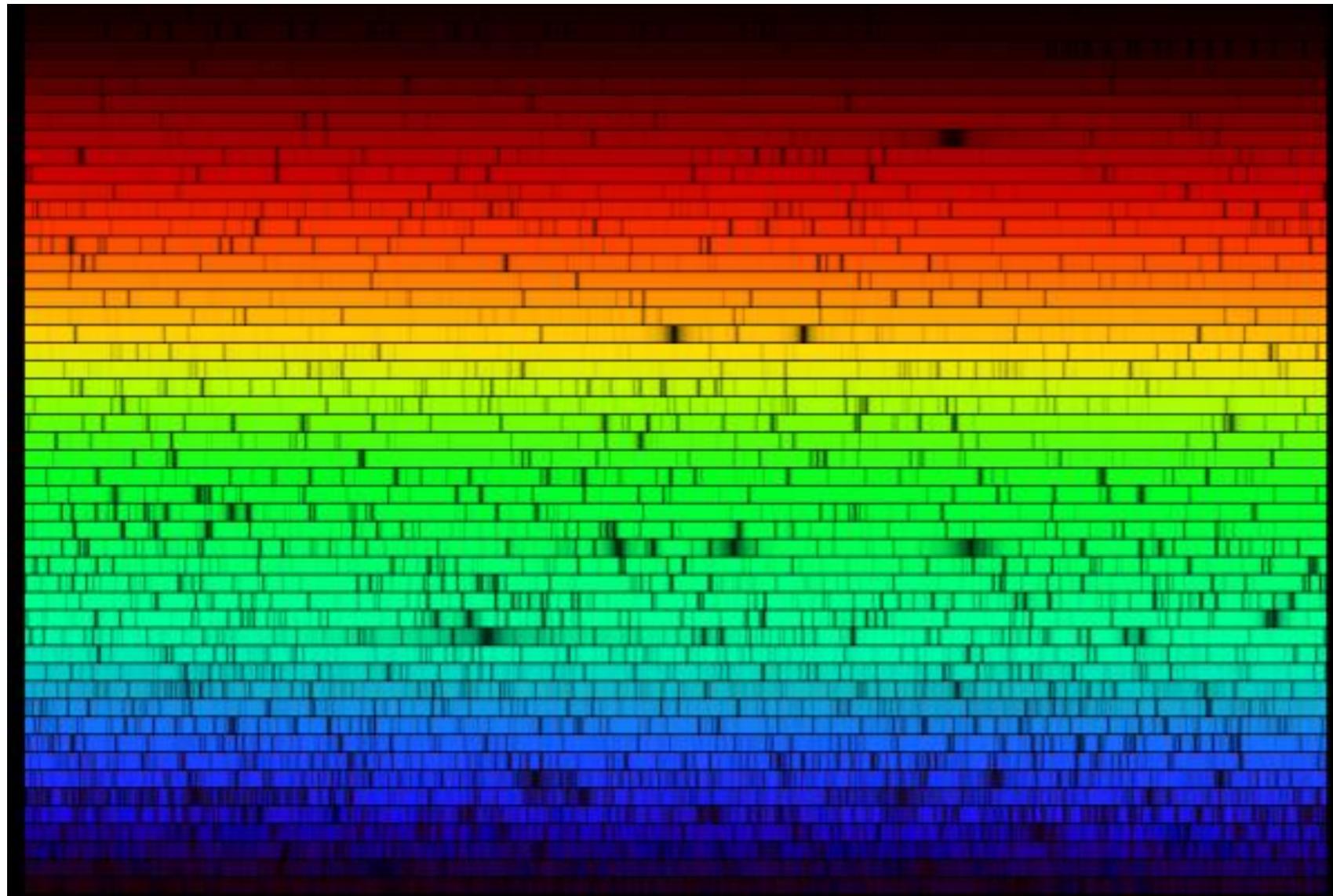
gives spatial variation

very good estimate of sky background



Echelle spectrographs

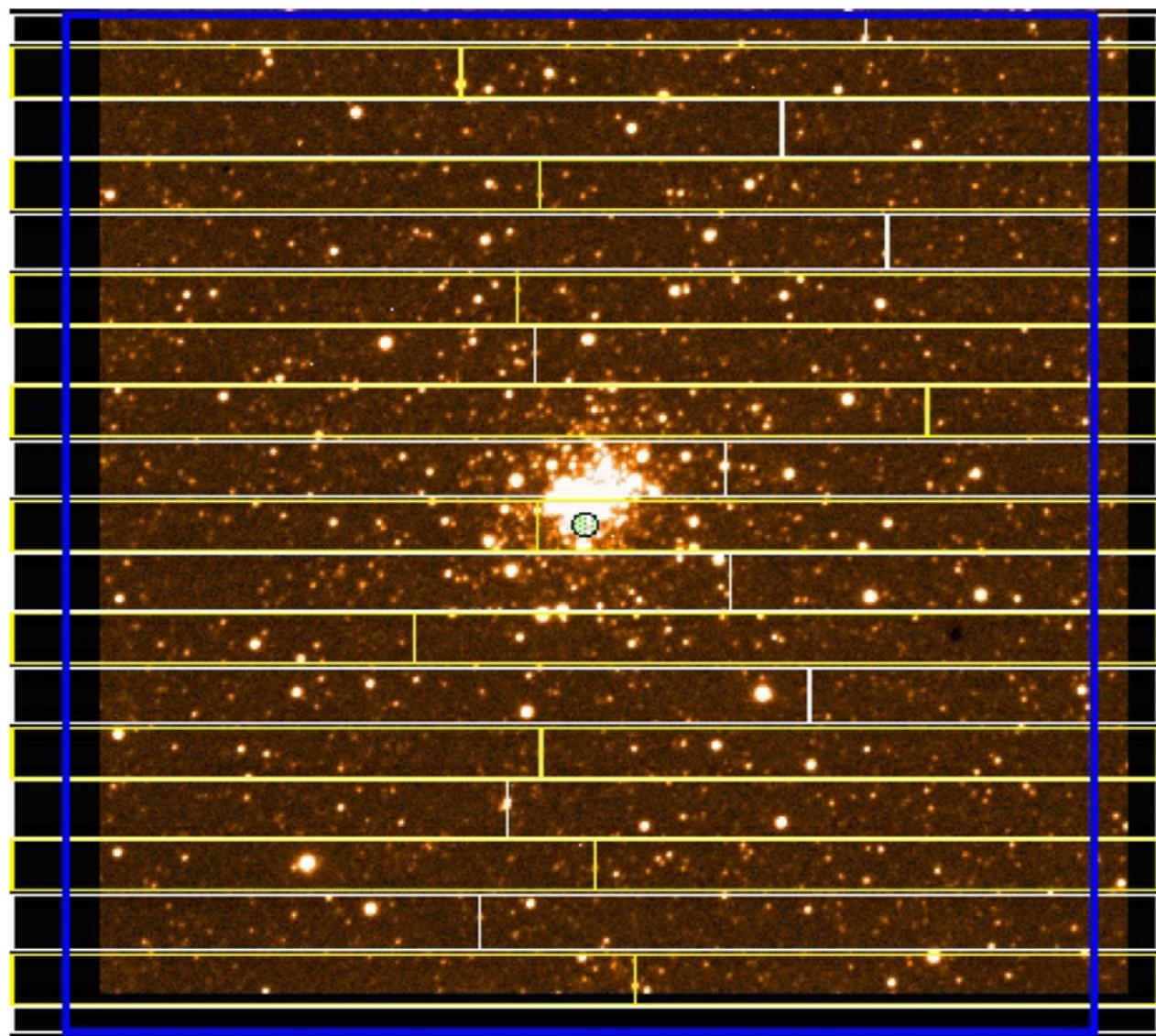
- very high resolution long-slit spectrographs
- have additional elements to fit entire spectrum onto CCD
- only for bright objects



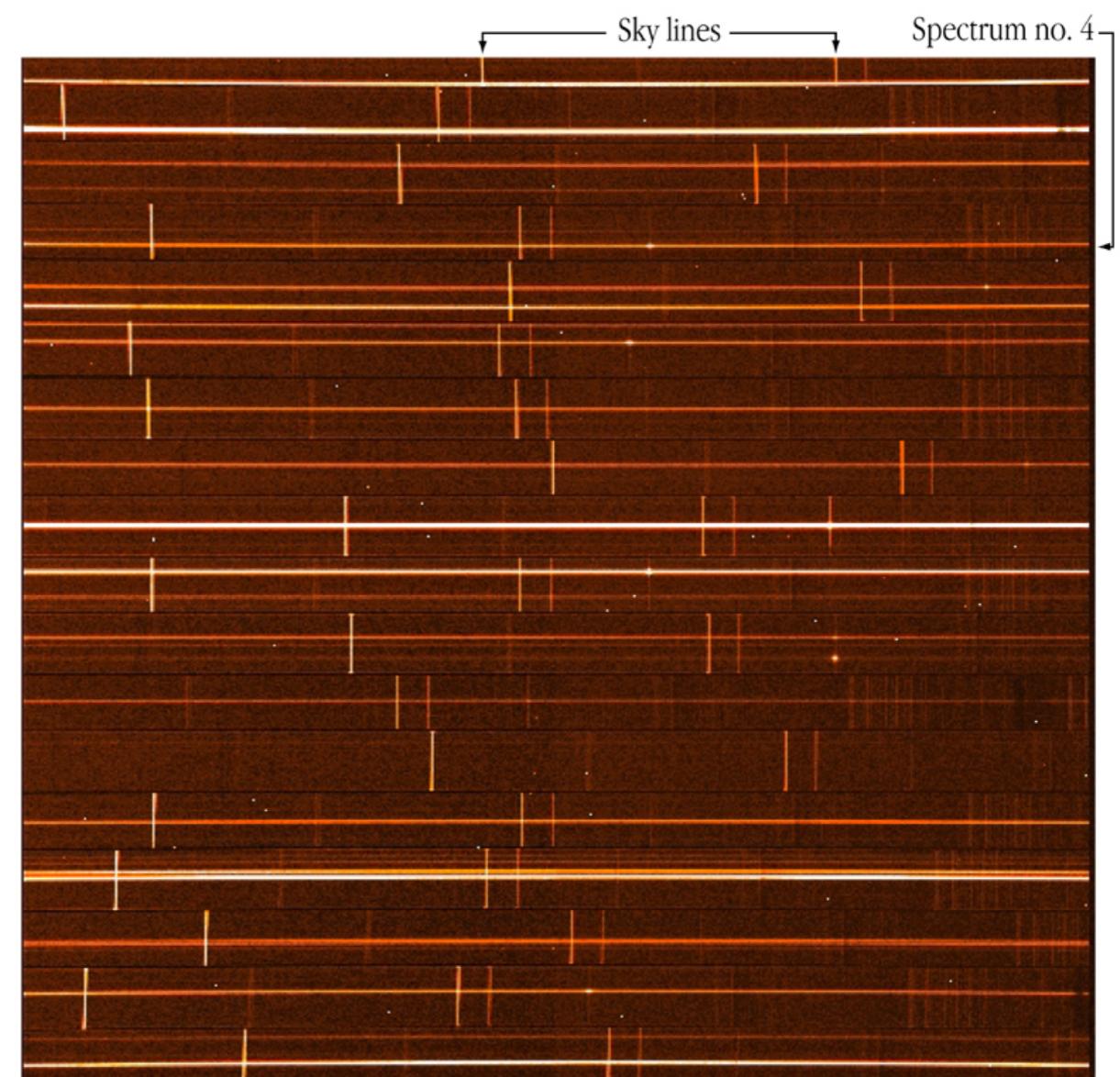
Echelle spectrum
of the Sun,
4000-7000Å

Multi-object spectrographs

make a mask with multiple slits, one per target



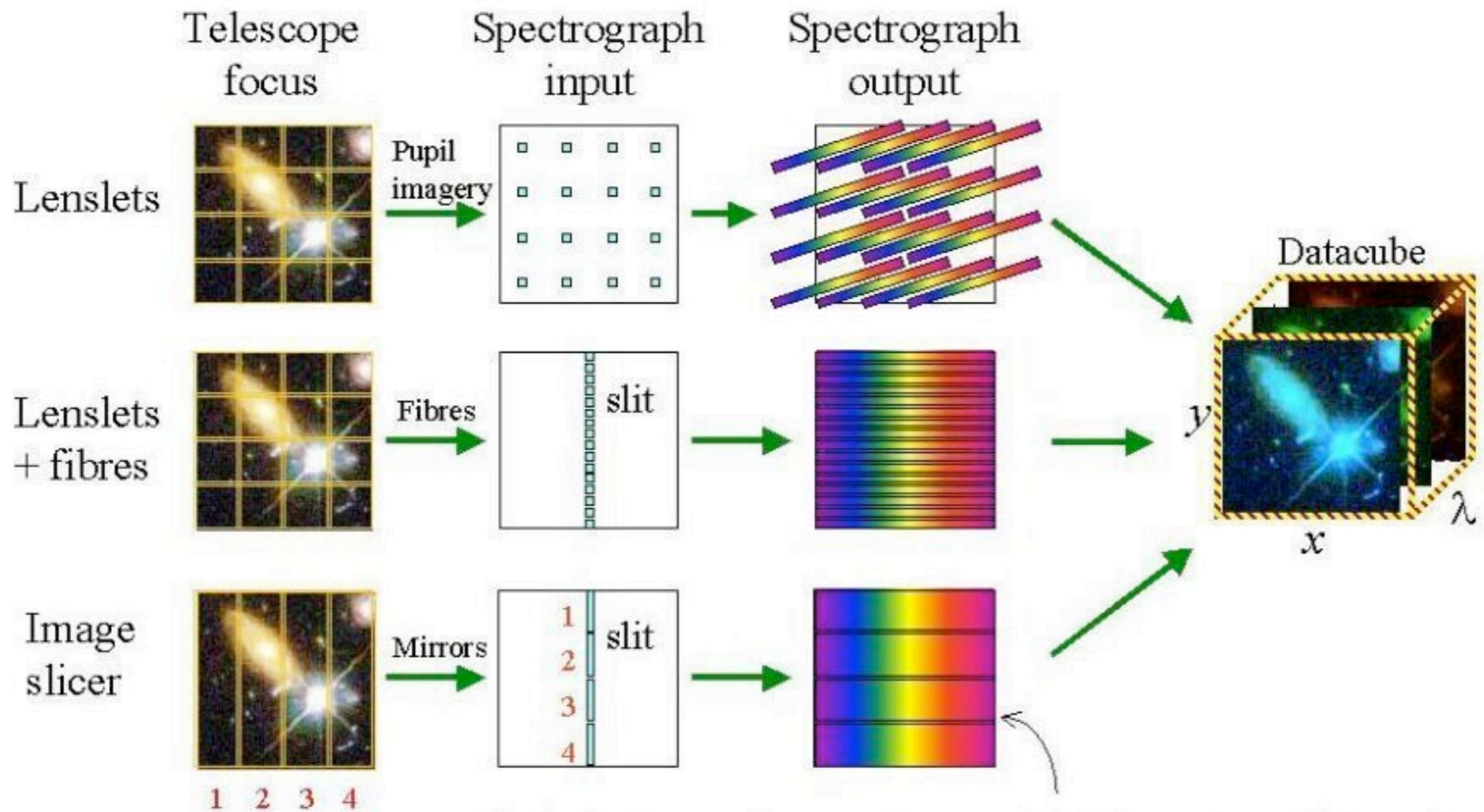
Open Cluster NGC 330 in SMC - VLT UT1 + FORS1 (MOS-mode)



Spectra of Stars in Open Cluster NGC 330 in SMC - VLT UT1 + FORS1 (MOS-mode)

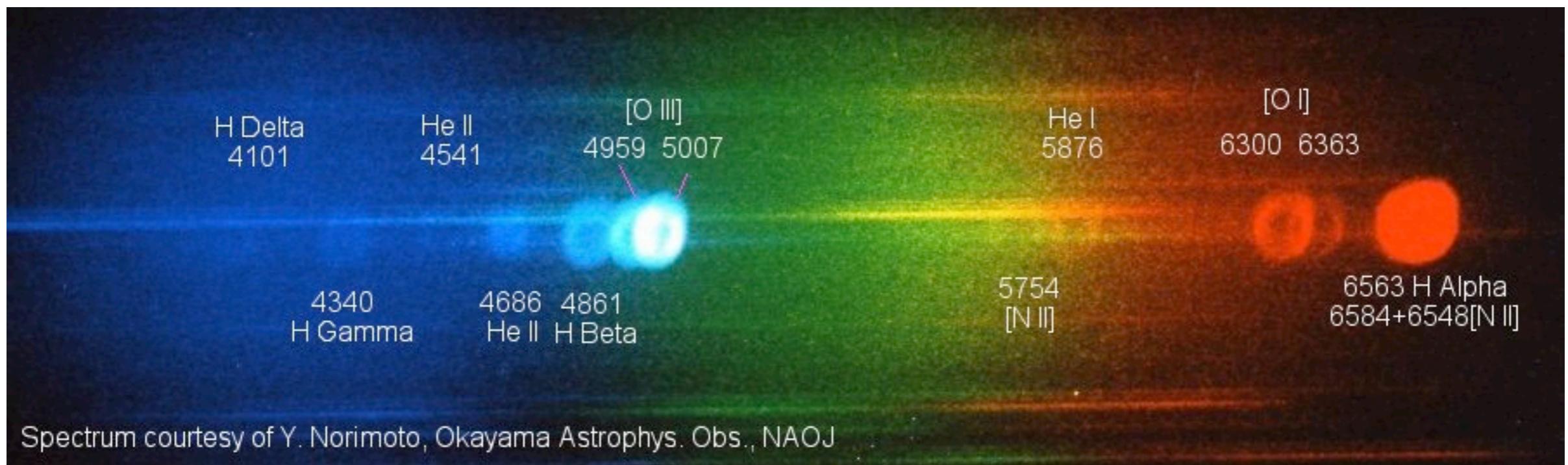
Integral-Field Units

divide image into “spaxels” (not quite pixels)



Lab 2: Spectroscopy Lab

measure strengths of several emission lines of a bright planetary nebula or star-forming nebula
use line ratios to determine gas temperature



slitless(!) spectrum of the Ring Nebula