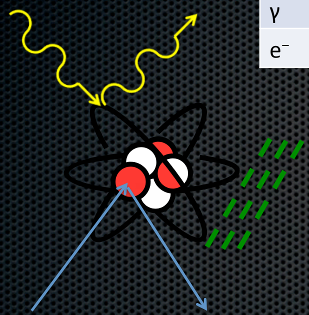
X-ray Detection

	Brightness	Mean Free Path	Absorption 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^{1}
e$^-$	10^{29}	10^{1}	10^{3}	0.05

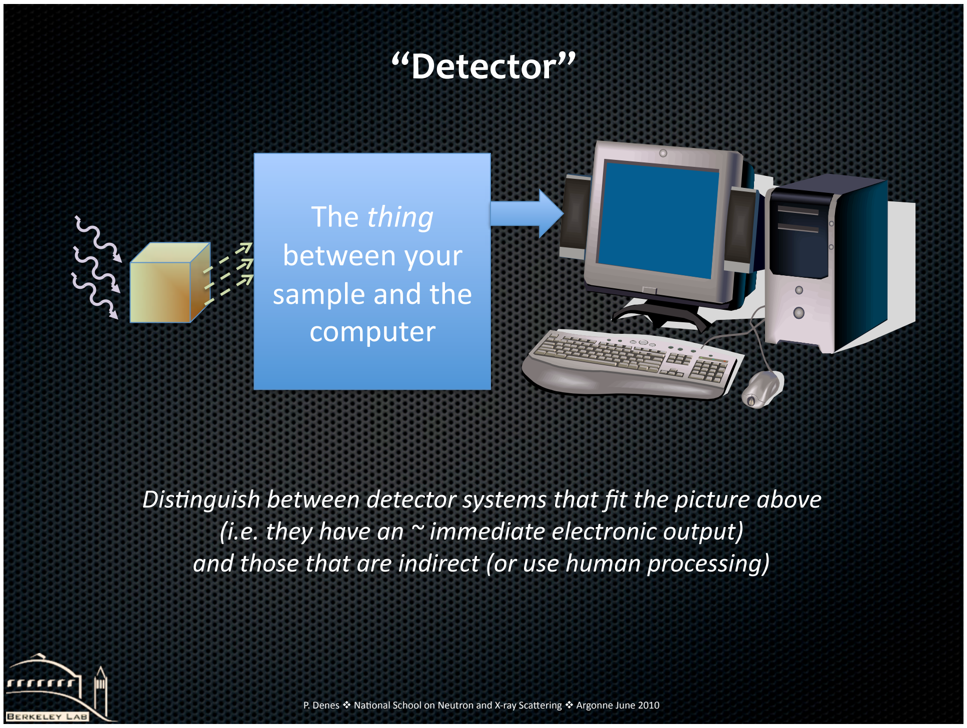


x-ray scattering (probe electronic states)
neutron scattering (probe nuclear states)
electron microscopy (focus, Coulomb interactions)

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      - Lots of terminology, much of it outdated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"
The thing between your sample and the computer
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)
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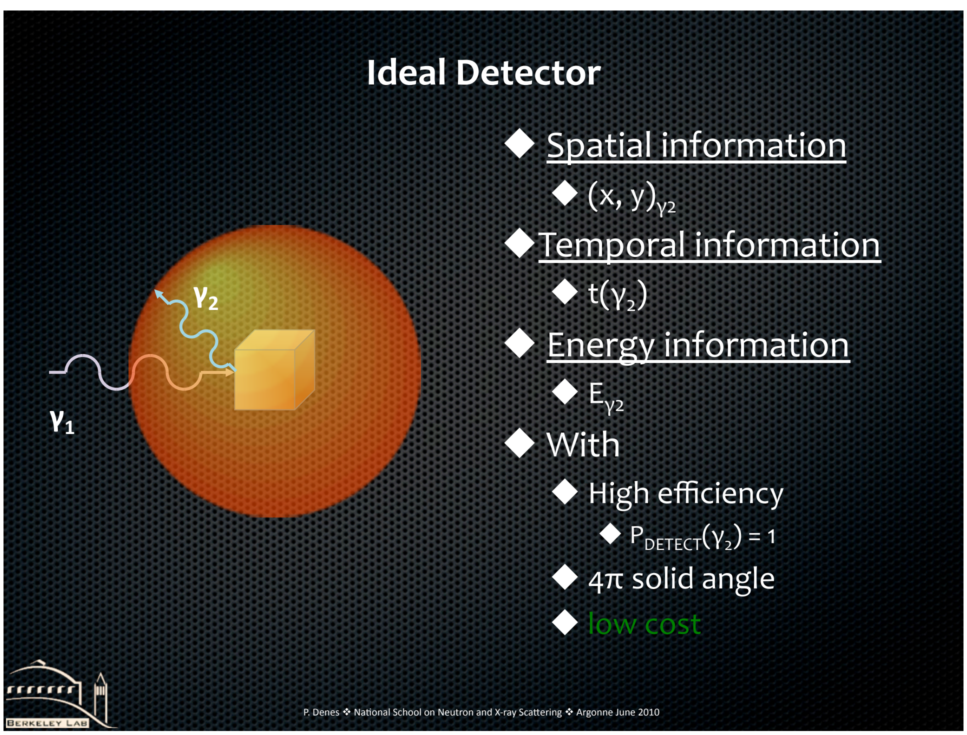
Ideal Detector
γ_1
γ_2
Spatial information
$(x, y)_{\gamma 2}$
Temporal information
$t(\gamma_2)$
Energy information
$E_{\gamma 2}$
With
High efficiency
$P_{DETECT}(\gamma_2) = 1$
4π solid angle
low cost
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Spatial Detectors

- "Count 'hits'"
- Spatial (or temporal) distribution
- "0", "1", "2" dimensional detectors

Detection system →

← Particle to be detected

Quantum Efficiency

Baseball:
Batting Average = hits / at bats

Particle detecton:
Quantum efficiency= detected / incident quanta

Note that the Q.E. may depend on the energy of the incident quanta (we'll come back to this)

Timing and Energy Resolution

- Our example has timing resolution
  - σ(t) is pretty good
  - ε(t) may not be that good
- Our example also has energy resolution
  - σ(E) more complicated

Calorimetric Photon Detector

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

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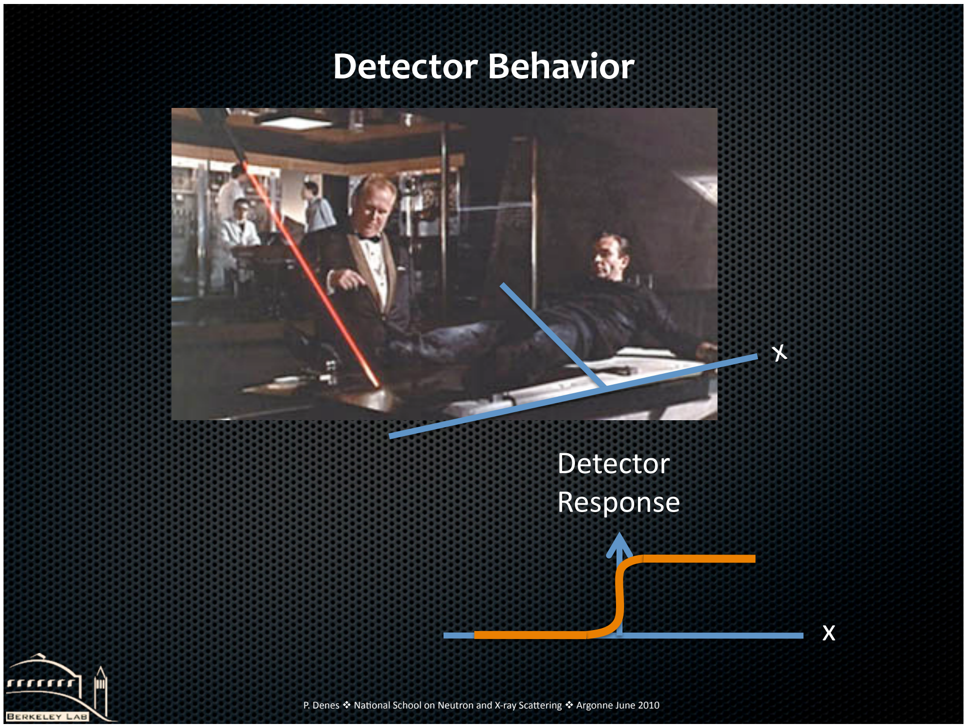
Detector Behavior
x
Detector
Response
x
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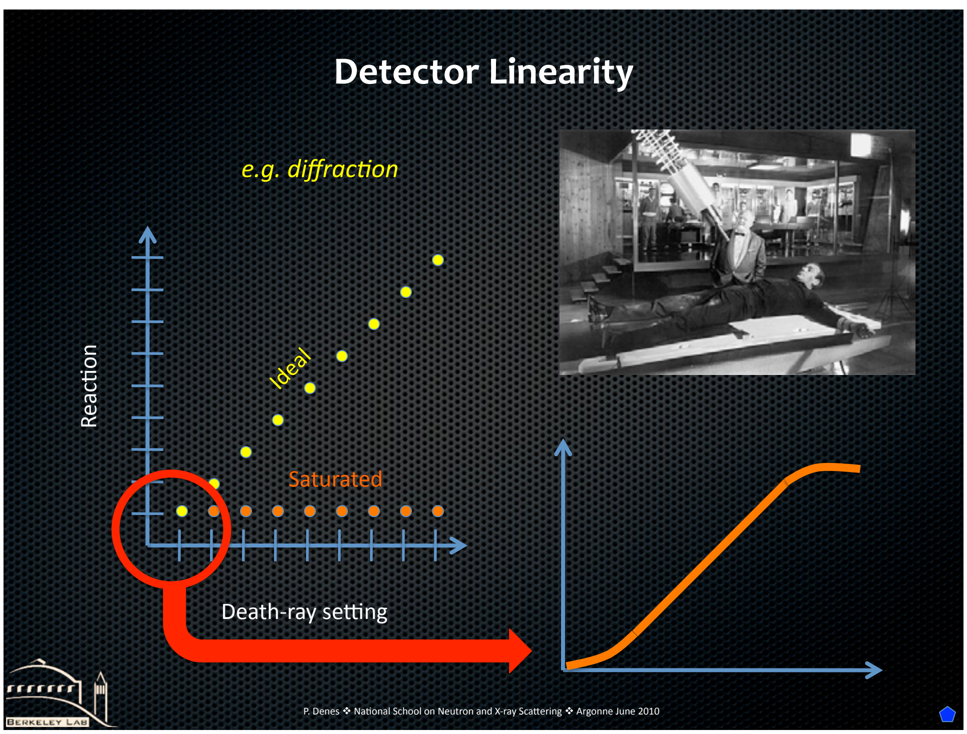
Detector Linearity
e.g. diffraction
Ideal
Reaction
Saturated
Death-ray setting
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Spatial Detector Properties

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

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

There may be additional information

Day-to-day 0D Detector Example

Airport (pulsed induction) metal detector

"yes / no" – along with additional information

Day-to-day 1D Example

Theory *Experiment*

Day-to-day 2D Detector Example

v=Δx/Δt

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

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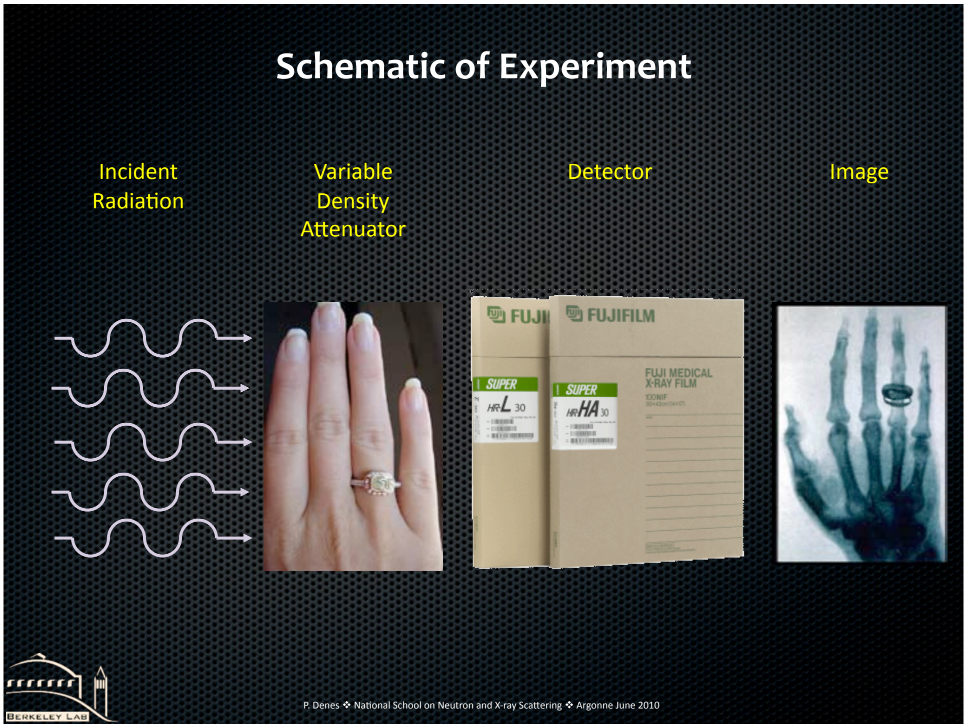

Schematic of Experiment
Incident Radiation
Variable Density Attenuator
Detector
Image
FUJIFILM
SUPER
HR-L 30
HR-HA 30
FUJI MEDICAL X-RAY FILM
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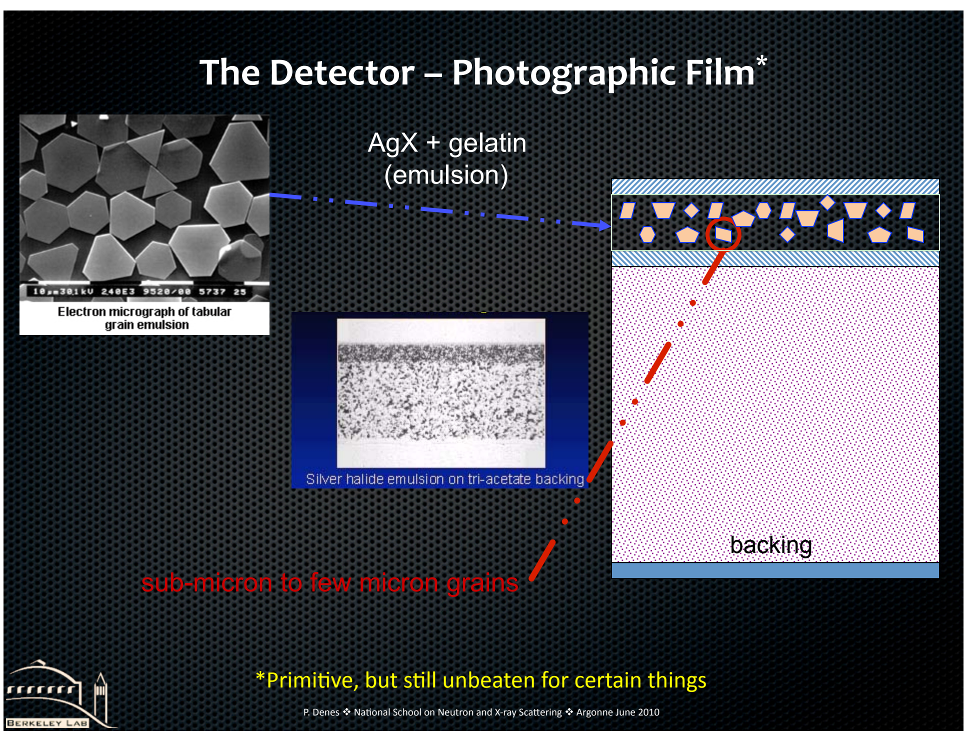

The Detector – Photographic Film*
AgX + gelatin (emulsion)
Electron micrograph of tabular grain emulsion
Silver halide emulsion on tri-acetate backing
backing
sub-micron to few micron grains
*Primitive, but still unbeaten for certain things
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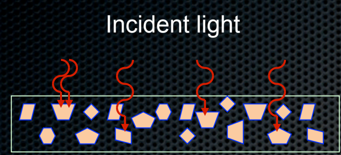
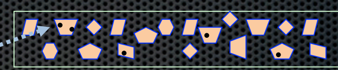
How it Works

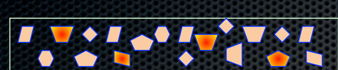




phototelectrons convert Ag^+ sites to Ag^o – at the same time, thermal fluctuations tend to "erase" the image. Generally, a few (visible) photons are required to leave a "latent" image on a grain

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

How it Works

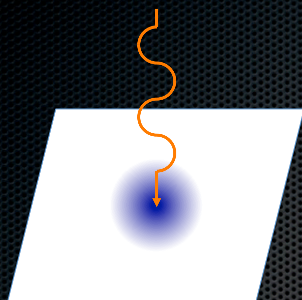


"develop" the image so that the sensitized AgX is reduced to black metallic silver

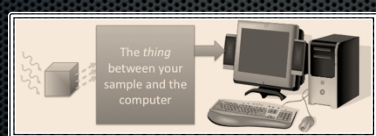
"fix" the image – removing the unexposed AgX

The chemistry and physics of photographic film is not trivial

Spatial Imaging Characteristics – PSF



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



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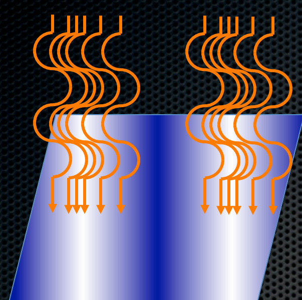
Spatial Imaging Characteristics – MTF



- Modulation Transfer Function
  - sin ωx input
  - MTF(ω)
    - $MTF(\omega_x, \omega_y)$
- MTF = | FT(PSF) |
- Related to **contrast**

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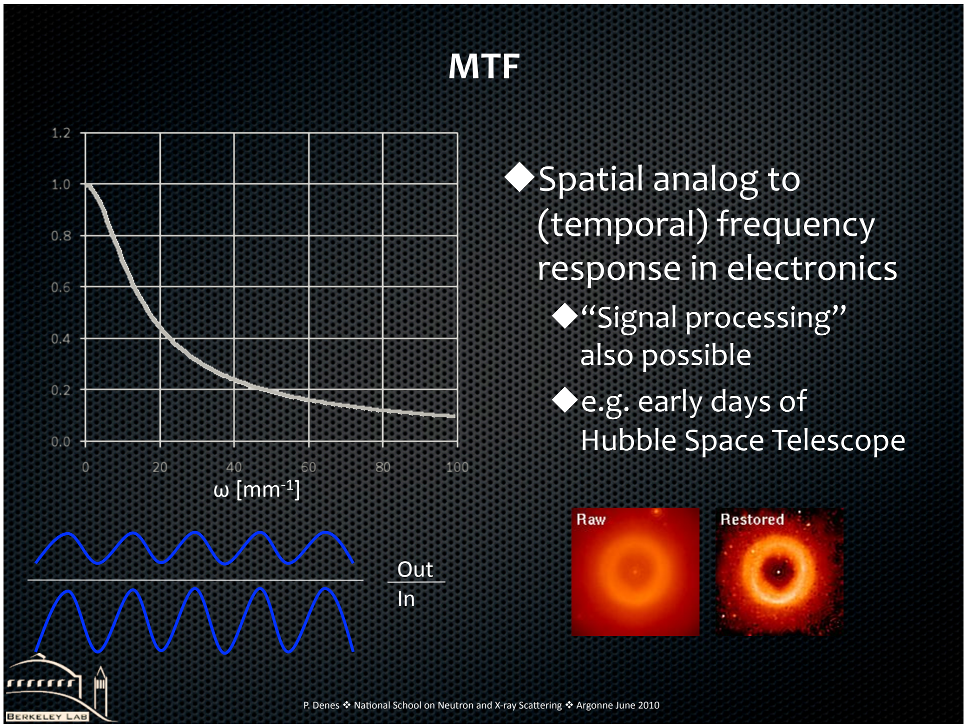
MTF
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
20
40
60
80
100
ω [mm-1]
Out
In
◆Spatial analog to (temporal) frequency response in electronics
◆"Signal processing" also possible
◆e.g. early days of Hubble Space Telescope
Raw
Restored
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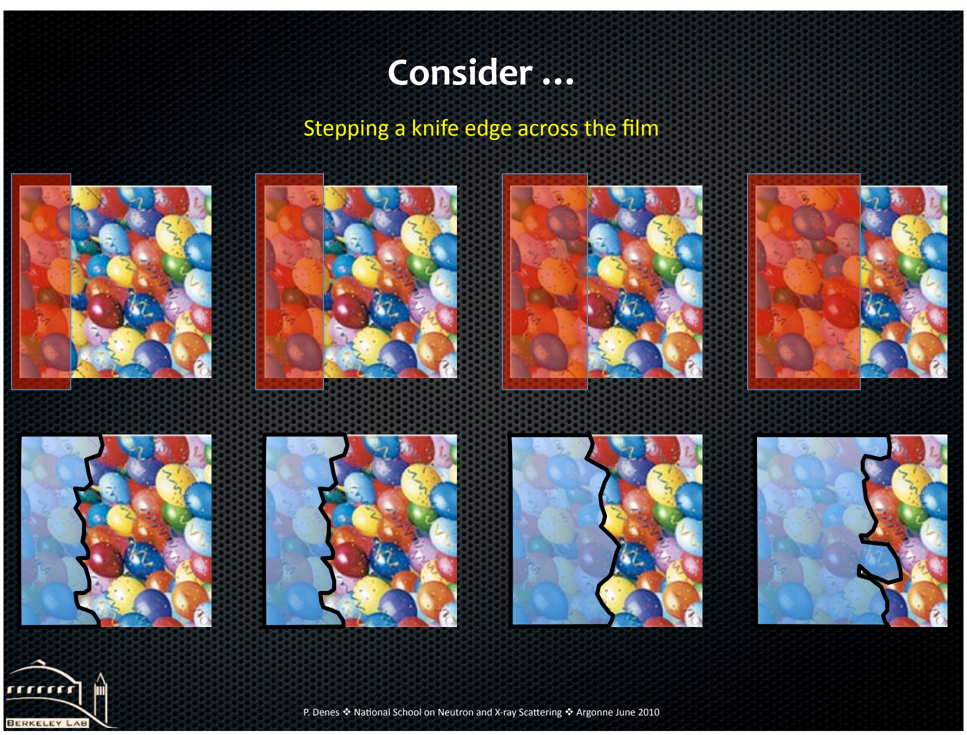
Consider …
Stepping a knife edge across the film
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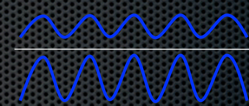
Spatial Detector Concepts

- Quantum Efficiency
  - Active area
- Contrast (PSF, MTF)
  - Spatial (frequency dependence)



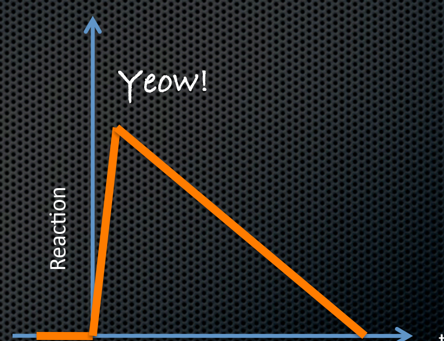
PSF = 0

PSF = 1%

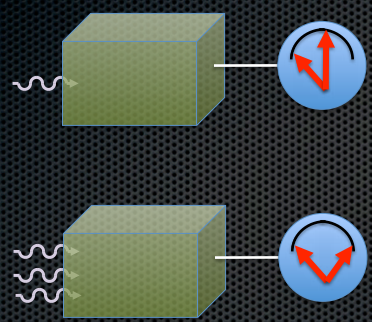
PSF = 5%

Detector Temporal Response

Pulsed Operation



"Counting" and "Integrating"

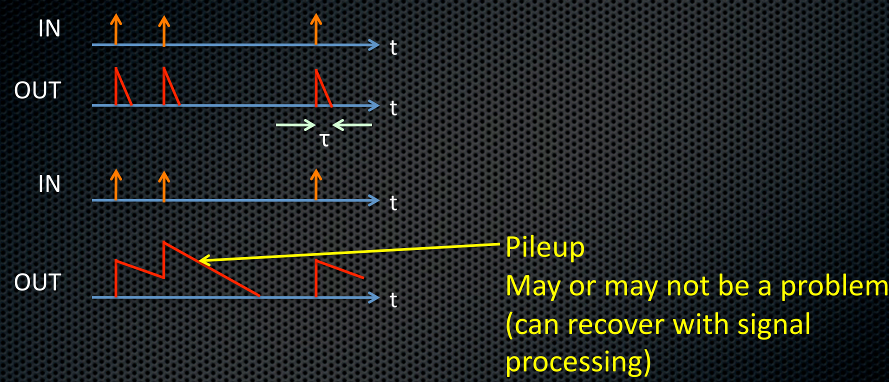


Consider temporal characteristics of
- source
- detector

"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



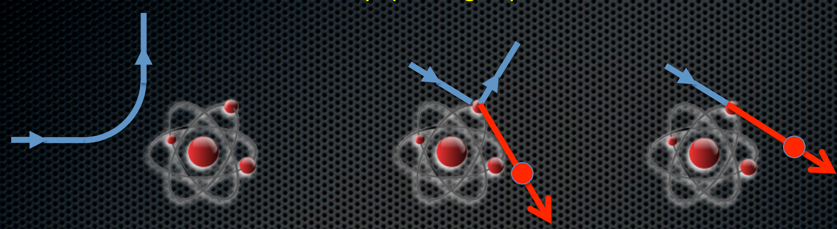
If photons arrive synchronously, maximum rate ~ $1/\tau$
If photons arrive at random, maximum rate ~ $1/10\tau$

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*

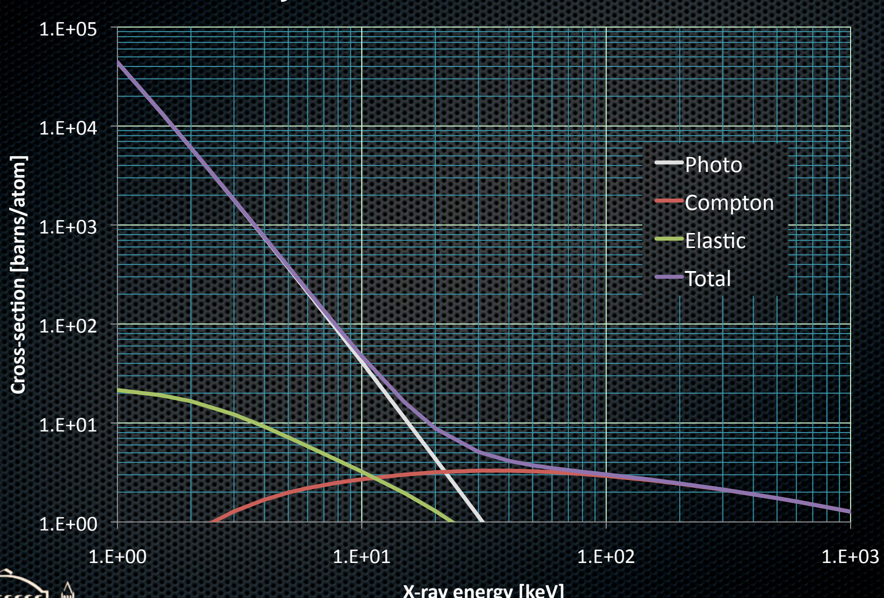
Practically speaking, 3 possibilities:

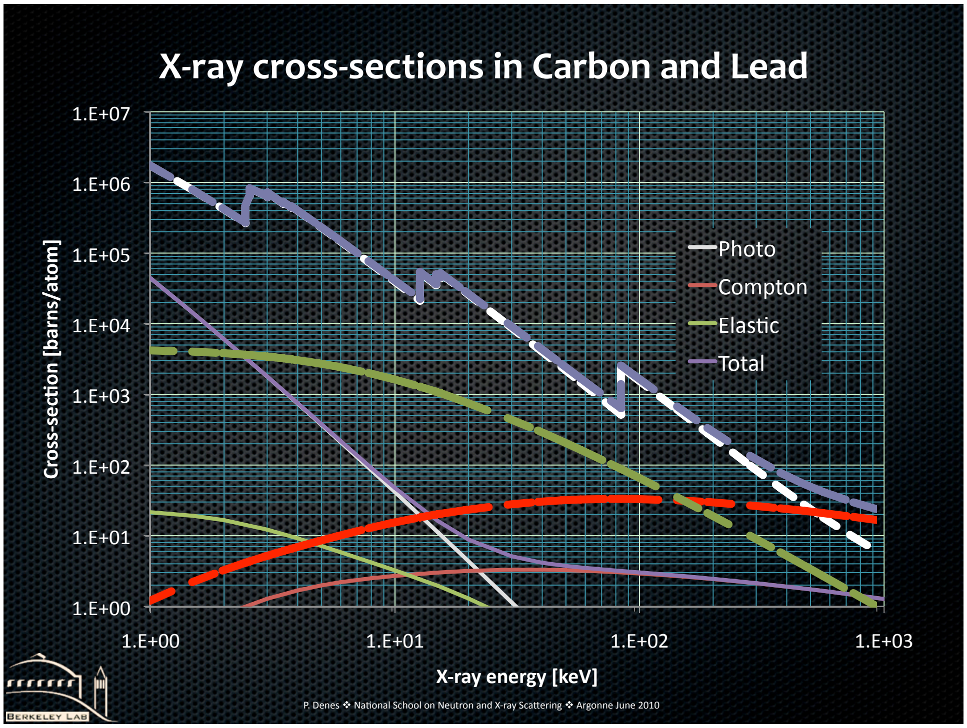


Elastic Scattering	Compton Scattering	Photoelectric Absorption
	$E_e \neq E_\gamma$	$E_e = E_\gamma$

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

X-ray cross-section in Carbon




X-ray cross-sections in Carbon and Lead
Cross-section [barns/atom]
1.E+07
1.E+06
1.E+05
1.E+04
1.E+03
1.E+02
1.E+01
1.E+00
1.E+00
1.E+01
1.E+02
1.E+03
X-ray energy [keV]
Photo
Compton
Elastic
Total
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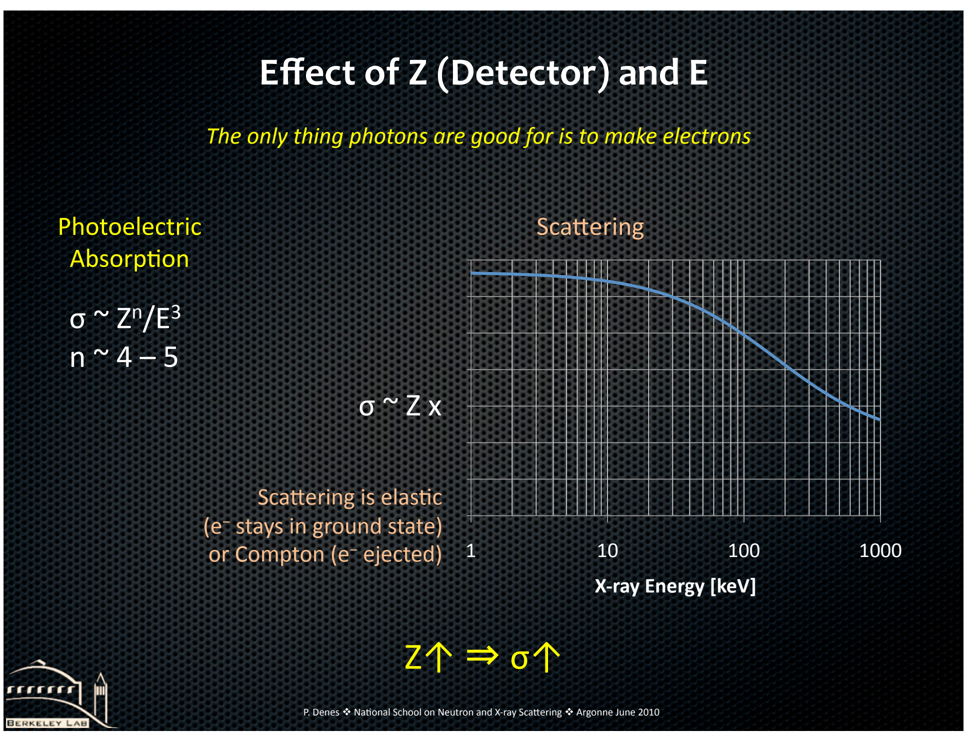
Effect of Z (Detector) and E
The only thing photons are good for is to make electrons
Photoelectric Absorption
σ ~ Zⁿ/E³
n ~ 4 – 5
Scattering
σ ~ Z x
Scattering is elastic
(e⁻ stays in ground state)
or Compton (e⁻ ejected)
1
10
100
1000
X-ray Energy [keV]
Z↑ ⇒ σ↑
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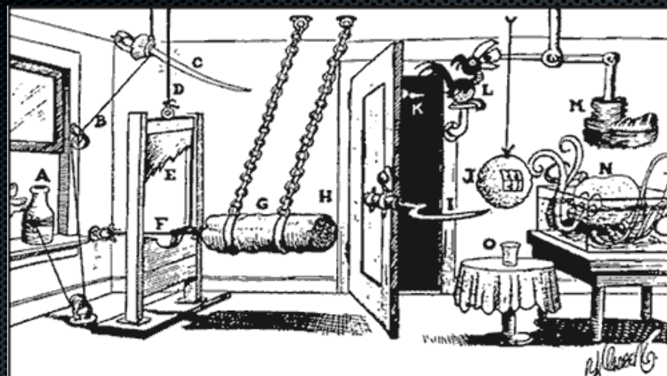
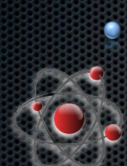
Quantum Efficiency (again)



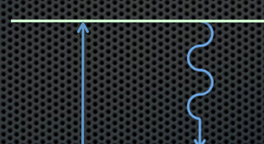
- Probability of detecting incident photon
  - Photon has to create ionization electron
  - Ionization electron has to be detected

What can the Ionization Electron Do?

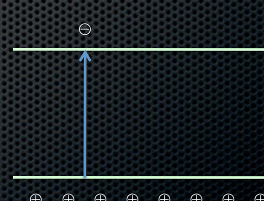
Form free charge



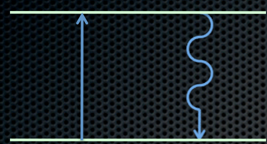
Scintillation (radiative)

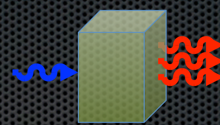


Charge collection in semiconductor



Scintillator





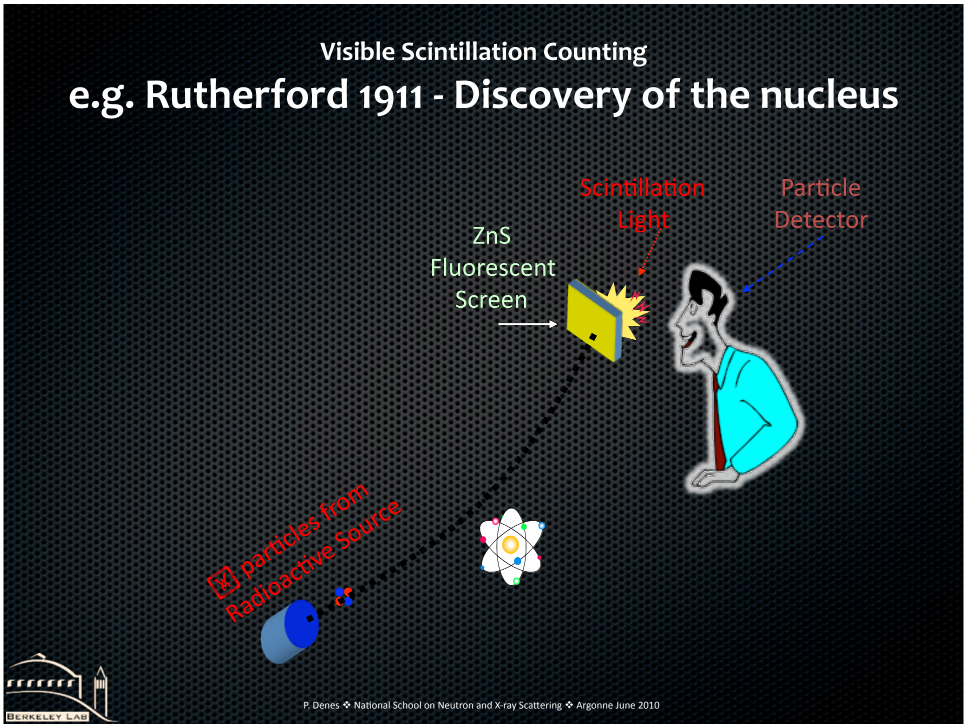
"Converts" x-ray (or other higher energy particle) into visible light

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

ρ, τ, N_γ, …

MATERIAL	DENSITY [g/cm³]	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
Scintillation Light
Particle Detector
ZnS Fluorescent Screen
particles from Radioactive Source
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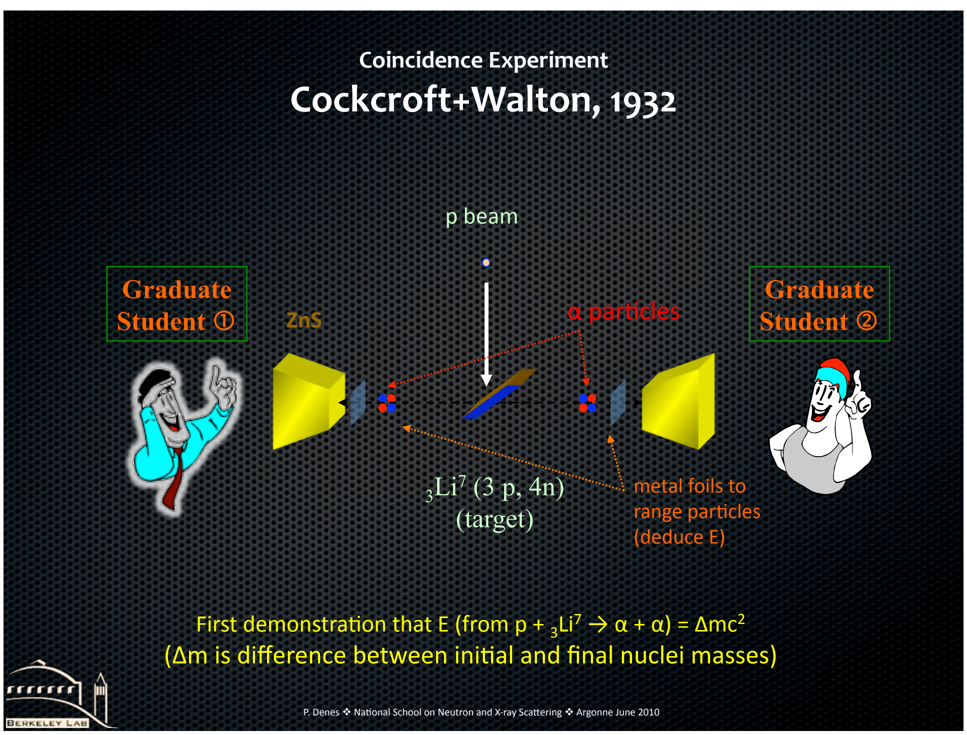
Coincidence Experiment
Cockcroft+Walton, 1932
p beam
Graduate Student ①
ZnS
α particles
Graduate Student ②
$_3Li^7$ (3 p, 4n) (target)
metal foils to range particles (deduce E)
First demonstration that E (from p + $_3Li^7$ → α + α) = Δmc^2
(Δm is difference between initial and final nuclei masses)
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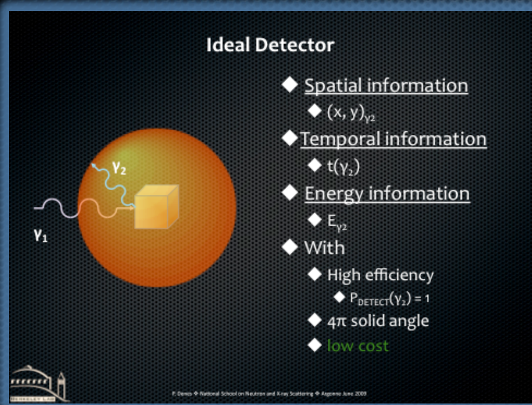
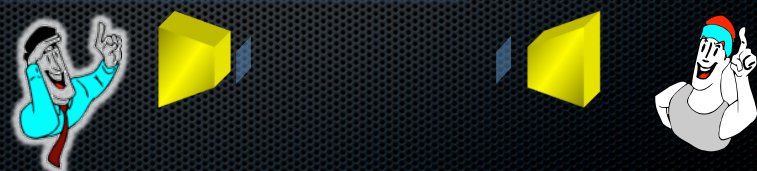
Detector Properties



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

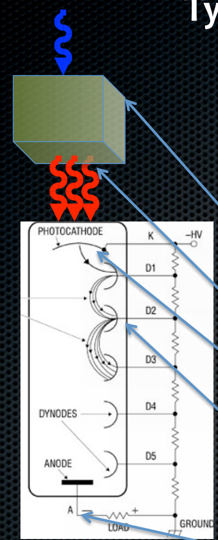
(although Marsden could distinguish α and p by brightness)

At λ ~ 500 nm, $\text{Threshold}_{\text{TRAINED OBSERVERS}}$ ~ 17 γ for $t_{\text{FLASH}} > 40$ μs

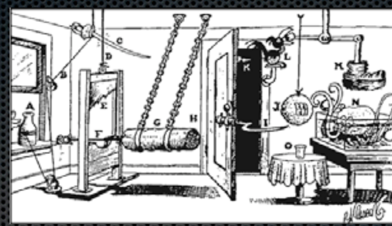
- Yield: *"…at one famous laboratory during this period all intending research students were tested in the dark room for their ability to count scintillations accurately. Only those whose eyesight measured up to the standards required were accepted for nuclear research; the others were advised to take up alternative, less exacting, fields of study"*

(from Birks)

Typical Scintillation Detector



Photomultiplier

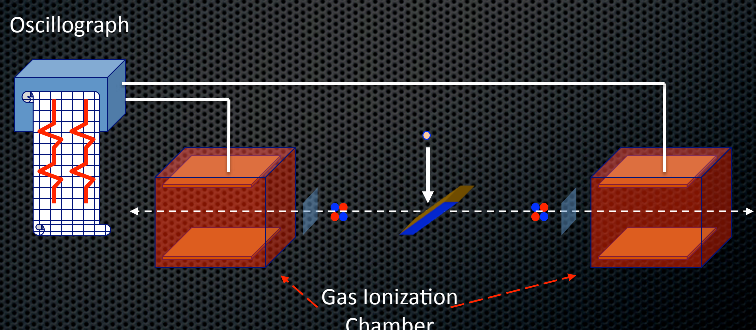


- Incident photon creates (ionization) electron
- Ionization generates visible photons
- Visible photons converted into electrons
- Electrons "amplified" by secondary emission
- Output current detected

Coincidence Experiment

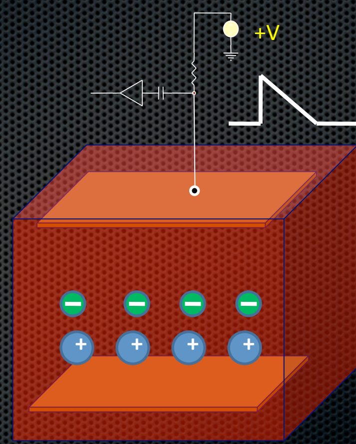
Cockcroft+Walton - Electronic Verification

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



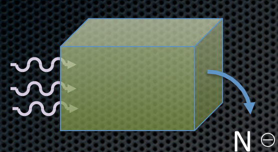
Ionization Chamber

- 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



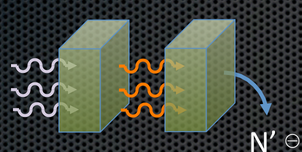
Electronic Detectors

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

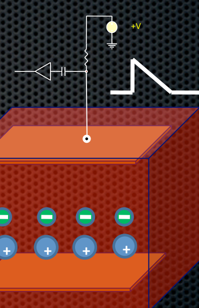
Energy Needed for Detection

"Sensor"	η = E per 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

Statistics – Fano Factor

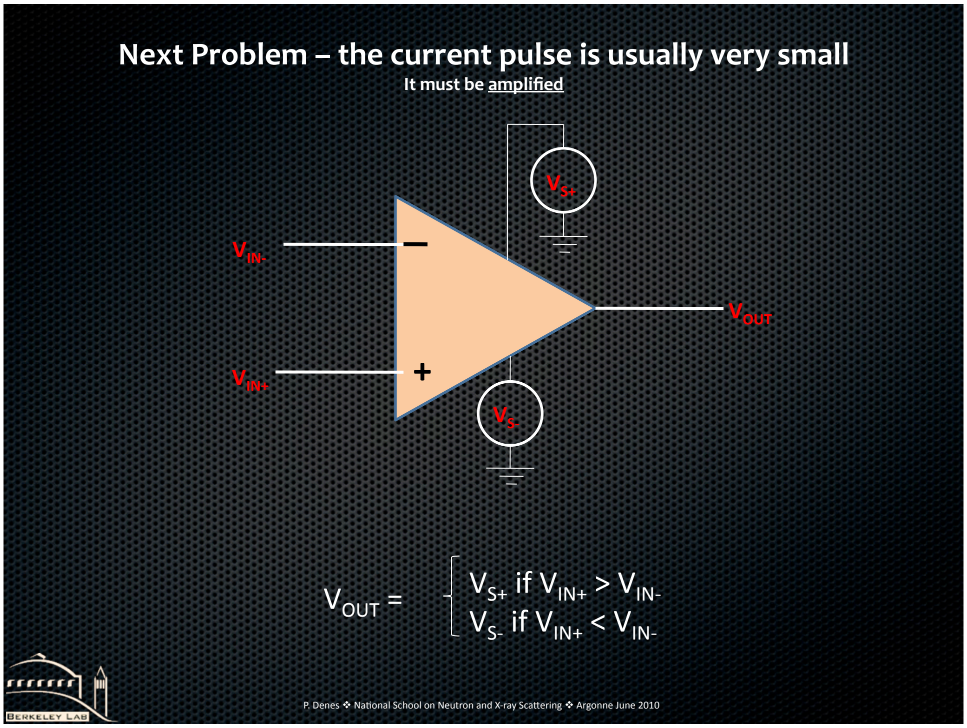
"Sensor"	η = E per secondary quanta	Mechanism
Gas	30 eV	e⁻/ion pairs
Scintillator	10 – 1000 eV	optical excitation
Semiconductor	1 – 5 eV	e⁻/hole pairs
Superconductor	~meV	breakup of Cooper pairs
Superconducting calorimeters	~meV	phonons



$$N_{\pm} = \frac{E}{\eta}$$

$$\sigma_N = \sqrt{FN}$$

- *Intrinsic resolution is Fano-limited*
- σ_N/N ↓ as η ↓
  - Hence interest in superconducting calorimeters
- There are additional ways to have fluctuations on N


Next Problem – the current pulse is usually very small
It must be amplified
V_S+
V_IN-
V_OUT
V_IN+
V_S-
V_OUT = { V_S+ if V_IN+ > V_IN-; V_S- if V_IN+ < V_IN-
BERKELEY LAB
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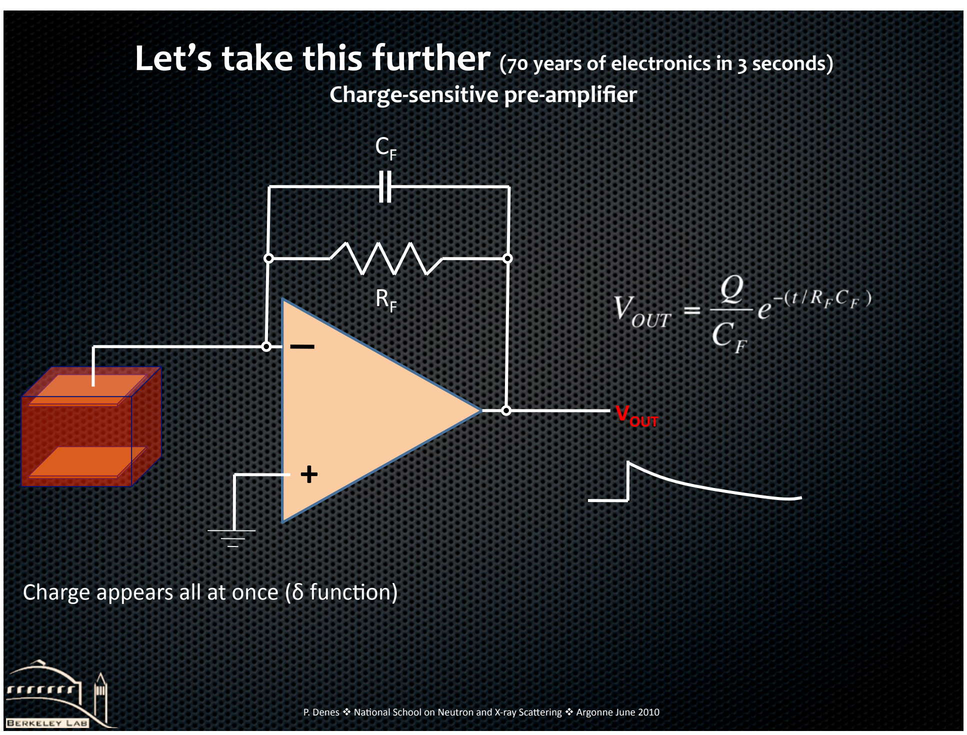
Let's take this further (70 years of electronics in 3 seconds)
Charge-sensitive pre-amplifier
C_F
R_F
$V_{OUT} = \frac{Q}{C_F} e^{-(t/R_F C_F)}$
V_OUT
Charge appears all at once (δ function)
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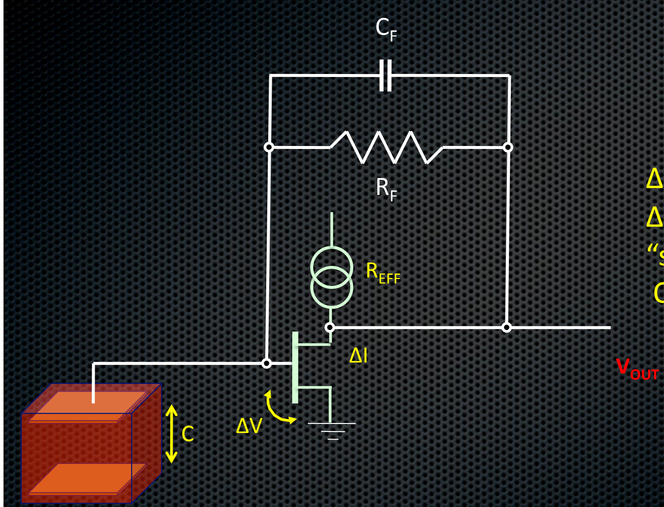
Almost Always Like This



$\Delta V = Q/C$

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

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

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

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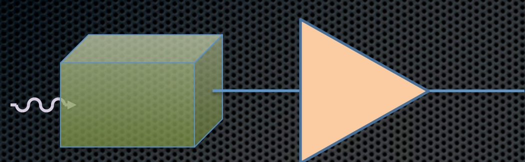
Noise and Statistics

Some terms to get started



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

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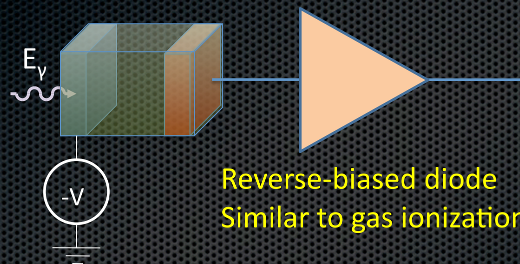
Semiconductor Detector

p-i-n diode



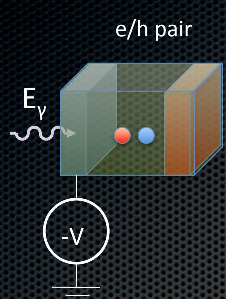
Reverse-biased diode
Similar to gas ionization chamber

$N = E_\gamma/\varepsilon$

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

Material	Si	Ge	GaAs	Diamond
η [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

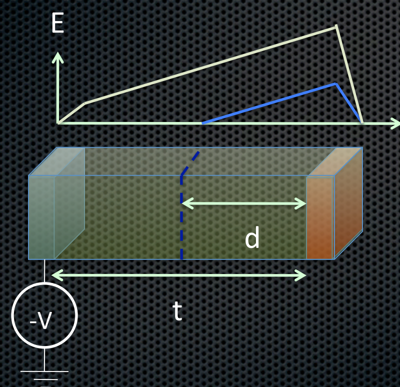
How it Works



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

Depletion

Fully depleted → minimize diffusion (and recombination)

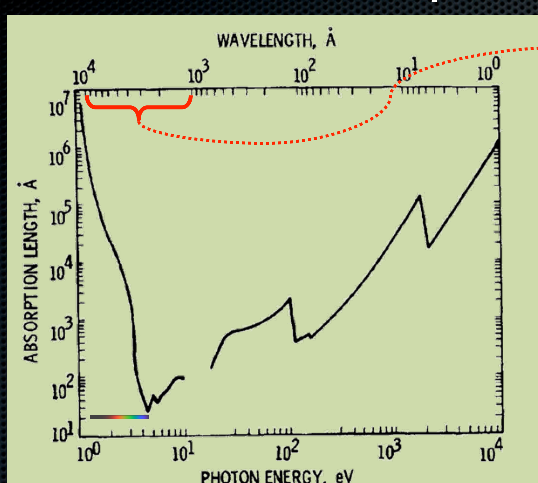


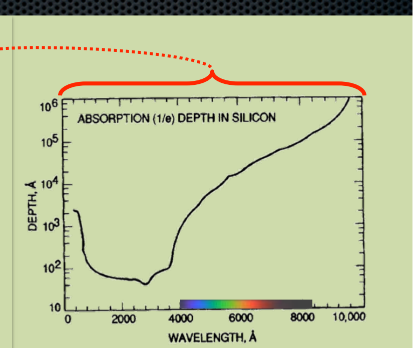
Fully depleted
Partially depleted

$$C = \frac{\varepsilon\varepsilon_0}{d}$$ capacitance per unit area

$$d \approx \sqrt{\frac{2\varepsilon\varepsilon_0}{qN_D}V}$$ depletion depth

Absorption in Si



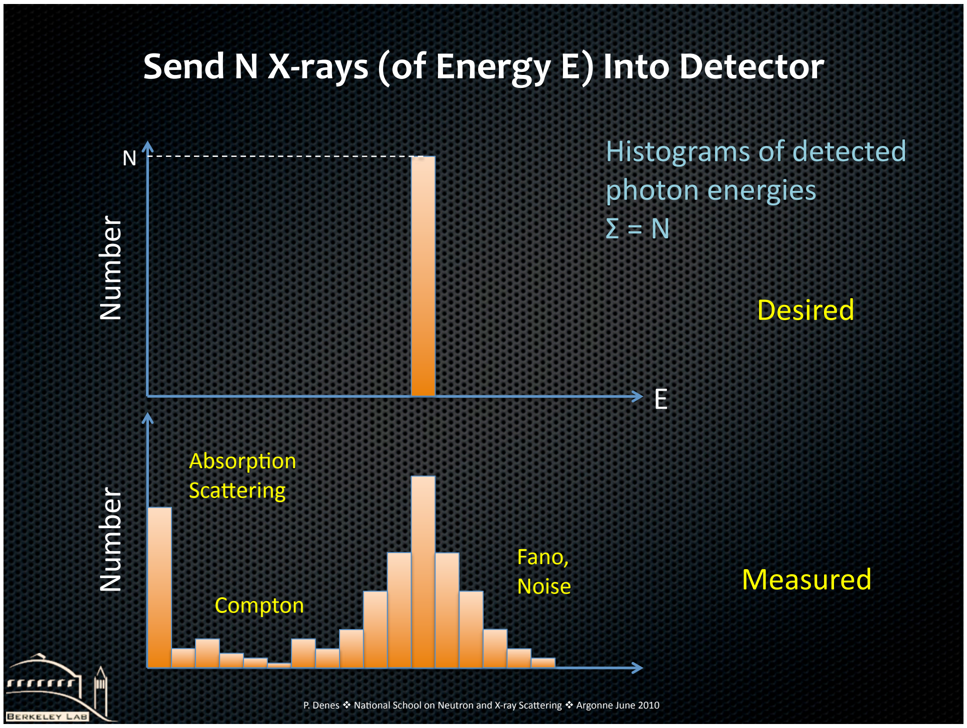


Ignoring reflection …

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
N
Number
E
Histograms of detected photon energies
Σ = N
Desired
Absorption
Scattering
Compton
Fano,
Noise
Number
Measured
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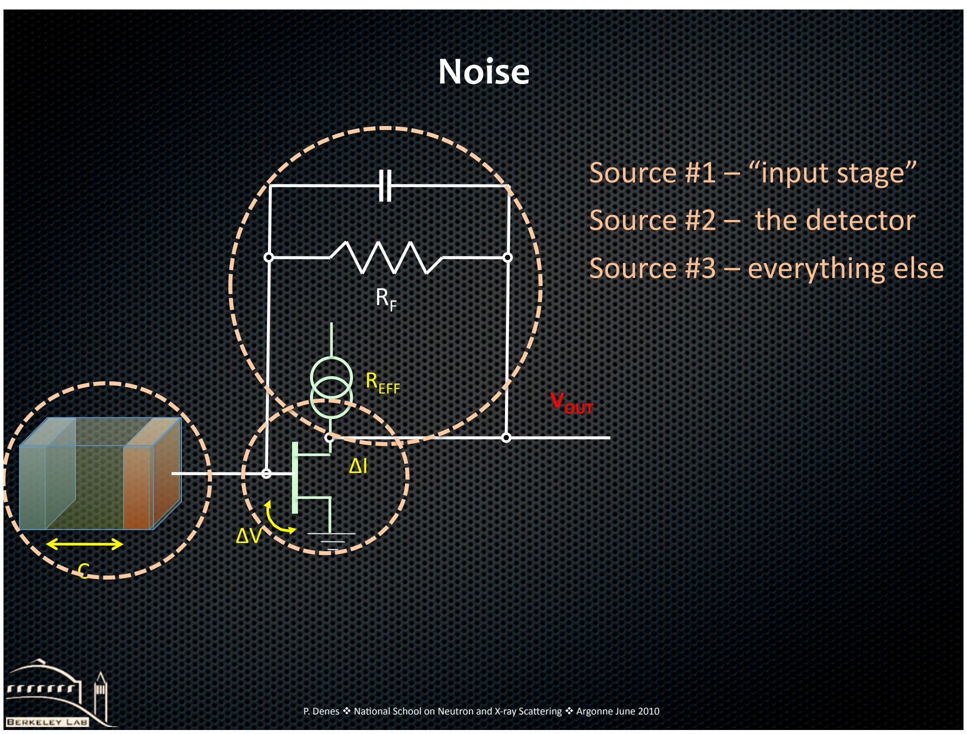
Noise
Source #1 – "input stage"
Source #2 – the detector
Source #3 – everything else
R_F
R_EFF
V_OUT
ΔI
ΔV
C
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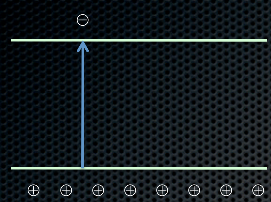
The Detector Makes Noise?

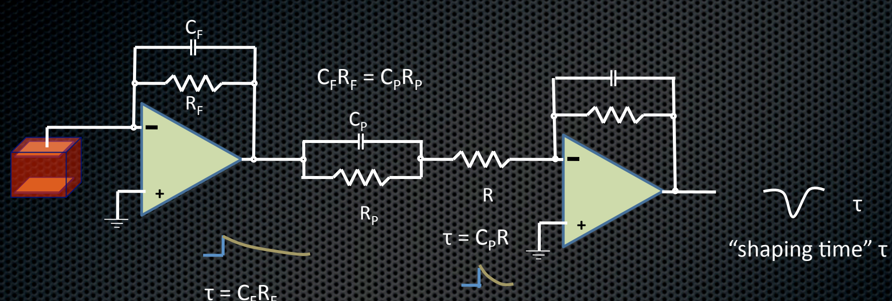


Semiconductor detector
i.e. valence band ~full,
conduction band ~empty

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

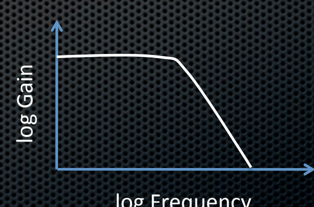
- Thermal excitation
  - "leakage" or "dark" current (I_{LEAK} e^-/s)
  - "looks like" signal
  - ("shot noise")
  - Reduced by cooling
- Noise, $\propto \sqrt{I_{LEAK}}$, because leakage is not orderly

Some More Electronics



Bandwidth = 1 / 2π τ

In frequency domain:



Things ∝ τ

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

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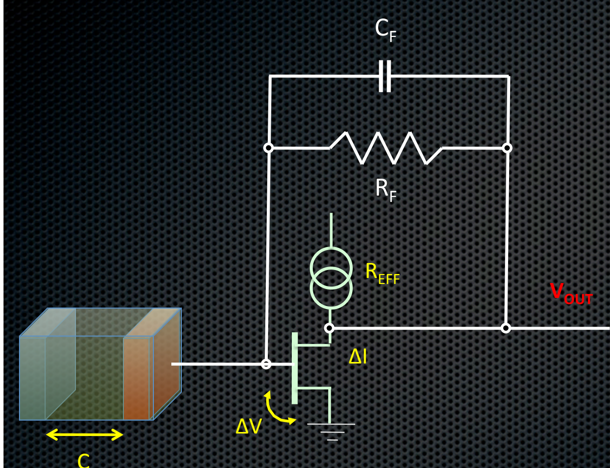
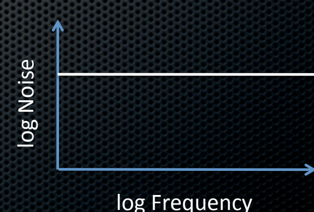
Electronic Noise



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

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



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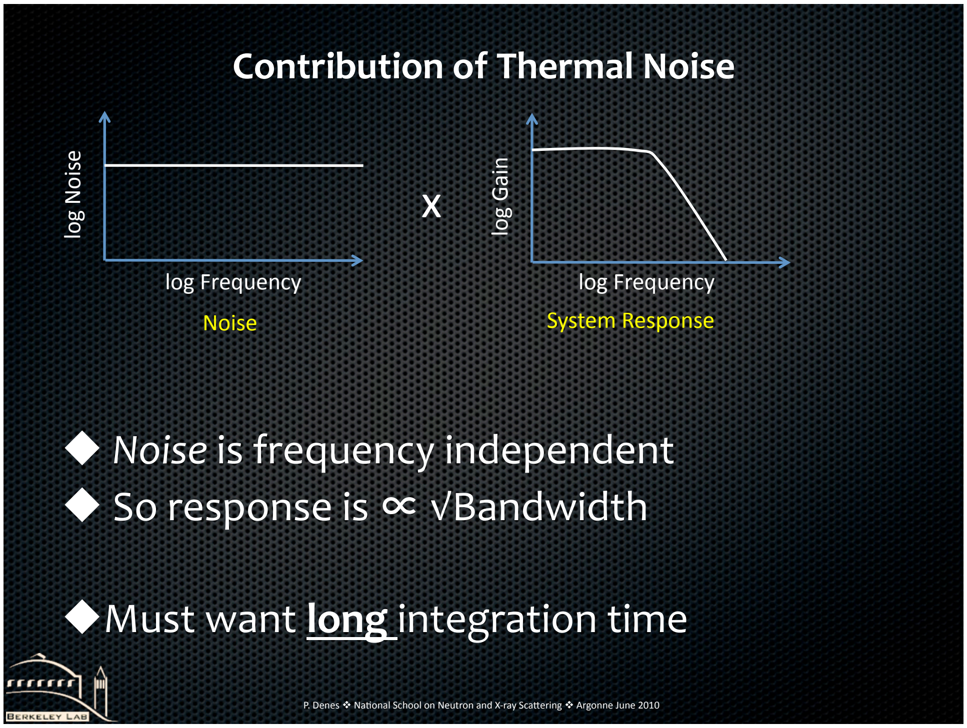
Contribution of Thermal Noise
log Noise
log Frequency
Noise
X
log Gain
log Frequency
System Response
◆ Noise is frequency independent
◆ So response is ∝ √Bandwidth
◆ Must want long integration time
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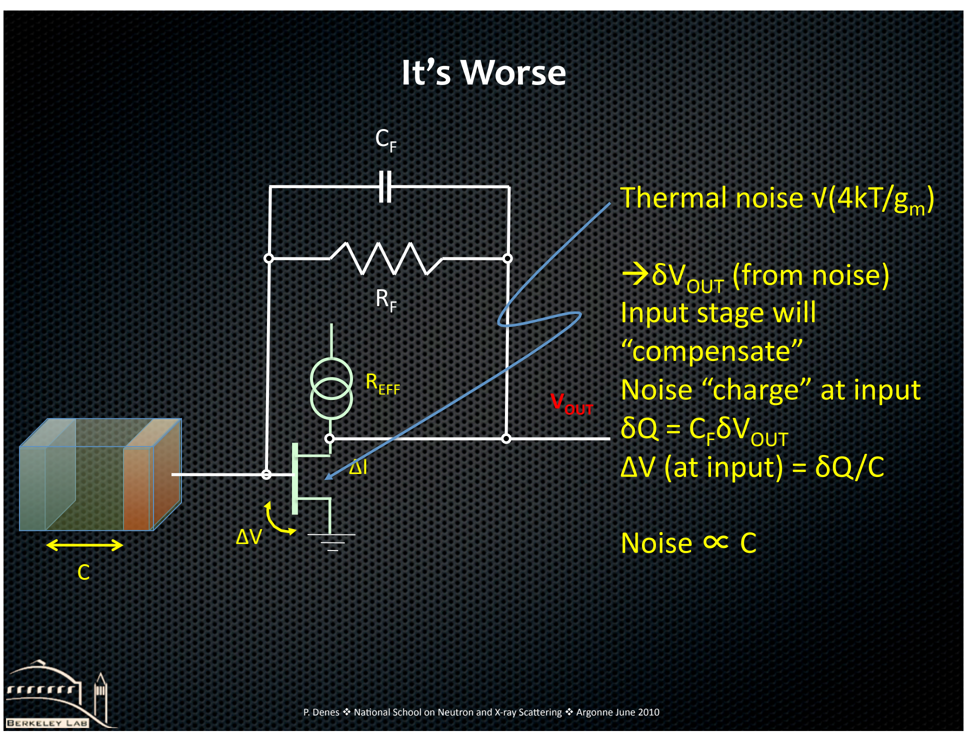
It's Worse
C_F
R_F
R_{EFF}
V_{OUT}
ΔI
ΔV
C
Thermal noise $\sqrt{4kT/g_m}$
→ δV_{OUT} (from noise)
Input stage will "compensate"
Noise "charge" at input
$\delta Q = C_F \delta V_{OUT}$
ΔV (at input) = $\delta Q/C$
Noise ∝ C
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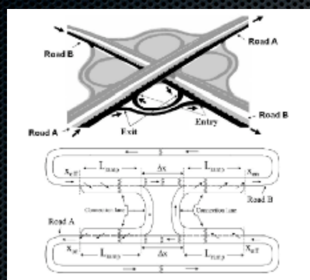
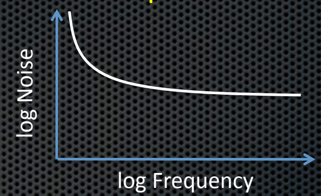
It's Even Worse

Many physical systems are subject to fluctuations ~ $1/f^{\alpha}$
You know this from driving:



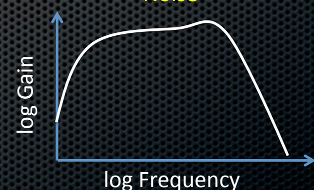
RMS of time you wait getting onto the freeway ~ $1/f$

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

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S/N, Dynamic Range, Number of Bits

Usually mis-stated!

- Si: η = 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!

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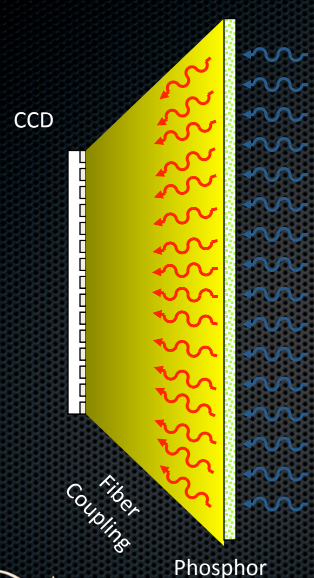
A tale of 3 different √N

- Uniform flux ϕ [$\gamma/cm^2/s$] on area A yields $N = \phi A$ [γ/s] $\pm \sqrt{N}$ incident photons/s
  - photostatistics
- Each one (that is converted) produces $N_\pm = NE/\eta \pm \sqrt{(FN_\pm)}$ e/h pairs/s
  - intrinsic resolution
- Which, as a current sampled in time τ has fluctuations $\sim \sqrt{(N_\pm \tau)}$
  - shot noise

"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

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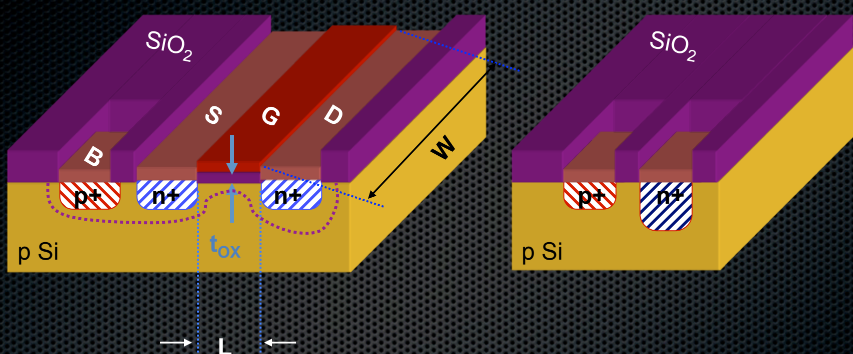
Si Processing: Integrated Circuit Elements



MOS Transistor

pn Diode

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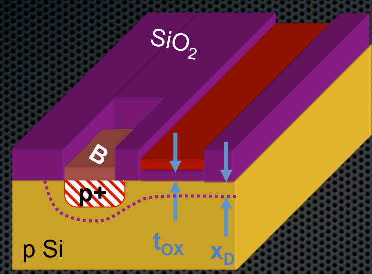
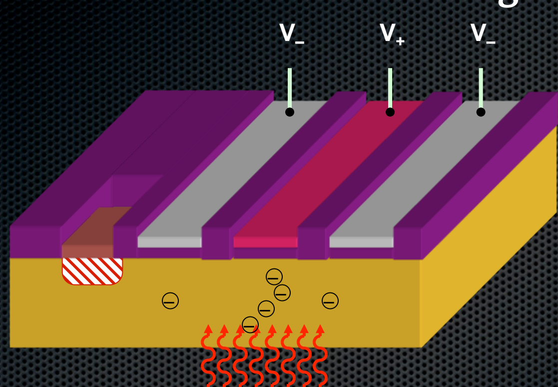
Integrated Circuit Elements



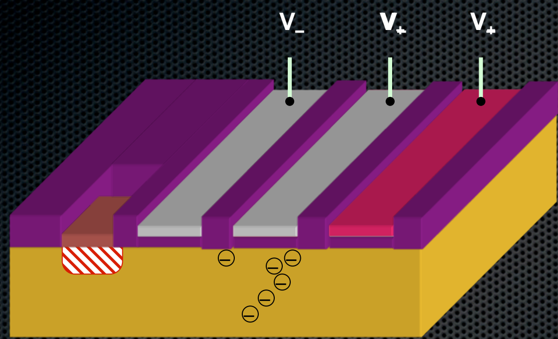
$$C = \frac{1}{\frac{1}{C_{OX}} + \frac{1}{C_{DEP}}}, \quad C_{OX} = \frac{\varepsilon_{SiO_2}}{t_{OX}}, C_{DEP} = \frac{\varepsilon_{Si}}{x_D}$$

MOS Capacitor

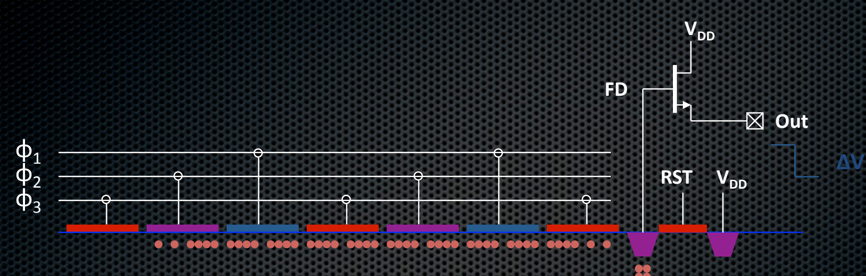
Accumulate Charge



Accumulate and Transfer Charge

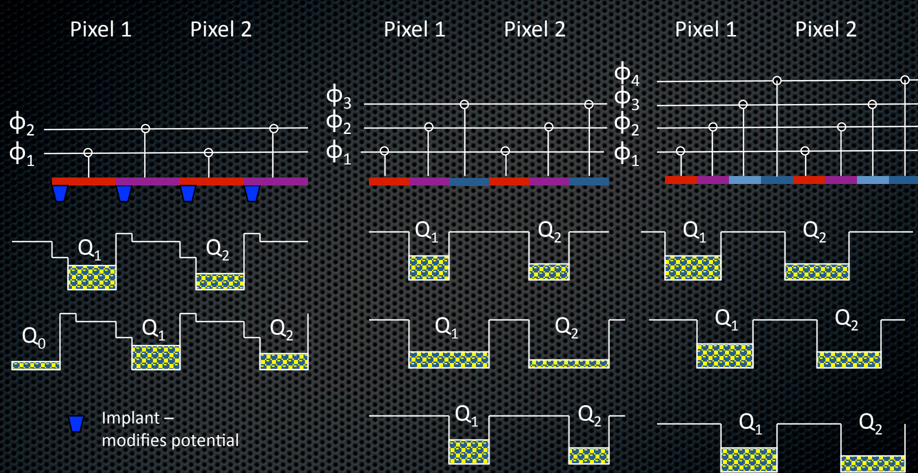


Conventional 3-Phase CCD



- 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



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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

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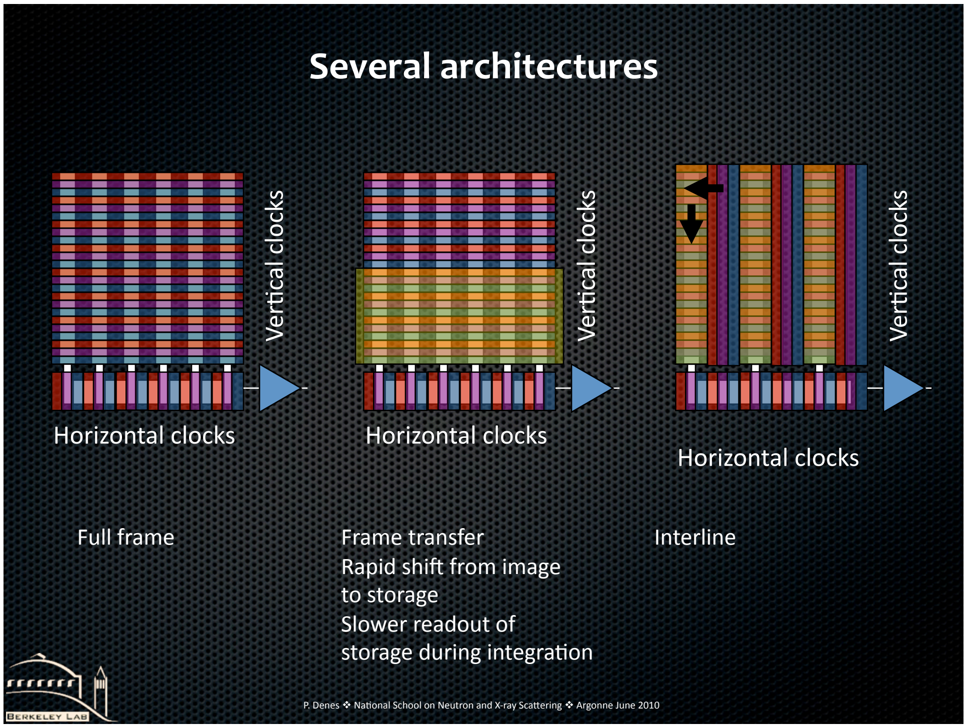
Several architectures
Vertical clocks
Vertical clocks
Vertical clocks
Horizontal clocks
Horizontal clocks
Horizontal clocks
Full frame
Frame transfer
Rapid shift from image
to storage
Slower readout of
storage during integration
Interline
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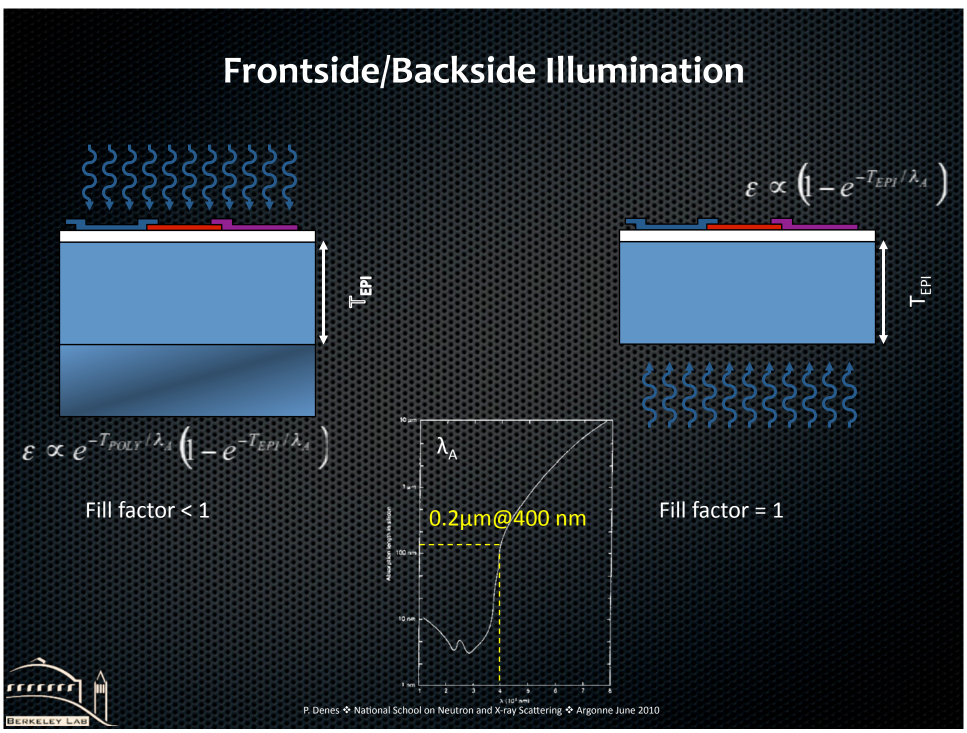
Frontside/Backside Illumination
$\varepsilon \propto \left(1 - e^{-T_{EPI}/\lambda_A}\right)$
T_{EPI}
T_{EPI}
$\varepsilon \propto e^{-T_{POLY}/\lambda_A}\left(1 - e^{-T_{EPI}/\lambda_A}\right)$
Fill factor < 1
λ_A
0.2µm@400 nm
10 µm
1 µm
100 nm
10 nm
1 nm
Absorption length in silicon
1
2
3
4
5
6
7
8
λ (10² nm)
Fill factor = 1
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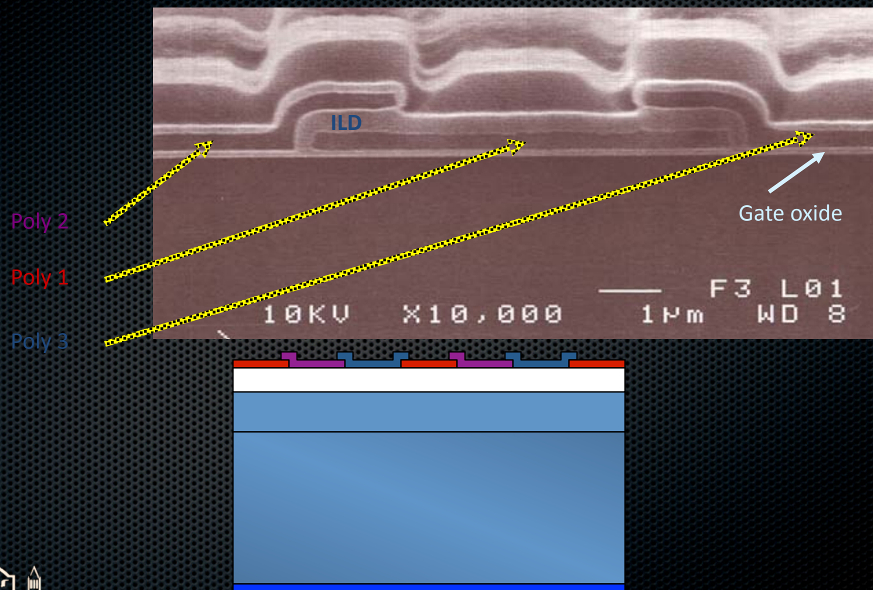
Triple Poly CCD Process



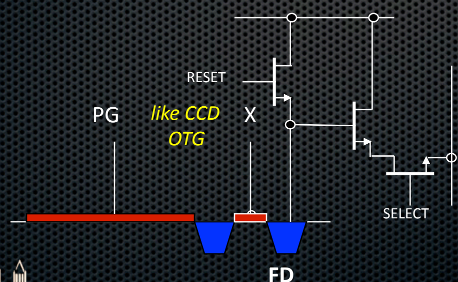
Monolithic Image Sensors

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

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

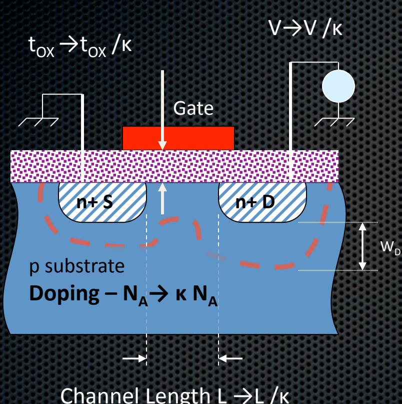
CCD vs APS

- 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

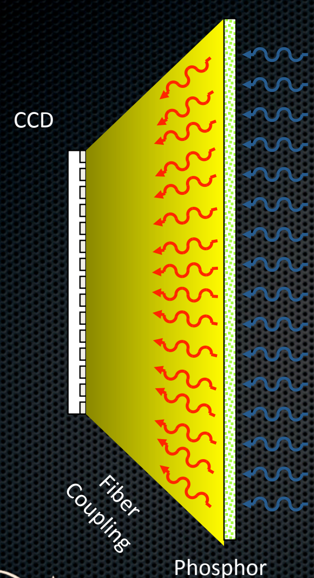


	CCD	CMOS
t_{OX} (Å)	500 - 1000	5-20
Well depth (μm)	2.5	0.5 deeper for RF
Implant (μm)	~1 channel stop	0.1 S/D implants
V	≥10	<3.3 <2.5 <1.x …
Poly layers	3 (2)	1 2 for analog
Subst. quality	Low leakage	Don't care Except opto

Why CCDs?

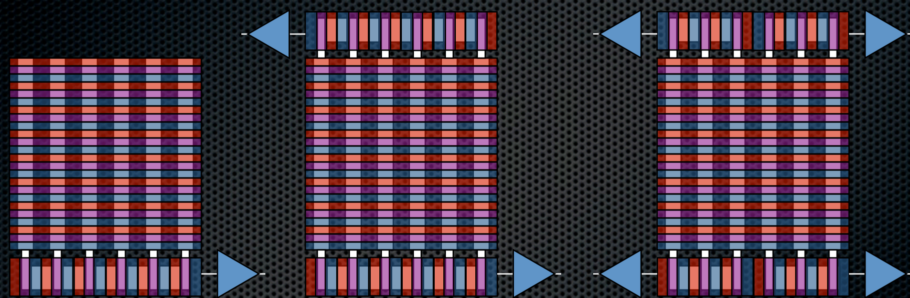
- Low noise (noiseless charge transfer, do everything to make C_{FD} small in order to get large conversion gain)
- Fill-factor = 1 (for backside illumination)
- Linear and easy to calibrate
- **Long history of scientific use**
- Large area devices easier (cheaper) to develop as CCDs than as state of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



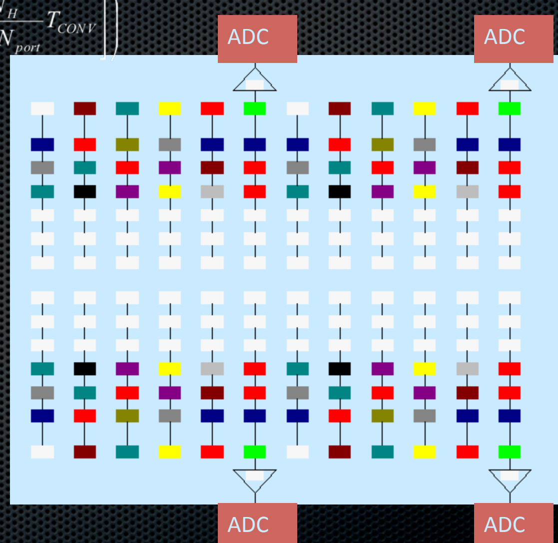
Now it gets more difficult

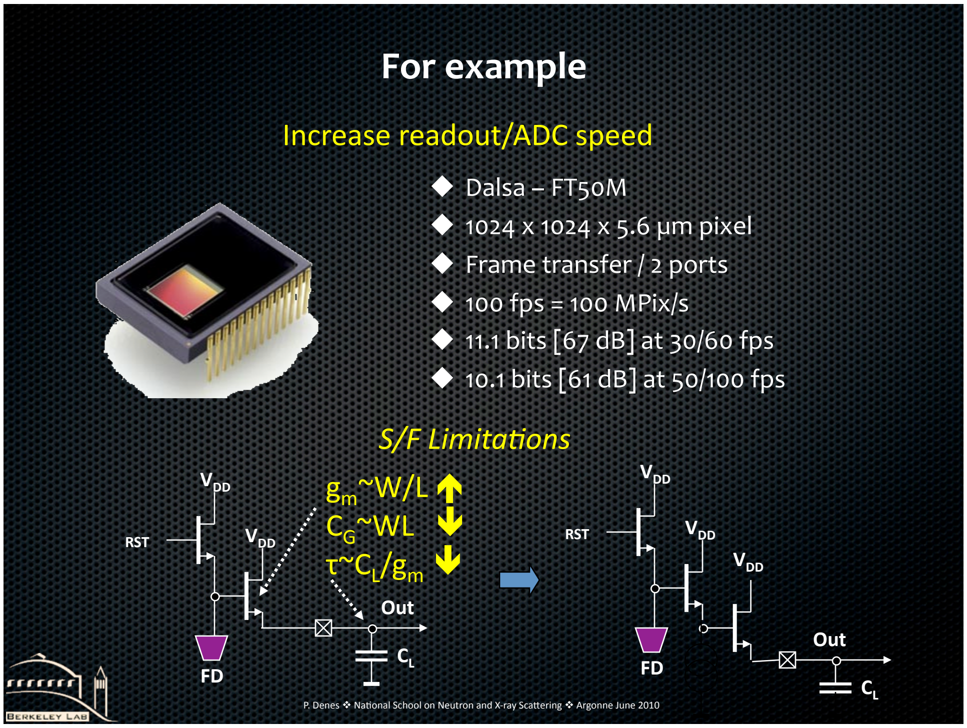
Increase ADC speed

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

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
g_m~W/L
C_G~WL
τ~C_L/g_m
V_{DD}
RST
FD
Out
C_L
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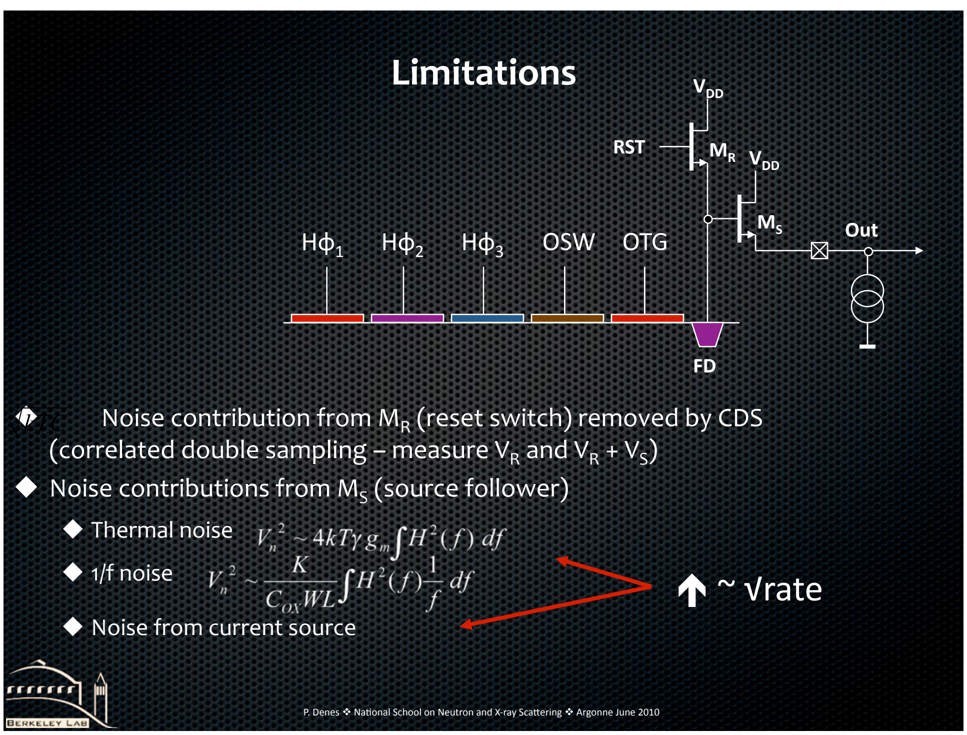
Limitations
V_{DD}
RST
M_R
M_S
Out
$H\phi_1$ $H\phi_2$ $H\phi_3$ OSW OTG
FD
Noise contribution from M_R (reset switch) removed by CDS (correlated double sampling – measure V_R and $V_R + V_S$)
Noise contributions from M_S (source follower)
Thermal noise $V_n^2 \sim 4kT\gamma g_m \int H^2(f)\, df$
1/f noise $V_n^2 \sim \frac{K}{C_{OX}WL}\int H^2(f)\frac{1}{f}\, df$
Noise from current source
~ √rate
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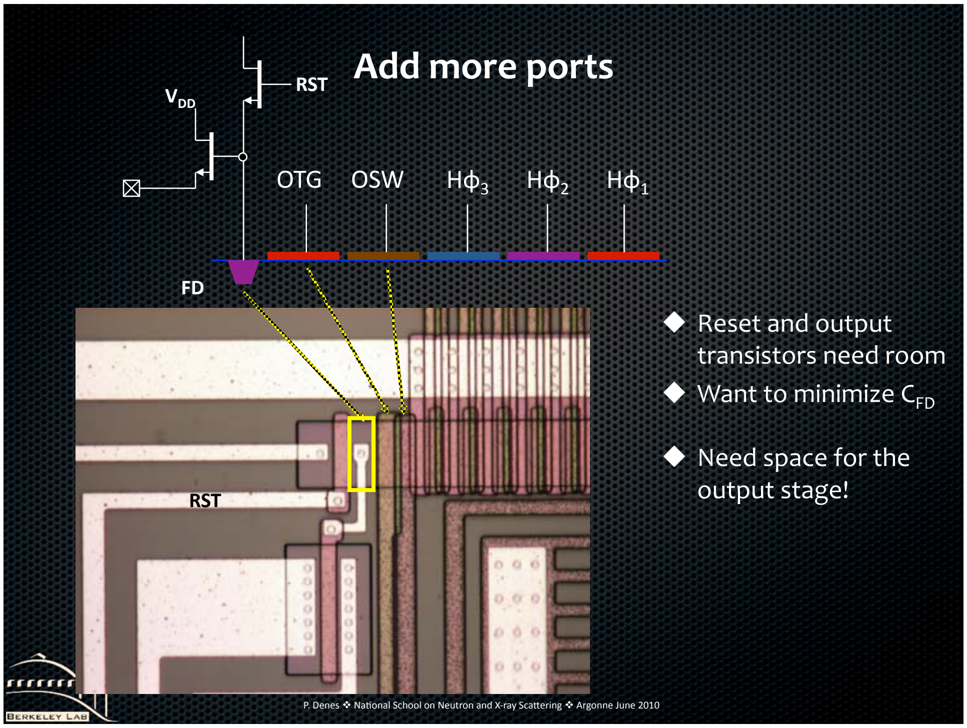
Add more ports
VDD
RST
OTG
OSW
Hφ3
Hφ2
Hφ1
FD
RST
Reset and output transistors need room
Want to minimize CFD
Need space for the output stage!
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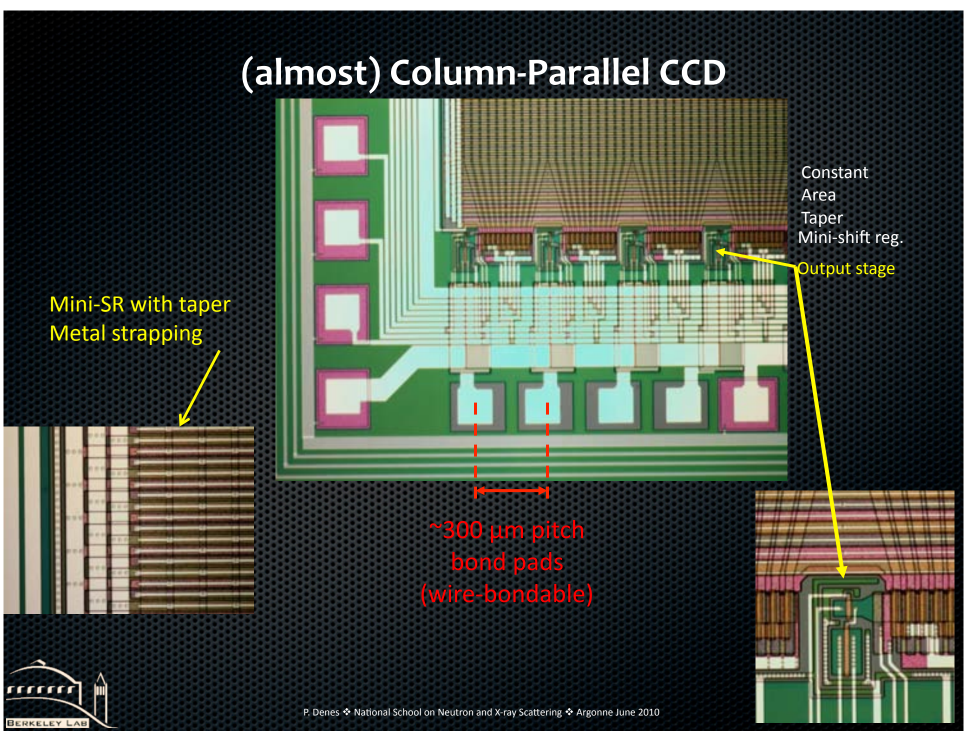
(almost) Column-Parallel CCD
Constant
Area
Taper
Mini-shift reg.
Output stage
Mini-SR with taper
Metal strapping
~300 µm pitch
bond pads
(wire-bondable)
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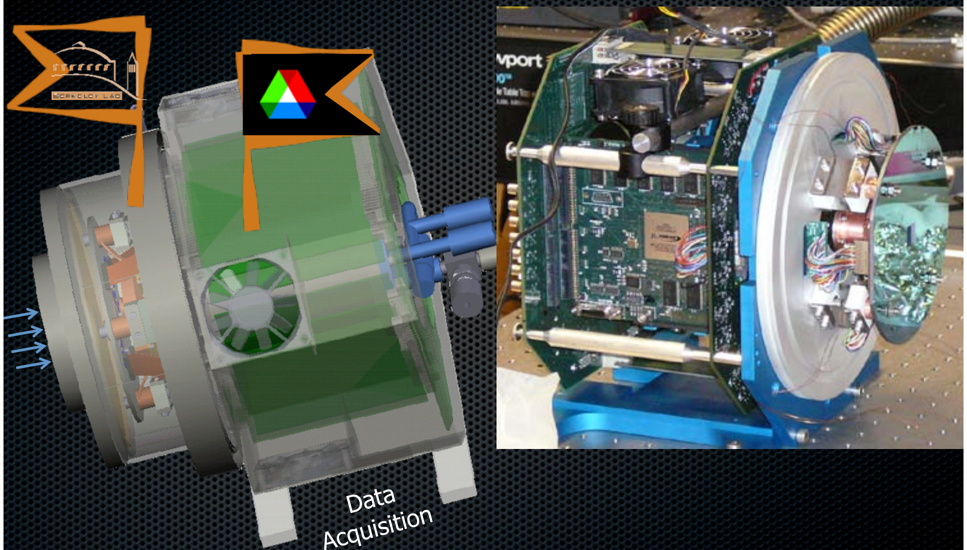
ALS / APS Collaboration

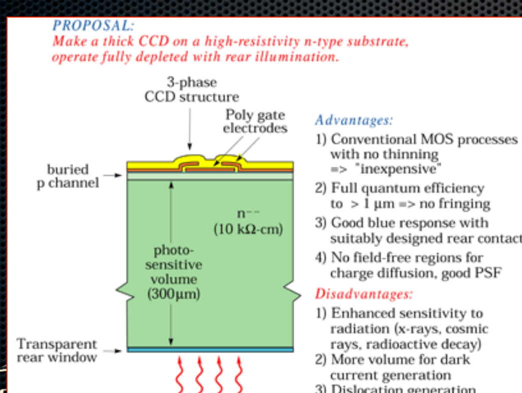


Direct Detection

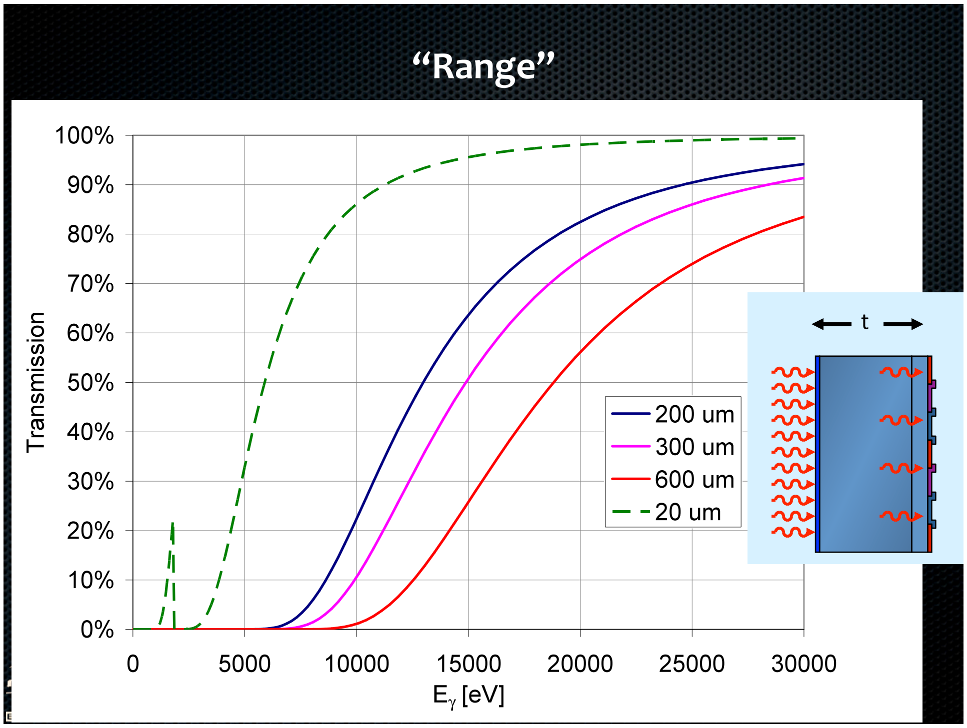
Previous example of CCD usage was for optical photons. What about x-rays?

This should be depleted – generally thin with conventional processes

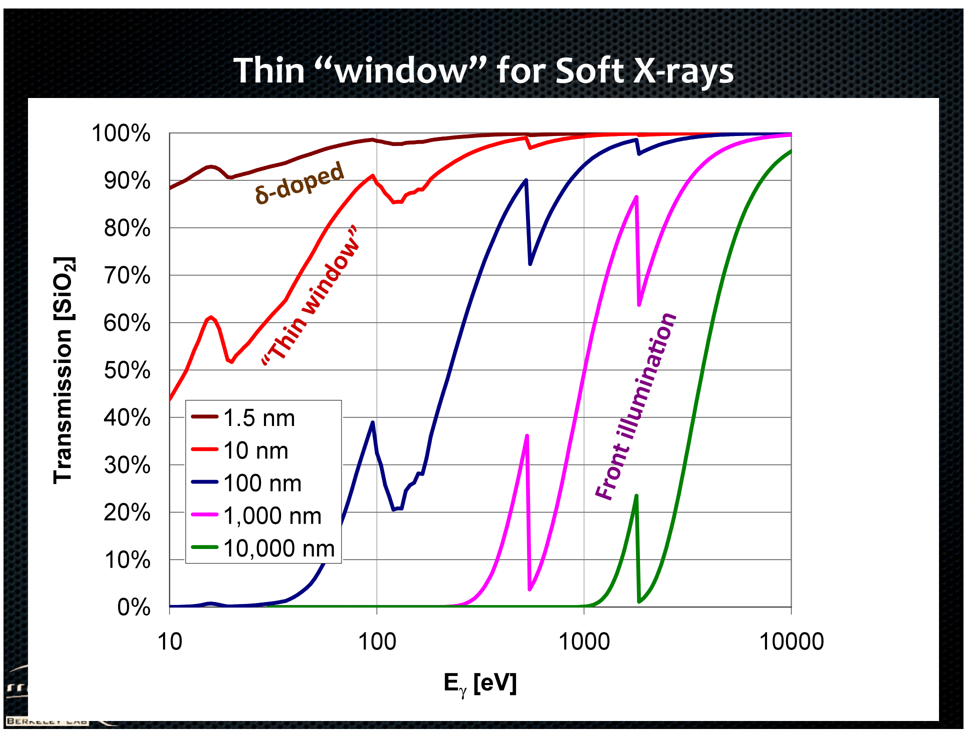
→ add a layer which can be used as an electrode



LBL CCD – S. Holland et al.



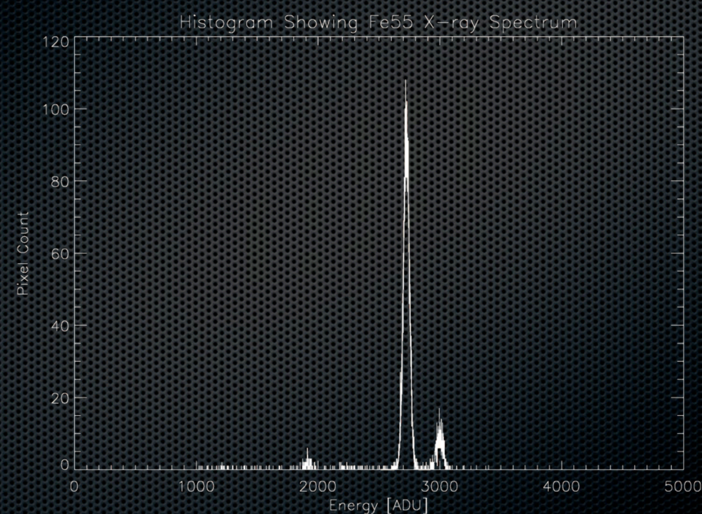
"Range"
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Transmission
0
5000
10000
15000
20000
25000
30000
Eγ [eV]
200 um
300 um
600 um
20 um
t



Thin "window" for Soft X-rays
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Transmission [SiO2]
10
100
1000
10000
Eγ [eV]
δ-doped
"Thin window"
Front illumination
1.5 nm
10 nm
100 nm
1,000 nm
10,000 nm

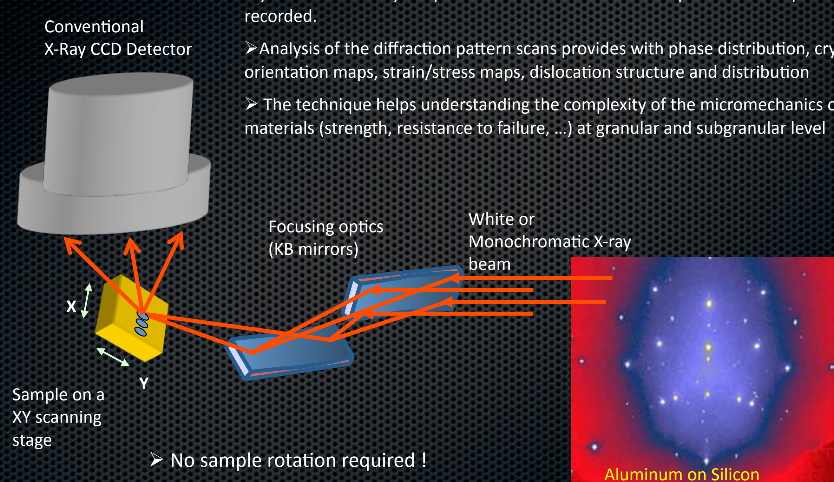
650 µm thick CCD

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



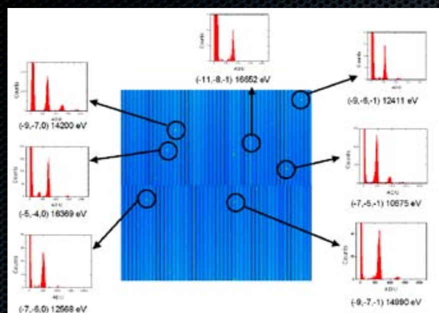
Example: X-Ray microdiffraction at the ALS

- 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

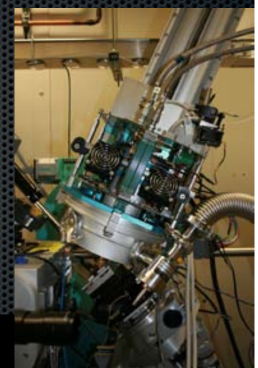


- No sample rotation required !

Microdiffraction



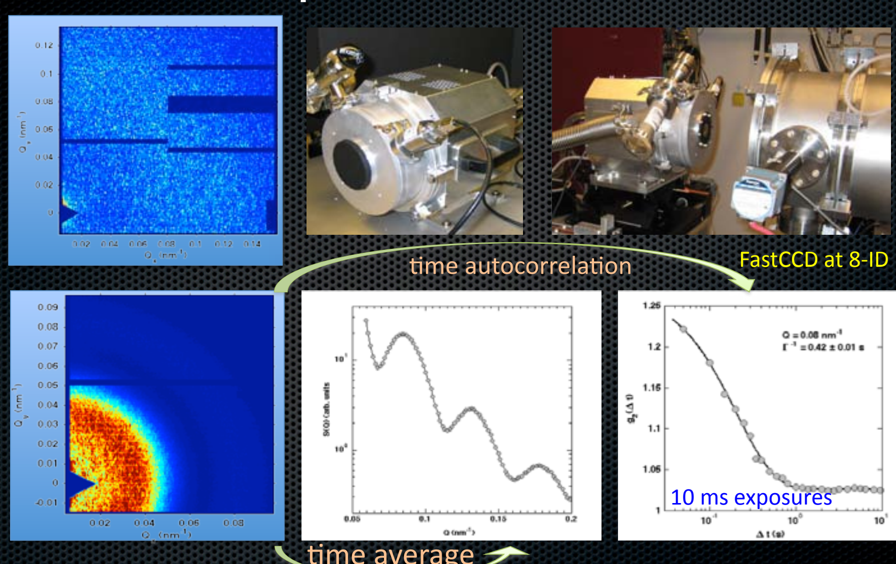
hours → seconds



KTP crystal indexed. The energy of each reflection can be measured …

- *Laue ab-initio indexation (of unknown structures, heterogeneous samples, …)*
- *Energy-resolved Laue diffraction for structure solution using Laue (pb of harmonics, scaling,…)*

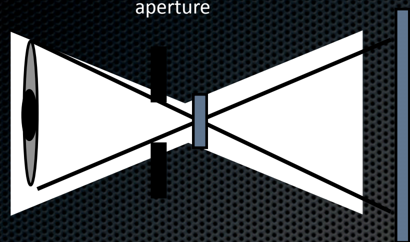
Example: XPCS at APS BL 8-ID

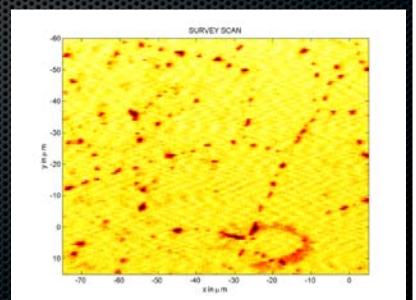


XPCS Example – 71nm radius latex spheres in glycerol at ~-20 deg C

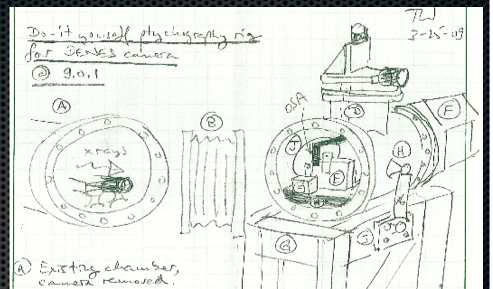
(Data courtesy of Suresh Narayanan and Alec Sandy)

Example: Coherent Imaging at ALS BL 9.0.1



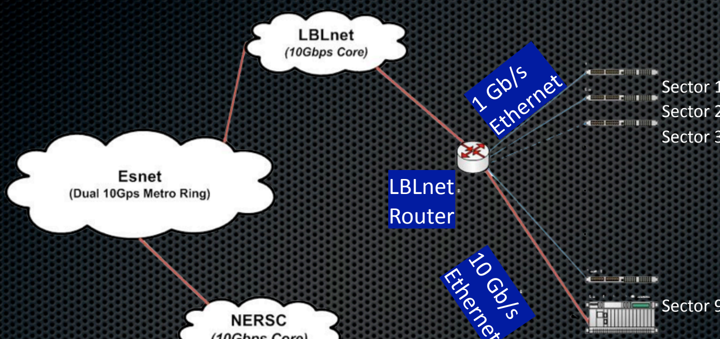


10 nm should be possible in near future

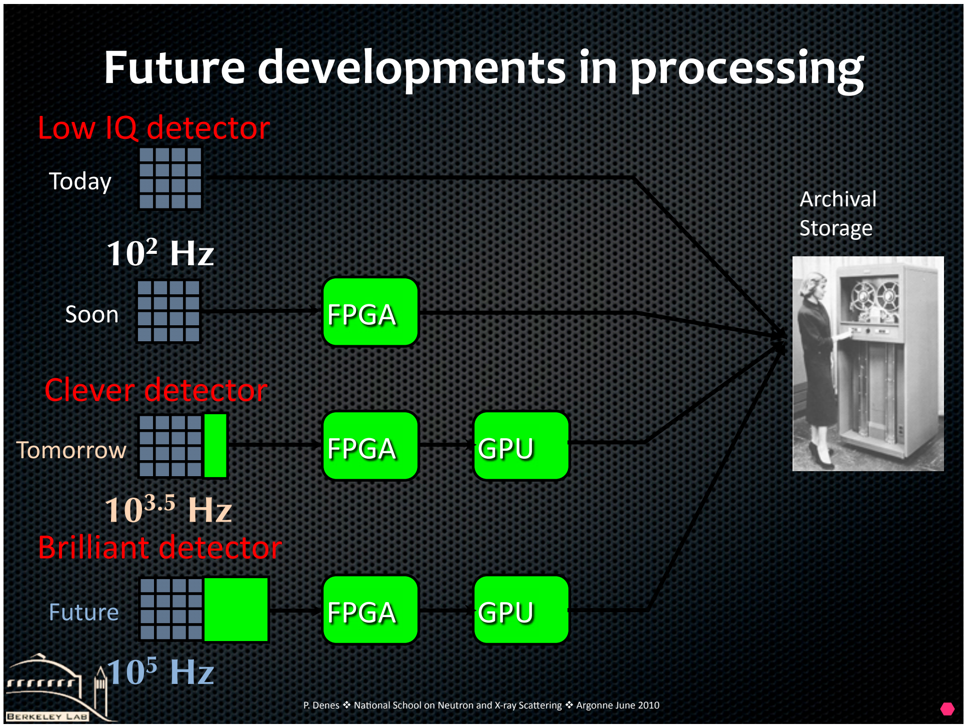


Soft X-ray Ptychography

Fast Readout = Lots of Data



Phase 1 - ATCA to LBLnet
Phase 2 - Install multiport 10 Gb/s switch at Sector 9


Future developments in processing
Low IQ detector
Today
10^2 Hz
Soon
FPGA
Archival
Storage
Clever detector
Tomorrow
FPGA
GPU
$10^{3.5}$ Hz
Brilliant detector
Future
FPGA
GPU
10^5 Hz
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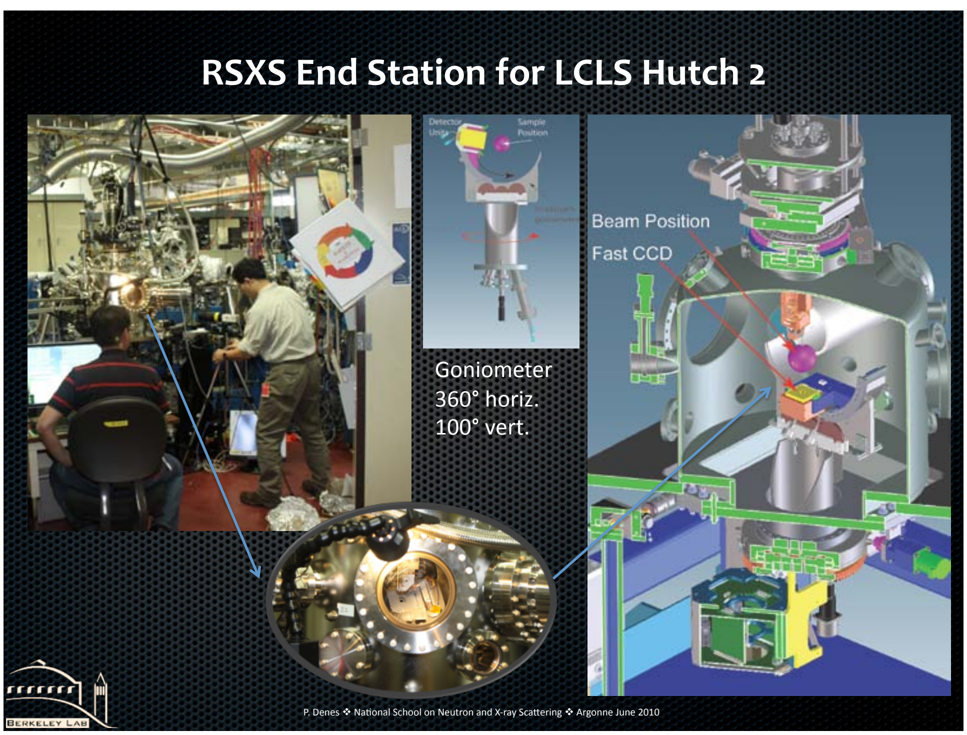
RSXS End Station for LCLS Hutch 2
Goniometer
360° horiz.
100° vert.
Beam Position
Fast CCD
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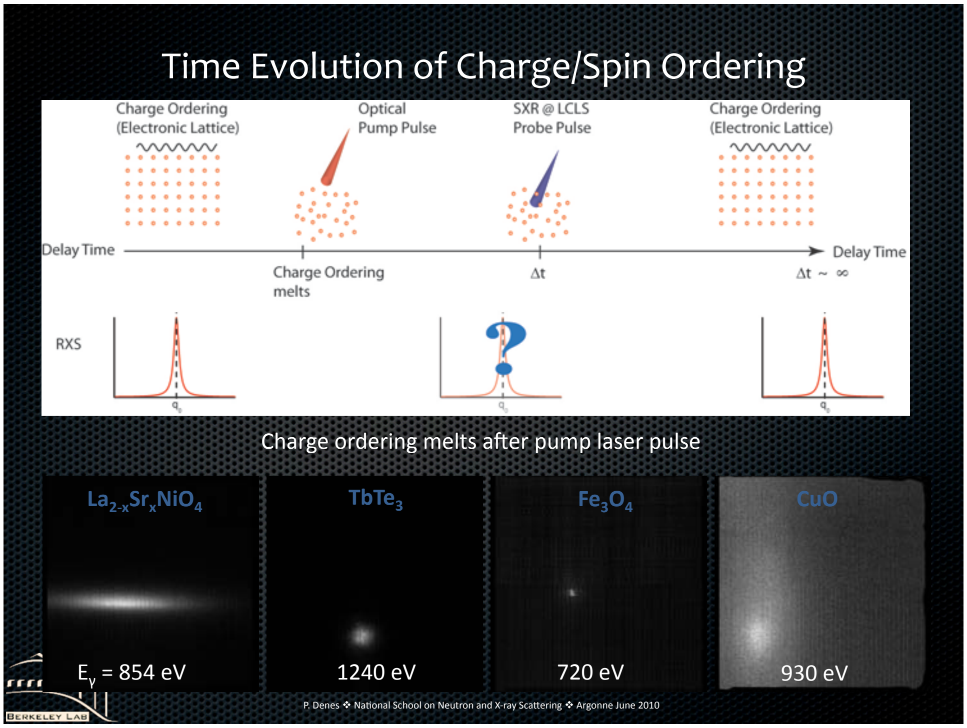
Time Evolution of Charge/Spin Ordering
Charge Ordering (Electronic Lattice)
Optical Pump Pulse
SXR @ LCLS Probe Pulse
Charge Ordering (Electronic Lattice)
Delay Time
Delay Time
Charge Ordering melts
Δt
Δt ~ ∞
RXS
Charge ordering melts after pump laser pulse
$La_{2-x}Sr_xNiO_4$
$TbTe_3$
Fe_3O_4
CuO
E_γ = 854 eV
1240 eV
720 eV
930 eV
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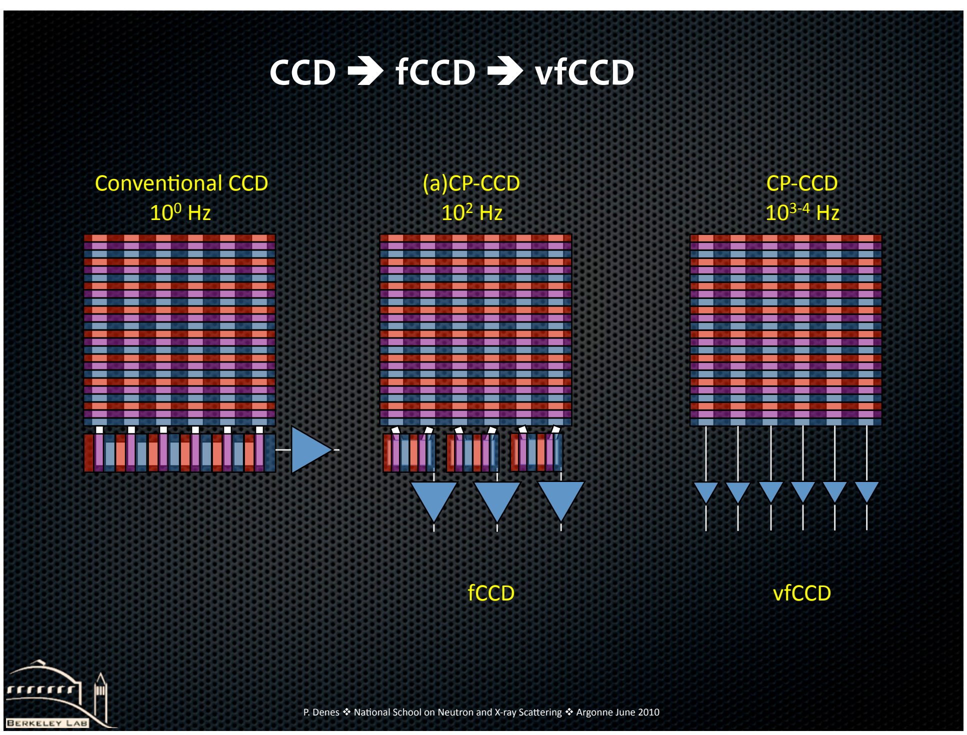
CCD → fCCD → vfCCD
Conventional CCD
10^0 Hz
(a)CP-CCD
10^2 Hz
CP-CCD
10^{3-4} Hz
fCCD
vfCCD
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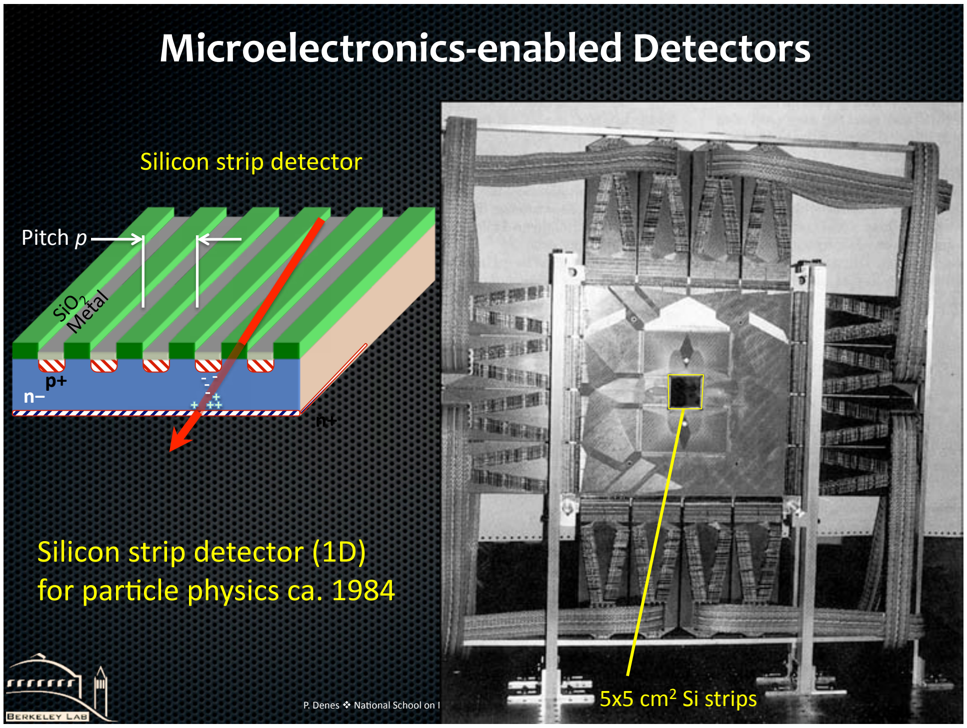
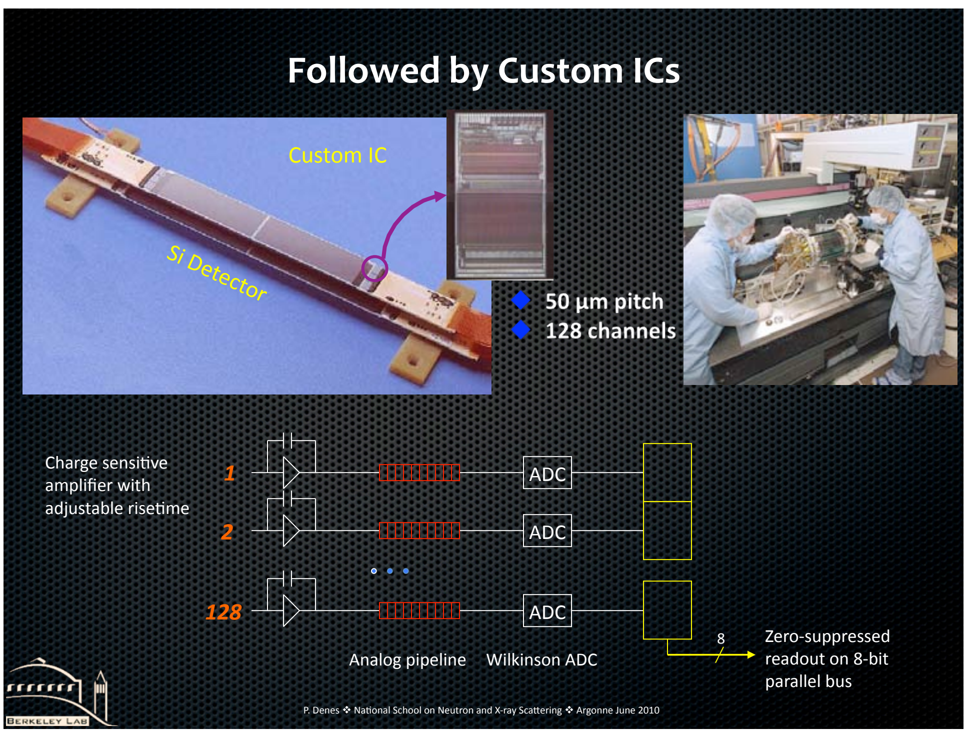

Microelectronics-enabled Detectors
Silicon strip detector
Pitch p
SiO2
Metal
p+
n−
Silicon strip detector (1D)
for particle physics ca. 1984
5x5 cm² Si strips
P. Denes ❖ National School on


Followed by Custom ICs
Custom IC
Si Detector
50 µm pitch
128 channels
Charge sensitive
amplifier with
adjustable risetime
1
2
128
ADC
ADC
ADC
Analog pipeline
Wilkinson ADC
8
Zero-suppressed
readout on 8-bit
parallel bus
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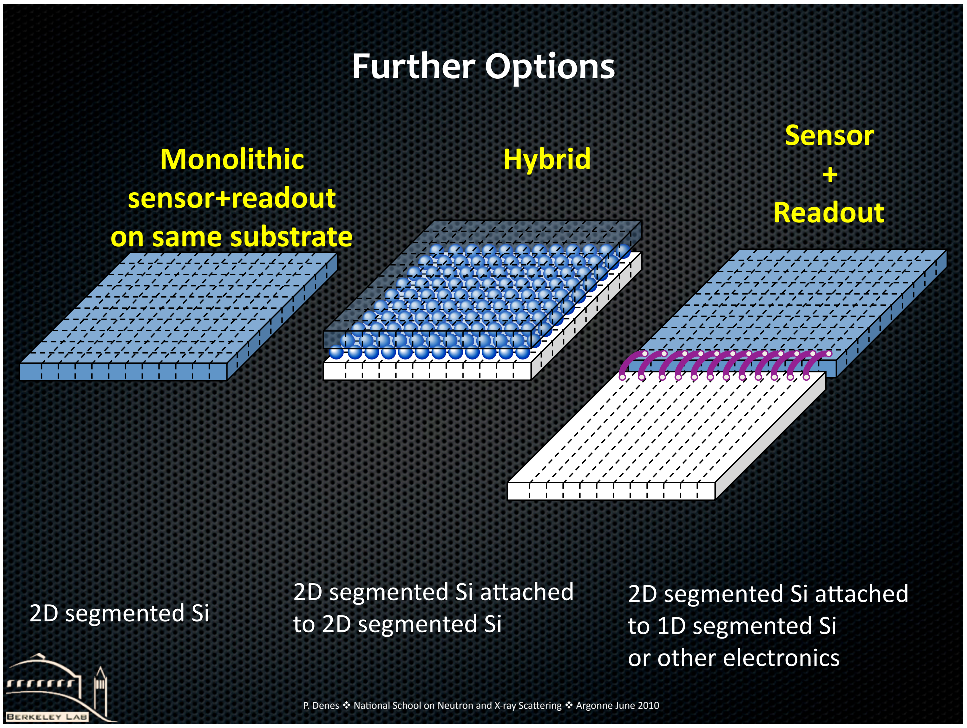
Further Options
Monolithic sensor+readout on same substrate
Hybrid
Sensor + Readout
2D segmented Si
2D segmented Si attached to 2D segmented Si
2D segmented Si attached to 1D segmented Si or other electronics
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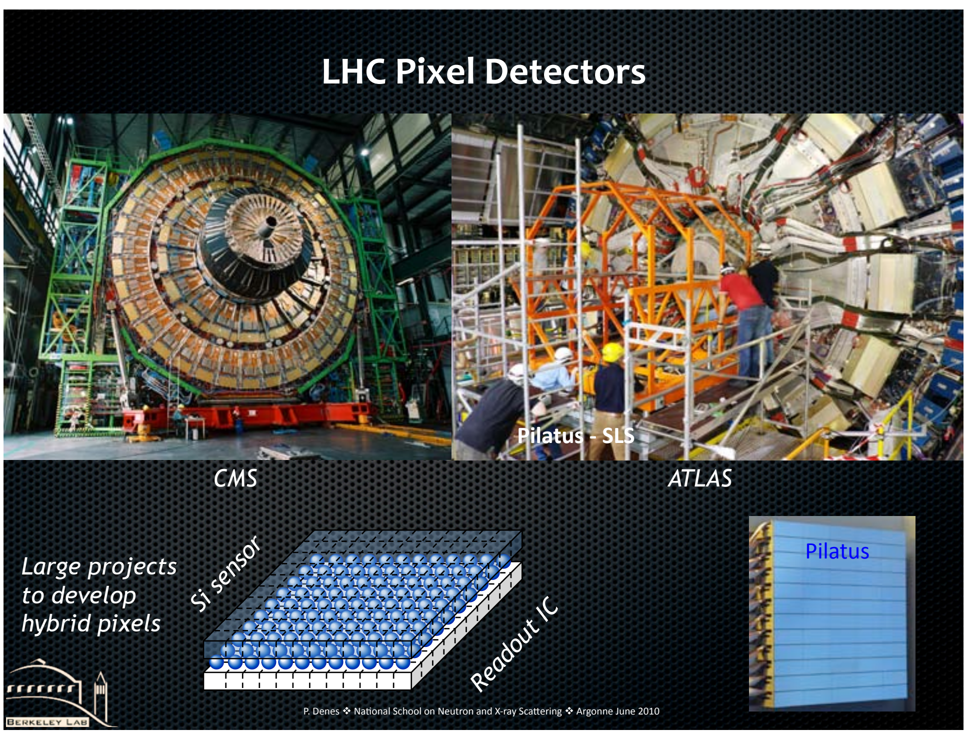
LHC Pixel Detectors
Pilatus - SLS
CMS
ATLAS
Large projects to develop hybrid pixels
Si sensor
Readout IC
Pilatus
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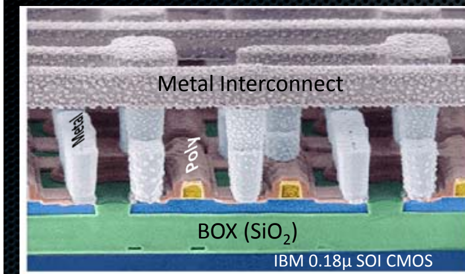
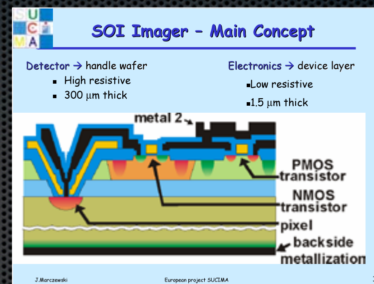
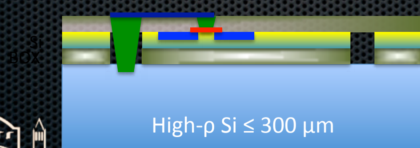
R&D: SOI ($IQ_{SOI} > IQ_{BULK}$)

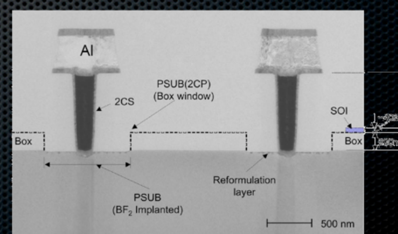




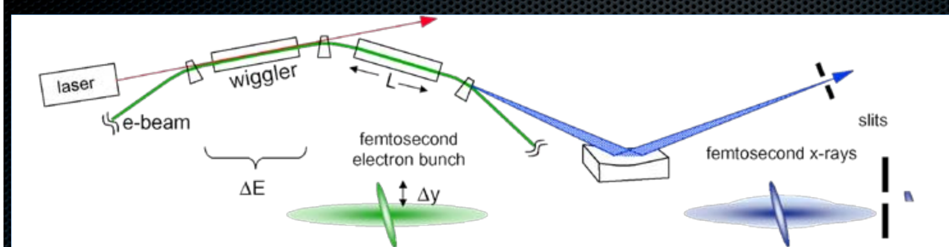
Silicon-on-high resistivity, thick, fully depleted detector-grade silicon

Oki SOI Process (KEK)





Example: ALS femtoslicing BL 6.0

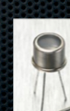


Zholents and Zolotorev, Physical Review Letters **76**, 916 (1996)., Schoenlein et al., Science **287**, 223 (2000)

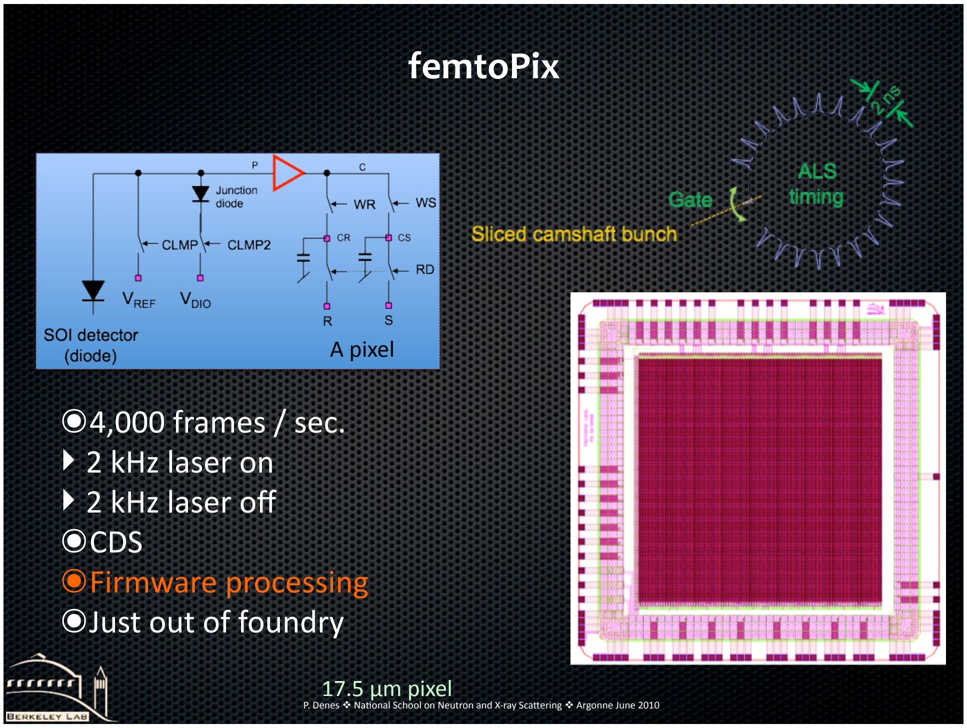
200 fs pulses
But low flux - 10^5 γ/s/0.1% BW

Millions of dollars invested
- in hardware
- in time to make this work

Detector used for last decade



Perkin Elmer C30902: single element APD, $100


femtoPix
P
C
Junction diode
WR
WS
CLMP
CLMP2
CR
CS
RD
VREF
VDIO
R
S
SOI detector (diode)
A pixel
2 ns
ALS timing
Gate
Sliced camshaft bunch
4,000 frames / sec.
2 kHz laser on
2 kHz laser off
CDS
Firmware processing
Just out of foundry
17.5 µm pixel
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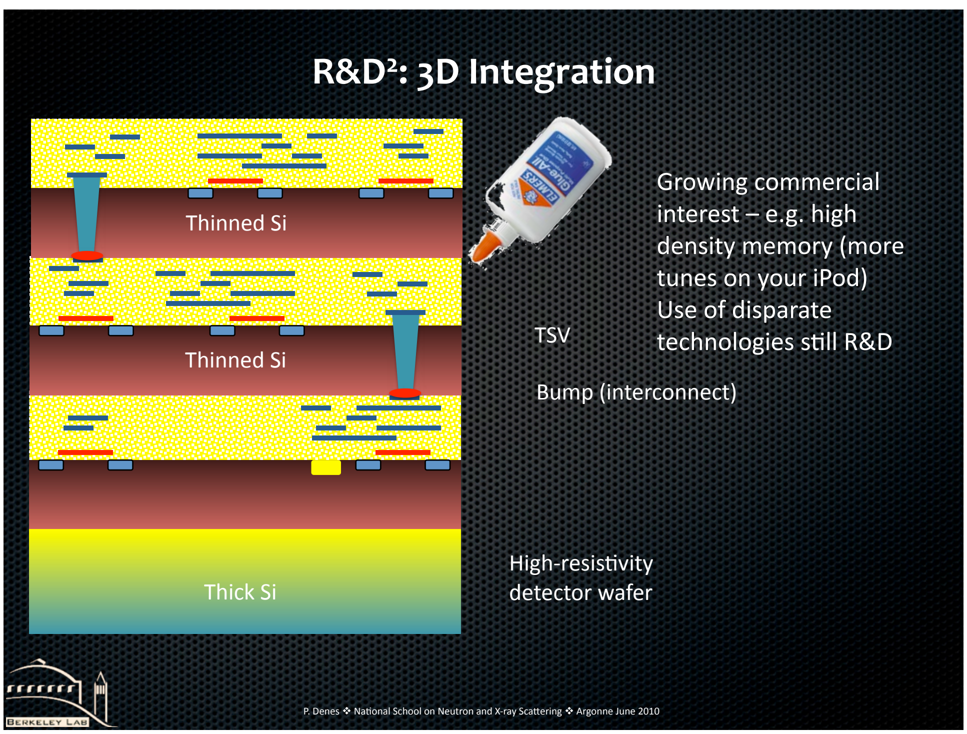
R&D²: 3D Integration
Thinned Si
Thinned Si
Thick Si
Growing commercial interest – e.g. high density memory (more tunes on your iPod)
Use of disparate technologies still R&D
TSV
Bump (interconnect)
High-resistivity detector wafer
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(Direct Detection) 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!)

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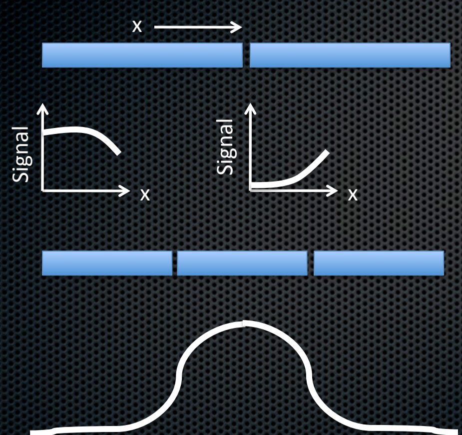
Pixel Size, Diffusion and Analog vs. Digital

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 – but center-of-gravity can give sub-pixel (µm) position resolution
(while adding noise!)

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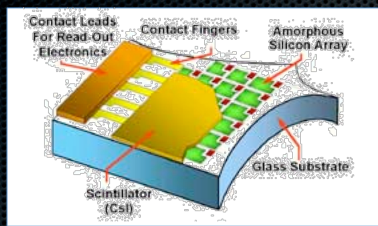
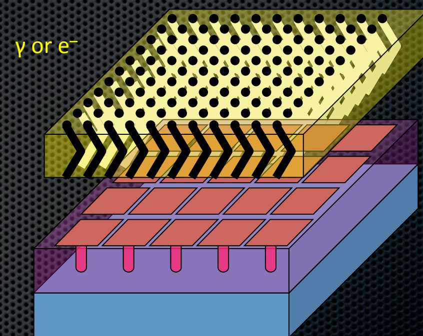
Other Examples of 2D Detectors



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



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

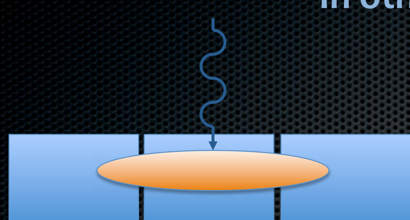
Summary (1)

- 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
  - $0 \leq E_e \leq E_\gamma$ 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)

In other words



- Photon incident at (0,0)
  - Probability Q.E. of creating a detectable* signal
  - Signal $\propto 1/\eta$
    - Photostatistics
    - Fano factor
  - Spatial resolution (PSF, MTF) (diffusion)
- *Detectable = f(Electronics)
  - DQE ~ 1/ [Electronic] Noise
    - Many ways to say 5σ (c.f. Rose criterion)
- $\sigma(E) \sim F \oplus$ Noise
- $\sigma(t) \sim$ Noise

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
- Semiconductor detectors!
- DAQ, computing and processing!
- Si excellent 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)

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Questions?

Grateful acknowledgements to:
ALS Experimental Systems Group
ALS Scientific Systems Group
APS Beamline Technical Support Group
Electronic Systems Group
Integrated Circuit Design Group
MicroSystems Laboratory
National Center for Electron Microscopy
Physics Division
Engineering Division