PHY 517 / AST 443: Observational Techniques in Astronomy

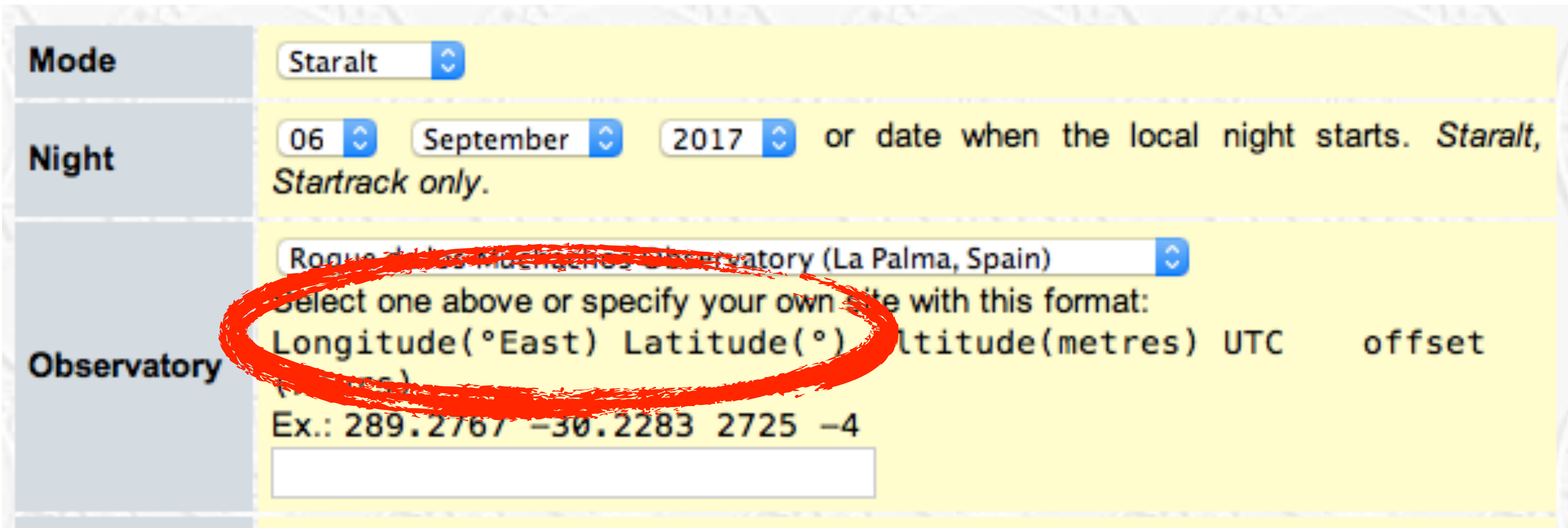
Lecture 3:
CCDs /
FITS files

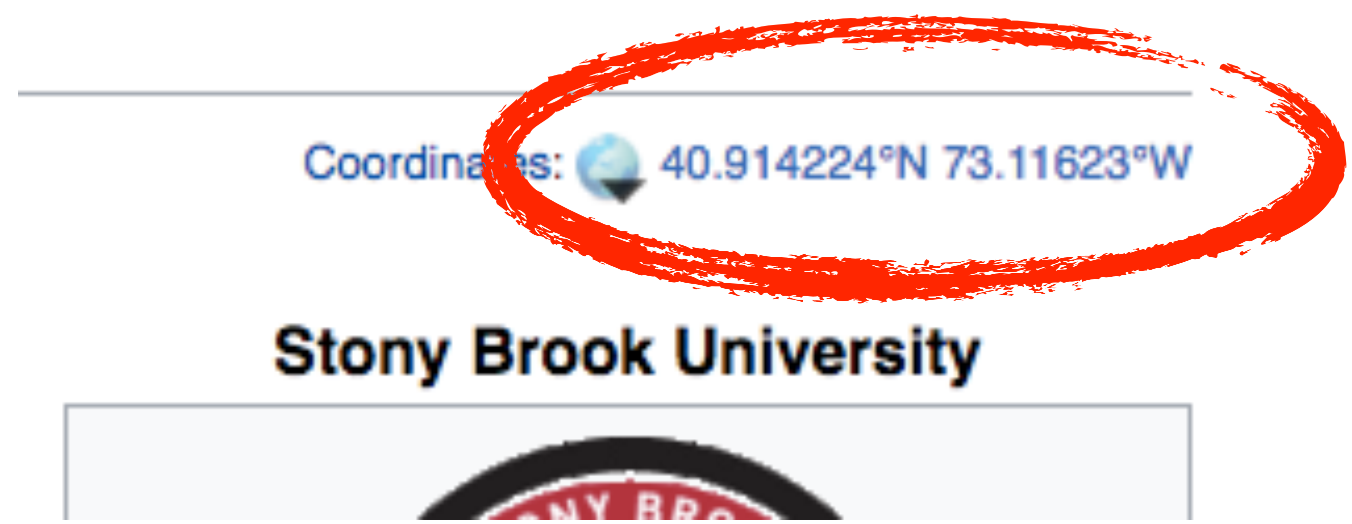
Office Hours

- during class (seriously!)
- easiest way to get in touch with me: slack
- office hours:
  - Ben: Mo 10-11am, ESS 450
  - Prof.: We 4:30-5:30pm, ESS 457-A
  - Prakruth: Fr 1-2pm, ESS 450
- by appointment

StarAlt

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



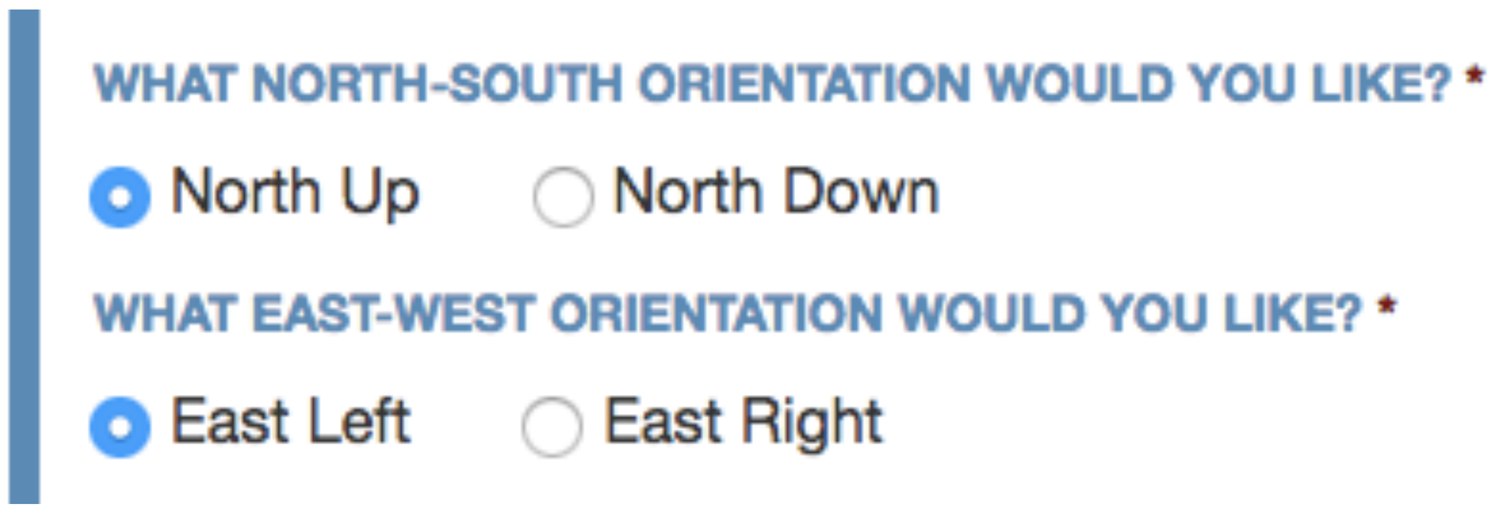


How are Mt. Stony Brook's coordinates correctly specified?

A) 40.9 73.1
B) 73.1 40.9
C) -40.9 73.1
D) 286.9 40.9

Finding Charts

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



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 uncertainty to one (or two) digits:

$$0.00455679 \to 0.005$$

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

(a) Which of these are examples of plagiarism? (More than one answer may be correct.)

i. Copying your lab-mate's introduction section of a lab report.

ii. Taking somebody else's lab report, slightly modifying each sentence / paragraph, and submitting it as your own.

iii. Copying your buddy's telescope proposal for the JWST telescope, and submitting it as your own.

iv. Stating a "fact" from wikipedia without citing the original source.

v. Using ChatGPT and quoting ChatGPT as the source.

(b) What happens when you get a "Q" grade? (Answer yes/no/maybe.)

maybe i. Immediate expulsion from school.

yes ii. You lose your scholarship.

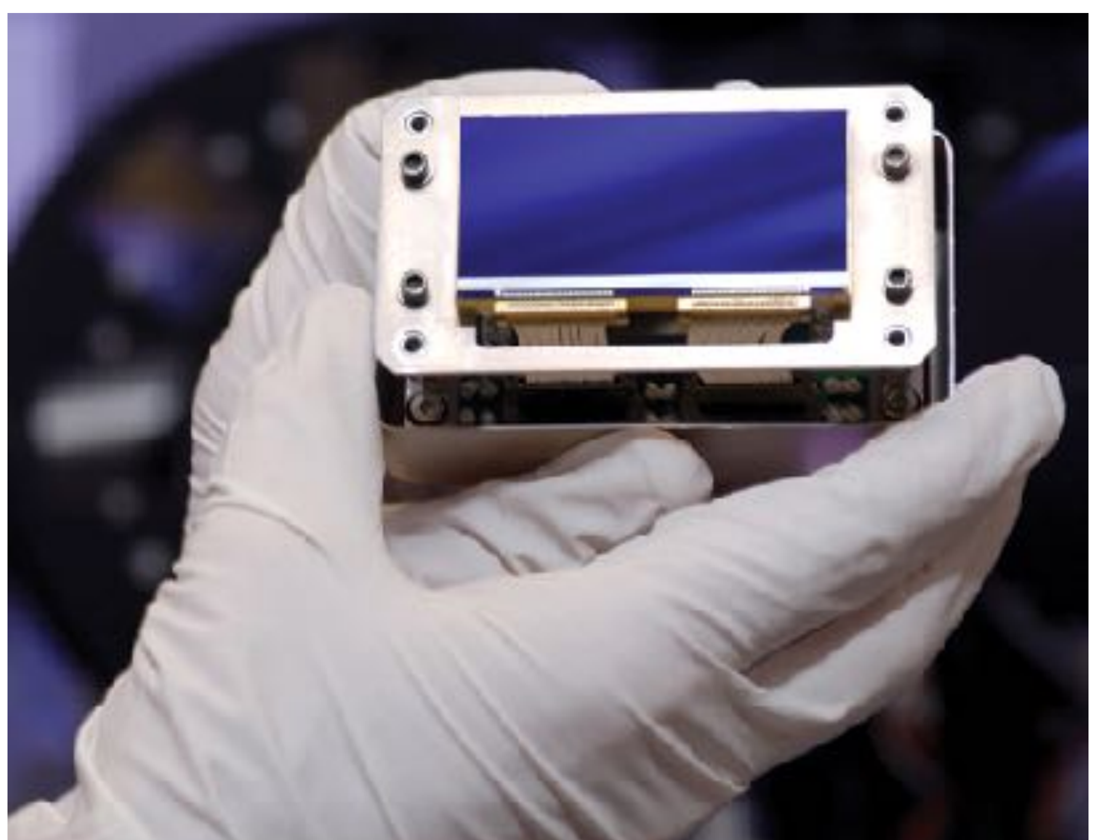
maybe iii. You receive an "F" for the course grade.

yes iv. You have to take the "Q" course.

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

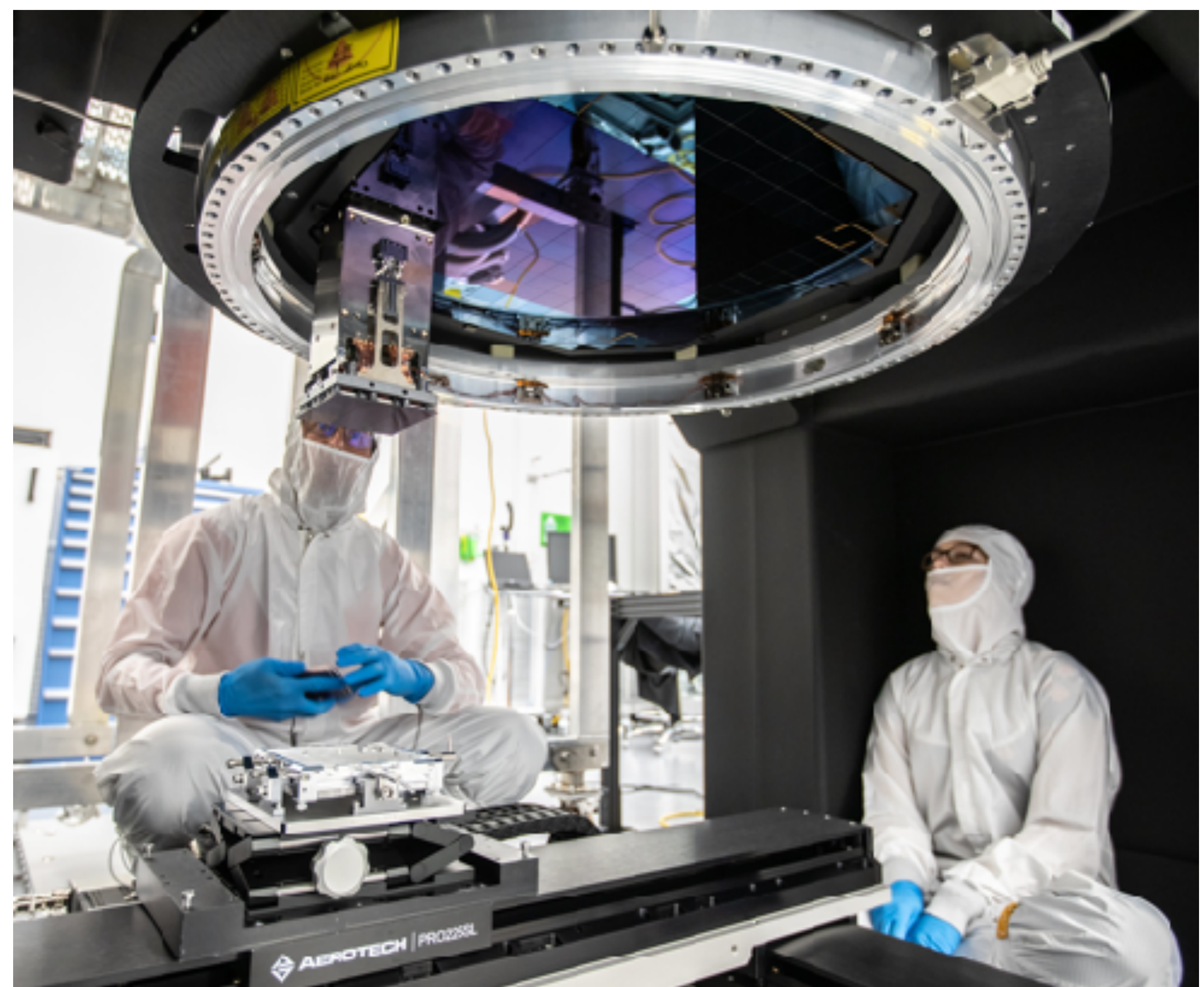


e2v

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

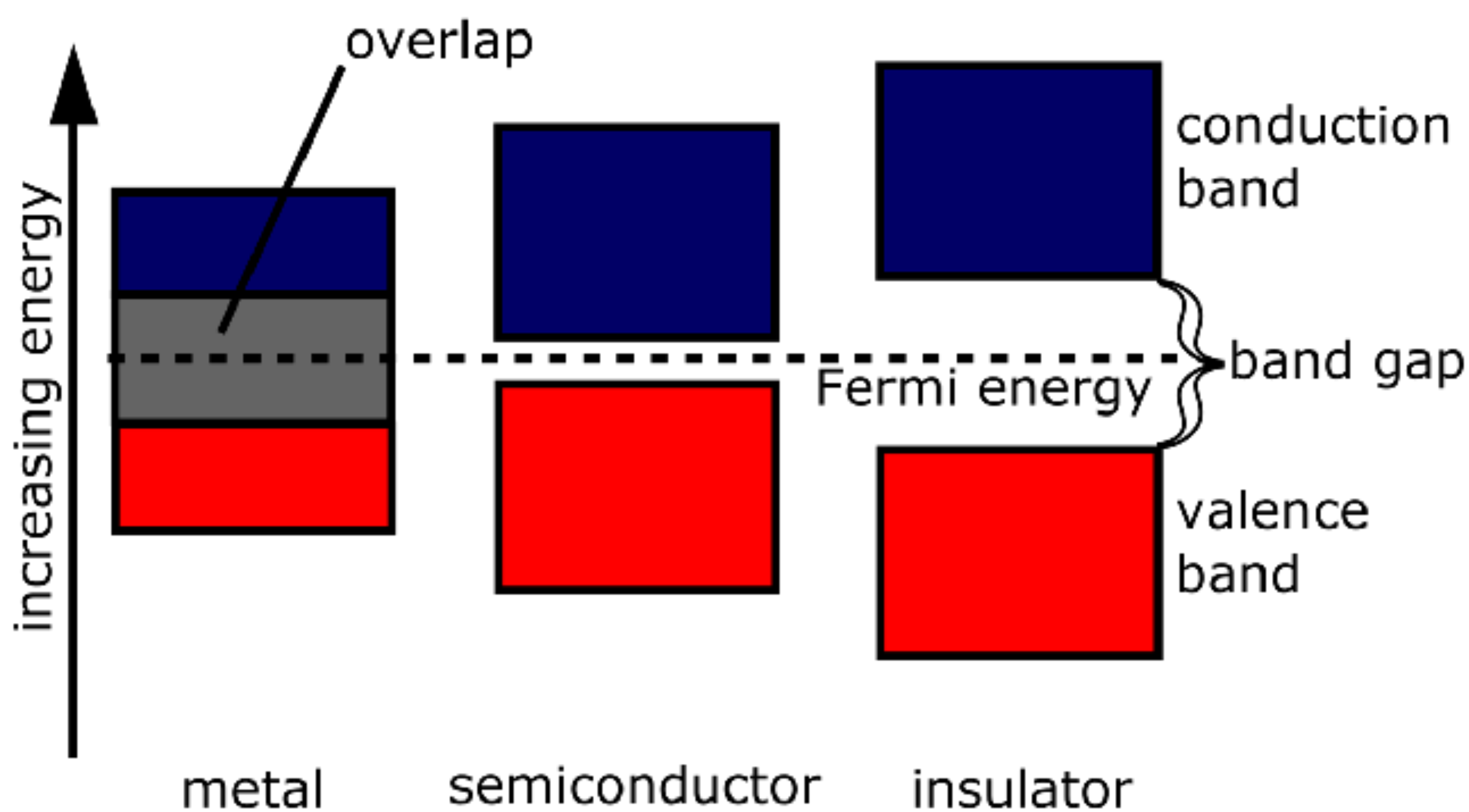


LSST Camera at SLAC

https://www6.slac.stanford.edu/news/2020-09-08-sensors-world-largest-digital-camera-snap-first-3200-megapixel-images-slac.aspx

Semi-Conductors

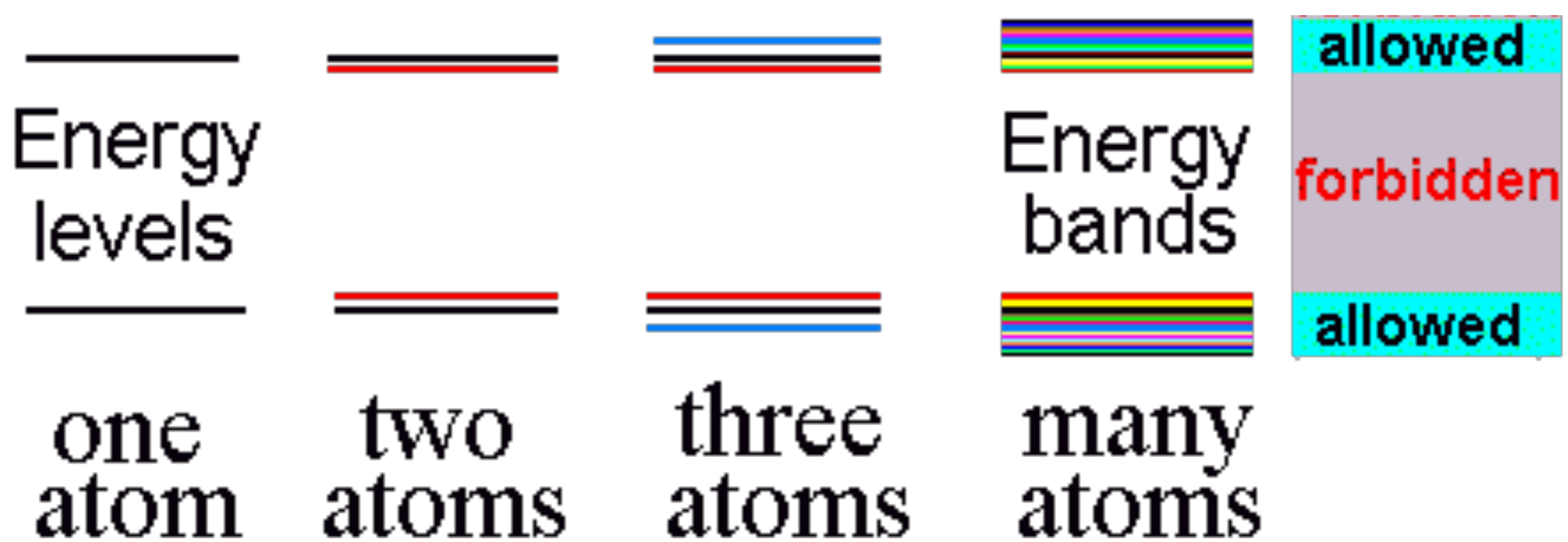
- CCDs are made of semi-conducting silicon wafers
- key feature: small energy gap between "valence band" (energy levels of outermost bound electrons) and "conduction band" (energy levels of free electrons)



wikipedia / inductiveload

Why energy bands?

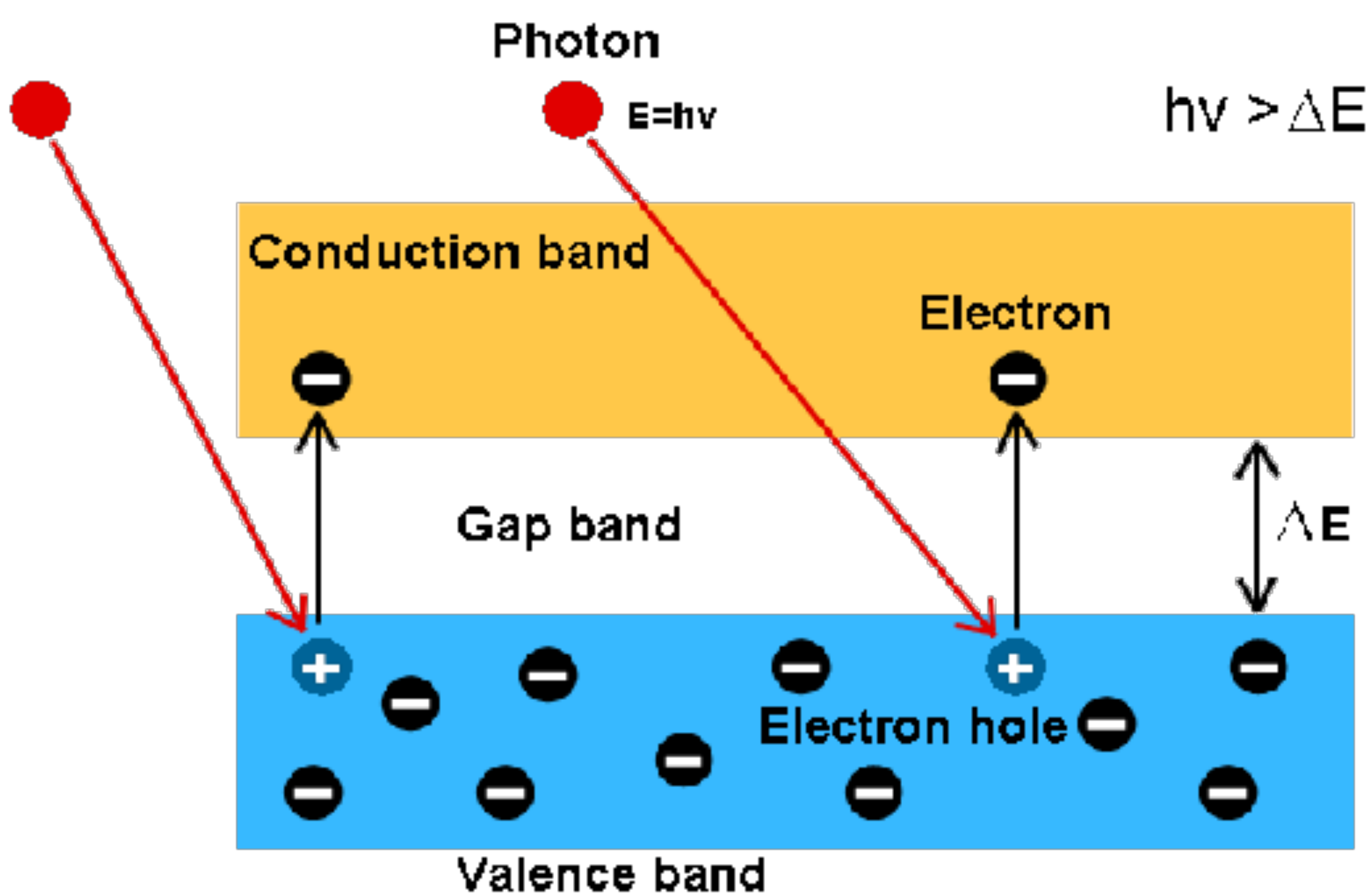
- single atom: discrete energy levels
- two atoms:
  - outer electron orbitals overlap
  - Fermi exclusion principle still holds → energy levels split to accommodate electrons
- many atoms: energy bands



G. Watson

Photoelectric effect

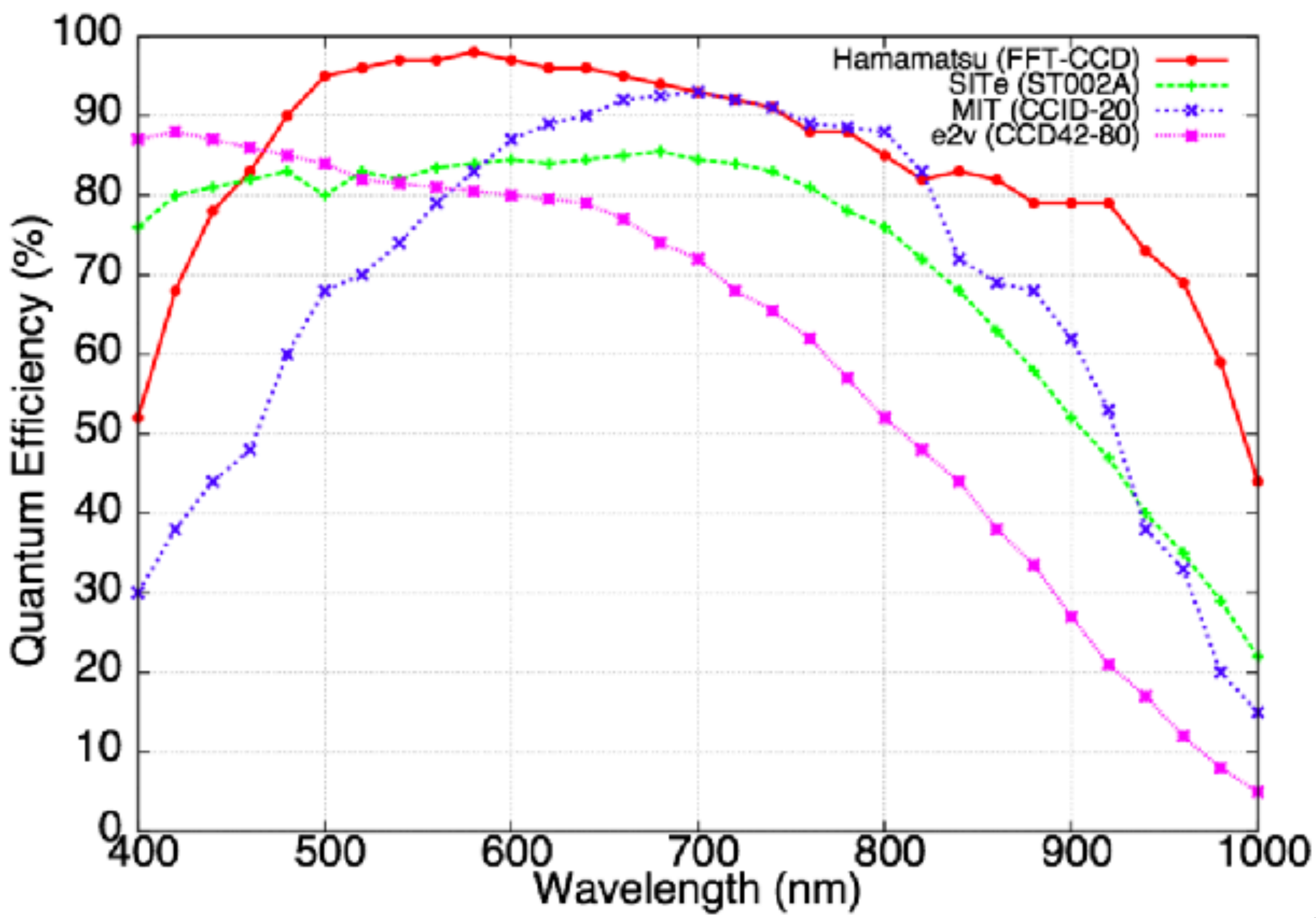
- light is quantized, "photons" $E = h\nu$
- when a photon is absorbed, the energy is transferred to an electron → "jumps" into conduction band



M. Poblocki

CCD Quantum Efficiency (QE)

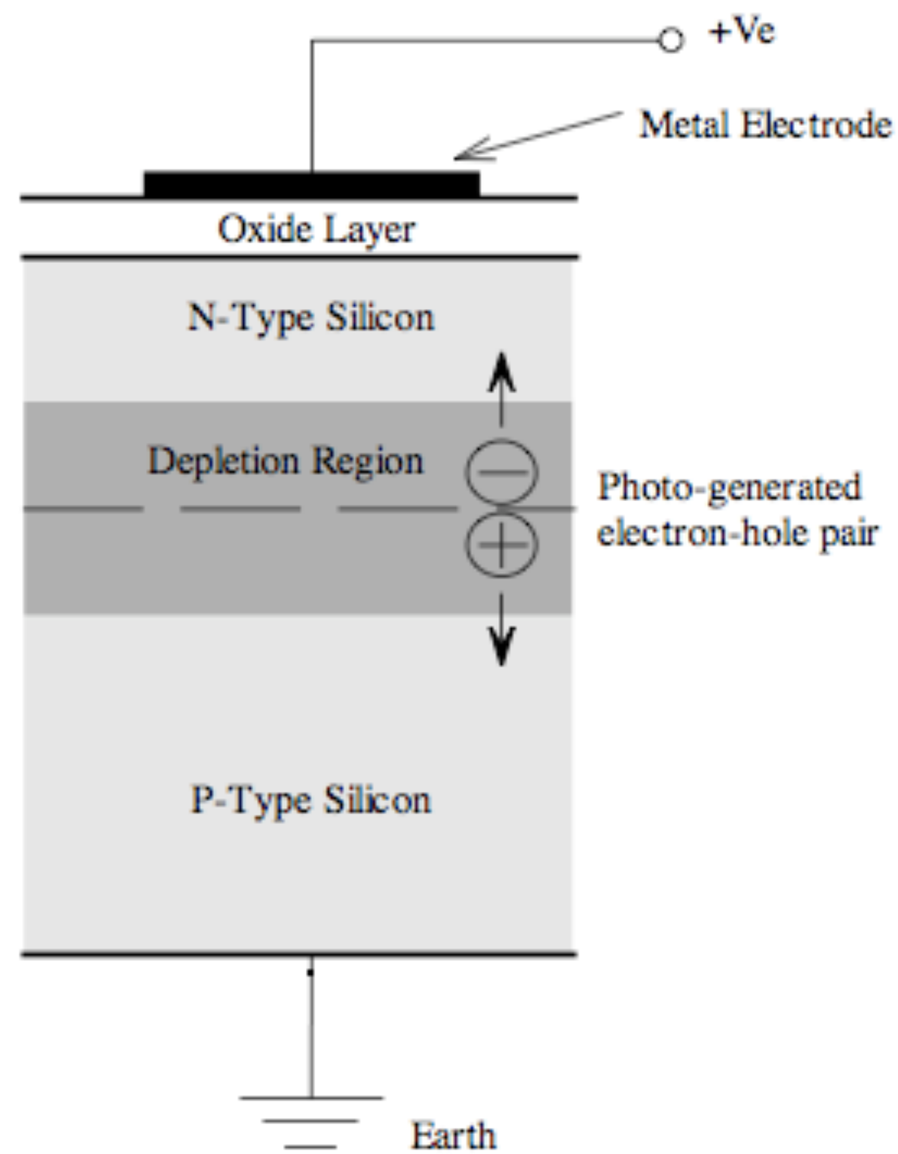
- fraction of photons that are absorbed
- depends on wavelength
- different technologies lead to red vs. blue optimized CCDs



Nakao et al. 2014

One pixel

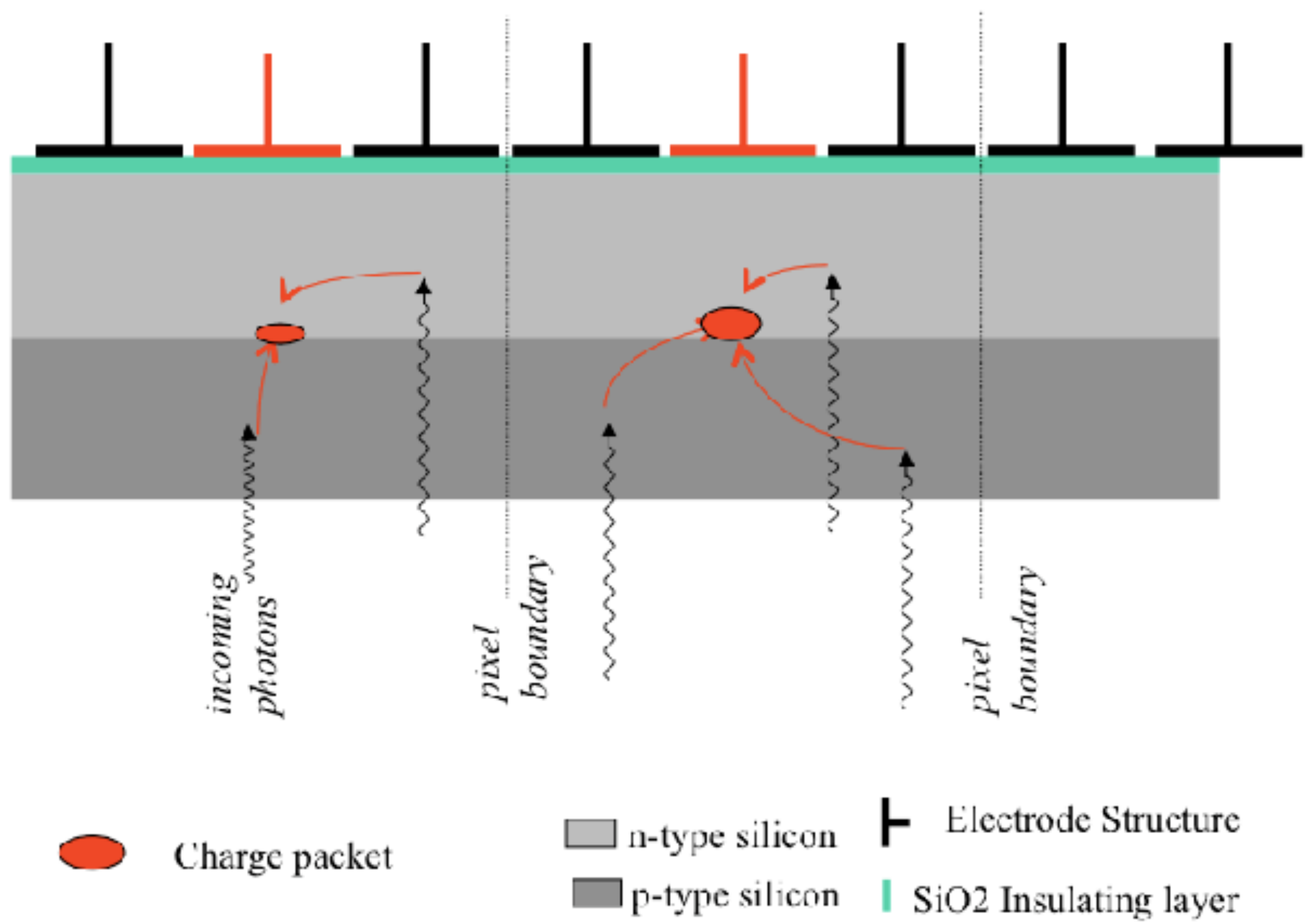
- apply an electric field to keep electrons / holes separated



Microsoft

Many pixels

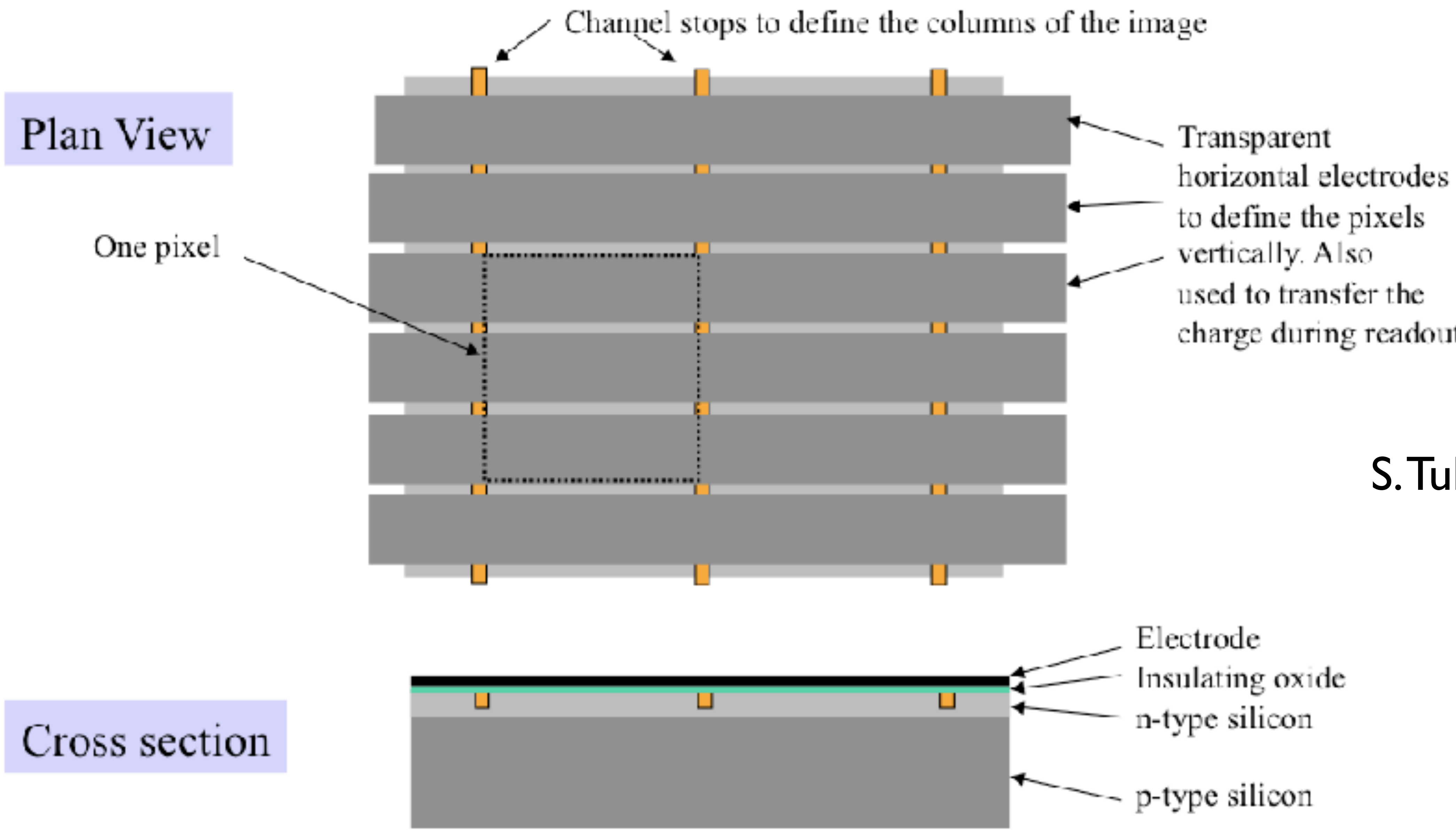
- pixels are defined by the electric field generated by the applied electrodes



S. Tullock

Many pixels

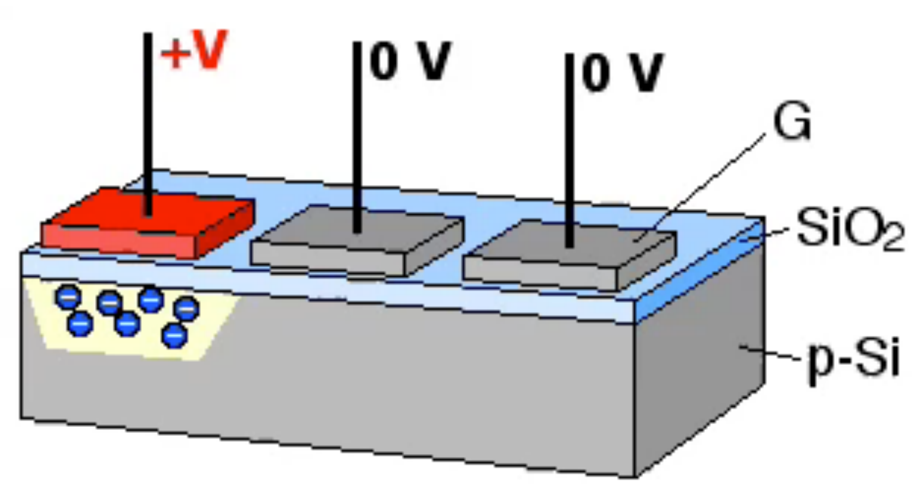
- … and by insulator strips between columns



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

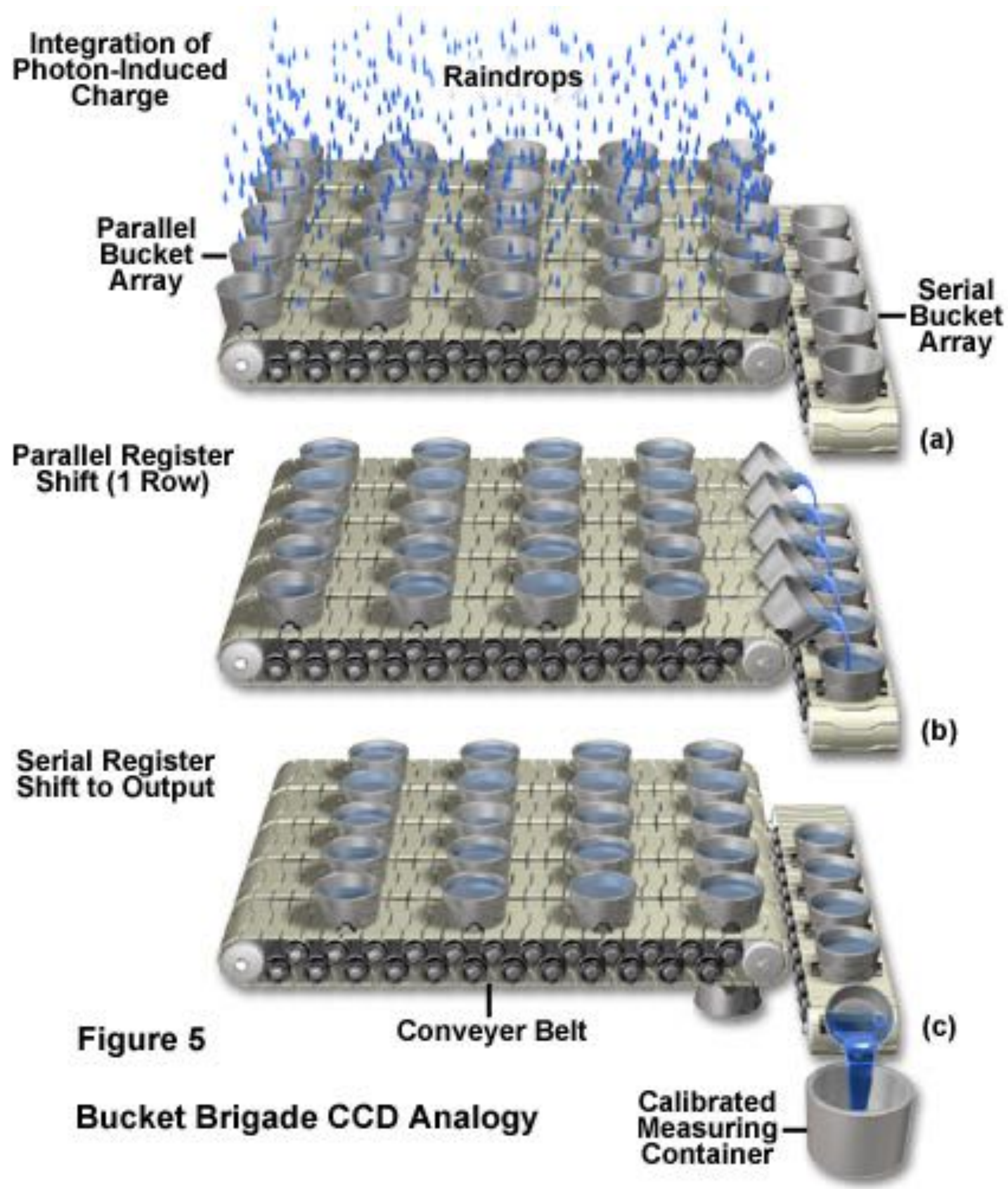


Figure 5

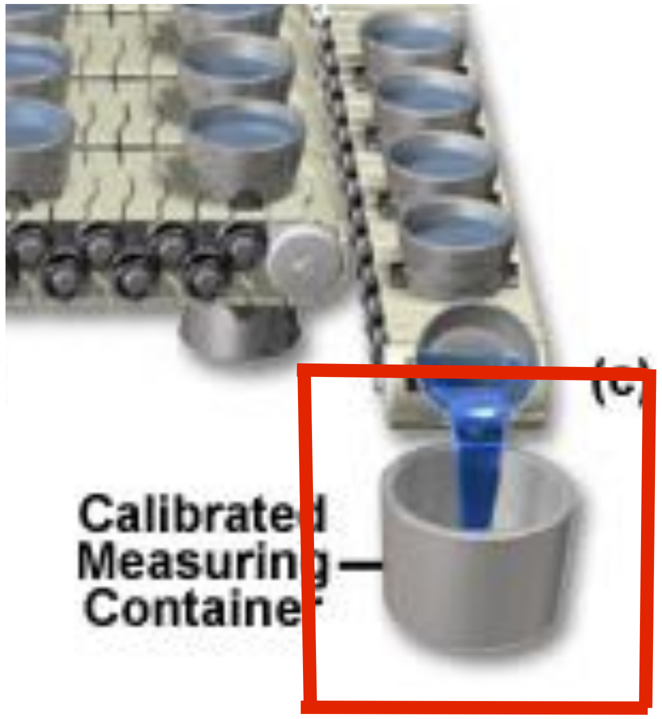
Bucket Brigade CCD Analogy

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

Measured number of counts

$$N_{\mathrm{electrons}} \;\propto\; N_{\mathrm{photons}}$$

- we want to measure $N_{photons}$ (or, flux)
- our CCD returns N_{counts}
- what else contributes to N_{counts}?

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 (i.e. the read-out noise) is NOT sqrt(N_{cts}[bias])

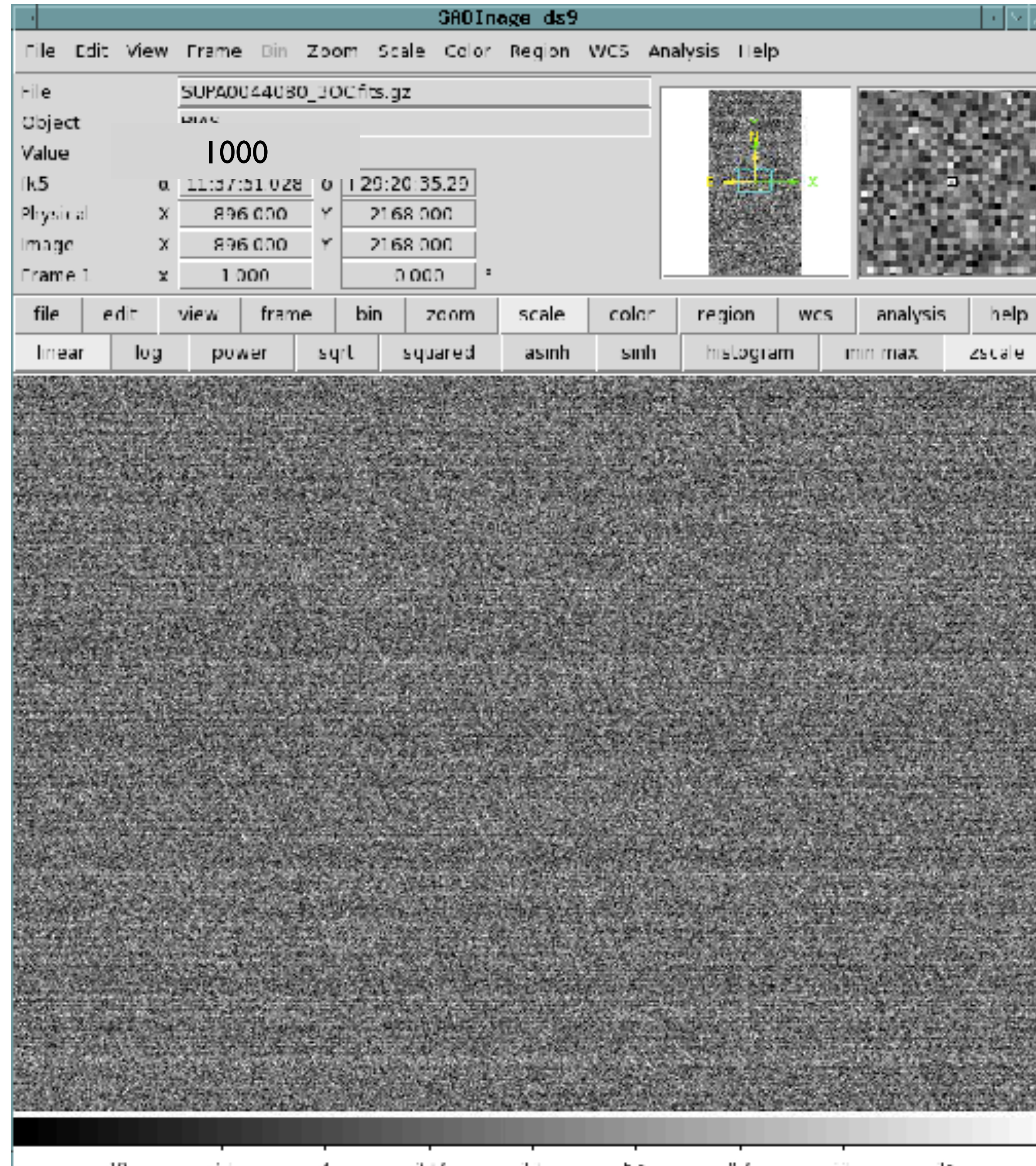
Read-out noise

- 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

- note: this is a noise term, i.e. it adds stochasticity to the measurement. it cannot be subtracted per se.

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 of many bias frames): read-noise is averaged out, remaining structure is due to electronics



A. von der Linden

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 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

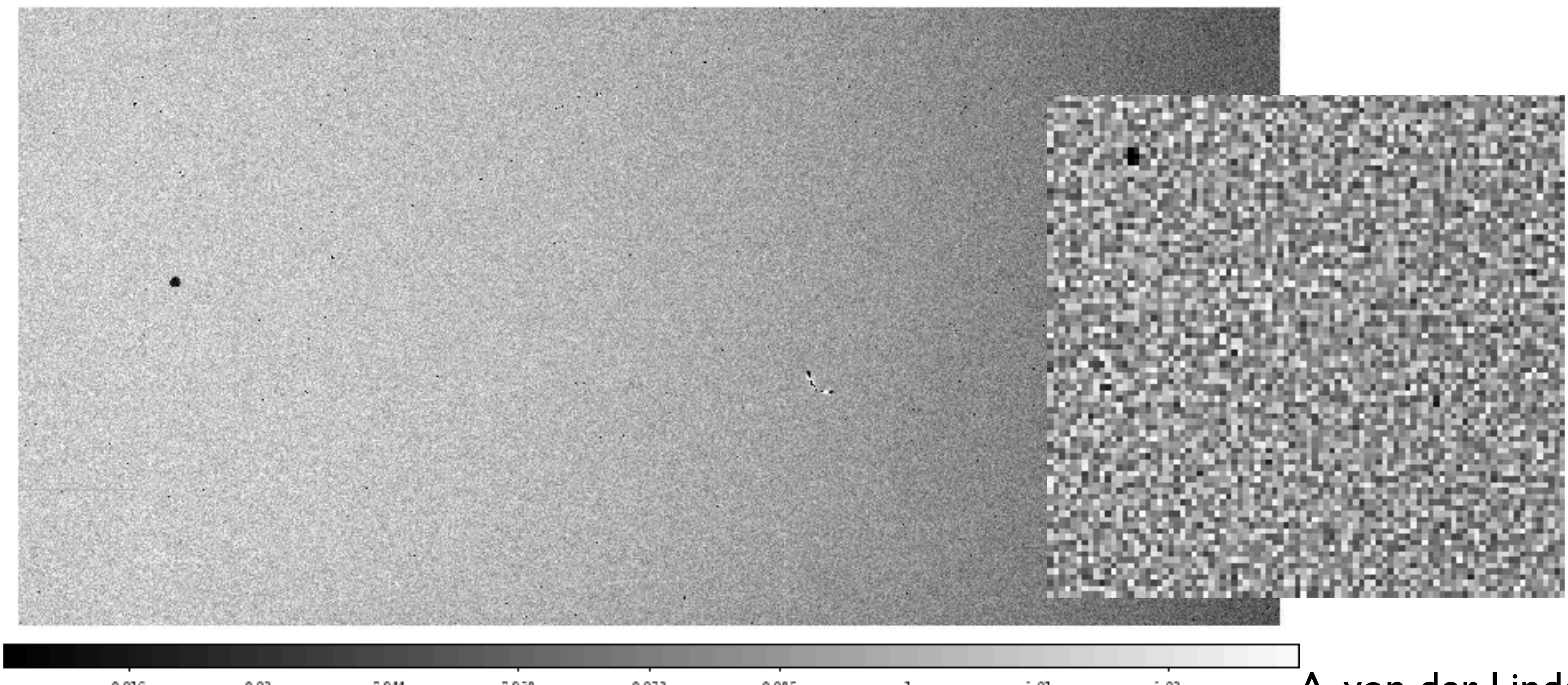
- the pixels in a CCD do *not* have uniform sensitivity
- due to variations in silicon crystal, electric field, pixel size, illumination (vignetting)

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

- 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 sensitivities



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 appropriate dark frame
- average the flat-field images (reduces counting noise)
  → master flat-field

- … *and then what?*

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

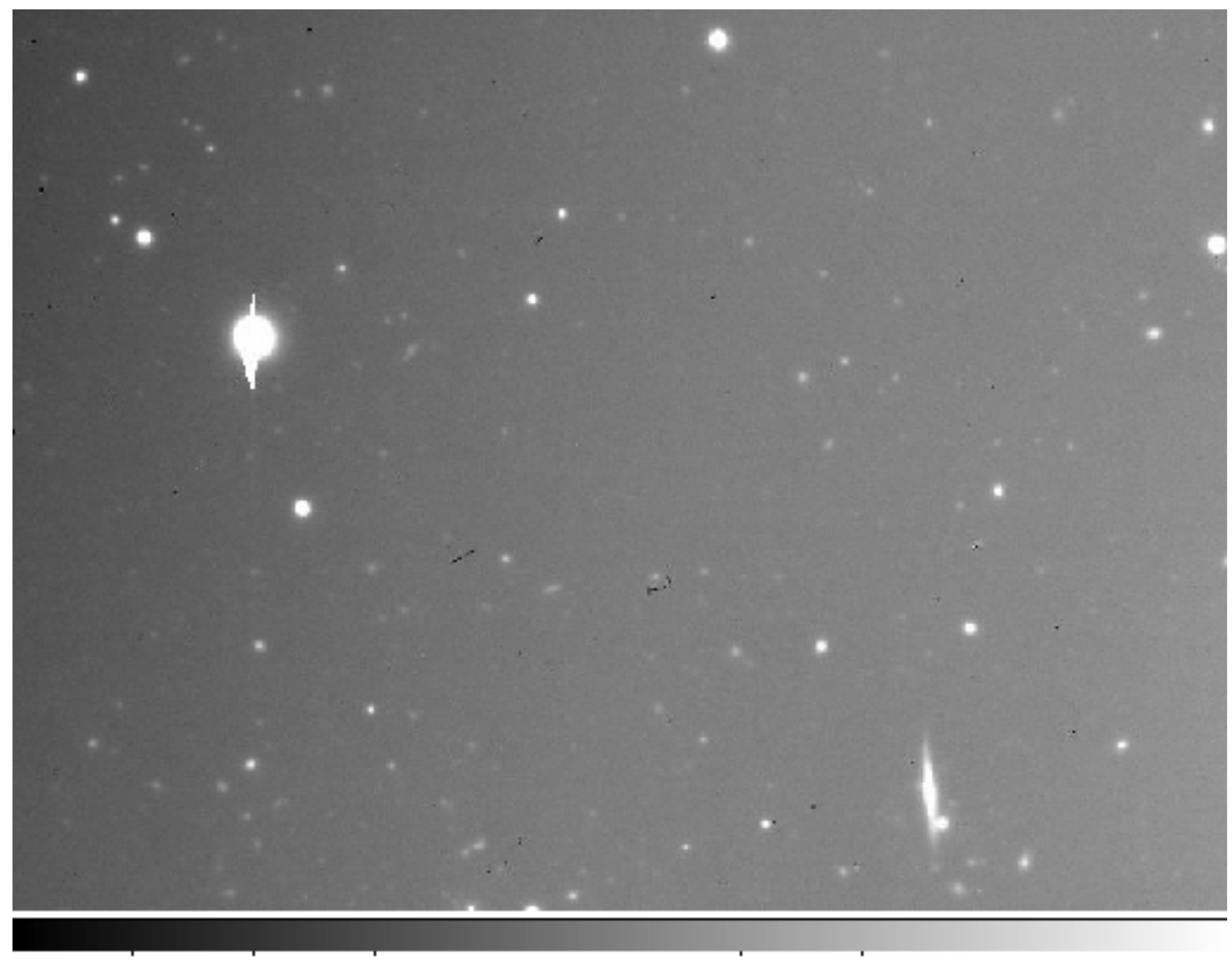
– variable

– 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)



A. von der Linden

✓ most similar to data

✓ uniform

– need "empty" fields

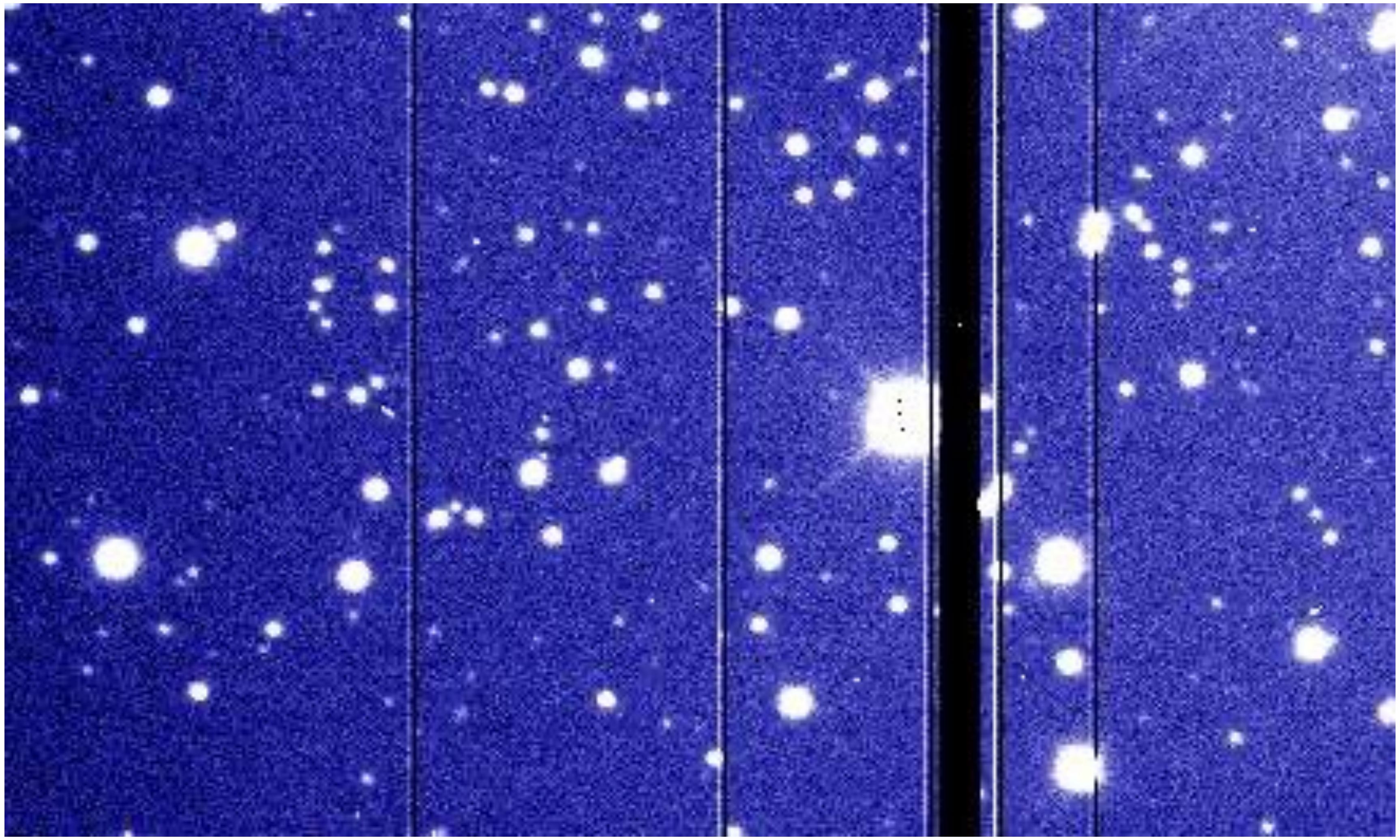
– need a lot of images

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

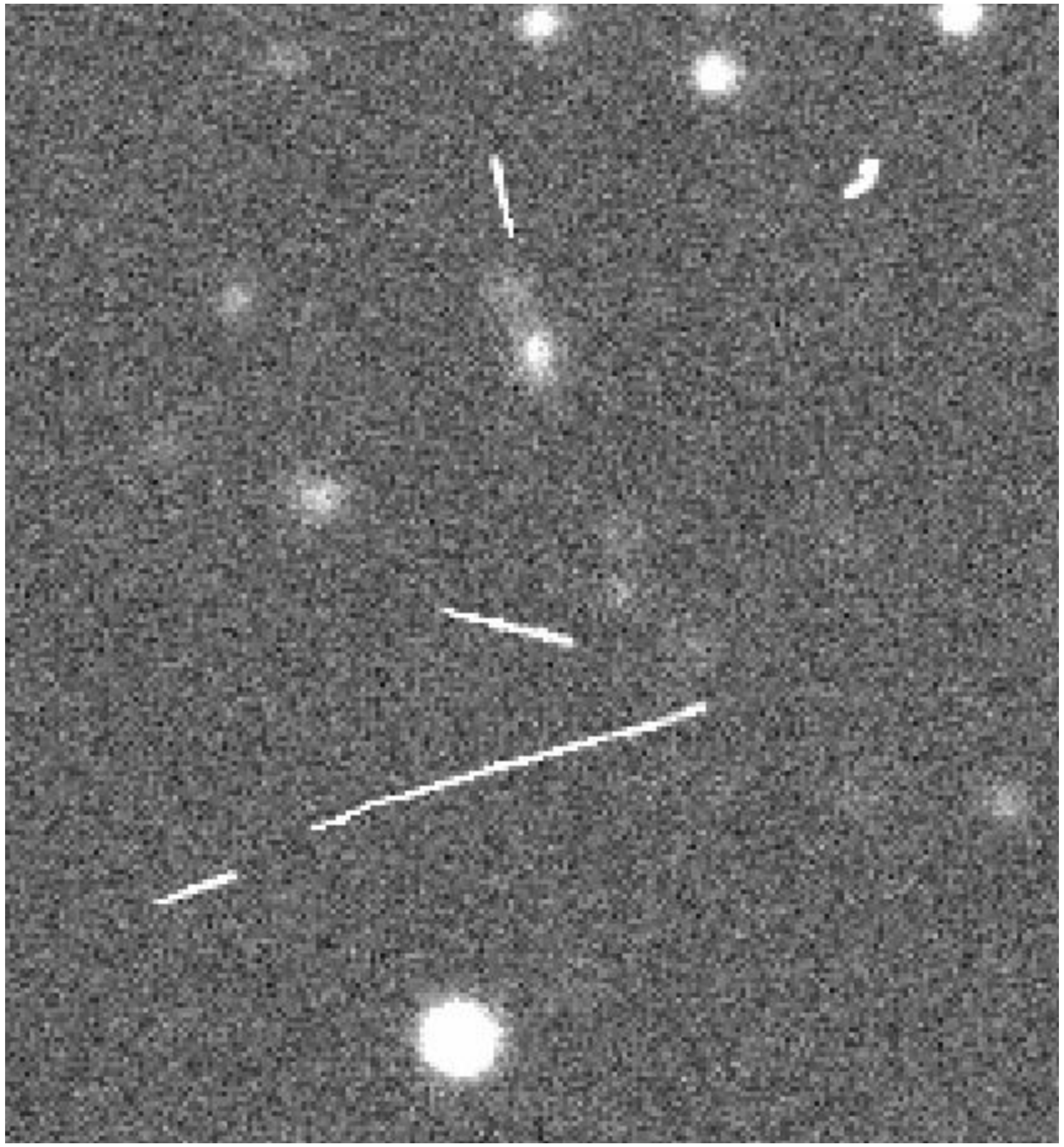


ESO

Artefacts

cosmic rays: charged particles hit the CCD

need to be masked - single exposure

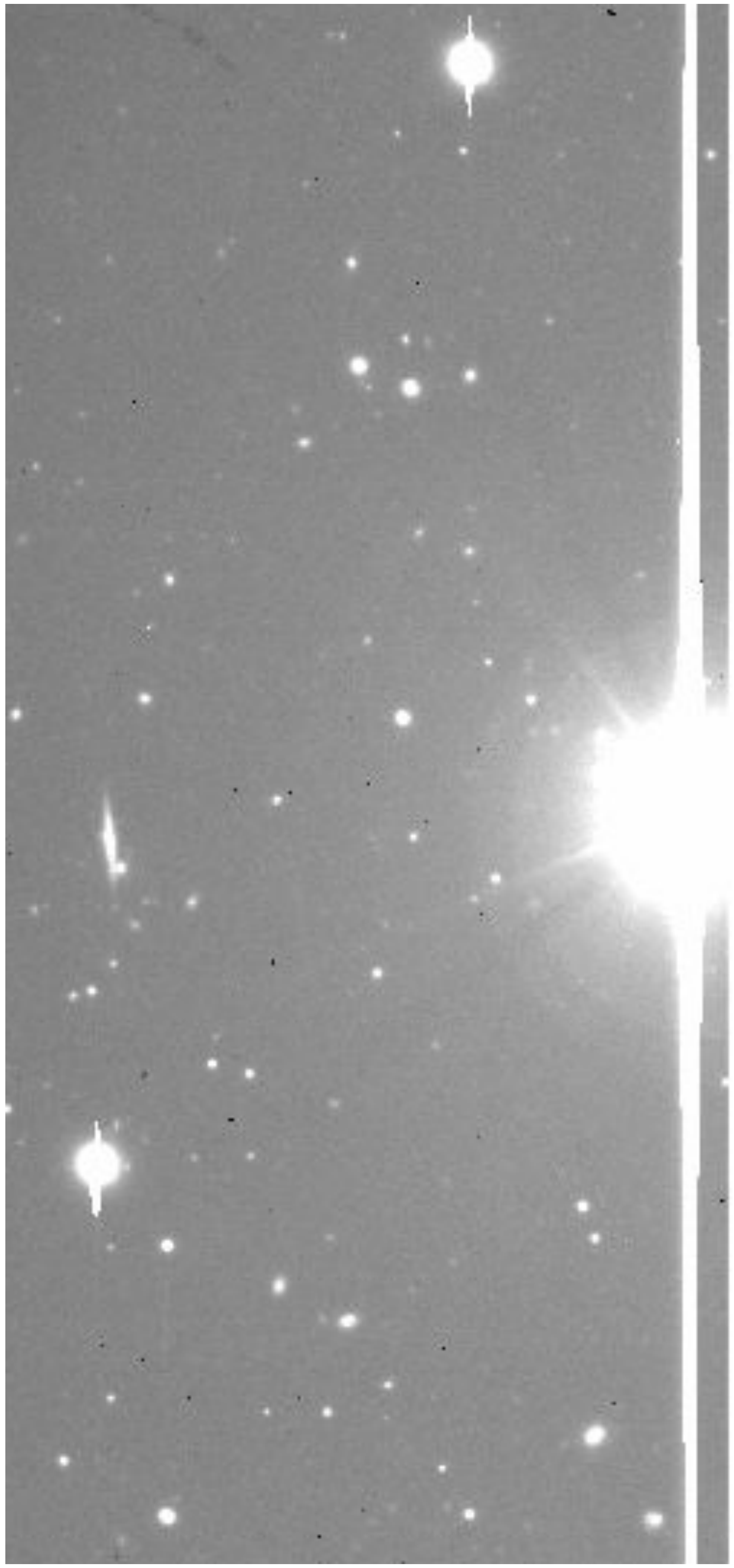


A. von der Linden

Artefacts

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

need to be masked - single exposure

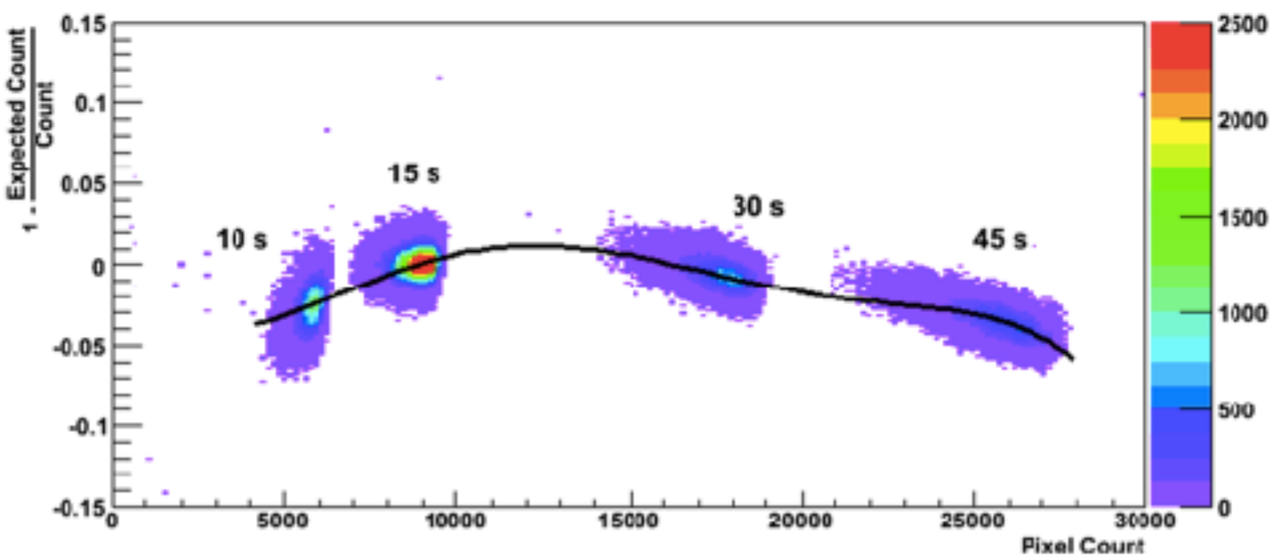


A. von der Linden

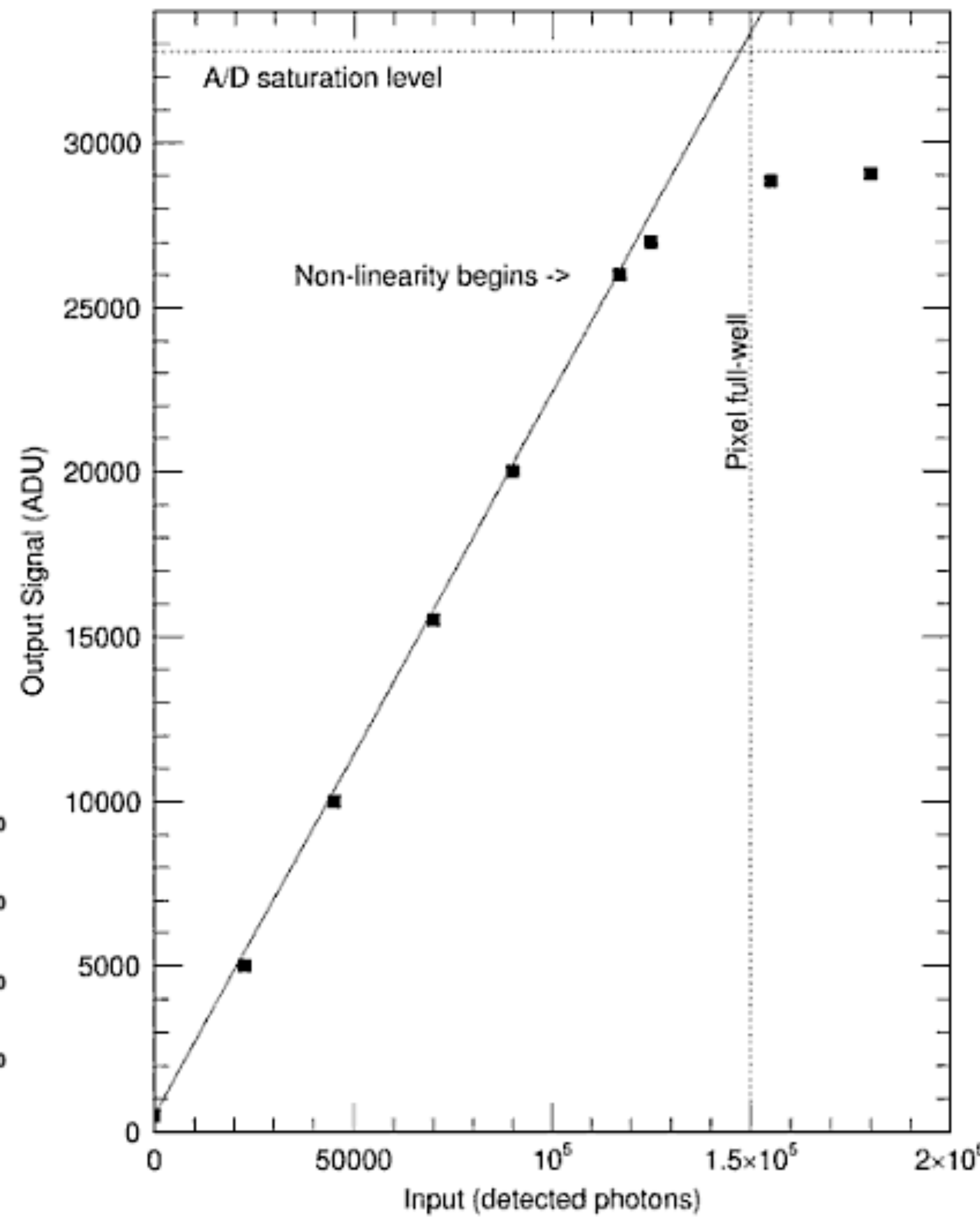
Artefacts

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*

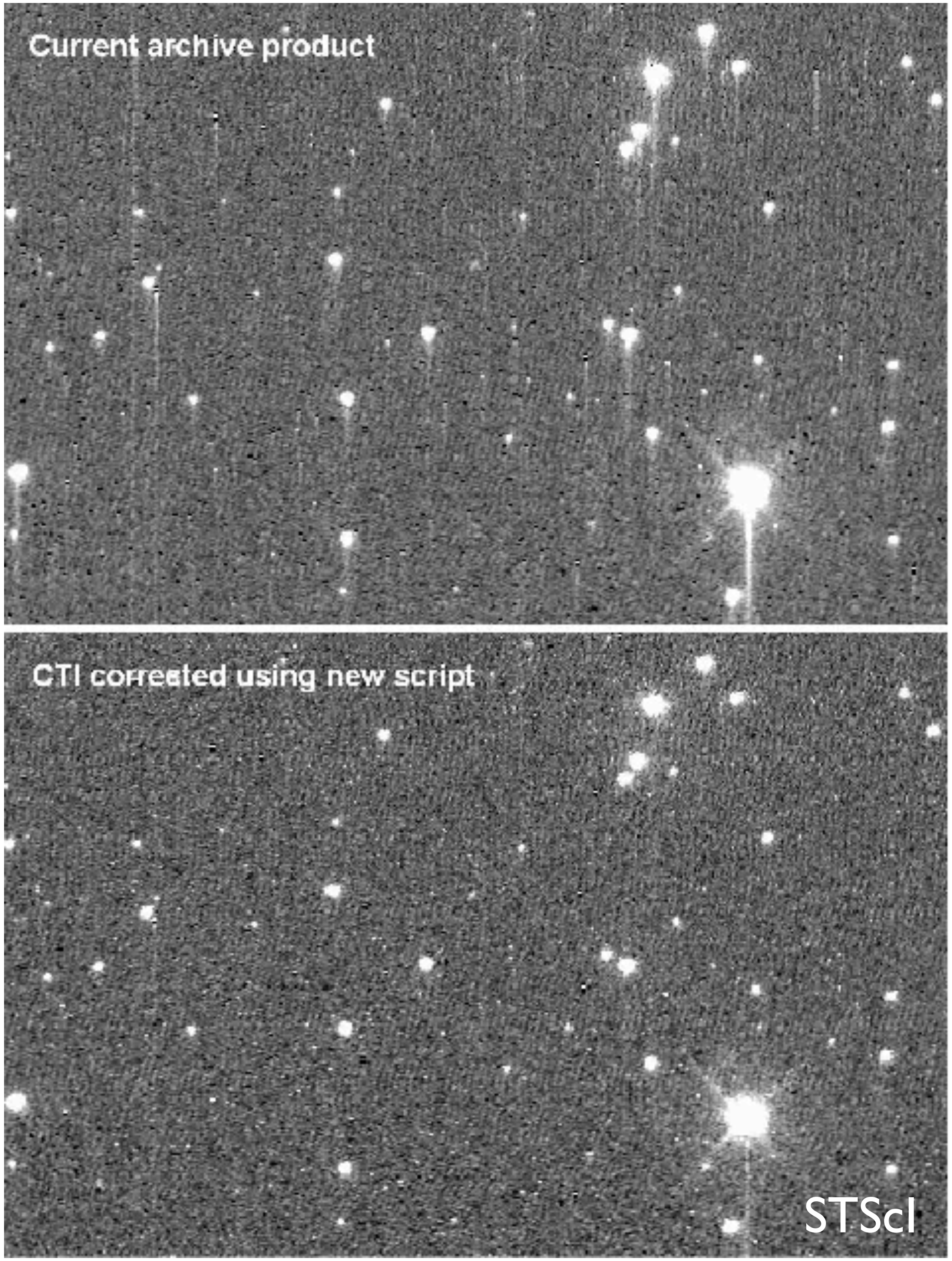
Artefacts

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

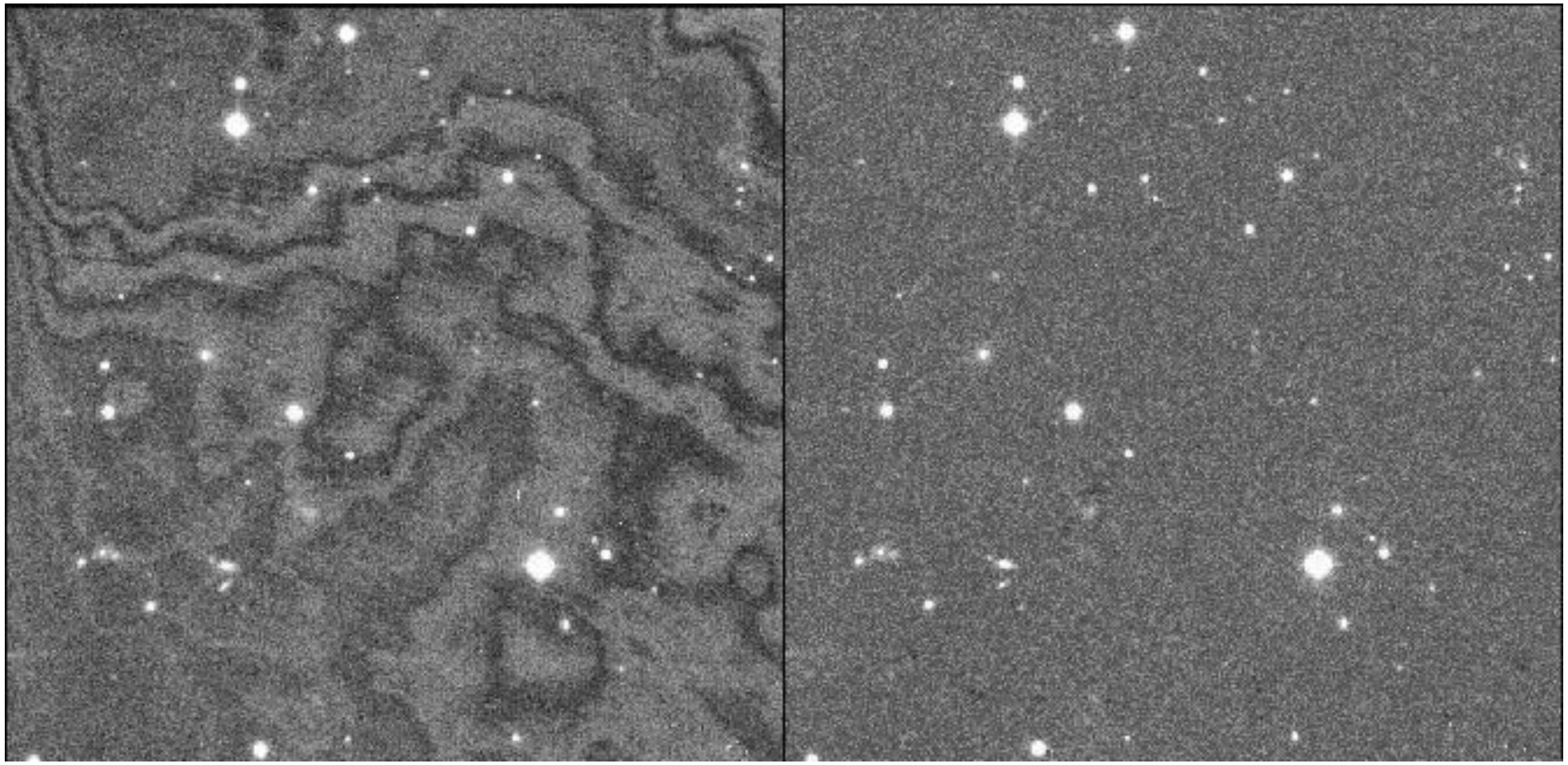
correction based on re-distributing charge



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)
- FITS is a standardized hdf5 format

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: NAXIS=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 = +0.00000000000E+000
APTDIA  = +3.56000000000E+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= -5.00000000000E+000
COLORCCD=                    0
DISPCOLR=                    1
IMAGETYP= 'Light Frame           '
CCDSEPT =                    1
```

```
OBSTDVER= 'SBFITSEXT Version 1.0'
FILTER  = 'Visual                '
EXPTIME = +1.00000000000E+001
EXPOSURE= +1.00000000000E+001
     CK =                  342
     TE =                  447
```

```
EXPSTATE=                  255
CCD-TEMP= -5.23215684599E+000
TEMPERAT= -5.23215684599E+000
INSTRUME= 'SBIG STL-1001 3 CCD Camera'
EGAIN   = +2.06000000000E+000
E-GAIN  = +2.06000000000E+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:

Specifying coordinates

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- 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

Specifying coordinates

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- 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:

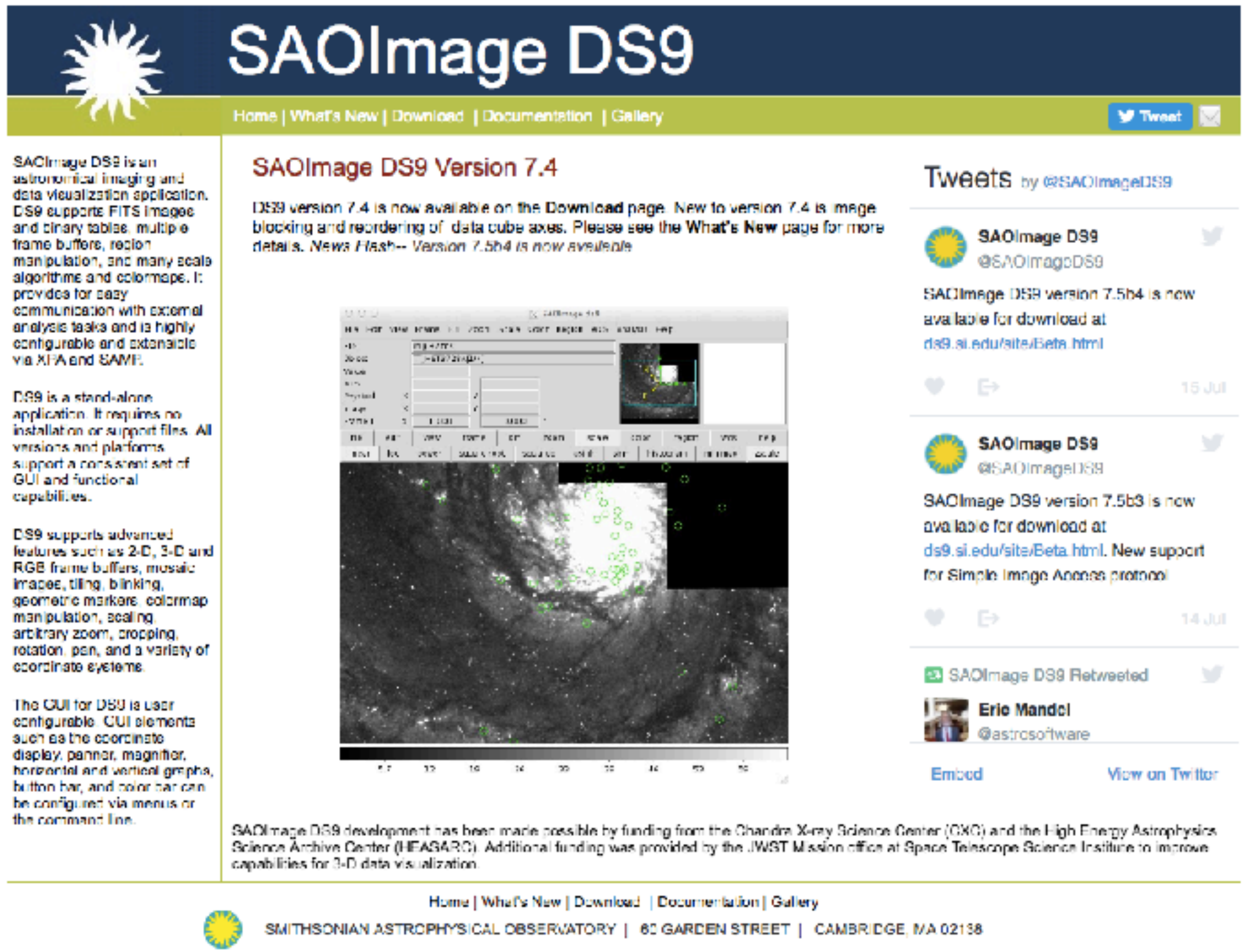
```
CTYPE1  = 'RA---TAN-SIP' / TAN (gnomic) projection + SIP distortions
CTYPE2  = 'DEC--TAN-SIP' / TAN (gnomic) projection + SIP distortions
EQUINOX =               2000.0 / Equatorial coordinates definition (yr)
LONPOLE =                180.0 / no comment
LATPOLE =                  0.0 / no comment
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 exoplanet lab

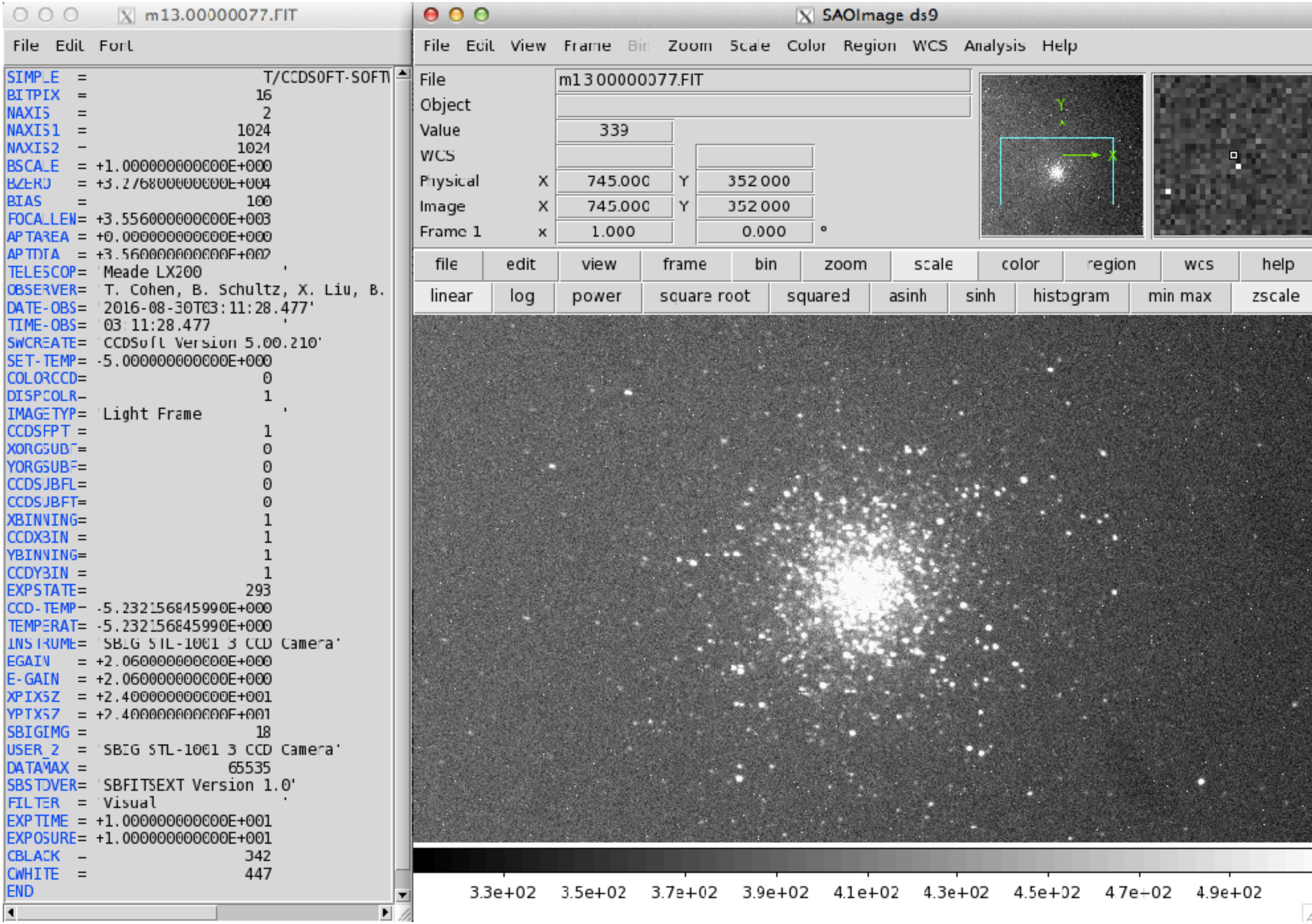
Viewing FITS images

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
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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), R, C, matlab, …
- 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
```

FITS image manipulation / math

- python: FITS file handling part of astropy (see tutorial)
- R: FITSio package
- matlab: fitsread, etc.
- C: cfitsio library

command line:

- FTOOLS, e.g.:

```
ftpixcalc out.fits "(a-b)" a=img1.fits b=img2.fits
```

Python Tutorials

github.com/anjavdl/PHY517_AST443/wiki/Python

There are a number of ways of working with python, in particular:

1. interactively on the command line (shell mode)
2. with python programs / scripts
3. through jupyter notebooks
4. through Google Colab notebooks

Shell mode

In shell mode, you simply type the command `python` or `python3` into a terminal, which will print some details about the version of python you have installed, the date, and the commands for how to get help, credits, and licensing information. The terminal will show `>>>`, which means you can now type in python commands and the interpreter will execute those commands. Note that on the Computing Lab machines, `python` invokes python2.7, so you need to call `python3` to get python3.

Python programs / script

The second way to use python is in script mode. You write a text file containing all of the python commands you want python to execute, in the order that you want them done. After you save this file, which is called a script, you type python into a terminal with your script filename as the first argument, and the python interpreter reads the script and executes it line by line. An example is the rdj2aau.py script that you can use to convert a list of RA, Dec, JD to azimuth, altitude, and UT date. In this case it takes two additional filenames for the input and output files:

```
python rdj2aau.py in.txt out.txt
```

Jupyter notebooks

Jupyter notebooks are a great way to keep code organized and documented. Jupyter can be used with several kernels, including python. Please see here for further instructions specific to this class.

Python Tutorials

and/or github, and thus to work collaboratively on code. Our experience shows that if you need a particular python package for your project, it is much easier to ``install'' it on Google Colab than your own computer or the Computing Lab.

Python tutorials for this class

General python tutorial
Data file for python tutorial: test_data.txt

Python notebook on reading FITS files, numpy, plotting histograms.
Fits files: 00000025.BIAS.FIT , 00000026.BIAS.FIT

Older tutorials in python 2.7: Python primer, notebook

Installing python on your laptop

Python is available for all common operating systems. The easiest way to install it is through anaconda. Anaconda includes all the packages needed for this lab, in particular numpy and astropy. Anaconda does take up significant disk space, so instead you could install miniconda along with the packages you need.

Python on the Astro Computing Cluster

By default, `python` on uhura starts `python2.7`. To get the latest `python3`, along with the latest versions of `astropy`, `numpy`, `scipy` and `matplotlib`, you should install in your own copy of `python3` through `miniconda` as follows (video version of these instructions):

1. Download Miniconda Linux 64 bit installer for linux from https://docs.conda.io/en/latest/miniconda.html#linux-installers.
2. Copy the Miniconda installer to your astrolab directory, e.g. `/astrolab/Fall_21/aeinstein` (replace `Fall_21/aeinstein` with the appropriate path to your data directory).
3. Run the Miniconda installer with bash, e.g. `/usr/bin/bash Miniconda3-py39_4.10.3-Linux-x86_64.sh` When prompted for the install directory YOU MUST SUPPLY YOUR astrolab directory, e.g. `/astrolab/Fall_21/aeinstein/conda`. Say "yes" to the prompt about initializing Miniconda3. The Miniconda installer

Python Tutorials

tutorials are in jupyter notebook format

on your laptop:

- if you installed python through anaconda on your laptop, jupyter is included
- python is not installed on your laptop? try google colab

on the machines in the computing lab:

- python3.9 is installed as default python
- to use jupyter, follow instructions for remote set-up on jupyter wiki tab

Preparing for your observations

Exoplanet lab 2 (photometry)

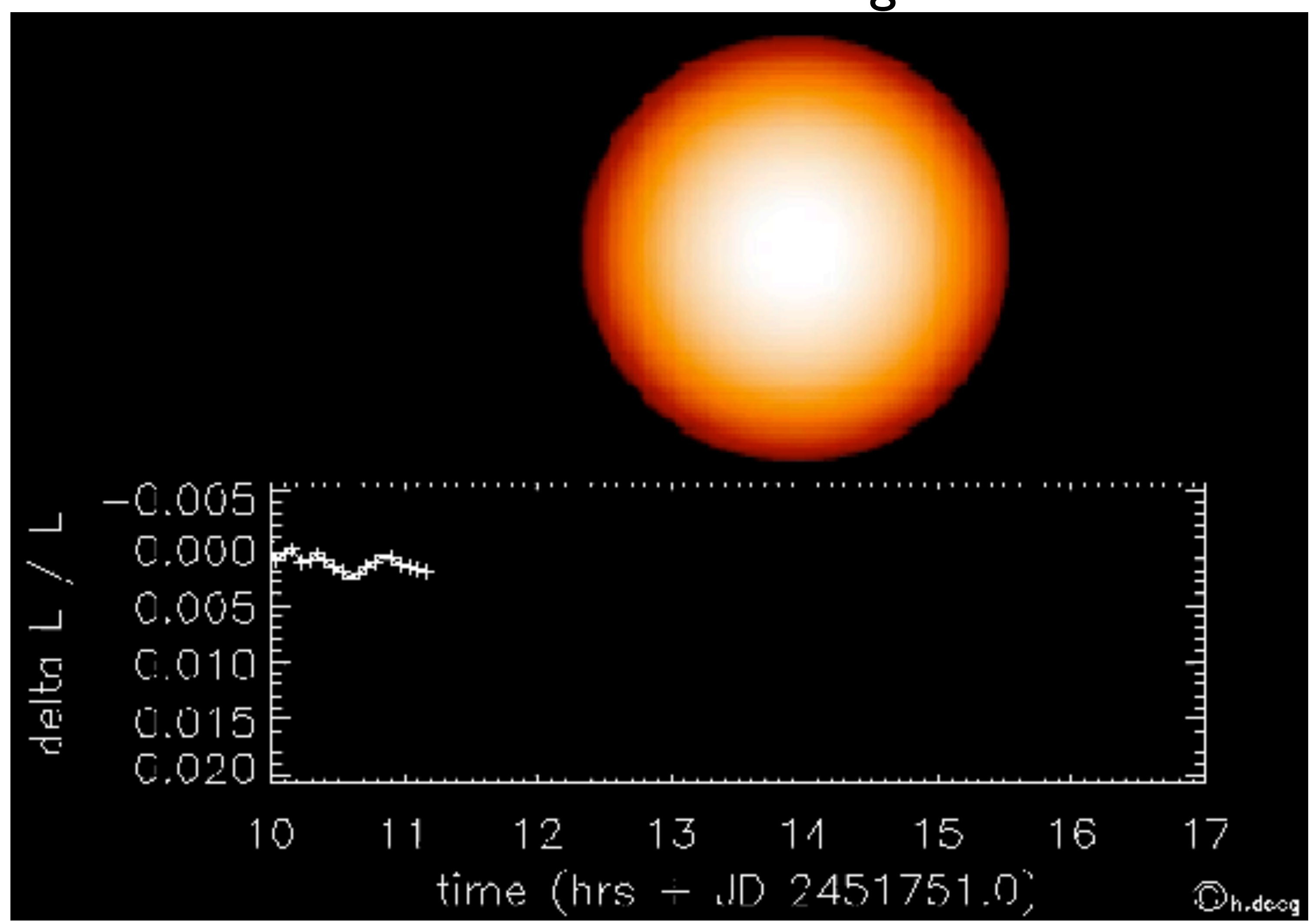
If you have not done so, please get started on predicting transits!

(It takes a while to get right!)

Preparation

Start preparations for Lab 2:
- optical astronomical imaging
- time-series photometry
- detect an exoplanet transit!

Deeg & Garrido 2000



method: detect the *relative* drop in flux from the host star

Preparation

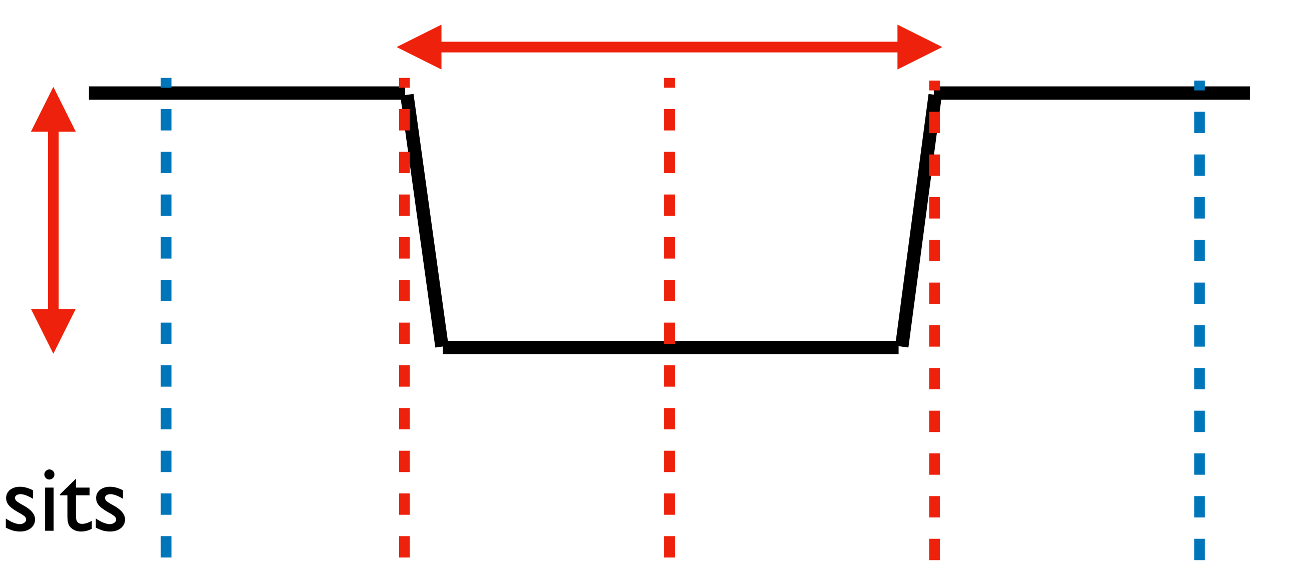
database of all known exoplanets, pre-selected for transiting exoplanets:

http://exoplanet.eu/catalog/all_fields/

select planets detected via "primary transit" and download the catalog

need to calculate:

- transit depth
- transit duration
- mid-points of future transits
- ingress + egress times
- start + end of observations



Preparation

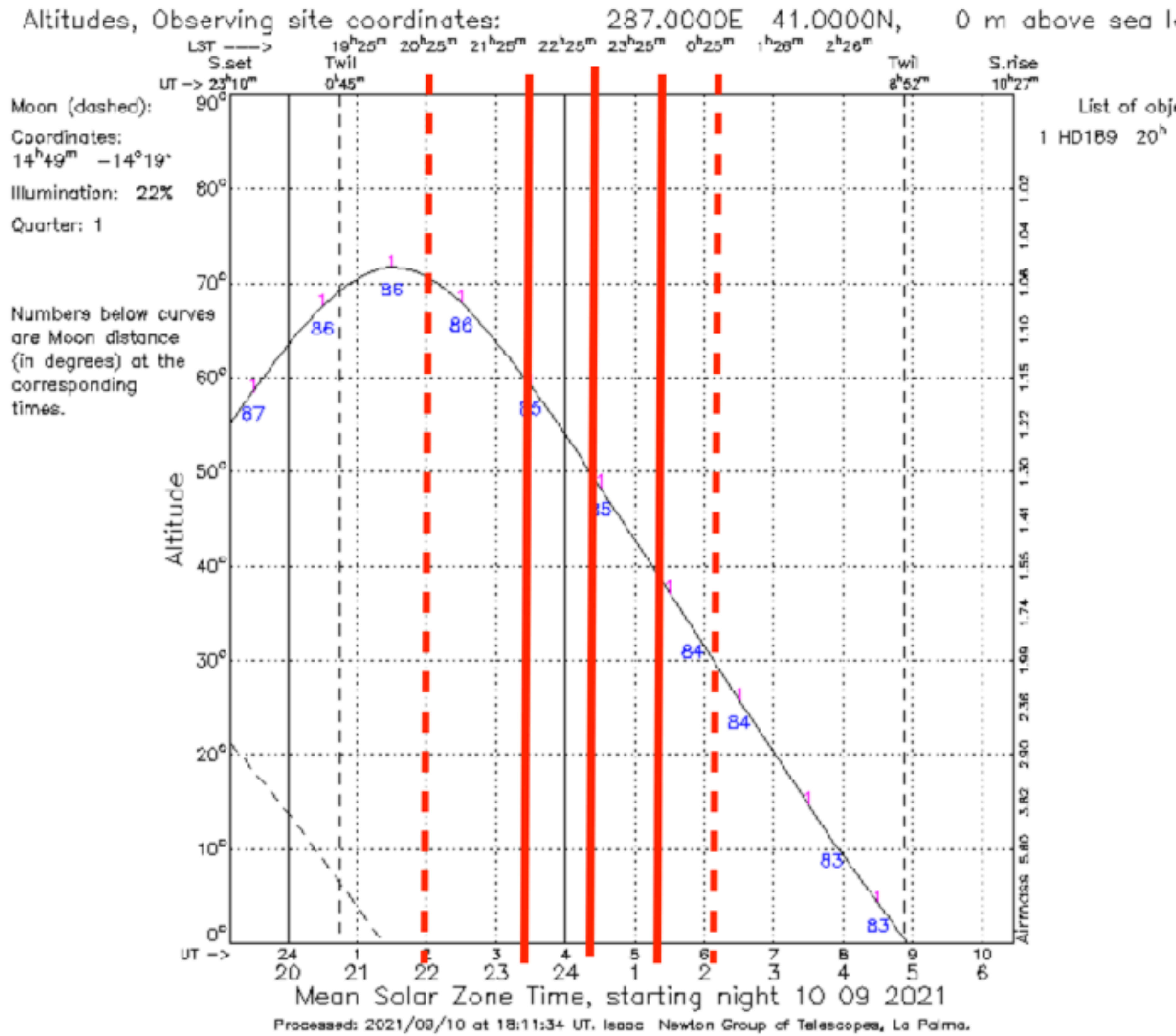
pick suitable targets:

- which host stars are visible from Mt Stony Brook?
- ... at night-time in the next ~month?
- is the transit depth large enough? (at least 0.008 flux drop)
- is the host star bright enough? ($V<12.5$)

Preparation

need to observe ~1h before, and ~1h after

set-up takes about 2 hours; your star needs to be visible for much of that



Preparation

triple-check your calculations!!!

pick 3 transits / observing nights between now and Oct. 05 (spread out to accommodate the weather), e-mail your request to me (first-come, first-serve)

- observing dates have to be AFTER your Lab 1 date
- the earlier you get your data, the better

check observing calendar (link on github wiki) for full moon and dates already taken

excerpt from Mt. Stony Brook observing calendar