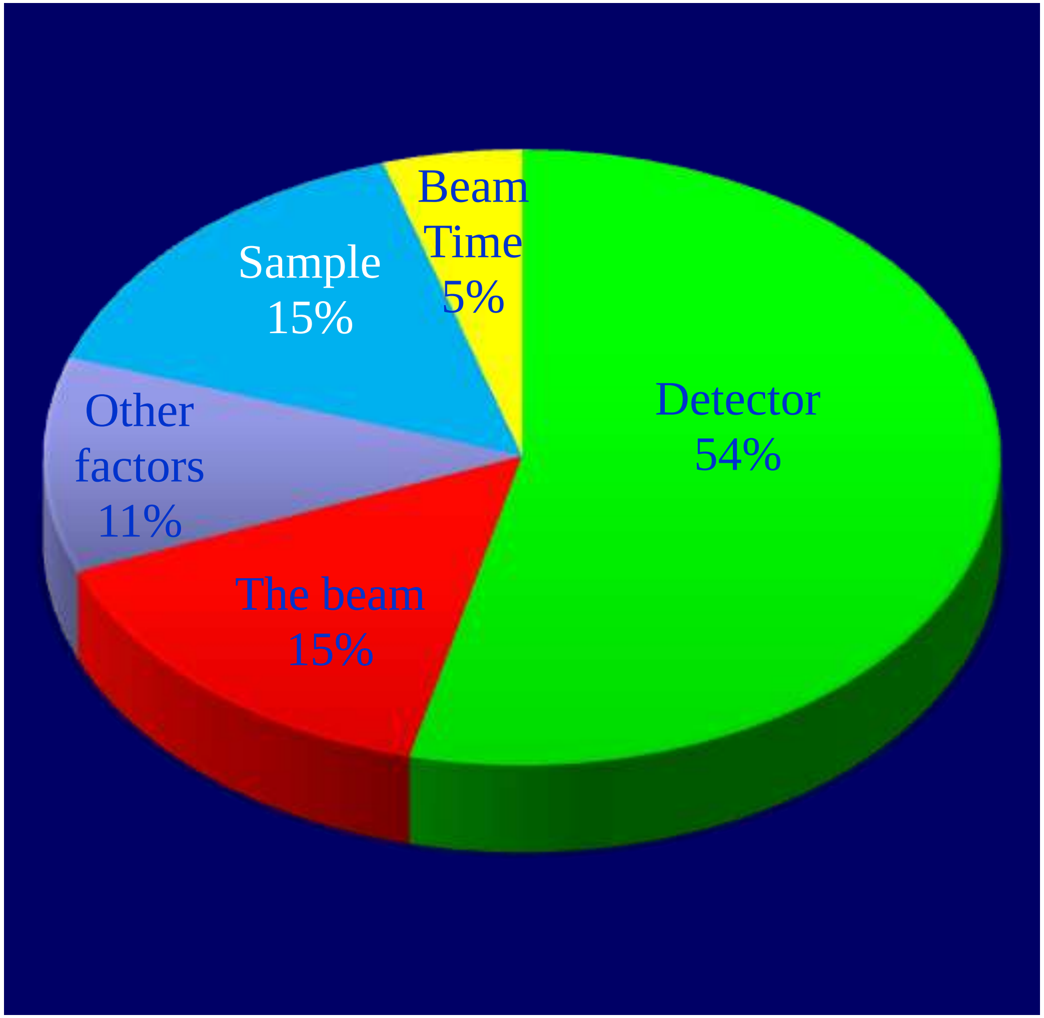
Detectors for Synchrotron Radiation

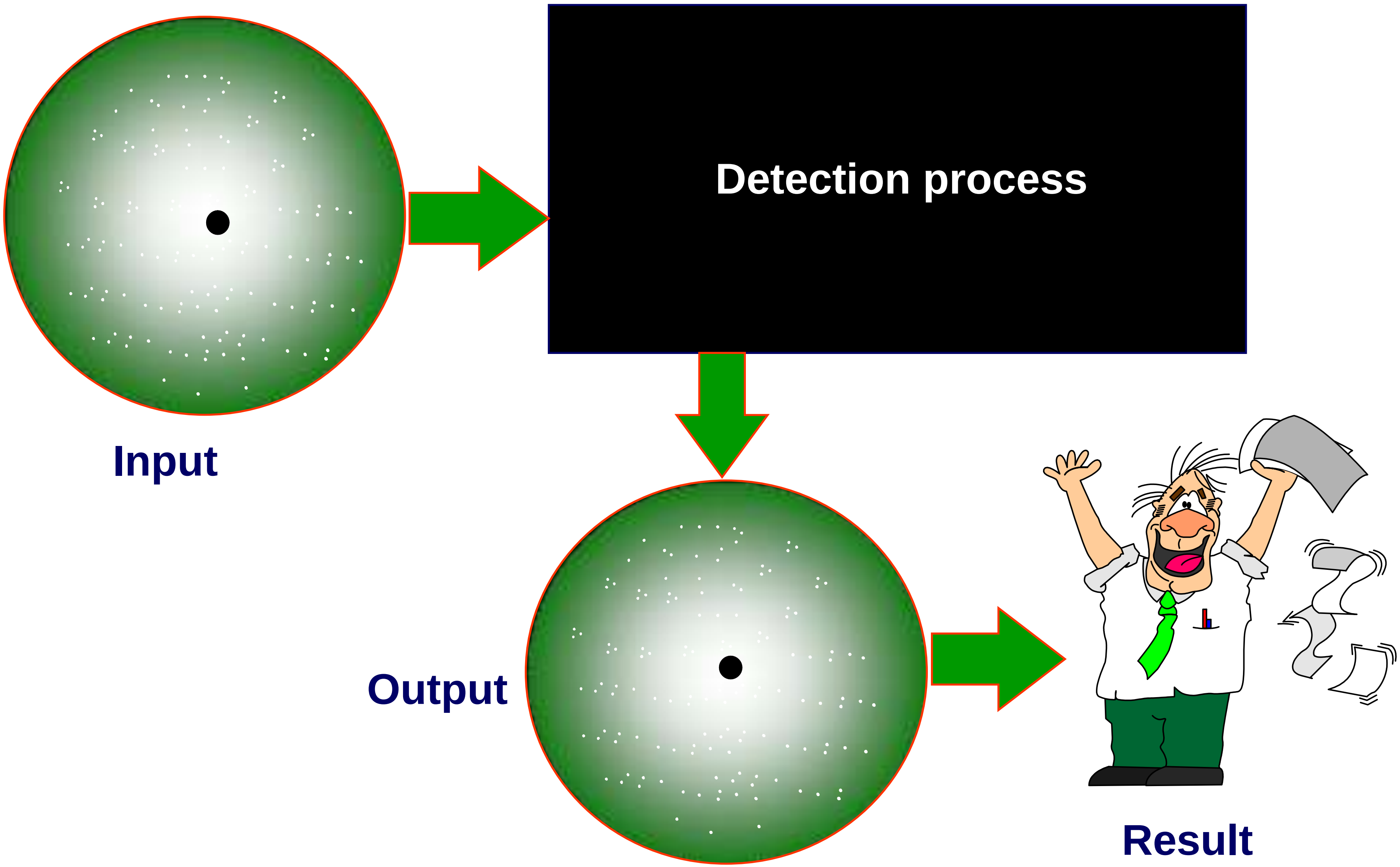
Rob Lewis

Factors Limiting Science

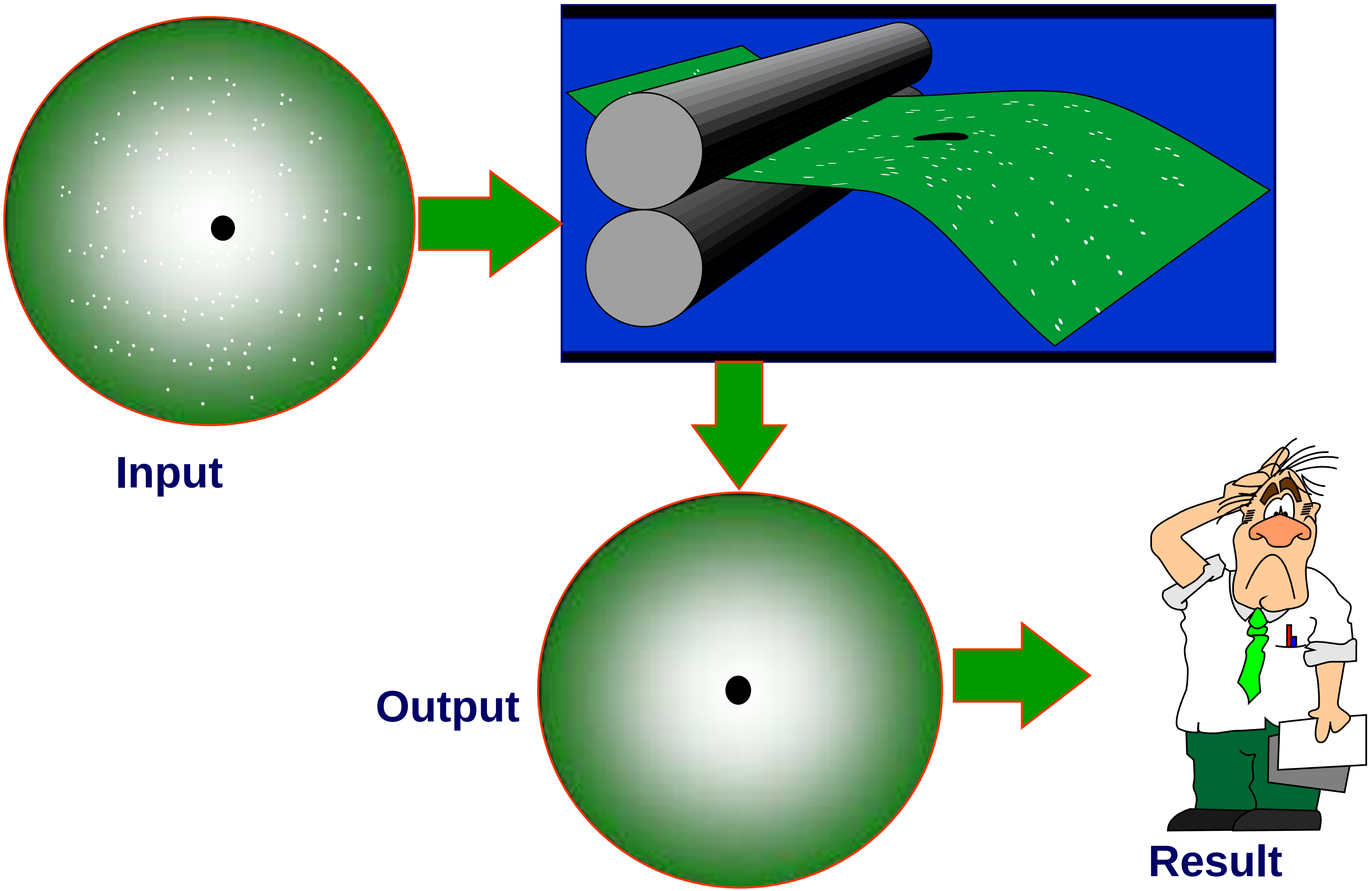
- Detectors are an oft-neglected but crucial part of an experiment
- They often limit the science



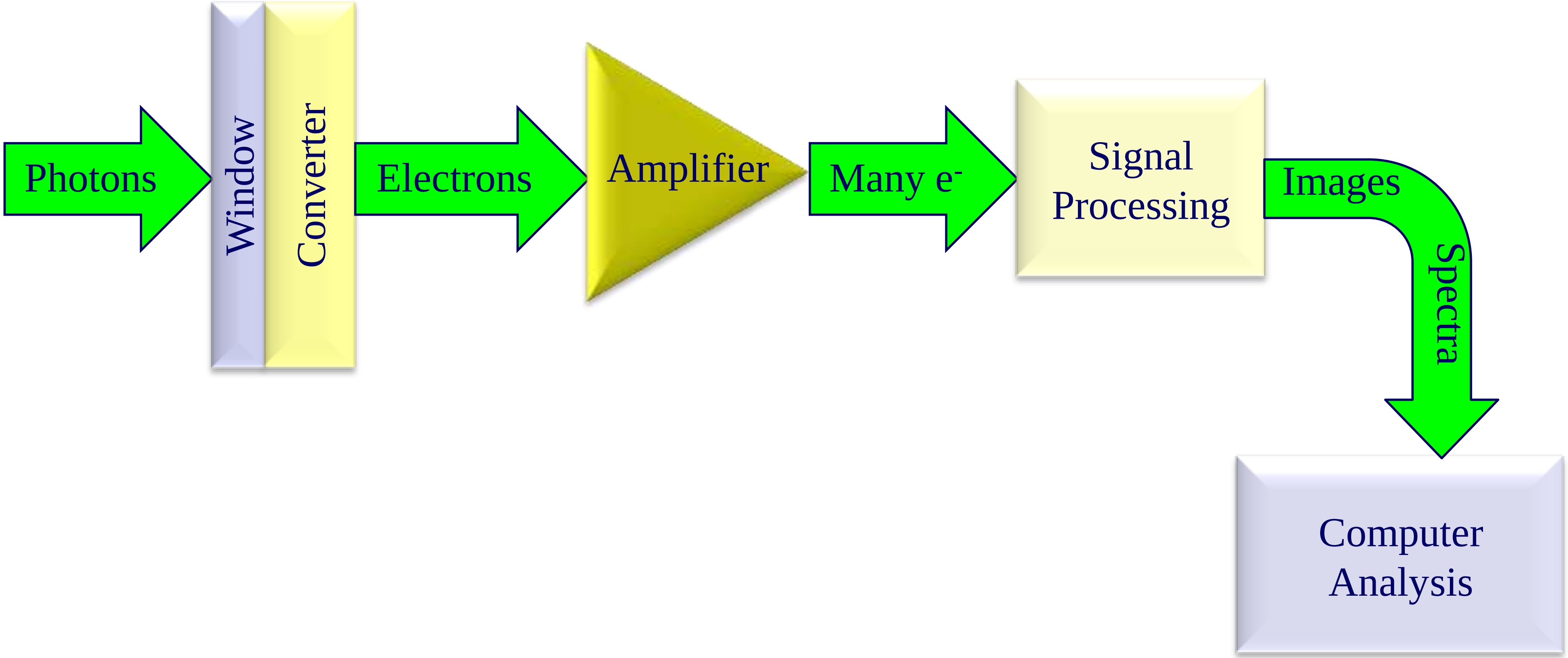
Scientist's View of Detector



The Truth!



Detector Chain of Events



Detection Mechanisms

- There are many means of detection. All require the interaction of photons/electrons with matter
- Examples include
  - Gas ionisation
    - Photons produce electrons and ions which are then detected
    - E.g. Ion chambers, proportional counters
  - Photoelectric effect
    - Photons eject electrons from a solid creating a current which is measured
    - E.g.. Beam monitors
  - Generation of electron hole pairs
    - Photons produce electrons and holes in a semiconductor which are then detected
    - E.g.. CCD
  - Fluorescence, scintillation and F centres
    - Photons produce prompt fluorescence or F centres
    - E.g. Image plates and Scintillation counters
  - Chemical effect
    - Photons create a chemical change such as dissociating Ag halide
    - E.g. Film

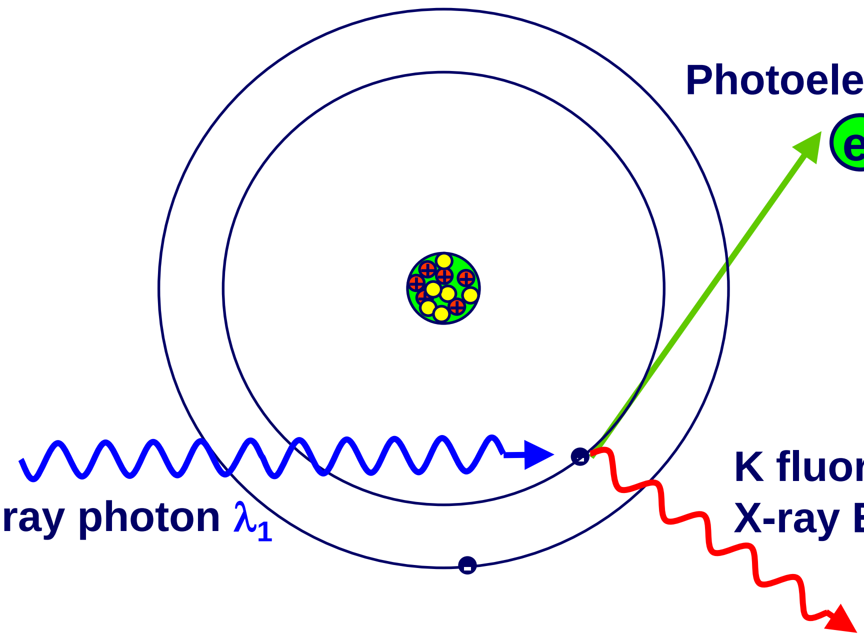
Albert Einstein

Germany and Switzerland
Kaiser-Wilhelm-Institut
(now Max-Planck-Institut)
für Physik
Berlin-Dahlem, Germany
1879 - 1955

Nobel prize in physics 1921

"for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect"

Photoelectric Effect



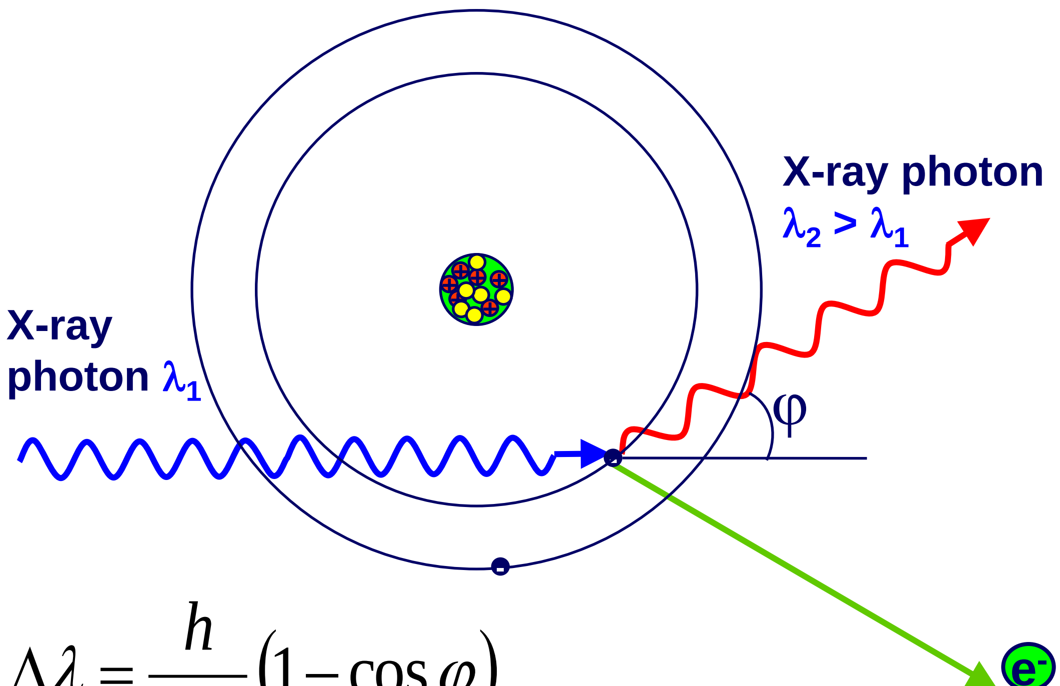
Arthur Holly Compton

University of Chicago
Chicago, IL, USA
1892 - 1962

Nobel prize in physics 1927

"for his discovery of the effect named after him"

Compton Effect

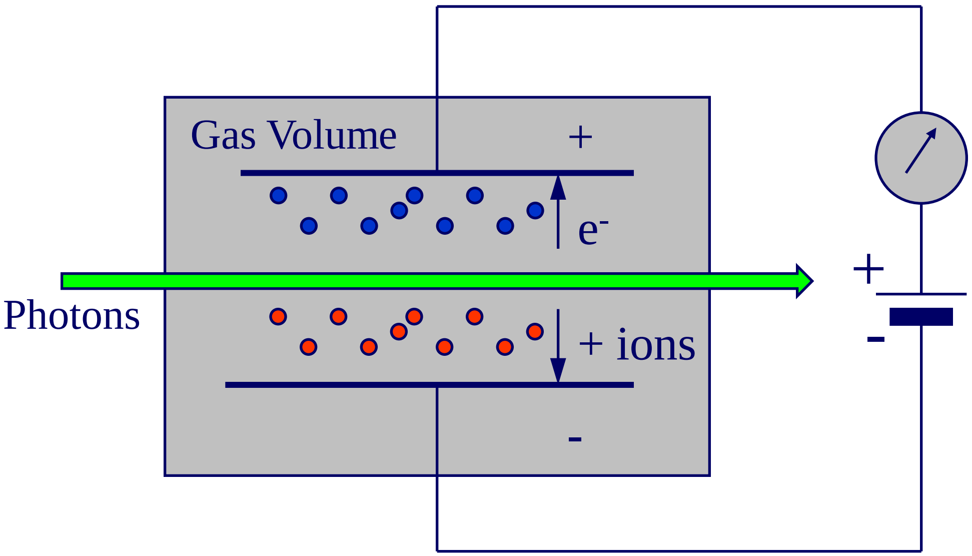


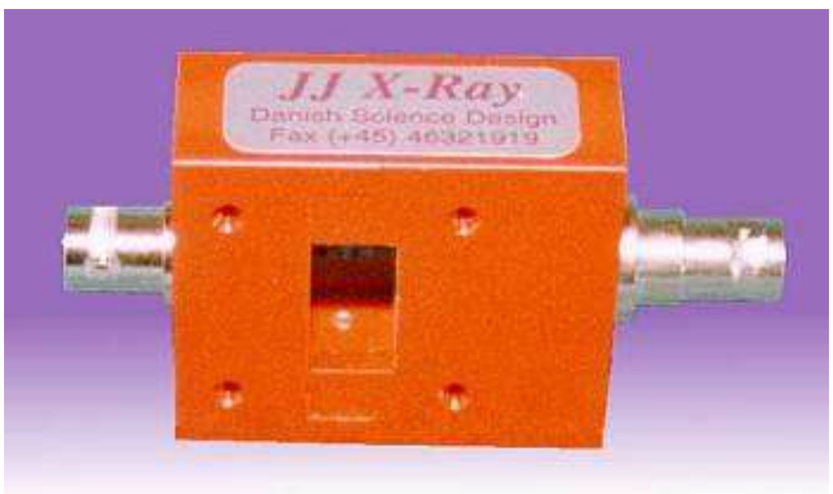
$$\Delta\lambda = \frac{h}{m_0 c}(1 - \cos\varphi)$$

An Example Detector

Echidna

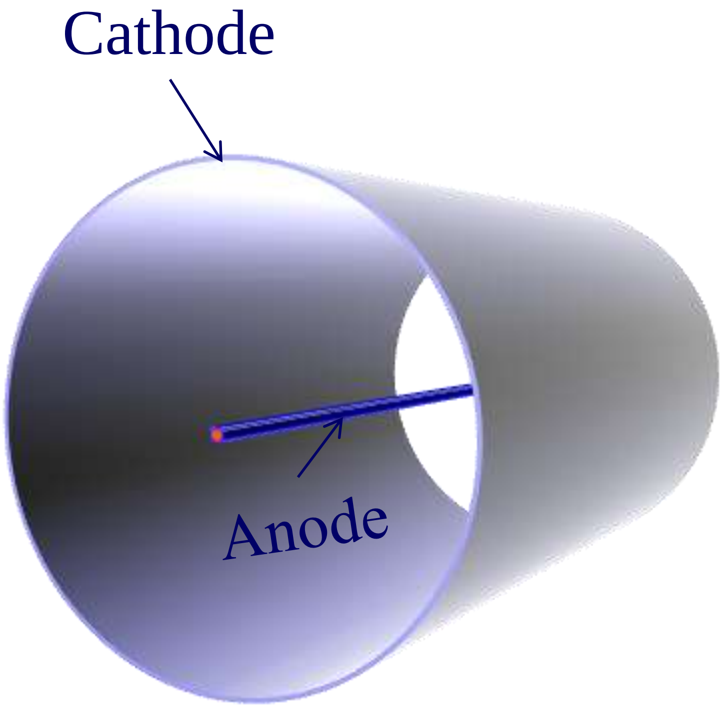
Ionisation Chamber

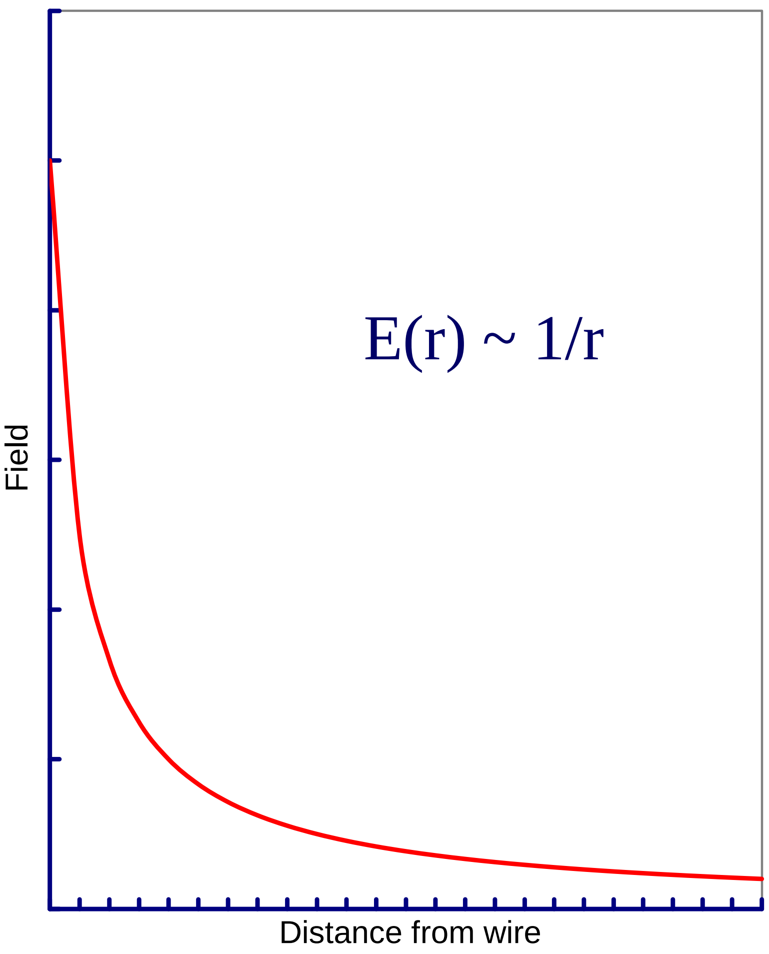




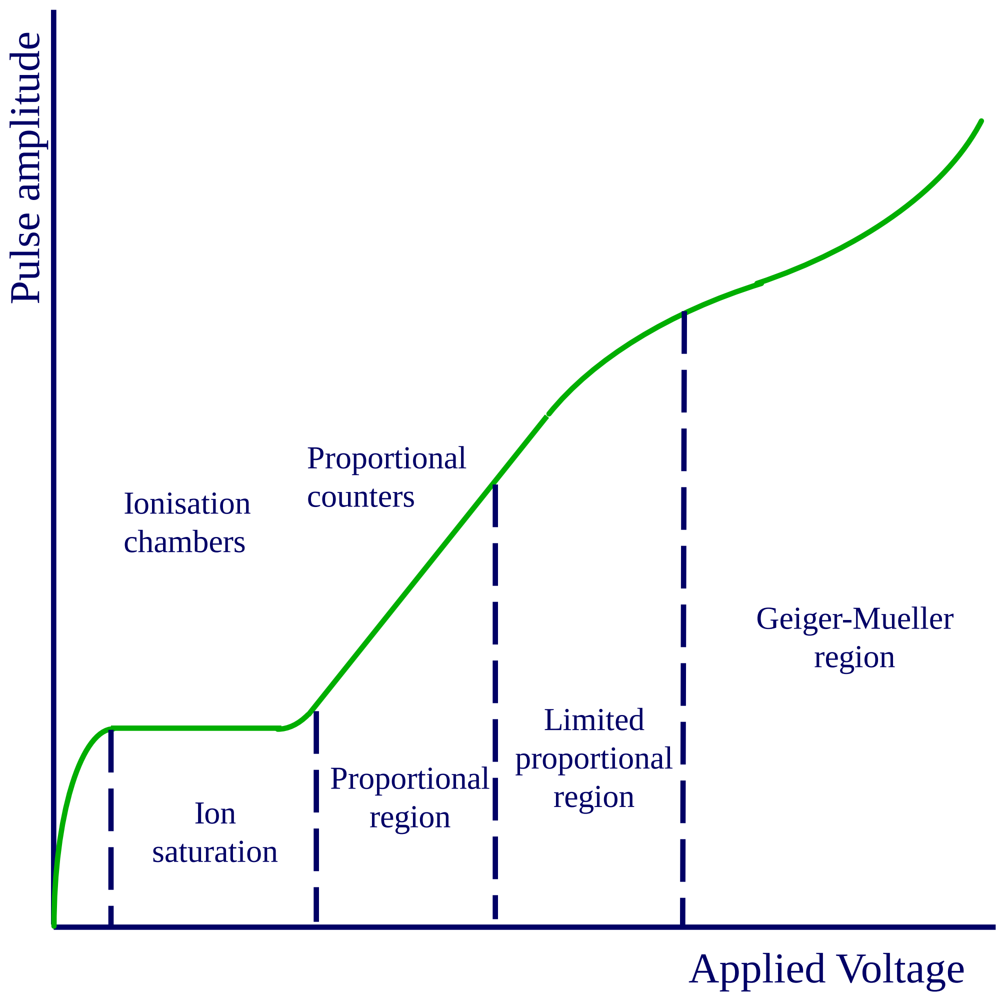
- Very simple device
- Approximately 1 e⁻ ion pair per 30eV deposited
- Important that recombination low as possible
  - Higher voltages required at higher rates since more carriers
  - Diffusion losses caused by separation of carriers minimised by higher voltages
  - Plates too close cause electron losses
- Ion chambers are sensitive to pressure and temperature

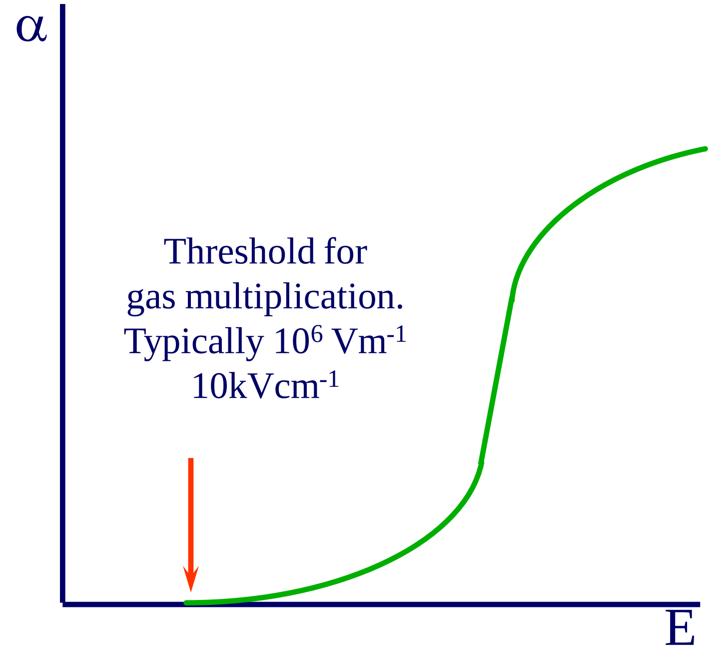
Field Variation





Operation regions of gas filled detectors





n is number of charges

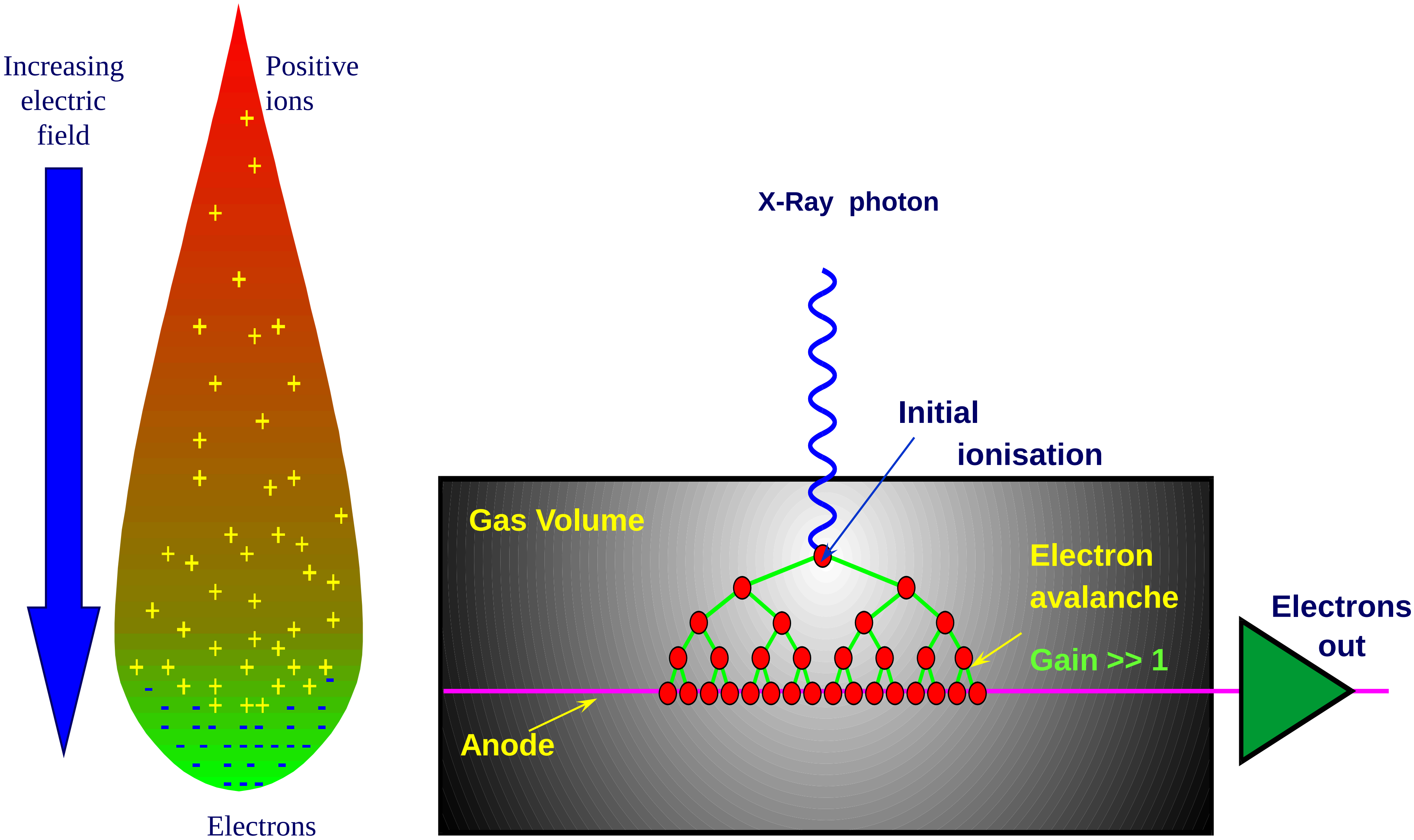
x is distance

α is the first Townsend coefficient

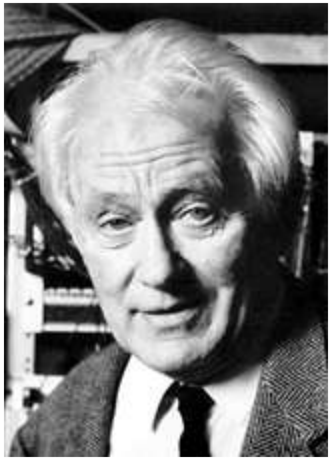
$$\frac{dn}{n} = \alpha dx$$

$$n(x) = n(0)e^{\alpha x}$$

Avalanche & Proportional Counter



Georges Charpak



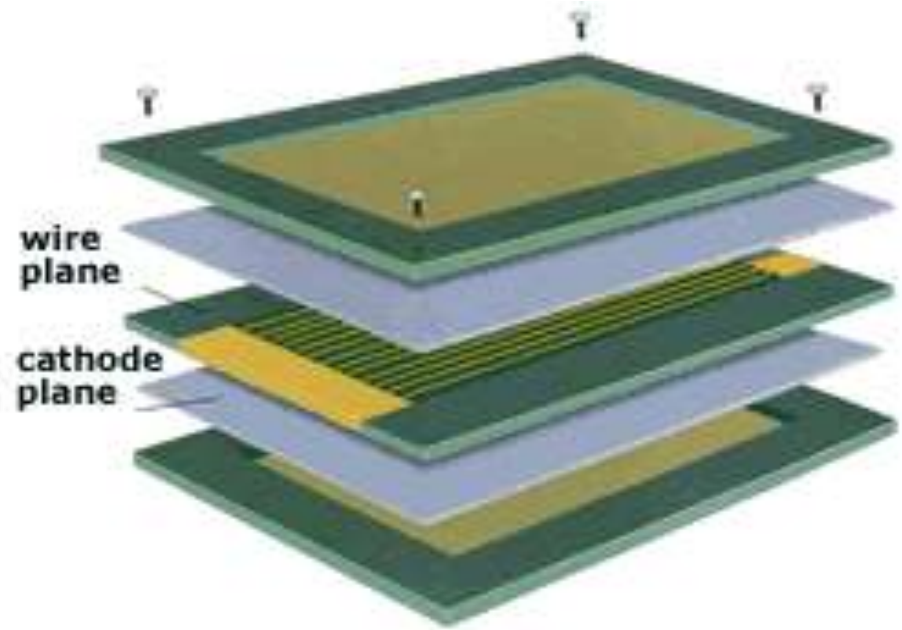
Nobel prize in physics 1992

"for his invention and development of particle detectors, in particular the multiwire proportional chamber"

Multi-wire Proportional Counter

France
École Supérieure de Physique et Chimie Paris, France; CERN Geneva, Switzerland

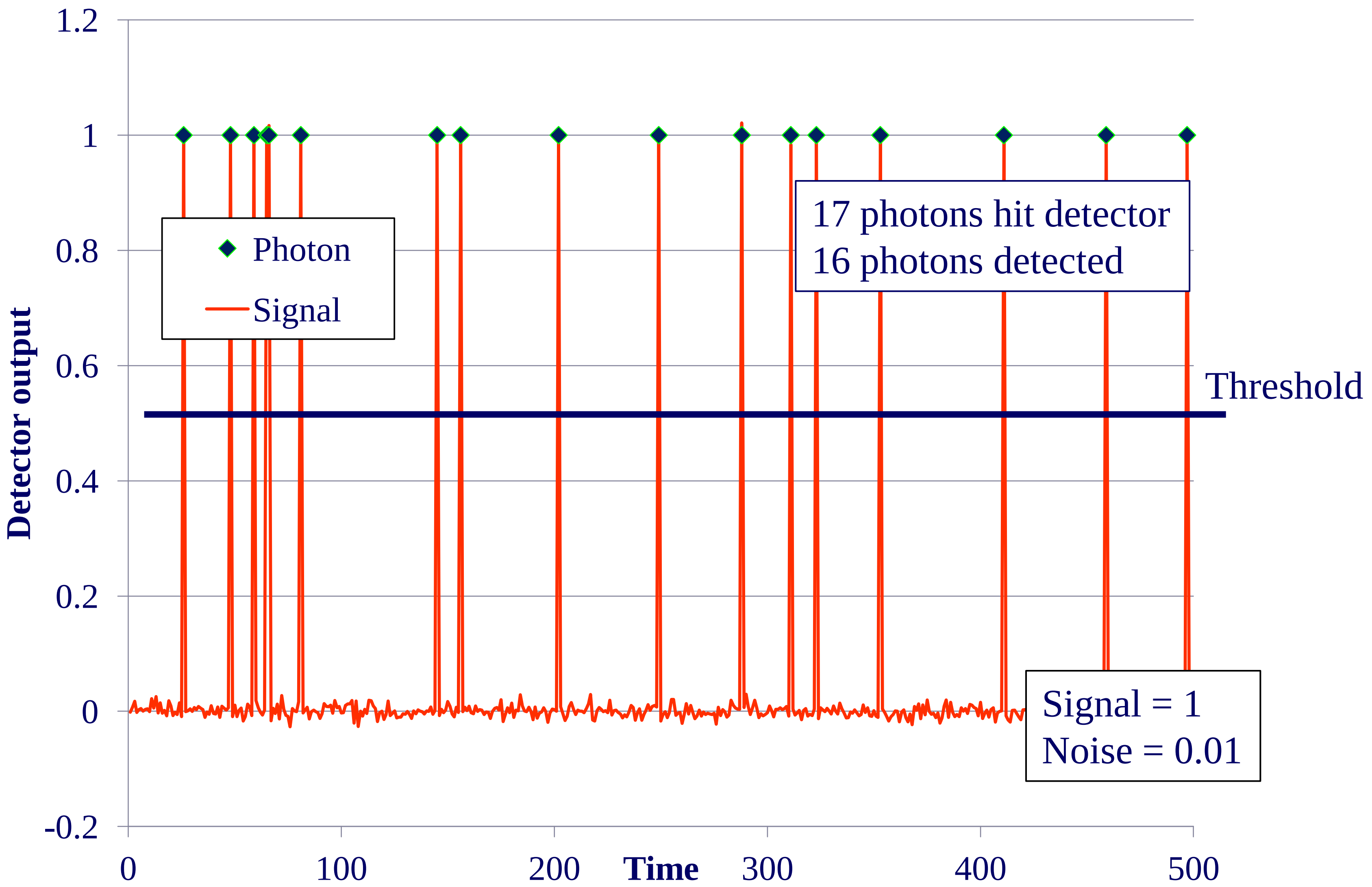
b. 1924
(in Dabrovica, Poland)



Counting and Integrating

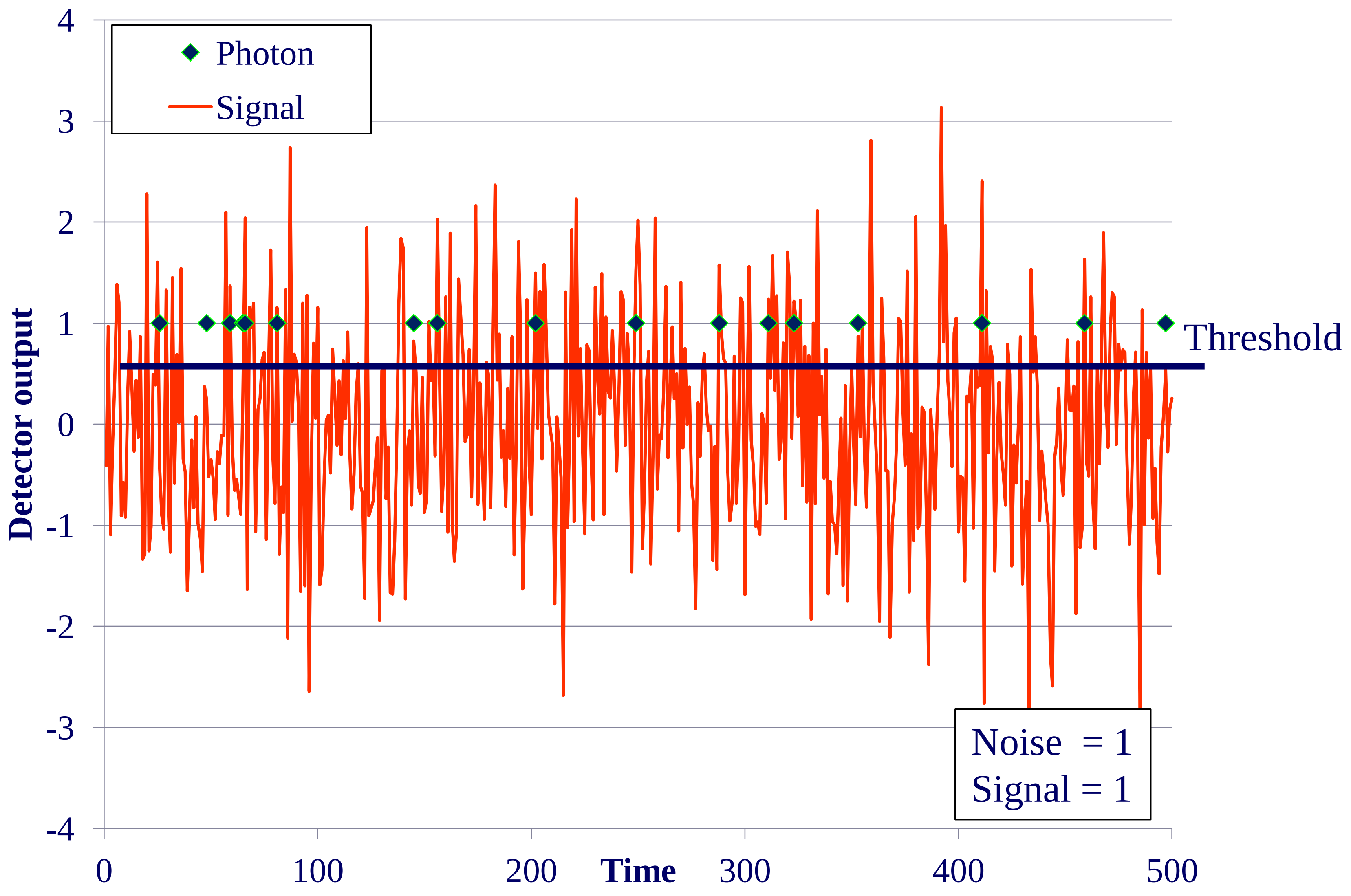
- If there is sufficient signal produced by the interaction of a photon or a particle in the detector then it is possible to operate the detector as a counter
- It's all about signal to noise ratio!

SNR = 100



1.2
1
0.8
0.6
0.4
0.2
0
-0.2
Detector output
0
100
200
Time
300
400
500
Photon
Signal
17 photons hit detector
16 photons detected
Threshold
Signal = 1
Noise = 0.01

SNR = 1

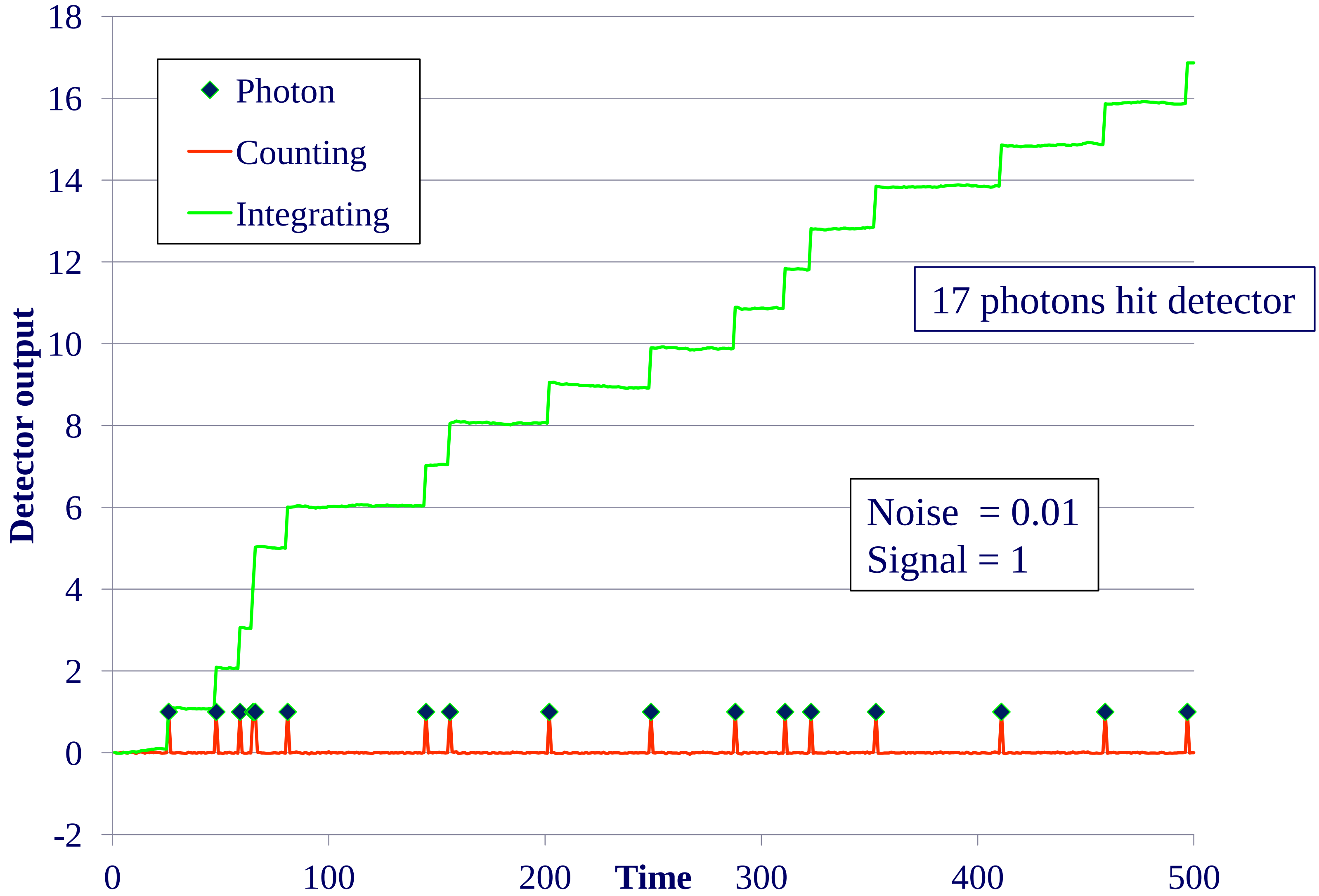


Photon
Signal
Threshold
Noise = 1
Signal = 1
Detector output
Time
4
3
2
1
0
-1
-2
-3
-4
0
100
200
300
400
500

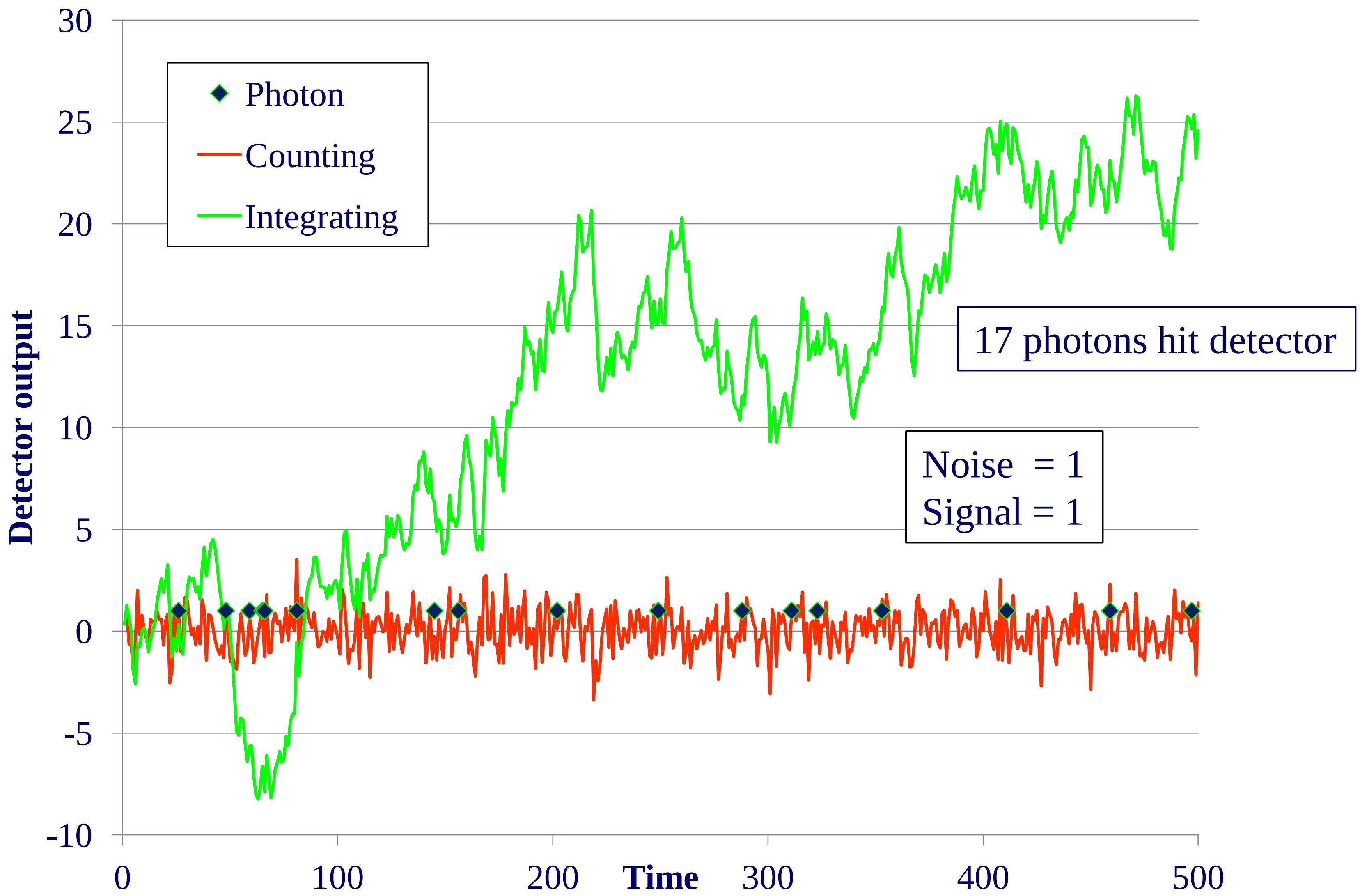
Counting and Integrating

- Usually SNR is insufficient and we have to accumulate many photons/particles before the signal becomes measurable

Counting & Integrating SNR =100

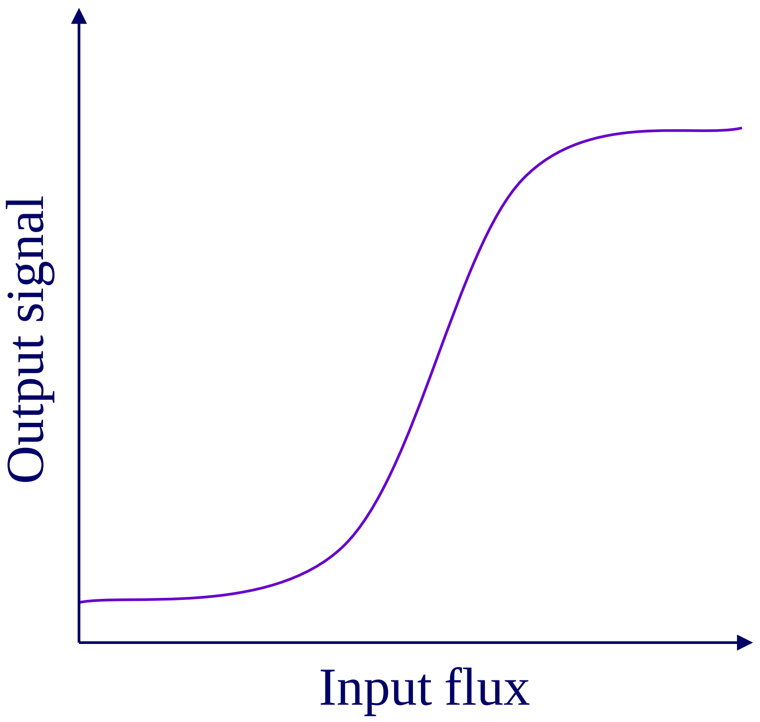


Counting & Integrating SNR = 1



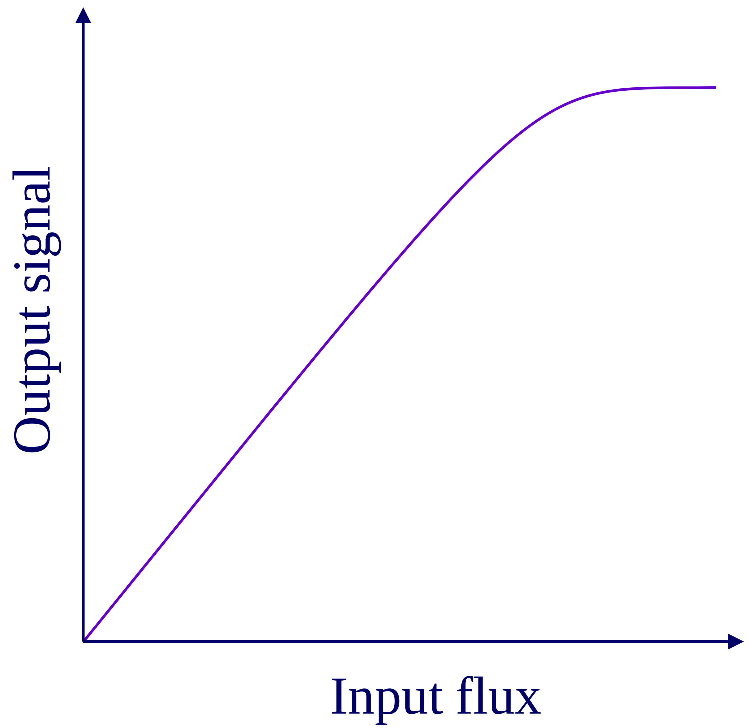
Integrating Detectors

- Mode
  - Measures deposited energy at end of integration period
- Characteristics
  - High input flux capability
  - Read noise dominates at low signal (“fog level”)
  - Dead time between frames
  - 2×20 keV phts = 1×40 keV photon i.e. Cannot perform simultaneous spectroscopy and positioning
  - Examples: Image plates, CCDs



Photon Counting Detectors

- Mode
  - Detects every photon as it arrives. Only active pixels read
- Characteristics
  - Quantum limited, Detector noise often negligible
  - No dead time between frames
  - Can measure position and energy simultaneously
  - Limited input flux capability
  - Examples: Prop counters, Scintillators



Types of Detectors

Crimson Rosella and King Parrot

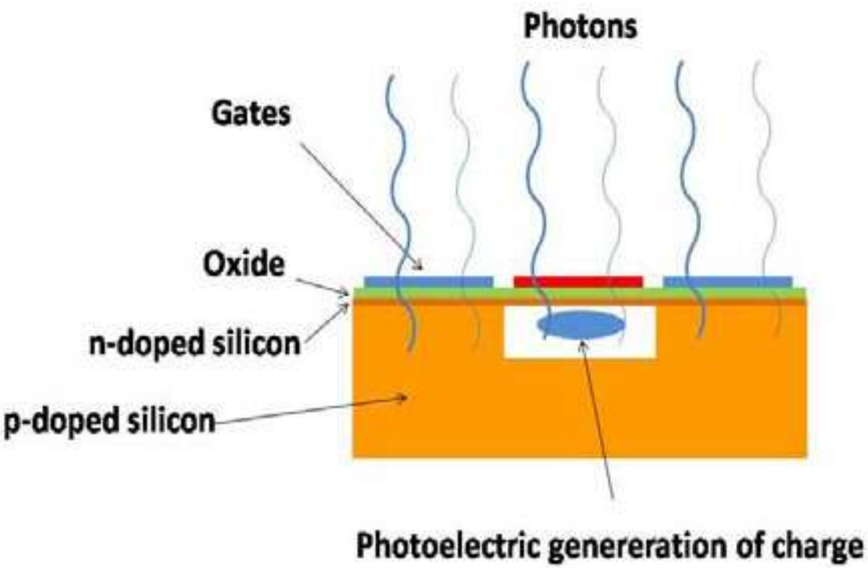
Willard S. Boyle & George E. Smith

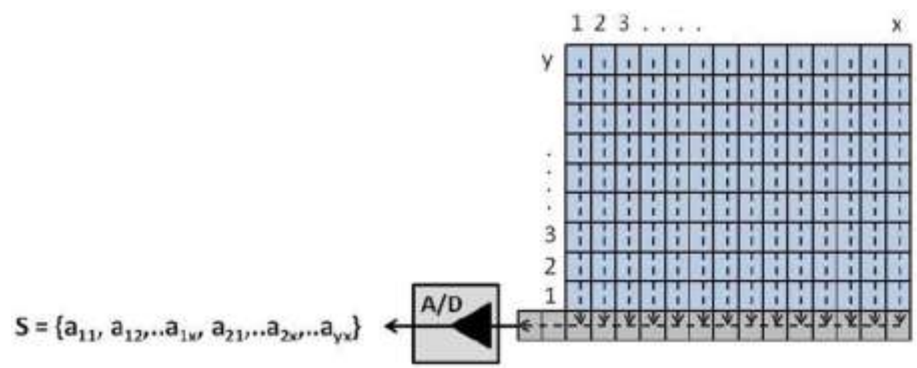
Bell Laboratories
Murray Hill, NJ, USA

Nobel prize in physics 2009

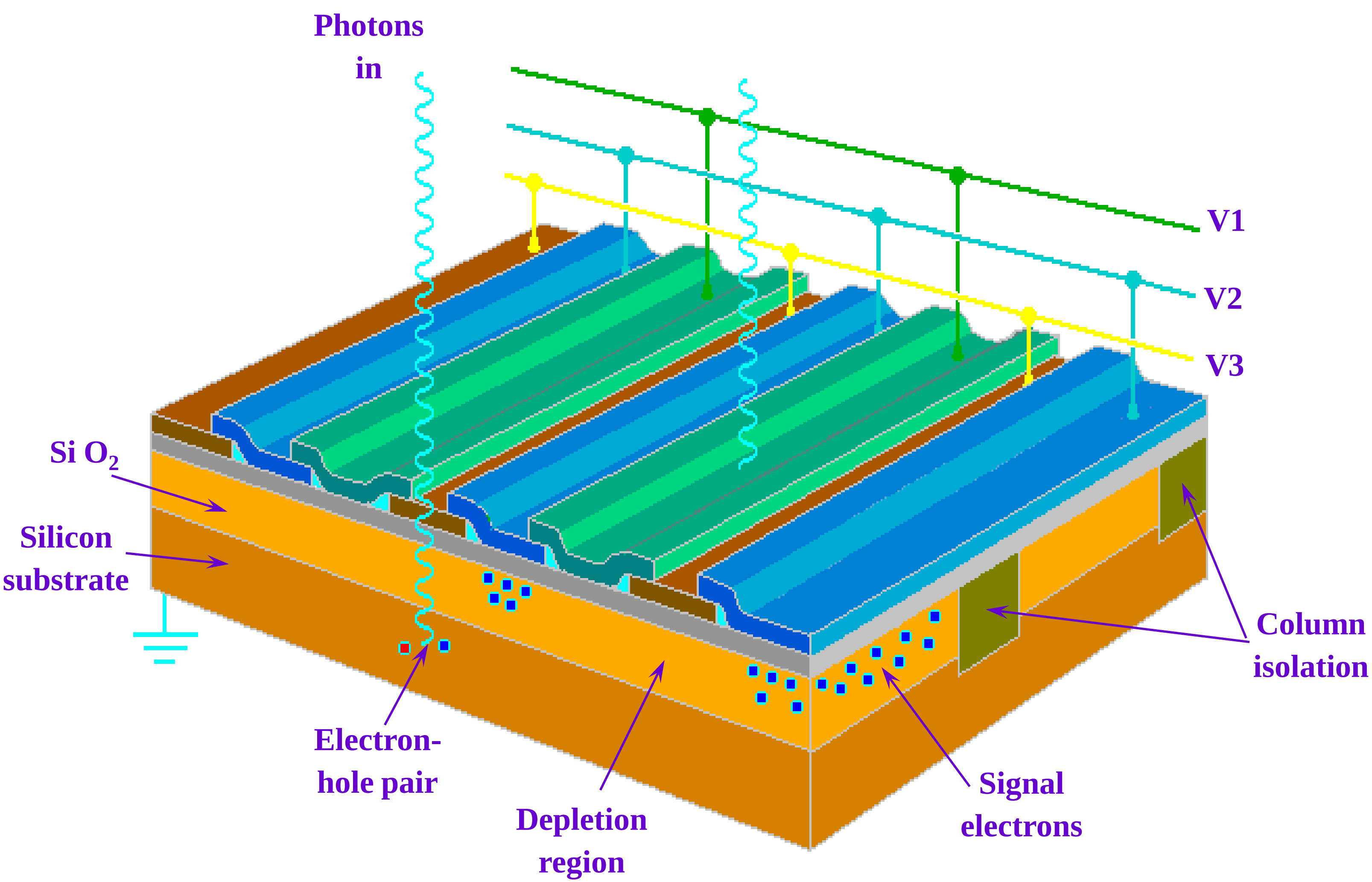
"for the invention of an imaging semiconductor circuit – the CCD sensor"

CCD

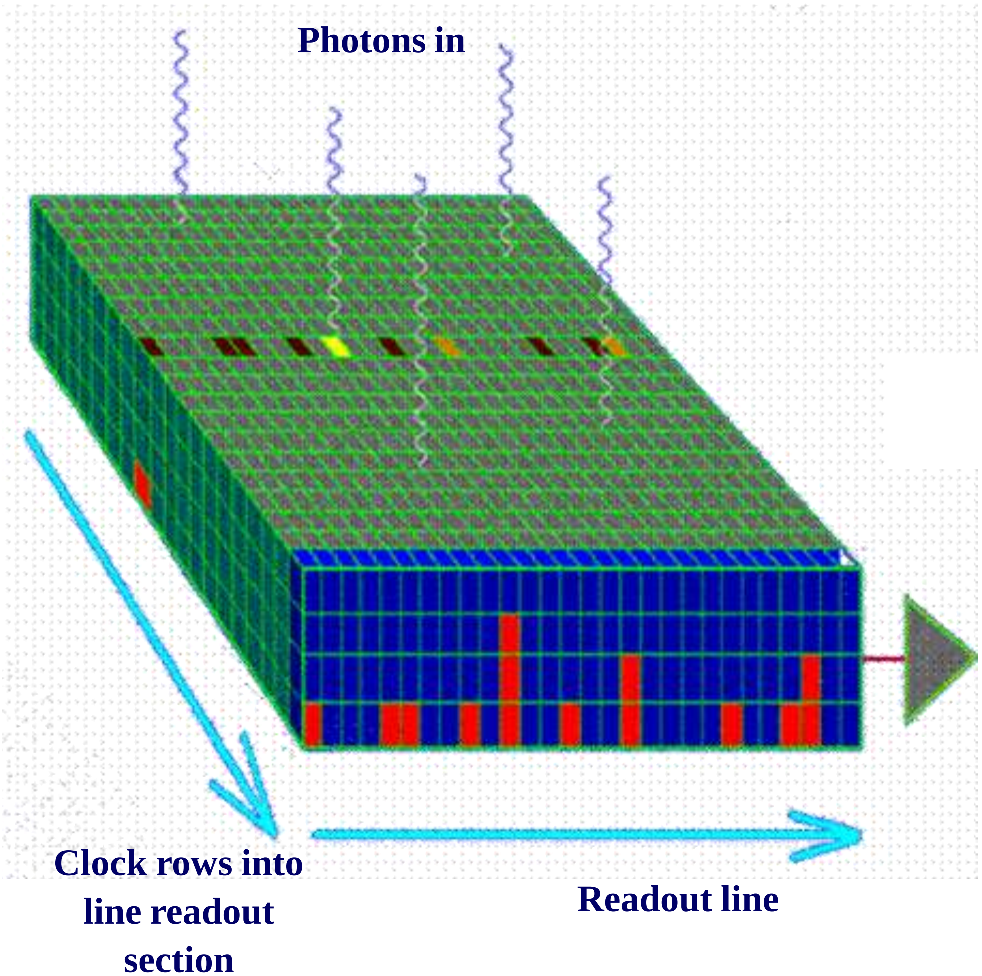


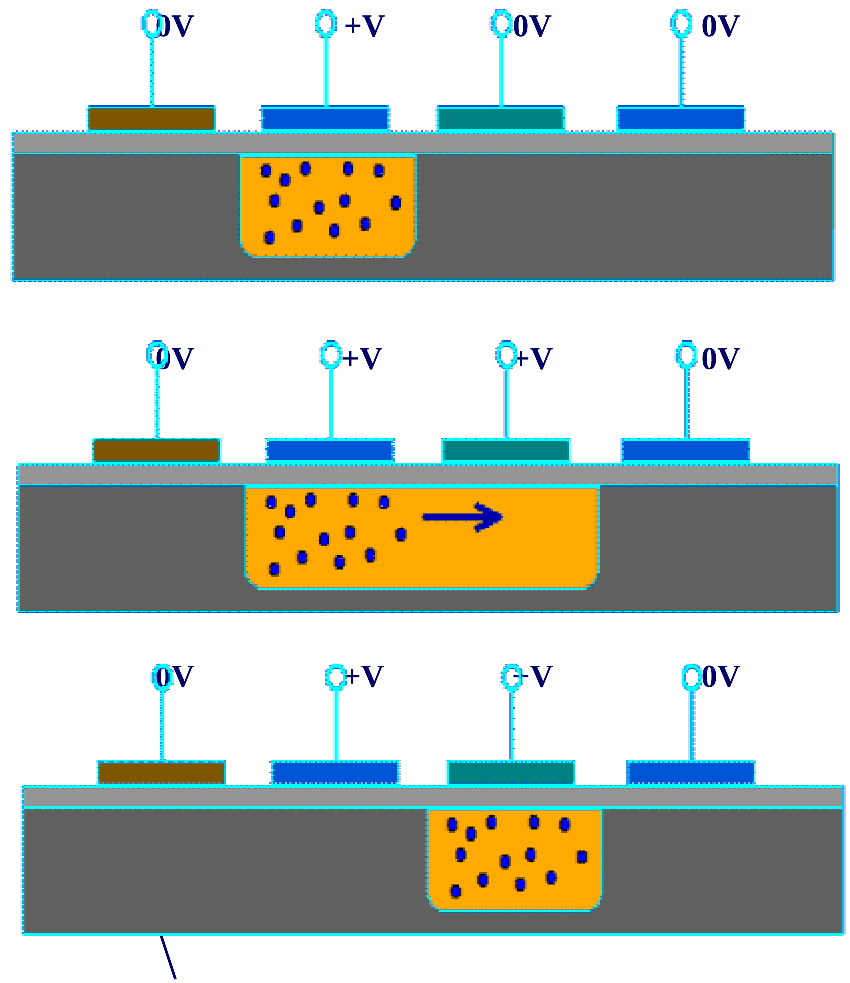


Charge Coupled Device



CCD Readout

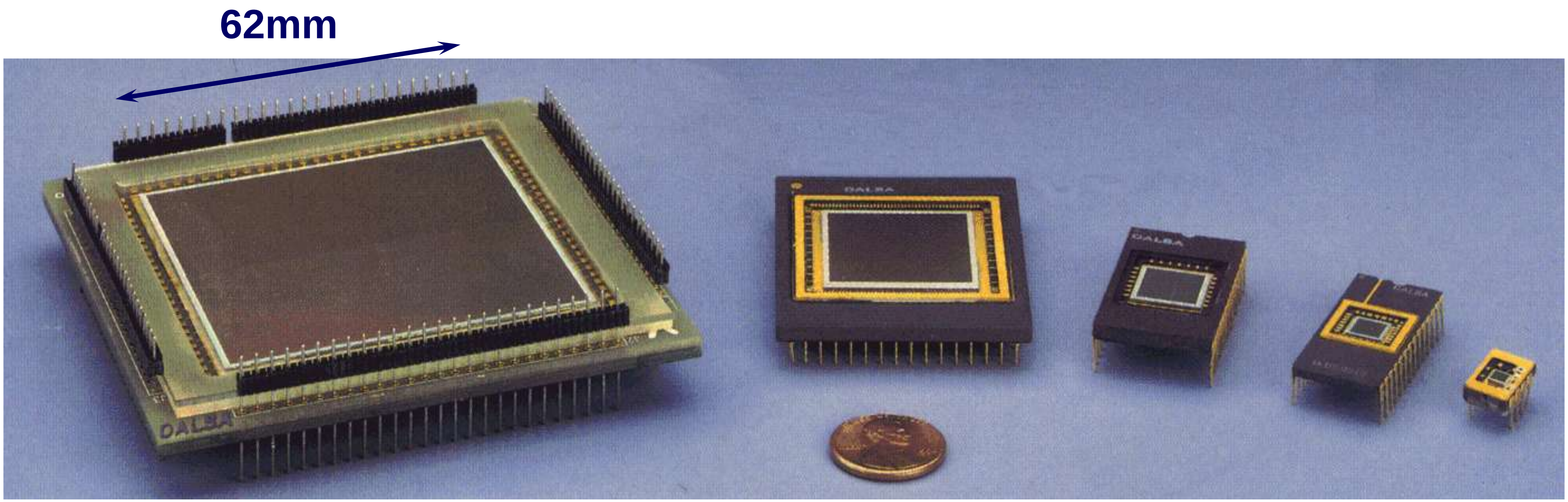

Photons in
Clock rows into
line readout
section
Readout line


0V
+V
0V
0V
0V
+V
+V
0V
0V
+V
0V

CCD Readout

- Charge is moved from pixel to pixel by clocking
- Each pixel has a limited capacitance (well depth) typically 10^4-10^5 e^-
- This limits dynamic range for direct detection
  - 10keV photon creates ~ 3000e^- so saturation = ~ 10 photons
- Speed of clocking is restricted by line capacitance and charge transfer efficiency
  - Size of CCD restricted by this
- Noise can be reduced by cooling
- Amplifier usually on chip
  - Heats up that part of chip

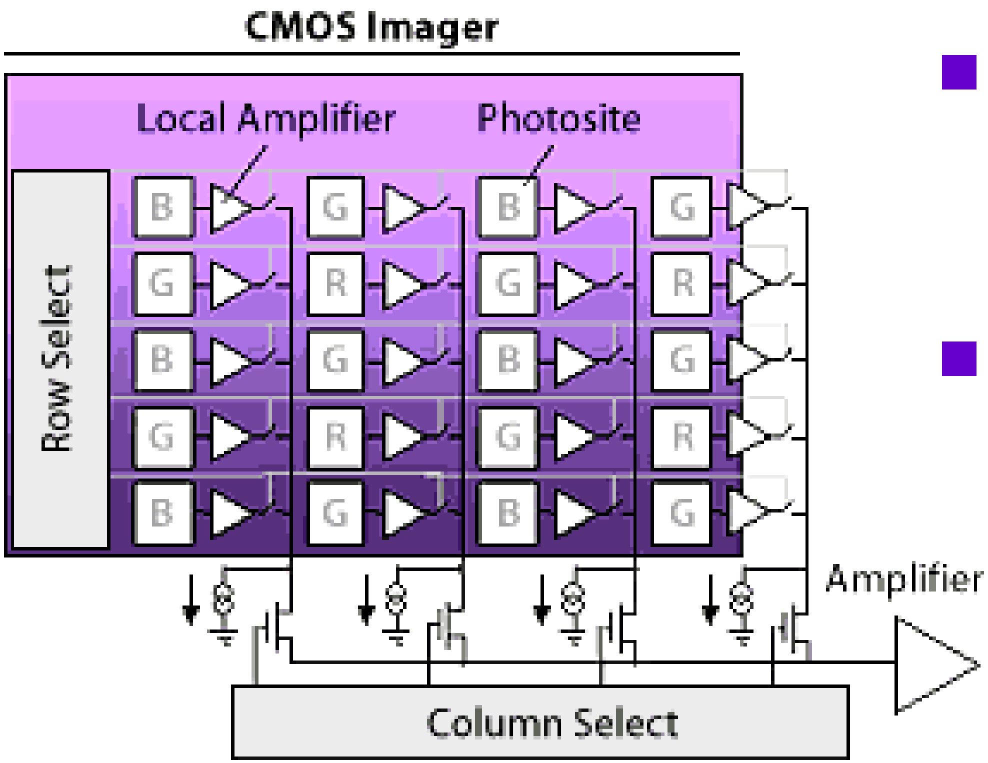
CCDs



Although sizes > 50mm are available, the read speed is slow to preserve low noise and cte (line capacitance becomes very high)

Shutter required

Complimentary Metal-Oxide Semiconductor (CMOS)



- A readout amplifier transistor on each pixel converts charge to voltage
- Allows random access to pixels, similar to the row-column memory cell access in RAM

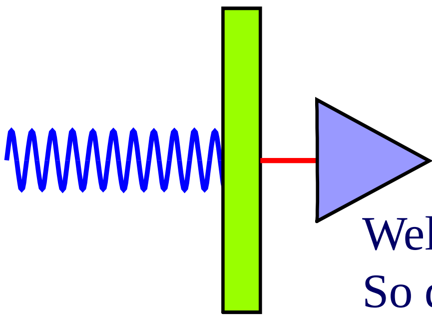
CMOS vs CCD

- Traditionally CCD higher sensitivity and lower noise
- Modern lithography means they are now similar
- CMOS sensors can have much more functionality on-chip than CCDs
  - On chip image processing, edge detection, noise reduction, and analog to digital conversion
- CMOS lower power → less heat → less noise

Use with X-rays

Direct detection

Gain ~ 2000e⁻ / 8keV x-ray



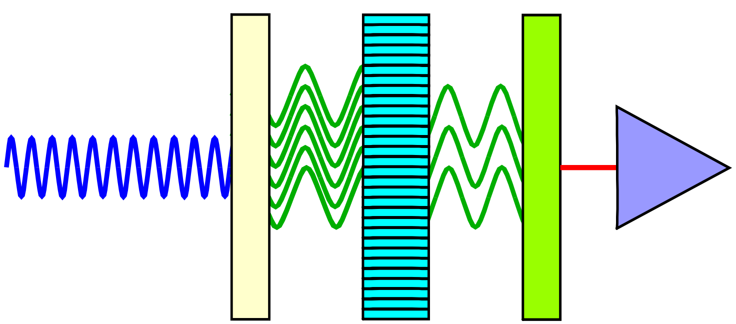
Well depth = 2×10^5

So dynamic range ~100

Phosphor coupled 1:1 to sensor

Phosphor gain >> 1

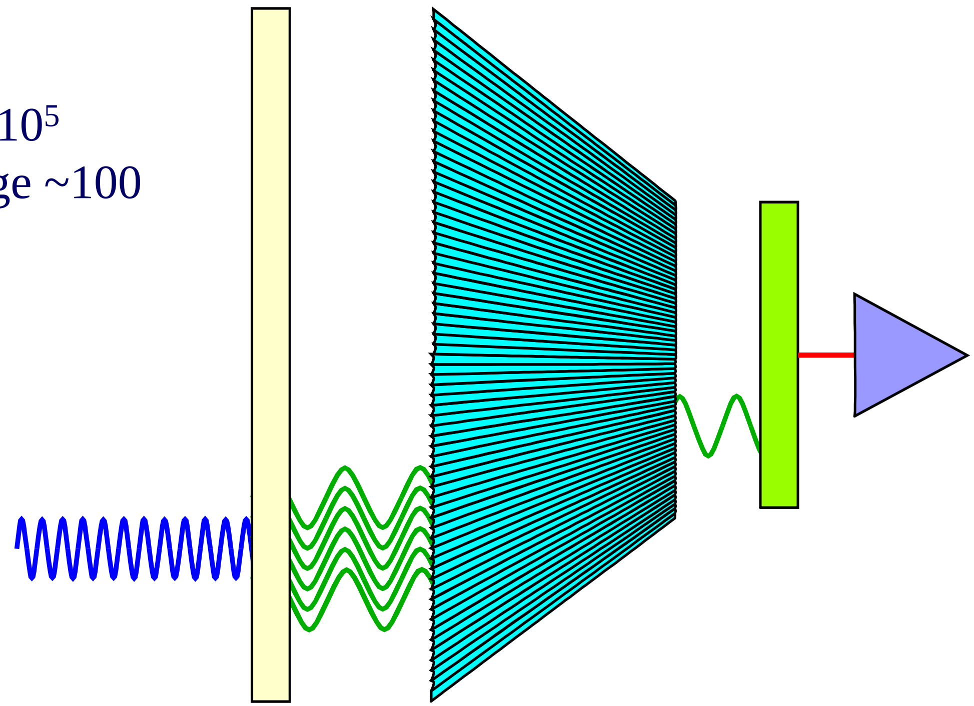
Optics Gain < 1



Phosphor coupled with reducing optics to sensor

Phosphor gain >> 1

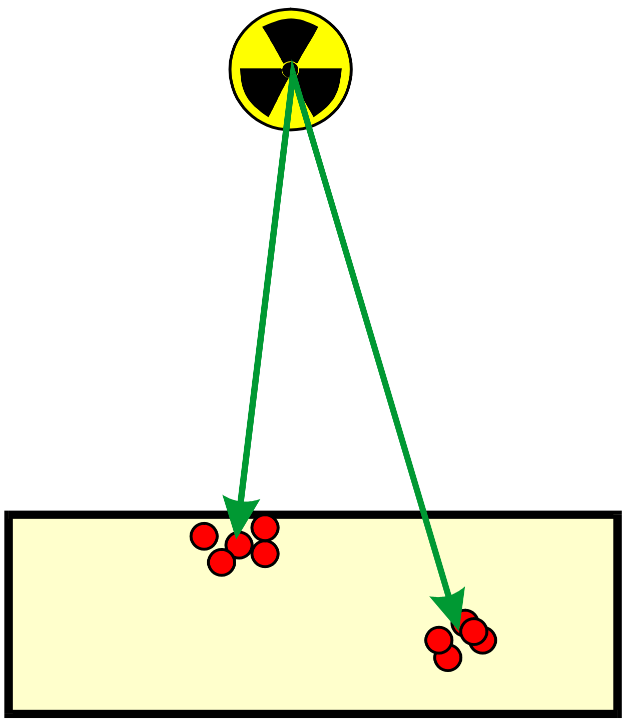
Optics Gain << 1



Computed Radiography-Image Plate

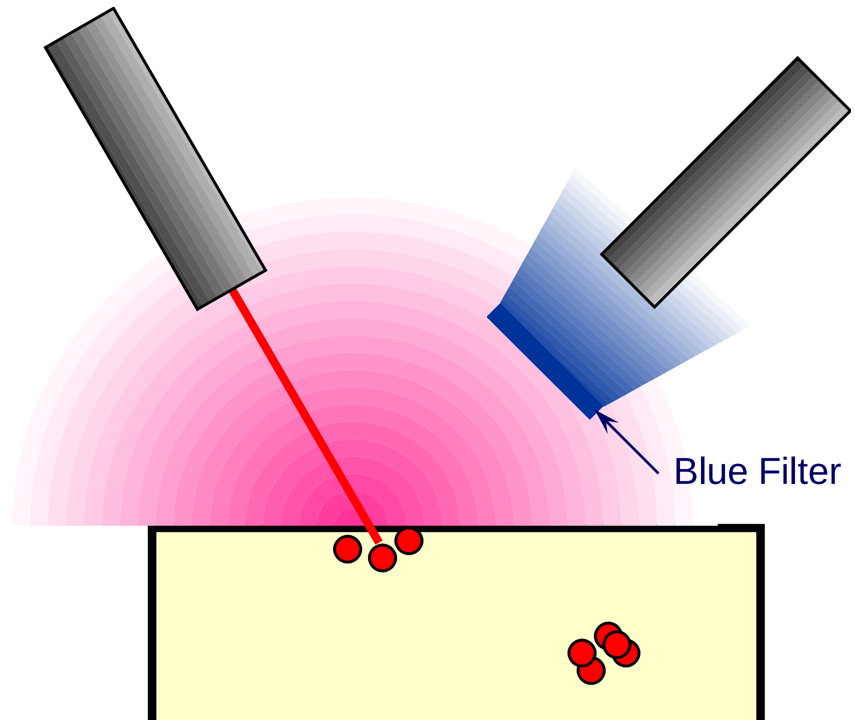
Exposure

Creation of F centres
Gain >> 1

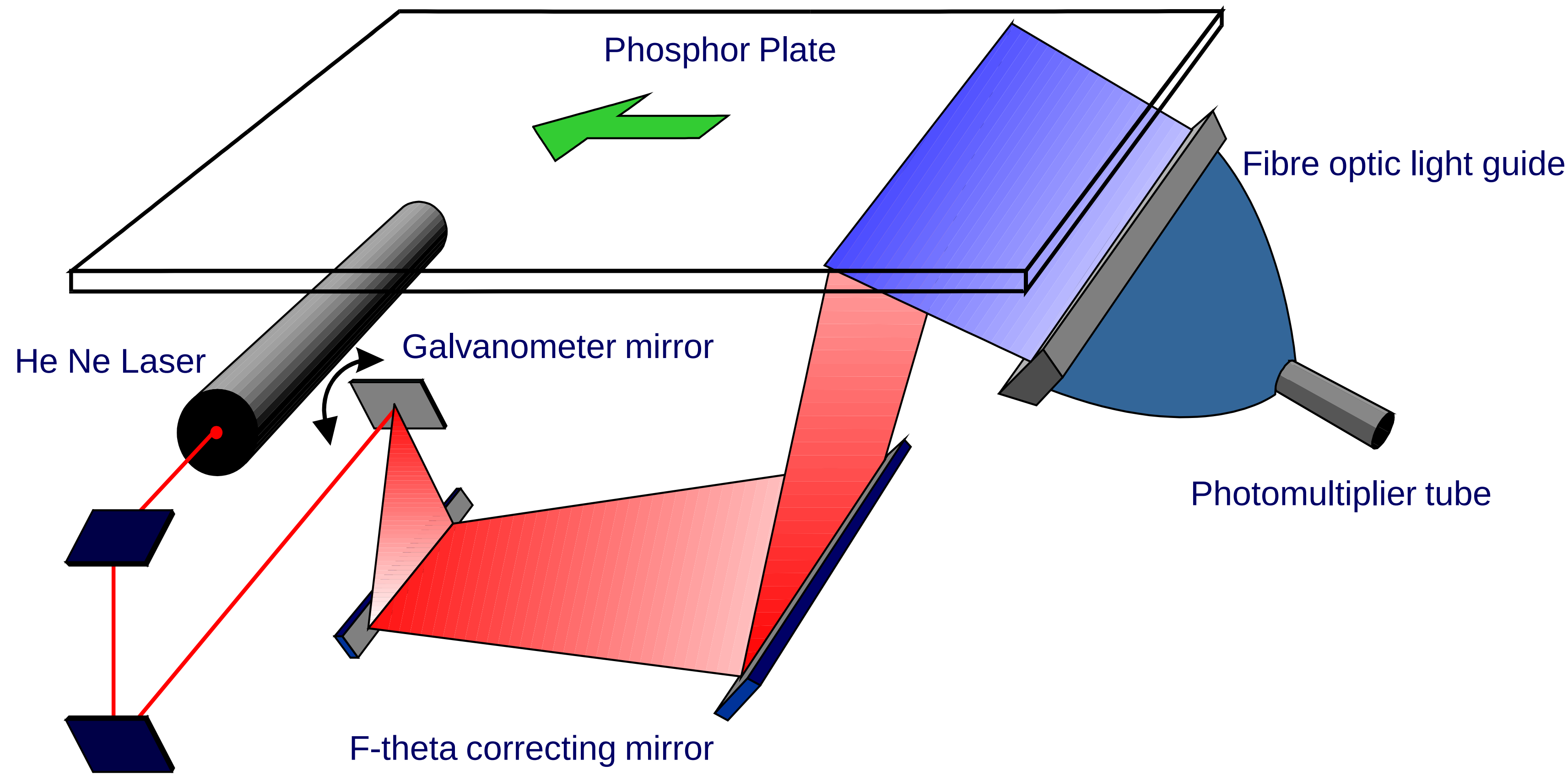


Scanning

Stimulation of PSL	Collection of PSL	PMT Amplification
Gain < 1	Gain < 1	Gain > 1

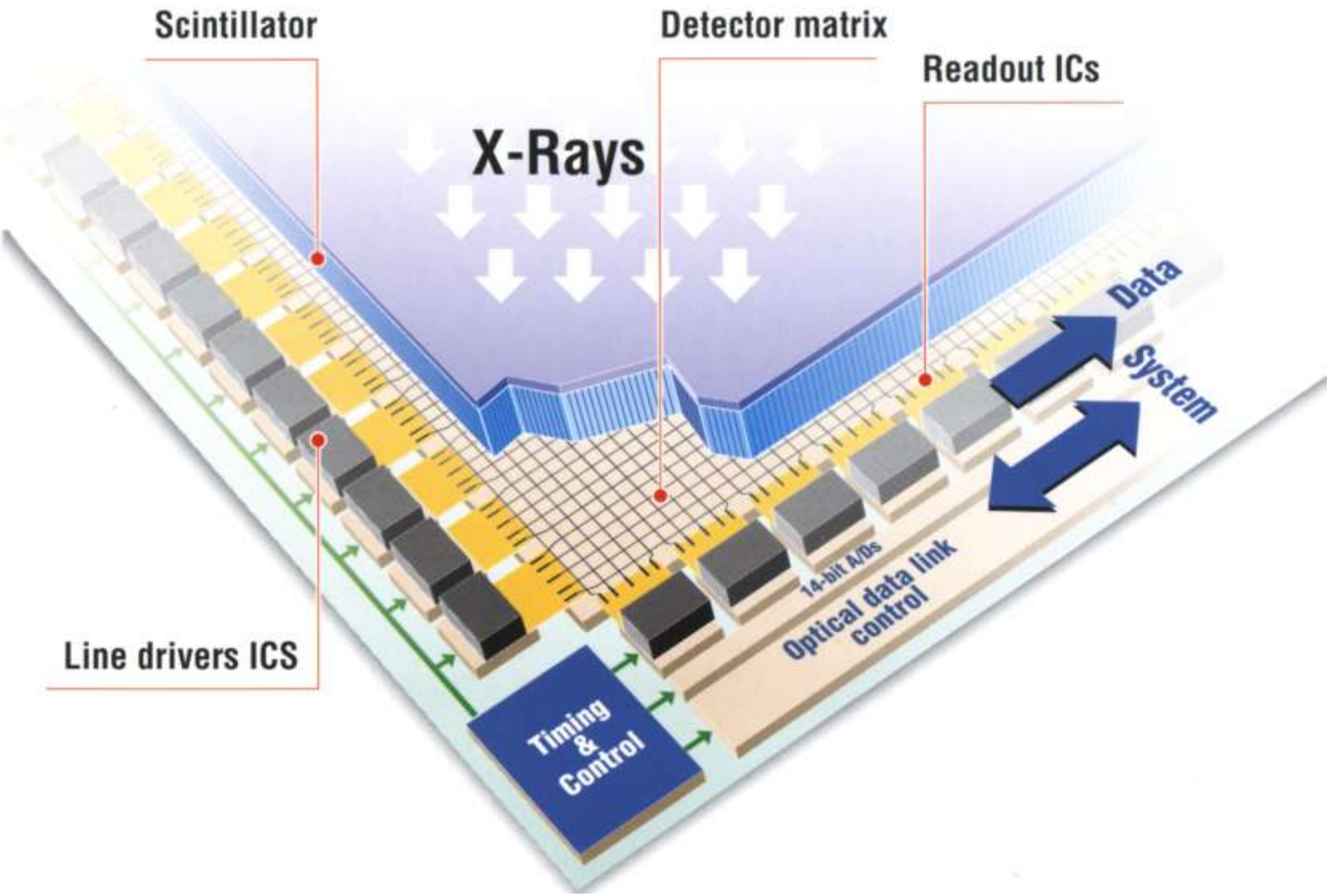


X-Y Flat bed Scanner



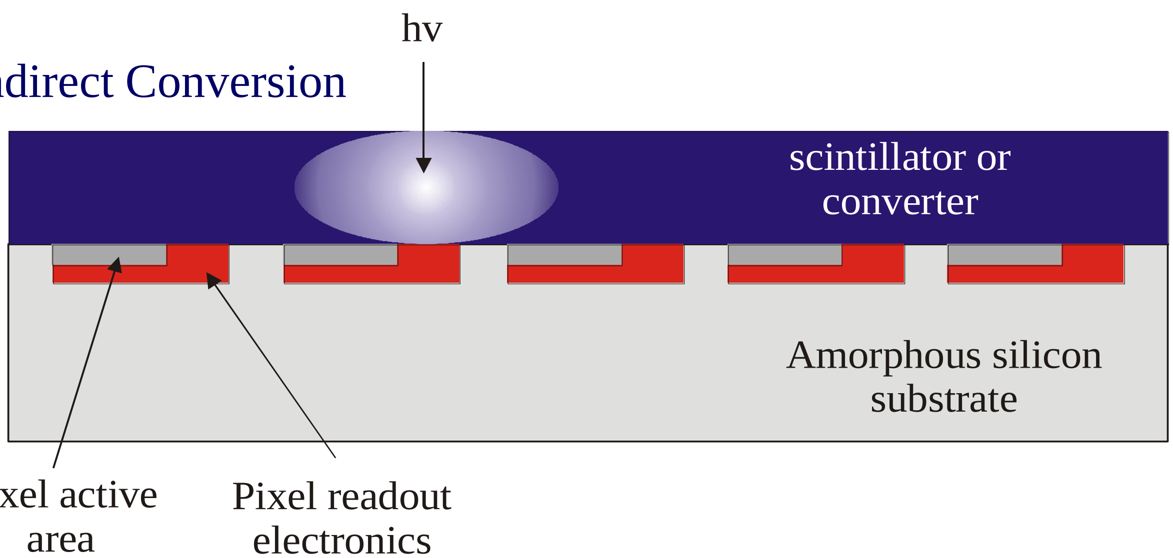
Distributed Light Collection

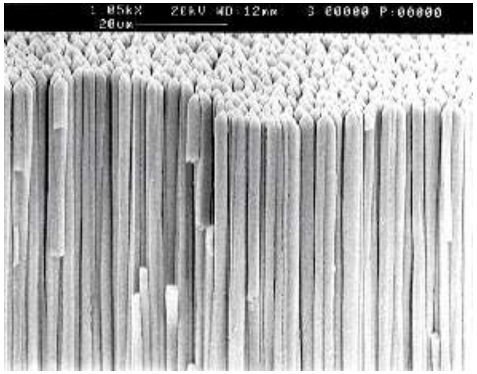
TFT Flat panel Detector



a-Si:H TFT arrays

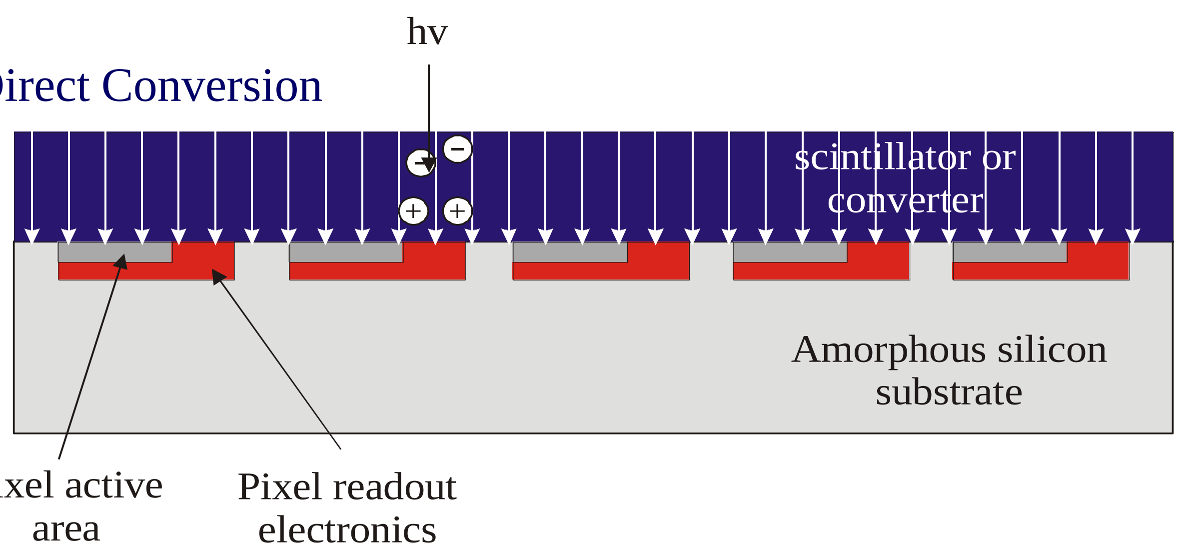
Indirect Conversion



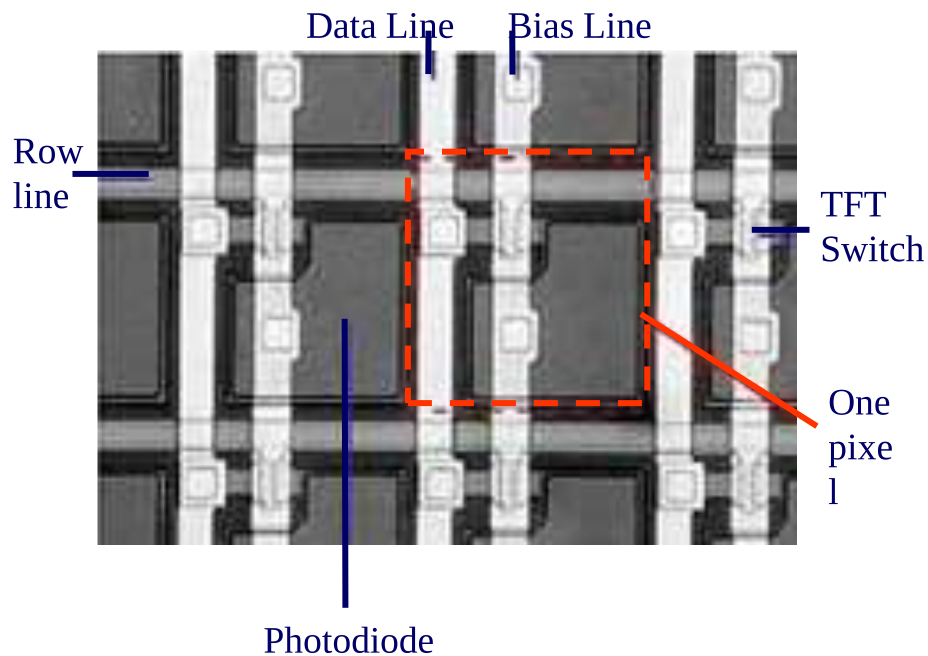


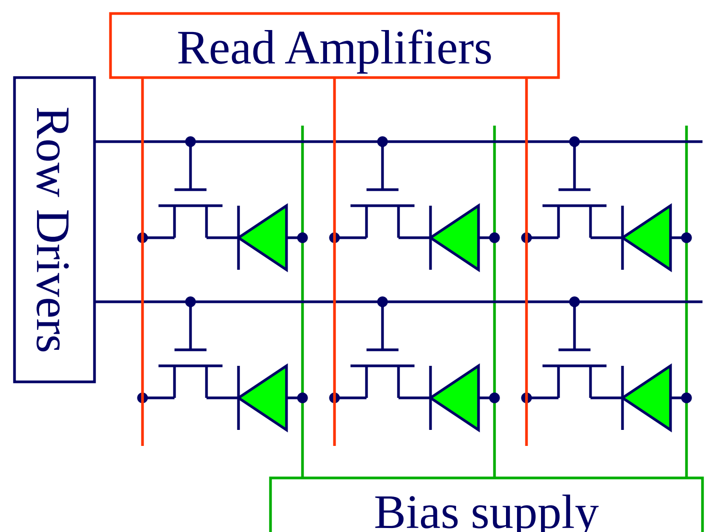
Needle diameter 6μm

Direct Conversion



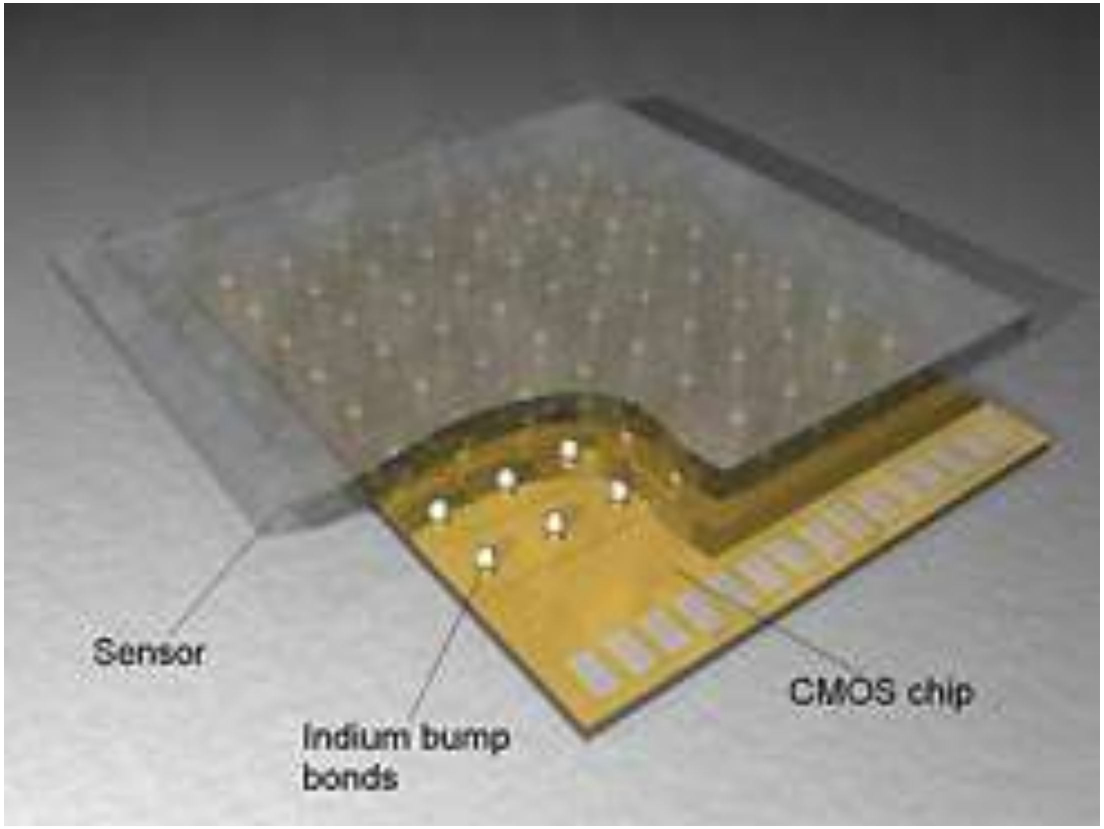
a-Si:H Array dpiX - Flashscan 30





PILATUS 6M Detector

DECTRIS
Next Generation X-Ray Detectors



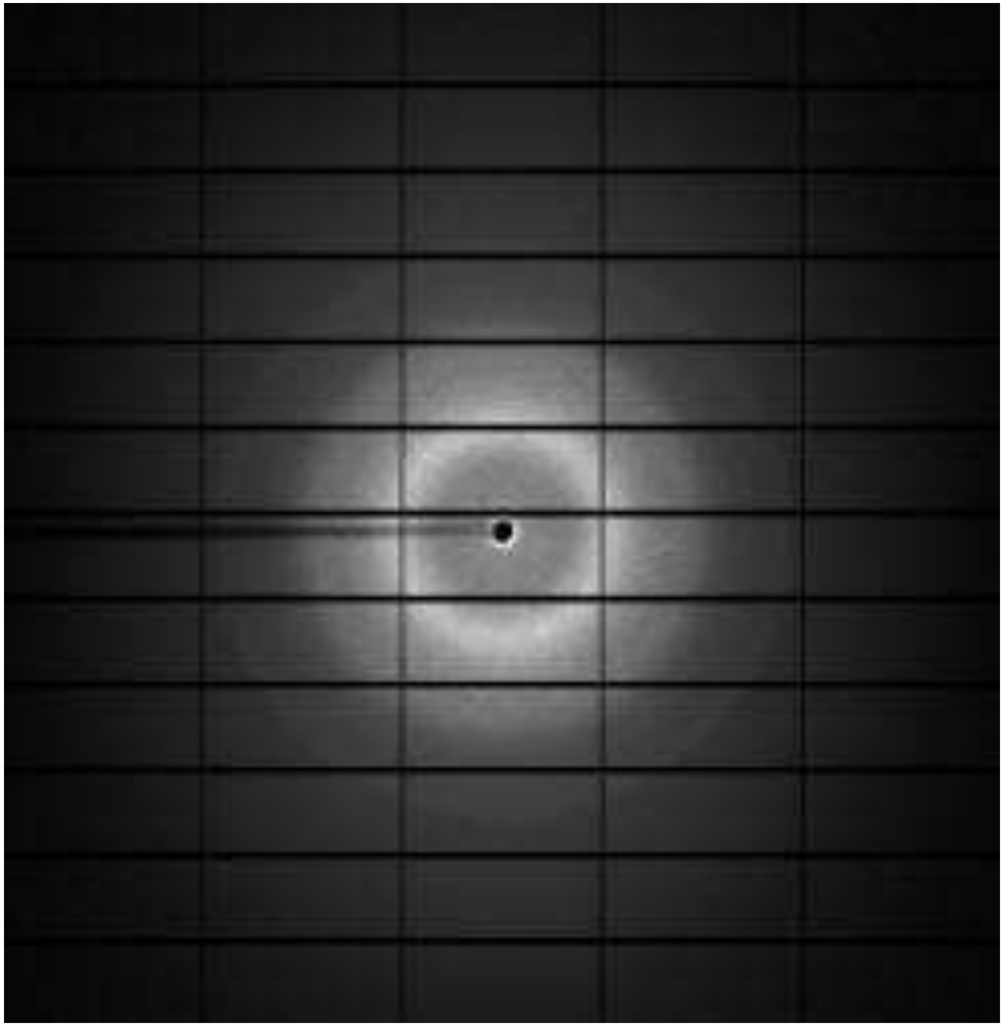
Ch. Brönnimann, E. Eikenberry, B.Schmitt, M. Naef, G. Hülsen (SLS); R. Horisberger, S. Streuli (TEM); Ch. Buehler (LOG); F. Glaus (LMN); M. Horisberger (LNS)

PILATUS 6M Detector

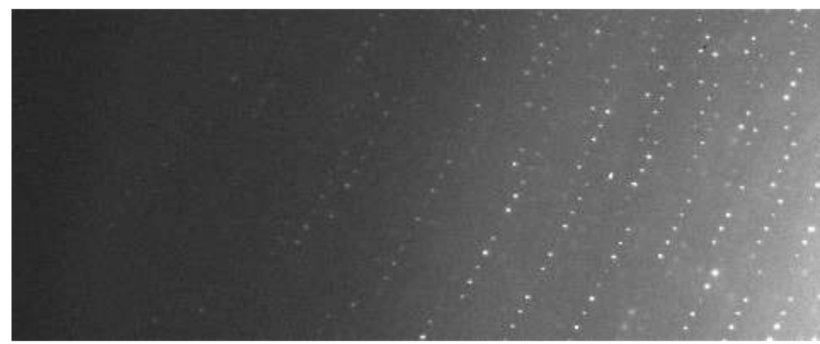
- Sensor 5 x 12 = 60 modules
  - Reverse-biased silicon diode array
  - Thickness 320 µm
  - Pixel size 172 x 172 μm^2
- 2463 x 2527 = 6,224,001 pixels
- Area 431 x 448 mm^2
- Intermodule gap x: 7 pixels, y: 17 pixels, 8.4% of total area
- Dynamic range 20 bits (1:1,048,576)
- Counting rate per pixel > 2 x 10^6 X-ray/s
- Energy range 3 – 30 keV
- Quantum efficiency (calculated)
  - 3 keV: 80%
    8 keV: 99%
    15 keV: 55%
- Energy resolution 500 eV
- Adjustable threshold range 2 – 20 keV
  Threshold dispersion 50 eV
- Readout time 3.6 ms
- Framing rate 12 Hz
- Point-spread function 1 pixel

PILATUS 6M Detector

DECTRIS
Next Generation X-Ray Detectors



- X-ray diffraction image recorded from a ferritin crystal (energy=16 keV, distance = 204 mm).



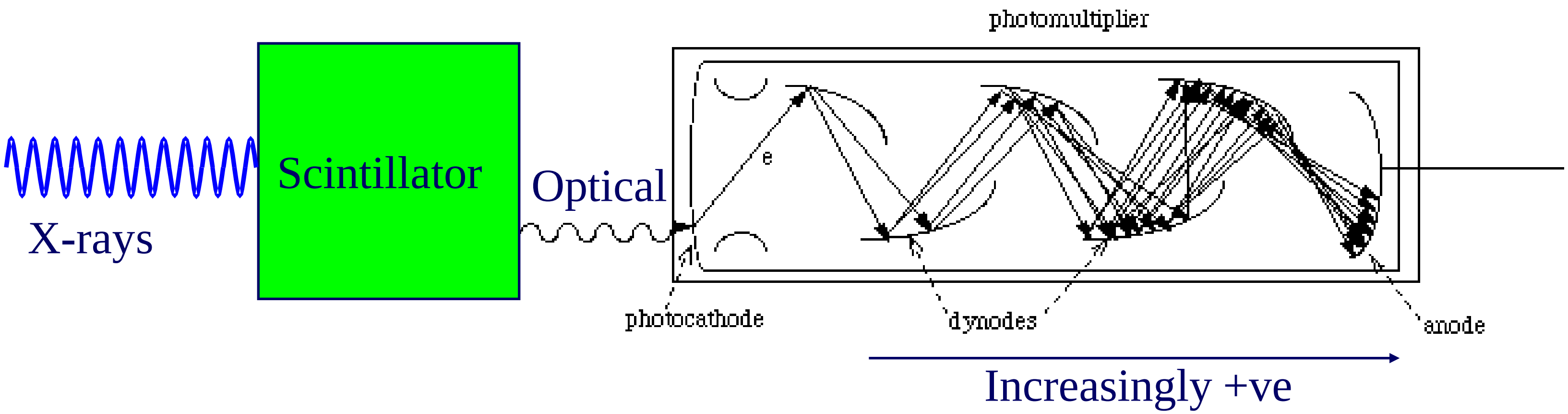
Spectroscopic Detectors

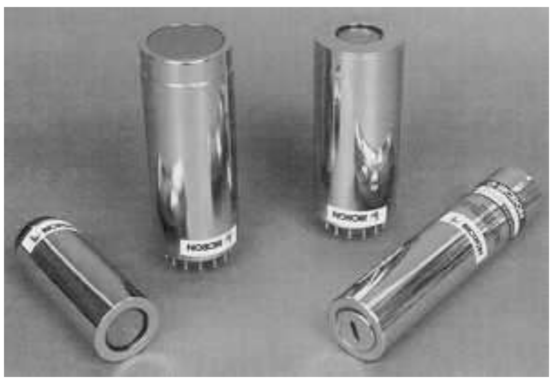
Rainbow Lorikeets

Spectroscopic Detectors

- For quantitative work, most are counting detectors that measure the size of individual energy deposits
- Alternative ids the use of filters as in optical colour cameras

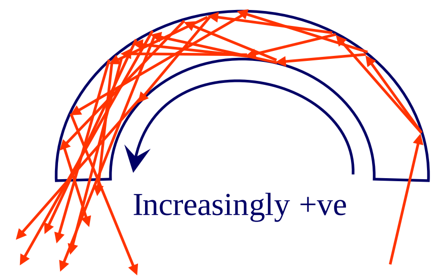
Electron multipliers & Scintillators





Channeltron is a similar with distributed dynode

Micro-channel plates are mutlichannel channeltrons with each channel being an electron multiplier.



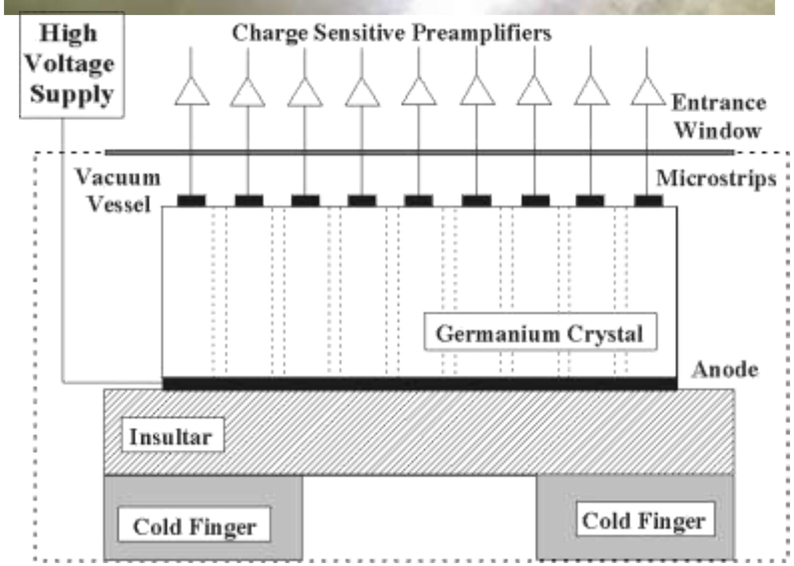
Multi Channel Spectoscopic Detectors

Canberra Ultra-LEGe detector

WRULEAD (Windowless, Retractable, Ultra Low Energy Array Detector) works down to 300eV

Multichannel devices up to 30 channels at 3×10^{5} cts s^{-1} channel^{-}1 have been built

SPring-8 128 channel Ge strip



- Ge
  - 55.5×50.5×6mm
- Strips
  - Number 128
  - Width 300μm
  - Interstrip 50μm
  - Length 5mm
- Readout
  - Single channel 100ns
  - 32 channels 3.2ms
- Max expected count rate
  - 14kcps

Spectral Resolution

- Average number of carriers, $N = E/w$

  where w is energy to create electron hole/ion pair
- Poisson statistics $\sigma = 1/\sqrt{N}$

  $$= (E/w)^{-½} = (w/E)^{½}$$
- $\Delta E/E$ fwhm $= 2.355\sigma$

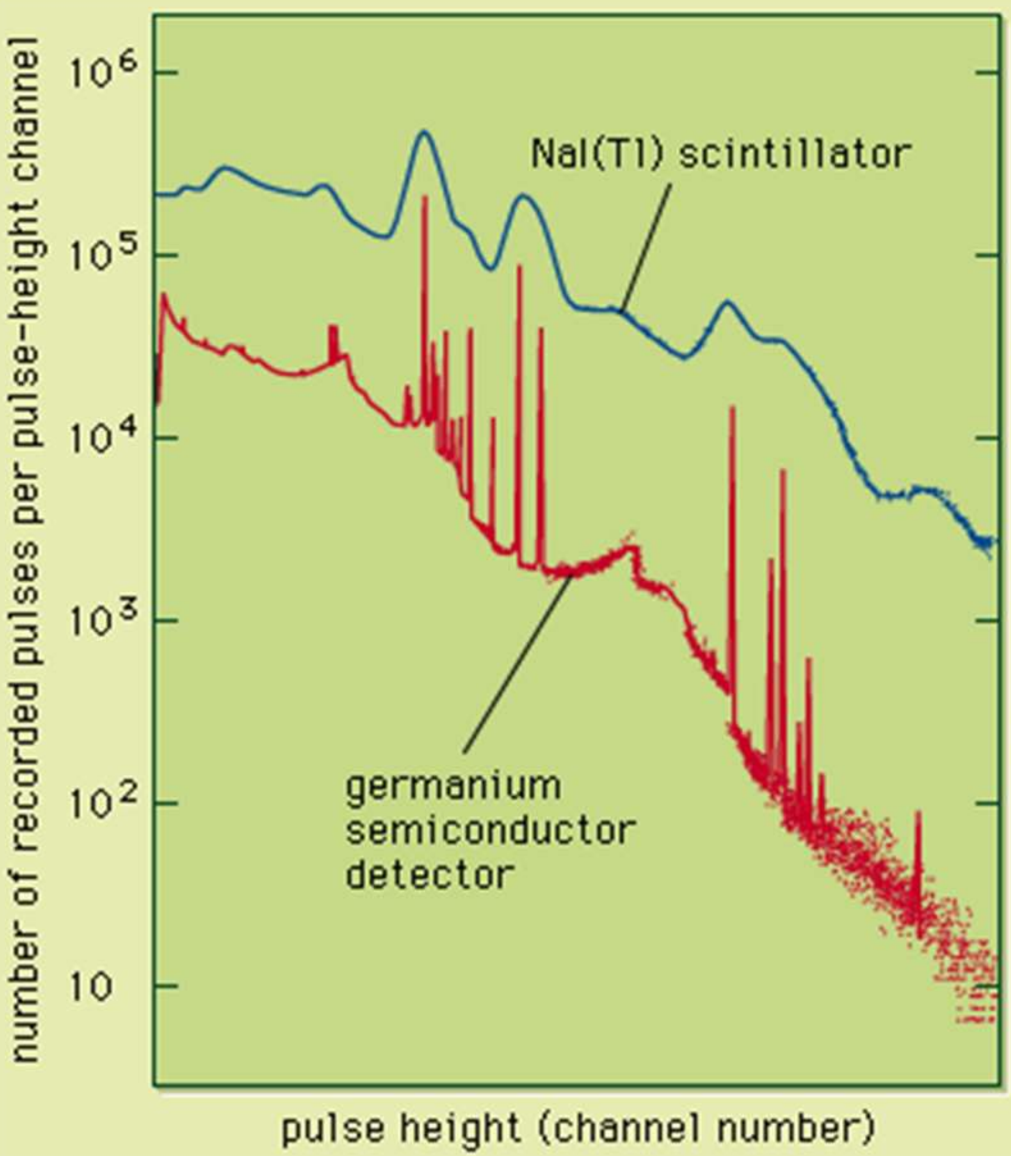
  $$= 2.355(w/E)^{½}$$

- For Ge, w = 3eV so at 10keV $\Delta E/E \sim 4\%$
- For NaI, w = 30eV so at 10keV $\Delta E/E \sim 13\%$

Fano Factor

- If all energy from photon or particle were converted into carriers there would be no variance
- Poisson statistics assume only a small fraction of energy goes into charge creation
- Reality is somewhere in between so we introduce Fano factor F
- Fano factor is defined as $$F = \frac{\sigma^2}{\mu}$$
  where σ^2 is the variance and μ is the mean number of carriers
- For a Poisson process, the variance equals the mean, so $F = 1$
- Examples
  - Si: 0.115
    Ge: 0.13
    GaAs: 0.10
    Diamond: 0.08
- Observed relative variance = F x Poisson relative variance

Scintillator vs Germanium

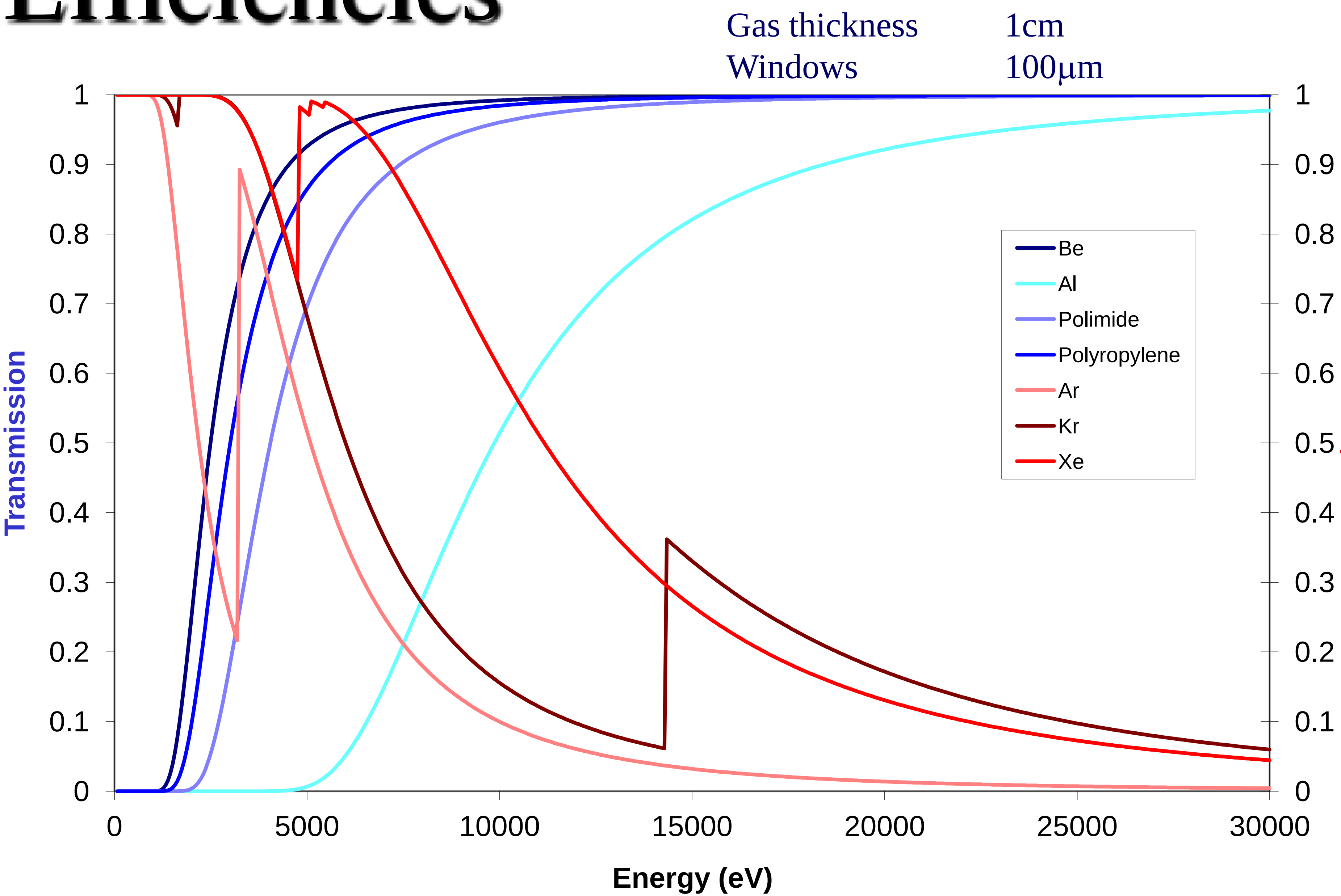


The top spectrum is from a scintillation detector, and the bottom is from a germanium semiconductor detector. The superior energy resolution of the germanium is evident from the much narrower peaks, allowing separation of gamma-ray energies that are unresolved in the scintillator spectrum.

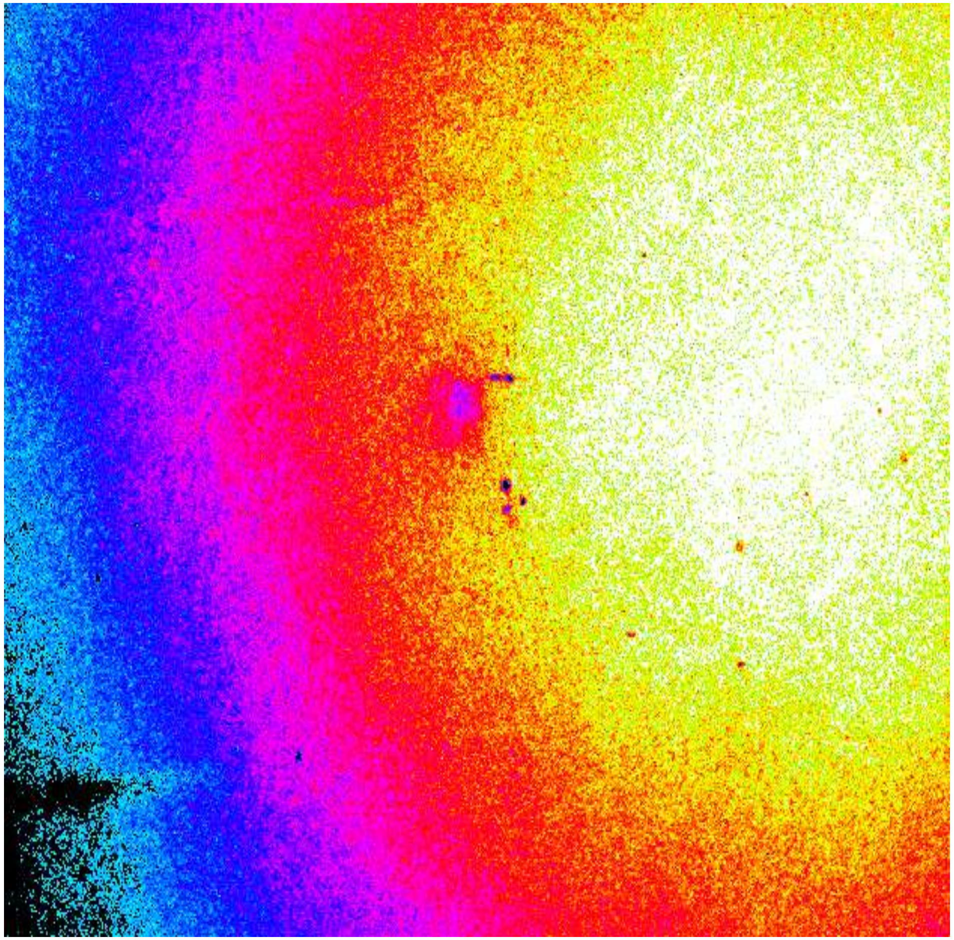
Things to Look Out For

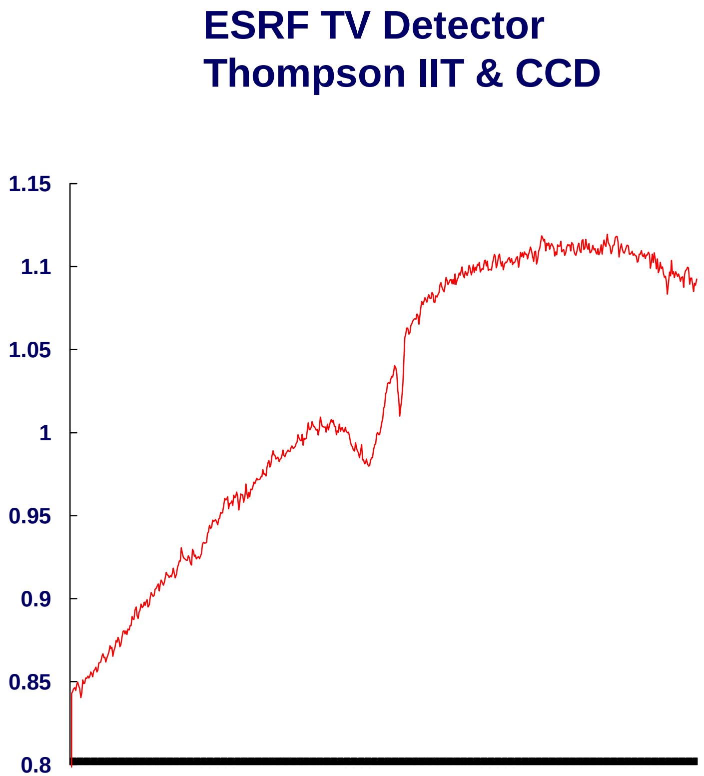
Crocodile

Efficiencies

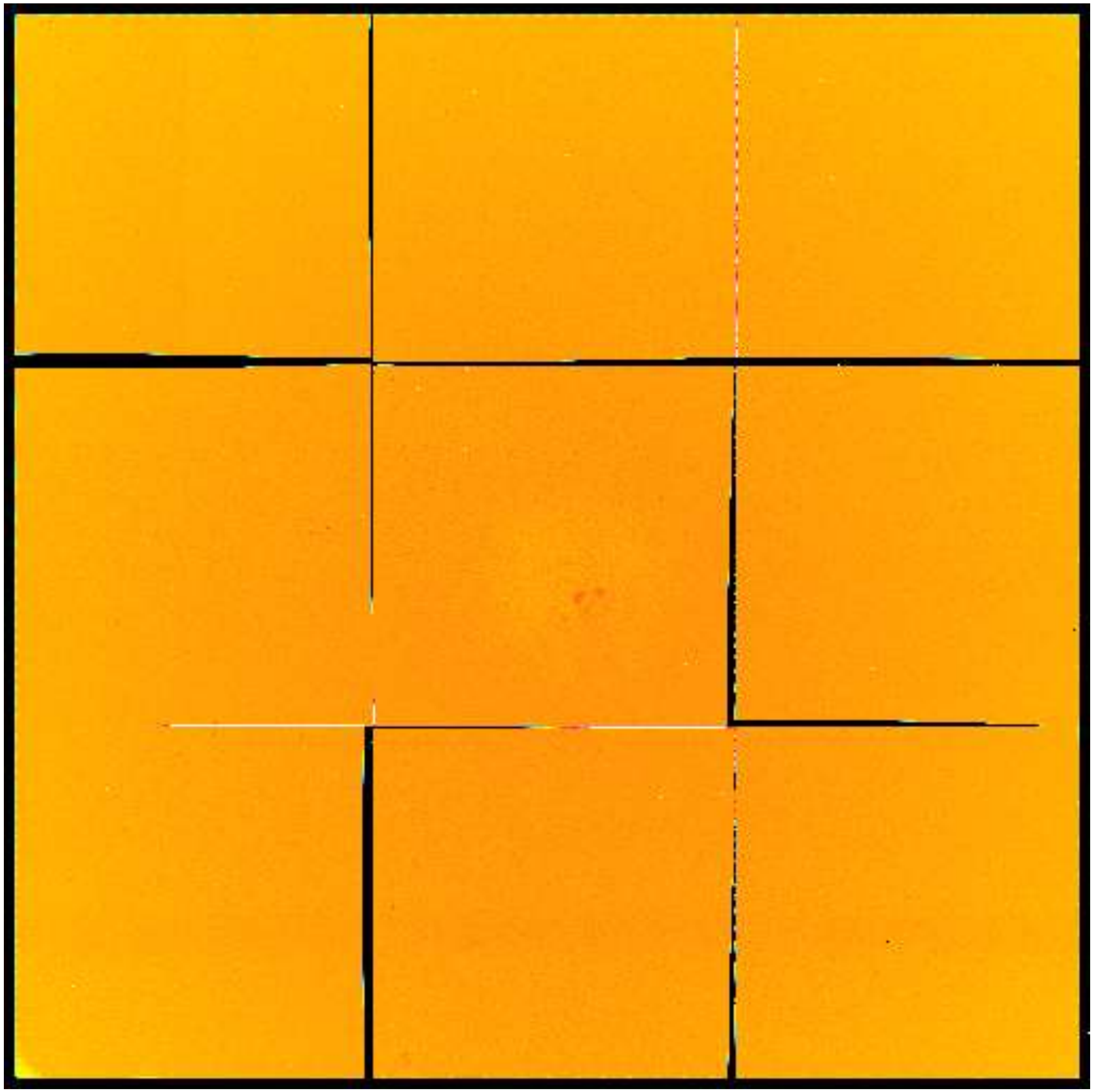


Response to Uniform Illumination



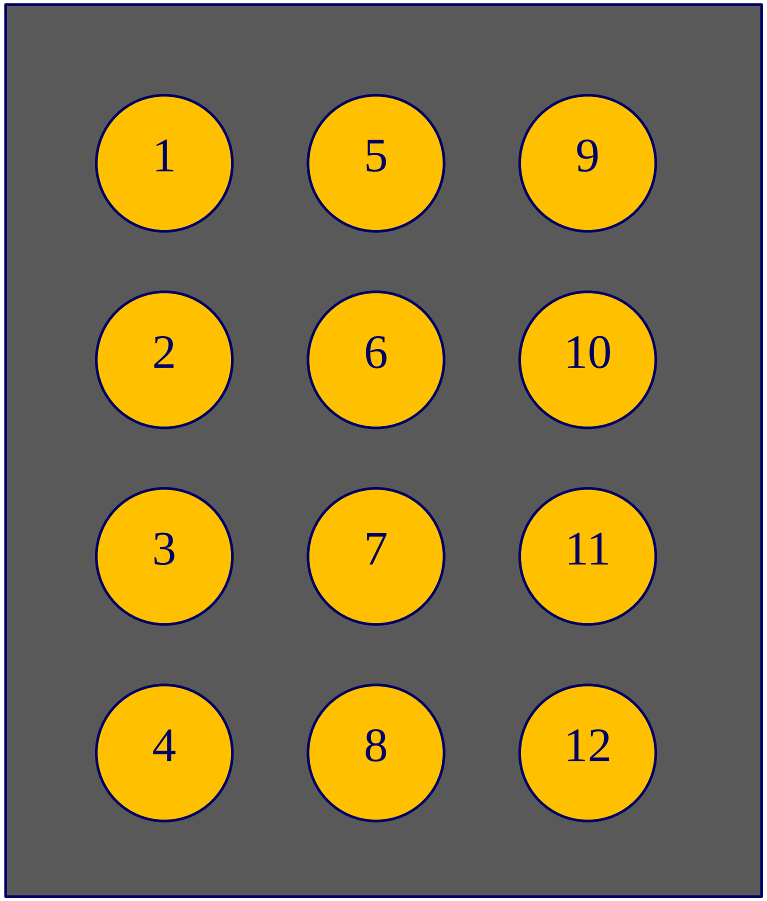


Gaps



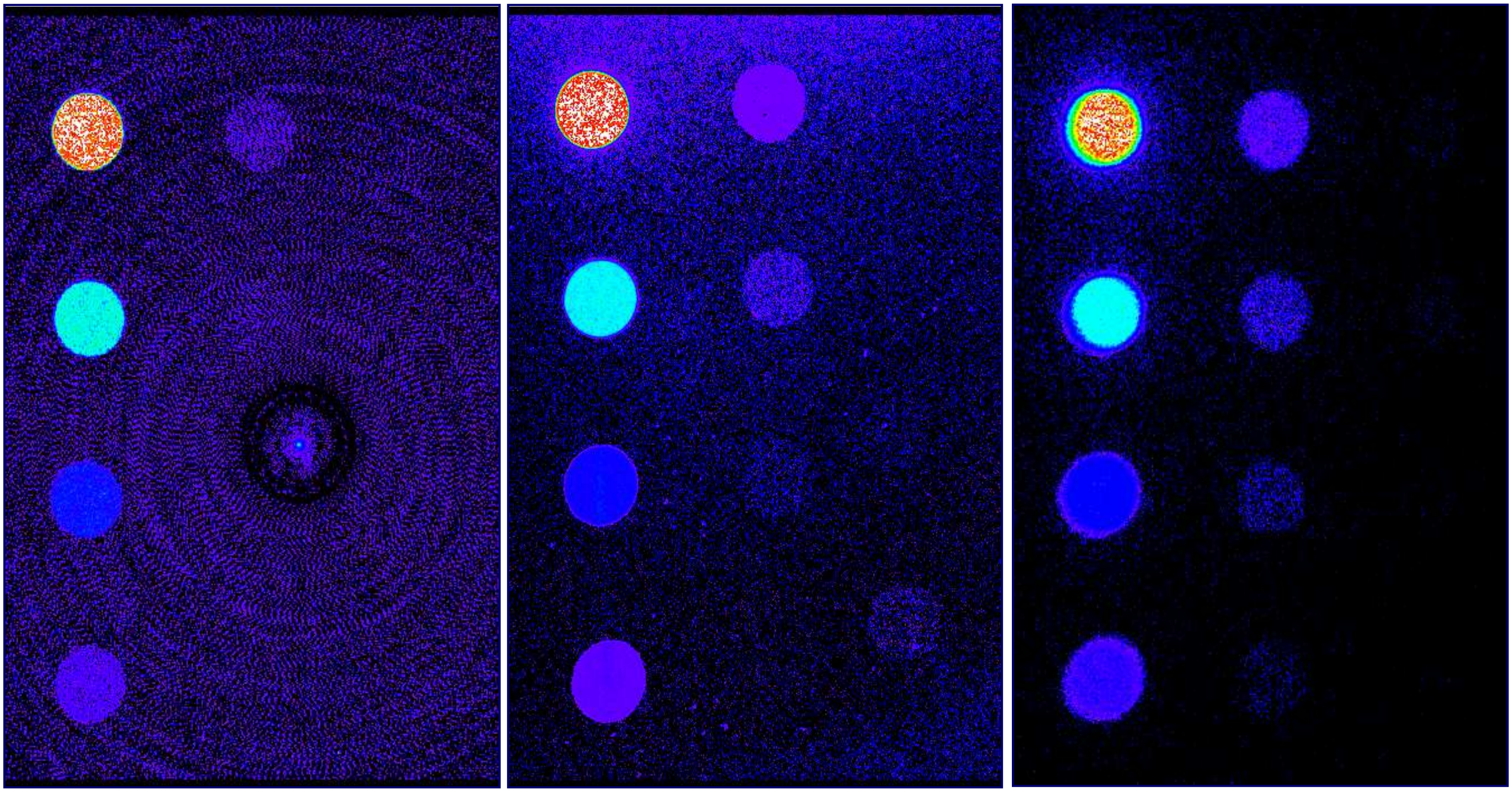
Spec	**0.2mm max**
Worst gap	**2.97mm**
Pixels in gaps	**513922** **5.45%**

Intensity Test

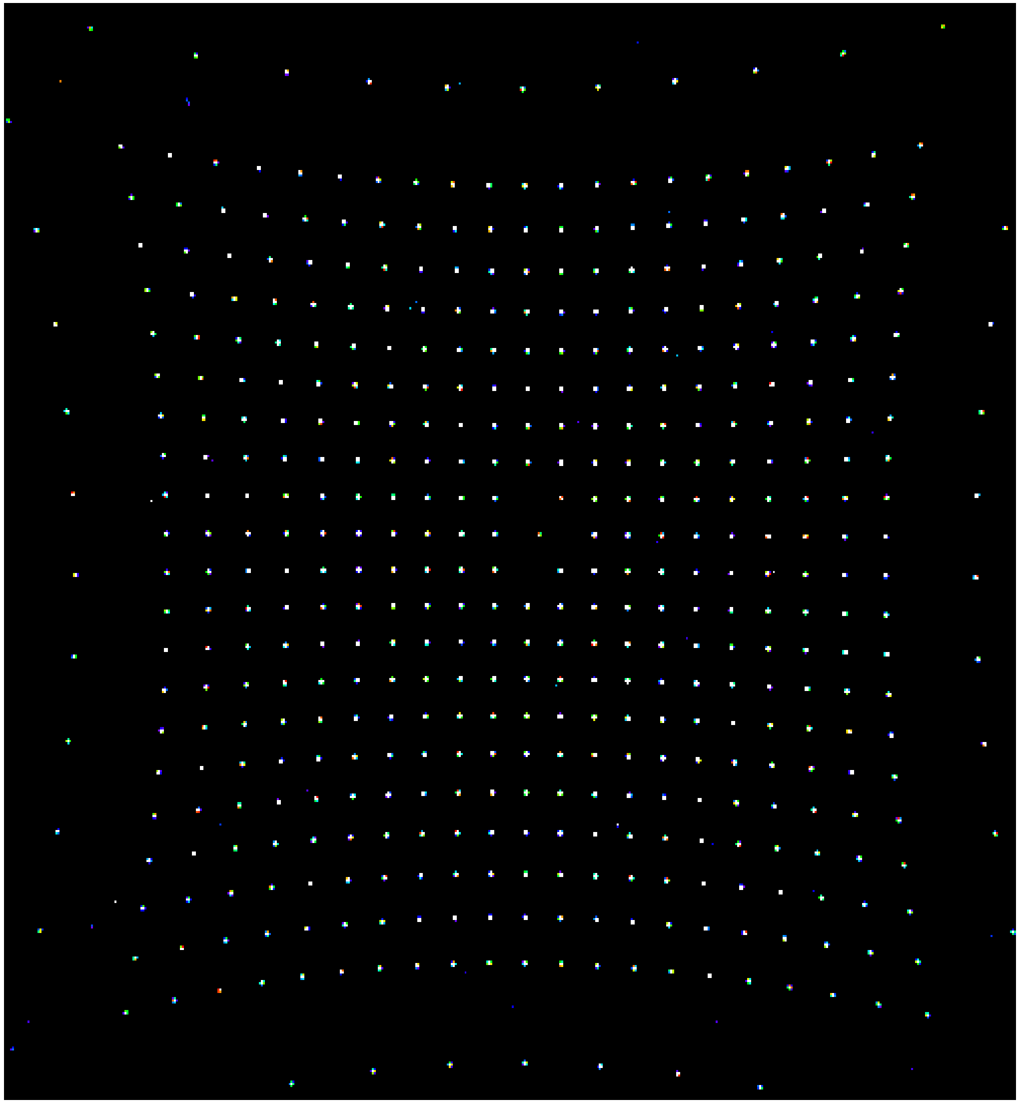


Graded Absorber Comparison

Mar Image Plate | ESRF-Thompson IIT / CCD | Daresbury MWPC

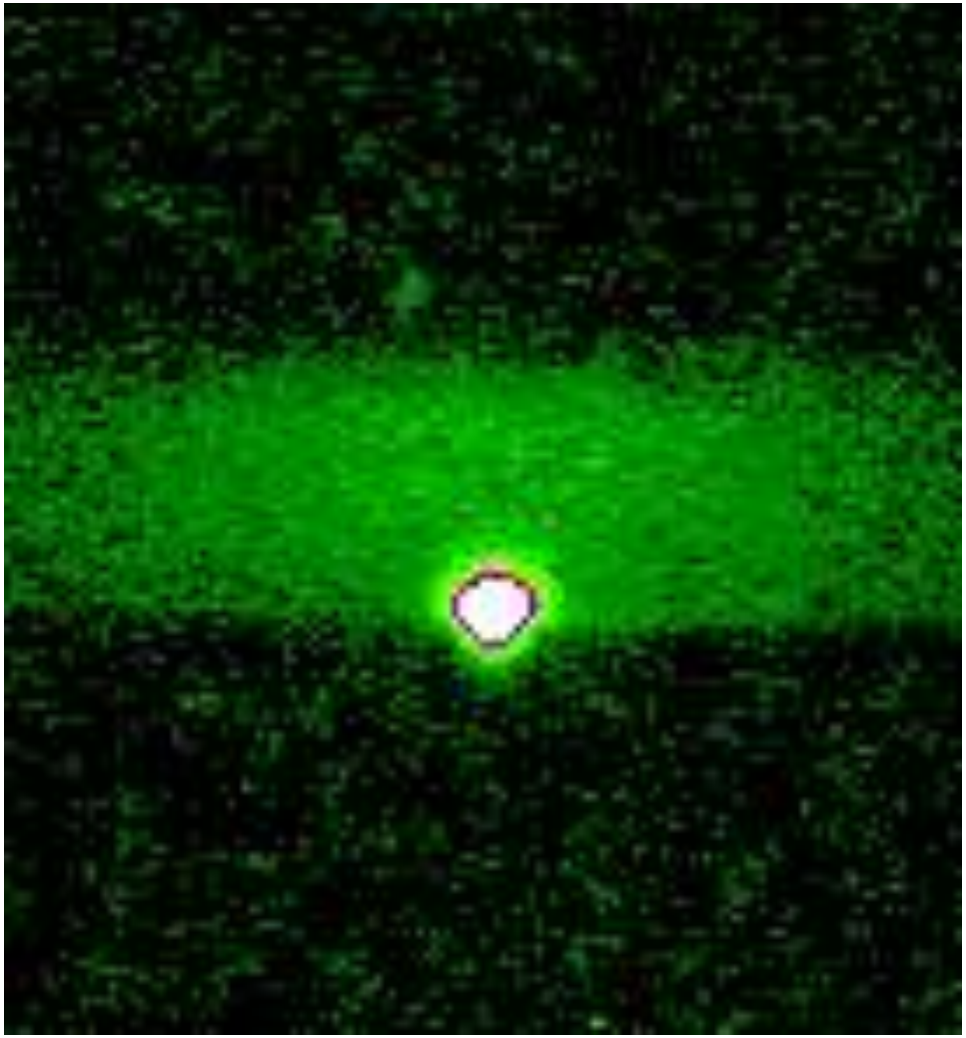


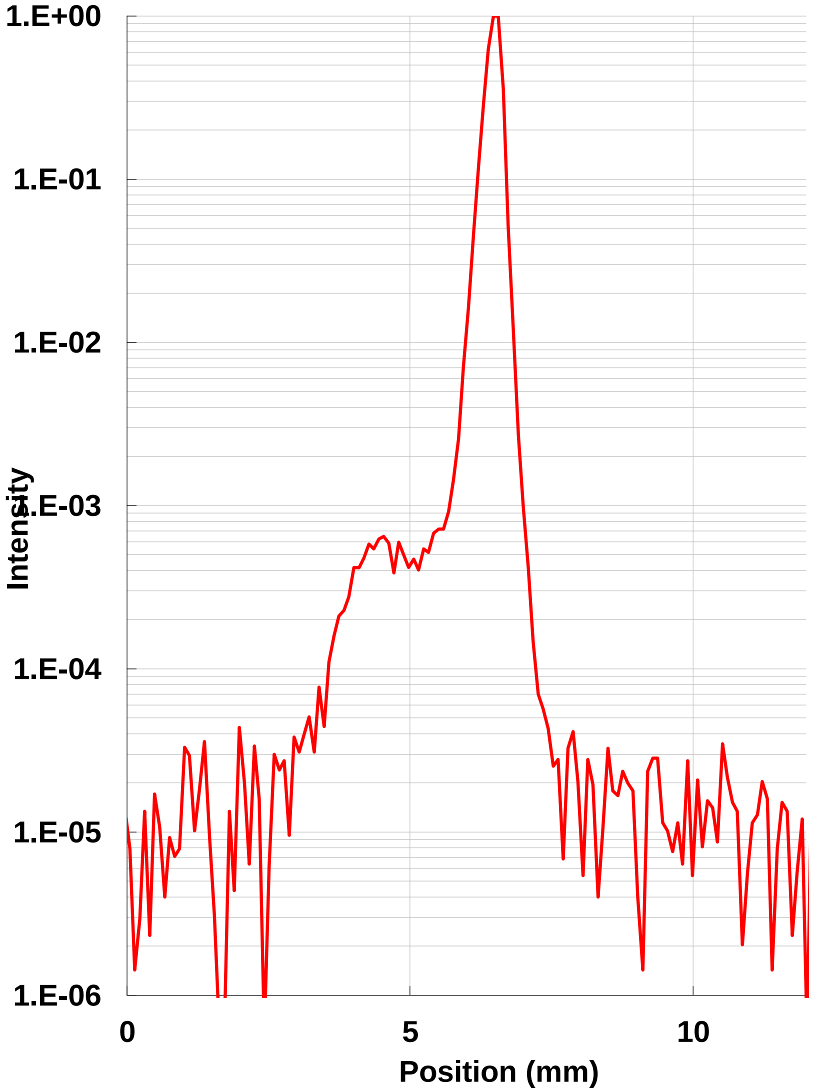
Spatial distortion



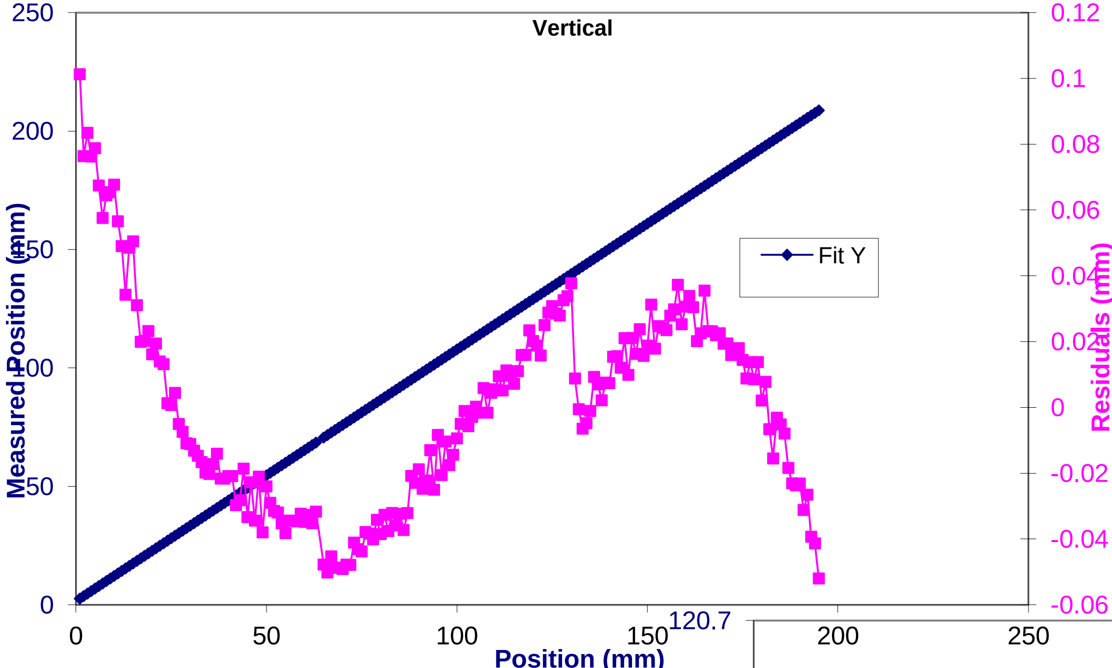
ESRF Image intensifier detector

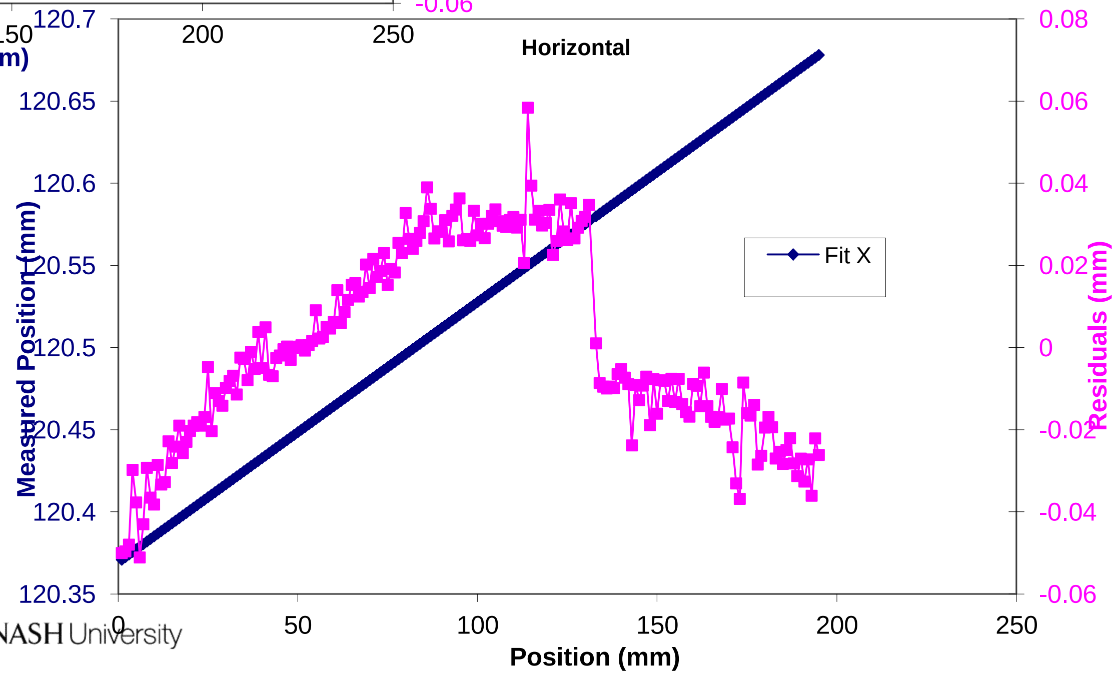
IPlate Single Peak PSF





Geometric Distortion





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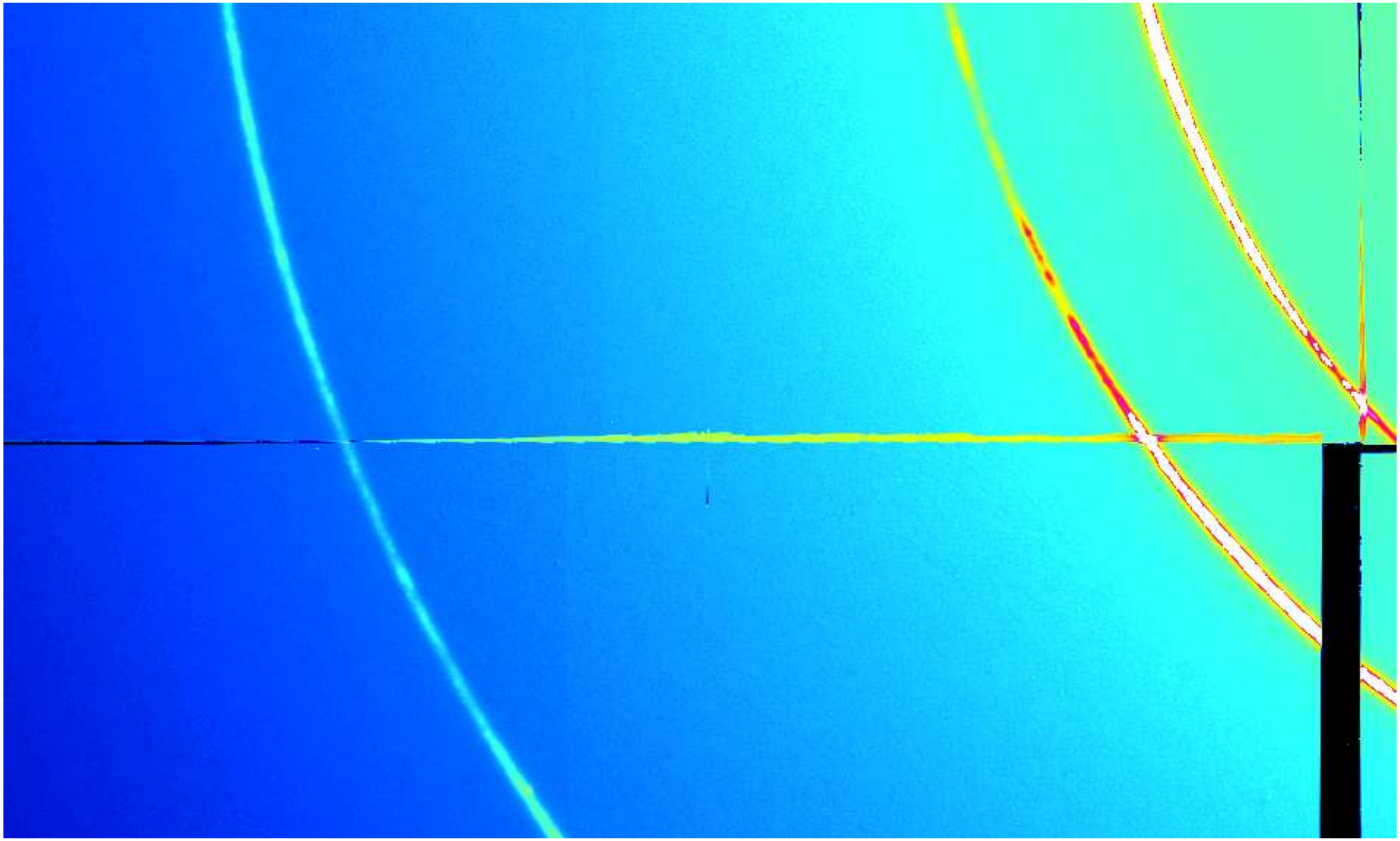
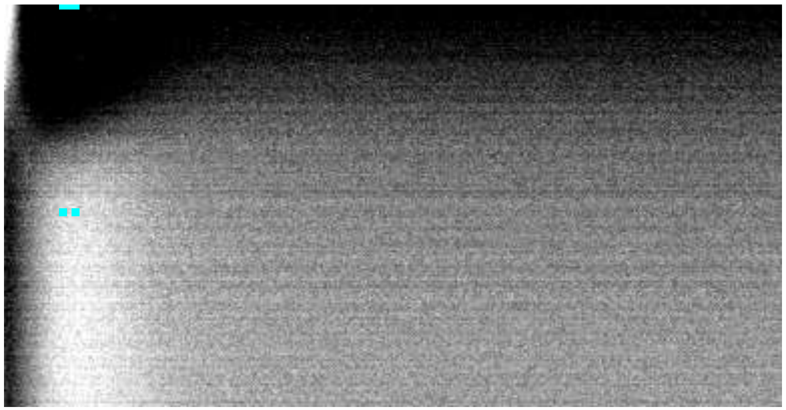
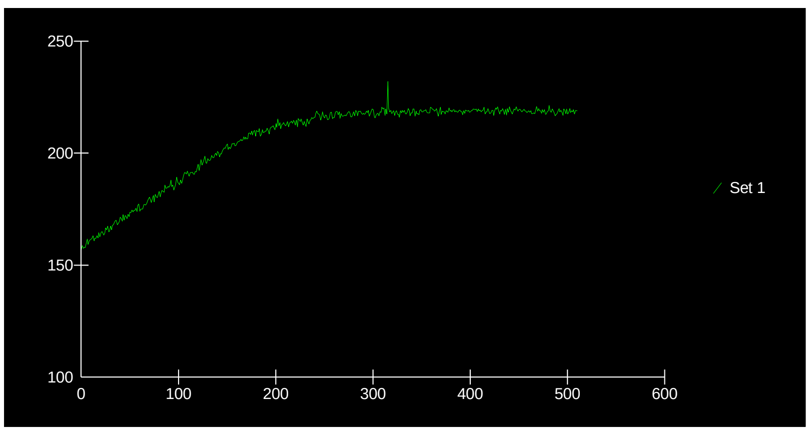
Overlaps



Dark Currents





Flat and Dark Correction

For each image, two correction images must be recorded.

1. A flat field (uniform illumination of the detector)

2. A dark image (no irradiation of detector)

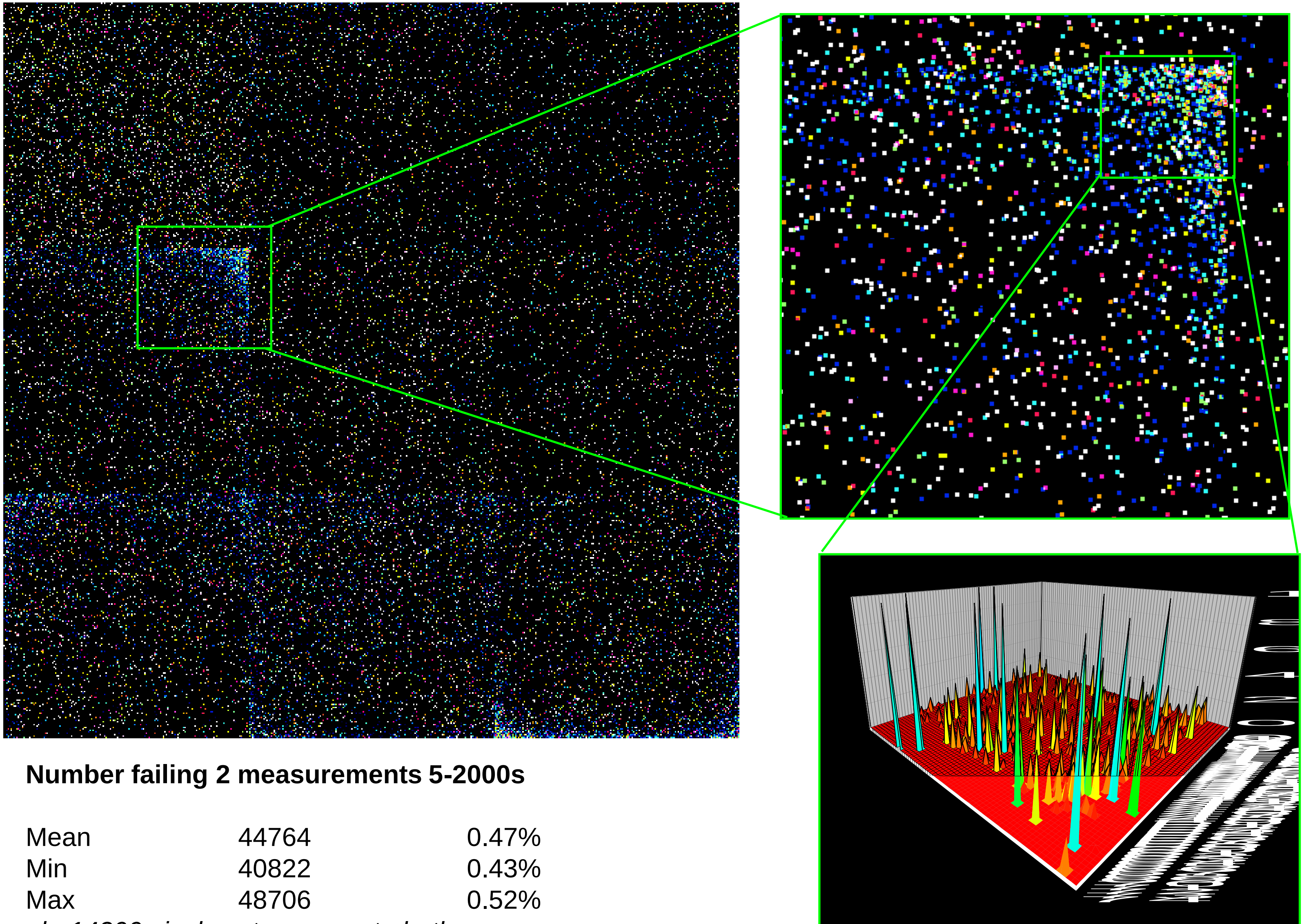
Both must be recorded with the same exposure time as the original image since dark current is a function of exposure time.

Then apply the following correction

$$Corrected = \frac{(image - dark)}{(flat - dark)}$$

Dark Current

Pixels above the 0.2 photons pix^{-1} specification

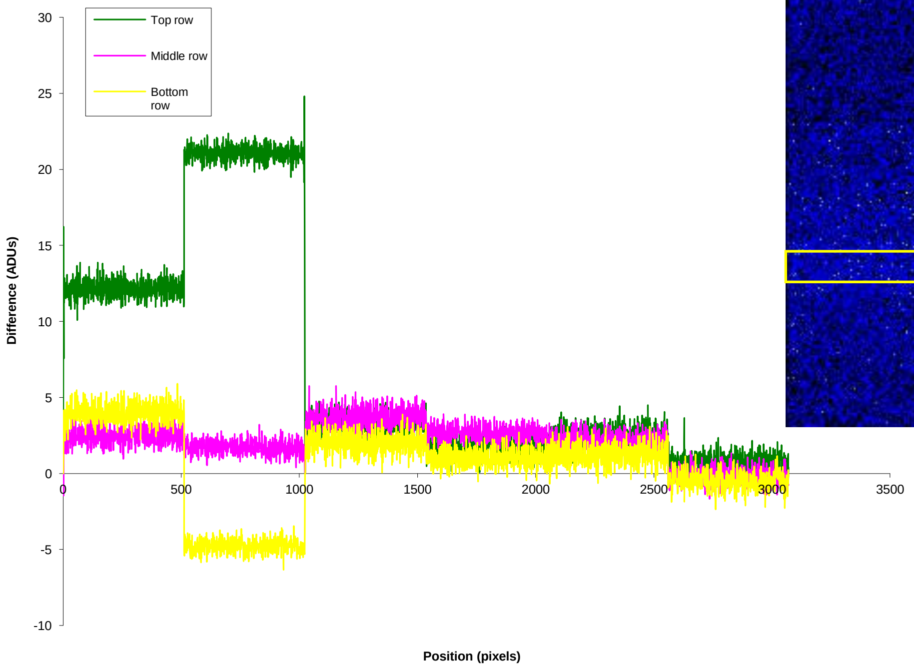


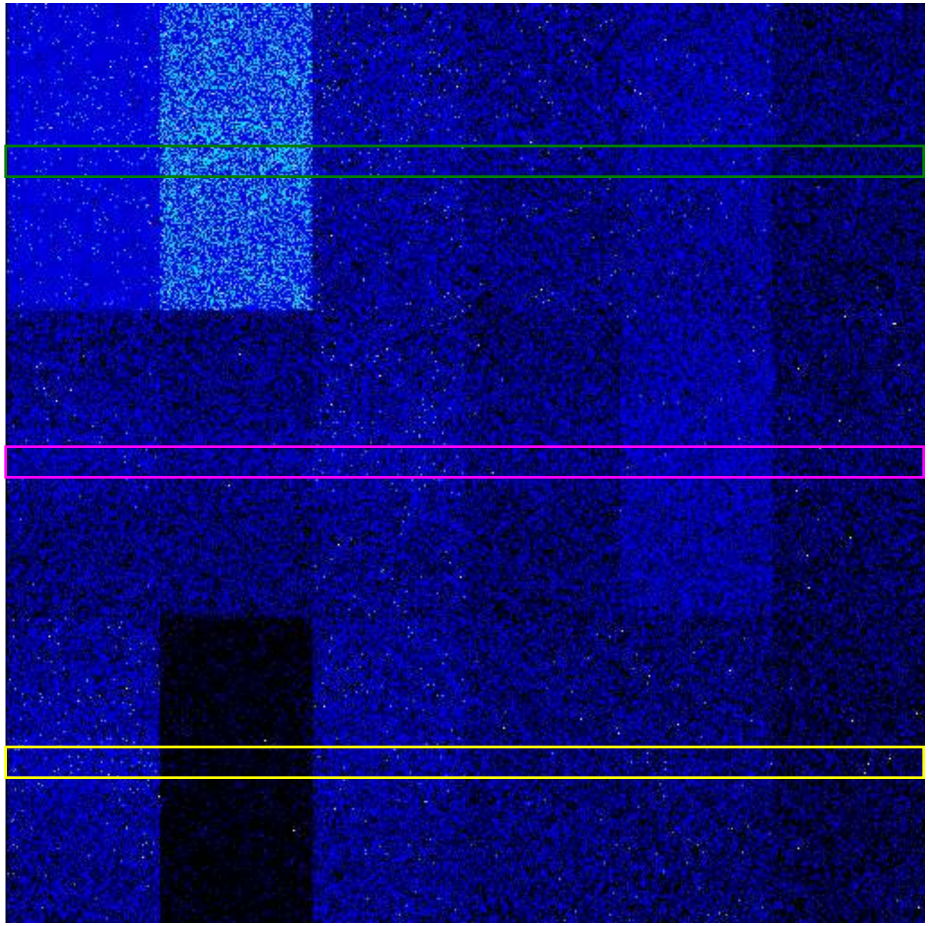
Number failing 2 measurements 5-2000s

Mean	44764	0.47%
Min	40822	0.43%
Max	48706	0.52%

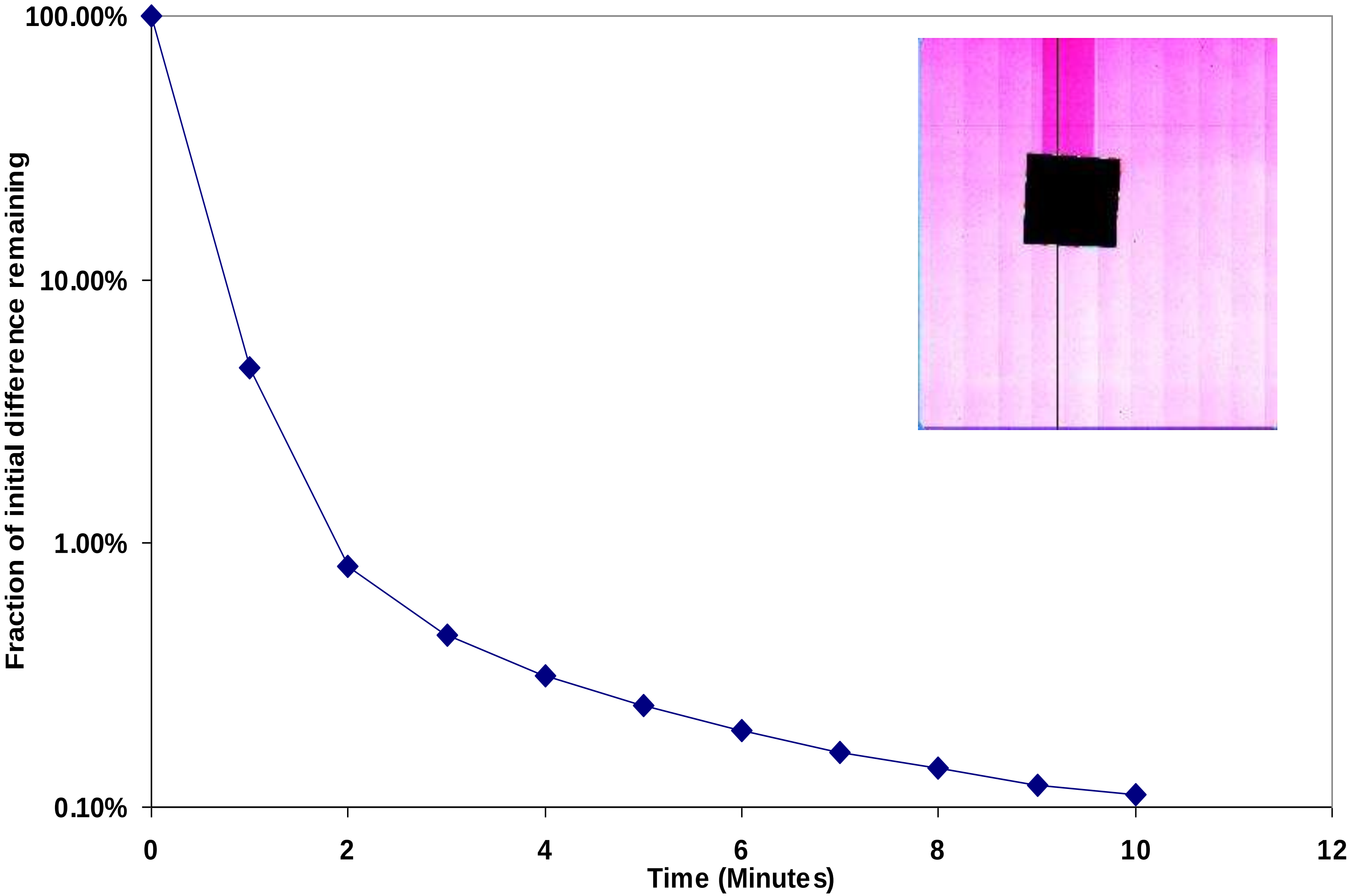
nb. 14300 pixels not common to both

Subtraction of dark images





Flashscan 30 - Image Lag



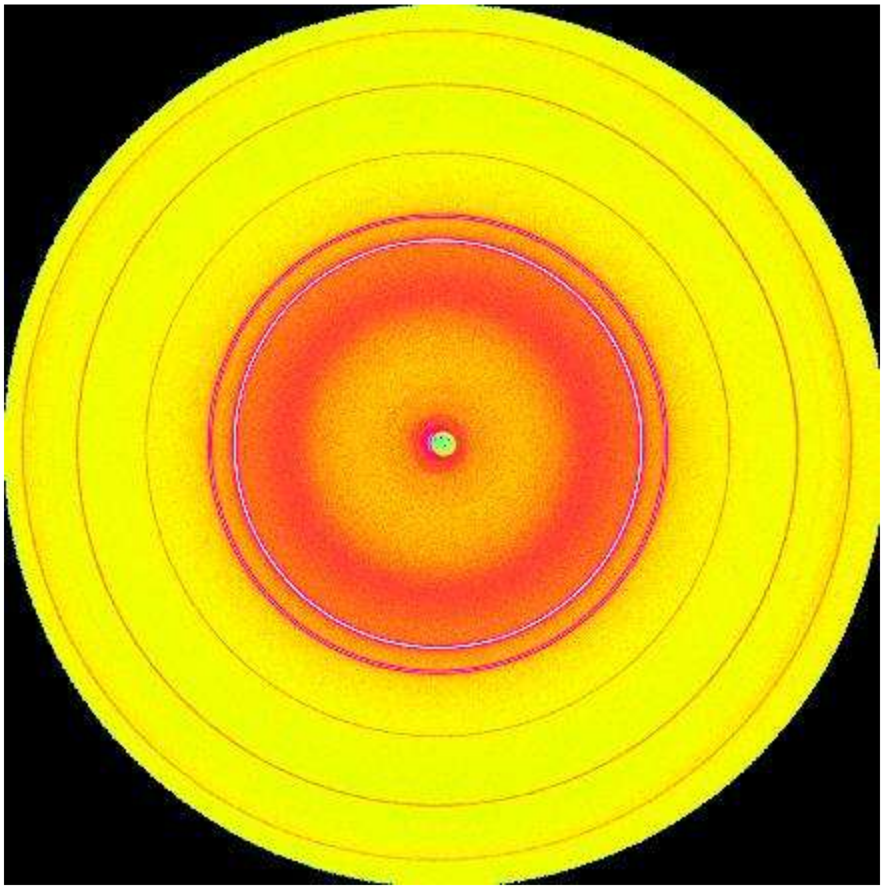
Radiation Damage (Medipix)

- Damage occurred at 40Gy or 1.3×10^{10}pht/mm^2 in the readout chip
- At 13 keV photon energy
  - Strong diffraction spots typically 10^5 phts/s or 10^6 phts/mm2/s
    - Damage requires ~ 8hours exposure
  - Direct beam (10^{10}–10^{13} photons/mm^2/s)
    - Damage in less than a second.

dpiX Flashscan 30 PaxScan 4030

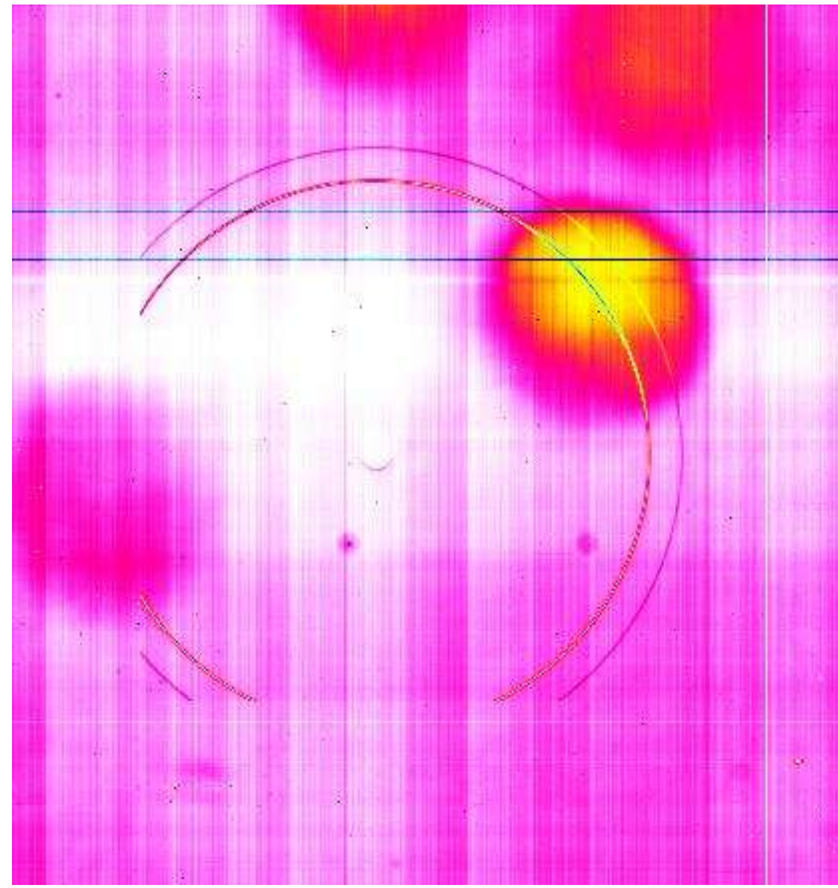
Flashscan 30 - Performance

Mar Image Plate



t_{int}=30s

Flashscan-30



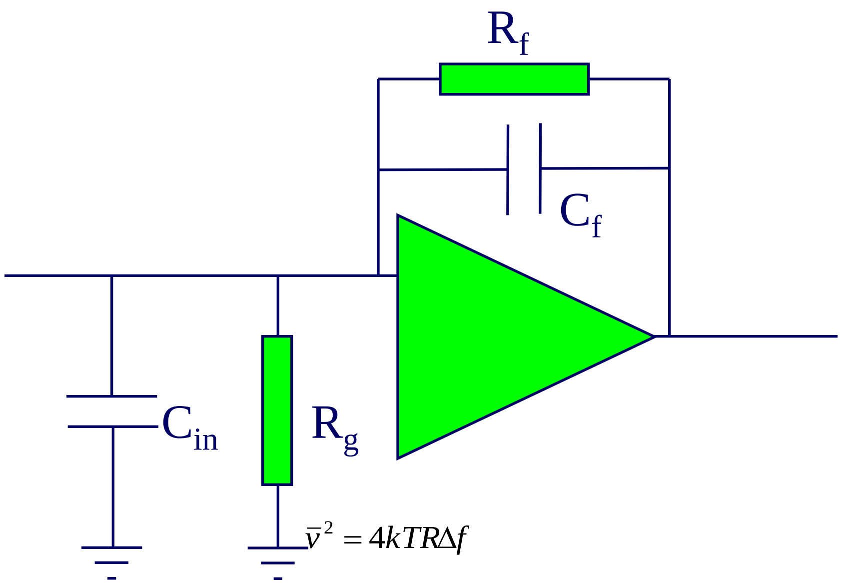
t_{int}=190s

Electronics Issues

Koalas

Albino Kookaburra

Amplification



- Voltage mode
  - Output ∝ input voltage
  - Effect of R_f dominates C_f
- Current mode
  - Output ∝ input current
  - Low input impedance
- Charge mode
  - Output ∝ input charge
  - C_f dominates R_f

- In almost all cases we require amplification
- Amplifier-detector interaction is critical
- Most important element is the input
- Noise is the major issue
  - Thermal or Johnson Noise
    - Brownian motion of electrons
    - No current flow or voltage required
    - White noise
  - Shot Noise
    - Fluctuations in current
    - White noise

$$\bar{i}^2 = 2q_e\bar{I}\Delta f$$

Equivalent Noise Charge

- Introduce ENC which is that signal charge that will produce the same output as the RMS noise

$$ENC^2 = \exp(2)\left[\frac{kT}{2R_g}\tau + \frac{eI_D}{4}\tau + \frac{kT(C_{in})^2}{2g_m\tau}\right]$$

Where

- k = Boltzman's constant
- T = temperature
- e = the electronic charge
- R_g = Load resistance and/or feedback resistance
- g_m = transconductance of input FET. (Links current in to voltage out)
- τ = Rise time of amplifier
- C_{in} = input / stray and feedback capacitance
- I_D = Drain current

- Note that ENC is directly related to energy resolution
- FWHM(keV) = 2.355×10^{-3} ENC/ew where w is the energy per electron

Noise Dependence

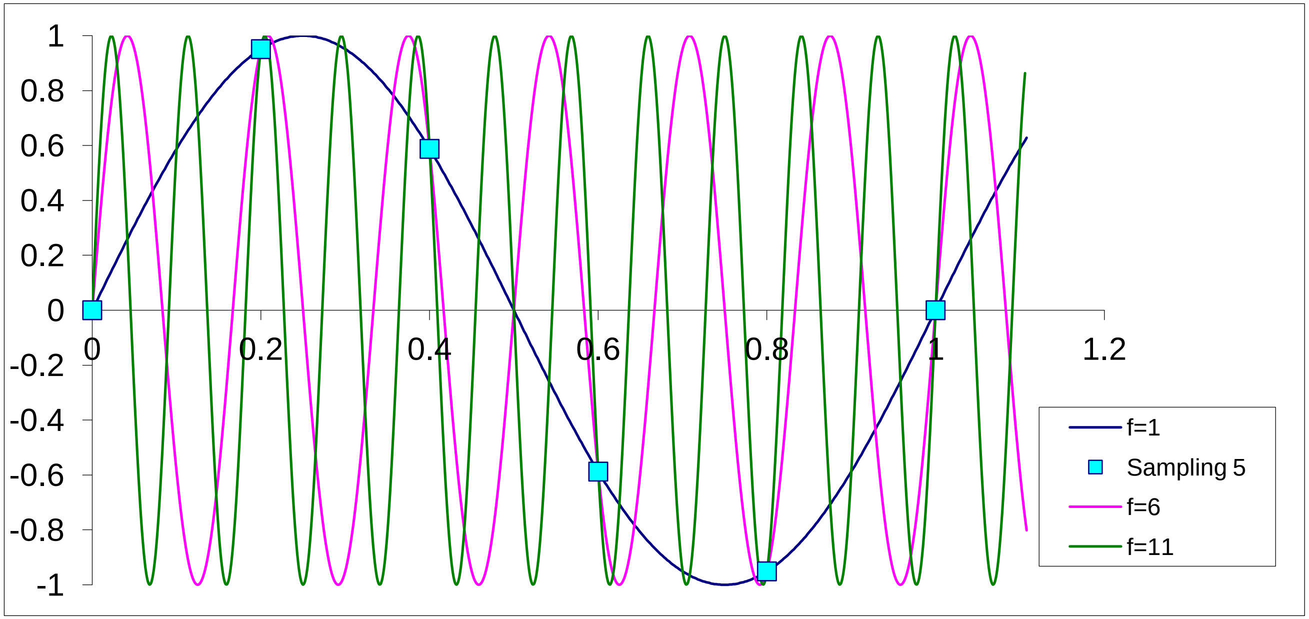
$$ENC^2 = e^2\left[\frac{kT}{2R_f}\tau + \frac{q_e I_D}{4}\tau + \frac{kT(C_{in})^2}{2g_m\tau}\right]$$

- τ optimum at

$$\tau_{opt} = \left[\frac{kT/2g_m}{(kT/2R_f) + (q_e I_D/4)}\right]^2 C_{in}$$

- Choosing optimum τ gives best noise performance but may not be fast enough
- We often have to sacrifice energy resolution for speed

Sampling & Aliasing

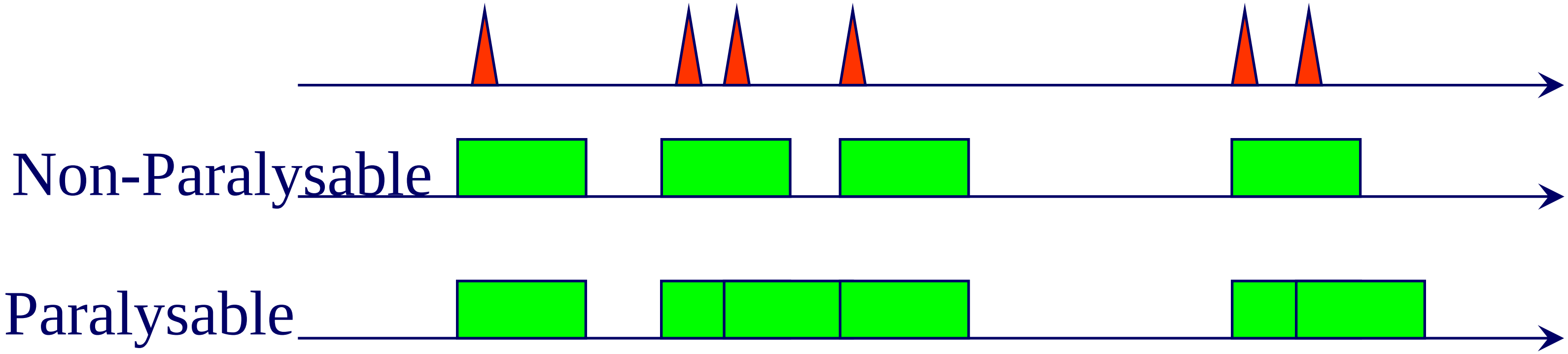


- Shannon's Theorem and Nyquist Criterion
  - The highest frequency that can be 'measured' is twice the sampling frequency
- If the input is not band limited to frequencies less than $f_s/2$, then aliasing will occurs at frequencies $f \pm nf_s$
  - where f = signal frequency, fs = sampling frequency, n = integer
- If you have 100μm pixels, the ideal spatial resolution (PSF) > 200μm

Synchrotron Detectors

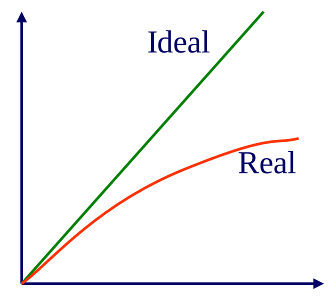
- A synchrotron source is used primarily when sensitivity is an issue
  - Signal too weak
  - Time resolution too poor
  - Sample too small
- More intensity can help this but…
- It places a major strain on detectors and **Flux is a major issue for detectors!**

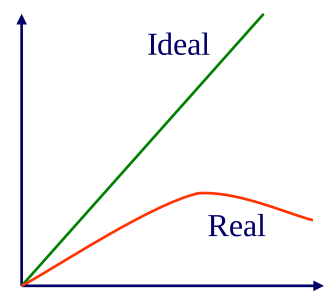
Dead Time



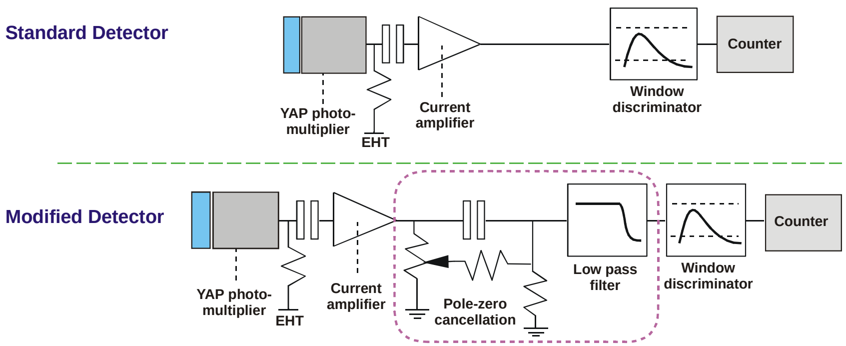
R_i=input rate, R_d=detected rate, τ dead time

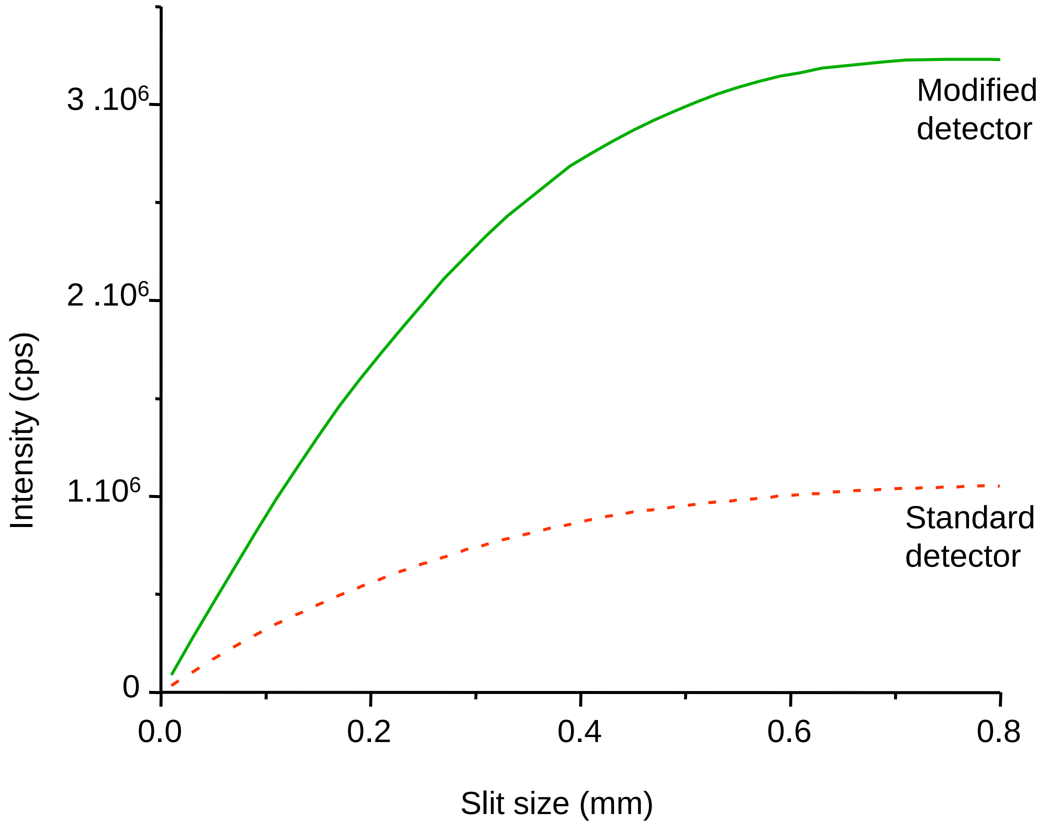
- Non-paralysable
  - Fraction of time detector is dead = $R_d\,\tau$
  - Live time is therefore = $1- R_d\,\tau$
  - Input rate = $R_i= R_d/(1- R_d\,\tau)$
- Paralysable
  - R_d = Probability of getting no event within τ of an event
  - Probability of n events in time t is $$P(n,t)=\frac{e^{-R_i t}(R_i t)^n}{n!}$$
  - Detected rate $$R_d = P(0,\tau) = R_i e^{-R_i \tau}$$





EDR Detector for Powder Diffraction



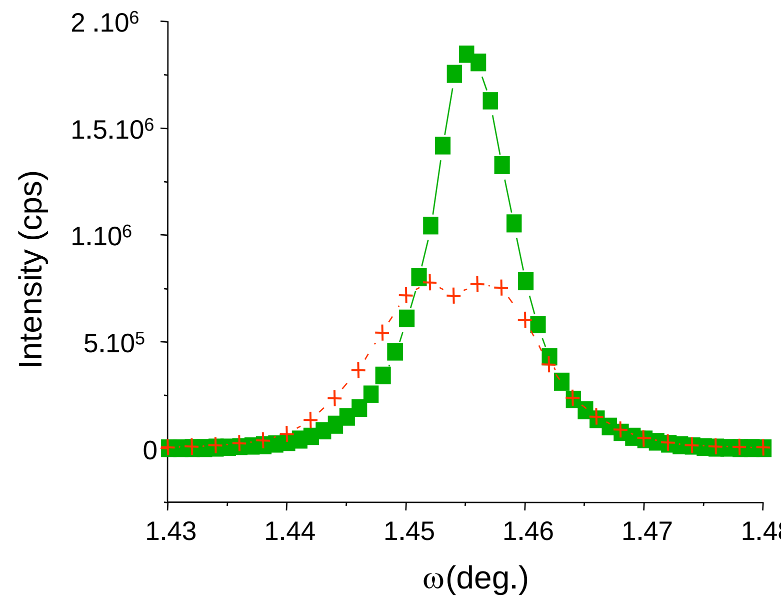


Standard detector

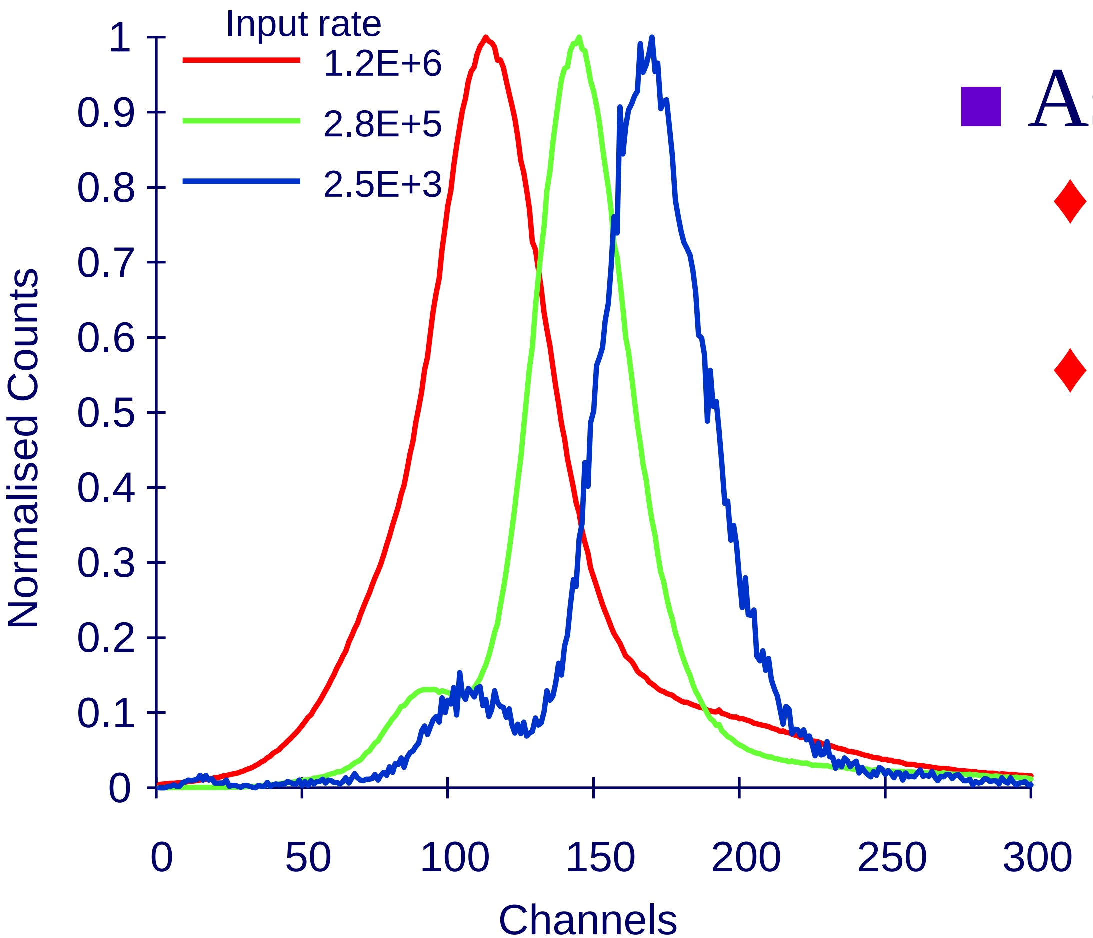
- Saturation count rate: 1 MHz
- Linear region: up to 300 kHz
- Electronic background: 0.2 cps
- Energy range: 4-25 keV

Modified detector

- Saturation count rate: 3 MHz
- Linear region: up to 2 MHz
- Electronic background: 0.7 cps
- Energy range: 4-25 keV



Spectral Peak Shift vs Rate



- As rate rises
  - Spectral resolution deteriorates
  - Note also the K escape feature

Detector Considerations

- Intensity Measurement
  - Uniformity across device
  - Ageing, radiation damage
  - Dynamic Range
  - Linearity of Response
  - Stability
- Spatial Measurement
  - Spatial Resolution
  - Spatial Distortion
  - Parallax
- Energy Measurement
  - Spectral Resolution
  - Linearity of Response
  - Uniformity of Response
  - Stability
- Time Measurement
  - Frame Rate
  - Photon Time Resolution
- Others
  - Size and weight
  - Cost

A Universal Specification?

Wombat

Counting Statistics

- Photons are quantised and hence subject to probabilities
- The Poisson distribution expresses the probability of a number of events, k occurring relative to an expected number, n

$$P(n,k) = \frac{n^k e^{-n}}{k!}$$

- The mean of P(n, k) is n
- The variance of P(n, k) is n
- The standard deviation or error (noise) is $\sqrt{n}$
- If signal = n, then SNR = $n/\sqrt{n} = \sqrt{n}$
- As n increases, SNR improves

Performance Measure - DQE

Perfect detector $SNR_{inc} = \sqrt{N_{inc}} \quad \therefore N_{inc} = SNR^2{}_{inc}$

Real detector $SNR_{Non-ideal} < \sqrt{N_{inc}}$

Can define $N_{photons}$ that describes real SNR

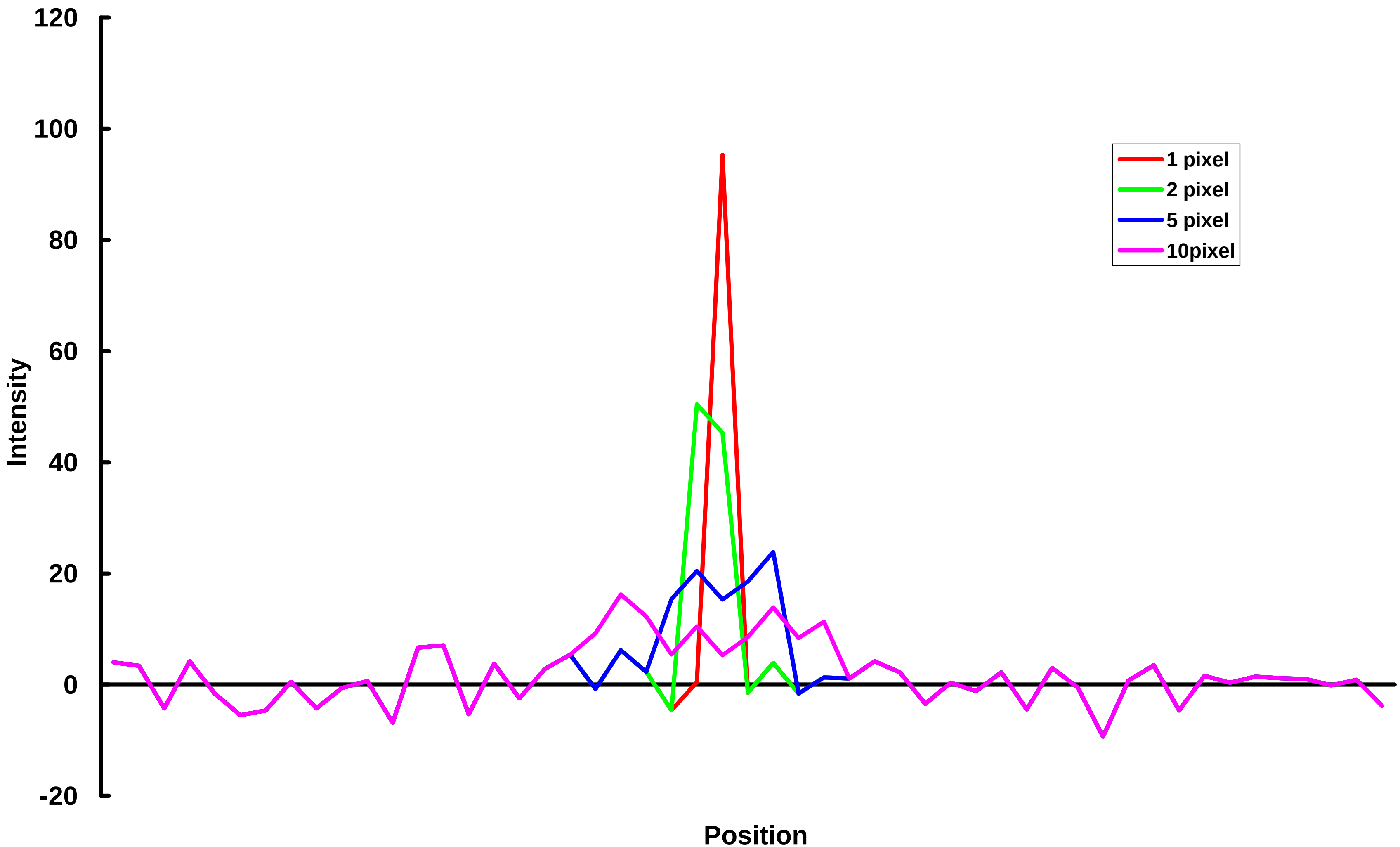
$$NEQ = SNR^2{}_{Non-ideal}$$

Ratio of this to N_{inc} is a measure of efficiency

$$DQE = \frac{NEQ}{N_{inc}} = \frac{SNR^2{}_{Non-ideal}}{SNR_{inc}{}^2}$$

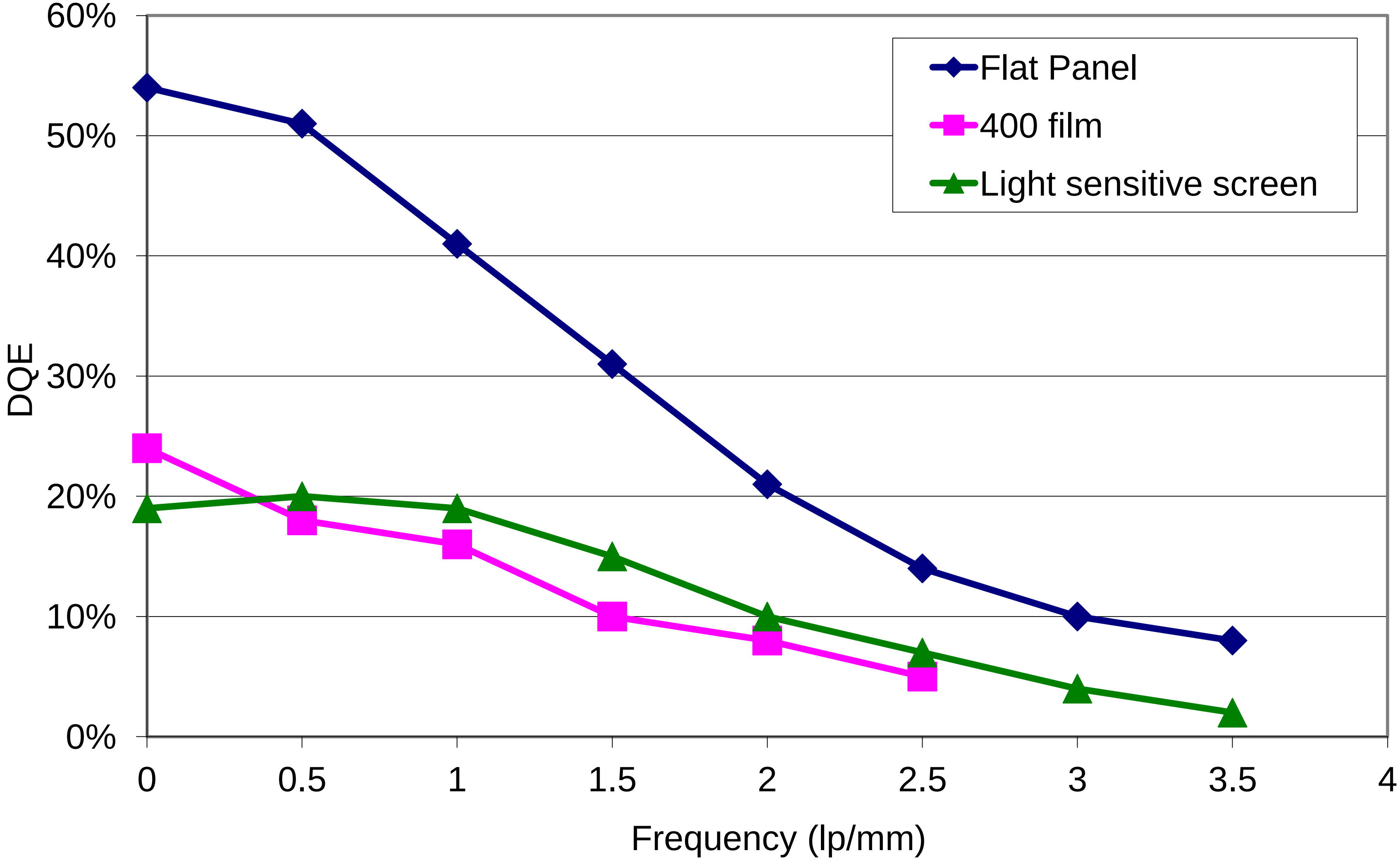
Note that DQE is f(spatial and spectral frequencies)

Effect of Peak Width



DQE Comparison

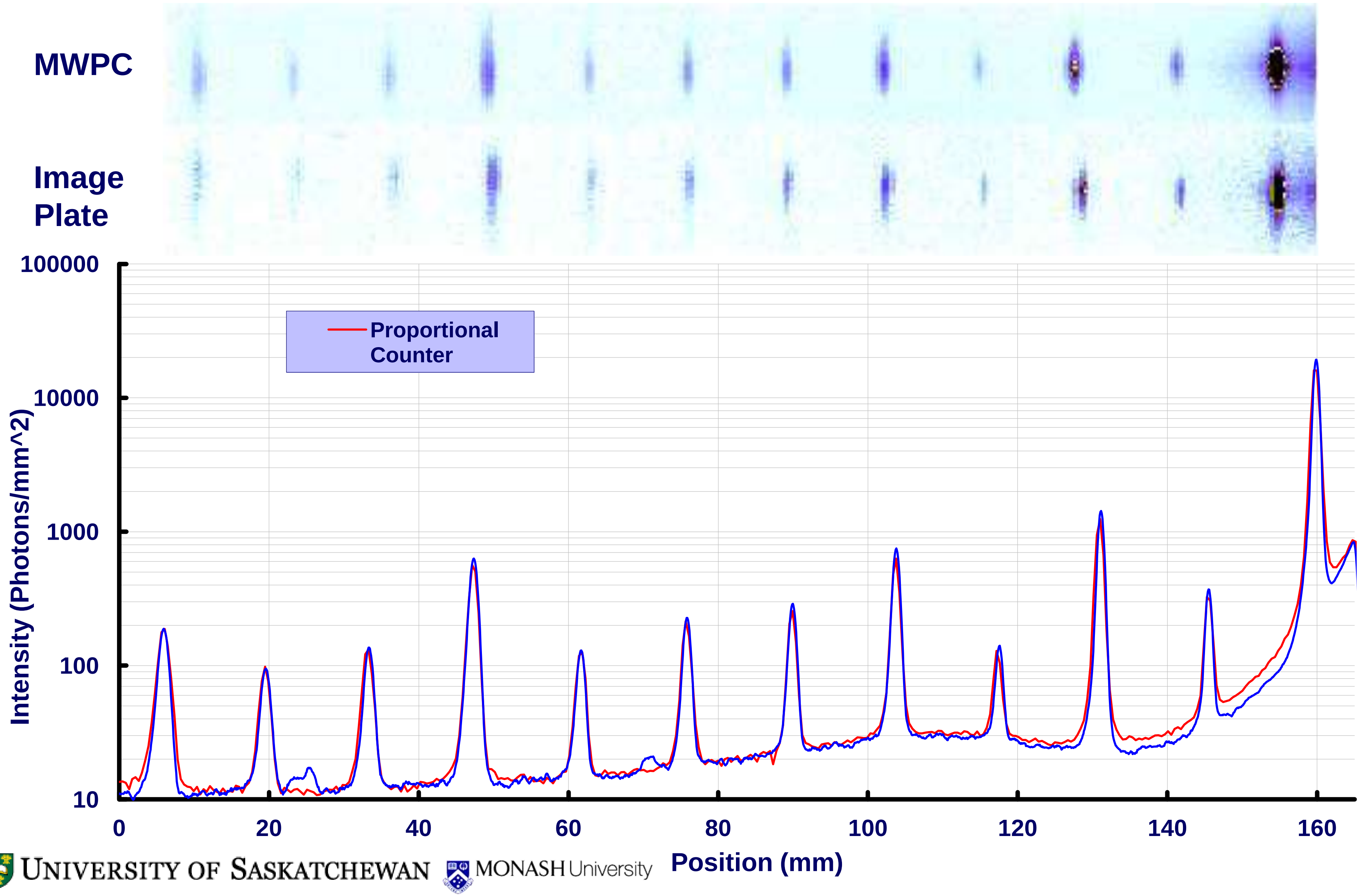
DN-5 beam
2.6μGy



To Count or Not to Count

Tasmanian Devil

Collagen 100s Exposure



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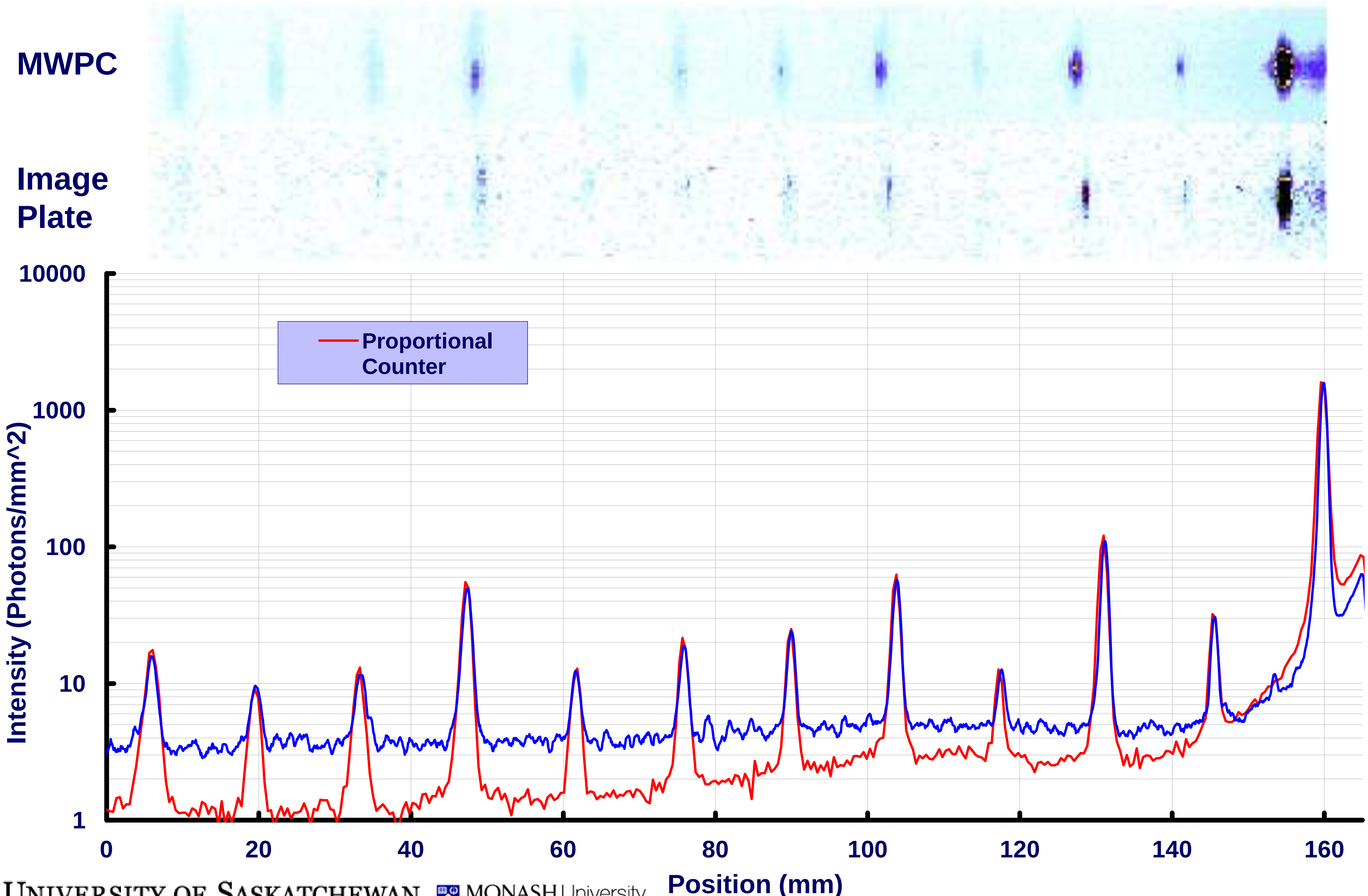
Collagen 10s Exposure



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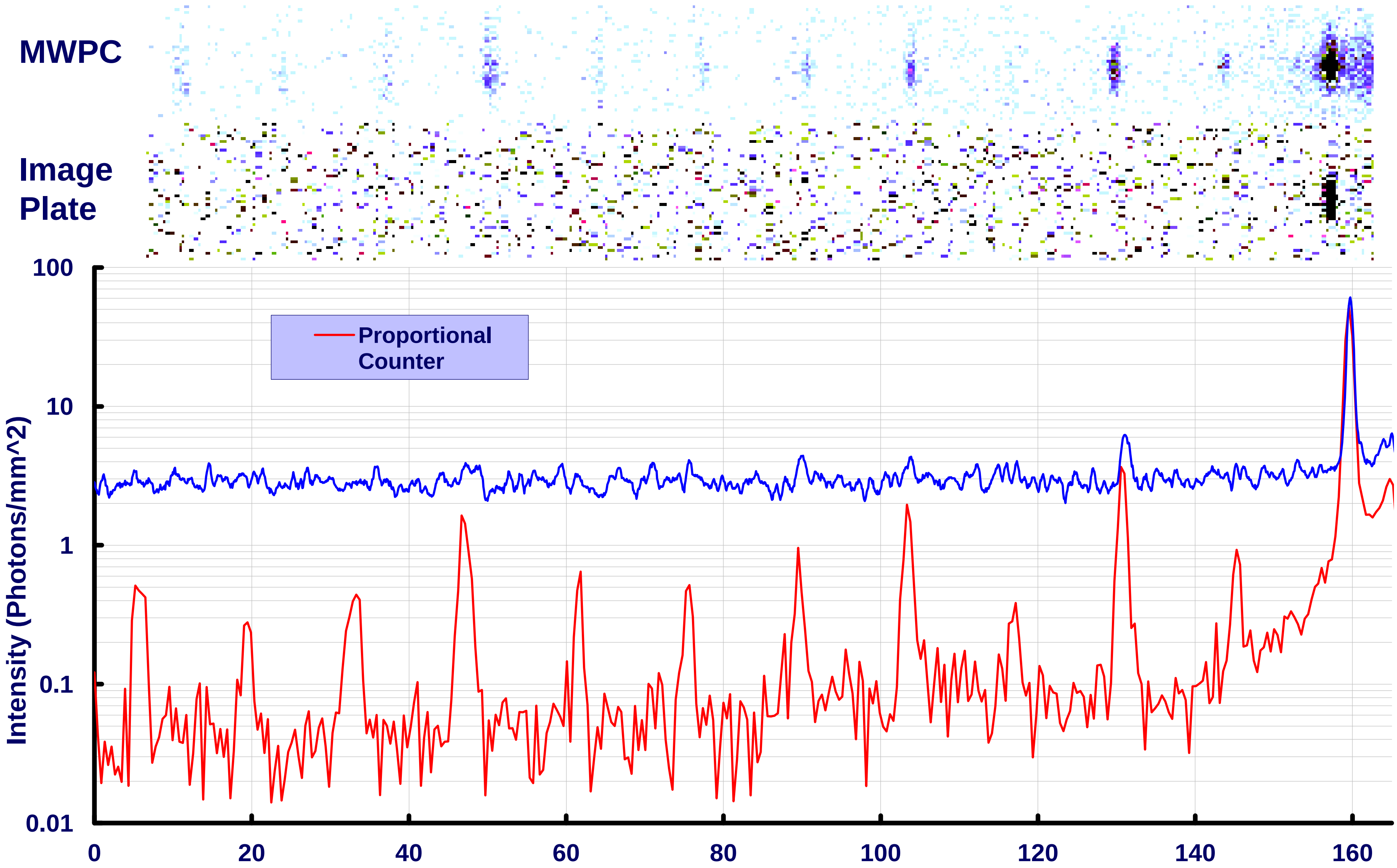
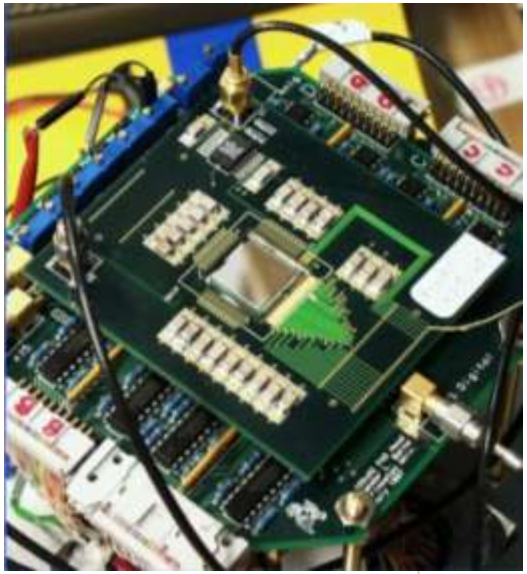
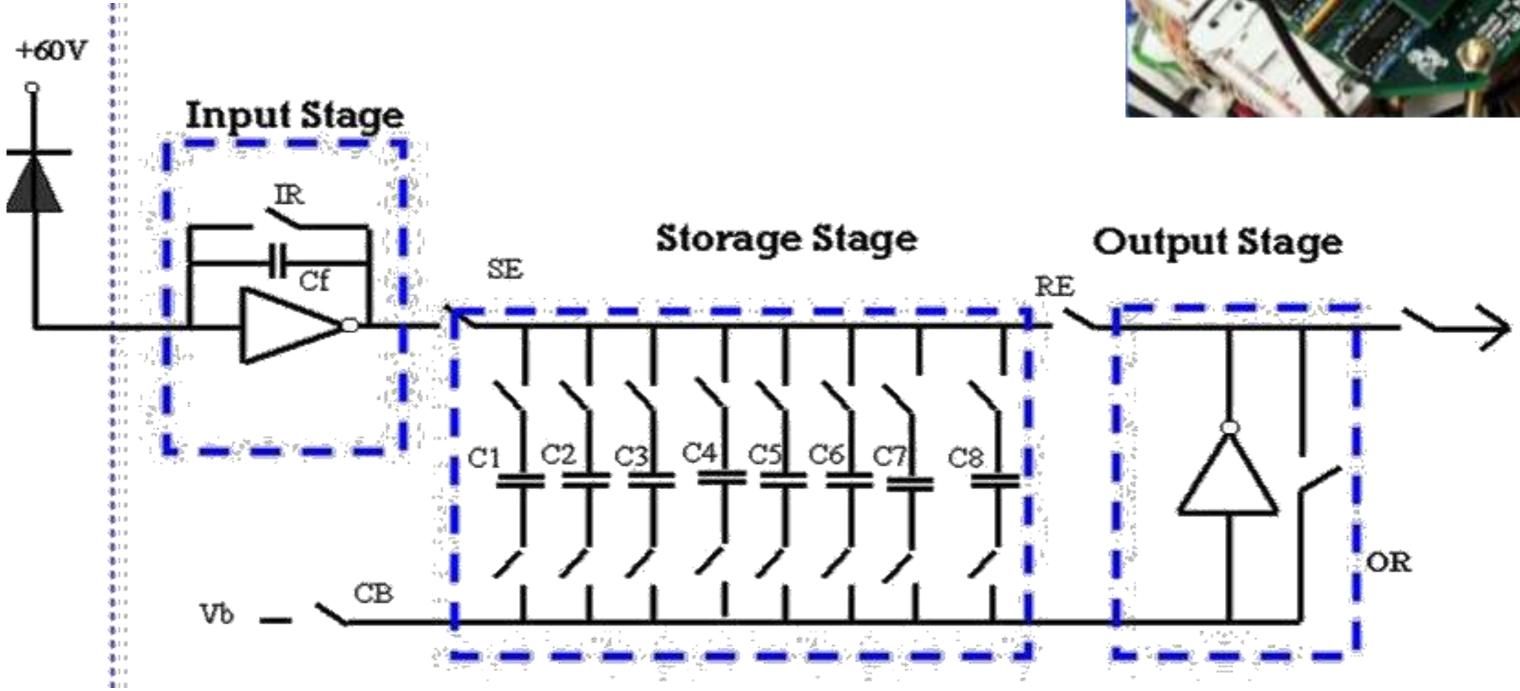
Collagen 0.3s Exposure



Cornell PAD (Integrating)

- Rapid Framing Imager
  - 15×13.8mm² active area
  - 150μm square pixel
  - Storage for 8 frames
  - Selectable T_{int} down to 1μs
  - Deadtime < 1μs





Diesel Fuel Injection Movie

- Injection
  - Supersonic injection 1350psi Cerium added
  - Chamber 1atm SF_6
  - 10^8-10^9 X-rays/s/pix (6keV)
  - 1.1ms Pulse
- Movie
  - Length 1.3ms
  - Frame length 5.13μs
  - Dead time 2.56μs / frame
  - 168 frames (21 groups of 8)
  - Average 20× to improve S/N
  - Sequence 5×10^4 images

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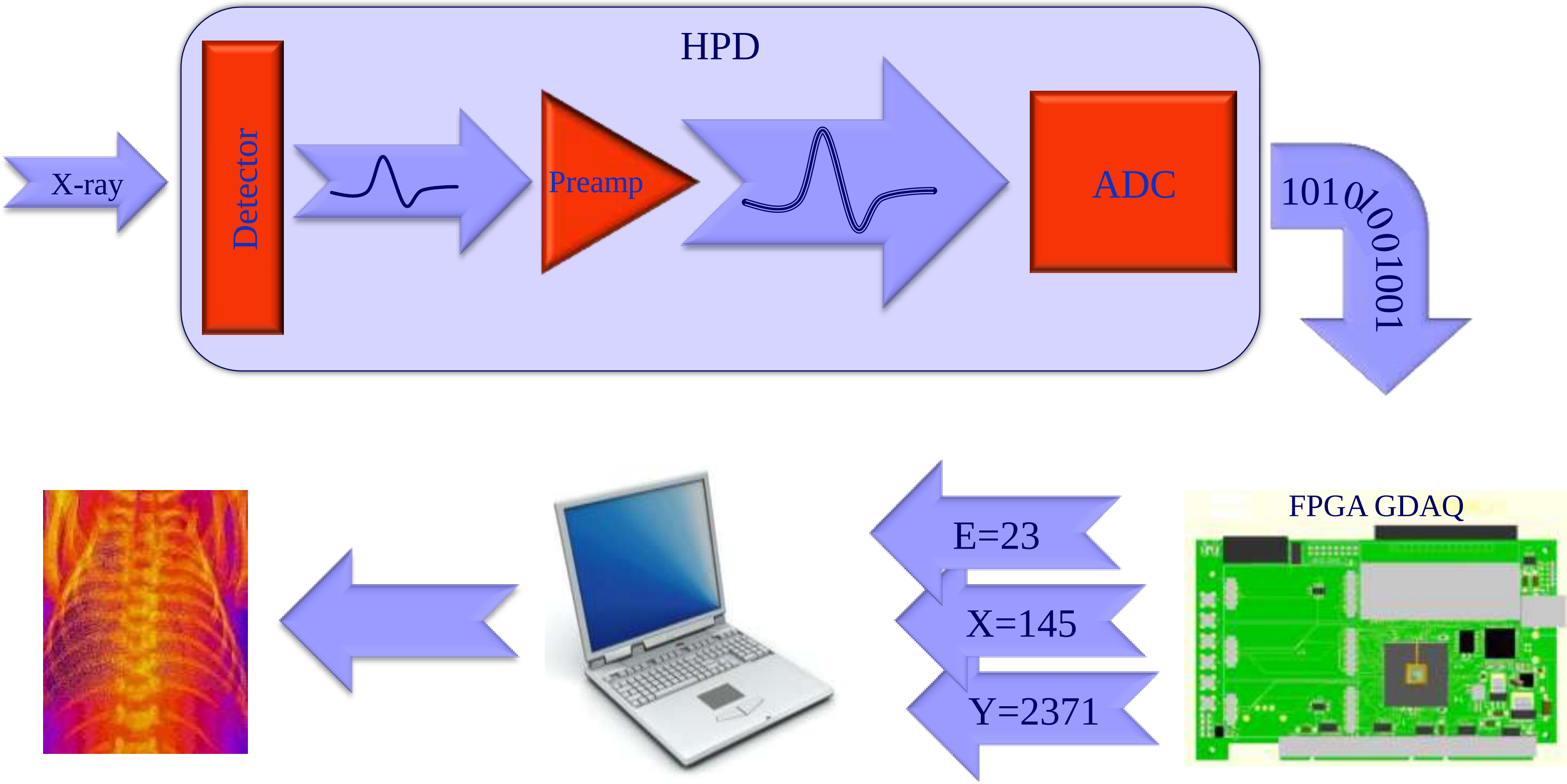
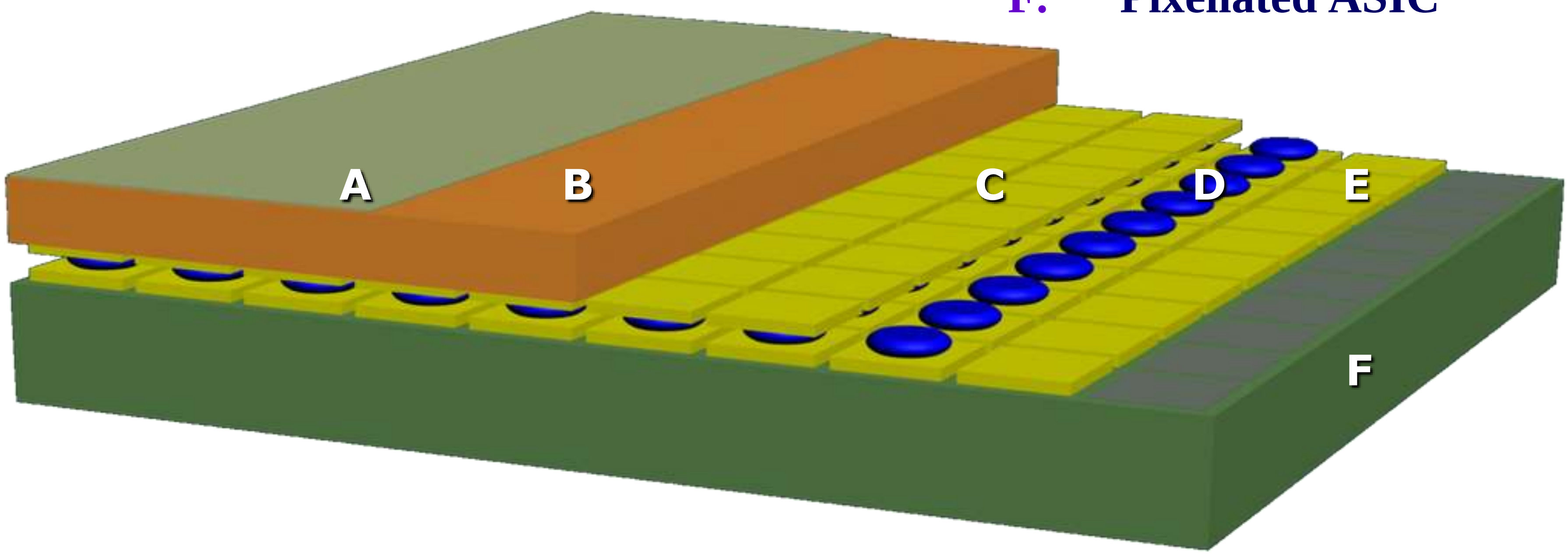
A. MacPhee et al, Science (2002) 295, 1761-1763

Combine Imaging and Spectroscopy



Pixel Array Detector

A. Top electrode
B. Pixellated semiconductor
C. Collection electrodes
D. Bump bonds
E. Input electrode
F. Pixellated ASIC



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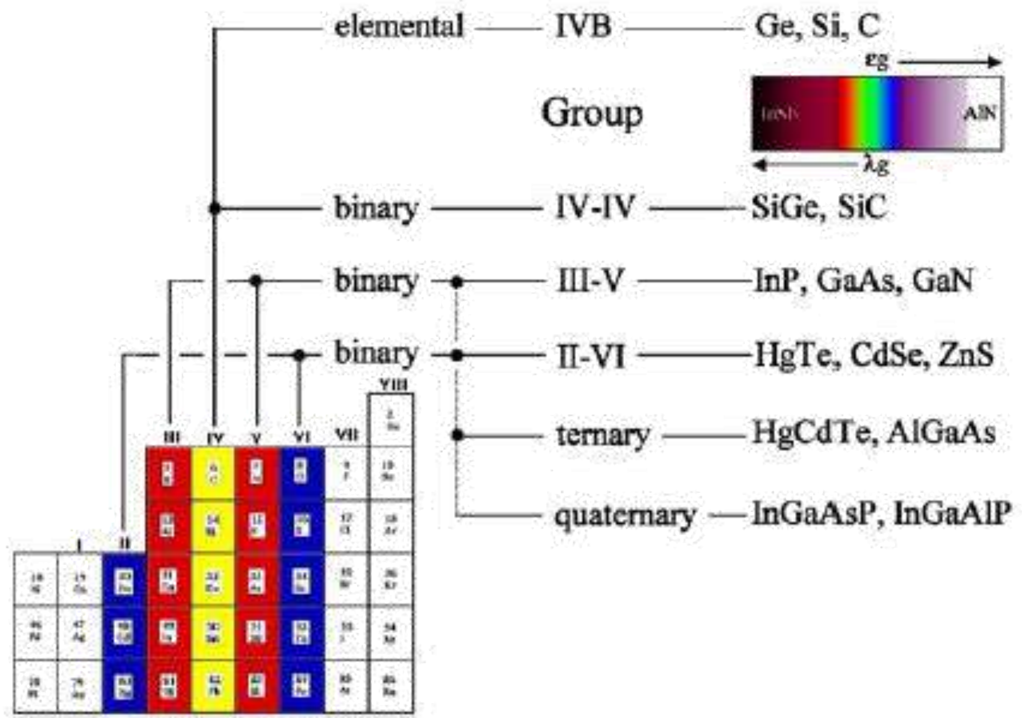
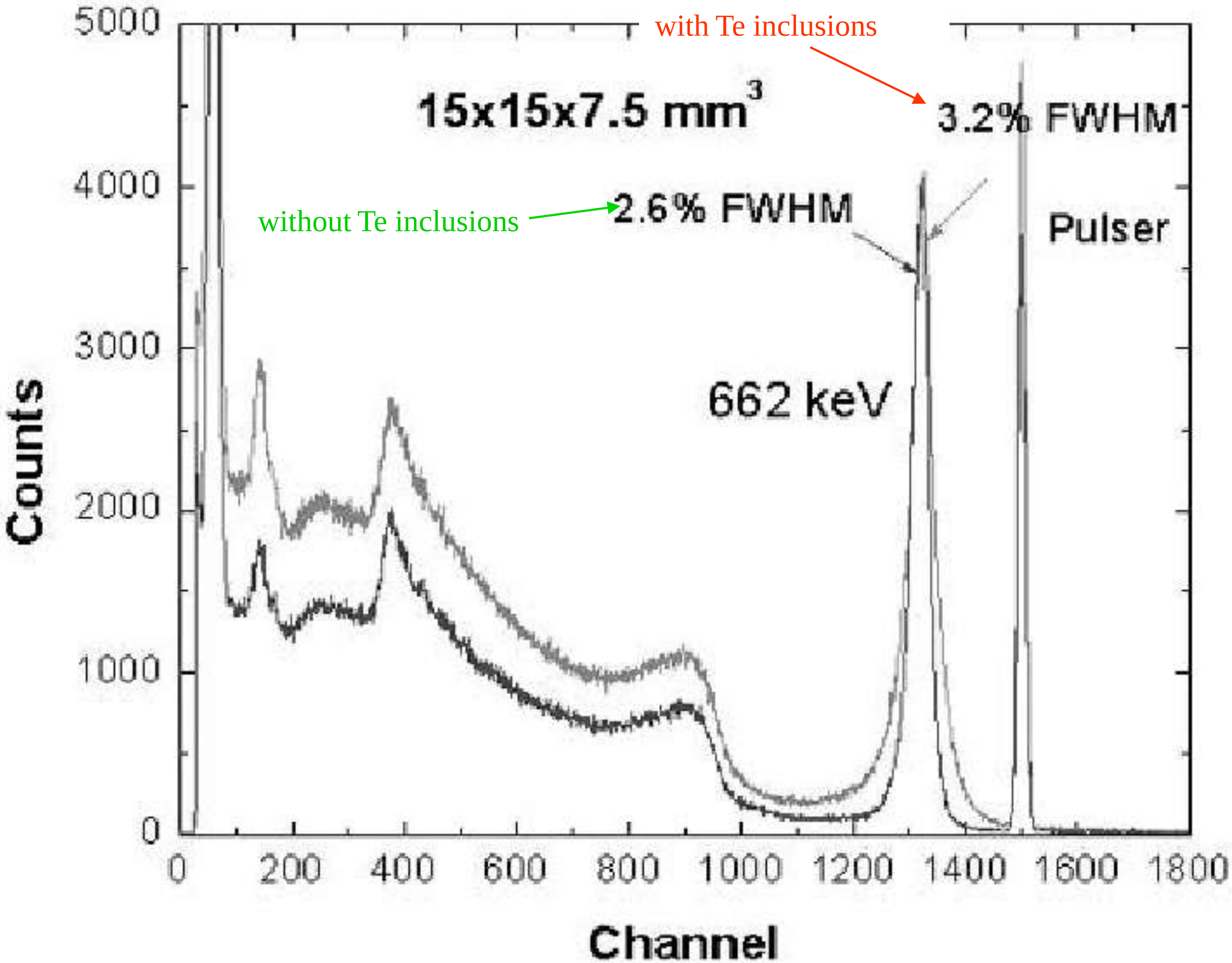
Available Compound Semiconductors

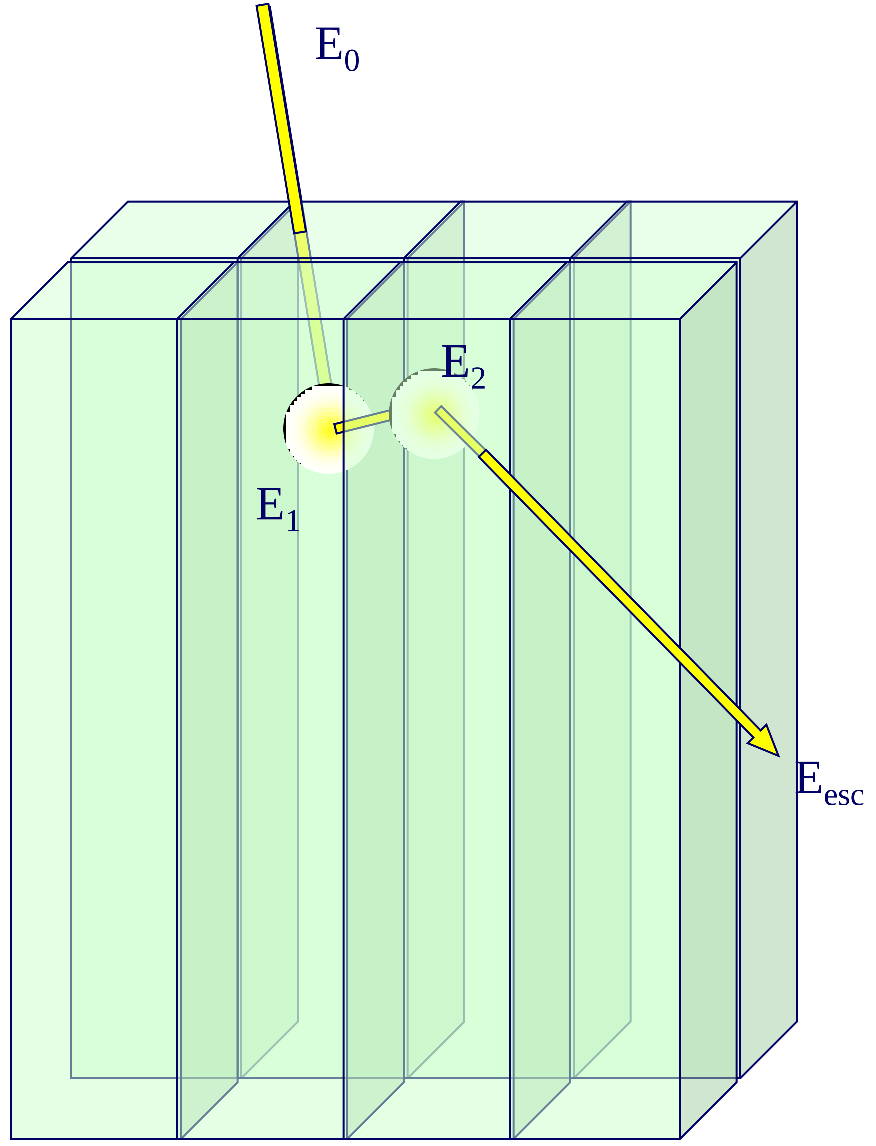
- Predominately CdZnTe, CdTe and GaAs.
- II-VI materials CdTe and CdZnTe cover a suitable range of band gaps:
  - 1.44 eV (CdTe), 1.57 eV (CdZnTe, 10% Zn), 1.64 eV (CdZnTe, 20% Zn)
- Resistivity of CdZnTe is higher than CdTe, hence lower dark current, higher spectroscopic resolution
- Poor hole transport requires electron-sensitive detectors



CdZnTe Spectral Resolution



The Problem of Multiple Scatters

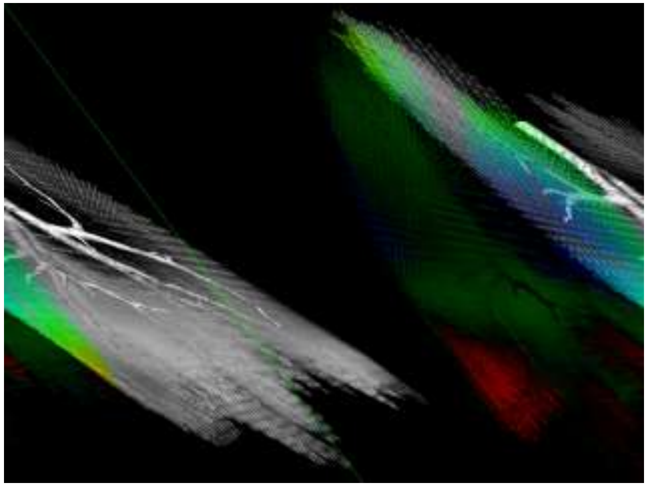


- Need to measure E_0
- $E_0=E_1+E_2+E_{esc}$
- Must be able to detect multiple deposits as single event
- Must minimise E_{esc}

Other Issues

- In addition to detector performance metrics such as
  - Spatial resolution
  - Spectral resolution
  - Etc. etc.
- Consider other issues such as synchronisation.
- Many experiments require triggers or measurements of multiple parameters.

4D PIV



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