UNIVERSITY OF SASKATCHEWAN

SCOTT automation + robotics

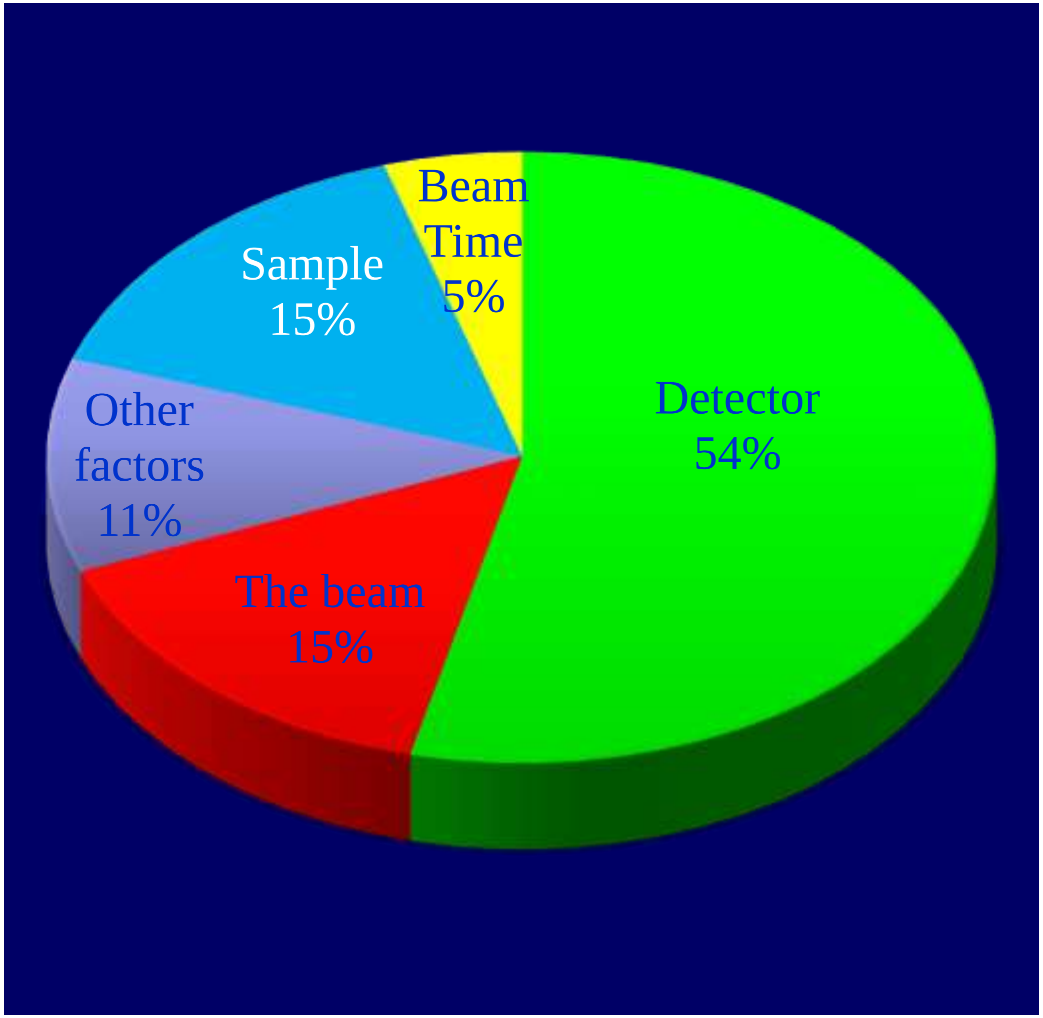
MONASH University

Detectors: Things you should know

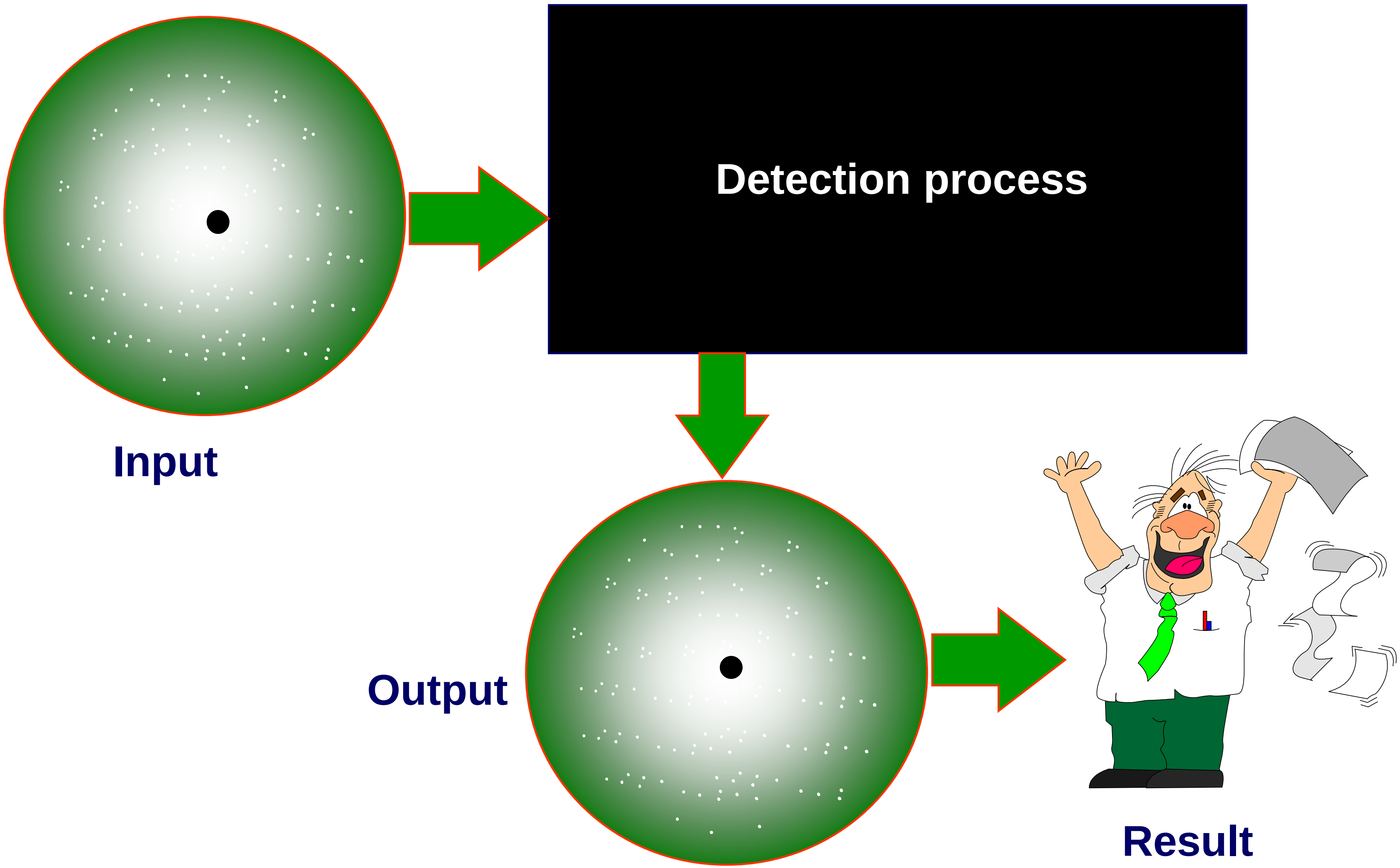
Rob Lewis
Medical Imaging, University of Saskatchewan
Medical Imaging and Radiation Sciences, Monash University
Scott Automation and Robotics

Factors Limiting Science

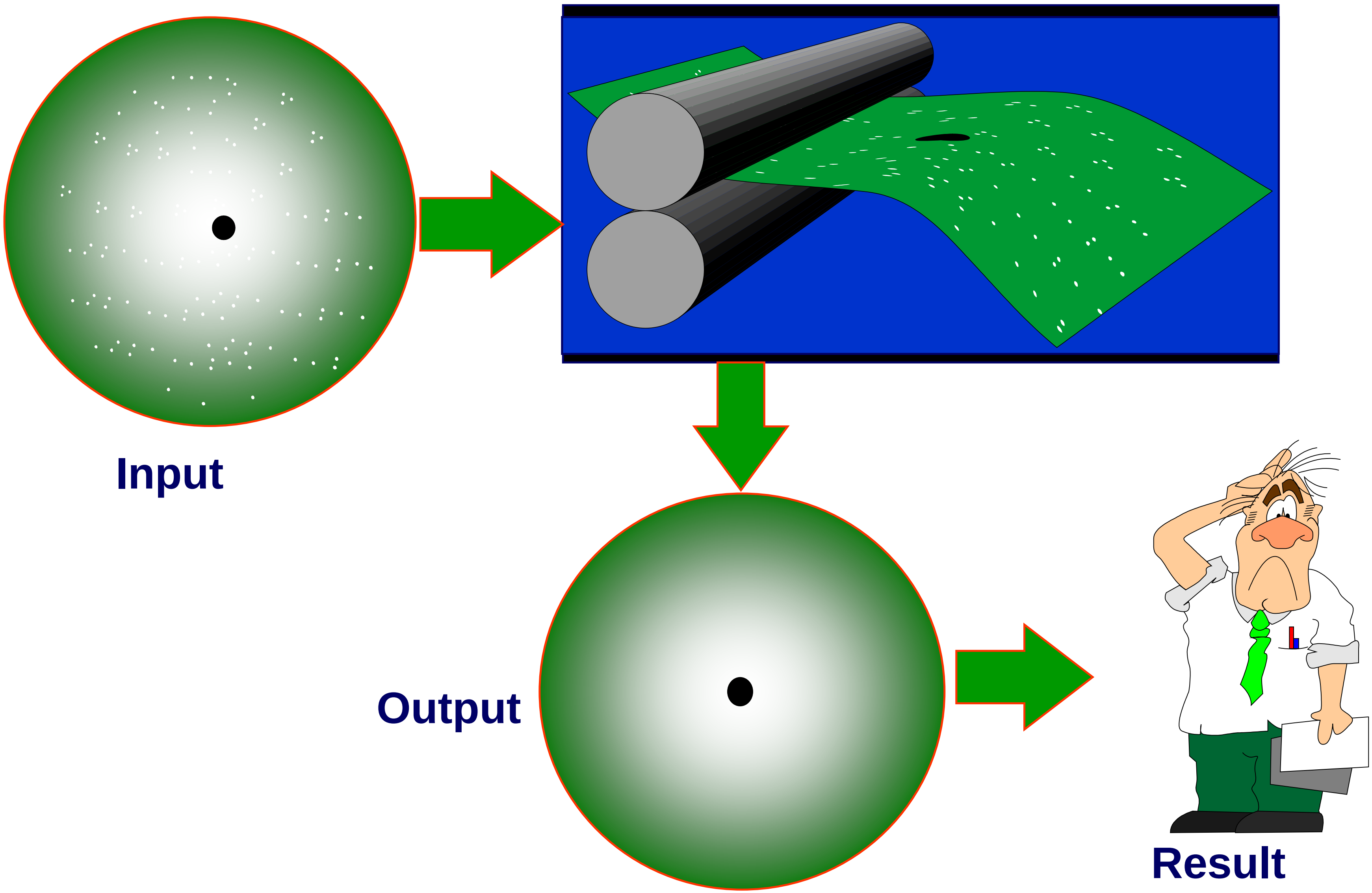
- Detectors are an oft-neglected but crucial part of an experiment
- They often limit the science



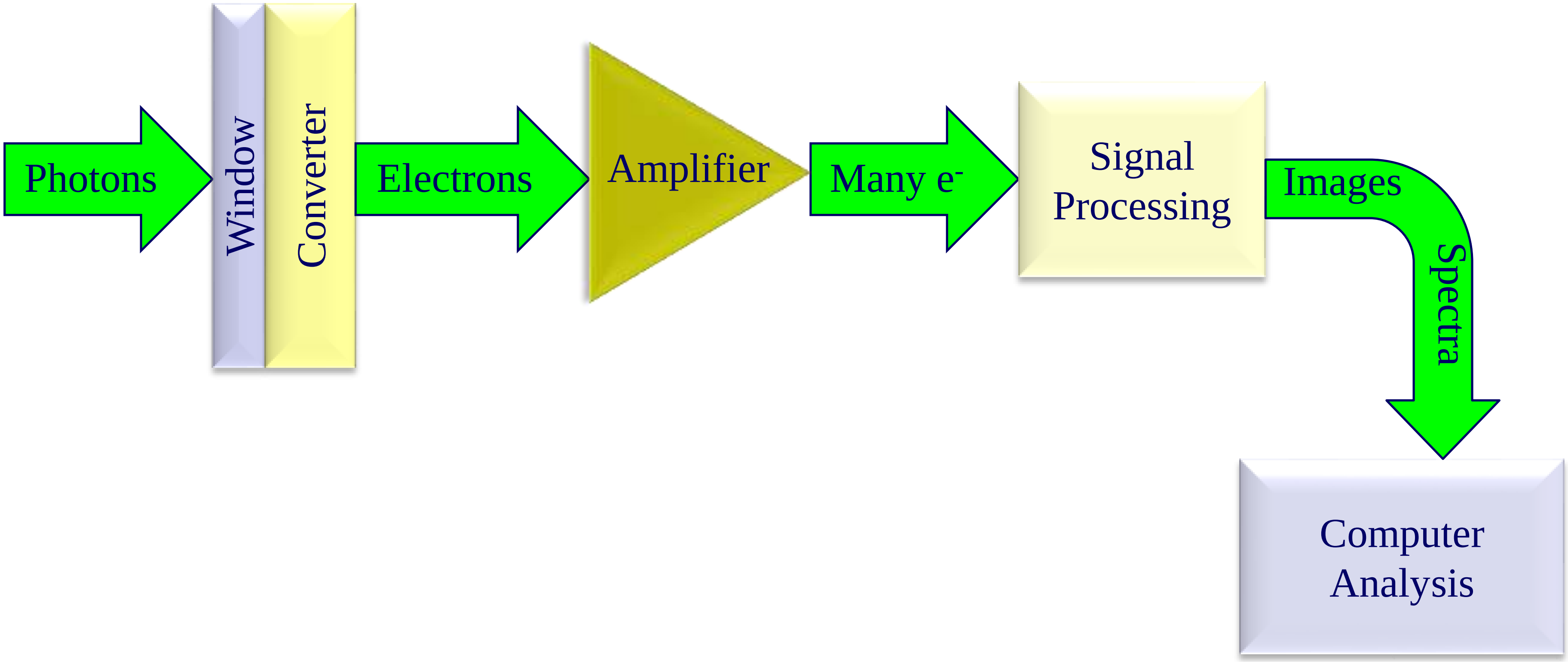
Scientist's View of Detector



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

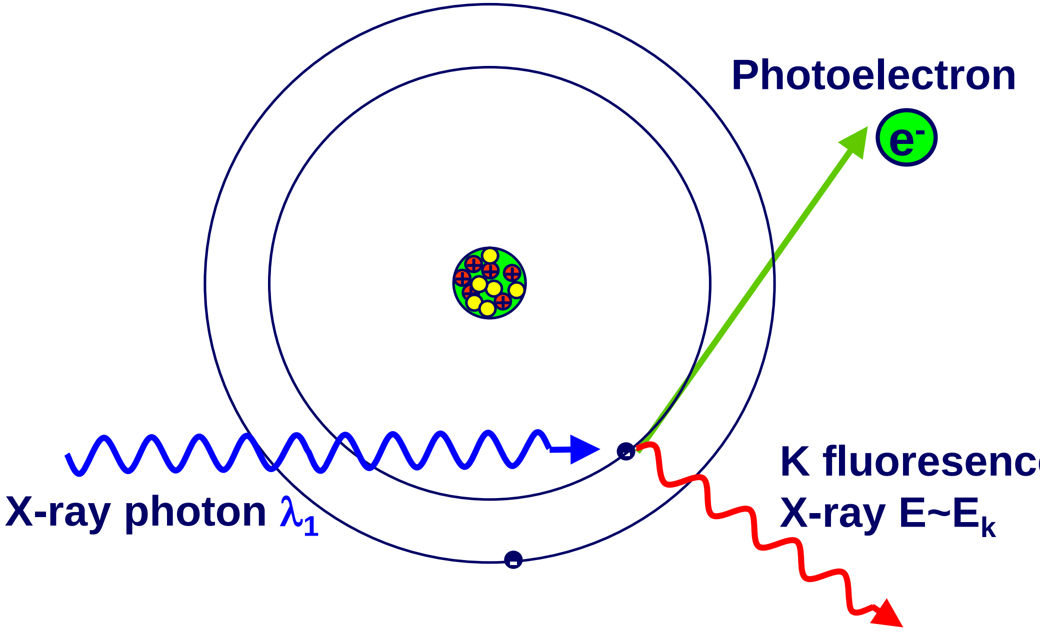
Albert Einstein

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



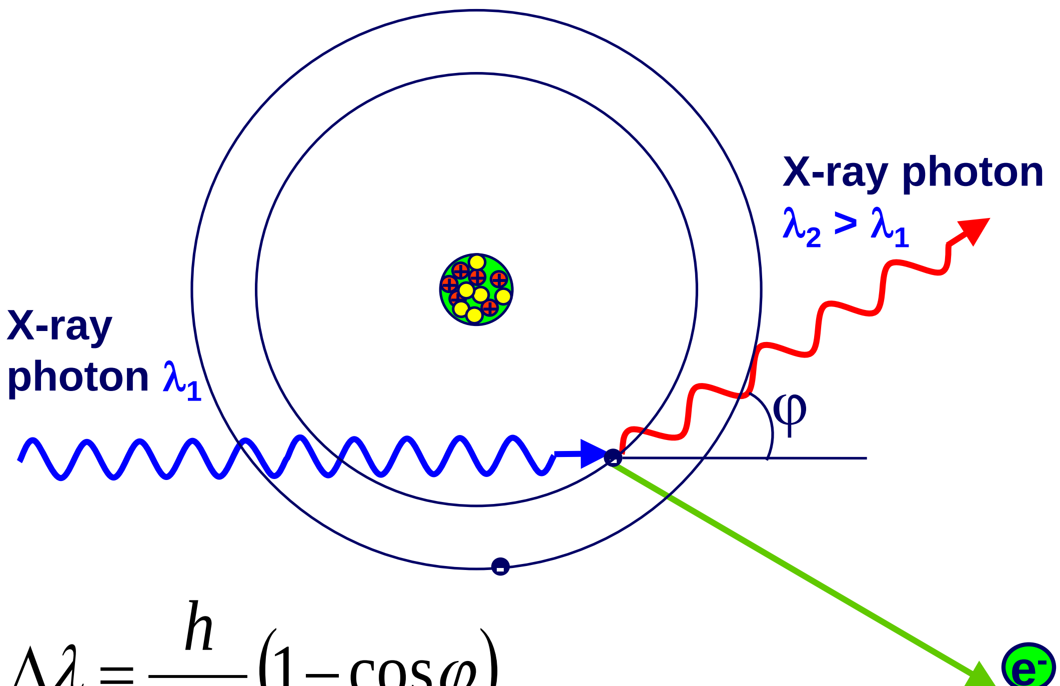
Arthur Holly Compton

University of Chicago
Chicago, IL, USA
1892 - 1962

Nobel prize in physics 1927

"for his discovery of the effect named after him"

Compton Effect

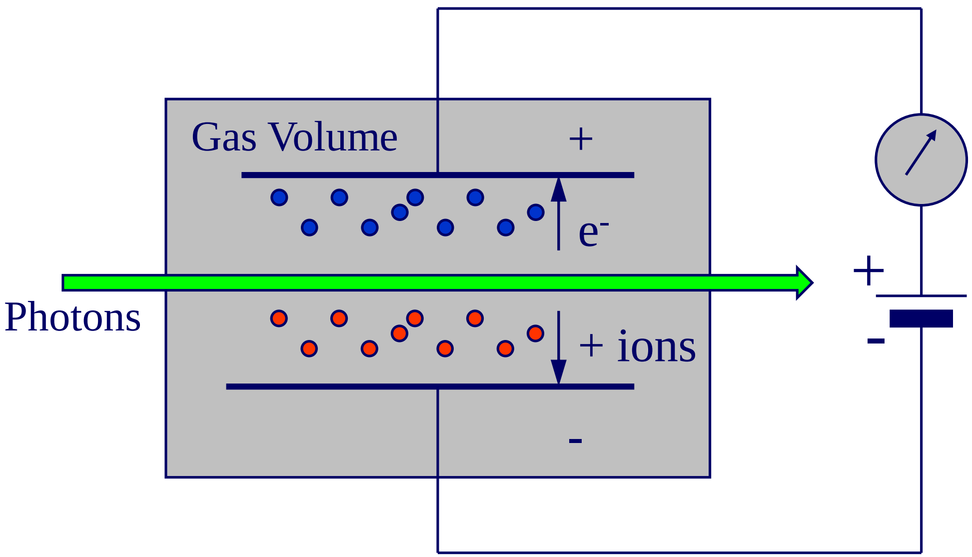


$$\Delta\lambda = \frac{h}{m_0 c}(1 - \cos\varphi)$$

An Example Detector

Echidna

Ionisation Chamber

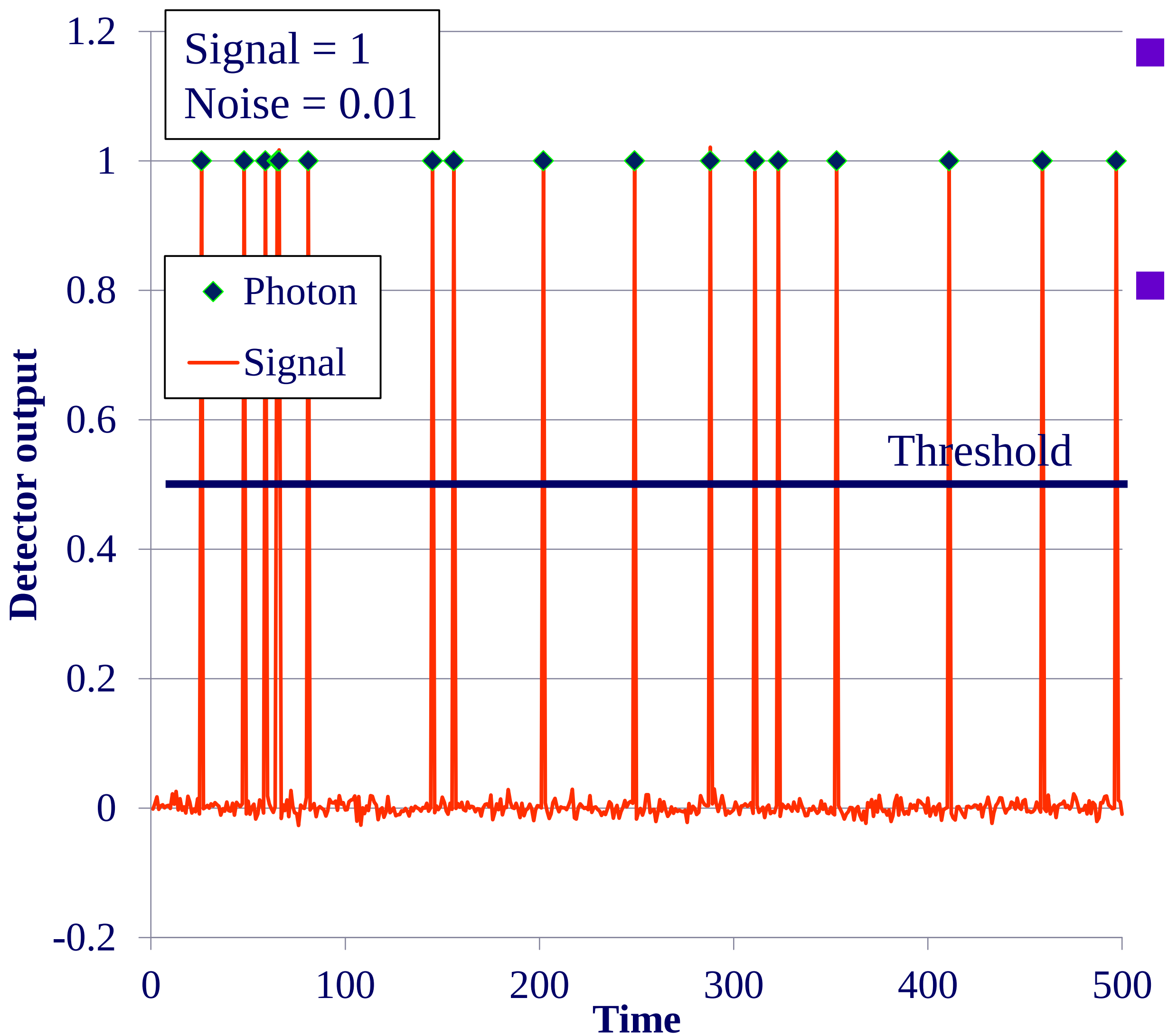


- Approx. 1 e^- ion pair per 30eV deposited (symbol often ***w***)
- IF ***w***, density and gas known, it is possible to convert current to flux
- Flux measurement can be affected by several factors
  - Recombination of e^- and ions
    - Higher voltages required at higher rates since more carriers
  - Diffusion losses due to ion and e^- gradient
    - Helped by higher voltages, small gap
  - Electron losses when e^- directly reach anode
    - Helped by larger gap
- Pressure, temperature and humidity affect density

Counting and Integrating

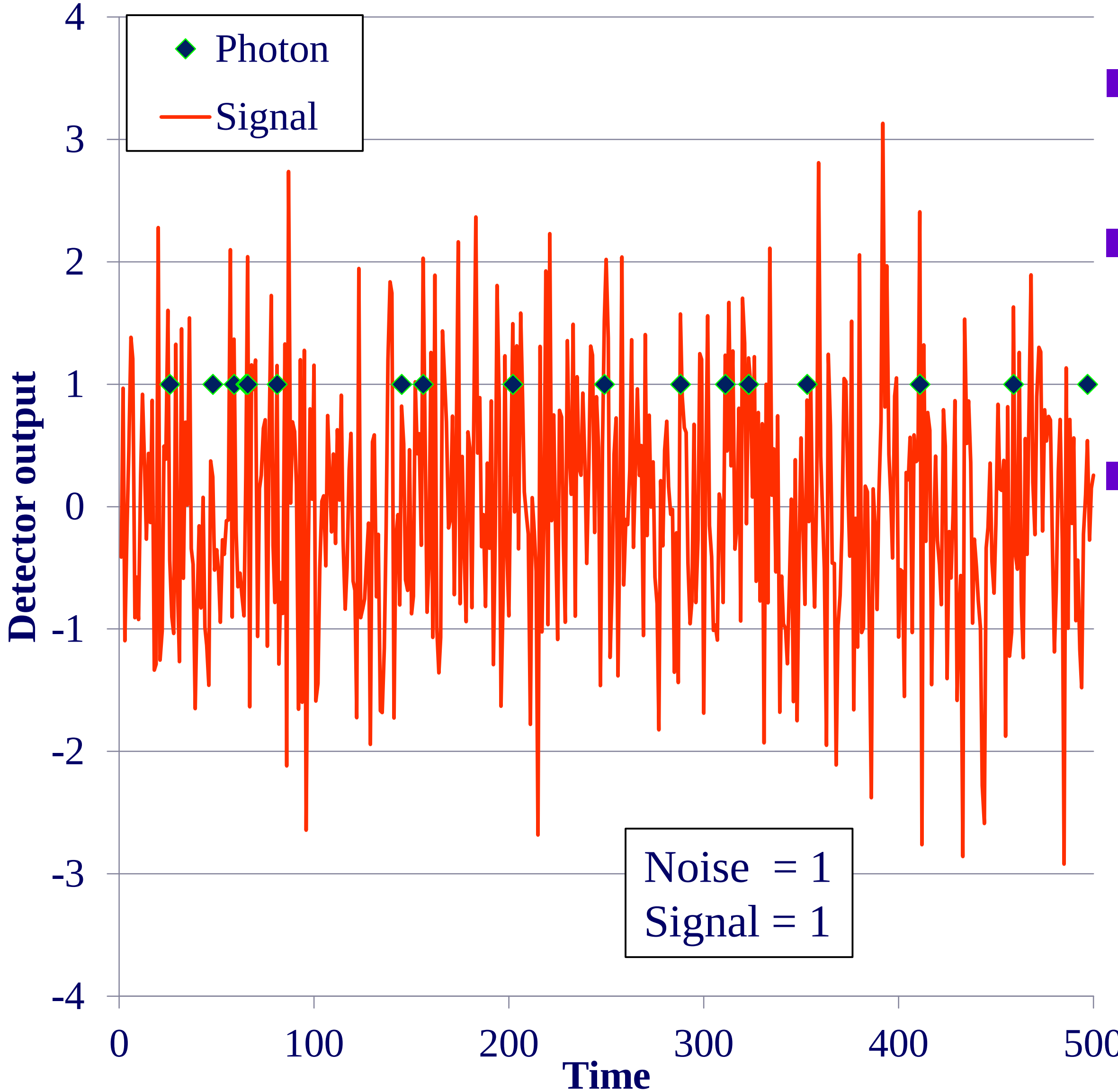
- If there is sufficient signal produced by the interaction of a photon or a particle in the detector then it is possible to operate the detector as a counter
- It’s all about signal to noise ratio!

SNR = 100



- In this case 17 photons hit detector but only 16 recorded
- Illustrates a problem with counting
  - Pulse pair resolution

SNR = 1

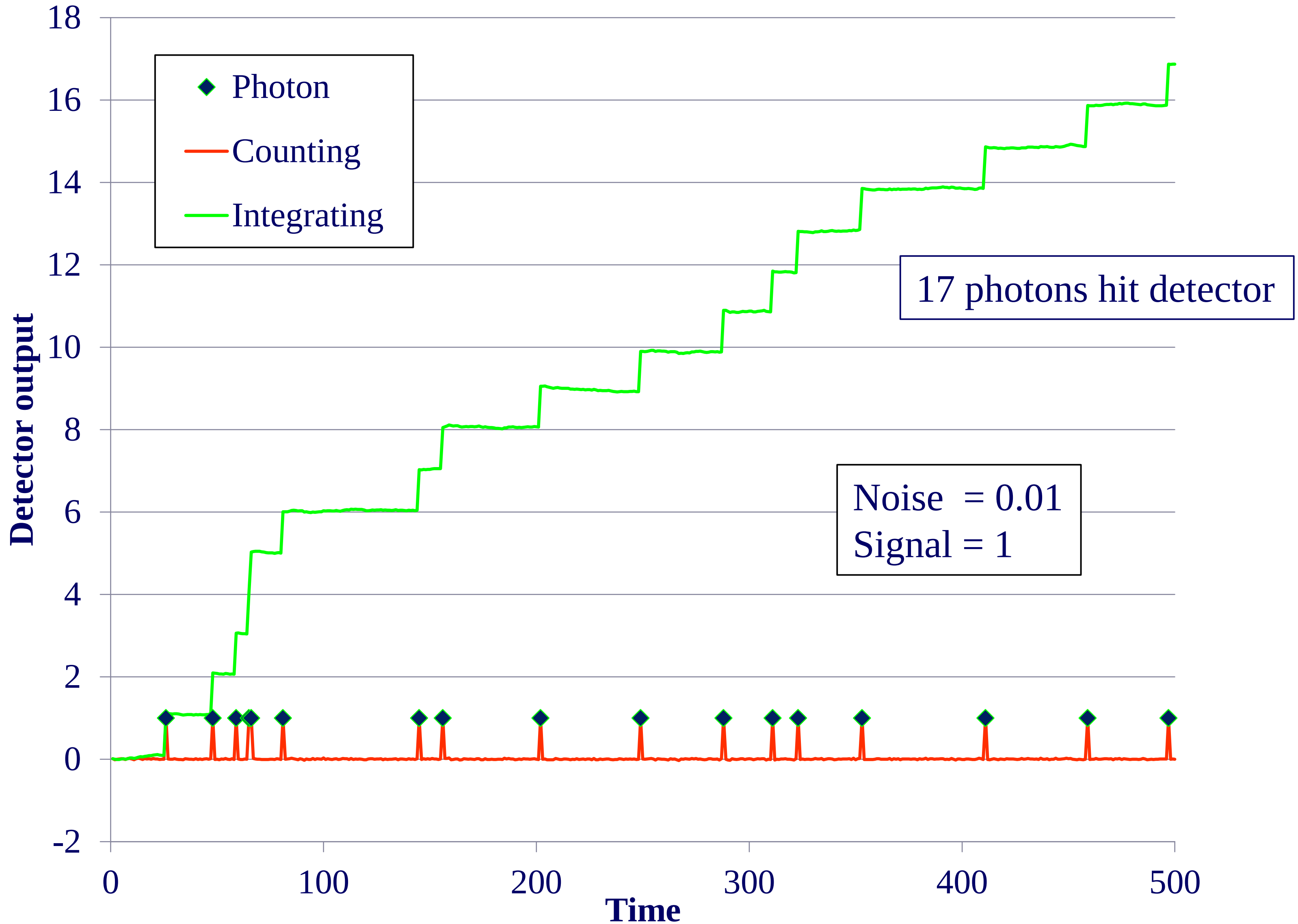


- Black dots show when photons arrive
- Impossible to decide where to set threshold
- Counting detectors require very high SNR

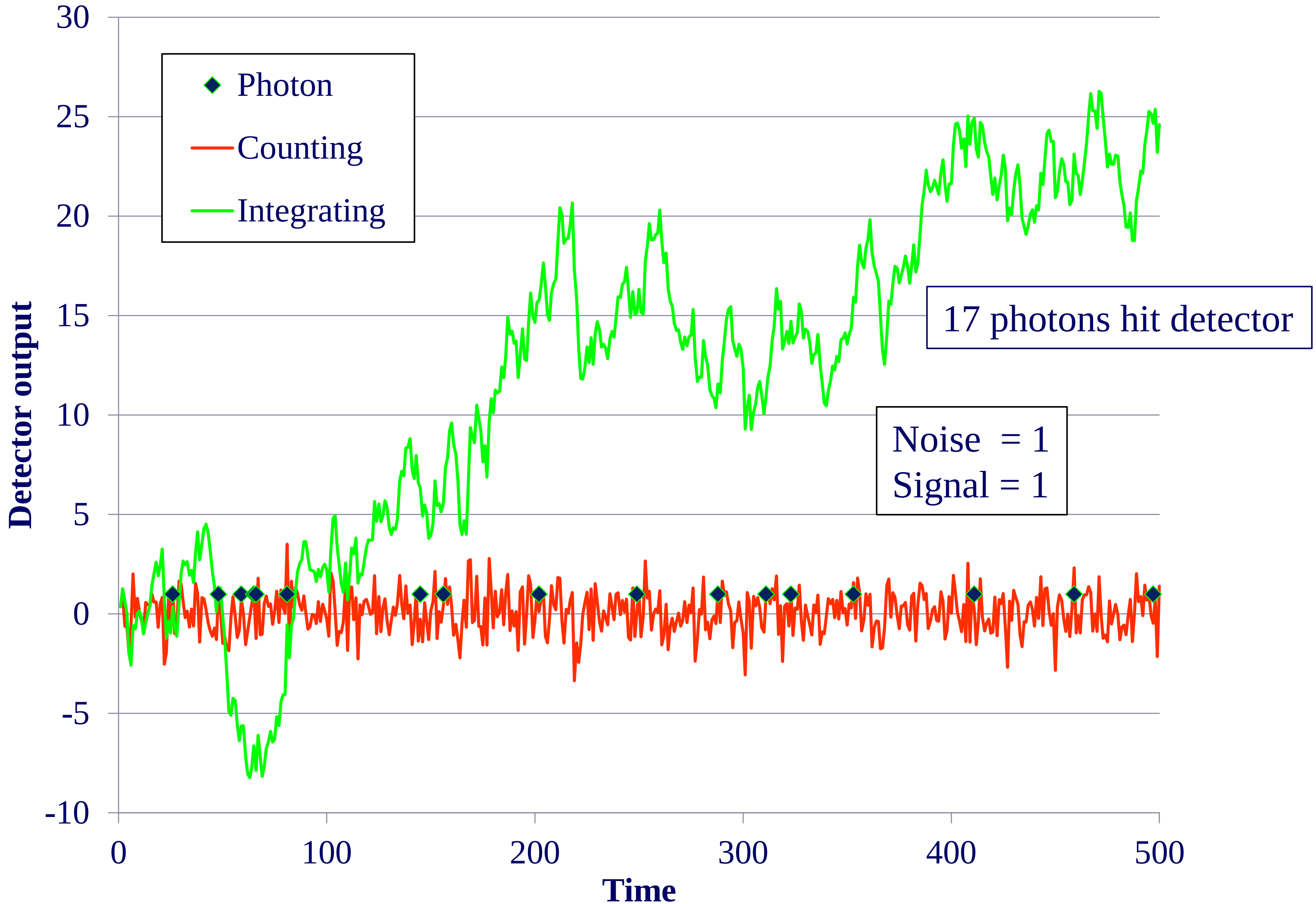
Counting and Integrating

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

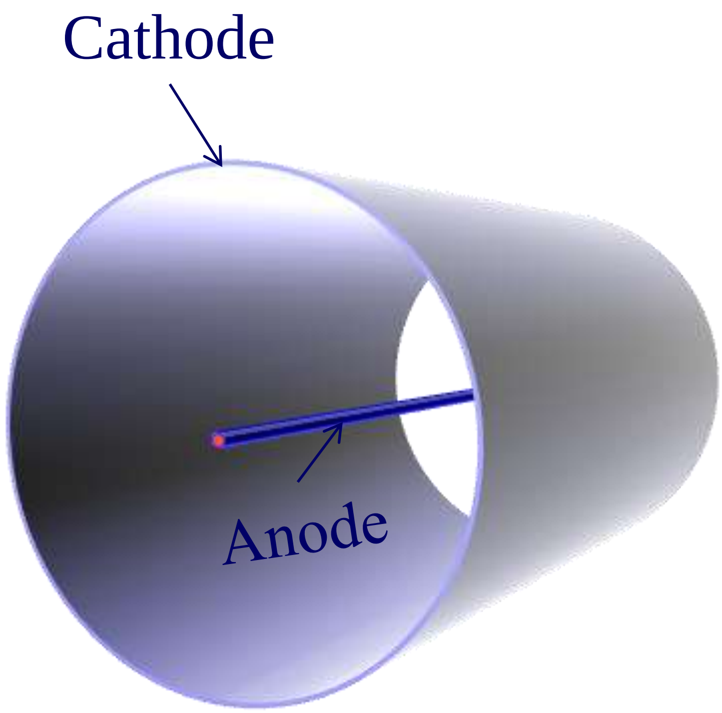
Counting & Integrating SNR =100

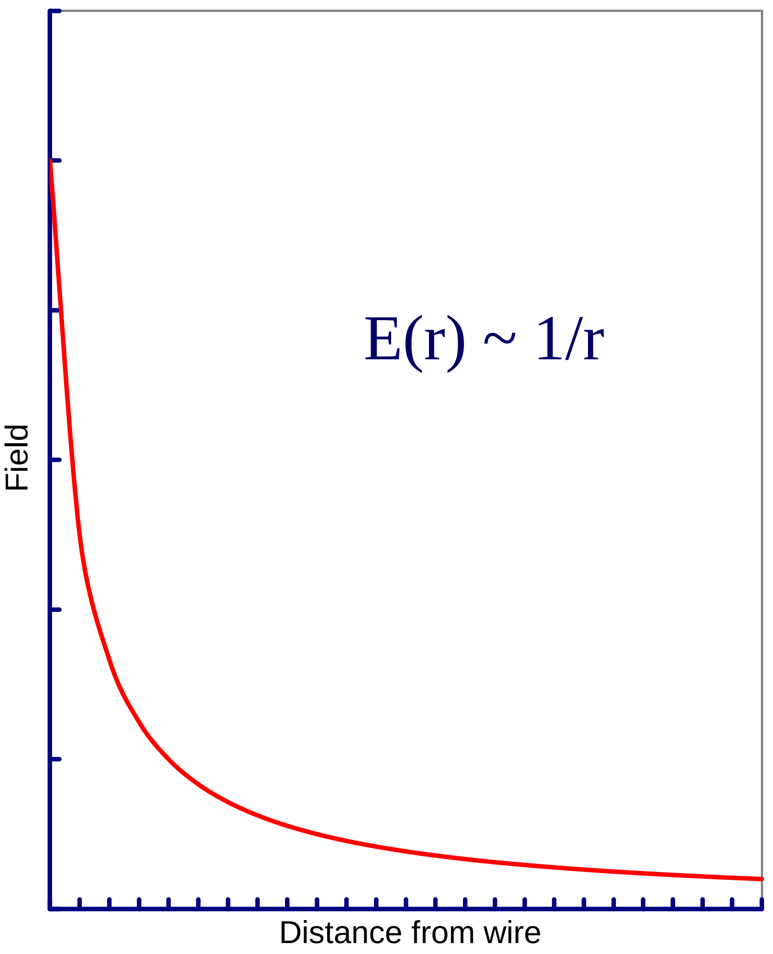


Counting & Integrating SNR = 1

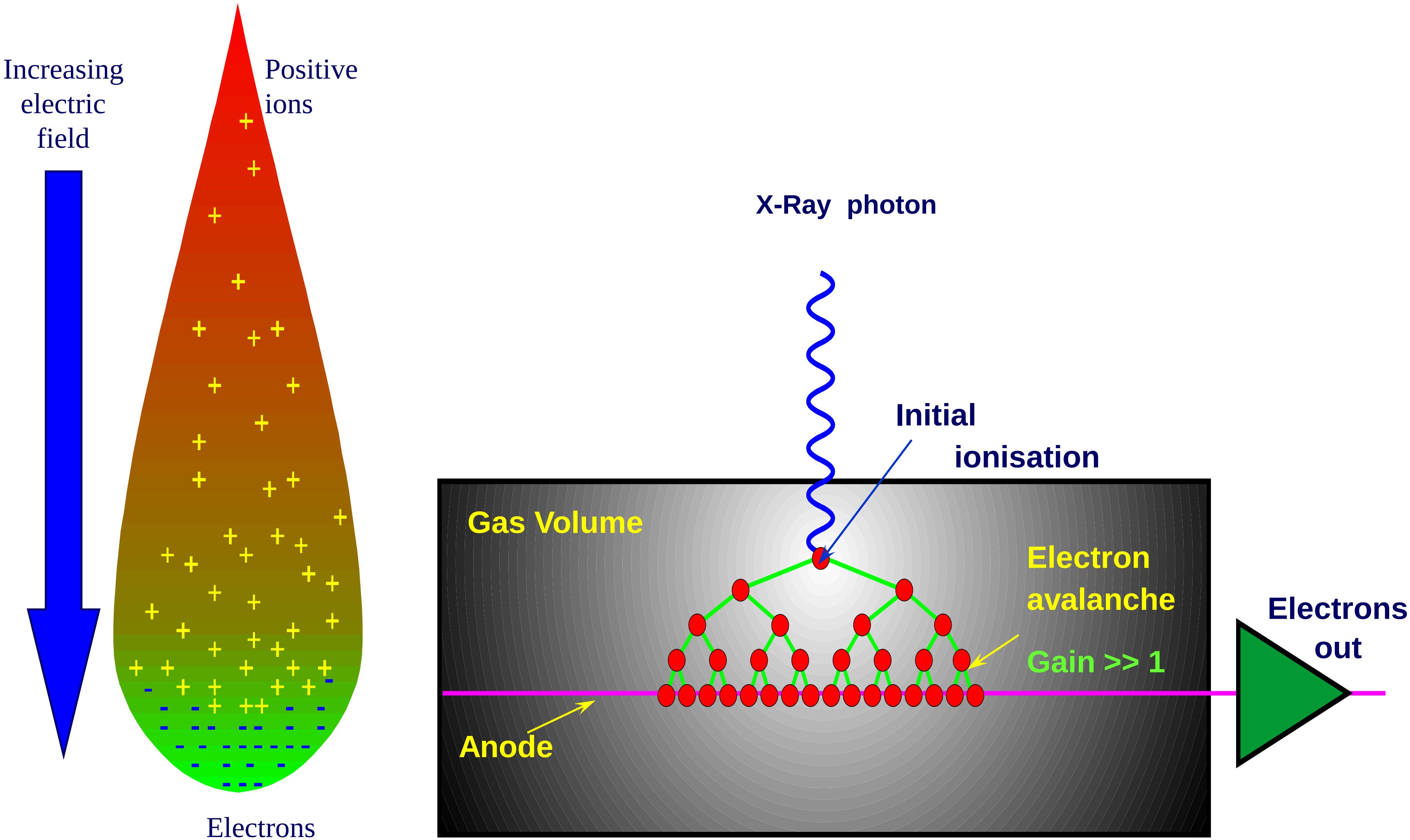


Geiger Tube and Proportional Counter

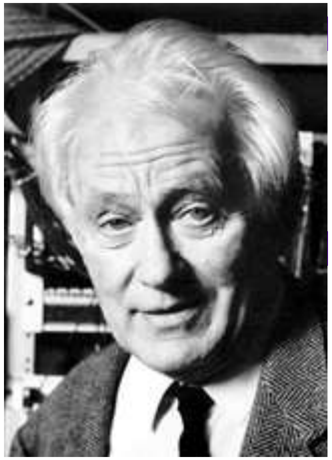




Avalanche & Proportional Counter



Georges Charpak



Which he invented in…..

1968 …….24 years publication to prize!

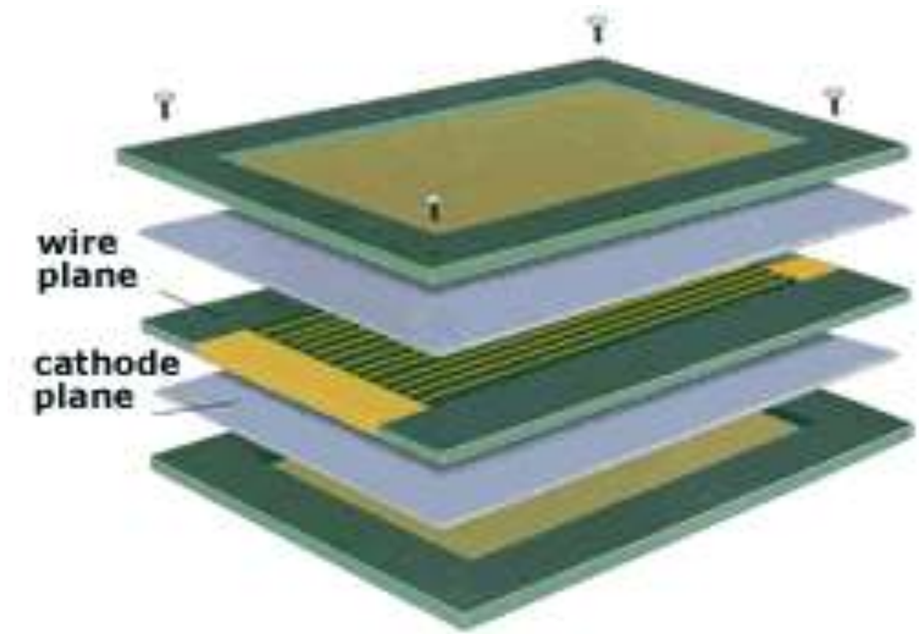
Nobel prize in physics 1992

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

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

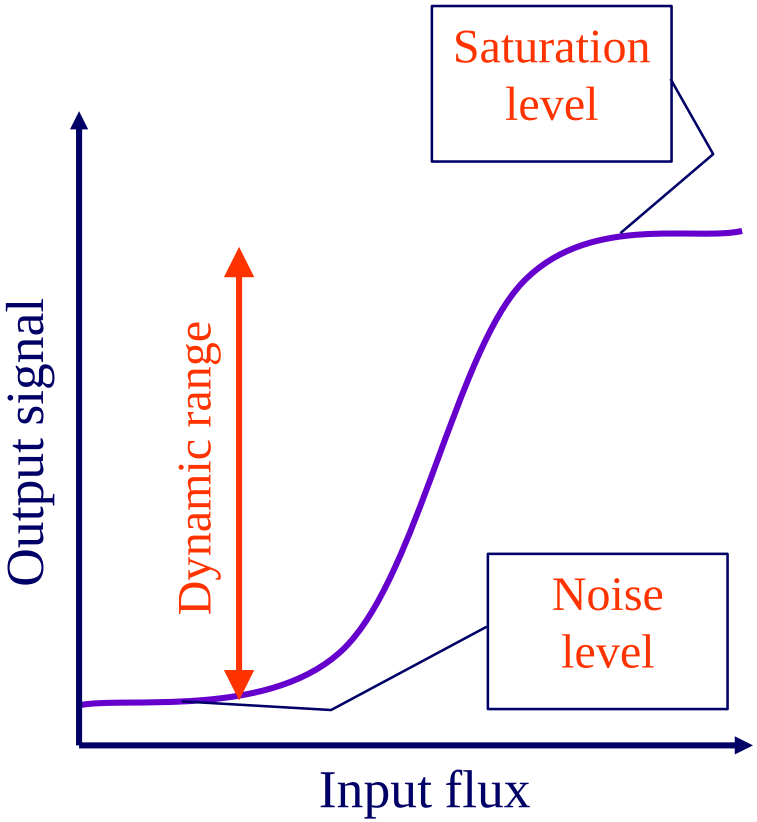
b. 1924
(in Dabrovica, Poland)

Multi-wire Proportional Counter



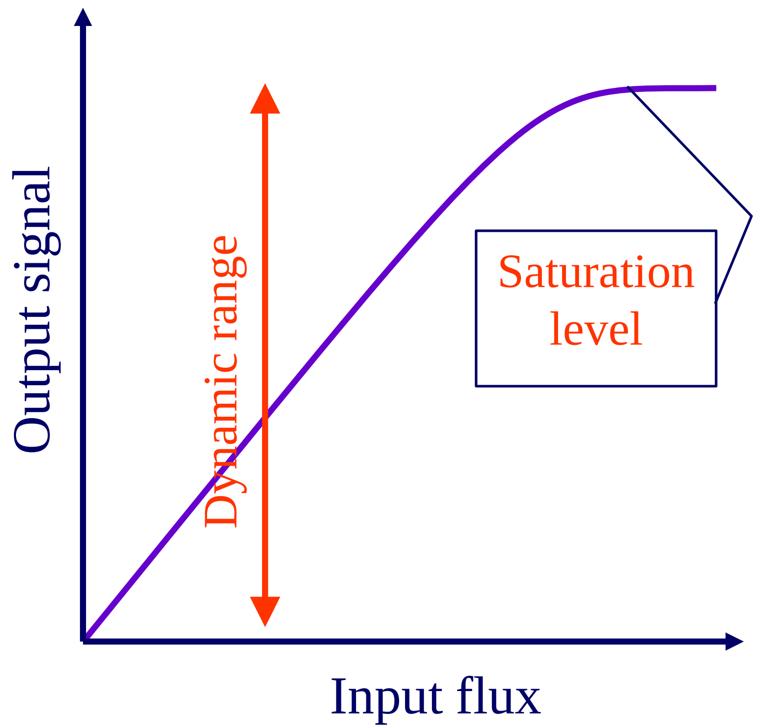
Integrating Detectors

- 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



Counting Detectors

- Mode
  - Detects every particle 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



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

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

We can define $N_{photons}$ that describes real SNR

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

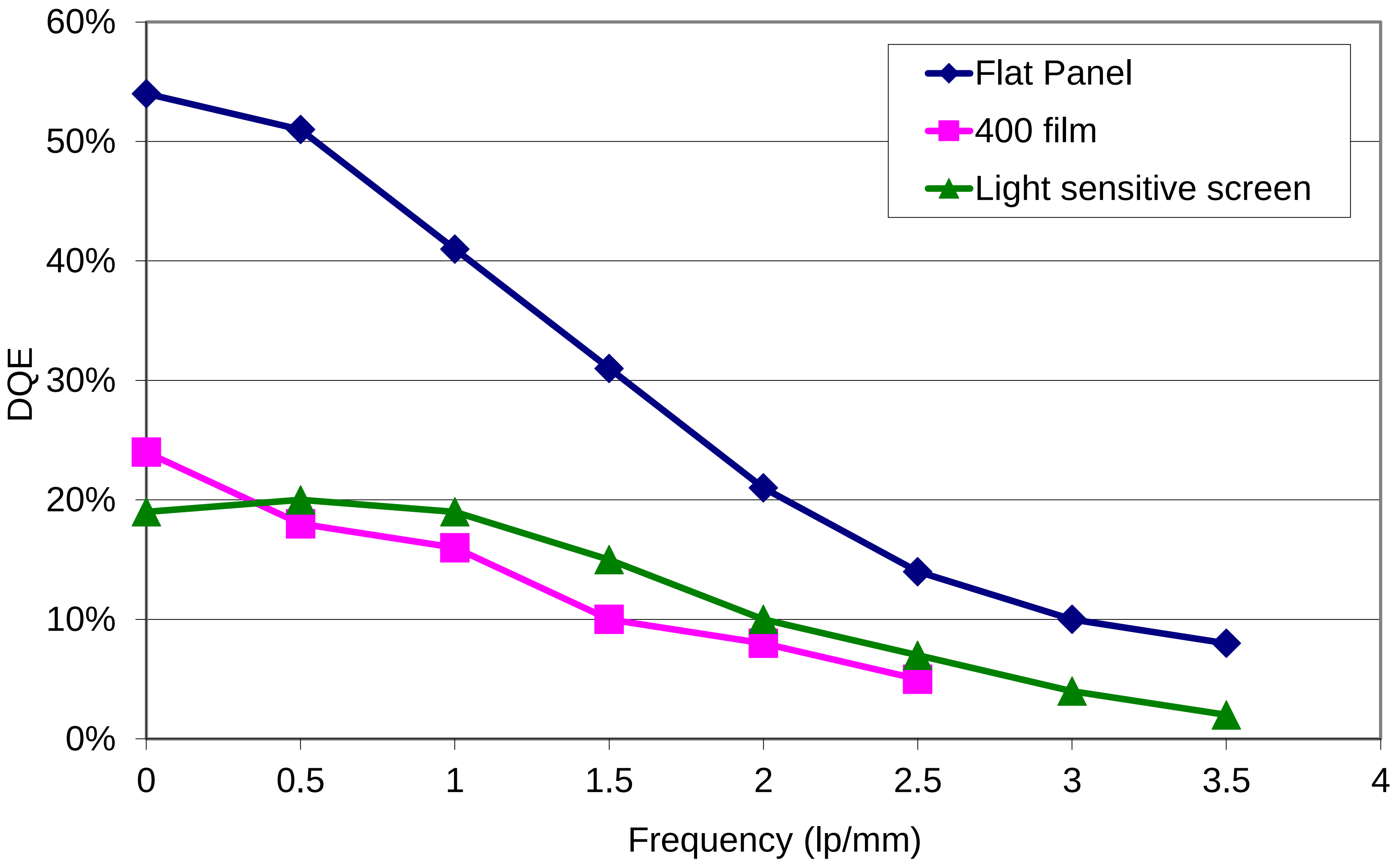
Ratio of NEQ to N_{inc} is a measure of efficiency

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

Note that DQE is f(spatial and spectral frequencies)

DQE Comparison

DN-5 beam
2.6μGy



Willard S. Boyle & George E. Smith

Bell Laboratories
Murray Hill, NJ, USA

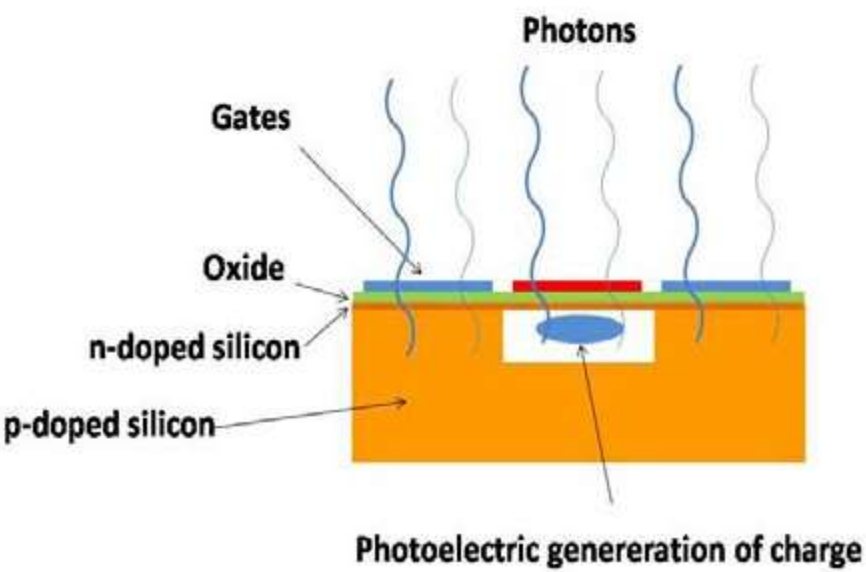
Which they invented in…..

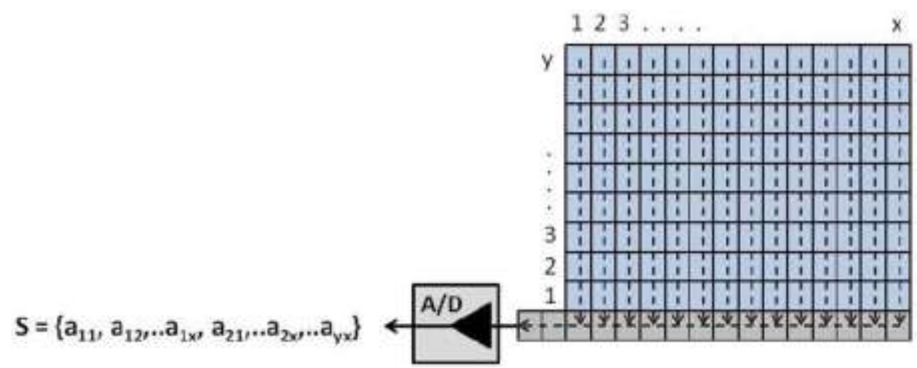
Nobel prize in physics 2009

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

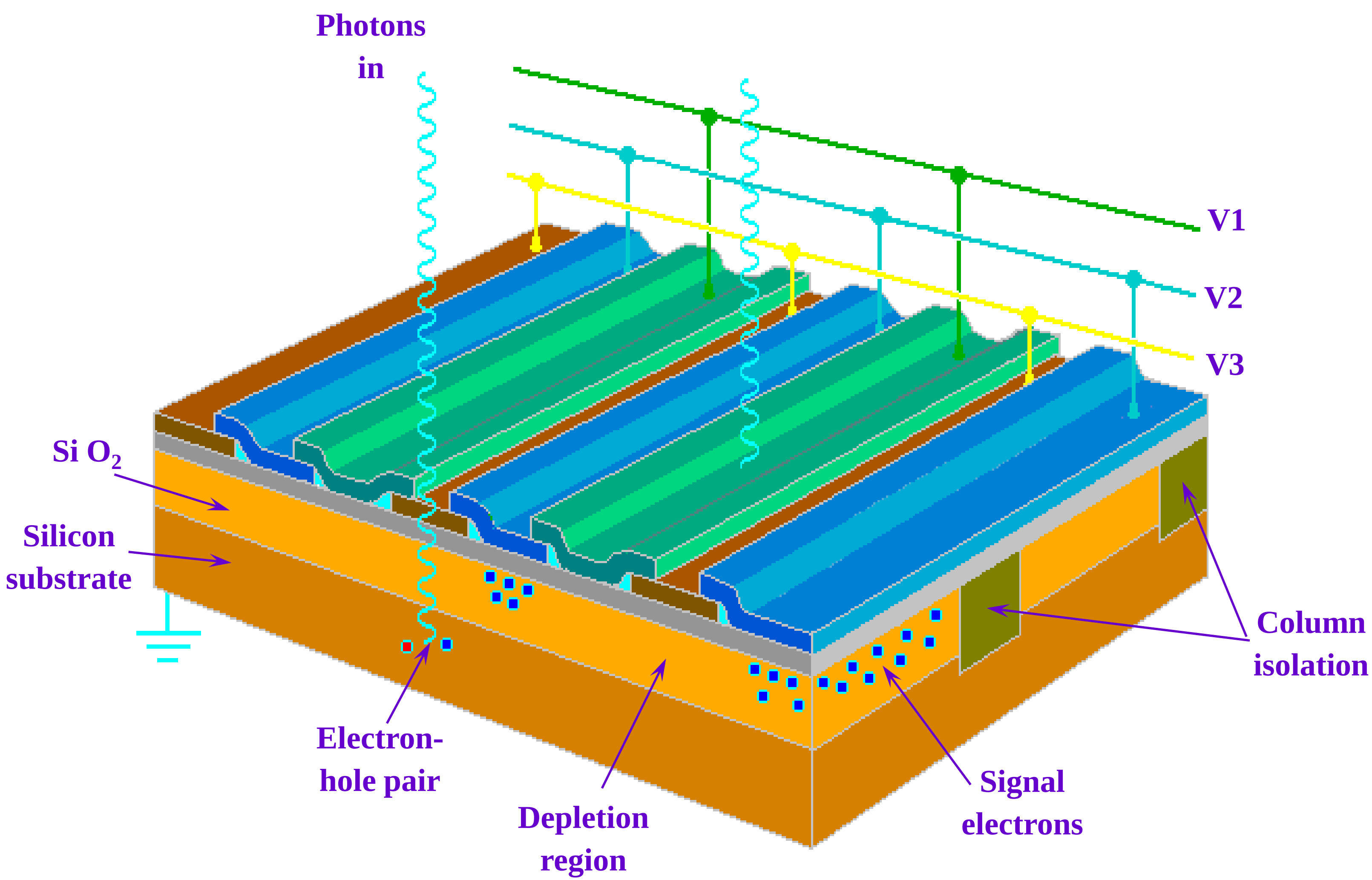
1969 …….40 years publication to prize!

CCD



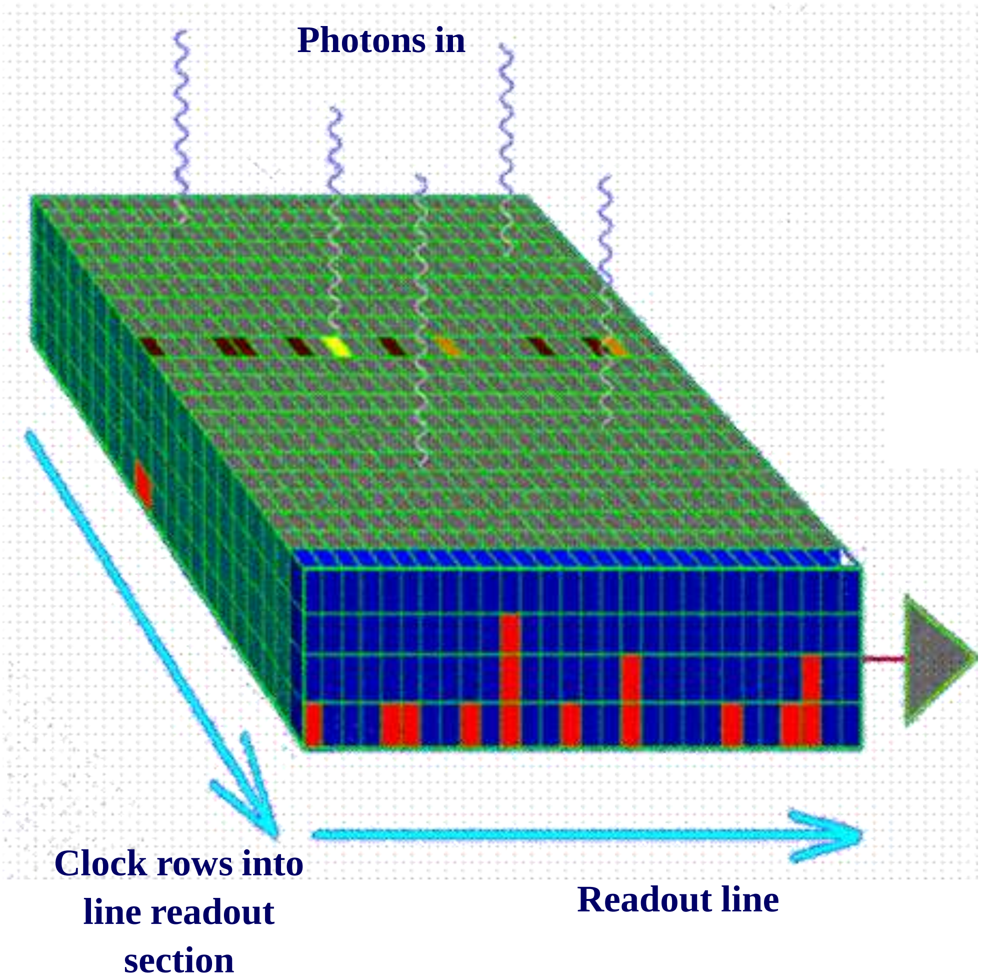


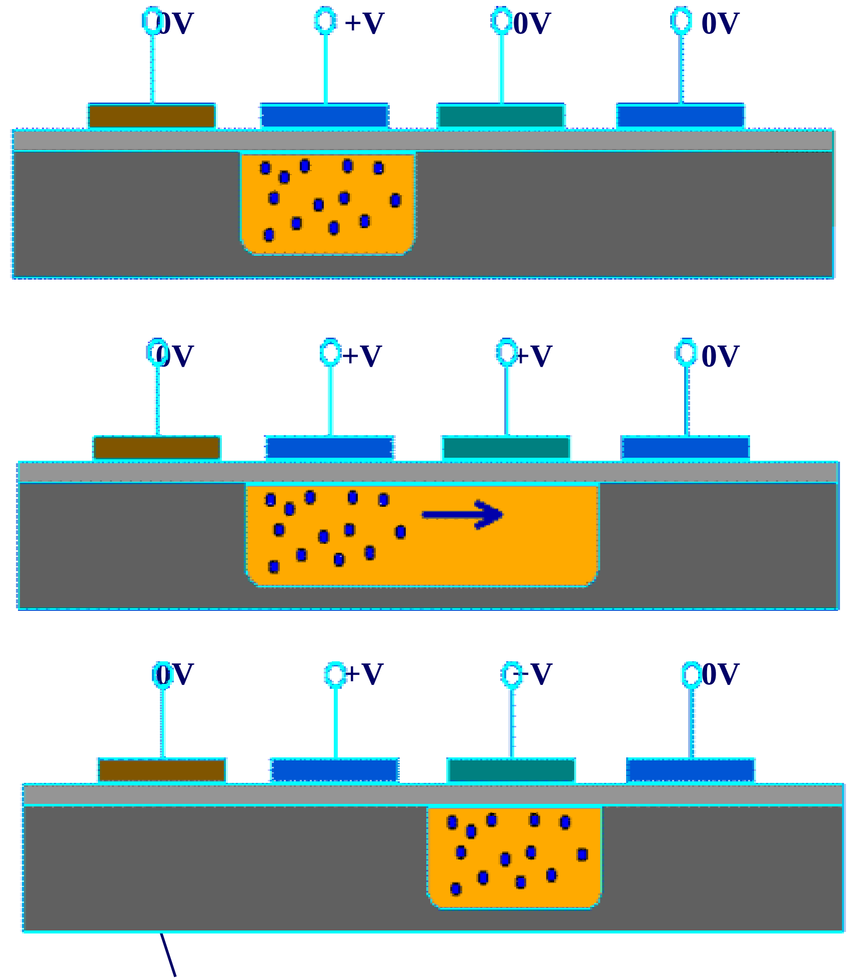
Charge Coupled Device



- 1 optical photon = 1 electron hole pair

CCD Readout



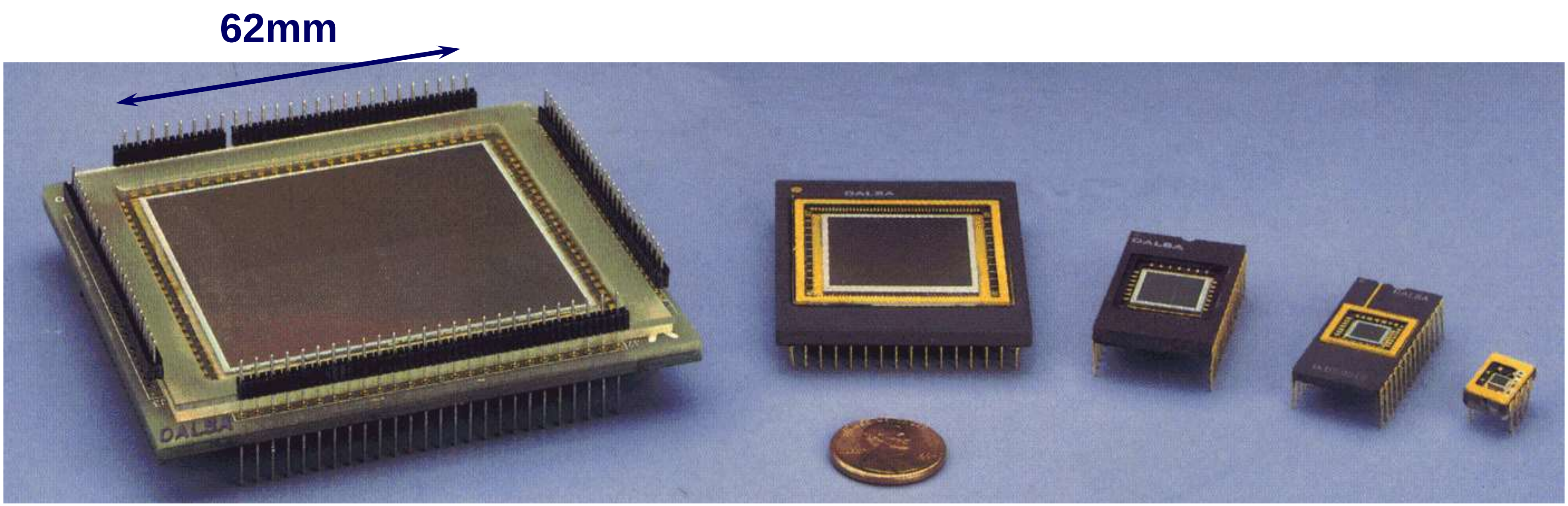


University of Saskatchewan MONASH University

CCD Readout

- Charge is moved from pixel to pixel by clocking
- Pixels have limited capacitance (well depth) ~10^4-10^5 e^-
- This limits dynamic range for direct detection of x-rays
  - 10keV photon creates ~ 3000e^- so saturation = ~ 10 photons
  - 1 optical photon = 1e^-
- Clock speed is restricted by line capacitance and charge transfer efficiency
  - Well depth and size of CCD restricted by this
- Noise can be reduced by cooling
  - Amplifier usually on chip, heats up that part of chip

CCDs



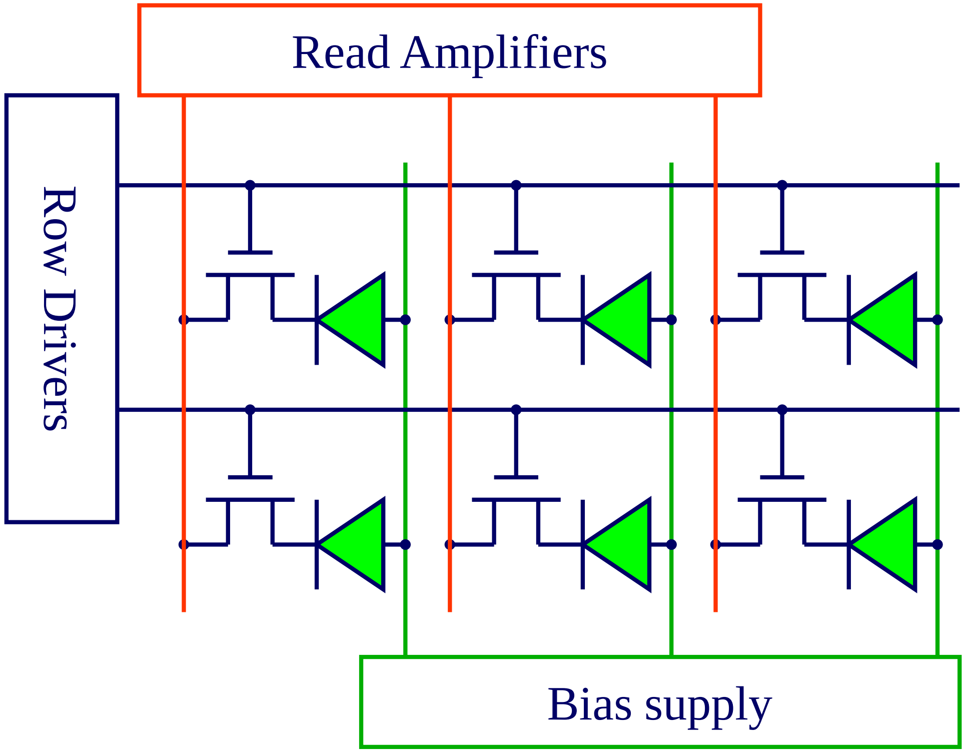
Although sizes > 50mm are available, the read speed is slow to preserve low noise and charge transfer efficiency (line capacitance becomes very high)

Shutter required

Agilent S2 CCD with Smart Sensitivity

- The S2 CCD detectors employ groundbreaking Smart Sensitivity Control, which tunes detector sensitivity to match the strength of the data observed. Similar to ISO settings in digital photography, this selects the widest dynamic range or the highest sensitivity, as needed, to maximize your data quality.

Complimentary Metal-Oxide Semiconductor (CMOS)

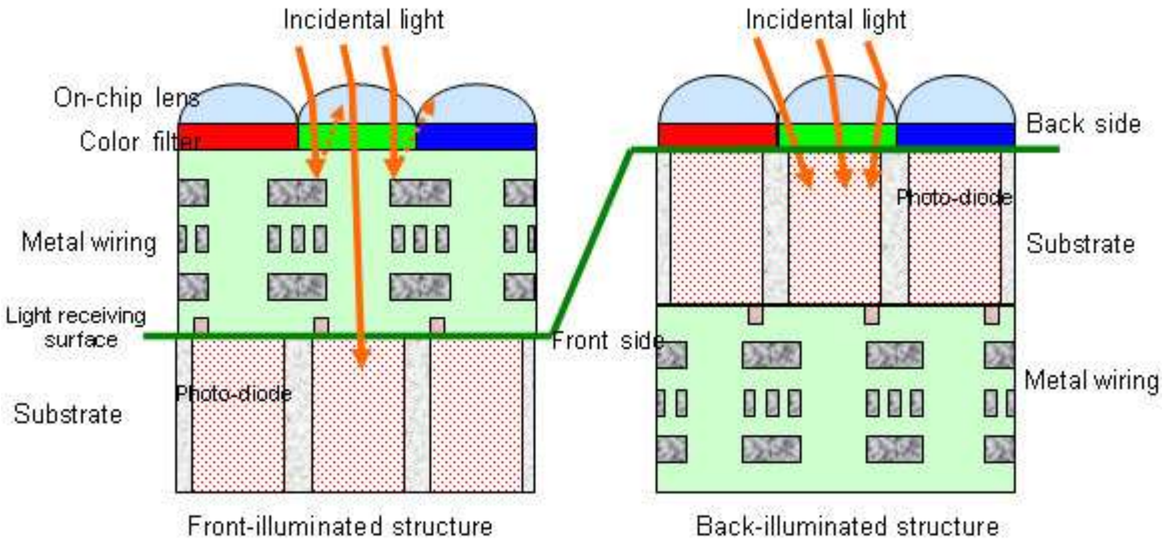


- A readout amplifier transistor on each pixel converts charge to voltage
- Allows random access to pixels, similar to the row-column memory cell access in RAM

CMOS vs CCD

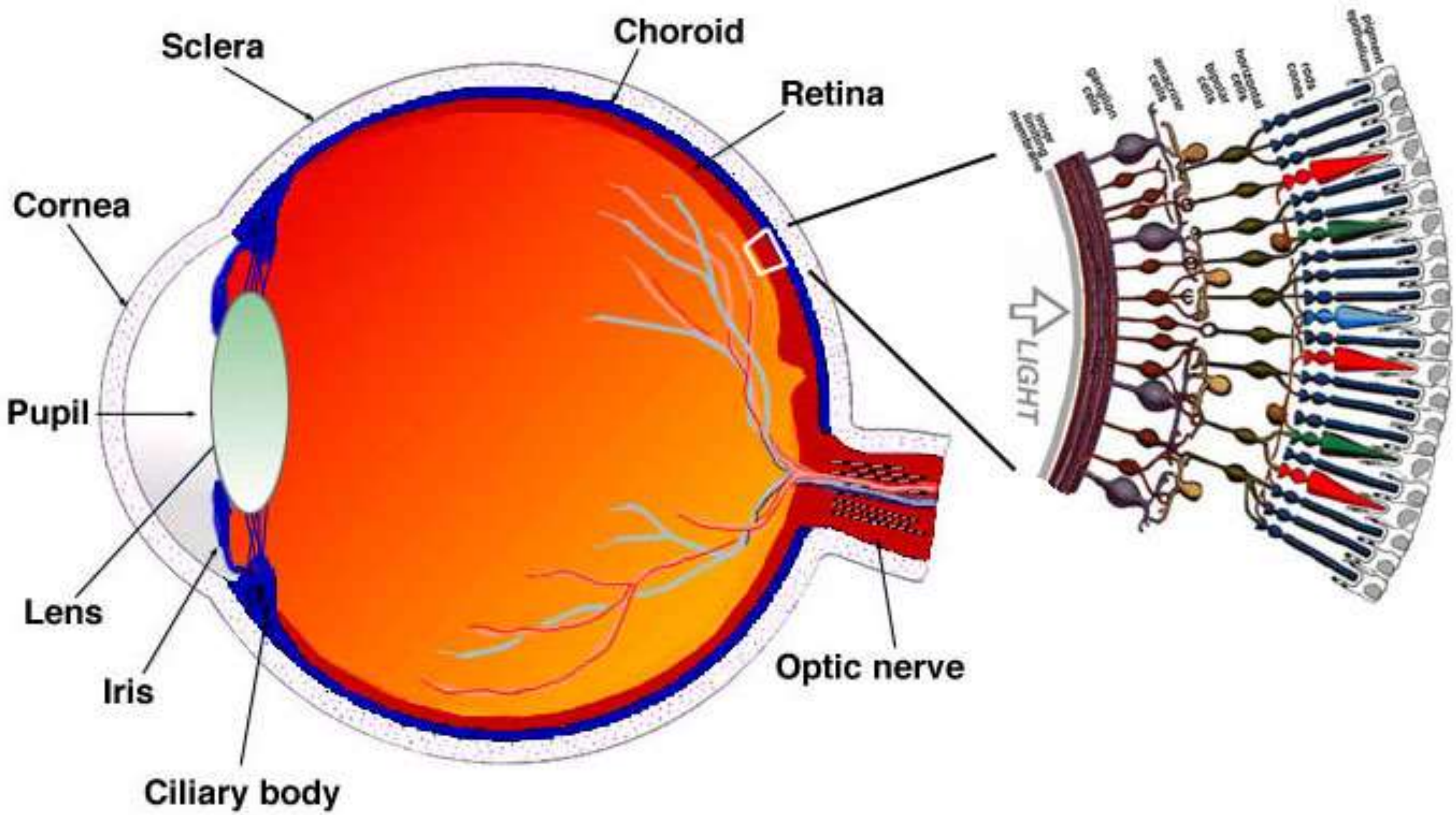
- Traditionally CCD has had higher sensitivity and lower noise
- Modern techniques mean that the differences are small
- CMOS sensors can have much more functionality on-chip than CCDs
  - On chip image processing, edge detection, noise reduction, and analog to digital conversion
- CMOS lower power → less heat → less noise

Front and Back Illumination



http://www.sony.net/SonyInfo/News/Press/200806/08-069E/index.html

Human Eye

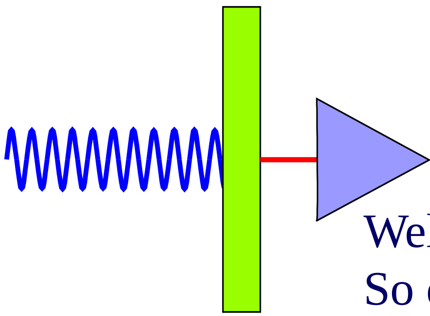


http://webvision.med.utah.edu/imageswv/Sagschem.jpeg

Use with X-rays

Direct detection

Gain ~ 2000e⁻ / 8keV x-ray



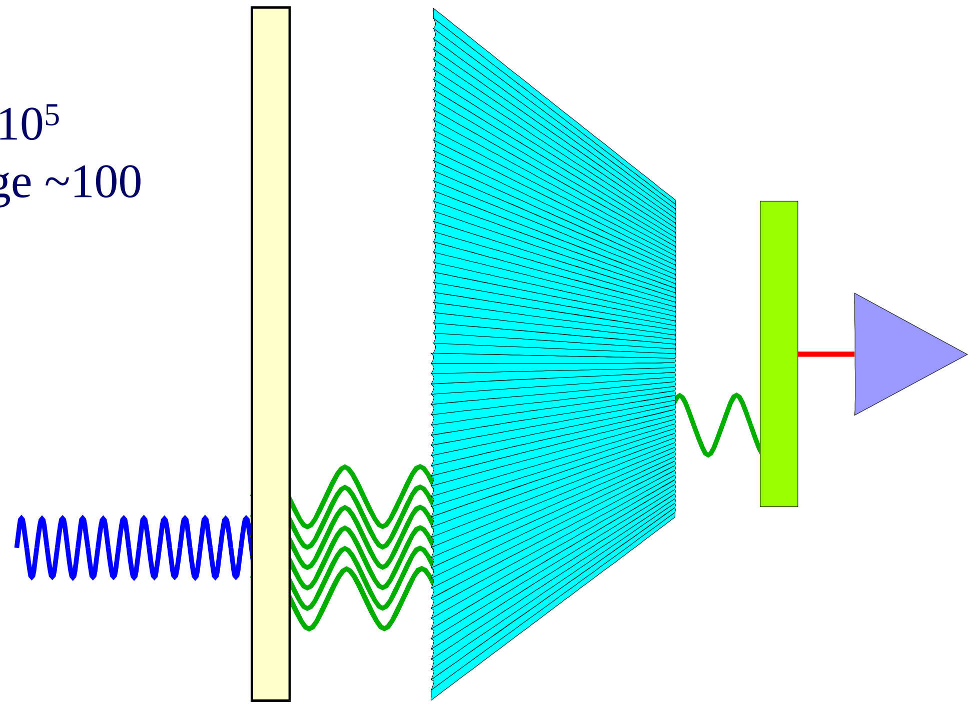
Well depth = 2×10^5

So dynamic range ~100

Phosphor coupled with reducing optics to sensor

Phosphor gain >> 1

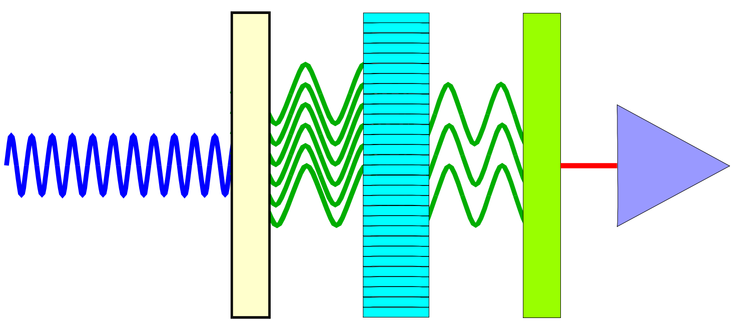
Optics Gain << 1



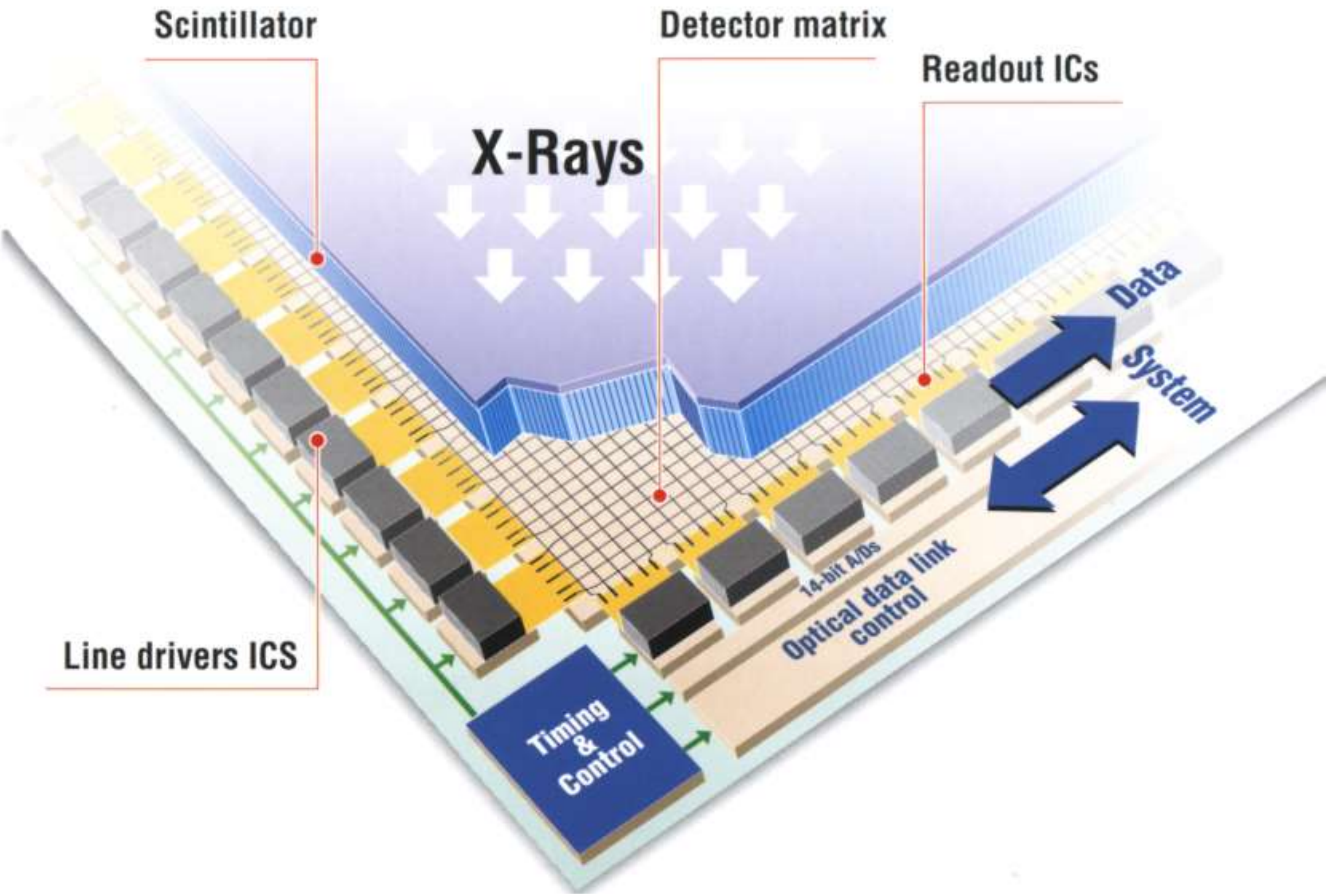
Phosphor coupled 1:1 to sensor

Phosphor gain >> 1

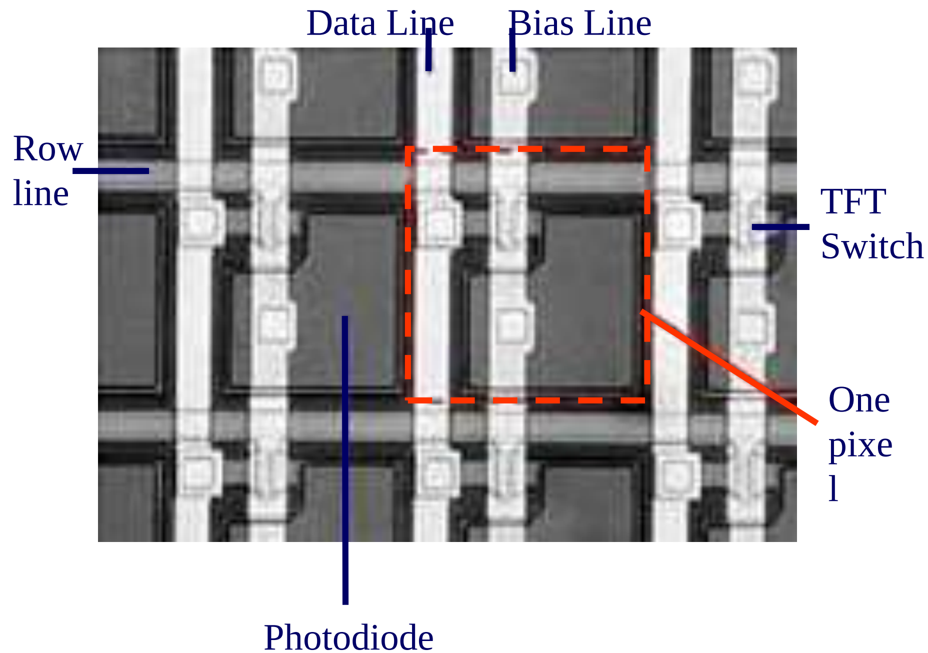
Optics Gain < 1

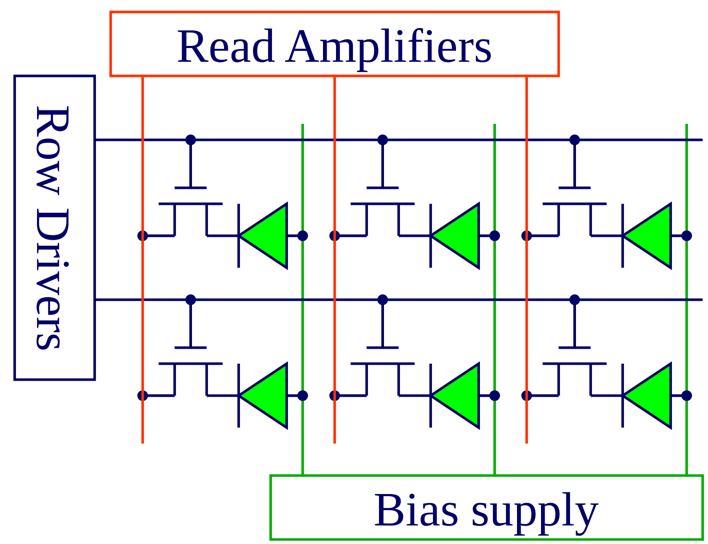


TFT Flat panel Detector



a-Si:H Array dpiX - Flashscan 30





Big CMOS

Gpixel INC. GMAX3005

150 Megapixels Full-Frame CMOS Image Sensor - GMAX3005

SCALE 1:1

Specifications

Gpixel INC.

GMAX3005

SENSOR SPECIFICATIONS

Photon-sensitive area	165mm(H) x 27.5mm(V)	SNR Max	43dB
Pixel size	5.5µm×5.5µm	Dark noise	3.94e-
Resolution	150MP - 30,000×5,000	Dark current	<10e-/s/pix (32° C)
Shutter type	electronic rolling shutter	Dynamic range	67dB (Intra-scene)
ADC	16bit	Dynamic range	75.4dB
Main clock rate	20MHz ~30MHz	Sensitivity (PGA=5.6x)	255DN/nJ/cm^2
Frame rate	10fps @ full frame	Full well charge	23000 e-
Data rate	24Gbit/s @10fps	Output interface	120 LVDS pairs
Supply voltage	3.3V / 1.8V	Operating temperature	-55° C ~ +85° C
Max Power	2.5W	Package	395 pins PGA

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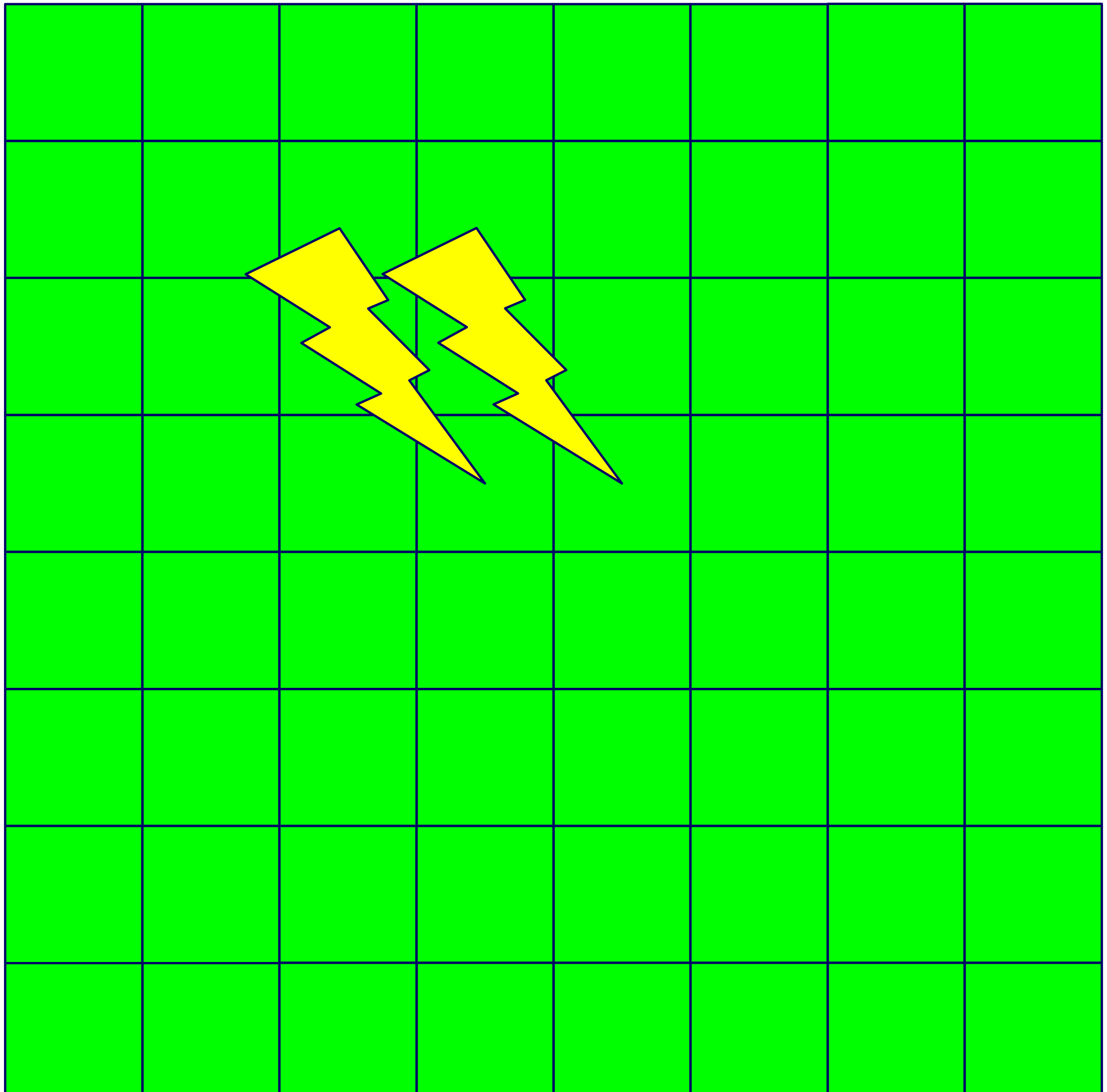
Resolution is NOT pixel size



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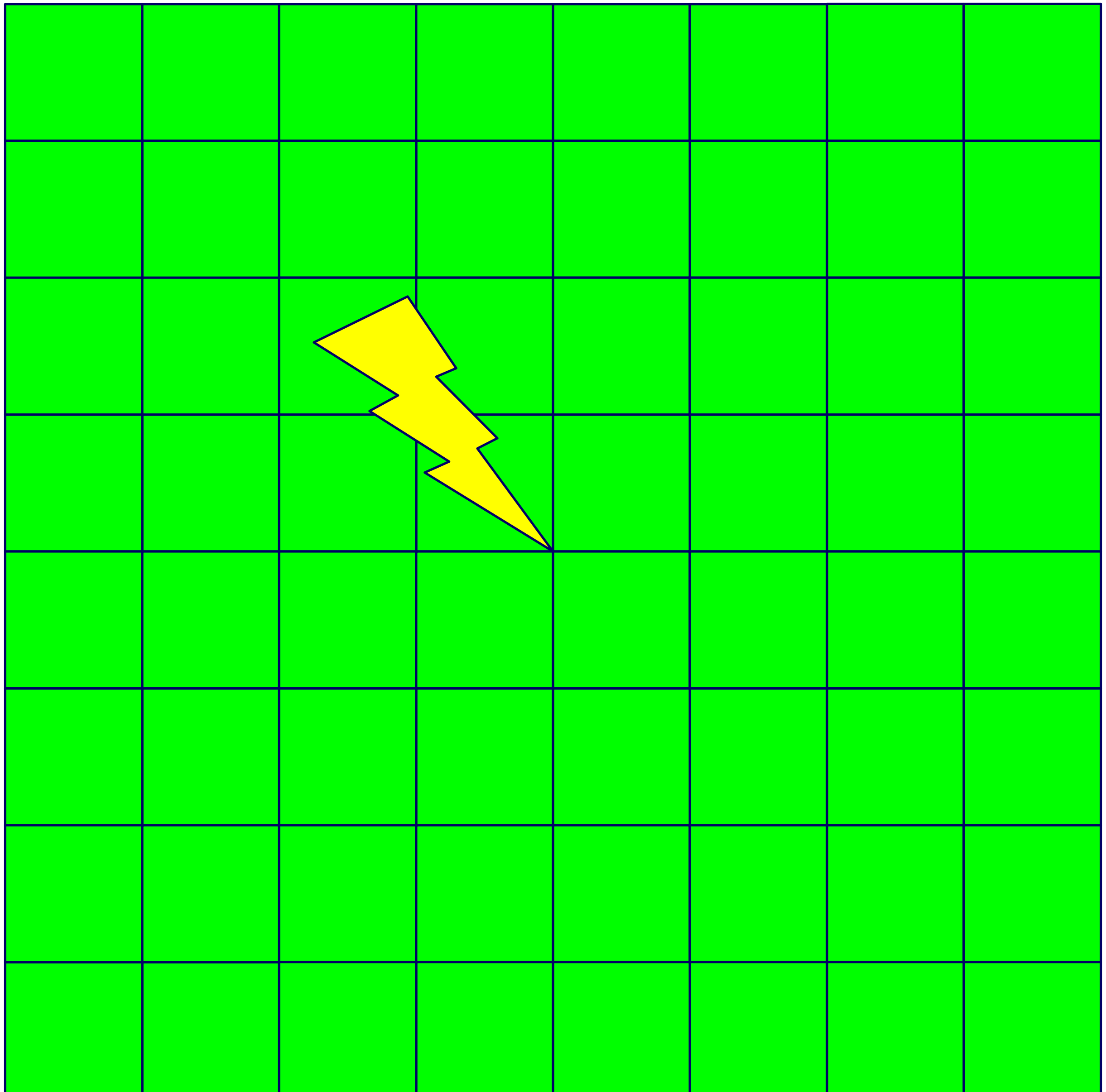
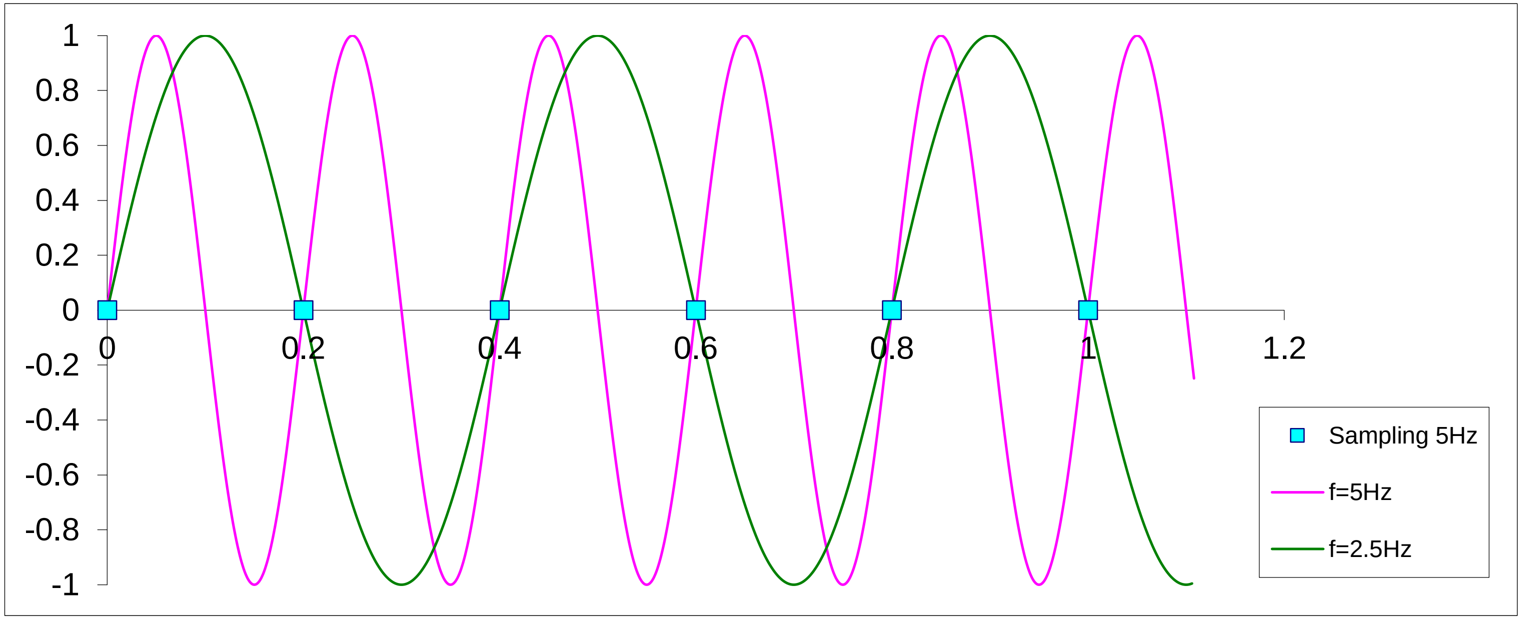
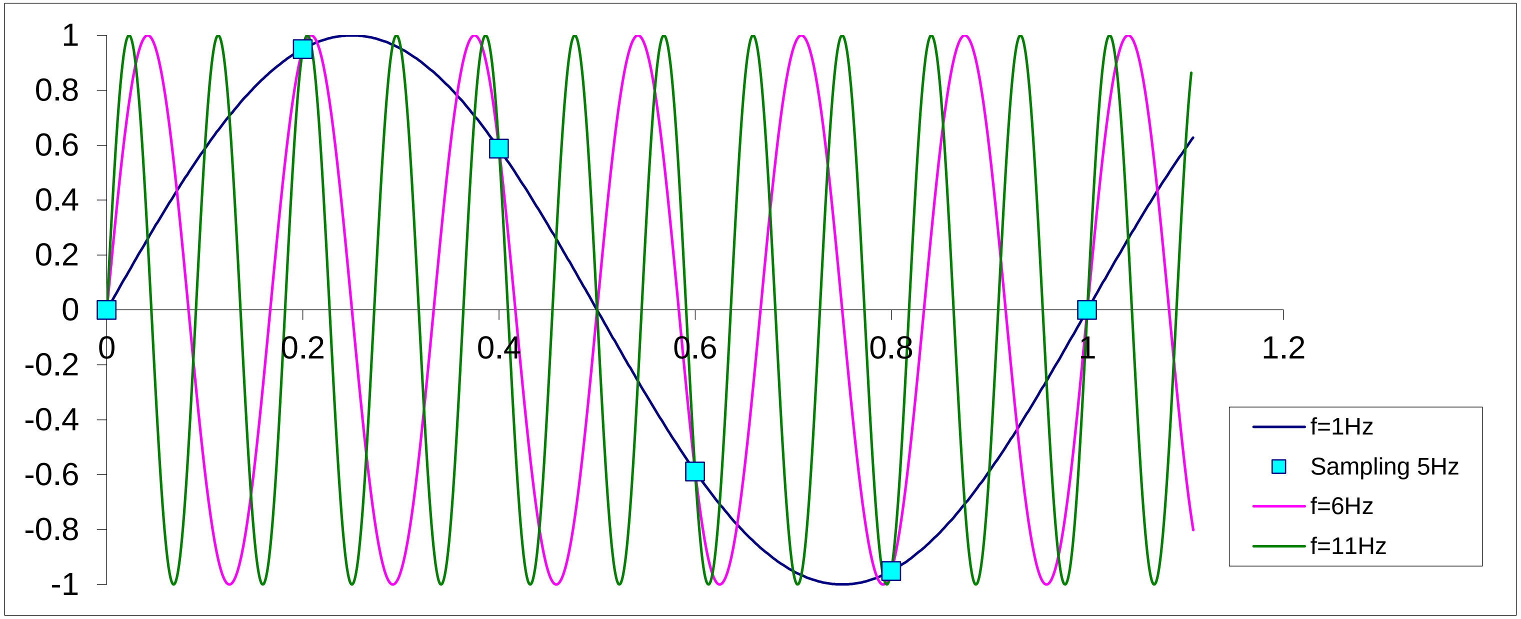


Sampling



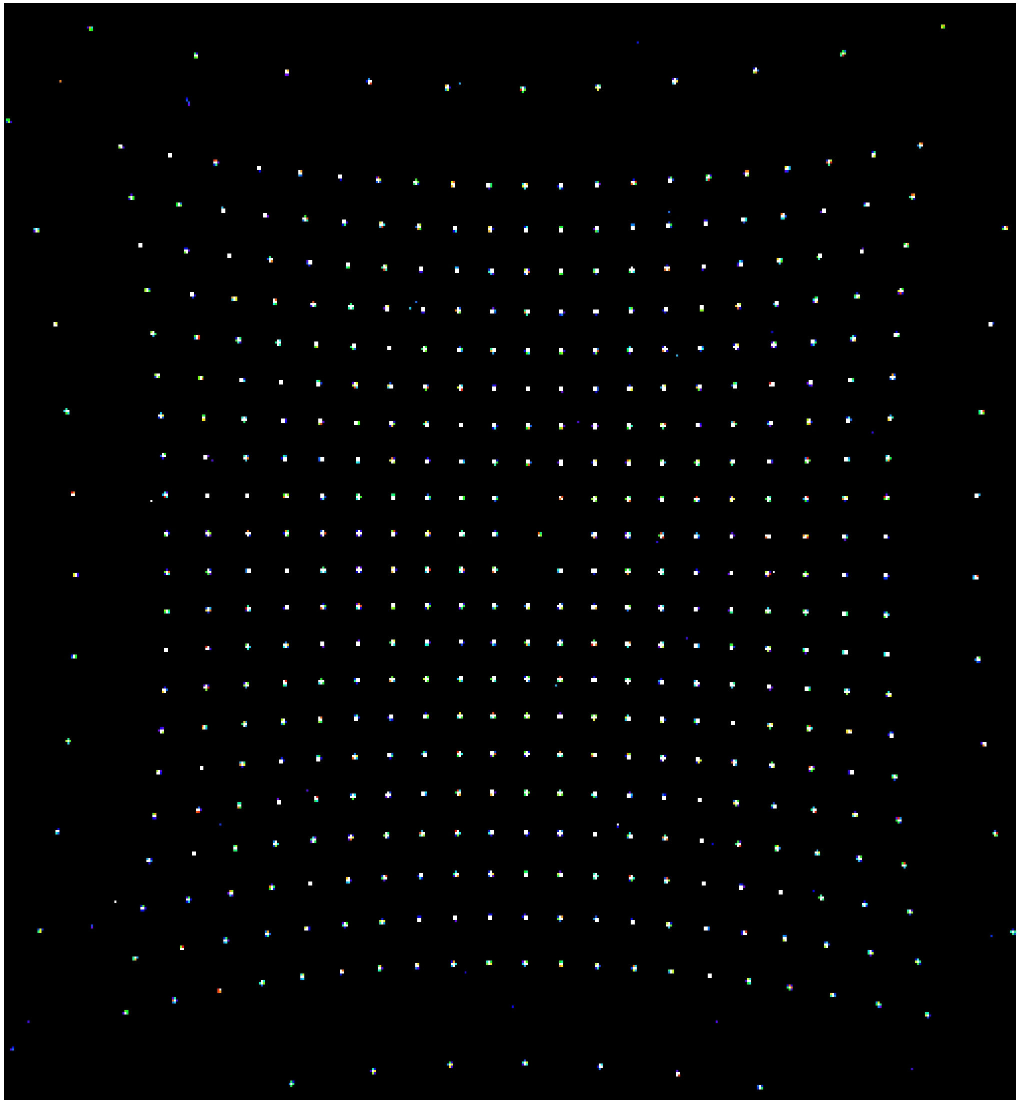
- Shannon’s Theorem and Nyquist Criterion
  - The highest frequency that can be ‘measured’ is HALF the sampling frequency

Aliasing



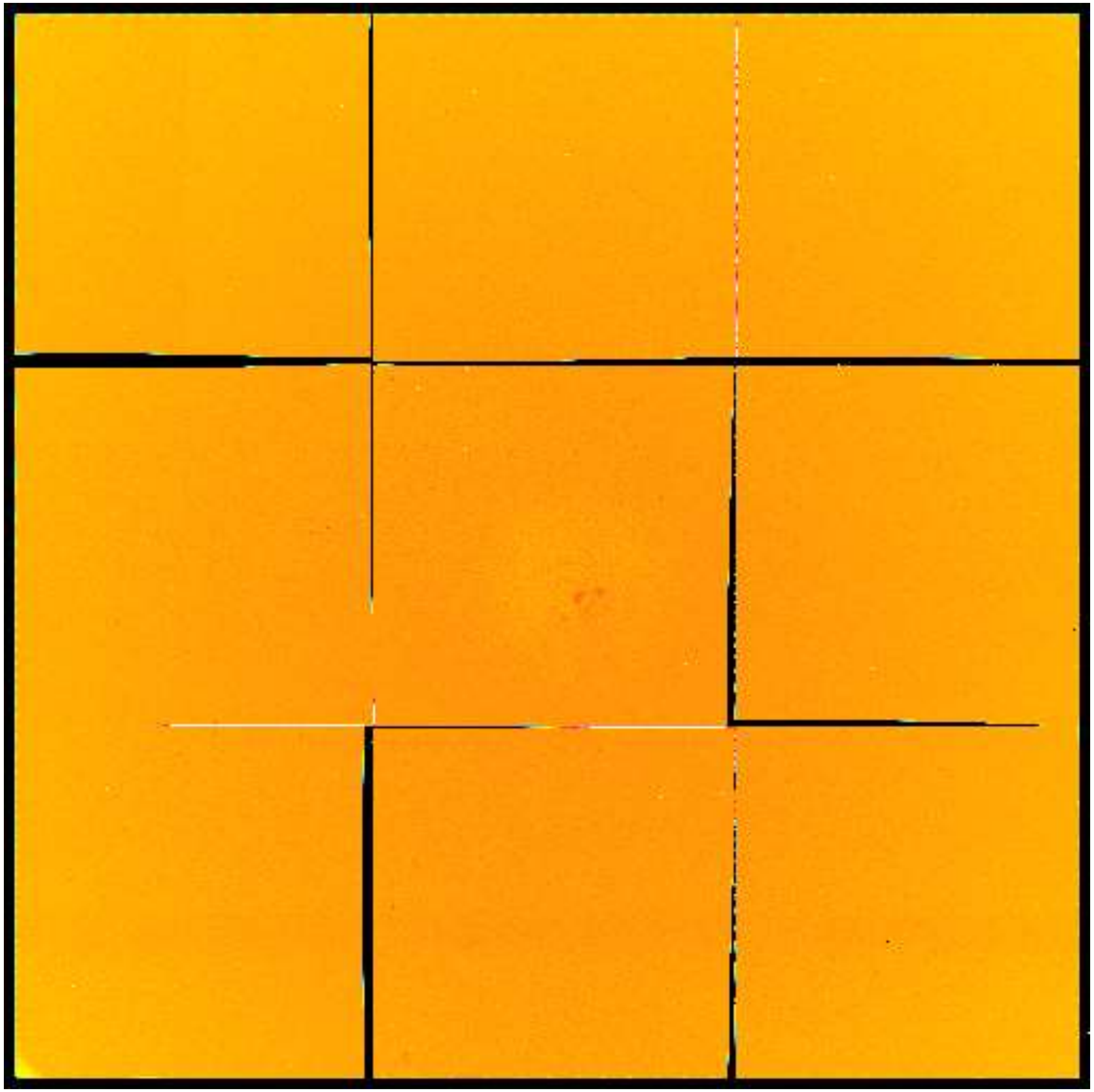
- If the input is not band limited to frequencies less than $f_s/2$, then aliasing will occurs at frequencies $f \pm nf_s$
  - where f = signal frequency, fs = sampling frequency, n = integer
- If you have 100µm pixels, the very best spatial resolution that you can expect (in the absence of noise) is 200µm
- In any real system > 200µm
- And that is all assuming NO DISTORTIONS!!

Spatial distortion x = f(y)



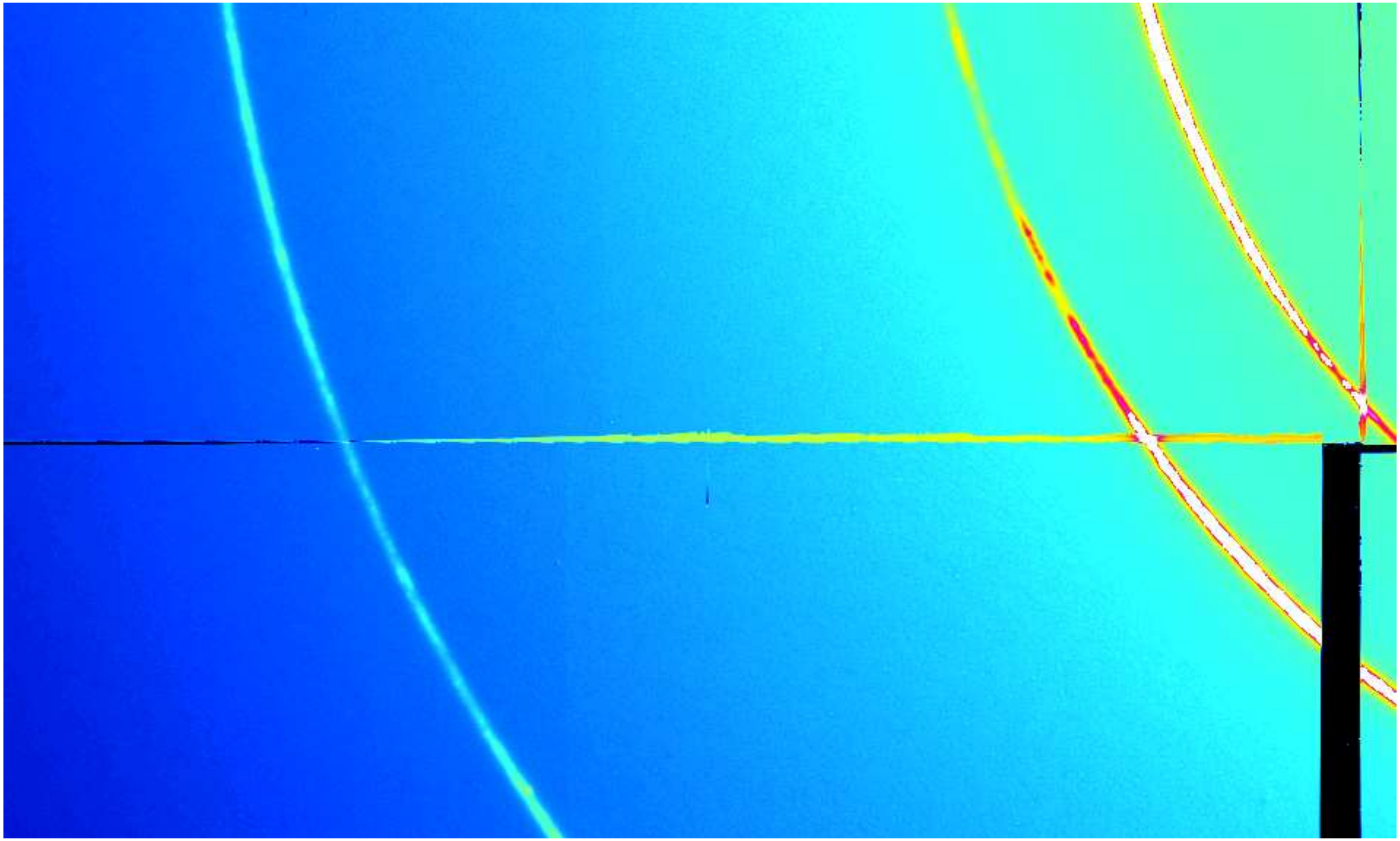
ESRF Image intensifier detector

Gaps



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

Overlaps



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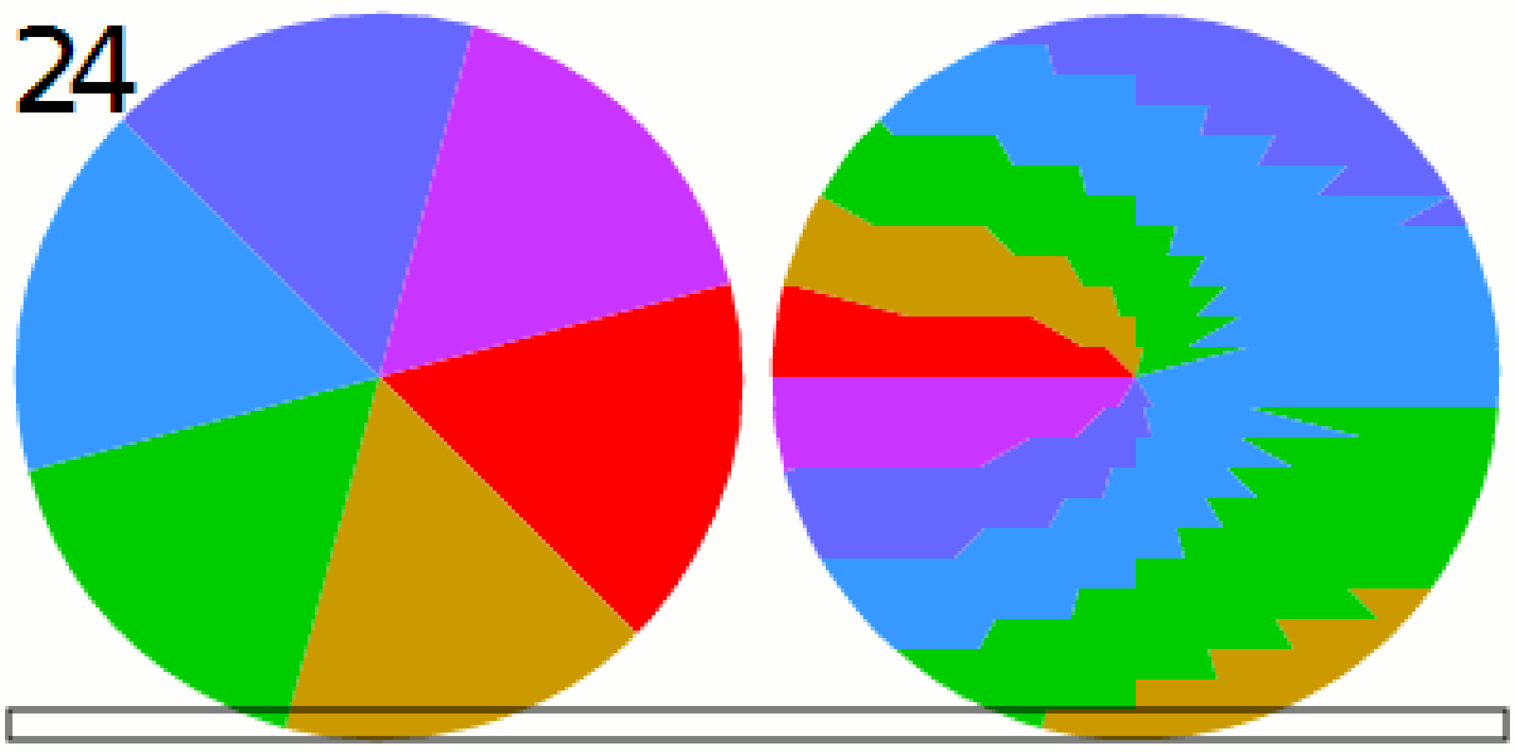
Electronic Rolling Shutter



https://en.wikipedia.org/wiki/Rolling_shutter

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Max Power	2.5W	Package	395 pins PGA

Data Rates

- 120 LVDS pairs at 200Mbps = 24Gbps
- Interfaces
  - USB2: 480 Mbps
  - USB3: 5 Gbps
  - USB3.1: 10 Gbps???
  - SATA III: 6 Gbps
  - Thunderbolt 2: 10 Gbps
- Disk write speeds
  - HDD: 200 Mbps
  - SSD: 530 Mbps
- So 45 SSDs required to store data!!!!

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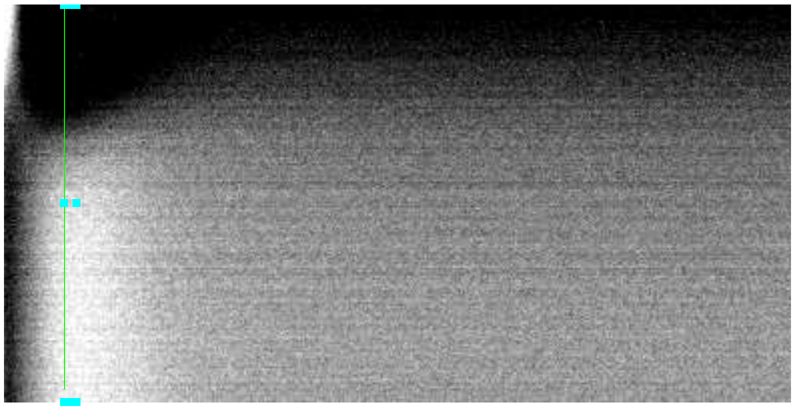
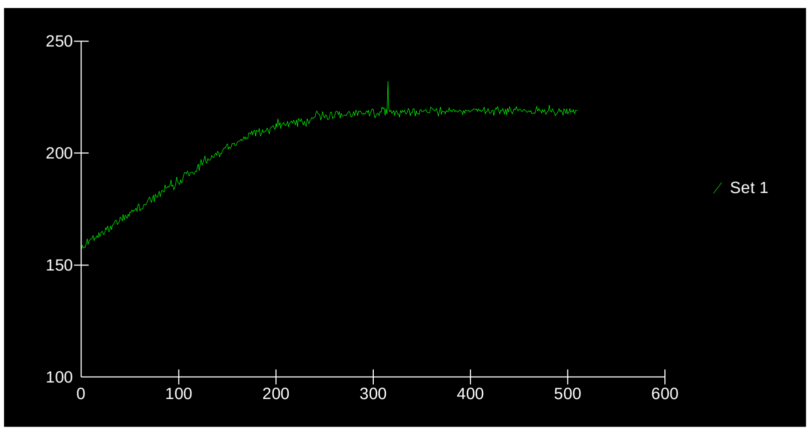
Supply voltage	3.3V / 1.8V	Operating temperature	-55° C ~ +85° C
Max Power	2.5W	Package	395 pins PGA

Dark Current

- Dark current is the signal produced under zero illumination
- Dark noise is a measure of the fluctuations in dark current
- Dark noise sets the minimum detectable signal

Dark Currents





Flat and Dark Correction

For each image, two correction images must be recorded.

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

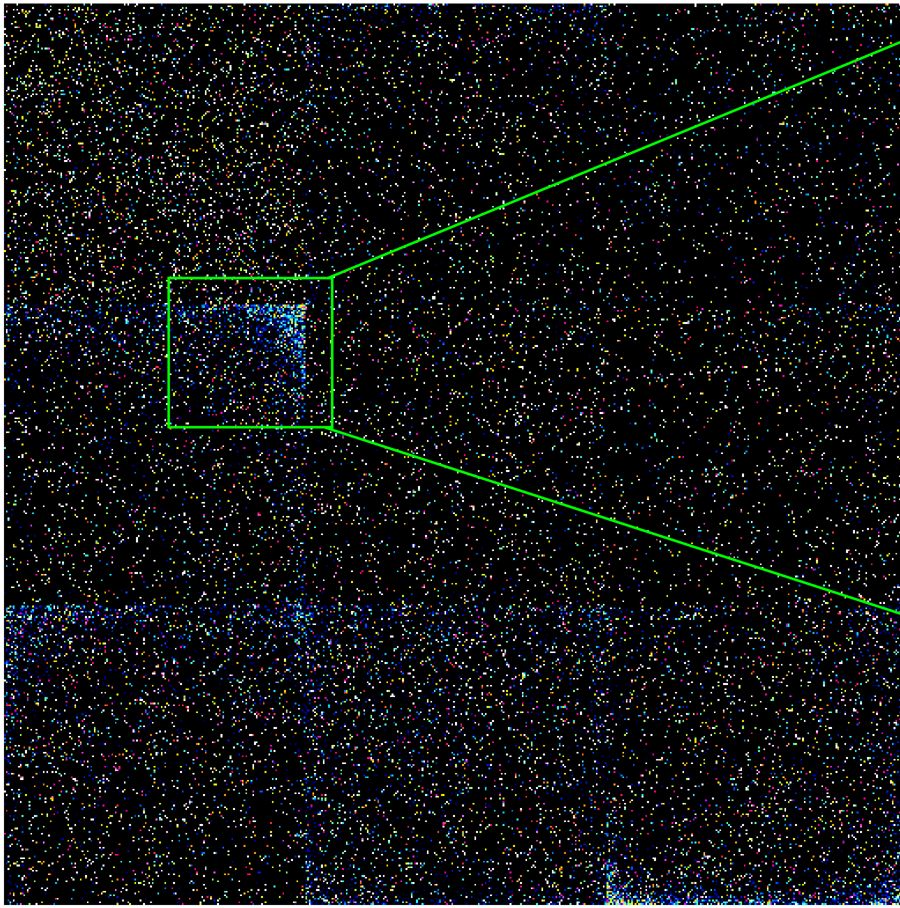
2. A dark image (no irradiation of detector)

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

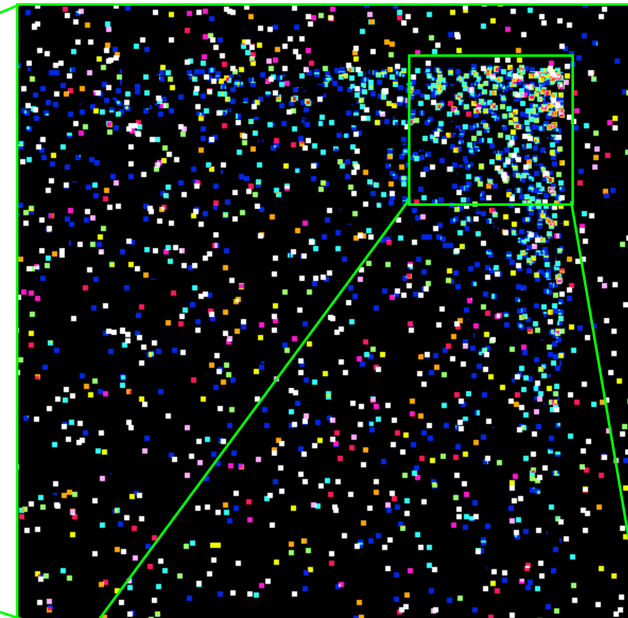
Then apply the following correction

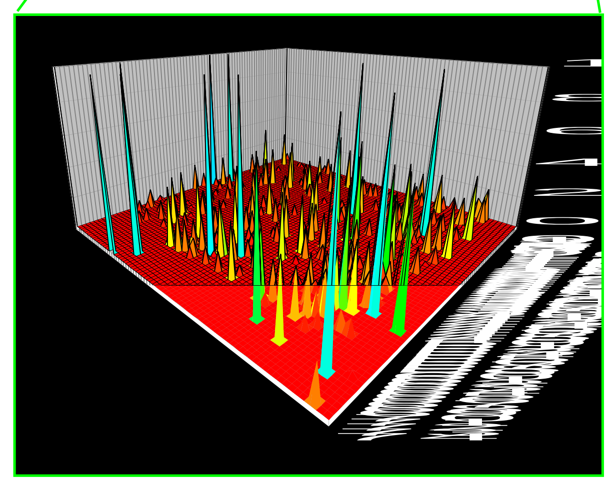
$$Corrected = \frac{(image - dark)}{(flat - dark)}$$

Dark Current



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



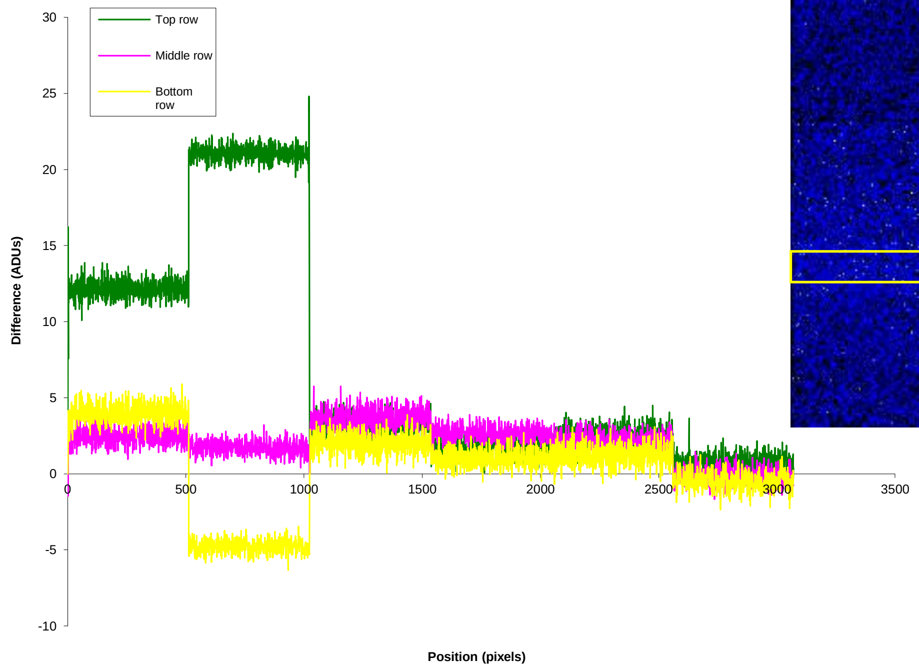


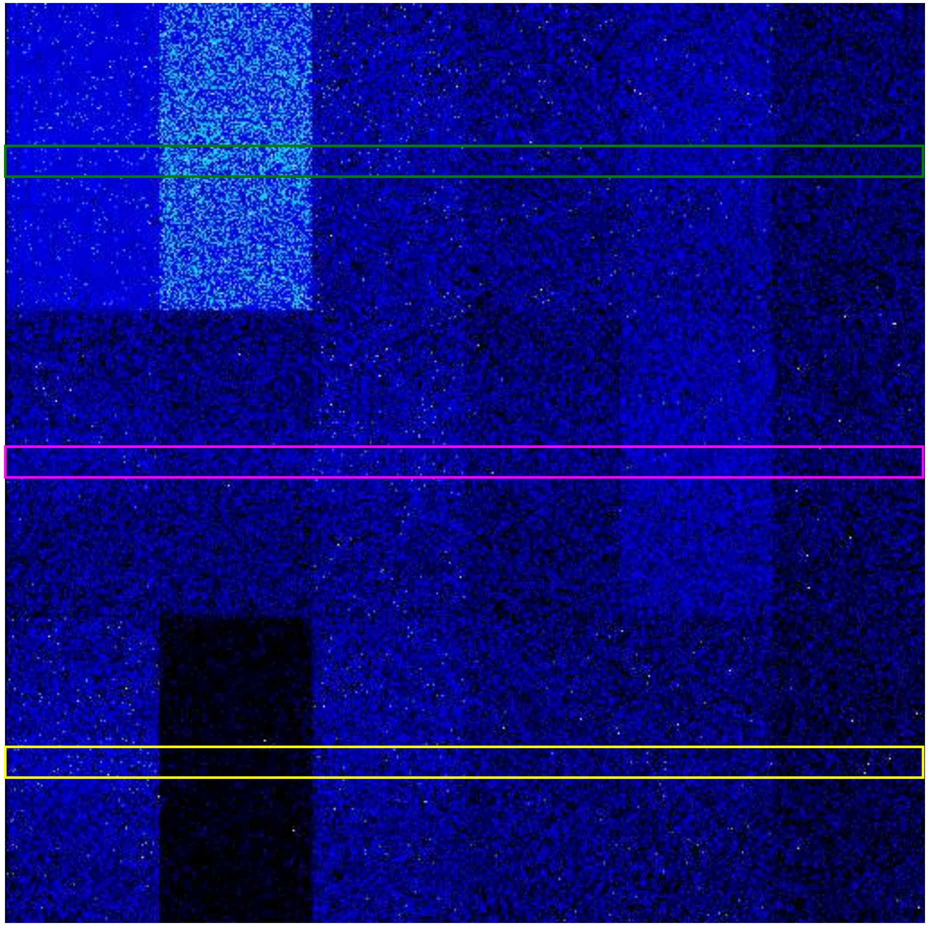
Number failing 2 measurements 5-2000s

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

nb. 14300 pixels not common to both

Subtraction of dark images

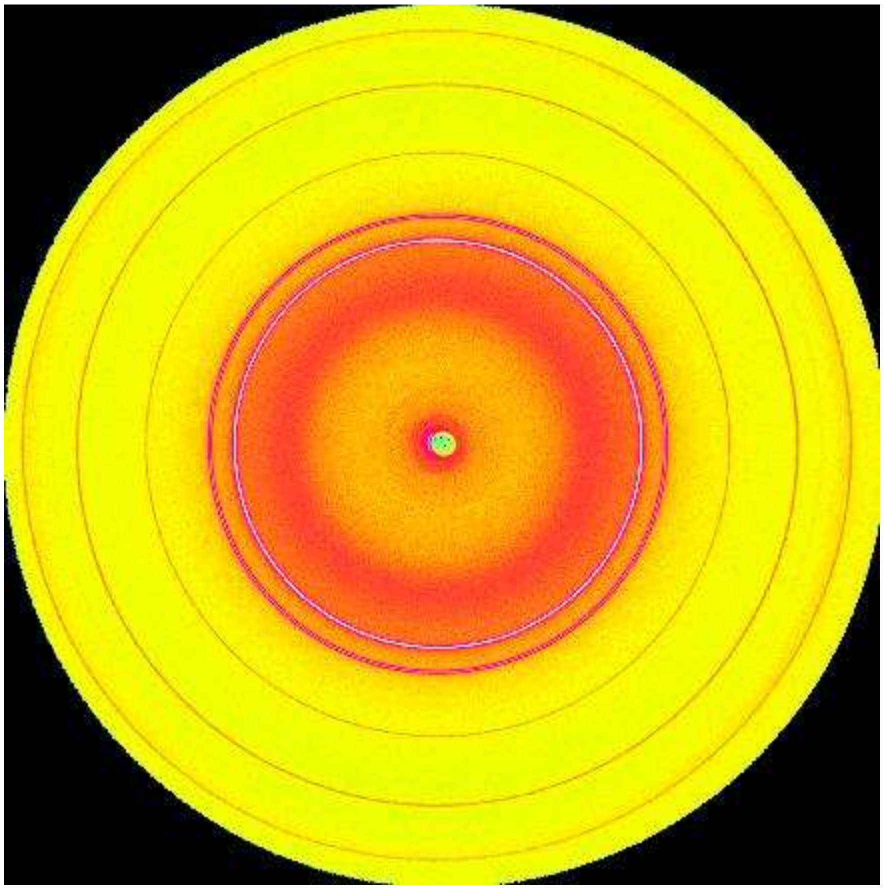




dpiX Flashscan 30 PaxScan 4030

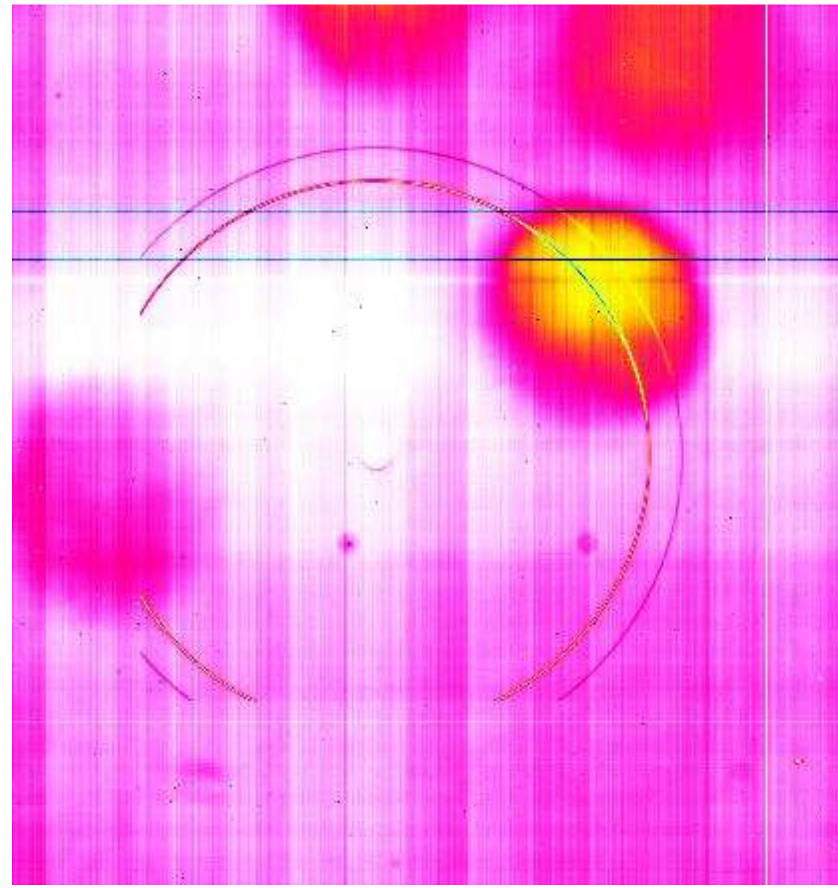
Flashscan 30 - Performance

Mar Image Plate



t_{int}=30s

Flashscan-30



t_{int}=190s

Specifications

Gpixel INC. GMAX3005

SENSOR SPECIFICATIONS

Photon-sensitive area	165mm(H) x 27.5mm(V)	SNR Max	43dB
Pixel size	5.5µm×5.5µm	Dark noise	3.94e-
Resolution	150MP - 30,000×5,000	Dark current	<10e-/s/pix (32° C)
Shutter type	electronic rolling shutter	Dynamic range	67dB (Intra-scene)
ADC	16bit	Dynamic range	75.4dB
Main clock rate	20MHz ~30MHz	Sensitivity (PGA=5.6x)	255DN/nJ/cm^2
Frame rate	10fps @ full frame	Full well charge	23000 e-
Data rate	24Gbit/s @10fps	Output interface	120 LVDS pairs
Supply voltage	3.3V / 1.8V	Operating temperature	-55° C ~ +85° C
Max Power	2.5W	Package	395 pins PGA

Sensitivity

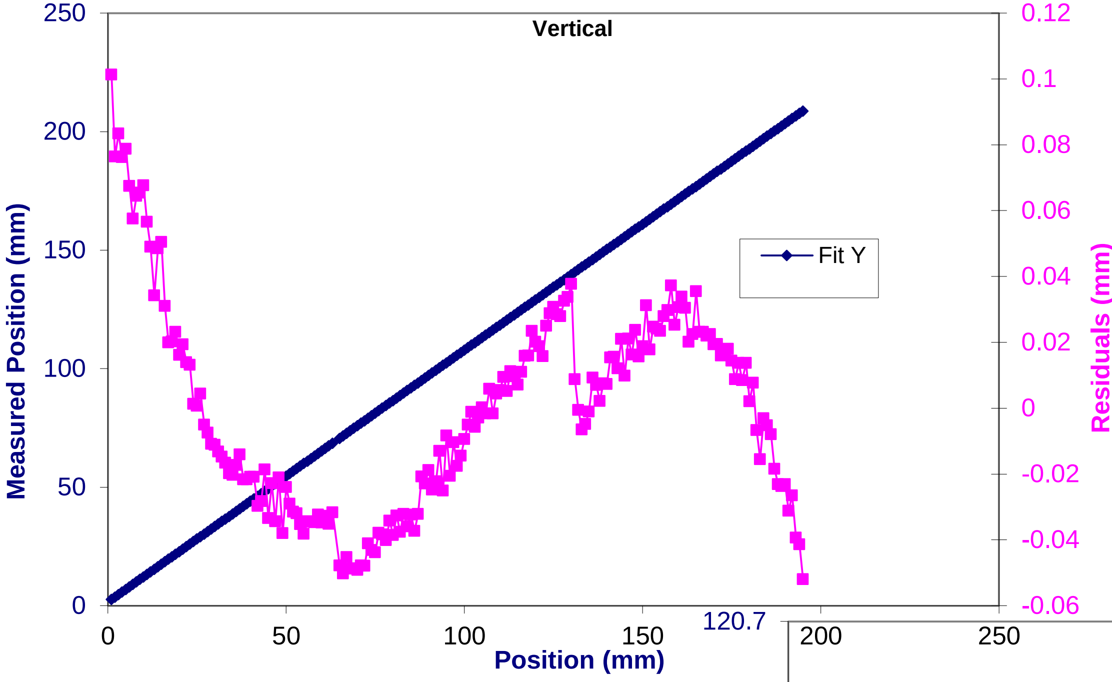
- 550nm photon $E = {}^{hc}/_{\lambda} = 3.6\times10^{-10}$ nJ
- So 1 nJ equates to 3×10^{9} photons
- 1 cm^2 = 3305785 pixels
- So 1 nJ/cm^2 = 908 phts / pixel
- Sensitivity is 255 $DN/nJ/cm^2$
- 1 LSB = 0.3 optical phts / pixel

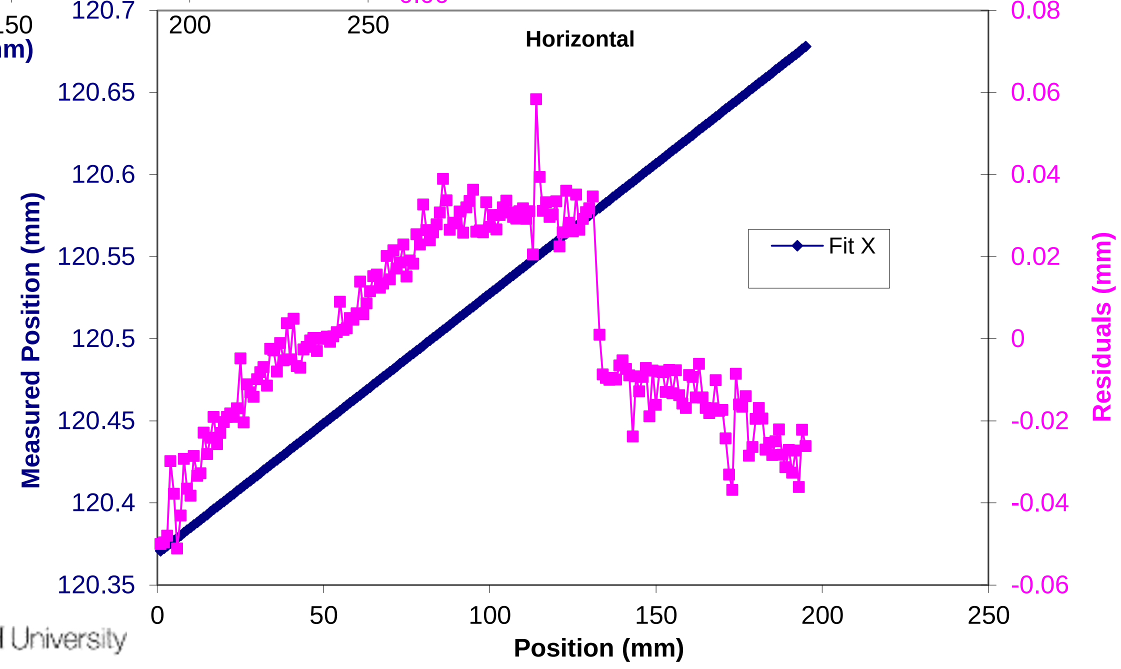
- But what does this mean for x-rays ?

Sensitivity

- Ideal sensitivity is 1 DN per x-ray photon detected
- Many factors beside chip sensitivity
  - Phosphor efficiency
    - Conversion x-rays to light (1 photon/30eV typical)
    - Ability for light to escape phosphor
  - Transfer efficiency from phosphor to chip, lens, FOT
    - Lenses poor f1.4 = 10% transmission (no reflections)
      - F1.0 = 20%
    - FOT better but distortions

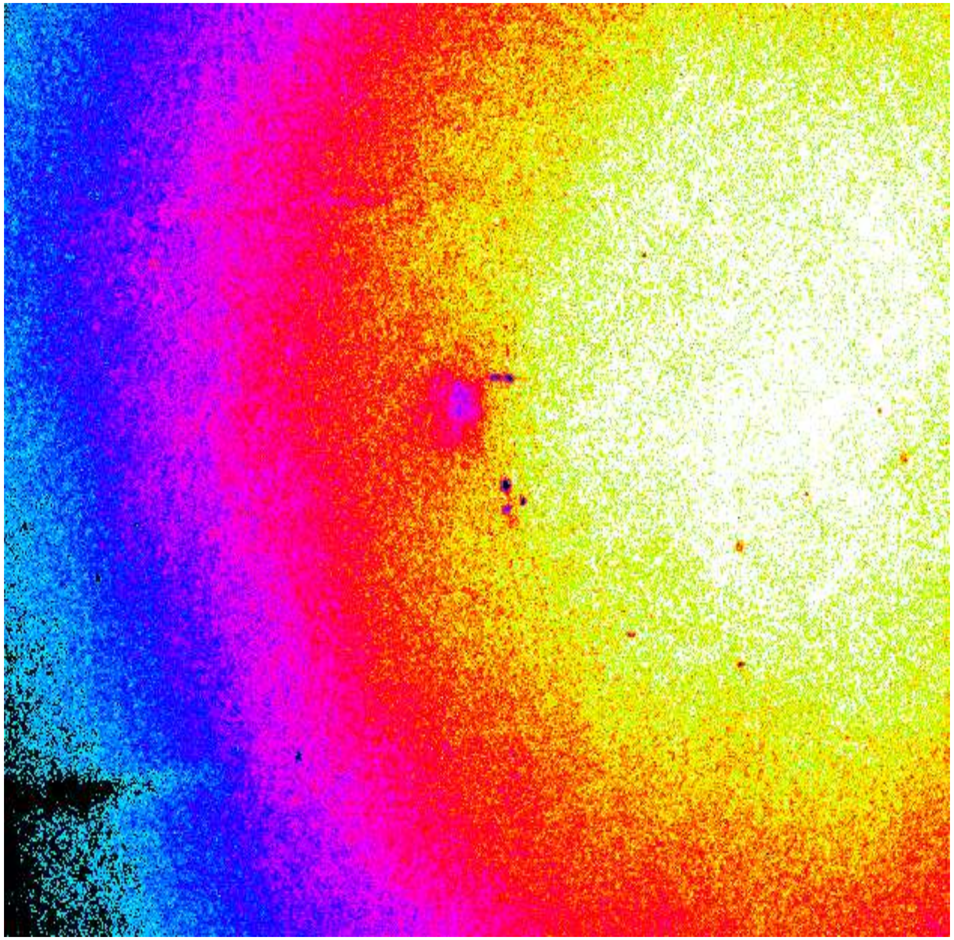
Geometric Distortion x ≠ f(y)



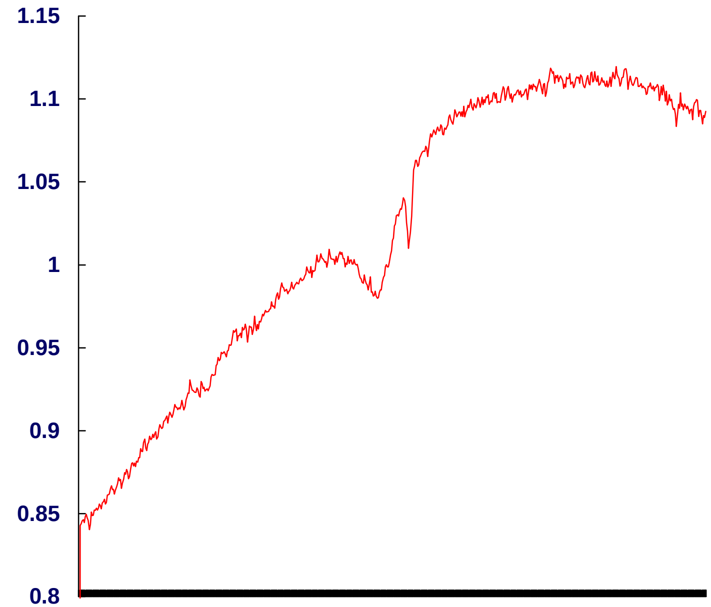


University of Saskatchewan MONASH University

Response to Uniform Illumination



ESRF TV Detector
Thompson IIT & CCD



We would like sensitivity to be a constant, neither varying in time or position

Specifications

Gpixel INC. GMAX3005

SENSOR SPECIFICATIONS

Photon-sensitive area	165mm(H) x 27.5mm(V)	SNR Max	43dB
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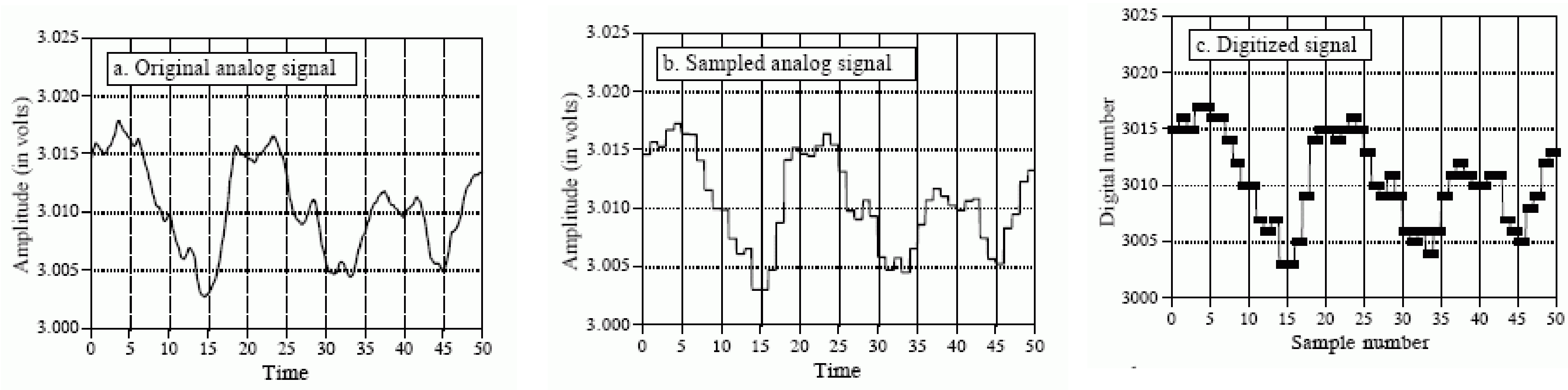
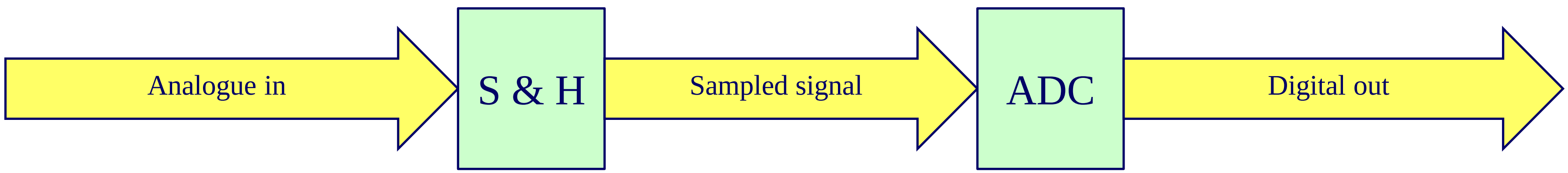
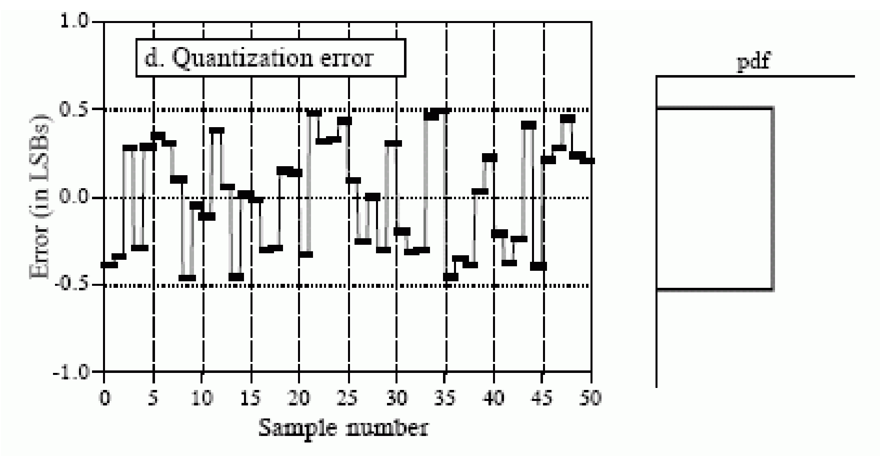
Quantisation Error







- Quantisation errors are ±½ LSB
- Quantisation errors look like random noise and can be treated as such

http://www.dspguide.com/ch3/1.htm

ADC Resolution and Noise

- Max noise is ±½ LSB
- Standard deviation $\sigma = \left({}^{1}/_{\sqrt{12}}\right) LSB$

nBits	8	10	12	16
nLevels	256	1024	4096	65536
Q error (%)	0.113	0.028	0.007	0.0015
Dynamic Range (dB)	48	60	72	96

- More bits = usually slower and more expensive
- Number of levels sets max dynamic range
- Dynamic range is max signal divided by min signal
- Often expressed in dB where dB = 20 $\log_{10}$ (Ratio)

Specifications

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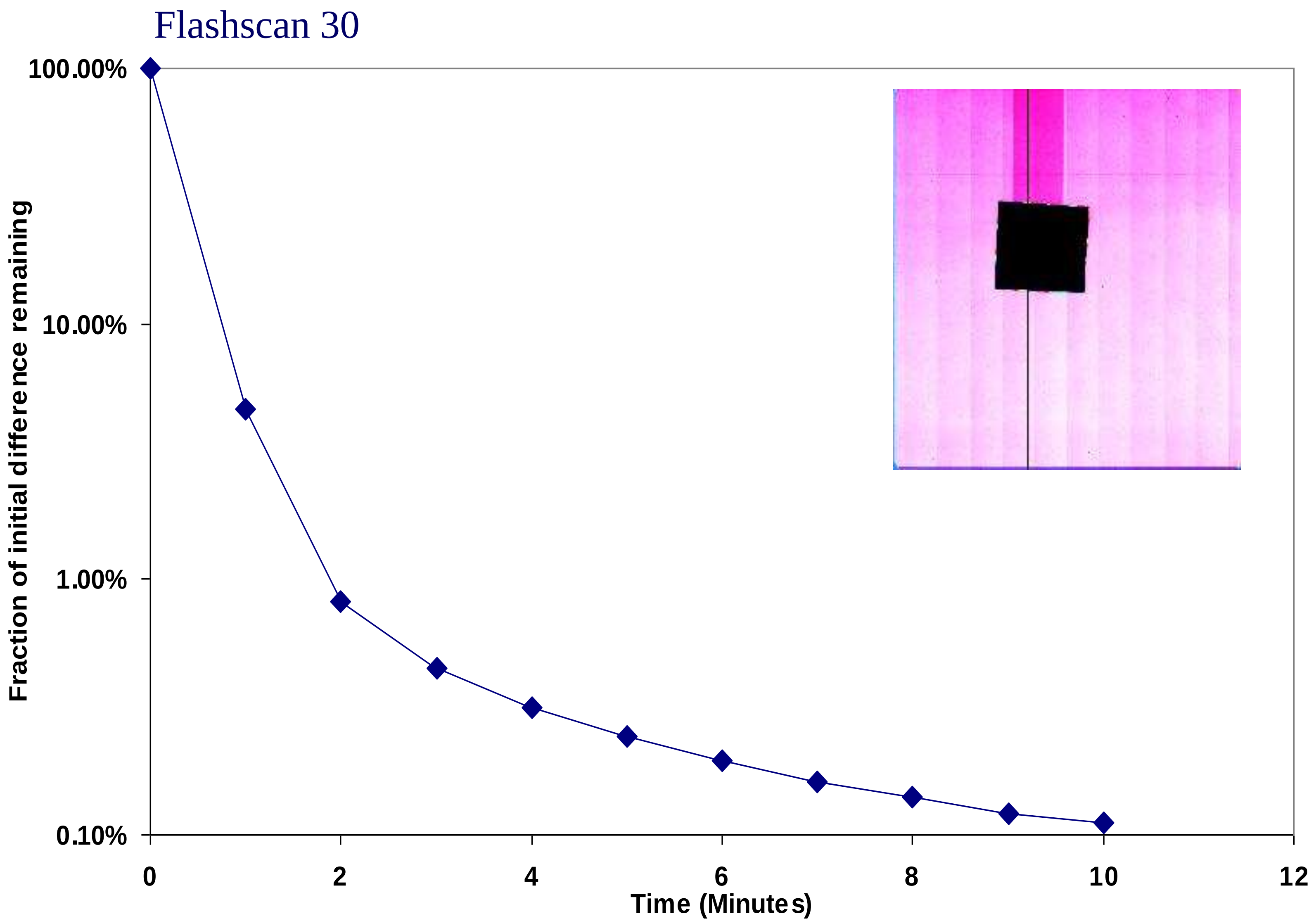
Dynamic Range

- $dB = 20 \log_{10} (Ratio)$
- $Ratio = 10^{dB/20}$

- Intra scene 67.0dB = 2339
- Inter scene 75.4dB = 5888

- Why the difference?

Image Lag


Flashscan 30
100.00%
10.00%
1.00%
0.10%
Fraction of initial difference remaining
0
2
4
6
8
10
12
Time (Minutes)

Specifications

Gpixel INC. GMAX3005

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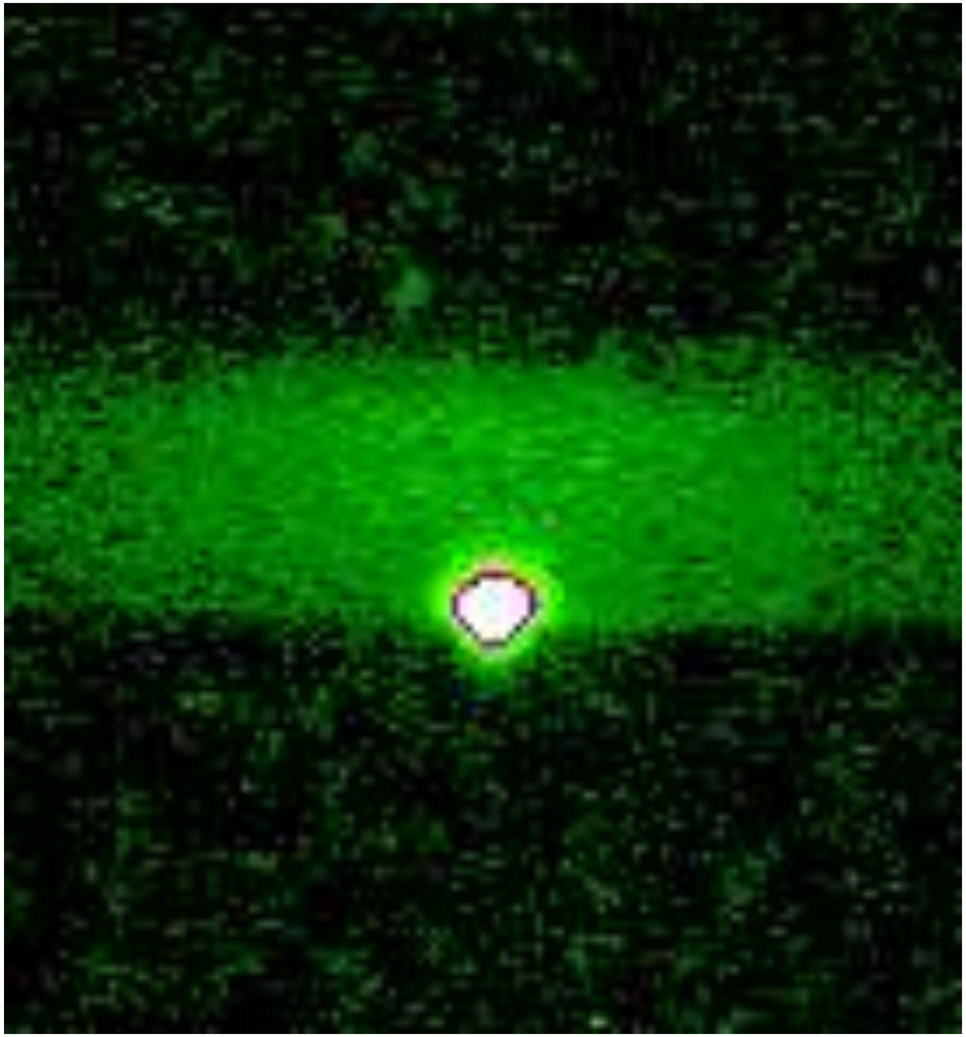
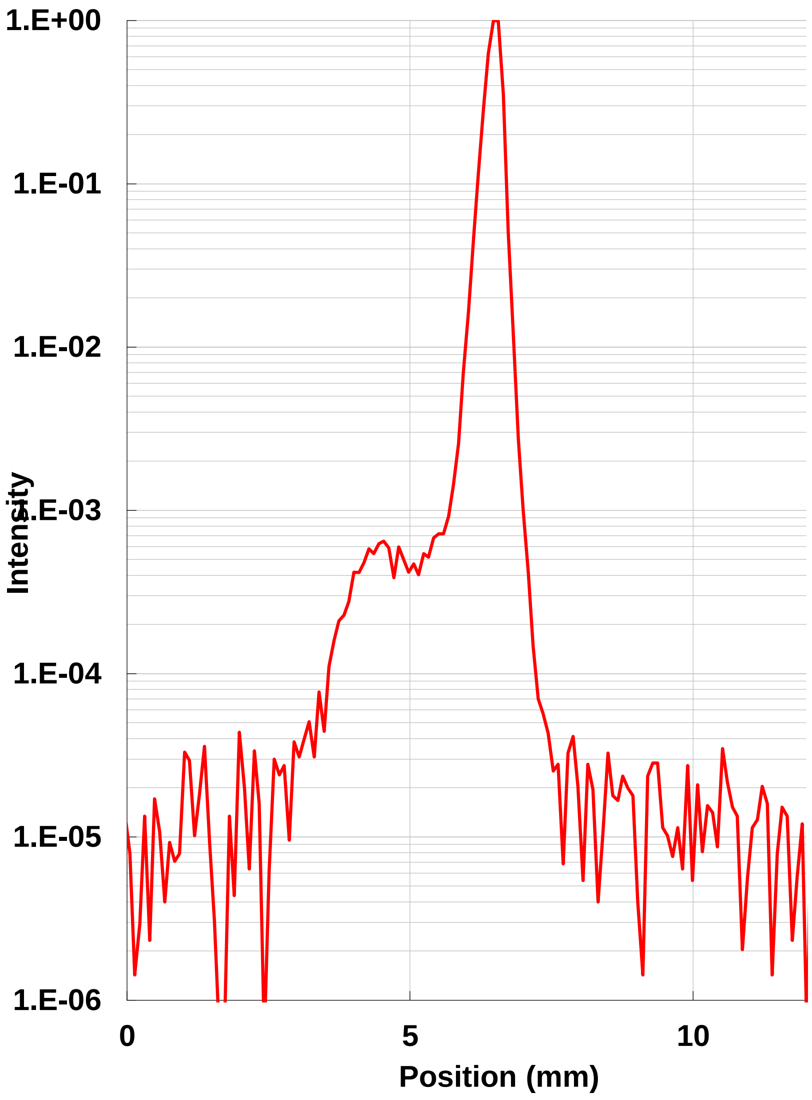
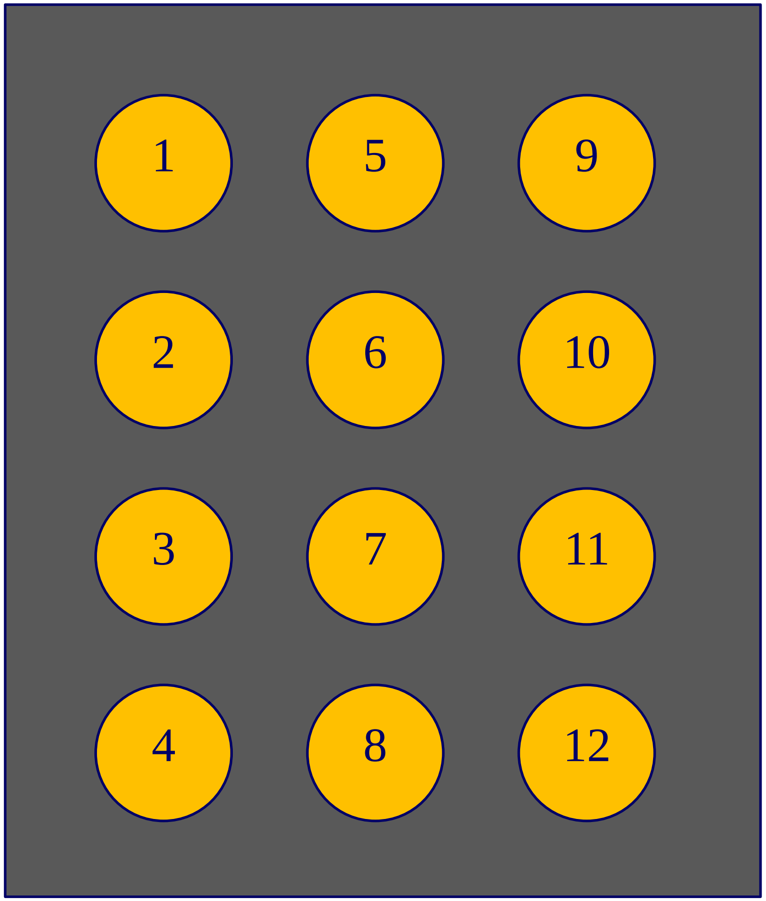
IPlate Single Peak PSF



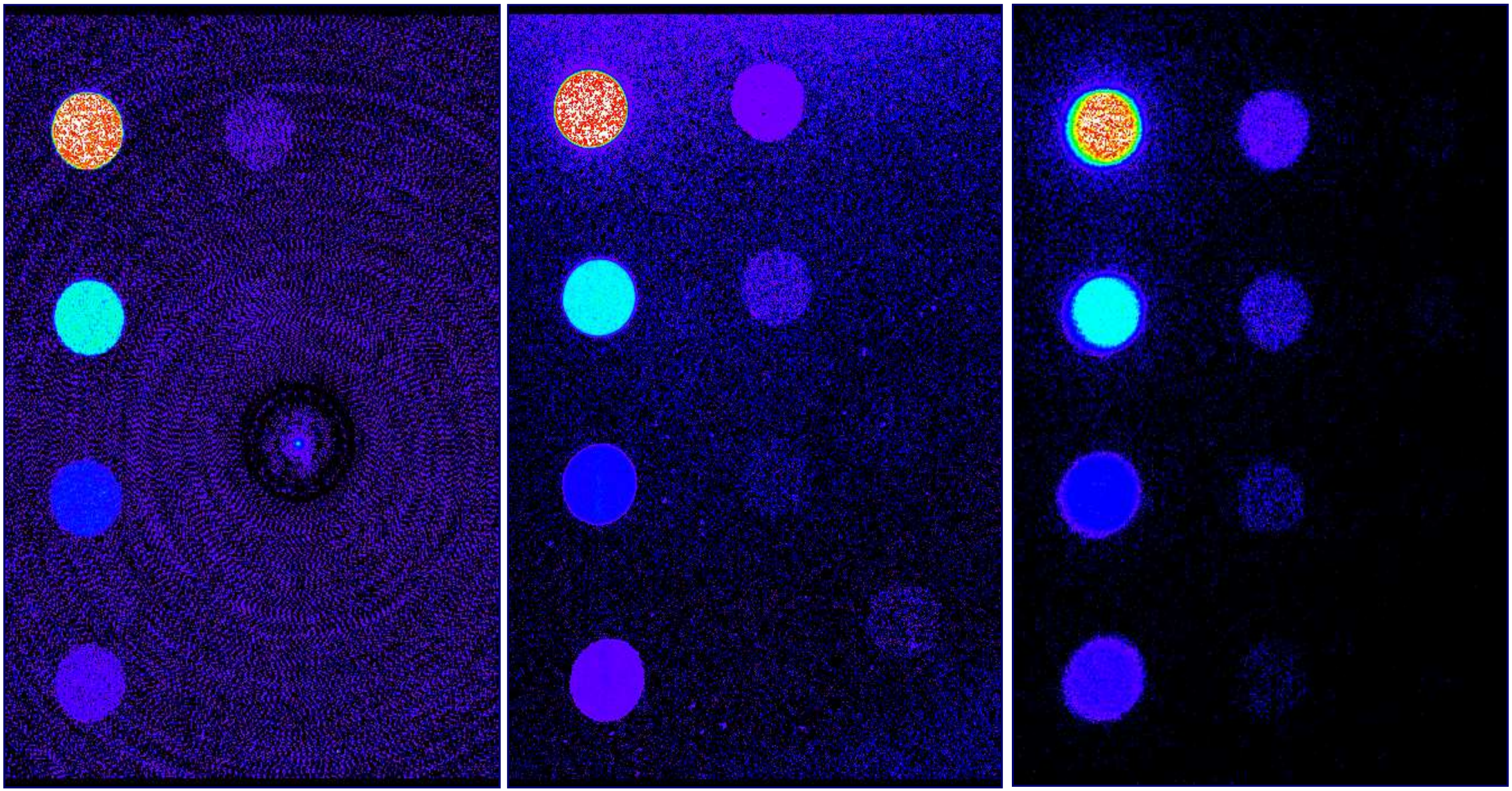


Intensity Test

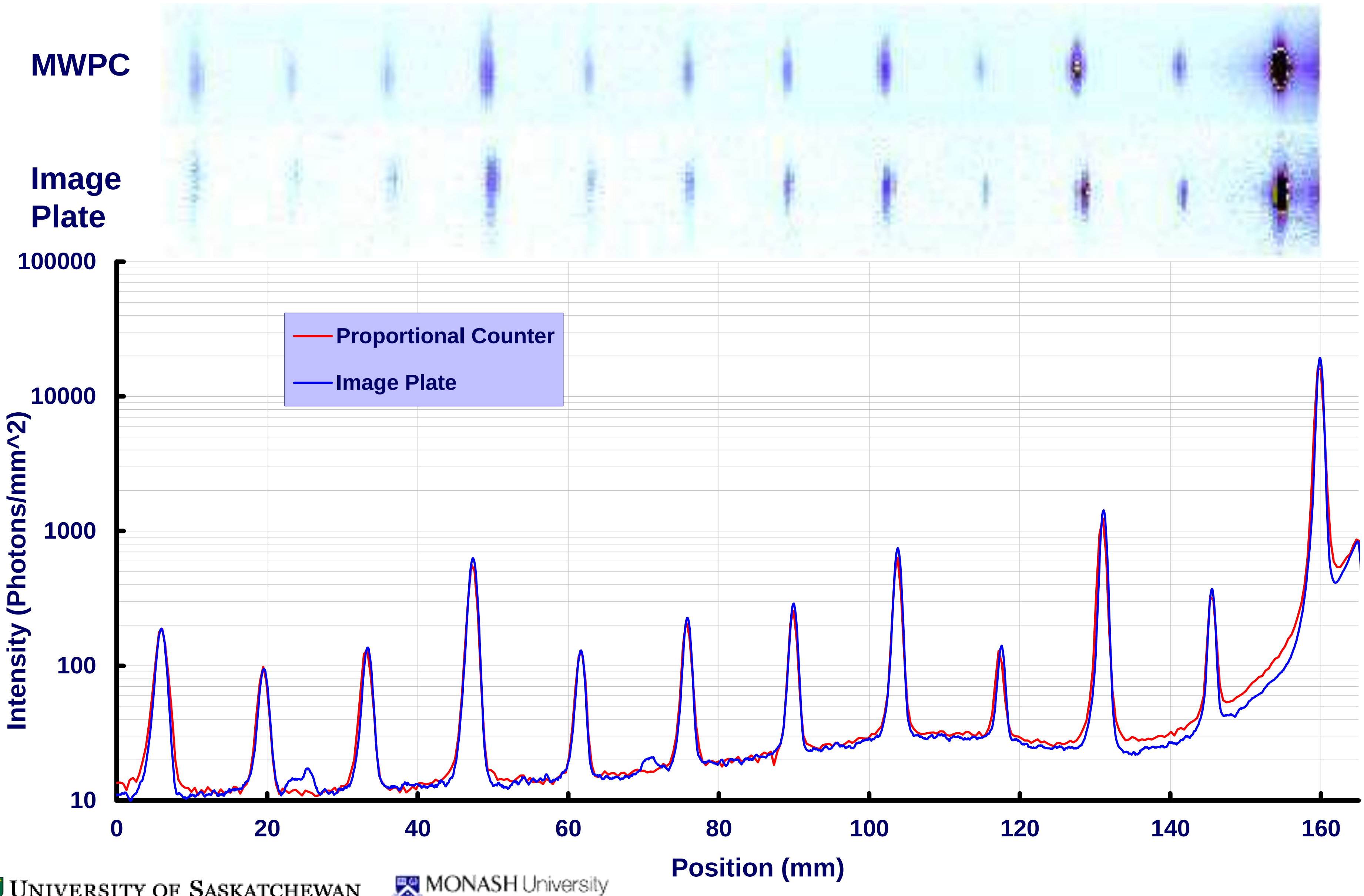


Graded Absorber Comparison

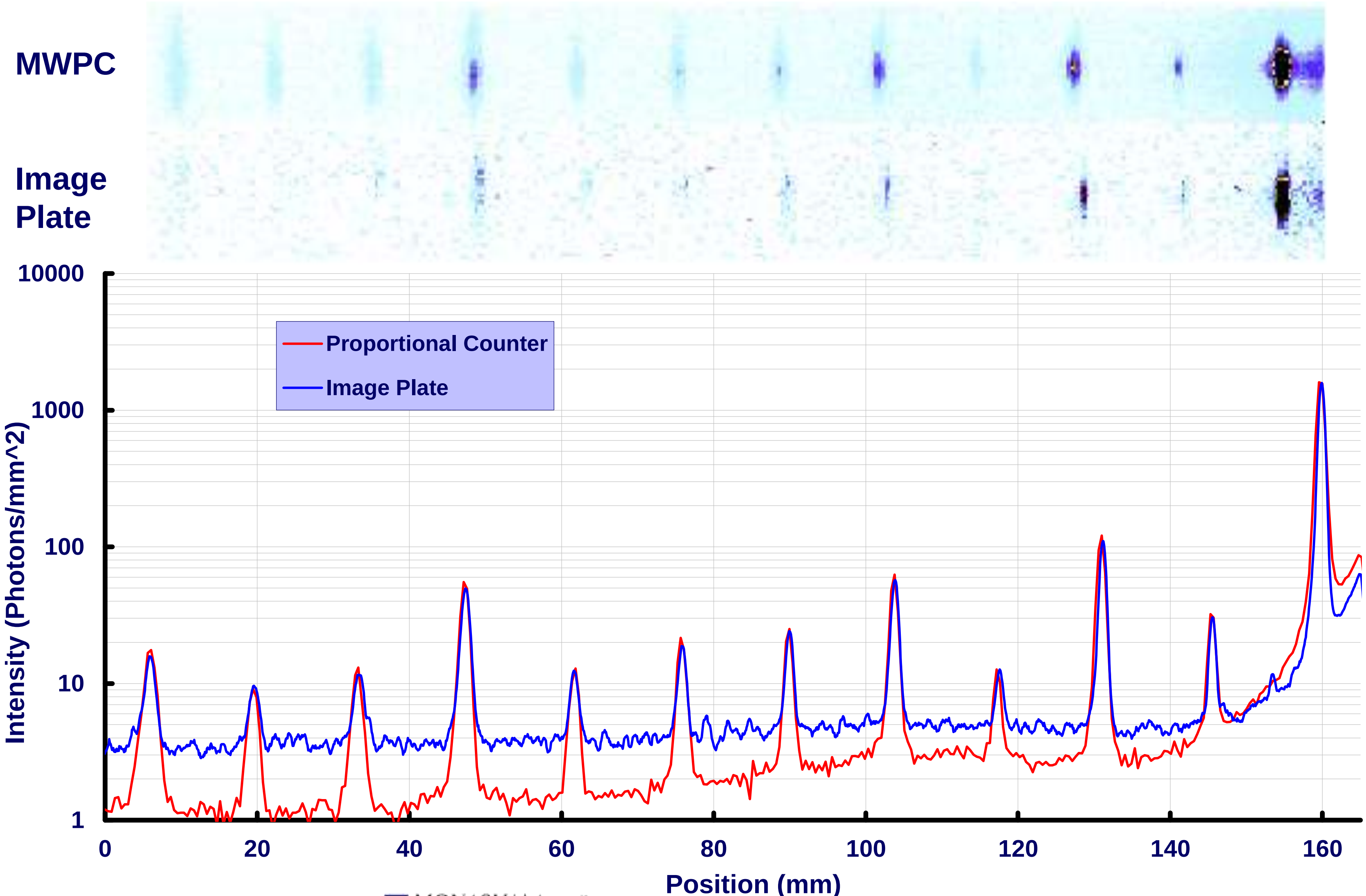
Mar Image Plate | ESRF-Thompson IIT / CCD | Daresbury MWPC



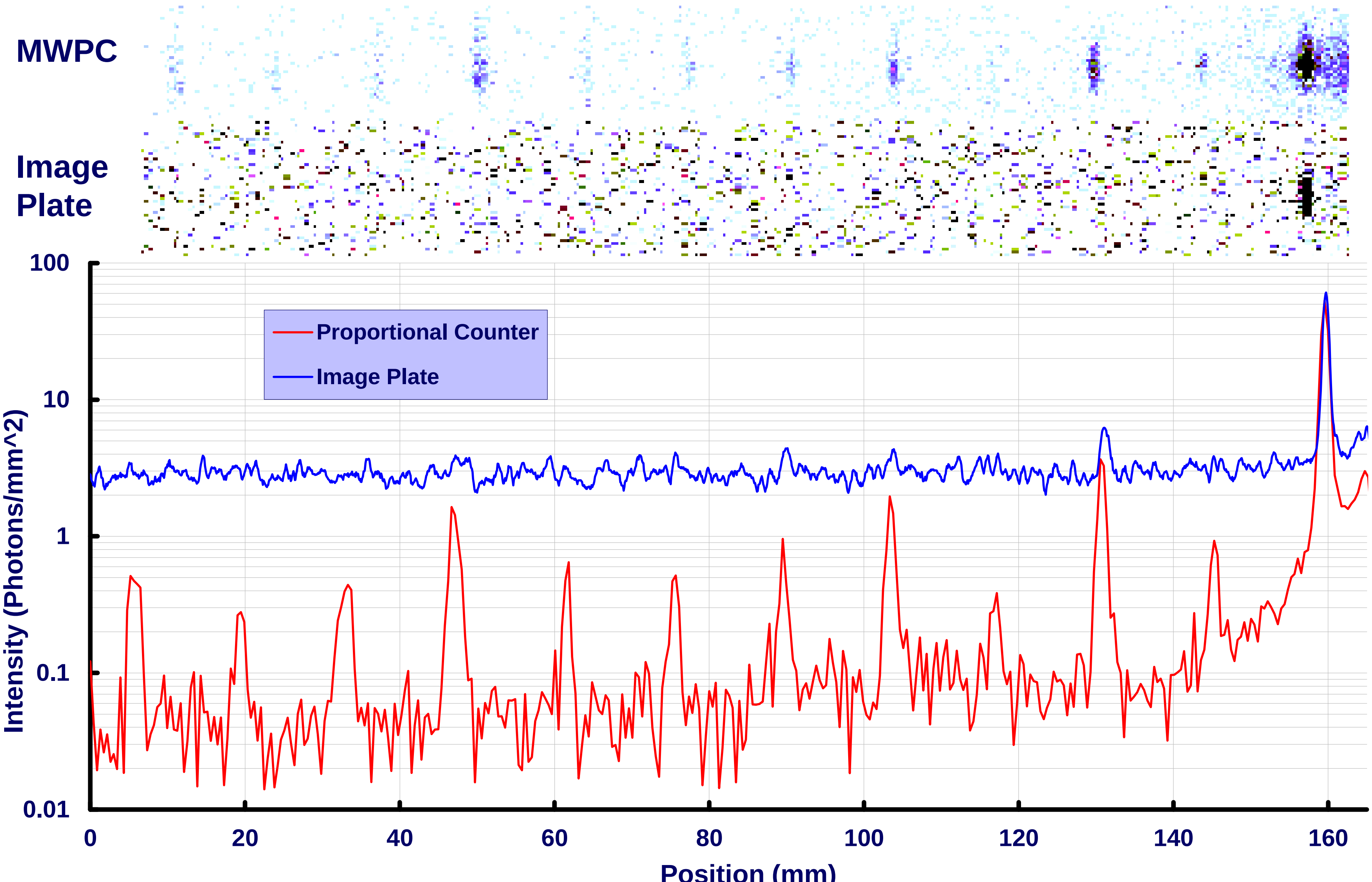
Collagen 100s Exposure



Collagen 10s Exposure



Collagen 0.3s Exposure



Specifications

Gpixel INC. GMAX3005

SENSOR SPECIFICATIONS

Photon-sensitive area	165mm(H) x 27.5mm(V)	SNR Max	43dB
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Supply voltage	3.3V / 1.8V	Operating temperature	-55° C ~ +85° C
Max Power	2.5W	Package	395 pins PGA

Well Depth

- 23000e$^-$ will saturate with 8 10keV photons
- Indirect detection is crucial to increase dynamic range
- Reduce number of electrons per x-ray photon.. but how much?

Radiation Damage

- Indirect detection is important for another reason……
- 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/mm^2/s
      - Damage requires ~ 8hours exposure
    - Direct beam (10^{10}–10^{13} photons/mm^2/s)
      - Damage in less than a second.

Specifications

Gpixel INC. GMAX3005

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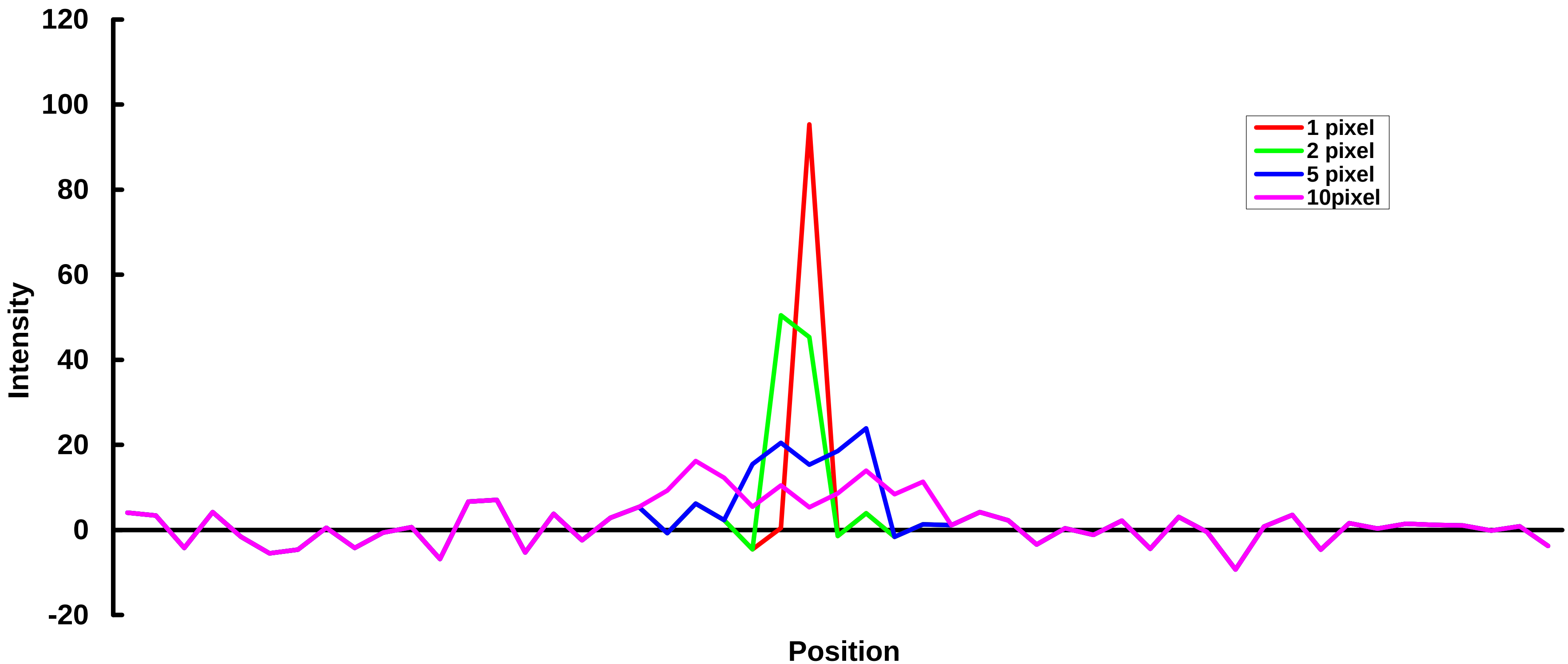
Dynamic Range and SNR

- Datasheet DNR = 75.4dB or 5888

- Datasheet SNR = 43.0dB or 141 !!!!
- Why the difference?
- DNR = Max signal / Detector Noise
  = 23000/3.2 = 7186 = 77.1dB
- SNR = Max signal / Sum of all noise
  = 23000/√23000 = 151.6= 43.6dB
  - Nb/ Poisson statistics apply to electrons as well as photons

- Difference between my calculation and their values is that they use FWC of 20000

Real SNR



- Usually better to have signal in fewer pixels becasue each pixel has its own noise

Spectroscopic Detectors

Rainbow Lorikeets

Spectroscopic Detectors

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

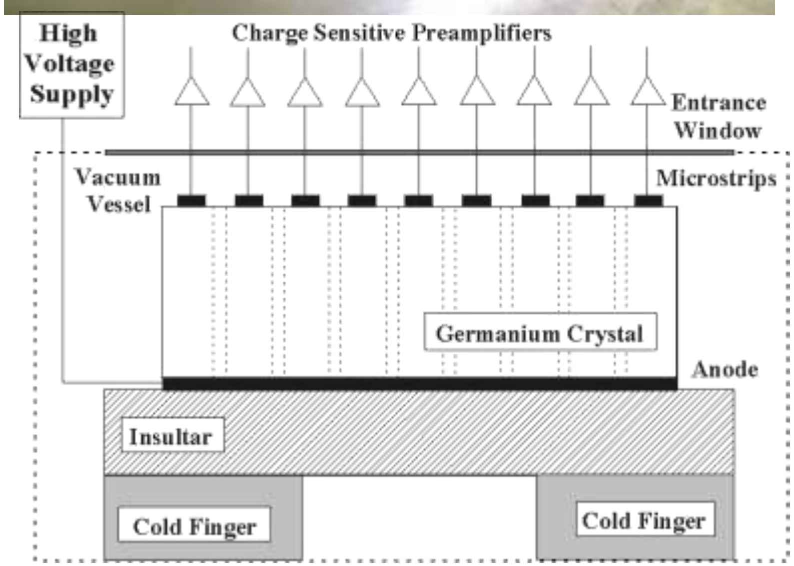
Multi Channel Spectoscopic Detectors

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 $\sigma = 1/\sqrt{N}$

  $= (E/w)^{-1/2} = (w/E)^{1/2}$
- $\Delta E/E$ fwhm $= 2.355\sigma$

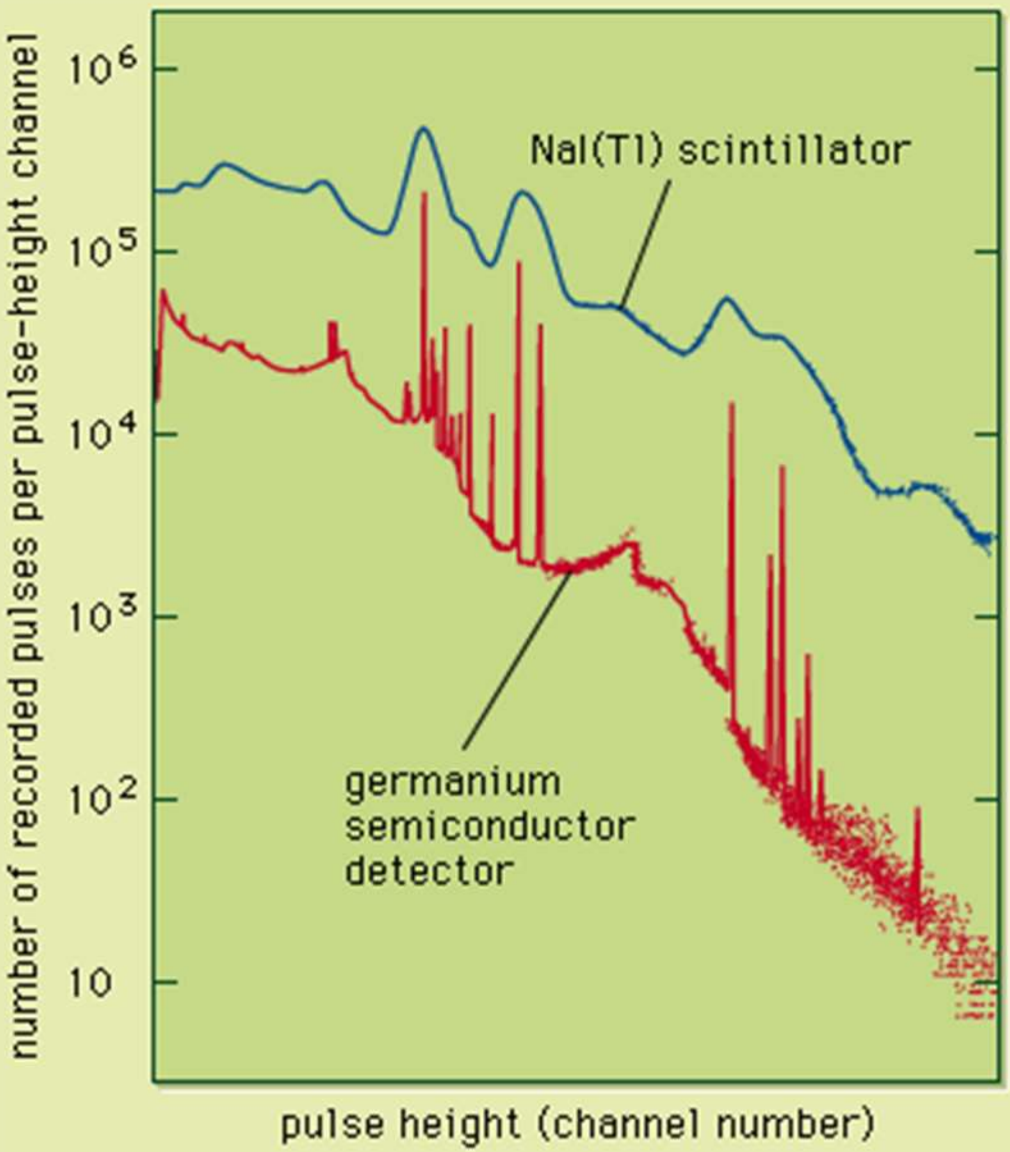
  $= 2.355(w/E)^{1/2}$

- For Ge, $w = 3$eV so at 10keV $\Delta E/E \sim 4\%$
- For NaI, $w = 30$eV 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. $\sigma = \sqrt{N}$
- Reality is somewhere in between so we introduce Fano factor F
- Fano factor is defined as $$F = \frac{\sigma^2}{N}$$
  where σ^2 is the variance and N 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



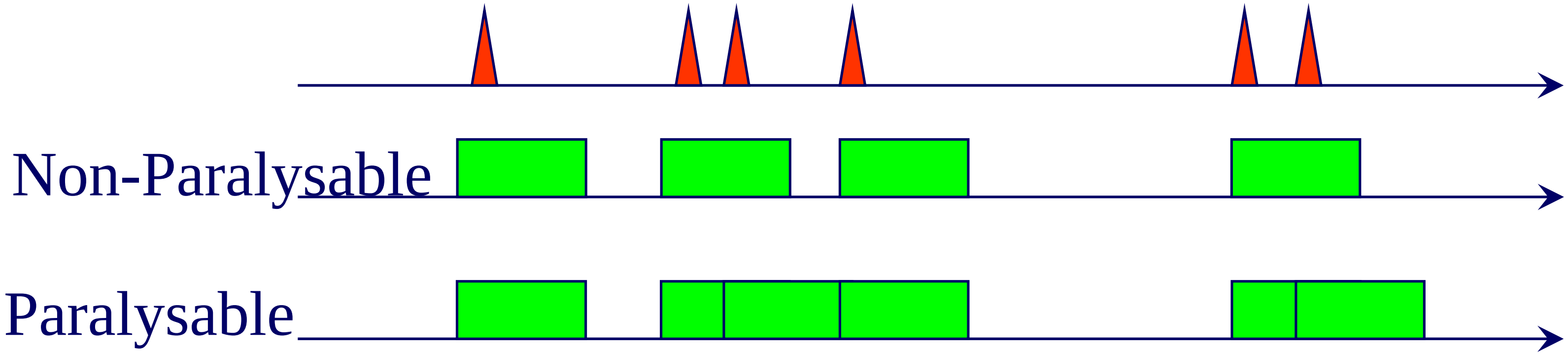
The top spectrum is from a scintillation detector, and the bottom is from a germanium semiconductor detector. The superior energy resolution of the germanium is evident from the much narrower peaks, allowing separation of gamma-ray energies that are unresolved in the scintillator spectrum.

Counting still sort after

- Xe-based gaseous avalanche detector
- Active area: 14 x 14 cm^2
- Number of pixels: 2048 x 2048
- Pixel Size: 68µm x 68µm
- Global Counting Rate
  - Maximum: 1.6 Mcps
  - Linear part (10% deviation from linearity): 0.9 Mcps
- Local Counting Rate
  - Max per point-like reflection: 250 kcps
  - Linear part (10% deviation from linearity): 160 kcps
- Background < 5 cps per whole area
- Maximum Dynamic Range
  10^9x sqrt(collection time in seconds)
- Radiation Hardness
  10^{12} X-rays/mm^2 (10^{16} photons in total)
- Accidental Irradiation Intensity
  No limit

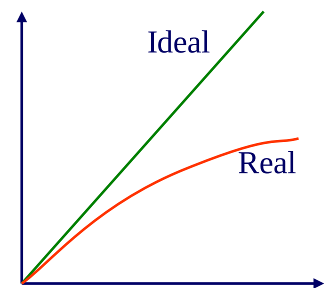
Bruker VÅNTEC-2000

Dead Time

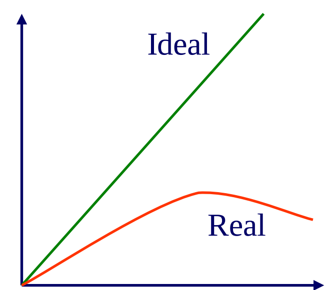


R_i=input rate, R_d=detected rate, τ dead time

- **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 $$R_d = P(0,\tau) = R_i e^{-R_i \tau}$$



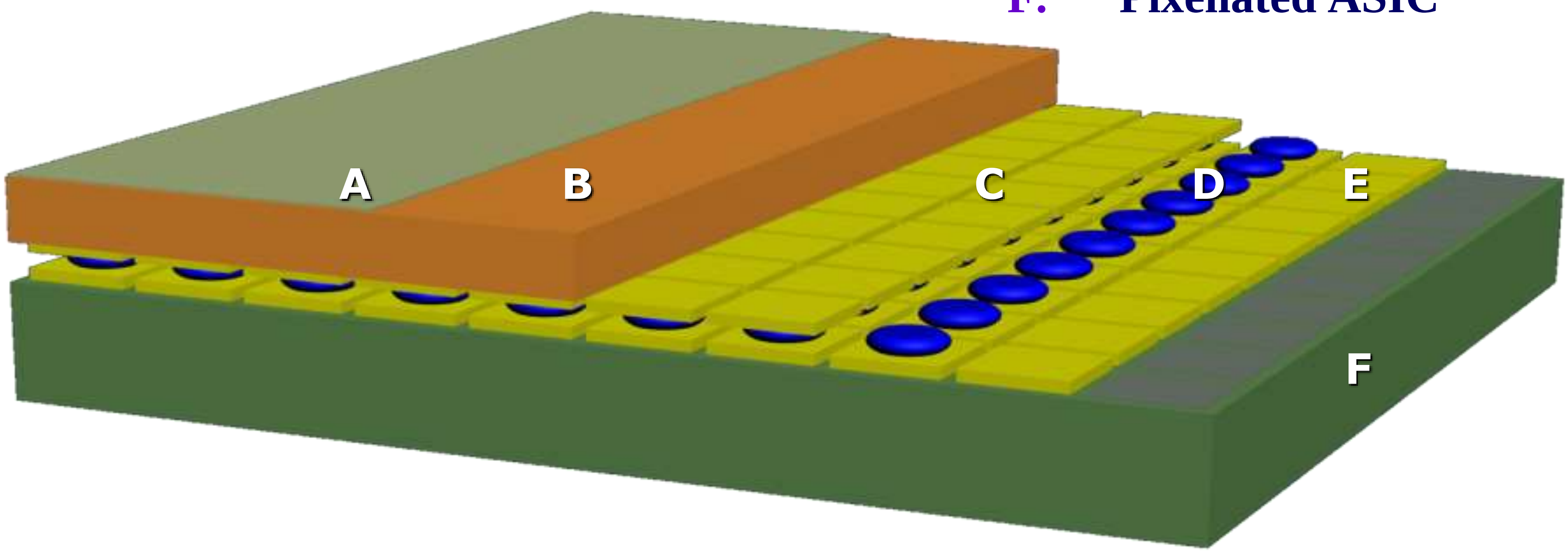
Synchrotron Detectors

- 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!

Pixel Array Detector

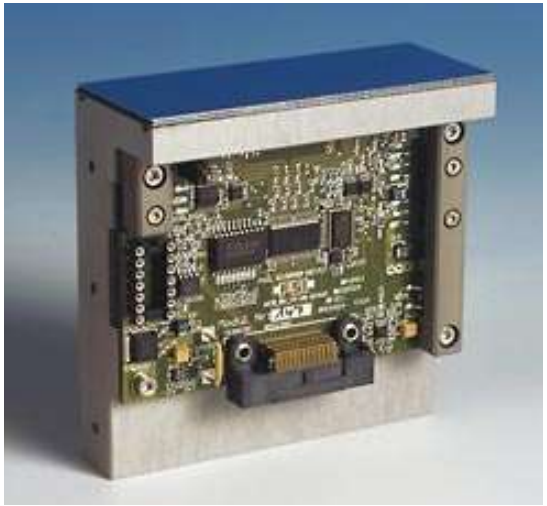
A. Top electrode
B. Pixellated semiconductor
C. Collection electrodes
D. Bump bonds
E. Input electrode
F. Pixellated ASIC



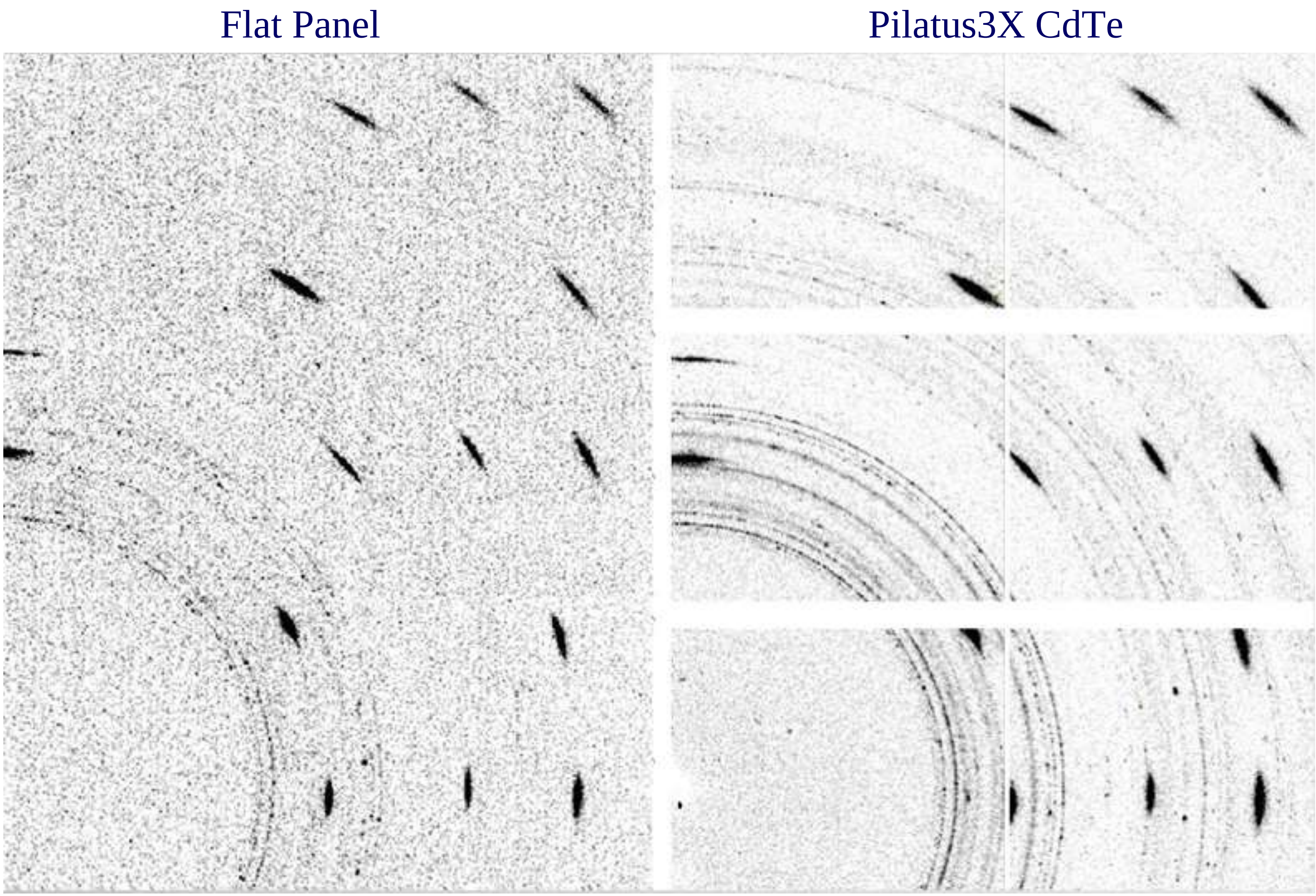
PILATUS3X Detector

- Pilatus has a 20 bit counter for each pixel
- Count rates up to 10 Mcts/sec/pixel
- No readout noise
- No dark current
- Room temperature operation
- Region of interest readout
- Built of modules

PILATUS3 X	1M	2M	6M
Number of detector modules	2 × 5	3 × 8	5 × 12
Sensitive area: width × height [mm²]	168.7 × 179.4	253.7 × 288.8	423.6 × 434.6
Pixel size [µm²]			
Number of pixels: hor. × ver.	981 × 1043	1475 × 1679	2463 × 2527
Gap width: hor. / ver. [pixel]	7 / 17	7 / 17	7 / 17
Inactive area [%]	7.2	8.0	8.5
Defective pixels			
Maximum frame rate, full frame [Hz]	500	250	100
Maximum frame rate, ROI [Hz]	500	500	500
Readout time [ms]		0.95	
Point-spread function		1 pixel (FWHM)	



PILATUS 3X CdTe Detector

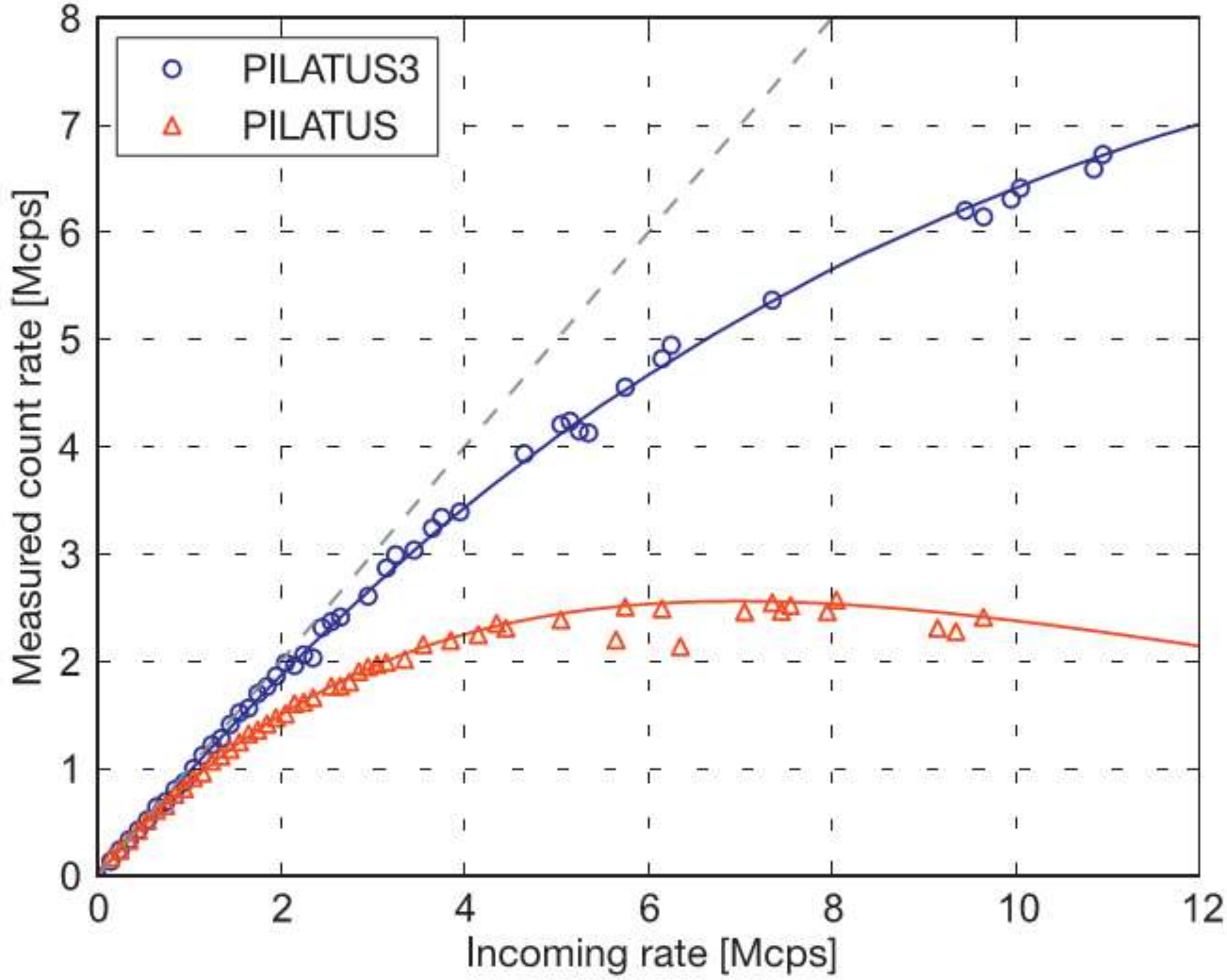


ESRF ID15A, 46.3keV, 100ms exposure

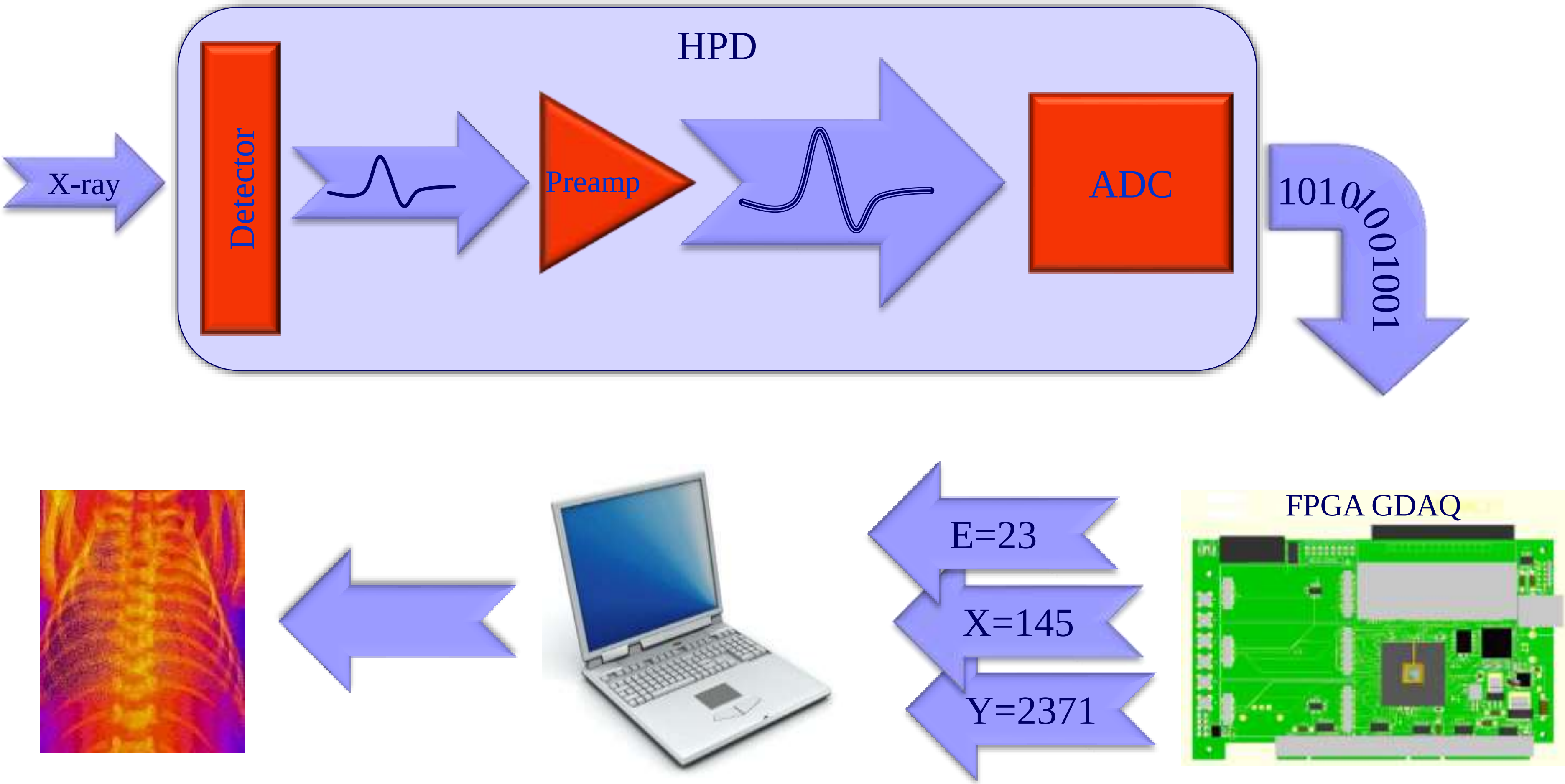
UNIVERSITY OF SASKATCHEWAN MONASH University

PILATUS3X Detector

DECTRIS
Next Generation X-Ray Detectors

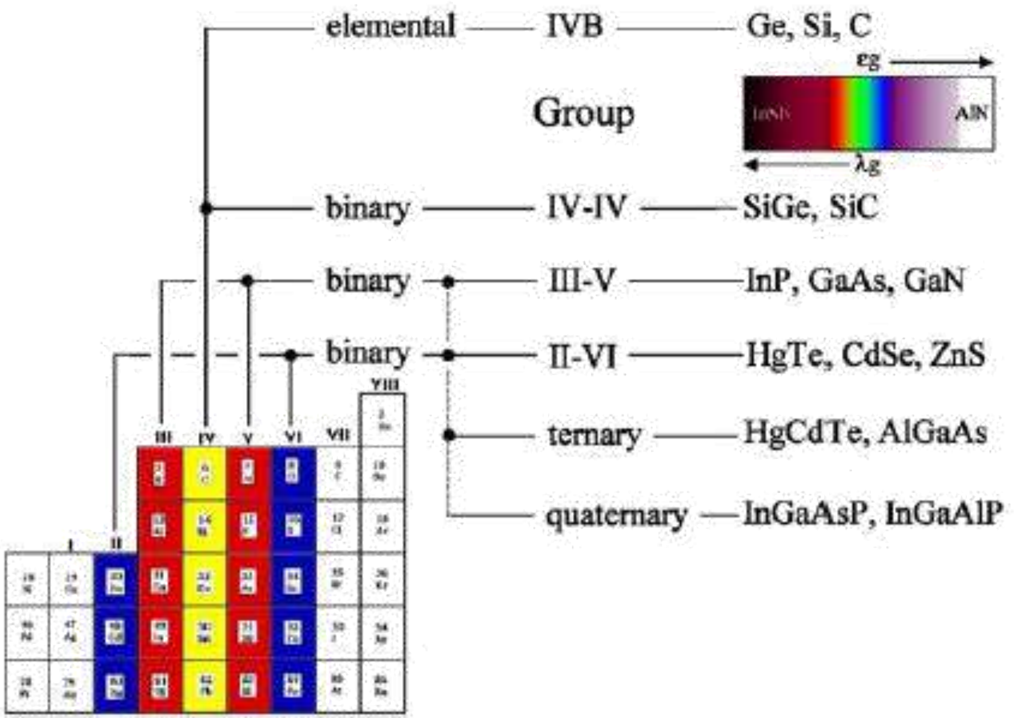


Combine Imaging and Spectroscopy

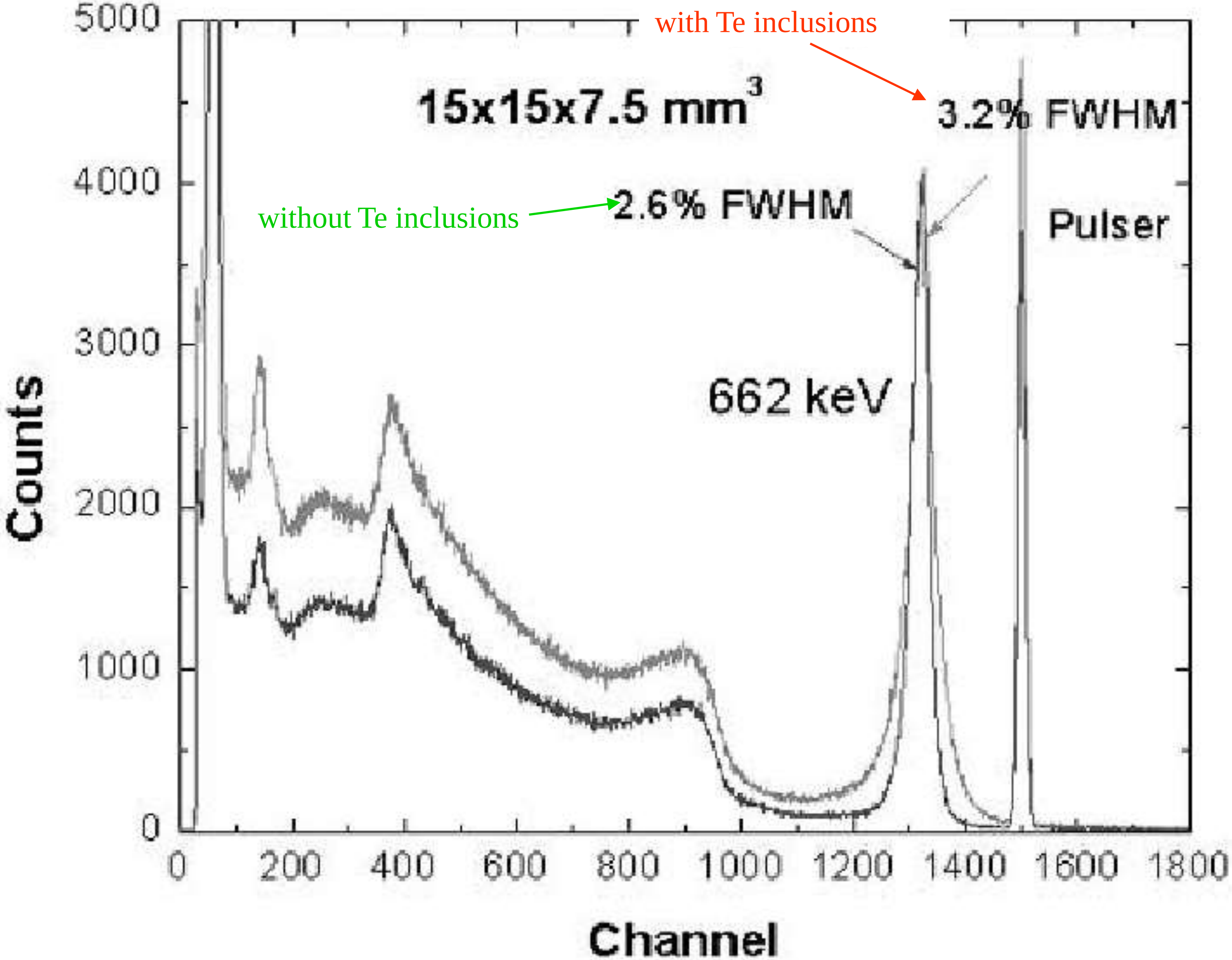


Available Compound Semiconductors

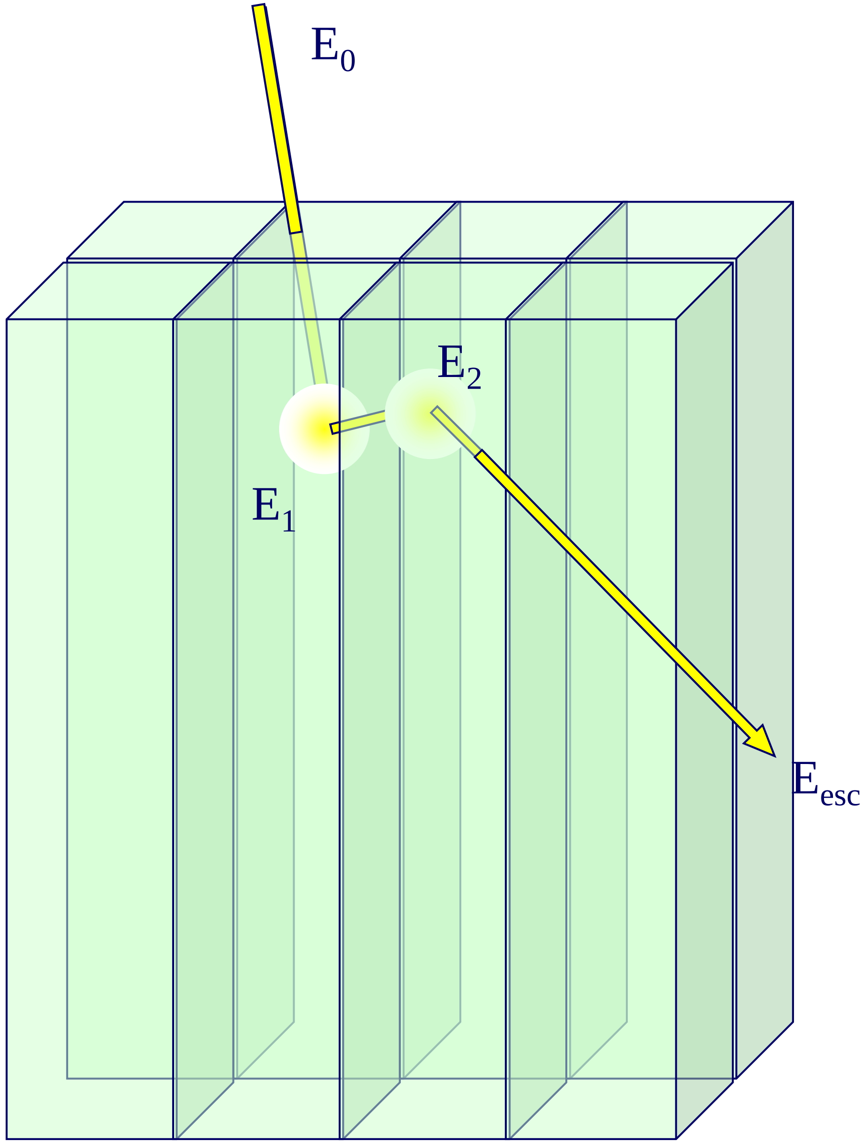
- Predominately CdZnTe, CdTe and GaAs.
- II-VI materials CdTe and CdZnTe cover a suitable range of band gaps:
  - 1.44 eV (CdTe), 1.57 eV (CdZnTe, 10% Zn), 1.64 eV (CdZnTe, 20% Zn)
- Resistivity of CdZnTe is higher than CdTe, hence lower dark current, higher spectroscopic resolution
- Poor hole transport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



CdZnTe Spectral Resolution



The Problem of Multiple Scatters



- We would like to know E_0 but…..
- $E_0=E_1+E_2+E_{esc}$
- We don't know E_{esc}
- E_1 and E_2 are separate events
- So we must be able to associate multiple energy deposits as single input photon
- We must also minimise E_{esc}
- Not a simple problem!

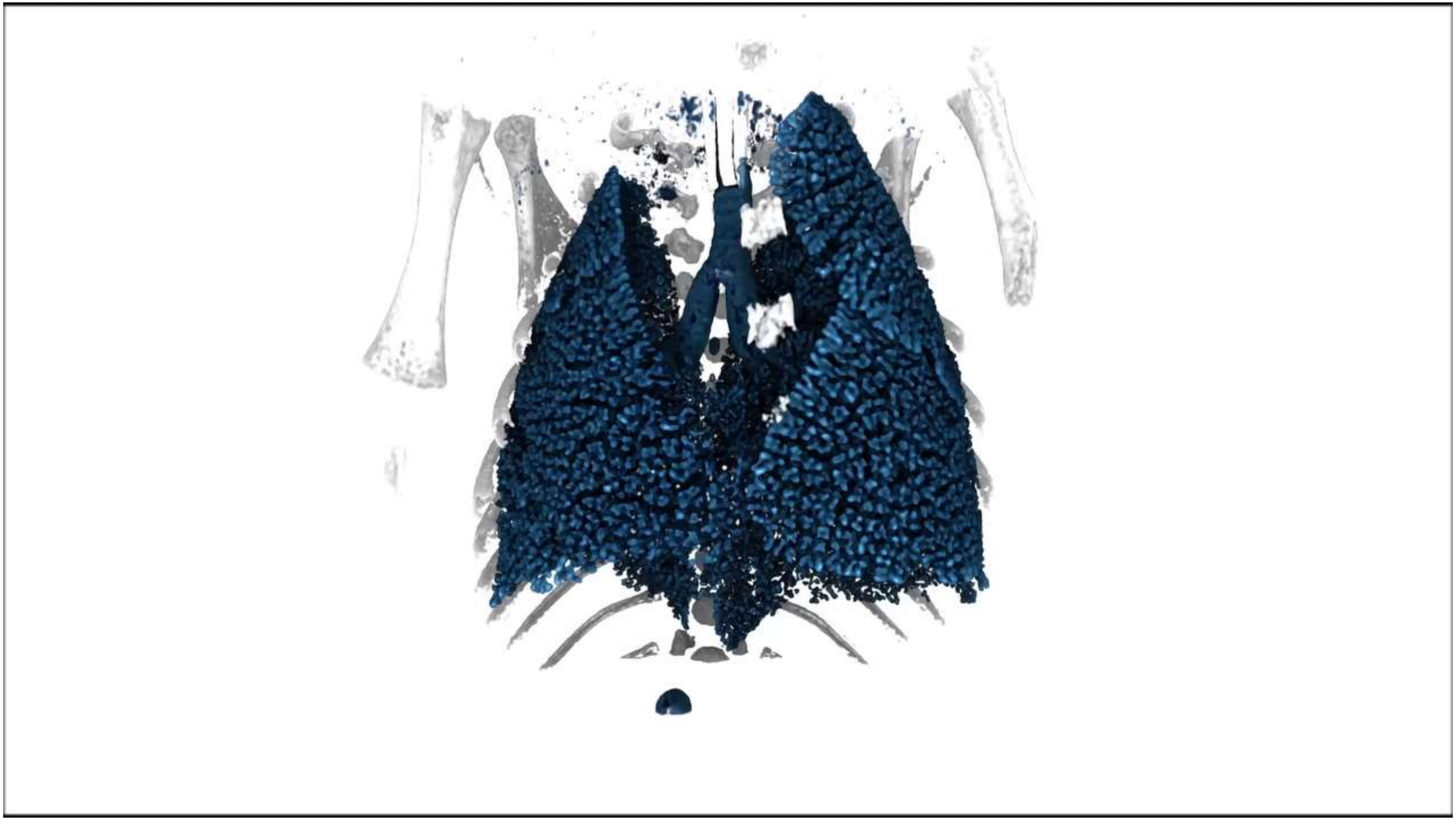
Detector Considerations

- 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

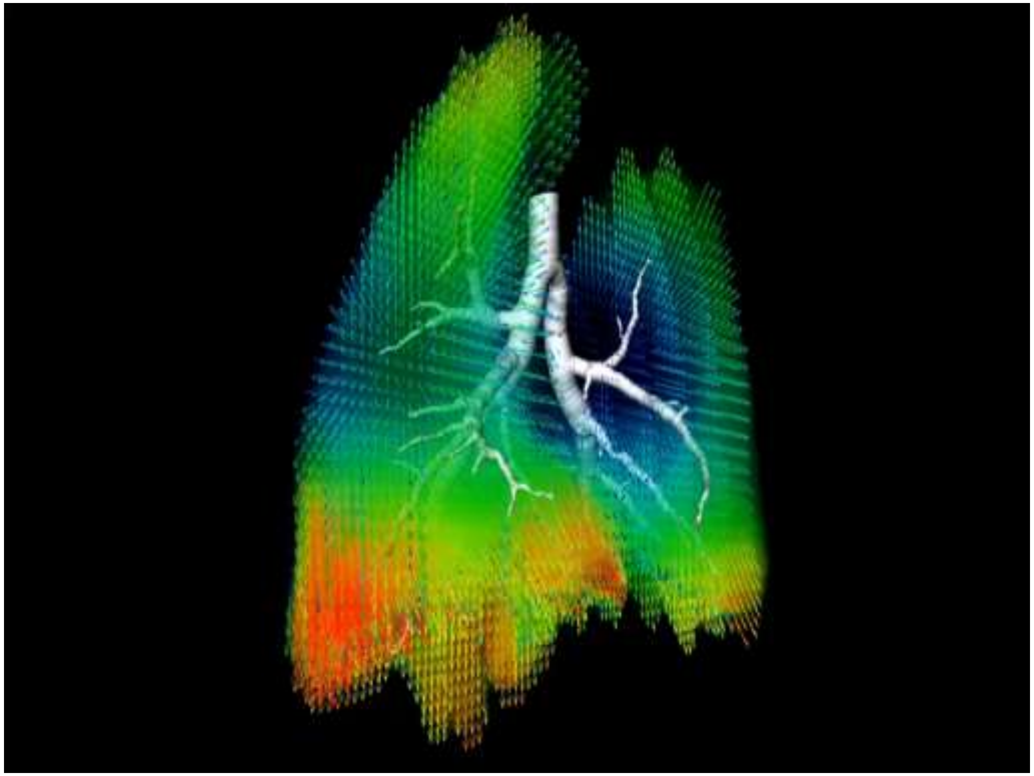
Other Issues

- In addition to detector performance metrics such as
  - Spatial resolution, Spectral resolution, etc.
- Often we need to measure **function** not form
- Requires that…
  - The detector respond to triggers
  - Be able to synchronise with other systems measuring multiple parameters
  - Do things like phase contrast

Whole Breath Lung Morphology



4D PIV



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