CCD CAMERAS FOR COSMOLOGY

From images to cosmological parameters

PAU Academic training
December 2007

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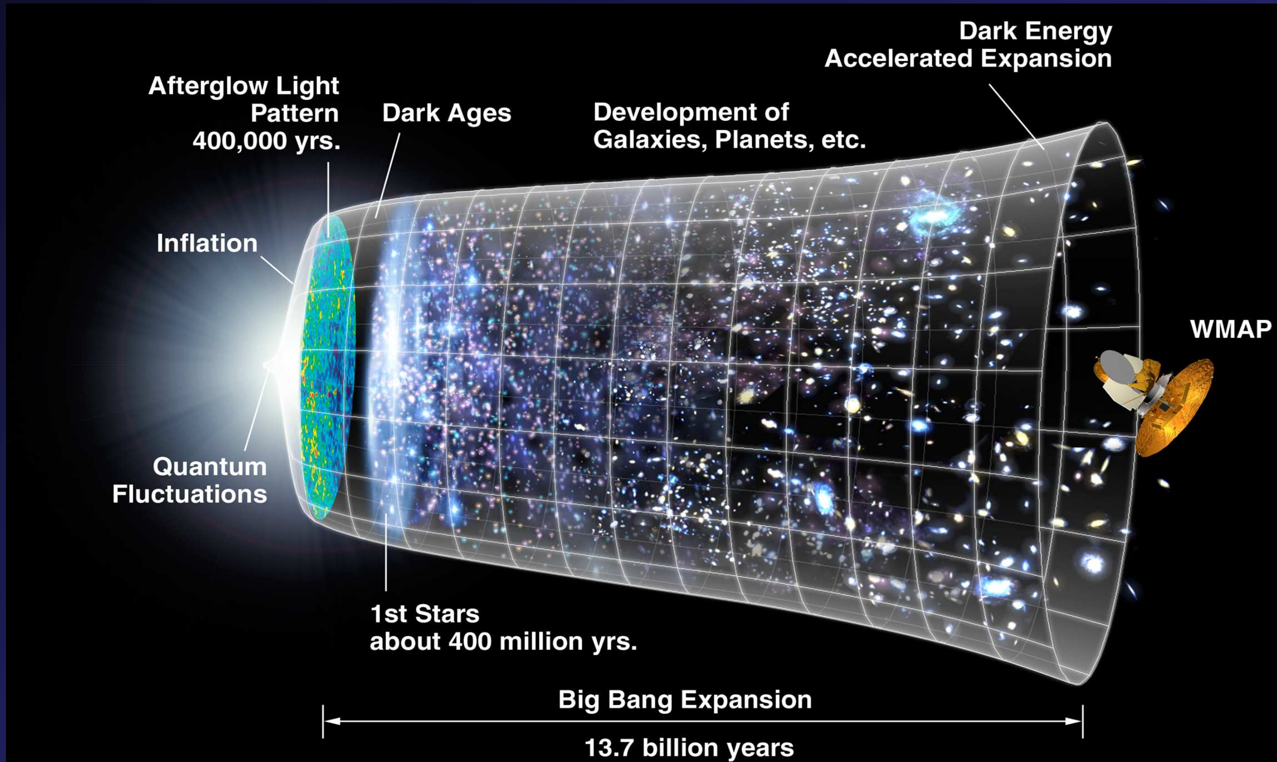
Outline

- Introduction
- CCDs
  - Properties of CCDs
  - CCD types
  - Sources of Noise
  - Steps to reduce data
  - CCDs .vs. Photographic plates
- Cameras
  - Examples of cameras
  - Diagram of a camera
- Other aspects

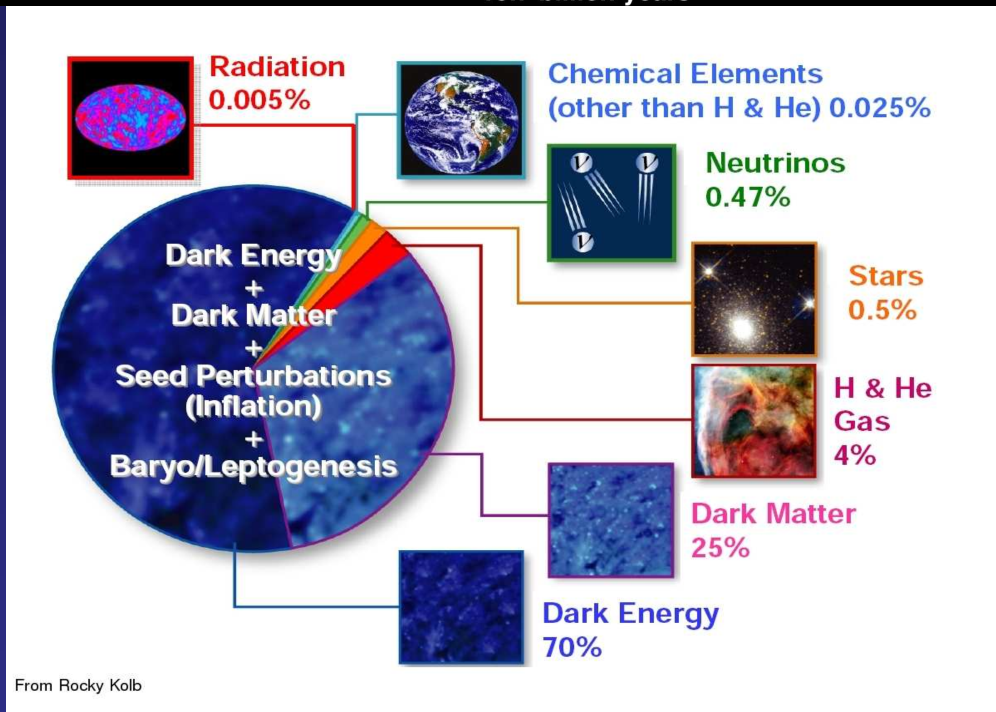
Introduction: Cosmology



New Standard model of Cosmology

Dark Matter

Dark Energy



To study cosmological parameters a large sky area a lot of objects are needed → **SURVEYS**

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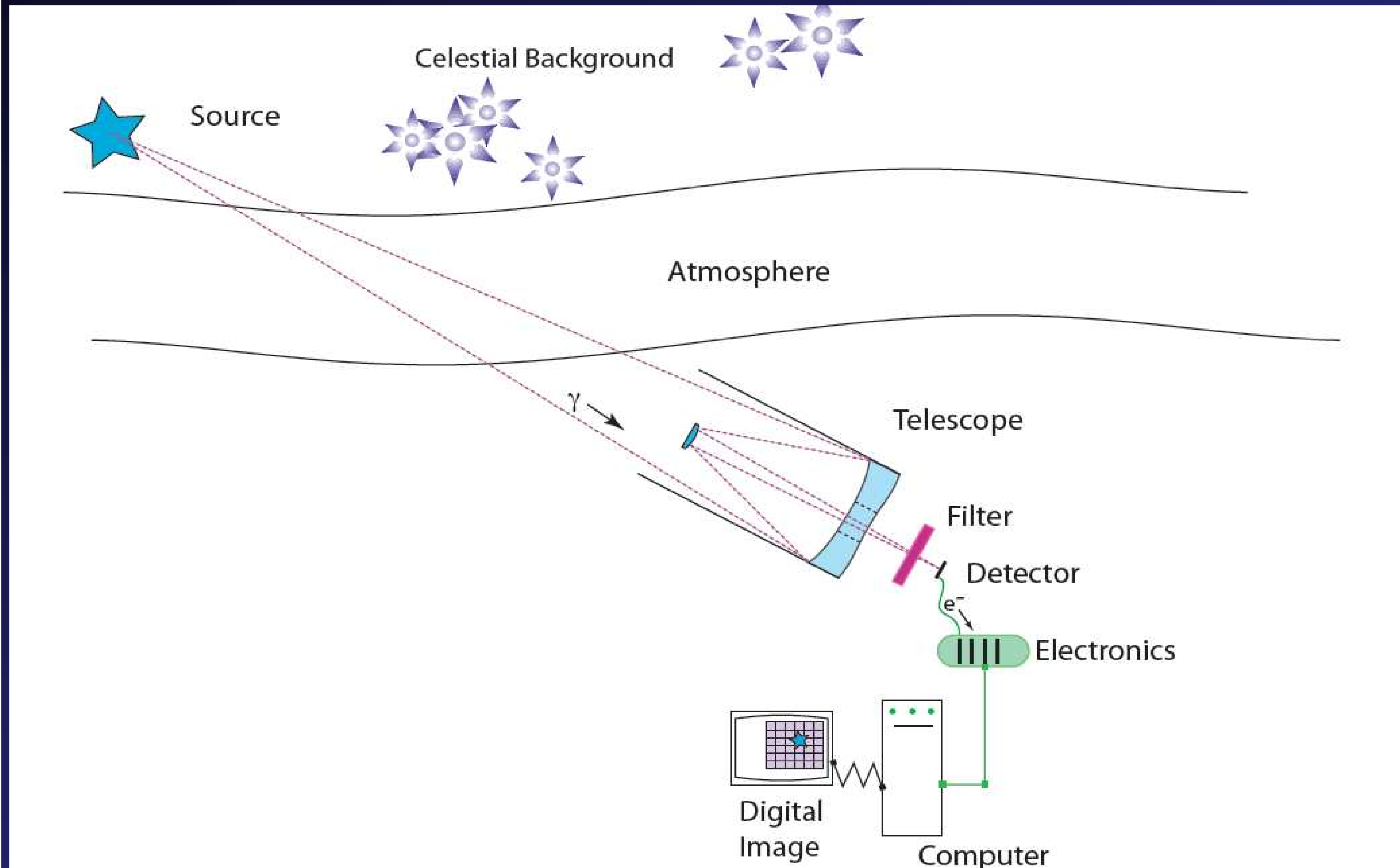
From CCDs to cosmology

We are interested in how we go from CCD-images to cosmology

What is needed to obtain scientific results:



The Source

Atmosphere: seeing, …

Telescope + optics: PSF…

Camera + electronics + DaQ: This is what we talk about today

Pipeline

Analysis

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From CCDs to Cosmology

3 main steps:

(1) “Low-level” processing:

- Bias removal (offset of charge in each pixel)
- Flat-fielding
- Fringe subtraction
- Identification of cosmic-rays and satellites
- Sky background subtraction

(2) “Higher-Level” processing

- Detection of objects (stars, galaxies, other…)
- Astrometry (link between pixel coordinate and position on the sky)
- Calibration (link between numbers in the image and photons from the source)

(3) Analysis

- Photometry, morphology, cosmology

This talk is about (1), Alberto´s talks will be mainly about (2) and Licia´s and Raul´s will be about (3)

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Types of astronomical observations

The information we obtain from the universe arrives in the form of particles: photons, charged particles, neutrinos and gravitational waves

Here we concentrate on photon measurement (in the visible and NIR range)

There are many types of observations: Imaging, spectra, time series, fourier components, … (PAU is an imaging survey)

Measure photon number as a function of energy, position, time and polarization

The usual quantities derived from these are

- Count rate: photons/second
- Flux: Photons/second/unit area at detector
- Spectrum: Photons/unit energy
- Spectral flux density: Joules/second/unit area/unit frequency
- Surface brightness: Joules/second/unit area/unit frequency/unit solid angle

Measure signal in detector → Properties of photons → Properties of astronomical source → Cosmological parameters

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Detectors

The purpose of any detector is to collect and record the light collected by the telescope.

All detectors transform the incident radiation into a some other form to create a permanent record, such as a chemical record (photographic plates, eyes), or charge (CCDs, PMTs).

There are several properties which define the utility of a detector:

1. Quantum Efficiency and Spectral Response
2. Temporal Response and Resolution
3. Dynamic Range
4. Linearity and Stability
5. Noise
6. Spatial Resolution and Field of View
7. Conversion to Digital Signal
8. Spectral Resolution

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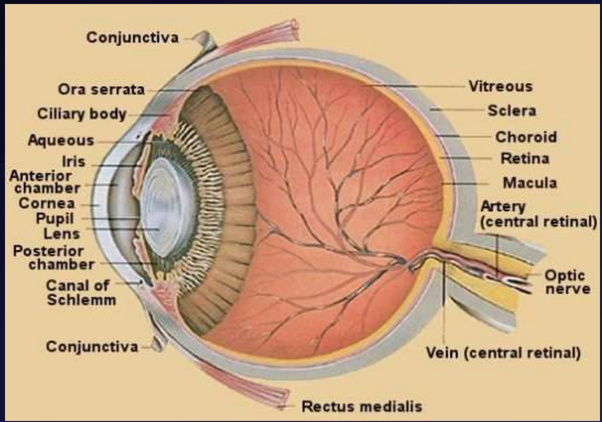
The First Detector in Astronomy

Eye: complete system of telescope (variable aperture, ~1cm max), detector, and data reduction processor



Retina: Light sensitive, chemical process

Rods: 100 million, 2μm wide, can detect low light levels

Cones: color information, 7 million, 1000 per square mm

Reusable: integration times 100 ms

PROBLEMS (for astronomy)

No record of observations so as to check results

Precise measurements cannot be made (position, magnitude, etc) because observations are not recorded or digitized

Integration time of eye is short so faint objects cannot be seen without using larger and larger telescopes

A LOT OF DISCOVERIES!!!

Naked Eyes:

- Nomenclature: Constellations, stars
- Astrometry: Stellar positions
- Magnitude scale
- Planets and orbits (Tycho, Kepler)
- Comets
- Supernovae explosions, variable stars
- Sunspots (by Chinese 800 B.C.)
- Solar corona (eclipse)
- Lunar Phases
- Star Clusters (e.g. Pleiades)

With telescopes:

- Sunspot cycle
- Saturn's rings, Jupiter's Red Spot
- Nebulae, Spiral Nebulae
- Parallax, astrometric measurements
- Asteroids, moons of most planets
- Craters on Moon

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Photographic Plates

Photographic plates were the first two-dimensional detectors

Advantages of photographic plates:

Wide field of view. Up to 3 sq-deg

Resolution, better than a CCD of the same area

Disadvantages of photographic plates:

Low quantum efficiency. The best plates have a QE of about 3%

Long exposure times, inefficient use of time

Reciprocity failure. It becomes less effective as exposure time increases

Non-linear color sensitivity. Plates are more sensitive to blue light

Storage. They are fragile and take up space. They also decay with age.

Digitisation. Must be scanned to put the data in digital form

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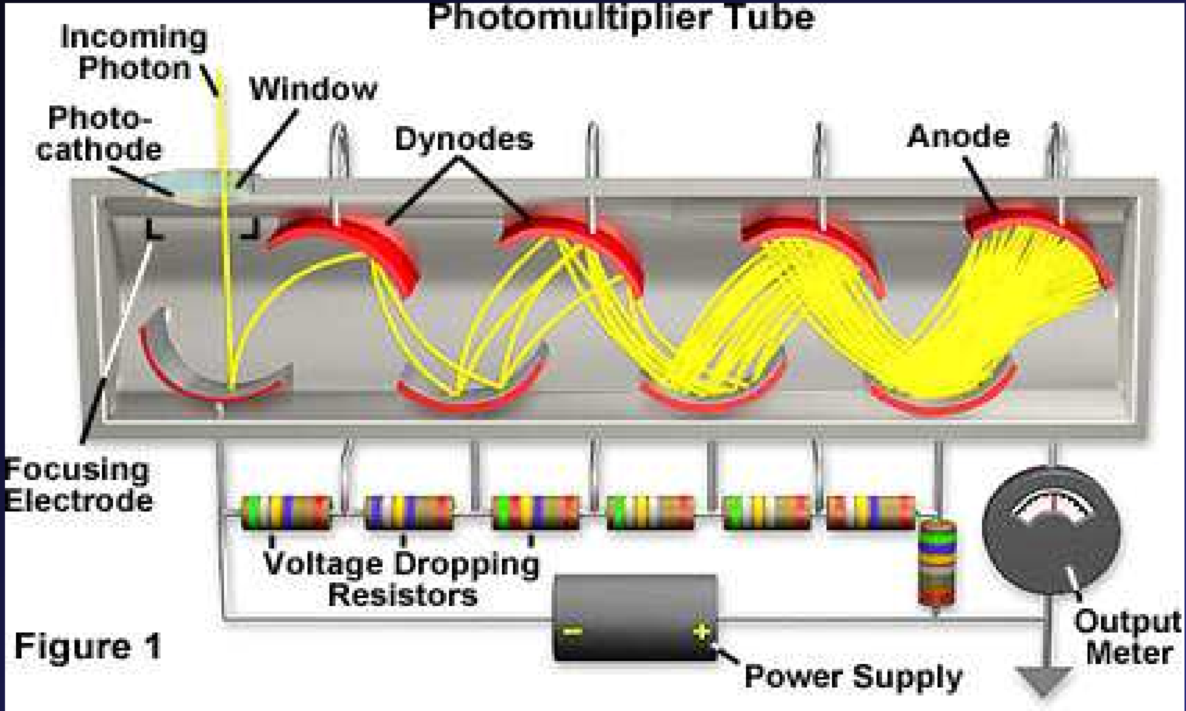
Photomultiplier tubes



In 1907 Joel Stebbins pioneered the use of photoelectric devices in Astronomy

Disadvantages of Photomultiplier tubes:

- Must be operated at high voltages
- High light levels can destroy the tube
- Not very efficient in optical regions: 3500 to 10.000 Å

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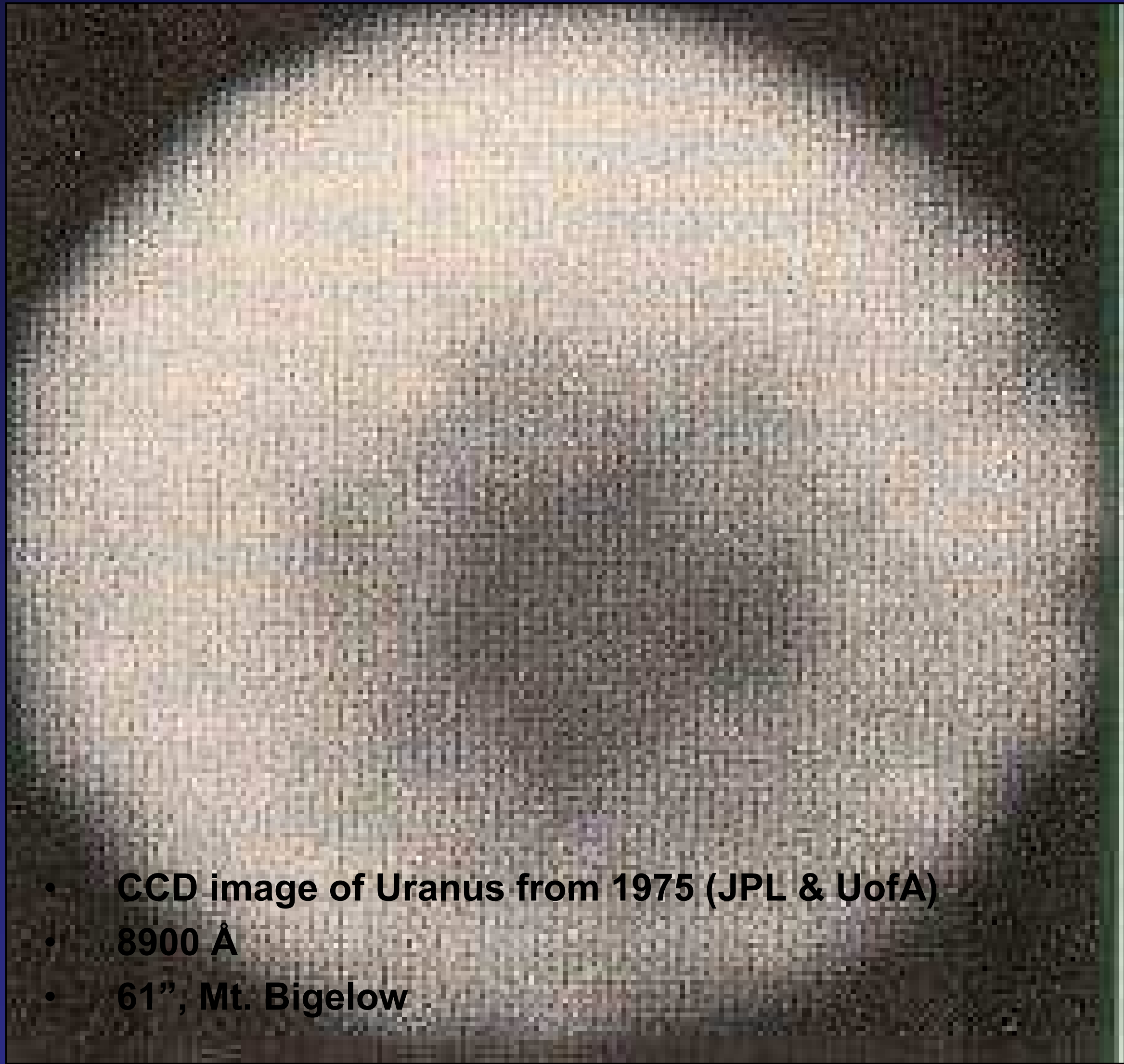
CCD: Charge Coupled Device

- First developed in the 1960s as memory storage devices
  - Sensitivity to light suggested imaging possibilities
- In the 1970s, CCDs were used primarily as experimental devices
- In the 1980s, their use became more widespread
- By the 1990s they'd essentially completely taken over almost all imaging applications
  - video and still cameras, scanners *etc.*
- Astronomy is a highly demanding application
  - low light
  - noise
  - cosmetics



CCDs work by converting light into a pattern of electronic charge in a silicon chip. This pattern of charge is digitised and stored as an image file on a computer.

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CCD properties and definitions

QUANTUM EFFICIENCY (QE): Ratio of number of detected photons to the number of incoming photons. Not all photons are detected.

SPECTRAL RANGE: The total wavelength range for which the CCD is sensitive, usually defined over the range where QE >5-10%

CHARGE TRANSFER EFFICIENCY (CTE): Percentage of charge clocked/transferred compared to that which was collected. Typically > 99.999%

GAIN: Number of electrons needed to generate 1 count of output signal in the device

FULL WELL: Maximum number of electrons that can be stored in each pixel "before buckets overflow"

ADC: Analog to Digital Converter. Converts analog voltage into ADUs for computer storage

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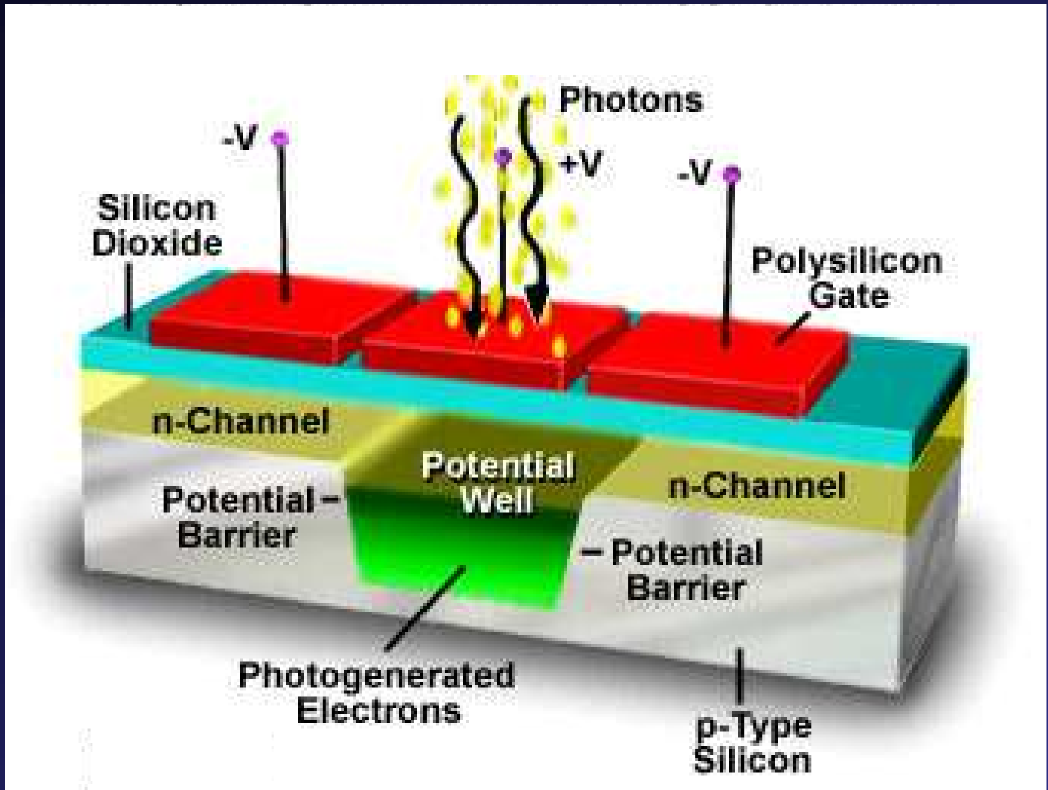
Basic Unit of a CCD



BASIC ELEMENT:

Semiconductor device

Depletion region under the central electrode (it is positive and the others are negative) → Deep potential well to trap electrons

Photoelectrons generated under the central electrode will be attracted towards the electrode a nd held below it. The corresponding holes are swept away into the bulk silicon

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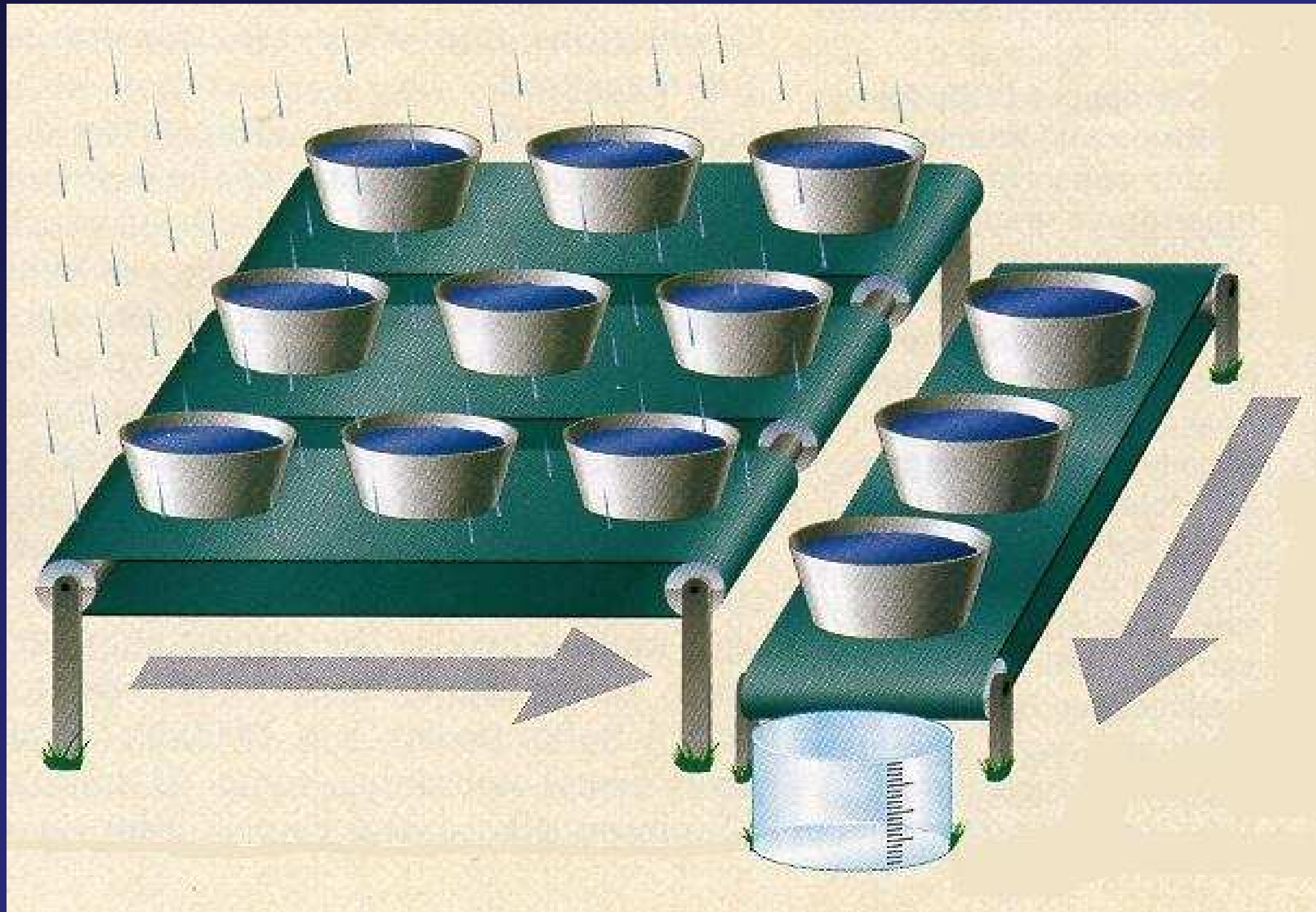
How do CCDs work? – charge transfer

Analogy of the CCD operation:
Water transport

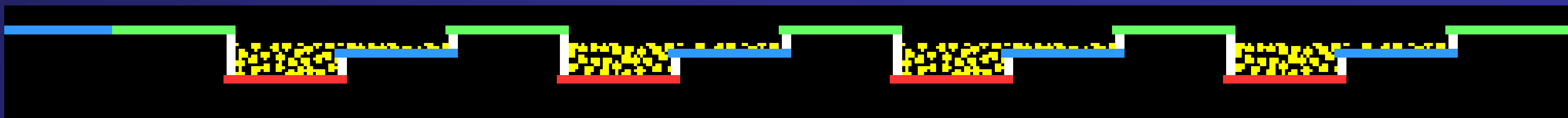
Rain = Source

Water transfer = Charge Transfer

Water Level measurement =
Charge measurement



1) Collect light
2) Transfer charge
3) Measure charge



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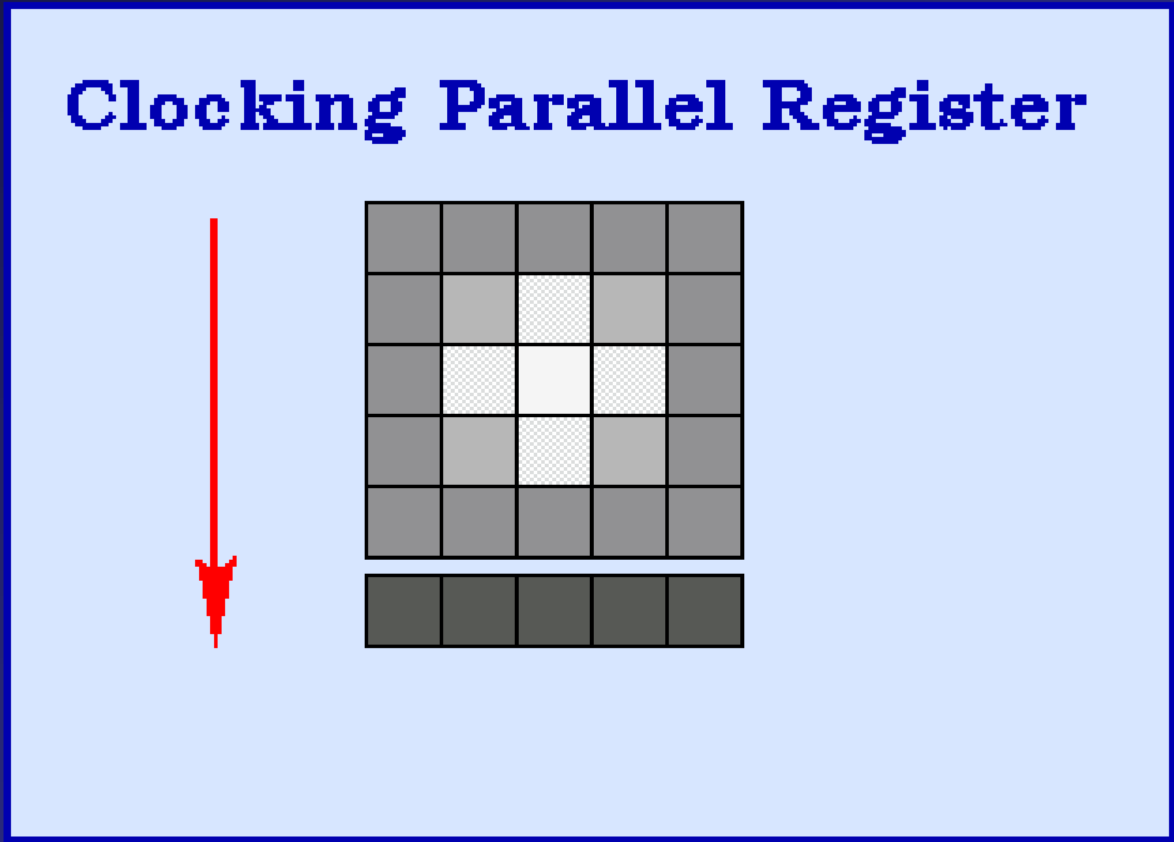
How a CCD works

Light (photons) is converted to a charge (electrons) by the photoelectric effect in a layer of silicon.



The charge is accumulated in "wells" during the exposure.

At the end of the exposure the CCD is "read out" - the charge is shifted to the readout register.

Typical scientific CCDs have 2000x2000 or 2000x4000 pixels

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Charge Transfer Efficiency

Typical Charge Transfer Efficiency of a CCD is >99.999 %

Suppose you have a 2048 x 2048 CCD and detect 40000 photons (electrons). Signal to Noise ratio = $\sqrt{N}$ = 200

Charge recorded = $40000 \times 0.99999^{4096} = 38394$

1605 electrons “lost“
S/N decreased to 195

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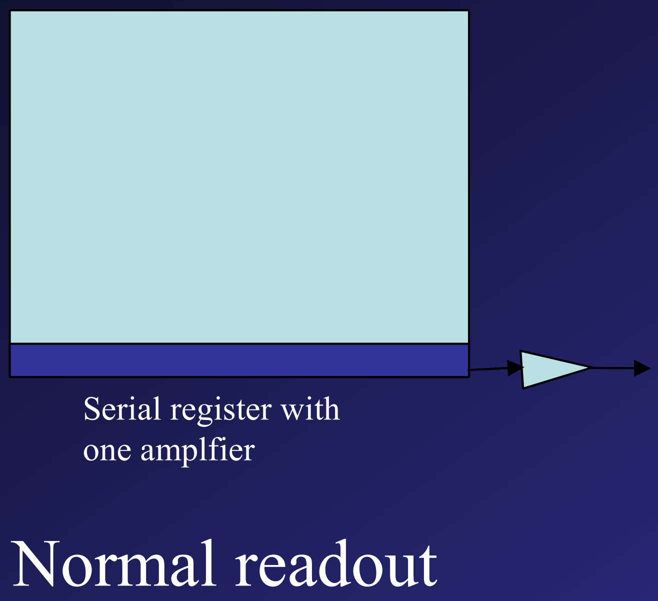
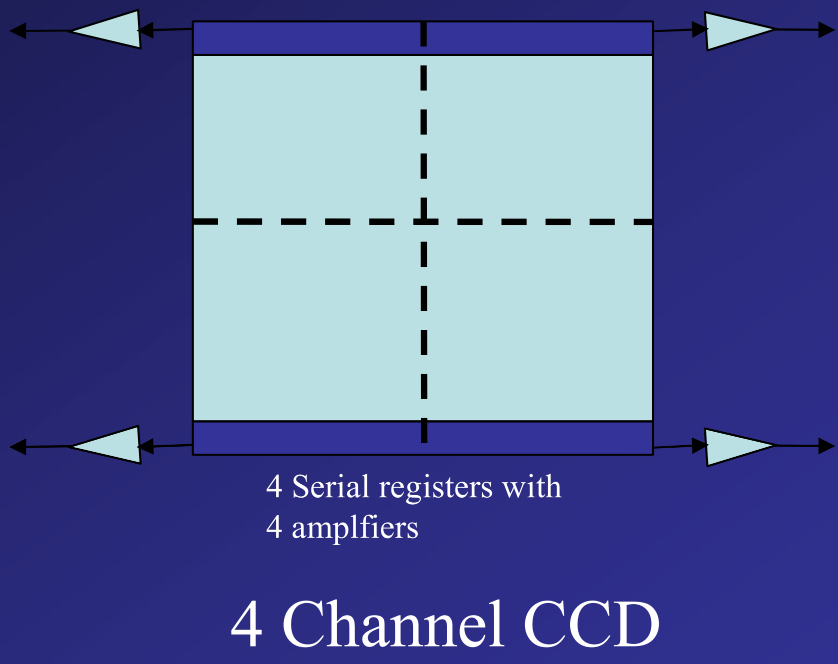
Readout Time

Typical CCD readout times are 30 – 240 secs, depending on the size of the CCD. This is for single amplifier CCDs. To reduce the readout time some devices can have 4 channels (amplifiers) for readout:





4 channel CCD cuts readout time by a factor of 4. Problem: each quadrant usually behaves differently, with its own bias, flat field response, etc. In the data reduction 4 channel CCDs have to be reduced as if they were 4 independent frames.

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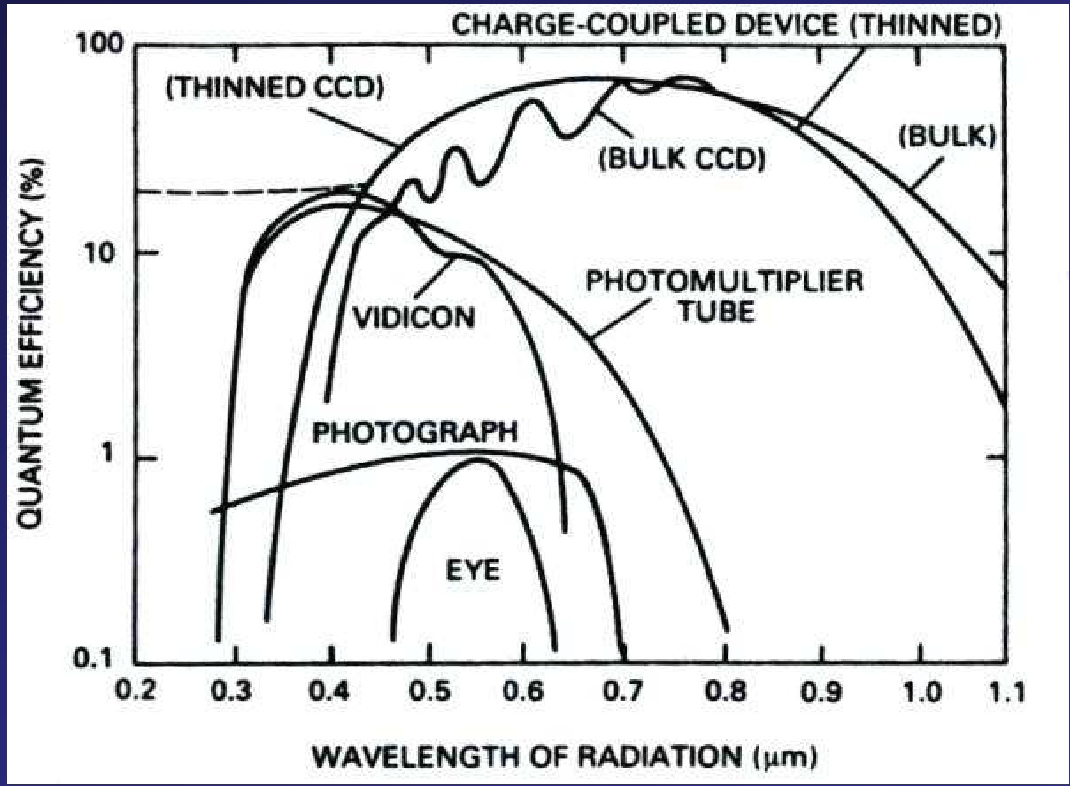
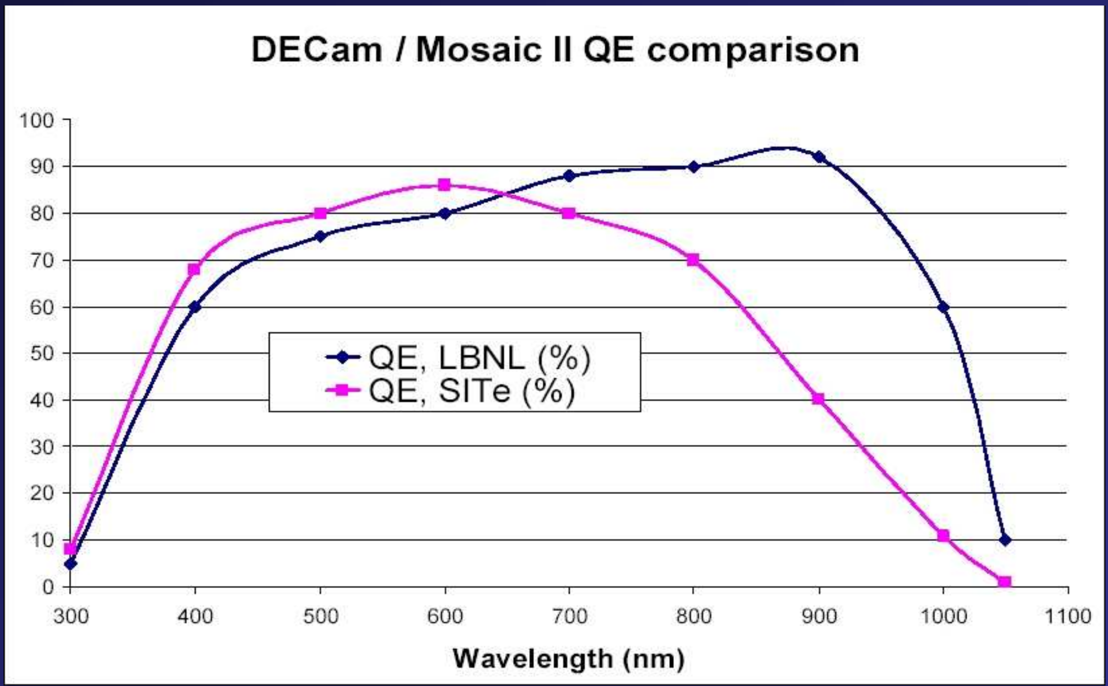
Quantum Efficiency

The real power of CCDs is their high quantum efficiency





New developments get high quantum efficiency in larger regions of the spectrum

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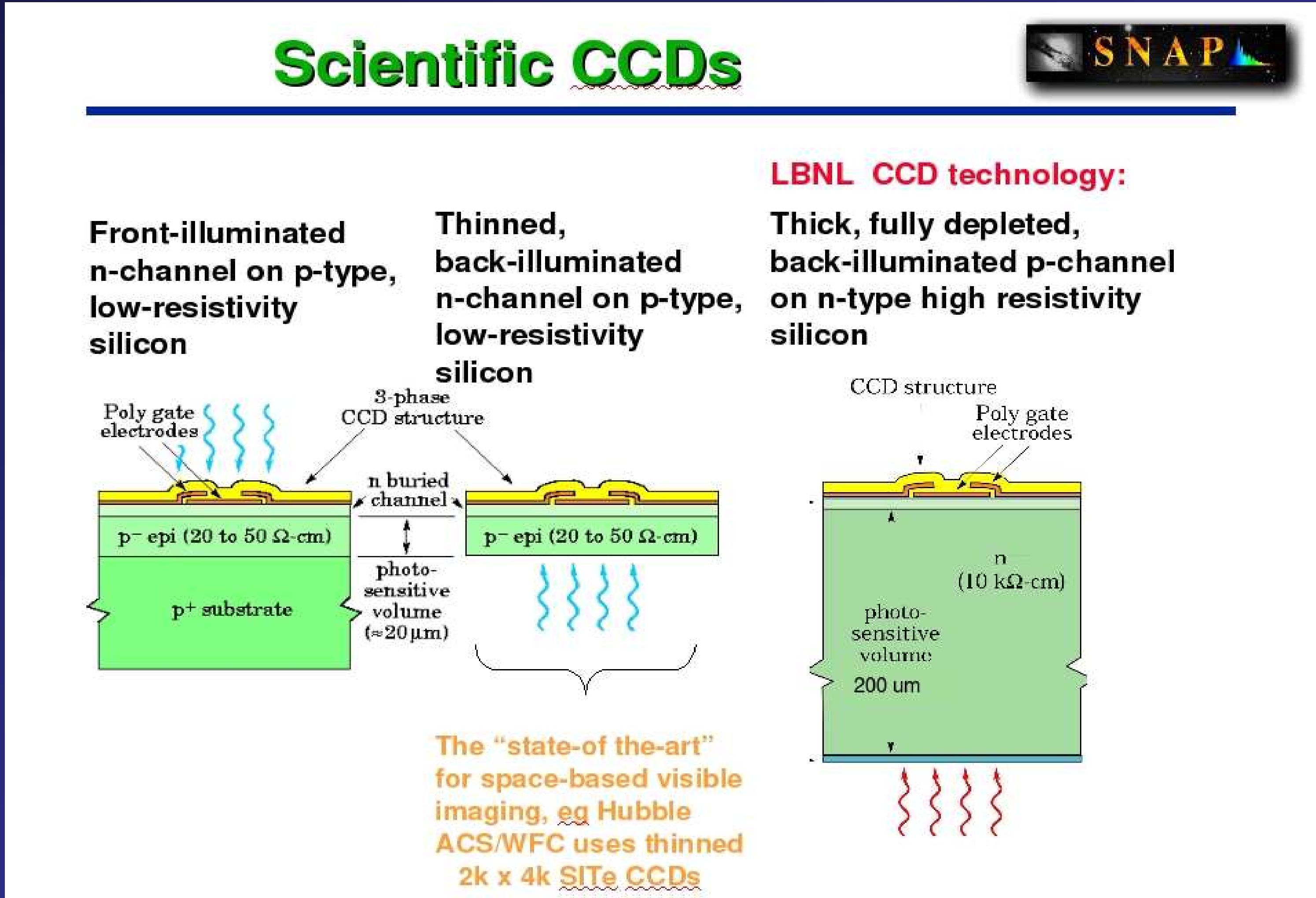
Types of CCDs

Front illuminated CCD: A CCD whose gate structure is located in front of the potential wells. In other words the light has to pass through the gates

Back illuminated CCD: A CCD whose thickness is reduced to 10 μm so that it can be focused on the front where there are no gates. A back illuminated CCD is just a front illuminated CCD flipped and thinned. It is more efficient, particularly in the blue.

Thin CCDs have a much higher quantum efficiency, particularly in the blue. Most CCDs in use are thinned as the thinning process is fairly reliable and it is rare when a CCDs is destroyed in the thinning process.



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Important CCD Parameters for Observations

Dynamic range: Largest possible signal / smallest possible signal

Gain: Converts ADU to number of photons detected. Important for Signal-to-Noise estimate.

Linearity: Detected counts should be proportional to the exposure time. If a CCD has a non-linear regime these level of counts should be avoided

Readout Noise: Noise introduced by CCD readout electronics. negligible for High Signal-to Noise observations

Dark current: Thermal noise. Negligible for High Signal-to-Noise observations. Most science grades CCDs are kept at –120 C or cooler.

Bias level: Constant level added to the data by the electronics to ensure that there are no negative numbers

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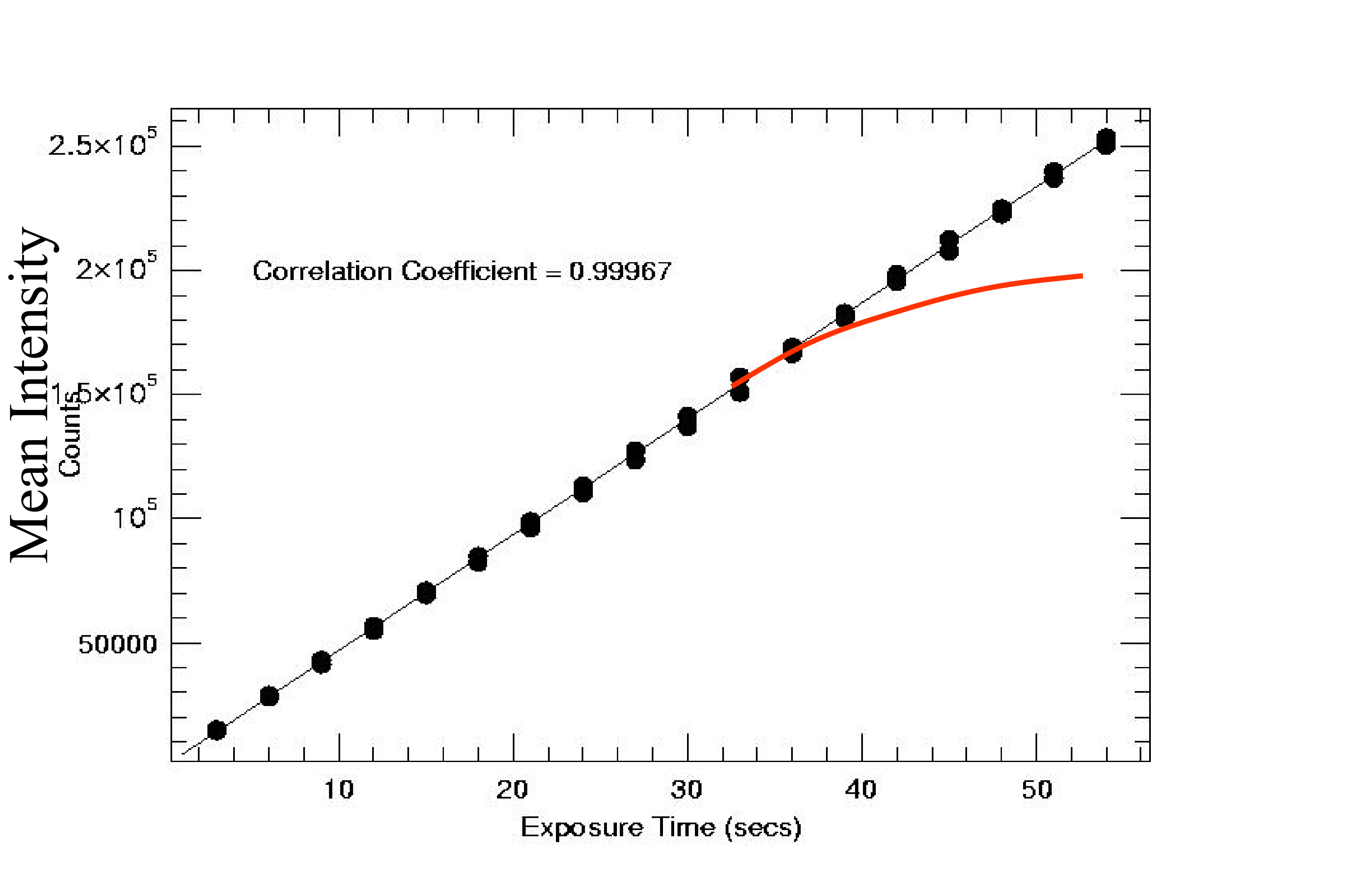
Noise Tests for CCD: Linearity

Take a series of frames of a low intensity lamp and plot the mean counts as a function of exposure time

If the curve followed the red line at the high count rate end (and some CCDs do!) then you would know to keep your exposure to under 150.000



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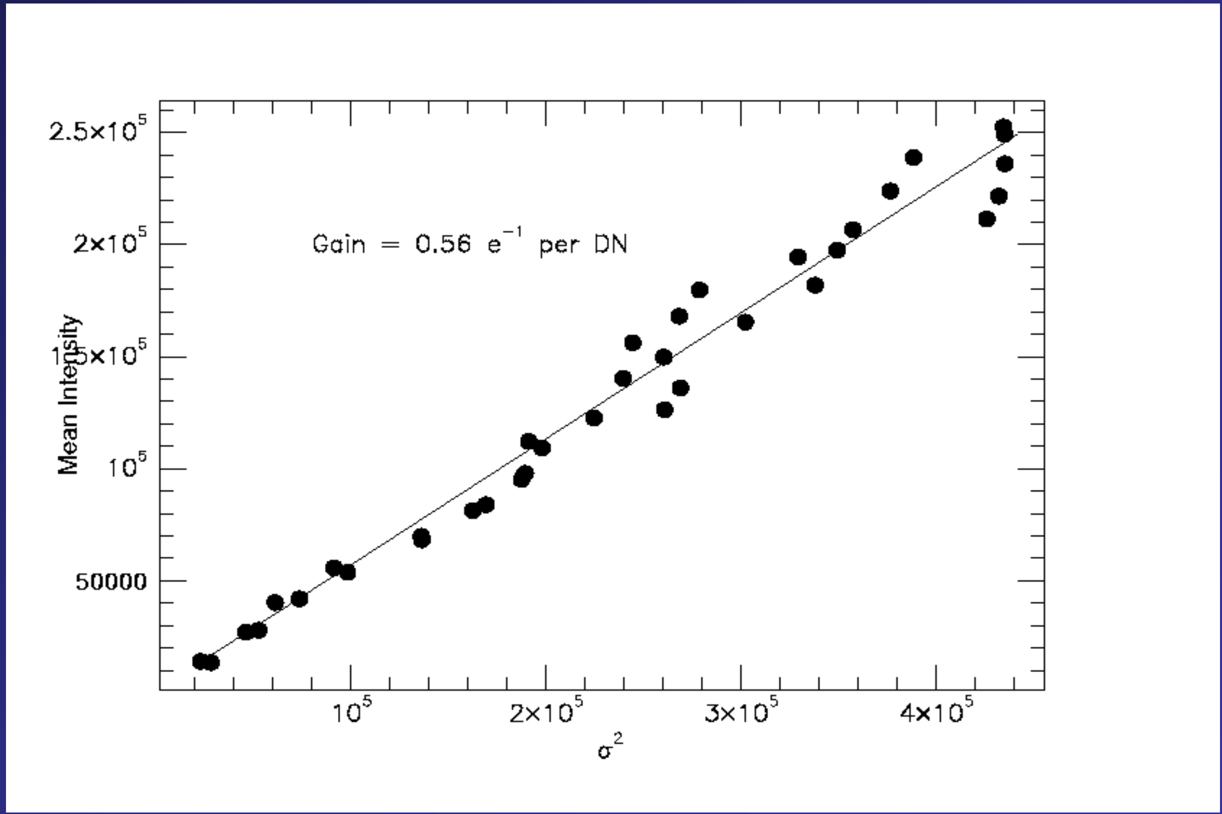
Noise Tests for CCD: Gain

For Photon statistics the variance, σ = √Photons. Therefore σ² should be a measure of the number of detected photons

Take a series of frames with a constant light level

- Compute σ for frames
- Change the exposure time and take another series of frames calculating a new σ
- Plot the observed mean intensity versus the variance squared (σ^2)
- The slope is a measure of the gain



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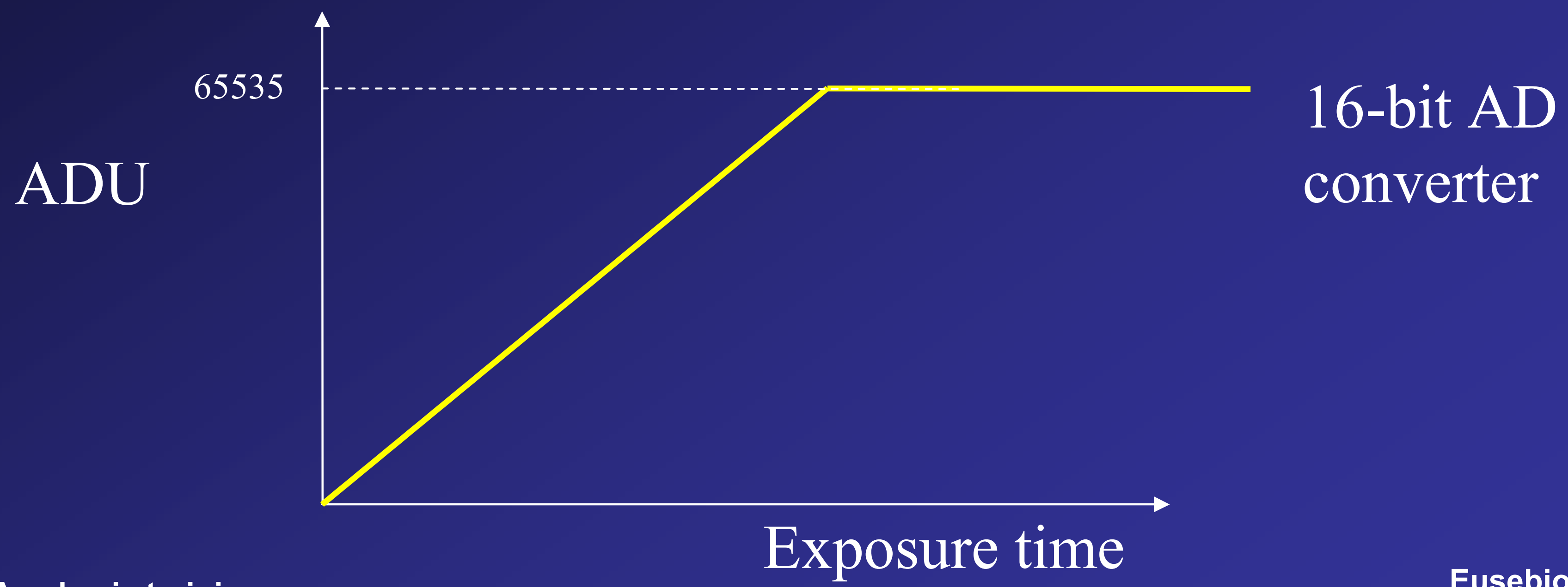
Problems and Pitfalls of CCD Usage

Saturation

If too many electrons are produced (too high intensity level)) then the full well of the CCD is reached and the maximum count level will be obtained. Additional detected photons will not increase the measured intensity level:



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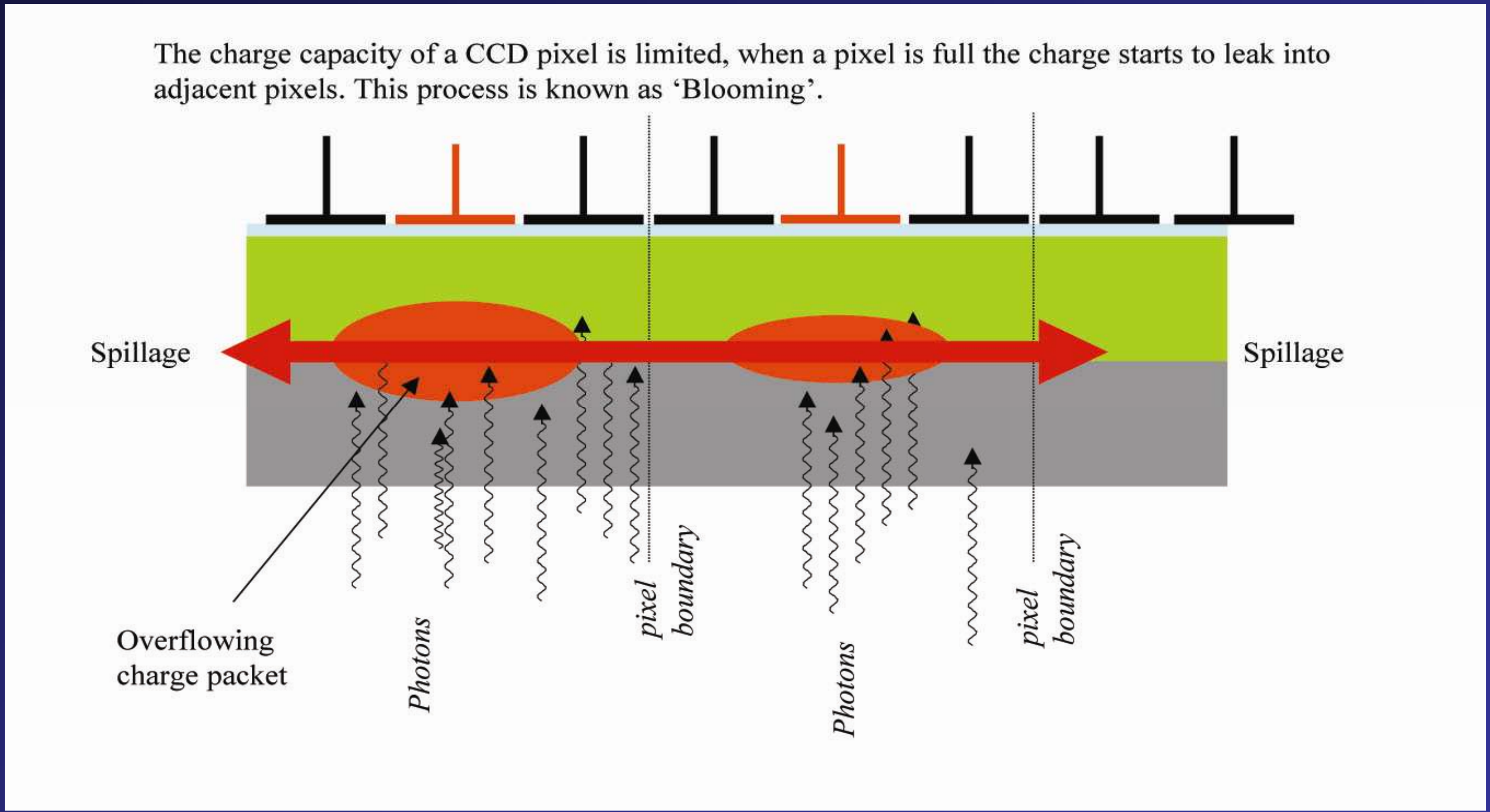
Problems and Pitfalls of CCDs

Blooming:

If the full well is exceeded then charge starts to spill over in the readout direction, i.e. columns. This can destroy data far away from the saturated pixels.



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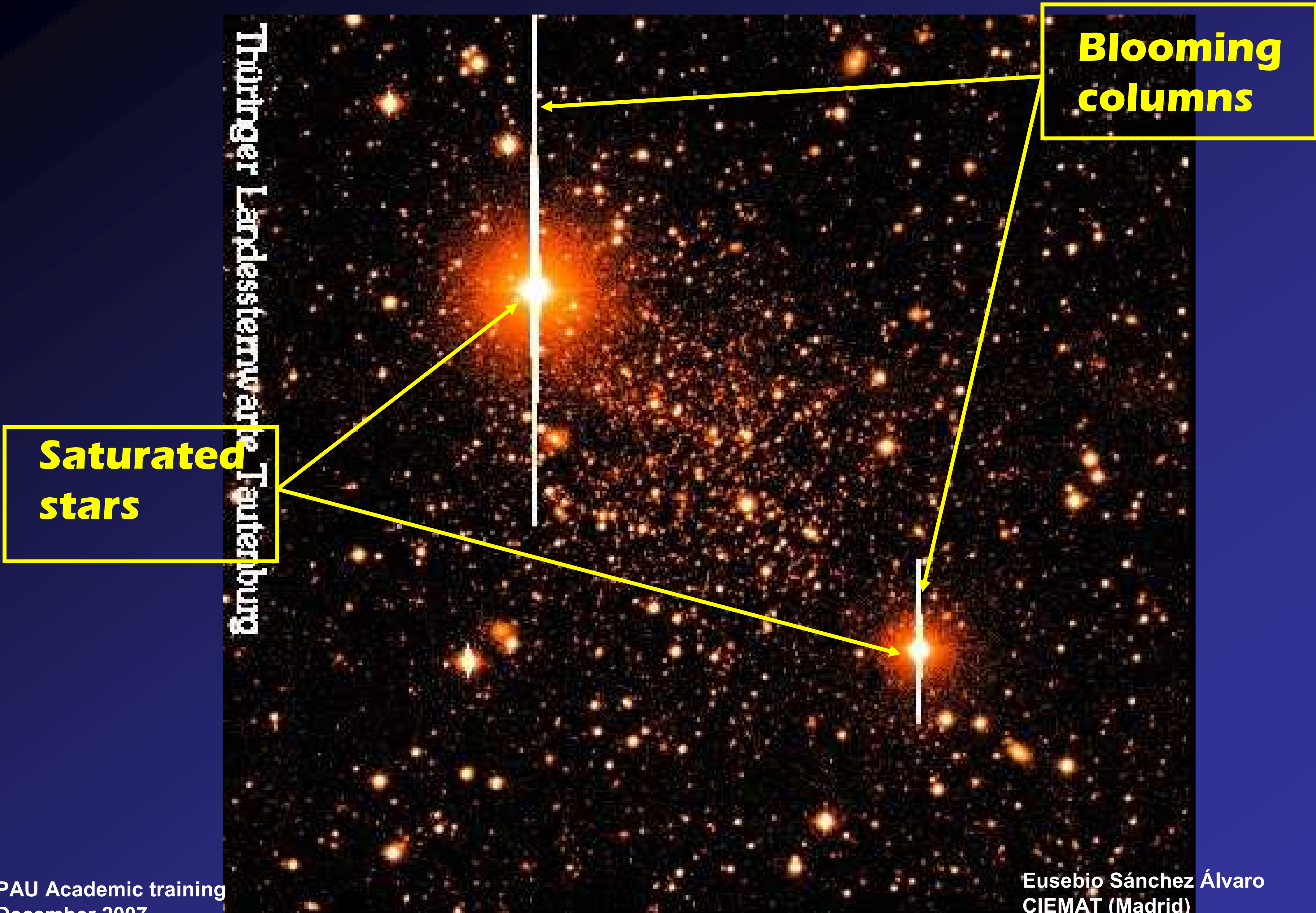
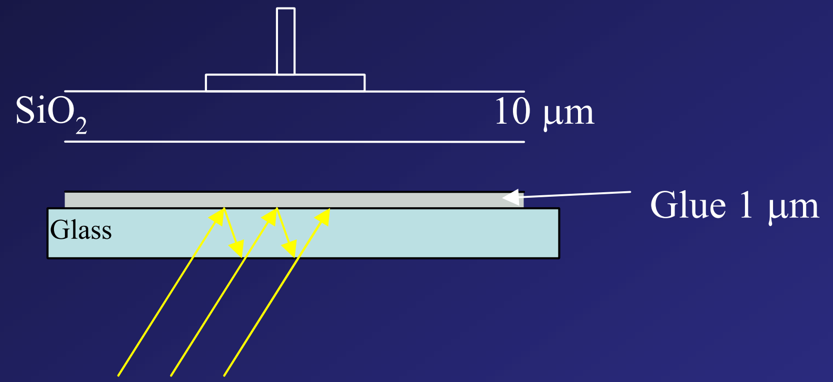

Blooming columns
Saturated stars
Thüringer Landessternwarte Tautenburg

Fringing

Affects more to thinned back illuminated CCDs



They usually have a glass cover

When the glass is illuminated by monochromatic light it creates a fringe pattern. Fringing can also occur without a glass plate due to the thickness of the CCD. This is suppressed in the thick LBNL CCDs.

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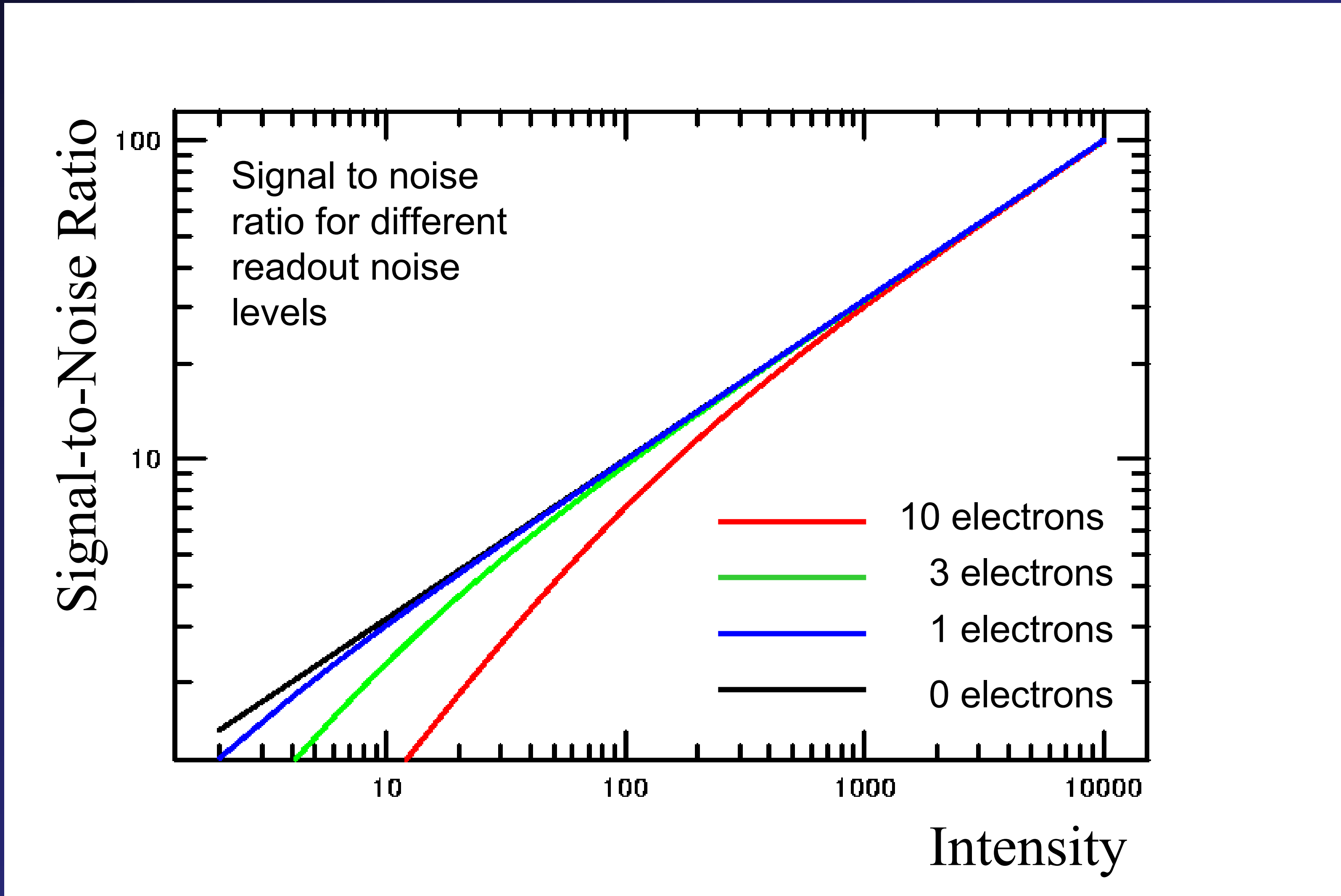
Readout Noise

It is produced by the electronics in the process of reading CCD charge (residual charges in capacitors)



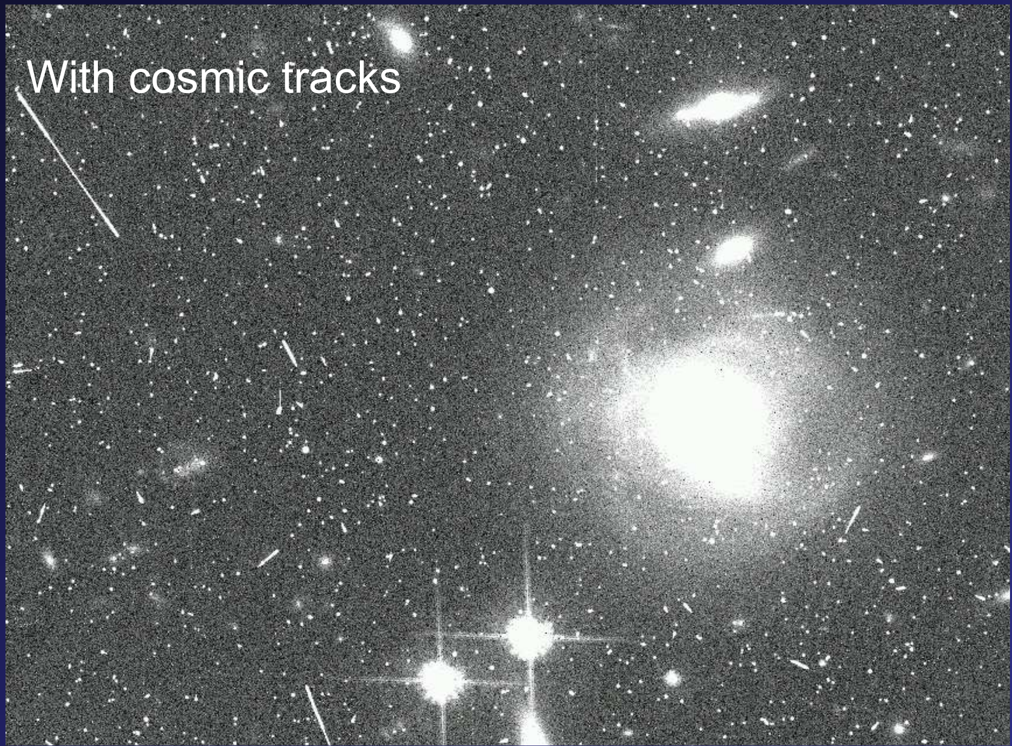
High readout noise CCDs (older ones) could seriously affect your Signal-to-Noise ratios of observations

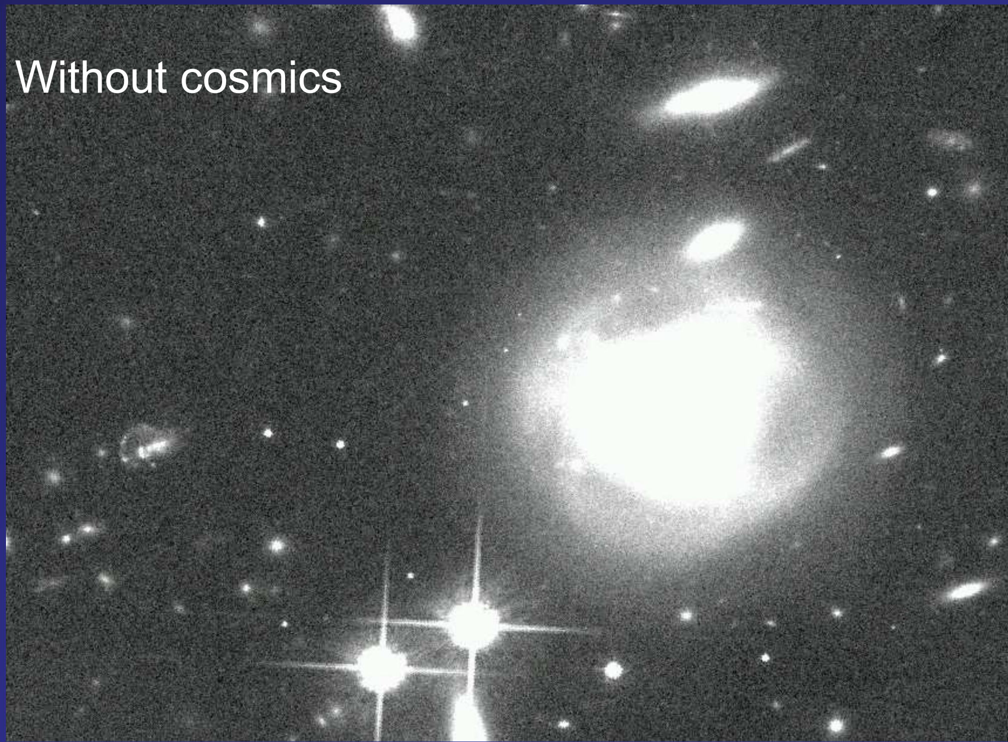
Cosmic Rays

CCDs are good cosmic ray detectors and cosmic rays are always found on long exposures

Cosmic rays are random, so they can be got rid of by combining many exposures.

If not removed, cosmic rays can yield spurious detections





Extreme case: Hubble Space telescope

Also satellites and aircrafts must be removed from data

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Steps to reduce Data

1. Subtract the Bias level. The bias level is an artificial constant added in the electronics to ensure that there are no negative pixels

2. Divide by a Flat lamp to ensure that there are no pixel to pixel variations

3. Removal of cosmic rays. These are high energy particles from space that create “hot pixels“ on your detector. Also can be caused by natural radiactive decay on the earth.

Photon noise, exposure time → There is always residual noise.

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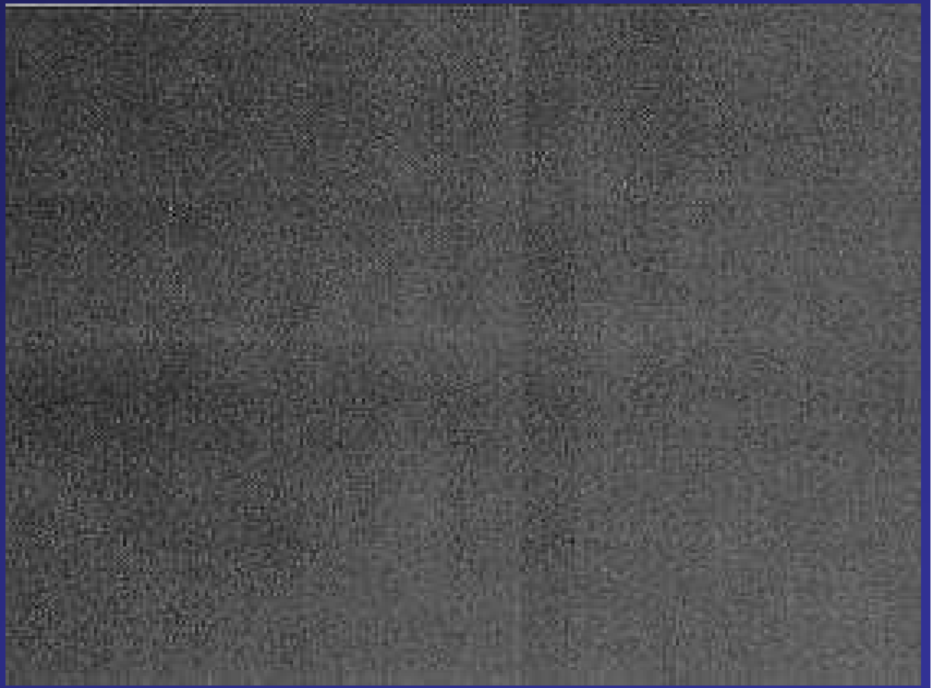
CCD Calibrations - Bias

- A BIAS frame is a zero-length exposure to show any underlying structure in the image from the CCD or electronics
- The bias consists of two components
  - a non-varying electronic zero-point level
  - plus any structure present
- CCD systems usually produce an overscan region to allow the zero-point for each exposure to be measured
- The bias structure is a constant and may simply be subtracted from each image
- Because of readout noise, average several (say, 10–20) bias frames to create a master bias frame



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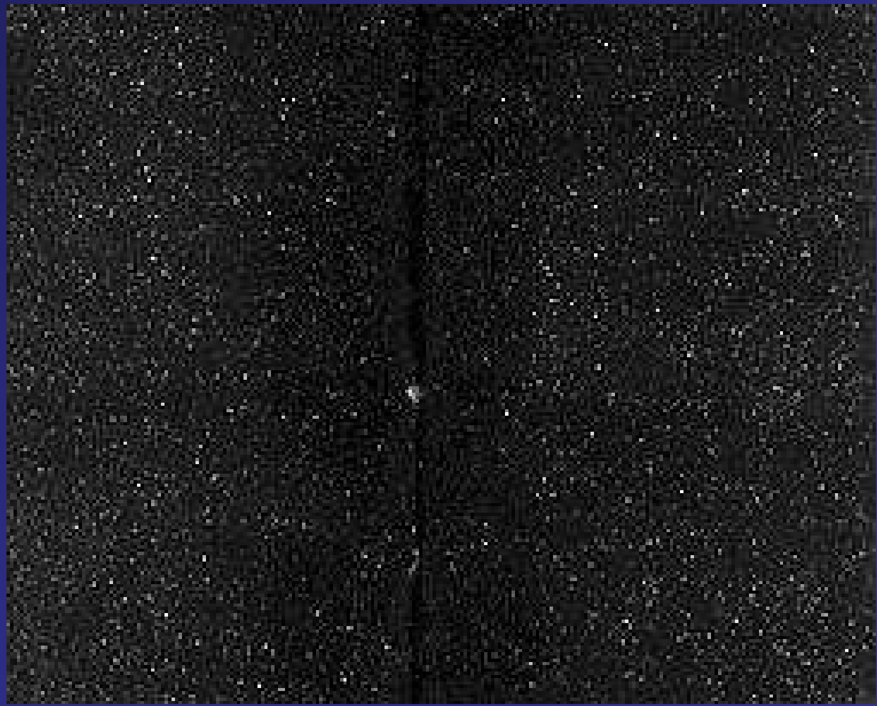
CCD Calibrations - Dark

- To remove dark current, take a series of DARK frames. A dark frame is the same length as a normal exposure but with no light on the CCD
- Since CCDs also detect cosmic rays, take several darks and combine them with a median filter to remove cosmic rays from the combined dark frame. Combining several dark frames also minimizes statistical variations.
- Subtract the combined dark frame from a normal image, provided they are of the same duration. (After the bias has been removed, of course.)
- All images, including darks, contain the bias. A shortcut often used is to not separate out the bias but subtract the dark+bias.
- Most research CCDs have very low dark current.



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CCD Callibration: Flat Field

Every CCD has different pixel-to-pixel sensitivity, defects, dust particles, etc, that not only make the image look bad, but if the sensitivity of pixels change with time can influence your results.

***Every* observation must be divided by a flat field after bias subtraction.**

The flat field is an observation with a uniform and known illumination.

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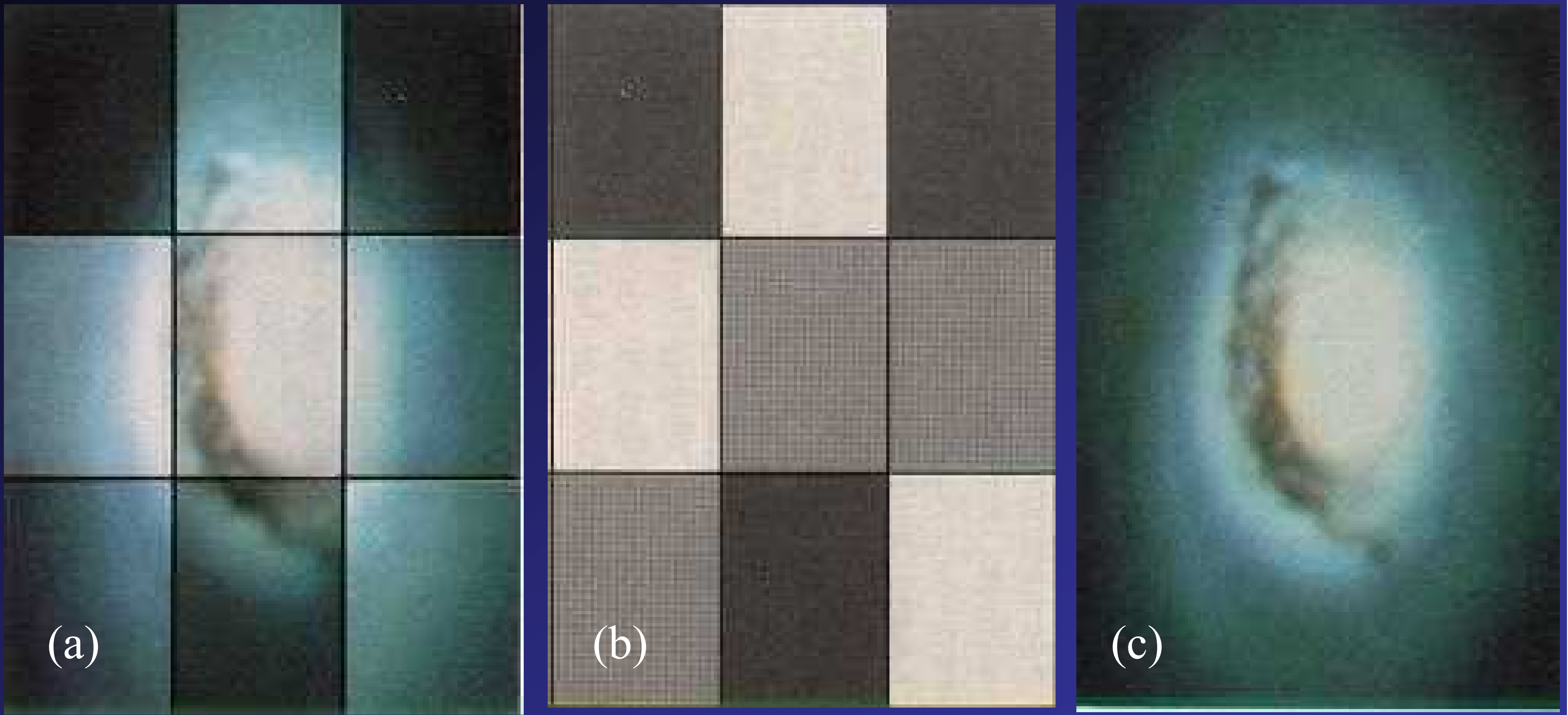
Flat Field Calibration - Divide (a) by (b) to get (c)



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Fringing

Owing to light reflection within the CCD, patterns of illumination across the field can be generated and must be subtracted to obtain the final image

If CCD was perfectly uniform, no pattern would be observed

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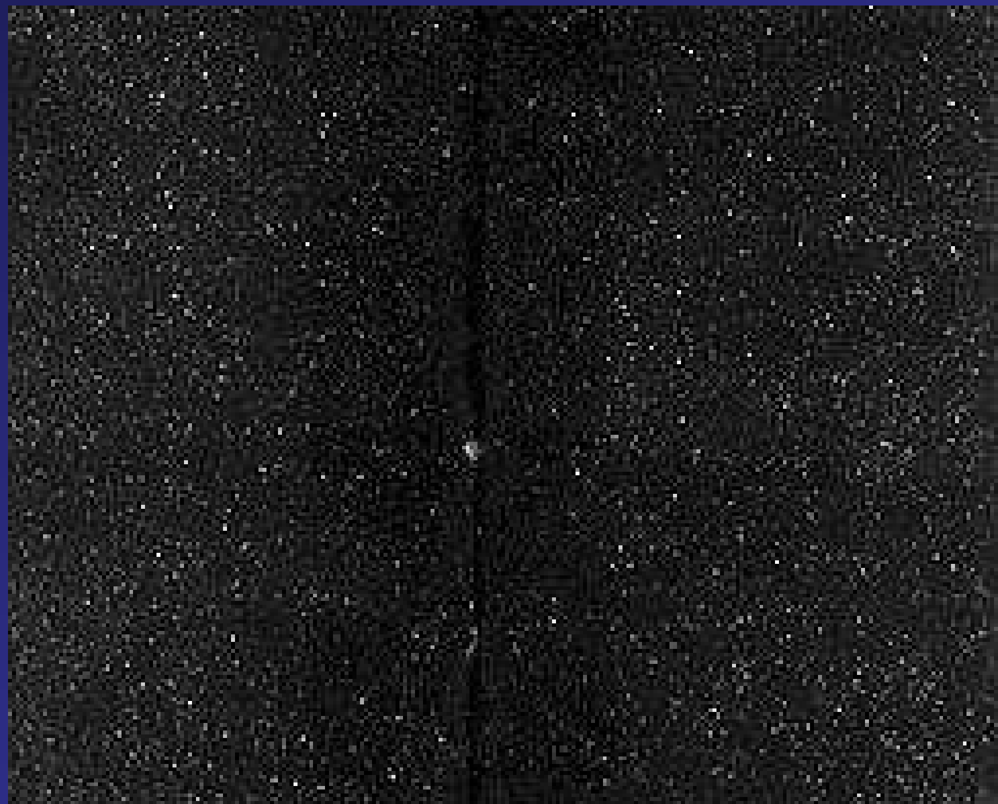
Cosmic Rays

• CCDs are good cosmic ray detectors

• Cosmic rays are always found on long exposures

• To correct for cosmic rays, take at least three object exposures, and combine them with a median filter



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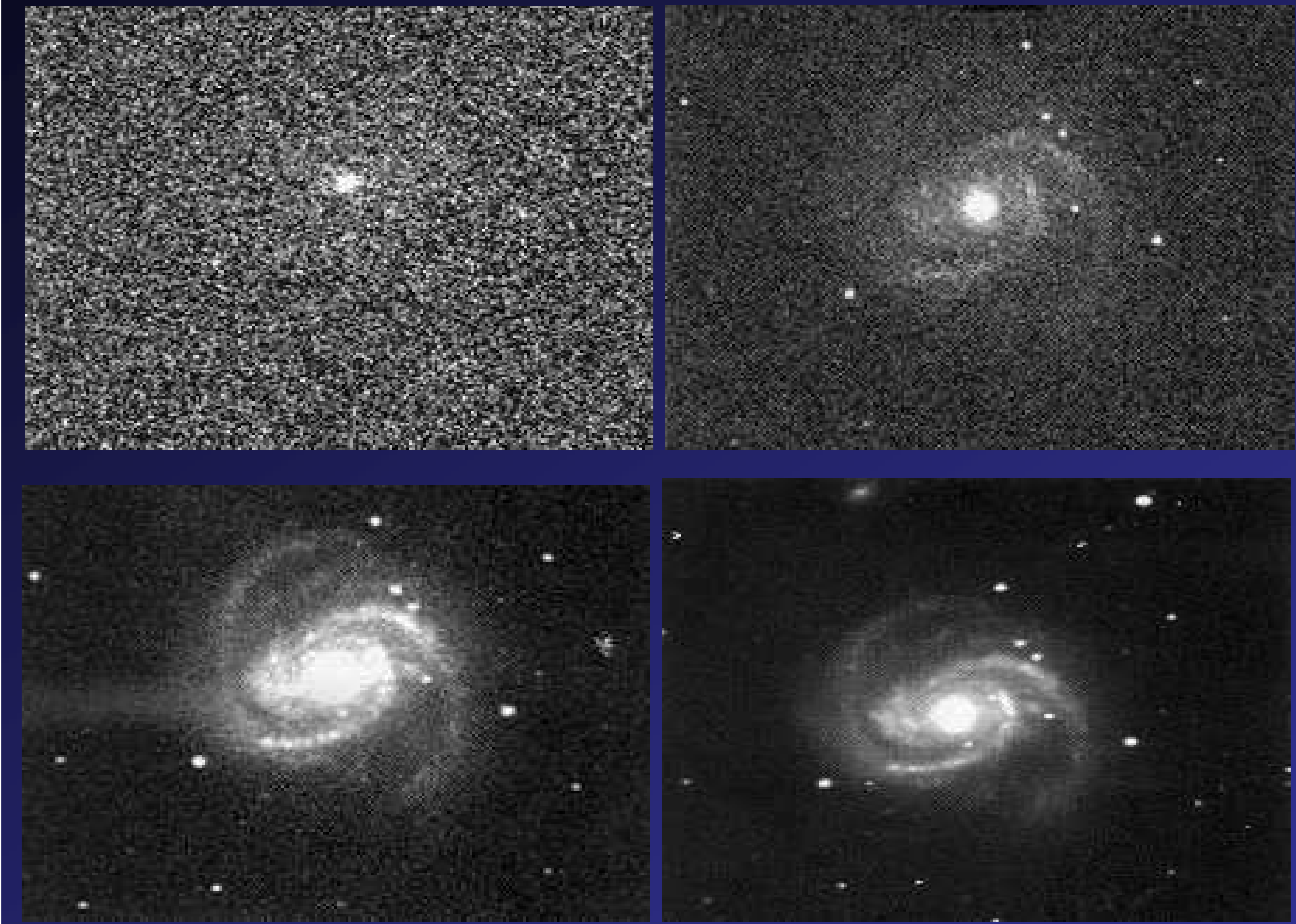
Observing with a CCD

1, 10, 100, 1000 seconds exposures of M100



- S/N ratio improves with exposure time
- Readout noise dominates in the shortest exposure
- Photon noise in the sky dominates for the longest exposure

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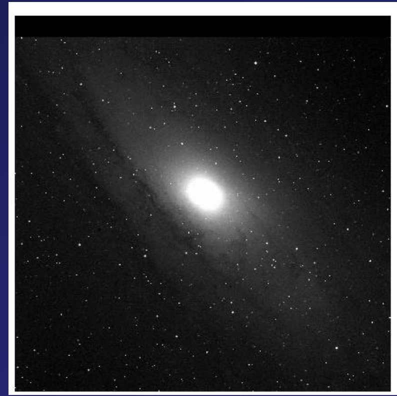
CCD versus Photographic Plate

Plate

3 x 3 deg (less since image is trimmed) in one exposure

Cost 100 €

Requires 20 m telescope to detect same number of photons as CCD



CCD

1/9 coverage

Cost: 120.000 €, ~1.000.000 € for same FOV

Cost per exposure over lifetime: < 1 €

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Astronomical cameras: Mosaics of CCDs

- The CCDs are small → Build mosaics
- Several CCDs in the same plane with small gaps
- Largest cameras now have ~30 CCDs. Next generation larger (PAU, DES, PanStarrs…)
- New problems arise: All CCDs in the same plane with precision less than 1 micron, electronics for several CCD, cross-talk, cooling, vacuum, interface with the telescope...
- New designs of CCDs to minimize gaps

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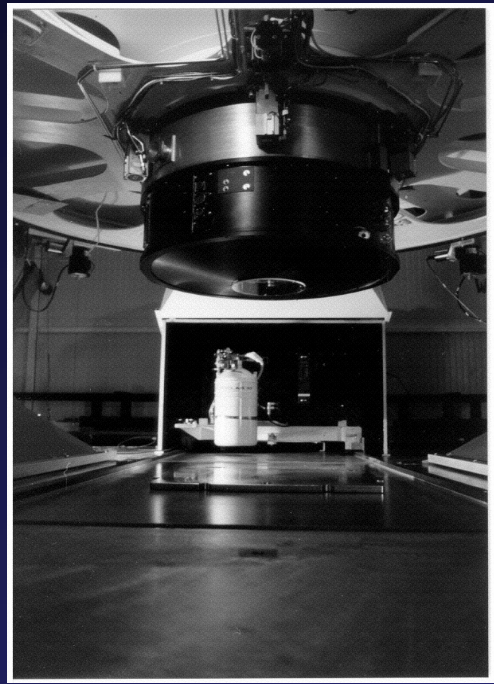
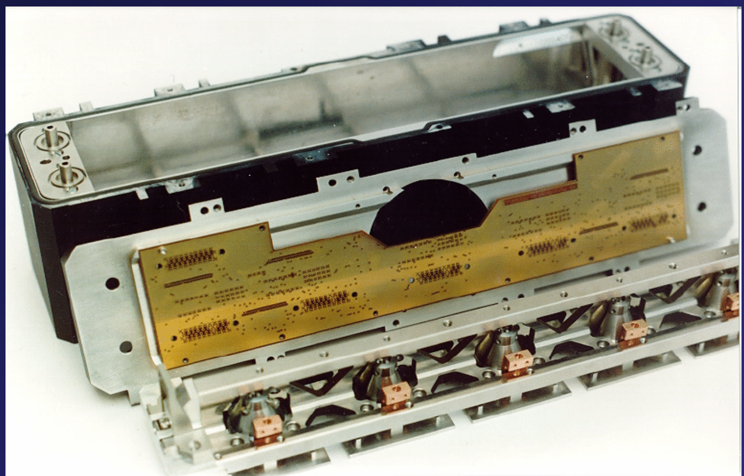
Examples of CCD Cameras:SDSS



Images from SDSS



30 CCDs (2048x2048 pixels), 5 filters

About 3 sq-deg FoV

Installed at a telescope of 2.5 m

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Examples of CCD Cameras: MegaCam

40 CCDs (20k x 18k pixels)

Installed in a 3.6 m telescope (CFHT)

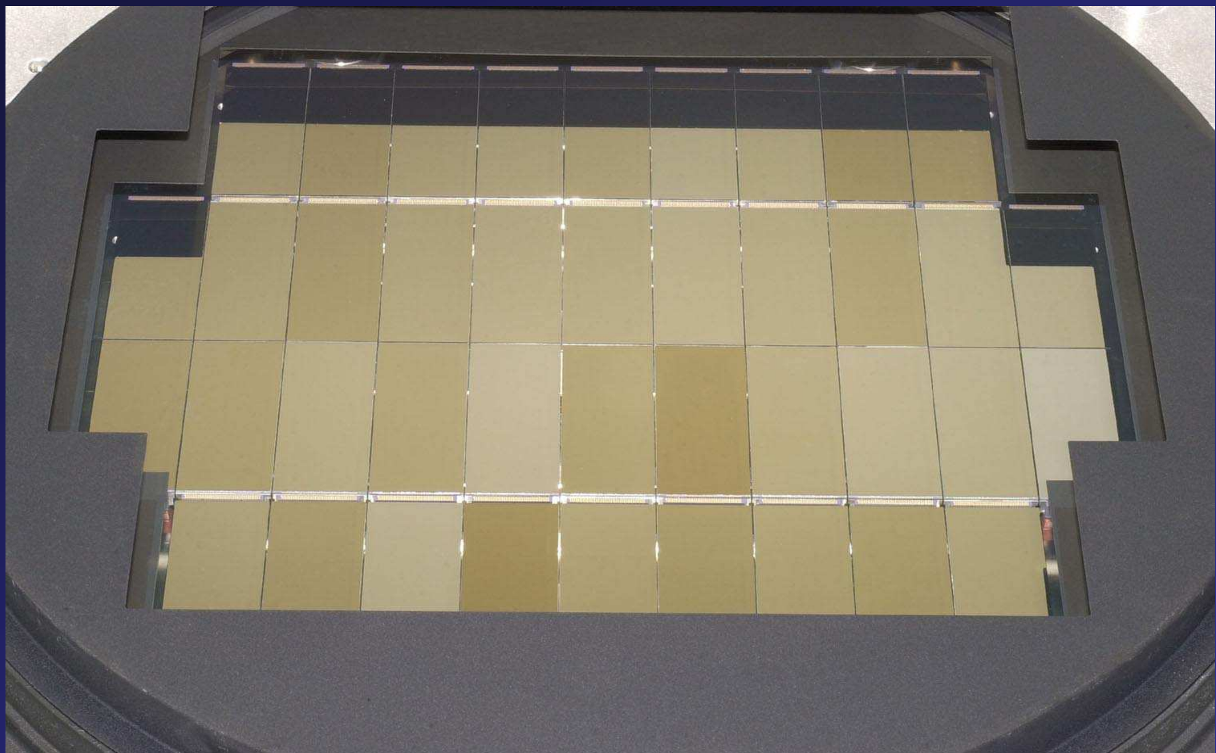
1 sq-deg FoV

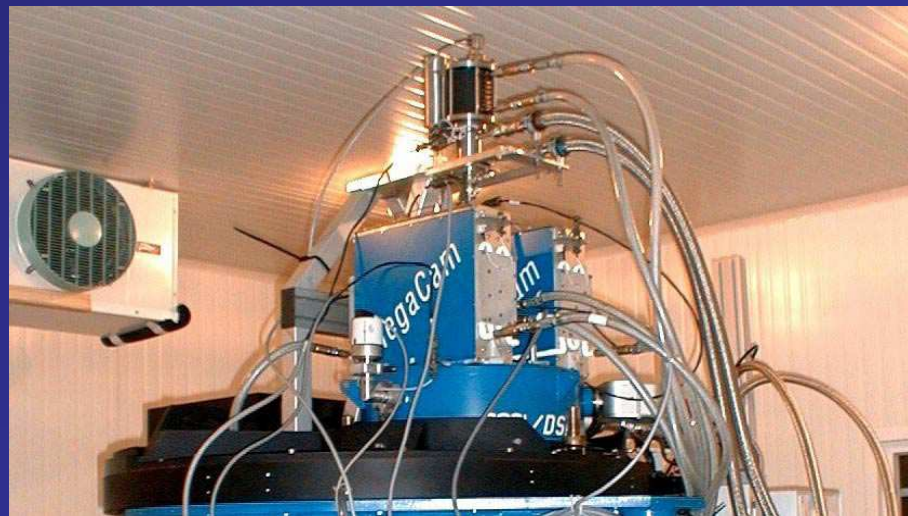
3 main parts:

CCD mosaic (focal plane)

Thermal system: Uniform temperature

Mechanical system: highly integrated, dilatations, vacuum, maintenance of CCDs





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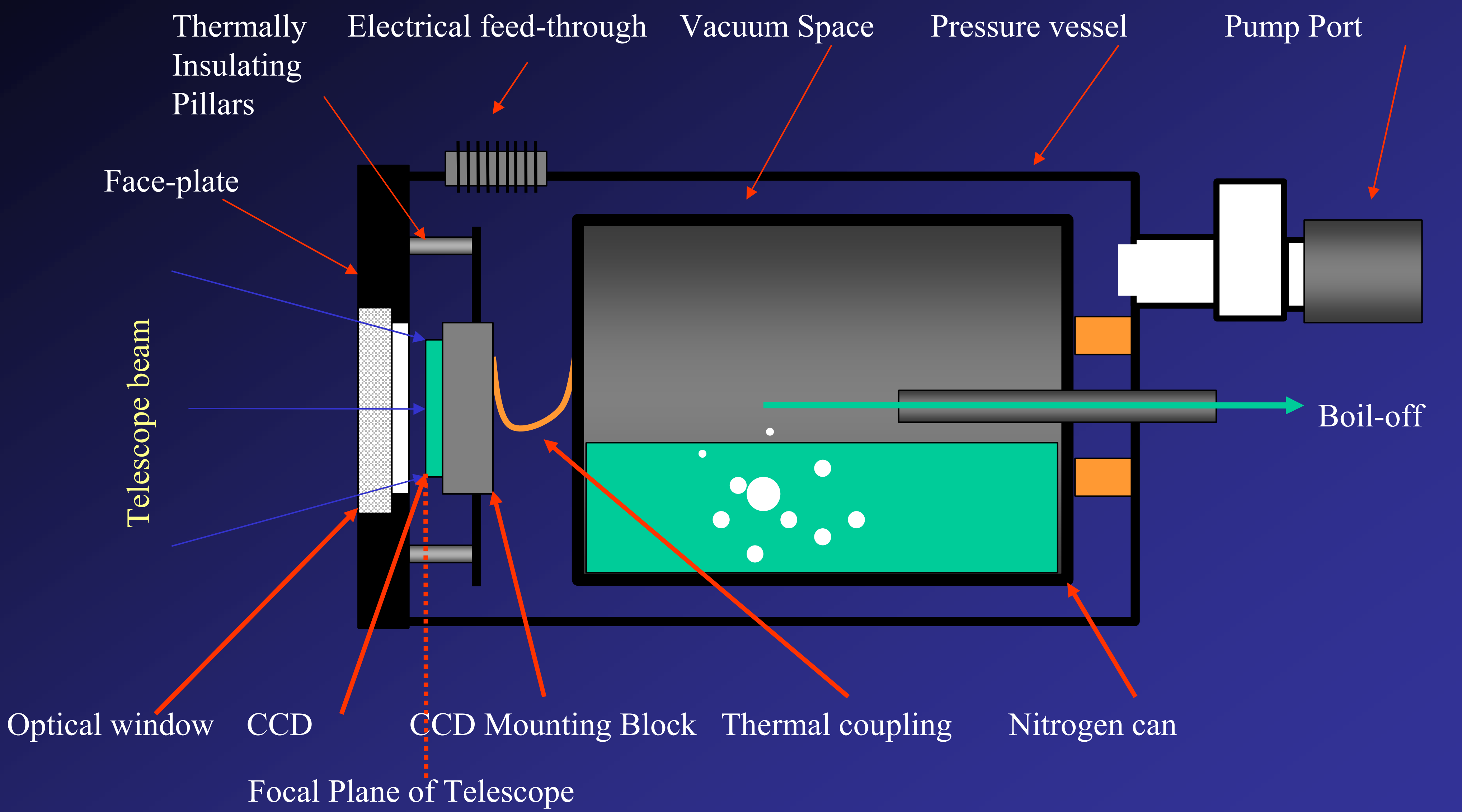
A simplified diagram of a camera



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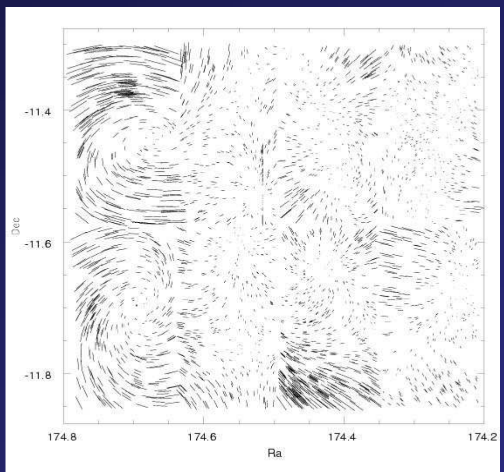
Other Aspects

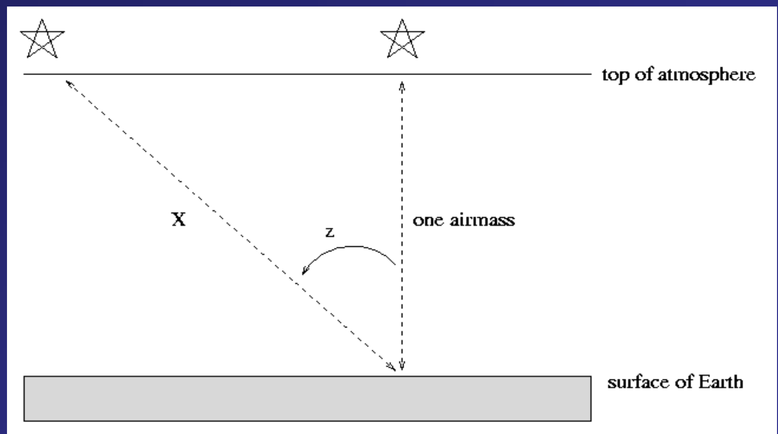
We have seen how to obtain scientific images using CCDs, but this is not the end of the story.

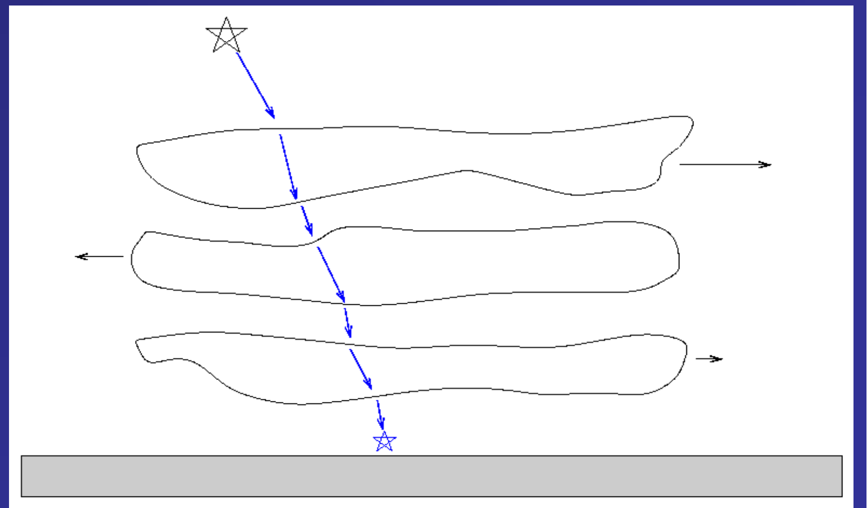
All the images of the same object must be combined (coadd images) to extract the full capabilities of the survey. But the images must be calibrated → Same positions, same references…

To do that and produce the data, we need:

- **ASTROMETRY:** Determine true coordinates of objects from their position in the image
  - One needs to coadd data from the same true (or sky) position, not the same pixel position. Precise mapping from sky coordinates to pixel coordinates
  - Take into account field distortion
  - Need reference stars with precisely known sky coordinates → Coordinate systems
- **PHOTOMETRY**: Measure magnitude of objects (in different ranges of wavelength)
  - Identify and separate objects
  - Compare with reference sources → Magnitude systems
- **ATMOSPHERE EFFECTS:** Extinction (dimmer objects) and seeing (blurry objects)







MORE ON NEXT TALKS!!

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Storage of images: Fits format

- Data are stored in FITS format.
- FITS → Flexible Image Transport System
- The standard format in astronomy
- Allows transport, analysis and storage of data sets
  - Multi dimensional arrays → 1d spectra, 2d images, data cubes
  - Tables
  - Header keywords
- The general structure of a fits file is:
  - One or more Header Data Units (HDU), that describe general features of data
  - Interleaved between data blocks
- Can be used from: c, c++, fortran, perl, python, idl, java…
- More on http://fits.gsfc.nasa.gov

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