Argonne NATIONAL LABORATORY

X-ray Detectors

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June 15, 2014

NX School

U.S. DEPARTMENT OF ENERGY

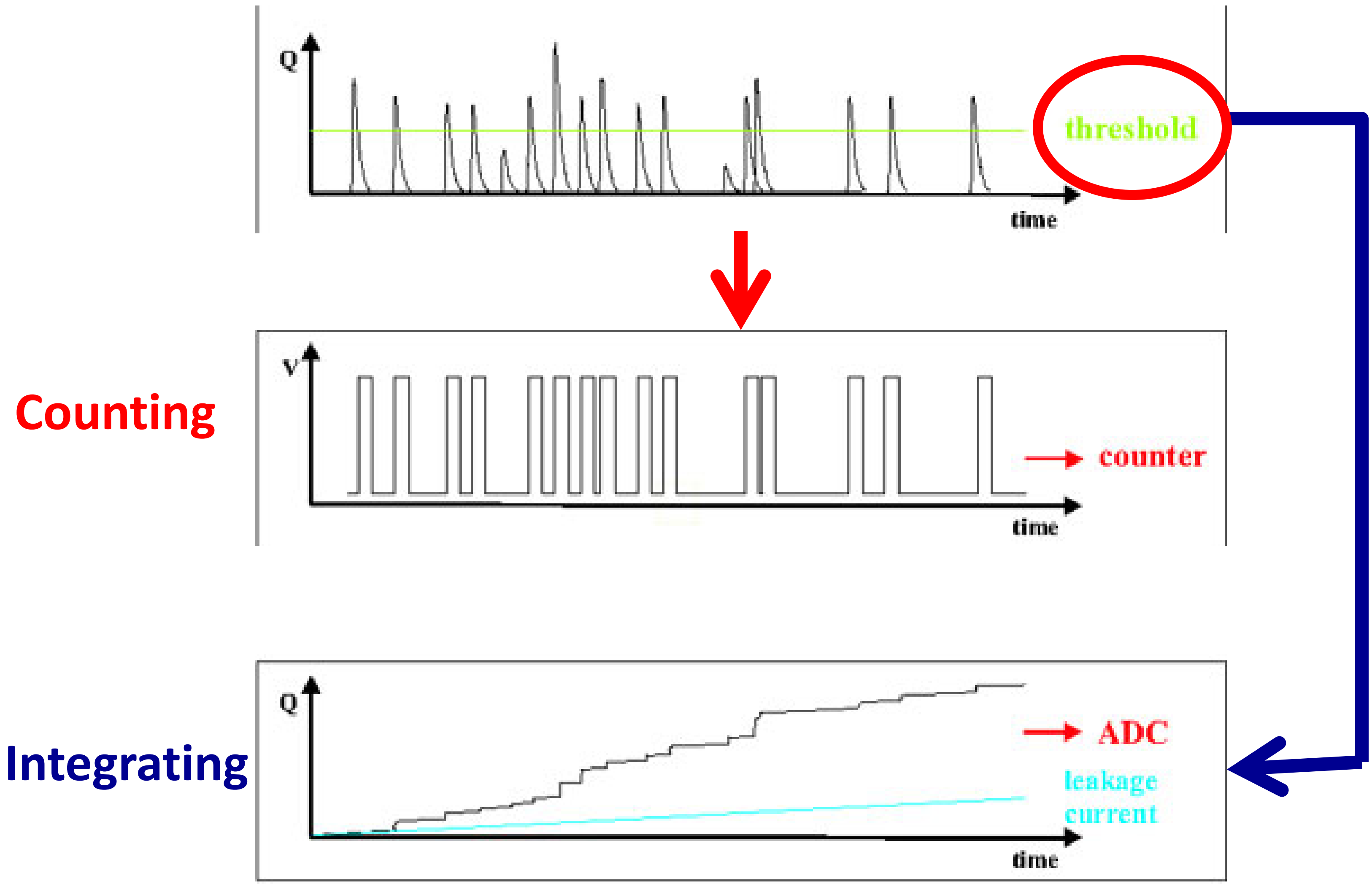
Outline

- **Counting vs. integrating**
- **Indirect versus direct detection**
  - Scintillation Counters
  - Area detectors using scintillators
    - Large area for diffraction (low spatial resolution, ~ 100 μm)
    - Small area for imaging (high spatial resolution, ~ 1 μm)
  - Ion Chambers
  - Pixel array detectors (e.g., Pilatus)
  - Energy resolving detectors (i.e., spectroscopic detectors)
    - Measuring the energy of photons
    - Silicon diodes
    - Superconducting detectors

How do you detect x-rays?

- Need to convert to something that you can measure
  - **Electrons**… Q = CV
    - **Indirectly (x-rays → optical photons → electrons)**
      - Scintillators + Optics + photomultiplier/CCDs
    - **Directly (x-rays → electrons)**
      - Ion Chambers, Pixel Array detectors (e.g., Pilatus)
  - **Temperature**
    - ➢ $\Delta T = E_\gamma$ / (Heat Capacity)
      - Superconducting calorimeters

Counting versus Integrating

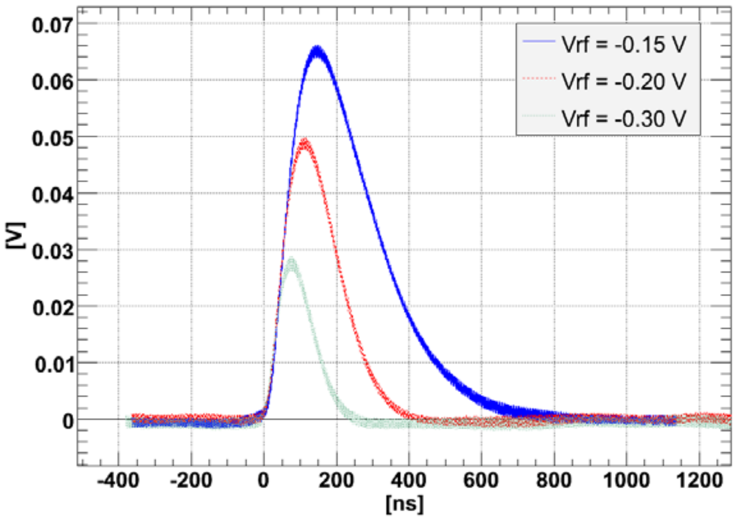


Counting versus Integrating

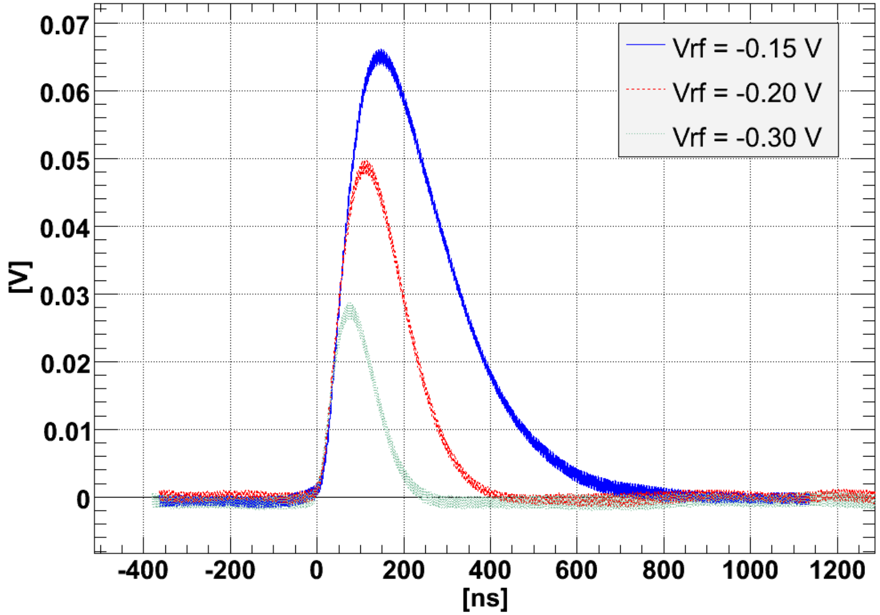
- **Counting**
  - Single photon counting
    - Scintillator counting detectors (e.g., Cyberstar)
    - Pilatus (counting pixel array detectors)
    - Energy-resolving Detectors (Silicon or Germanium diode detectors)
  - Deadtime limitations!!!
  - Dark current rejected with a sufficiently high threshold.
- **Integrating**
  - Signal accumulates
  - CCDs, Ion chamber
  - No deadtime limitations
  - Read noise and dark current are issues to consider

Shaping time – counting detectors

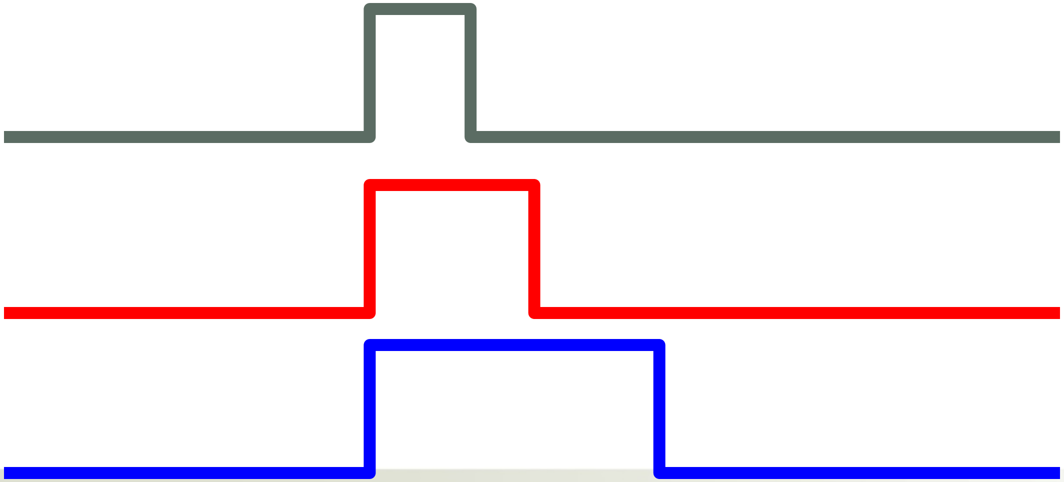
- Response time of detector
- Gain is usually associated with longer shaping time.
- Longer shaping time improved the energy resolution
  - But reduced the total count rate throughput.



Deadtime limitations for counting detectors



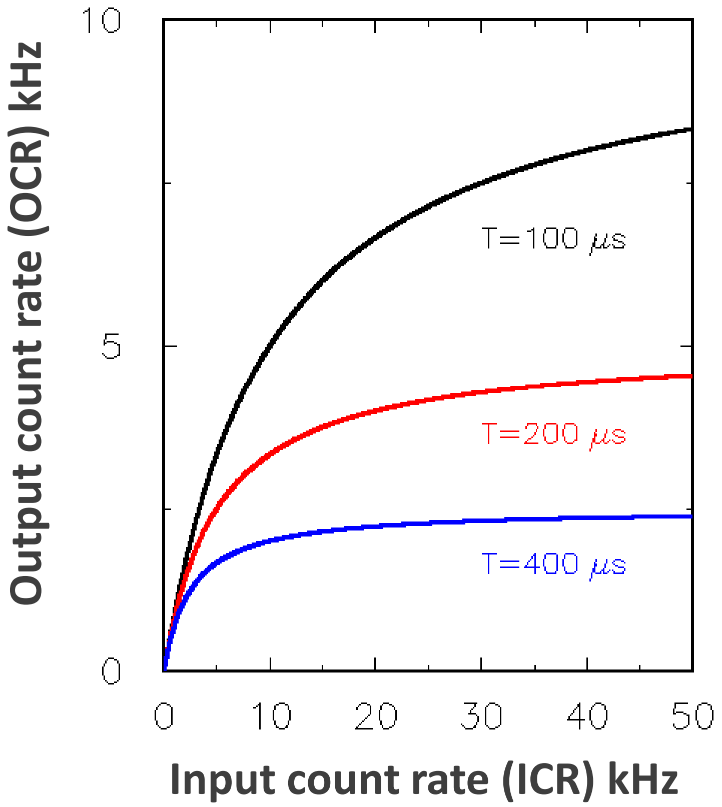
Analog pulses



Discriminator output

Deadtime

- As you increase the input count rate (ICR), does the output count rate (OCR) follow linearly?
  - The longer the shaping time, the lower the ICR before deviating from linearity.



When to worry?

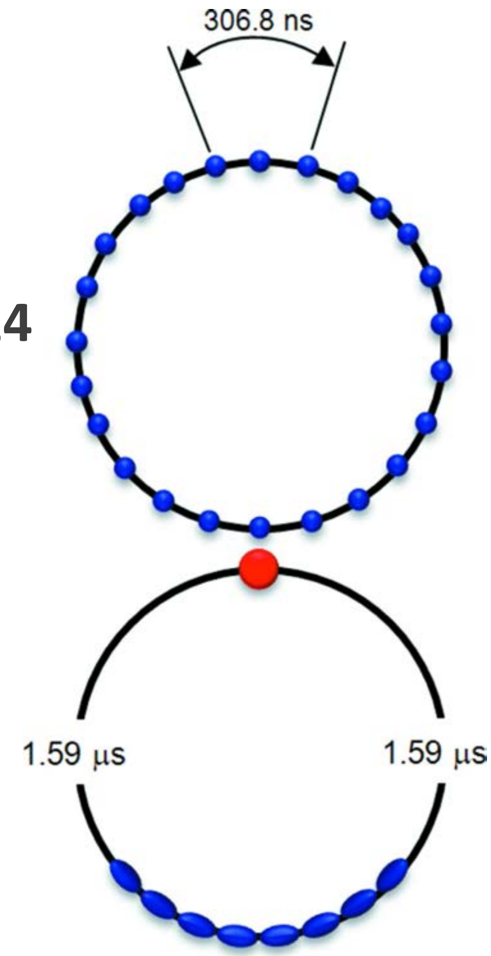
- Rate > 1 / (2 x τ)

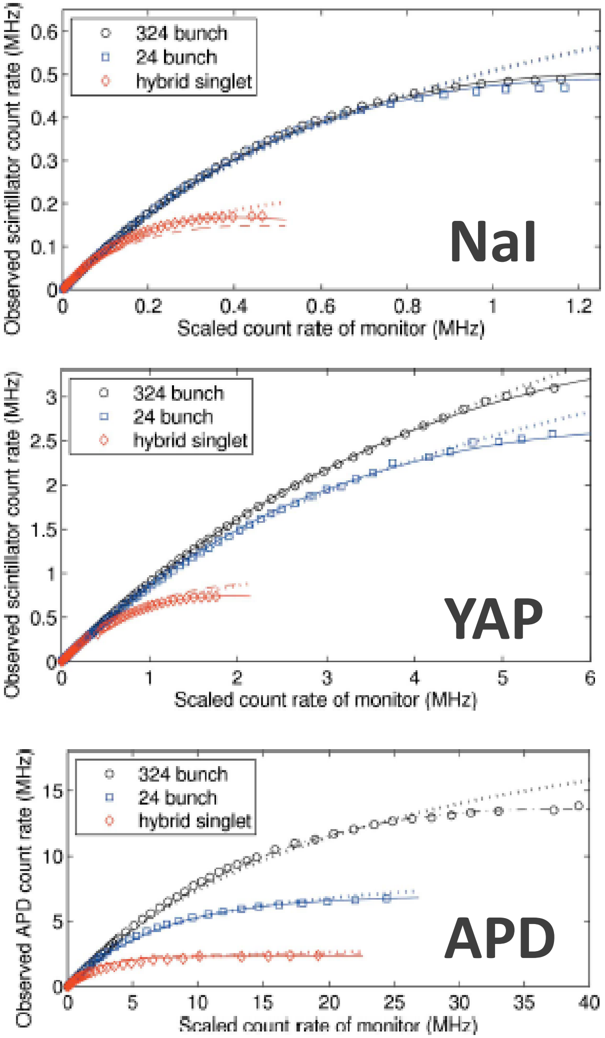
Deadtime for synchrotron (pulsed source)

- Depends on the fill pattern and speed of the detector

324 or 24 bunch mode

Hybrid Singlet



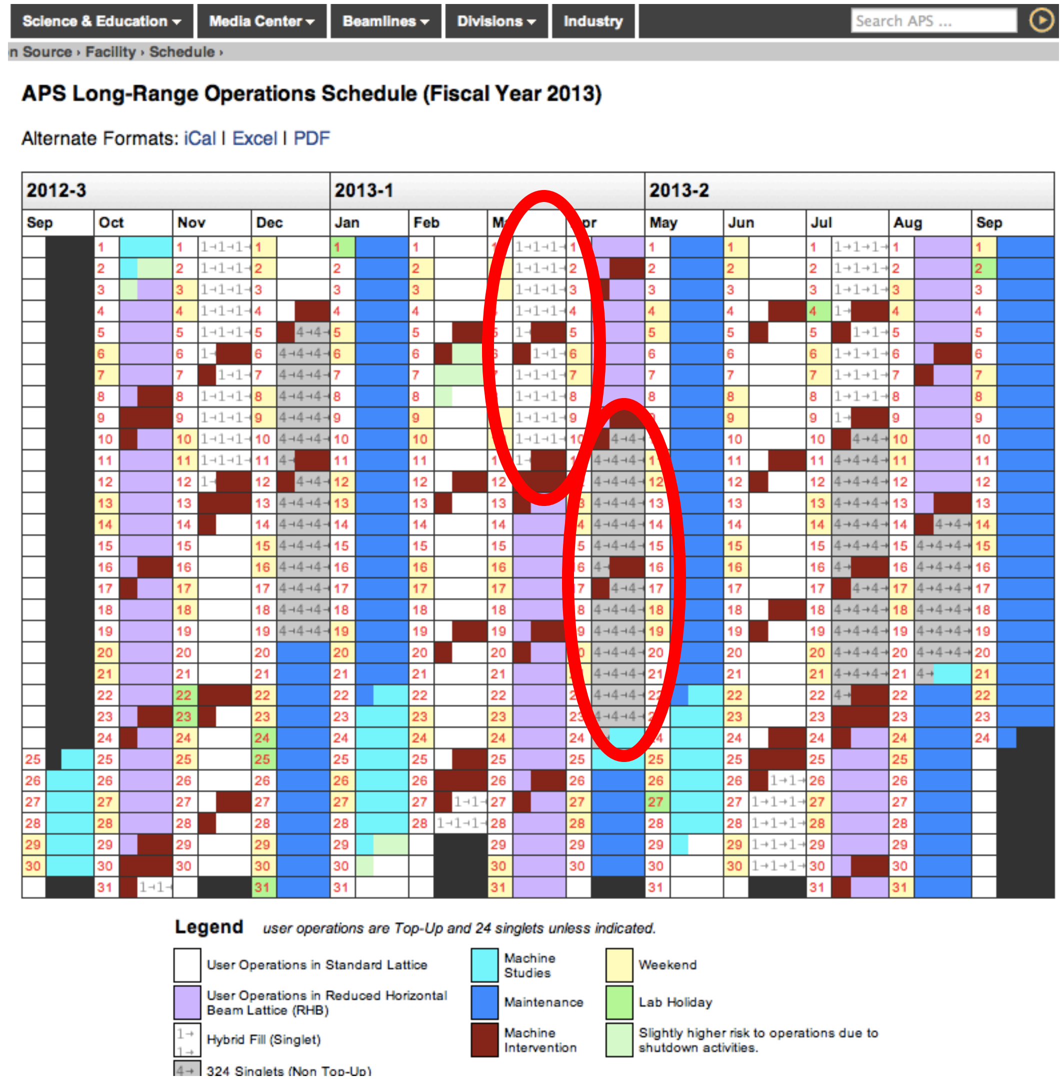


Fast detector (shorter shaping time)

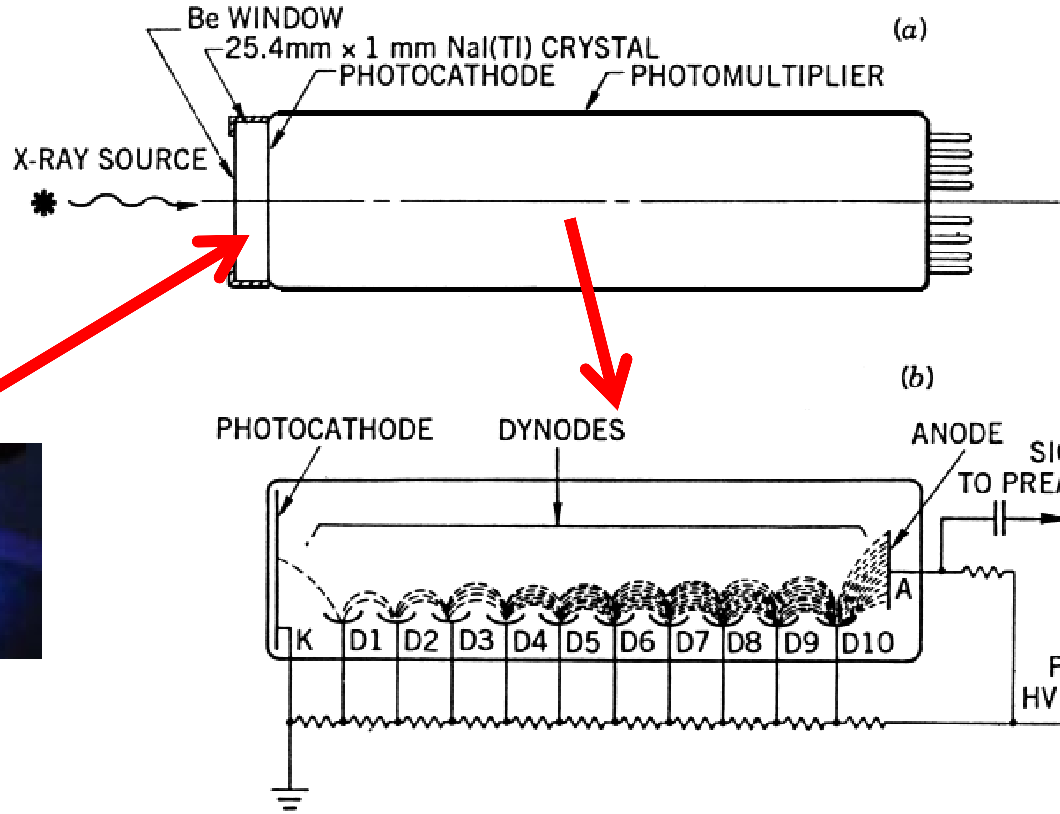
D.A. Walko, D.A. Arms, E.C. Landahl, J. Synchro. Rad. 15 (2008) 612; http://dx.doi.org/10.1107/S0909049508022358

What fill pattern pattern will you be using???

- Hybrid singlet and 324 bunch mode each 2 weeks a run.
- Hybrid singlet useful for special timing experiments.
    - Not great for high count rate experiments.



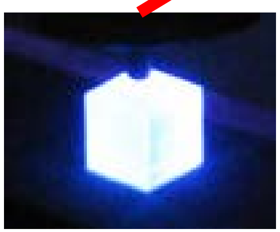
Indirectly (x-rays → optical photons → electrons)
<u>Scintillation Counters</u>



One pixel

- "Point detector"

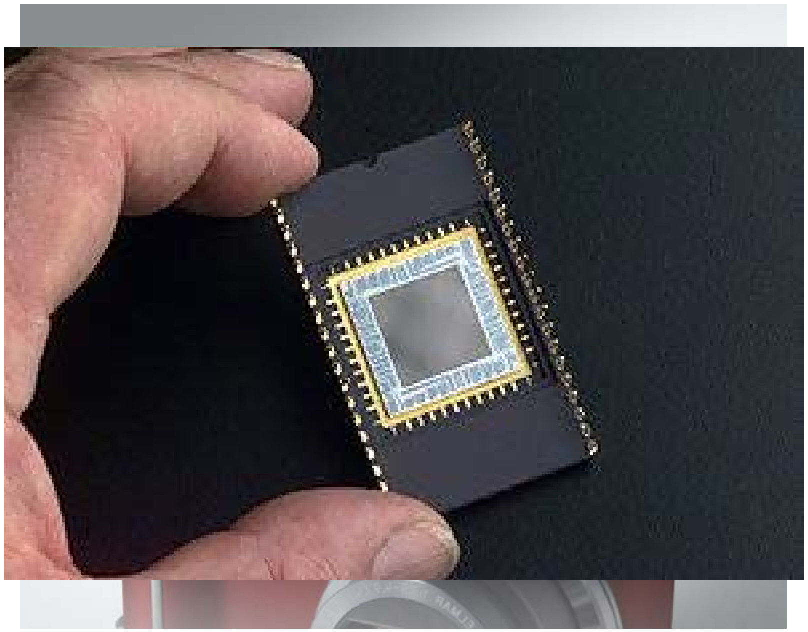
Still workhorse for high resolution diffraction experiments (plus a pair of slits)

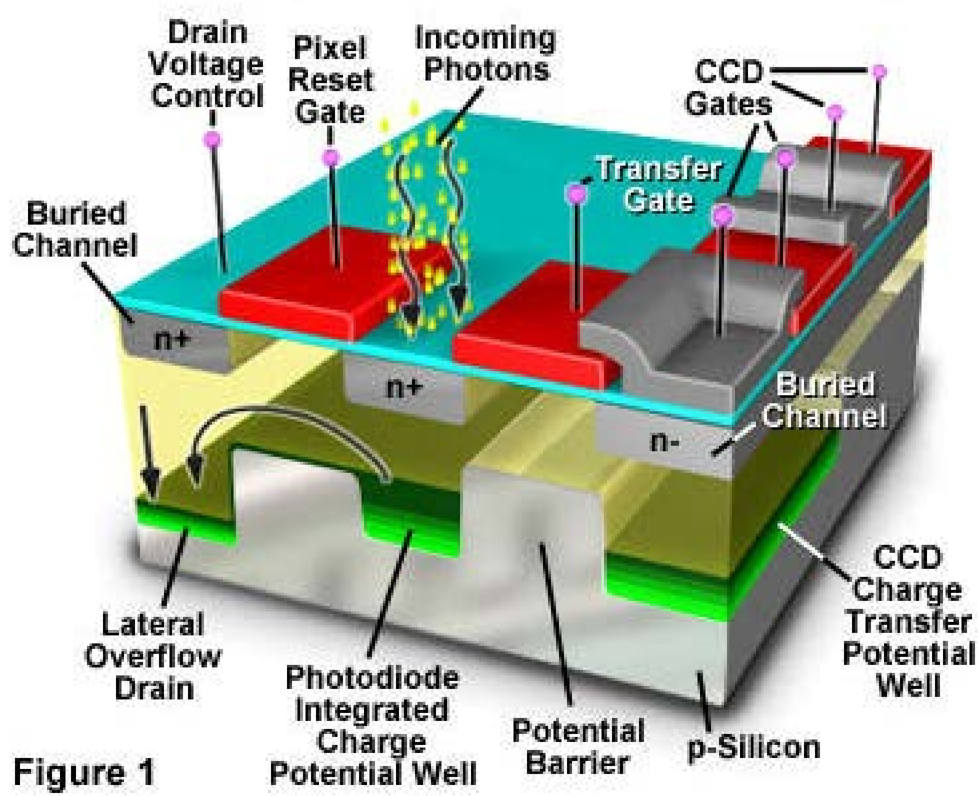


NaI(Tl) is the most common scintillator and gives a energy resolution (ΔE/E) of about 35% - 40%. Organic (plastic) scintillators are used for higher speed applications but energy resolution is sacrificed.

Indirectly (x-rays → optical photons → electrons)
Charge Coupled Devices (CCDs)

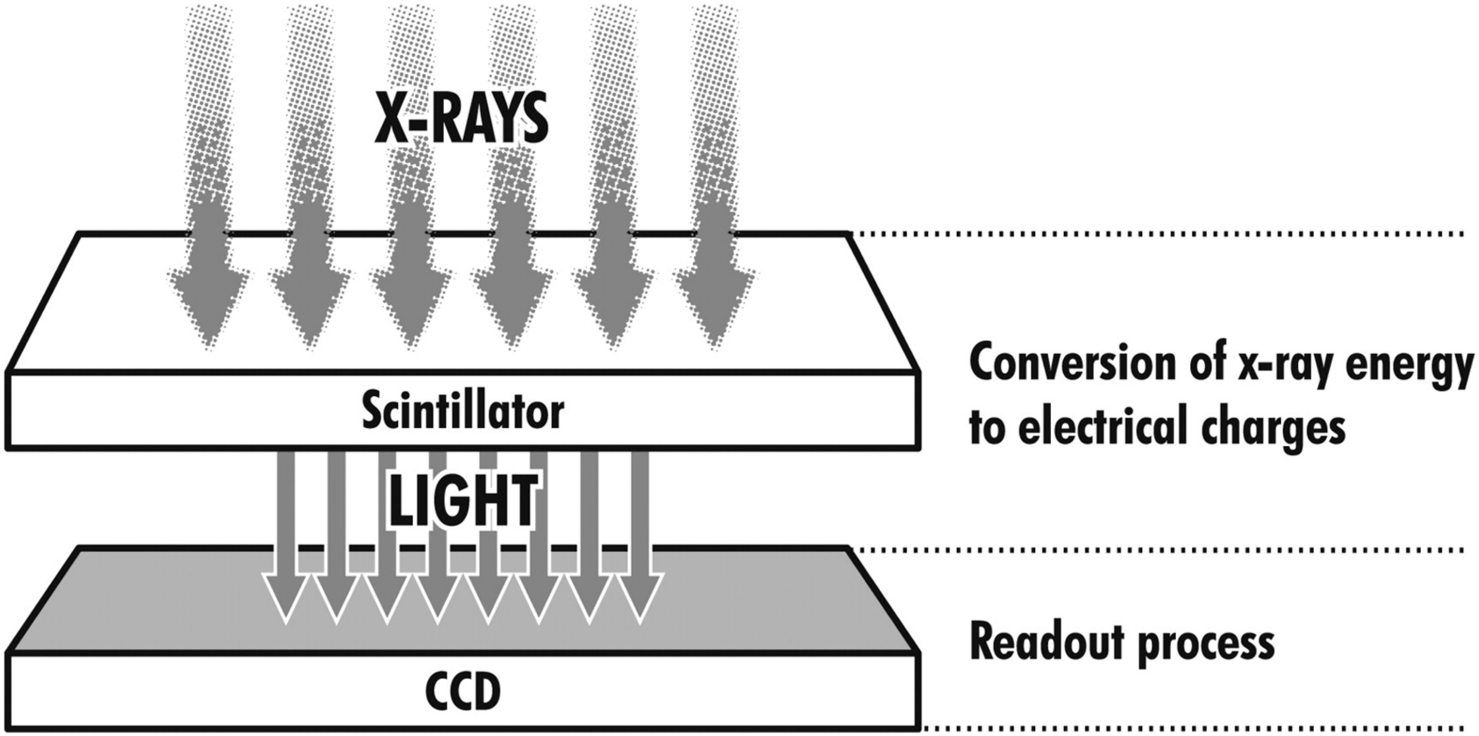
- Optical detectors are everywhere in our lives… camera phones, etc.





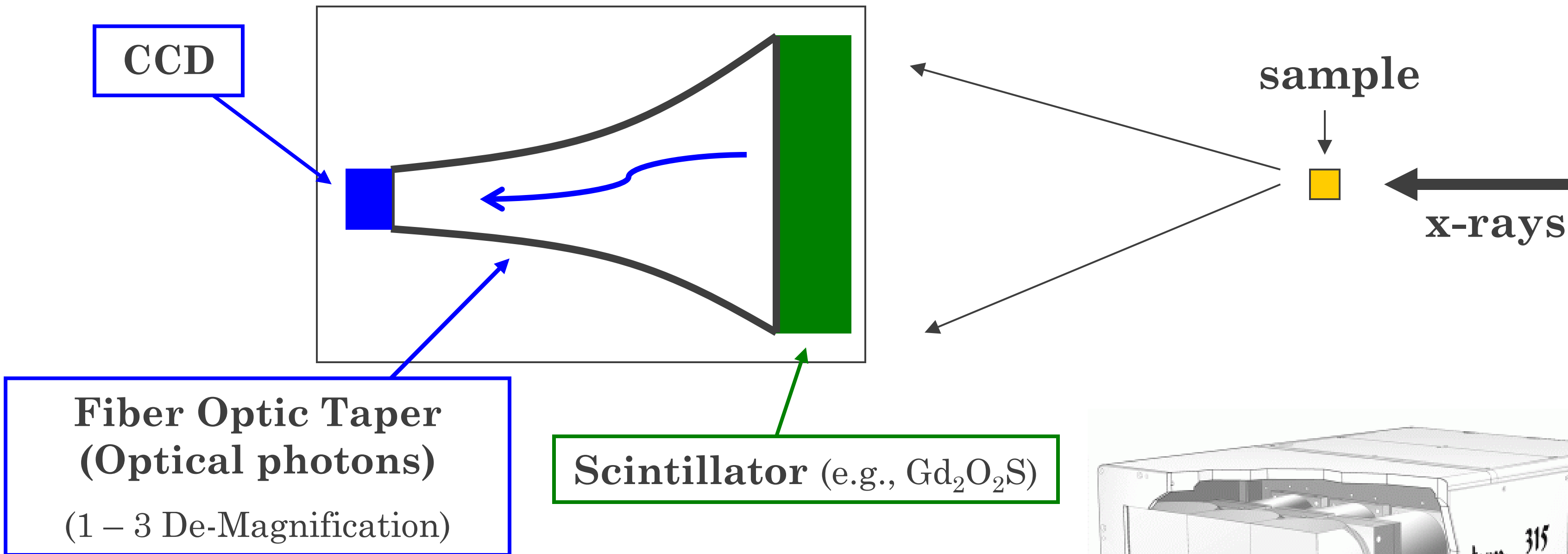
CCDs are integrating detectors. No dead-time issues, but read noise and dark current

Indirectly (x-rays → optical photons → electrons)
Charge Coupled Devices (CCDs) + x-ray scintillators

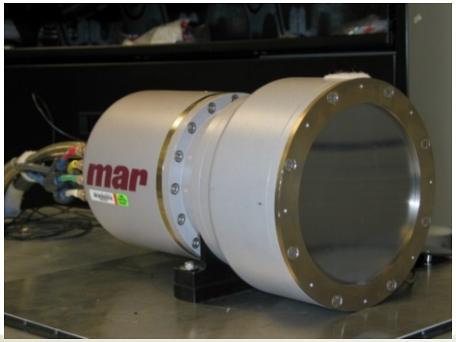


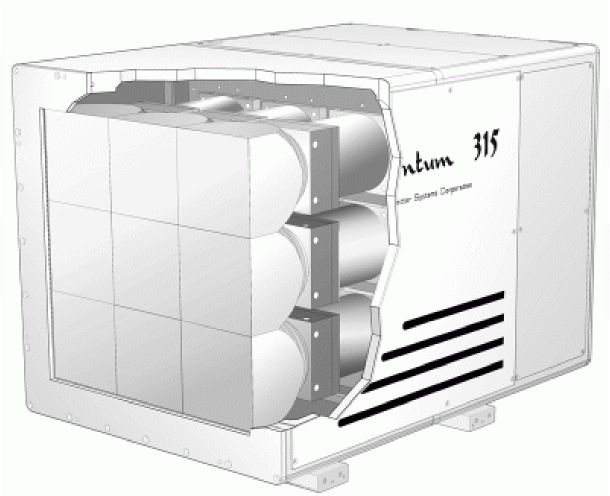
Indirectly (x-rays → optical photons → electrons)
Charge Coupled Devices (CCDs) + x-ray scintillators

- With demagnification for large area detectors
  - Diffraction (< 30 keV)



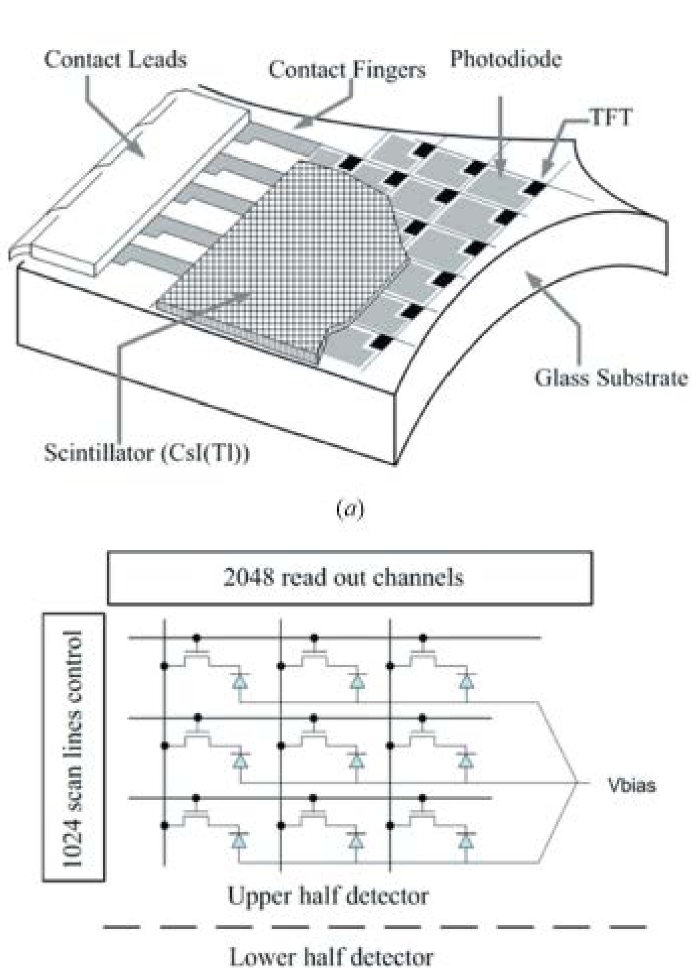
- Spatial resolution ~ 100 μm
- No deadtime correction
- Calibrations
  - Dark Subtraction
  - Spatial Distortion
  - Spatial gain variations

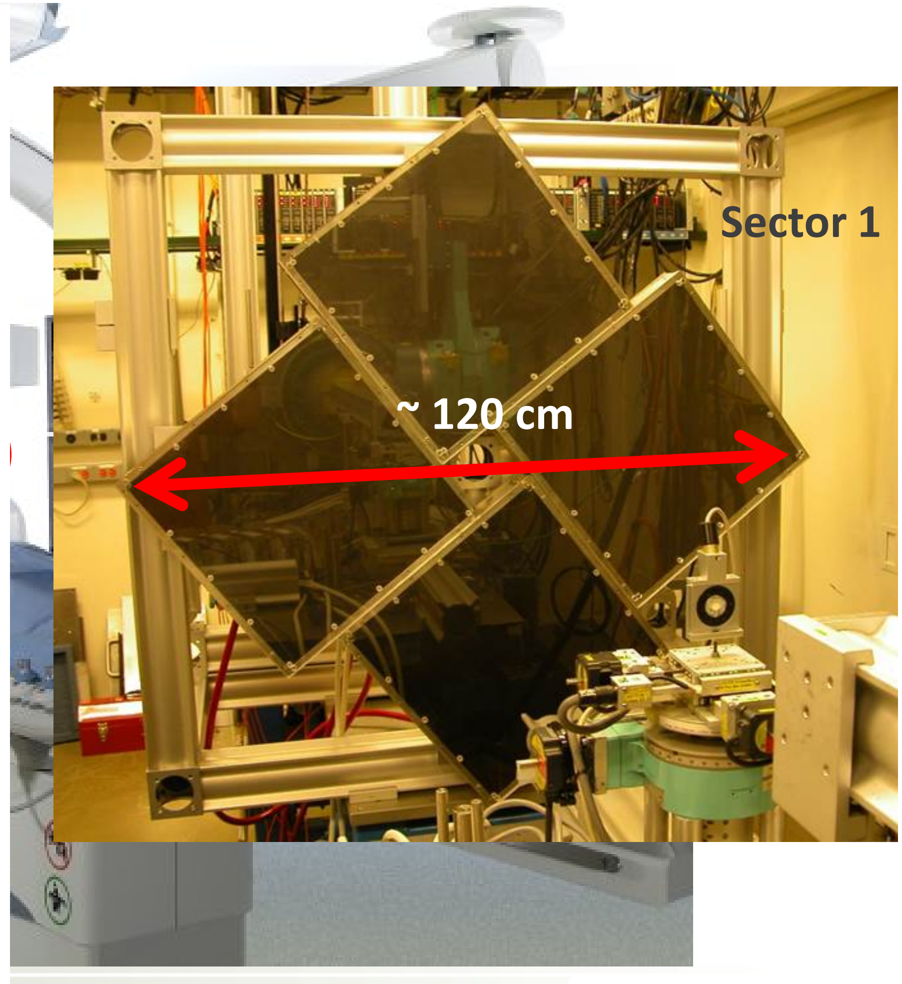




Indirectly (x-rays → optical photons → electrons) Amorphous Silicon Flat Panel + x-ray scintillators

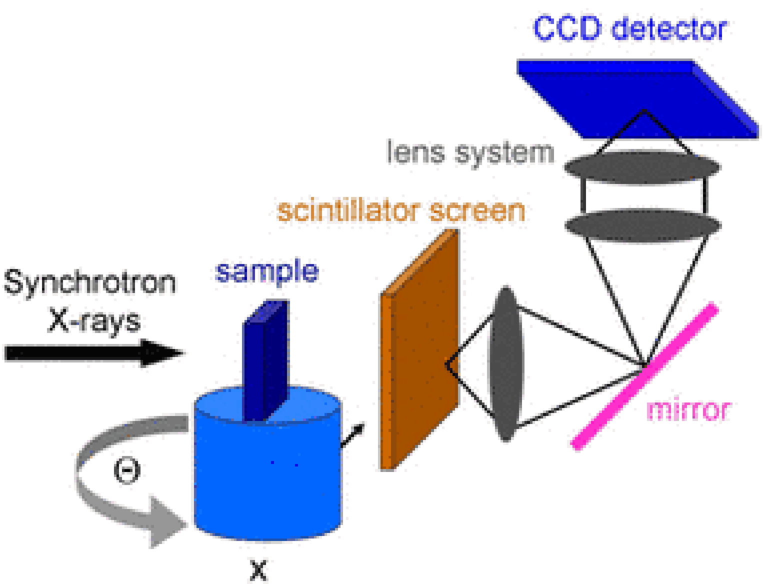
- Used at higher energies (> 50 keV)
- Thin film transistor (TFT) technology (a-Si photo-sensors) allows large area detectors
  - Cheaper than CCDs, but more noise!



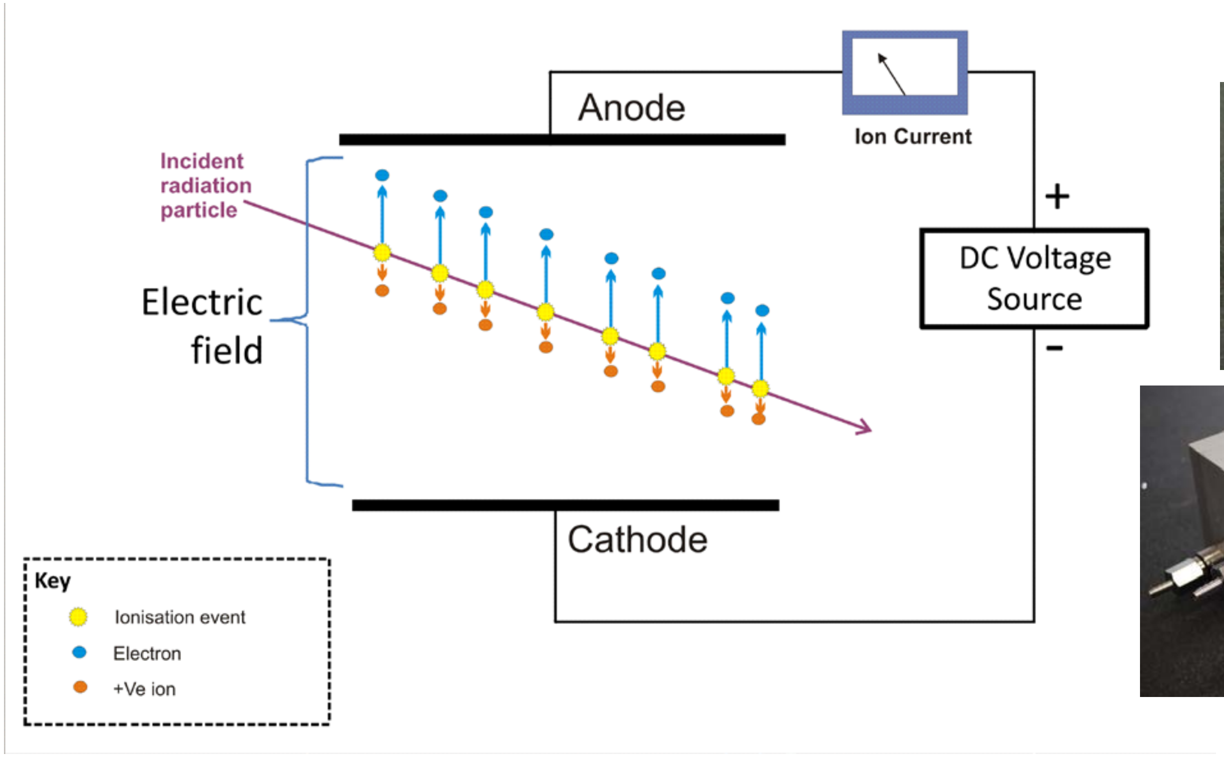


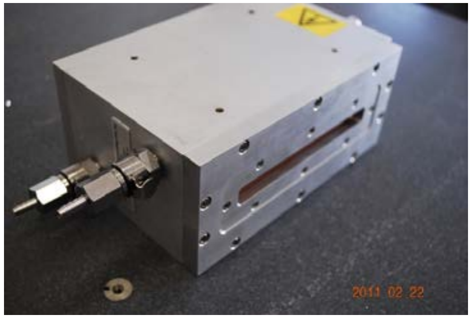
Indirectly (x-rays → optical photons → electrons)
Charge Coupled Devices (CCDs) + x-ray scintillators

- Magnification → Microscopy
  - μm-scale spatial resolution with x-rays



Directly (x-rays → electrons)
Ion Chambers





- Integrating detectors… ion current ~ x-ray flux
- Used to monitor beam intensity
- Used to normalize data to the beam intensity ("I0")
- Also used for transmission XAS measurements.

Directly (x-rays → electrons)
<u>Pixel Array Detectors (e.g., Pilatus)</u>

Diode Detection Layer

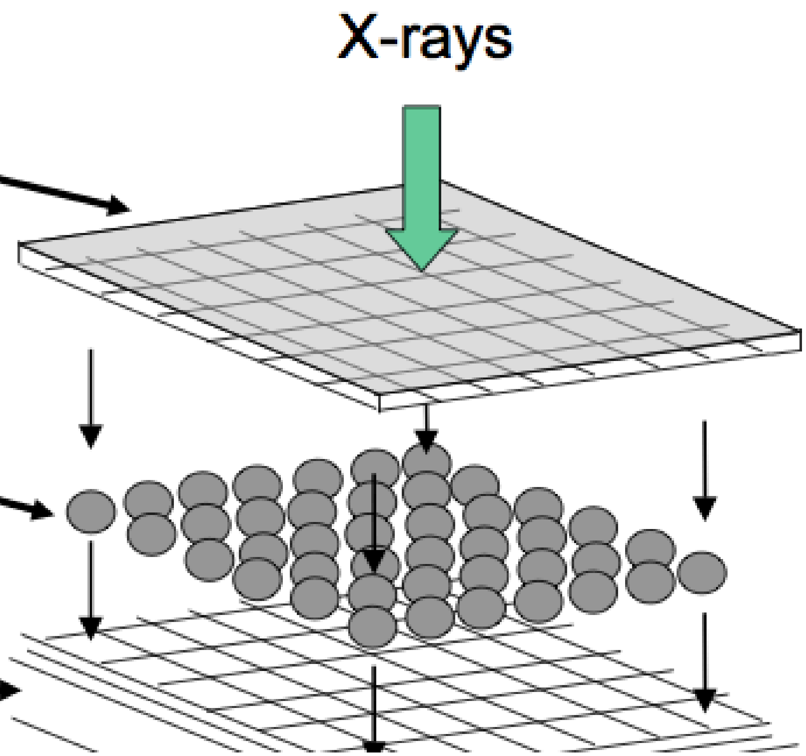
- Fully depleted, high resistivity
- Direct x-ray conversion in Si

Connecting Bumps

- Solder, 1 per pixel

CMOS Layer

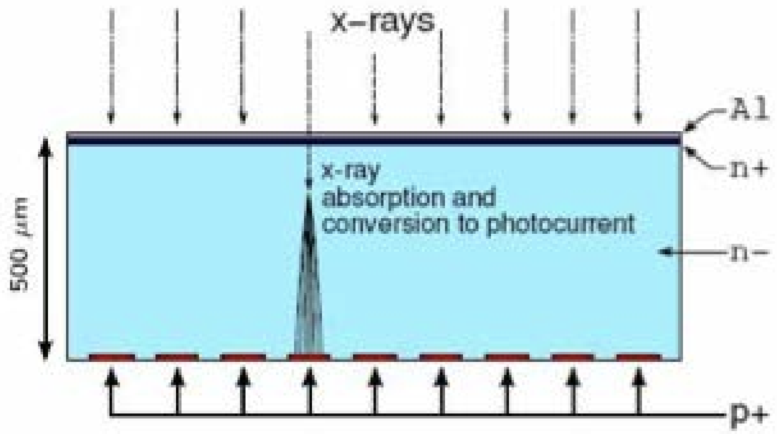
- Signal processing
- Signal storage & output



Sol Gruner et al

Directly (x-rays → electrons)
Pixel Array Detectors (e.g., Pilatus)

Diode Layer (Sensor)



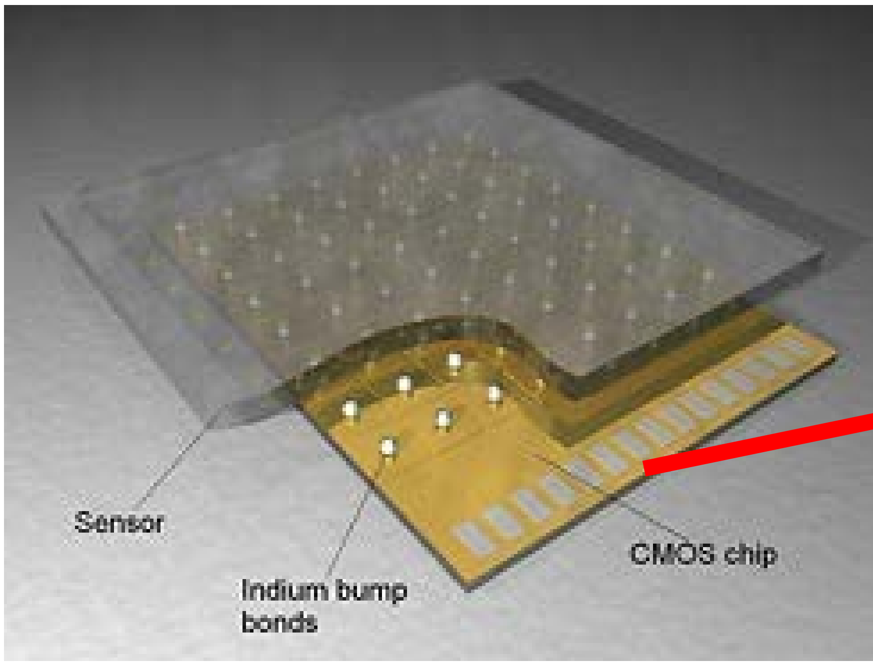
Diode Cross Section

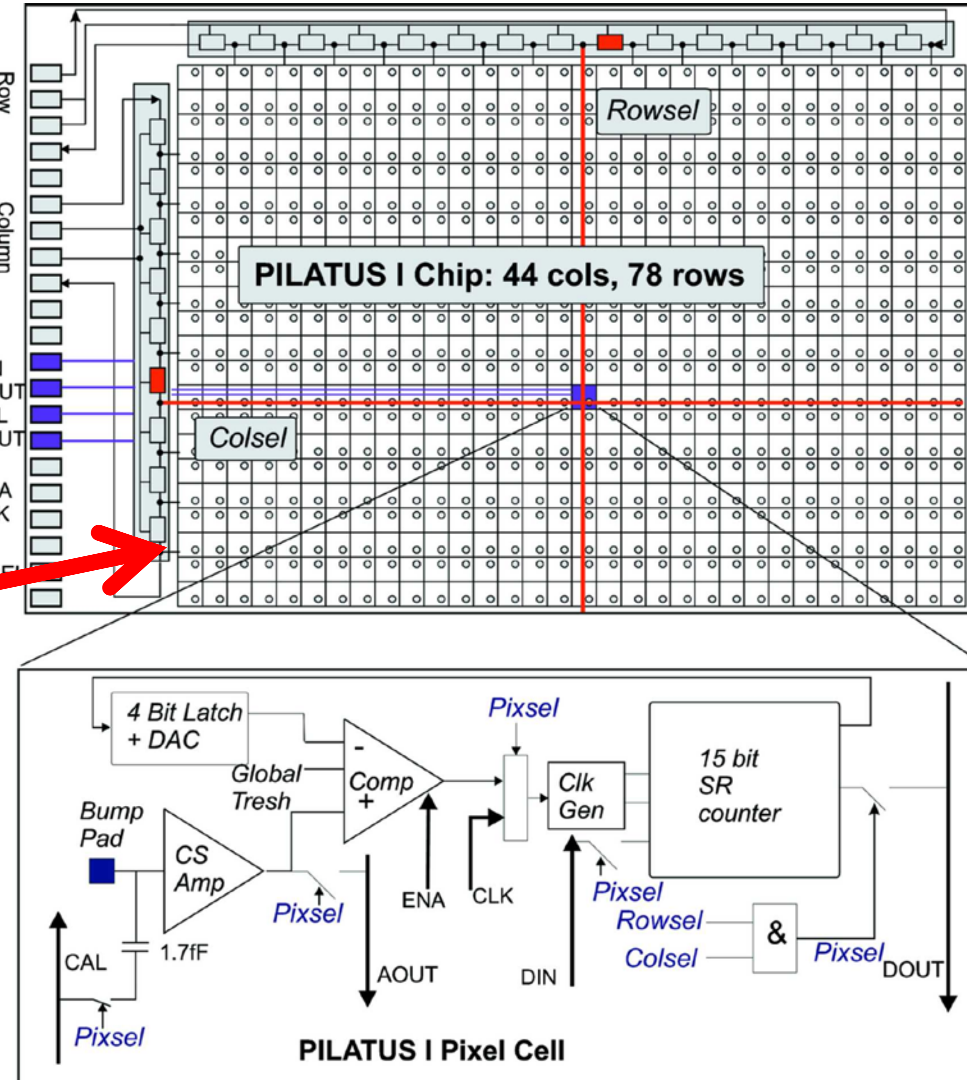
- Photodiode layer → high resistivity silicon (3,000–10,000 ohm-cm).
- Thick detector → effective up to 20 keV x-rays.

Sol Gruner et al

Directly (x-rays → electrons)
Pixel Array Detectors (e.g., Pilatus)

CMOS readout chip (i.e., Application Specific Integrated circuit, ASIC)





Pilatus is a *digital* PAD (photon counting)

PSI/SLS Detector Group

Directly (x-rays → electrons)
Integrating Pixel Array Detectors

- You can design the CMOS readout in anyway you like.
  - e.g., with an integrating front end.

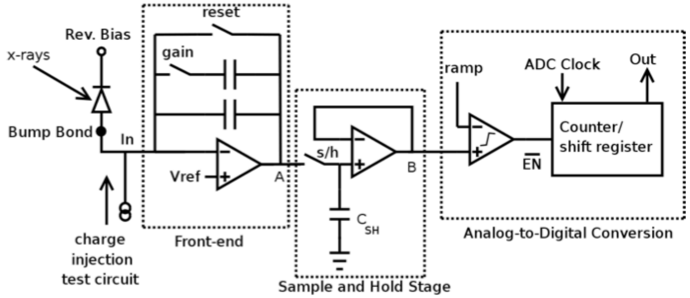


Figure 1: Simplified pixel schematic. The hybridized detector will have the bump-bonding connections between the detector diode and CMOS electronics at the node labeled "IN". All pixels have a switched capacitor charge injection circuit for testing pixel functionality and secondary verification of the calibrated gain profile.

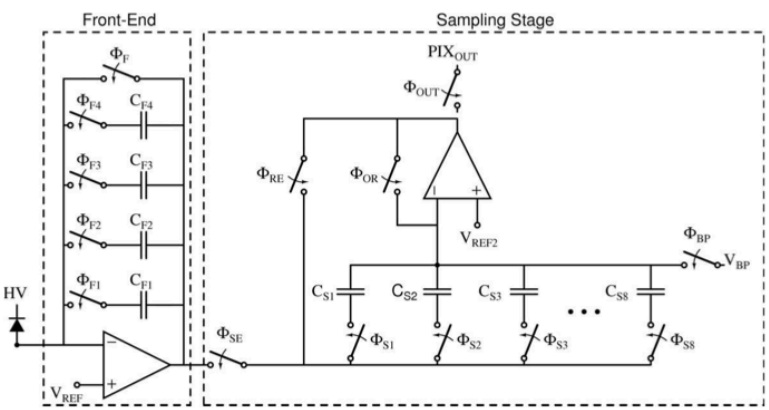
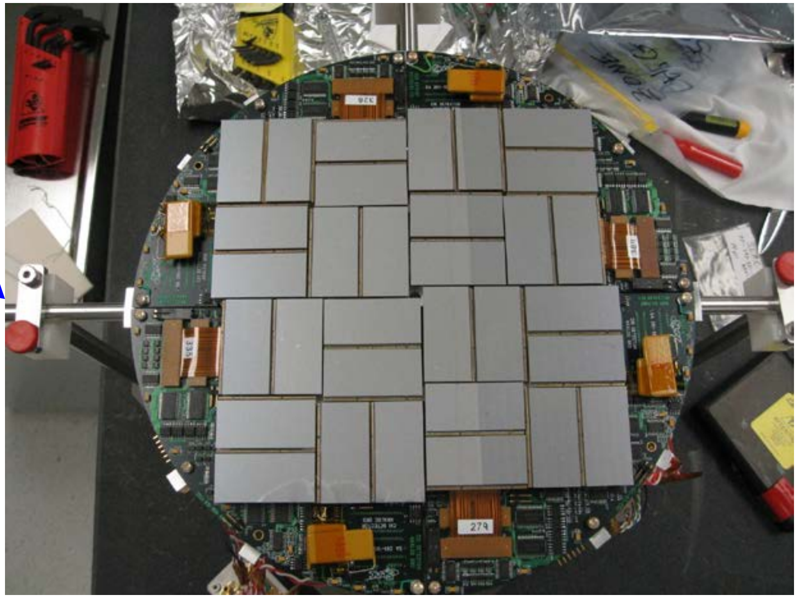


Figure 1
Simplified pixel schematic that differentiates the front-end stage and the sampling stage. The reversed biased diode represents the high-resistivity detector layer.

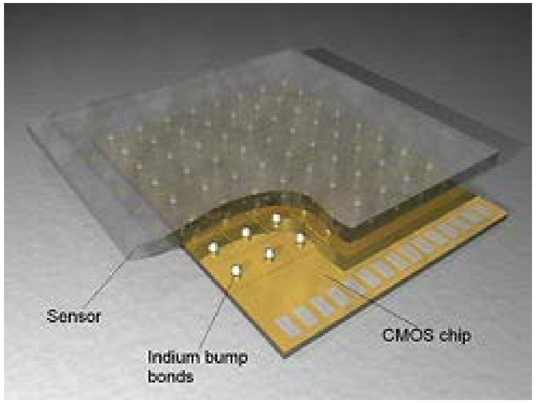


CSPAD at LCLS

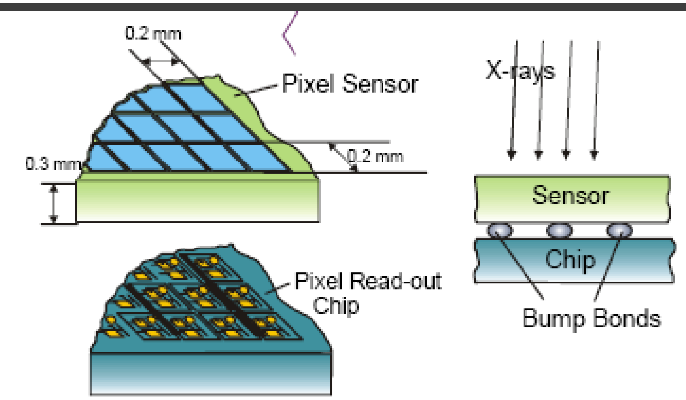
Gruner *et al.*,

Directly (x-rays → electrons)
Pixel Array Detectors (e.g., Pilatus)

- Each pixel is a single photon counting detectors!
- Thus has count rate limitations

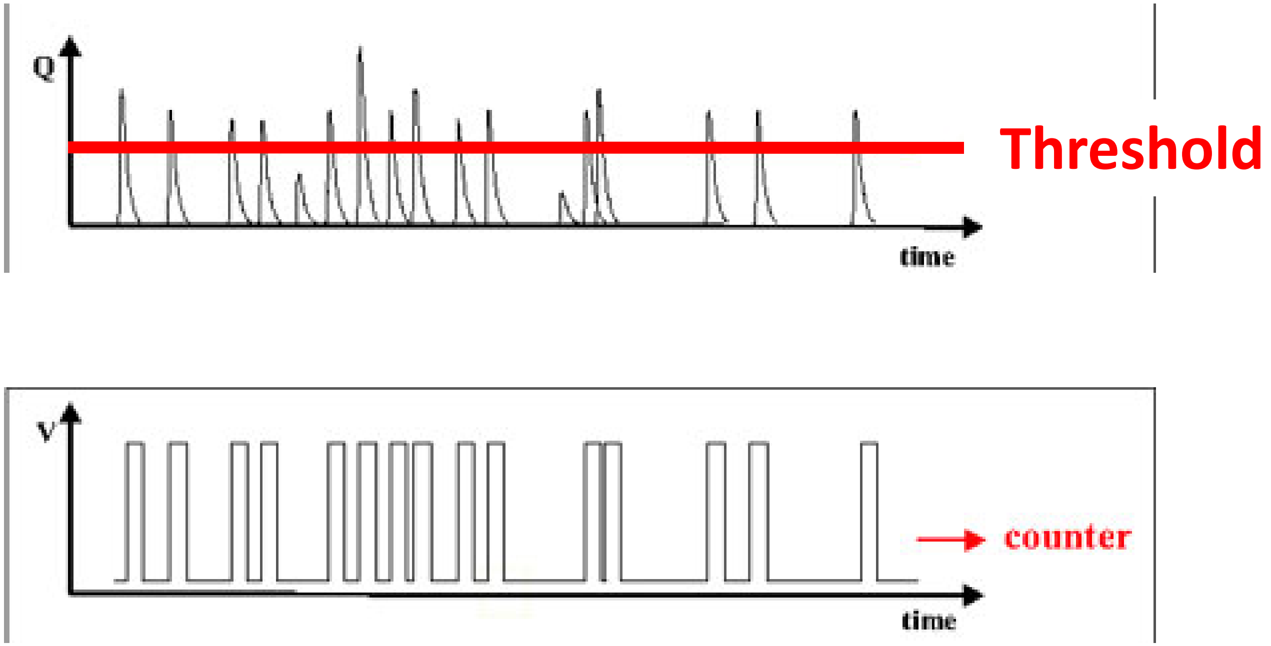


- 487 x 195 pixels (172 μm)
- 8.3 cm x 3.3 cm Area
- Count Rate ~ 1 MHz/pixel
- 20-bit counter/pixel
- 5ms readout (Frame Rate = 200 Hz !!)
- 320 micron thick Silicon sensor
- Gateable & electronic shutter
- Lower Level Discriminator only



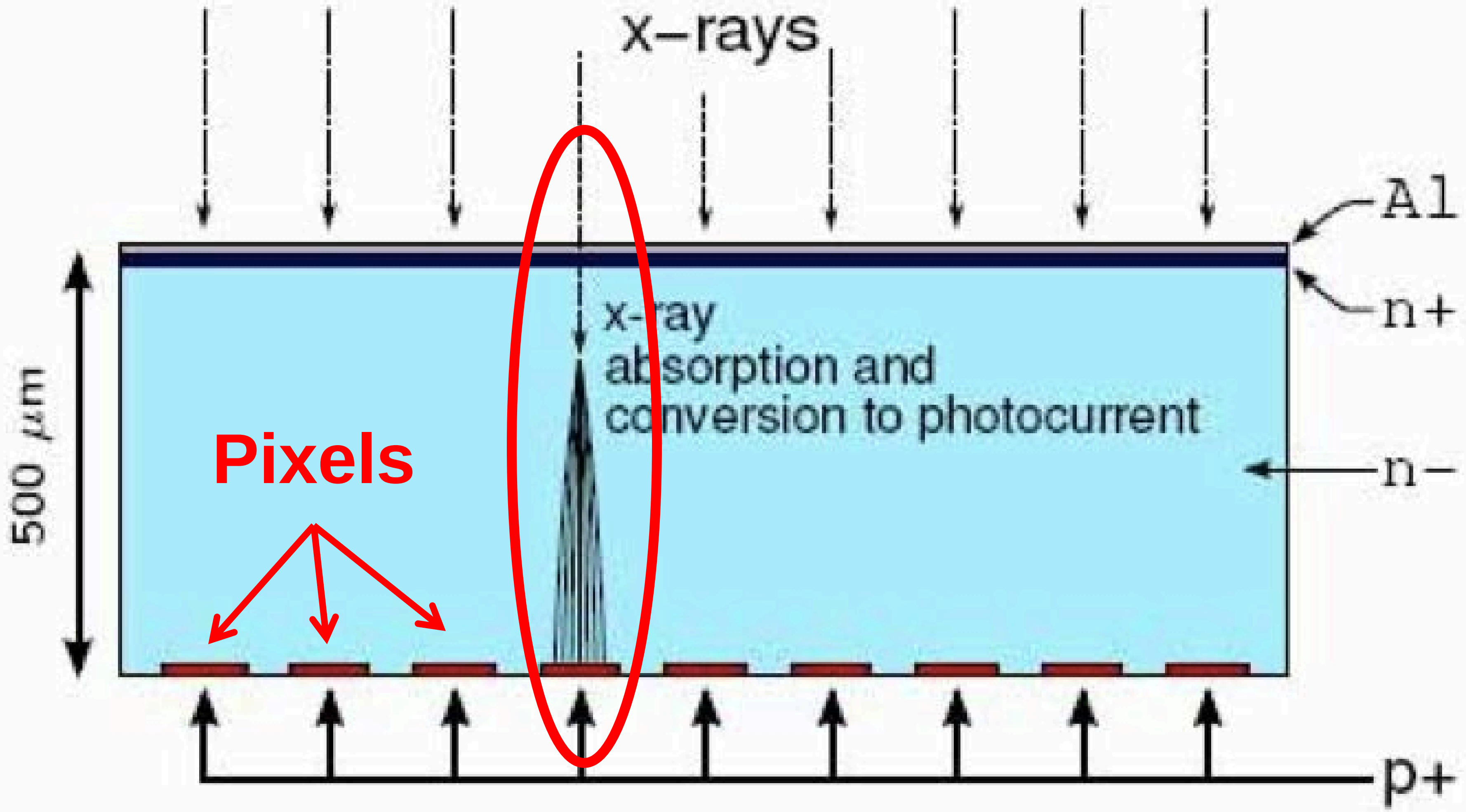
Brönnimann *et al.* @ PSI in Switzerland (Dectris)

Directly (x-rays → electrons)
Pixel Array Detectors – Pilatus Threshold



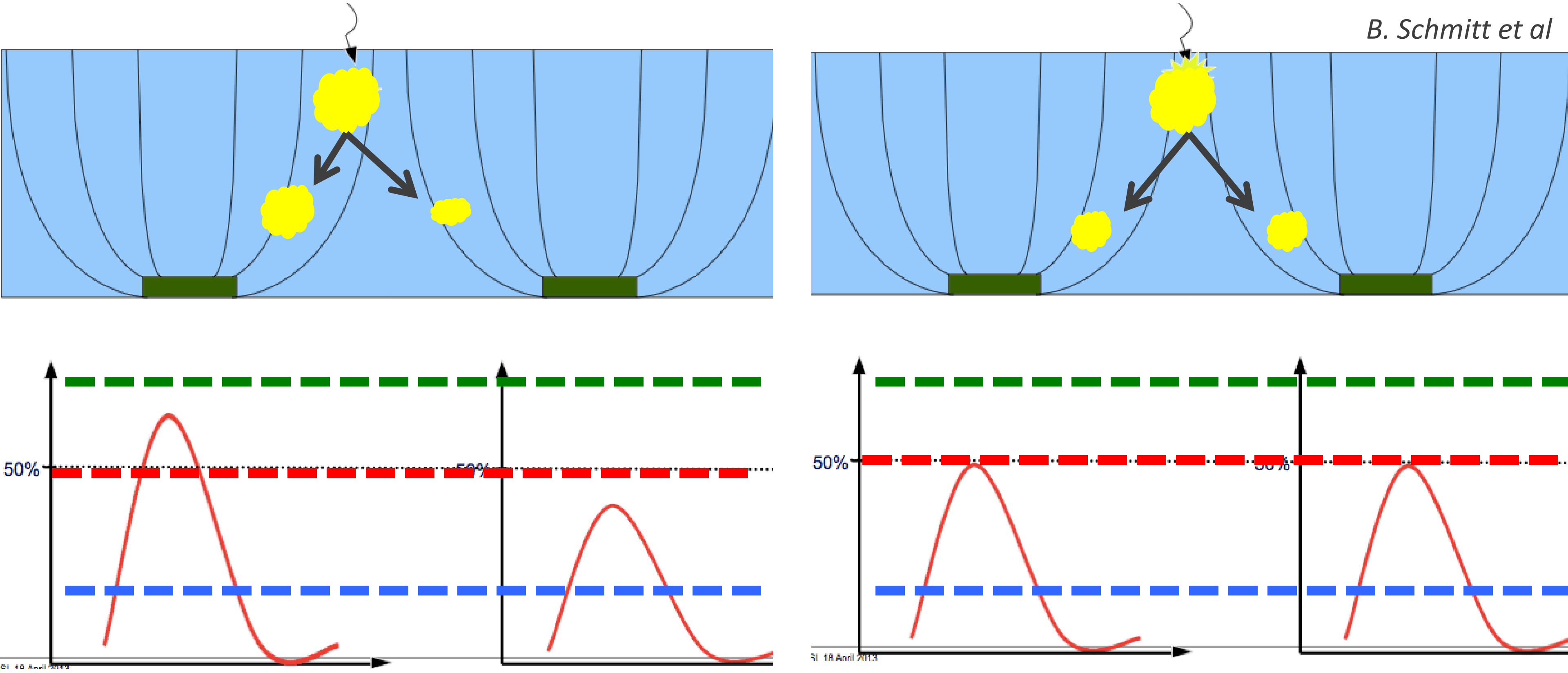
- Where to set the threshold?
- Is there an "optimal" threshold?

Pilatus Threshold – pixel charge sharing



Pilatus Threshold – pixel charge sharing

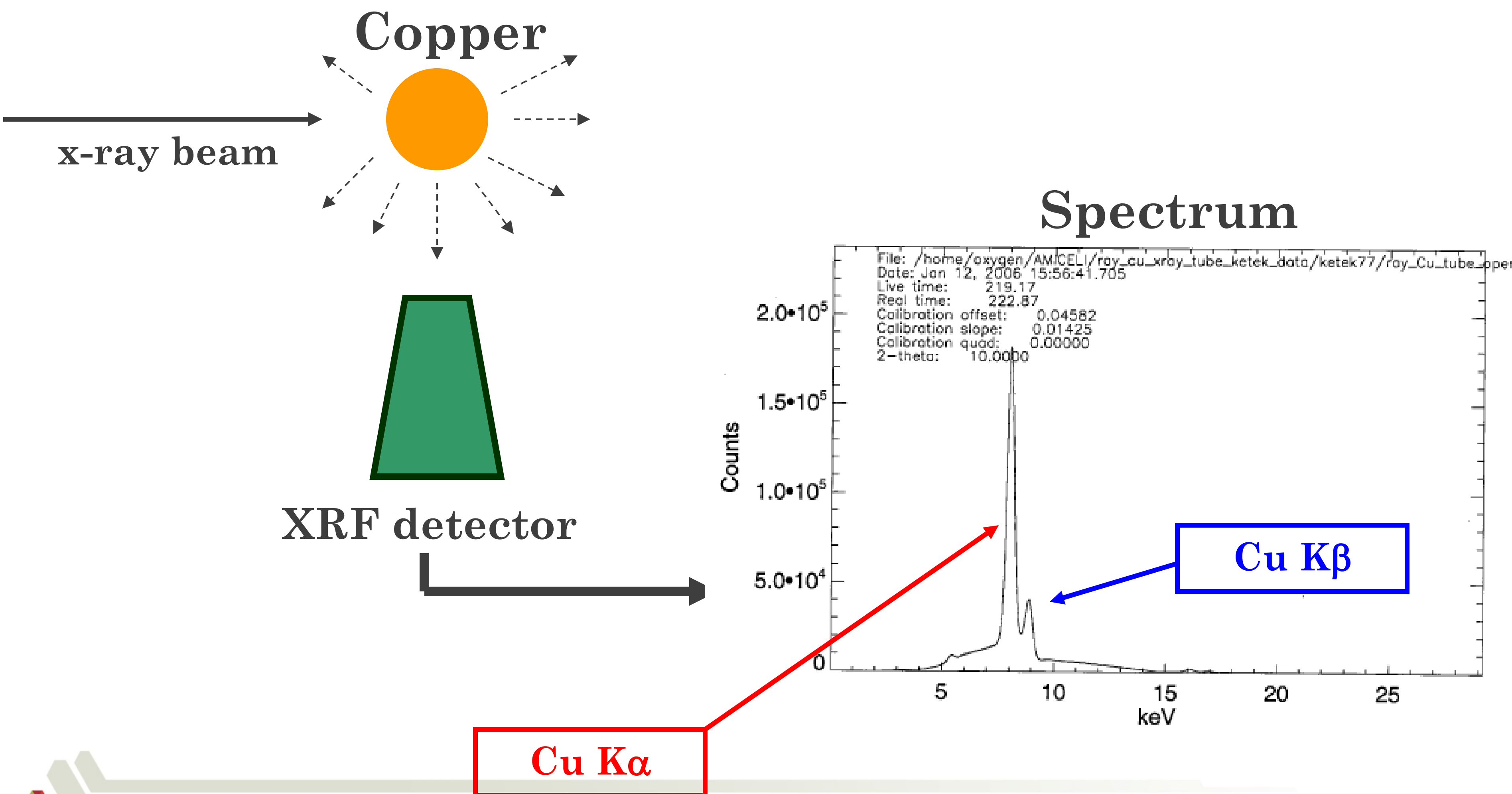
B. Schmitt et al



- If threshold is too high, then you under count events (effectively a small pixel)
- If threshold is too low, then you double count events
- "Optimal" threshold is 50% of beam energy
  - Unless you need to reject fluorescent background.

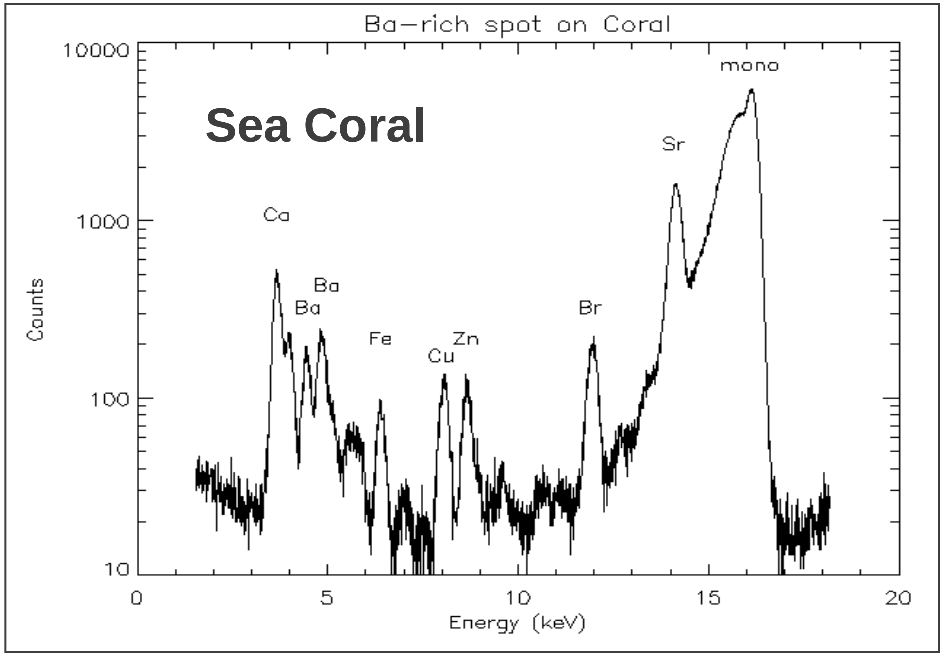
Energy Resolving Detectors

(aka Energy Dispersive Detectors)
(aka Spectroscopic Detectors)
(aka XRF detector)

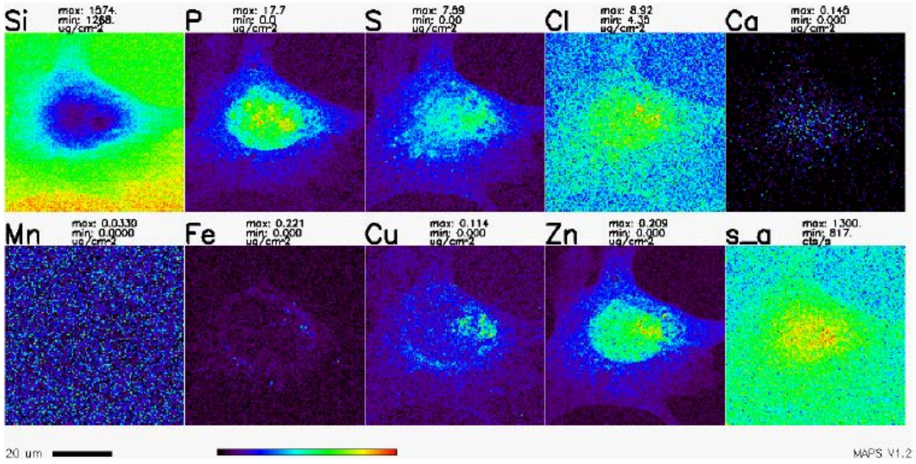


Fluorescence (XRF) Measures…

- Abundance (ppm level) and spatial correlations of heavy elements



Matt Newville, 13-id



Need to collect >10 elemental ROIs ⇒ energy dispersive detector

Barry Lai, 2-id

Elemental Compositions of Comet 81P/Wild 2 Samples Collected by Stardust (Flynn et al 2006)

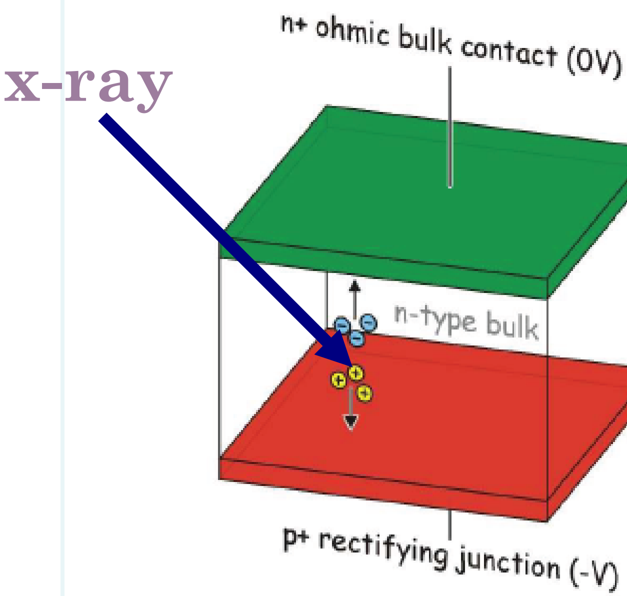
Solid-phases and desorption processes of arsenic within Bangladesh sediments (Polizzotto et al 2006)

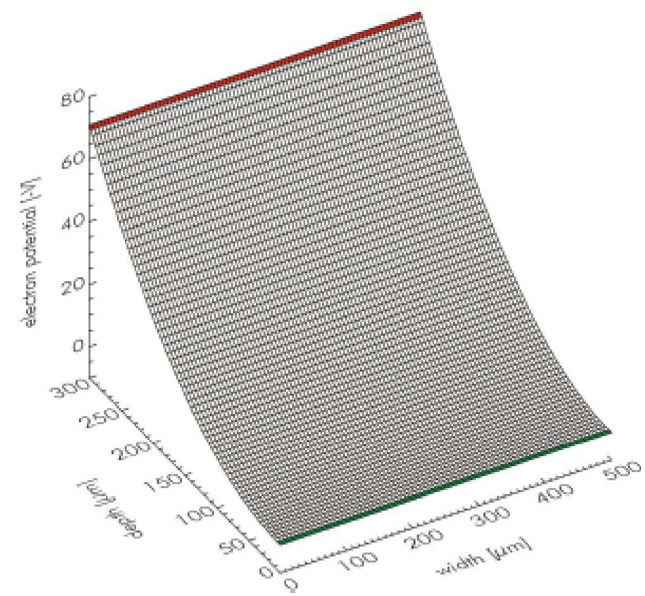
A link between copper and dental caries in human teeth identified by X-ray fluorescence elemental mapping (Harris et al 2008)

Levels of Zinc, Selenium, Calcium, and Iron in Benign Breast Tissue and Risk of Subsequent Breast Cancer (Cui et al 2007)

Spectroscopic Detectors

- **Diode** (Silicon or Germanium)





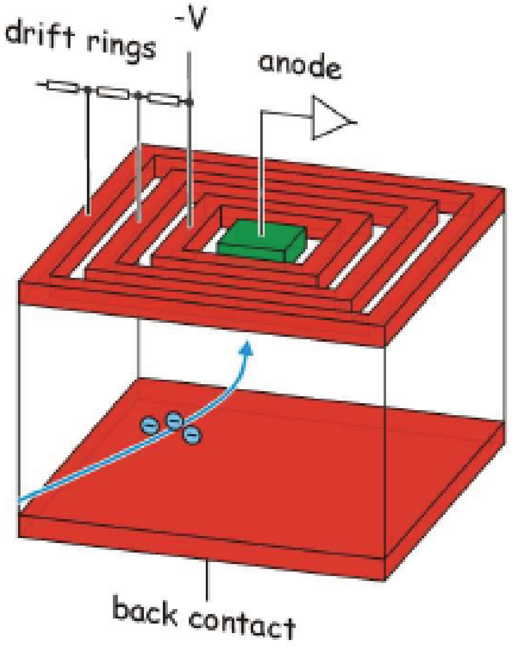
X-Ray Energy ~ # of e-h pair

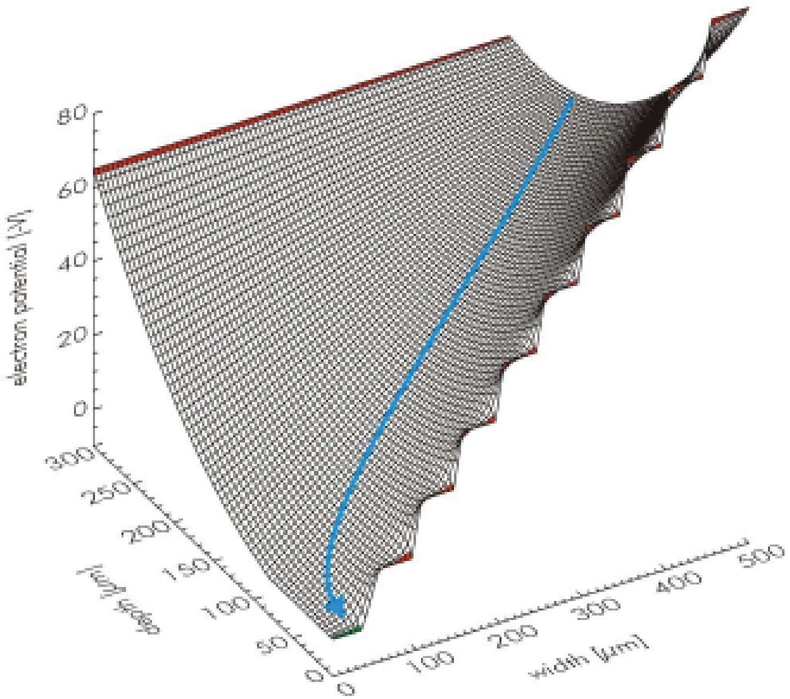
(3.67 eV are need to produce 1 e-h pair for Silicon!!)

In reality, we use *Silicon Drift* Diodes ...

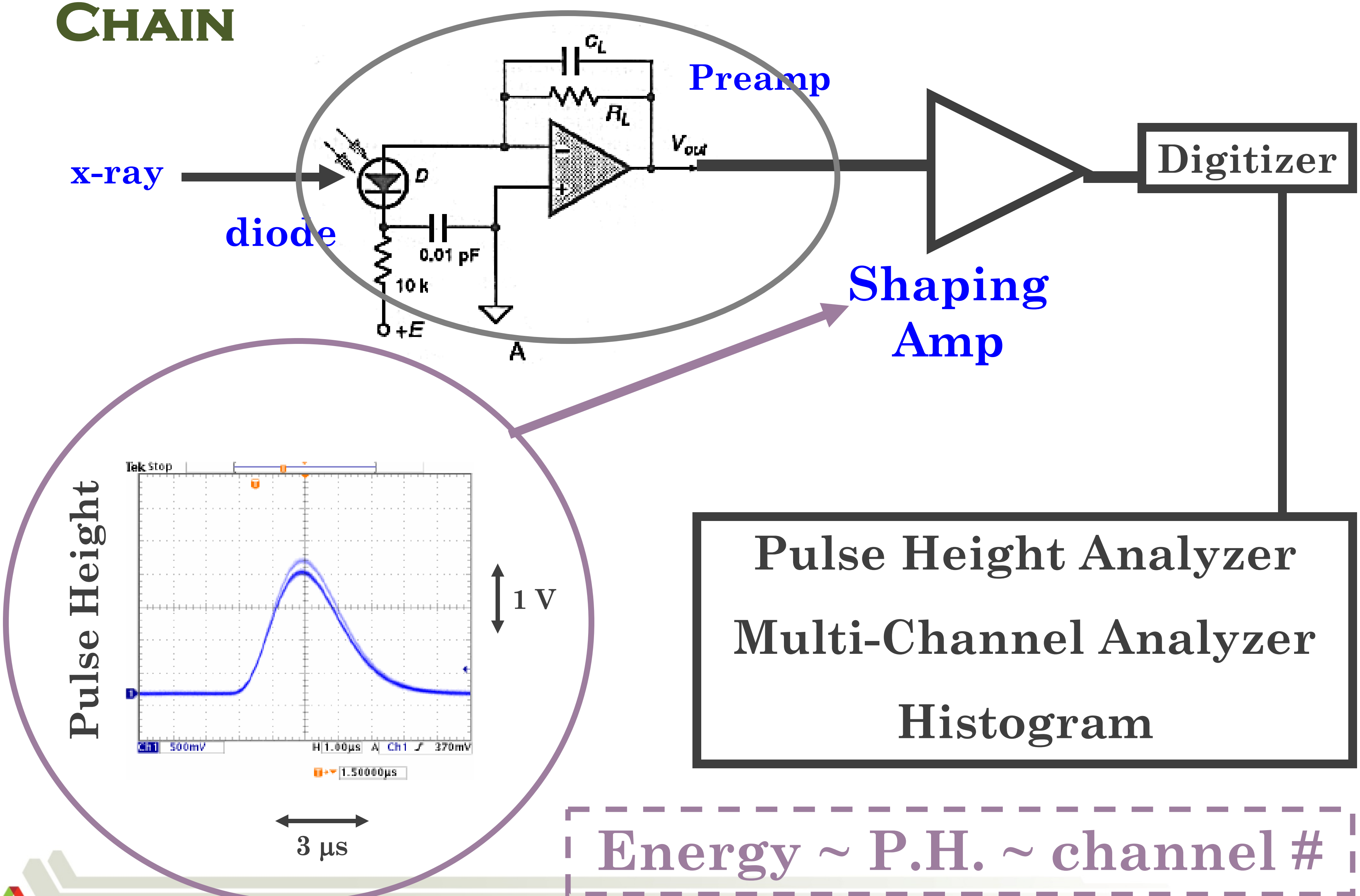
Spectroscopy SDD

Josef Kemmer & Gerhard Lutz, 1987



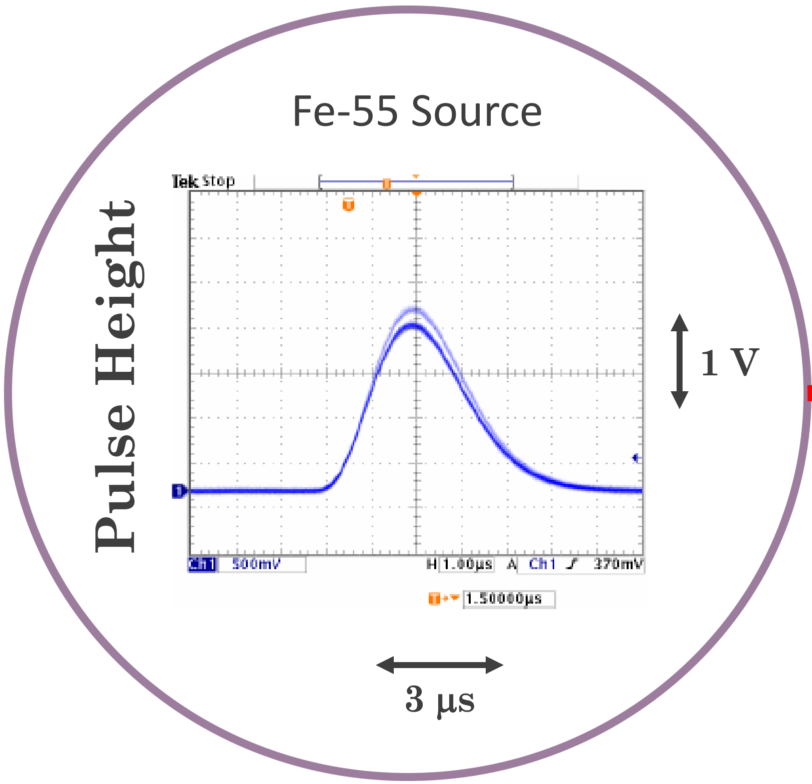


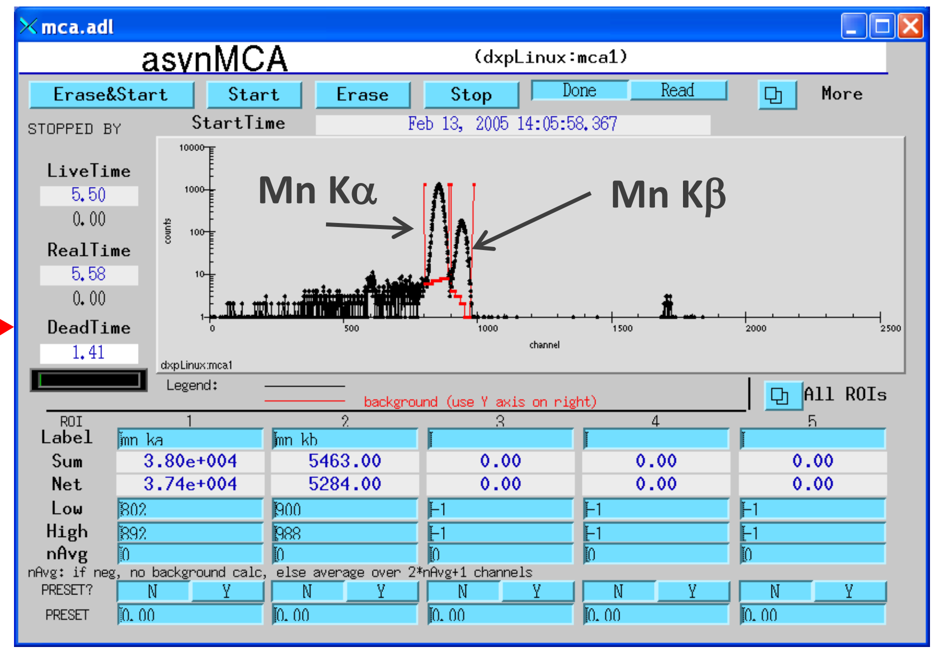
Spectroscopic Detectors – Signal Chain



Energy ~ P.H. ~ channel #

Spectroscopic Detectors – Pulses to Histograms



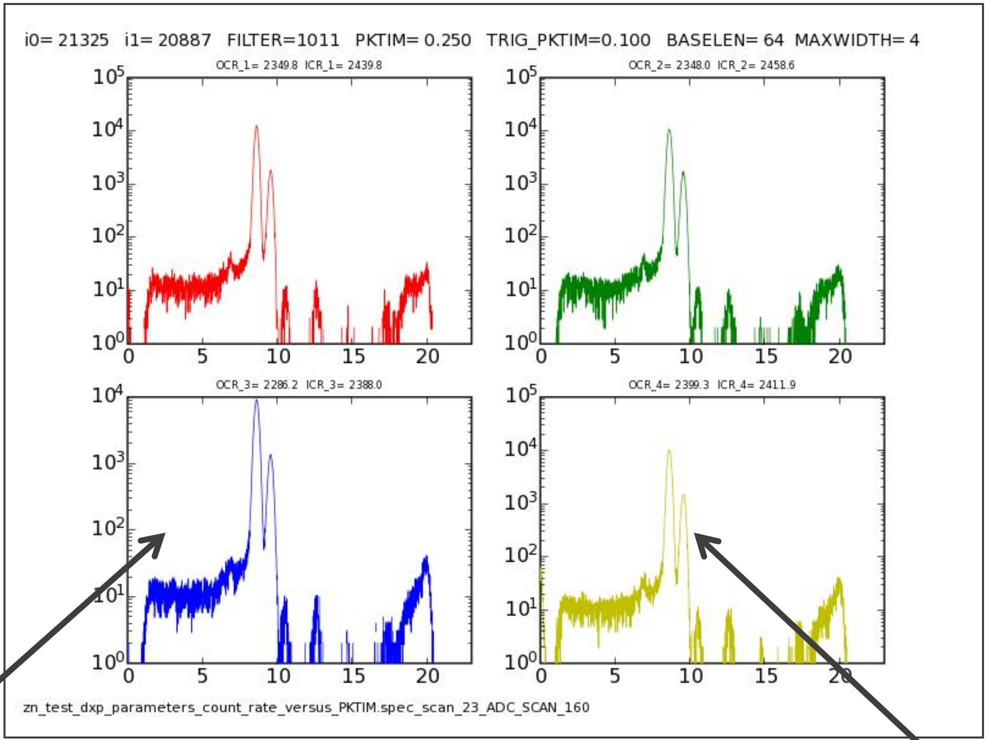


MCA = histogram (e.g., 2048 channels)

SCA = Single Channels (i.e., ROIs)

4-element Silicon Drift Diode

4-element SDD (SII Nano Inc)



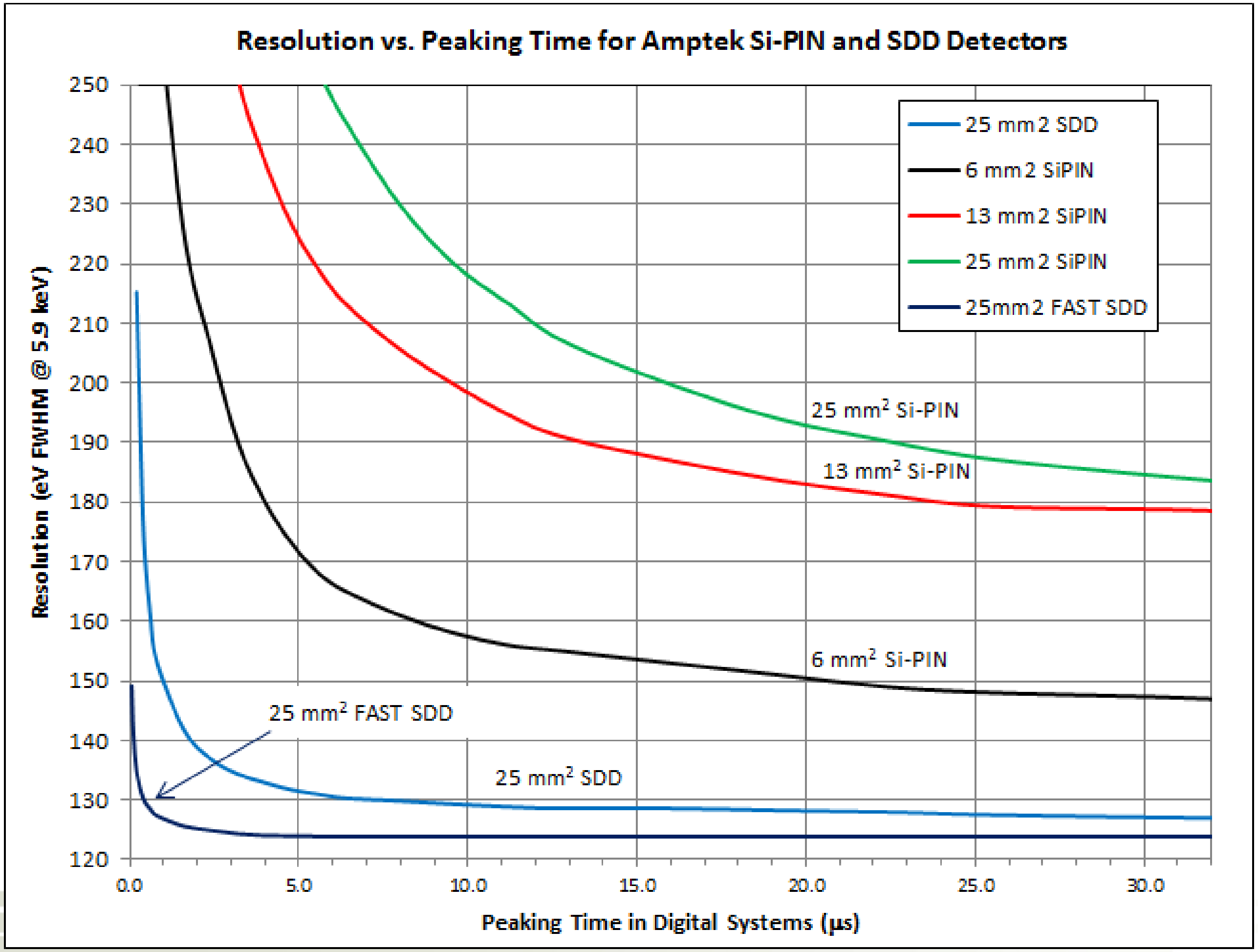
Peak-to-Background Important!!!

- Usually signal is buried here!
- Recombination, incomplete charge capture, etc.

Best Energy Resolution ~ 150eV

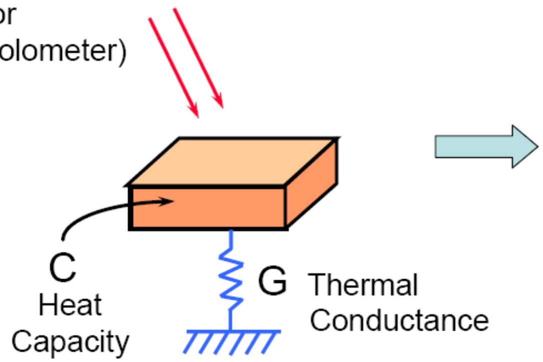
Trade-off between count rate and energy resolution!!!

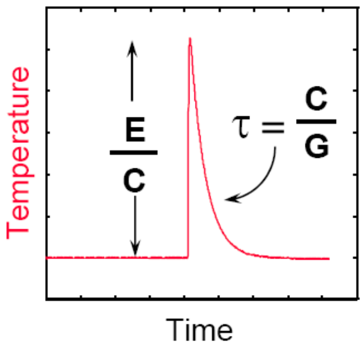
- Shorter shaping time (length of pulse) means more count rate, but less energy resolution.
  - Depends on your experiment.



Beyond Silicon … Superconducting sensors

Thermal sensors

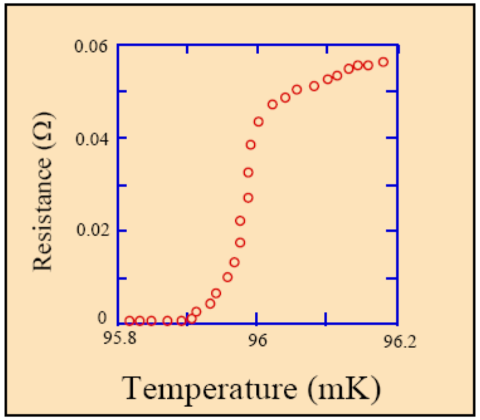




1/e response time = 100 µs - 1 ms

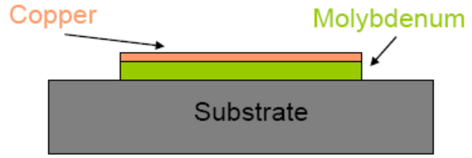
- Transition-Edge Sensor (TES) = thin-film biased in superconducting-normal transition

- Use strong dR/dT in transition as thermometer



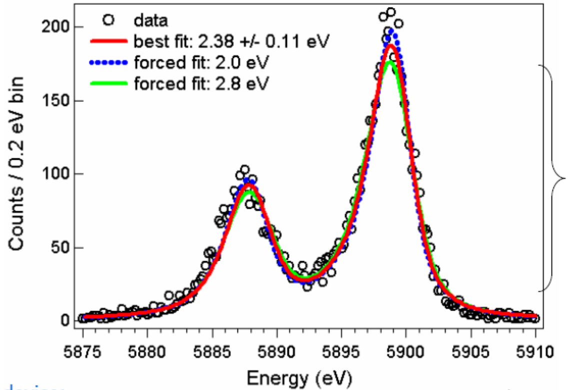
Kent Irvin et al, NIST-Boulder

- molybdenum-copper:
  - robust and temperature stable
  - Molybdenum T_c ~ .92 K
  - Copper normal



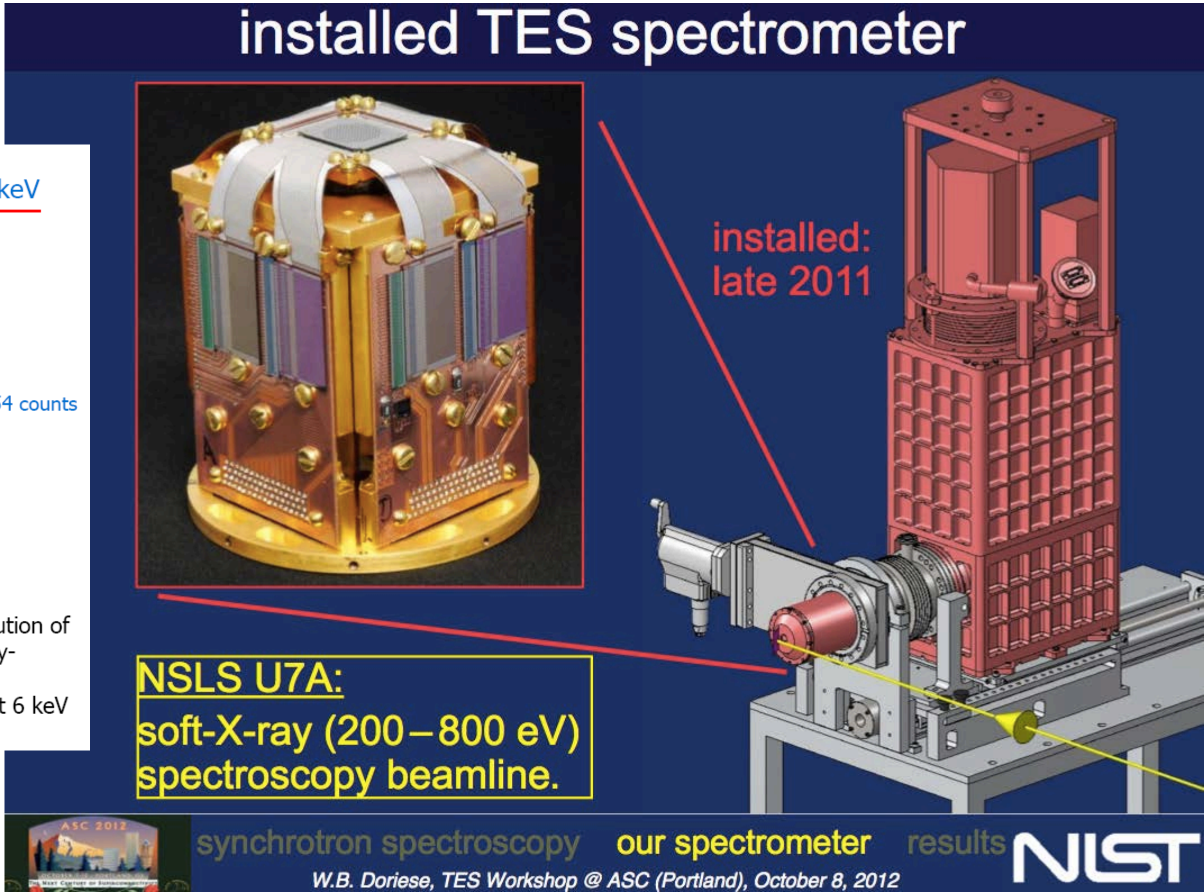
Transition Edge Sensors

Optimized TES: energy resolution = 2.4 eV FWHM at 5.9 keV



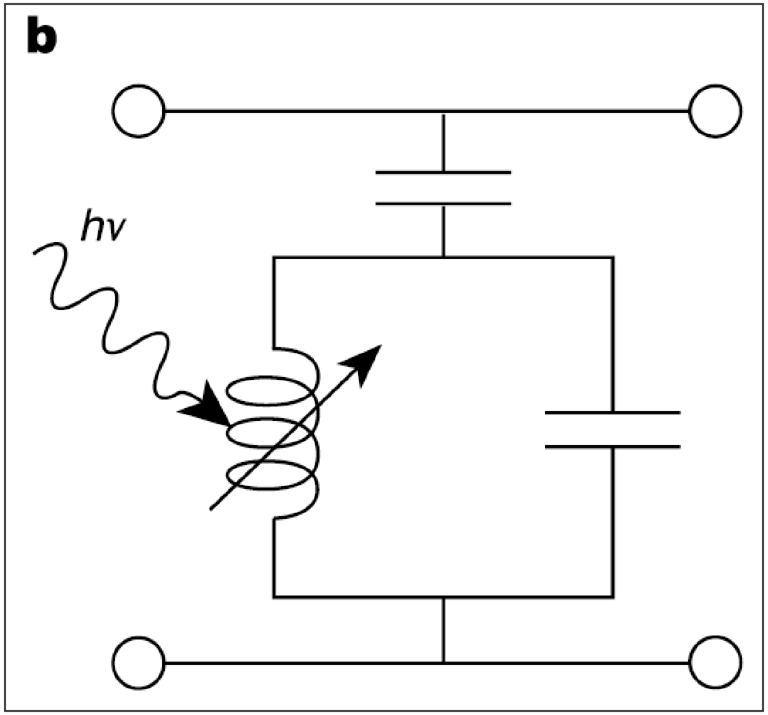
useful device:
- integrated into close-packed array
- 1.5 µm Bi absorber ⇨ QE ~ 55% at 5.9 keV
- 260 µs decay time

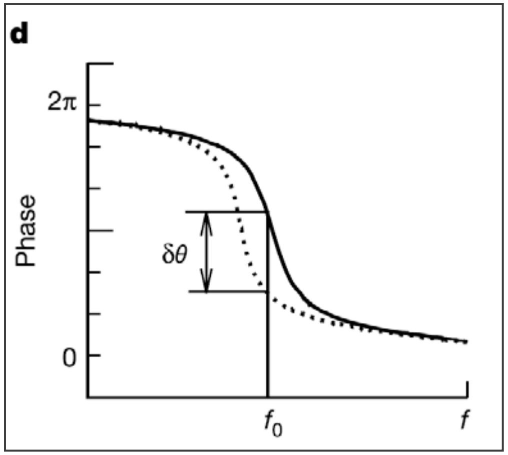
best resolution of any energy-dispersive detector at 6 keV

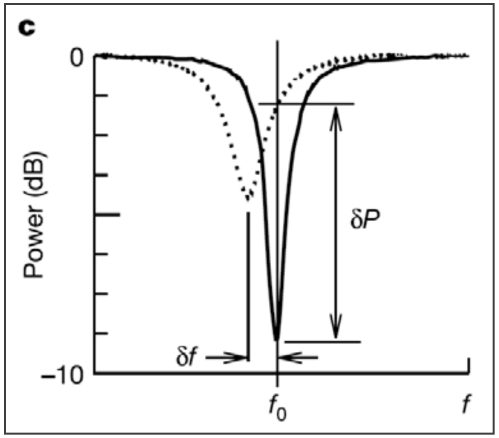


High resolution, low count rates → Need to make arrays

Microwave Kinetic Inductance Detectors

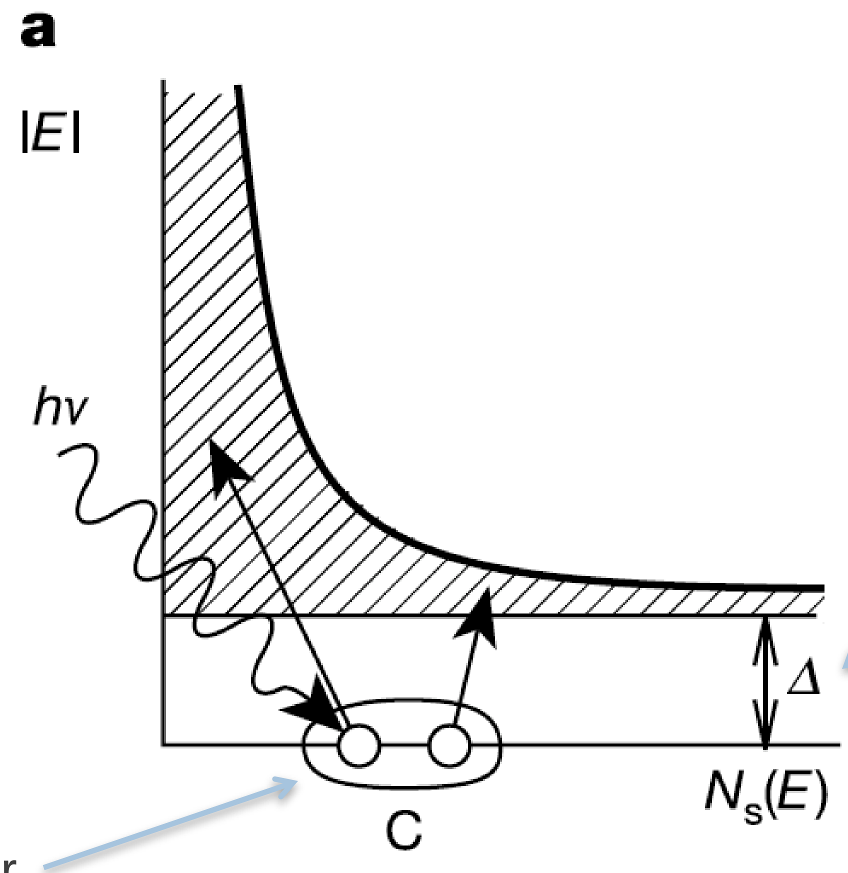






'Microwave' refers to the readout frequency!

Why use Low Temperature Superconductors?



Cooper Pair

Energy Gap

Silicon – 1.10000 eV

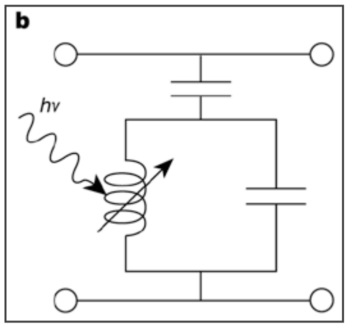
Aluminum – 0.00018 eV

Energy resolution:

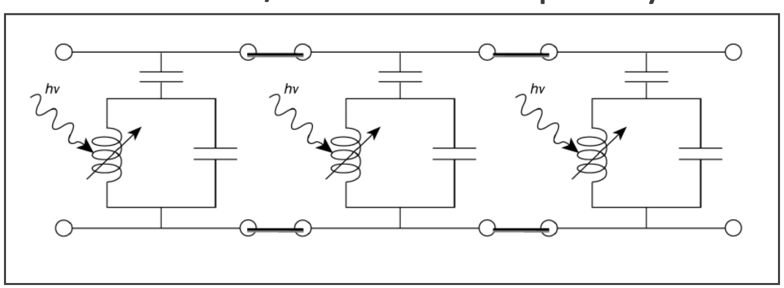
$$R = \frac{1}{2.355}\sqrt{\frac{\eta h\nu}{F\Delta}}$$

Microwave Kinetic Inductance Detectors

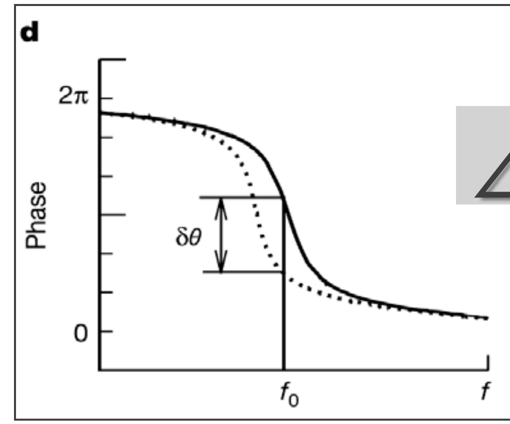
- **Excess quasiparticles or ΔT generated by x-ray causes an inductance increase (i.e., "kinetic inductance")**
  - **Measure inductance change in a LC resonating circuit**



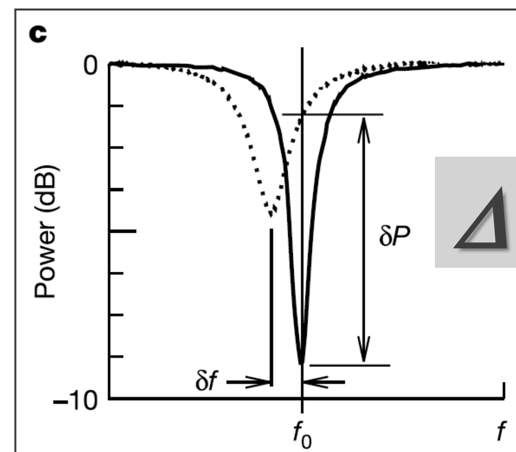
Multiplexing: Lithographically vary geometric inductance/resonant frequency…



Observables….



ΔL_s

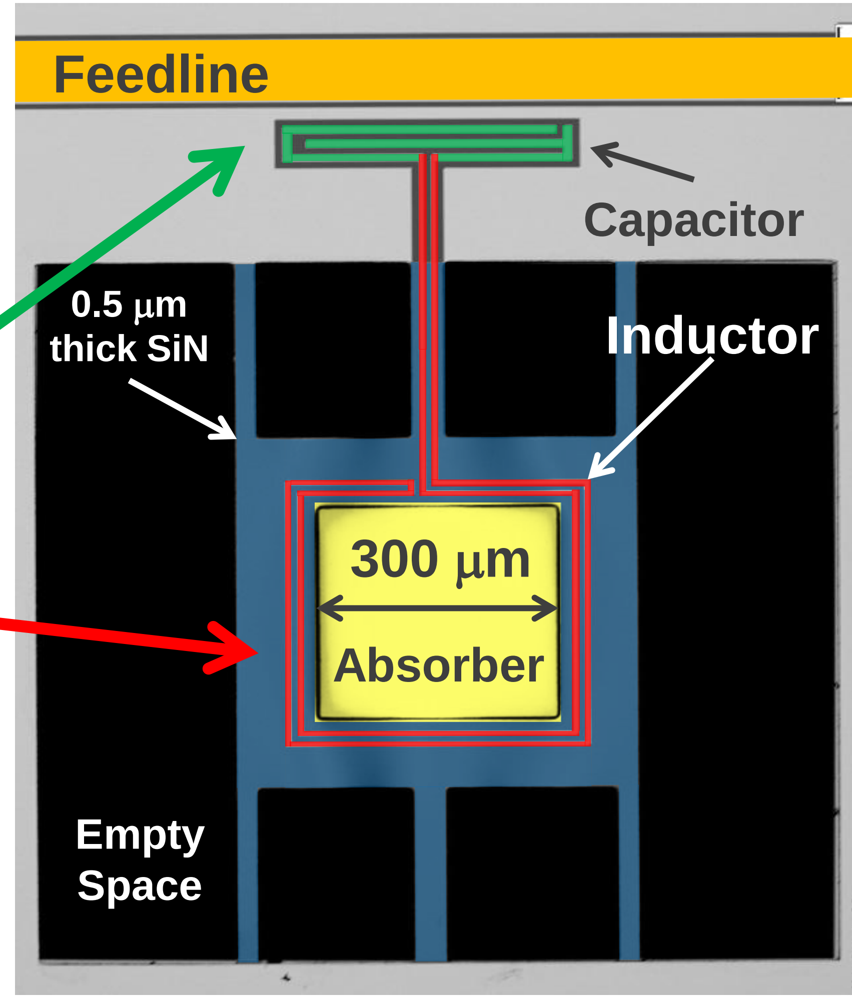


ΔR_s

Cryogenic Detector R&D at APS

- The goal is energy resolution < 5eV with good count rate capabilities (> 100kcps)
- Three Main Aspects:
  1. **Device Fabrication**
     - Completely in-house with dedicated deposition chamber
  2. **Cryogenics and Device Characterization**
     - Turnkey 100 mK cryostat (cryogen-free)
  3. **Readout electronics**
     - Multi-pixel implementation in progress

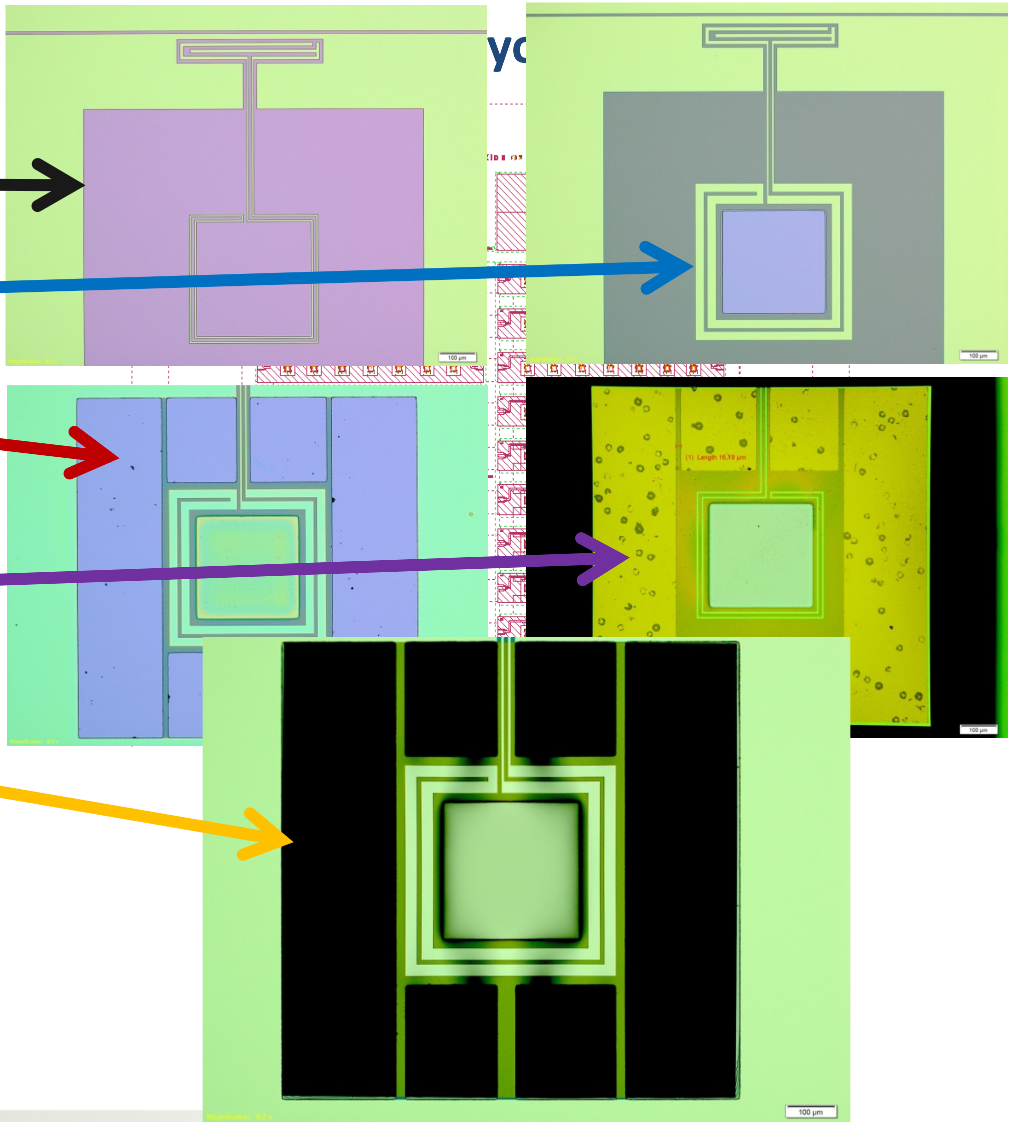
Anatomy of a thermal MKID (i.e., calorimeter)



0.5 x 300 x 300 μm Tantalum Absorber
100 nm WSi_2 resonator

Microfabration Fabrication Process

1. 0.5 µm SiN + 300 µm Silicon wafer
2. Resonator deposition (@ APS)
3. Resonator Lithography (MA-6, CNM)
4. Resonator Etch (Oxford RIE, CNM)
5. Resist strip (1165 remover, CNM)
6. Absorber Lithography (MA-6, CNM)
7. Absorber deposition (@ APS, CNM)
8. Absorber liftoff (1165 remover, CNM)
9. SiN bridge lithography(MA-6, CNM)
10. Backside SiN membrane lithography (MA-6, CNM)
11. Backside SiN etch (March etcher, CNM)
12. Bulk Si etch (KOH, CNM)
13. Backside protective Al depositions (@ APS)
14. SiN bridge etch (March etcher, CNM)
15. Al wet etch (CNM)
16. Resist strip (1165 remover, CNM)



Conclusions

- **Take a moment to analyze what kind of detector you are using!**
  - Counting or Integrating?
    - Counting: Deadtime limitations (what’s the fill pattern during my experiment?)
    - Integrating: Dark Subtraction?
  - Pilatus detector (counting pixel array detectors)
    - What threshold should use?
  - Energy resolving detectors?
    - What shaping time to use?
      - Speed versus resolution
  - Interested in detector physics? Come talk to me!
    - Looking for some young minds to develop new detectors!