Introduction to X-ray astronomy

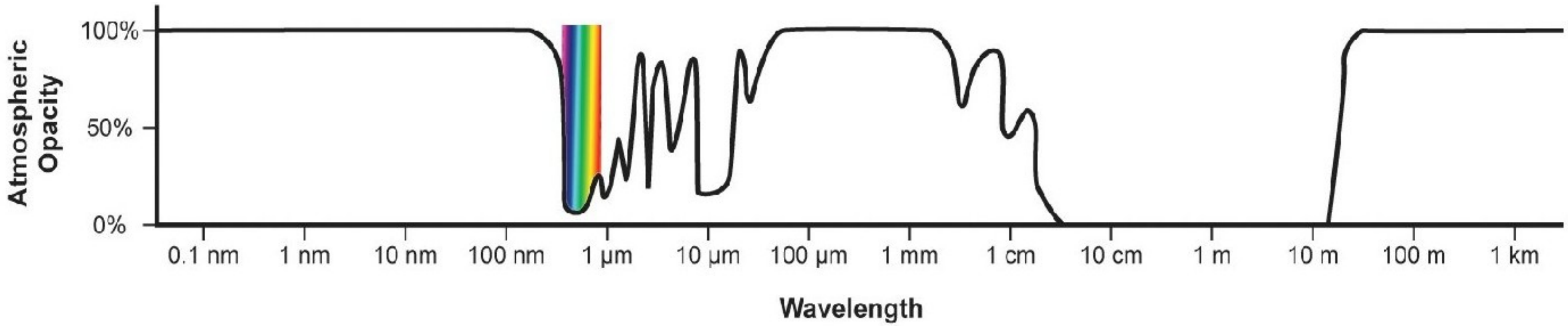
http://sagittarius.star.bris.ac.uk/~ayoung/dokuwiki/doku.php

Overview

- History
- Detecting X-rays
- Statistics
- Current observatories
- Calibration & background issues
- X-ray data analysis

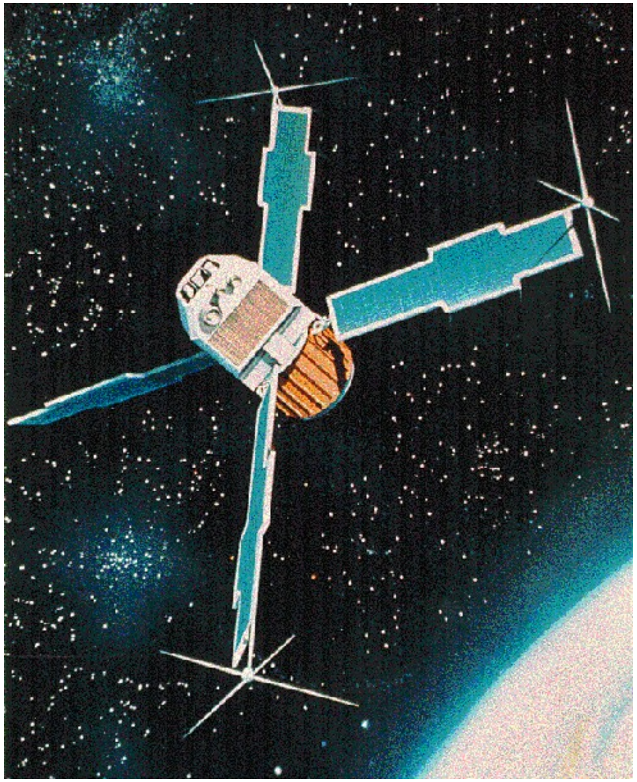
X-ray astronomy

- At very short wavelengths we deal with photon energies instead of λ
  - Measured in electron Volts, eV
- X-rays: energies of approx 100eV to 100keV
  - Absorbed by the atmosphere so observatories are space based



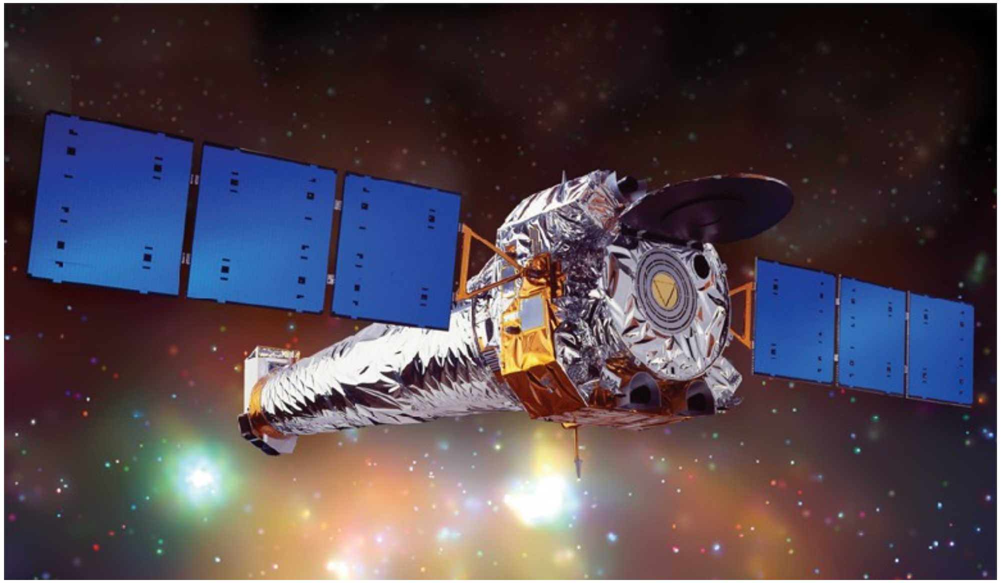
History

- 1960s rockets carried balloons with X-ray detectors
- 1970 NASA's Uhuru was 1st X-ray satellite
- 1979 NASA's Einstein launched
  - focussed X-rays (good spatial resolution)
  - data still used
- 1990 ROSAT (German/USA/UK)
  - operated for 9 years
  - ROSAT all sky survey
- 1993 ASCA (Japan)
  - good spectral resolution
  - 1st to use CCD X-ray detectors



New Millennium

- 1999 saw launch of Chandra and XMM-Newton
  - NASA's Chandra high spatial resolution
  - ESA's XMM high sensitivity
- 2005: Japan's Suzaku mission launched
  - High resolution X-ray spectrometer failed after launch, imager still performing useful science



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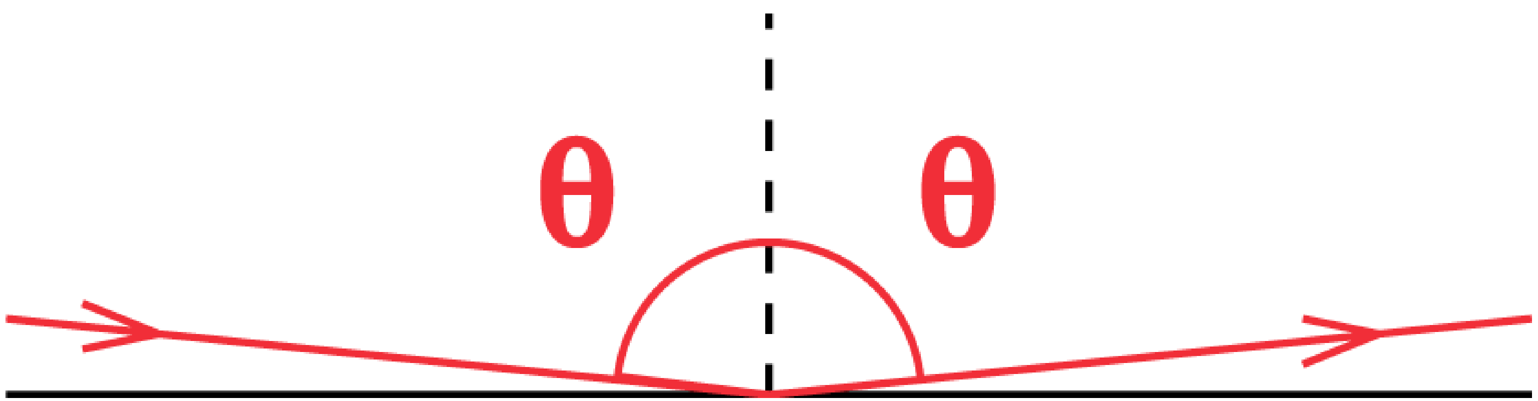
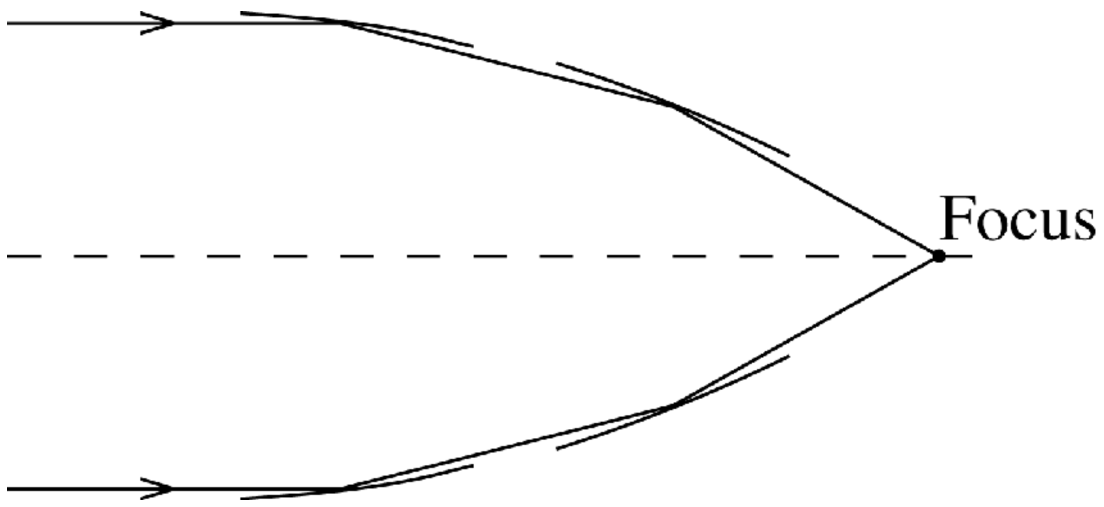
X-ray Telescopes

- X-rays energetic enough to pass through normal mirrors
- **Grazing incidence** reflection can occur for 'soft' X-rays (energies ≤10keV)
- Incident angles must be ≥89º
- Surface finish must be extremely smooth
  - 1nm equivalent to wavelength of 1.24keV X-ray



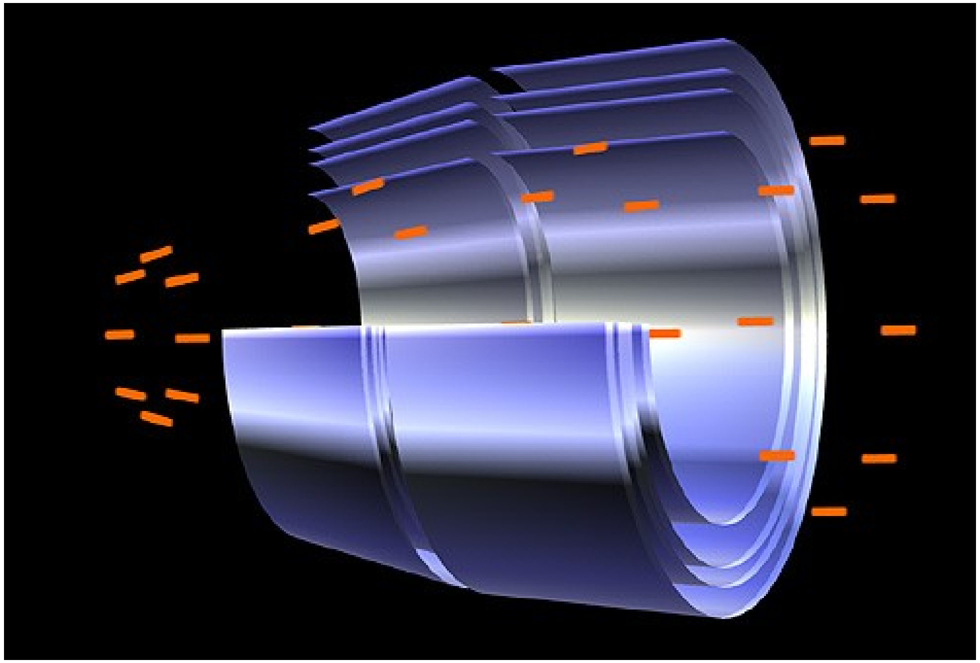
X-ray Telescopes

- Hans Wolter developed mirrors using this effect in 1950s
- Use paraboloid and hyperboloid sections in annular arrangement
- X-rays brought to focus by successive grazing reflections
- Effective area low due to small grazing angles



X-ray Telescopes

- Nest several Wolter mirrors inside one another
  - Increases the effective collecting area
- Chandra X-ray observatory uses 4 nested mirrors

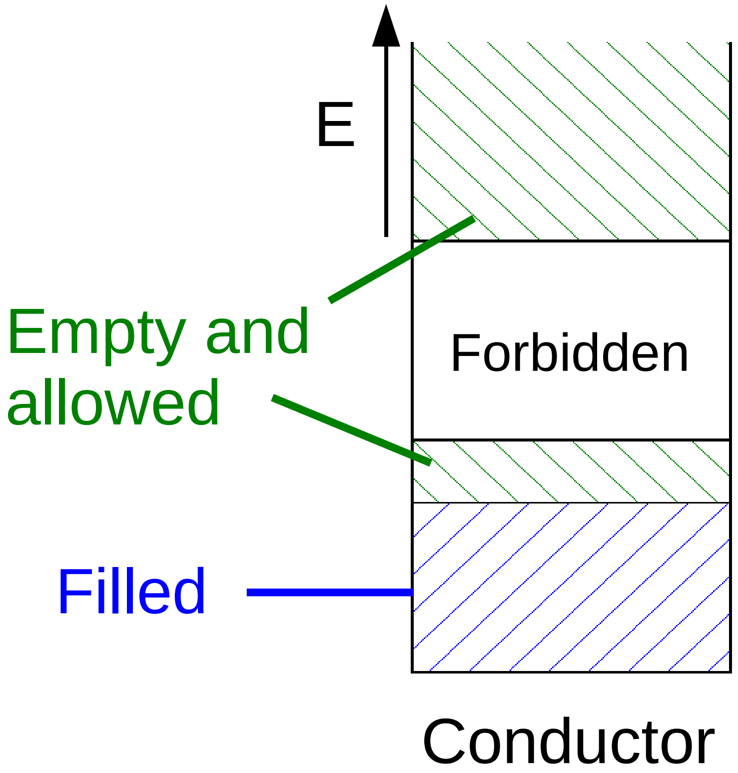


Charge-Coupled Devices

- Standard detector type in astronomy
- Used from near infra-red to X-rays
- Constructed from semi-conductors
- In a solid, electrons have allowed and forbidden **bands** of energy, not well defined energy levels as in atoms
- Size of forbidden gap between bands and completeness with which lower energy band is filled determine if solid is
  - Conductor
  - Insulator
  - Semi-conductor

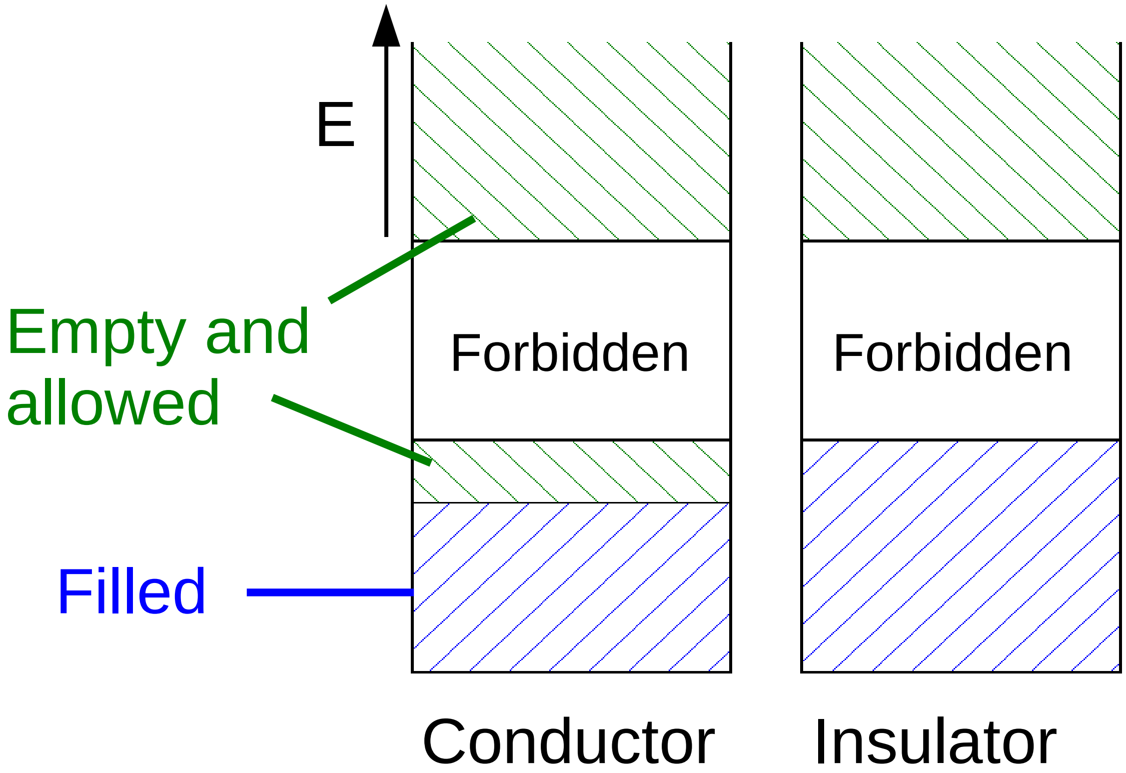
In a conductor

- Lower energy band not completely filled
- Electrons may travel freely in this unfilled part and conduct electricity



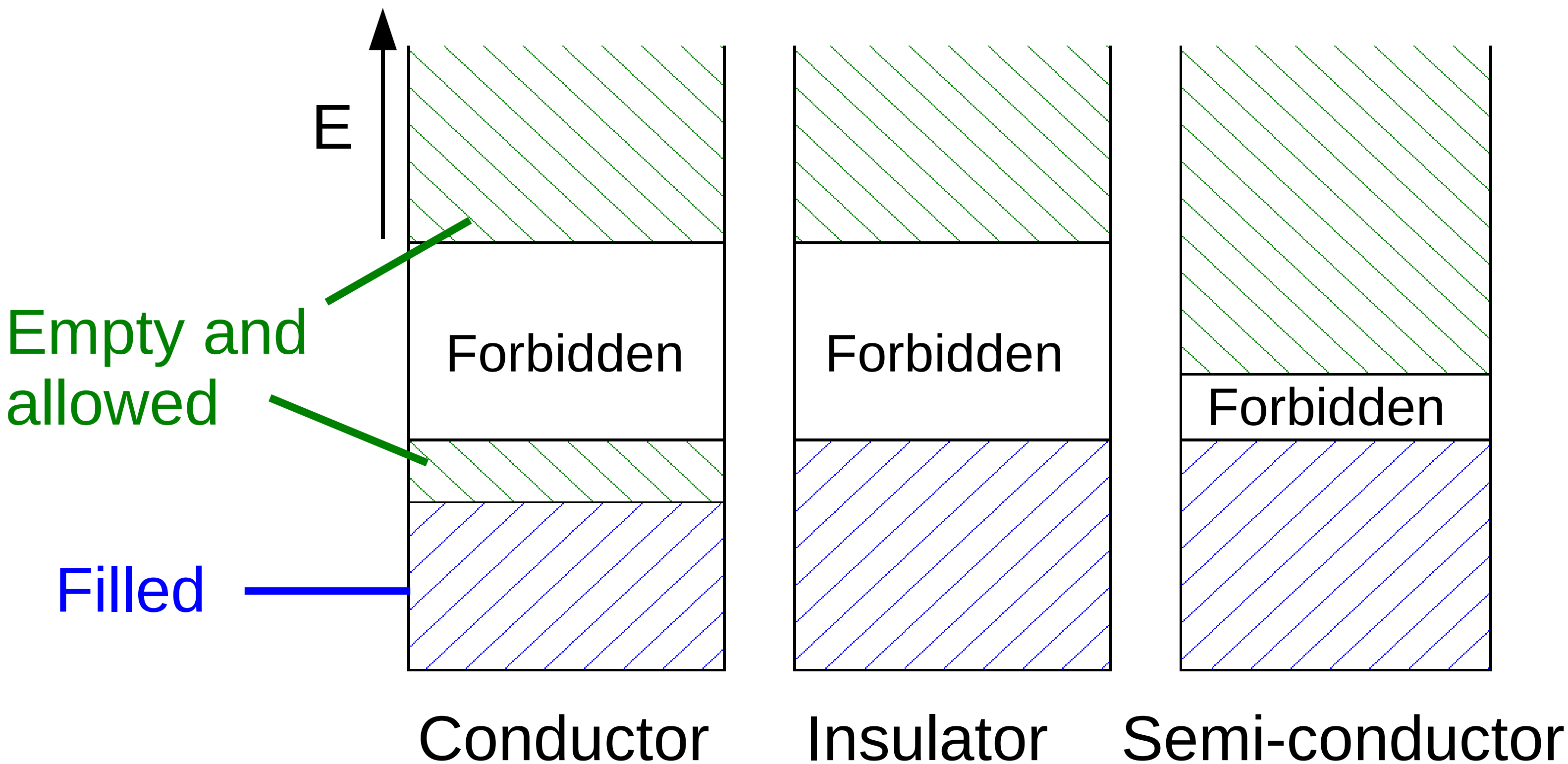
In an insulator

- Lower energy level is full
- Electrons require great deal of energy to move into upper allowed band and conduct

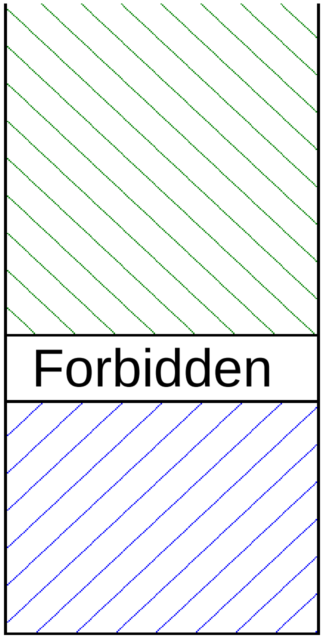


In a semi-conductor (e.g. Silicon)

- Lower energy level is full
- Forbidden gap is small enough that electron may be excited across it thermally or by absorbing a photon
- Produces an electron-hole pair, both of which contribute to conductivity

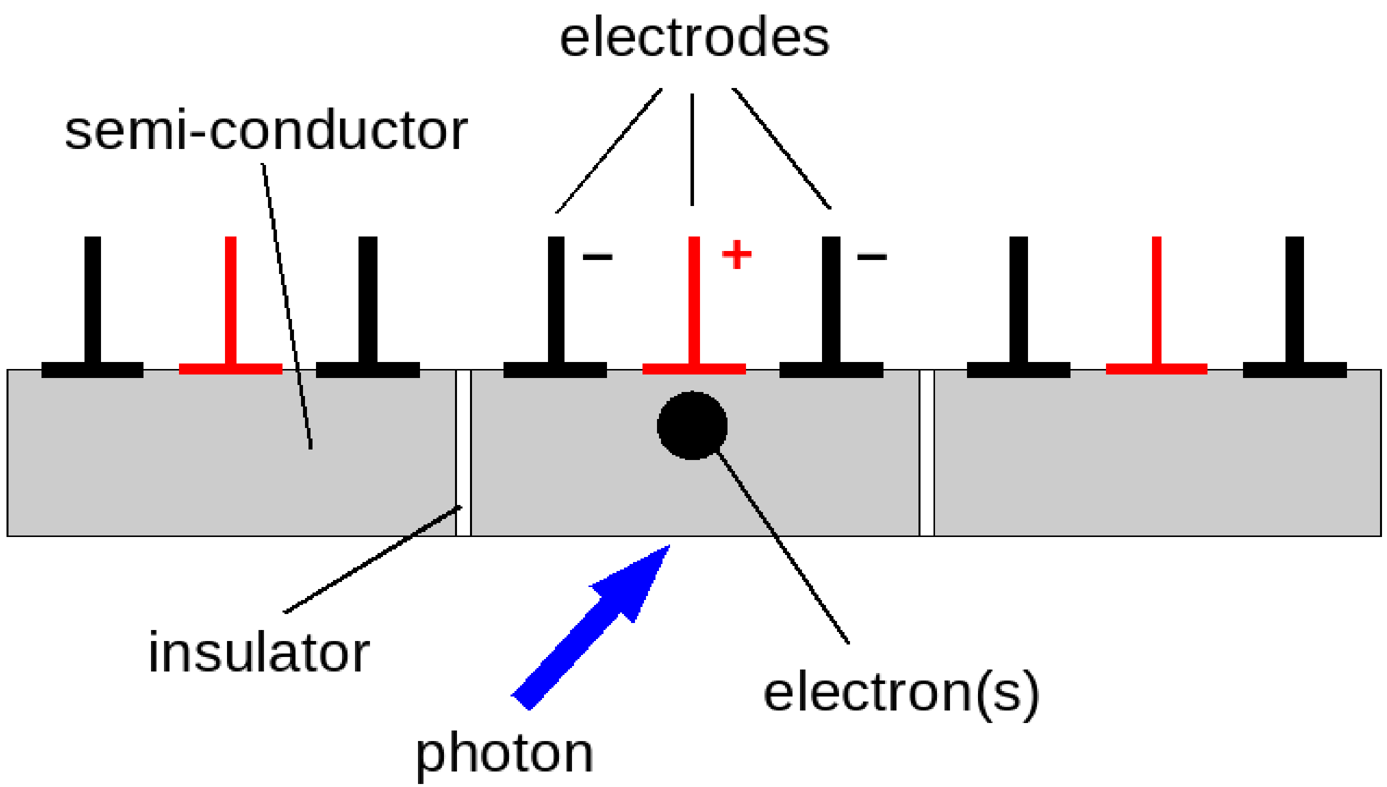


- CCDs make use of this property of semiconductors
- Photons striking the semiconductor free electrons (**photoelectric effect**) which are then stored
  - Record the number of photons
- Size of forbidden band in Silicon fixes the infra-red limit for CCD use at ~1.1μm
  - At longer λ not enough energy to free electrons
- Cooling detector reduces background
  - Fewer electrons thermally excited through forbidden band

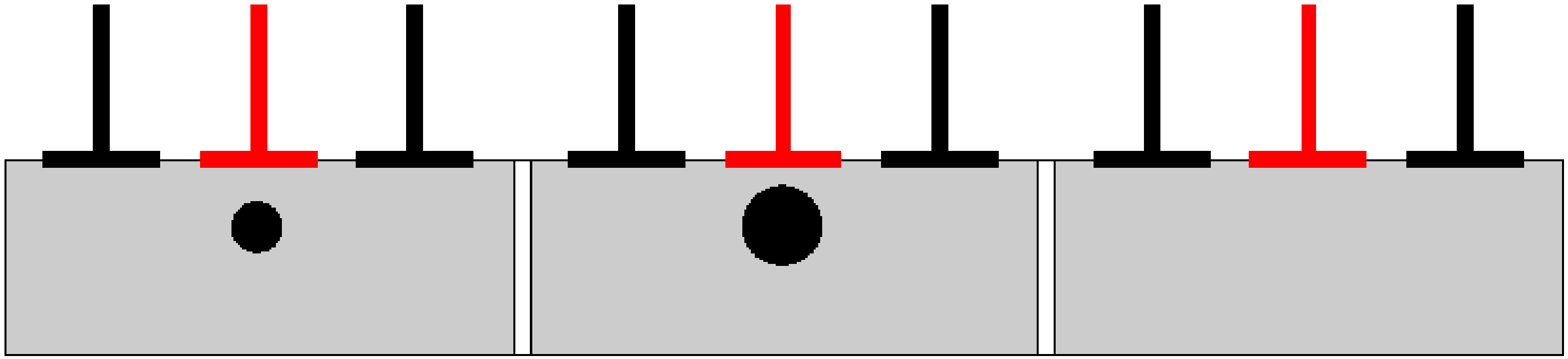


Semi-conductor

- CCDs divided into pixels ~20μm square by thin layers of insulator
- Incident photon liberates electron which is collected in electric field near +ve electrode
- Charge held and more electrons added if more photons arrive until readout



- During read-out voltages on electrodes are cycled to transfer charge from pixel to pixel
- In readout direction, insulators are actually electrode gates on which the voltage can be varied to allow charges to pass



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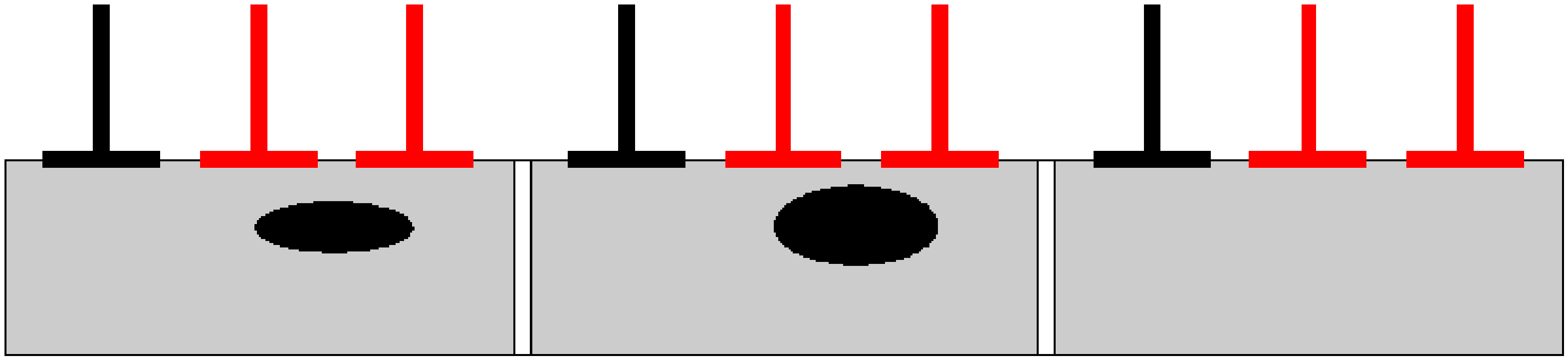

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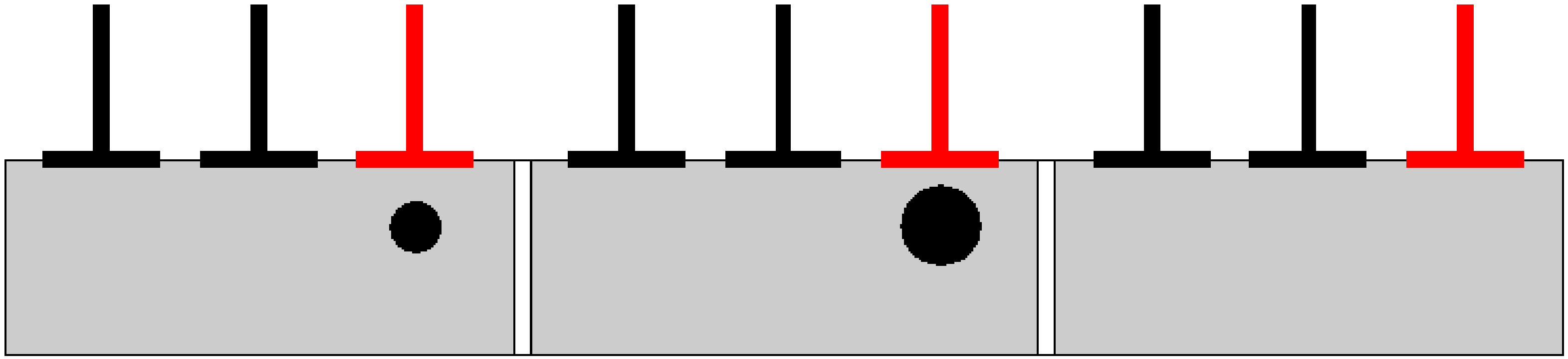

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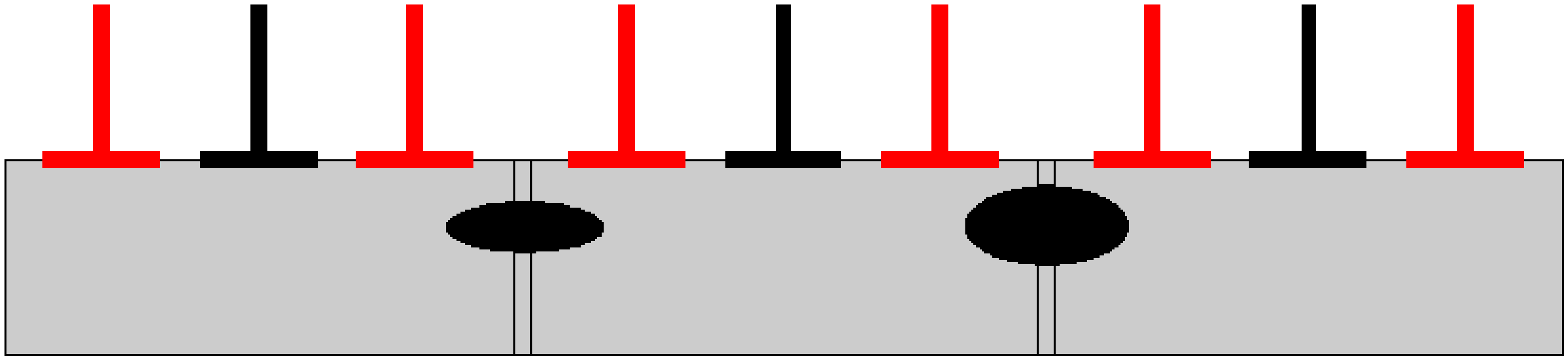

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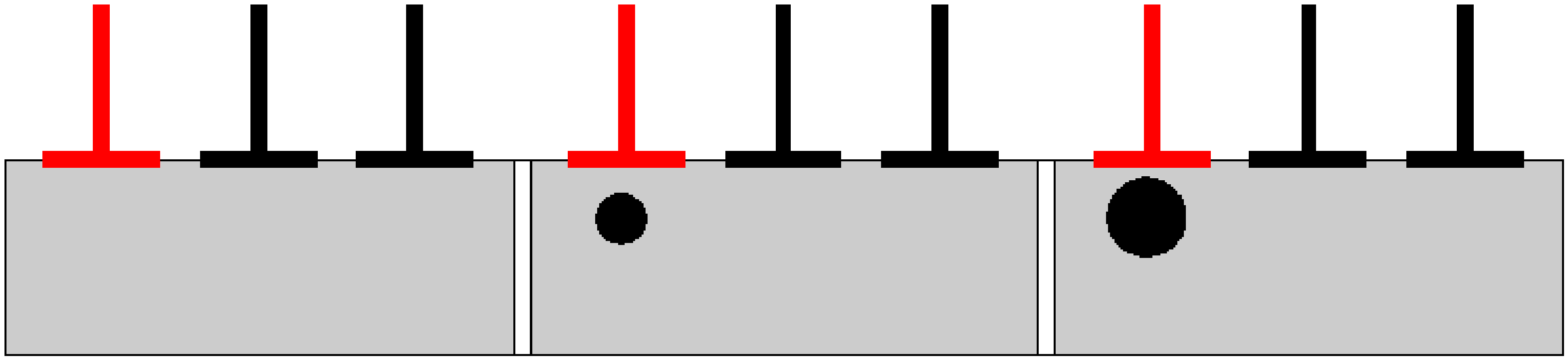

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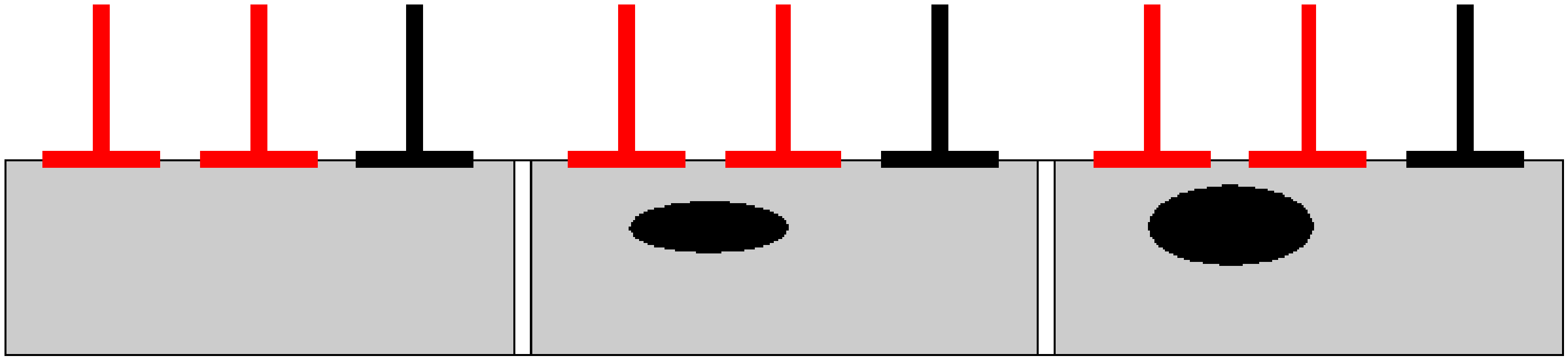

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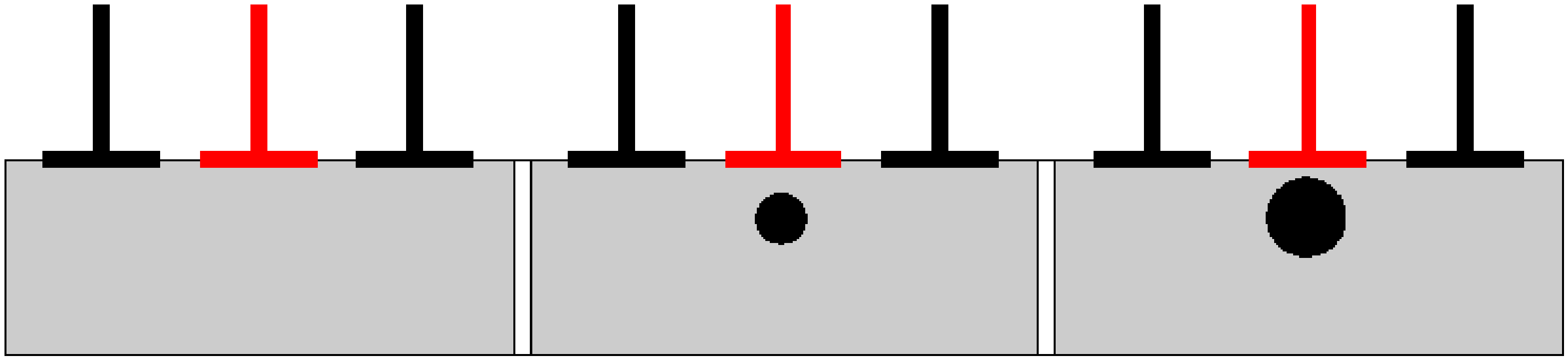
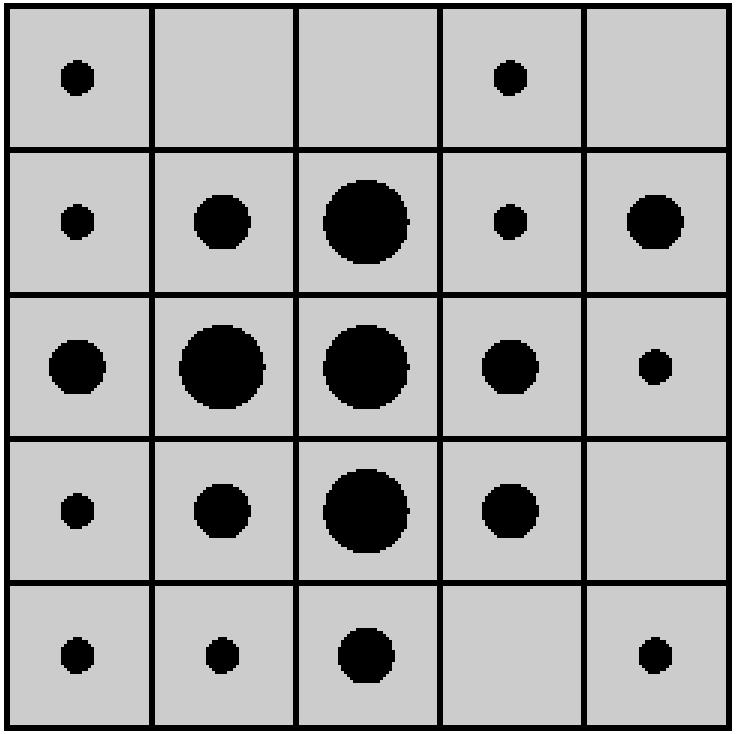


- Charge is transferred along a row and read out



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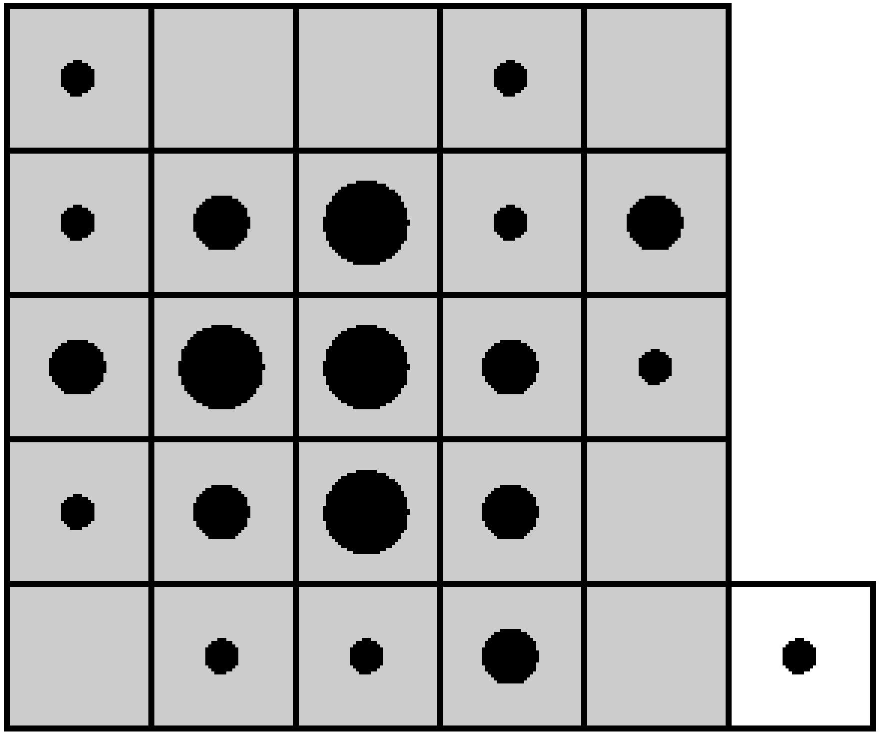

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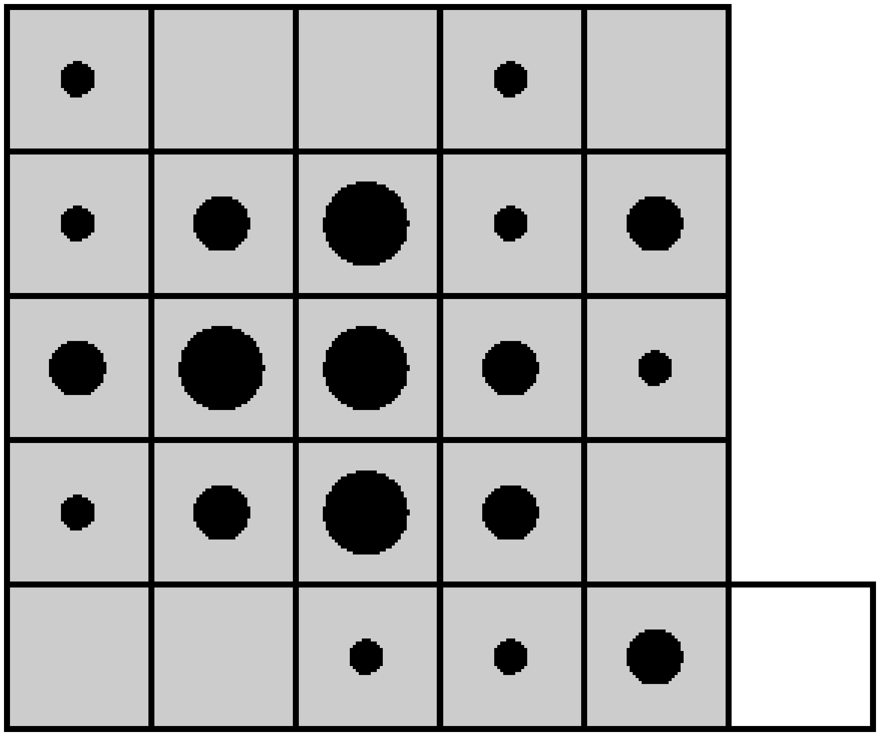

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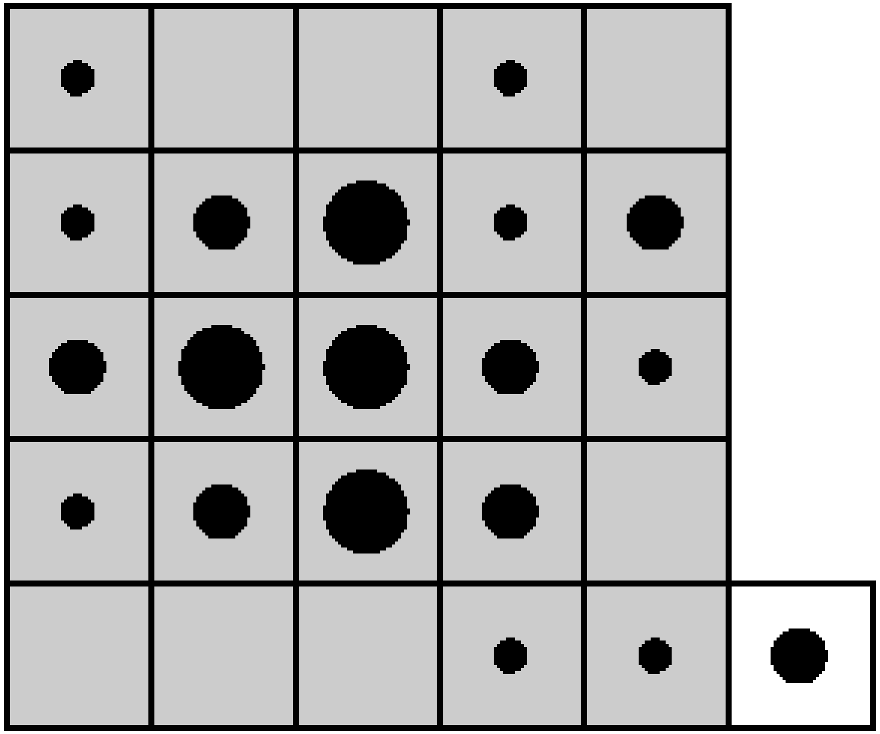

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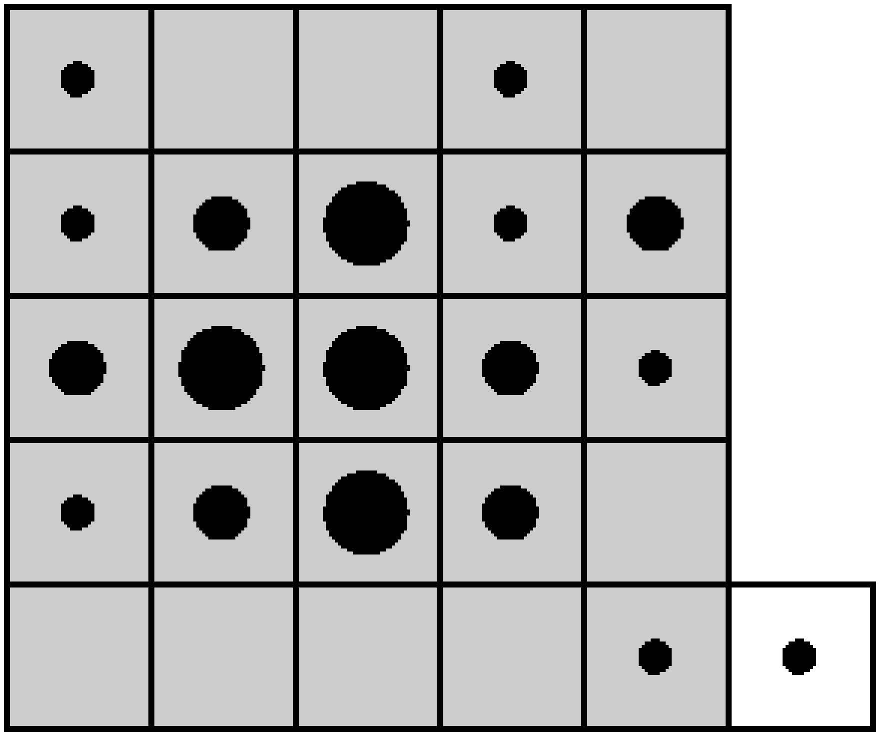

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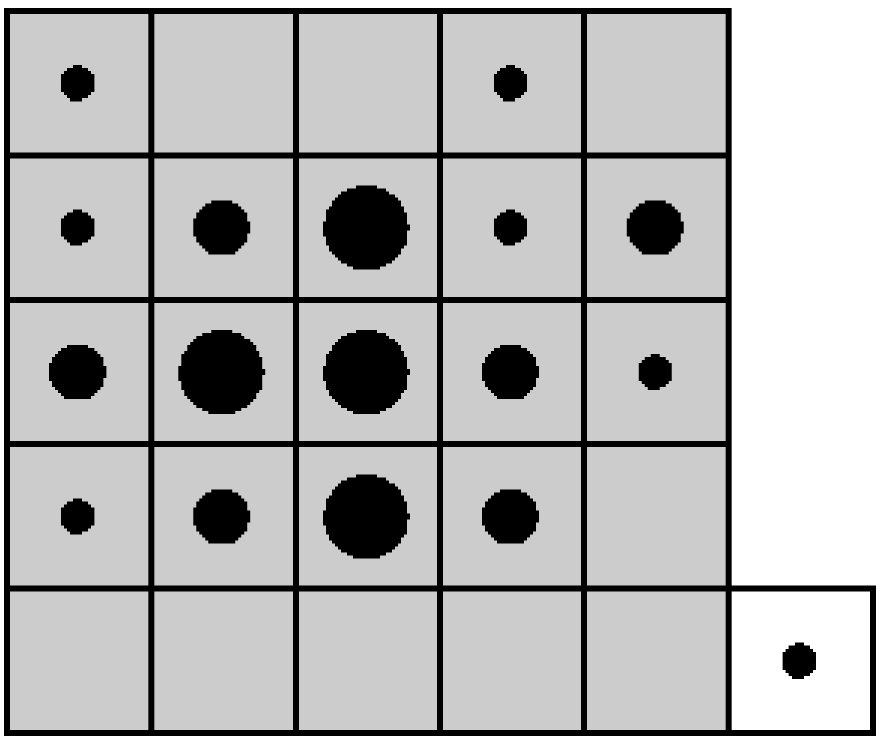
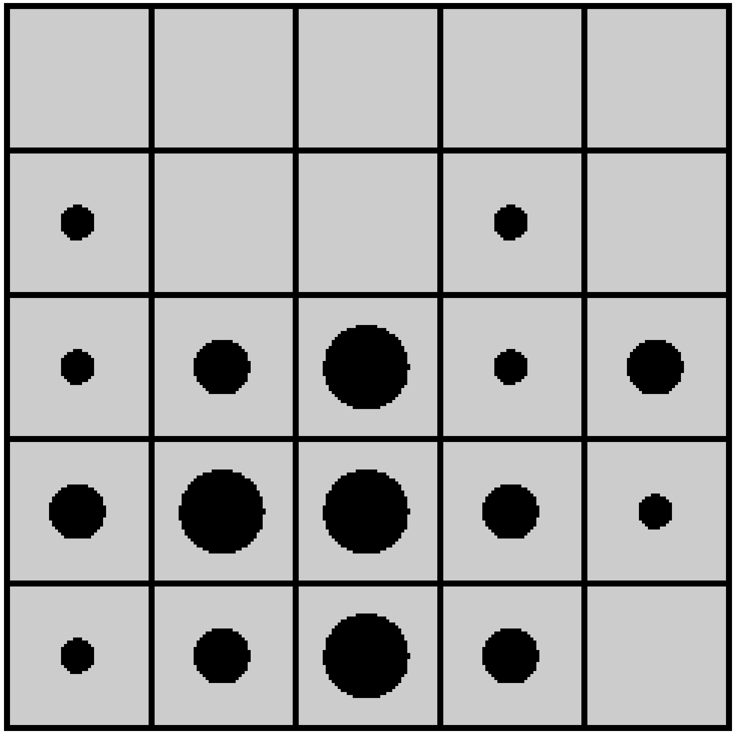


- Charge is transferred along a row and read out
- Then the next row is transferred down to the readout row and the process repeats



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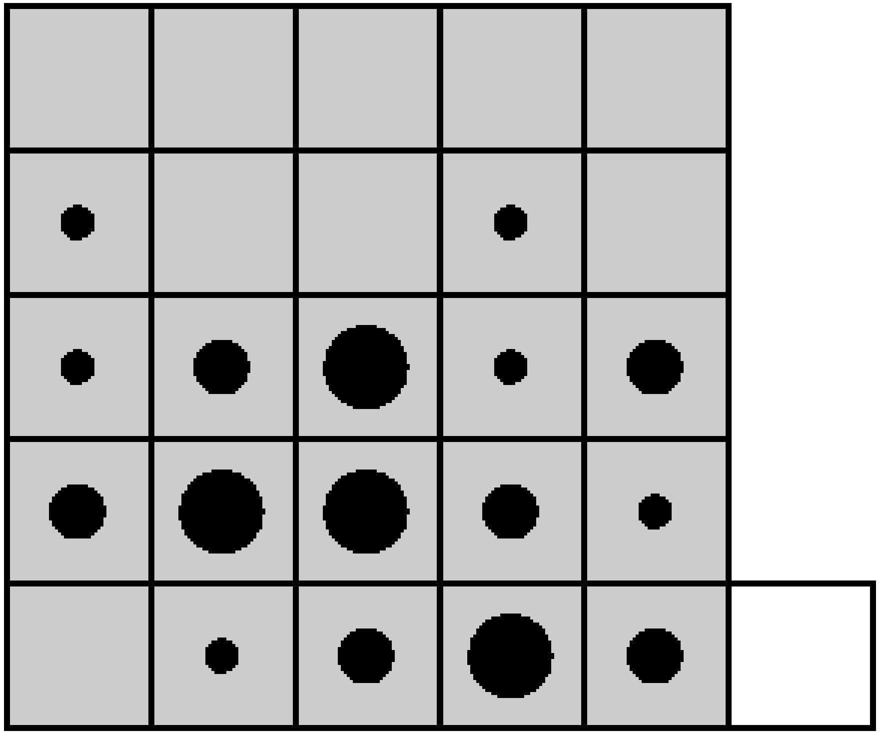

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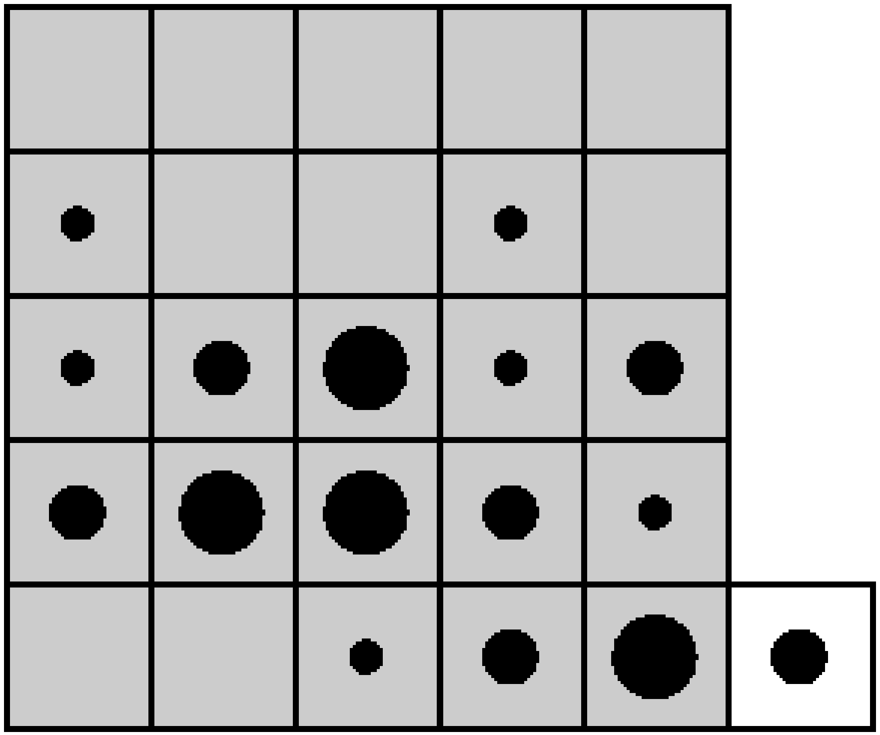
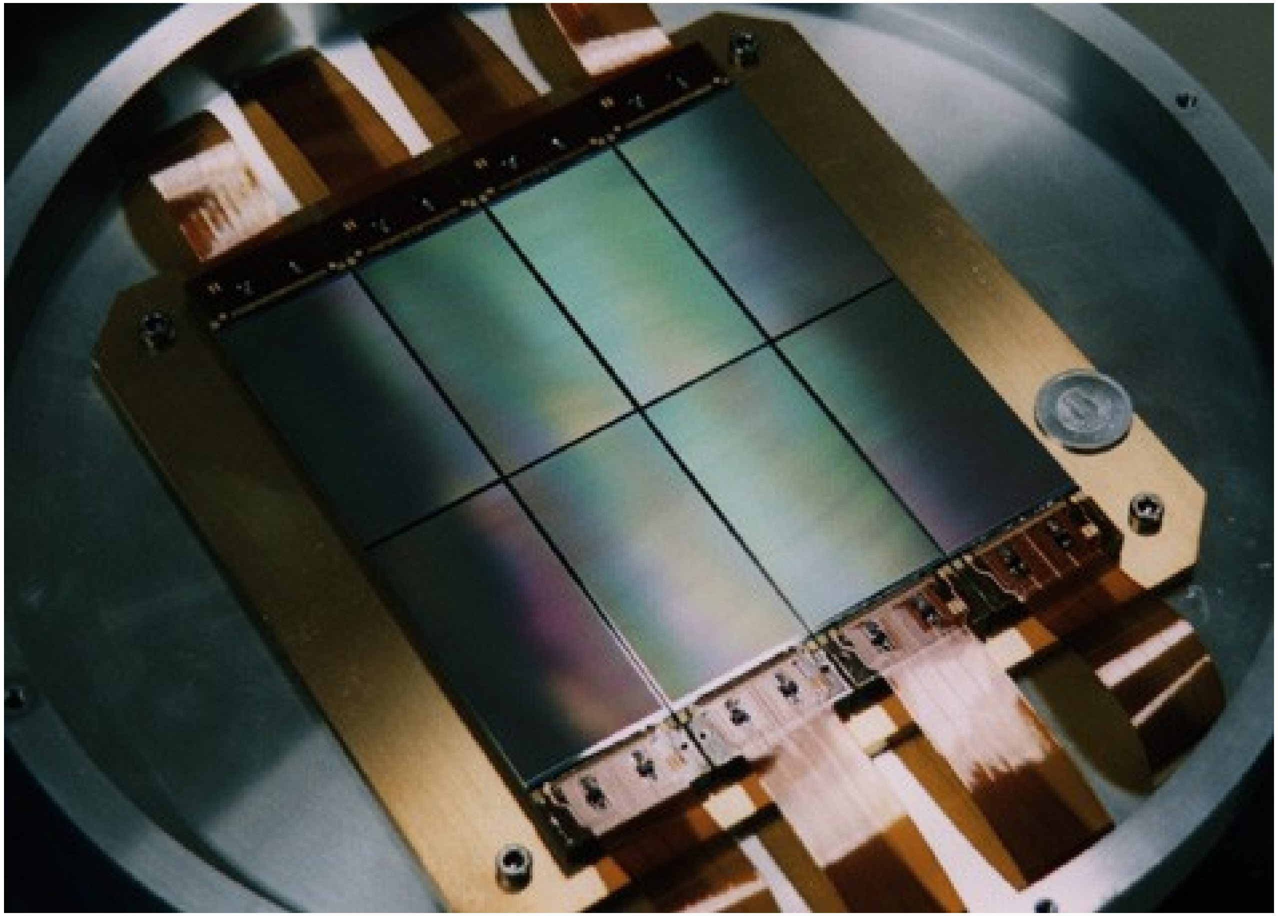


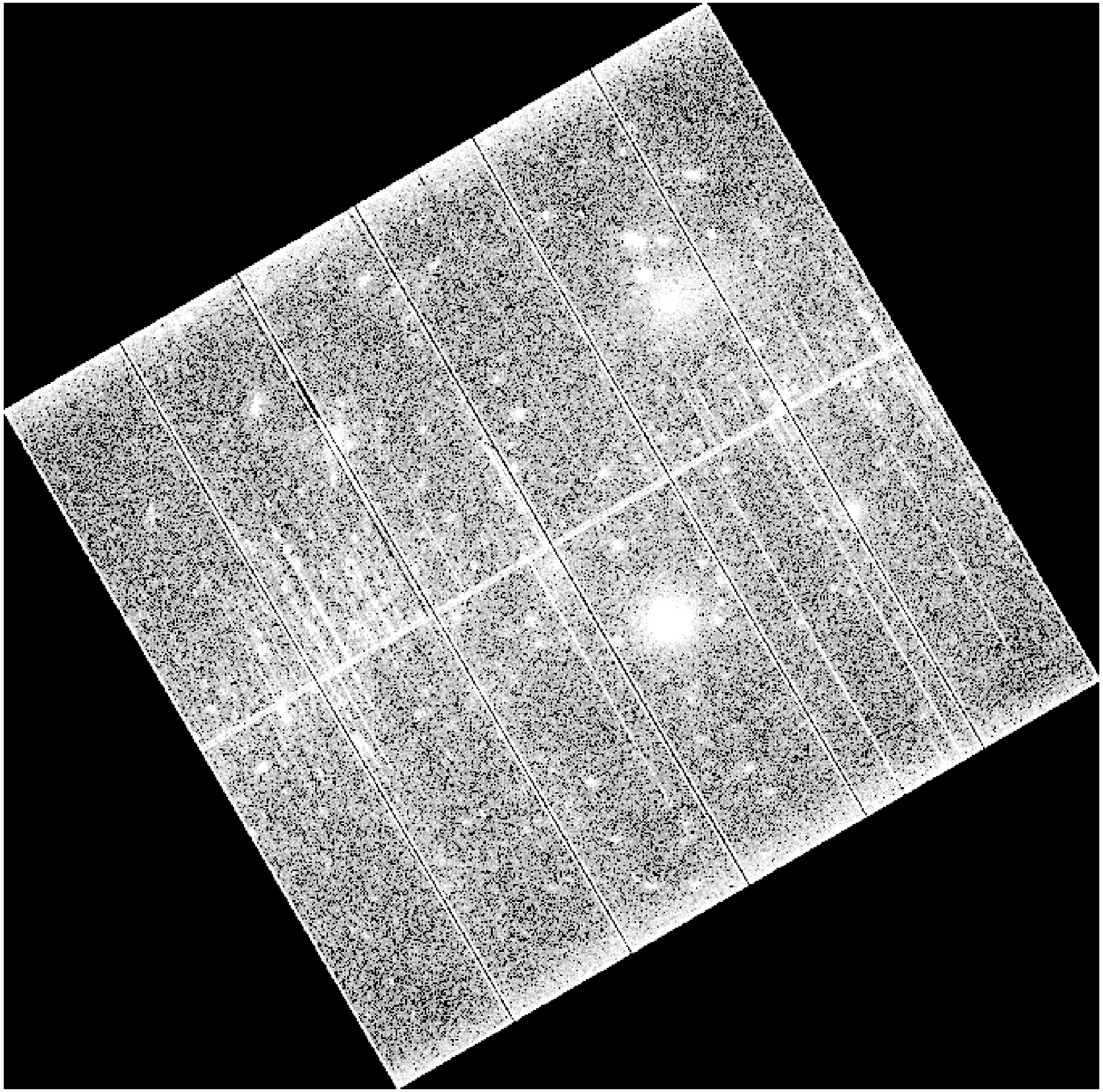
- Typical CCDs are 2048 x 2048 pixels
- Number of charge transfers could be up to 4096 for last pixel in last row
  - Charge transfer efficiency must be > 99.9999%

- Even largest CCDs are small compared to sizes possible with photographic plates
- However, can use mosaiced arrays of CCDs to cover a larger field of view
  - Connections must be restricted to one edge



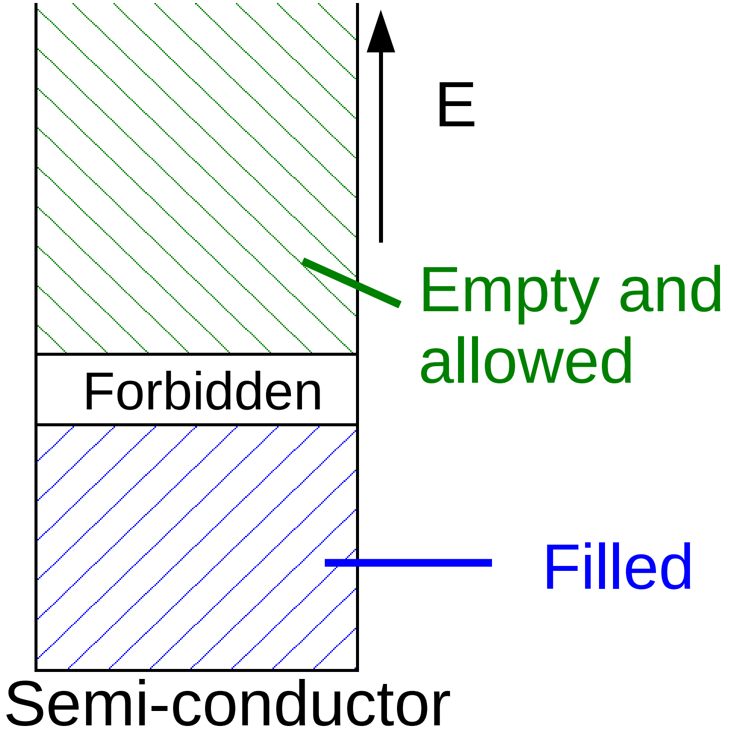
Array of 2048 x 4096 CCDs used on Subaru

- Gaps between CCD chips can be removed by combining slightly offset images or dithering



X-ray CCDs

- CCDs can be used in soft X-ray region
- Design very similar to optical CCDs
  - In optical, each photon liberates electron in a pixel
  - Number of electrons at end of exposure = number of photons received

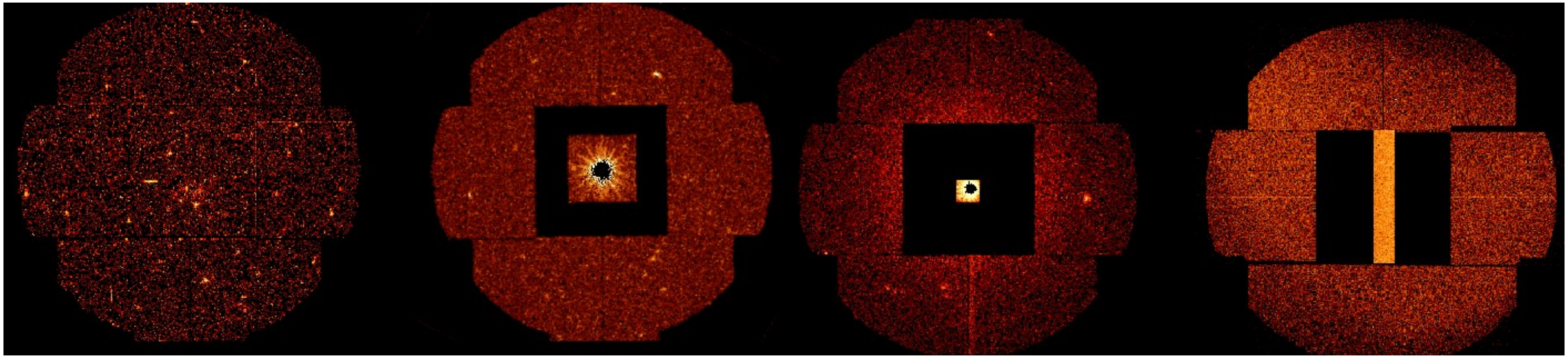


X-ray CCDs

- Energy of single X-ray sufficient to release many electrons in pixel
- Charge on a pixel when read out gives energy of photon
  - Providing only one photon detected by pixel
- Even brightest X-ray sources emit few photons per unit time compared to optical sources
- In a short exposure (~1s), each CCD pixel receives 0 or maybe 1 photon
- Long exposure built up from many short exposures and readouts
- Record position, energy and time of each photon

Time Resolution

- Time of arrival of photon determined from which short exposure & readout it was detected in
- The time taken to shuffle the charges between pixels to read out CCD places limit on time resolution
- Improve by only activating small part of CCD
  - reduces readout time
  - e.g. different timing modes of EPIC MOS camera on XMM-Newton

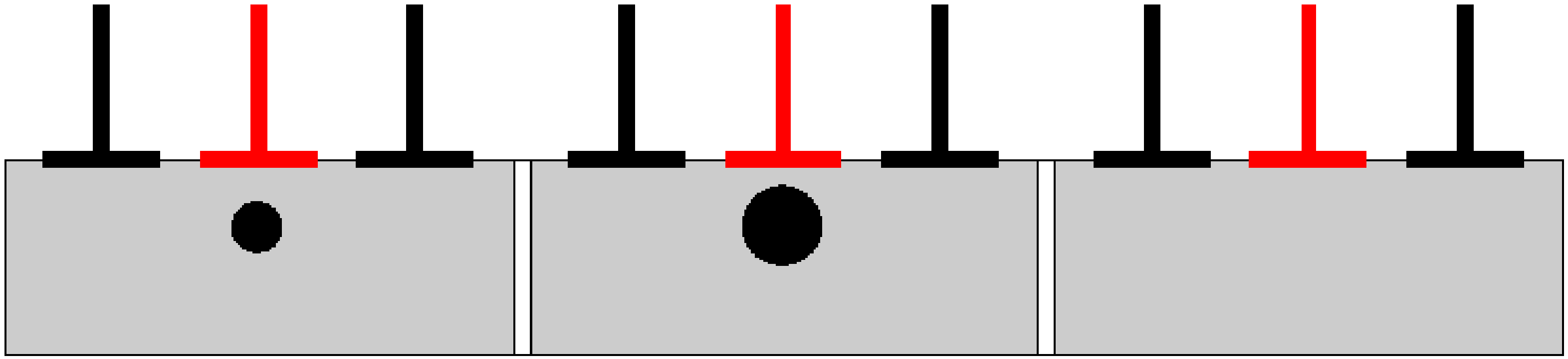


Pile Up

- For extremely bright, compact source, more than one X-ray photon may be incident on a single pixel during short exposure
- Adds more electrons to charge on pixel
- At readout, extra charge from additional photons mistaken for single high energy photon
- Condition called **pile up**
- Incorrect energies of X-rays

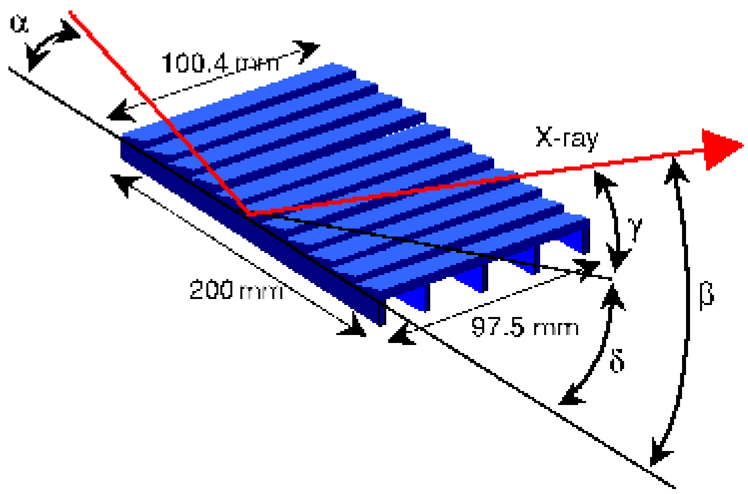
Front and Back Illumination

- Front illuminated (FI) CCDs - the side of the CCD with the readout electronics is exposed
  - Easy to manufacture, lower background
- Back illuminated (BI) CCDs - the other side is exposed to incident photons
  - Improved quantum efficiency and energy resolution
  - Harder to manufacture



X-ray Gratings

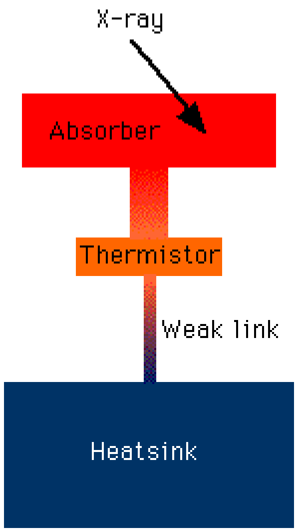
- While CCDs provide good energy resolution, high energy resolution requires grating spectrometers
- Transmission or reflection gratings diffract X-rays

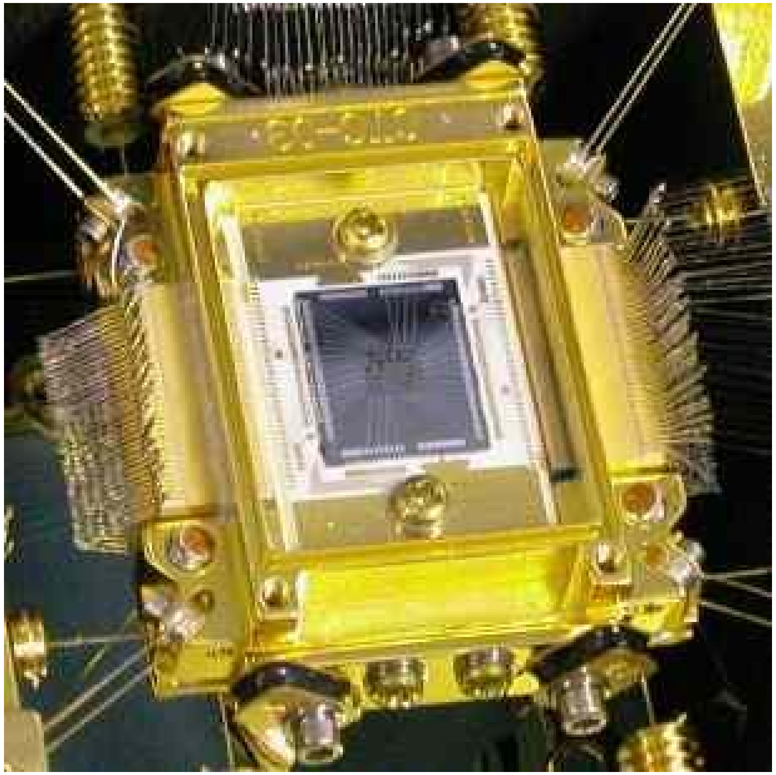


- Reflection gratings on XMM have ~650 lines/mm
  - 10x energy resolution of CCDs
- Good for studying narrow spectral features (lines)

X-ray Calorimeter

- First space-based calorimeter on Suzaku failed, but a calorimeter will be flown in the (near?!) future
- Detects the change in temperature due to the arrival of a single X-ray photon
- Uses Transition-Edge Sensors
  - resistance changes rapidly near critical temperature at which pixel becomes superconductor
- Excellent energy resolution
  - few eV or better

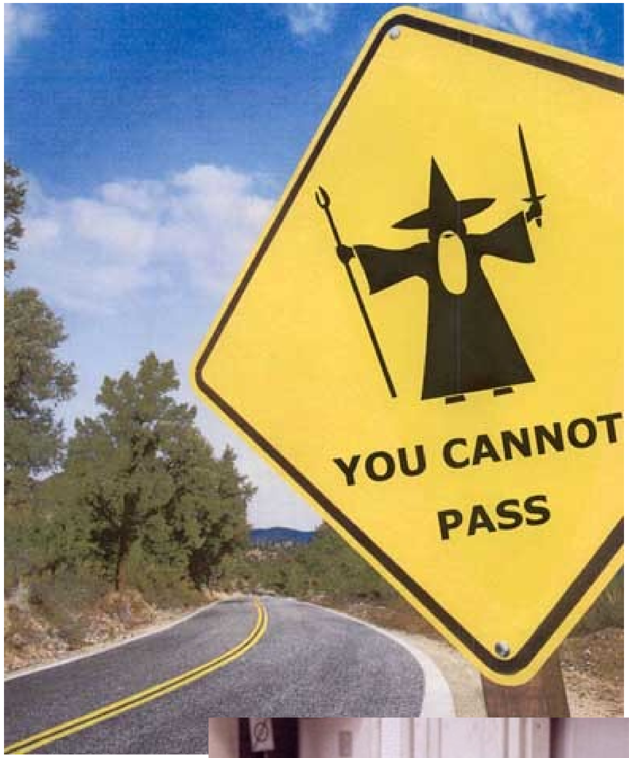




Key Points

- X-ray telescopes use grazing reflections
- Most modern detectors are arrays of CCDs
- Energy of X-ray determines charge released in pixel
- Use grating spectrometers for higher energy resolution
- Record position, energy, time of each photon

Switch Brains Off



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Photon Counting

- X-ray astronomy is photon-starved; count individual photons
  - counting statistics are extremely important
- Suppose a detector has a background level of 1 photon per second
  - In 100s we detect 120 photons – is there a source there?

Statistics

- Statistics help us to decide what is real
- Statistics are much used/abused in everyday life:
  - news
  - advertising
- Advertisement in cinema:
  - “One in three children in Birmingham wait longer to be adopted”

- “Data Reduction and Error Analysis” - Bevington
- “Astrostatistics” - Babu & Feigelson

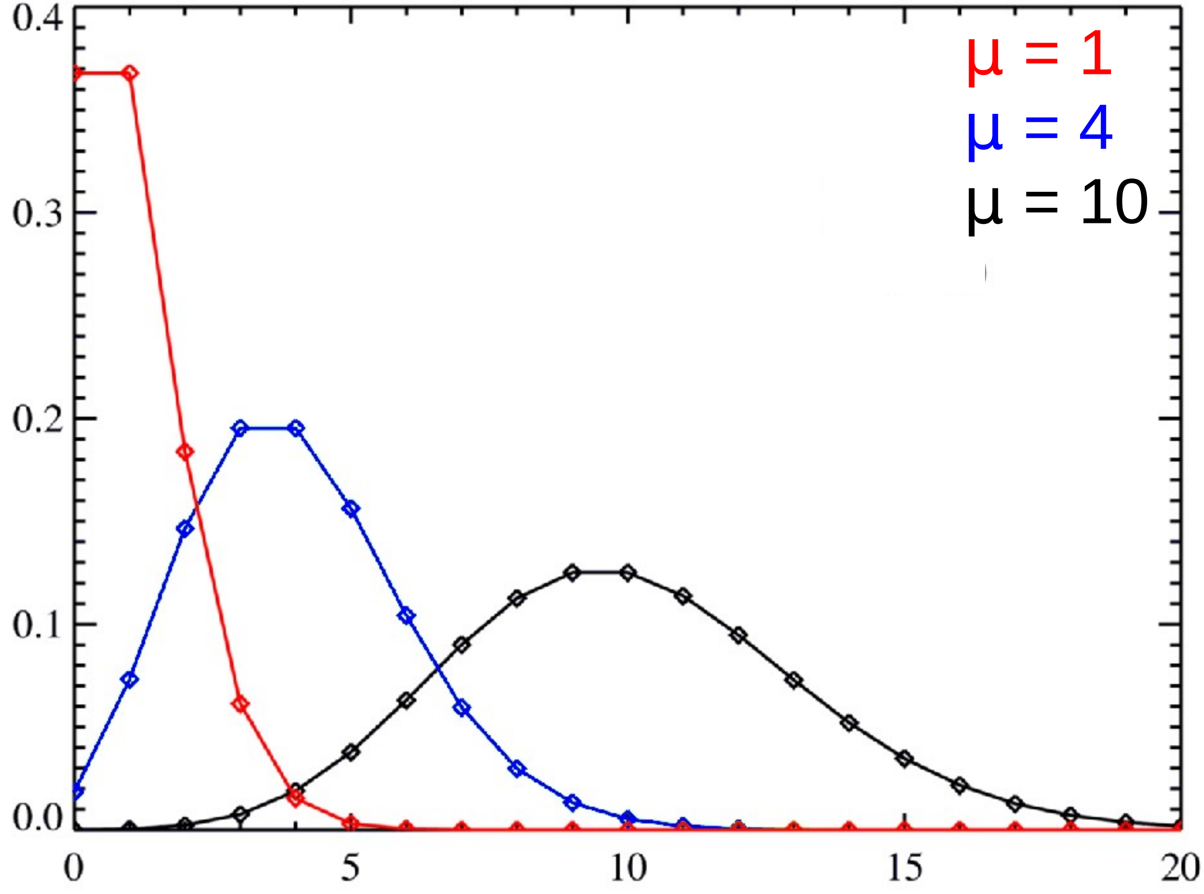
Photon Counting

- If the mean count rate of a source is 1.25 photons/s how many are emitted in 10s?
- 12.5? ✕ (but true on average)
- 12? 13? 9? ... maybe!

- Emission of photons is a random process described by the Poisson probability distribution

$$P(N)=\frac{\mu^N e^{-\mu}}{N!}$$

- Gives the probability of N events occurring depending on the mean number μ expected
- N is integer, μ is real



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$$P(N) = \frac{\mu^N e^{-\mu}}{N!}$$

In a 10s observation μ=12.5

- P(N=12) = 0.113
- P(N=13) = 0.109
- P(N=9) = 0.077

So if we made 100 ten second observations of this source, we would detect 9 photons in about 8 of them

Each observation is a “random” snapshot of reality

- The mean of the Poisson distribution is μ
- The standard deviation (spread) of distribution is $\sqrt{\mu}$
  - Corresponds to uncertainty on N
- So for $\mu=10$, fractional spread is

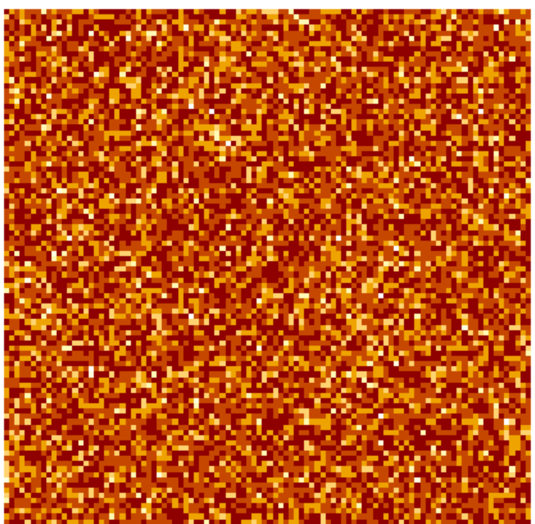
$$\sqrt{\mu}/\mu = 33\%$$

- And for $\mu=100$, fractional spread is

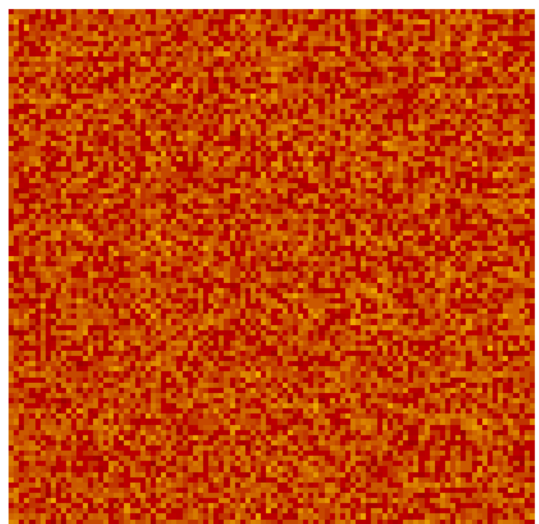
$$\sqrt{\mu}/\mu = 10\%$$

- So for higher numbers of photons (bright sources or long exposures) statistical noise is smaller fraction of source signal

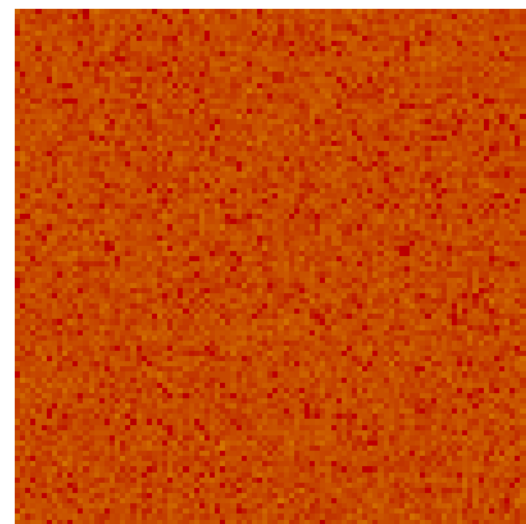
- e.g. A flat smooth source imaged with a detector of 100 x 100 pixels
- Source rate is 1 count per pixel per second



1 second



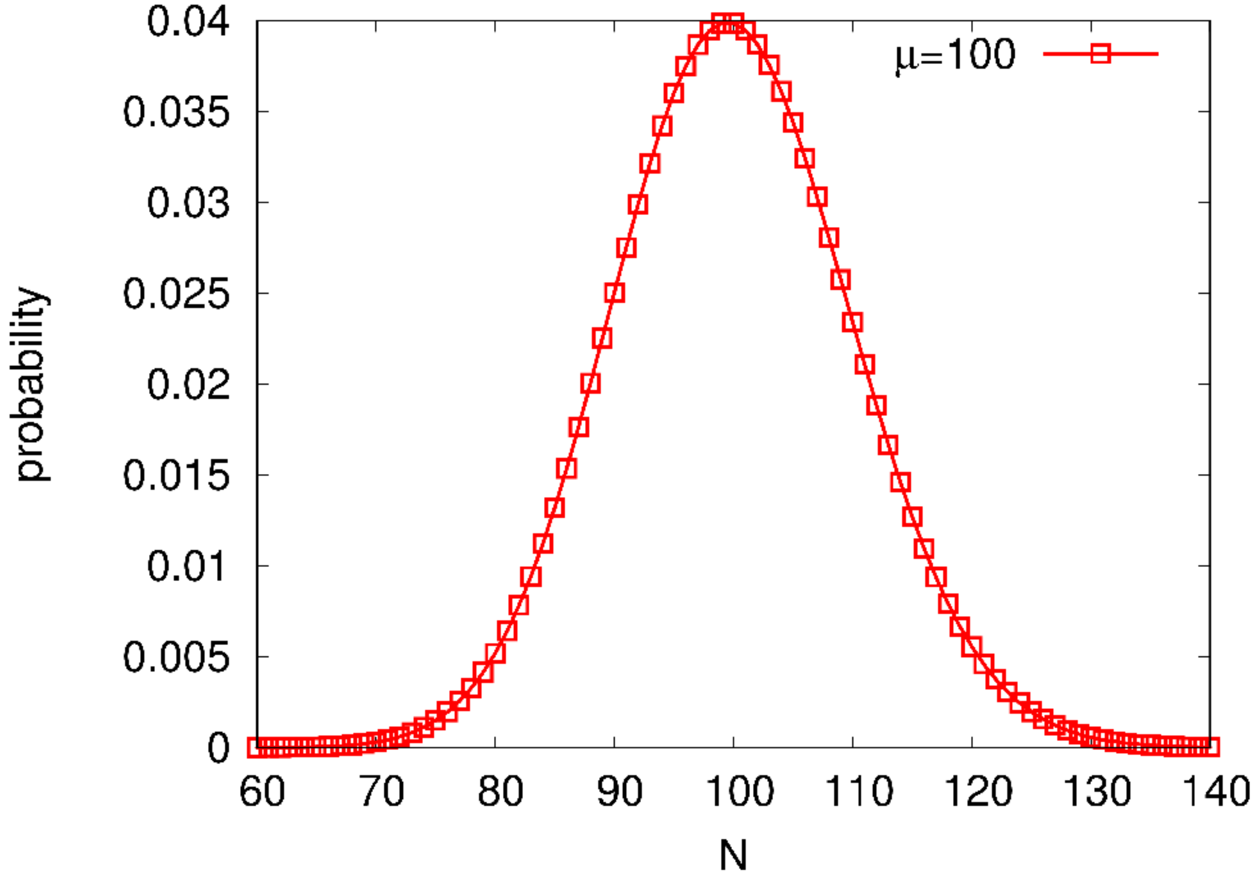
10 seconds



100 seconds

Signal to Noise

- A detector has a background level of 1 photon per second
- In 100s we detect 120 photons – is there a source there?
  - Maybe
  - Maybe noise



Consider a detector counting individual photons from a source with count rate **s** photons/s, on a background of **b** photons/s

- In time **t** seconds, total number of counts

$$N_{tot} = (s+b)t \pm \sqrt{(s+b)t}$$

- Assume can neglect uncertainties on background, total bg counts

$$N_{bg} = bt$$

- So our estimate of the number of source photons is

$$N_{src} = N_{tot} - N_{bg} = st \pm \sqrt{(s+b)t}$$

$$N_{src} = N_{tot} - N_{bg} \; = \; st \; \pm \sqrt{(s+b)t}$$

- So to measure s

$$\frac{N_{src}}{t} \; = \; s \; \pm \sqrt{(s+b)/t}$$

- The ratio

$$\boxed{s/\sqrt{(s+b)/t}}$$

- Is called the **signal to noise ratio** (SNR) – measures the quality of the data
- Equivalently, can write

$$\boxed{SNR = N_{src}/\sqrt{N_{tot}}}$$

Signal to Noise

- Signal to noise ratios (SNR) measure quality of data:
  - SNR = 3 is a borderline detection
  - SNR = 5 is a solid detection
  - SNR = 10 can do some analysis of data
  - SNR = 100 very good data, detailed analysis

Return to our example:

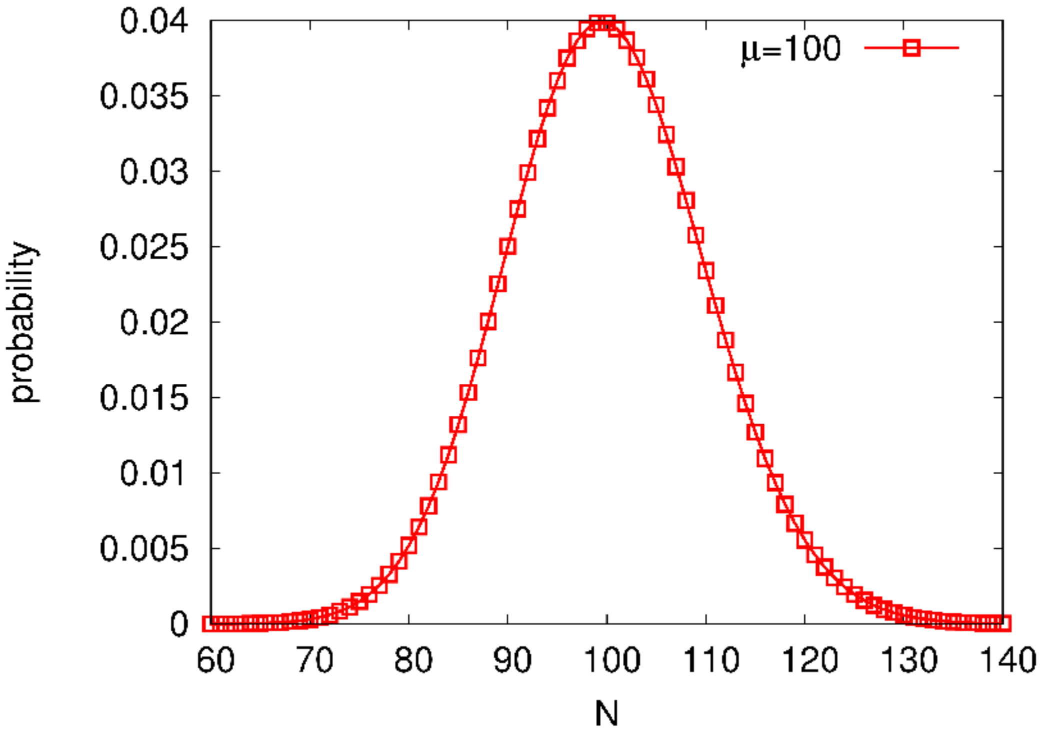
- A detector has a background level of 1 photon/s
- In 100s we detect 120 photons – what is SNR?

$$N_{tot} = (s+b)t = 120, \quad N_{bg} = bt = 100$$

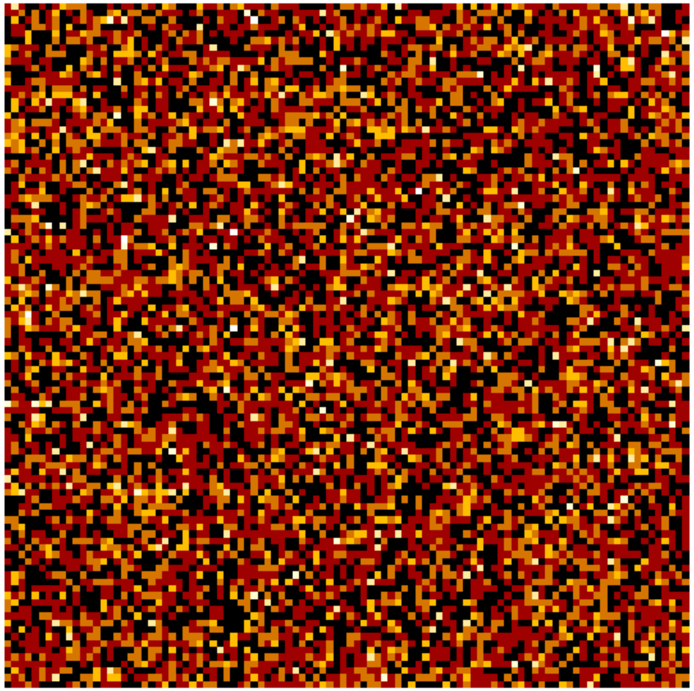
$$s = (N_{tot} - N_{bg})/t \pm ((s+b)/t)^{1/2}$$

$$s = 0.20 \pm 0.11$$

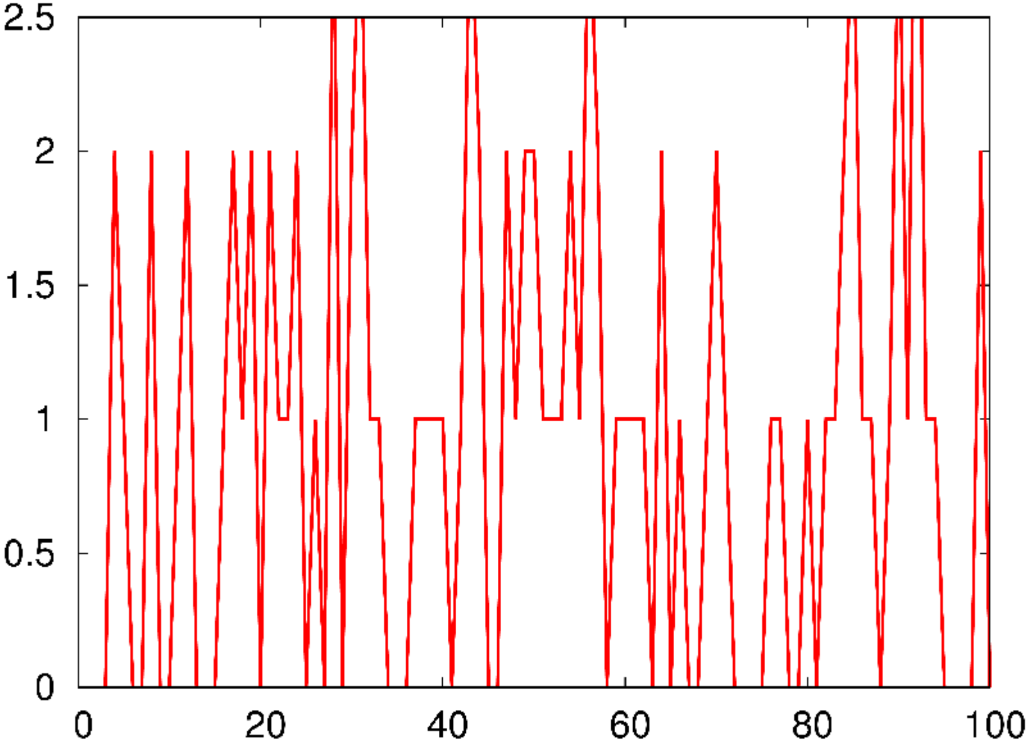
- SNR = 0.20/0.11 = 1.8
- Not significant detection
- May be a source but need longer observation to be certain



- $SNR = s/((s+b)/t)^{1/2}$ → increases with increasing t
- So can detect sources with s<<b if t long enough
- To illustrate:
  - detector with 100 x 100 pixels with background level of 1 photon/pixel/s
  - Source with peak level of 0.2 photon/pixel/s



t = 1s



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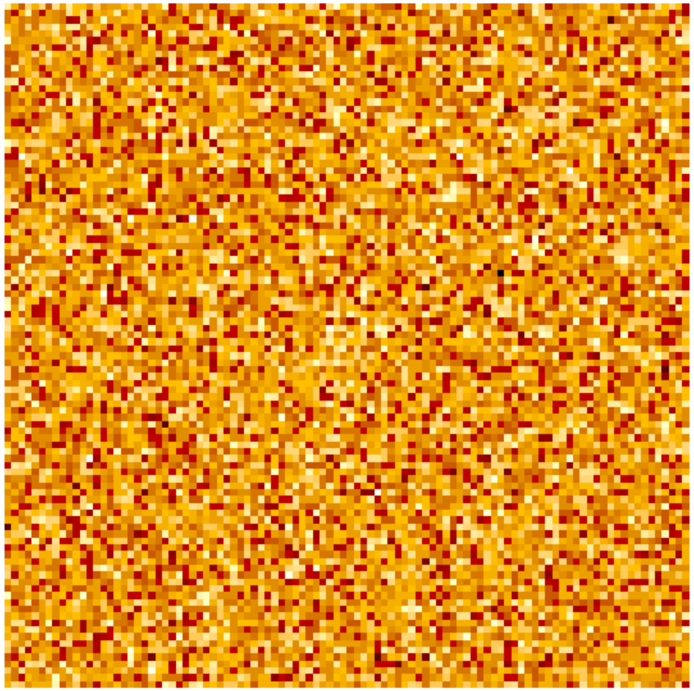
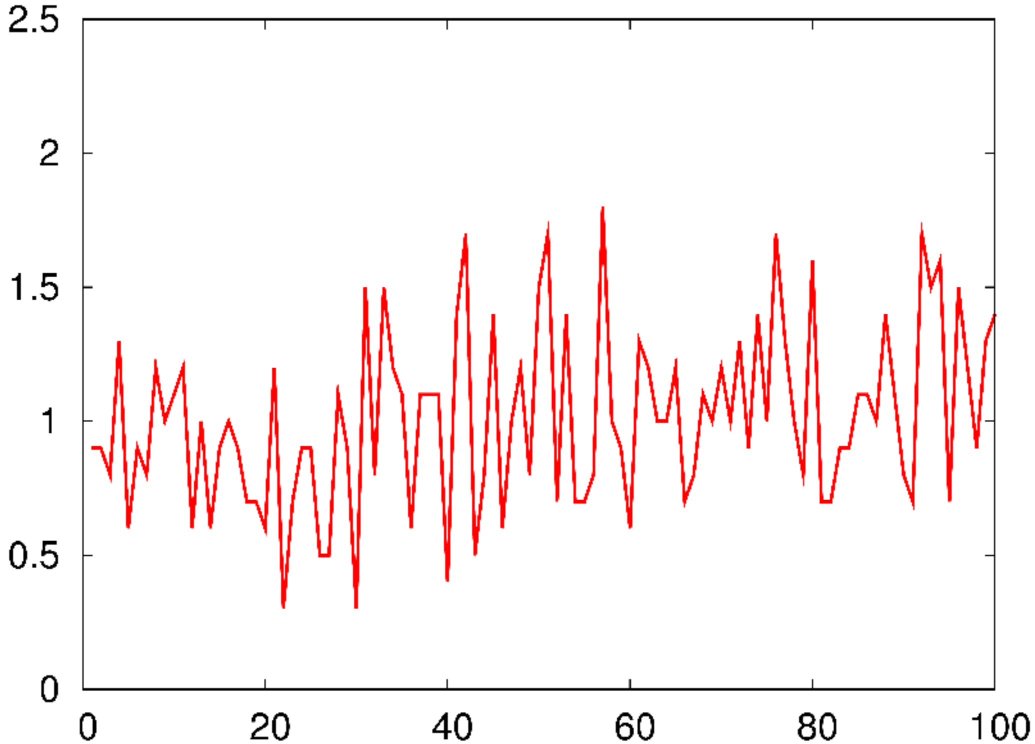
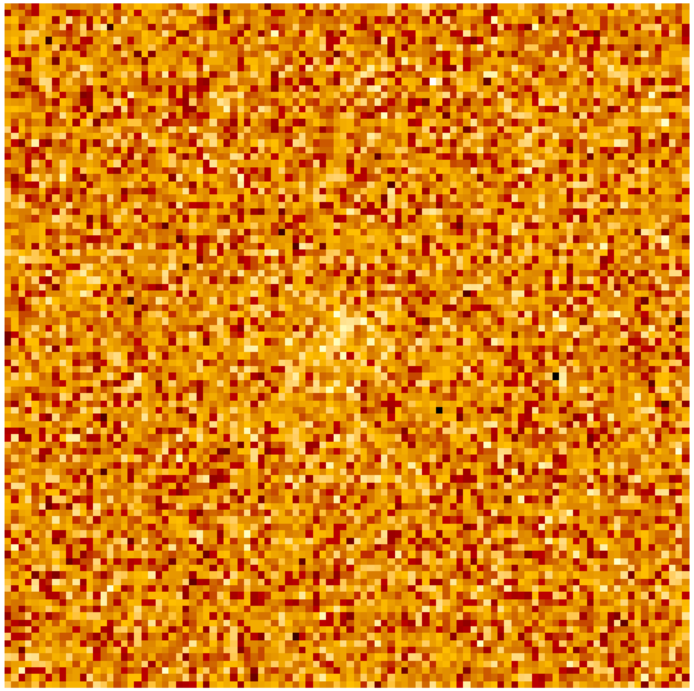
  - detector with 100 x 100 pixels with background level of 1 photon/pixel/s
  - Source with peak level of 0.2 photon/pixel/s



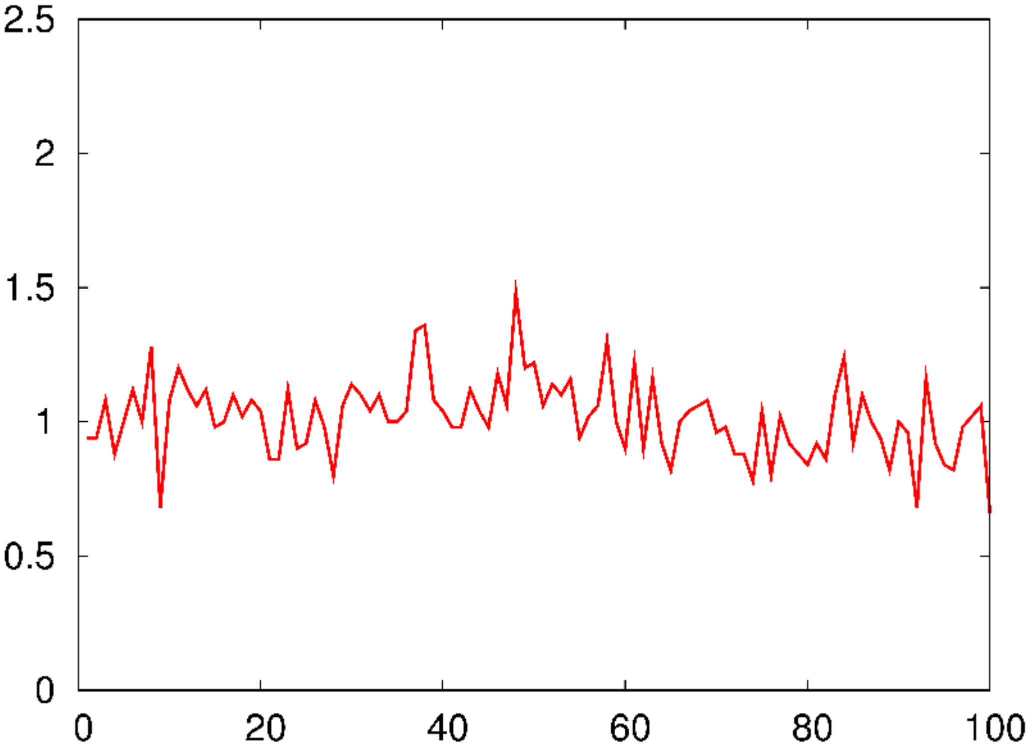
t = 10s



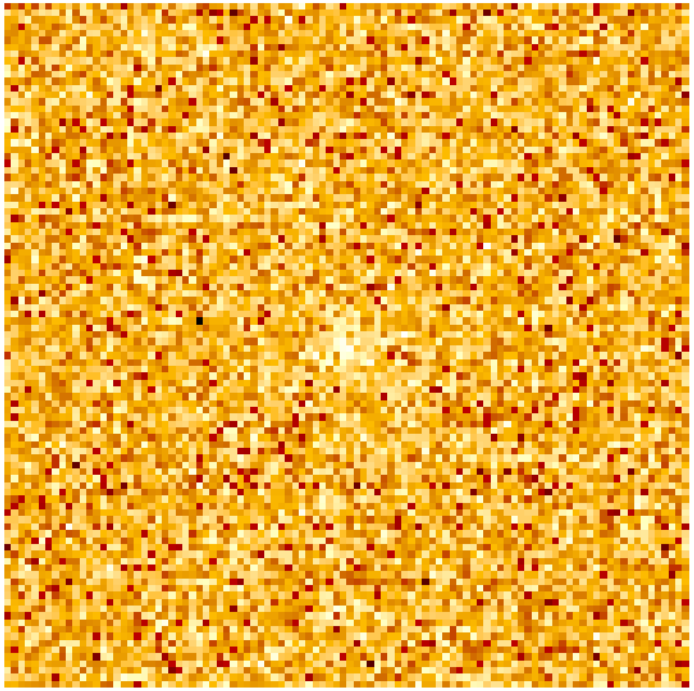
- SNR = $s/((s+b)/t)^{1/2}$ → increases with increasing t
- So can detect sources with s<<b if t long enough
- To illustrate:
  - detector with 100 x 100 pixels with background level of 1 photon/pixel/s
  - Source with peak level of 0.2 photon/pixel/s



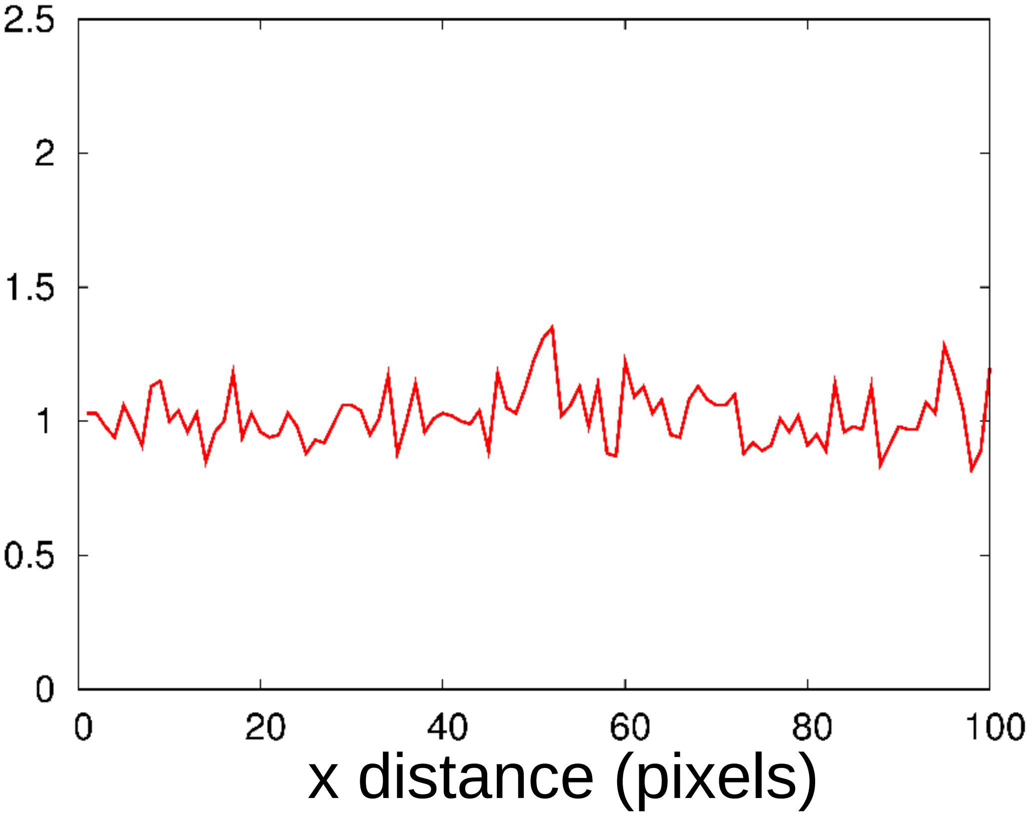
t = 50s



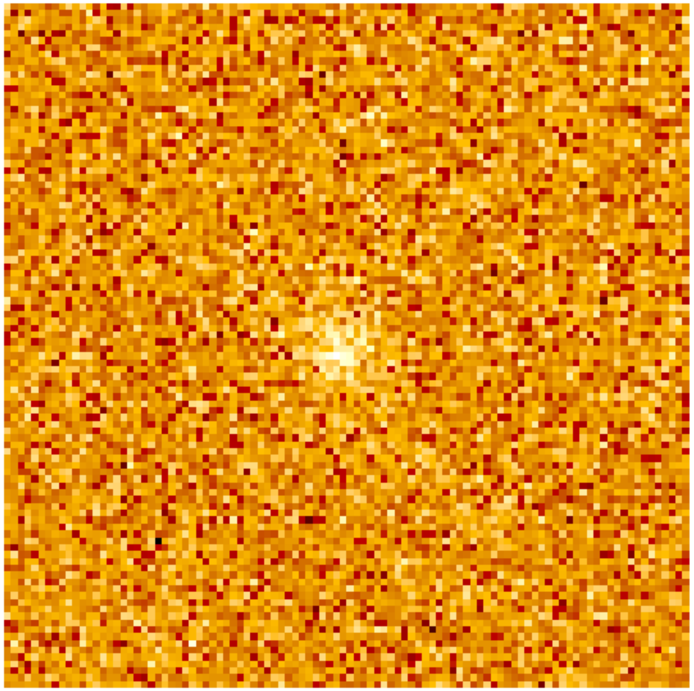
- SNR = $s/((s+b)/t)^{1/2} \rightarrow$ increases with increasing t
- So can detect sources with s<<b if t long enough
- To illustrate:
  - detector with 100 x 100 pixels with background level of 1 photon/pixel/s
  - Source with peak level of 0.2 photon/pixel/s



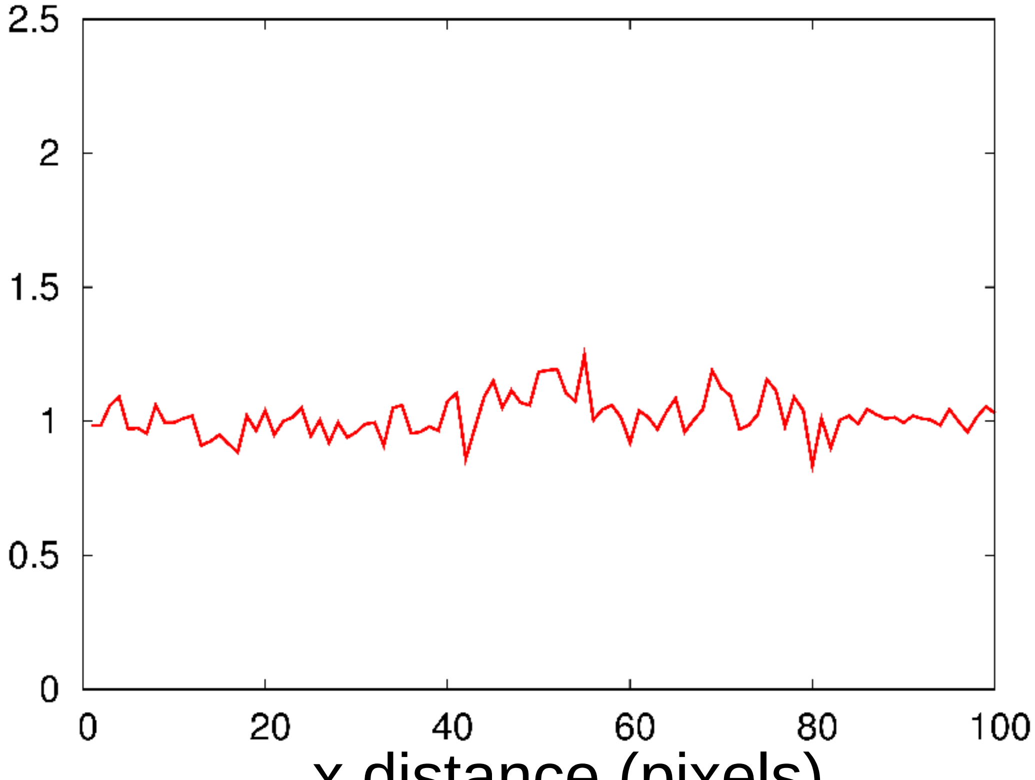
t = 100s



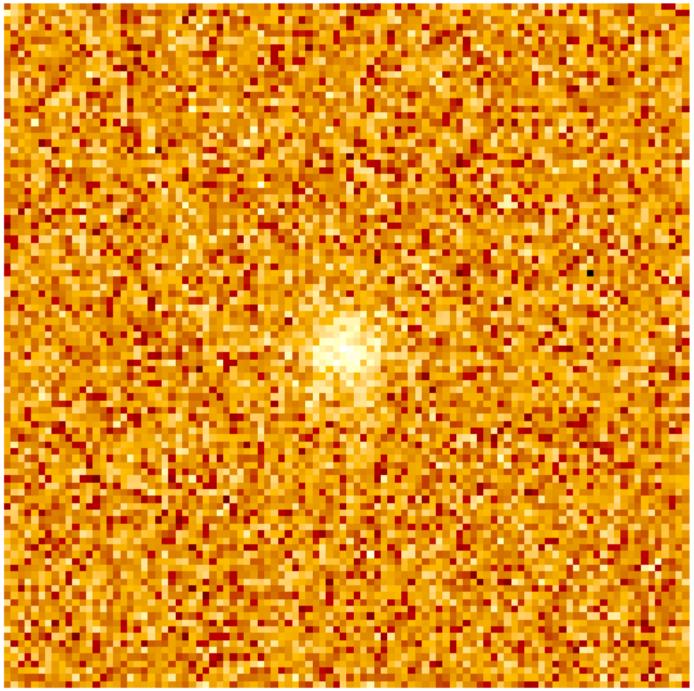
- SNR = $s/((s+b)/t)^{1/2}$ → increases with increasing t
- So can detect sources with s<<b if t long enough
- To illustrate:
  - detector with 100 x 100 pixels with background level of 1 photon/pixel/s
  - Source with peak level of 0.2 photon/pixel/s



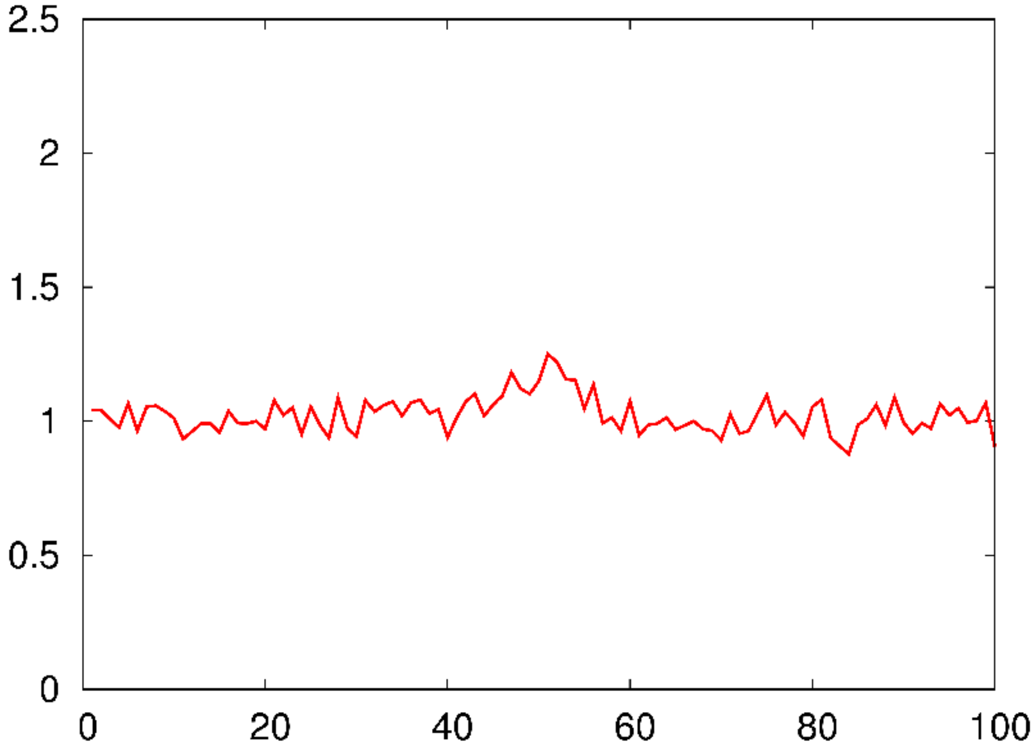
t = 200s



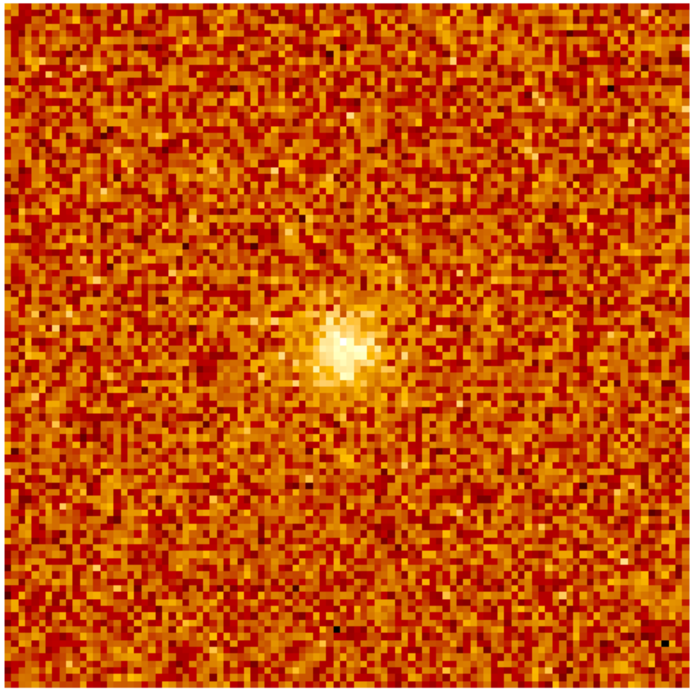
- SNR = $s/((s+b)/t)^{1/2}$ → increases with increasing t
- So can detect sources with s<<b if t long enough
- To illustrate:
  - detector with 100 x 100 pixels with background level of 1 photon/pixel/s
  - Source with peak level of 0.2 photon/pixel/s



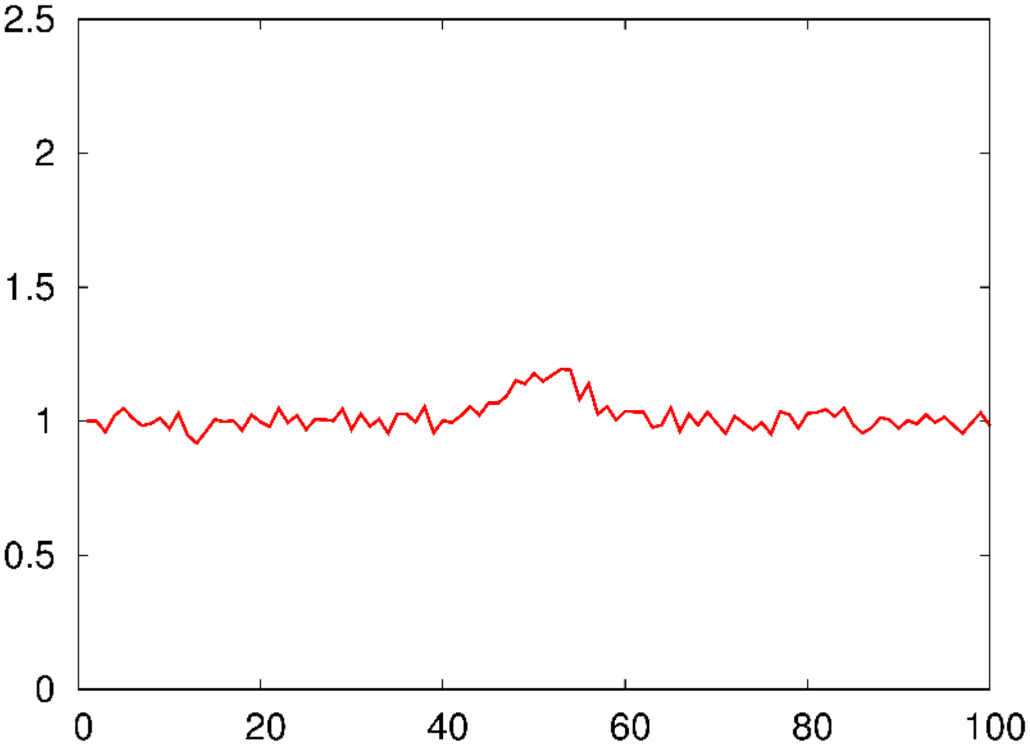
t = 450s



- SNR = $s/((s+b)/t)^{1/2}$ → increases with increasing t
- So can detect sources with s<<b if t long enough
- To illustrate:
  - detector with 100 x 100 pixels with background level of 1 photon/pixel/s
  - Source with peak level of 0.2 photon/pixel/s

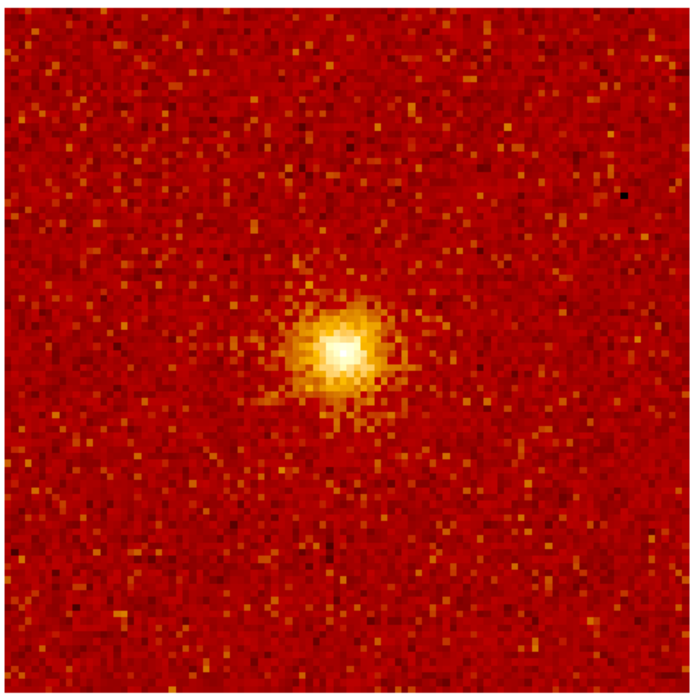


t = 1000s

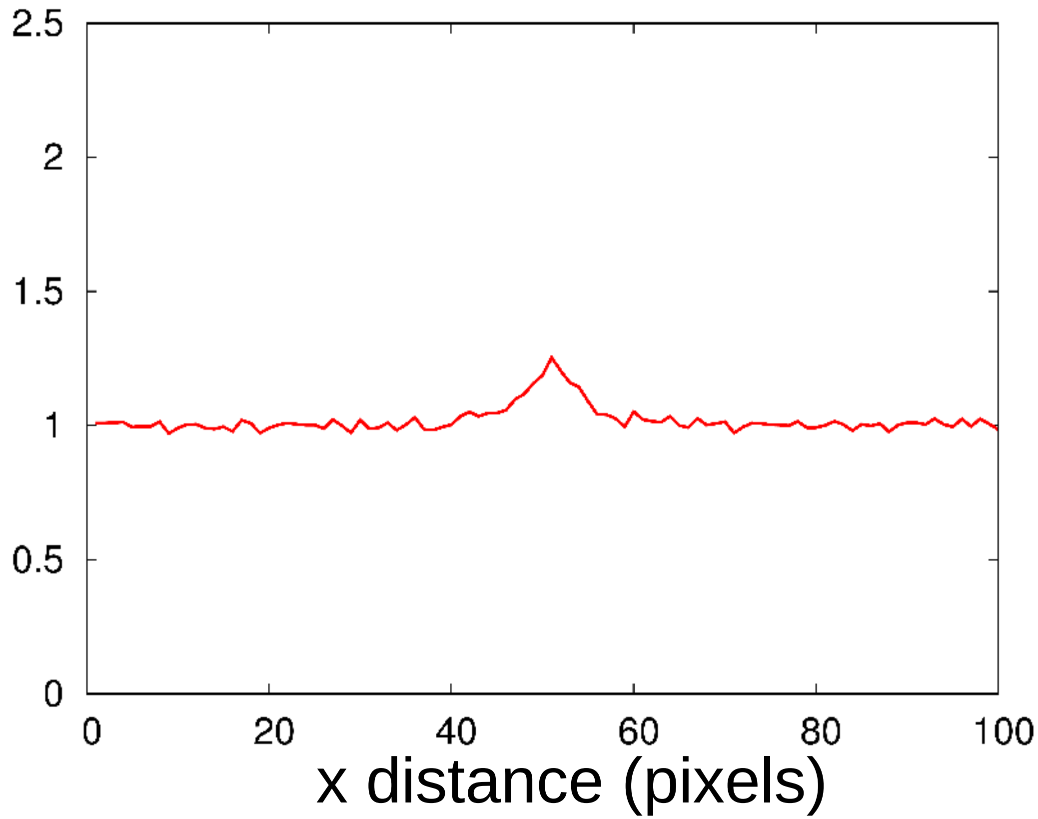


x distance (pixels)

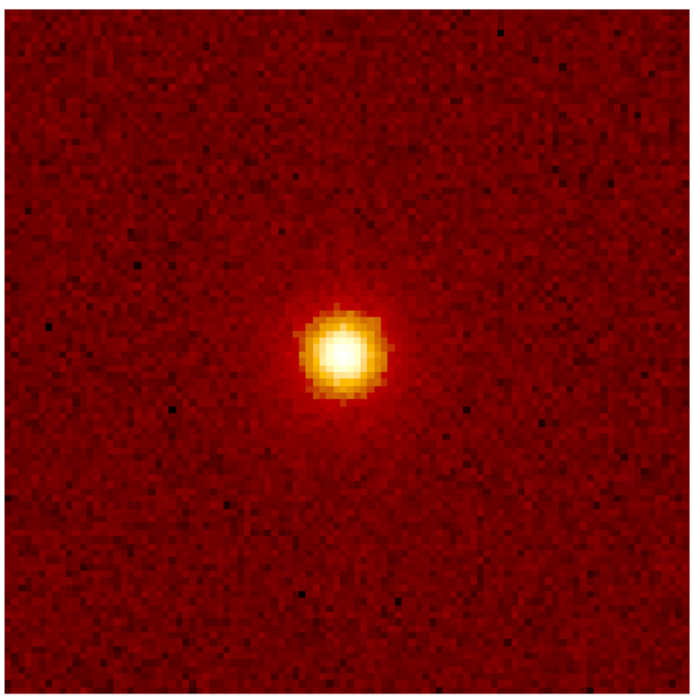
- SNR = s/((s+b)/t)$^{1/2}$ → increases with increasing t
- So can detect sources with s<<b if t long enough
- To illustrate:
  - detector with 100 x 100 pixels with background level of 1 photon/pixel/s
  - Source with peak level of 0.2 photon/pixel/s



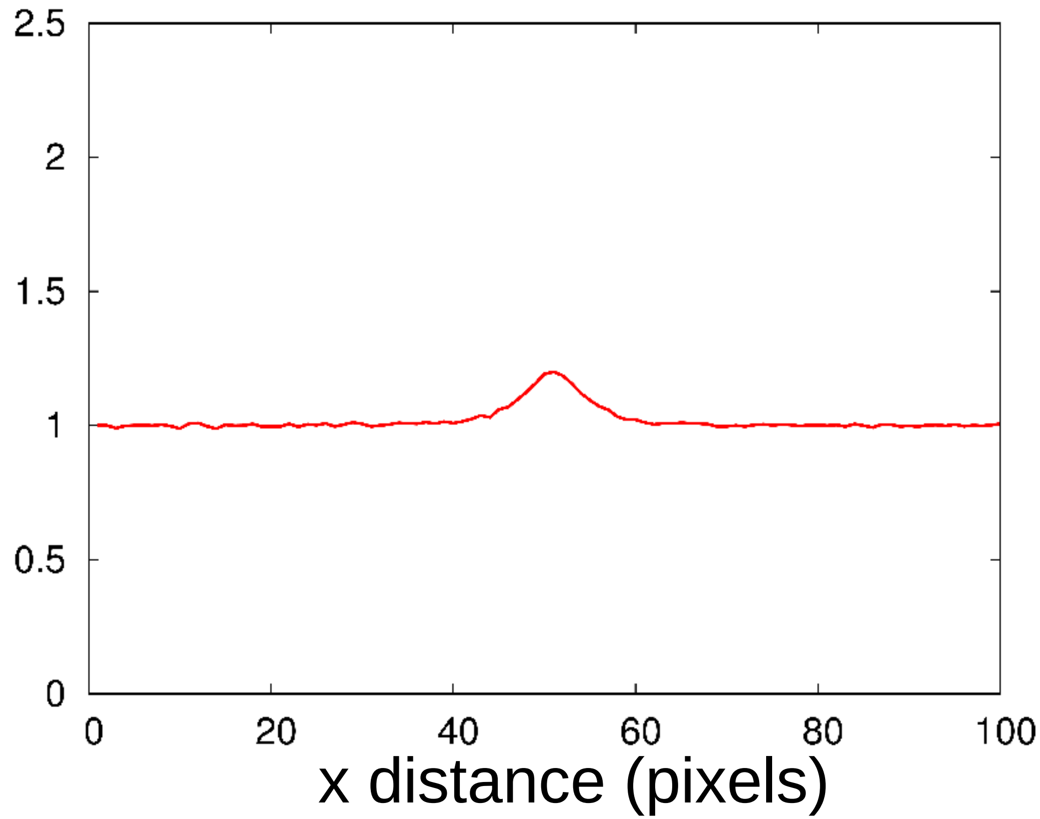
t = 5000s



- SNR = $s/((s+b)/t)^{1/2}$ → increases with increasing t
- So can detect sources with s<<b if t long enough
- To illustrate:
  - detector with 100 x 100 pixels with background level of 1 photon/pixel/s
  - Source with peak level of 0.2 photon/pixel/s

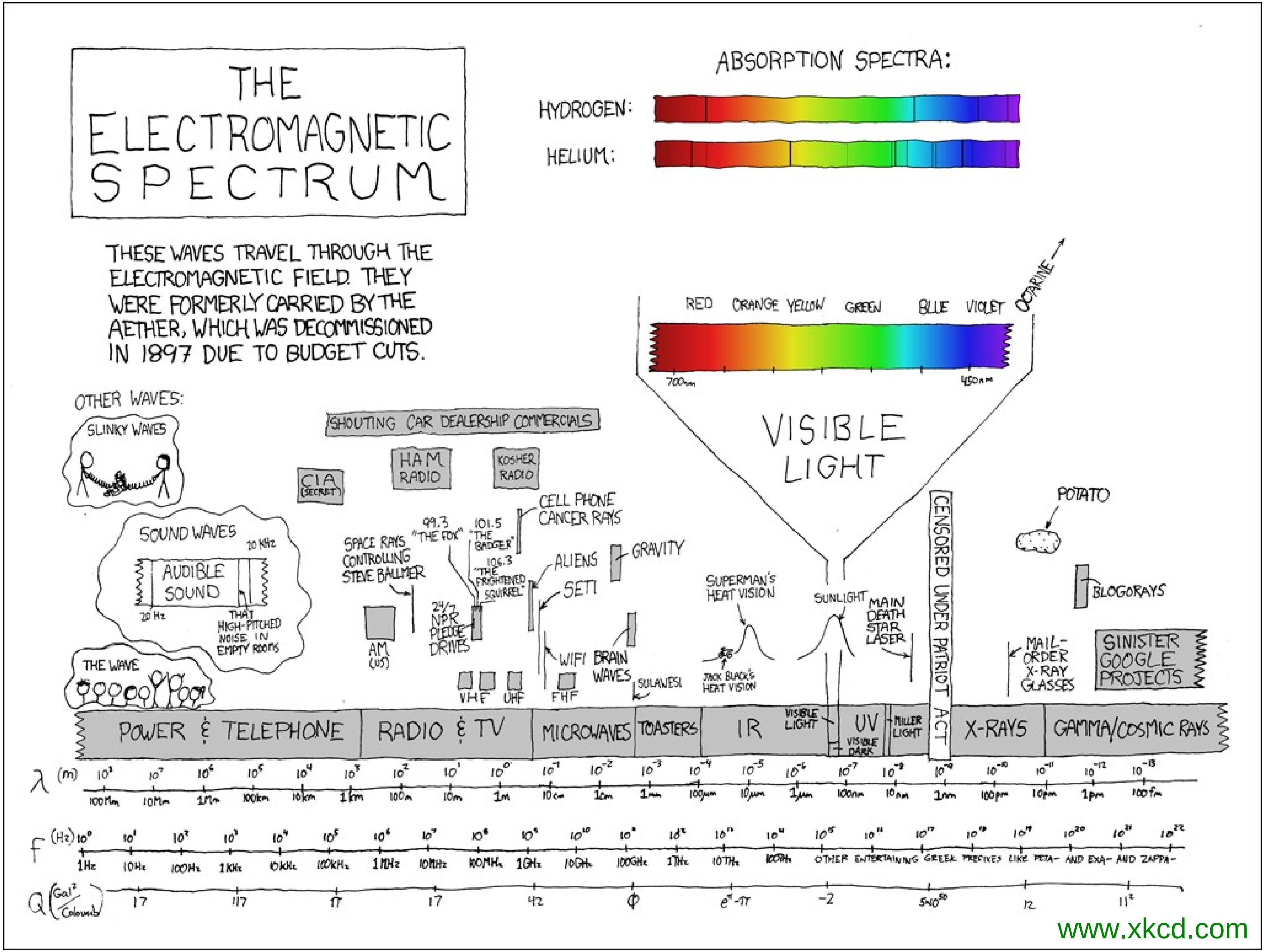


t = 50000s



Key Points

- X-ray astronomy is photon starved
- Photon emission is Poissonian
- Counting uncertainty is $\sqrt{N}$
- SNR is basically signal divided by uncertainty
  - measures data quality
- SNR increases with time so can detect sources much fainter than background


THE ELECTROMAGNETIC SPECTRUM
THESE WAVES TRAVEL THROUGH THE ELECTROMAGNETIC FIELD. THEY WERE FORMERLY CARRIED BY THE AETHER, WHICH WAS DECOMMISSIONED IN 1897 DUE TO BUDGET CUTS.
ABSORPTION SPECTRA:
HYDROGEN:
HELIUM:
RED
ORANGE
YELLOW
GREEN
BLUE
VIOLET
OCTARINE
700nm
450nm
VISIBLE LIGHT
OTHER WAVES:
SLINKY WAVES
SOUND WAVES
20 KHz
AUDIBLE SOUND
20 Hz
THAT HIGH-PITCHED NOISE IN EMPTY ROOMS
THE WAVE
SHOUTING CAR DEALERSHIP COMMERCIALS
CIA (SECRET)
HAM RADIO
KOSHER RADIO
CELL PHONE CANCER RAYS
SPACE RAYS CONTROLLING STEVE BALLMER
99.3 "THE FOX"
101.5 "THE BADGER"
106.3 "THE FRIGHTENED SQUIRREL"
24/7 NPR PLEDGE DRIVES
AM (US)
VHF
UHF
FHF
ALIENS
SETI
GRAVITY
WIFI
BRAIN WAVES
SULAWESI
SUPERMAN'S HEAT VISION
JACK BLACK'S HEAT VISION
SUNLIGHT
MAIN DEATH STAR LASER
CENSORED UNDER PATRIOT ACT
POTATO
BLOGORAYS
MAIL-ORDER X-RAY GLASSES
SINISTER GOOGLE PROJECTS
POWER & TELEPHONE
RADIO & TV
MICROWAVES
TOASTERS
IR
VISIBLE LIGHT
UV
VISIBLE DARK
MILLER LIGHT
X-RAYS
GAMMA/COSMIC RAYS
λ (m)
10^{8} 10^{7} 10^{6} 10^{5} 10^{4} 10^{3} 10^{2} 10^{1} 10^{0} 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12} 10^{-13}
100Mm 10Mm 1Mm 100km 10km 1km 100m 10m 1m 10cm 1cm 1mm 100μm 10μm 1μm 100nm 10nm 1nm 100pm 10pm 1pm 100fm
f (Hz)
10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7} 10^{8} 10^{9} 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20} 10^{21} 10^{22}
1Hz 10Hz 100Hz 1KHz 10KHz 100KHz 1MHz 10MHz 100MHz 1GHz 10GHz 100GHz 1THz 10THz 100THz
OTHER ENTERTAINING GREEK PREFIXES LIKE PETA- AND EXA- AND ZAPPA-
Q (Gal²/Coulomb)
17 117 1T 17 42 Φ $e^{\pi}-\pi$ -2 5×10^{30} 12 11^{2}
www.xkcd.com

Overview

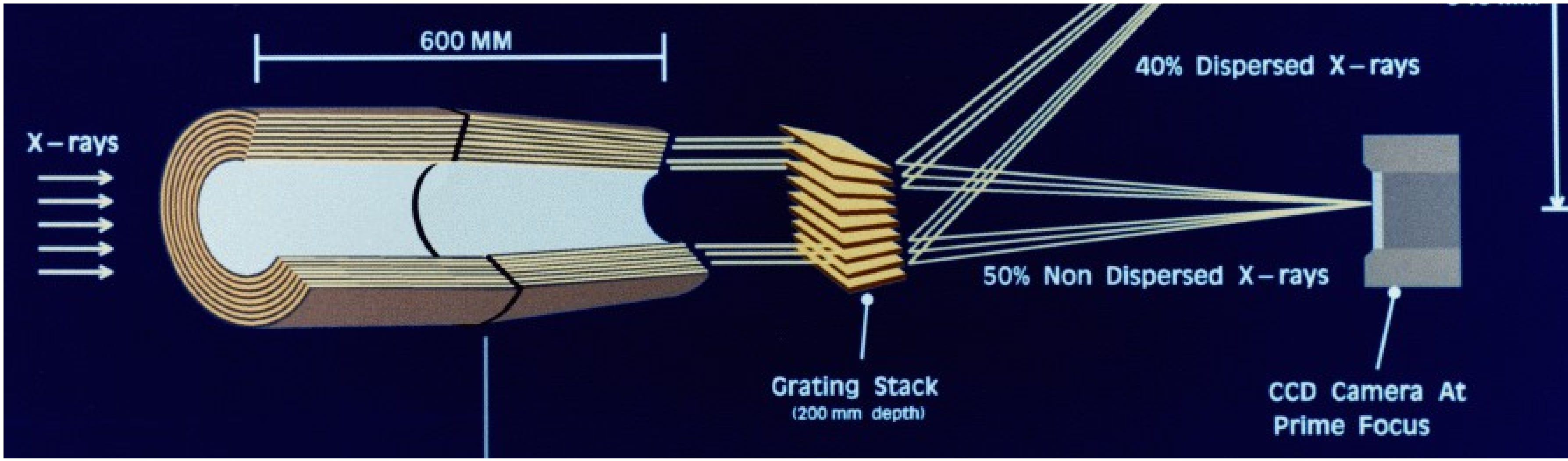
- History
- Detecting X-rays
- Statistics
- Current observatories
- Calibration & background issues
- X-ray data analysis

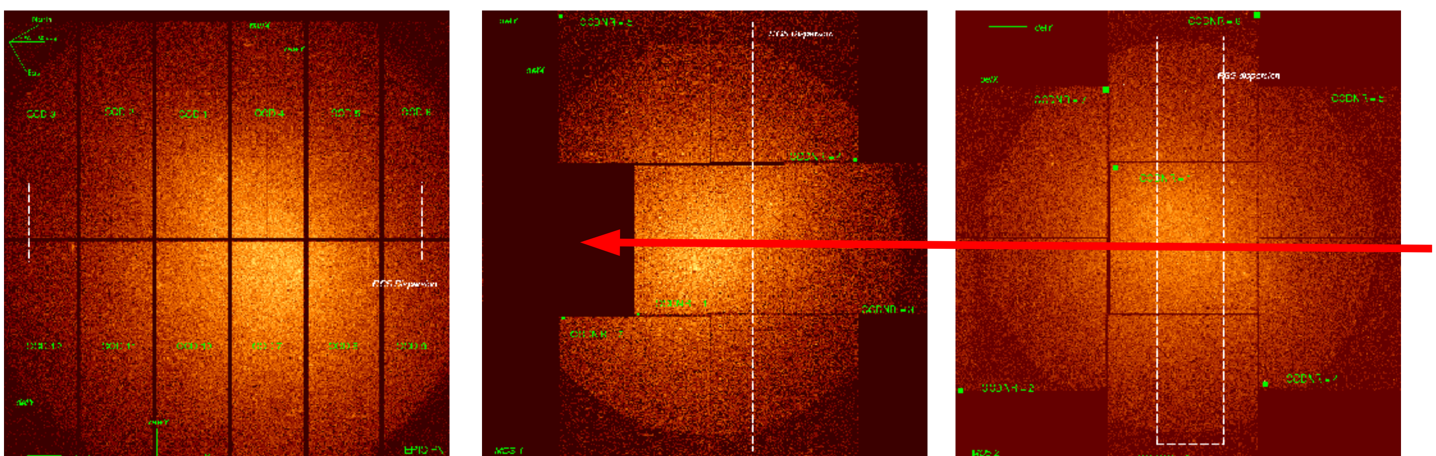
XMM-Newton 1999-

- 3 X-ray telescopes each with 58 nested Wolter mirrors
- Effective area approx 0.4 m^2

XMM-Newton 1999-

- 1 EPIC-pn BI CCD camera
- 2 EPIC-MOS FI CCD cameras with gratings





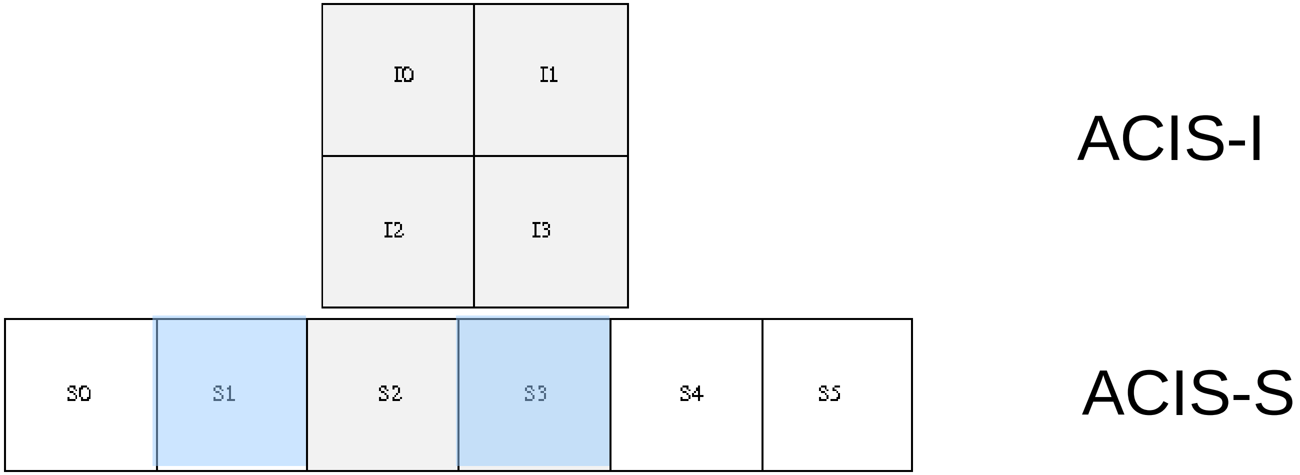
MOS1 CCD damaged by micrometeorite in 2005

Chandra X-ray Observatory 1999-

- Single X-ray telescope with 4 nested Wolter mirrors
- Effective area approx 0.1 m^2
- Lower sensitivity than XMM-Newton
- PSF of 0.5 arcsec compared to 15 arcsec for XMM
- CCD camera and diffraction grating

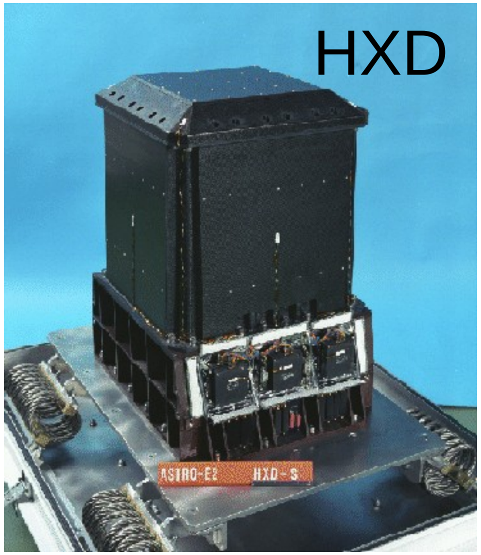
Chandra ACIS

- ACIS Camera consists of 2 CCD arrays (I & S)
- Optional transmission gratings disperse X-rays along ACIS-S
- Use subset of 6 chips for observations
- 2 BI CCDs, rest FI
  - FI chips suffered radiation damage early in mission
  - Slightly degraded energy resolution



Suzaku X-ray Observatory 2005-

- 4 X-ray telescopes
- Effective area ~0.3-0.4 m^2 at 1.5 keV
- PSF ~2 arcmin
- CCD camera
- Hard X-ray detector
  - Non-imaging, collimated hard X-ray instrument
  - 10 – 600 keV
- Calorimeter failed on launch



Overview

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X-ray Data

- X-ray observatories record position, time and energy of every event detected in an **events list**
- Extract information we are interested in from events list
  - Take N(x,y) and make image
  - Take N(t) and make lightcurve
  - Take N(E) and make spectrum
- In practice, perform additional filtering
  - e.g. make image in particular energy band
  - e.g. extract spectrum from spatial region

FITS files

- Majority of X-ray data handled in FITS files
- FITS file contains one or more extensions that can be images or tables
- Convention is that extension 0 is always an image, even if it is empty
- Many tools exist for extracting and performing operations on data in FITS files

0 – Empty image extension

1 – Events table (x, y, t, e, ...)

2 – Good time interval table for CCD 1

3 – Good time interval table for CCD 2

...

Typical FITS events list structure

FITS files

- Each extension consists of a header and then data
- Header contains set of keywords and values of useful information

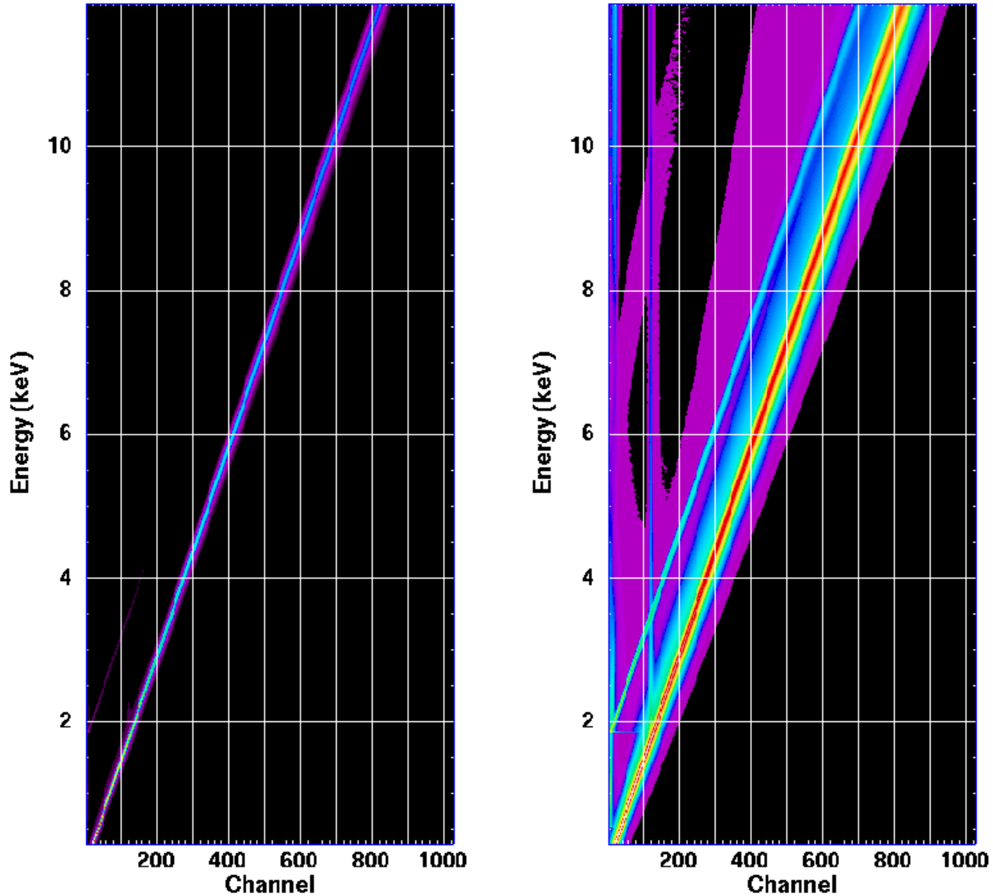
TELESCOP	-	Chandra
INSTRUME	-	ACIS-I
EXPOSURE	-	25000
	...	

- In addition to X-ray data, also need files to describe calibration of instrument
  - Describe everything that happens to a photon from when it reaches telescope to when it is recorded in events list

Redistribution Matrix Files

- RMF files describe probability that a photon of a given energy will be detected in a given "channel"
- Channels are discrete energy bins in which events are detected
- Design detectors to have tightest RMF possible
- Primarily used when fitting models to extracted spectra

Plots show log and linear colourscale of a Chandra RMF

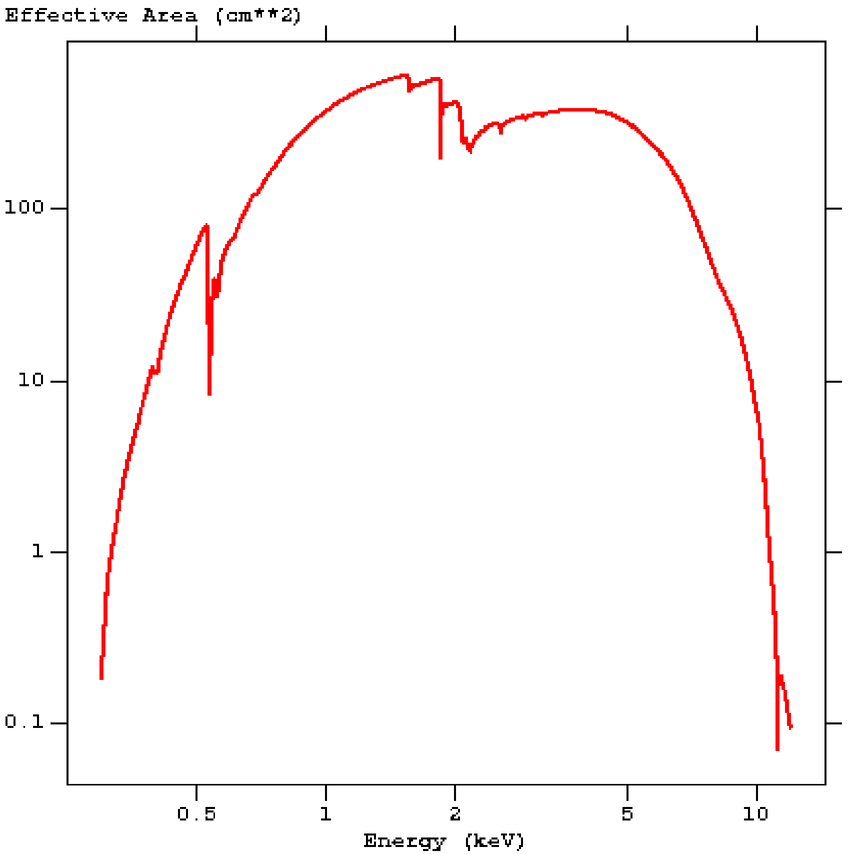


Ancillary Response File

- ARF describes effective area of telescope as function of photon energy
- Significantly changes shape of incident spectrum

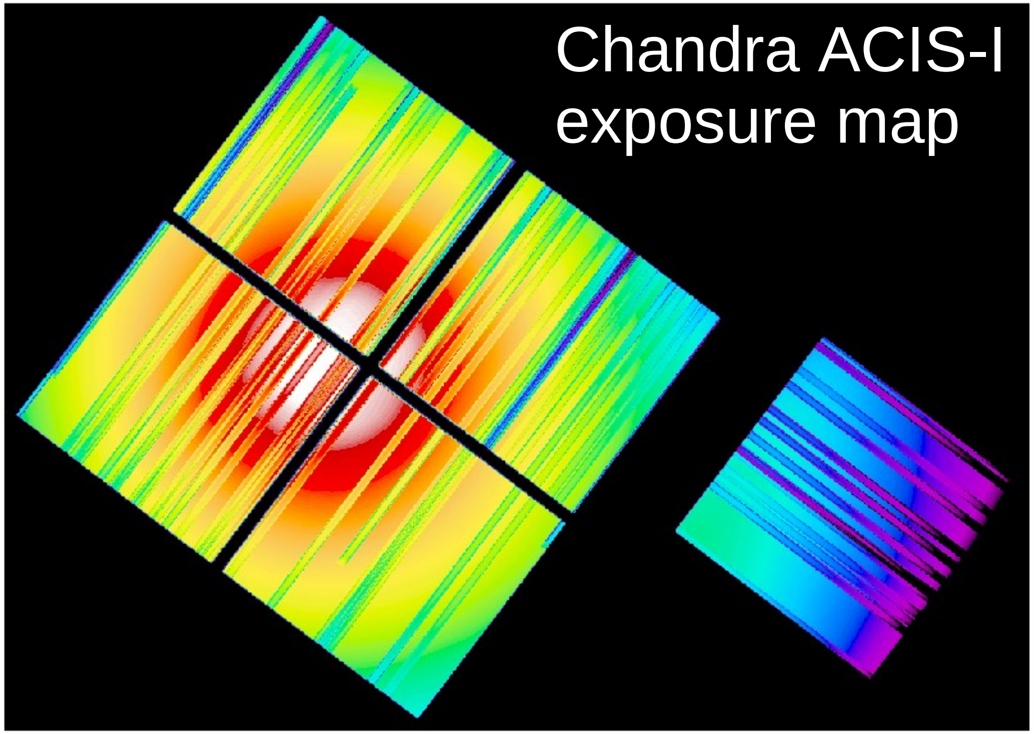
- Used primarily in spectral fitting
- **Response** of observatory is product of ARF and RMF

Chandra ARF



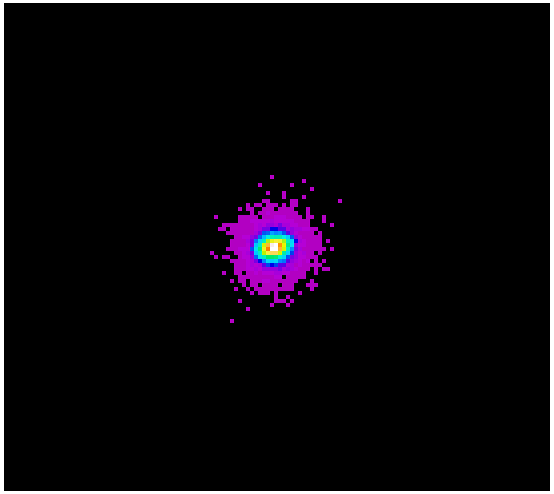
Exposure Map

- Effective area decreases away from optical axis (**vignetting**)
- Exposure map is image describing this variation in effective area
- Includes CCD gaps, bad pixels & columns etc
- Used in image analysis
- Divide image by exposure map to correct for these effects
- Energy-dependent

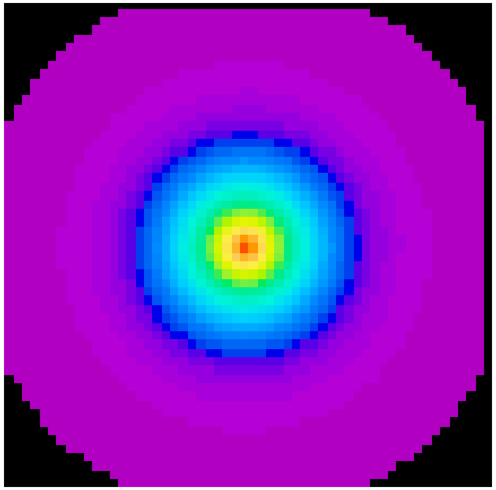


Point Spread Function

- PSF describes spread of photons around ideal point source
- Limits angular resolution of images
- Depends on photon energy and off-axis angle
- Chandra FWHM is 0.5”
- XMM FWHM is 15”
- Important for detection, analysis and exclusion of point srcs & image analysis



Chandra PSF



XMM PSF

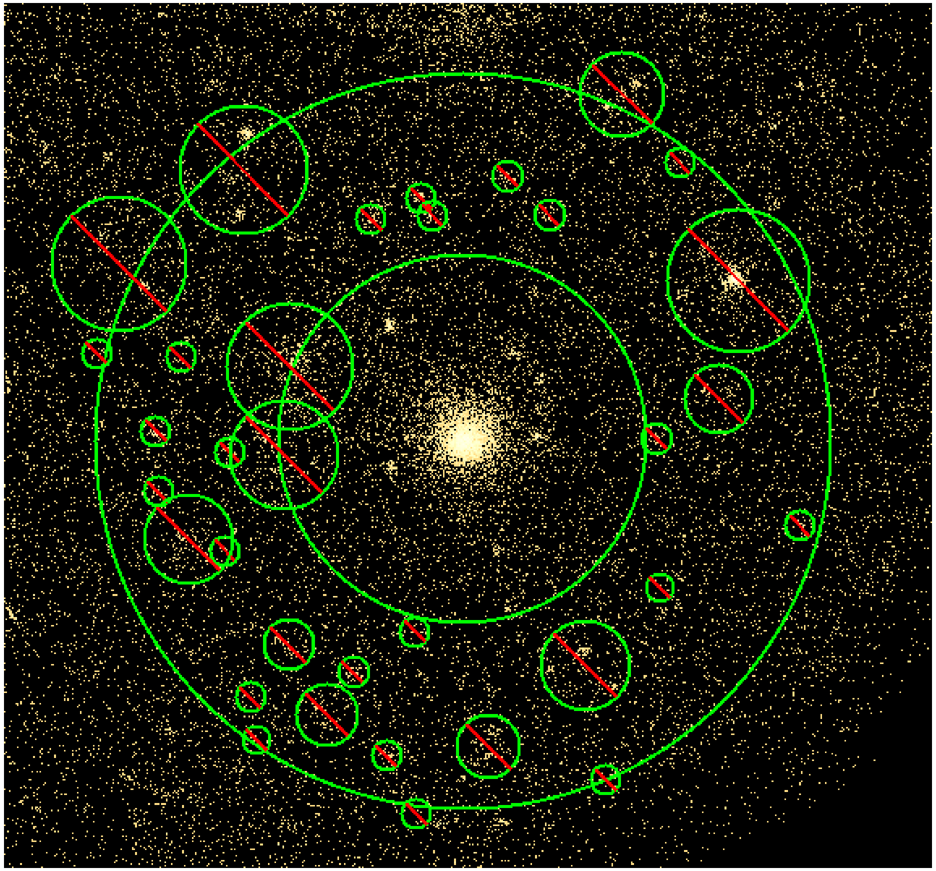
X-ray background

- For virtually all types of analysis, have to consider the background emission
- For X-ray data, background consists of:
  - particle background
    - high energy cosmic rays hitting detectors
  - fluorescent background
    - particles hitting parts of satellite and producing X-rays
  - soft proton background
    - low energy protons hitting detectors – highly variable
  - unresolved X-ray sources
  - soft Galactic foreground
    - varies with position on sky

Background Subtraction

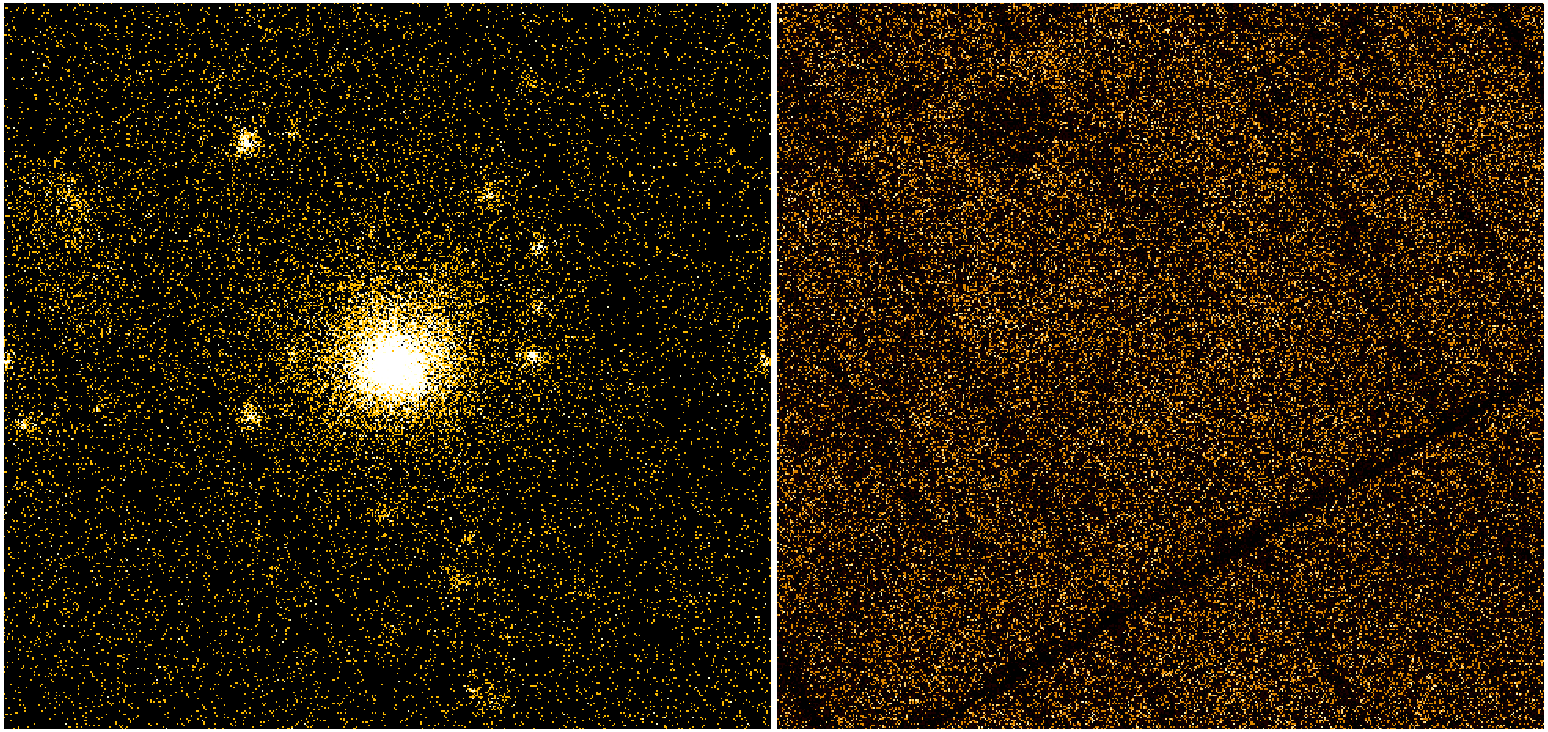
- Subtract or model bg to measure source properties
  - need to know what bg is
- Measure background near to source in same observation
  - local bg
- Take background from observation(s) of fields with no sources
  - blank-sky bg

Local Background



- BG measured at same time and nearly same point on sky
- BG measured at different detector position to source

Blank-sky Background



- BG measured at same detector position as source
- Long bg exposures, so better statistics
- BG measured at different time(s) and position(s) on sky

Key Points

- FITS files contain extensions with headers
- RMF – probability photon energy E is assigned to particular detector channel
- ARF – effective area Vs energy
- Exposure map – effective area Vs position (vignetting)
- PSF – point spread function

- Background must be subtracted or modelled to study source
  - local background
  - blank sky background

Overview

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Data Analysis

- Brief and general overview of type of steps you'll follow when analysing X-ray data
  - Data preparation
  - Imaging analysis
  - Spectroscopy
  - Model fitting

Data Preparation

- Data we get from satellites has already had some processing performed (level 1 events list)
- Additional steps required before analysis
  - Apply calibrations
  - Clean and filter data

- Reprocess level 1 events with latest calibration products
  - Correct for e.g. charge transfer inefficiency, gain
- Remove “bad” events based on grades or flags
  - Eliminates some non X-ray events

Data Cleaning

- Data from XMM (and Chandra) are frequently affected by soft proton flares
- Periods of observations with extremely high bg
- Create a lightcurve of observation and filter
  - Create a good time interval (GTI) file
- N.B. Low-level flares harder to detect
- Background spectrum during flares is significantly different than quiescent BG
  - Residual flares can affect results

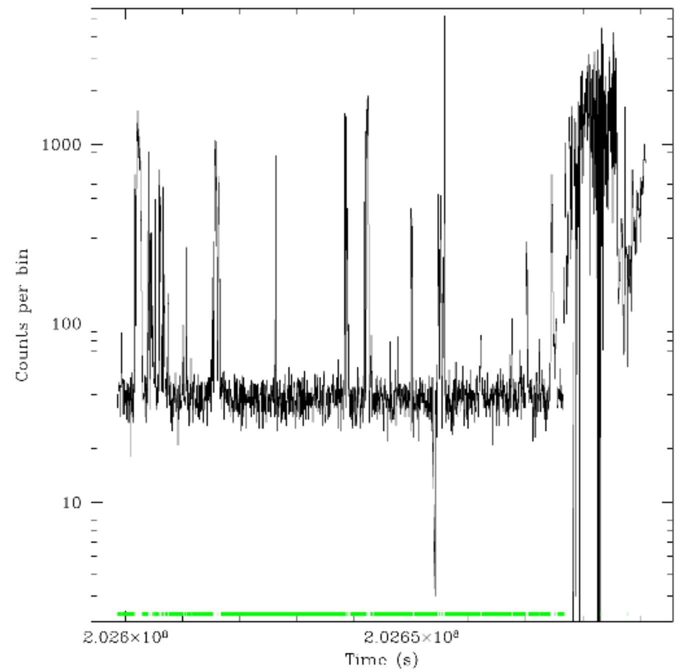
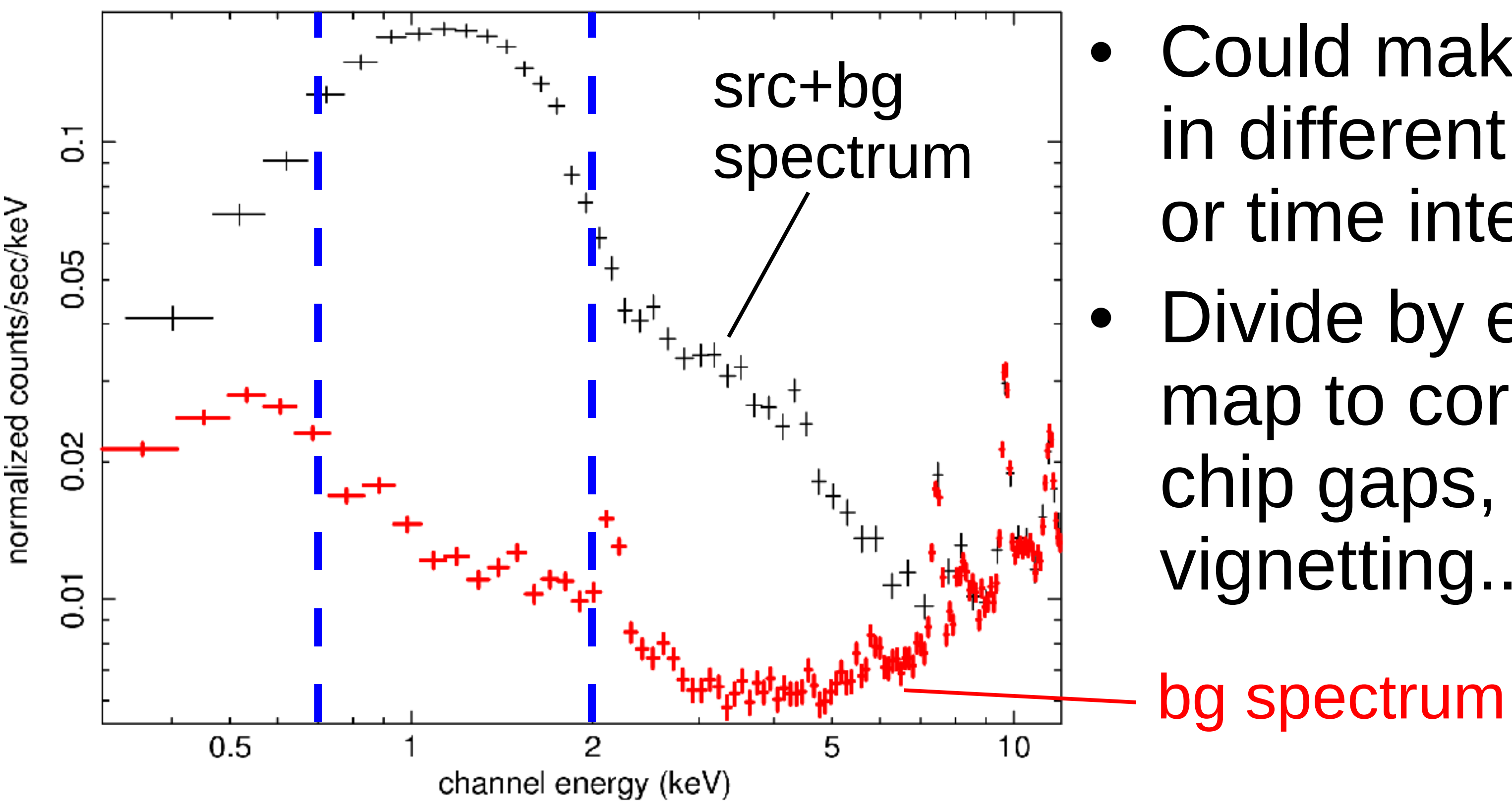


Image Analysis

- Typical image related tasks we might want to perform
  - Make image
  - Exposure correction
  - Source detection
  - Smoothing
  - Flux estimates
  - Radial profile

Making an Image

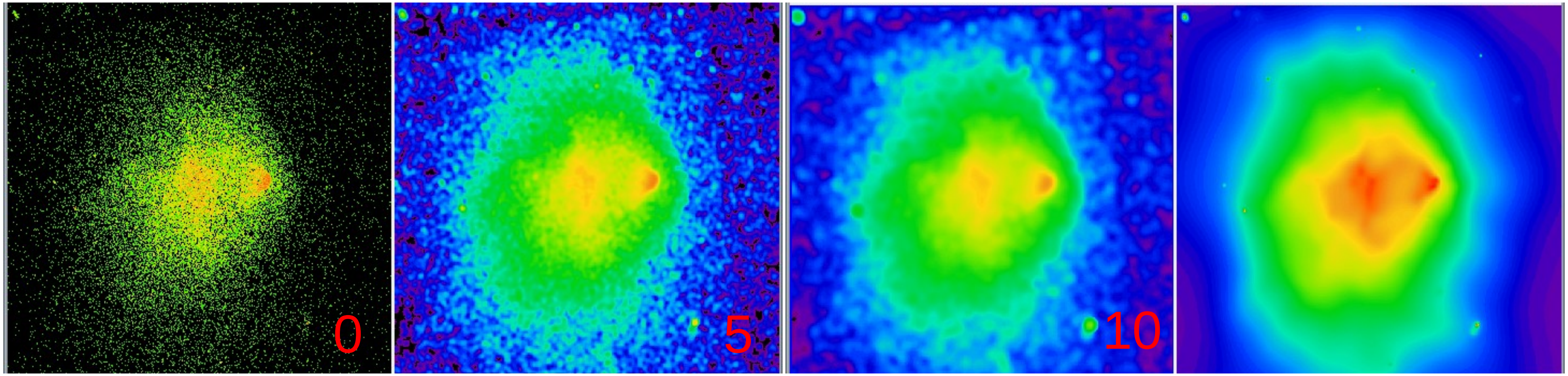
- Basically make image by recording N counts in each pixel
- Spectrum of source and bg are different
  - improve SNR by selecting energy band for image



- Could make images in different E bands or time intervals
- Divide by exposure map to correct for chip gaps, vignetting...

Image Smoothing

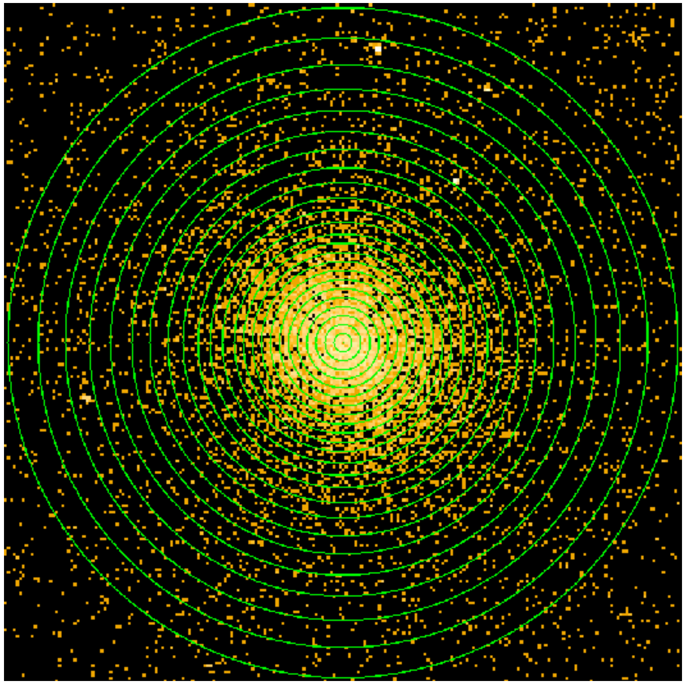
- Smoothing an image by convolving it with a kernel (usually Gaussian)
  - Helps improve contrast of faint extended features
  - Improves appearance for cosmetic purposes

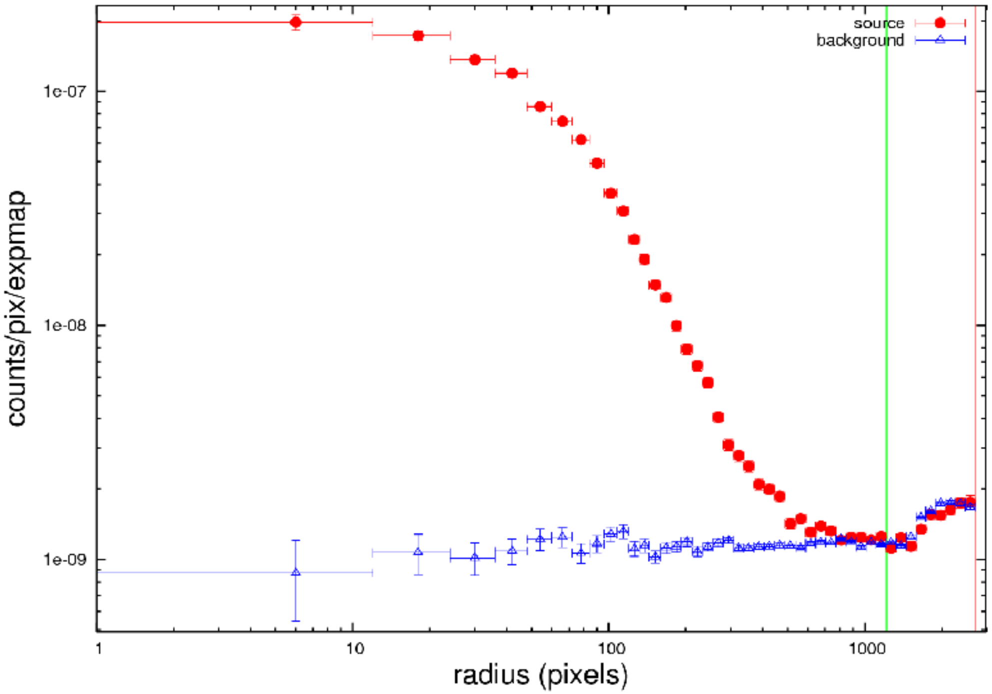


- Adaptive smoothing varies size of smoothing kernel to maintain minimum SNR in structures

Radial Profiles

- Measure the surface brightness of source in a series of annular bins
- Useful way to characterise distribution of extended sources
- Test if source is extended/resolved



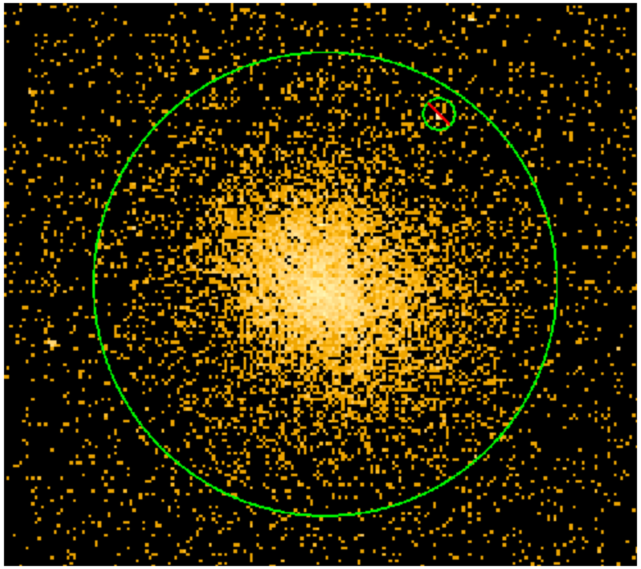


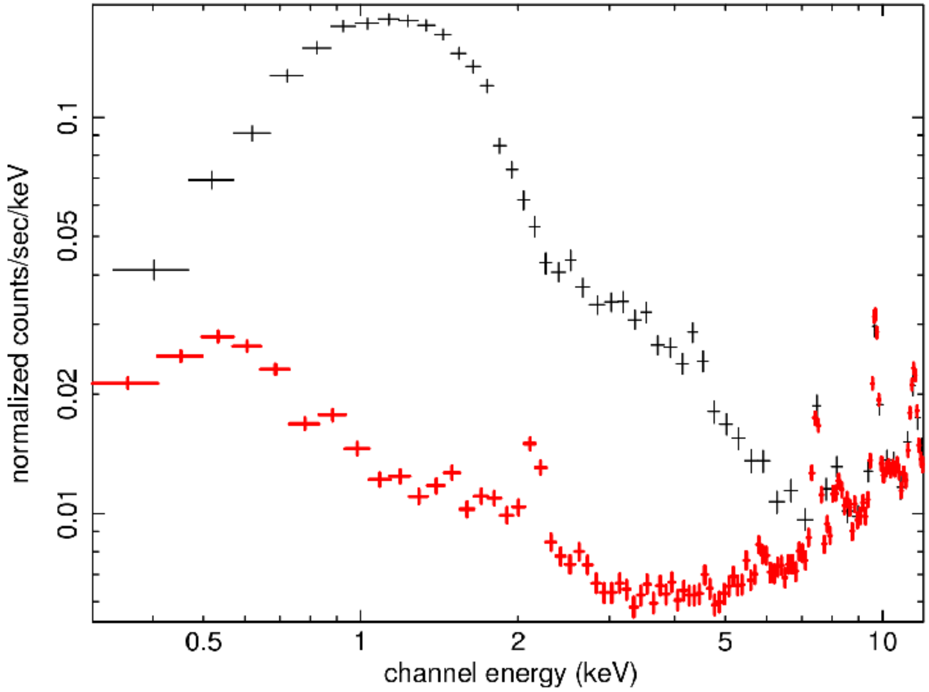
Spectral Analysis

- Extracting spectra and fitting models key way to investigate source properties
- For imaging spectroscopy
  - Define source (and bg) region
  - Extract source and bg spectra
  - Generate ARF and RMF
  - Fit physical model to data

Spectral Analysis

- Define src region to maximise SNR
- Extract spectrum – N photons detected in each energy bin
- Extract local or blank-sky bg

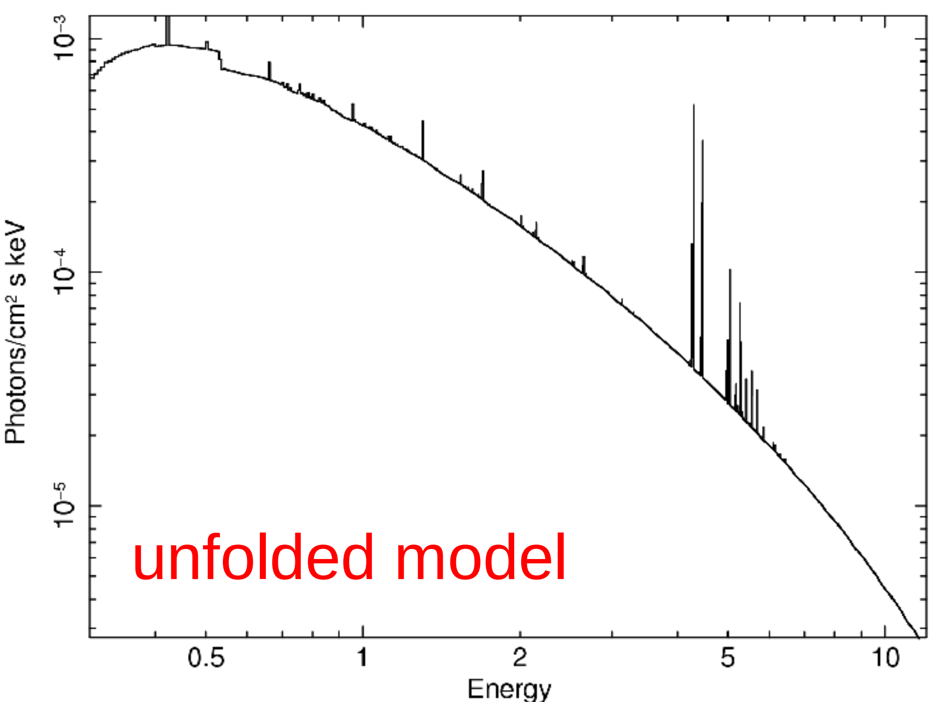


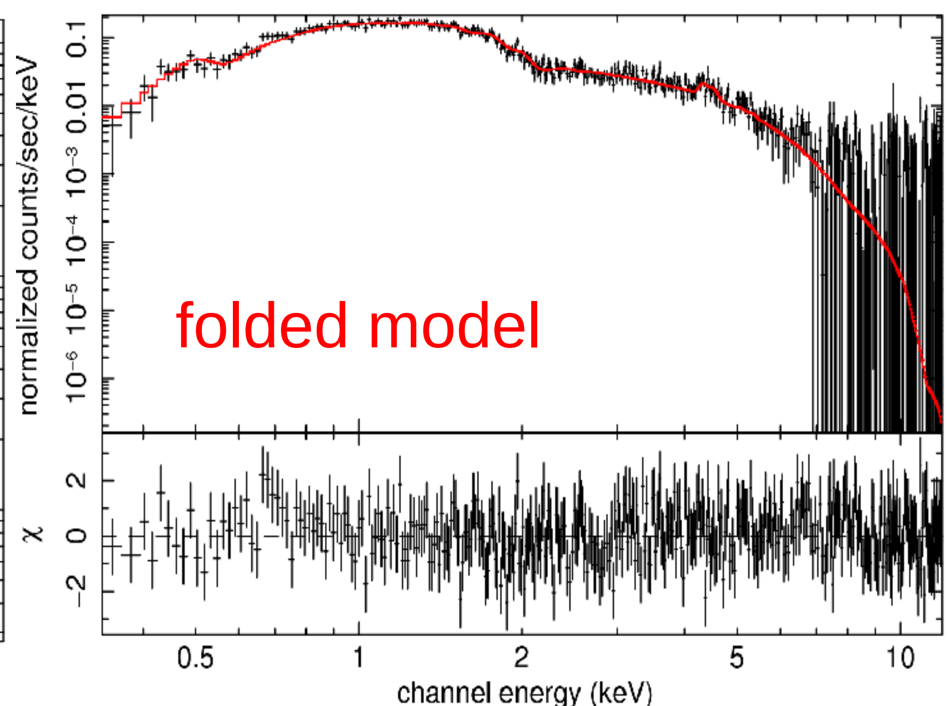


- Depending on fitting method, may need to regroup spectrum so minimum number counts per bin
  - e.g. χ^2 assumes Gaussian errors

Spectral Fitting

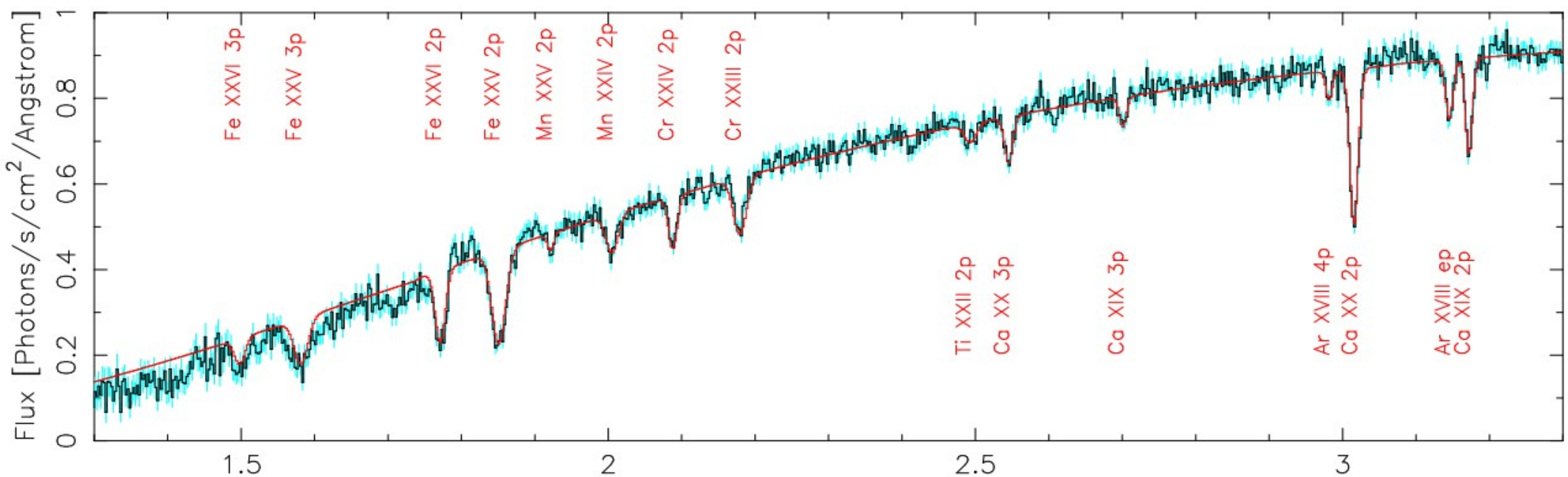
- Spectral model is “folded through” response before being compared to data using e.g. χ^2 statistic
- e.g. ARF changes model shape, RMF blurs emission lines
- Find model parameters that give best agreement with data
- Model here is absorbed thermal plasma
  - All extra-galactic sources absorbed at low-E by atomic H





High Resolution Spectroscopy

- The RMF for gratings data is more “diagonal” than for CCDs
- Gratings offer high spectral resolution (can even look like optical spectra!) and are ideal for studying narrow spectral features
- Electron transitions in ions produce absorption and emission lines at specific wavelengths (a quantum mechanical effect)
- Can tell us about ionization state, temperature, bulk velocity, velocity dispersion, column density, etc.



Emission Mechanisms

- Common radiative processes in high-energy astrophysics
  - Synchrotron (& cyclotron) radiation
    - Electrons gyrating around magnetic field lines
  - Compton scattering
    - Photon—electron interaction (photon loses energy)
  - Inverse-Compton scattering
    - Photon—electron interaction (photon *gains* energy)
  - Thermal bremsstrahlung
    - Electron—ion interaction (also called “free-free” radiation)
- Good book is Radiative Processes in Astrophysics by Rybicki & Lightman

Software

- ds9 – visualise images and events lists
- ciao – Chandra specific and general FITS tools
- sas – XMM specific and general FITS tools
- ftools – general FITS tools
- zhtools – general FITS tools
- funtools – general FITS tools
- xspec – spectral fitting
- isis – spectral fitting, high-resolution spectroscopy
  - pvm + isis allows parallelization of data analysis
- perl / shell scripts – *very* useful when you need to repeat a data extraction / analysis task