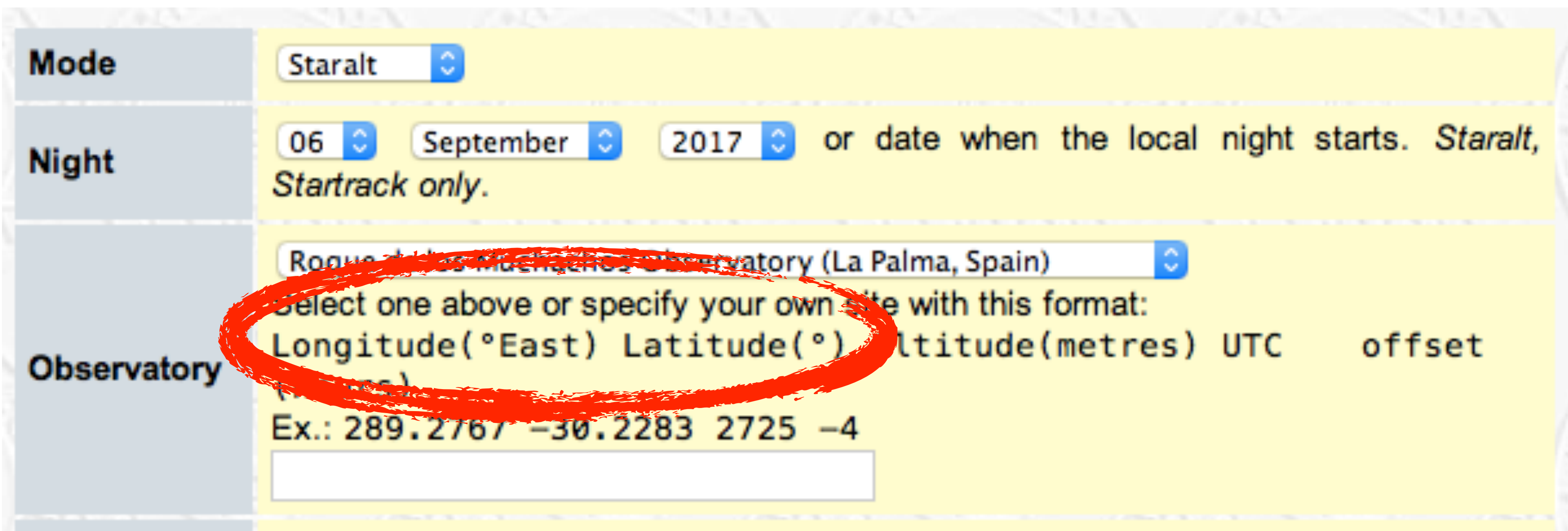
PHY 517 / AST 443: Observational Techniques in Astronomy

Lecture 3: CCDs / FITS files / Spectroscopy

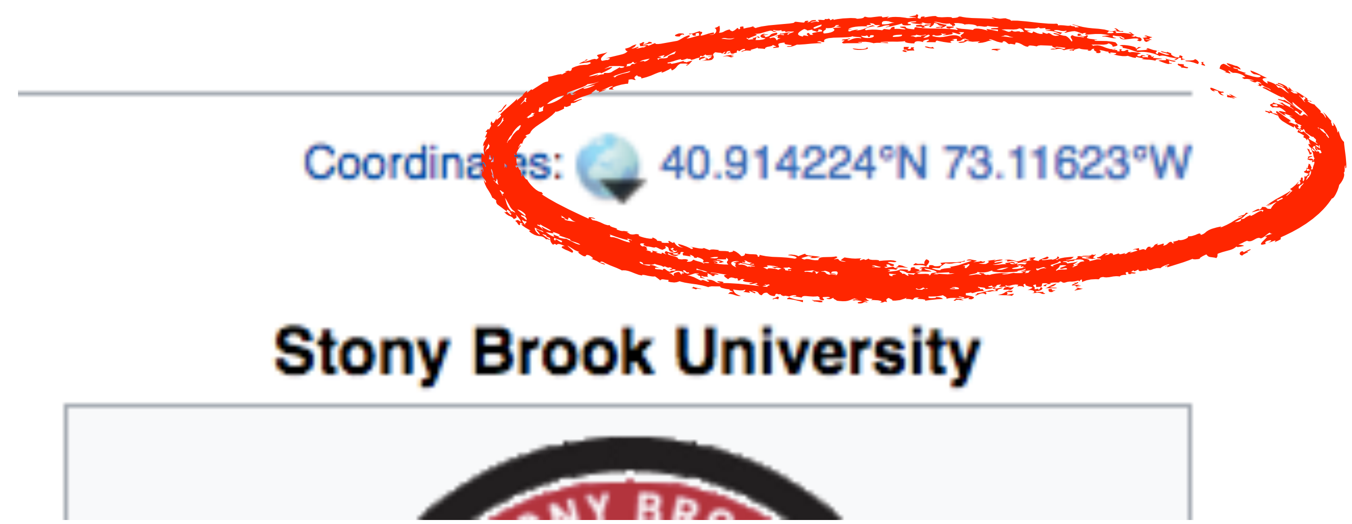
StarAlt

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



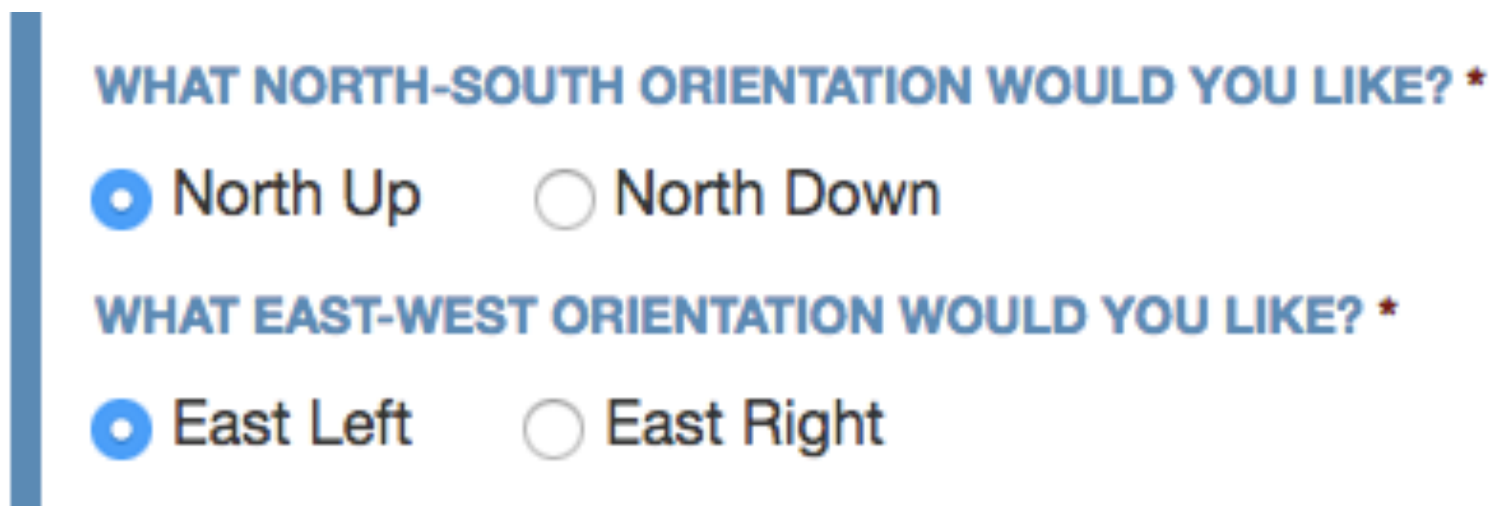
How are Mt. Stony Brook’s coordinates correctly specified?

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



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:

$$99.123 \pm 0.005$$

Plagiarism

Q: *Can a Q grade lead to immediate expulsion?*

A: Maybe (if it's the second or more offense).

ASTRO CLUB

STONY BROOK UNIVERSITY

Thursdays at 8:00pm in ESS 450

Stony Brook Astronomy Club

sbu.astro.club@gmail.com

bit.ly/sbuastroclub

@sbuastroclub

Open to all majors!

No astronomy knowledge required.

Observing on the roof after meetings!

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 (*uhura* and *vulcan*)
- your data and scripts should go into /astrolab/Fall_2019/*username*
- only *uhura* and *vulcan* have all of the required software
- *make sure to back up your data!!!*
- log out - do not block a machine by leaving it in screensaver mode; if you do, you have to write a letter of apology to Prof. Swesty
- change your password and keep it safe - else, see above

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 anjavdl / PHY517_AST443_Fall2016

Unwatch 2 | Star 0 | Fork 1

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

NamHoNguyen changed the title from **J2000.0 coordinates from http://exoplanet.eu/catalog/all_fields/?f=%22transit%22+IN+detection** to **J2000.0 coordinates from http://exoplanet.eu/catalog/** 10 minutes ago

anjavdl commented just now Owner

Labels

None yet

Milestone

No milestone

Assignees

No one—assign yourself

2 participants

Notifications

Unsubscribe

You're receiving notifications because you commented.

Class Material

slides, homeworks, tutorials, etc. *as used in this year's class* are linked from the schedule on the wiki

anjavdl / **PHY517_AST443**

Unwatch 22 | Star 5 | Fork 5

Code | Issues 6 | Pull requests 0 | Projects 0 | Wiki | Security | Insights | Settings

Schedule Fall 2019

Edit | New Page

anjavdl edited this page 1 minute ago · 1 revision

Date	Topics	Slides	Tutorials	Homework
Aug 26	Intro, Coordinate Systems, Time	Lecture 0, Lecture 1		HW1, due Aug 28
Aug 28	Magnitudes, Atmosphere, Telescopes		Tu1	HW2, due Sept. 4
Sep 4	CCDs, FITS files, spectroscopy			
Sep 9	Statistics 1			
Sep 11	Statistics 2			
...	Data Analysis Help Sessions	unless	announced	otherwise
Oct 9	Proposal deadline, 5pm			
Oct 16	Time Allocation Committee			
...	Data Analysis Help Sessions	unless	announced	otherwise
Dec 4	Final presentations			
Dec 9	Final presentations			

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General Information

- Schedule
- Grading
- Academic Policies

Labs and Write-Ups

- Guidelines
- How to write a decent lab report
- Observing Equipment
- Observing Calendar
- Lab 0: CCDs
- Lab 1: Exoplanet transit
- Lab 2: Diffuse Nebula Spectroscopy
- Lab 3: Your own proposal
- *Discontinued:* Radio Interferometry
- Weather
- End-of-night report

Computing

- Computing Resources
- Astro Software Overview
- LaTeX
- Bash

Today < > September 2019 Month

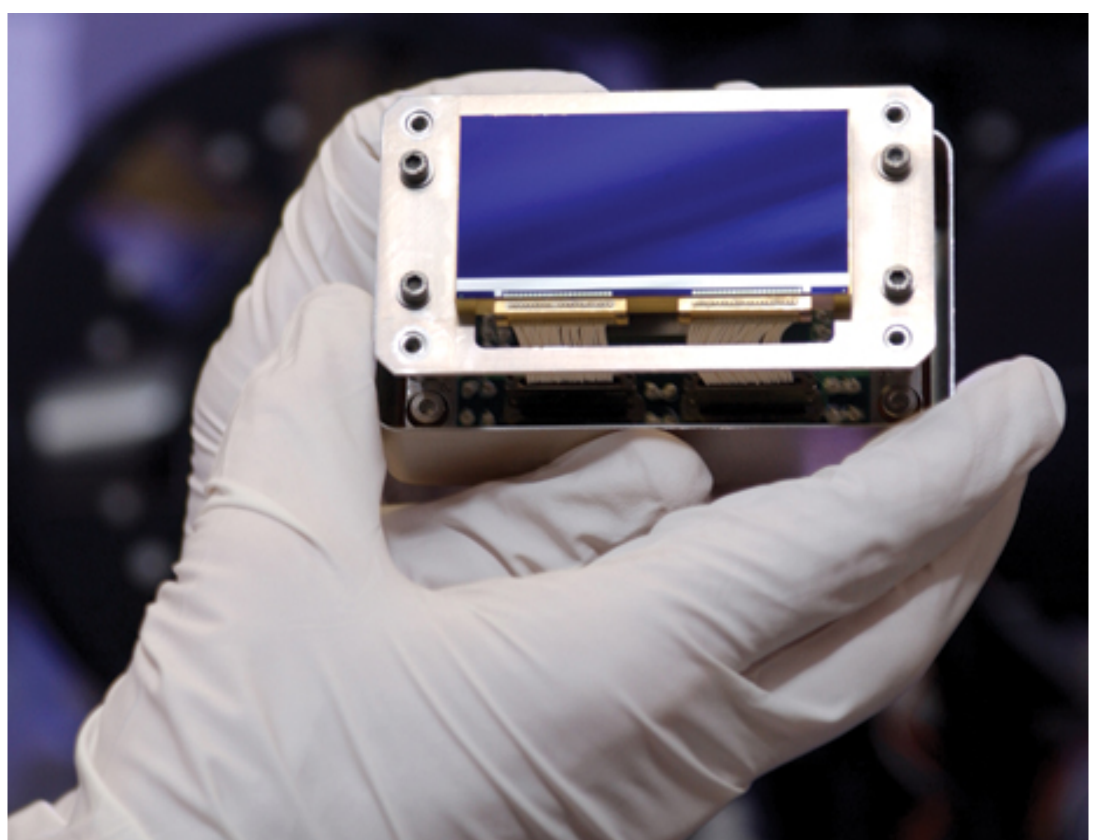
MON	TUE	WED	THU	FRI	SAT	SUN
26 6pm Lecture 1	27	28 6pm Lecture 2	29 4pm Lab 0: Chowdhury,	30 New Moon	31	Sep 1
2 Labor Day	3	4 1pm Lab 0: Degrendele, 6pm Lecture 3	5 2pm Lab 0: Isola, Murpl	6	7	8
9 6pm Lecture 4	10	11 No observing 6pm Lecture 5	12 No observing	13 No observing	14 No observing Full Moon	15 No observing
16 No observing	17 No observing	18	19	20	21	22
23	24	25	26	27	28 New Moon	29
30	Oct 1	2	3	4	5	6

excerpt from Mt. Stony Brook observing 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



e2v

Figure 3. Kepler CCD in handling jig.

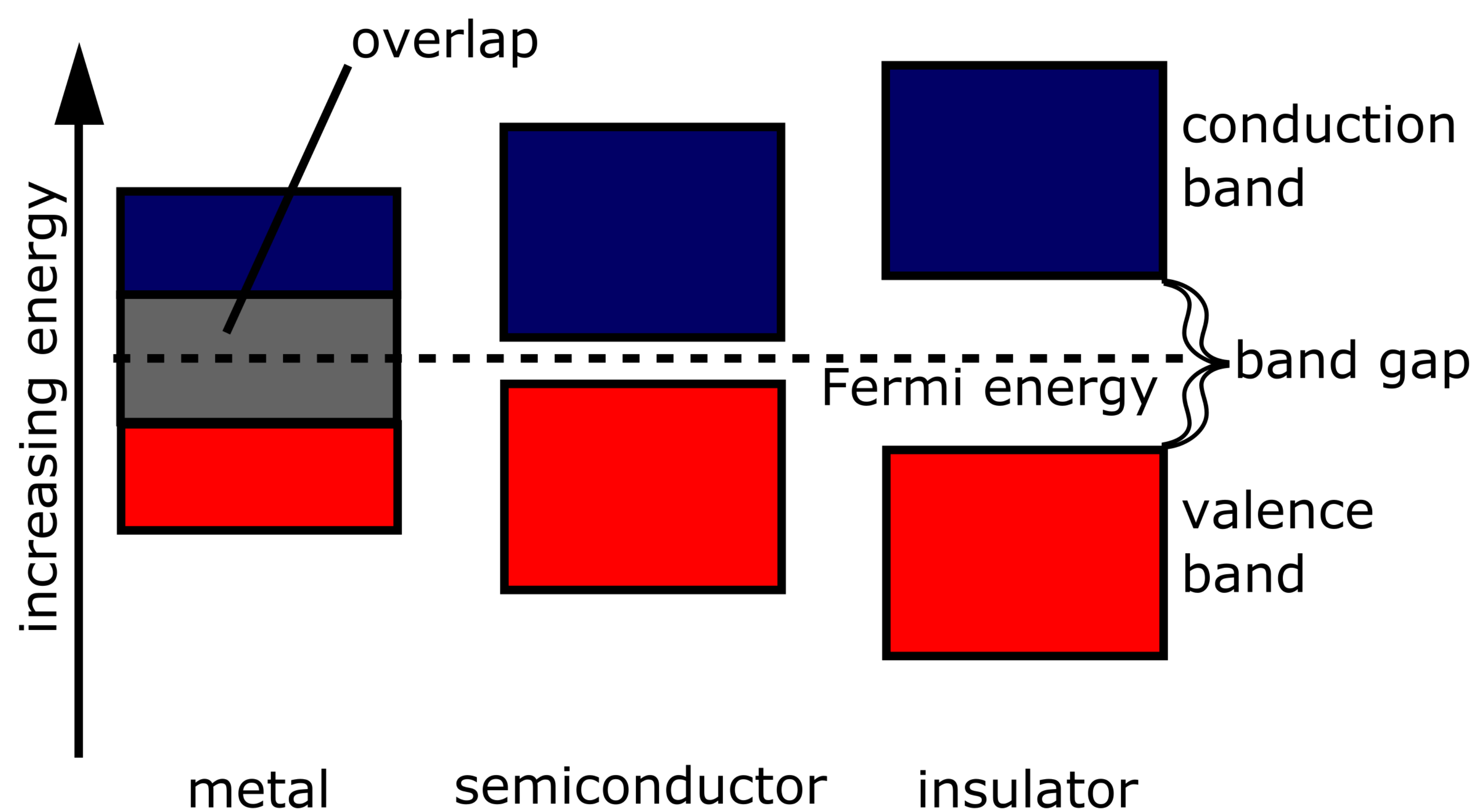
CCDs - Advantages

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

CFHT MegaPrime

Semi-Conductors

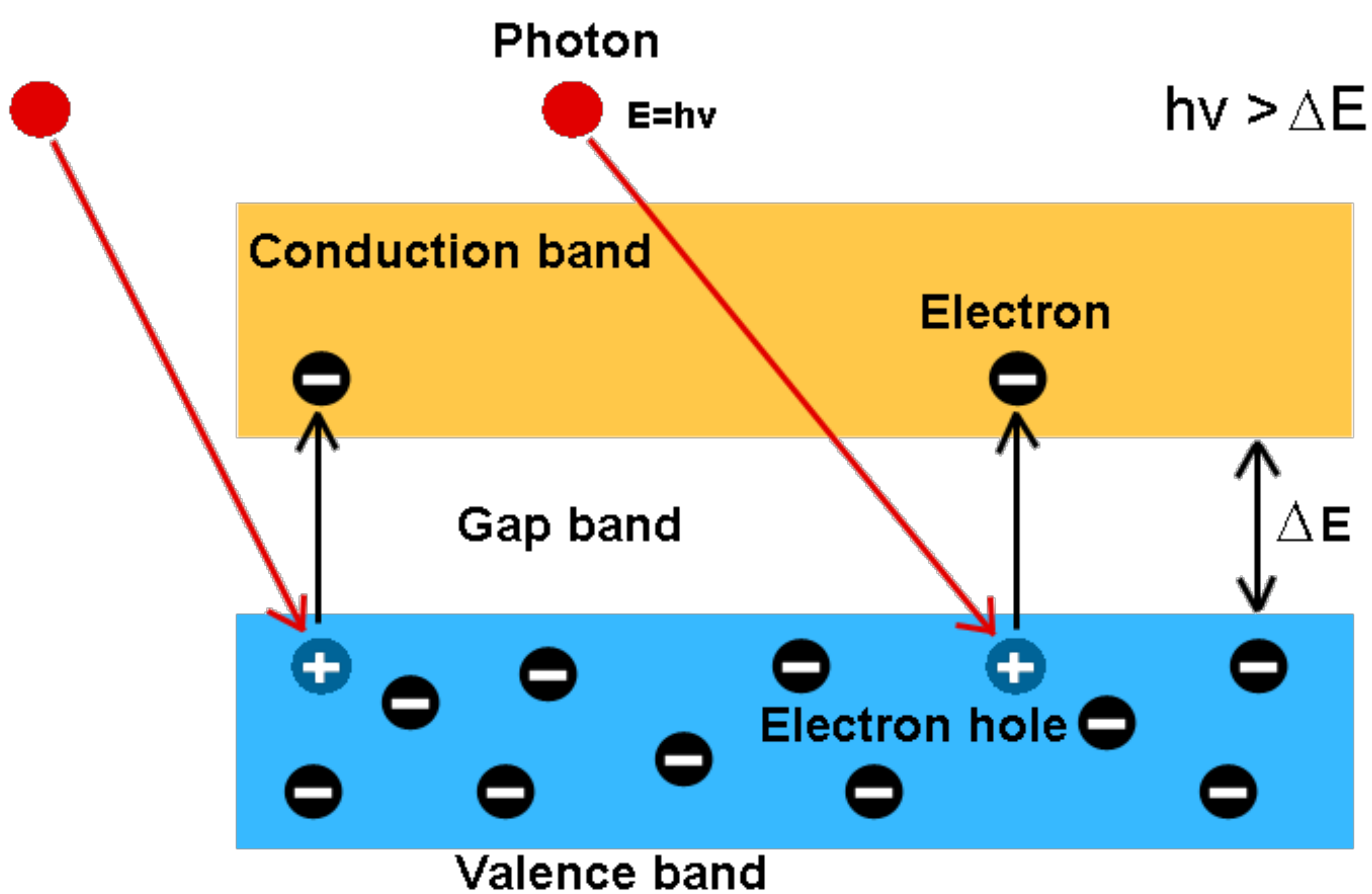
- CCDs are made of semi-conducting silicon wafers
- key feature: small energy gap between "valence band" (energy levels of outermost bound electrons) and "conduction band" (energy levels of free electrons)



wikipedia

Photoelectric effect

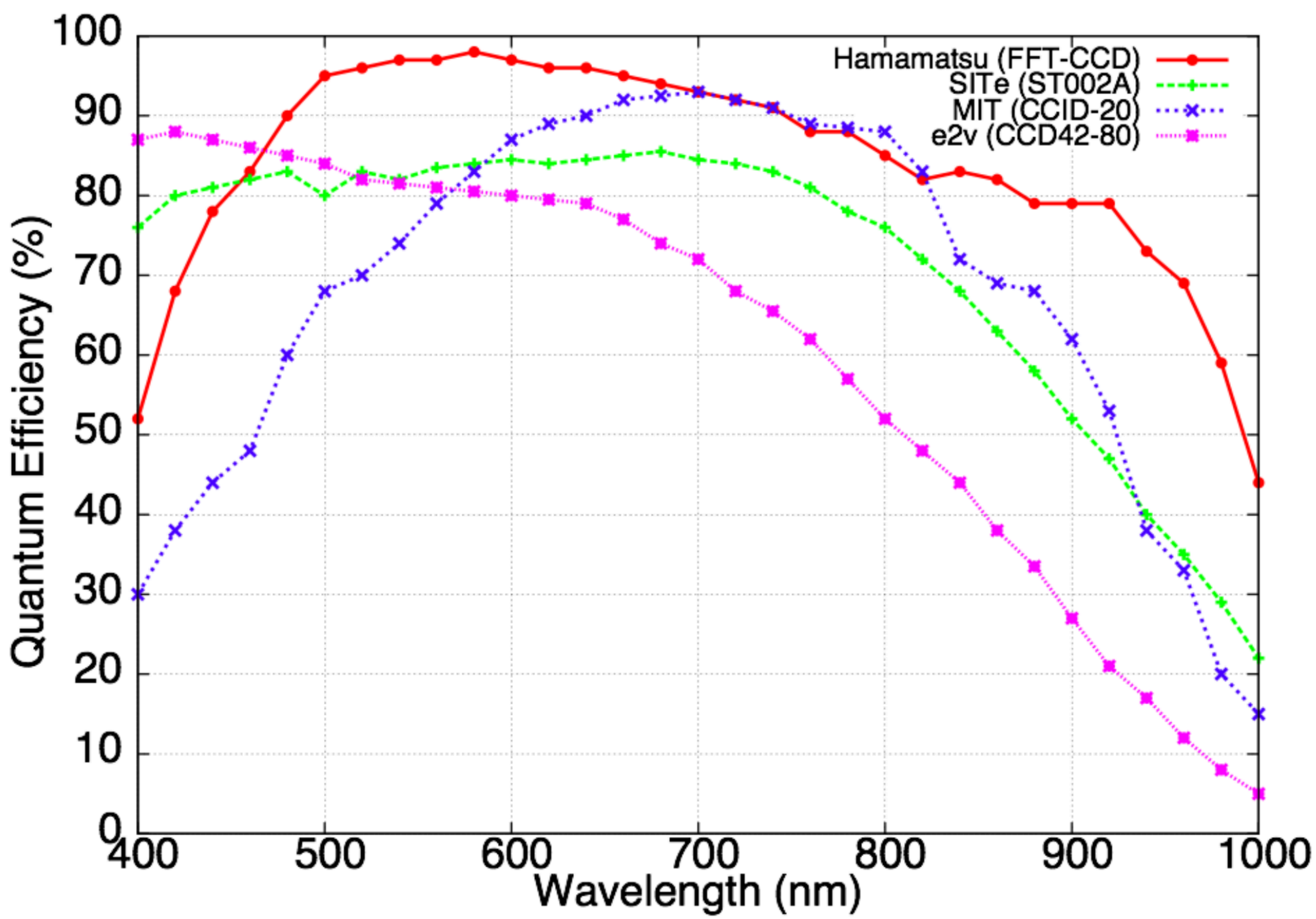
- light is quantized, "photons" $E = h\nu$
- when a photon is absorbed, the energy is transferred to an electron → "jumps" into conduction band



M. Poblocki

CCD Quantum Efficiency (QE)

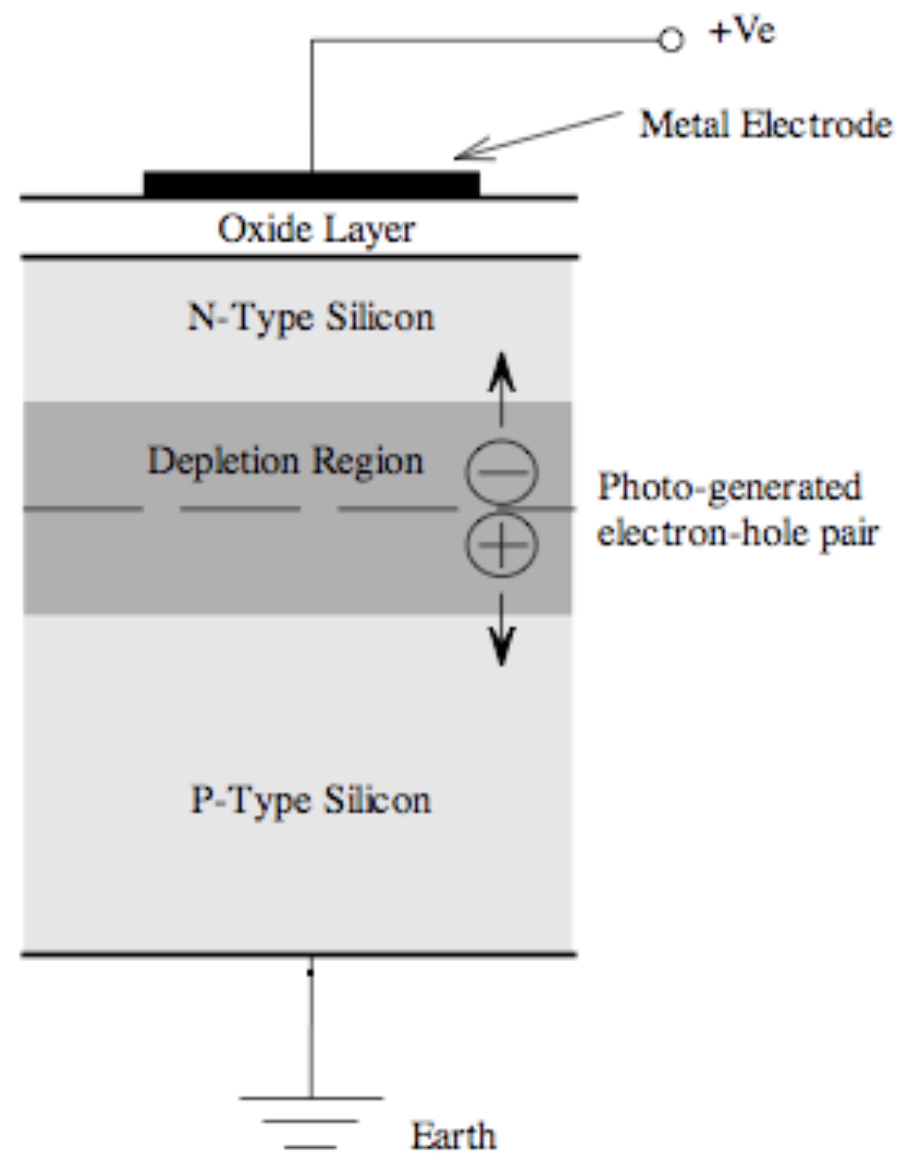
- fraction of photons that are detected
- depends on wavelength
- different technologies lead to red vs. blue optimized CCDs



Nakao et al. 2014

One pixel

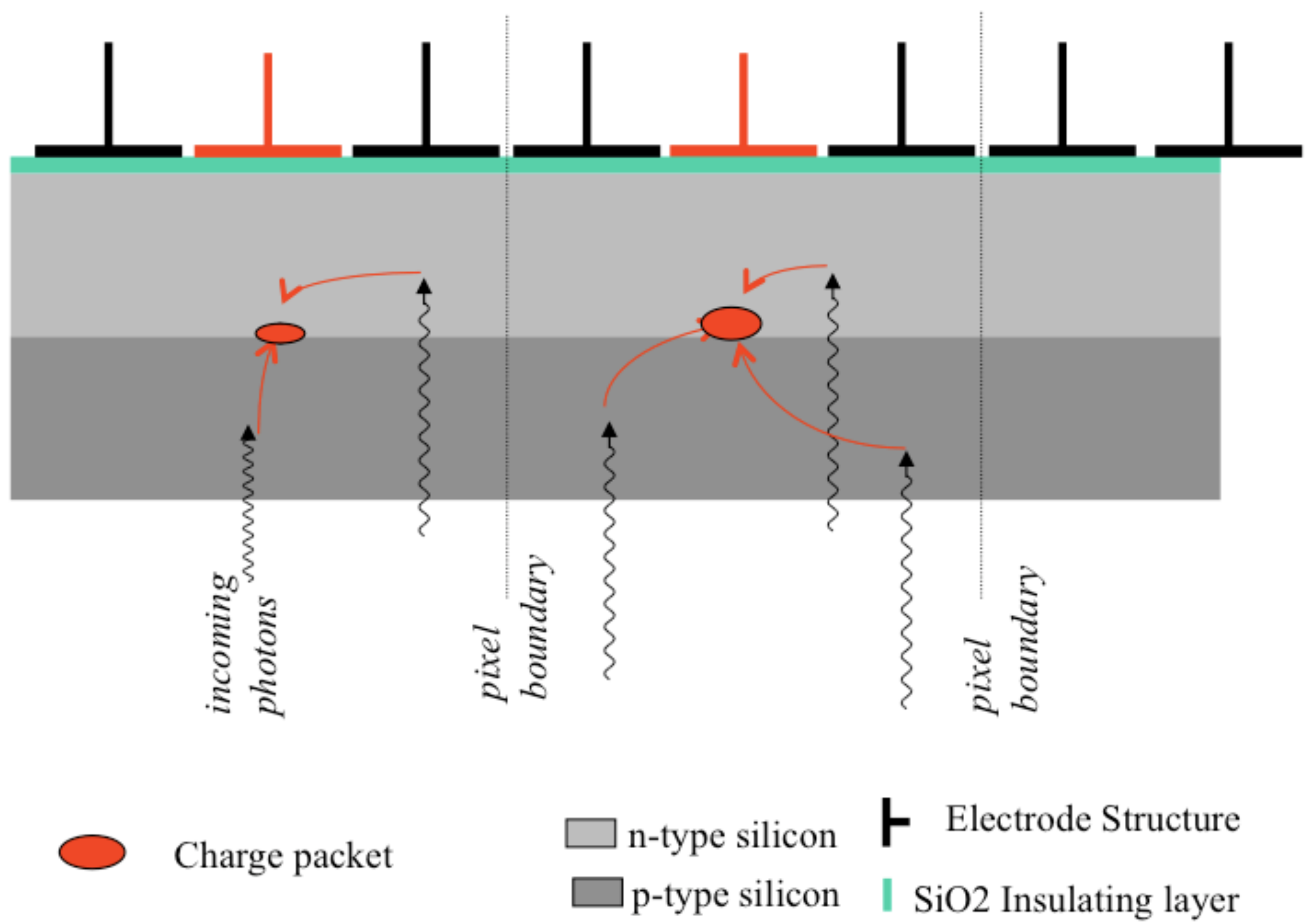
- apply an electric field to keep electrons / holes separated



Microsoft

Many pixels

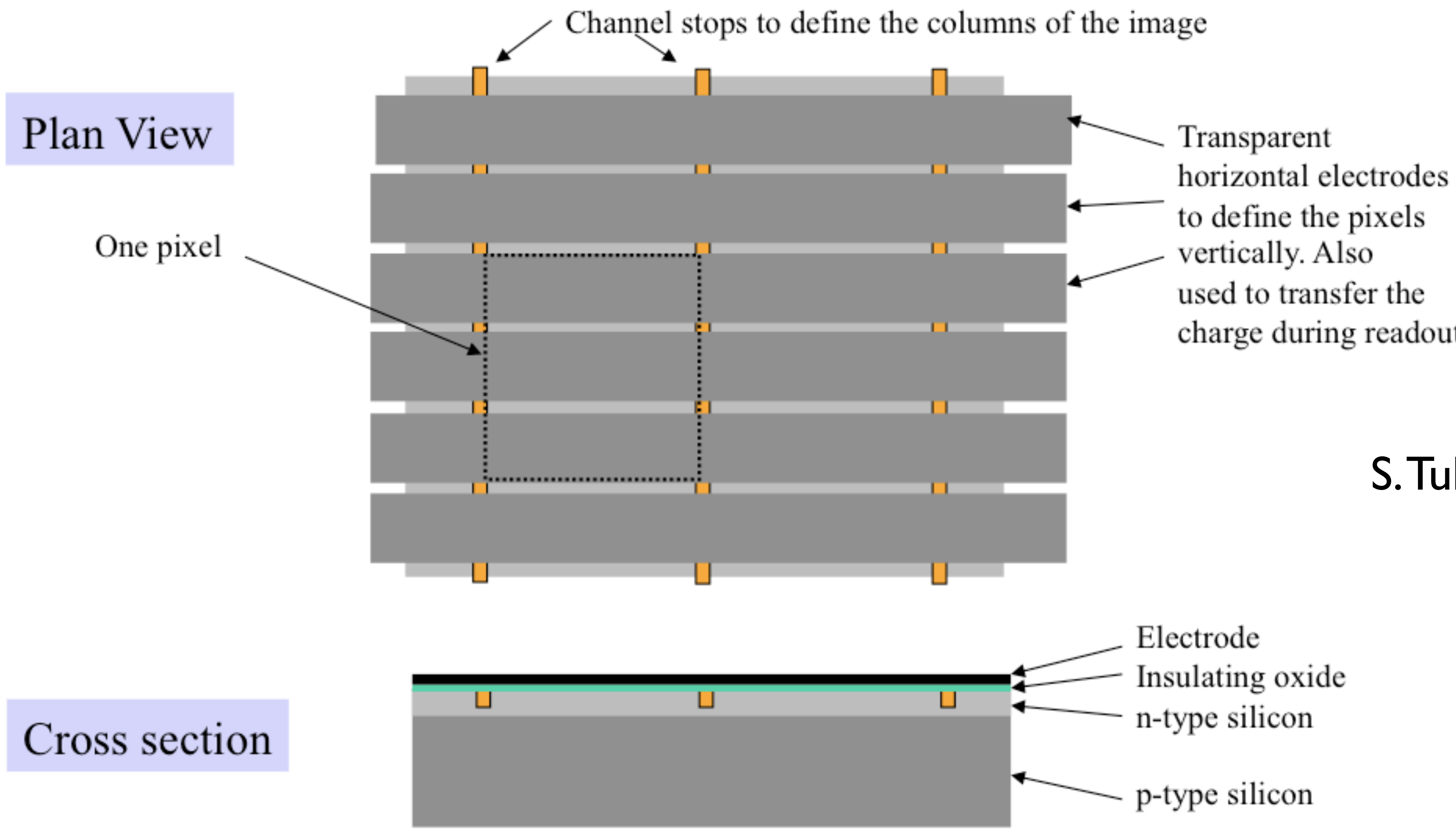
- pixels are defined by the electric field generated by the applied electrodes



S. Tullock

Many pixels

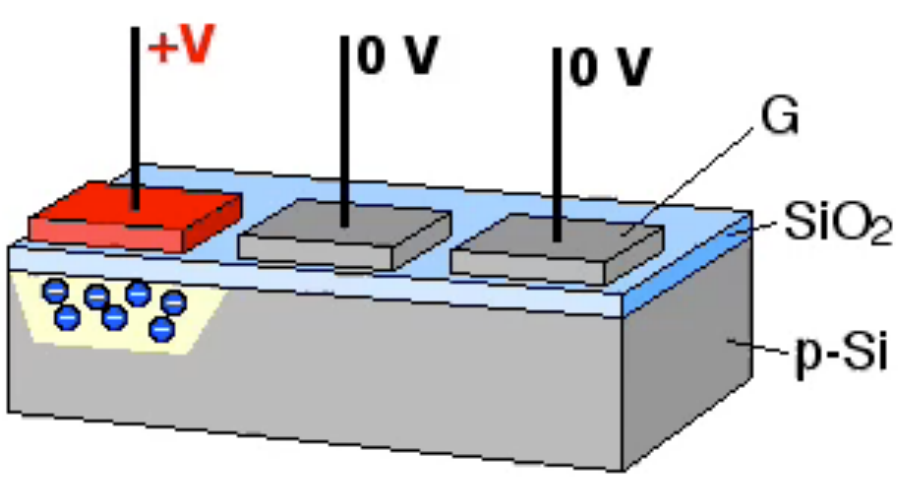
- … and by insulator strips between columns



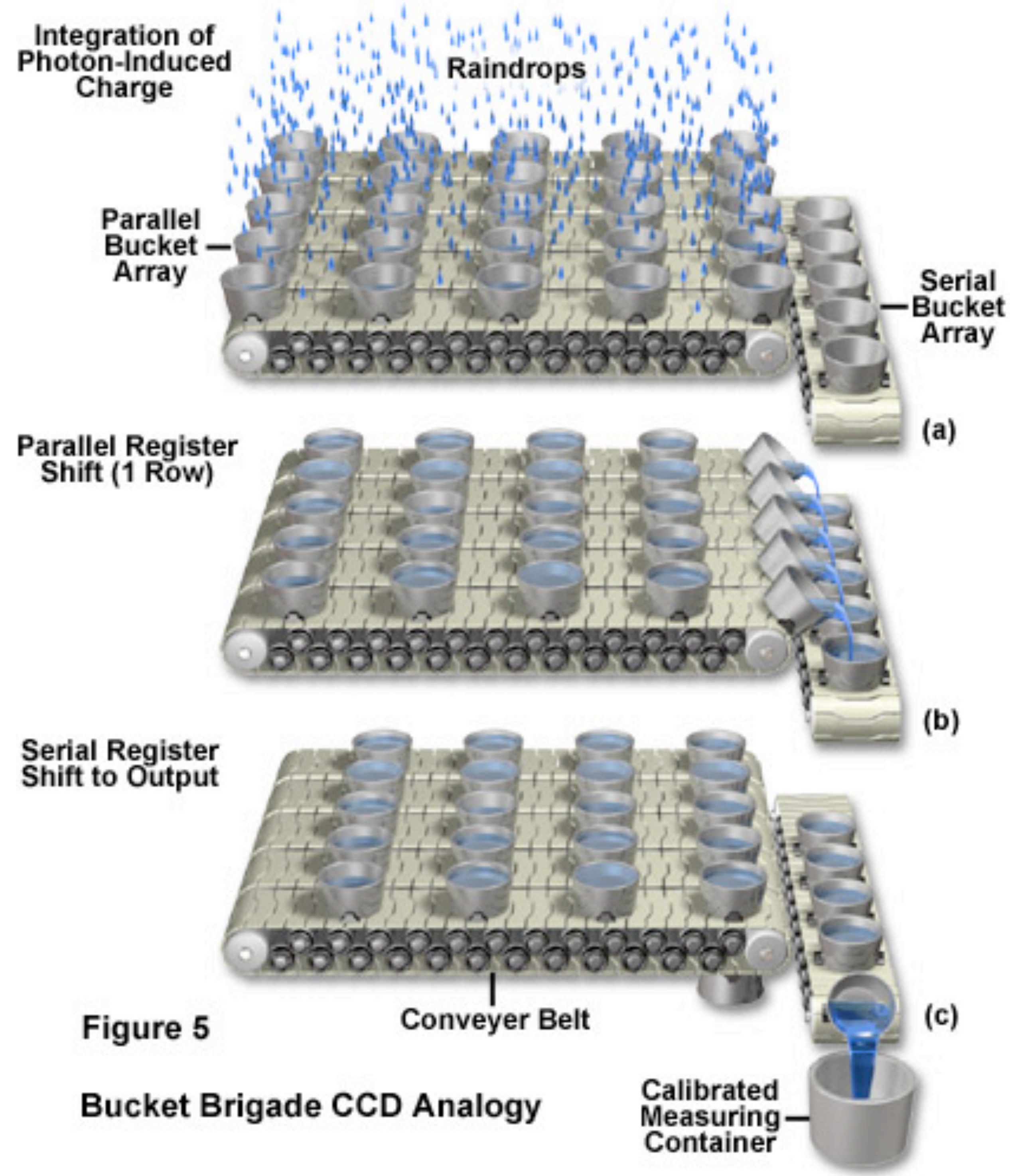
S. Tullock

Reading out CCDs

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



M. Schmidt / wikipedia

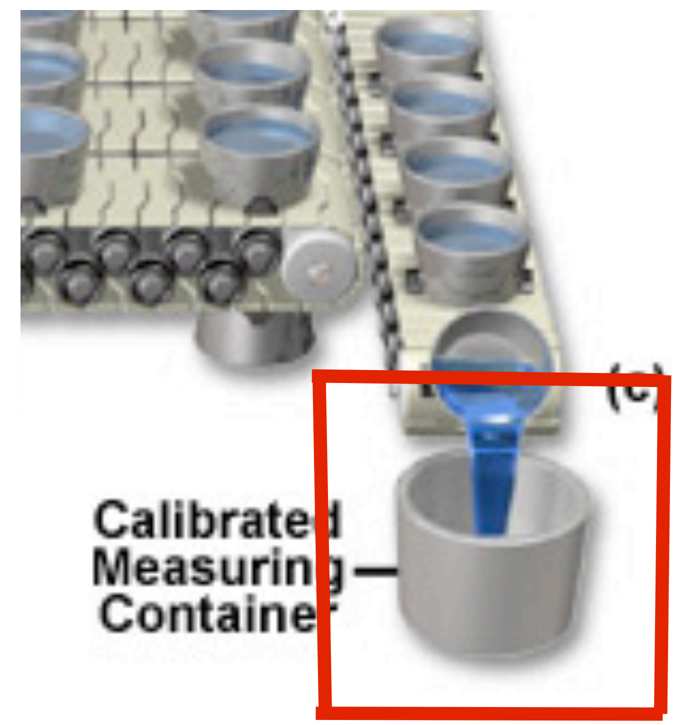


Cold Spring Harbor Protocols

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"

Cold Spring Harbor Protocols



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

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

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 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

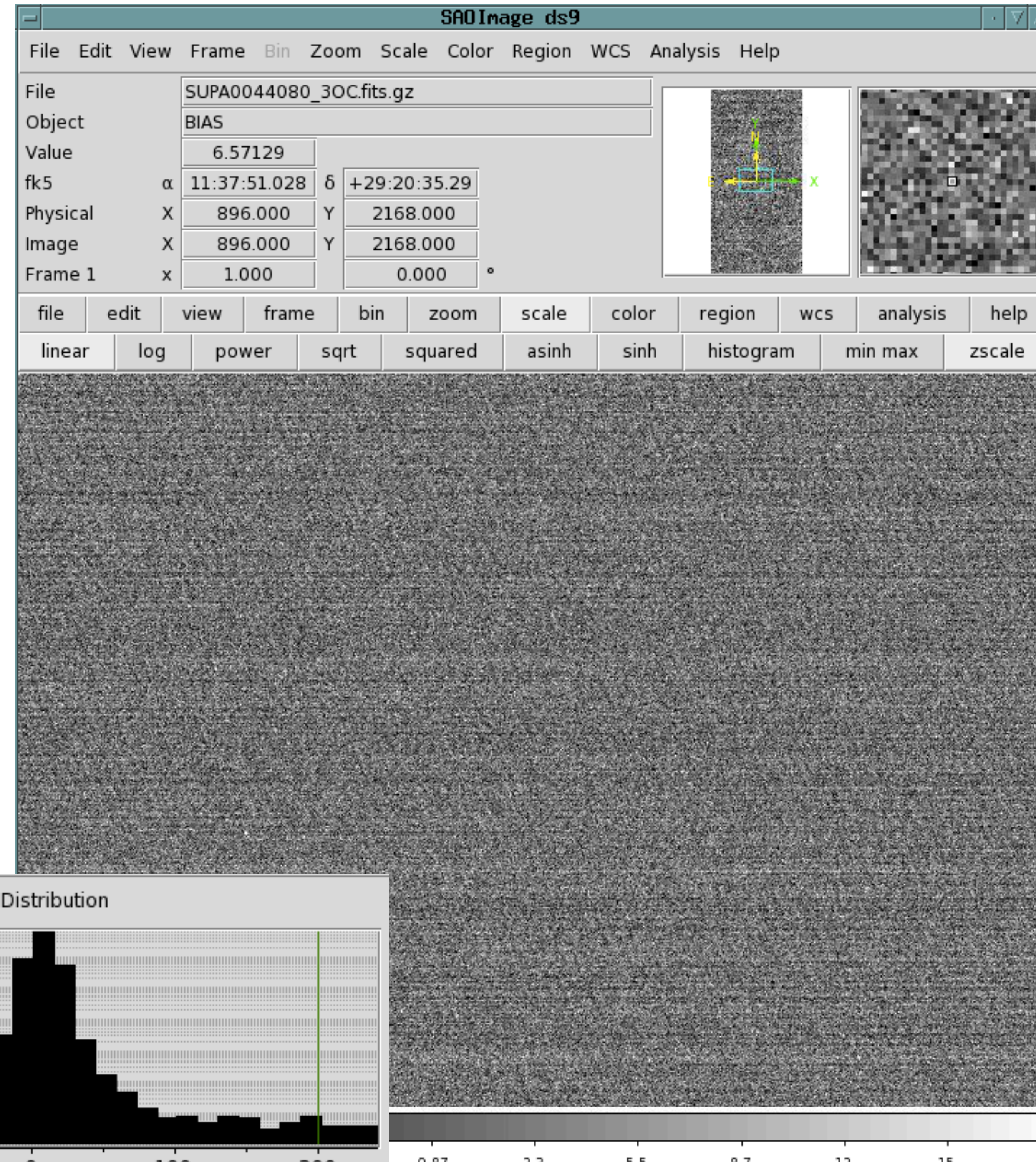
- note: the bias level is not a "counting process", i.e. the standard deviation of the bias values is NOT sqrt(N_{cts}[bias])

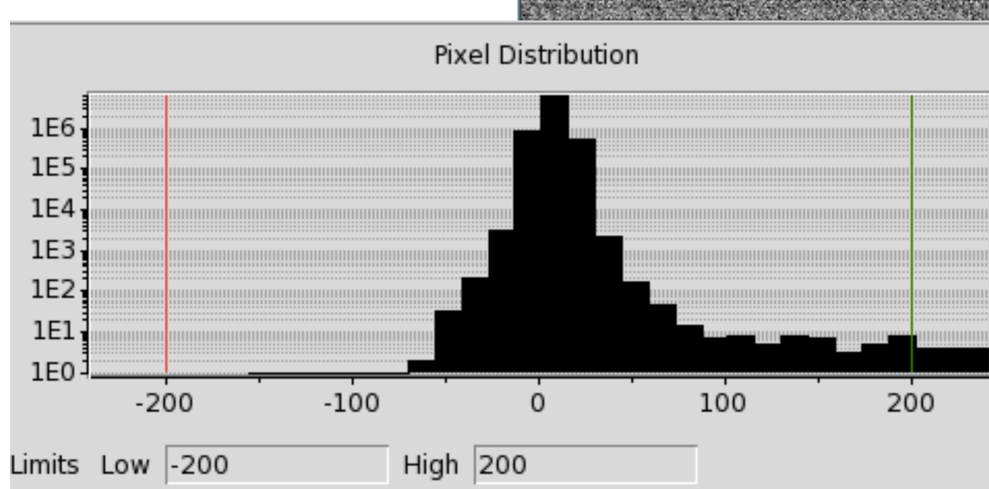
Overscan region

- 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)

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





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

A. von der Linden

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 frames

- dark frame: images taken with closed shutter
- similar to bias frames; need to be subtracted
- (subtracting non-bias corrected darks subtracts the bias, too)
- our cameras have no overscan and substantial dark current → we will use dark frames instead of bias frames
- *Q: What temperature and exposure time do the dark frames have to have?*

Flat-field

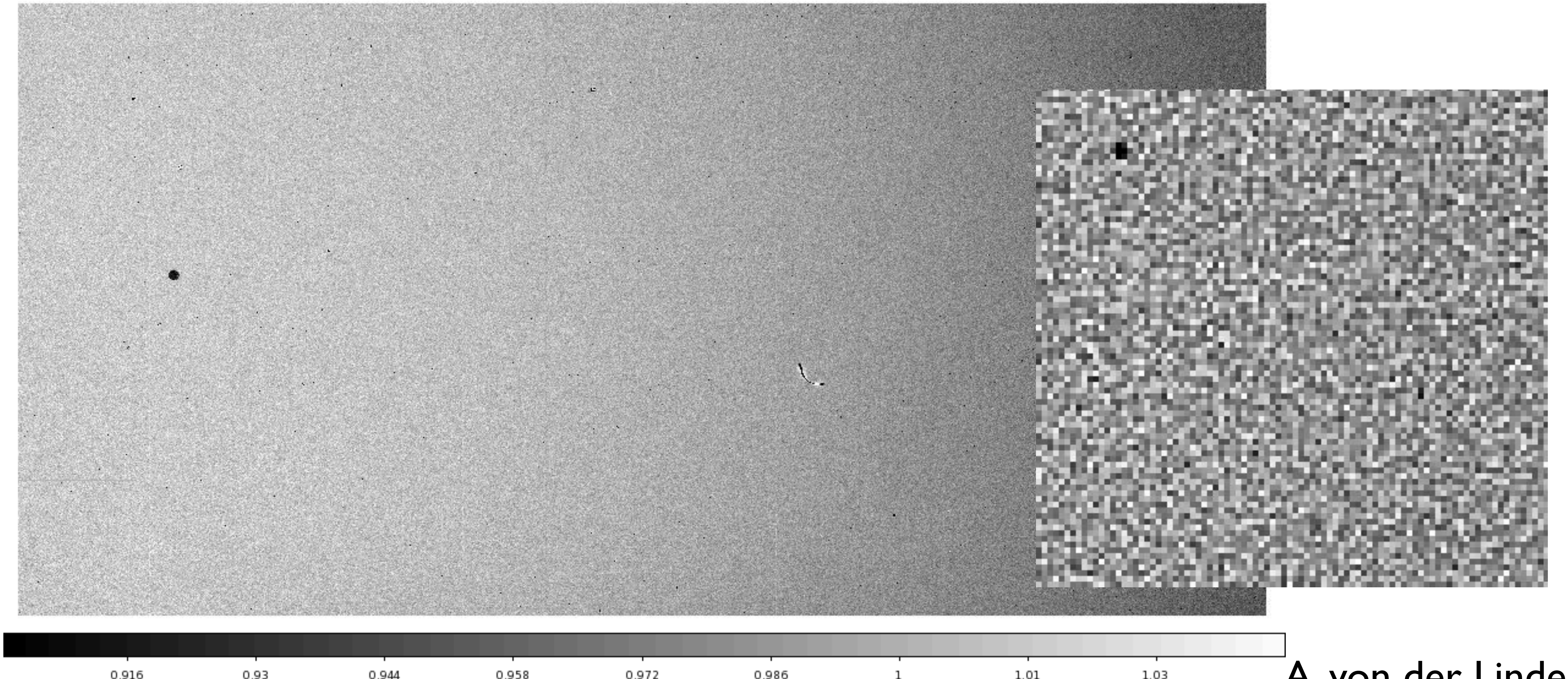
- the pixels in a CCD do *not* have uniform sensitivity
- due to variations in silicon crystal, electric field, pixel size, illumination (vignetting)

$$N_{\mathrm{electrons}} \; = \; A_{ij} \; N_{\mathrm{photons}}$$

- 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 sensitivies



A. von der Linden

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), or dark frame
- 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

A. von der Linden

Types of flat fields

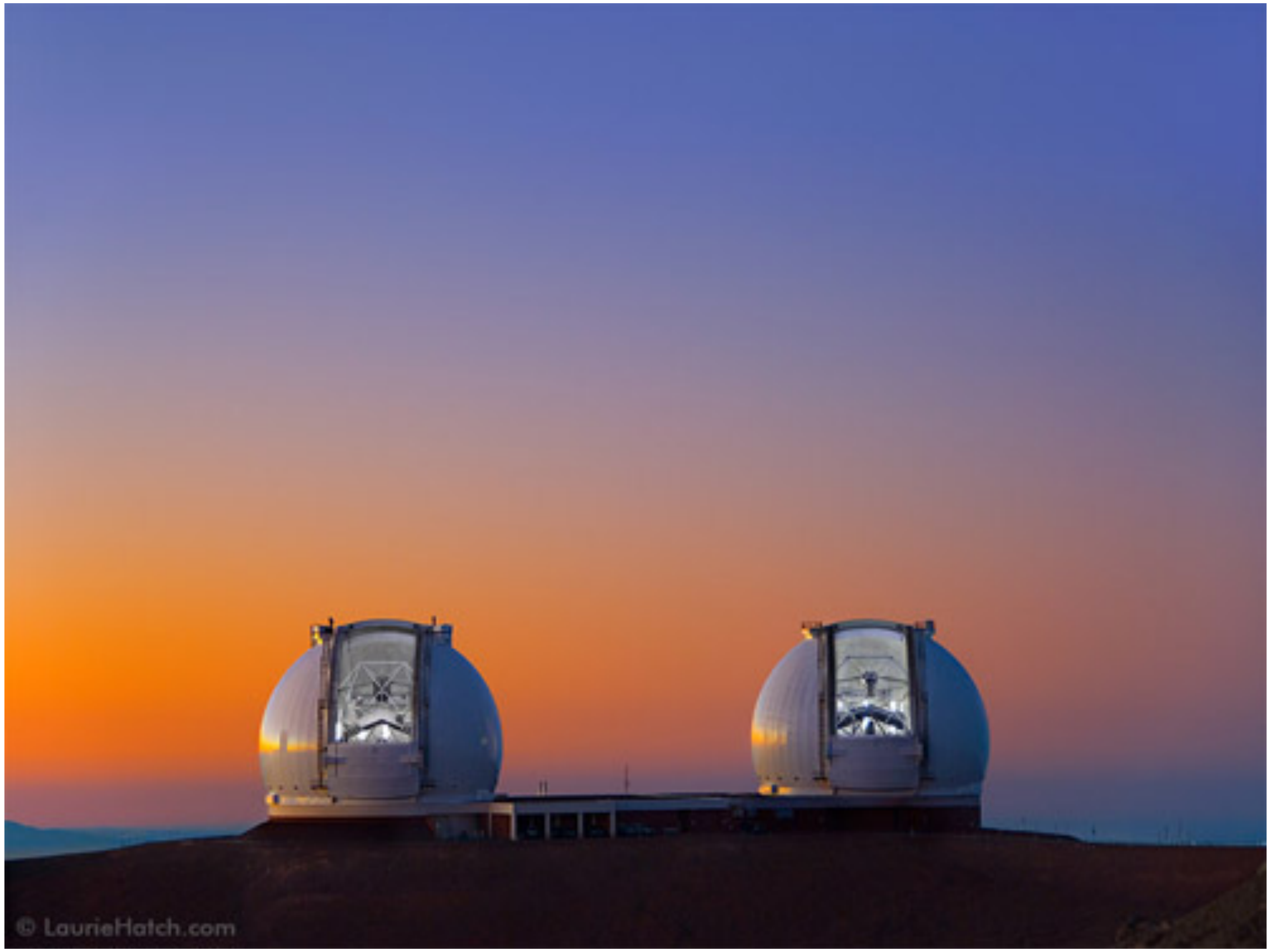
twilight flats:

✓ same "source"

✓ almost uniform

– variable

– difficult



L. Hatch

Types of flat fields

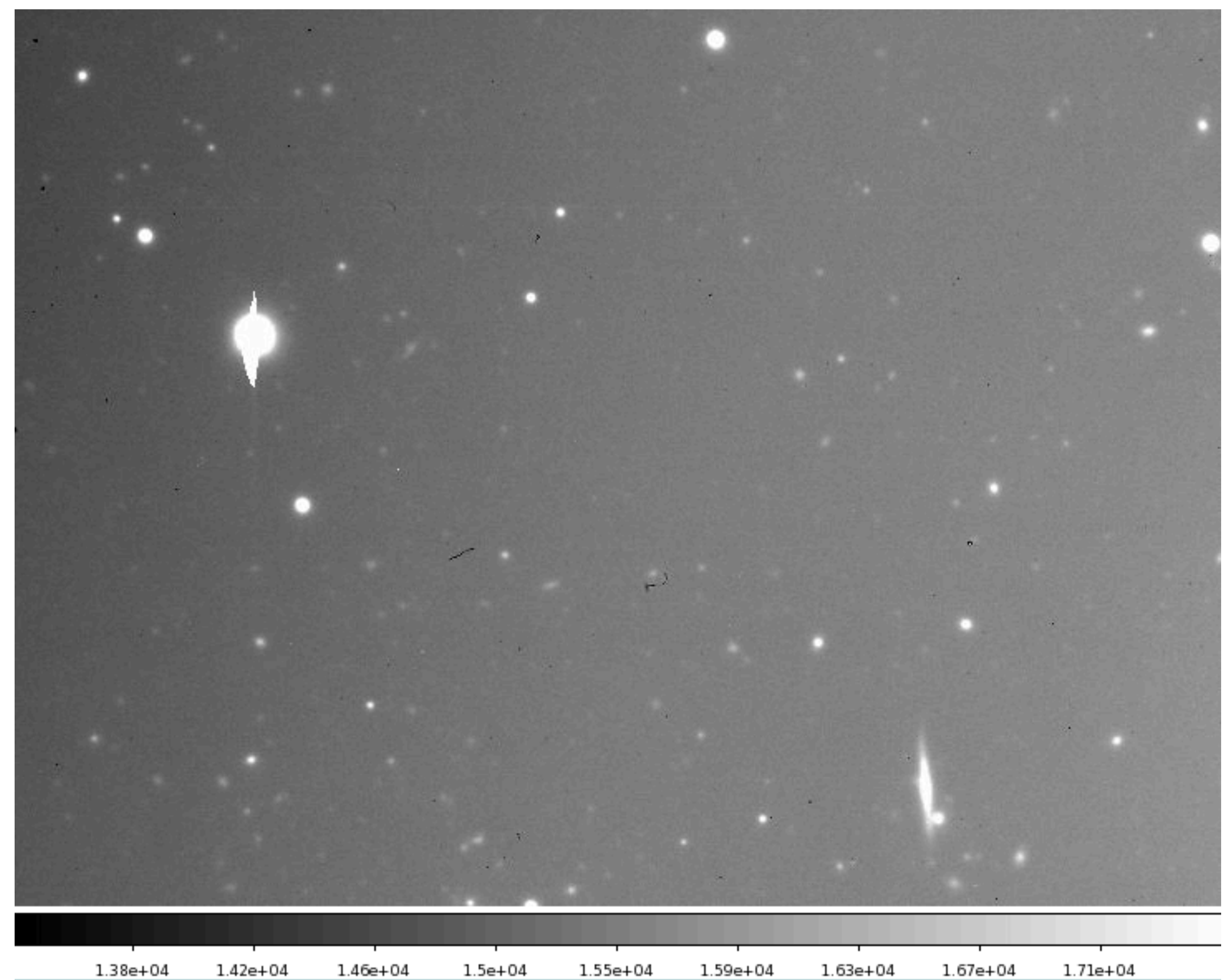
night-sky flats: if observations of several different targets are taken in one night, can average these images into flat-fields assembled from the sky background (best to mask out detected objects)

✓ most similar to data

✓ uniform

– need "empty" fields

– need a lot of images



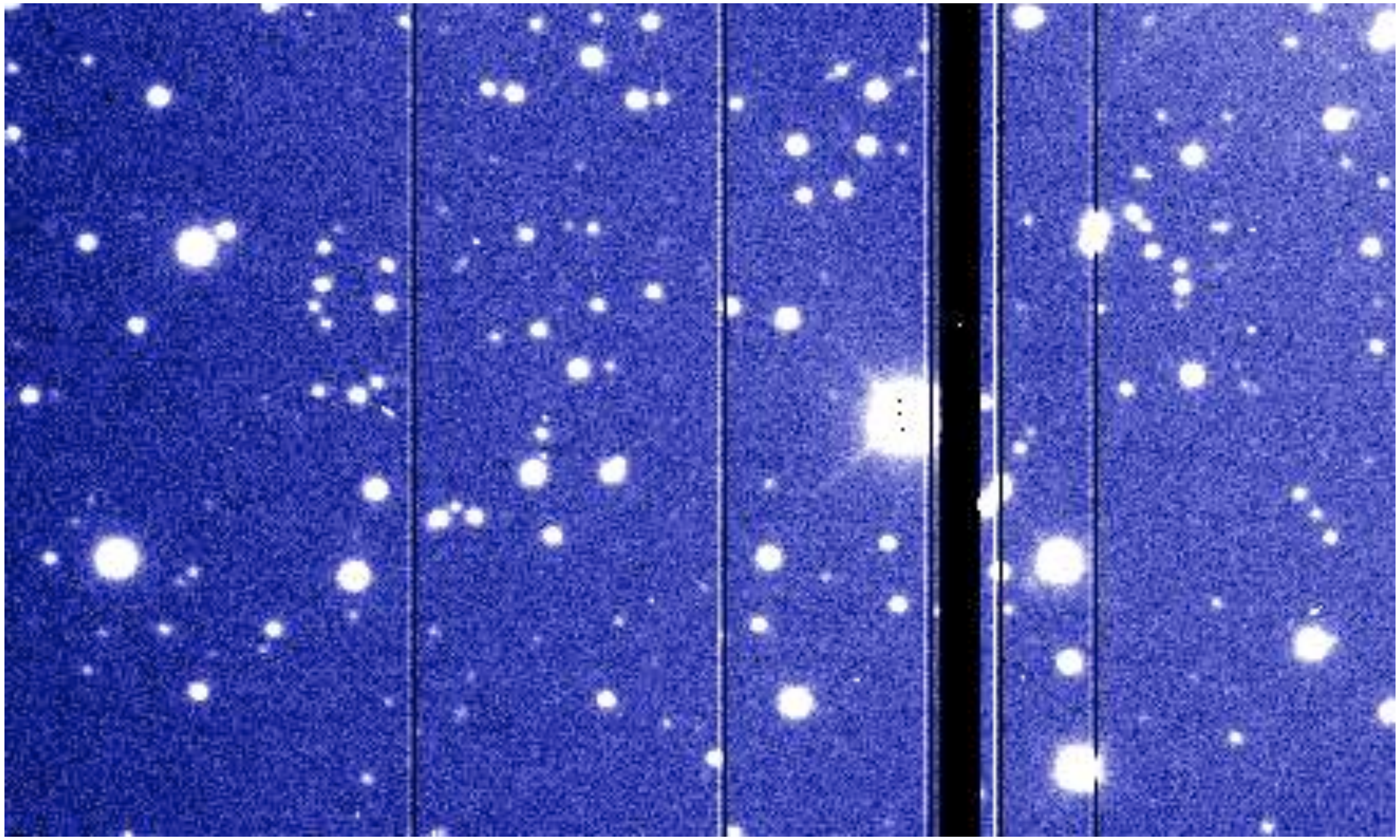
A. von der Linden

Artefacts

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

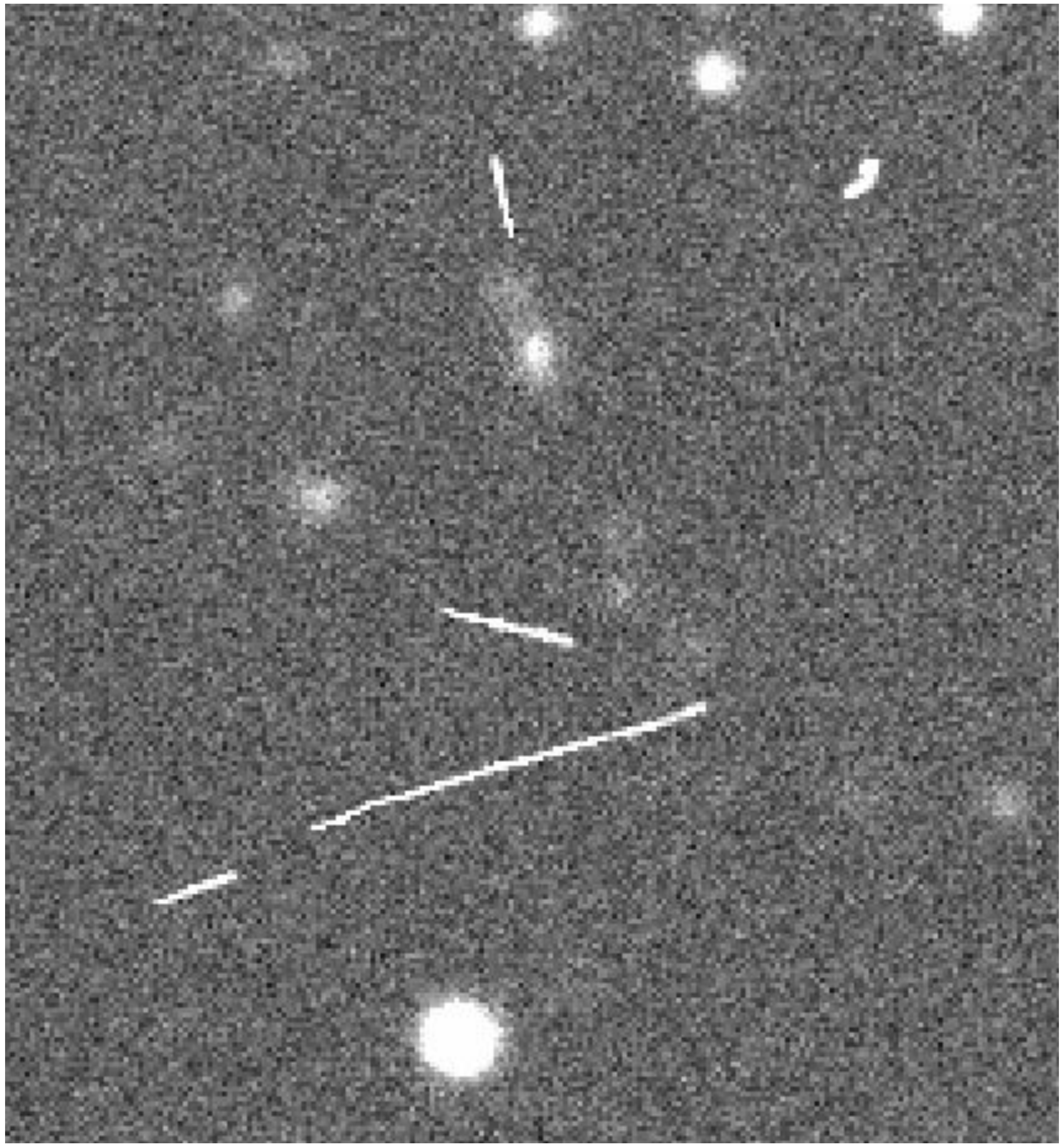


ESO

Artefacts

cosmic rays: charged particles hit the CCD

need to be masked - single exposure

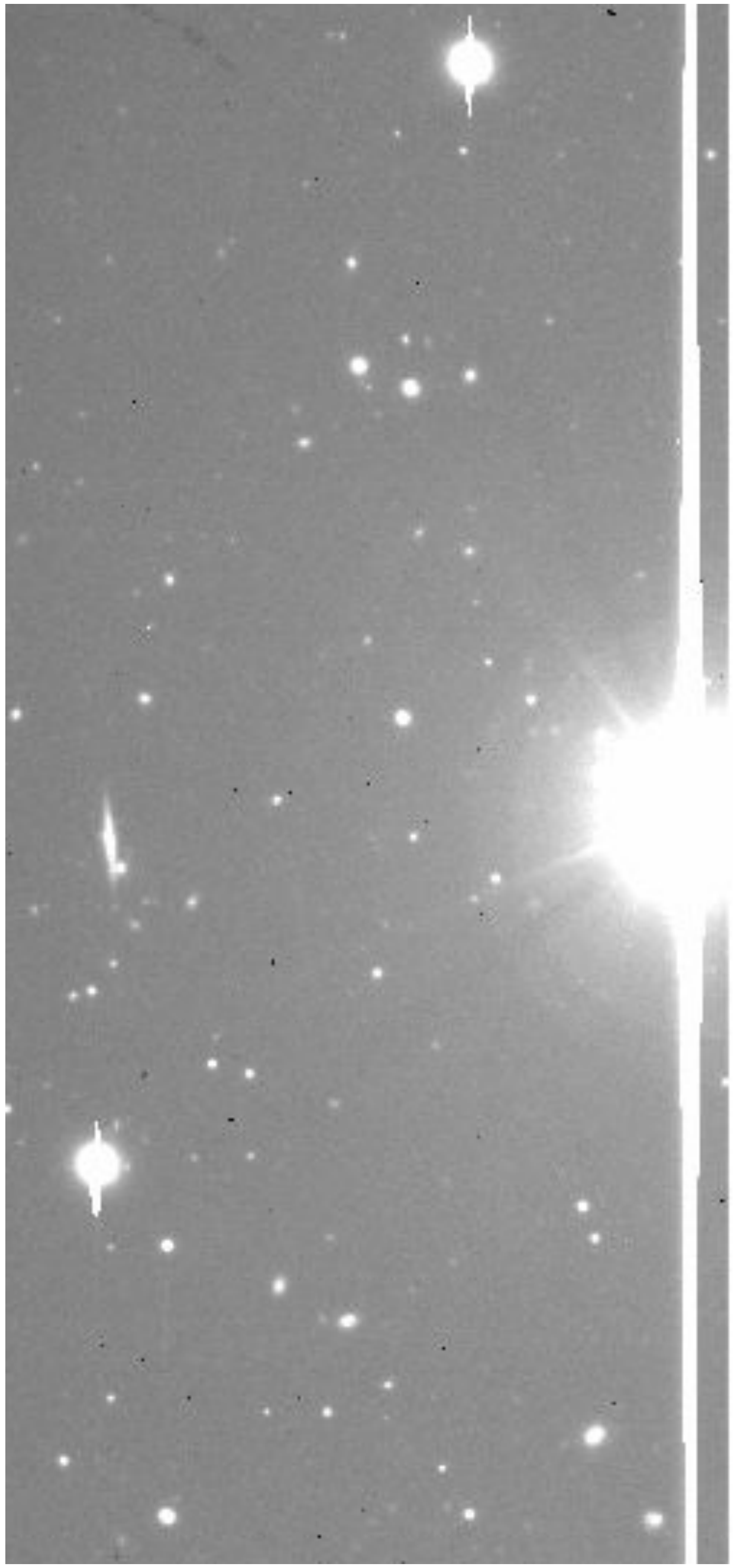


A. von der Linden

Artefacts

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

need to be masked - single exposure

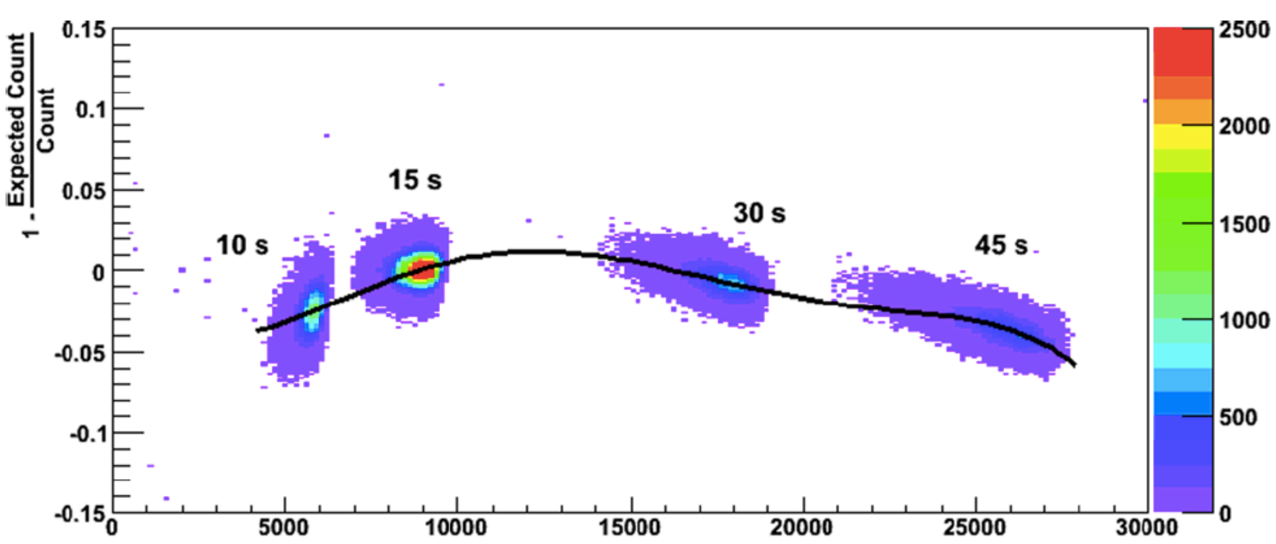


A. von der Linden

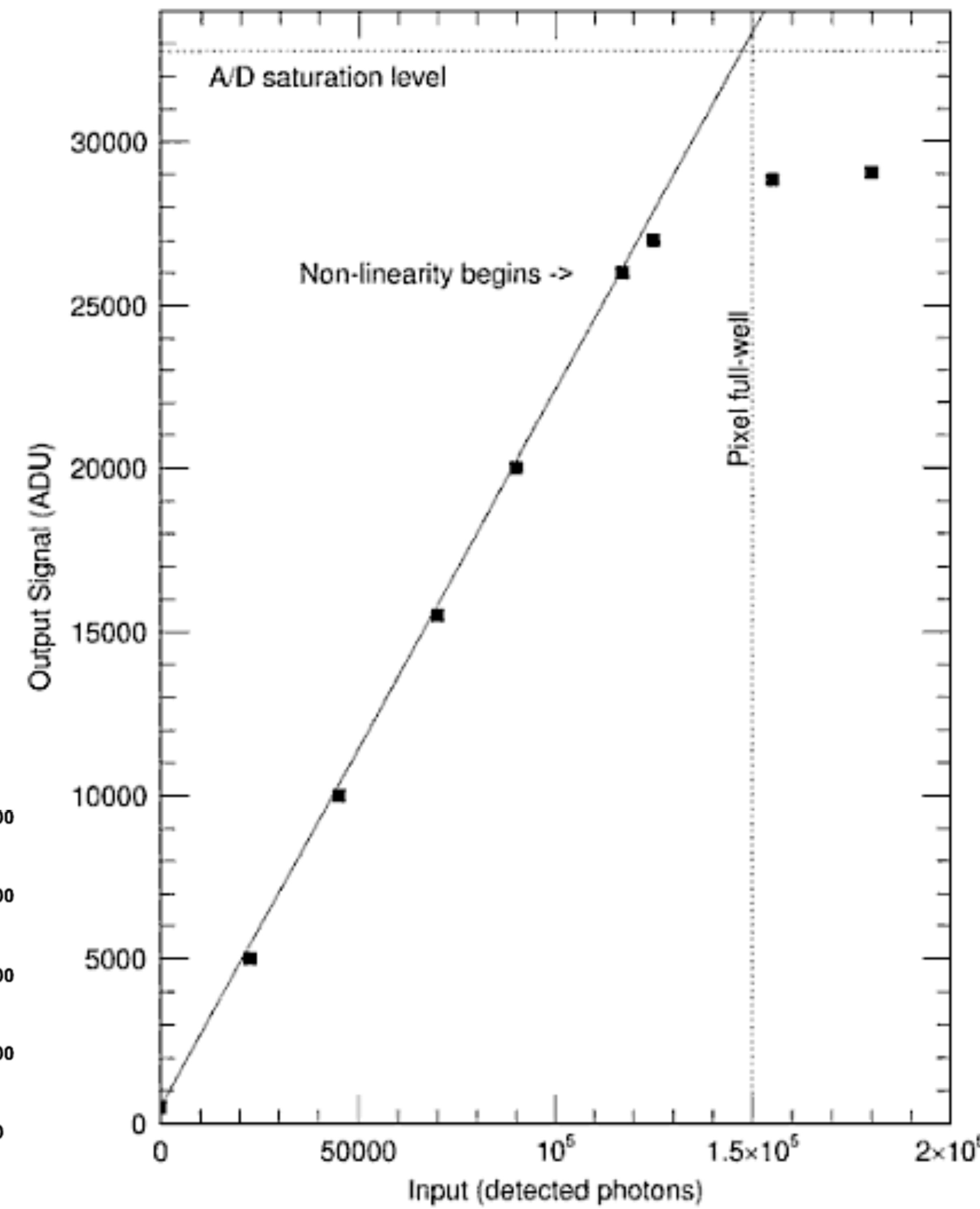
Artefacts

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

can be measured from dome-flats



von der Linden et al., 2014a



Howell, *Handbook of CCD Astronomy*

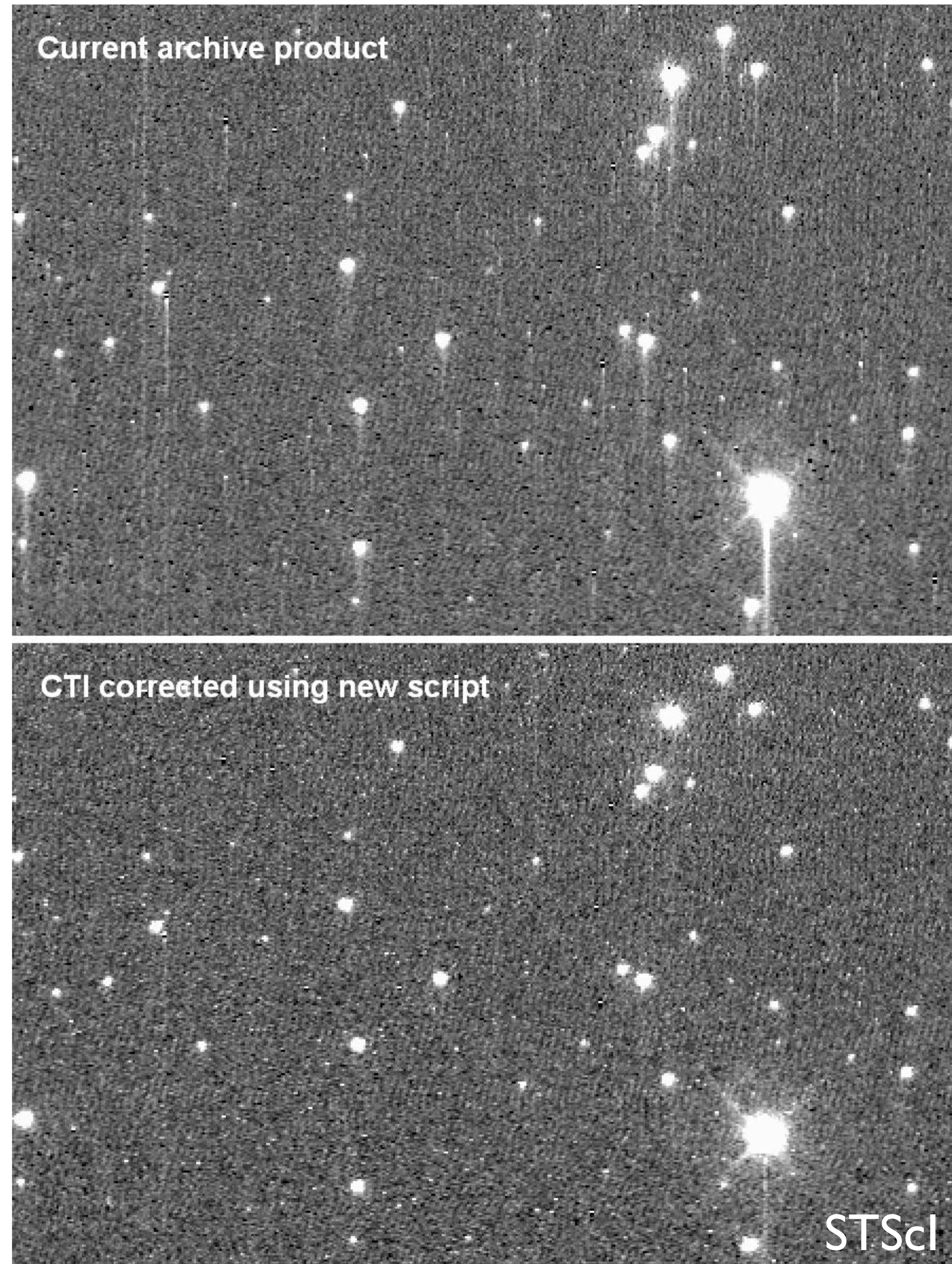
Artefacts

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

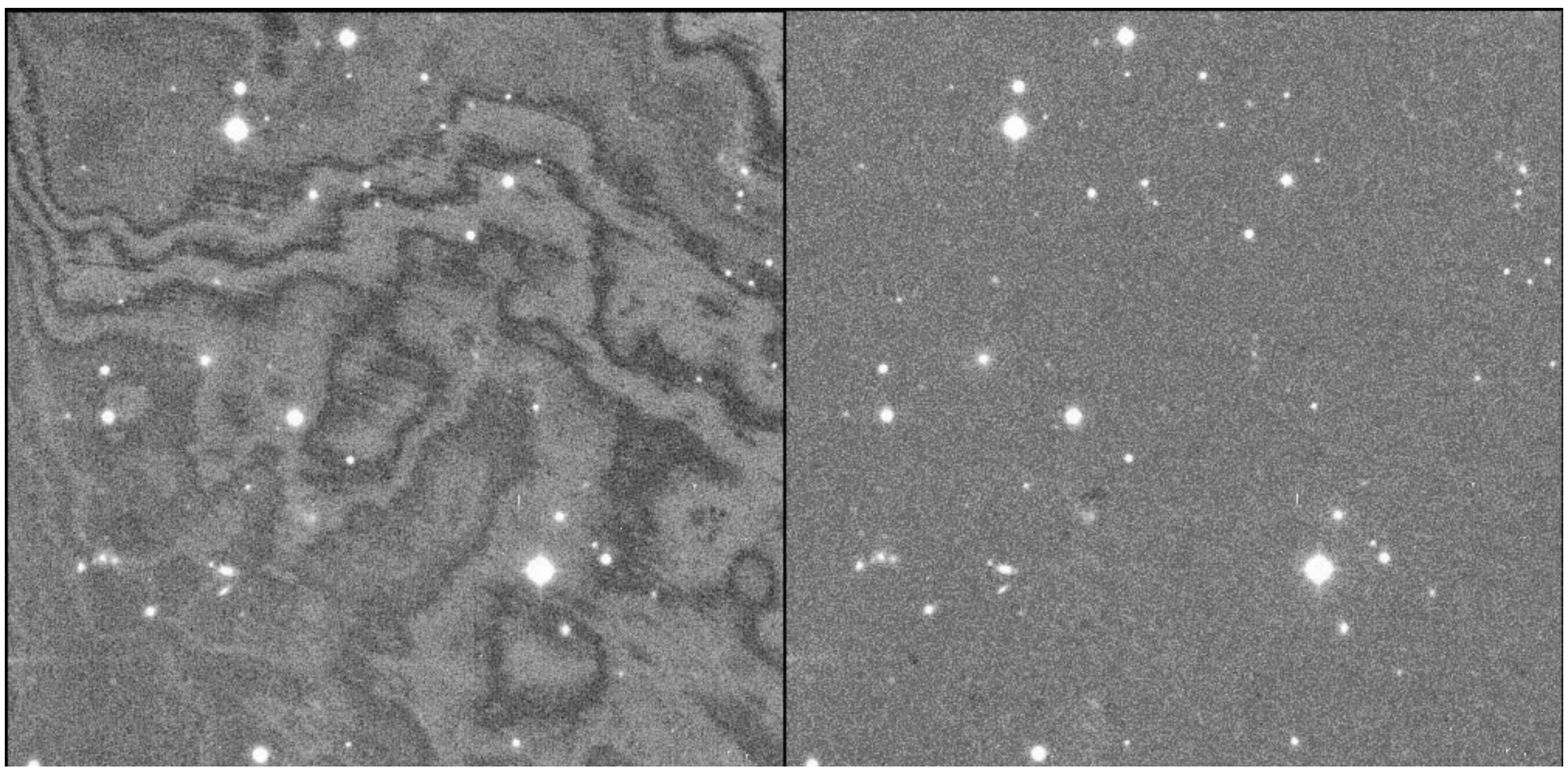
correction based on re-distributing charge



Artefacts

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

fringing increases with wavelength, and decreases with thickness of CCDs



M. Schirmer

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:

Table 5.1: Mandatory keywords for primary header.

1	SIMPLE
2	BITPIX
3	NAXIS
4	NAXISn, n = 1, ..., NAXIS
	(other keywords)
last	END

Conforms to standard:
T(rue) / F(alse)

Bits per pixel:
16: integer
32: float

Number of axes:
2d image -> 2

Image dimensions

End of header

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
APTAREA = +0.00000000000E+000
```

How big is the image (pixels by pixels)?

Example

Images from our CCD camera:

```
APTAREA = +0.000000000000E+000
APTDIA  = +3.560000000000E+002
TELESCOP= 'Meade LX200            '
OBSERVER= '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= -5.000000000000E+000
COLORCCD=                       0
DISPCOLR=                       1
IMAGETYP= 'Light Frame            '
CCDSEPT =                       1
```

```
OBSTDVER= 'SBFITSEXT Version 1.0'
FILTER  = 'Visual                 '
EXPTIME = +1.000000000000E+001
EXPOSURE= +1.000000000000E+001
     CK =                     342
     TE =                     447
```

```
EXPSTATE=                     255
CCD-TEMP= -5.232156845990E+000
TEMPERAT= -5.232156845990E+000
INSTRUME= 'SBIG STL-1001 3 CCD Camera'
EGAIN   = +2.060000000000E+000
E-GAIN  = +2.060000000000E+000
```

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)*:

$$\begin{pmatrix} \alpha - \mathrm{CRVAL1} \\ \delta - \mathrm{CRVAL2} \end{pmatrix} = \begin{pmatrix} \mathrm{CD1\_1} & \mathrm{CD1\_2} \\ \mathrm{CD2\_1} & \mathrm{CD2\_2} \end{pmatrix} \begin{pmatrix} x - \mathrm{CRPIX1} \\ y - \mathrm{CRPIX2} \end{pmatrix}$$

Specifying coordinates

After astrometric calibration:

```
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
```

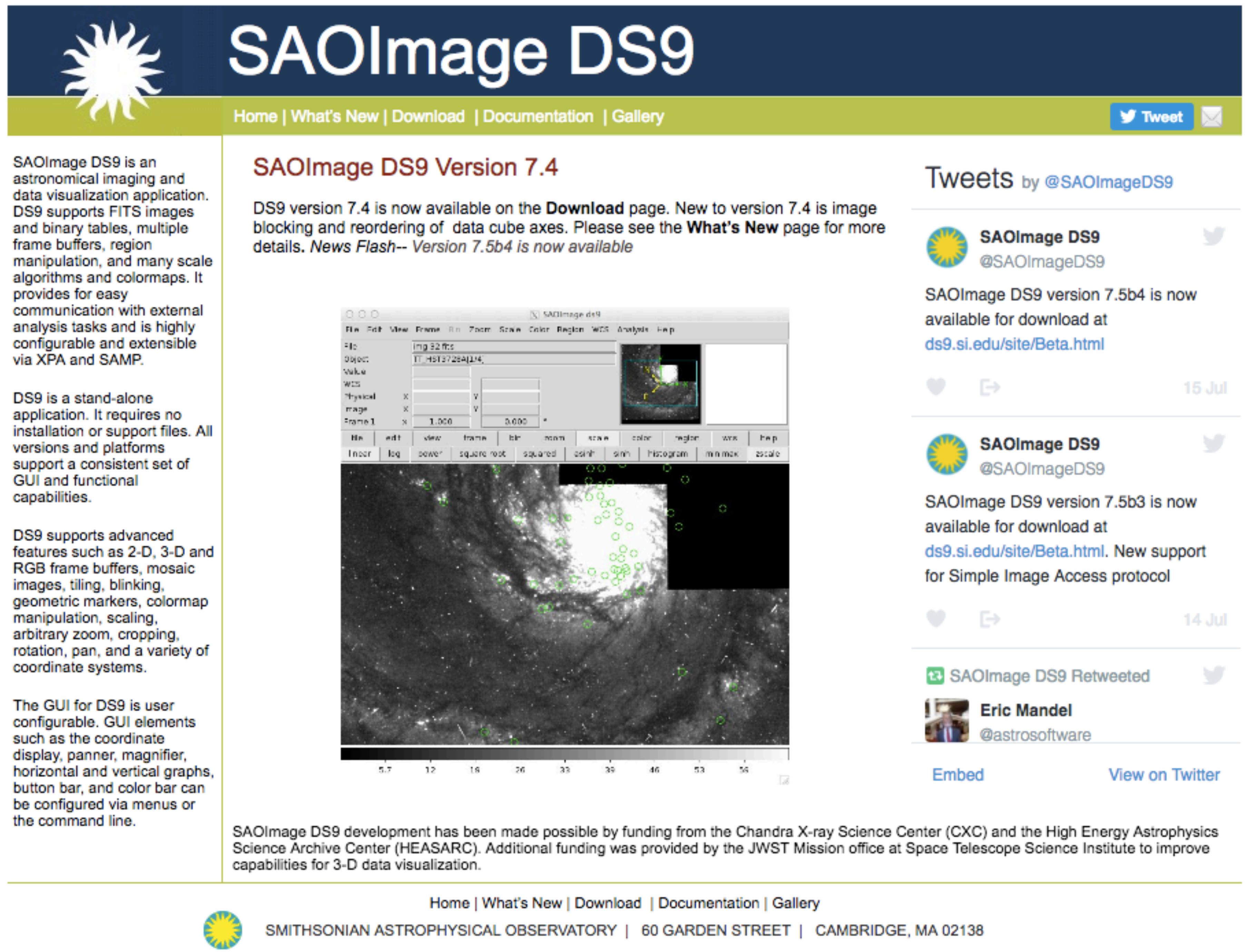
Our camera does not know where the telescope is pointing
- astrometric calibration is important e.g. for Lab 1

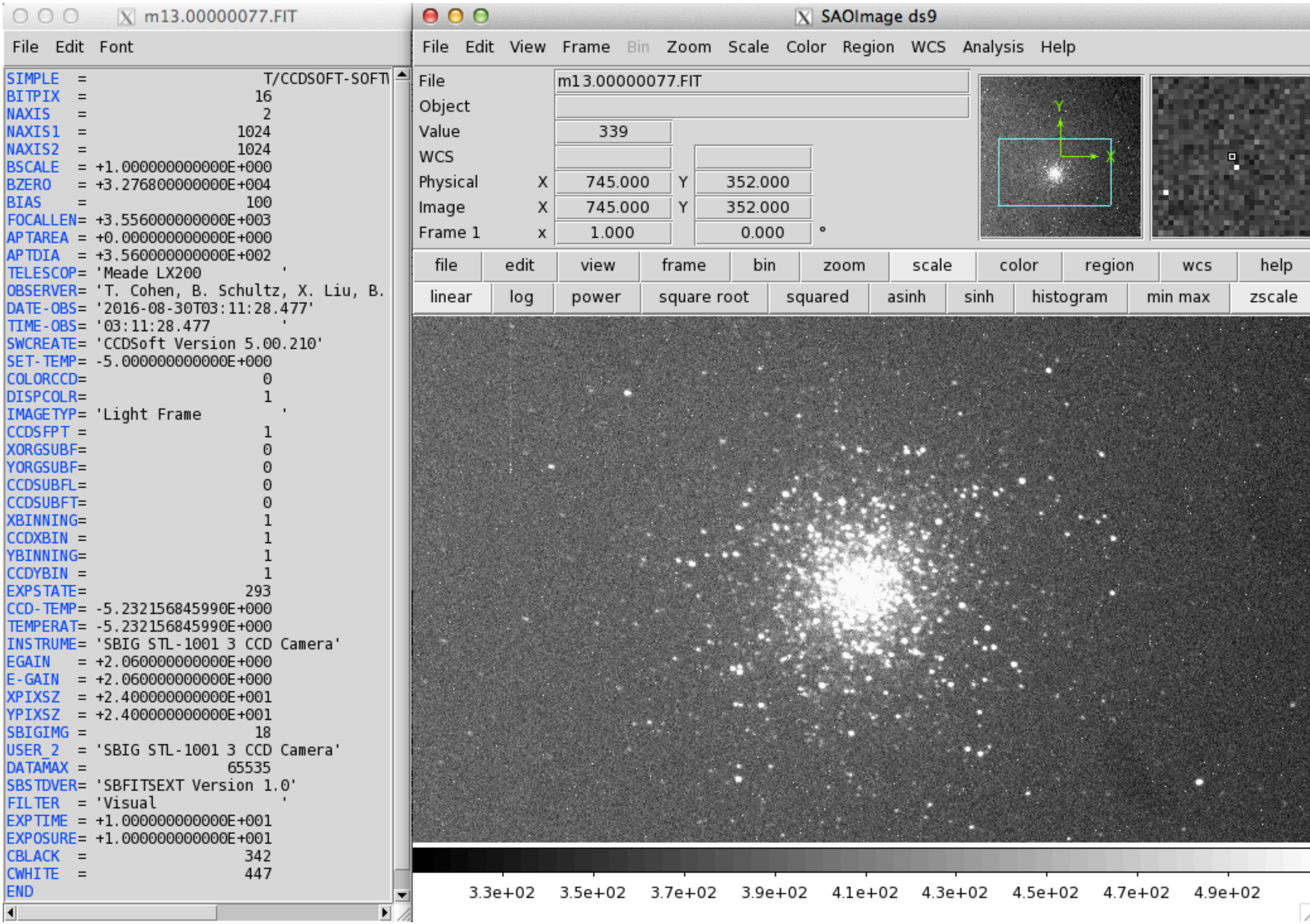
Viewing FITS images

best done with specialized software

e.g. ds9 (by Smithsonian Observatory)

http://ds9.si.edu




m13.00000077.FIT
File Edit Font
SIMPLE = T/CCDSOFT-SOFT
BITPIX = 16
NAXIS = 2
NAXIS1 = 1024
NAXIS2 = 1024
BSCALE = +1.000000000000E+000
BZERO = +3.276800000000E+004
BIAS = 100
FOCALLEN= +3.556000000000E+003
APTAREA = +0.000000000000E+000
APTDIA = +3.560000000000E+002
TELESCOP= 'Meade LX200 '
OBSERVER= 'T. Cohen, B. Schultz, X. Liu, B.
DATE-OBS= '2016-08-30T03:11:28.477'
TIME-OBS= '03:11:28.477 '
SWCREATE= 'CCDSoft Version 5.00.210'
SET-TEMP= -5.000000000000E+000
COLORCCD= 0
DISPCOLR= 1
IMAGETYP= 'Light Frame '
CCDSFPT = 1
XORGSUBF= 0
YORGSUBF= 0
CCDSUBFL= 0
CCDSUBFT= 0
XBINNING= 1
CCDXBIN = 1
YBINNING= 1
CCDYBIN = 1
EXPSTATE= 293
CCD-TEMP= -5.232156845990E+000
TEMPERAT= -5.232156845990E+000
INSTRUME= 'SBIG STL-1001 3 CCD Camera'
EGAIN = +2.060000000000E+000
E-GAIN = +2.060000000000E+000
XPIXSZ = +2.400000000000E+001
YPIXSZ = +2.400000000000E+001
SBIGIMG = 18
USER_2 = 'SBIG STL-1001 3 CCD Camera'
DATAMAX = 65535
SBSTDVER= 'SBFITSEXT Version 1.0'
FILTER = 'Visual '
EXPTIME = +1.000000000000E+001
EXPOSURE= +1.000000000000E+001
CBLACK = 342
CWHITE = 447
END
SAOImage ds9
File Edit View Frame Bin Zoom Scale Color Region WCS Analysis Help
File m13.00000077.FIT
Object
Value 339
WCS
Physical X 745.000 Y 352.000
Image X 745.000 Y 352.000
Frame 1 x 1.000 0.000 °
file edit view frame bin zoom scale color region wcs help
linear log power square root squared asinh sinh histogram min max zscale
3.3e+02 3.5e+02 3.7e+02 3.9e+02 4.1e+02 4.3e+02 4.5e+02 4.7e+02 4.9e+02

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
BSCALE  = +1.000000000000E+000
```

```
[anja@ki-ls08 test_data]$ dfits *.DARK.FIT | fitsort EXPTIME CCD-TEMP
FILE                    EXPTIME                 CCD-TEMP
00000011.DARK.FIT       +1.000000000000E+001    -5.232156845990E+000
00000012.DARK.FIT       +2.000000000000E+001    -5.232156845990E+000
00000013.DARK.FIT       +4.000000000000E+001    -4.817803680962E+000
00000014.DARK.FIT       +8.000000000000E+001    -4.817803680962E+000
00000015.DARK.FIT       +1.600000000000E+002    -4.817803680962E+000
```

Viewing FITS headers

- if dfits and fitsort not available: use "fold" command

```
[anja@ki-ls08 test_data]$ fold 00000001.BIAS.FIT | more
SIMPLE  =                    T/CCDSOFT-SOFTWARE BISQUE 3
BITPIX  =                   16
NAXIS   =                    2
NAXIS1  =                 1024
NAXIS2  =                 1024
```

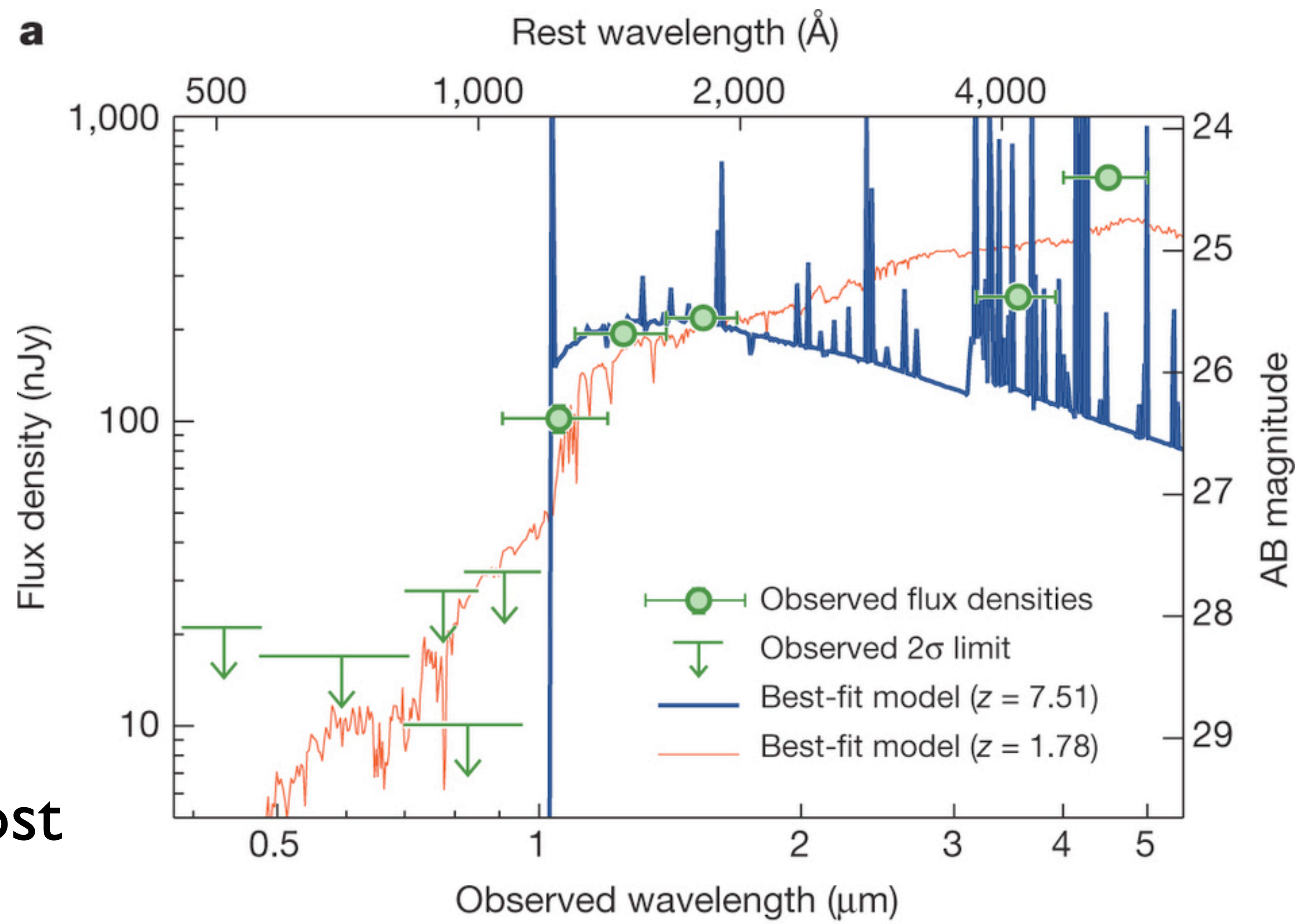
Spectroscopy

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



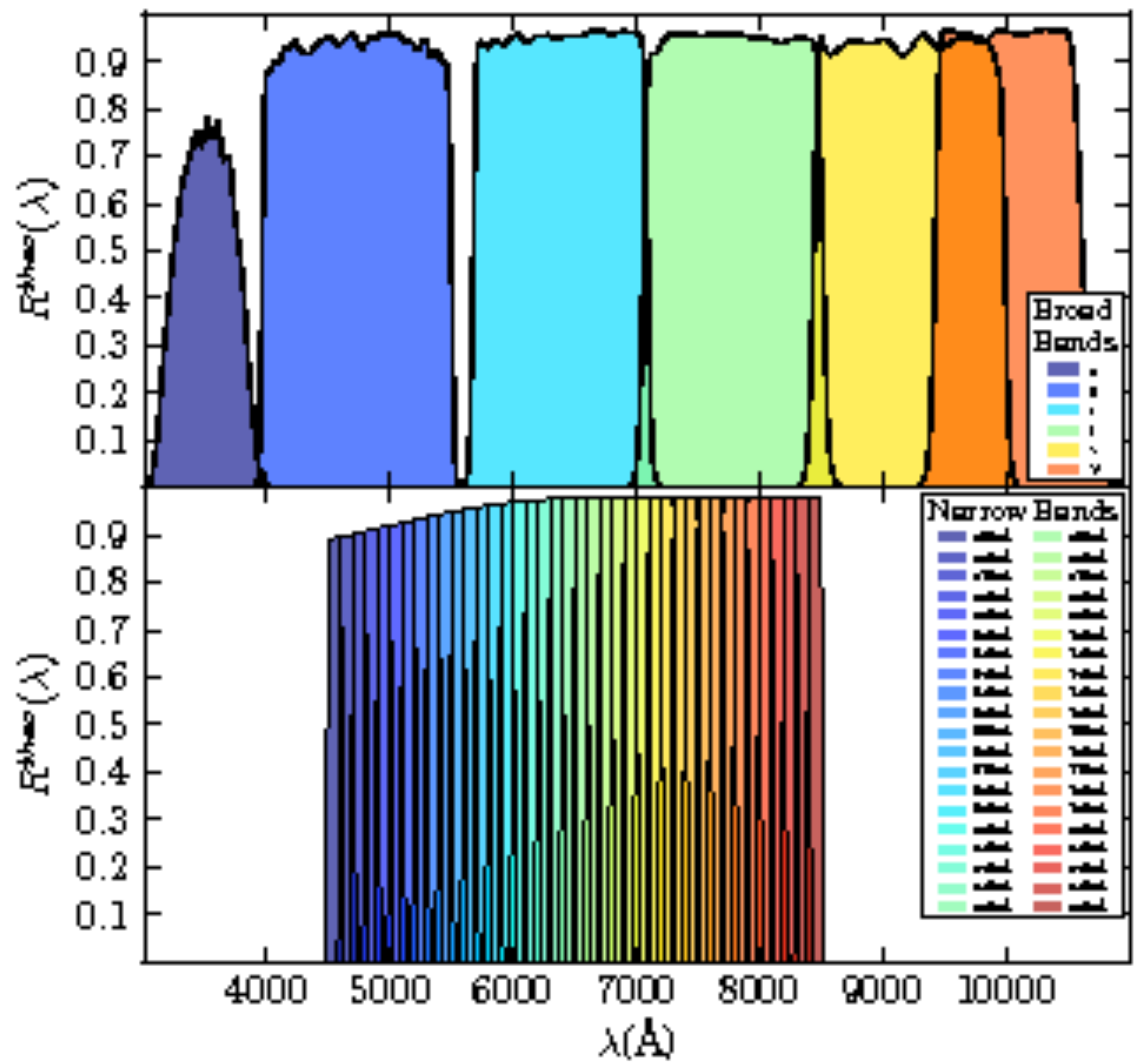
Finkelstein et al. 2013

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!

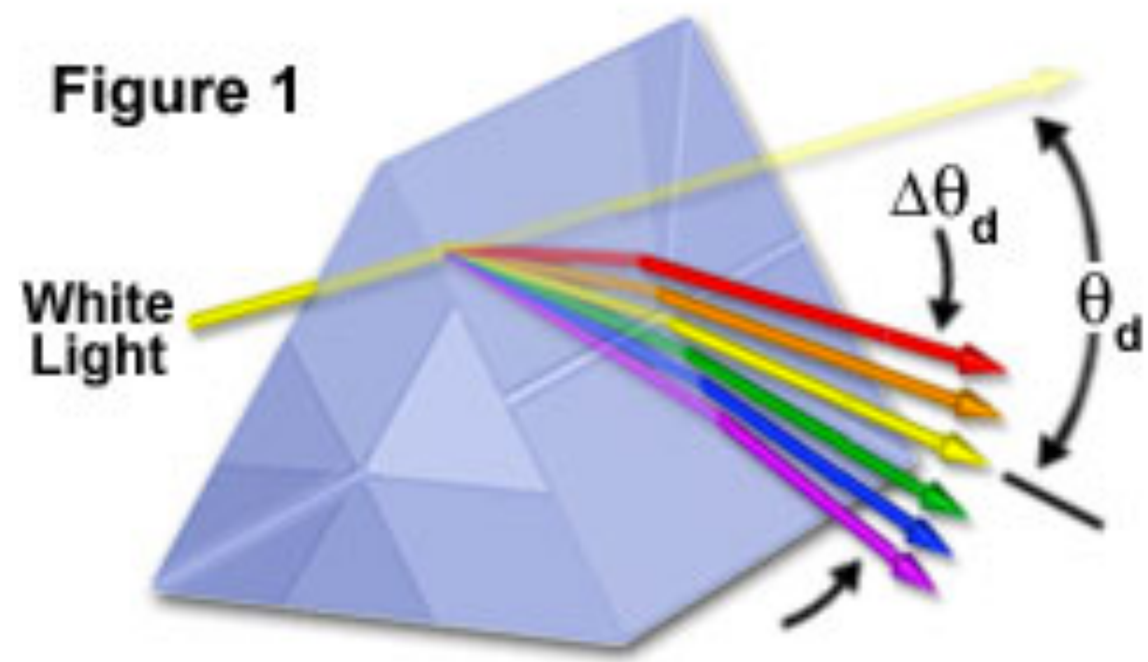


The PAU Survey

Spectroscopy

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

e.g. a prism:

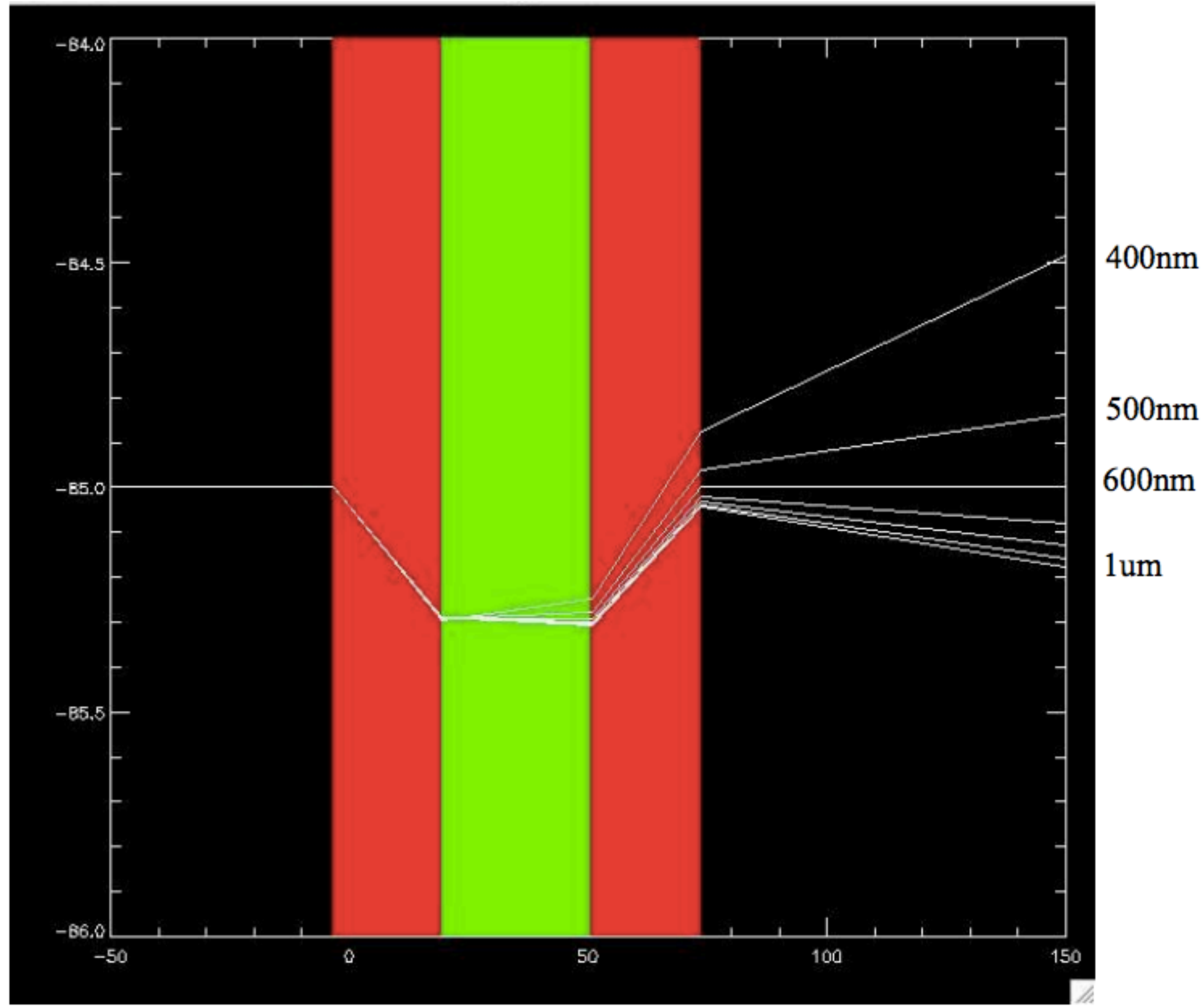


Olympus

Prism Spectroscopy

only few astronomical spectrographs use prisms

- low dispersion (resolution)
- dispersion varies with wavelength

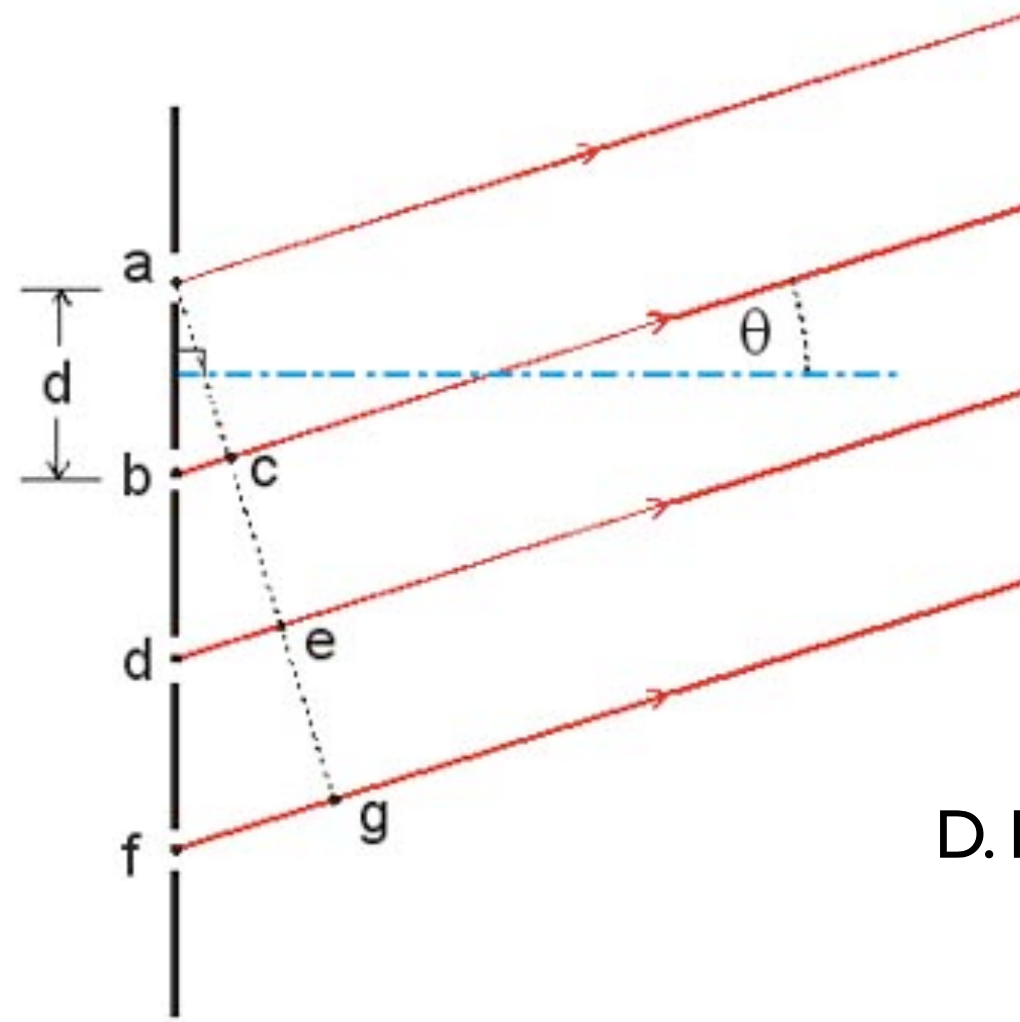


LDP Prism description

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

Diffraction gratings

make use of wave properties of light: interference



D. Pogosian

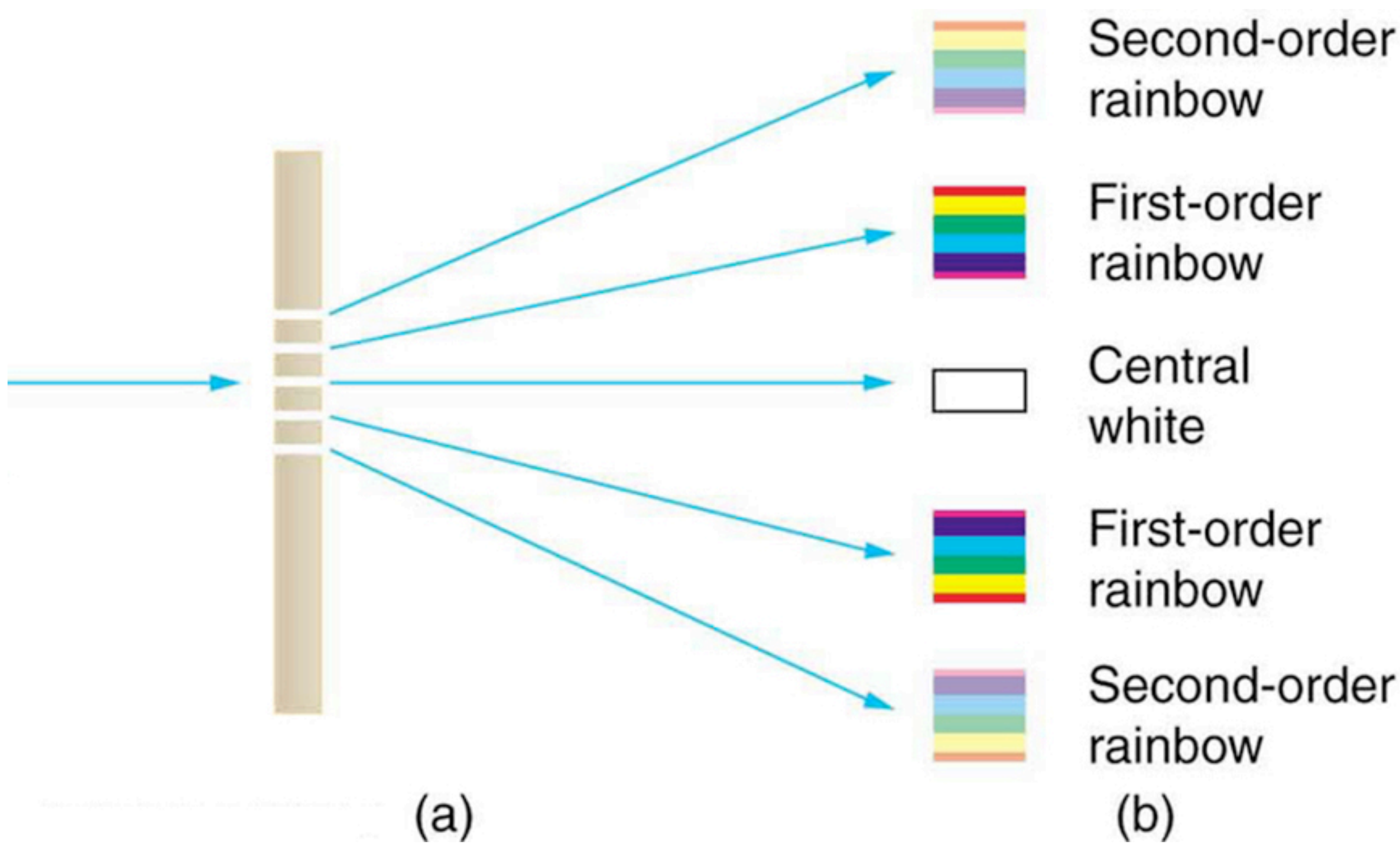
grating: many parallel lines (~500/mm)

similar to single-slit and double-slit experiments

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

position of *n*th order: $$n\lambda = d \sin\theta$$

Diffraction gratings

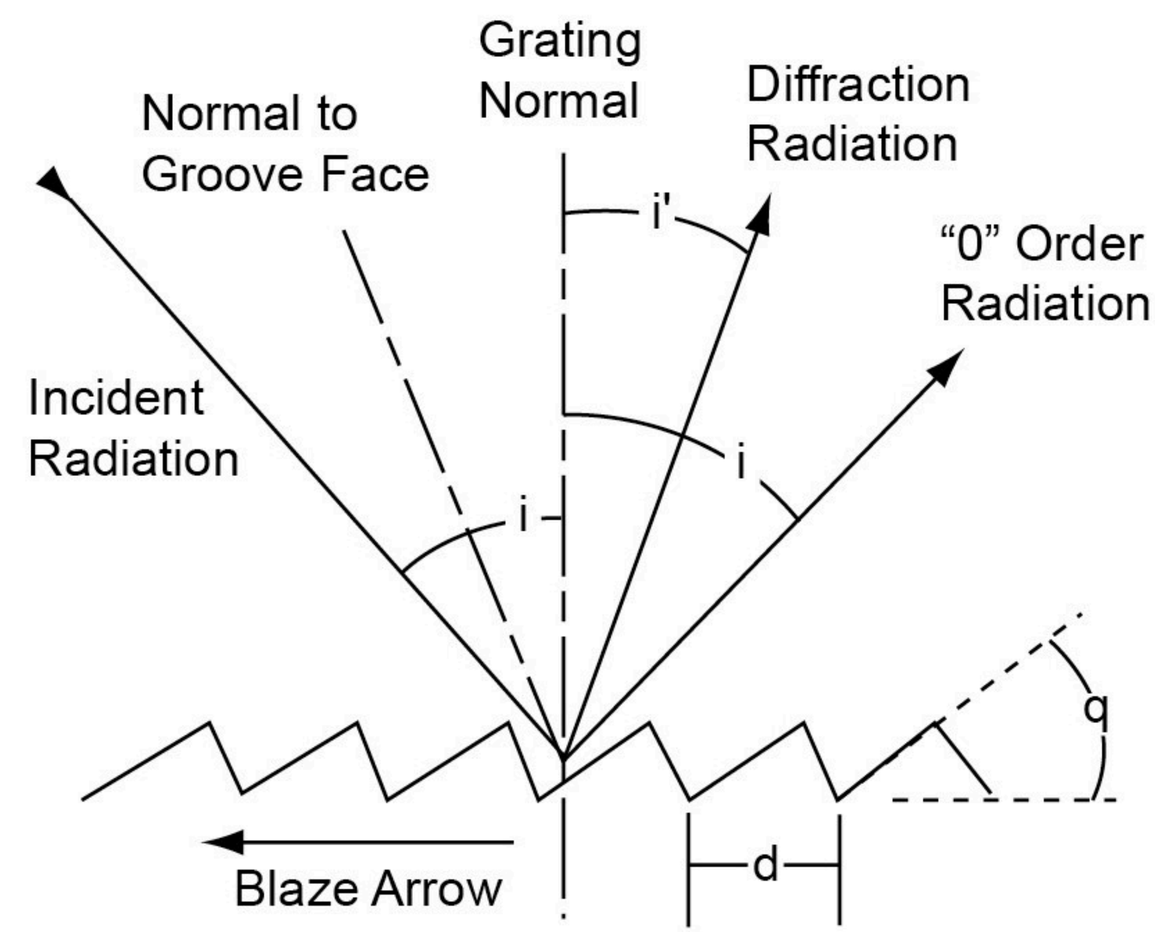


OpenStax University

Diffraction gratings

can be transmission gratings or reflection gratings

most astronomical spectrographs use reflection gratings



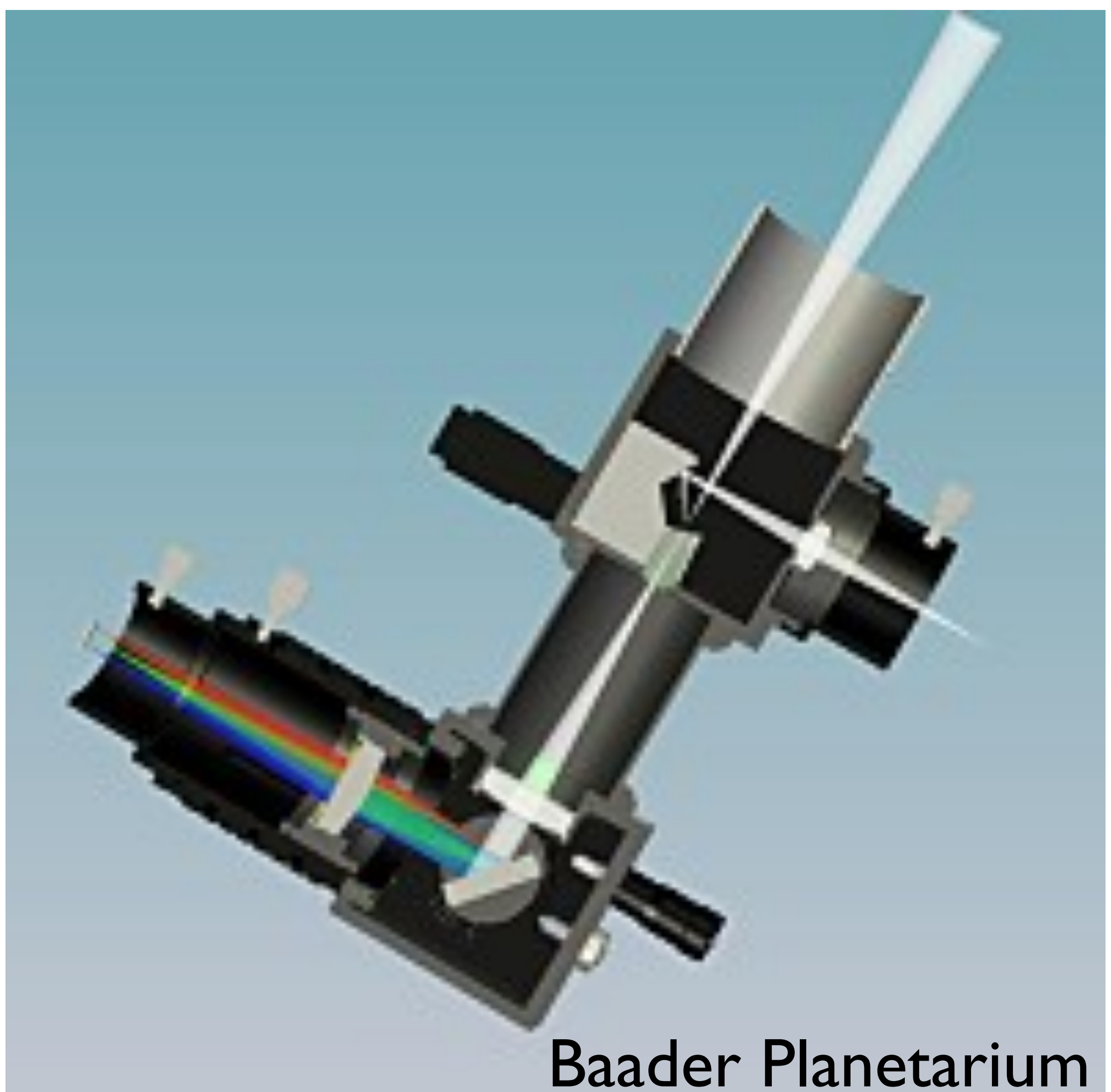
Dynasil Corp.

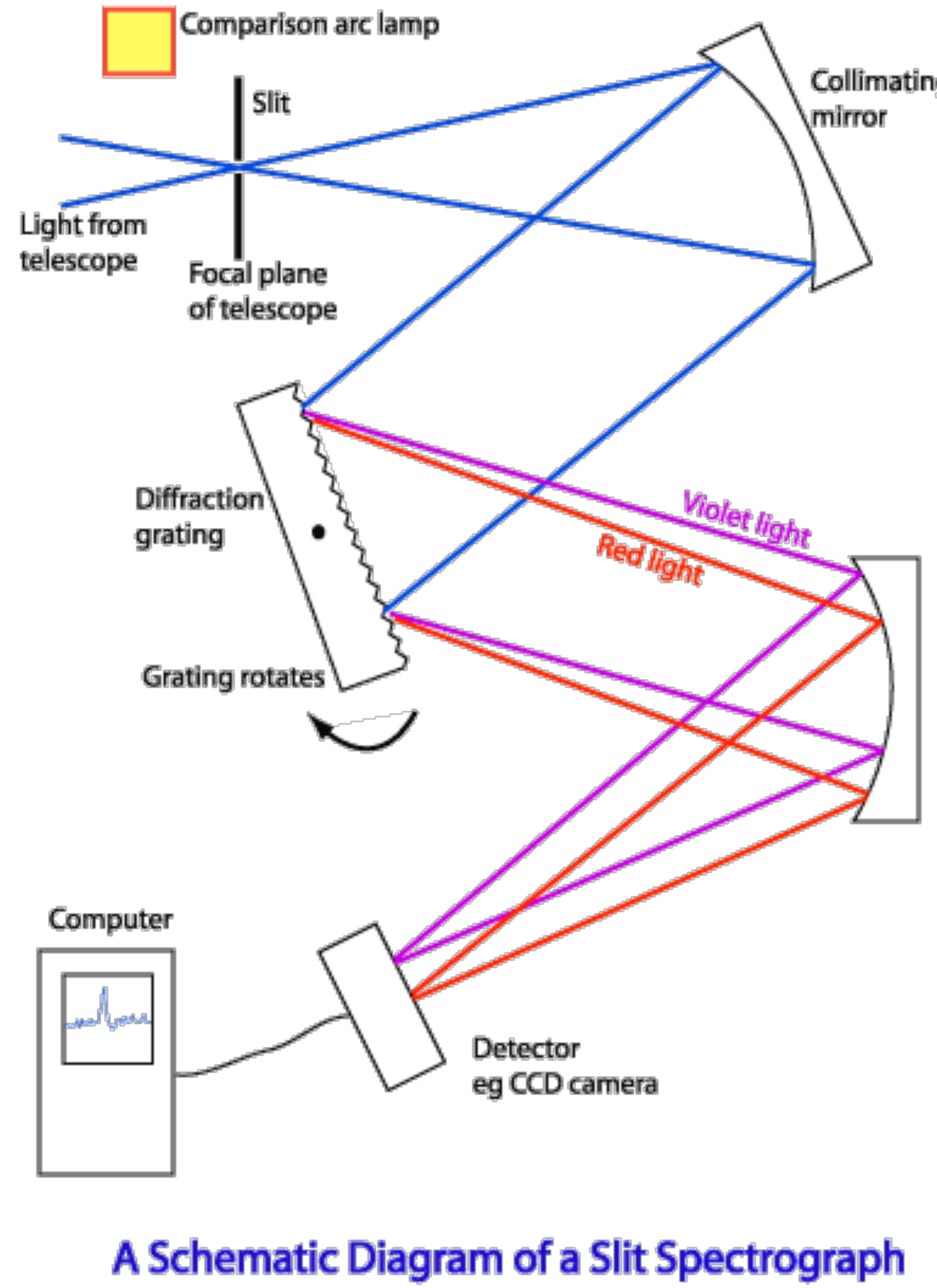
blaze wavelength: wavelength for direction of reflection coincides with desired spectral order
→ maximal efficiency

Typical spectrograph

entrance: usually a slit, similar to seeing size

collimator: converts a diverging beam to a parallel beam


Baader Planetarium



Kaler, *Stars and their Spectra*

Spectral Resolution

defined by smallest wavelength difference Δλ 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 Δλ

dispersion: length Δλ’ of spectrum over single pixel, [Å/px]

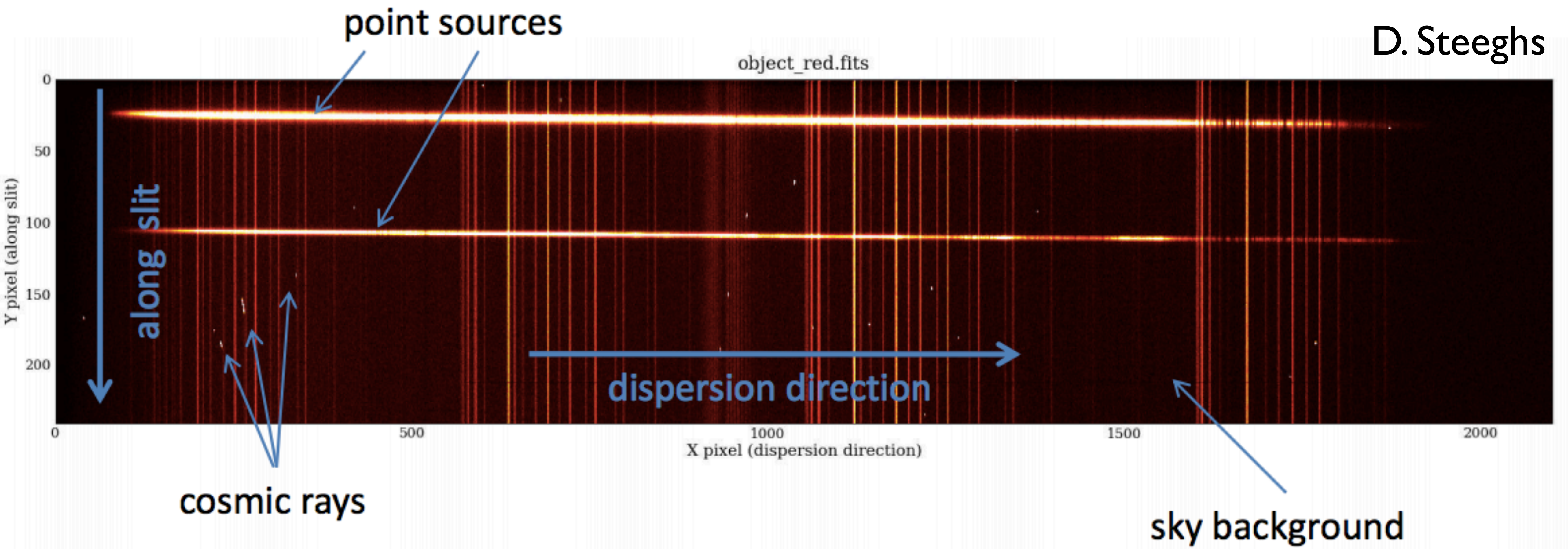
to properly sample the spectrum:

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

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



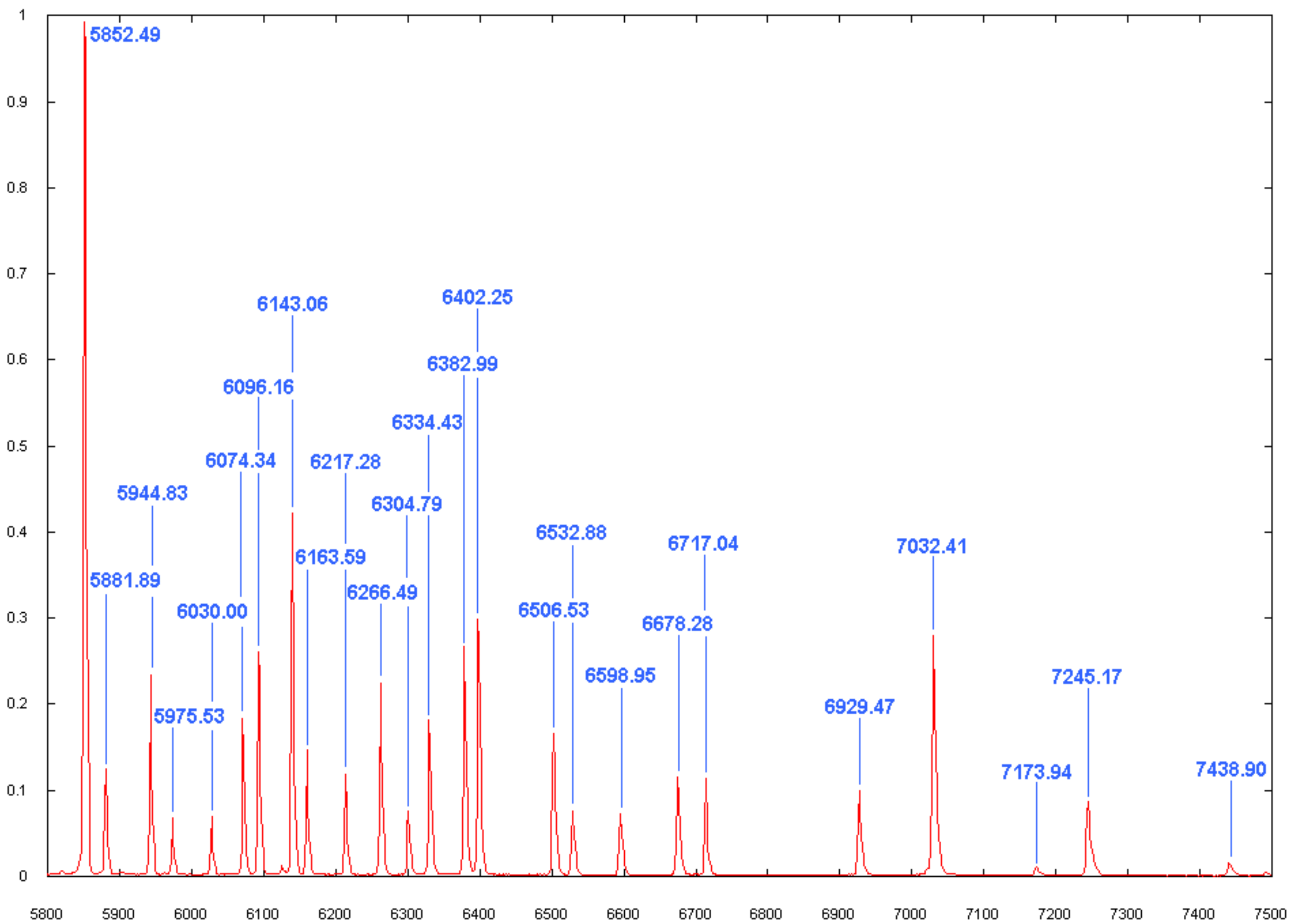
- long axis of CCD used to sample spectrum
- spatial information along slit still available: two objects, lots of sky
- sky background has a lot of emission lines!

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

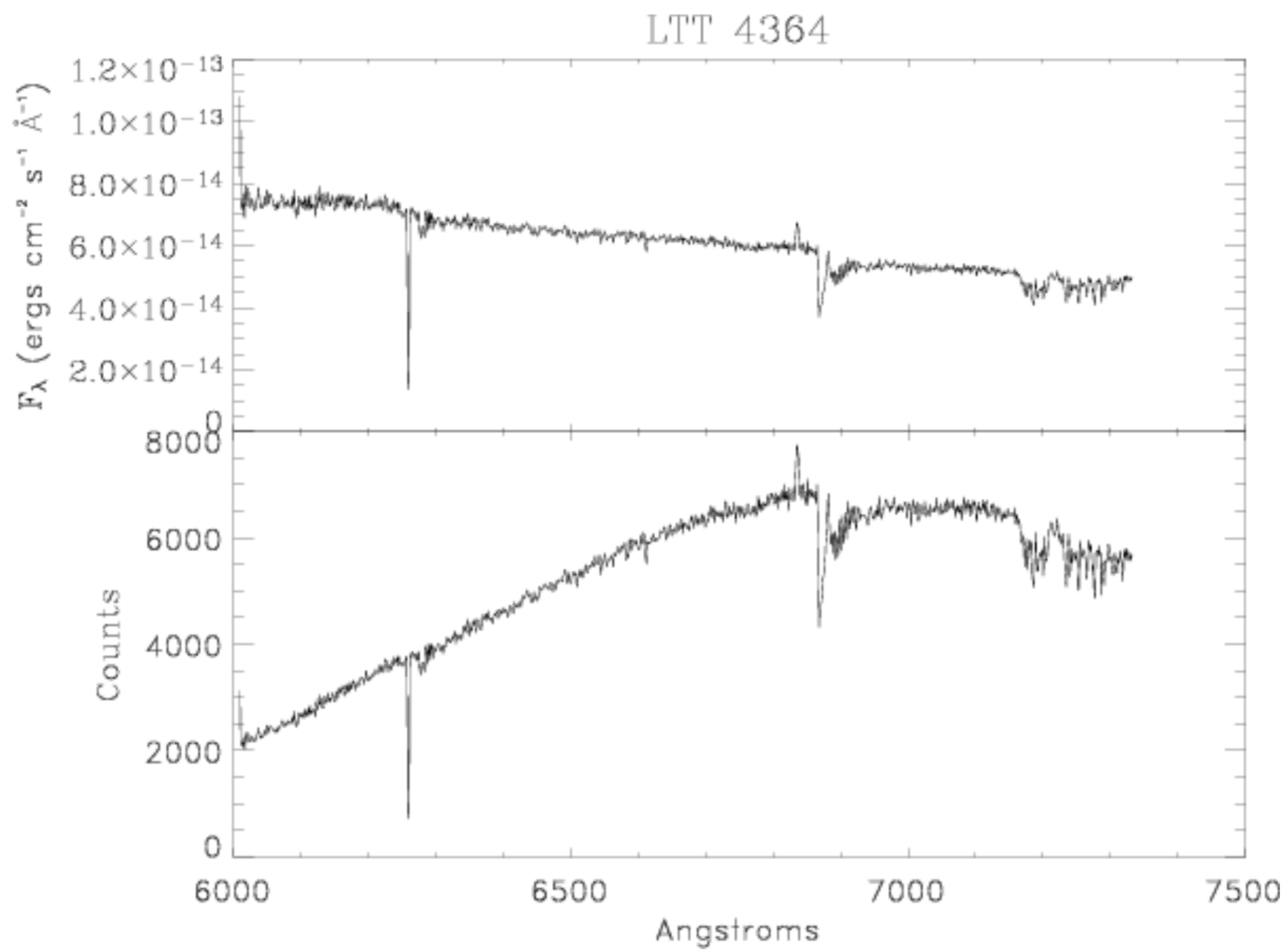


C. Buil / astrosurf

Spectroscopic Calibration

flux calibration:
observe
spectrophotometric
standard star

compare observed
spectrum (counts)
to known spectrum



F. Walter

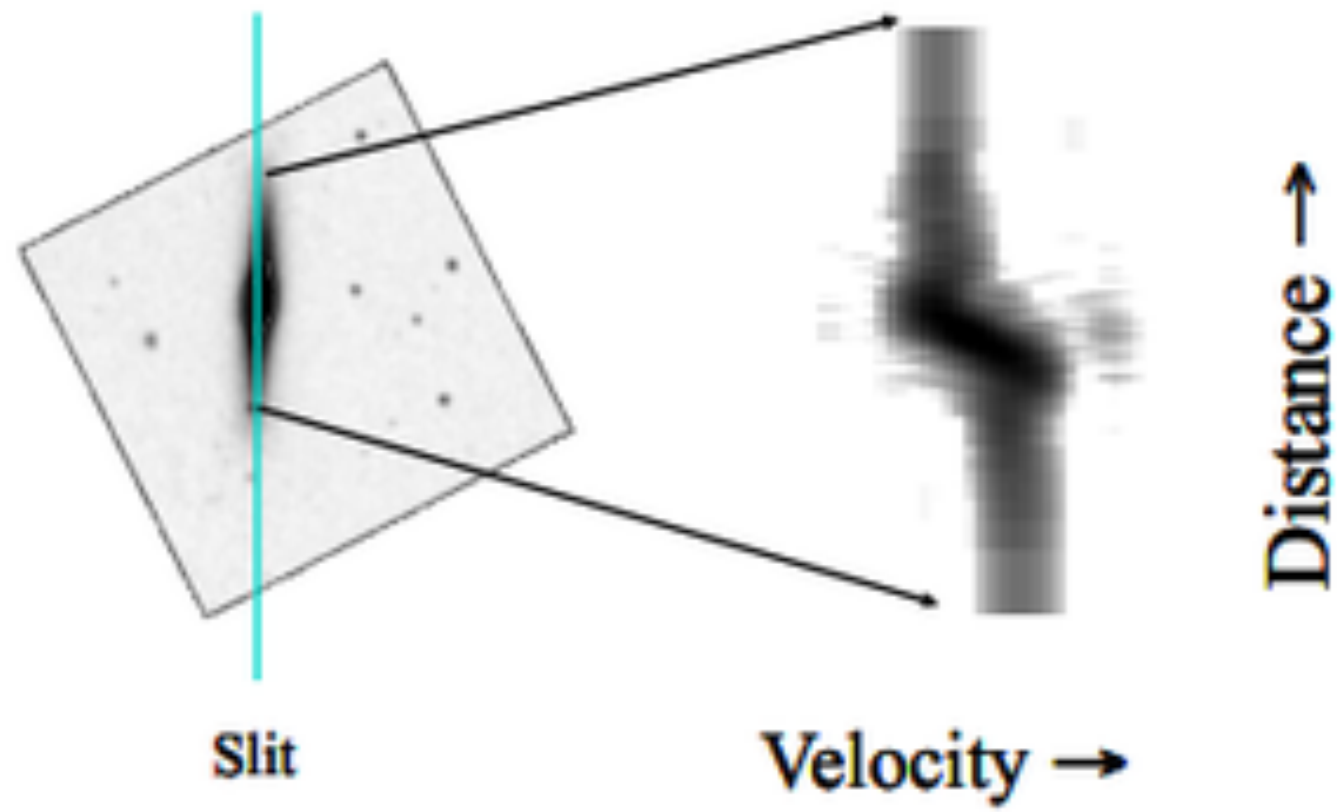
Long-slit spectrographs

most common spectrograph

can only target one (or a few) objects

gives spatial variation

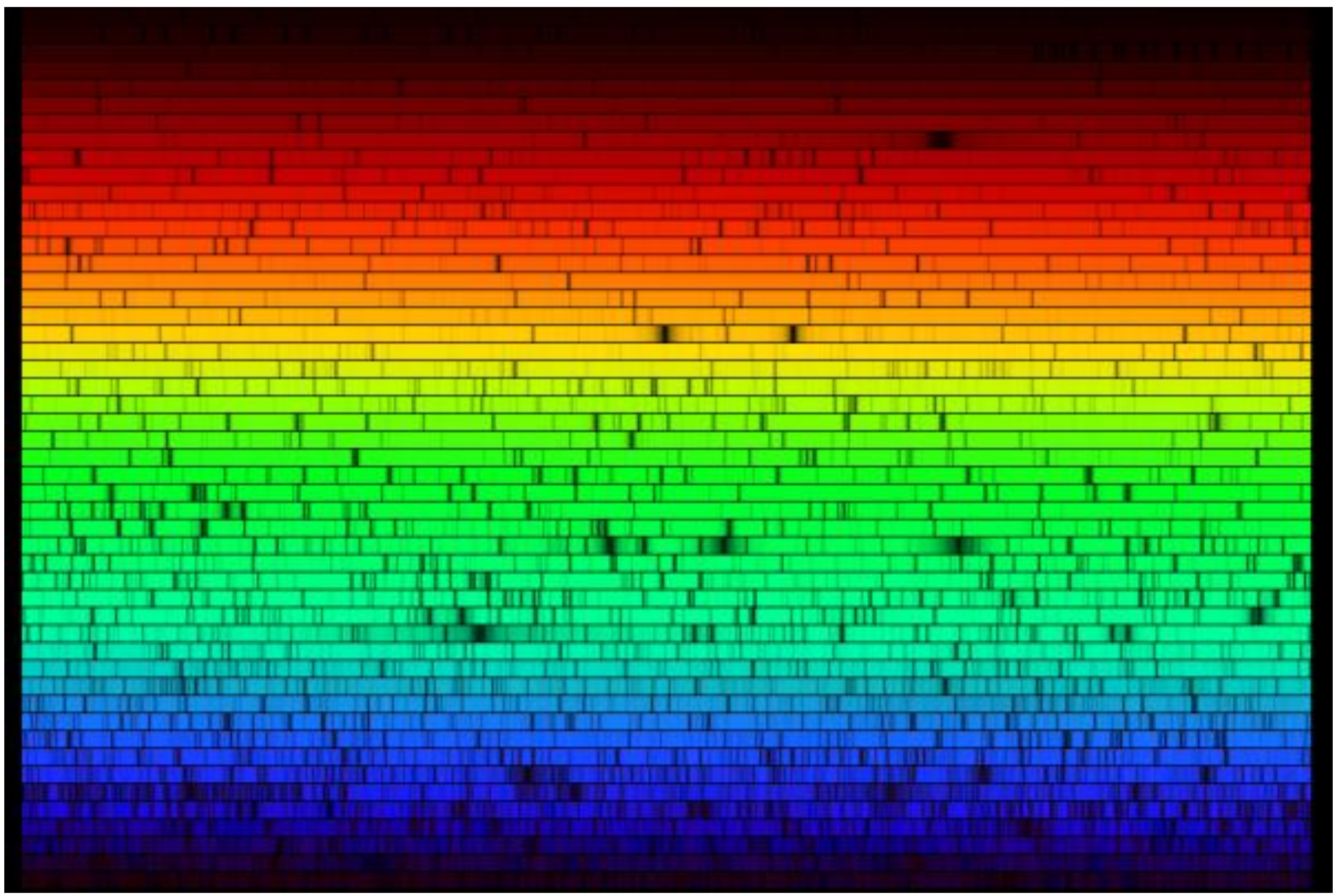
very good estimate of sky background



wikipedia

Echelle spectrographs

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

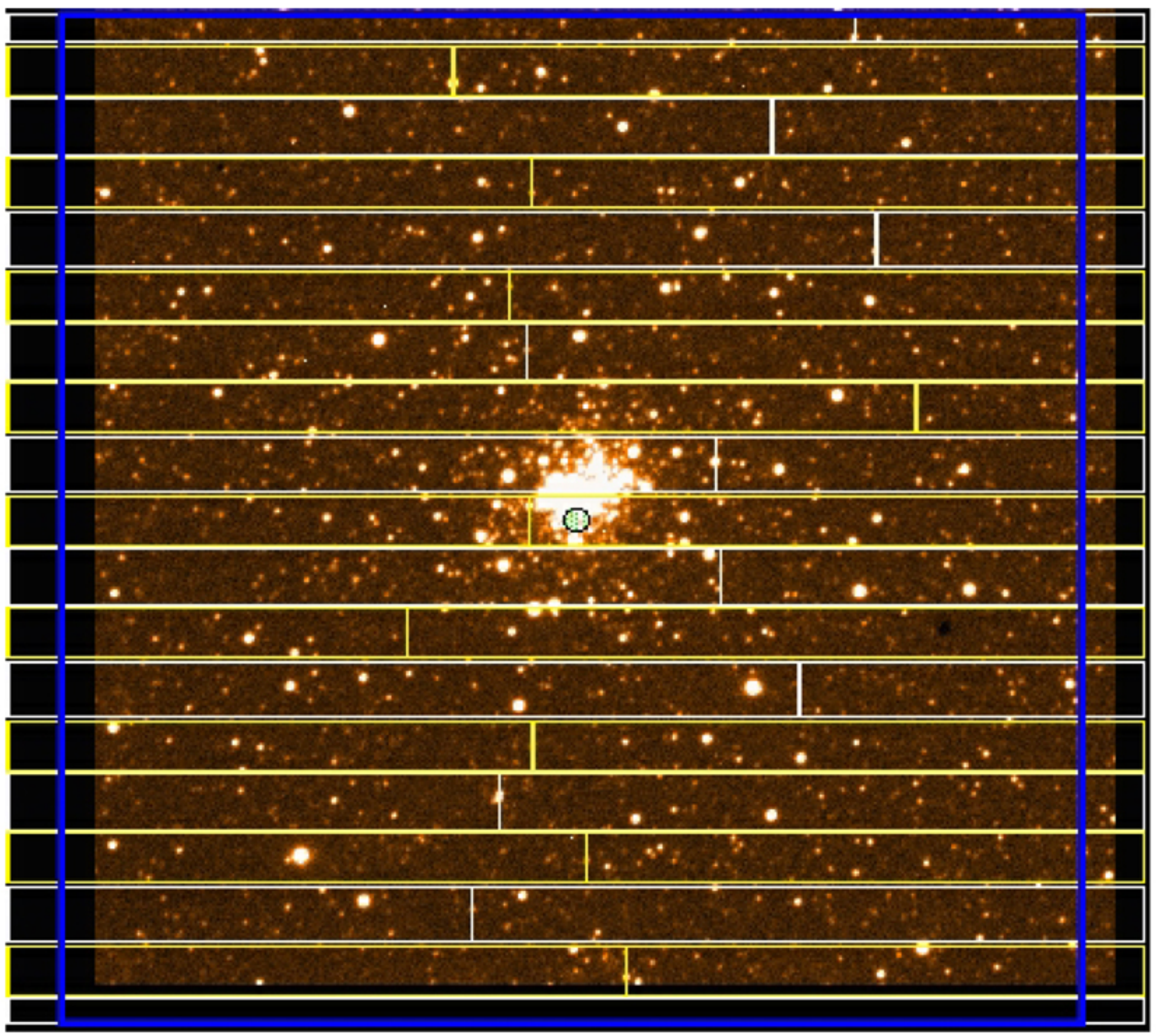


Echelle spectrum of the Sun, 4000-7000Å

NOAO

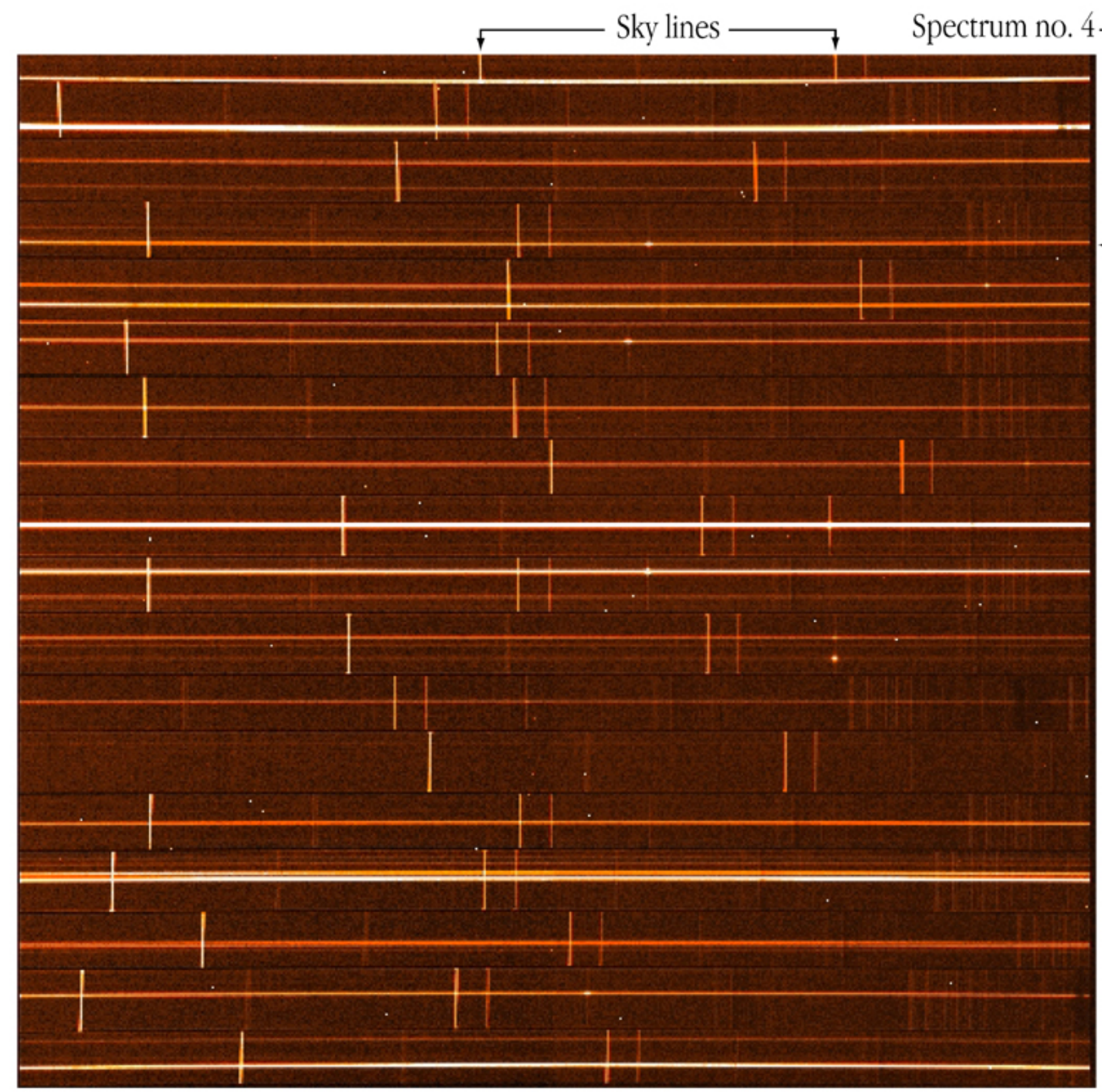
Multi-object spectrographs

make a mask with multiple slits, one per target



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

ESO PR Photo 38c/98 (7 October 1998)

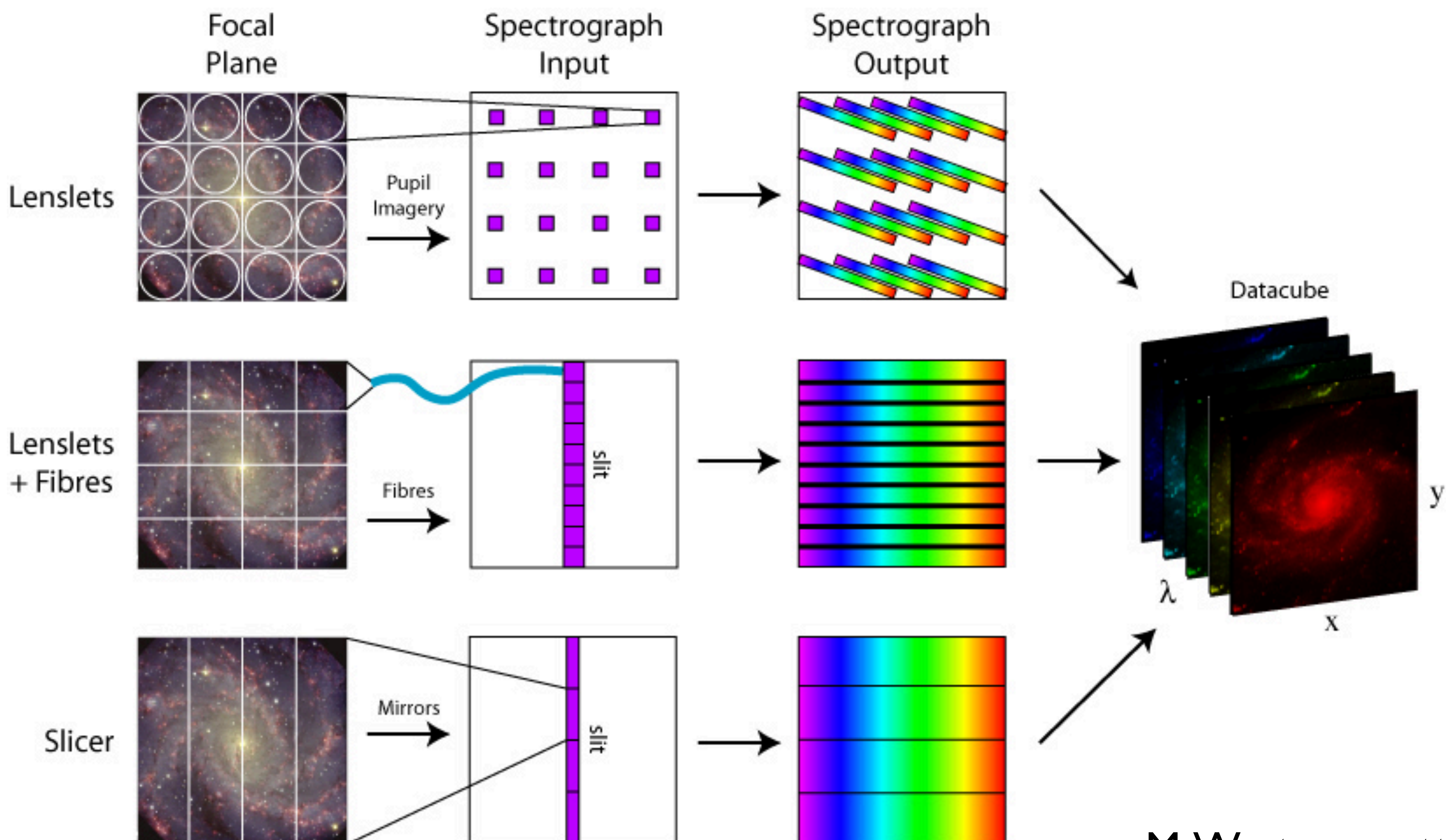


Spectra of Stars in Open Cluster NGC 330 in SMC - VLT UT1 + FORS1 (MOS-mode)

ESO PR Photo 38d/98 (7 October 1998)

Integral-Field Units

divide image into "spaxels" (spectroscopic pixels)

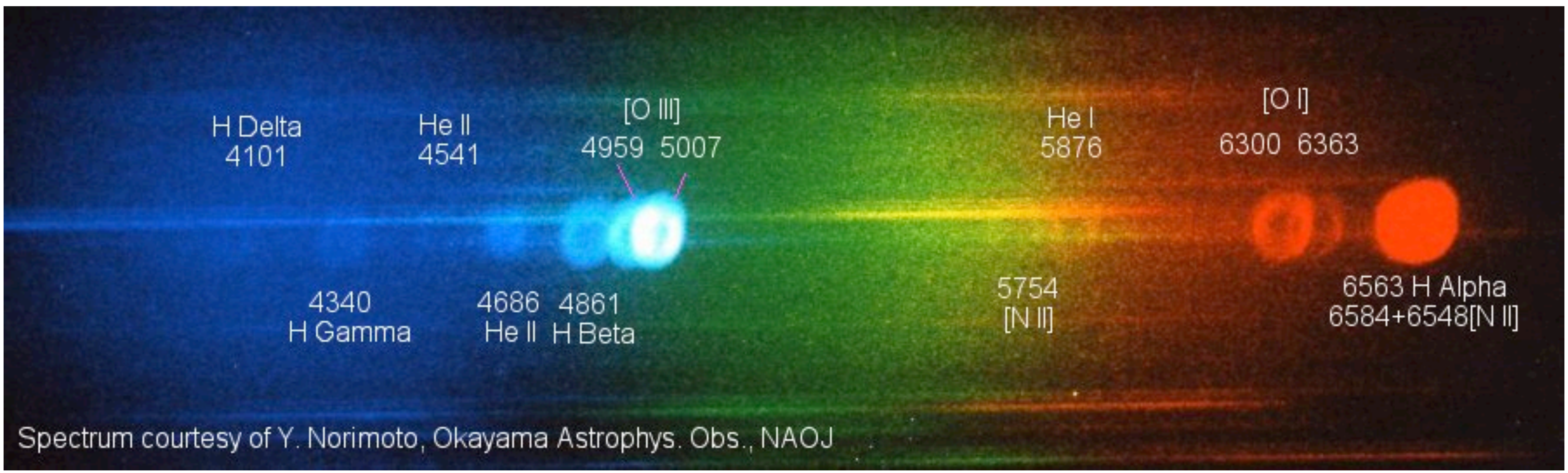


M. Westmoquette

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 temperate



slitless(!) spectrum of the Ring Nebula