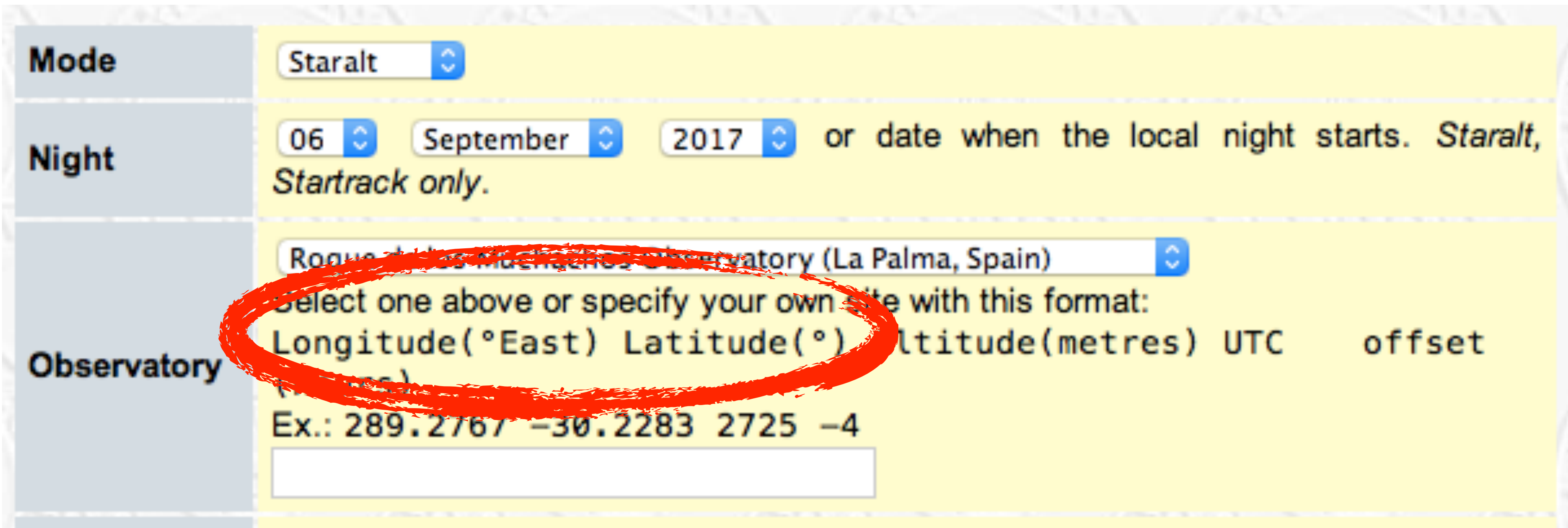
PHY 517 / AST 443:
Observational Techniques in Astronomy

Lecture 3:
CCDs /
FITS files

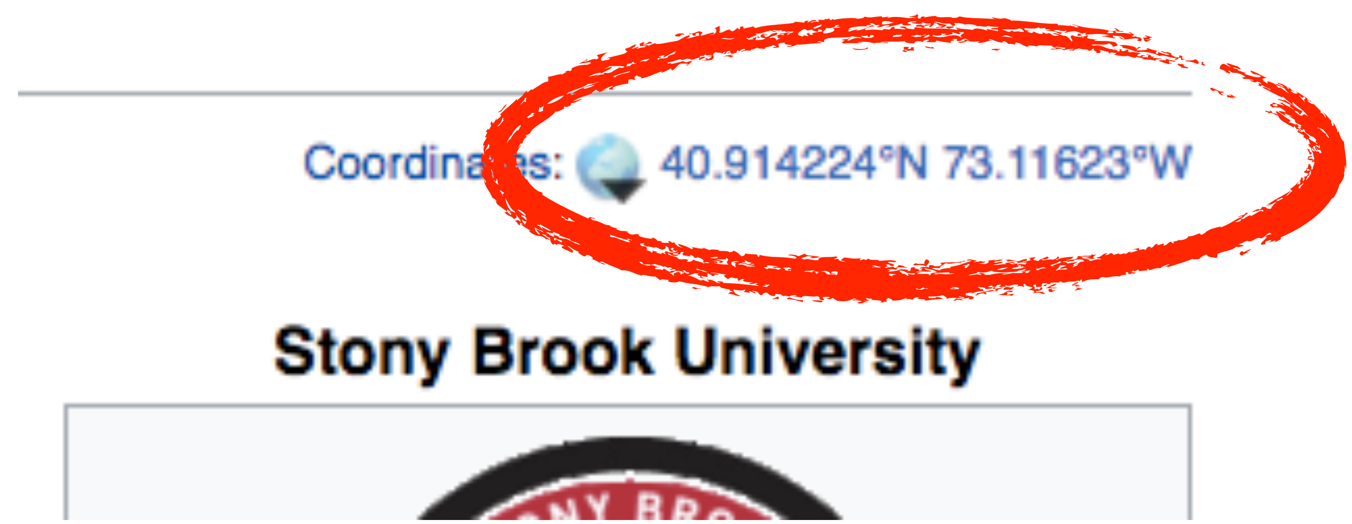
StarAlt

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



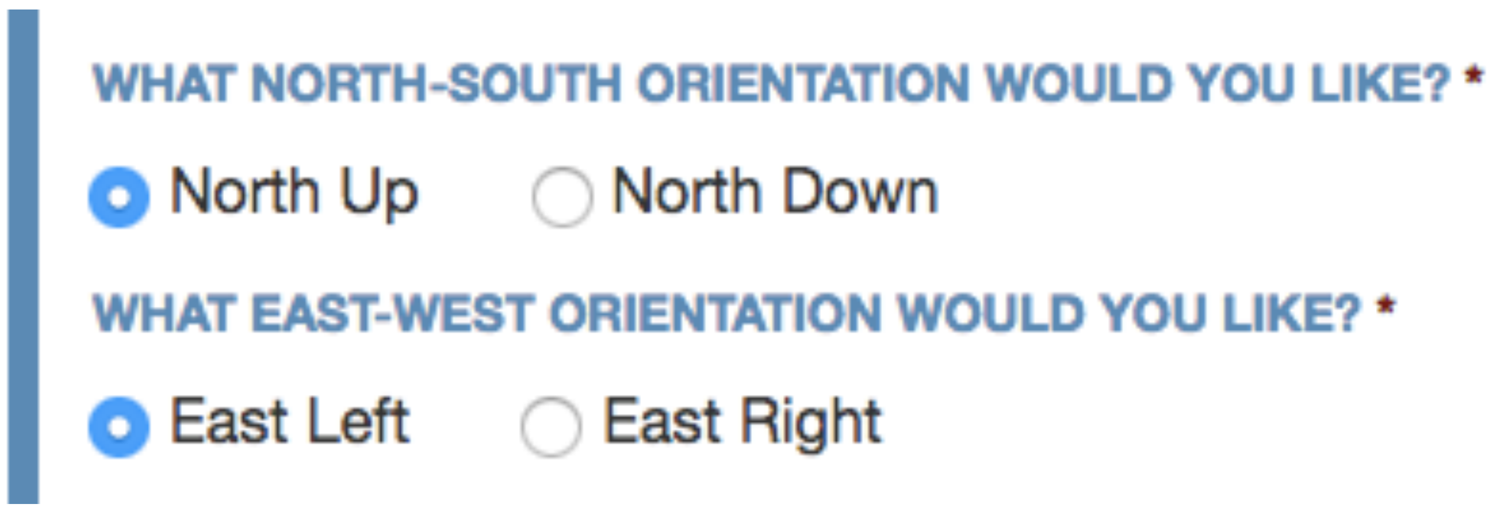
How are Mt. Stony Brook's coordinates correctly specified?

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"



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!

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/Spring_2021/*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

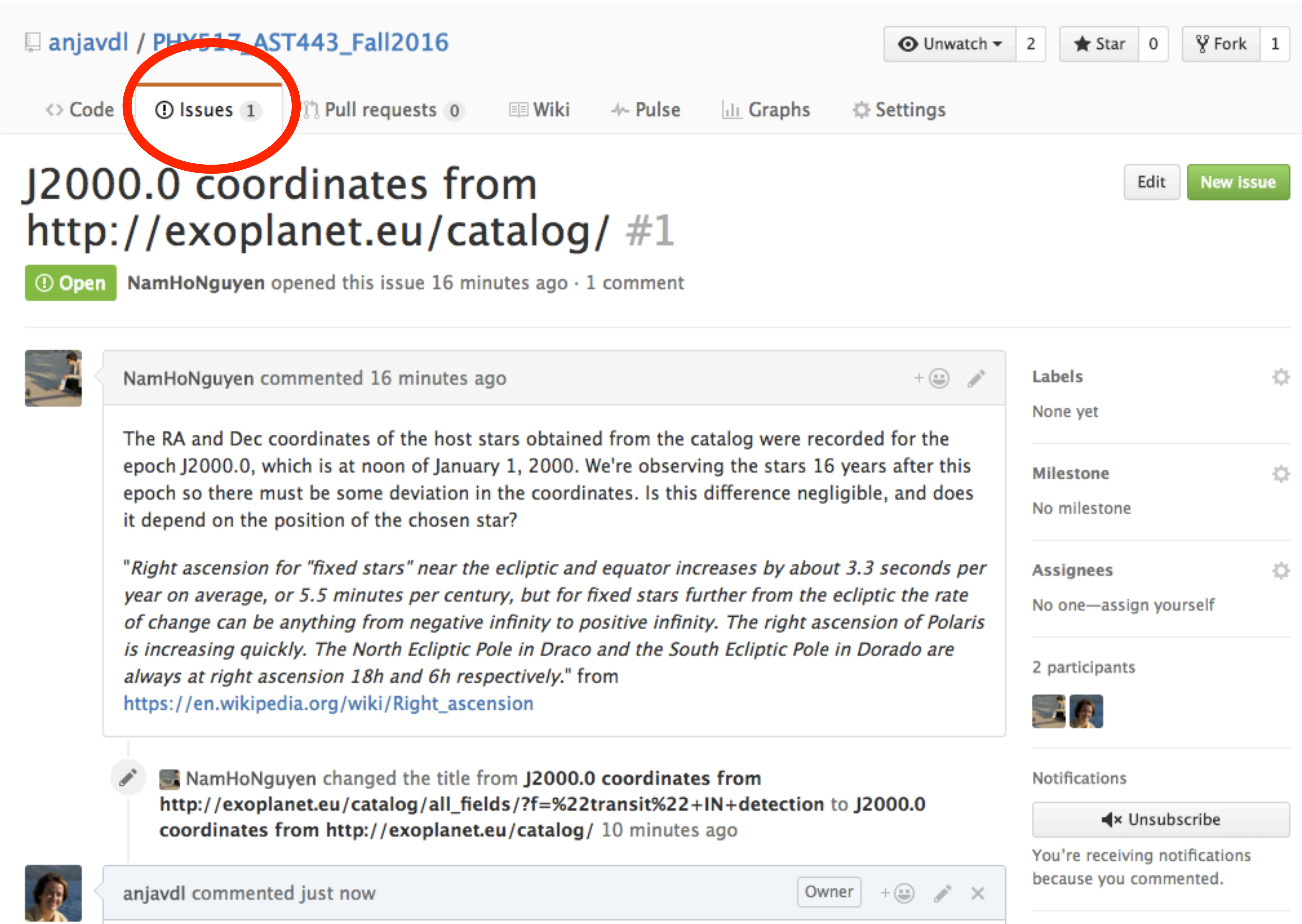
Github

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

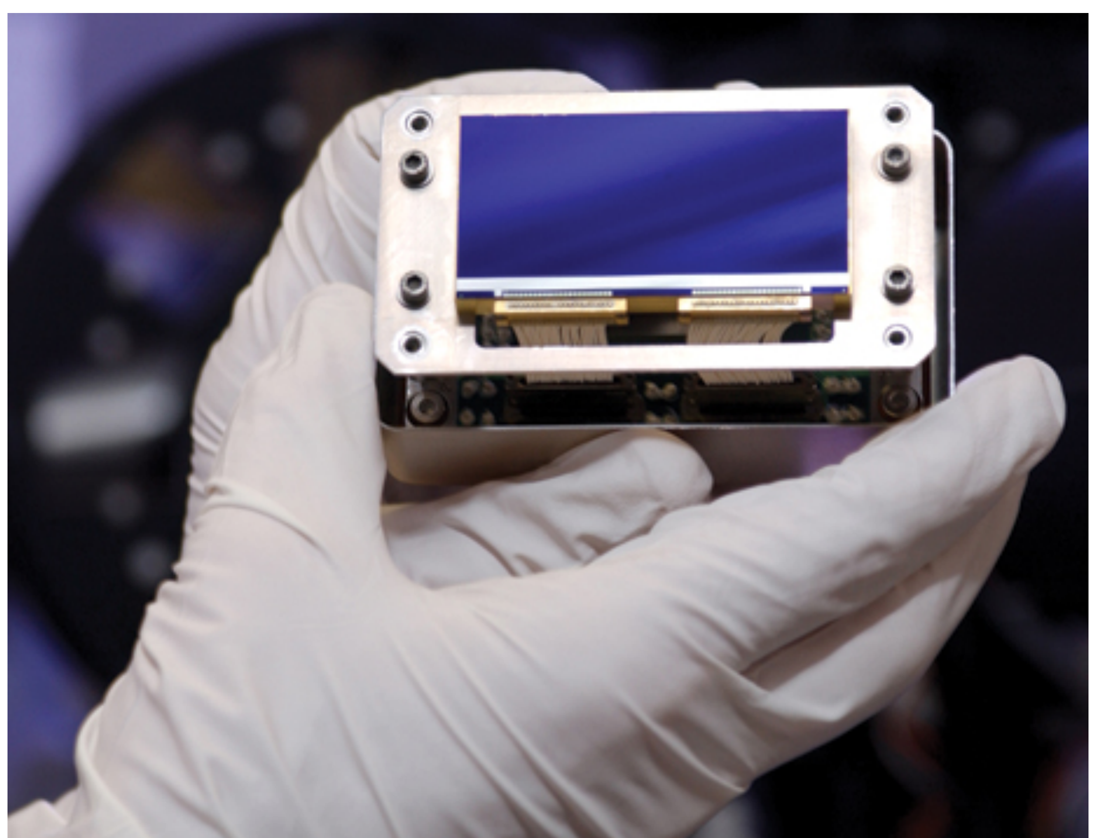
announcements, bug reports, "issue" discussions will take place on github - you will only be notified if you are "watching" the class repository


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.

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

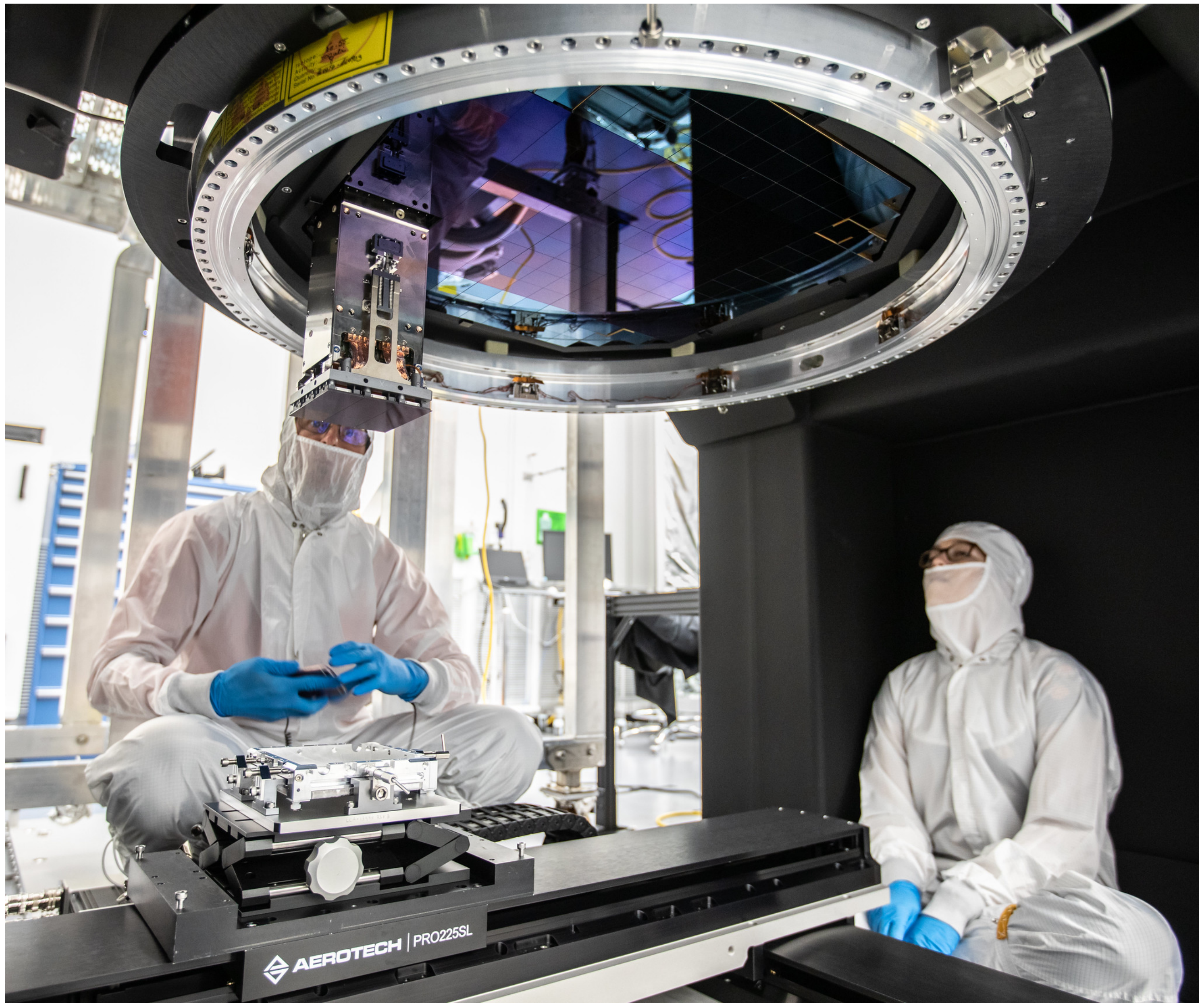


e2v

Figure 3. Kepler CCD in handling jig.

CCDs - Advantages

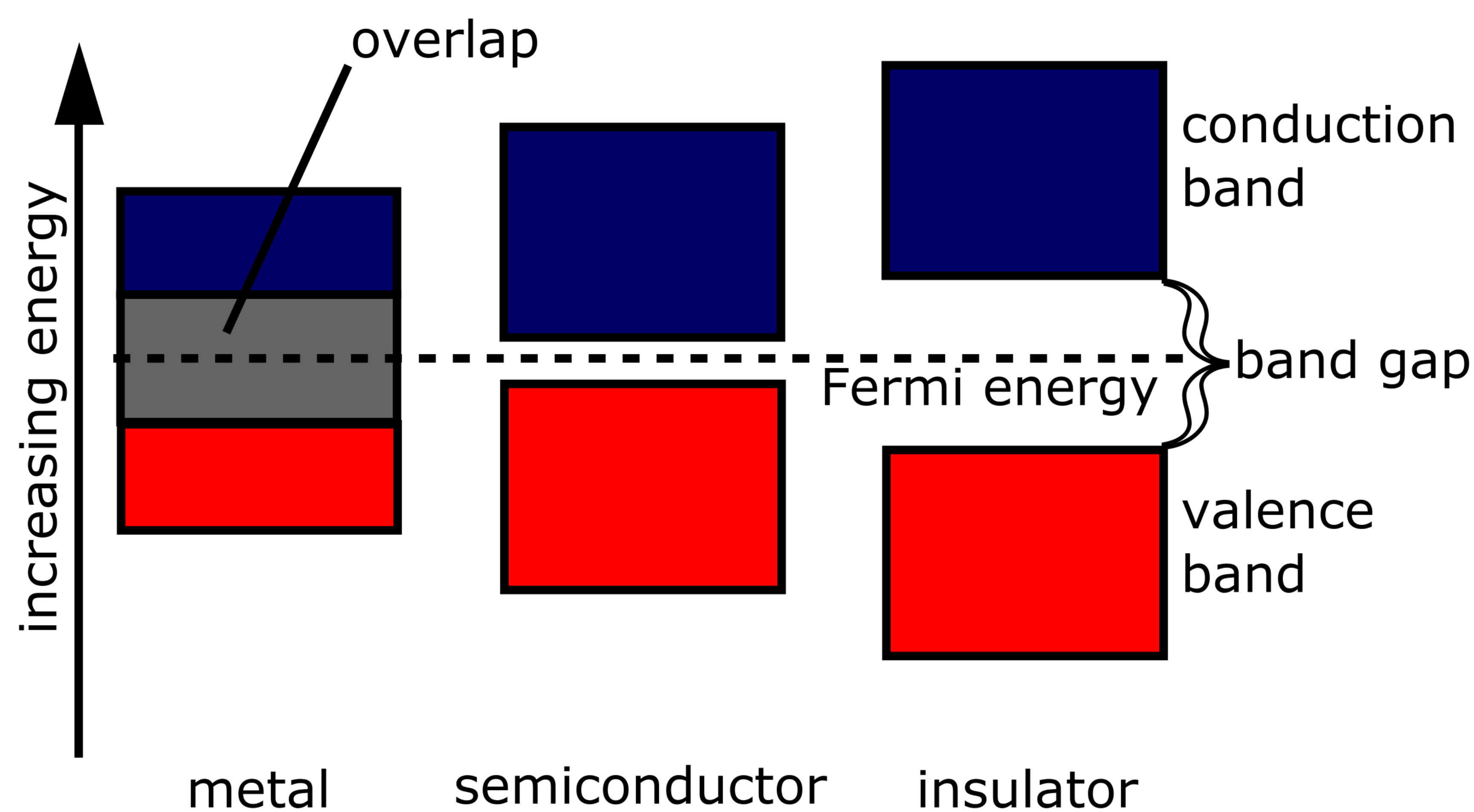
- (nearly) linear response $N_{\text{electrons}} \propto N_{\text{photons}}$
- high sensitivity
- low noise (especially when cooled)
- built-in digitization



LSST Camera at SLAC

Semi-Conductors

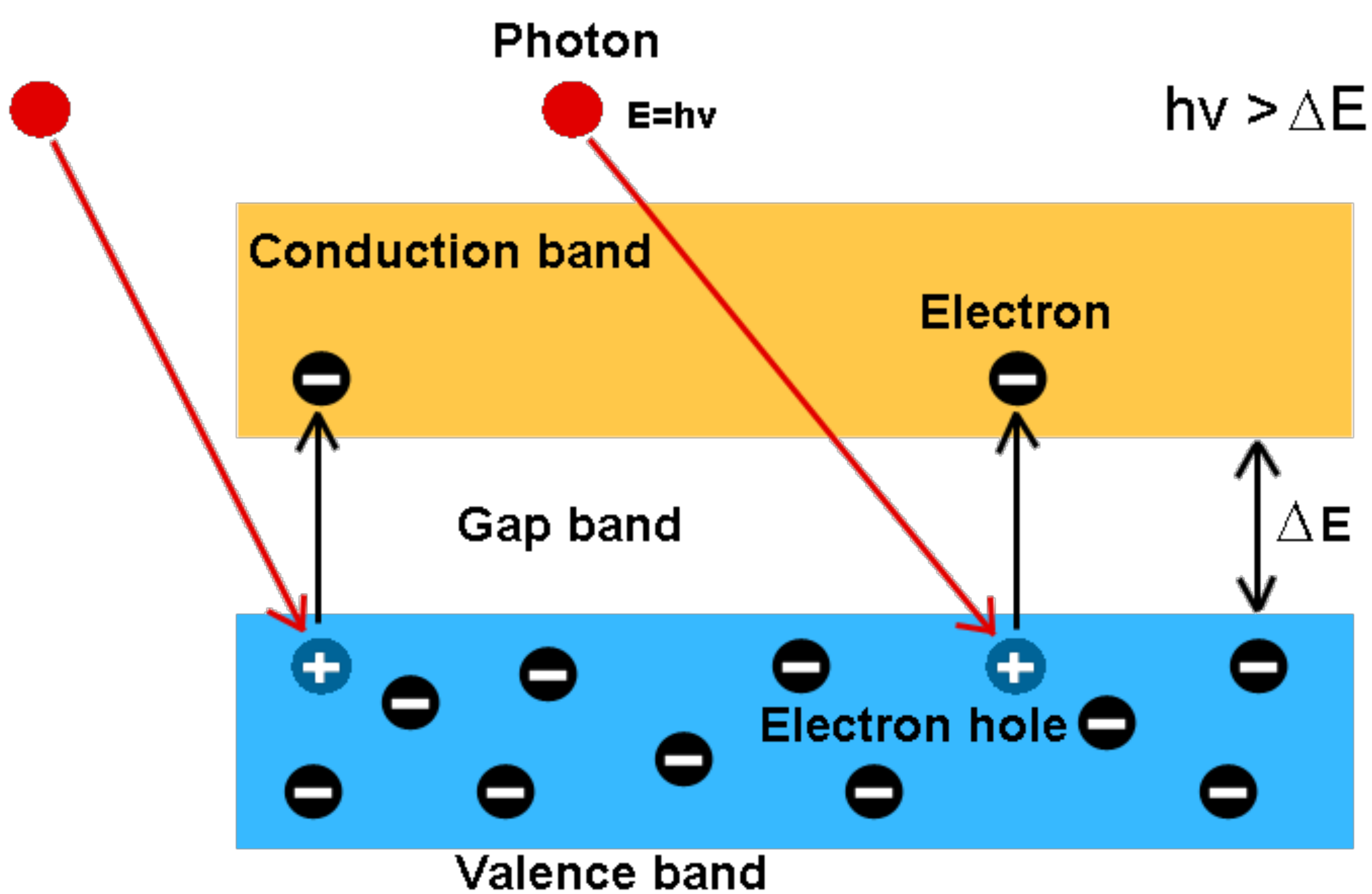
- CCDs are made of semi-conducting silicon wafers
- key feature: small energy gap between "valence band" (energy levels of outermost bound electrons) and "conduction band" (energy levels of free electrons)



wikipedia

Photoelectric effect

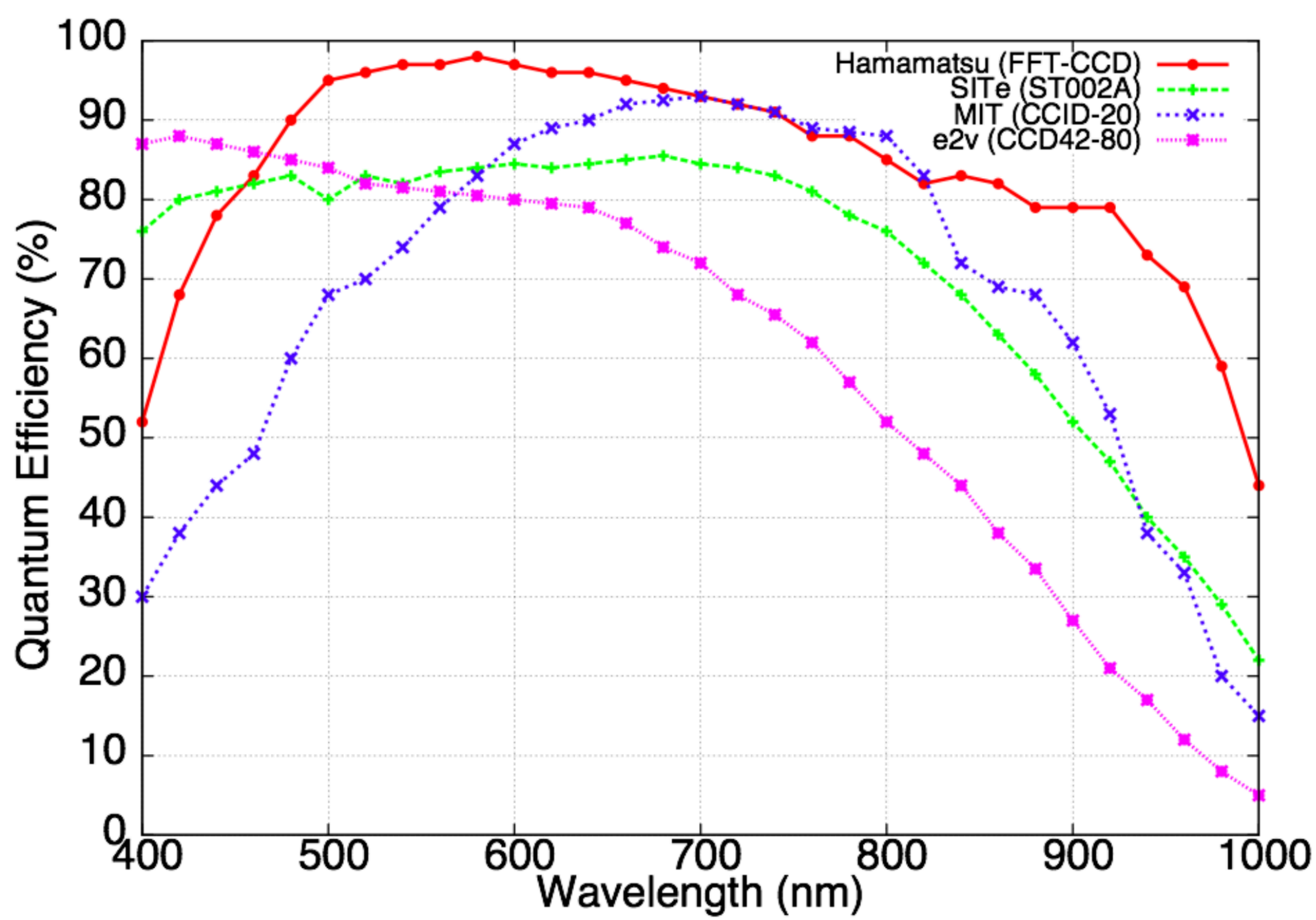
- light is quantized, "photons" $E = h\nu$
- when a photon is absorbed, the energy is transferred to an electron → "jumps" into conduction band



M. Poblocki

CCD Quantum Efficiency (QE)

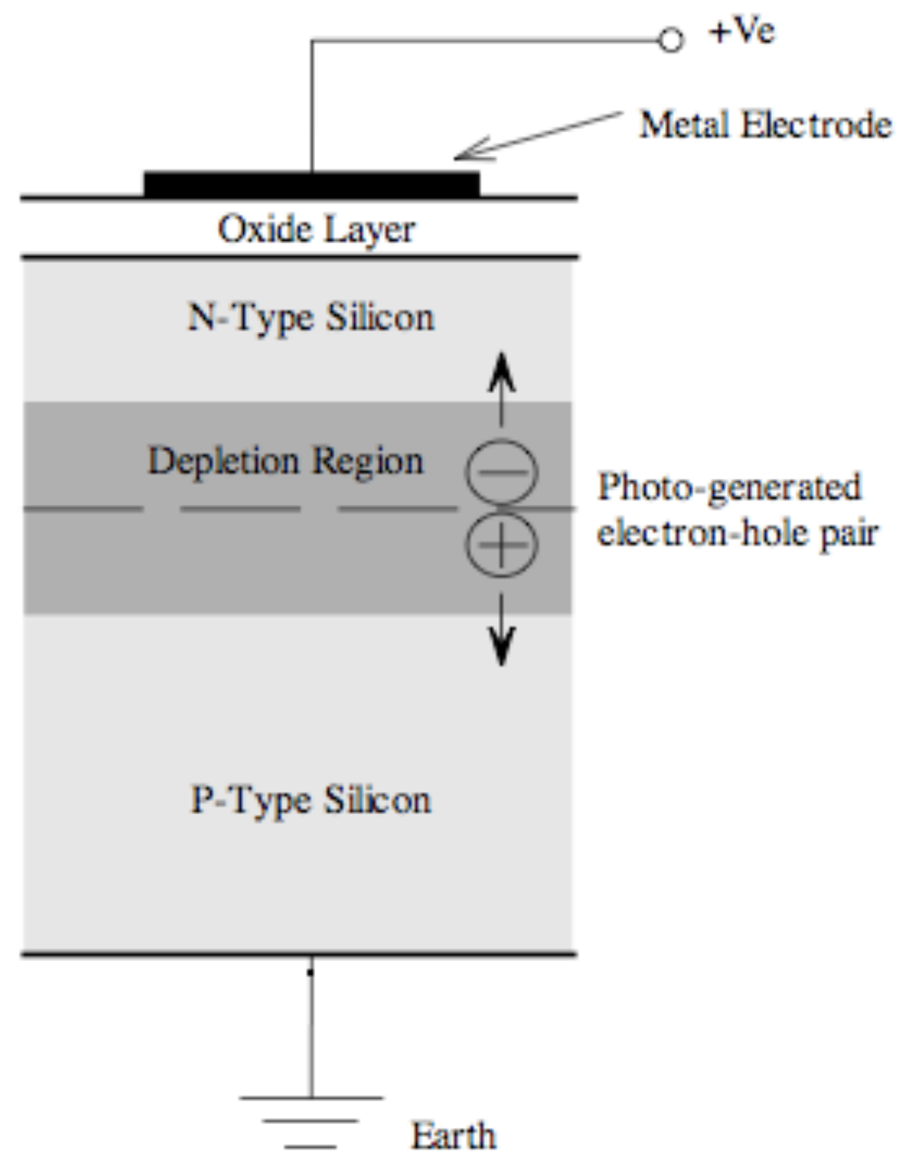
- fraction of photons that are detected
- depends on wavelength
- different technologies lead to red vs. blue optimized CCDs



Nakao et al. 2014

One pixel

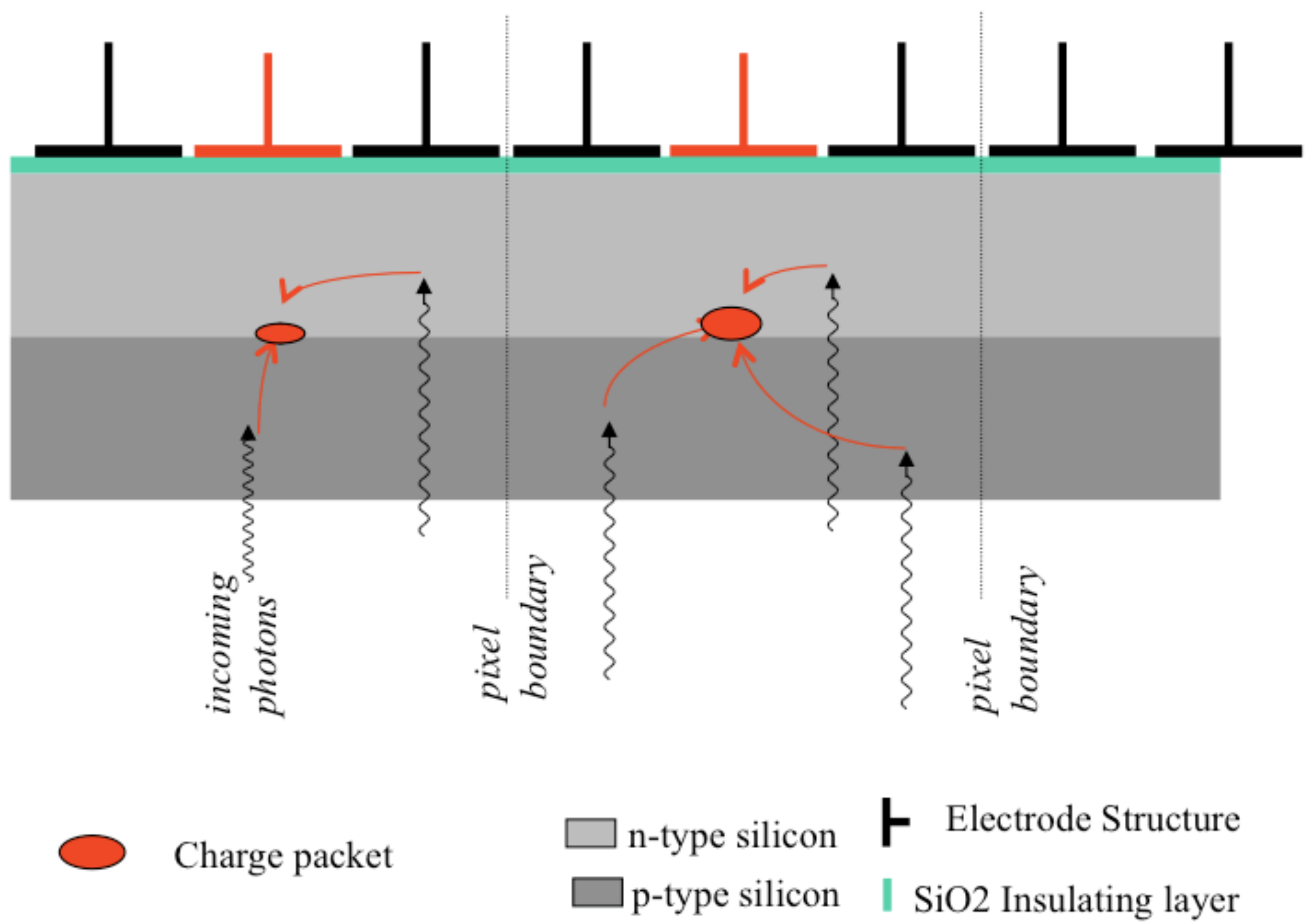
- apply an electric field to keep electrons / holes separated



Microsoft

Many pixels

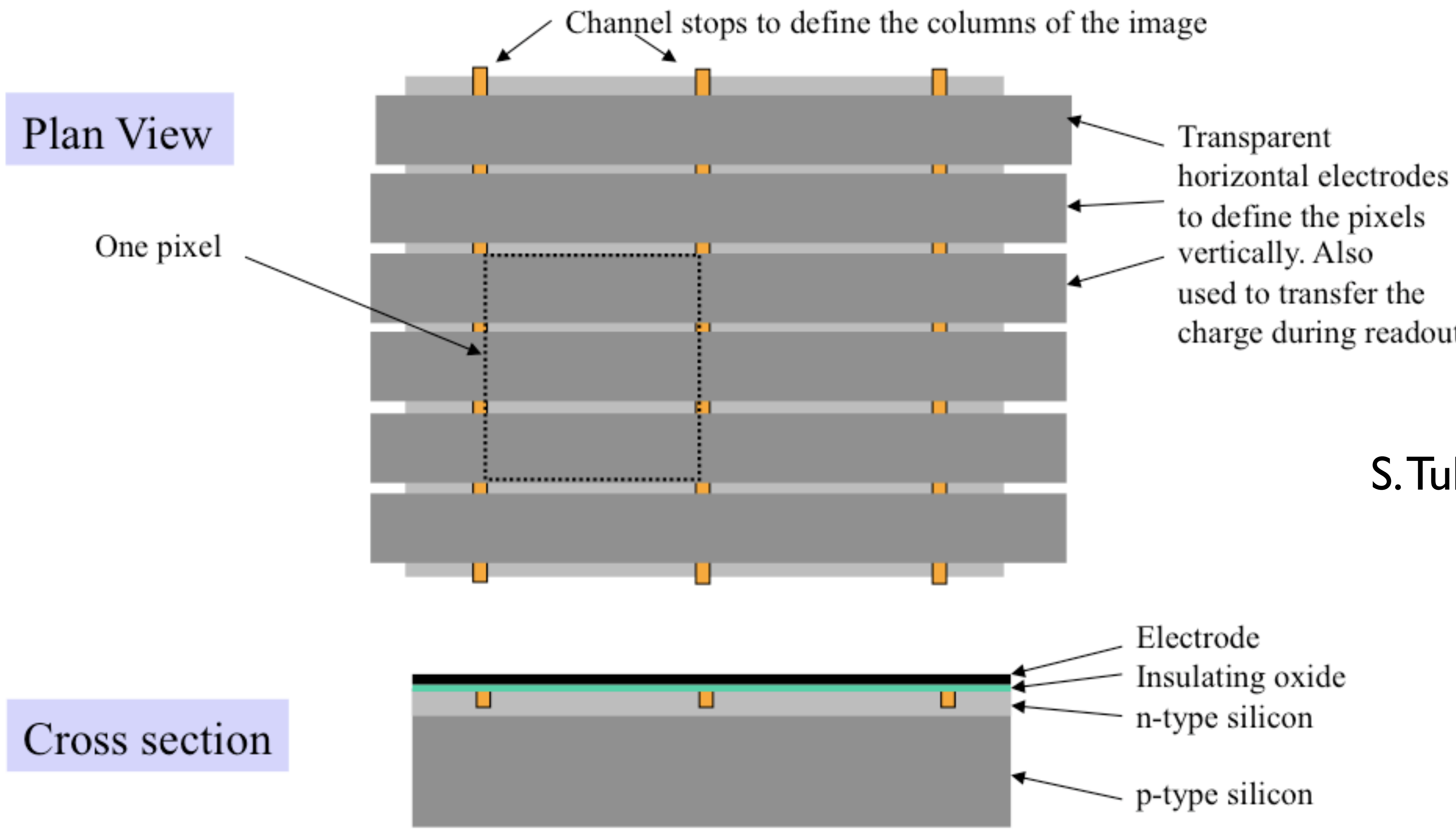
- pixels are defined by the electric field generated by the applied electrodes



S. Tullock

Many pixels

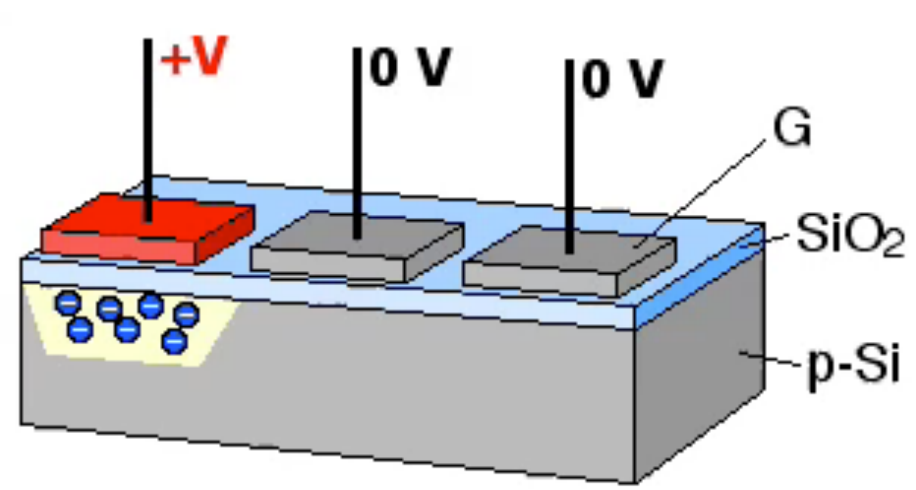
- … and by insulator strips between columns



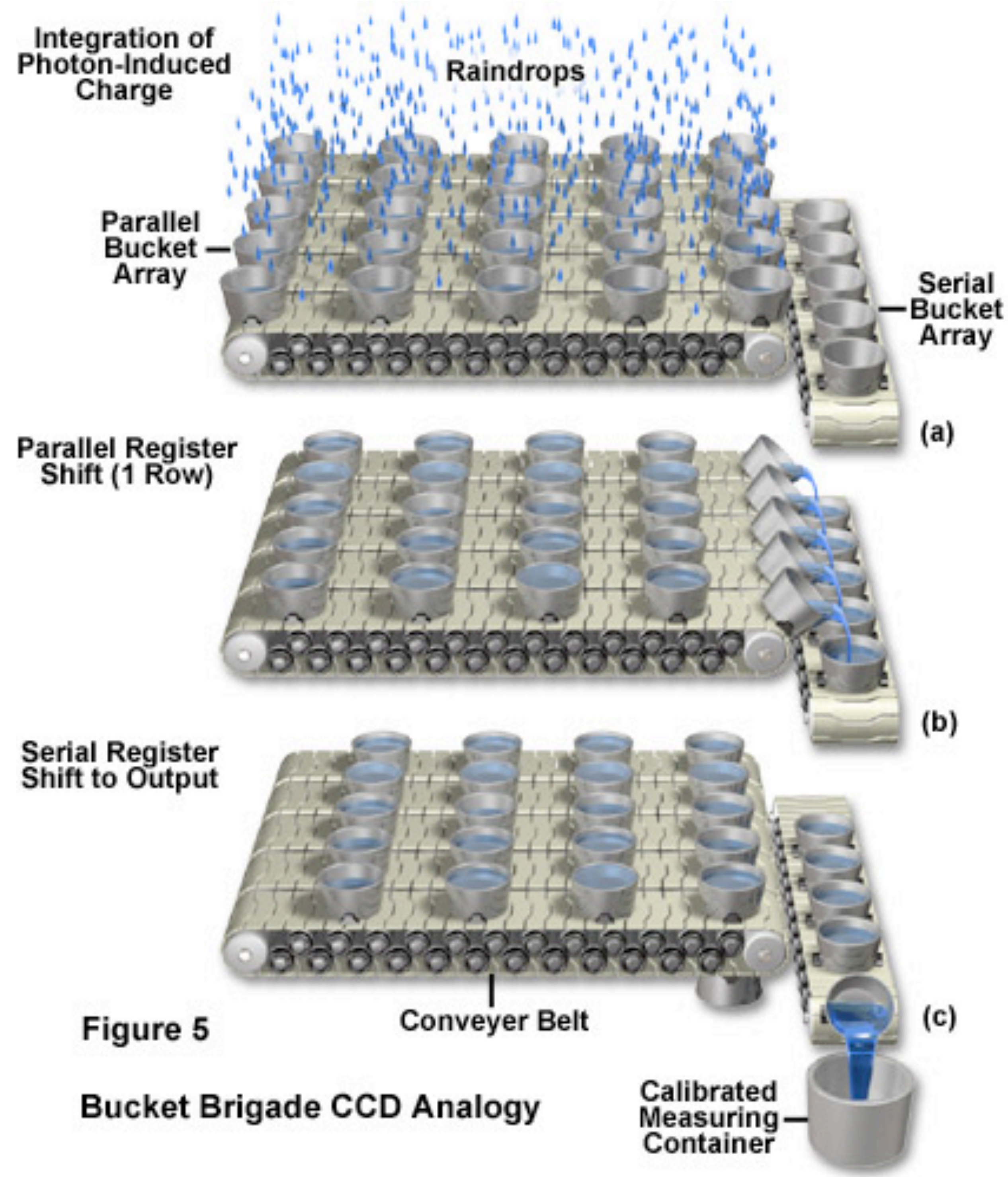
S. Tullock

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

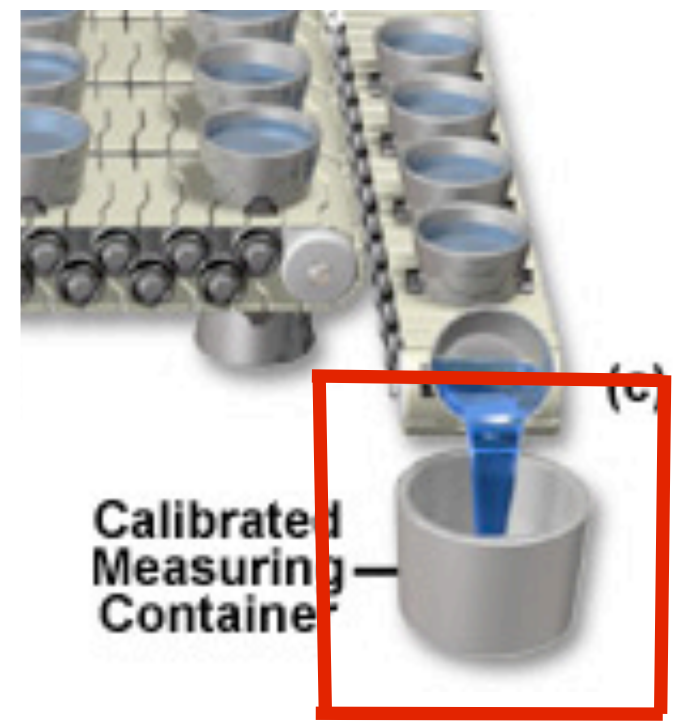


Cold Spring Harbor Protocols

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

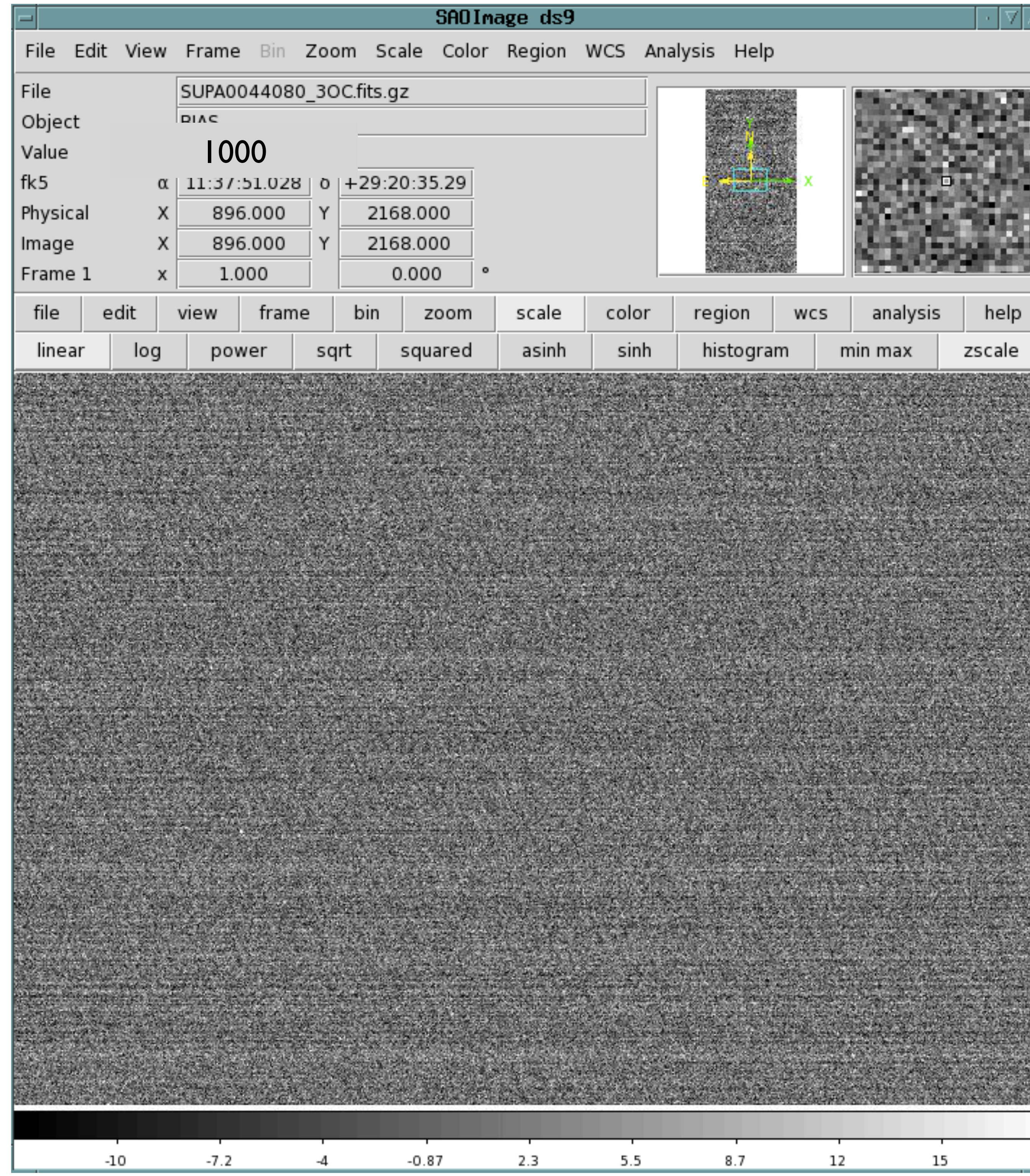
Bias level

- 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])

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



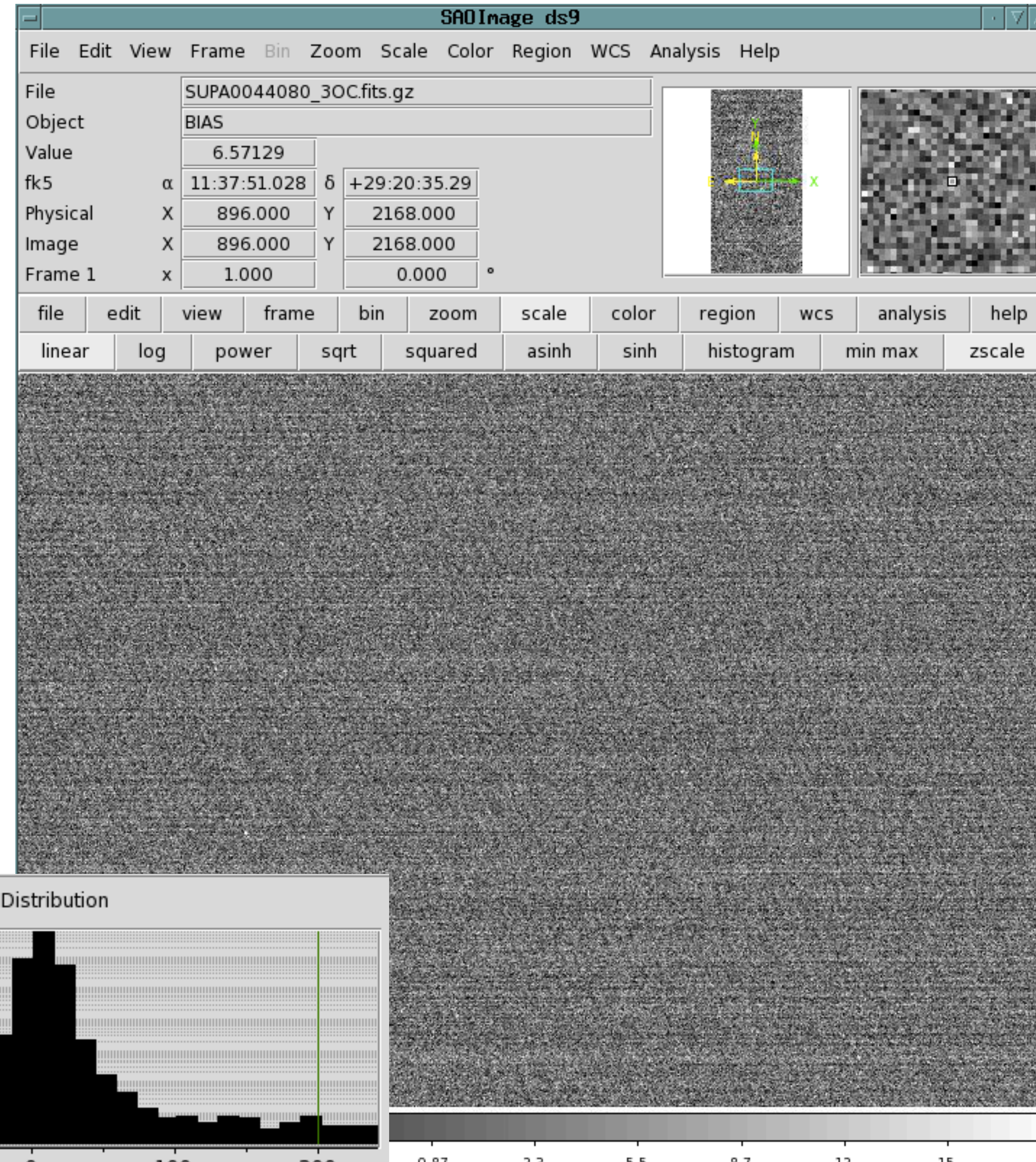
A. von der Linden

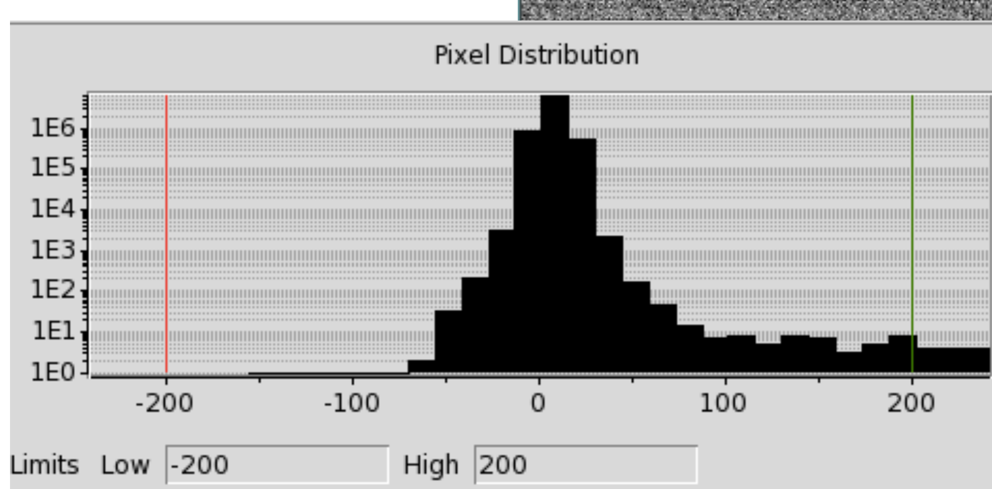
Overscan region

- 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)

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

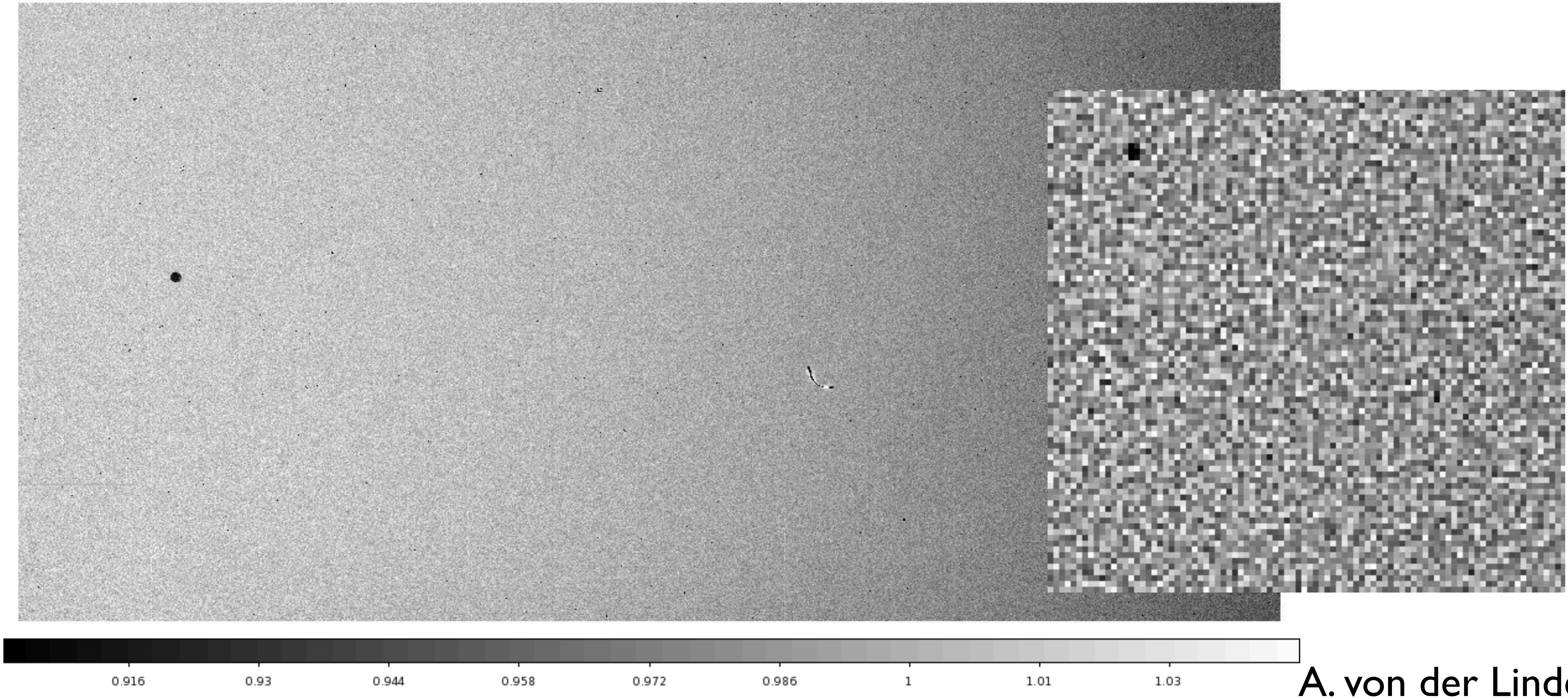
- the pixels in a CCD do *not* have uniform sensitivity
- due to variations in silicon crystal, electric field, pixel size, illumination (vignetting)

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

- 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 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

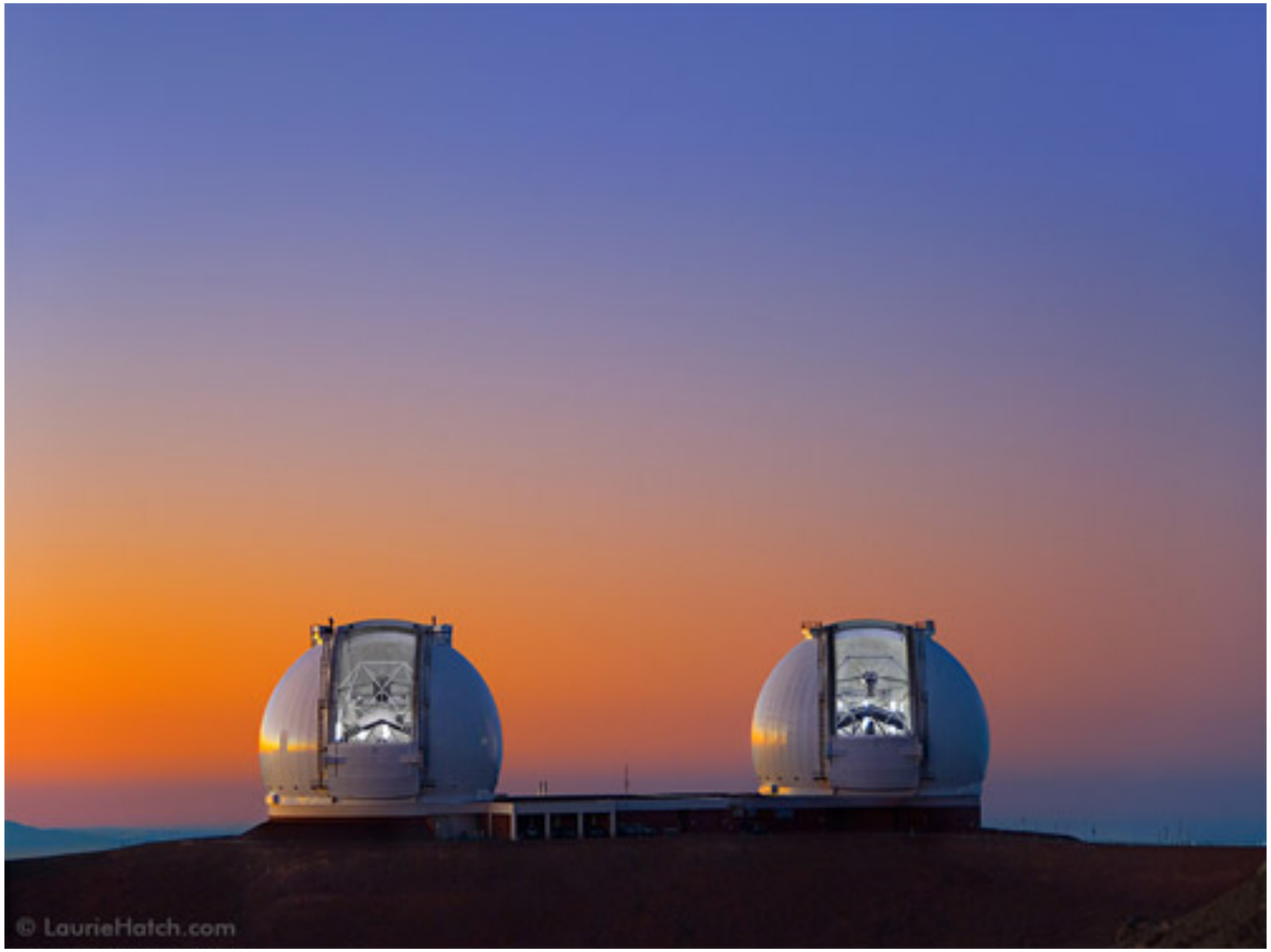
twilight flats:

✓ same “source”

✓ almost uniform

– variable

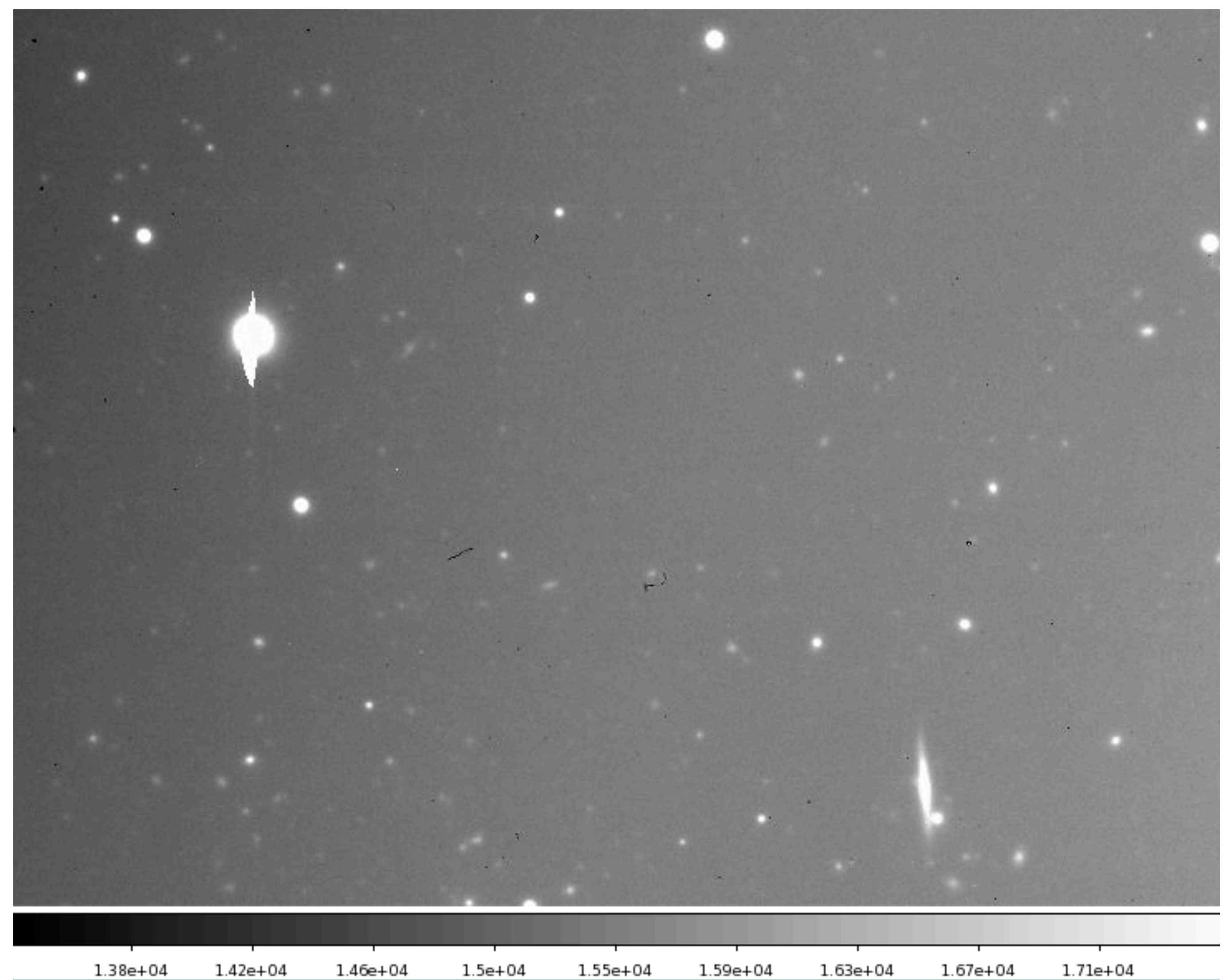
– difficult



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)



✓ most similar to data

✓ uniform

– need "empty" fields

– need a lot of images

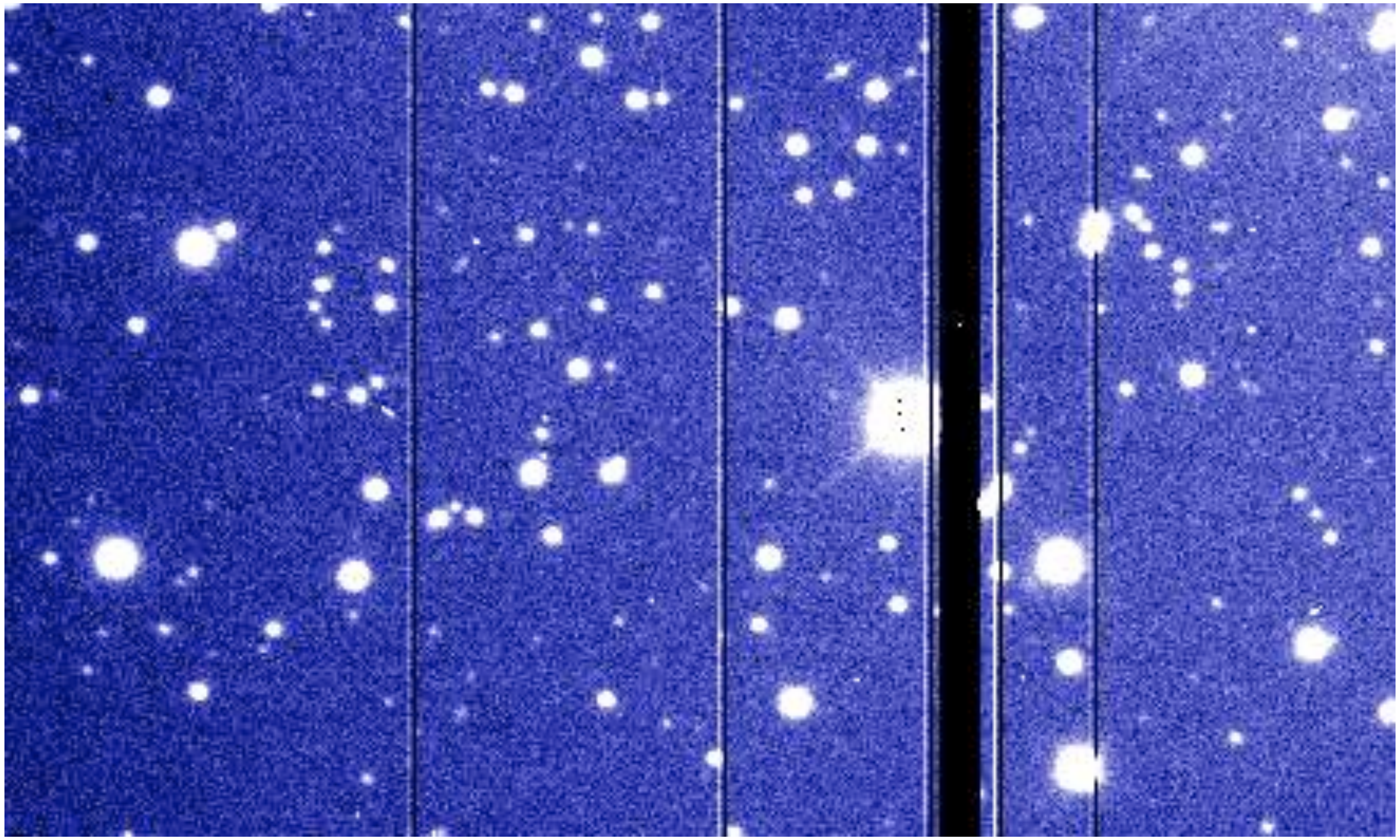
A. von der Linden

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

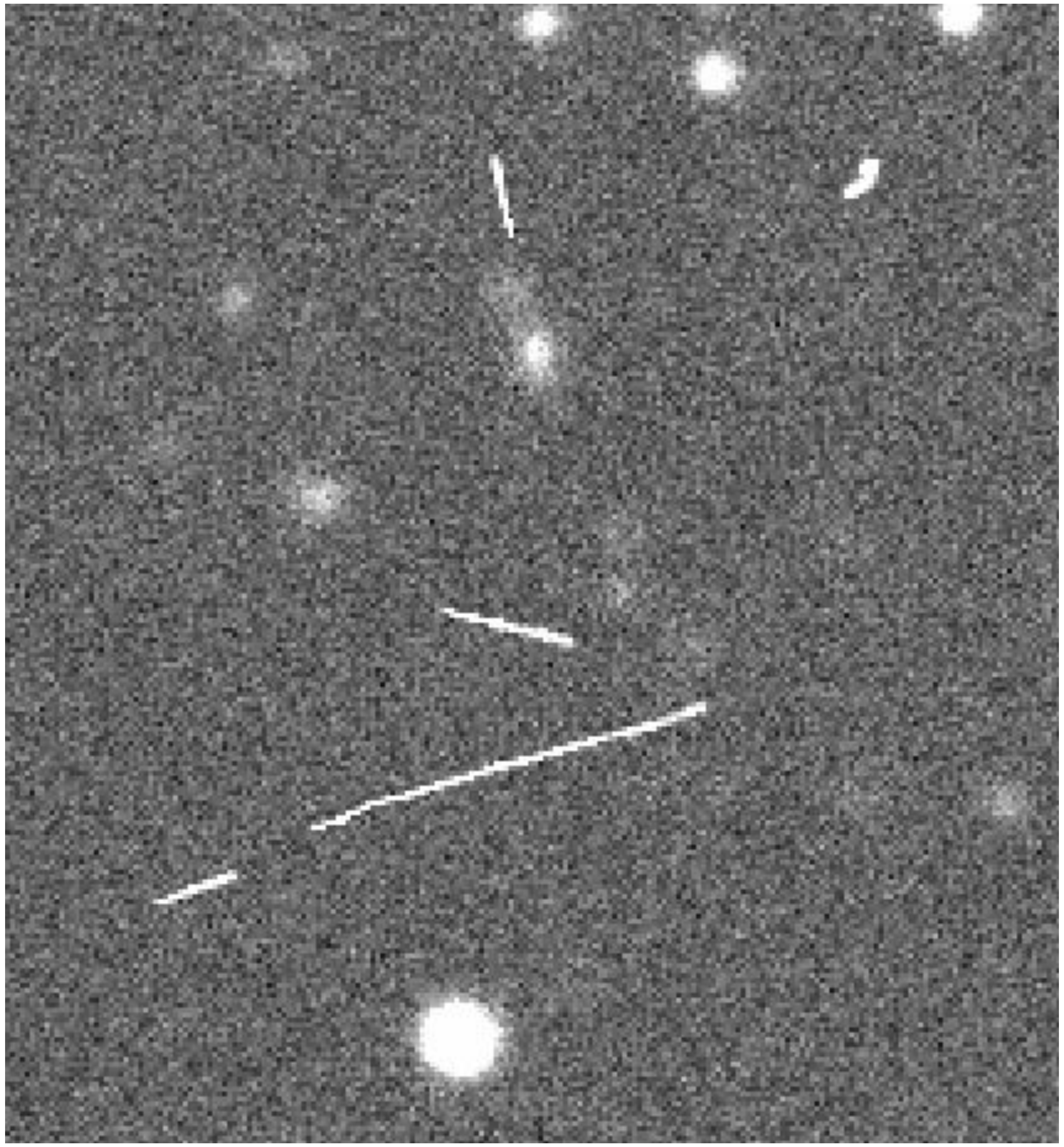


ESO

Artefacts

cosmic rays: charged particles hit the CCD

need to be masked - single exposure

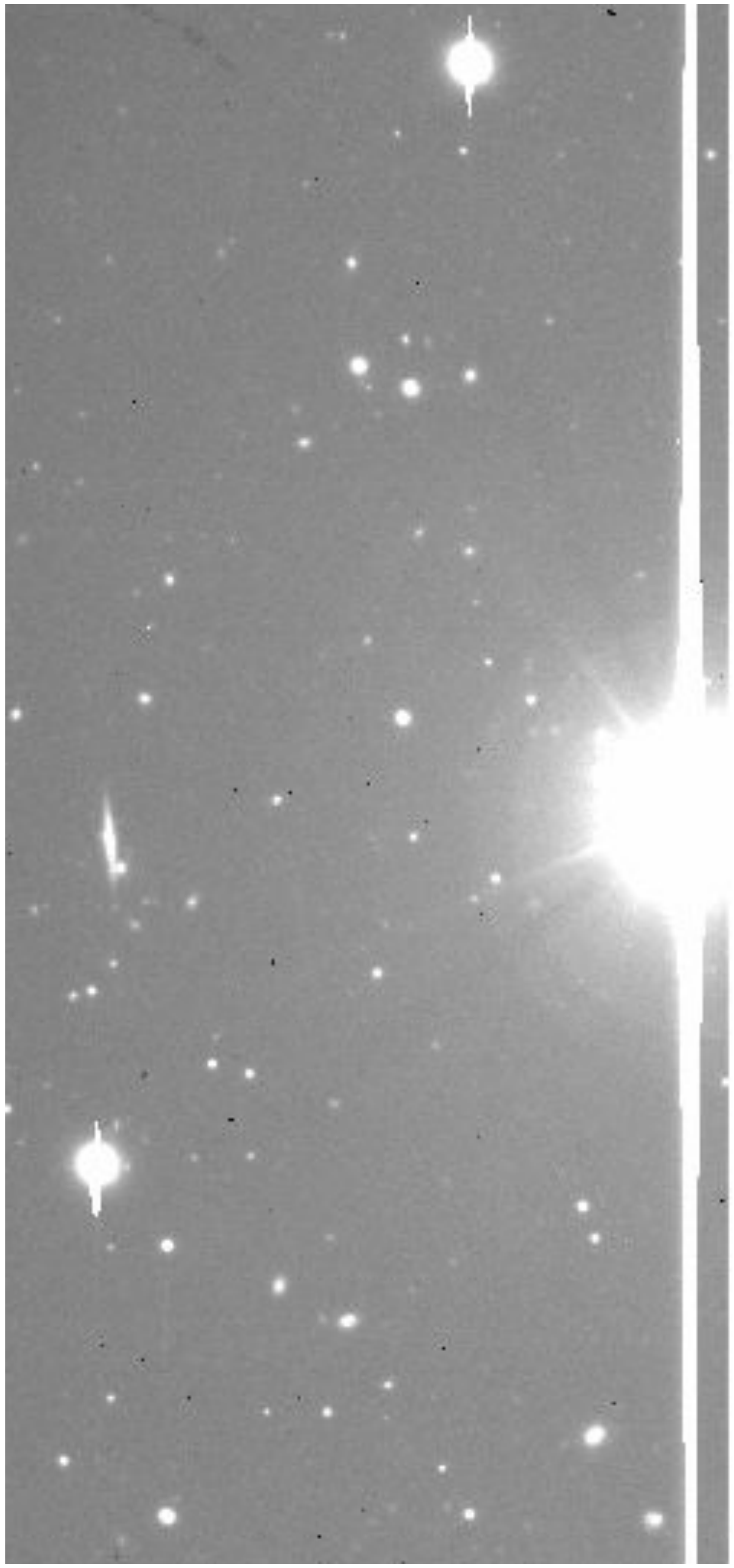


A. von der Linden

Artefacts

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

need to be masked - single exposure

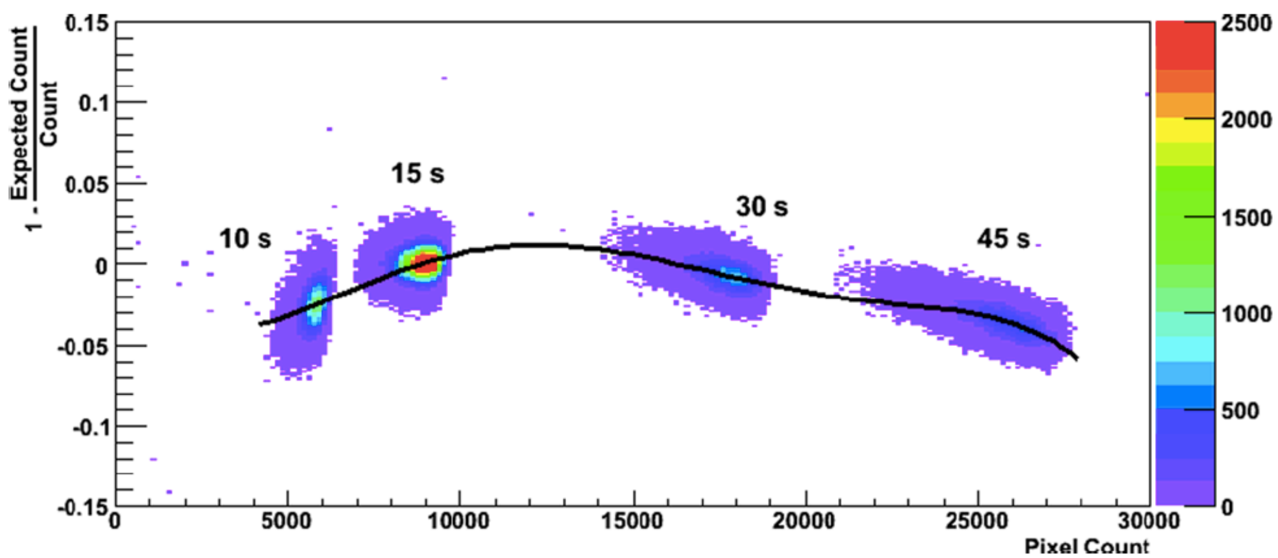


A. von der Linden

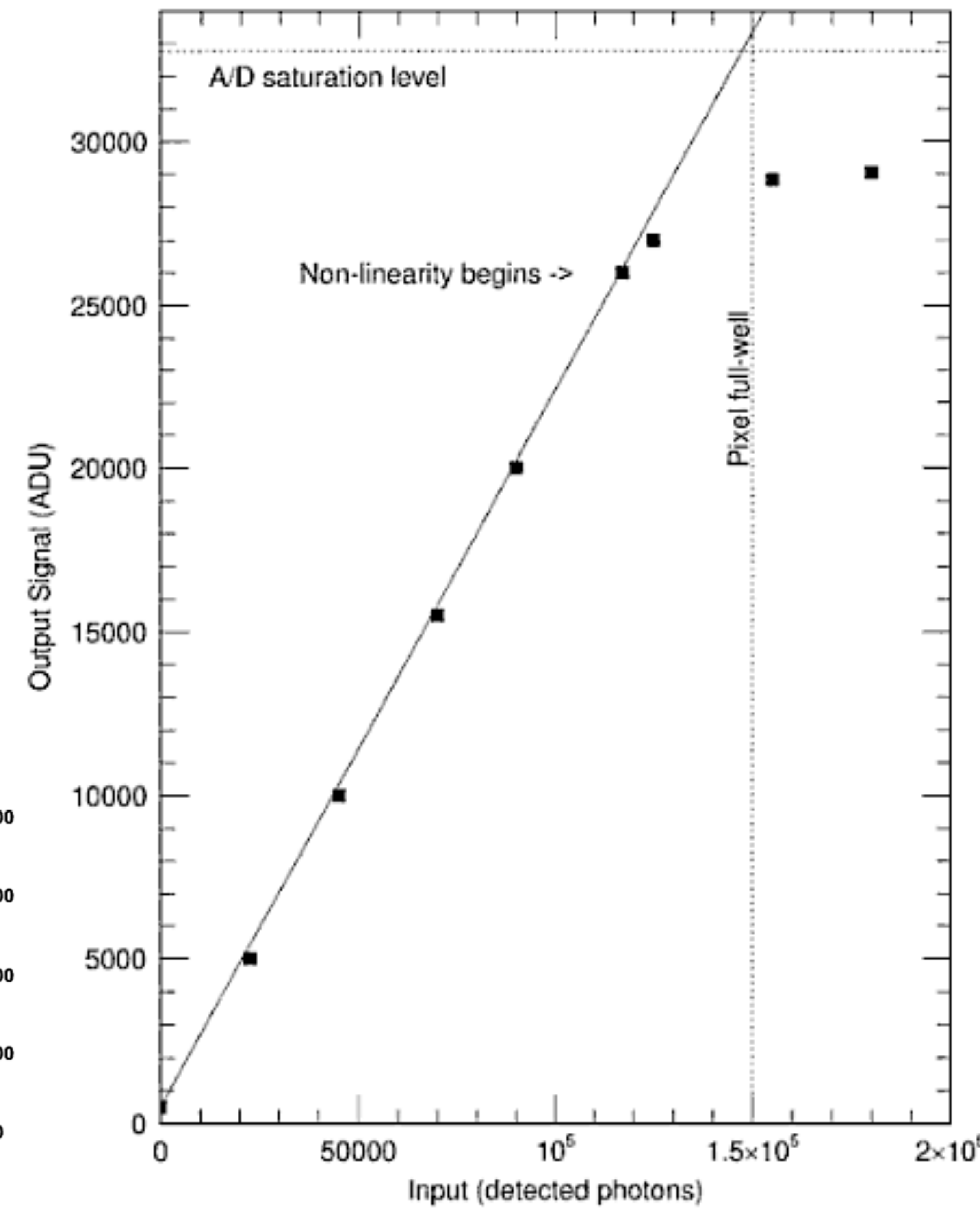
Artefacts

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*

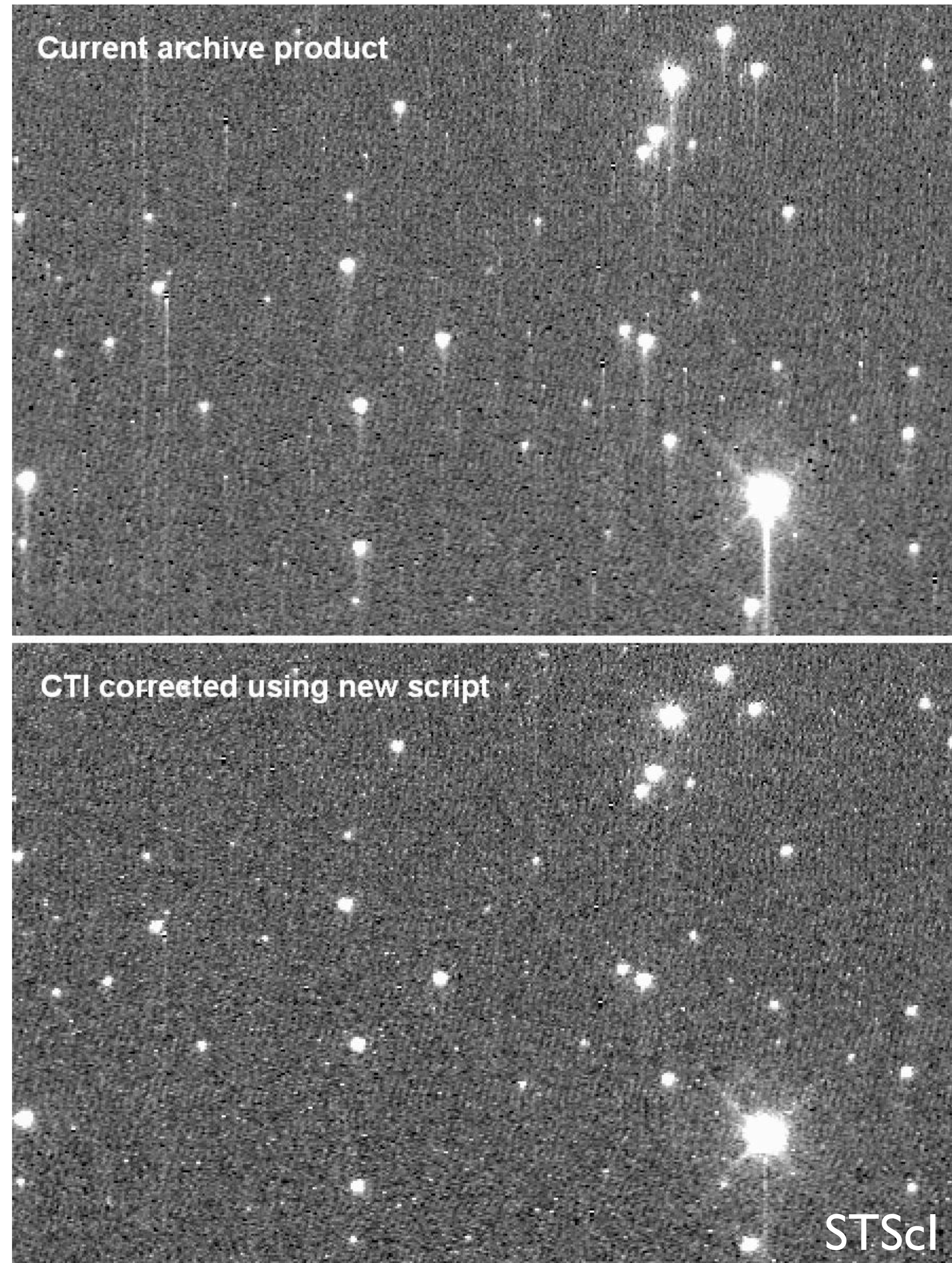
Artefacts

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

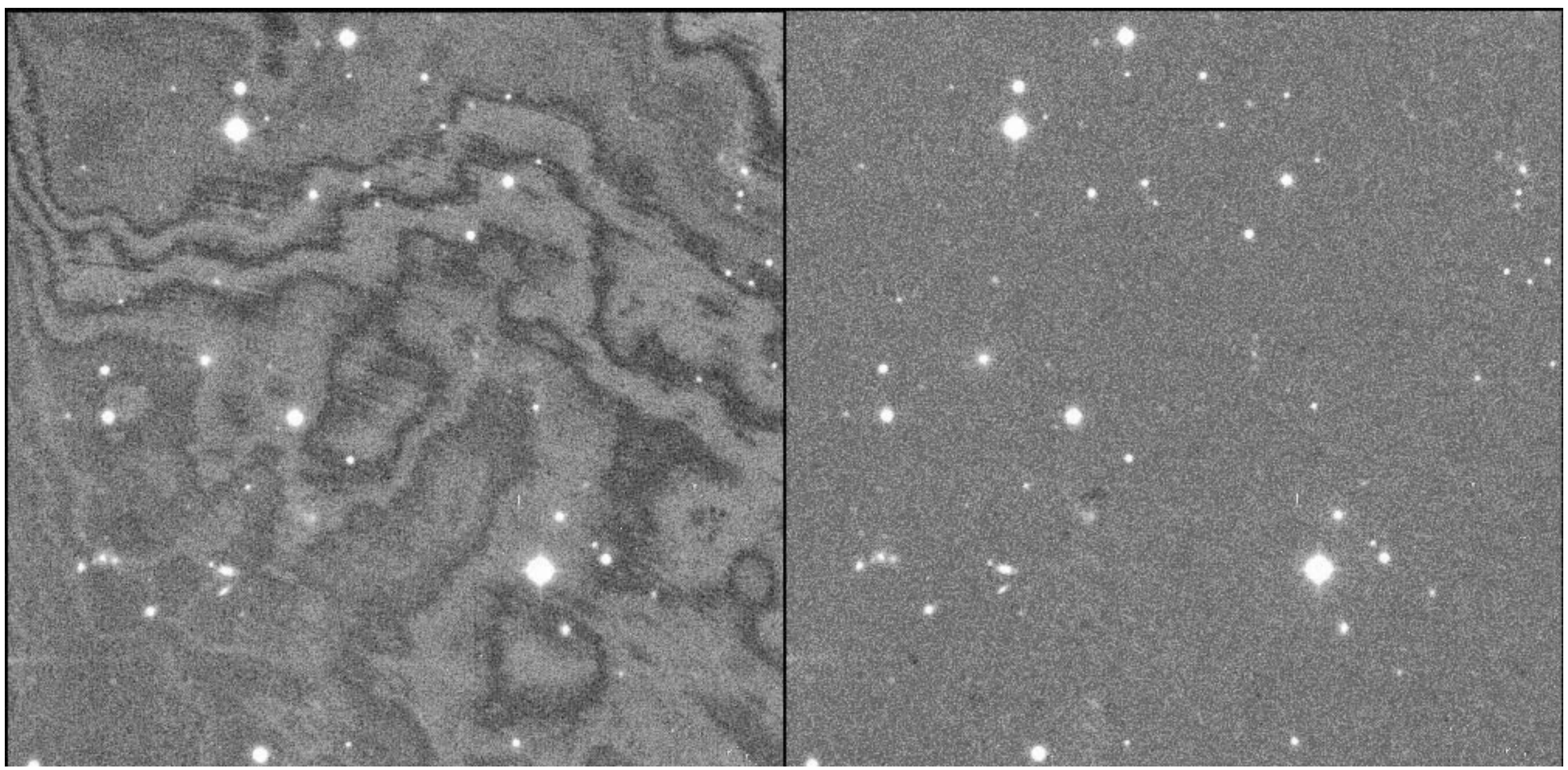
correction based on re-distributing charge



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:

```
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
```

```
FILTER  = 'Visual                '
EXPTIME = +1.000000000000E+001
EXPOSURE= +1.000000000000E+001
    CK  =                   342
    TE  =                   447
```

```
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
```

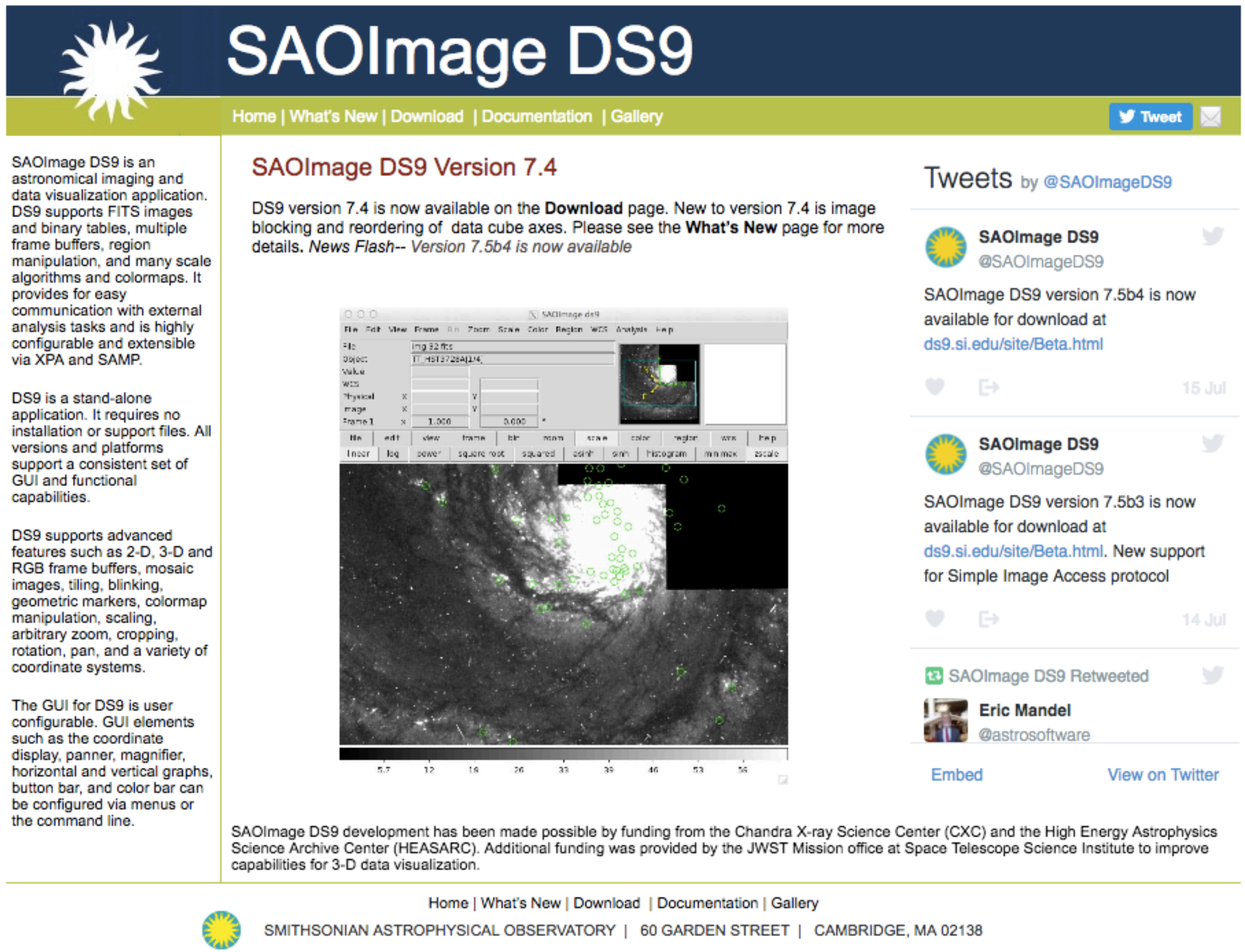
Our camera does not know where the telescope is pointing
- astrometric calibration is important e.g. for exoplanet lab

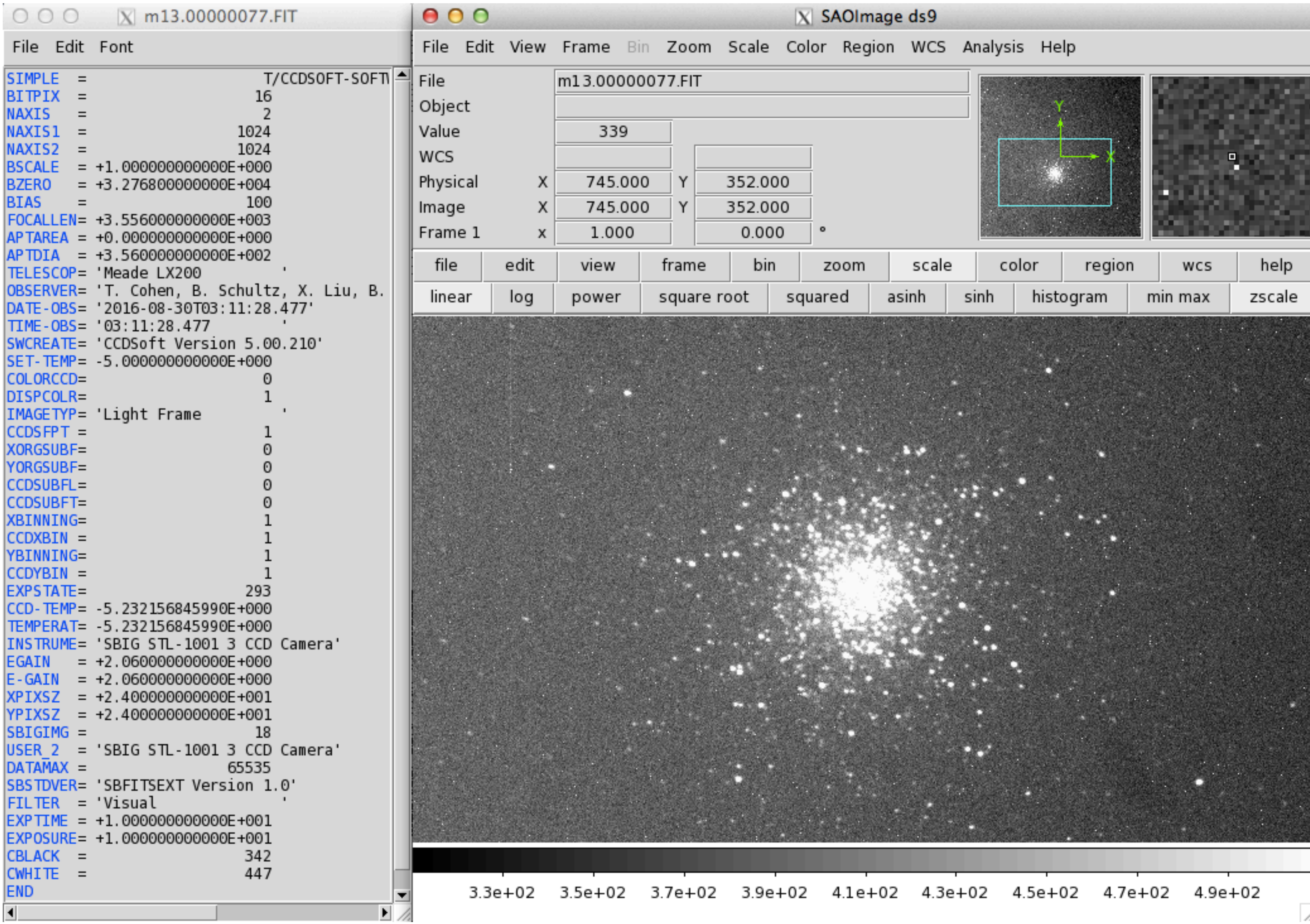
Viewing FITS images

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
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
```