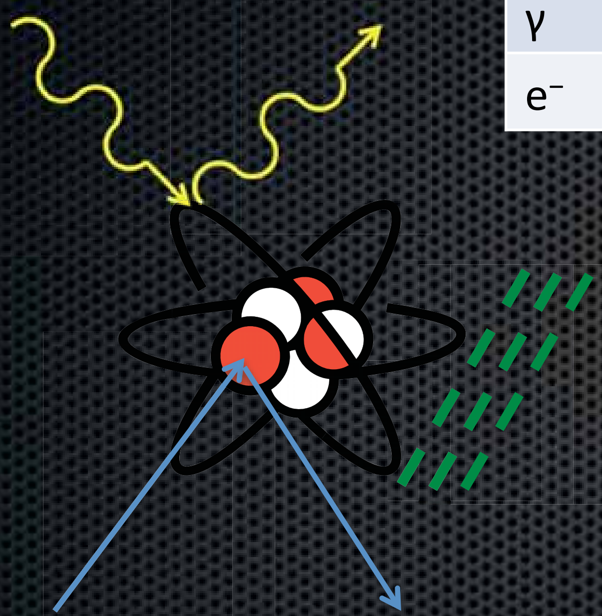
X-ray Detection

	Brighntess	Mean Free Path	Absoroption Length	Spatial Resolution
	$/cm^2/sr/eV$	nm	nm	nm
n	10^{14}	10^7	10^8	10^6
γ	10^{26}	10^3	10^5	10^2
e^-	10^{29}	10^1	10^3	0.05



x-ray scattering (probe electronic states)
neutron scattering (probe nuclear states)
electron microscopy (focus, Coulomb interactions)

Peter Denes
Lawrence Berkeley National Laboratory
Engineering Division - *Director (acting)*
Advanced Light Source - *Deputy for Engineering*
Integrated Circuit Design Group Leader

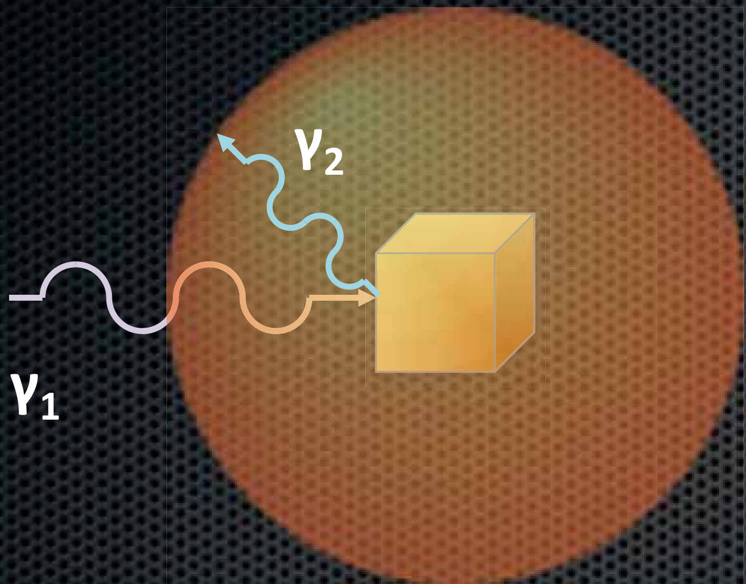
Outline

- Basic concepts
  - "phenomenological"
    - Field of "detectors" is a bit more than 100 years old.
      - Can't cover everything
      - Lots of terminology, much of it outdated
  - ***what*** can be measured
    - or so you think!
- Types of detectors
  - With emphasis on semiconductor detectors
- Silicon imaging detectors (what I do)

“Detector”

Distinguish between detector systems that fit the picture above (i.e. they have an ~ immediate electronic output) and those that are indirect (or use human processing)

Ideal Detector



- Spatial information
  - $(x, y)_{\gamma 2}$
- Temporal information
  - $t(\gamma_2)$
- Energy information
  - $E_{\gamma 2}$
- With
  - High efficiency
    - $P_{DETECT}(\gamma_2) = 1$
  - 4π solid angle
  - low cost

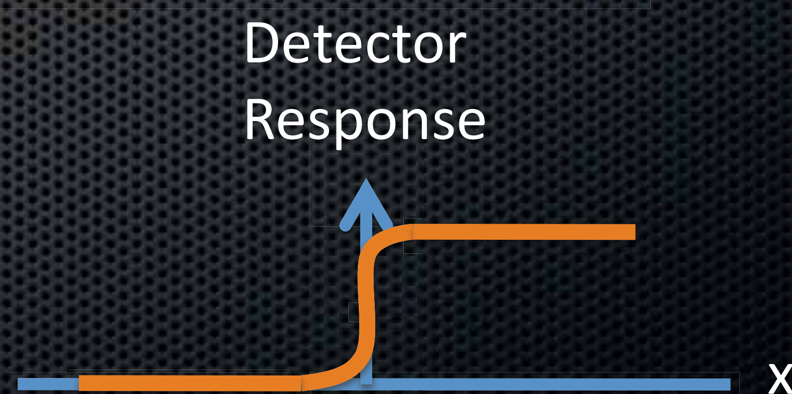
Calorimetric Photon Detector

Photon Source

Thermally Reactive Detector

Calorimetric detector: absorbed energy measured by change of temperature (more generally, "calorimeters" measure total absorbed energy)

Detector Behavior

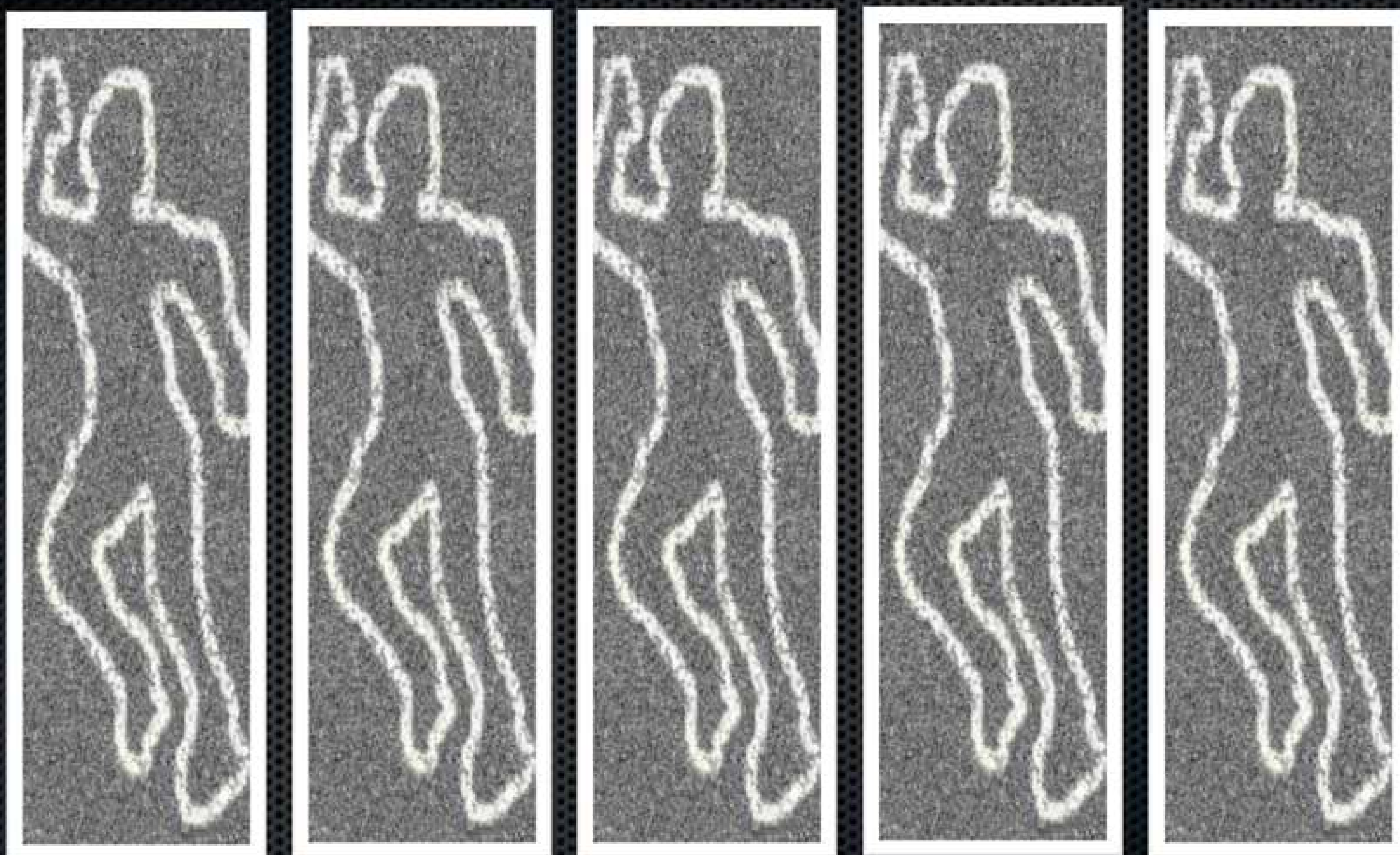


Spatial Detector Properties

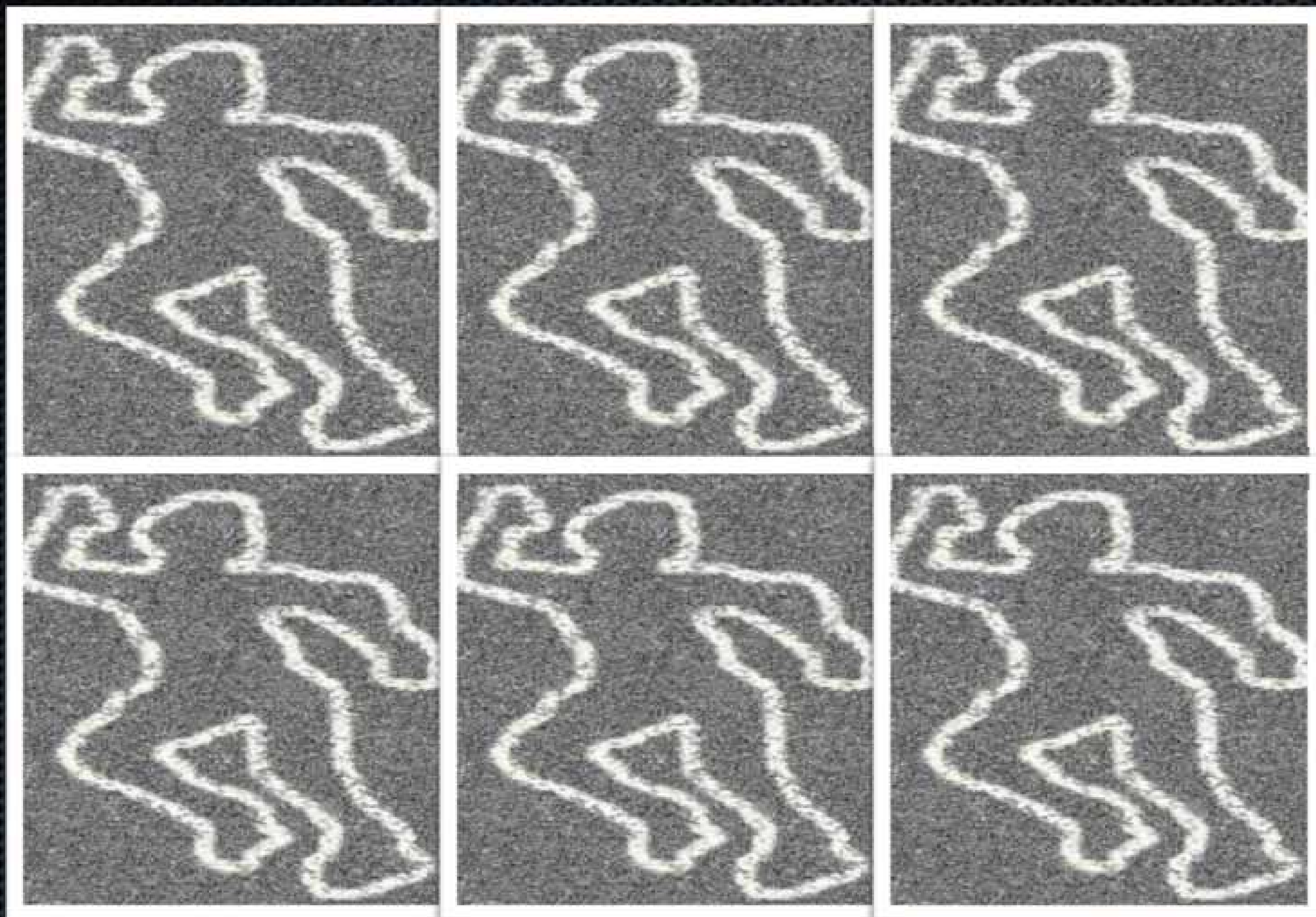
A "point" detector ("0D")
Responds to hits in sensitive area

No way to know where in the sensitive area the hit occurred

1D Detector

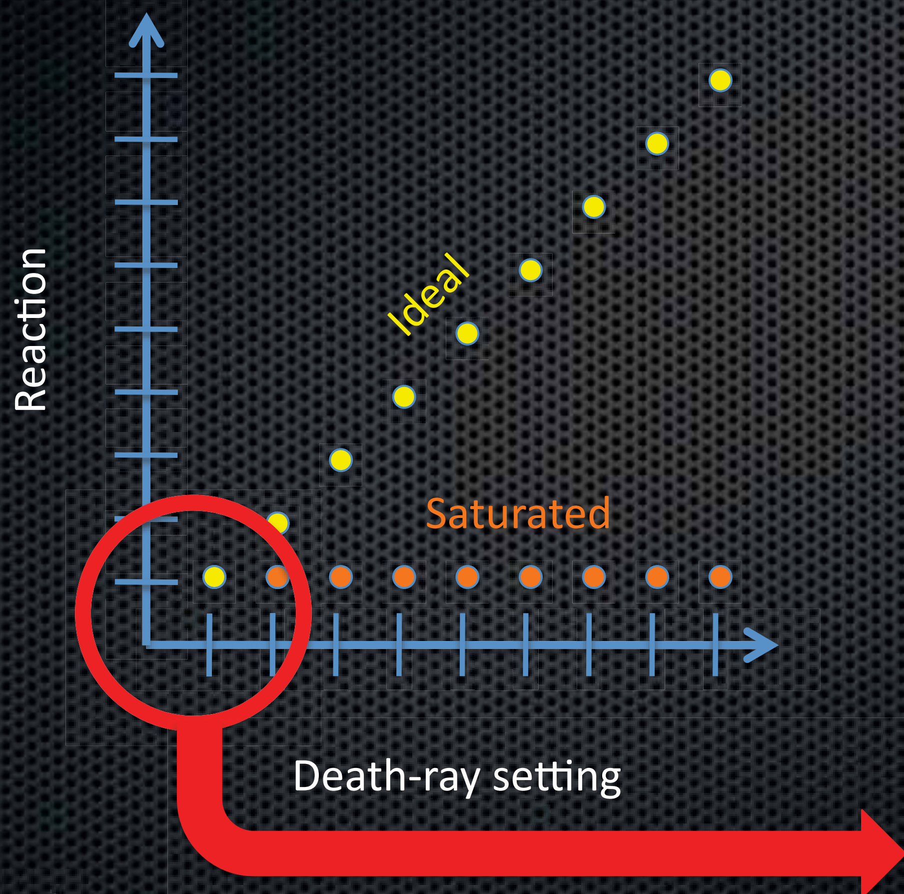


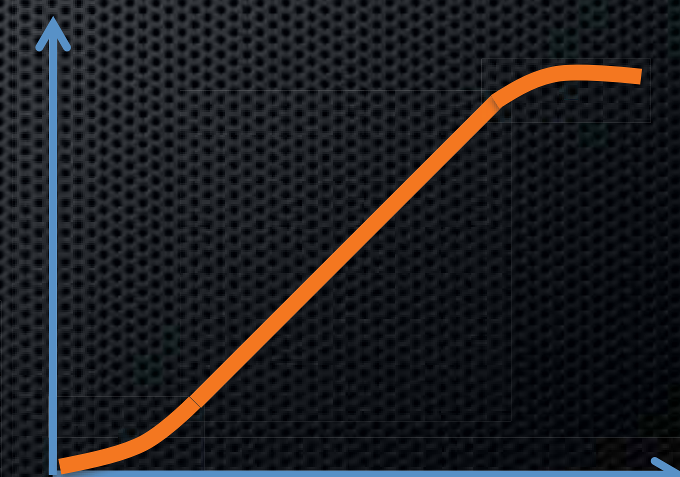
2D Detector



Detector Linearity

e.g. diffraction





An Example 2D Detector

- 2D arrangement of our 0D detector elements
- Which are quite non-linear
- Arranged in random sizes and orientations
- But with each element very small

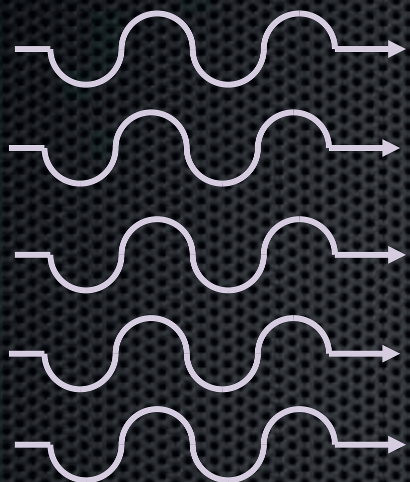
Early X-ray Detection

Herr Röntgen

Frau Röntgen

Schematic of Experiment

Incident Radiation

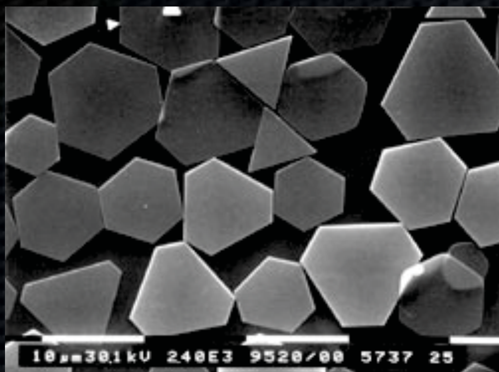


Variable Density Attenuator

Detector

Image

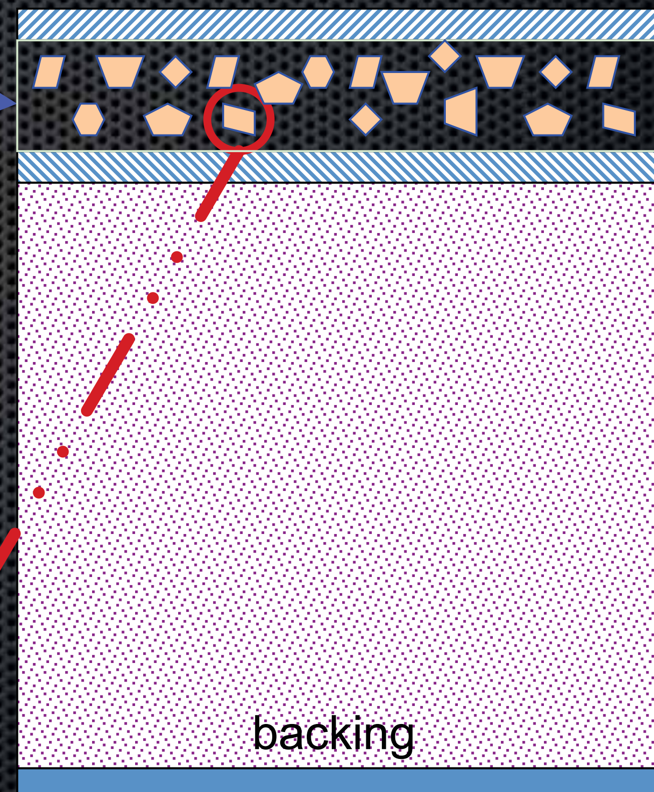
The Detector – Photographic Film*



Electron micrograph of tabular grain emulsion

AgX + gelatin
(emulsion)

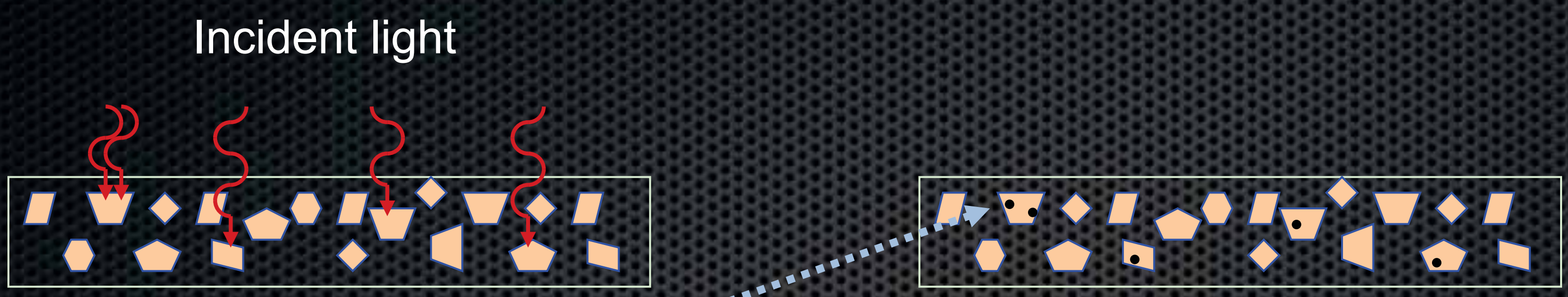
Silver halide emulsion on tri-acetate backing



sub-micron to few micron grains

*Primitive, but still unbeaten for certain things

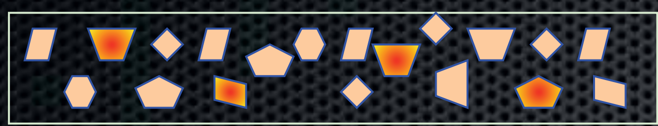
How it Works



phototelectrons convert Ag^{+} sites to Ag^{0} – at the same time, thermal fluctuations tend to “erase” the image. Generally, a few (visible) photons are required to leave a “latent” image on a grain

larger grains have larger cross section, so they are more likely to get hit. Thus, larger grains are “faster” but “grainier”

How it Works

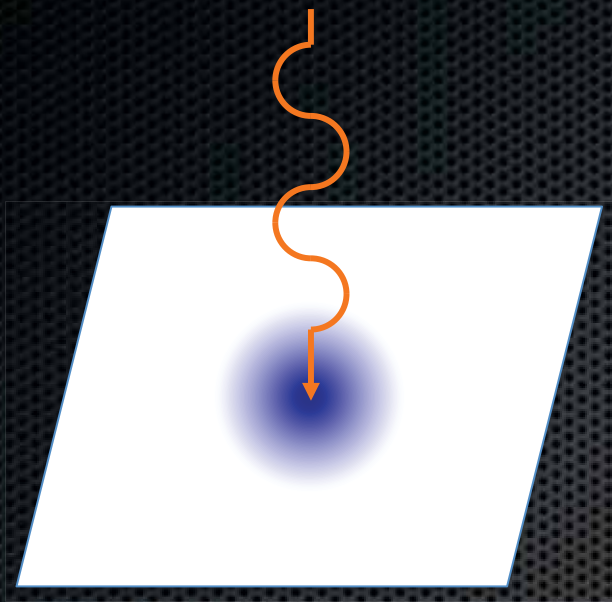


“develop” the image so that the sensitized AgX is reduced to black metallic silver

“fix” the image – removing the unexposed AgX

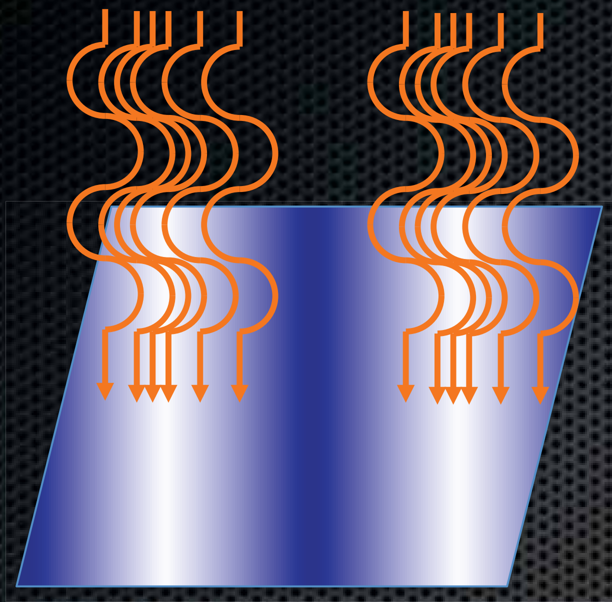
The chemistry and physics of photographic film is not trivial

Spatial Imaging Characteristics – PSF



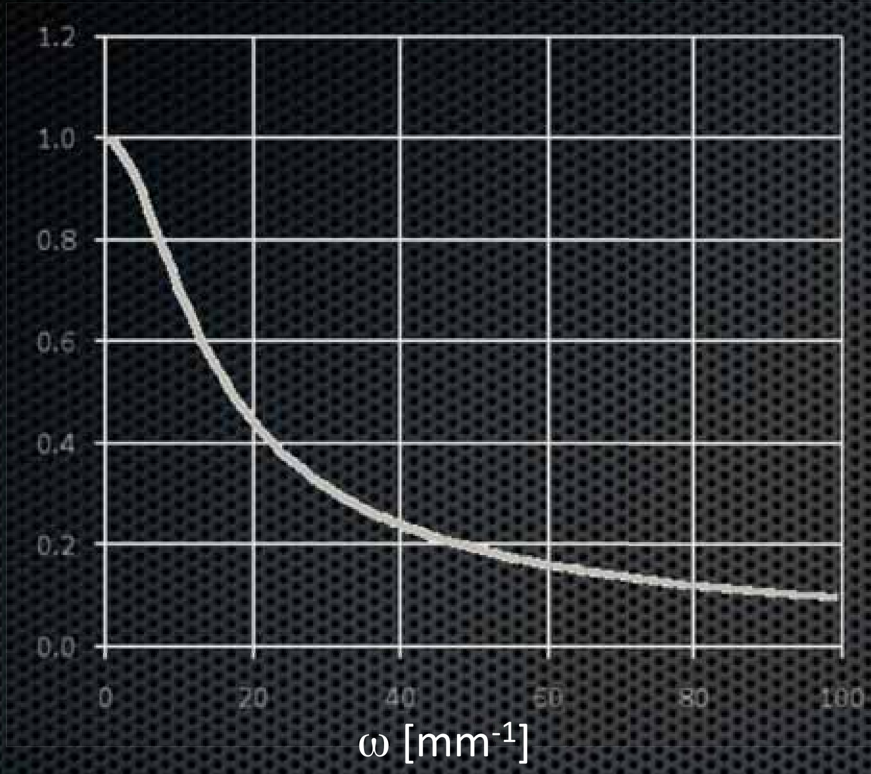
- Point Spread Function
  - δ-function input
  - PSF(x_0, y_0, x, y)
- Image is convolution of input at PSF
- "Black box" PSF includes all effects that might broaden or scatter the input

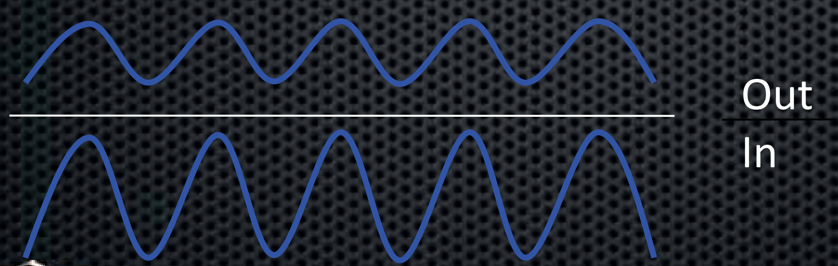
Spatial Imaging Characteristics – MTF



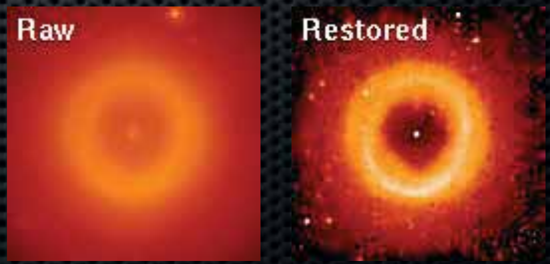
- Modulation Transfer Function
  - sin ωx input
  - MTF(ω)
    - MTF(ω_x, ω_y)
- MTF = | FT(PSF) |
- Related to **contrast**

MTF





- Spatial analog to (temporal) frequency response in electronics
  - "Signal processing" also possible
  - e.g. early days of Hubble Space Telescope

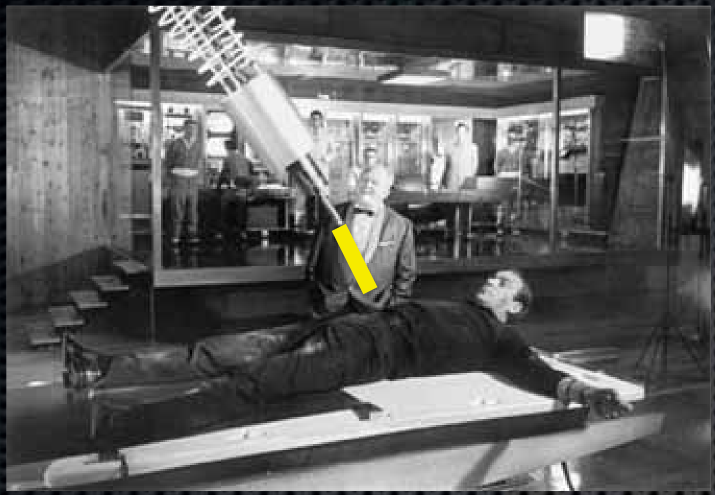


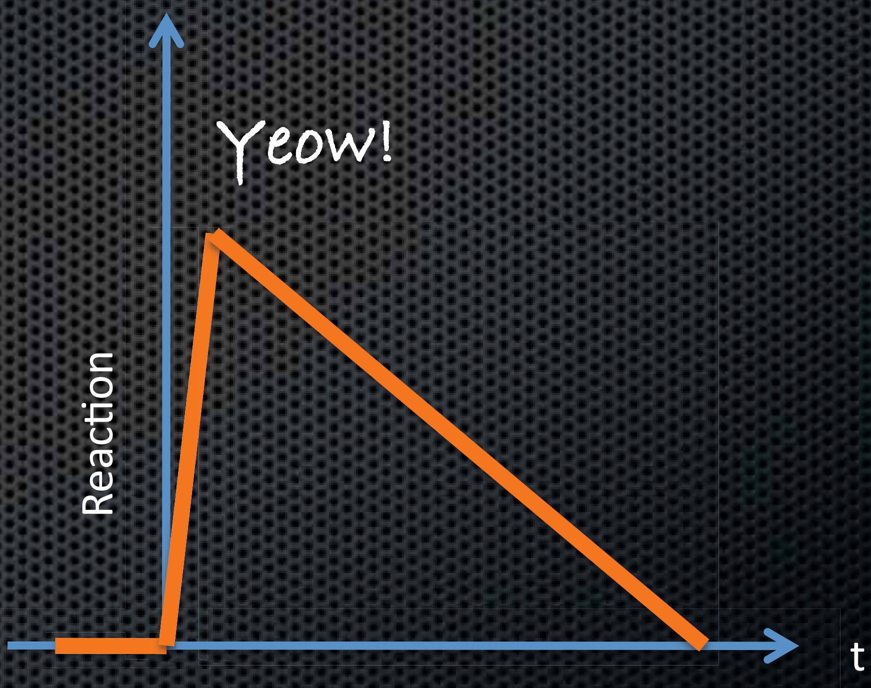
Consider …

Stepping a knife edge across the film

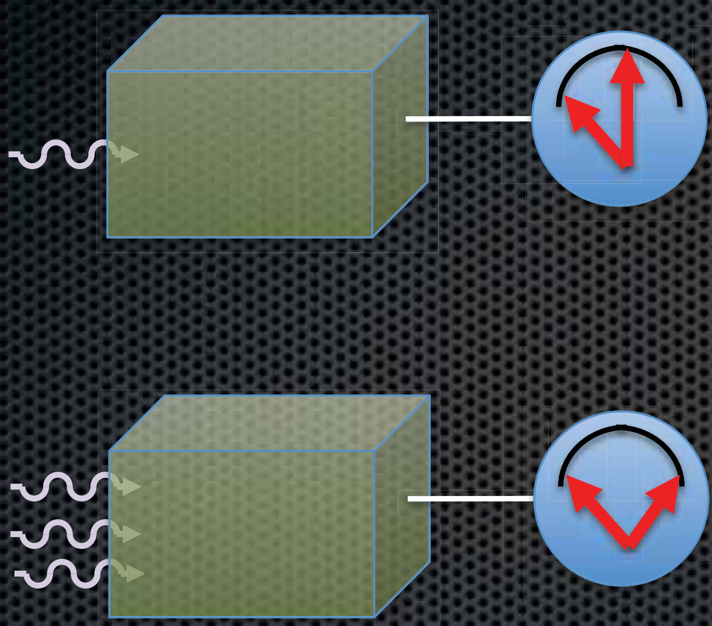
Detector Temporal Response

Pulsed Operation





"Counting" and "Integrating"



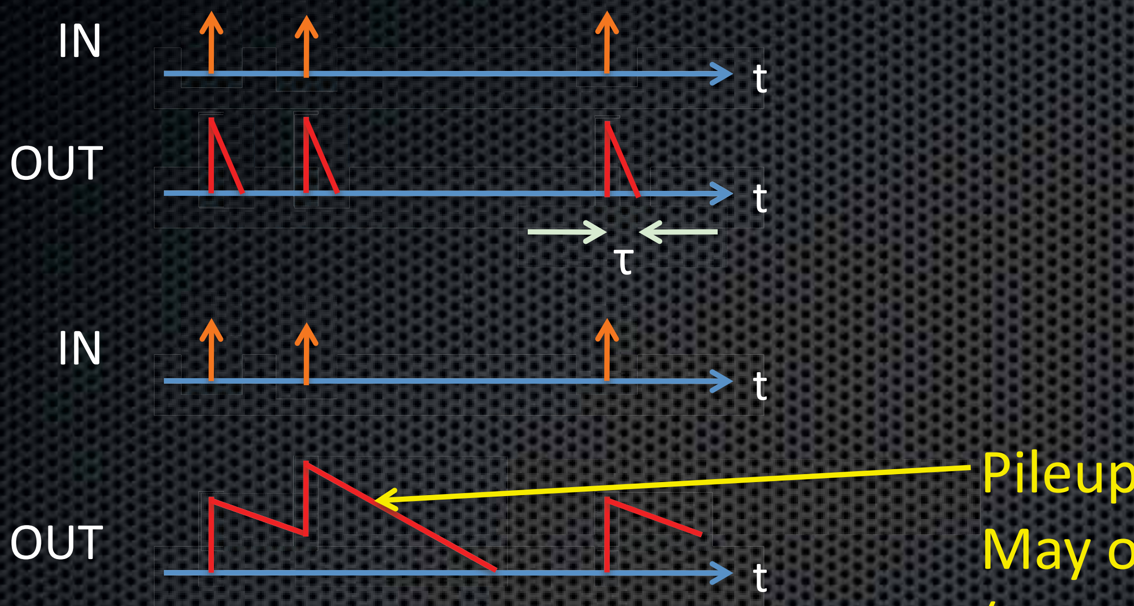
Consider temporal characteristics of
- source
- detector

"Counting" and "Integrating"

- $\Delta t\,(\gamma_1, \gamma_2) \gg \tau_{DETECTOR}$, and $P(N_\gamma > 1) \ll 1$
  - Detector "counts" single photons
- $\Delta t\,(\gamma_1, \gamma_2) \gg \tau_{DETECTOR}$, and $P(N_\gamma > 1) \not\ll 1$ **and** detector can quantize N_γ
  - Detector "counts" single photons
- $\Delta t\,(\gamma_1, \gamma_2) \not\gg \tau_{DETECTOR}$
  - Measure a "current"

- Example: ALS Δt_{BUNCH} = 2 ns, LCLS Δt_{BUNCH} = 8 ms

Pileup, Double Pulse Resolution



May or may not be a problem (can recover with signal processing)

If photons arrive synchronously, maximum rate ~ 1/τ

If photons arrive at random, maximum rate ~ 1/10τ

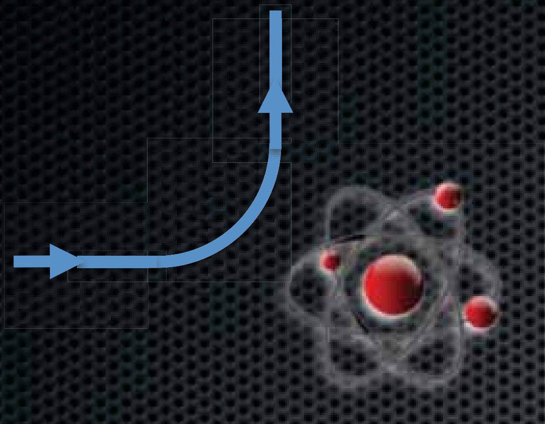
Look Further Into "Detector"

- *Rarely* does a (practical) photon detector actually detect photons
- Generally the photon is converted into one (or more) secondary particles
- Those secondary particles (usually electrons) are then detected, or create tertiary particles which are detected

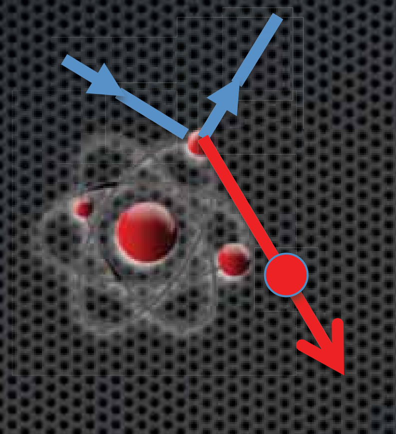
- $\gamma \rightarrow e^-$

X-ray Interaction in *Detector*

Practically speaking, 3 possibilities:

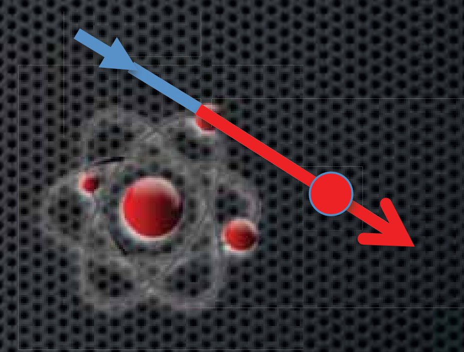


Elastic Scattering



Compton Scattering

$E_e \neq E_\gamma$

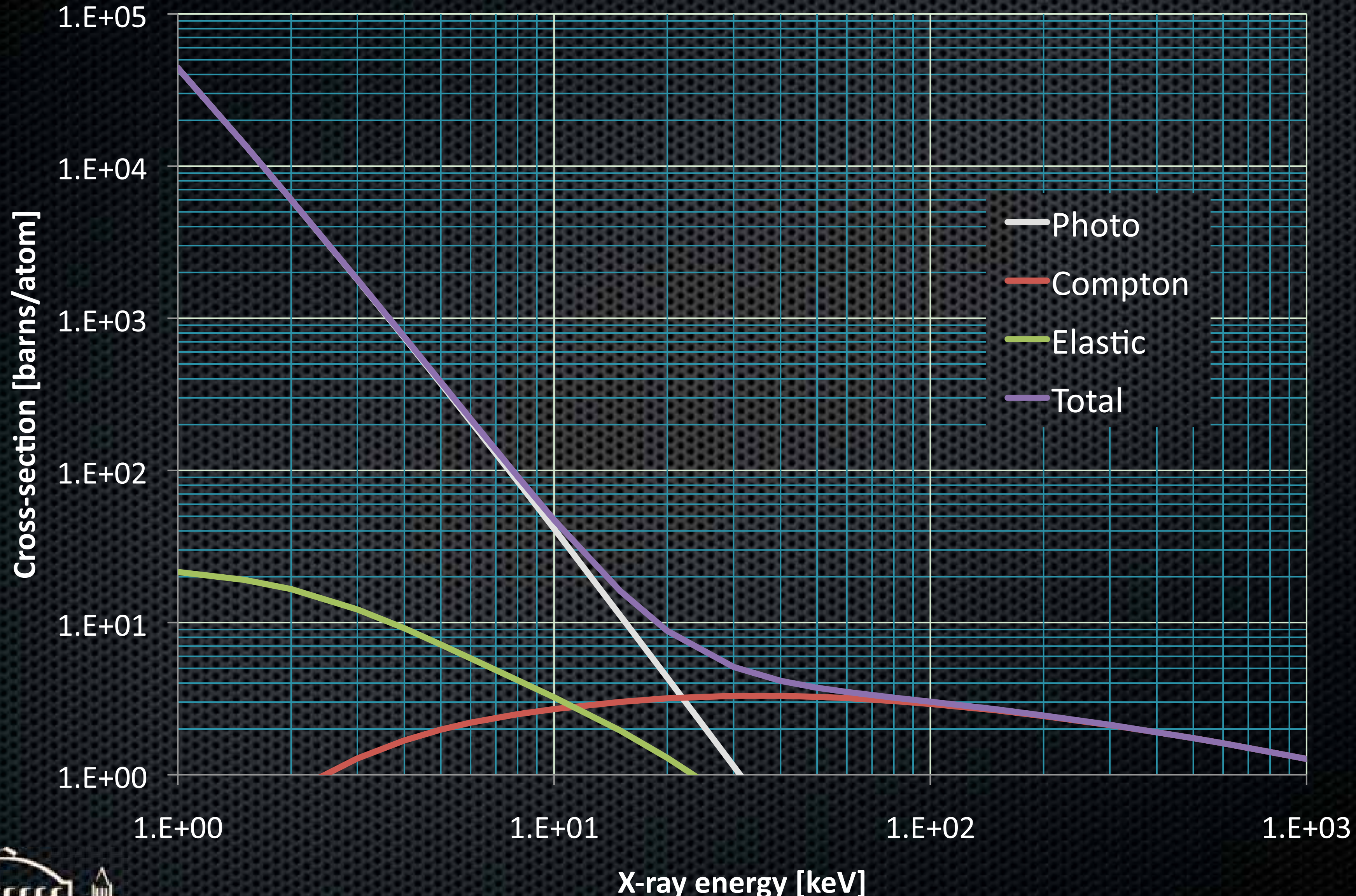


Photoelectric Absorption

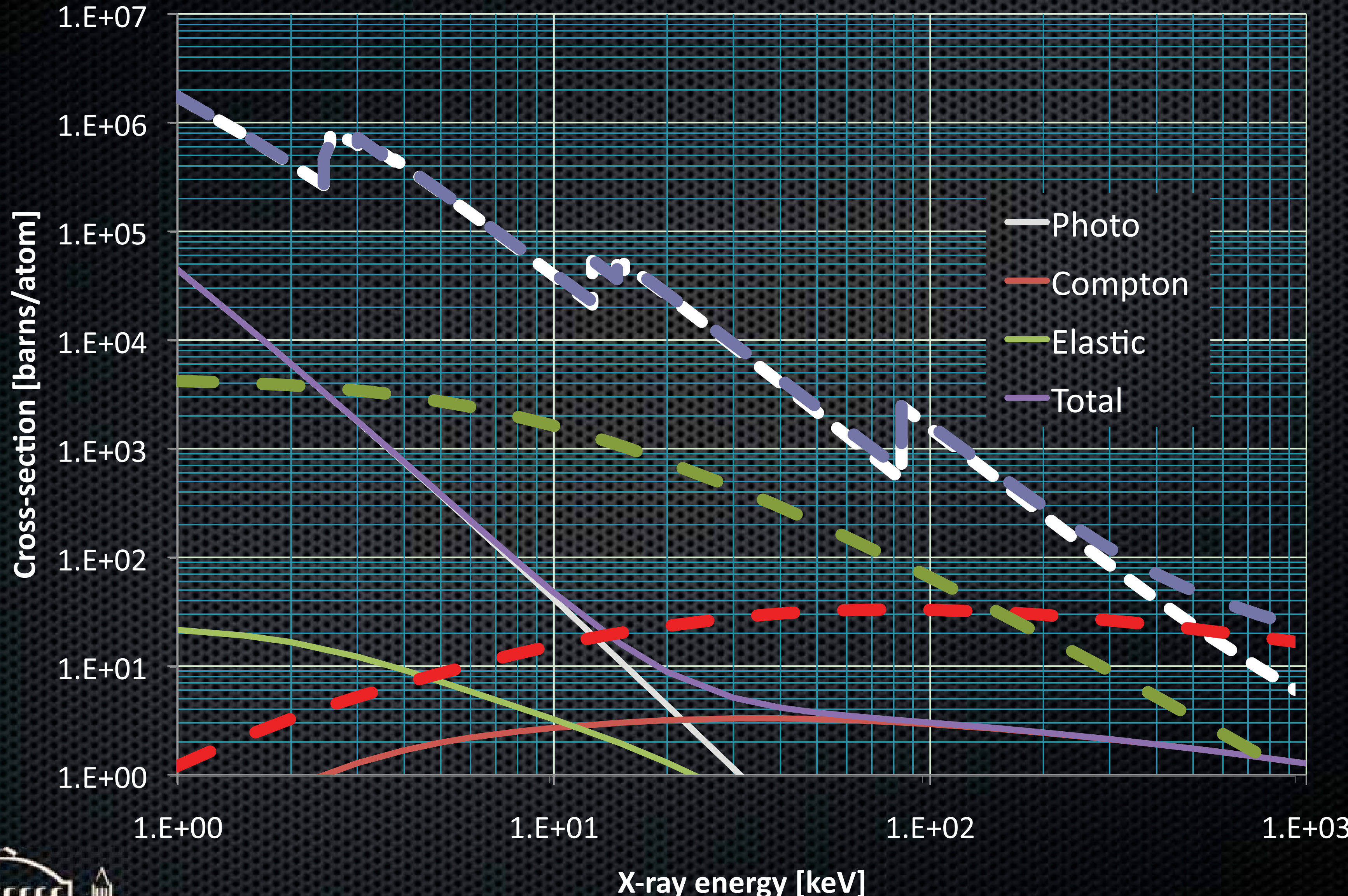
$E_e = E_\gamma$

Electron range (very crudely) R [μm] ≈ E [keV]

X-ray cross-section in Carbon



X-ray cross-sections in Carbon and Lead



Effect of Z (Detector) and E

The only thing photons are good for is to make electrons

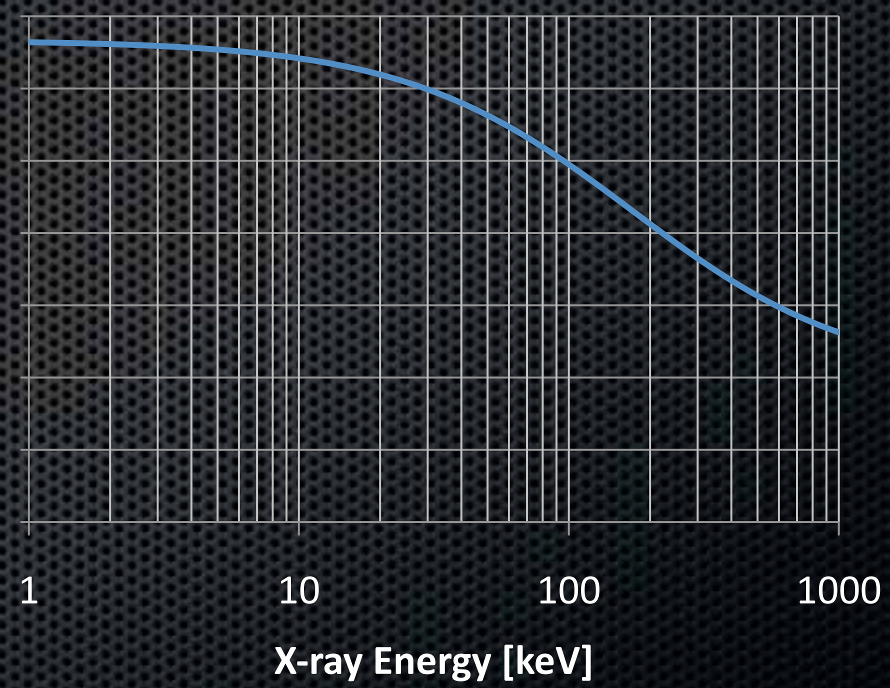
Photoelectric Absorption

$\sigma \sim Z^n/E^3$

$n \sim 4 - 5$

Scattering

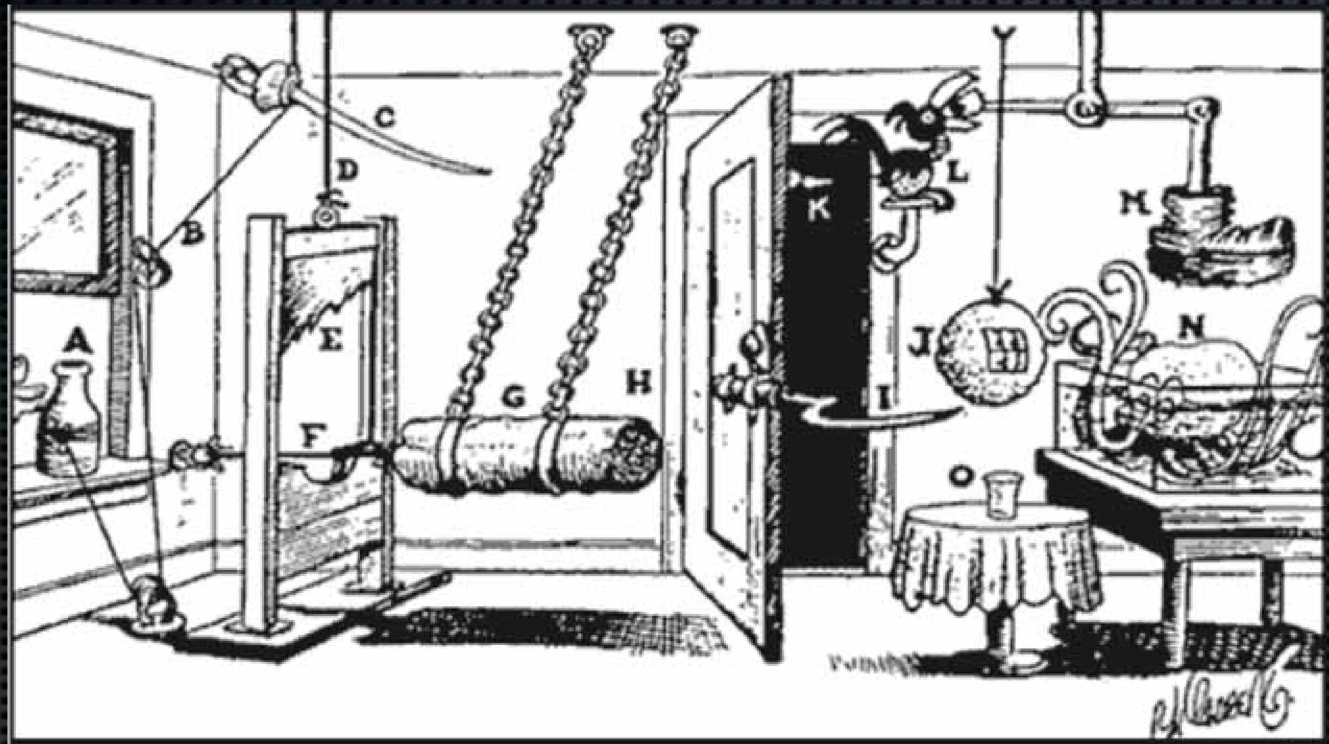
$\sigma \sim Z\,x$



Scattering is elastic
(e^- stays in ground state)
or Compton (e^- ejected)

$Z\uparrow \Rightarrow \sigma\uparrow$

Quantum Efficiency

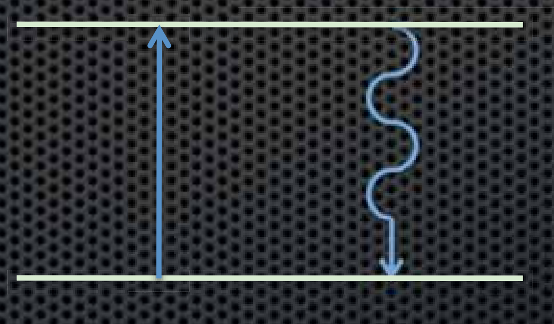


- Probability of detecting incident photon
  - Photon has to create ionization electron
  - Ionization electron has to be detected

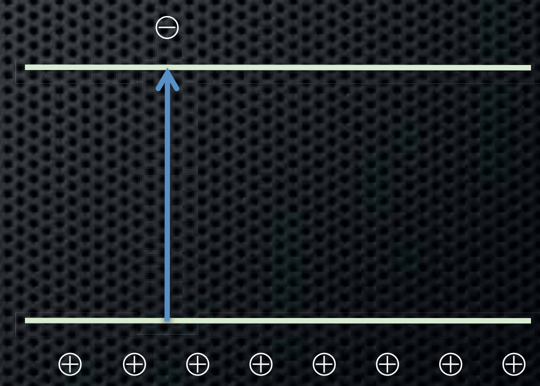
What can the Ionization Electron Do?

Form free charge

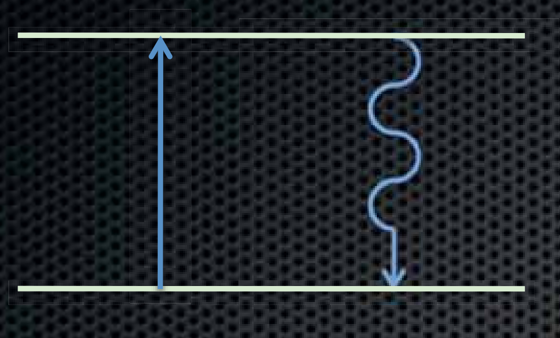
Scintillation (radiative)

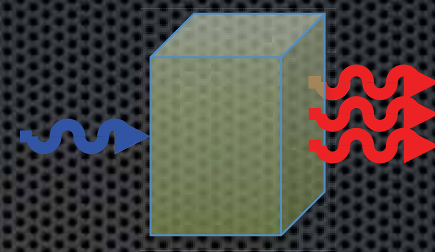


Charge collection in semiconductor



Scintillator





"Converts" x-ray (or other higher energy particle) into visible light

- Organic
- In-organic
- Mono-crystals
- Powders
- Liquids
- Plastics
- …

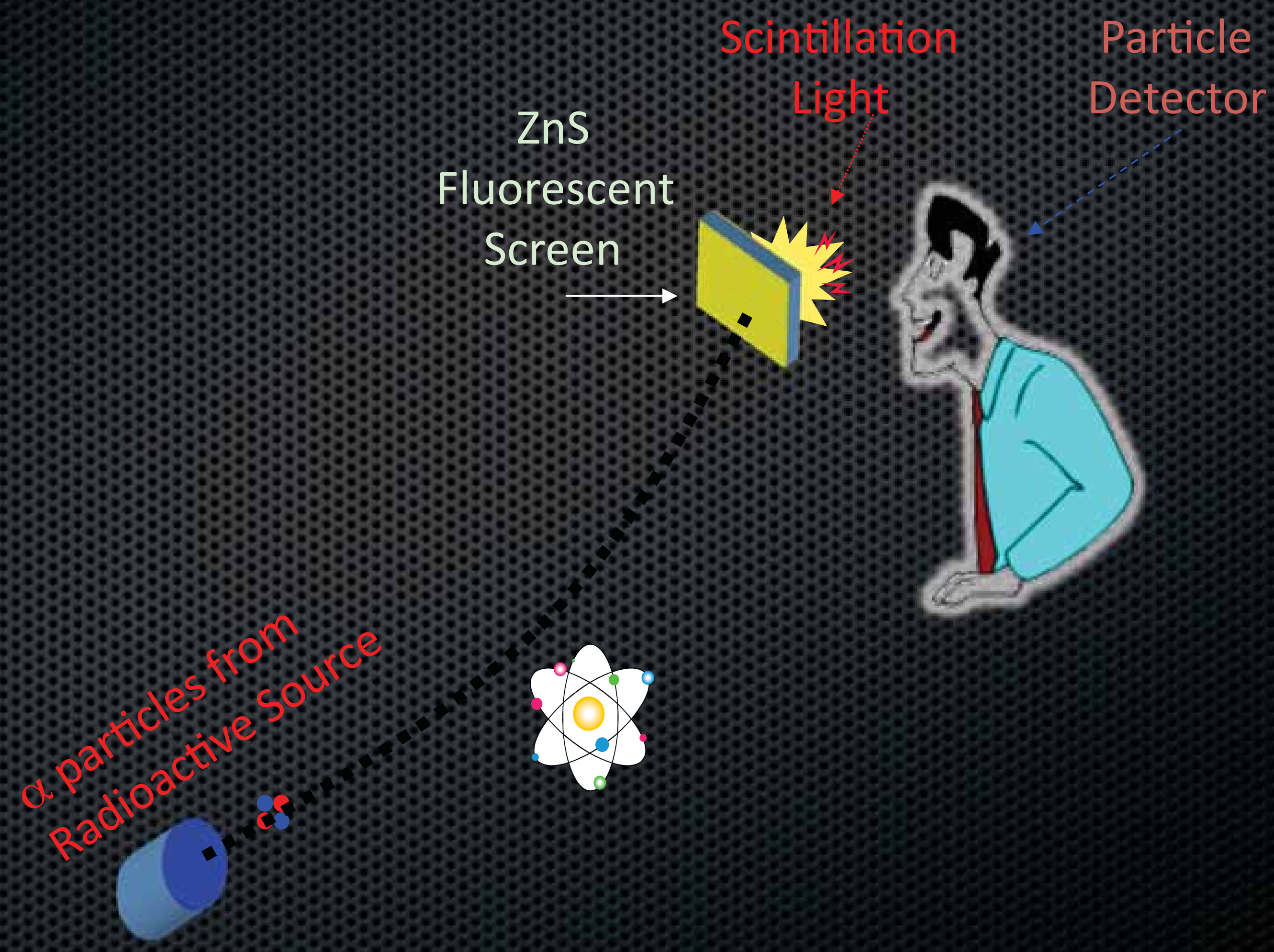
ρ, τ, N_γ, …

MATERIAL	DENSITY [g/cm^3]	EMISSION MAXIMUM [nm]	DECAY CONSTANT (1)	REFRACTIVE INDEX (2)	CONVERSION EFFICIENCY (3)	HYGRO-SCOPIC
NaI(Tl)	3.67	415	0.23 ms	1.85	100	yes
CsI(Tl)	4.51	550	0.6/3.4 ms	1.79	45	no
CsI(Na)	4.51	420	0.63 ms	1.84	85	slightly
CsI (undoped)	4.51	315	16 ns	1.95	4 - 6	no
CaF_2 (Eu)	3.18	435	0.84 ms	1.47	50	no
^{6}LiI (Eu)	4.08	470	1.4 ms	1.96	35	yes
^{6}Li - glass	2.6	390 - 430	60 ns	1.56	4 - 6	no
CsF	4.64	390	3 - 5 ns	1.48	5 - 7	yes
BaF_2	4.88	315 220	0.63 ms 0.8 ns	1.50 1.54	16 5	no
YAP (Ce)	5.55	350	27 ns	1.94	35 - 40	no
GSO (Ce)	6.71	440	30 - 60 ns	1.85	20 - 25	no
BGO	7.13	480	0.3 ms	2.15	15 - 20	no
$CdWO_4$	7.90	470 / 540	20 / 5 ms	2.3	25 - 30	no
Plastics	1.03	375 - 600	1 - 3 ms	1.58	25 - 30	no

For more, see http://scintillator.lbl.gov/

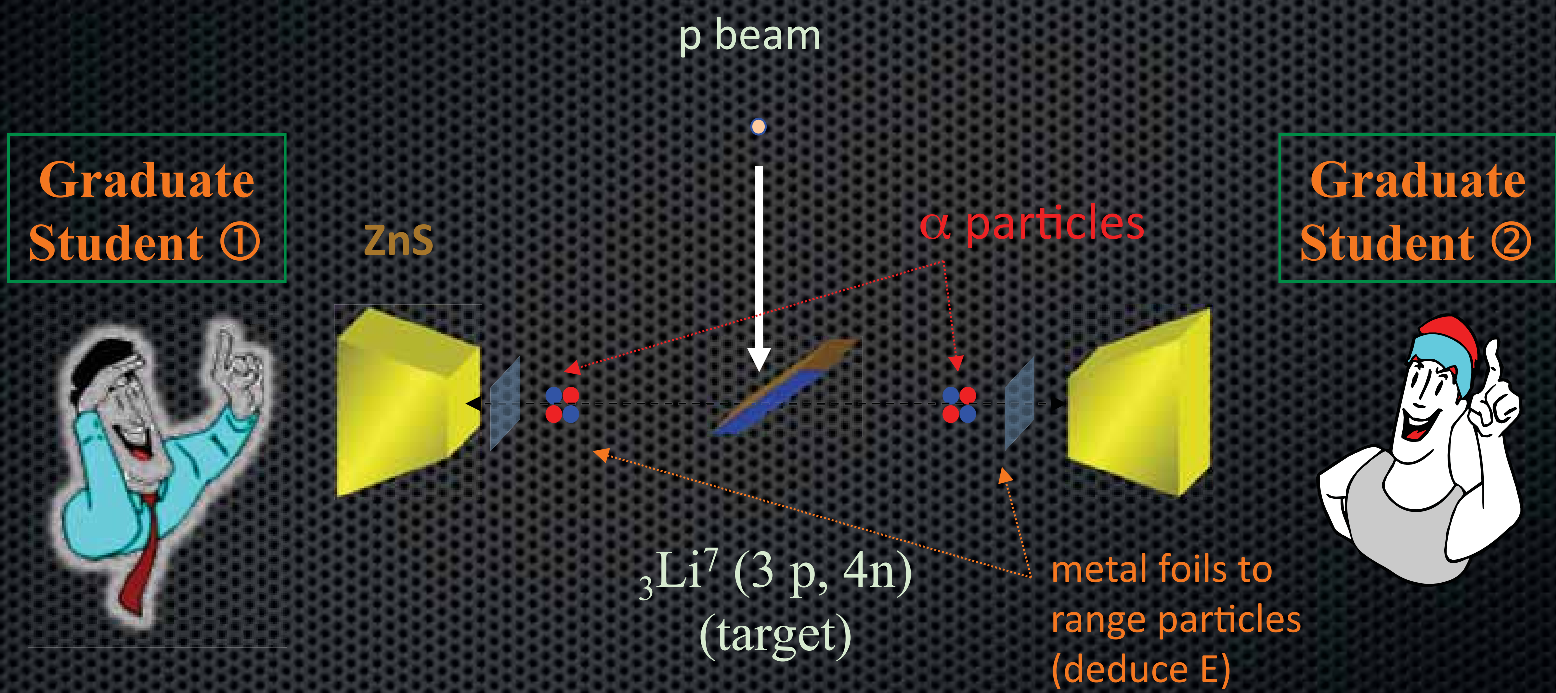
Visible Scintillation Counting

e.g. Rutherford 1911 - Discovery of the nucleus



Coincidence Experiment

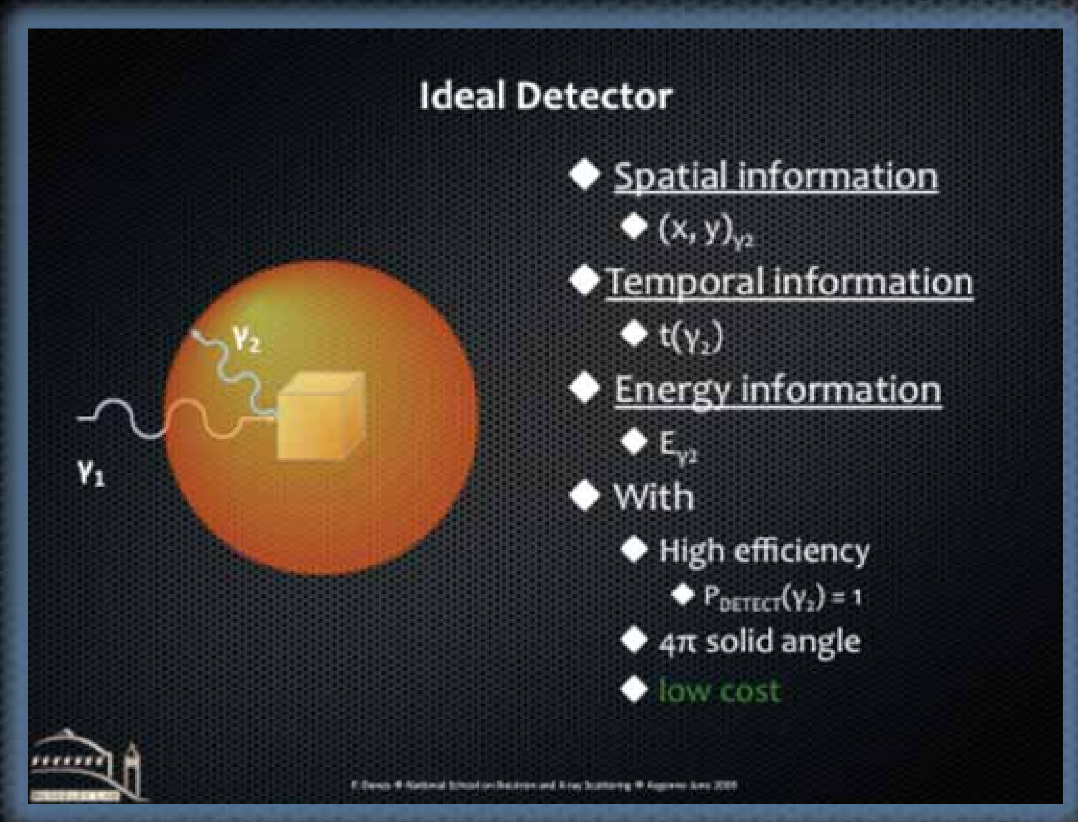
Cockcroft+Walton, 1932



First demonstration that E (from $p + {}_3Li^7 \rightarrow \alpha + \alpha$) = Δmc^2

(Δm is difference between initial and final nuclei masses)

Detector Properties



2 x 0D detectors

Coincidence technique
~Hz data rate

E via attenuation

+ and - of this technique

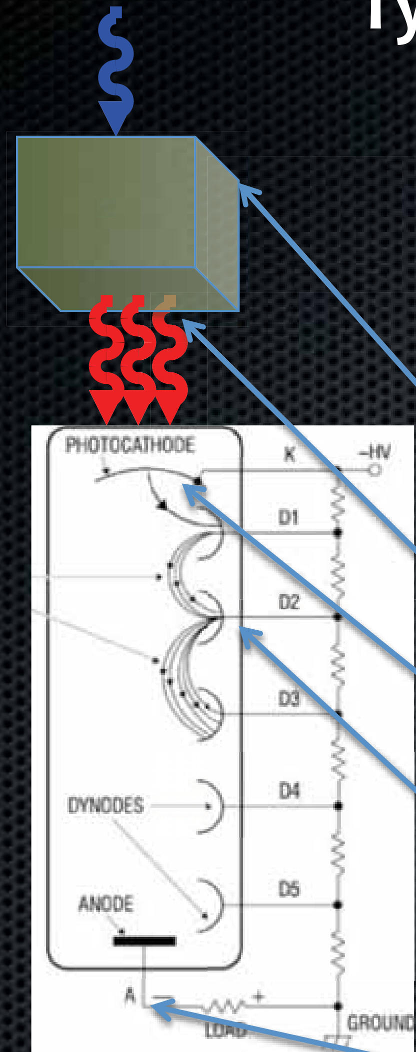
- Low Power (graduate students don't need much food)
- Low Speed - counting rate limitations ~ 1 Hz
- Threshold sensitivity

  (although Marsden could distinguish α and p by brightness)

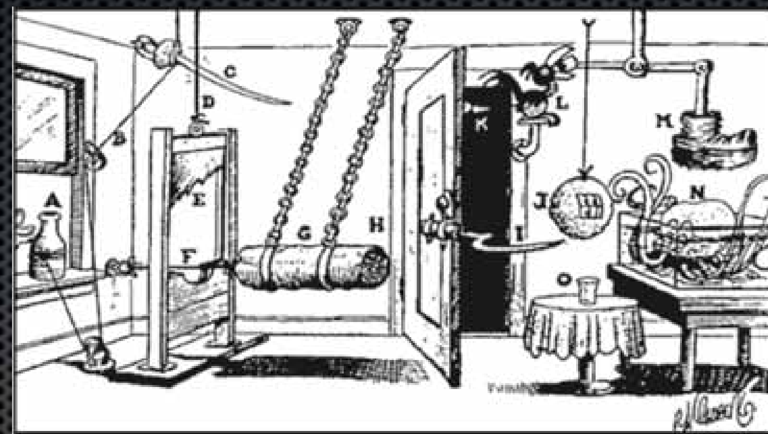
  At λ ~ 500 nm, $\text{Threshold}_{\text{TRAINED OBSERVERS}}$ ~ 17 γ for $t_{FLASH} > 40\ \mu s$
- Yield: *"…at one famous laboratory during this period all intending research students were tested in the dark room for their ability to count scintillations accurately. Only those whose eyesight measured up to the standards required were accepted for nuclear research; the others were advised to take up alternative, less exacting, fields of study"*

(from Birks)

Typical Scintillation Detector



Photomultiplier

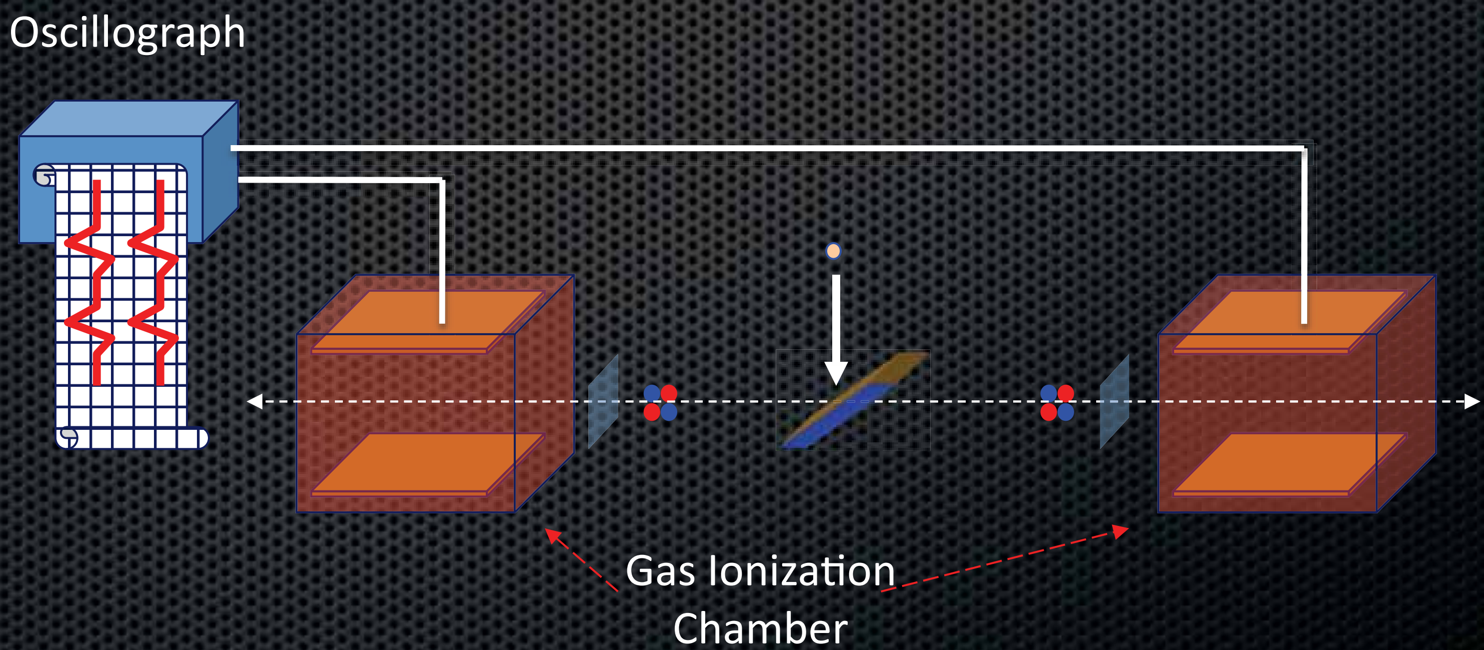


- Incident photon creates (ionization) electron
- Ionization generates visible photons
- Visible photons converted into electrons
- Electrons "amplified" by secondary emission
- Output current detected

Coincidence Experiment

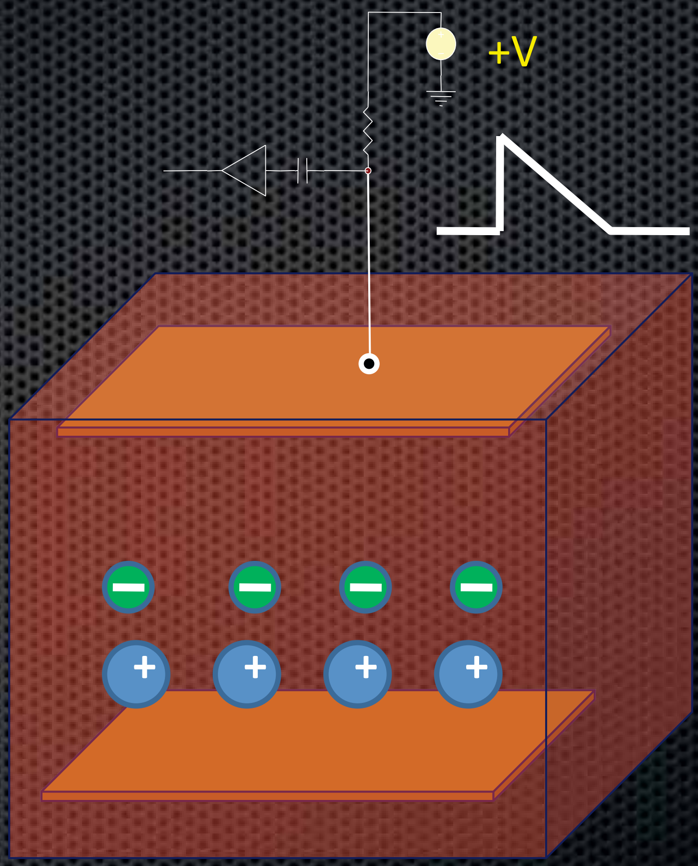
Cockcroft+Walton - Electronic Verification

One of the last visual counting experiments
(and one of the first electronic counting experiments)



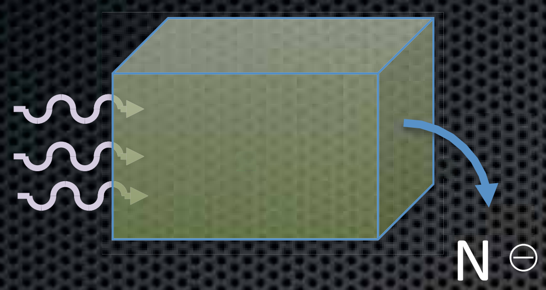
Ionization Chamber

- Particle passes through chamber and creates an ionization track
  - Image charge Q_0 appears on positively charged plate
- Electrons move (with speed = ***drift velocity***) towards positively charged plate
  - As the electrons arrive, they reduce the charge on the plate
- A current pulse has been created at the same time the particle has passed through the chamber



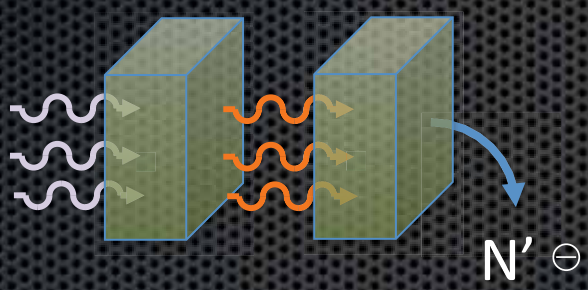
Electronic Detectors

Direct



Incident radiation converted into N charges inside "Sensor"

Indirect



Incident radiation converted into some other form of radiation, which in turn is converted into N' charges inside "Sensor"

Historical terms
Semi-meaningless

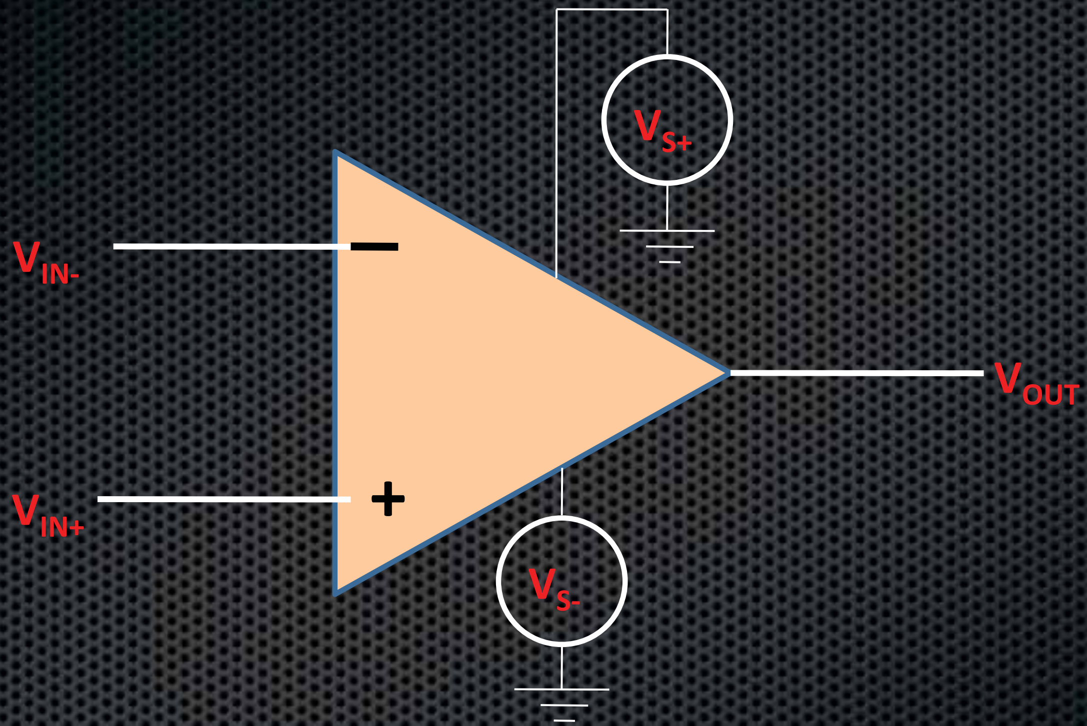
Energy Needed for Detection

"Sensor"	E for secondary quanta	Mechanism
Gas	30 eV	e⁻/ion pairs
Scintillator	10 – 1000 eV	optical excitation
Semiconductor	1 – 5 eV	e⁻/hole pairs
Superconductor	~meV	breakup of Cooper pairs
Superconducting calorimeters	~meV	phonons

Stolen from H. Spieler

Problem – the current pulse is usually very small

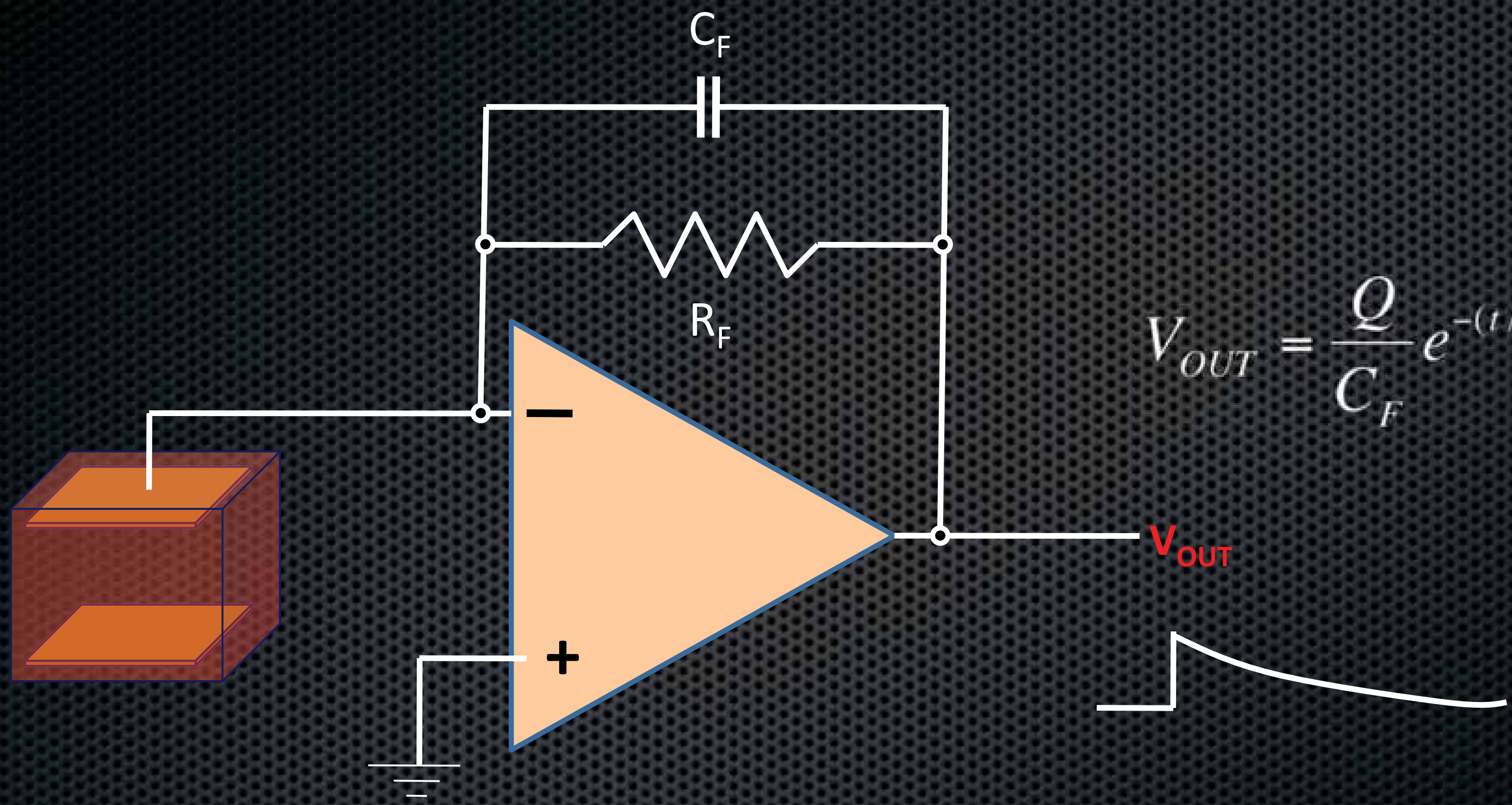
It must be amplified



$$V_{OUT} = \begin{cases} V_{S+} \text{ if } V_{IN+} > V_{IN-} \\ V_{S-} \text{ if } V_{IN+} < V_{IN-} \end{cases}$$

Let's take this further (70 years of electronics in 3 seconds)

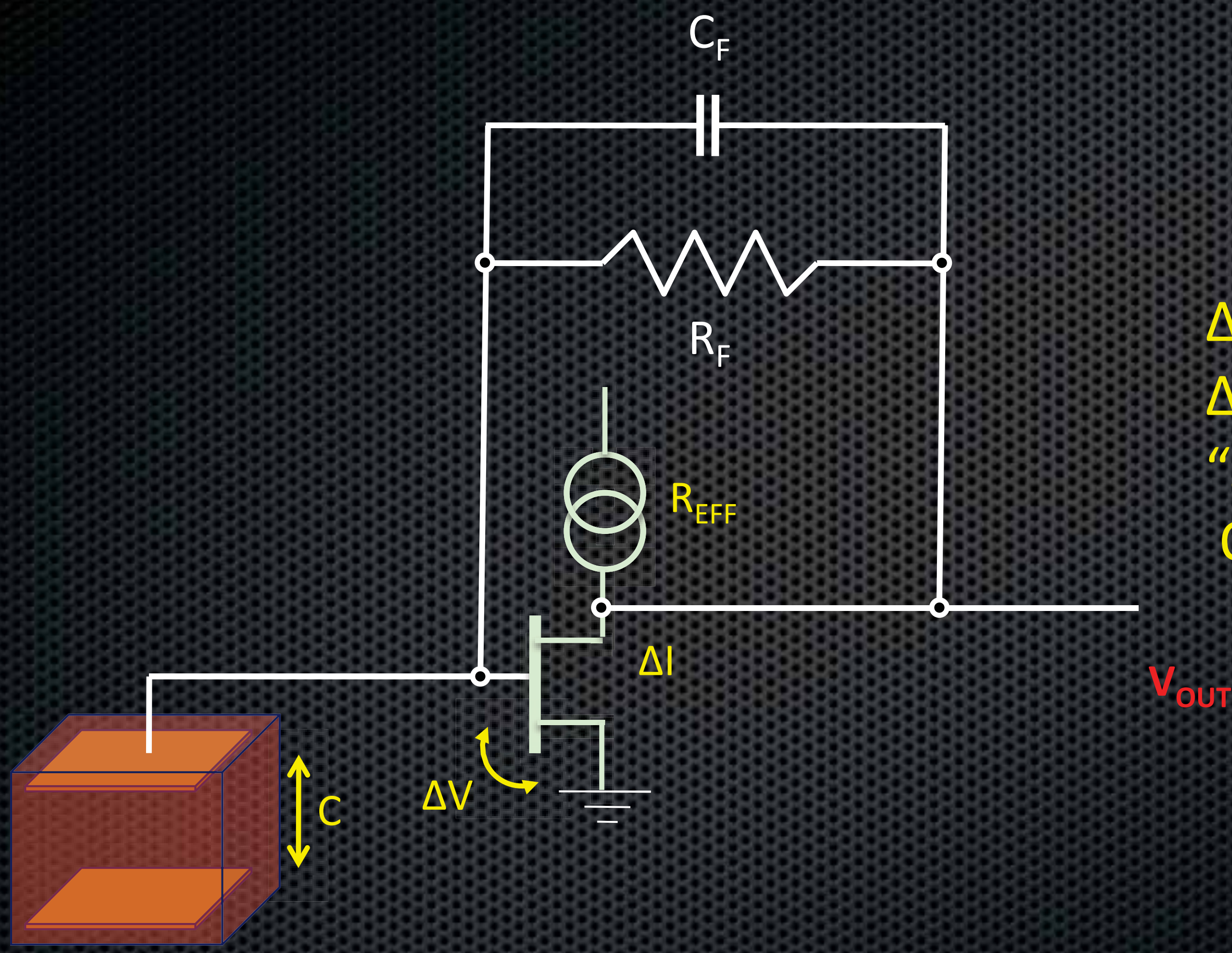
Charge-sensitive pre-amplifier



$$V_{OUT} = \frac{Q}{C_F} e^{-(t/R_F C_F)}$$

Charge appears all at once (δ function)

Almost Always Like This



$\Delta V = Q/C$

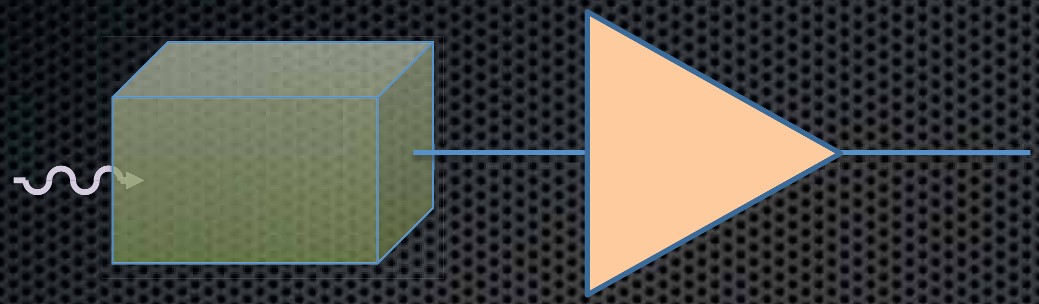
$\Delta I = g_m \bullet \Delta V$

"swing" $= \Delta I \bullet R_{EFF}$

$Q_{FB} = Q = C_F \bullet V_{OUT}$

Noise and Statistics

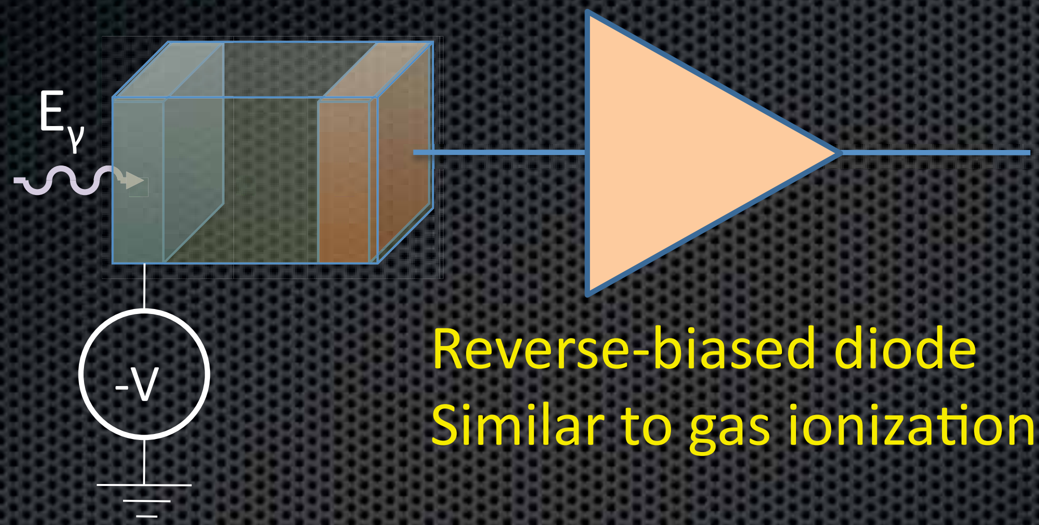
Some terms to get started



- Incident photon creates electron of energy E_γ (photoelectric) or $< E_\gamma$ (Compton) (with probability "QE")
- Electron creates **on average** $N = E_e/\varepsilon$ e/h pairs
- Output pulse height = Gain x N Volts
- Output electronic noise V_N Volts

Semiconductor Detector

p-i-n diode



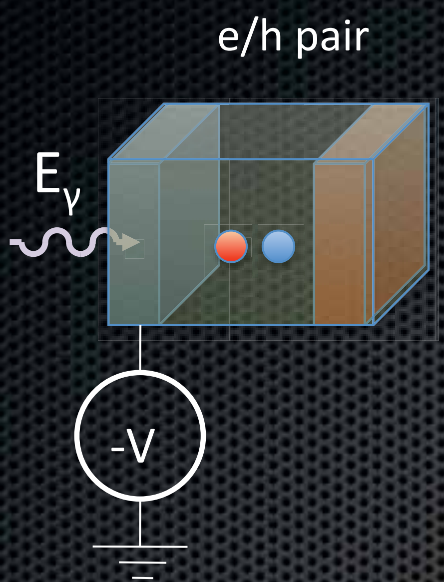
Reverse-biased diode
Similar to gas ionization chamber

$N = E_\gamma/\varepsilon$

$\sigma^2_N = F \bullet E_\gamma/\varepsilon$, F = Fano factor

Material	Si	Ge	GaAs	Diamond
ε [eV]	3.6	3.0	4.4	13.1
F	0.12	0.13	0.10	0.08
ρ [g/cm³]	2.3	5.3	5.3	3.5

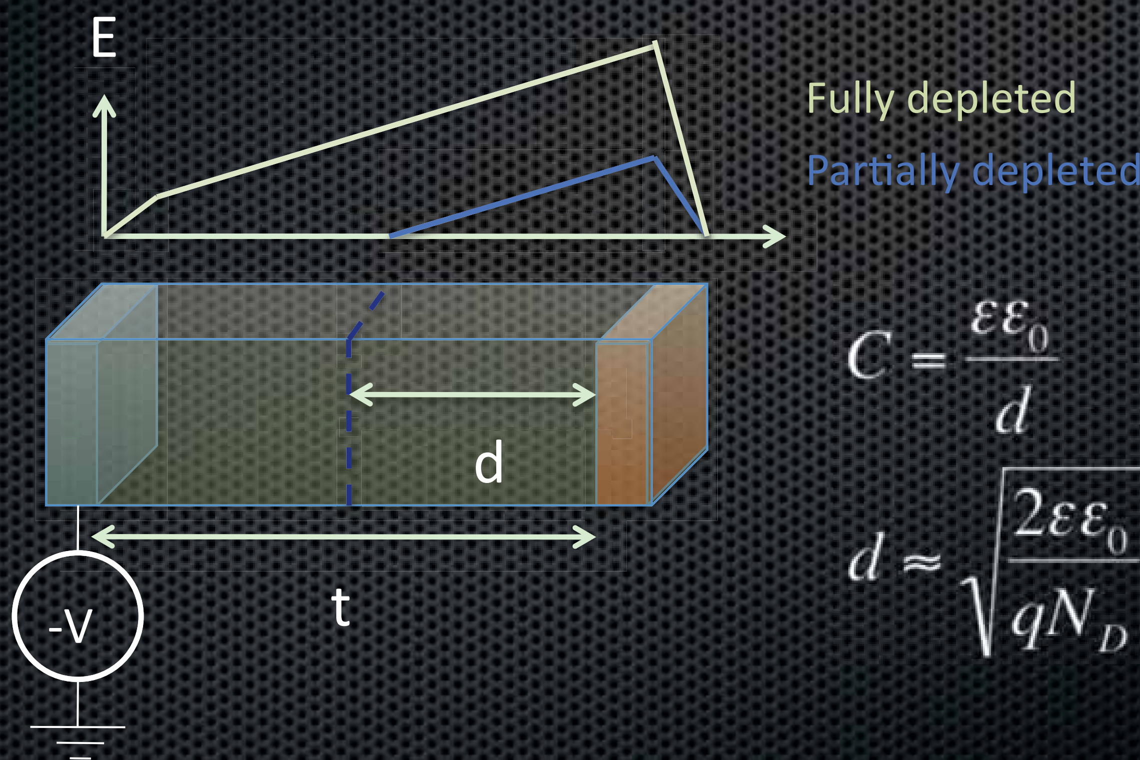
How it Works



- Recombination
  - e^- recombination time $\propto$ 1 / hole concentration
- Diffusion
  - In field-free region, e^- diffuses (into 4π) $D = (kT/q)\mu$ (μ = mobility)
- Drift
  - In non-zero field region e^- moves towards postive plate with velocity $\mu \bullet E$

Depletion

Fully depleted → minimize diffusion (and recombination)



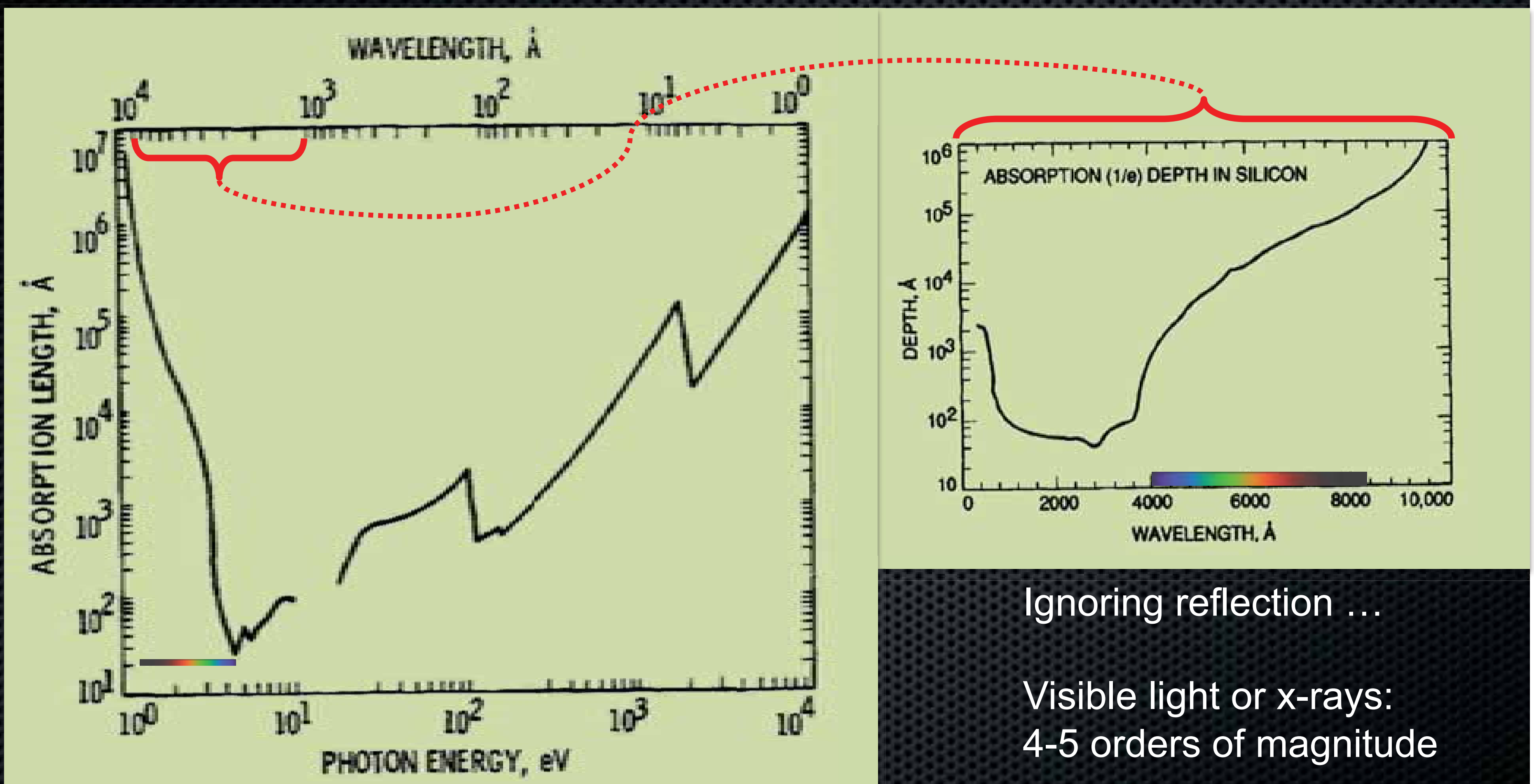
$$C = \frac{\varepsilon \varepsilon_0}{d}$$

capacitance per unit area

$$d \approx \sqrt{\frac{2\varepsilon \varepsilon_0}{q N_D} V}$$

depletion depth

Absorption in Si



Ignoring reflection …

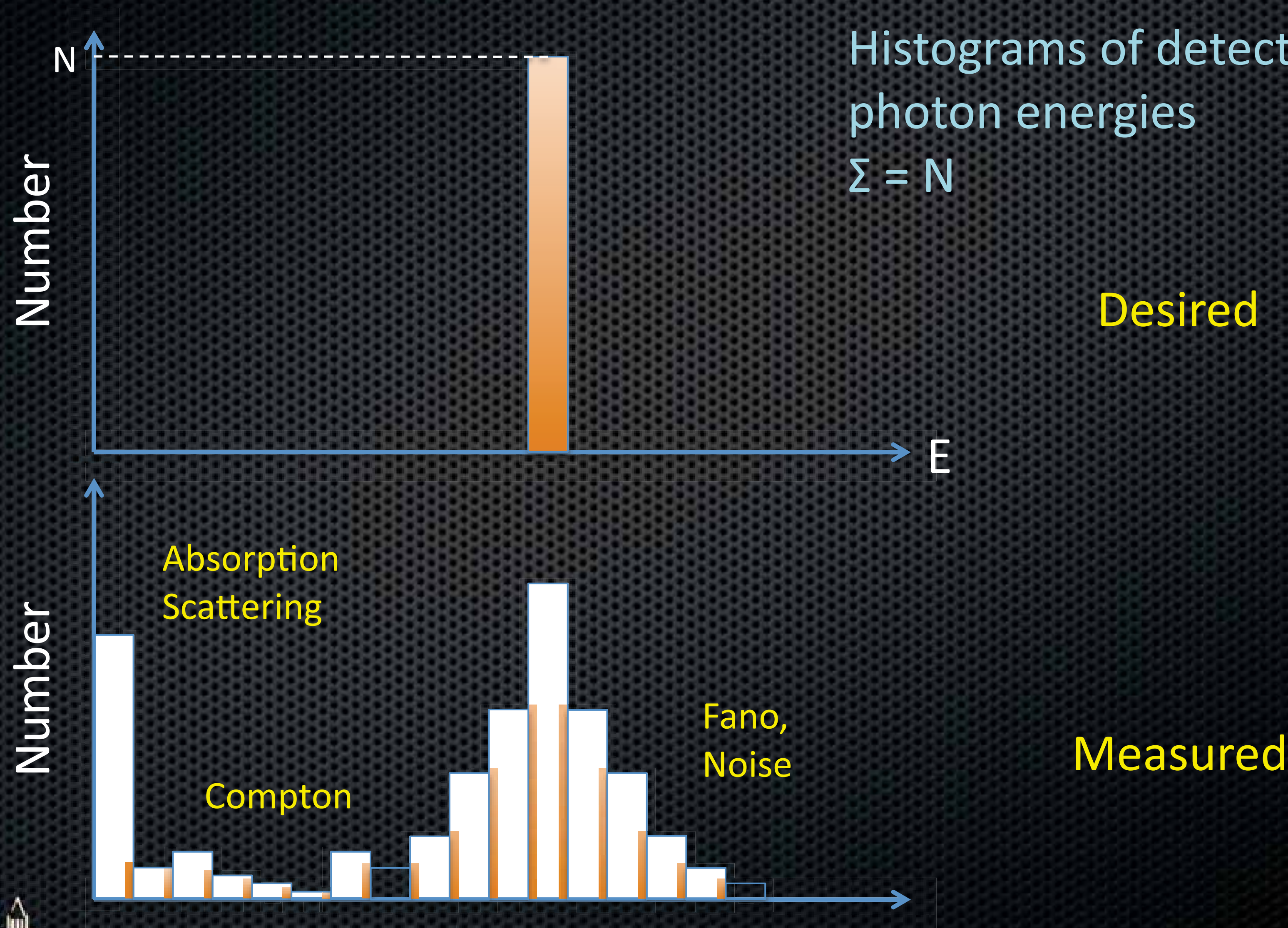
Visible light or x-rays:
4-5 orders of magnitude

Bandgap of Si at 300K = 1.1 eV
→ pure Si transparent for λ > 1.1 μm

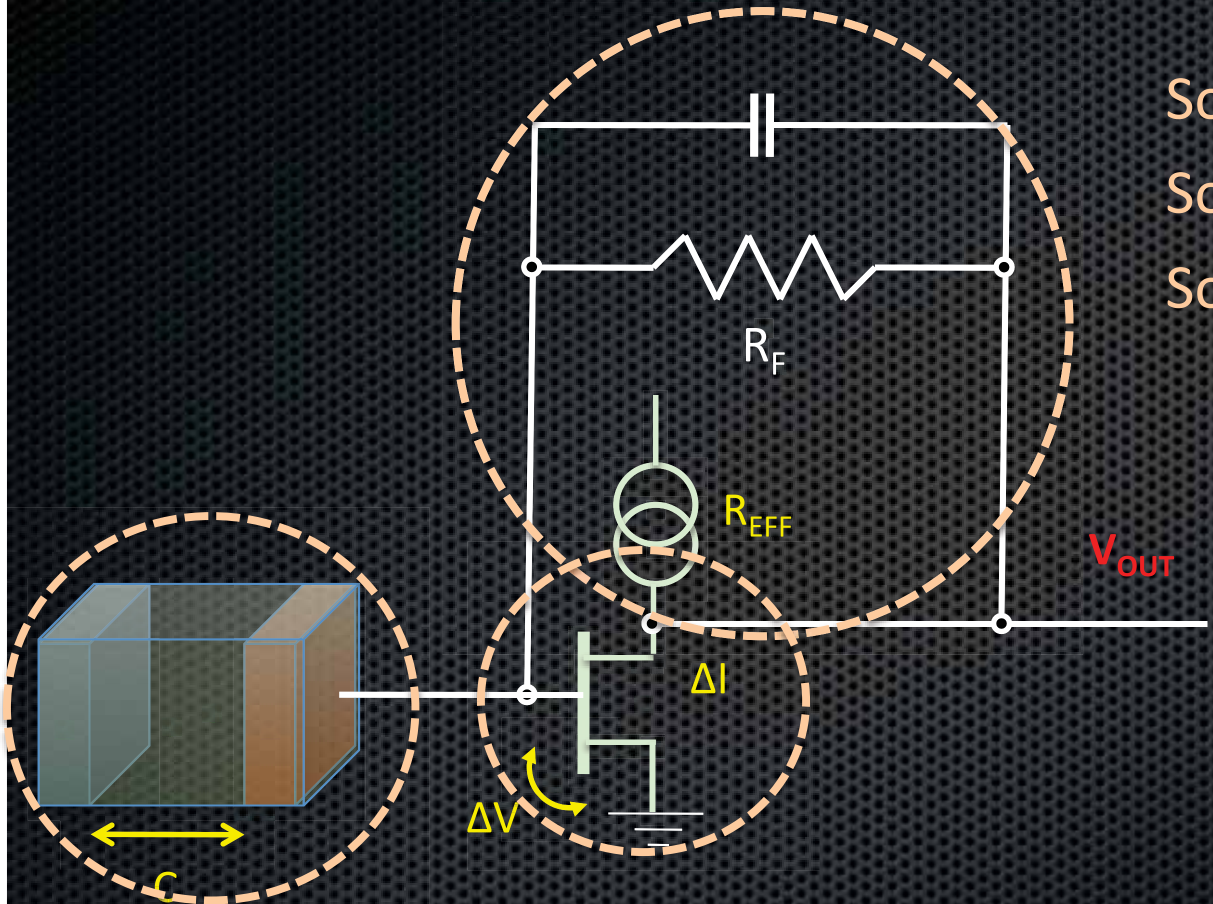
From Janesick

Send N X-rays (of Energy E) Into Detector

Histograms of detected photon energies
Σ = N



Noise

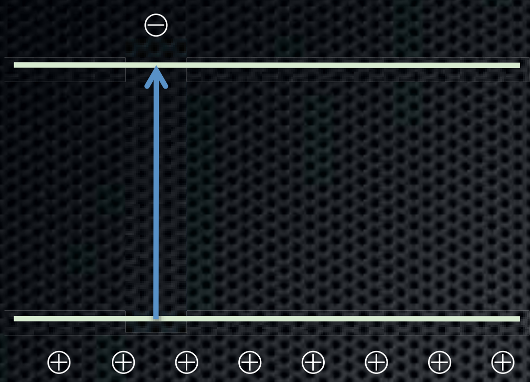


Source #1 – “input stage”

Source #2 – the detector

Source #3 – everything else

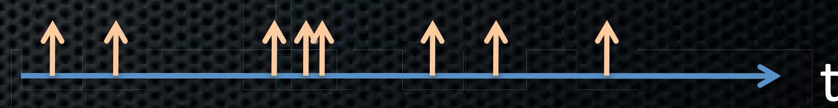
The Detector Makes Noise?



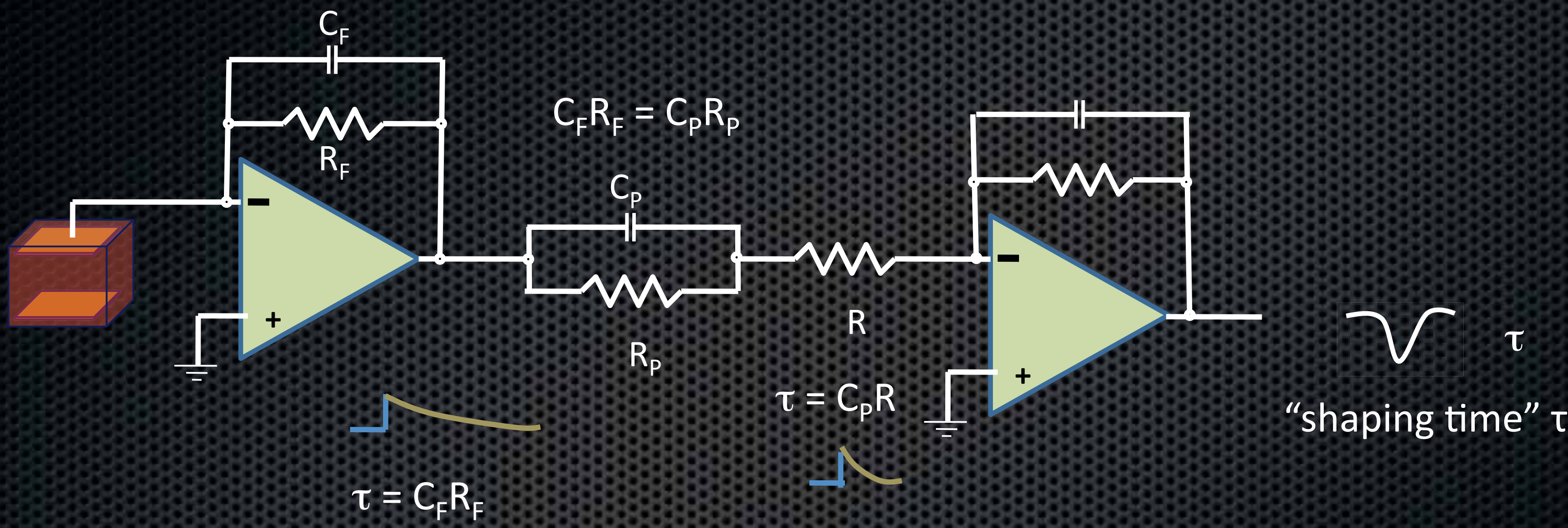
Semiconductor detector
i.e. valence band ~full,
conduction band ~empty

eV band gaps → **thermal excitation** of carriers

- Thermal excitation
  - "leakage" or "dark" current (I_{LEAK} e^-/s)
  - "looks like" signal
  - ("shot noise")
  - Reduced by cooling
- Noise, $\propto \sqrt{I_{LEAK}}$, because leakage is not orderly

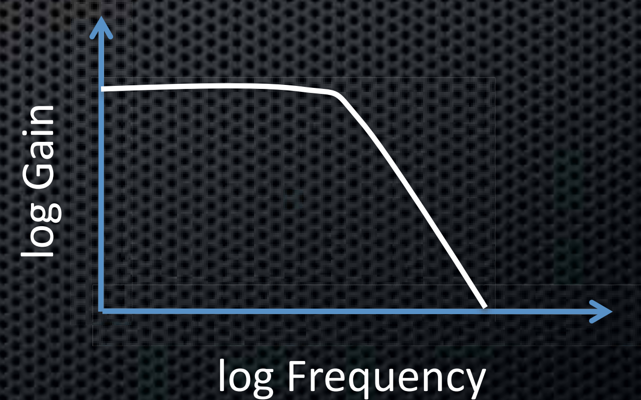


Some More Electronics



Bandwidth = 1 / 2π τ

In frequency domain:

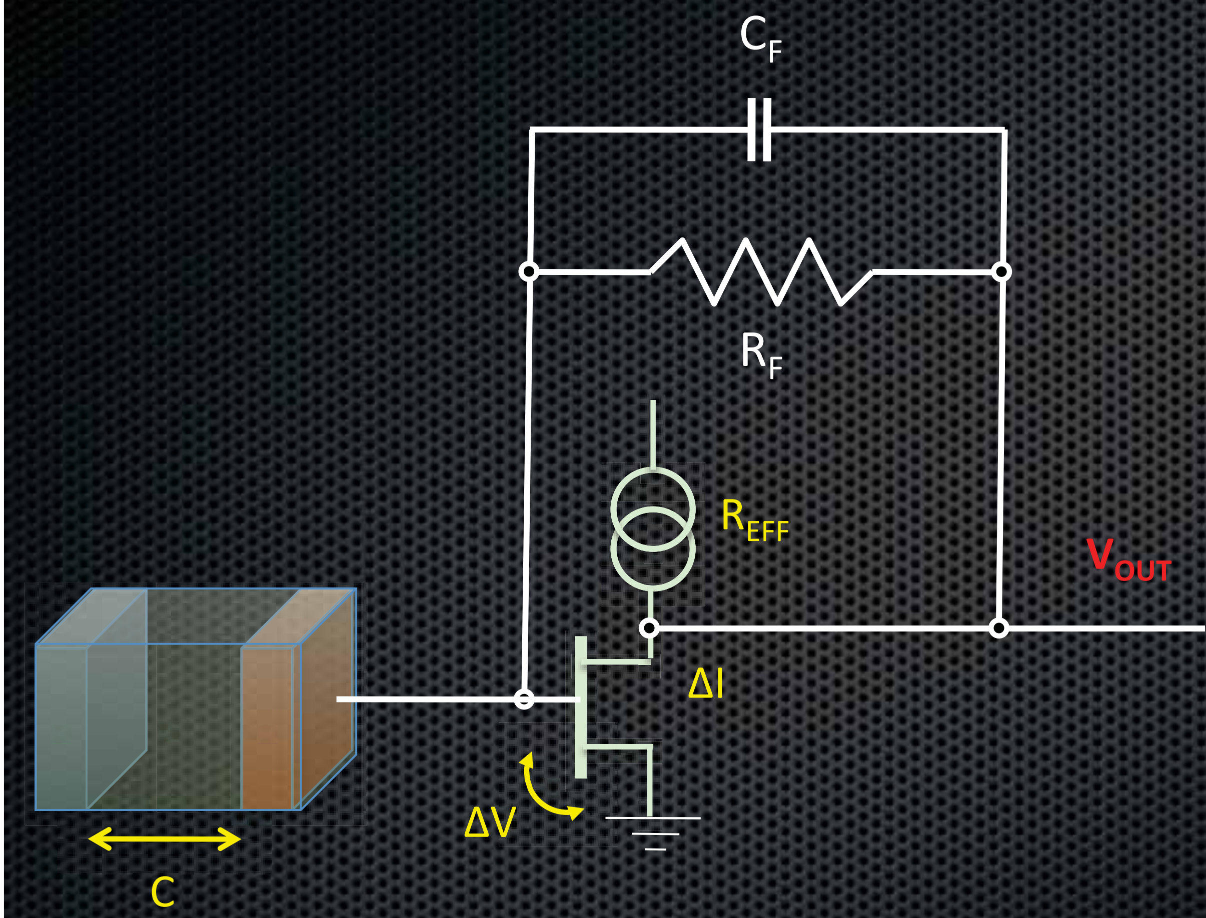


Things ∝ τ

- Double pulse resolution ∝ τ
- Noise due to leakage current ∝
  - √I – random arrival of leakage charge
  - $I \sim e^{-T}/T^2$
  - √τ – i.e. $\sqrt{[e^-/s]\cdot[s]}$
- Longer integration time (τ) increases noise due to leakage current

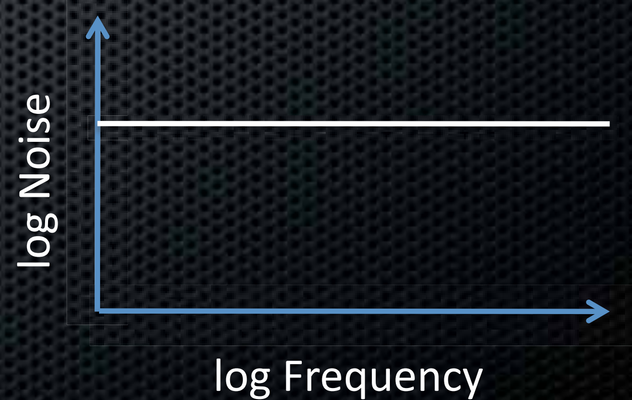
- Must want **short** integration time

Electronic Noise

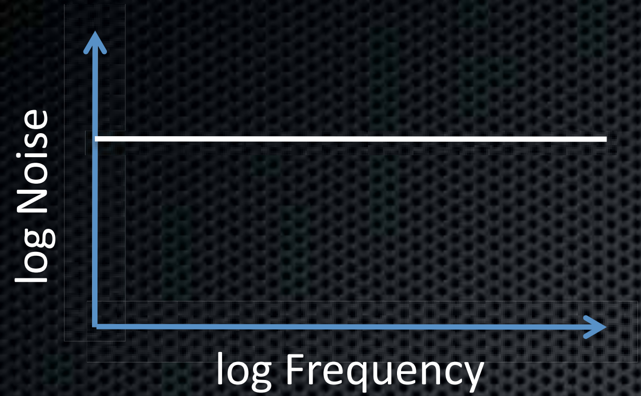


Resistors make noise (Thermal excitation of carriers in resistor means I x R = V_{NOISE}.)

Thermal noise is truly random, $V_N \sim \sqrt{4kTR}$

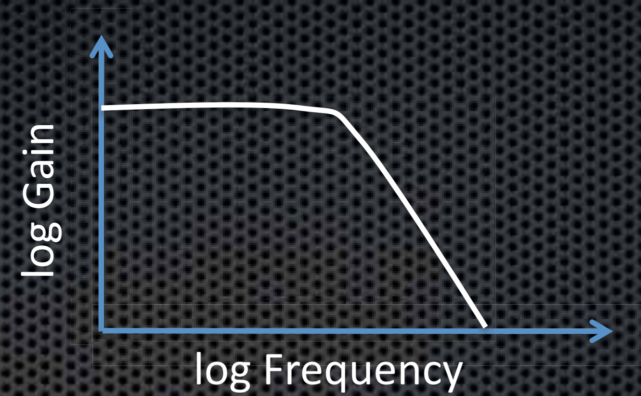


Contribution of Thermal Noise



Noise

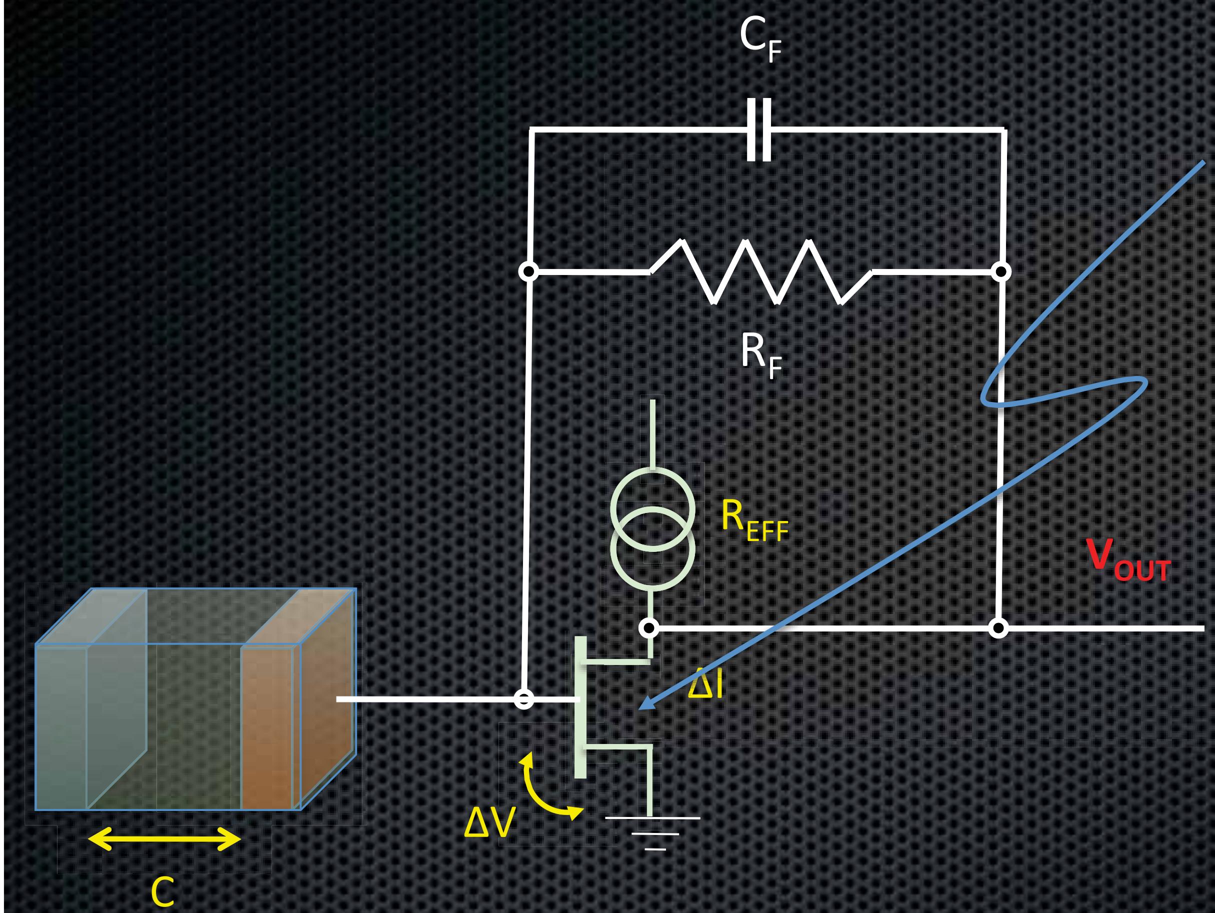
X



System Response

- *Noise* is frequency independent
- So response is ∝ √Bandwidth
- Must want **long** integration time

It's Worse



Thermal noise $\sqrt{(4kT/g_m)}$

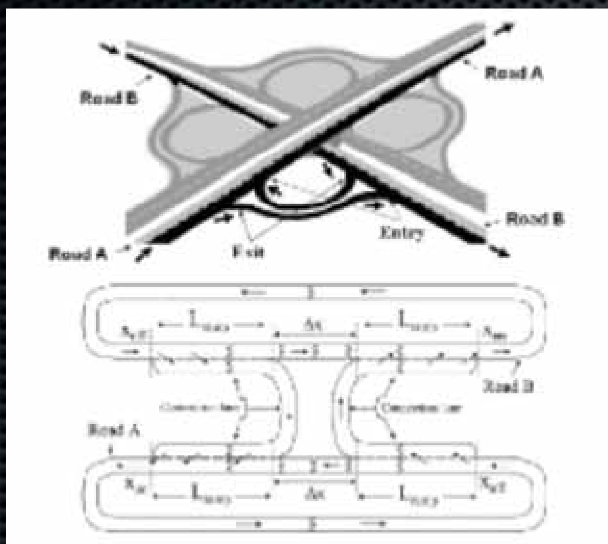
→ δV_{OUT} (from noise)
Input stage will "compensate"
Noise "charge" at input
$\delta Q = C_F \delta V_{OUT}$
ΔV (at input) $= \delta Q / C$

Noise ∝ C

It’s Even Worse

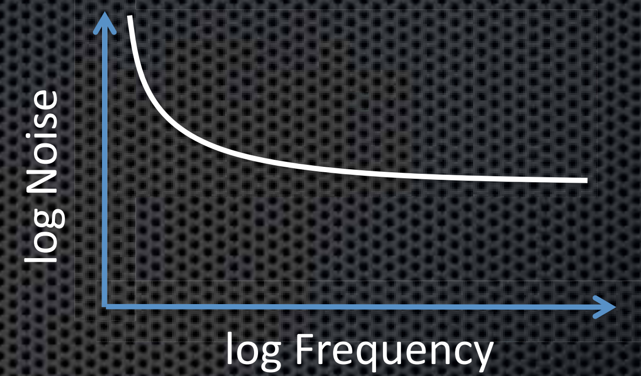
Many physical systems are subject to fluctuations ~ $1/f^{\alpha}$

You know this from driving:



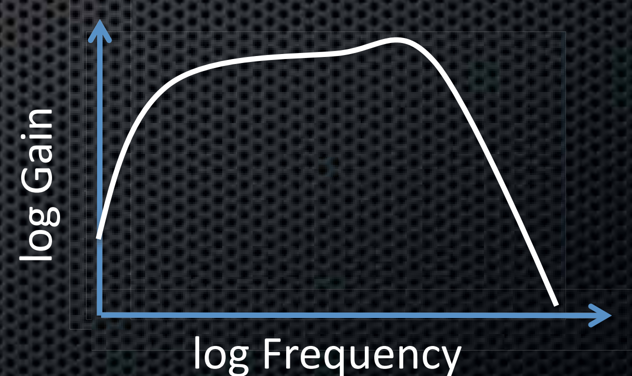
RMS of time you wait getting onto the freeway ~ $1/f$

Same with electronics. So there is an optimum



Noise

X



System Response

Not so Simple

1. Fluctuations in number of photons "absorbed"
2. Fluctuations in number of secondary particles created
3. (Fluctuations in number of tertiary particles created)
4. Electronic noise

◆ **Energy** resolution: 2, 3 and 4

◆ Quantum efficiency: 1 (but maybe 2, 3 and 4)

Detective Quantum Efficiency

- Combine notion of Quantum Efficiency (probability of detecting a particle) with spatial response (probability of detecting/quantifying N(x,y) particles → DQE
  - How faithfully does the detector transfer the (spatially varying) fluctuations of the input signal
  - DQE(ω_x, ω_y)

- Many definitions – most common is $DQE = \frac{(S/N)^2_{OUT}}{(S/N)^2_{IN}}$
- Example, flat field illumination (flux ϕ) of detector with certain QE
  - $(S/N)_{IN} = \frac{\phi A \tau}{\sqrt{\phi A \tau}}$ (Poisson)
  - $(S/N)_{OUT} = \frac{QE \times \phi A \tau}{\sqrt{QE \times \phi A \tau + \sigma_N^2}}$

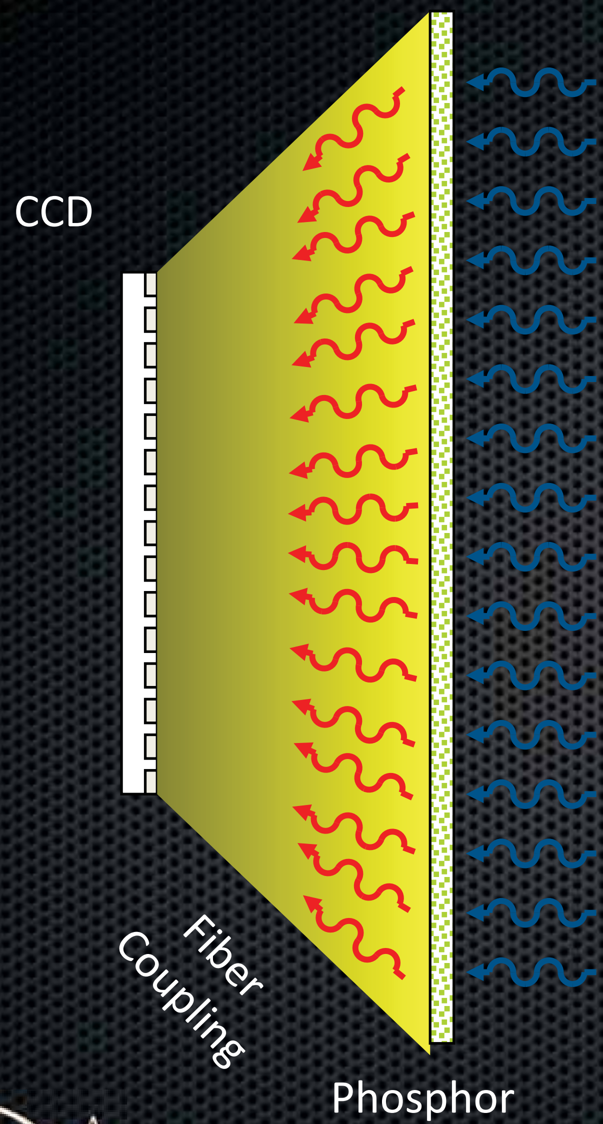
  for electronic noise σ_N

S/N, Dynamic Range, Number of Bits

Usually mis-stated!

- Si: ε = 3.6 eV. Inject 3.6 keV γs (generates on average 1,000 e/h pairs) and measure the output pulse height → "conversion gain" = Volts / e^- = V_e
- RMS noise at output = V_N
  - **ENC** (*Equivalent Noise Charge*) = V_N/V_e
- If the maximum voltage that the system can measure is V_{MAX}, then the dynamic range is V_{MAX} / V_N
  - Example: V_e = 1 μV / e^- , V_N = 100 μV
    - ENC = 100 e^- = 360 eV [RMS]
    - V_{MAX} = 1V → DR = 1V / 100 μV = 10^4
  - N_{BITS} = *ln*(DR) / *ln*(2)
    - *ln*(10^4) / *ln*(2) = 13 bits (i.e. $2^{13} \approx 10^4$)
- S/N has specific meanings, that are not any of these!

"Classical" X-ray Detector



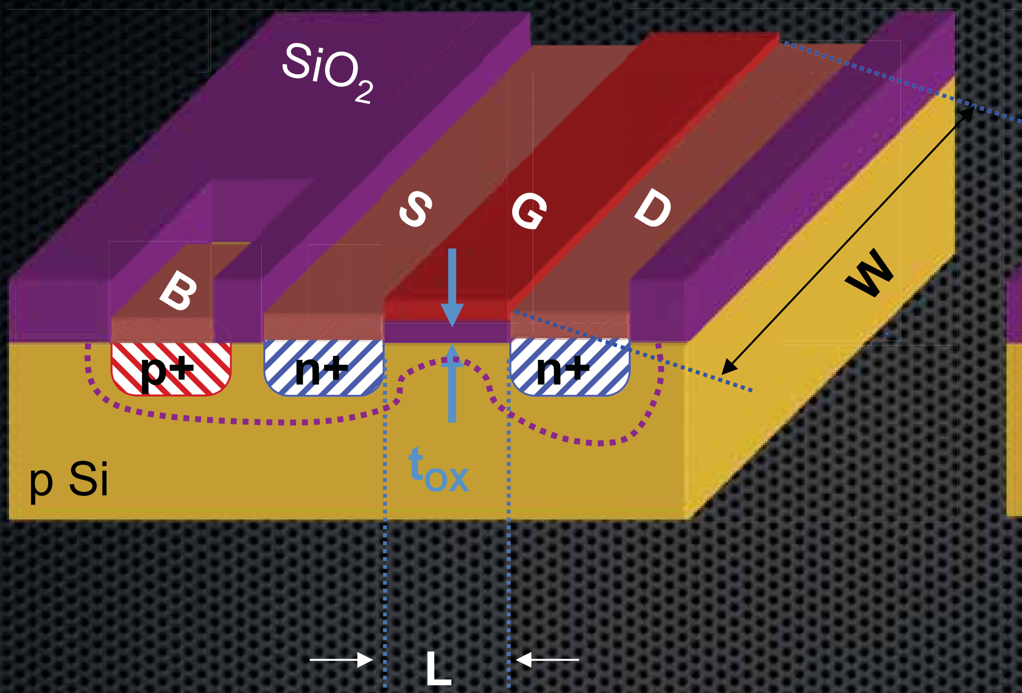
- Phosphor (powdered scintillator)
- Fiber-optically coupled to a CCD (2D solid-state detector) camera
- + and –
  - "general purpose"
  - radiation damage
  - area
  - phosphor
  - fiber-optic

Scientific CCDs (Charge-Coupled Devices)

Dumbbell nebula - LBNL CCD
Blue: H-α at 656 nm
Green: SIII at 955 nm
Red: 1.02 mm

- CCD invented in 1969 by Boyle and Smith (Bell Labs) as alternative to magnetic bubble memory storage
- LST ("Large Space Telescope" – later Hubble) 1965 – how to image?
  - Film was obvious choice, but - It would "cloud" due to radiation damage in space Changing the film in the camera not so trivial
  - 1972 CCD proposed

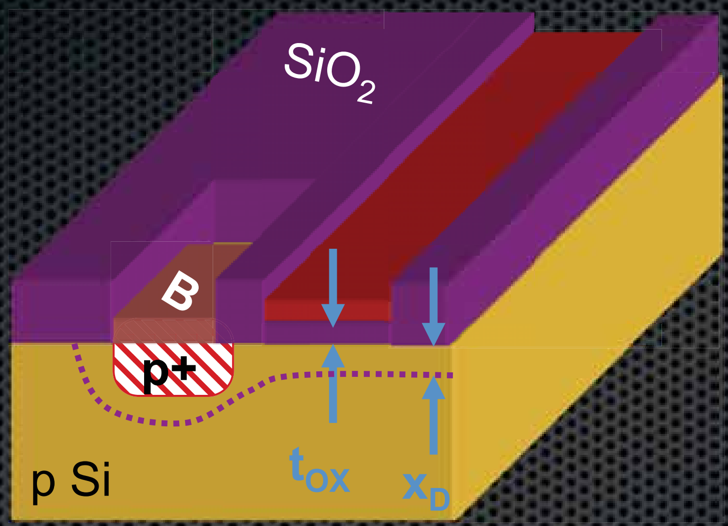
Si Processing: Integrated Circuit Elements



MOS Transistor

pn Diode

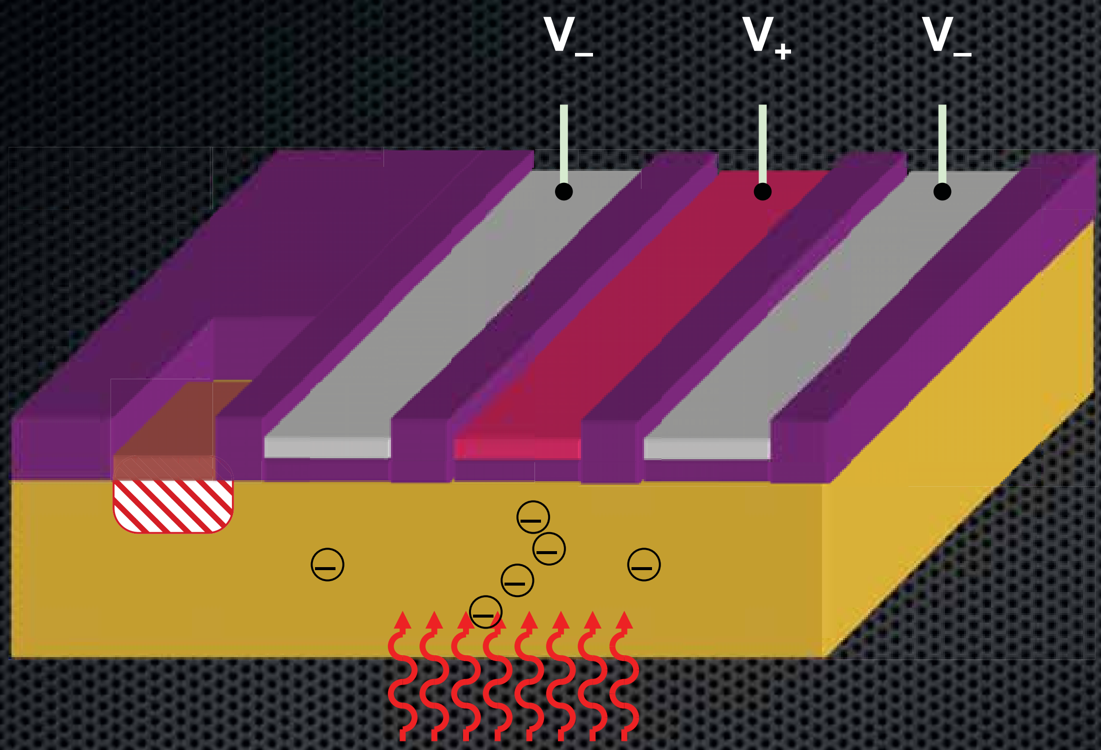
Integrated Circuit Elements



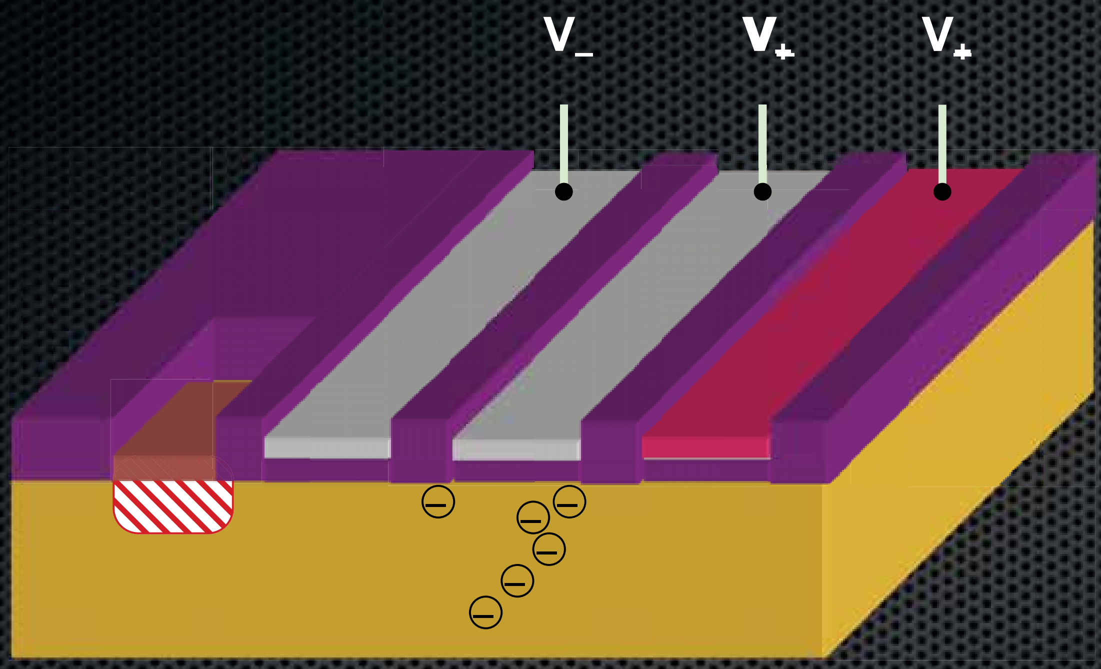
$$C = \frac{1}{\frac{1}{C_{OX}} + \frac{1}{C_{DEP}}}, \quad C_{OX} = \frac{\varepsilon_{SiO_2}}{t_{OX}}, C_{DEP} = \frac{\varepsilon_{Si}}{x_D}$$

MOS Capacitor

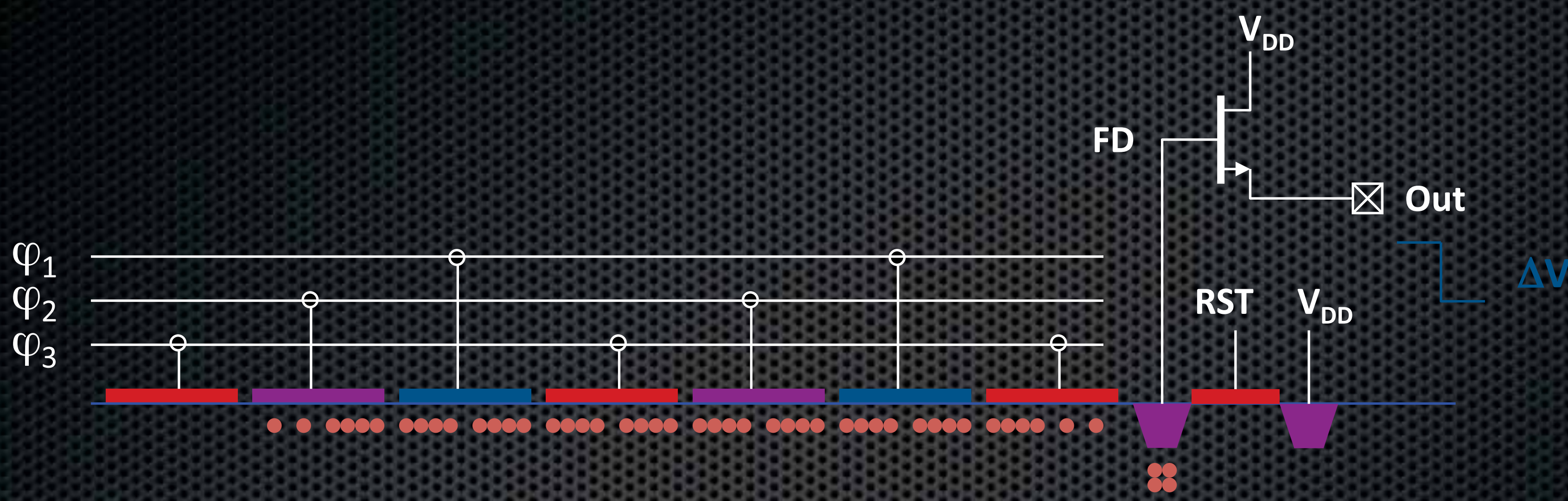
Accumulate Charge



Accumulate and Transfer Charge

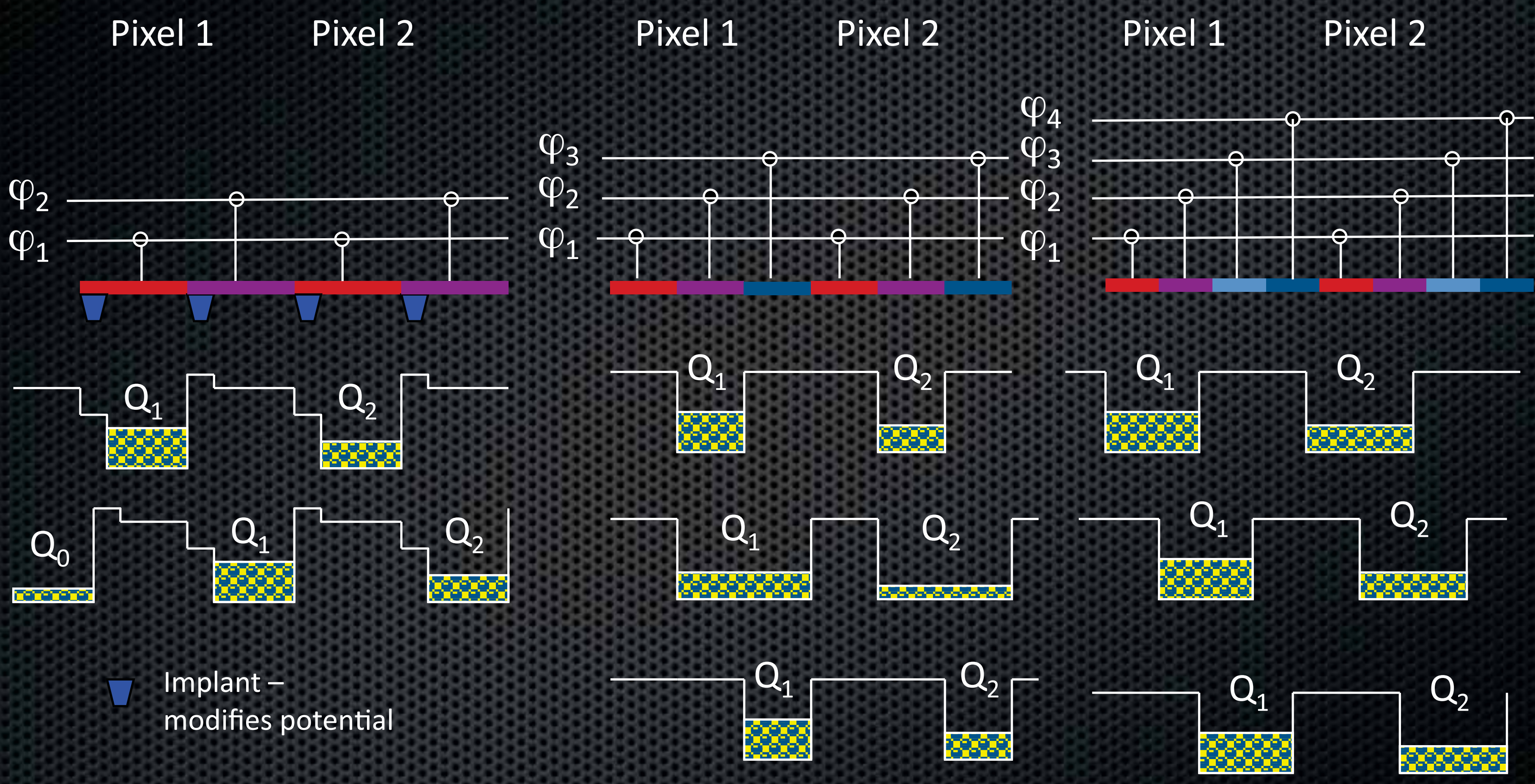


Conventional 3-Phase CCD

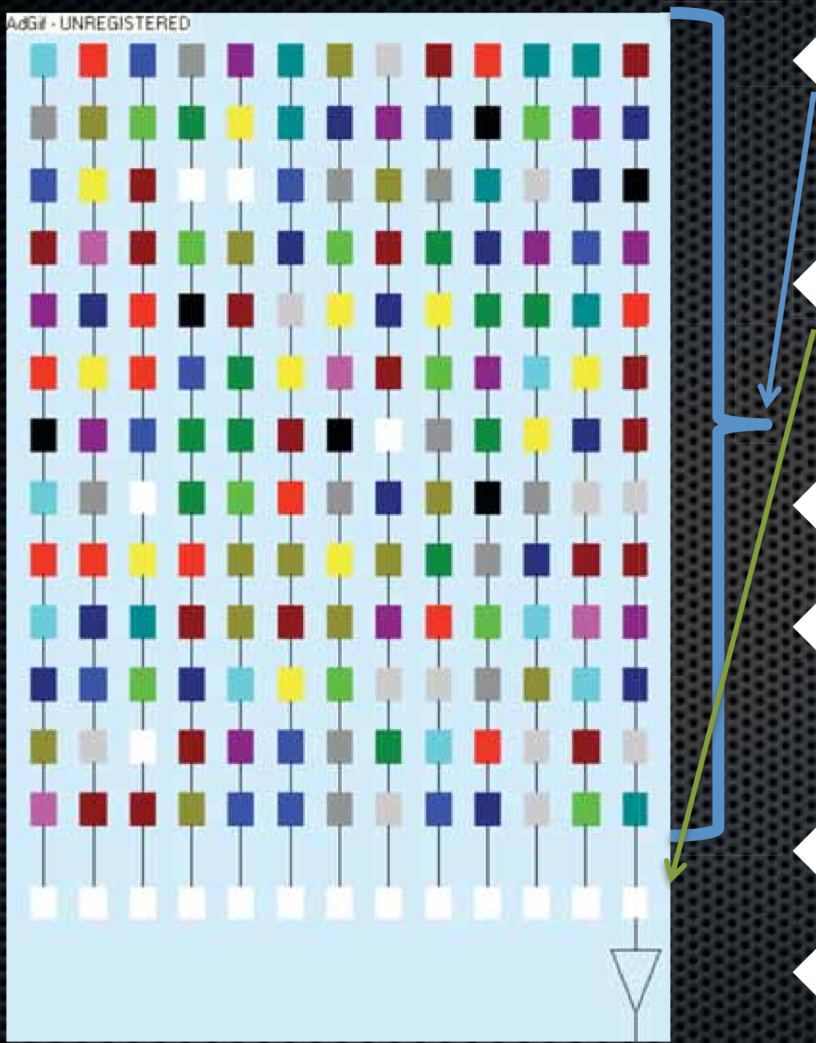


- Noiseless, ~lossless charge transfer
- High gain charge-to-voltage conversion $\Delta V = q/C_{FD}$
- Output amplifier (source follower, or …) on-chip

Many ways to do this

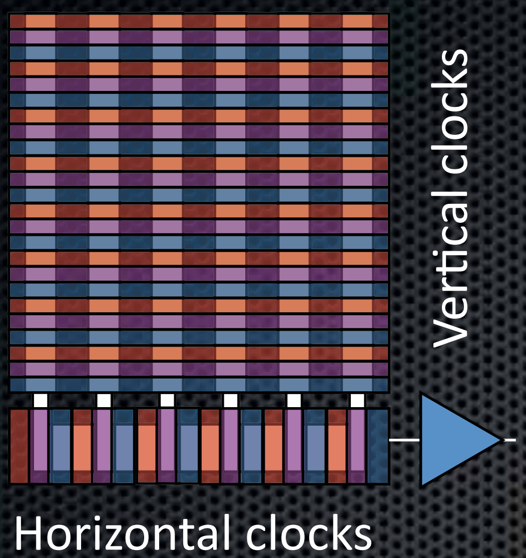


How it Works

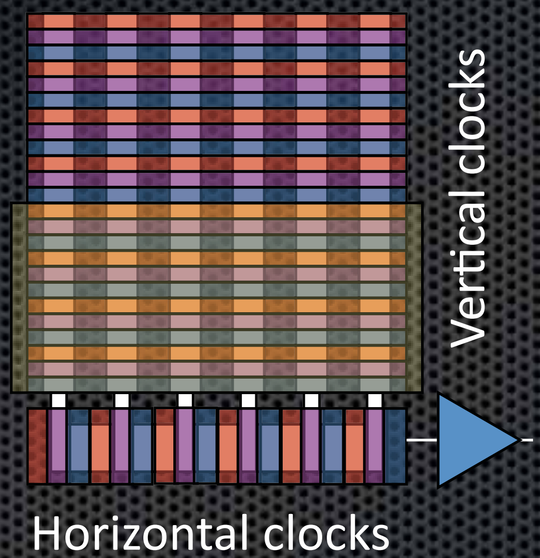


- Image area – N_X x N_Y pixels
- Output shift register (N_X pixels)
- Expose image area
- Shift one row into output shift register
- Shift out each pixel
- Repeat

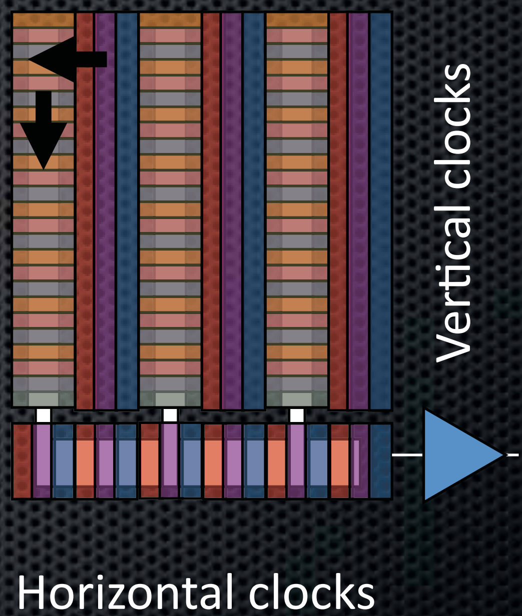
Several architectures



Full frame

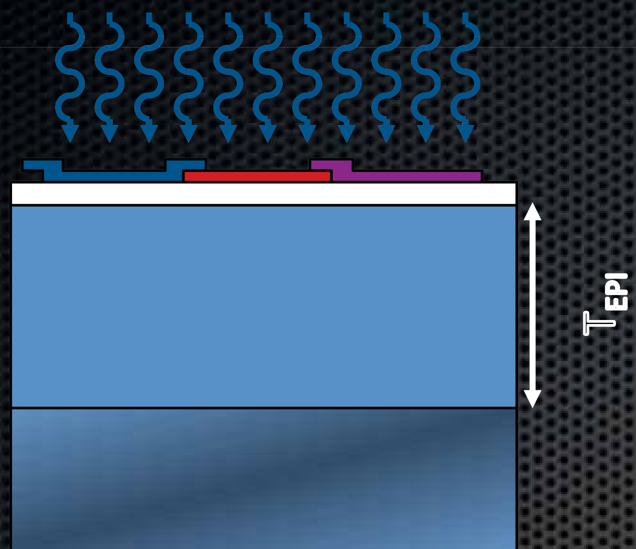


Frame transfer
Rapid shift from image to storage
Slower readout of storage during integration



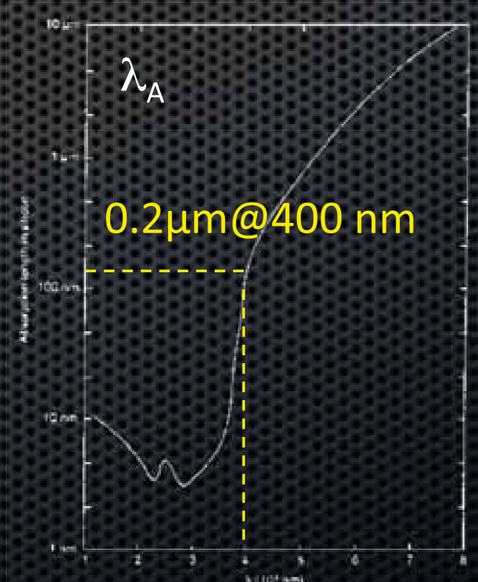
Interline

Frontside/Backside Illumination

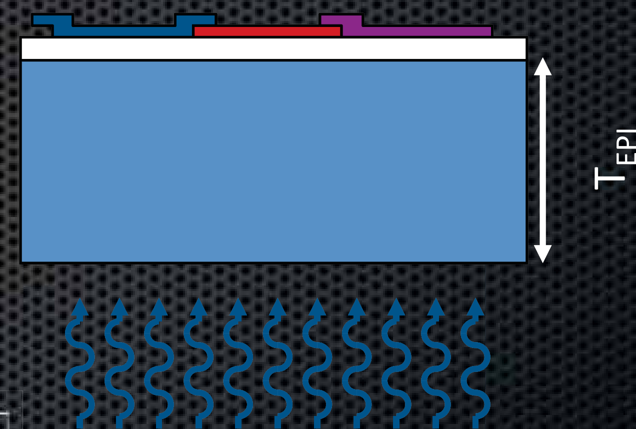


$$\varepsilon \propto e^{-T_{POLY}/\lambda_A}\left(1-e^{-T_{EPI}/\lambda_A}\right)$$

Fill factor < 1

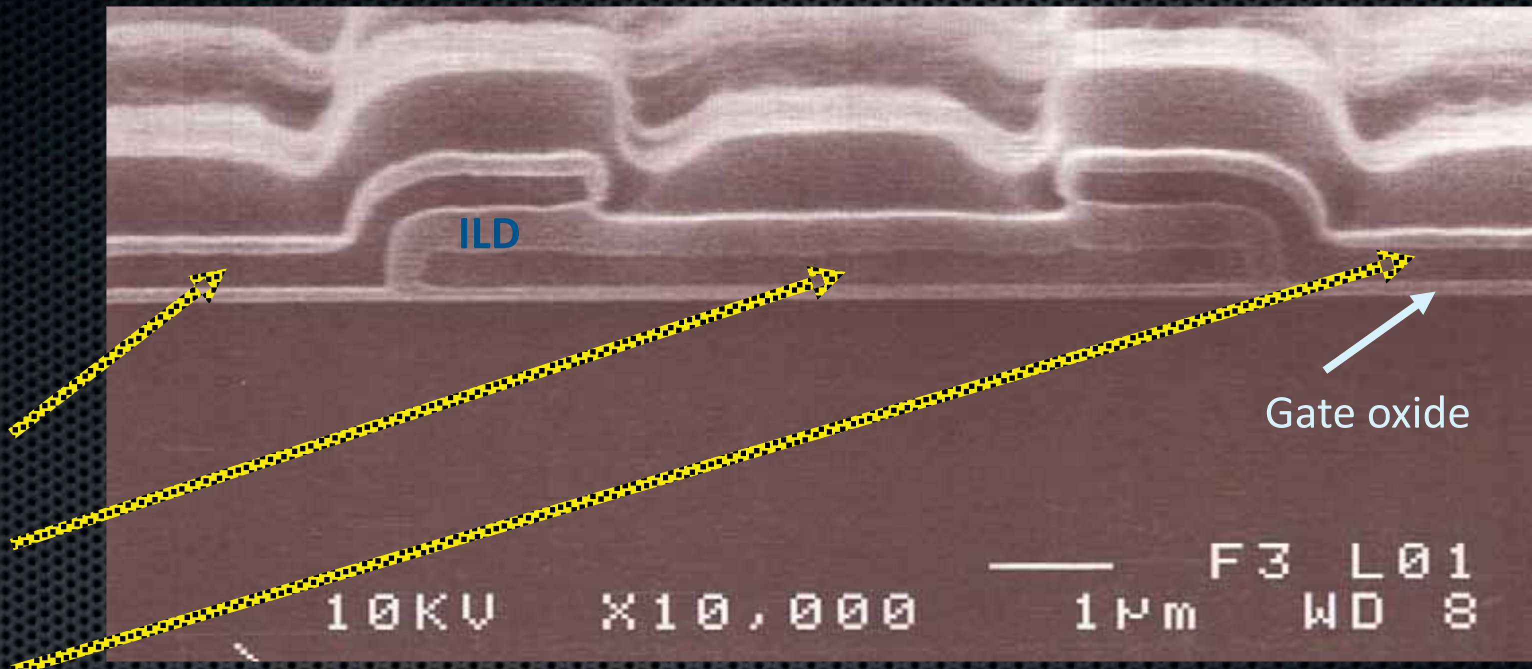


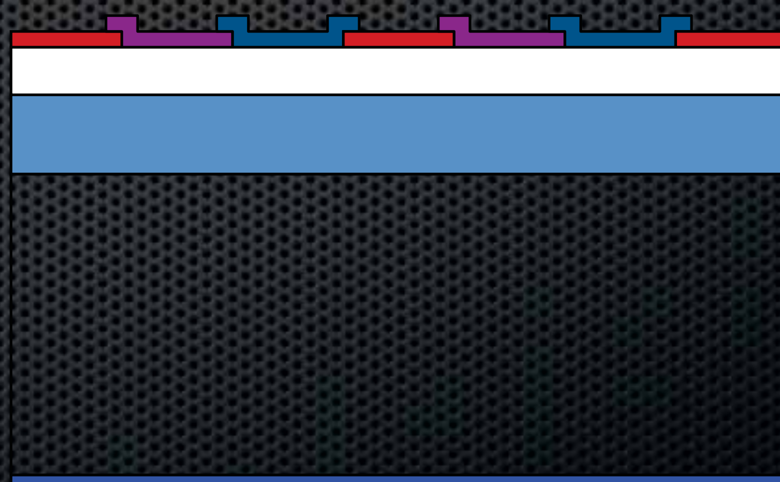
$$\varepsilon \propto \left(1-e^{-T_{EPI}/\lambda_A}\right)$$



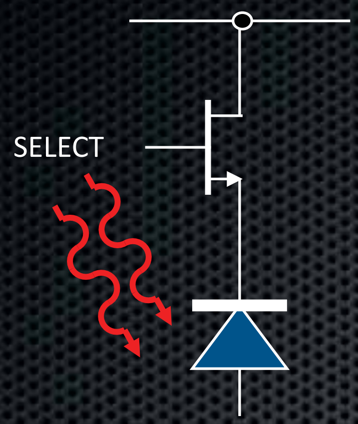
Fill factor = 1

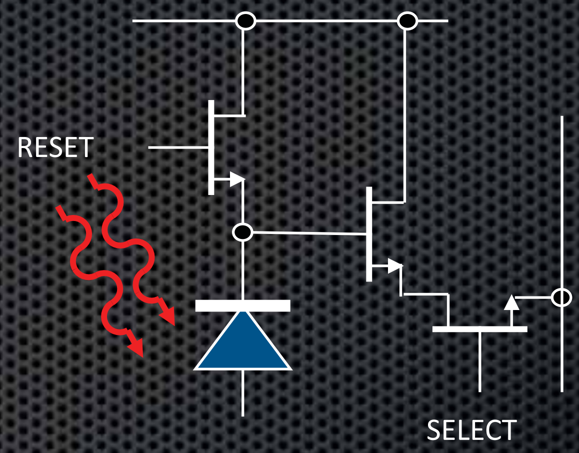
Triple Poly CCD Process





Monolithic Image Sensors



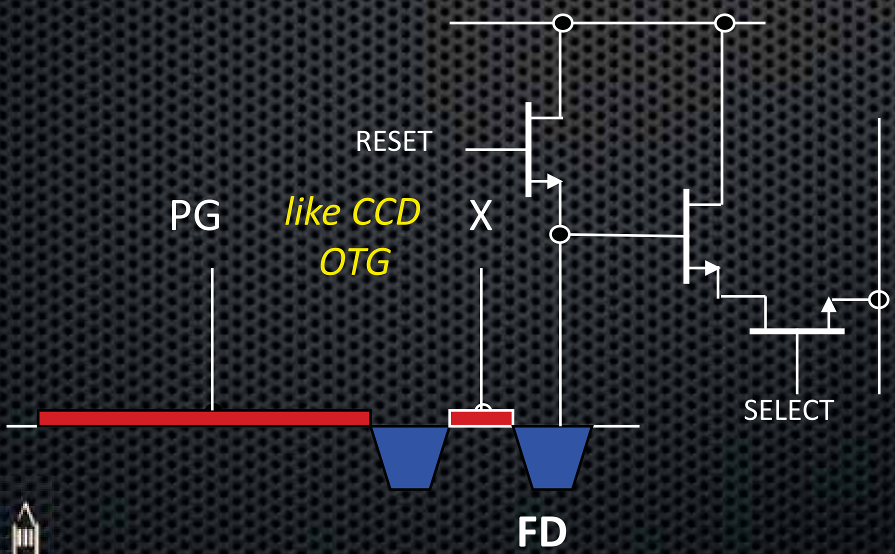


- Passive Pixel Sensor
- Proposed 1968
- No Reset, no in=pixel amplifier

- Active Pixel Sensor
- *Also* proposed 1968
- Many ways to make the photodiode

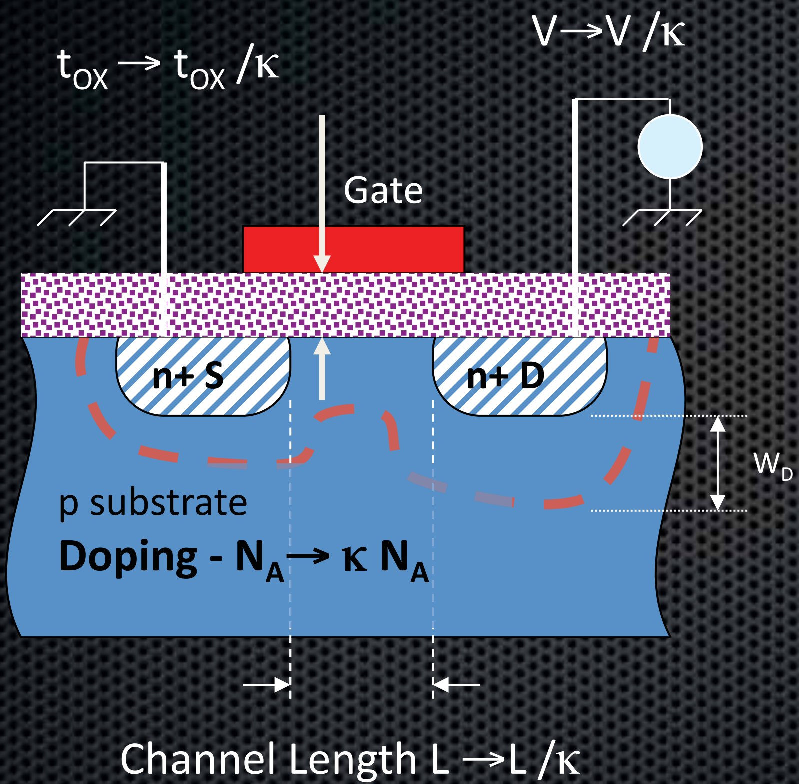
CCD vs APS

- APS – transfers a *voltage* down the column
- CCD – (noiselessly) transfers a *charge* down the column
- APS – can be more sensitive (source follower does not have to drive off-chip)
- APS – fill factor < 1 in general
- Photogate APS – like a matrix of individual CCDs
- Backside illumination – attempted for APS, work-in-progress



CMOS, CMOS "opto" and CCD processes

CMOS driven by
constant field scaling

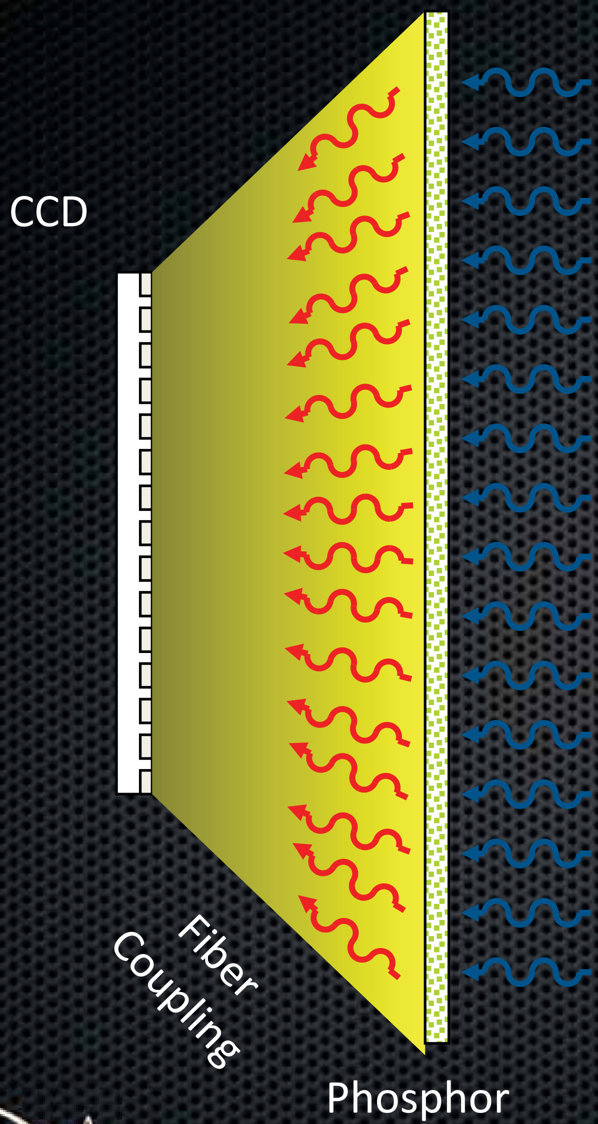


	CCD	CMOS
t_{OX} (Å)	500 - 1000	5-20
Well depth (µm)	2.5	0.5 deeper for RF
Implant (µm)	~1 channel stop	0.1 S/D implants
V	≥10	<3.3 <2.5 <1.x …
Poly layers	3 (2)	1 2 for analog
Subst. quality	Low leakage	Don't care Except opto

Why CCDs?

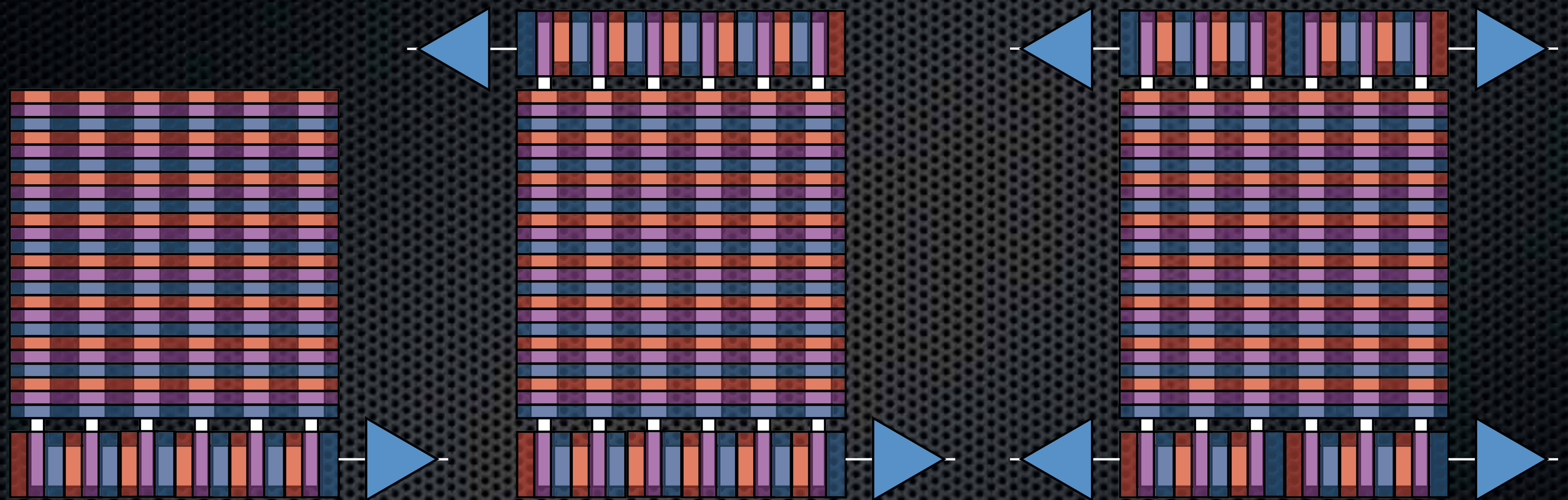
- Low noise (noiseless charge transfer, do everything to make C_{FD} small in order to get large conversion gain)
- Fill-factor = 1 (for backside illumination)
- Linear and easy to calibrate
- **Long history of scientific use**
- Large area devices easier (cheaper) to develop as CCDs than as state of the art CMOS devices
  - Readily wafer scale
- Commercially produced

“Classical” X-ray Detector



- Phosphor (powdered scintillator)
- Fiber-optically coupled to a CCD (2D solid-state detector) camera
- + and –
  - “general purpose”
  - radiation damage
  - area
  - phosphor
  - fiber-optic

CCDs are Wonderful, but SLOW

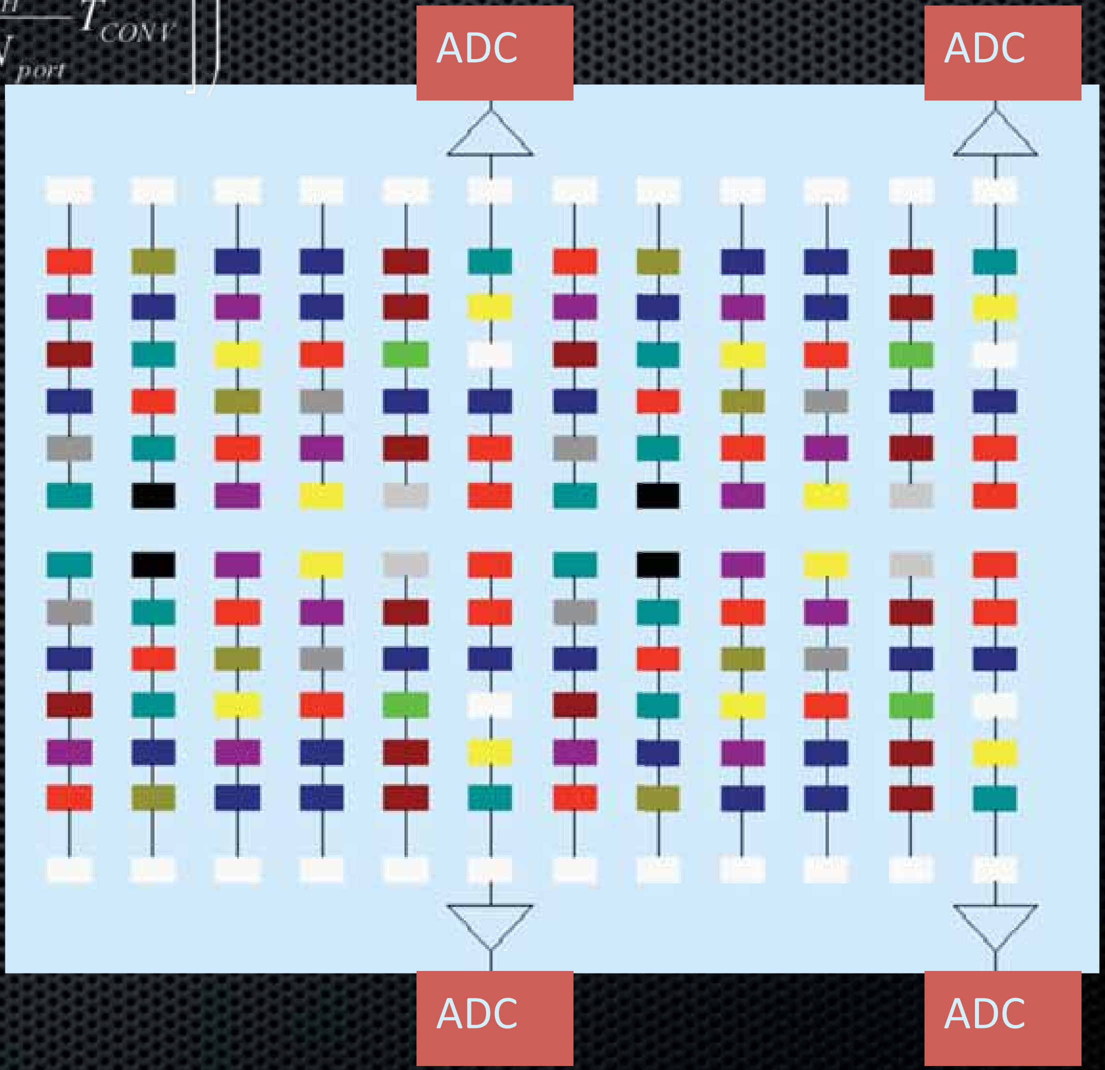


Now it gets more difficult

Increase ADC speed

$$T_f = \frac{N_V}{2}\left(T_V + \frac{1}{B_V}\left[B_H T_H + \frac{N_H}{B_H N_{port}} T_{CONV}\right]\right)$$

top+bottom readout



N_V, N_H = # H, V pixels

B_V, B_H = H, V binning

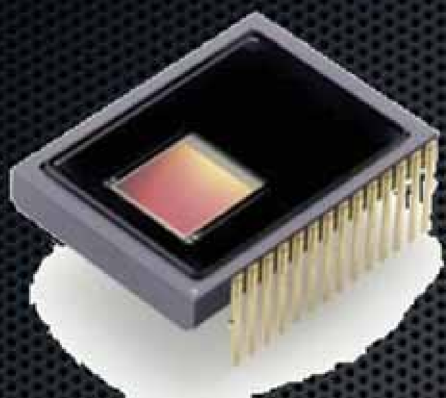
T_V, T_H = H, V shift time

N_{port} = # ports

T_{CONV} = total conversion time including reset, summing well, …

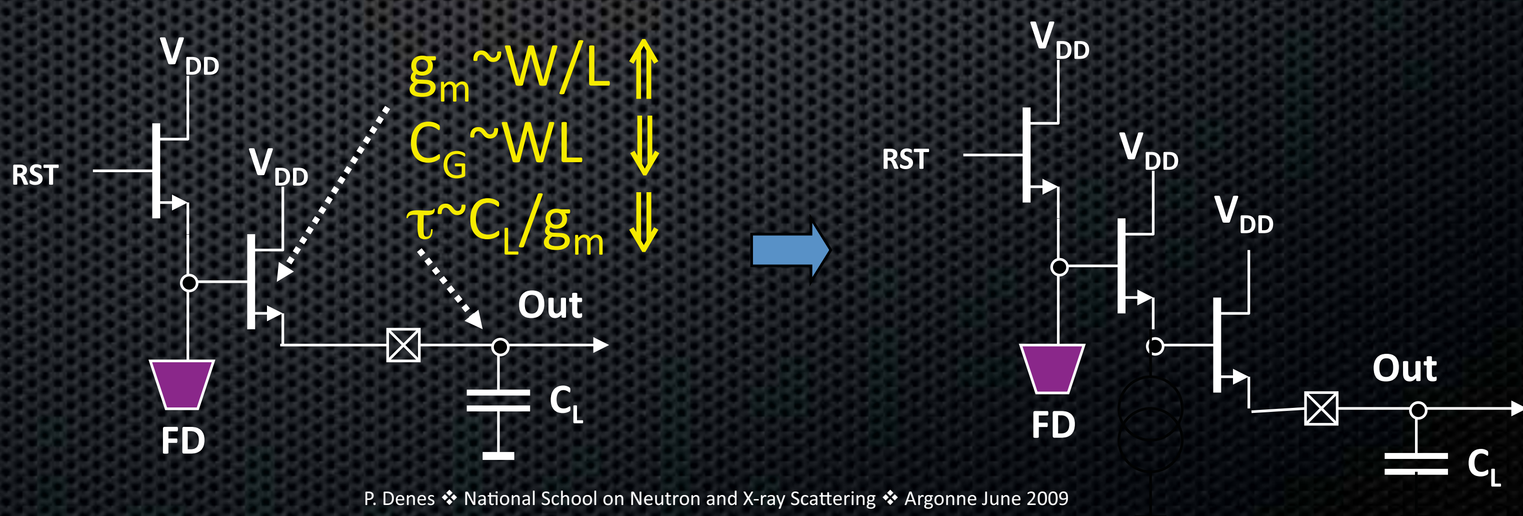
For example

Increase readout/ADC speed

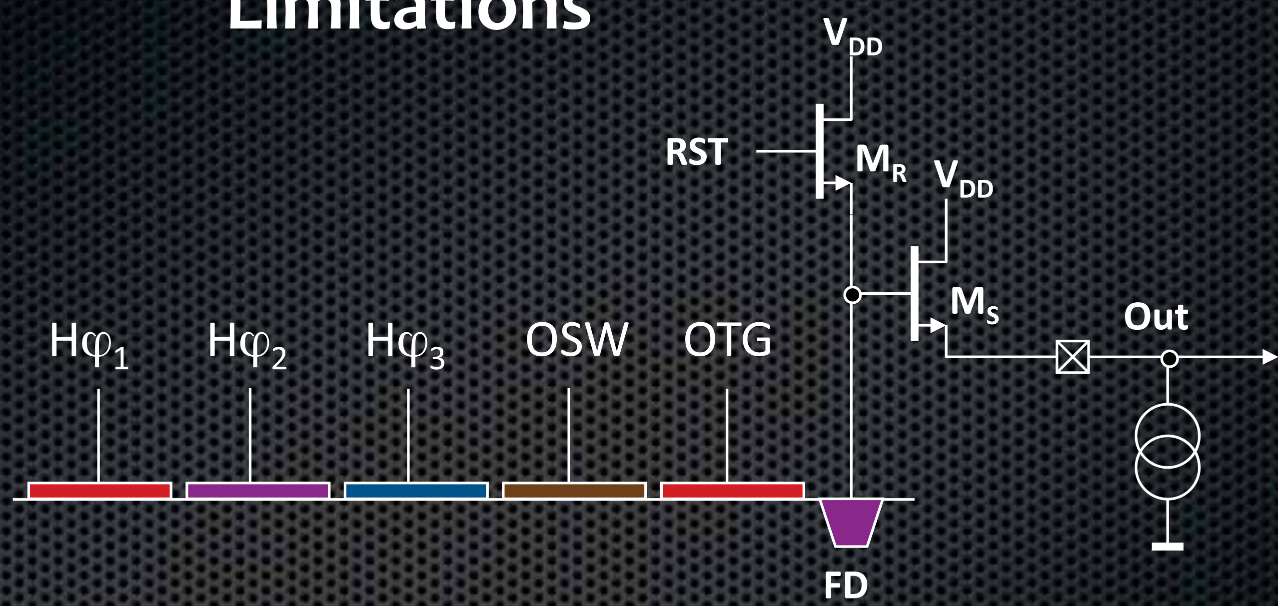


- Dalsa – FT50M
- 1024 x 1024 x 5.6 µm pixel
- Frame transfer / 2 ports
- 100 fps = 100 MPix/s
- 11.1 bits [67 dB] at 30/60 fps
- 10.1 bits [61 dB] at 50/100 fps

S/F Limitations



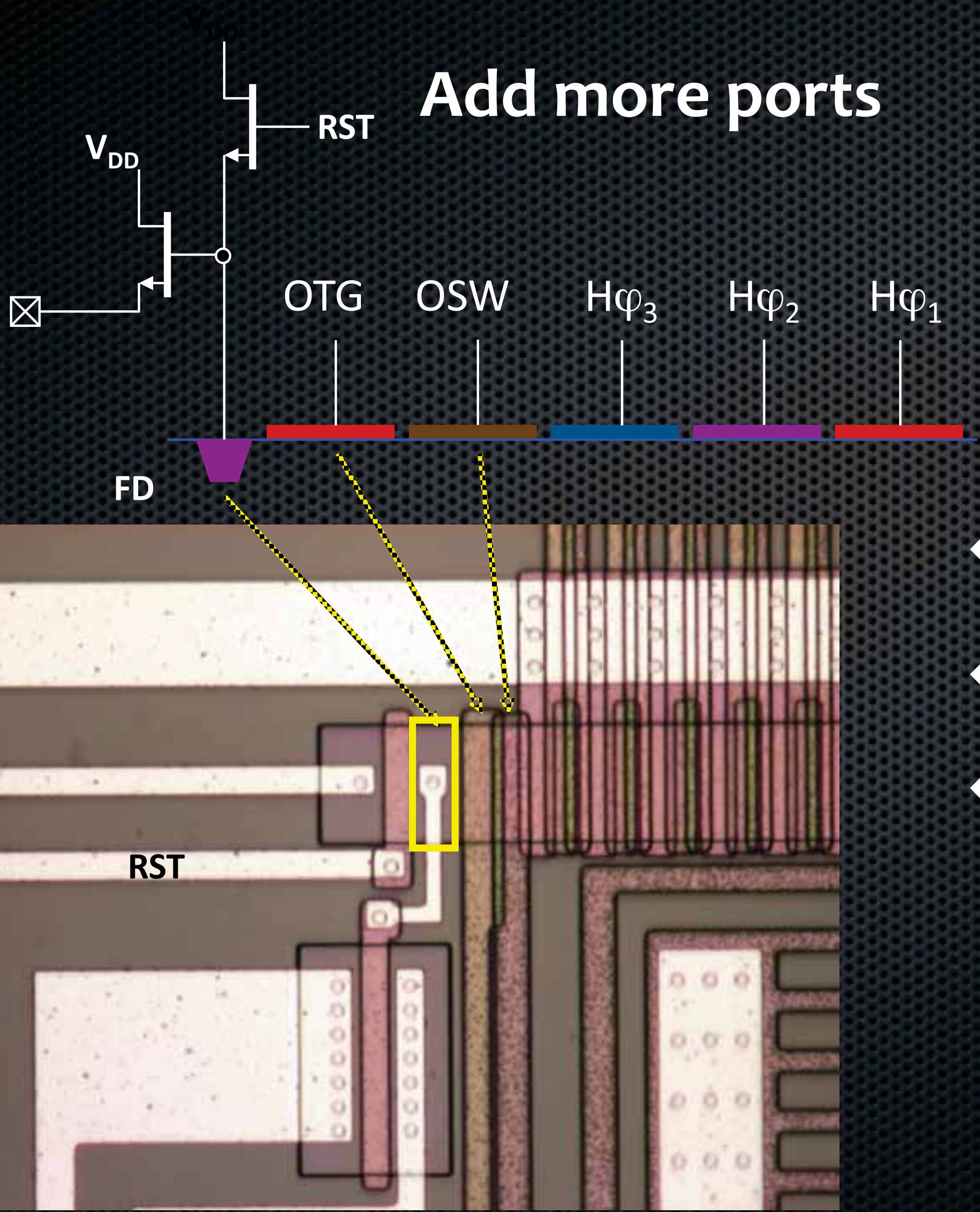
Limitations



- $\sqrt{kTC}$ Noise contribution from M_R (reset switch) removed by CDS (correlated double sampling – measure V_R and $V_R + V_S$)
- Noise contributions from M_S (source follower)
  - Thermal noise $V_n^2 \sim 4kT\gamma g_m \int H^2(f)\, df$
  - 1/f noise $V_n^2 \sim \frac{K}{C_{ox}WL}\int H^2(f)\frac{1}{f}\, df$
  - Noise from current source

↑ ~ √rate

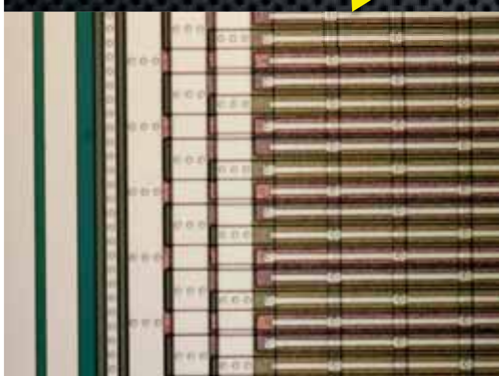
Add more ports

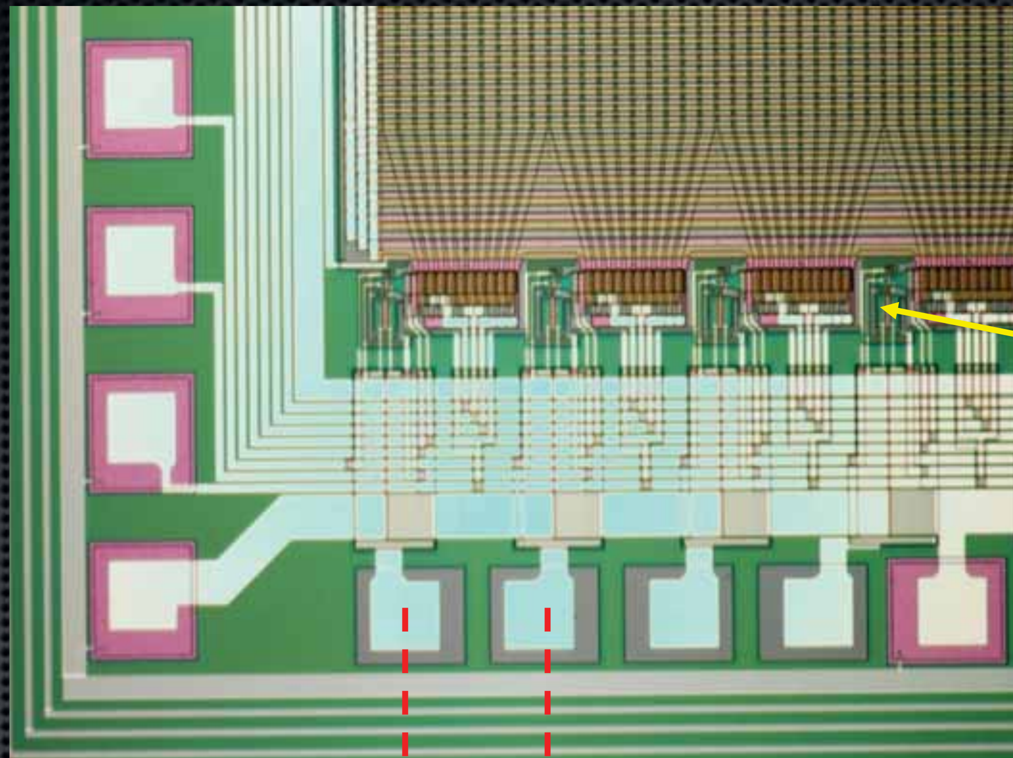


- Reset and output transistors need room
- Want to minimize C_{FD}
- Need space for the output stage!

(almost) Column-Parallel CCD

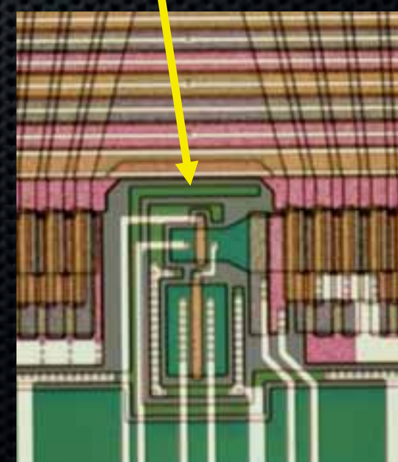
Mini-SR with taper
Metal strapping



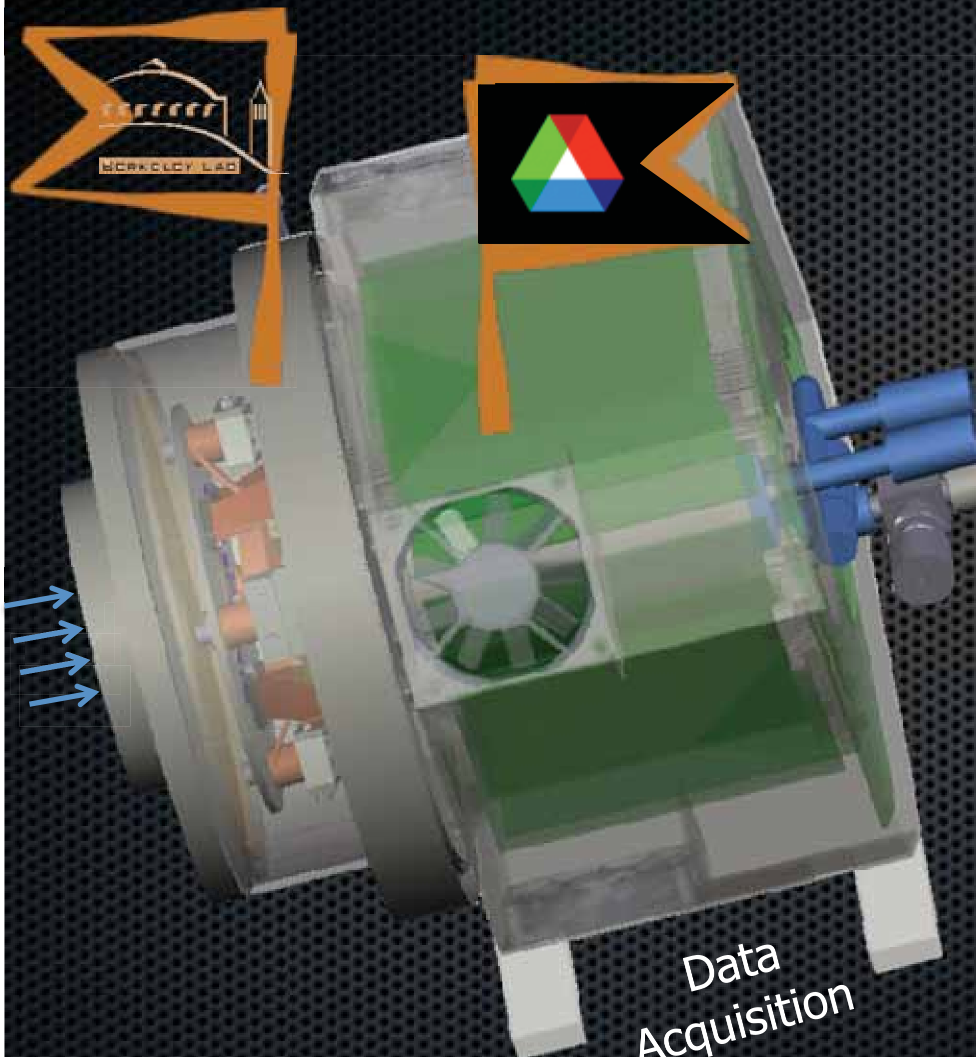


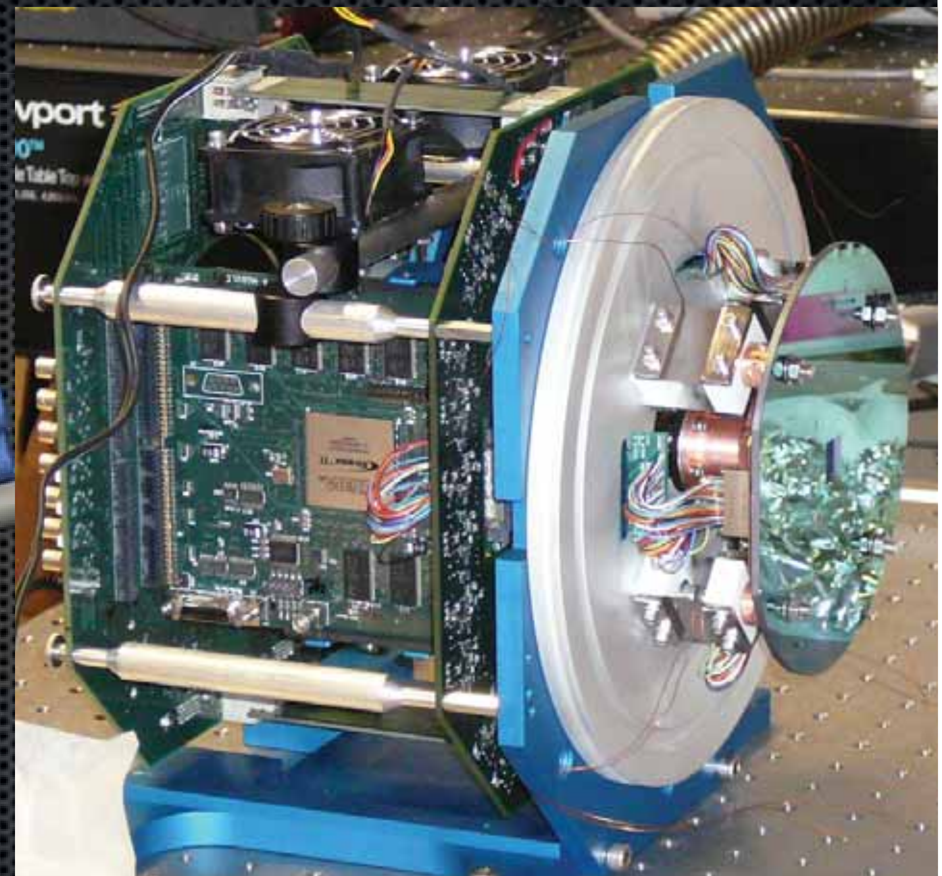
Constant
Area
Taper
Mini-shift reg.
Output stage

~300 µm pitch
bond pads
(wire-bondable)



ALS / APS Collaboration



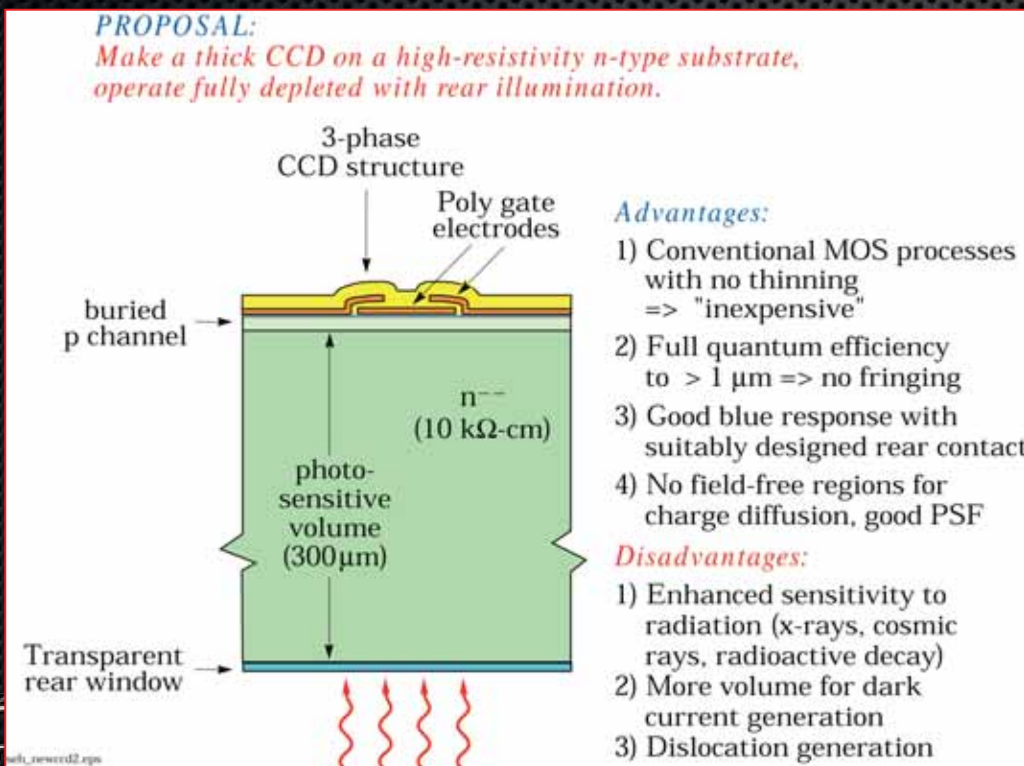


Direct Detection

Previous example of CCD usage was for optical photons. What about x-rays?

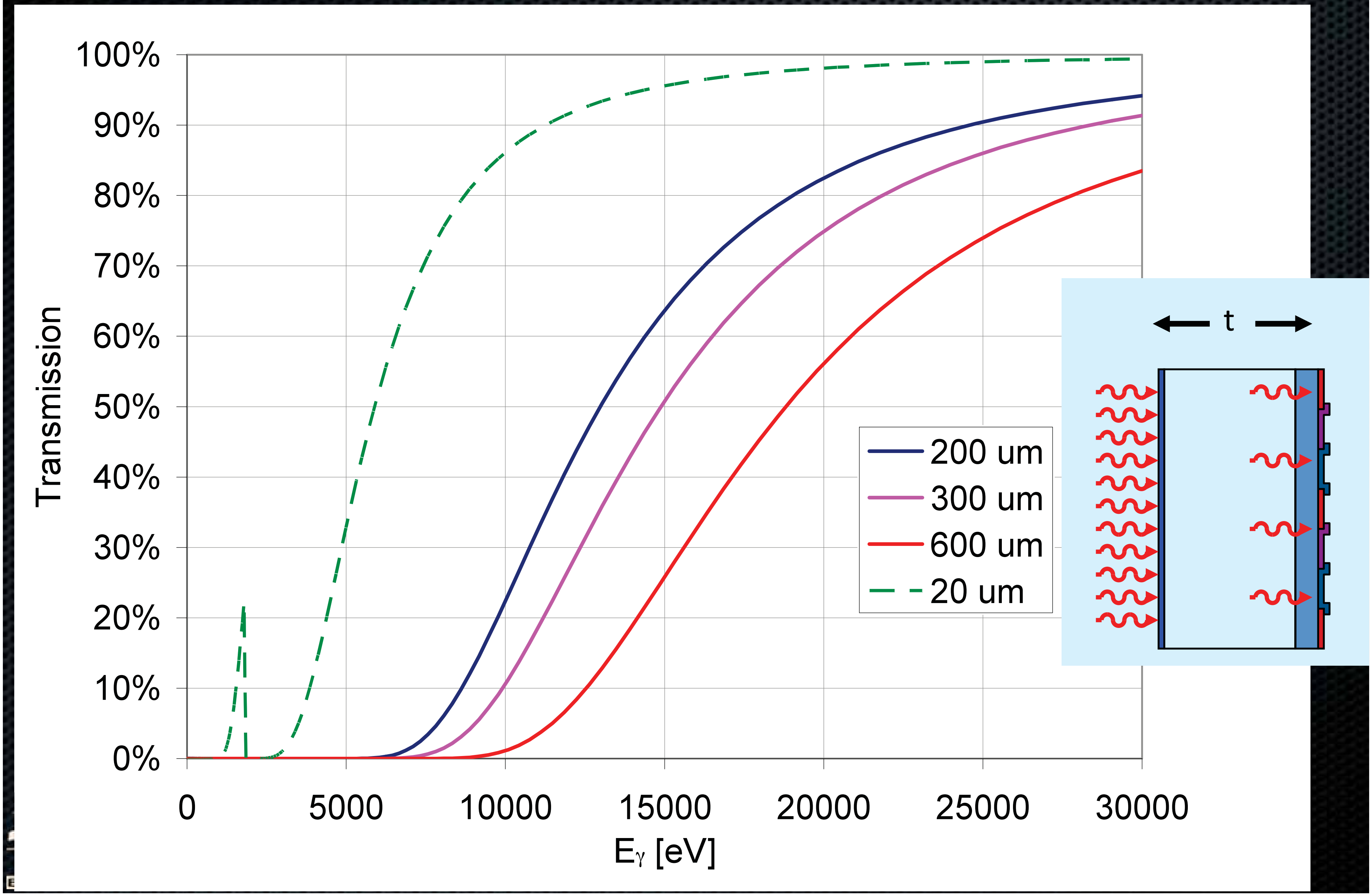
This should be depleted – generally thin with conventional processes

→ add a layer which can be used as an electrode



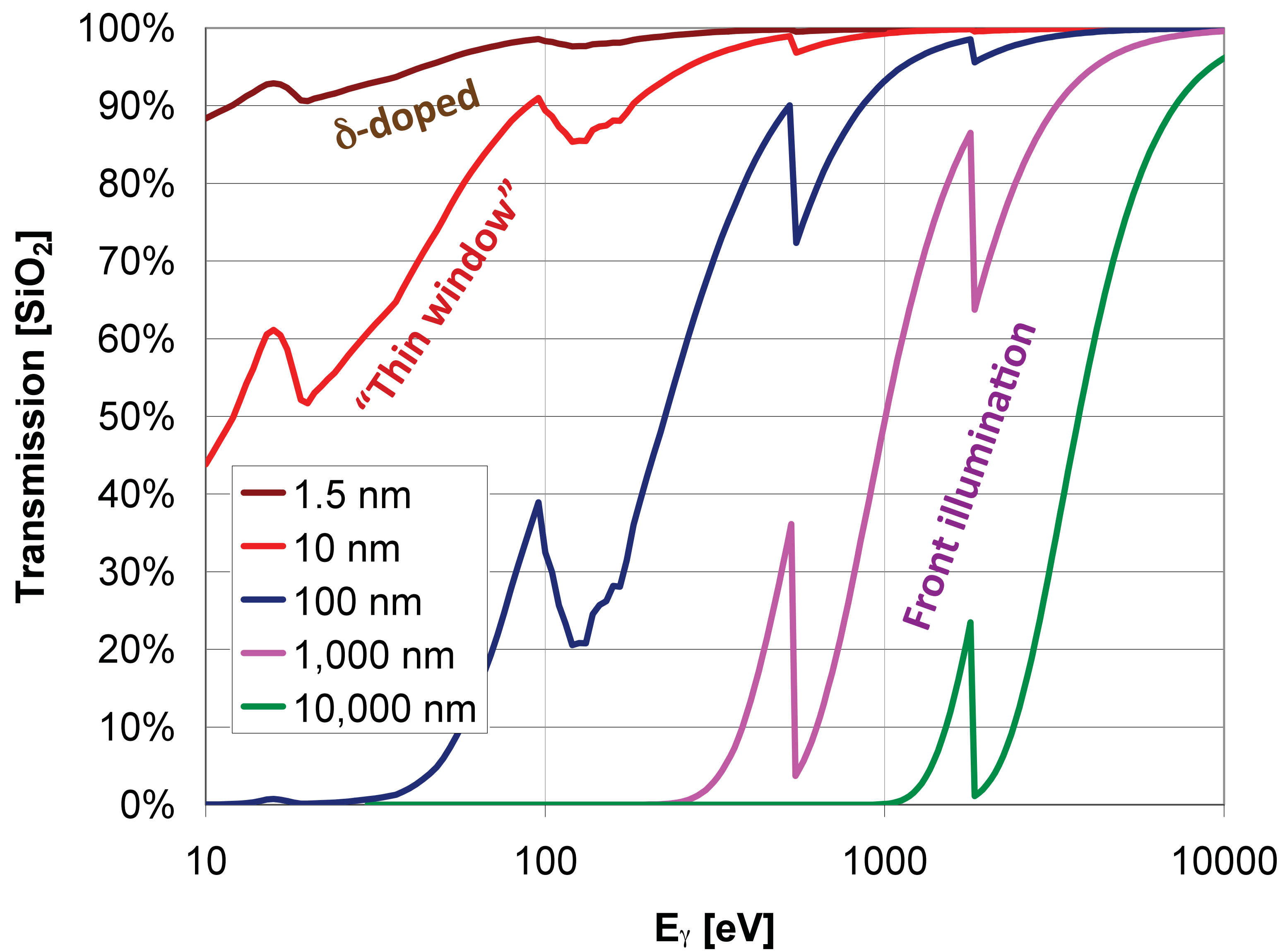
LBL CCD – S. Holland et al.

"Range"



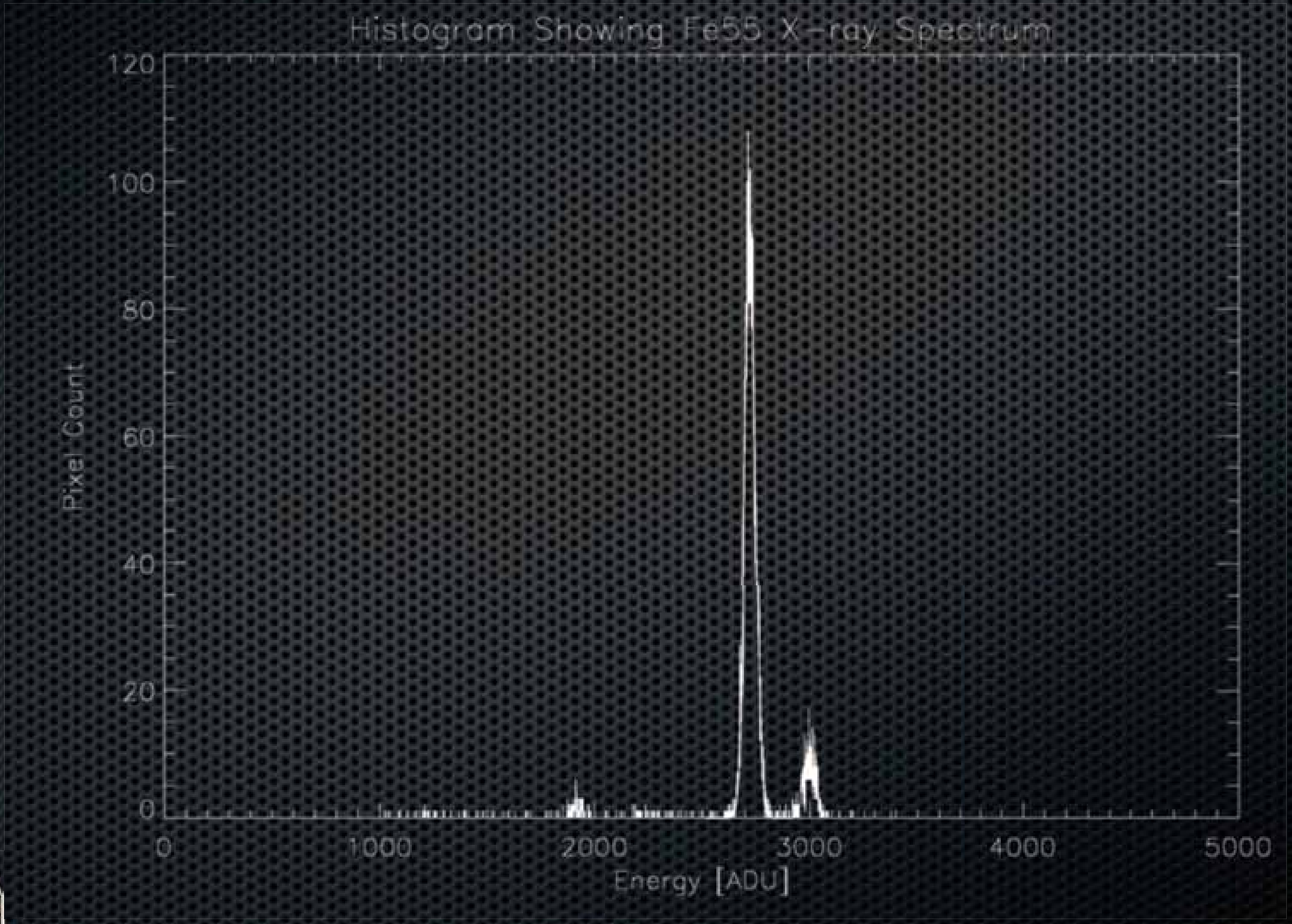
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Transmission
0
5000
10000
15000
20000
25000
30000
Eγ [eV]
200 um
300 um
600 um
20 um
t

Thin "window" for Soft X-rays



650 µm thick CCD

^{55}Fe K_α and K_β. Resolution ~ 126 eV at 5.6 keV

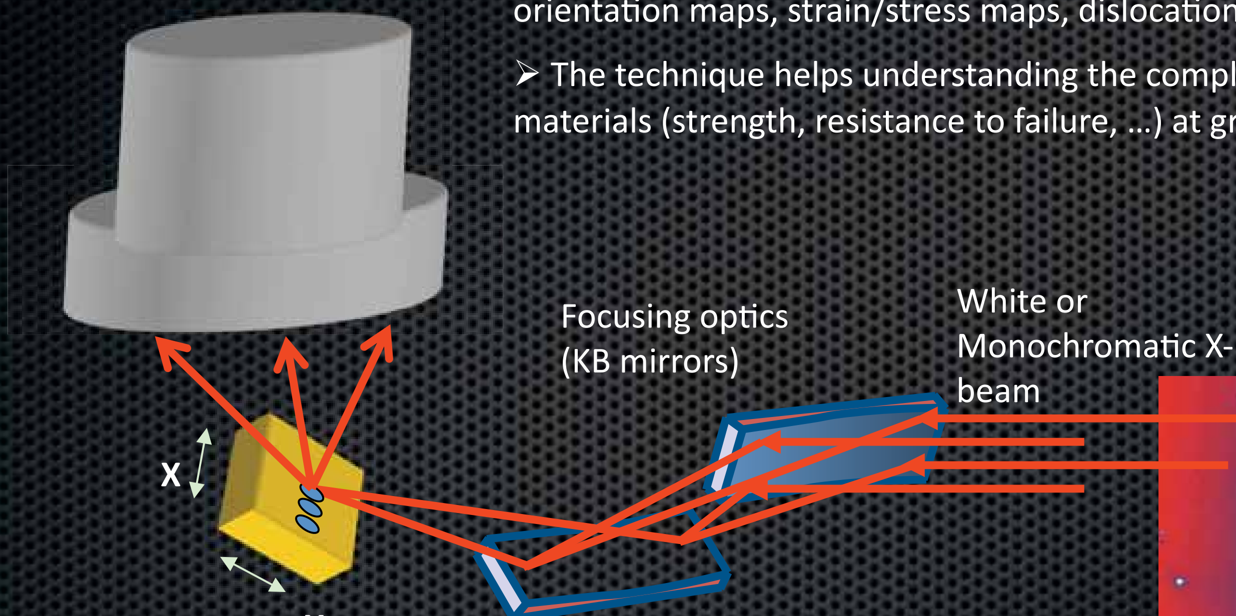


X-Ray microdiffraction at the ALS (BL 12.3.2)

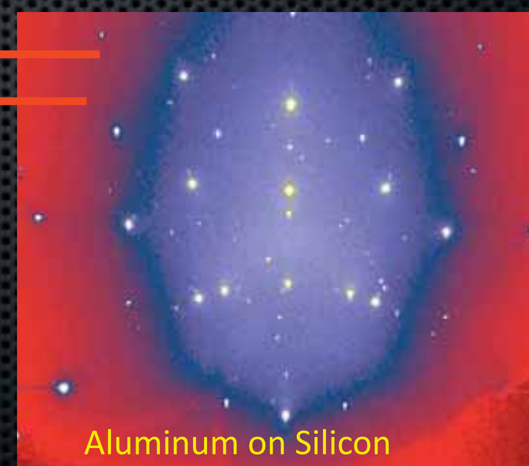
➢ Sample is raster-scanned under a submicron-sized white (or monochromatic) X-ray beam focused by Kirkpatrick-Baez mirrors. At each step a diffraction pattern is recorded.

➢Analysis of the diffraction pattern scans provides with phase distribution, crystal orientation maps, strain/stress maps, dislocation structure and distribution

➢ The technique helps understanding the complexity of the micromechanics of materials (strength, resistance to failure, …) at granular and subgranular level

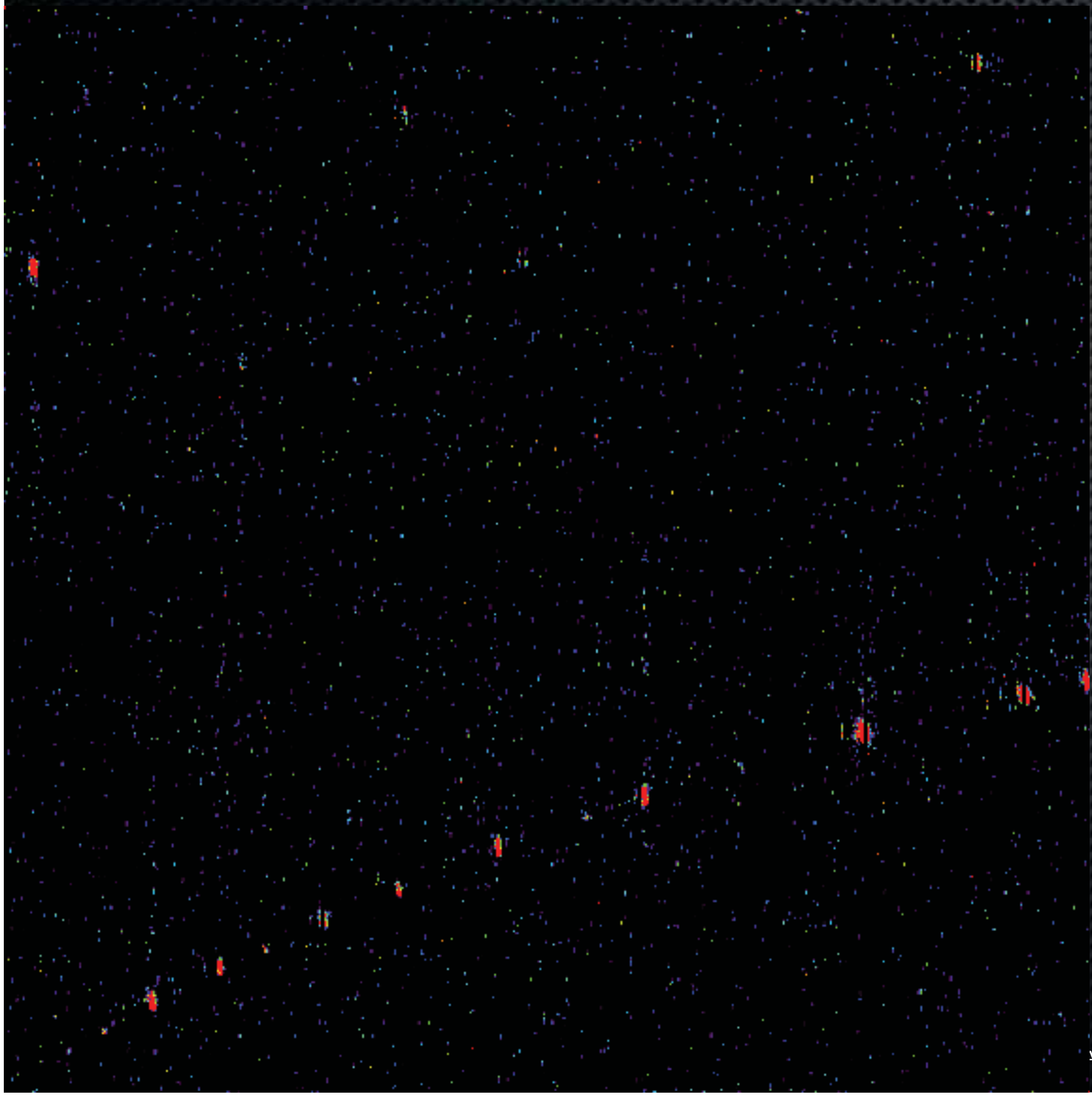


➢ No sample rotation required !



Laue pattern captured by a X-Ray CCD detector

Energy resolving capabilities: toward fast energy-resolved Laue



A fast alternative to monochromator energy scan

Potassium Titanyl Phosphate KTiOPO4 (or KTP)

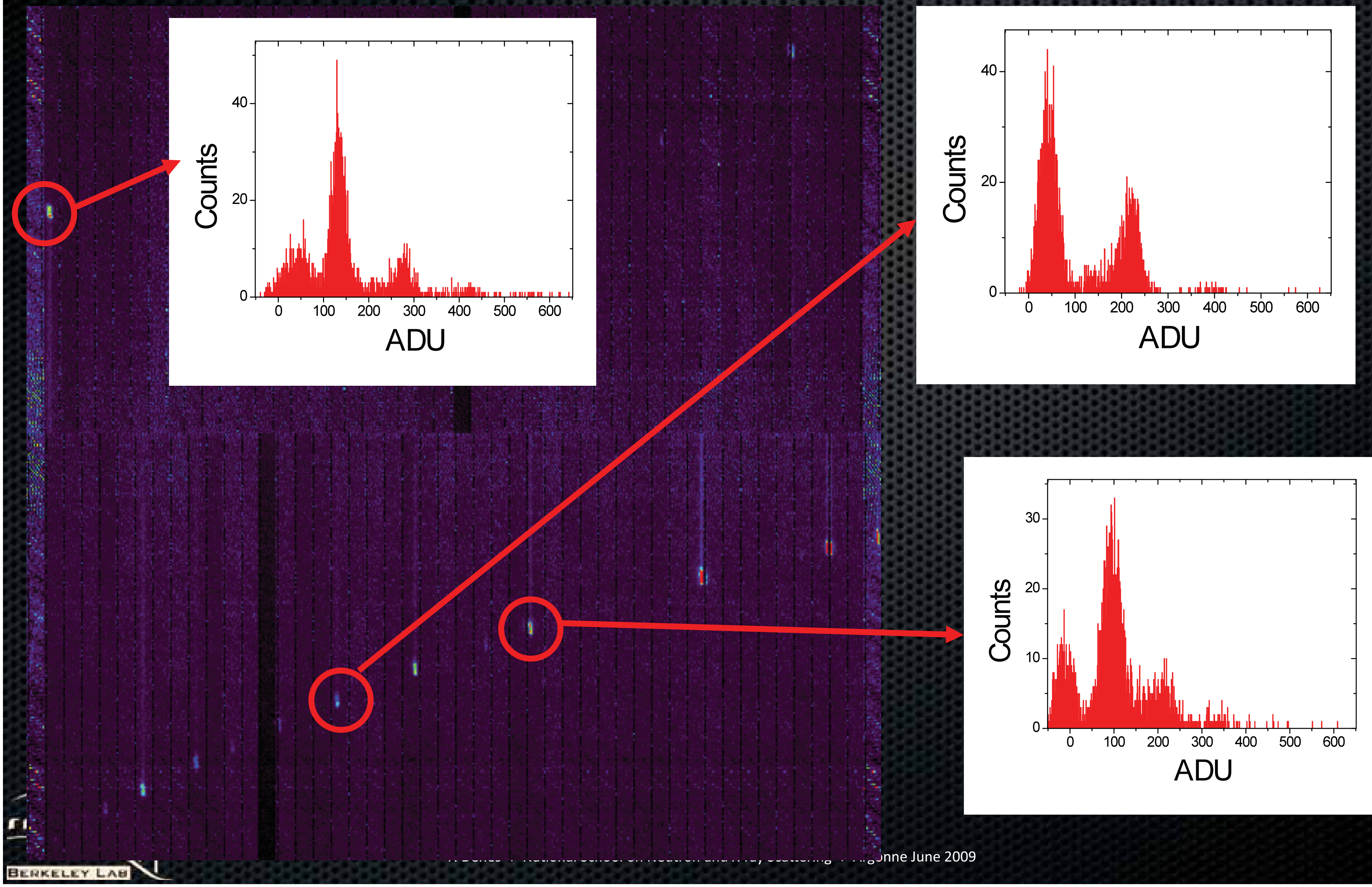
Orthorhombic:

a= 1.28193 nm

b= 0.63991 nm

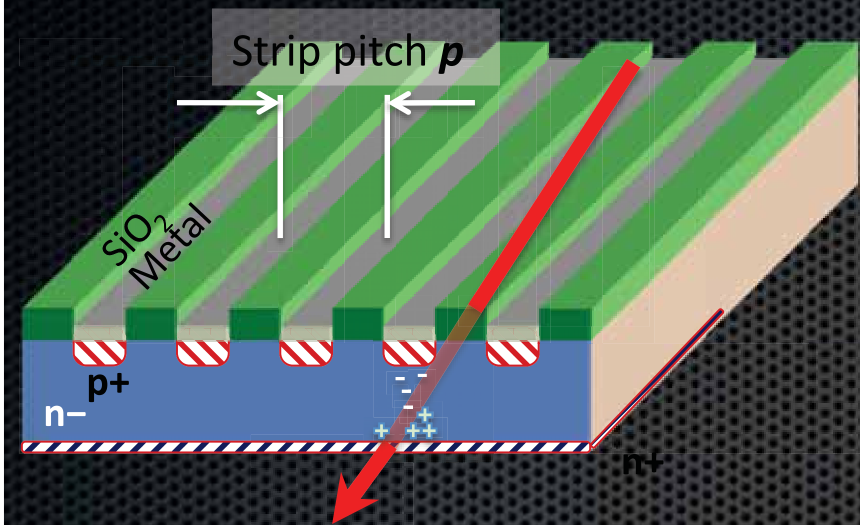
c= 1.05842 nm

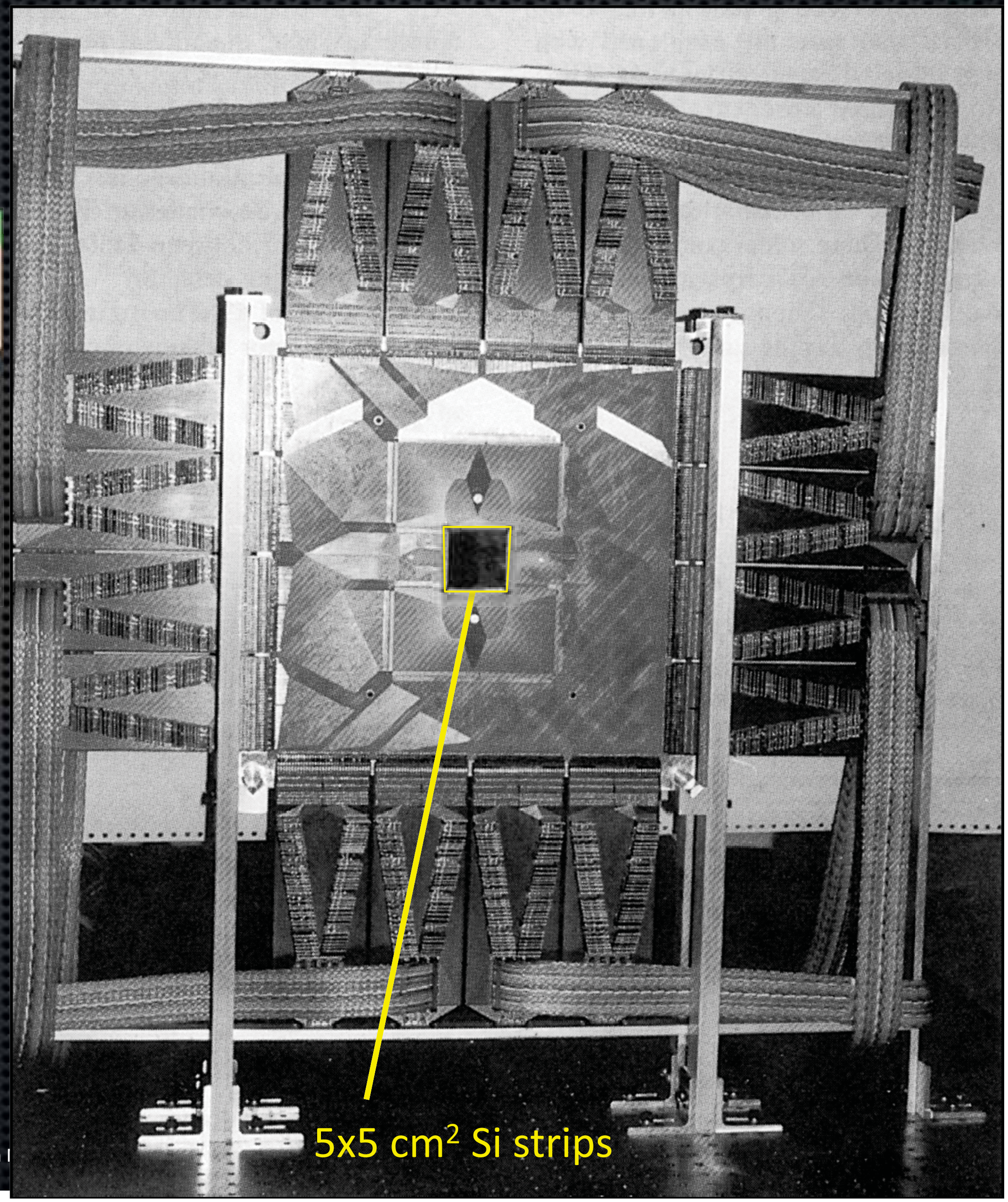
Energy resolving capabilities: toward fast energy-resolved Laue



Microelectronics-enabled Detectors

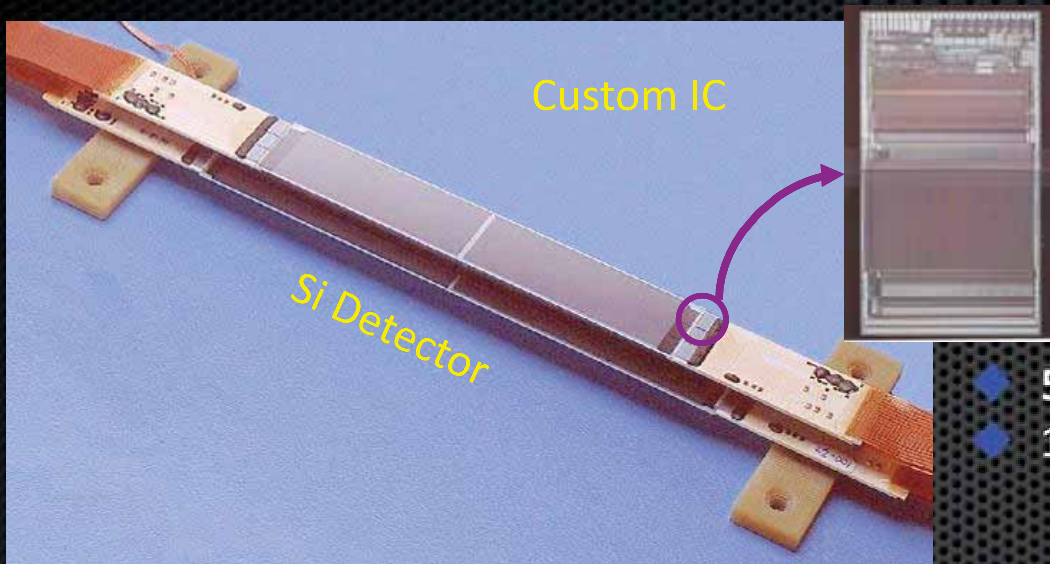
Silicon strip detector





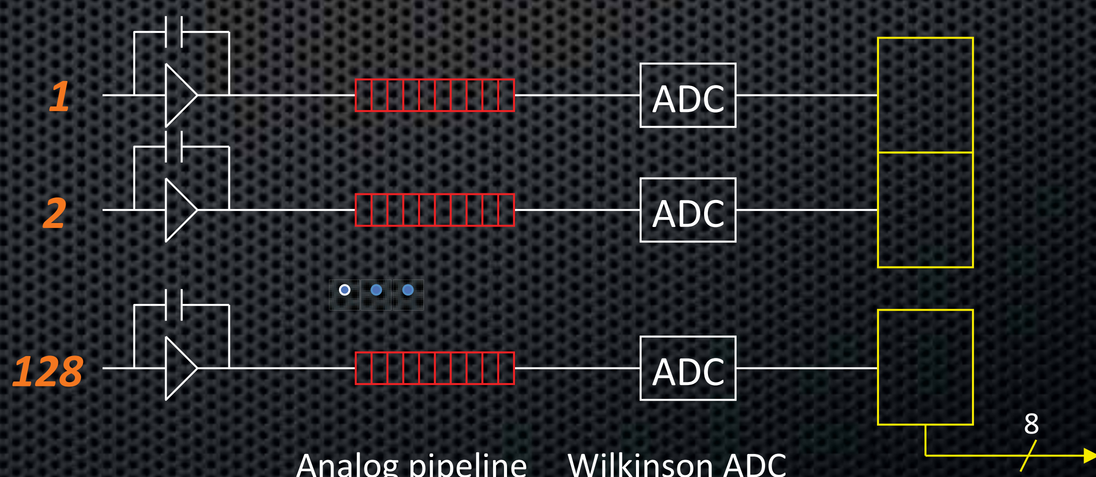
Silicon strip detector (1D)
for particle physics ca. 1984

Followed by Custom ICs



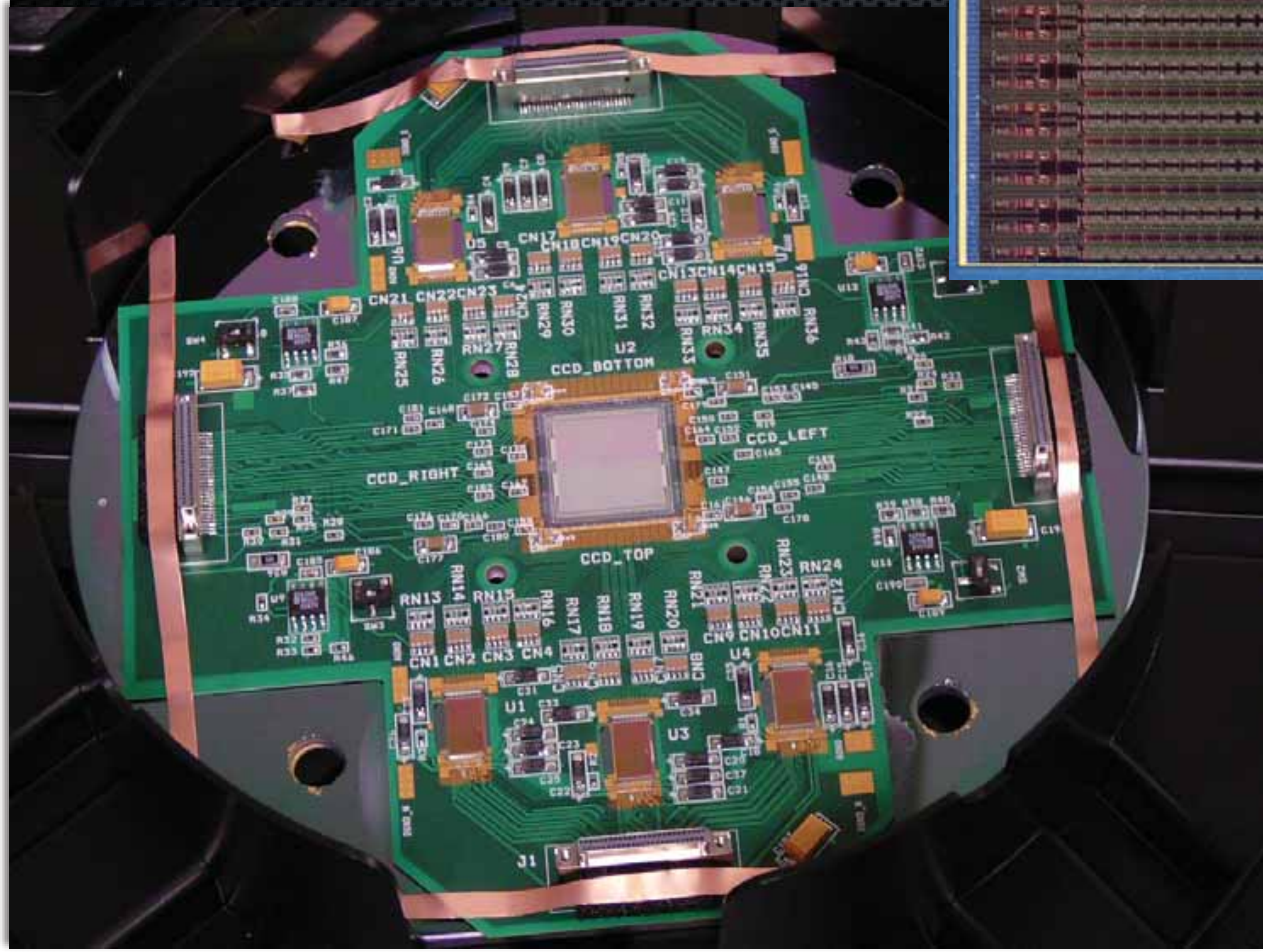
- 50 µm pitch
- 128 channels

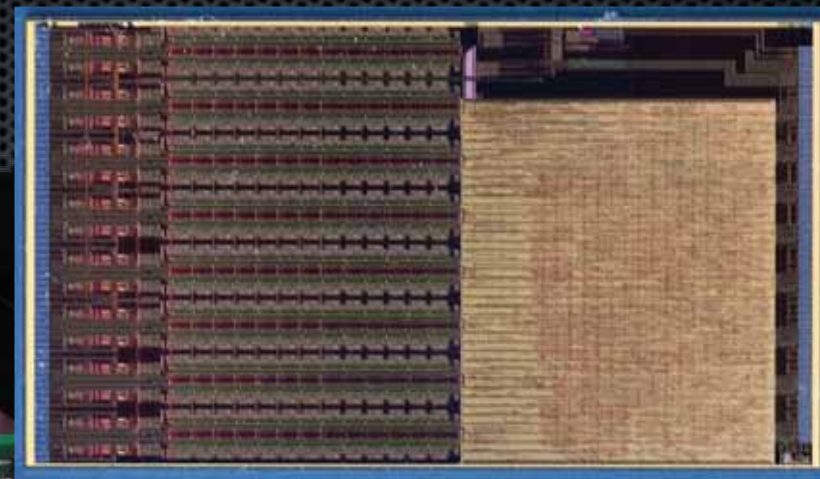
Charge sensitive amplifier with adjustable risetime



Zero-suppressed readout on 8-bit parallel bus

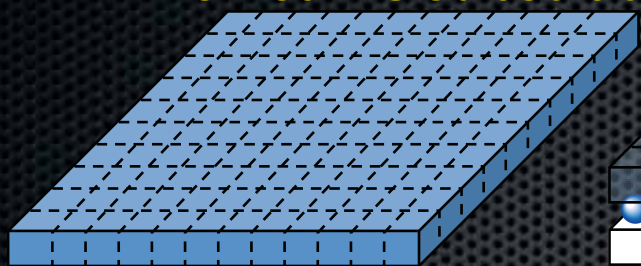
e.g. Custom IC for FastCCD





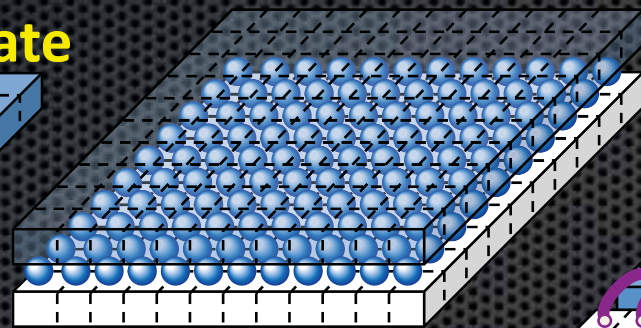
Further Options

Monolithic sensor+readout on same substrate



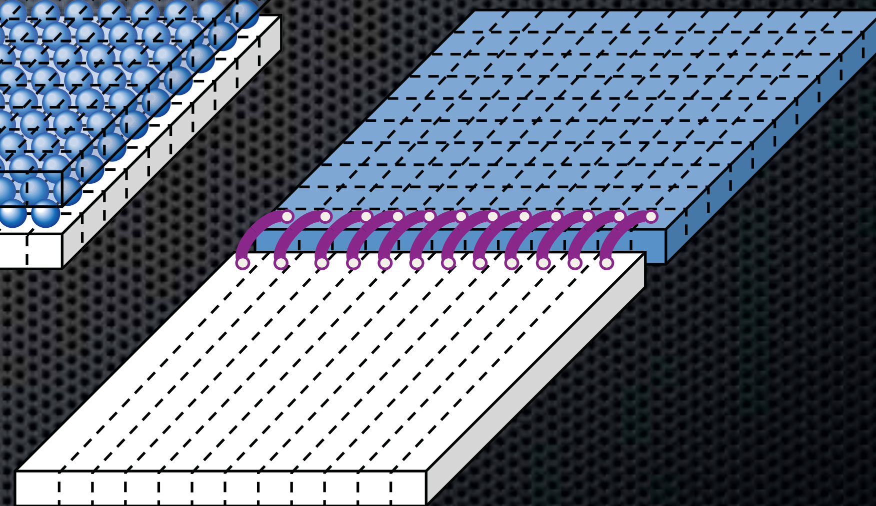
2D segmented Si

Hybrid



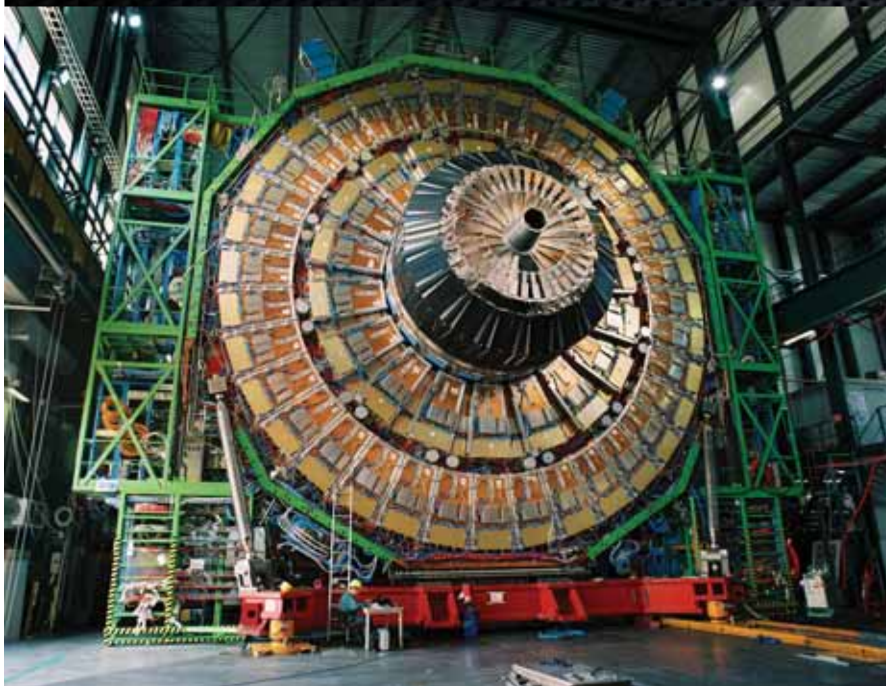
2D segmented Si attached to 2D segmented Si

Sensor + Readout

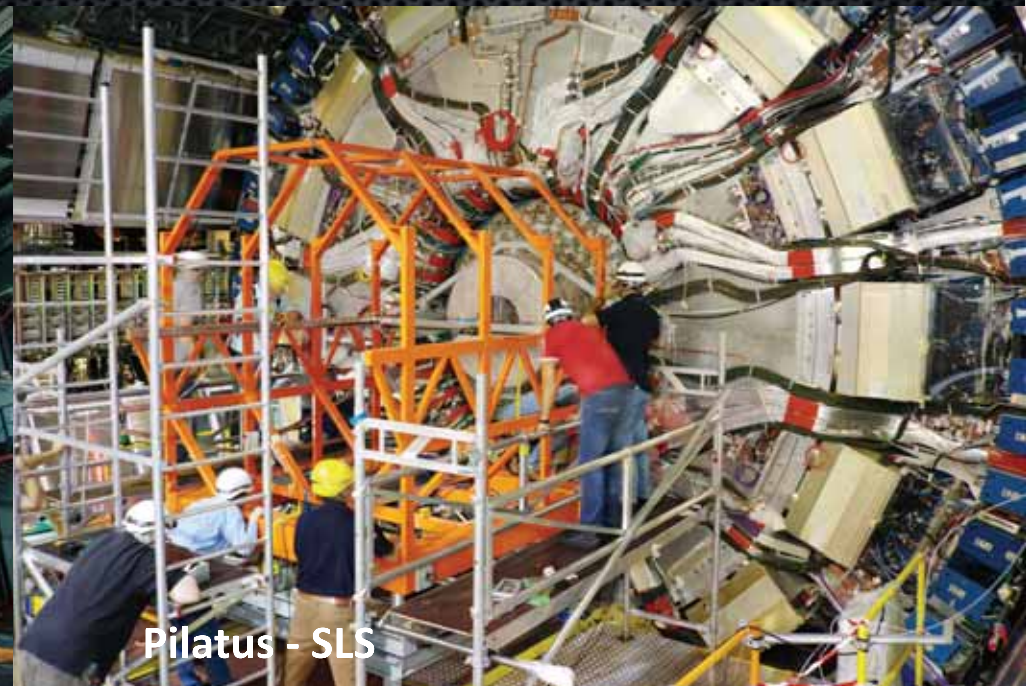


2D segmented Si attached to 1D segmented Si or other electronics

LHC Pixel Detectors

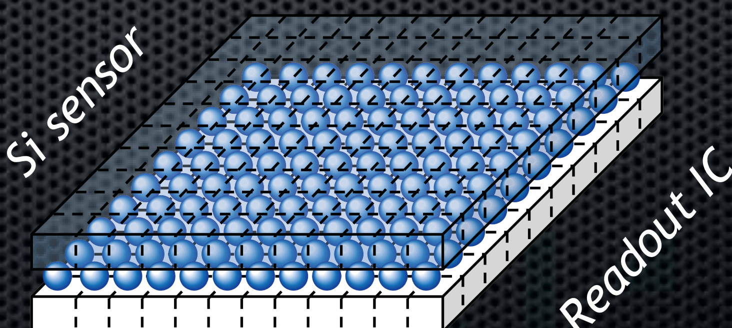


CMS

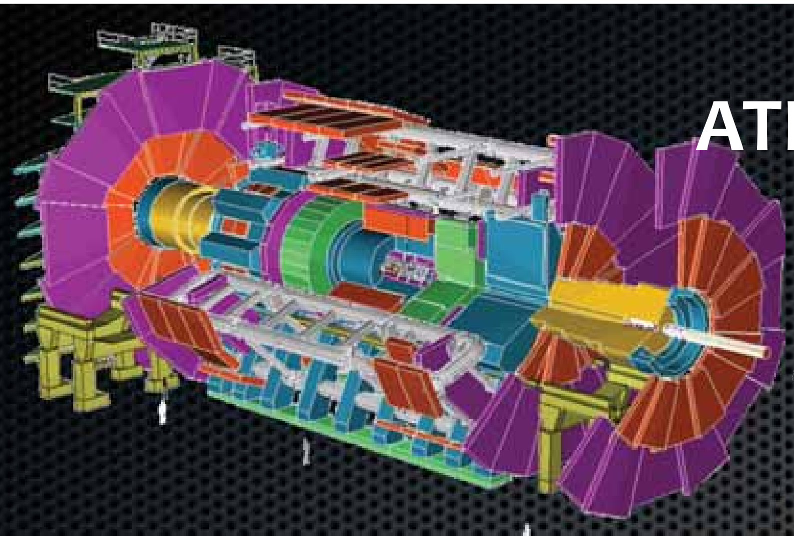


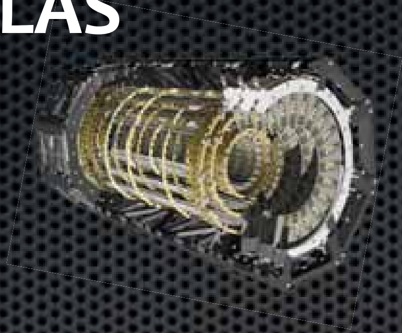
ATLAS

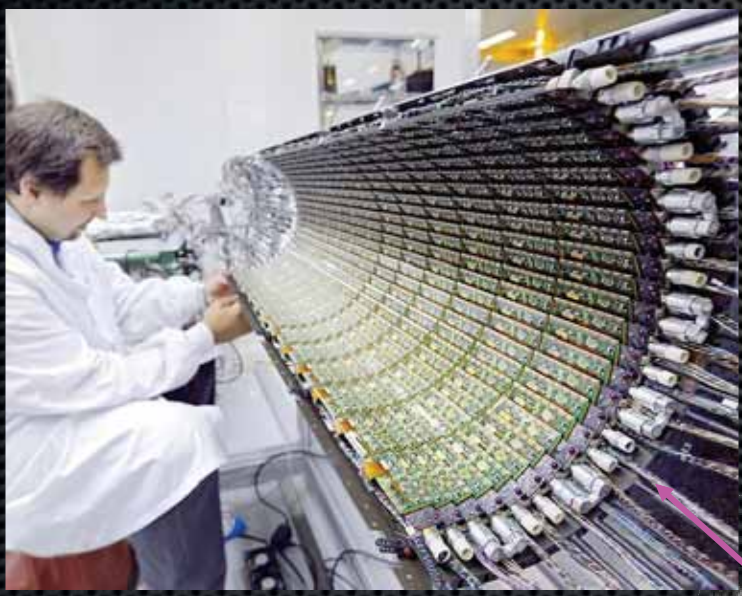
Large projects to develop hybrid pixels



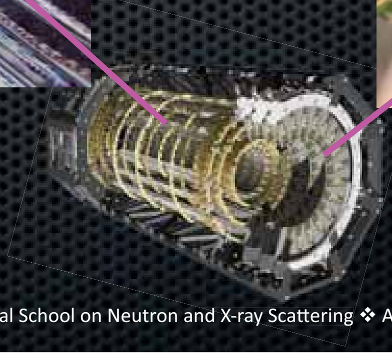
ATLAS

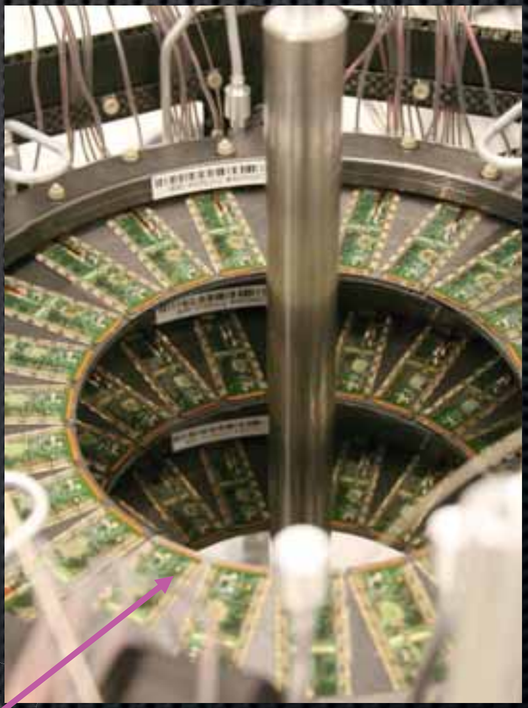




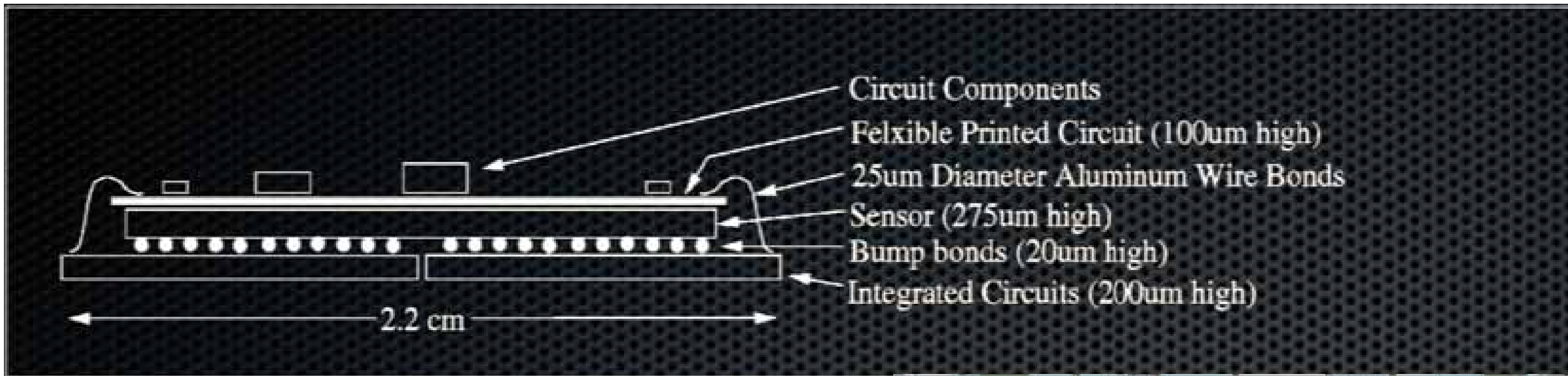


Barrel outer half-layer
338 modules
15.6M pixels

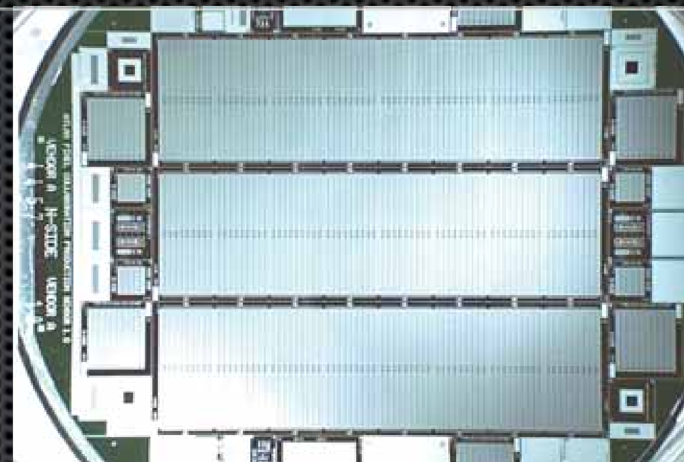




A-side end cap
144 modules
6.6M pixels



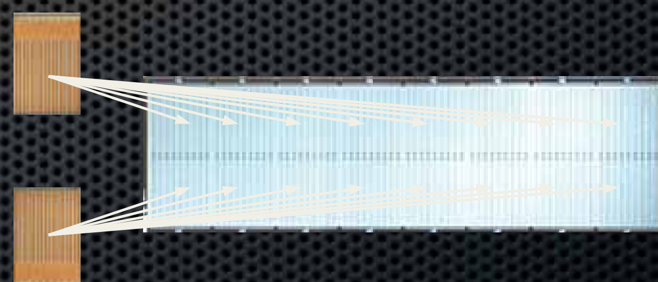
100 mm wafer with 3 Si sensors



Readout ICs

18x160 pixels

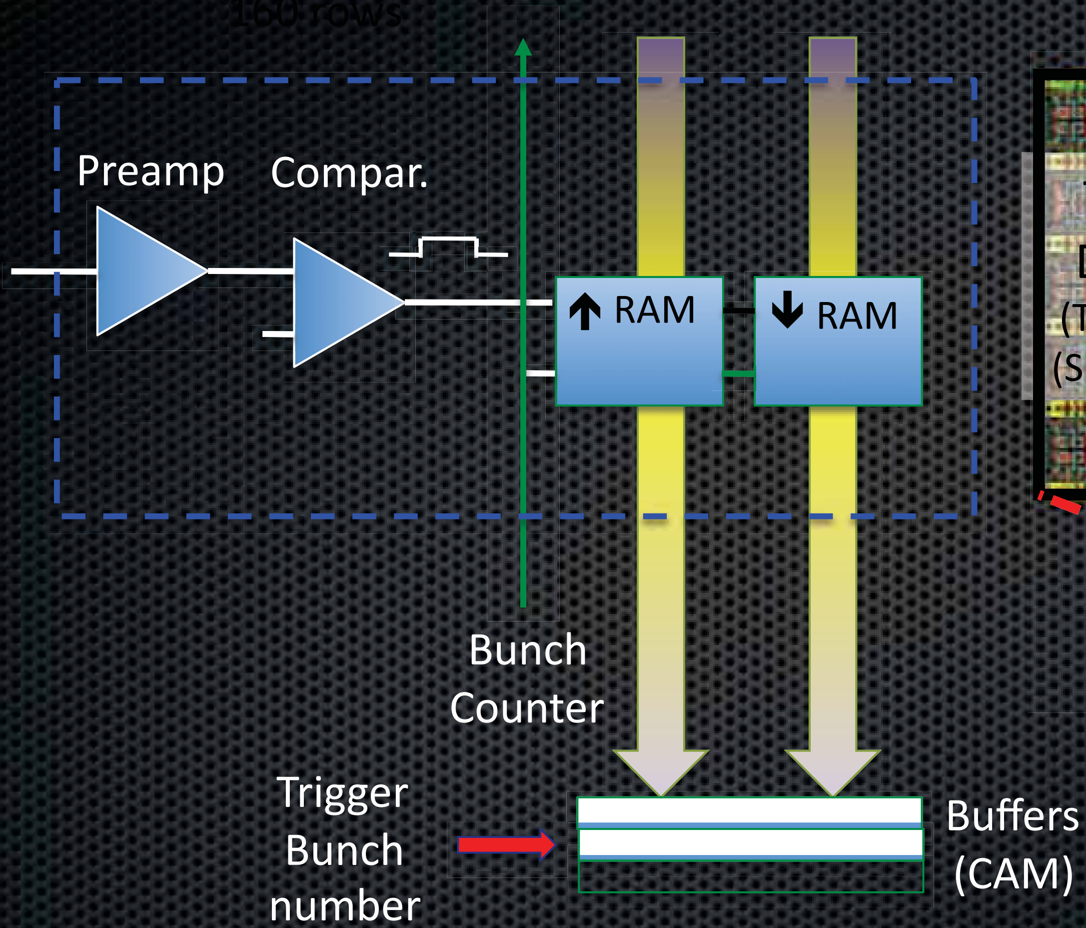
Readout

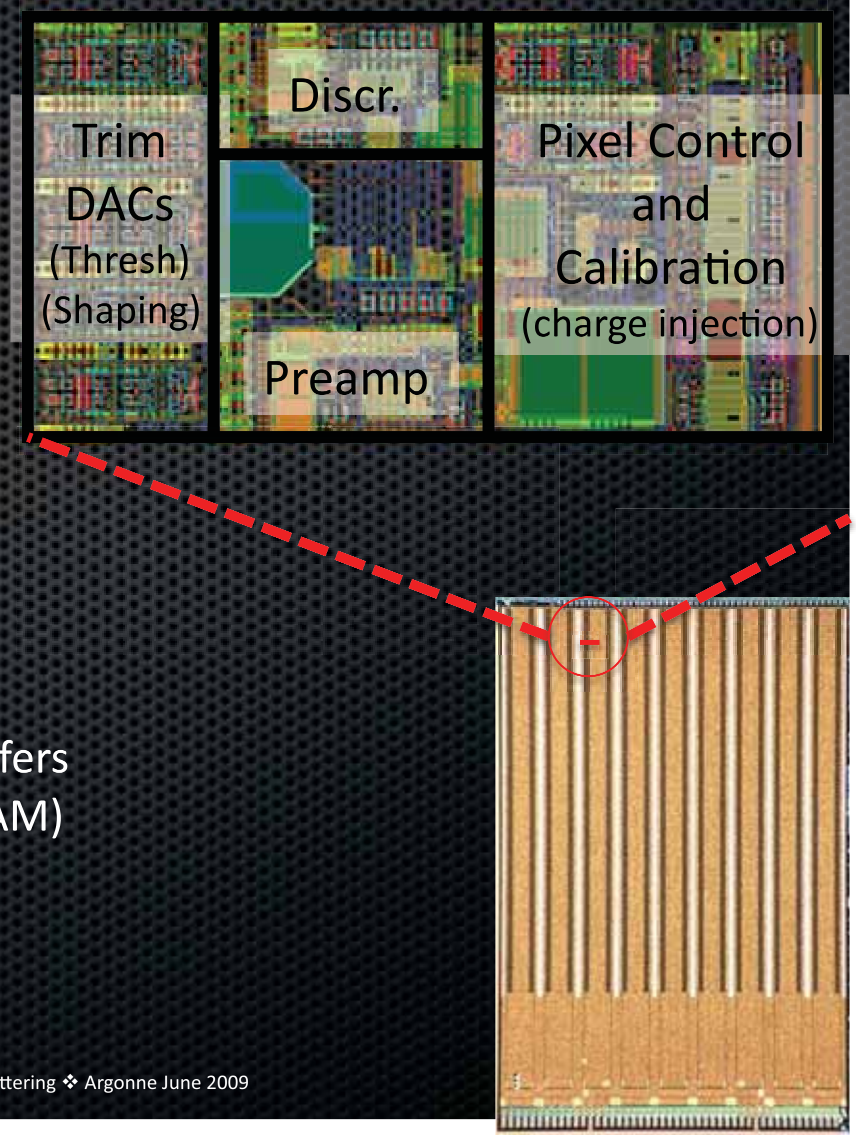


A “module” is 1 sensor with 2x8 bump-bonded chips

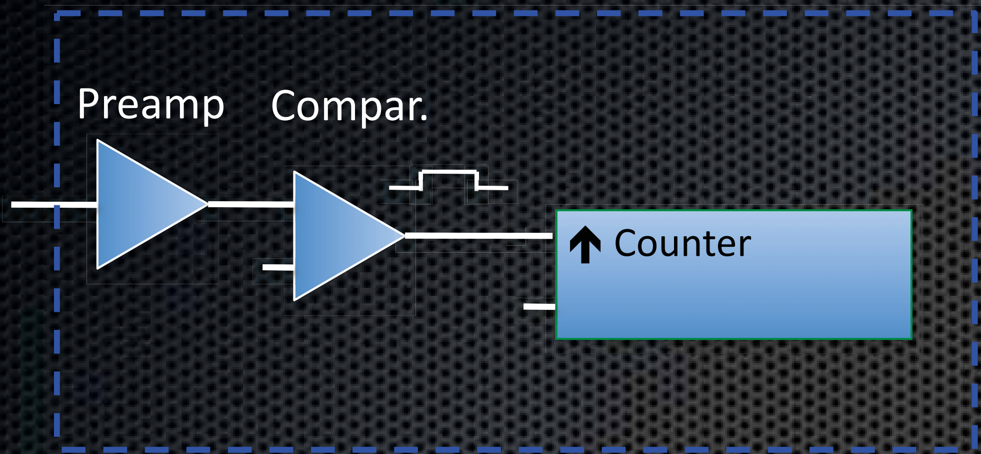
Architecture

18 columns
160 rows

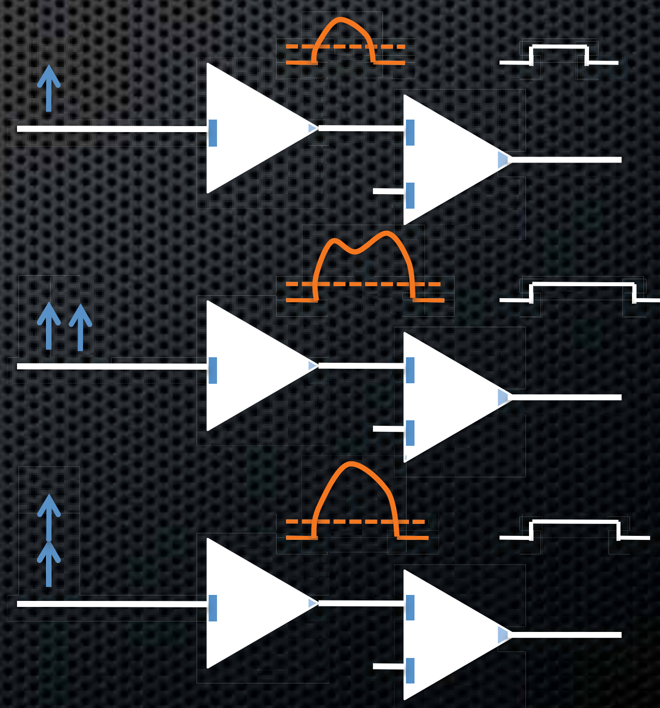




For X-rays

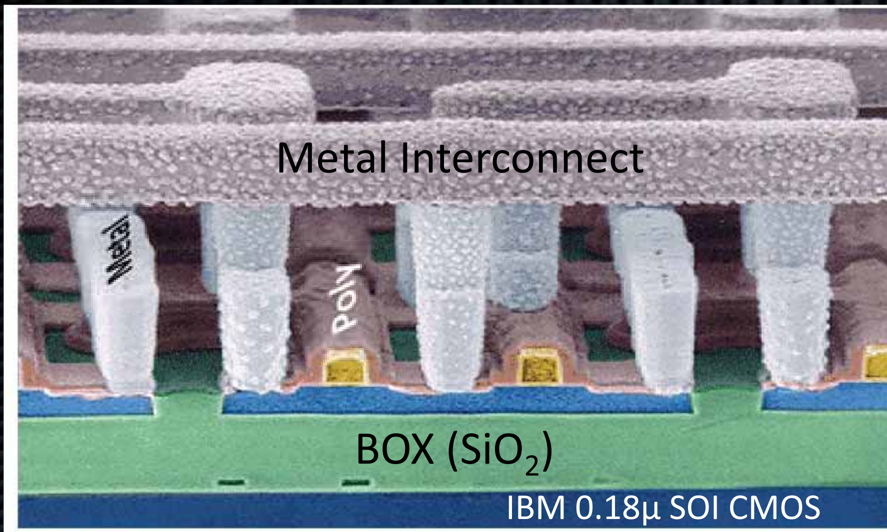


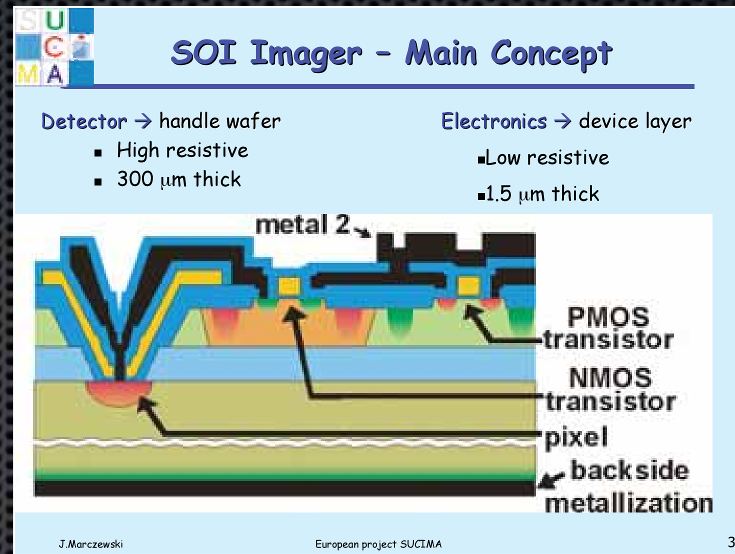
Deadtime:
Each of these cases counts ***one*** photon



- Variants
  - analog or digital pre-scaling
  - multiple comparators

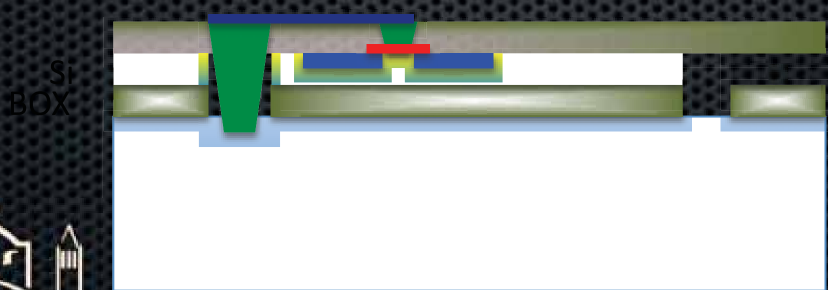
R&D: SOI ($IQ_{SOI} > IQ_{BULK}$)

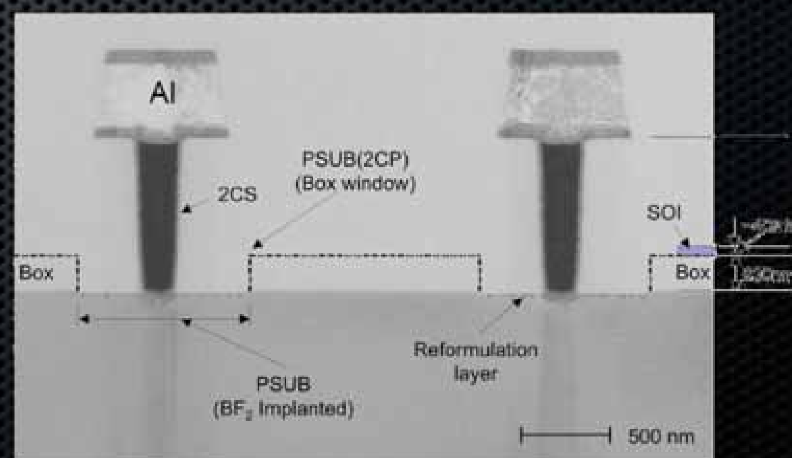




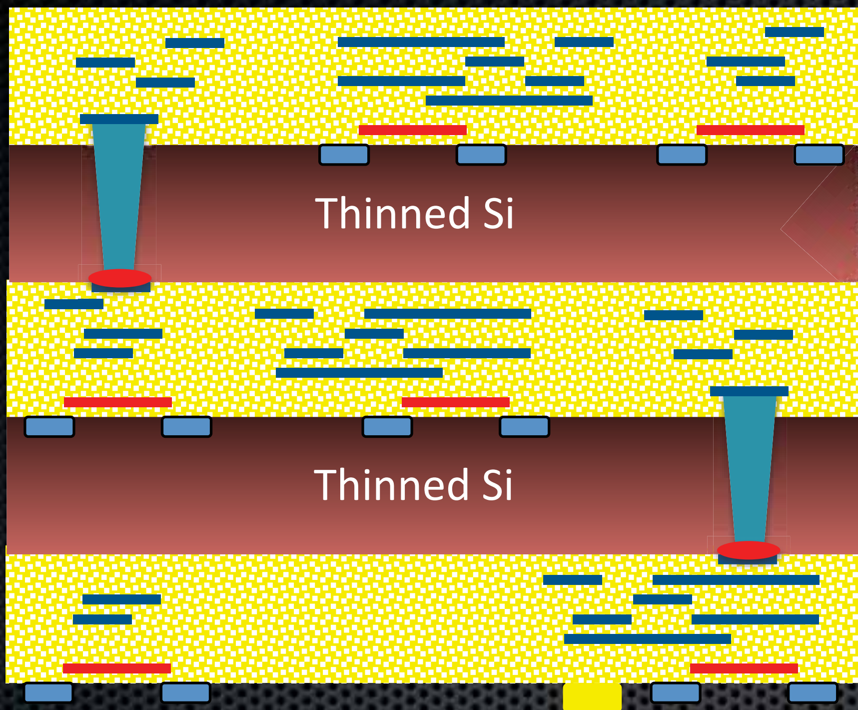
Silicon-on-high resistivity, thick, fully depleted detector-grade silicon

Oki SOI Process (KEK)





R&D²: 3D Integration



TSV

Bump (interconnect)

Thick Si

High-resistivity detector wafer

- Growing commercial interest – e.g. high density memory (more tunes on your iPod)
- Use of disparate technologies still R&D

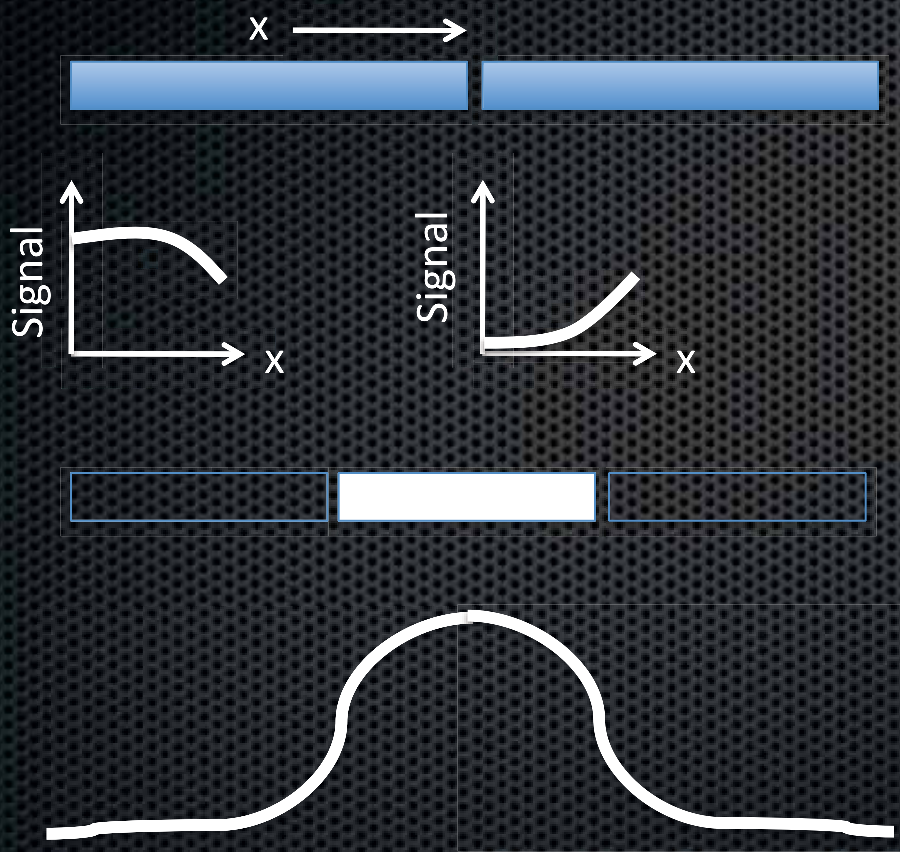
(Direct Detection) Pixel Complexity

	CCD on thick, high-ρ Si	SOI on thick, high-ρ Si	Hybrid on thick, high-ρ Si	3D on thick, high-ρ Si
Size	$10^2 - 10^3\ \mu m^2$	$10^2 - 10^3\ \mu m^2$	$10^4\ \mu m^2$	$10^2\ \mu m^2$
 /pix	0	$10^1 - 10^2$	$10^2 - 10^3$	$10^1 - 10^2$
ENC	$10^0 - 10^1\ e^-$	$10^1\ e^-$	$10^2\ e^-$	?

Disclaimer: ALS is a soft x-ray facility – ideal for Si (except for noise!)

Pixel Size, Diffusion and Analog vs. Digital

Even a fully-depleted detector will have 5 – 10 µm RMS diffusion
(so there will be some charge sharing)



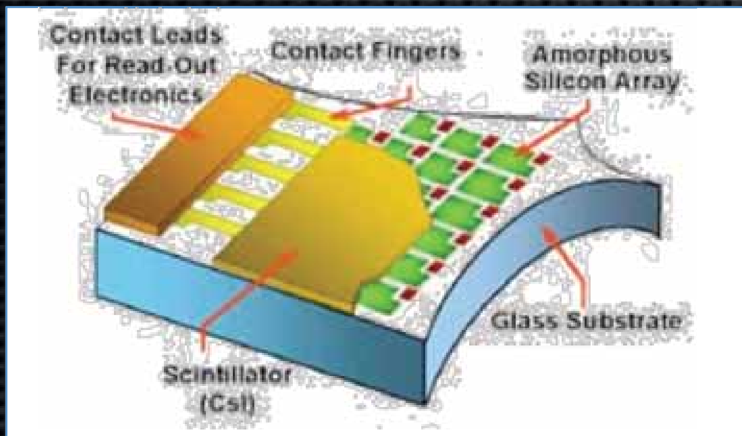
2 "large" digital (counting) pixels

Some region (depending on diffusion σ) where counting is complicated (double count? missed counts?)

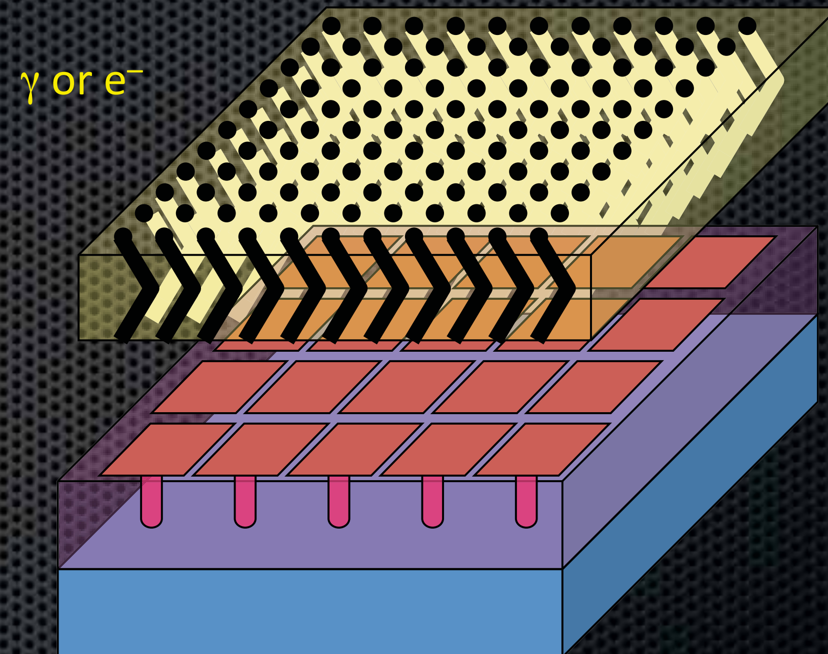
3 "small" analog pixels

Diffusion spreads charge across pixels – bug center-of-gravity can give sub-pixel (µm) position resolution
(But adding noise!)

Other Examples of 2D Detectors



- Large-area, flat-panel x-ray detector
- Scintillator [e.g. CsI(Tl)]
- aSi + TFT Passive Pixel readout



- MCP
  - Photocathode
- Hybrid pixel IC (or CCD)

Summary (1)

- For a detector, the only useful thing a photon can do is create an electron
  - Note to accelerator people: the only useful thing an electron can do is create a photon
- Detection mechanisms
  - “Direct” (includes film, image plates, …)
  - “Indirect” – usually via scintillator
- Sensor “properties” critical
  - Density (stopping power, σ_{PE}, …)
  - Band gap, light yield, …

Summary (2)

- Fluctuations
  - $0 \le E_e \le E_\gamma$ in “detector”
  - Number ($N \propto E_e$) of secondary (tertiary) particles
  - Electronic noise
    - Thermal
    - Faster is (generally) noisier
- Spatial resolution (PSF, MTF) (diffusion)
- Temporal resolution (noise is important)
- DQE
- Radiation damage (not discussed, but important)

BERKELEY LAB

Summary (3)

- Like parking spaces, “no lack of detectors, only lack of imagination”
  - Microelectronics-enabled detector development in particle physics starting to spill over into synchrotron radiation research
  - Certainly in Europe, but see this at LCLS
- Semiconductor detectors!
- Si fantastic for E < 10 keV (and benefits from commercial processing)
  - Other developments, e.g. involving avalanche multiplication, that there was no time to discuss
  - For higher energies, have candidate materials (GaAs, Ge, CdTe, …) but need R&D
- Future will be detectors designed for experiments (not experiments designed for detectors)

BERKELEY LAB