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Radiation Detectors and Signal Processing

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These course notes and additional tutorials at
http://www-physics.lbl.gov/~spieler

More detailed discussions in
H. Spieler: Semiconductor Detector Systems, Oxford University Press, 2005

WHY?

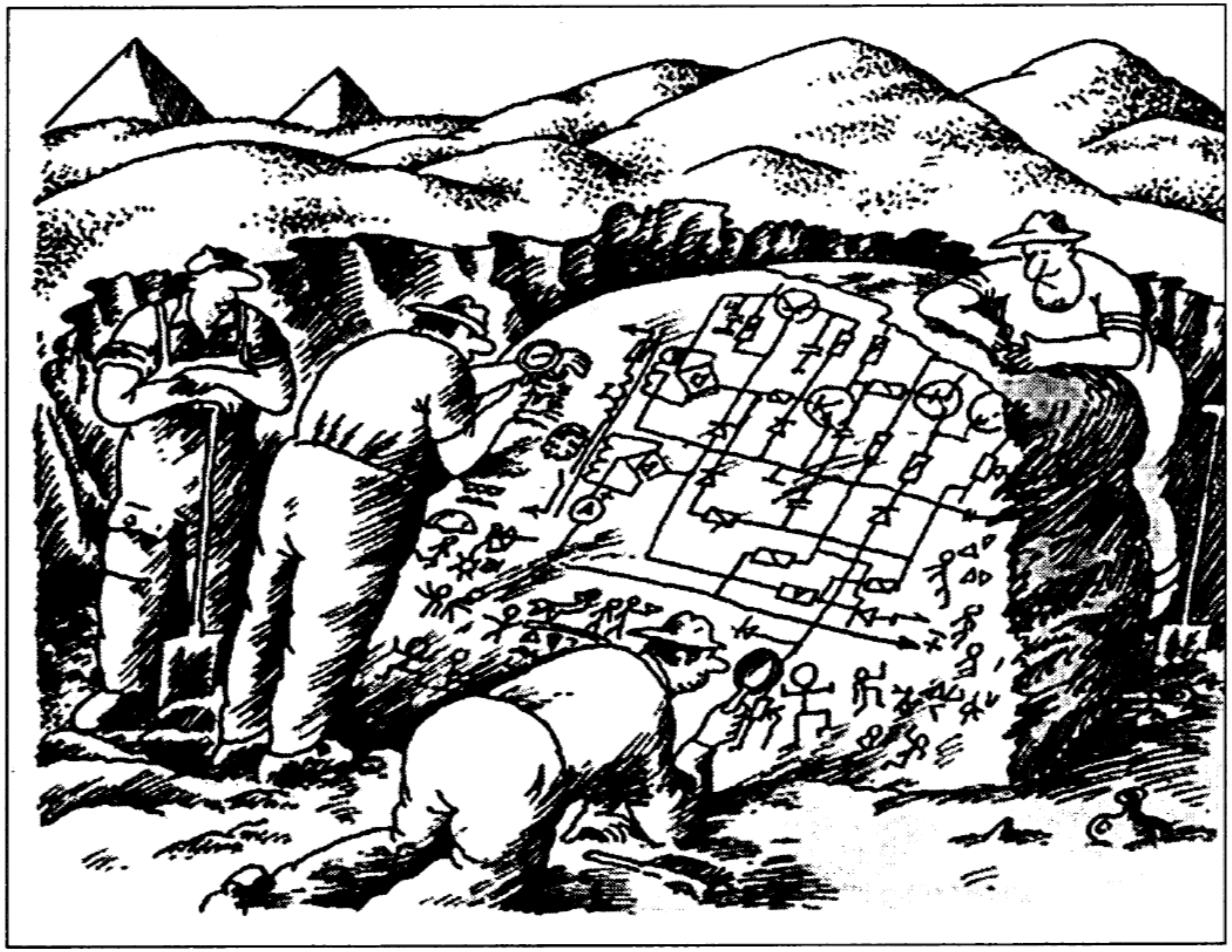
Radiation is the only observable in processes that occur on a scale that is either too brief or too small to be observed directly. It also is the only access to processes that are very far away.

Originally developed for atomic, nuclear and elementary particle physics, radiation detectors now are applied in many diverse areas of science, engineering and everyday life.

Progress in science is driven not just by the interplay of theory and experiment, but also by breakthroughs in instrumentation.

On a very practical level, experiments don't always work.

> Experimentalists must understand apparatus to recognize flaws in data and troubleshoot system. Often requires some digging.



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1. Some Applications and Example Detectors

2. The Signal

   Magnitude

   Fluctuations

3. The Problem

   Signal and noise spectra

   Filtering

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Some examples as introduction….

- Imaging in astronomy
  (thanks to Steve Holland, Engineering Div. LBNL)

- Medical imaging –
  positron emission tomography
  (thanks to Bill Moses, Life Sciences Div. LBNL)

- Detection of trace elements by x-ray fluorescence
  (thanks to Joe Jaklevic, Engineering Div. LBNL)

- High-energy physics

- Failure analysis in silicon integrated circuits

- Detection of gravity waves

1. Astronomical Imaging

(thanks to Steve Holland, Engineering Div. LBNL)

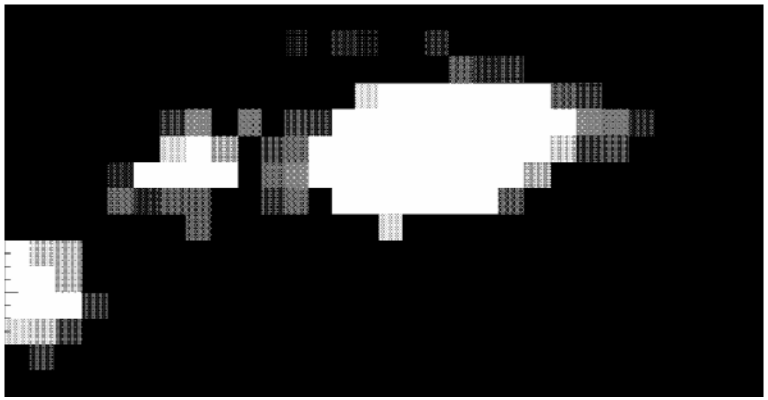
Practically all faint light imaging in astronomy relies on electronic sensors

- visible light
- IR
- UV
- x-rays

Example: Supernova Search

(S. Perlmutter et al., see www-physics.lbl.gov)

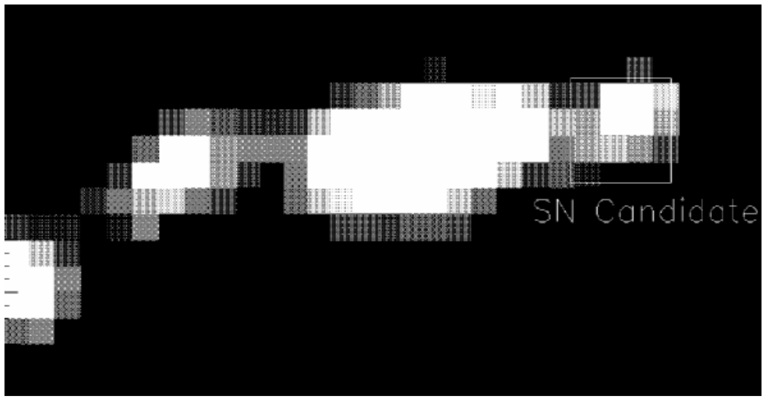
Reference Image



New Galaxy Image

SN Candidate

↓



The image sensors are arrays of pixelated semiconductor detectors, called CCDs

(charge coupled devices).

Pixel size typ. 10 – 30 μm.

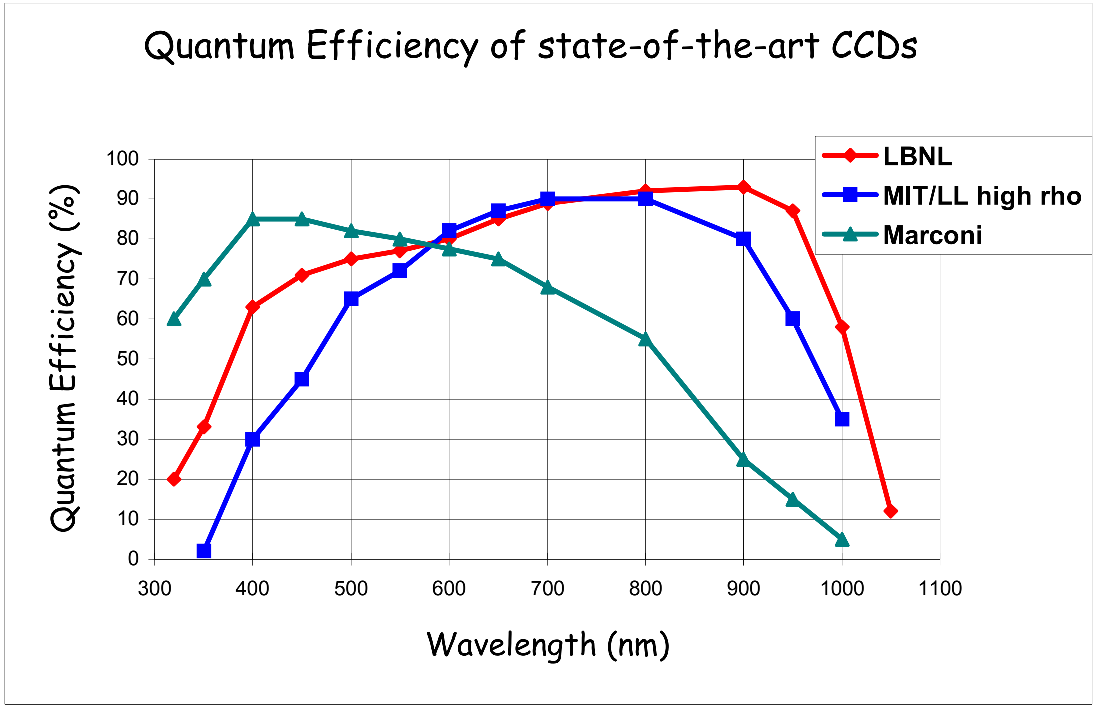
Planetary Nebula NGC7662 (CCD at -120° C)

Photon flux in outer halo
is ~35 photons/s per pixel

Generated from 100 s exposures
at different λ, Lick 1m trelescope

Similar CCDs are widely used in camcorders, but astronomical imaging requires much greater sensitivity and the ability to record *very* small signals (order 1 electron).

At LBNL a novel CCD has been developed in conjunction with the supernova group.
Utilizes technology developed for high energy physics.



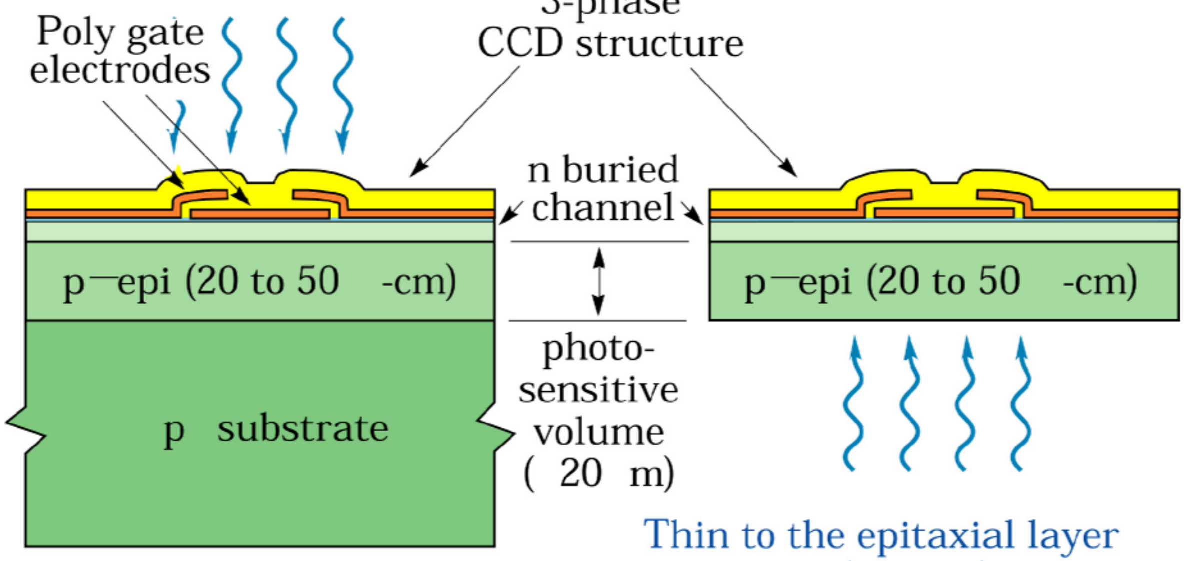
Use of a fully depleted substrate provides extended red response.

Since no thinning is required, yields increase and costs drop by a factor of 10 – 100.

Conventional CCD Structure

Front-illuminated CCD:

Thinned CCD with back-illumination:



Thin to the epitaxial layer thickness (20 m)

Drawbacks:

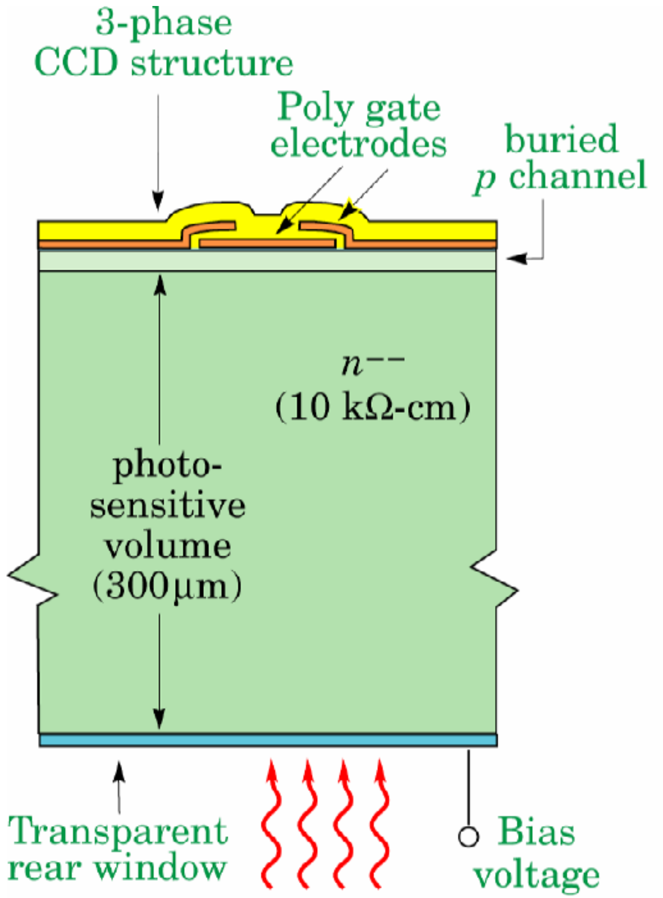
1) Poor blue response due to absorption in polysilicon gate electrodes
2) Poor near-IR response due to thinness of the epitaxial layer
3) Interference patterns due to gate structure

Drawbacks:

1) Thinning is difficult and expensive
2) Poor near-IR response
3) Interference (fringing)
4) Lateral diffusion in field-free region (degraded PSF)

Fully Depleted CCD

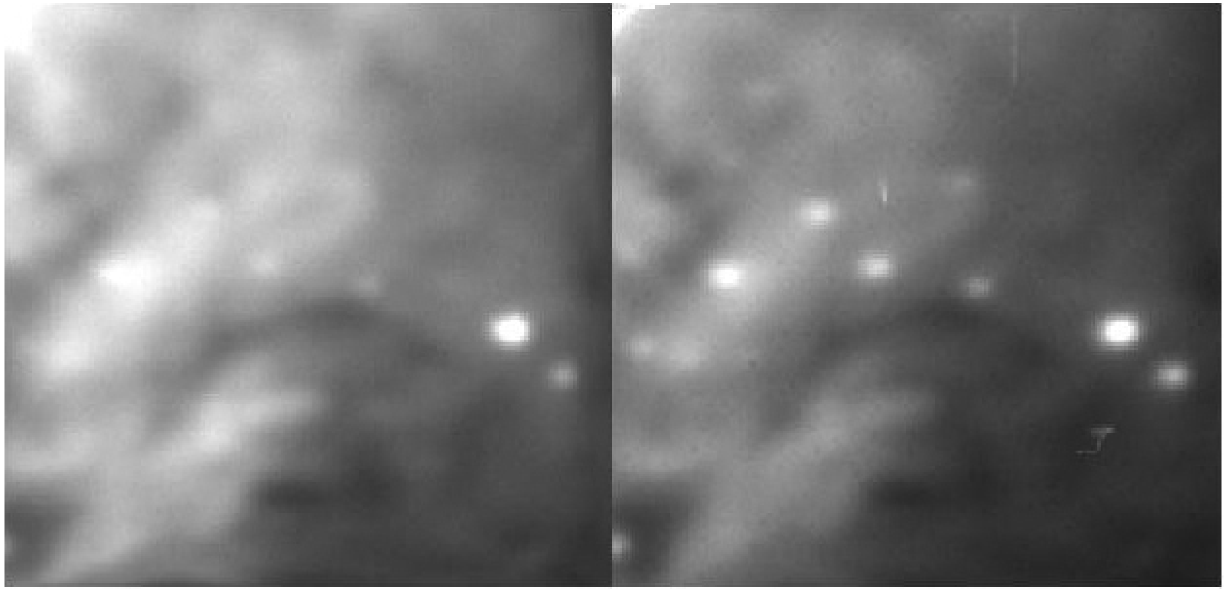
- high resistivity n-type substrate,
  fully depleted
- backside illumination
- transparent window with
  antireflection coating
  thin for good blue response
- 300 μm active thickness
  ⇒ good QE up to λ= 1 μm
- no costly thinning of devices



Comparison between thinned CCD (bottom) and deep depletion device.

Interstellar dust tends to absorb in the blue, so extended red response of LBNL CCD shows features obscured in thinned CCDs.

"Conventional" thinned CCD | Deep Depletion CCD

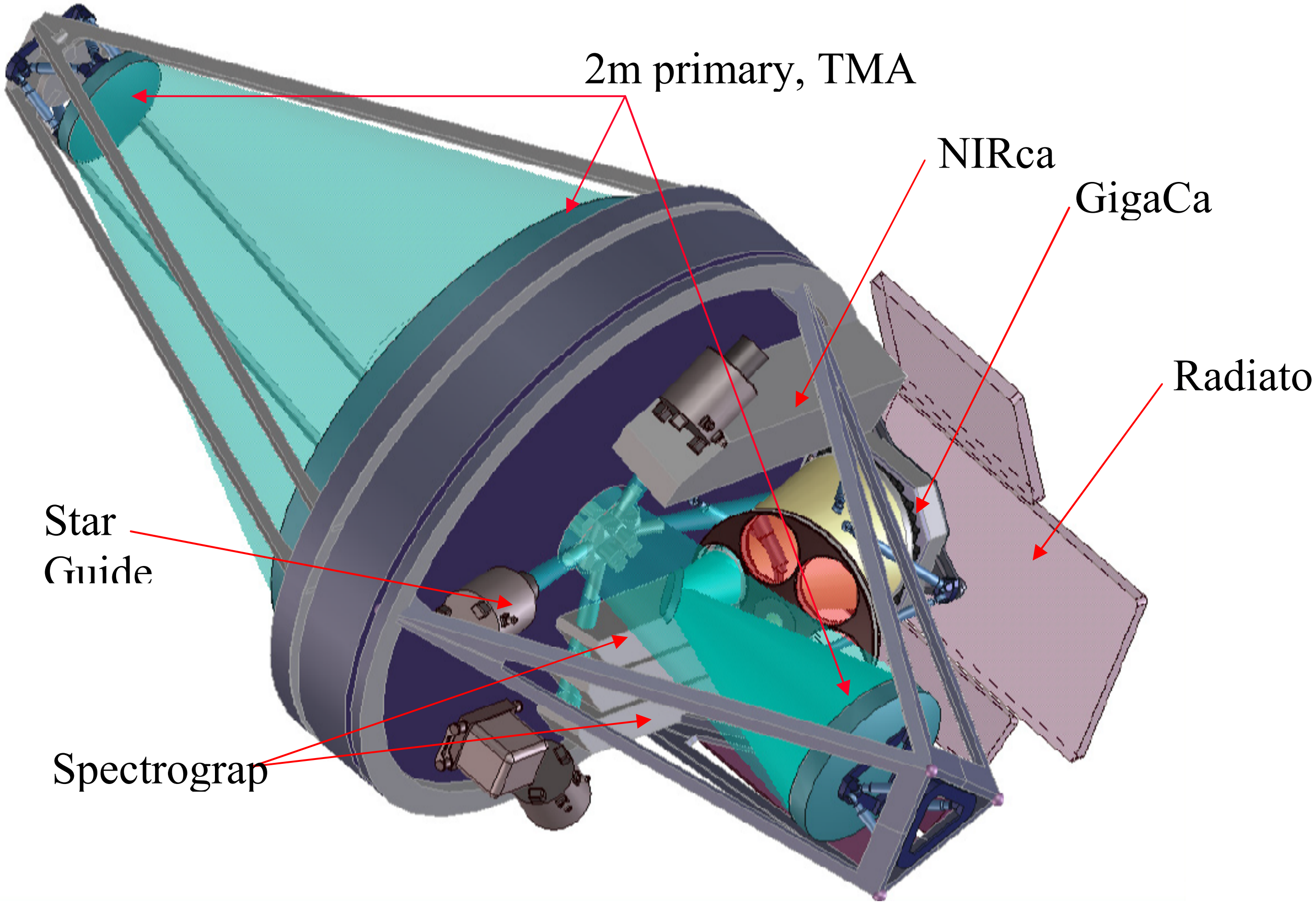


Lick 1m telescope, 4-Dec-1996

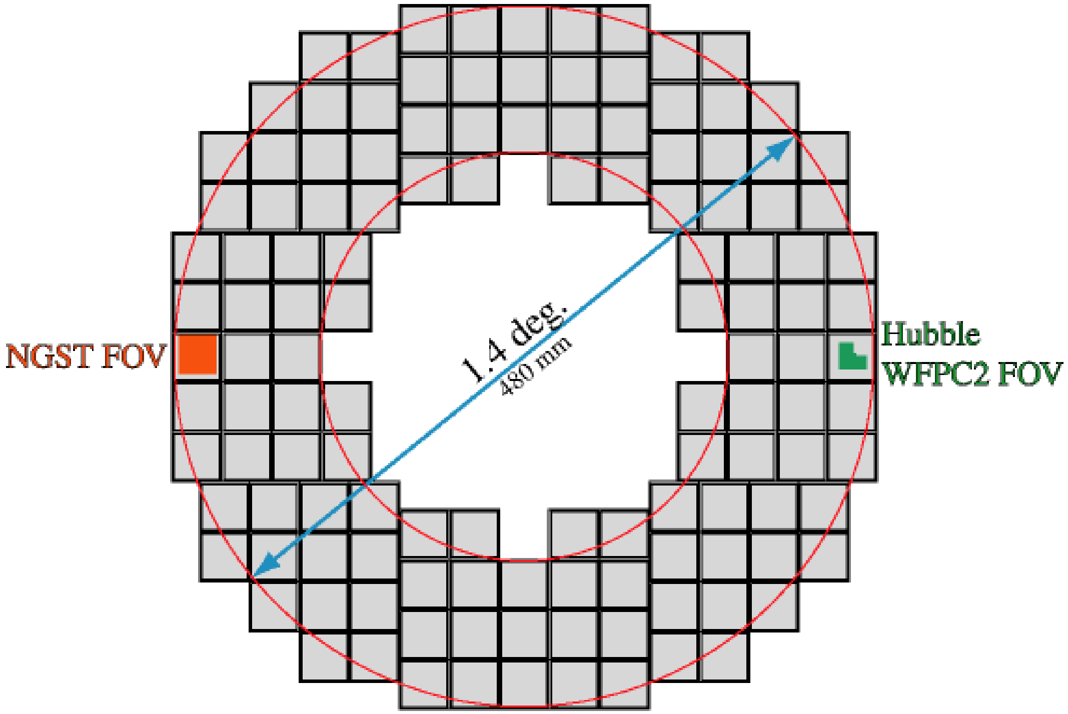
Low cost CCDs core of a new project: SuperNova Acceleration Probe – SNAP

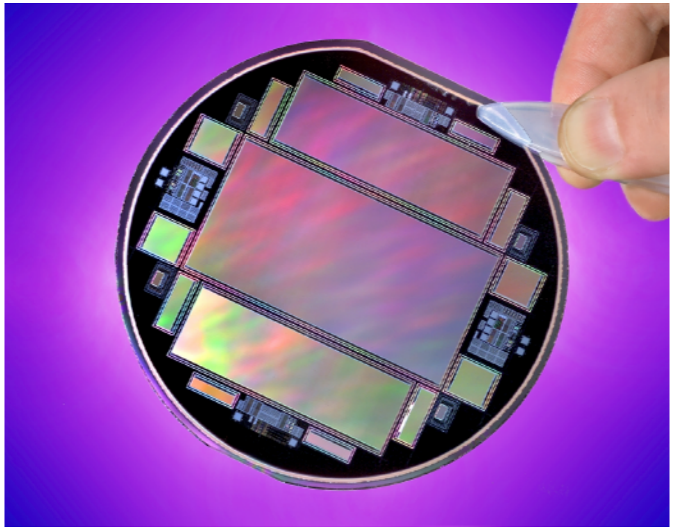
Extend supernova measurements to high red-shifts.

Gain better understanding of “dark energy”.



Combine many CCDs to form Gigapixel array





100 mm test wafer

includes

2K x 4K (15 μm),

1.5K x 4.8K (10.5 μm)

and

1.3K x 4.2K (12 μm) CCDs

+ test structures

new runs on 150 mm wafers.

For more information see http://snap.lbl.gov

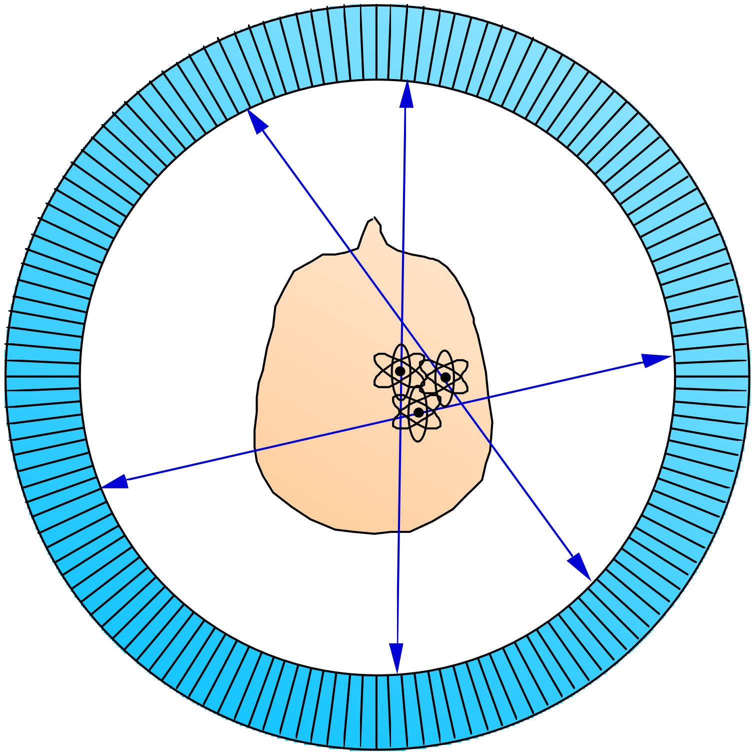
2. Medical Imaging – Positron Emission Tomography

(thanks to Bill Moses, Life Sciences Div. LBNL)

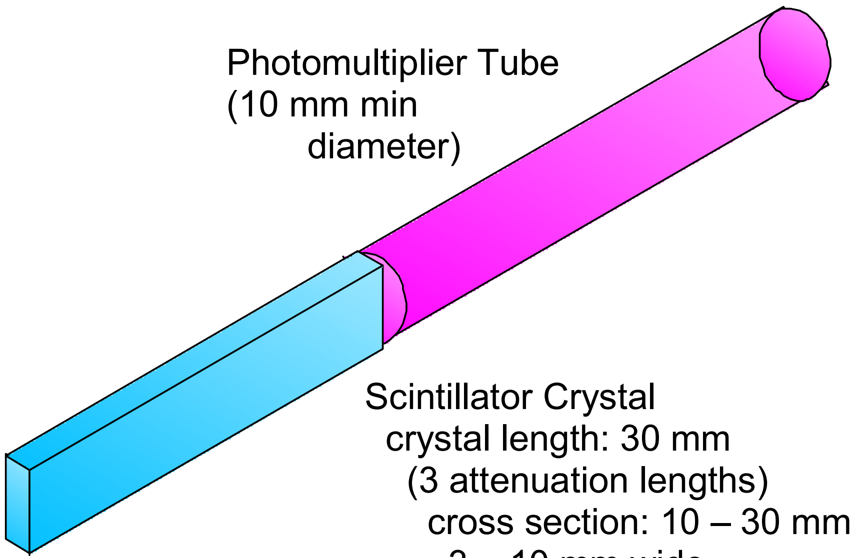
What is Positron Emission Tomography (PET)?

- Patient injected with drug having β^+ emitting isotope.
- Drug localizes in patient.
- Isotope decays, emitting β^+.
- β^+ annihilates with e^- from tissue, forming back-to-back 511 keV photon pair.
- 511 keV photon pairs detected via time coincidence.
- Positron lies on line defined by detector pair (a *chord*).

Forms planar image of a “slice” through the patient.

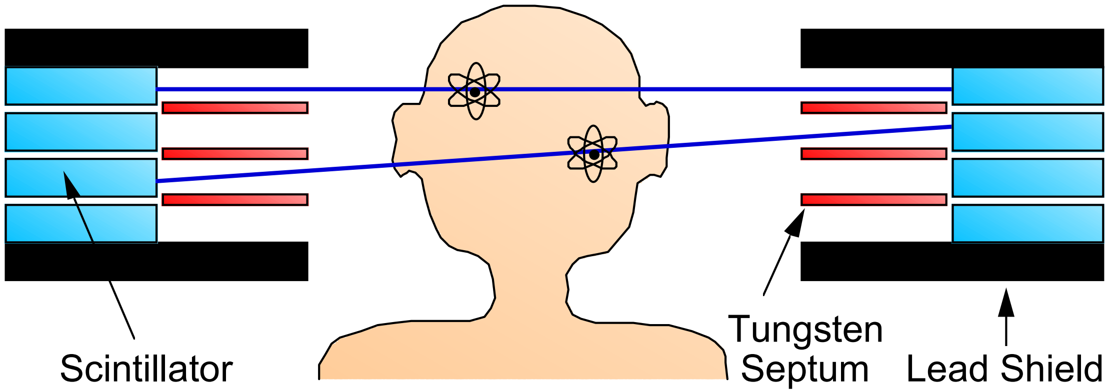


Individual Detector Element



Scintillator converts photon energy into light
Photomultiplier tube converts light into electrical signal

Multi-Layer PET Cameras



- Can image several slices simultaneously
- Can image cross-plane slices
- Can remove septa to increase efficiency ("3-D PET")

However,

- More expensive

Planar images are "stacked" to form 3-D image

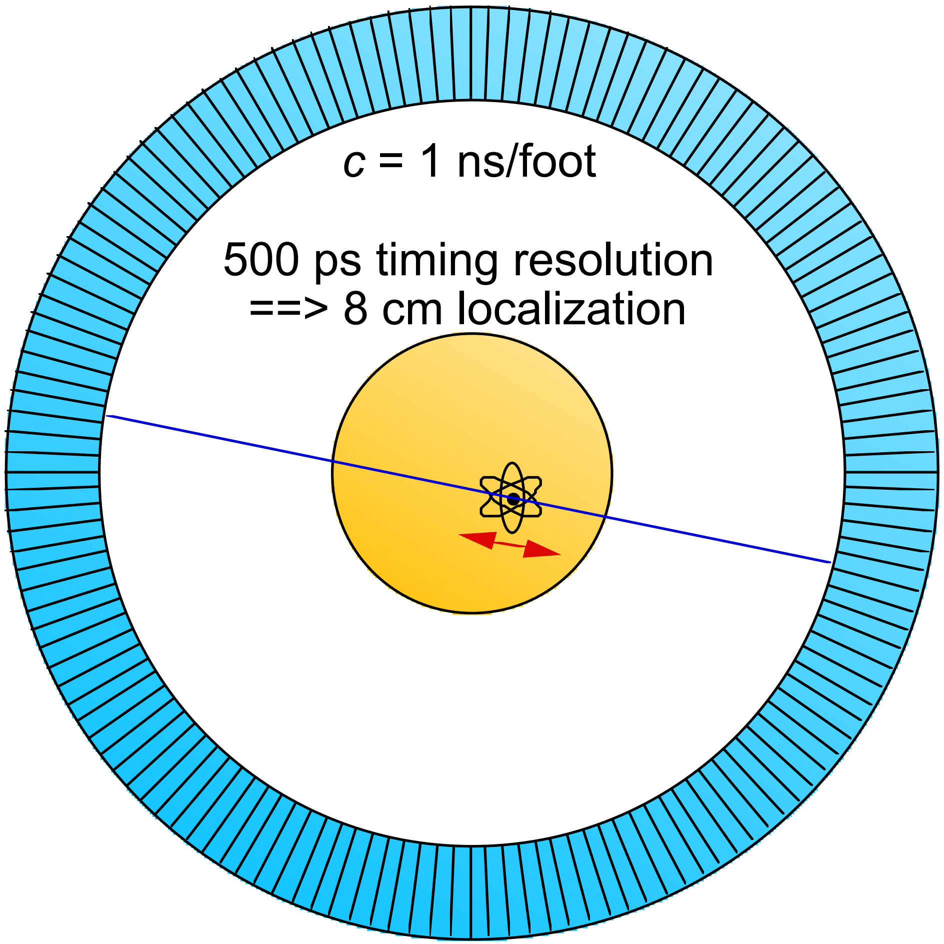
Time-of-Flight Tomograph

- Utilize difference in time of arrival between the two detectors
- Can localize source along line of flight
- Time-of-flight information reduces noise in images

However,

- Difficult to control timing of all detectors
- More expensive

Typically used to augment “standard” PET to reduce background.



Typical Tomograph Parameters

- Patient port 30 cm diameter (head machine) or 50 cm diameter (body machine).
- 3.5 to 6 mm scintillator crystal width.
- 24 to 48 layers, covering 15 cm axially.
- 8 liters of BGO scintillator crystal.
- 500 photomultiplier tubes.
- "Several" million dollars

    Scintillator is 25% of total parts cost

    PMTs are 25% of total parts cost

    Next component is <5% total parts cost

Applications

Tumor vs. Necrosis

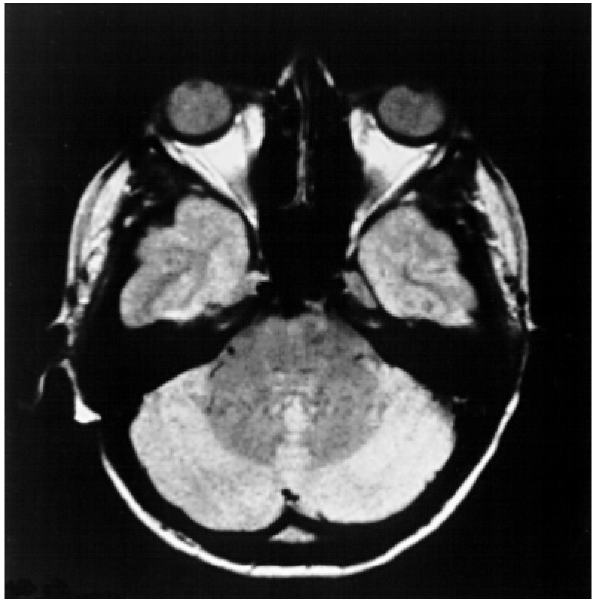
- Brain tumor treated by radiation therapy.
- Symptoms recur
- Too much or too little radiation
- Check with PET

Too much radiation $\Rightarrow$ dead area

Too little radiation $\Rightarrow$ rapid metabolism
blood circulation
increases
tracer concentration

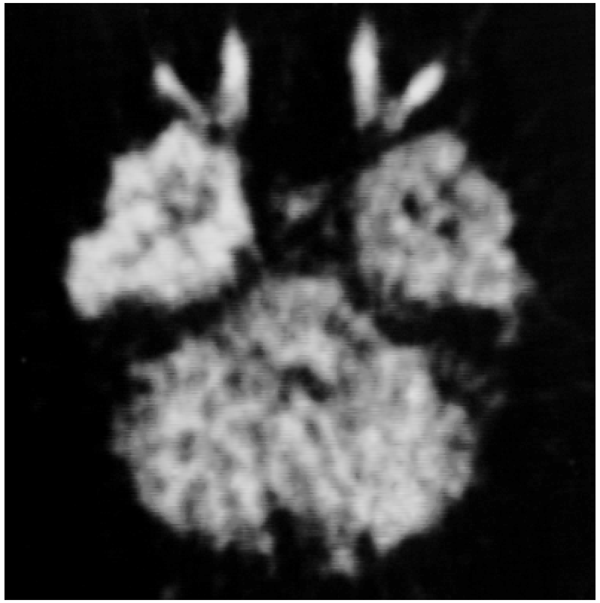
Epilepsy – Comparison of NMR with PET

NMR
(now called MRI)



PET

note bright left
frontal lobe of brain



NMR and PET are complementary.

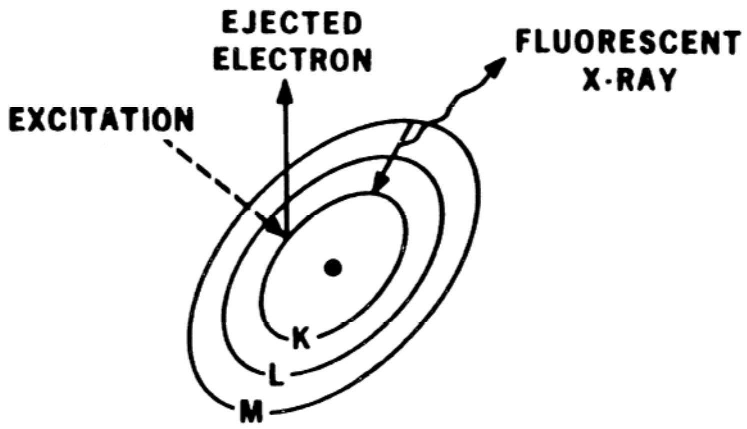
PET depends on rate of metabolism
– allows dynamic measurements.

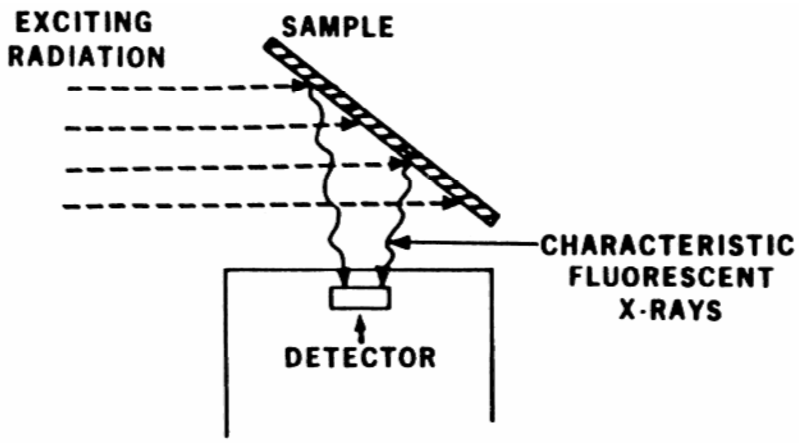
3. X-Ray Fluorescence

(thanks to Joe Jaklevic, Engineering Div. LBNL)

When excited by radiation of sufficient energy, atoms emit characteristic x-rays that can be used to detect trace contaminants.

Experimental Arrangement





The incident radiation can be broad-band, as long as it contains components of higher energy than the atomic transitions of the atoms to be detected.

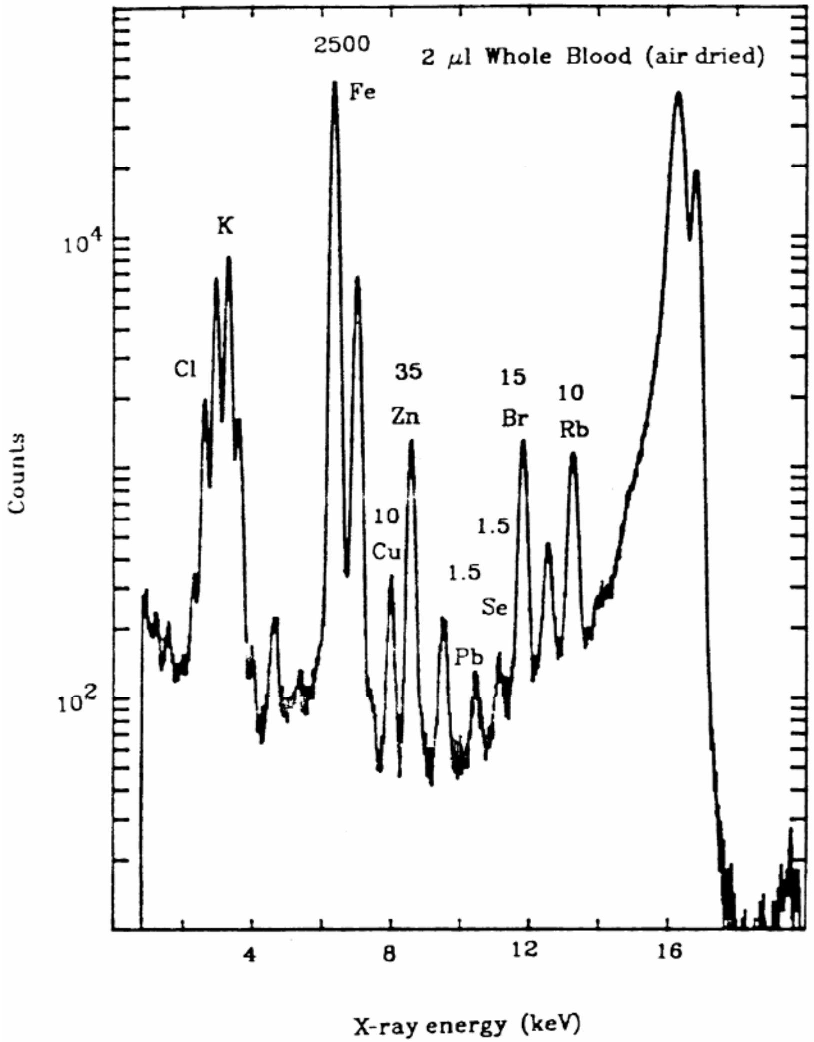
X-ray fluorescence can provide high sensitivity with small samples.

Spectrum taken from 2 μl (2 mm^3) of blood.

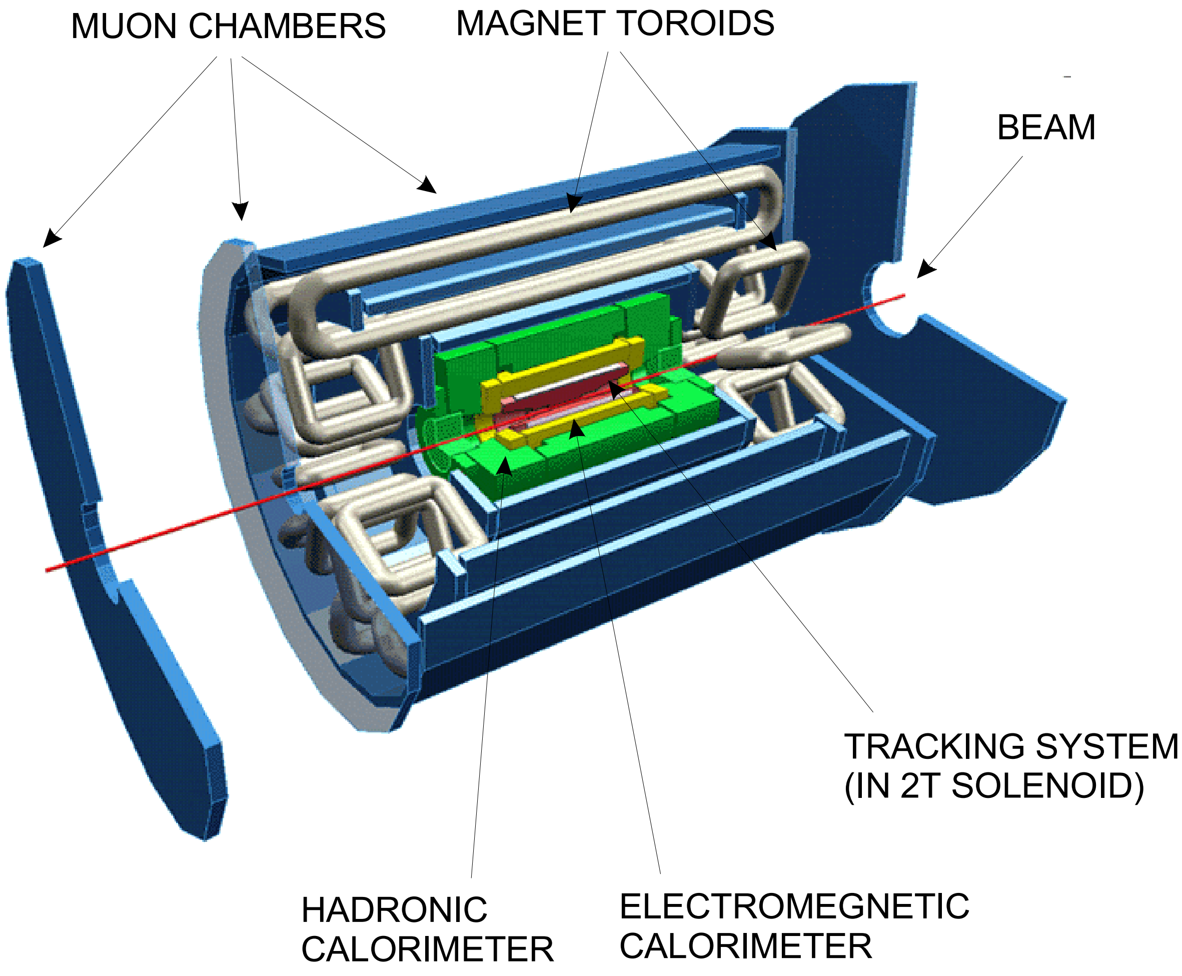
Concentrations are given in parts per million

Note the Pb peak

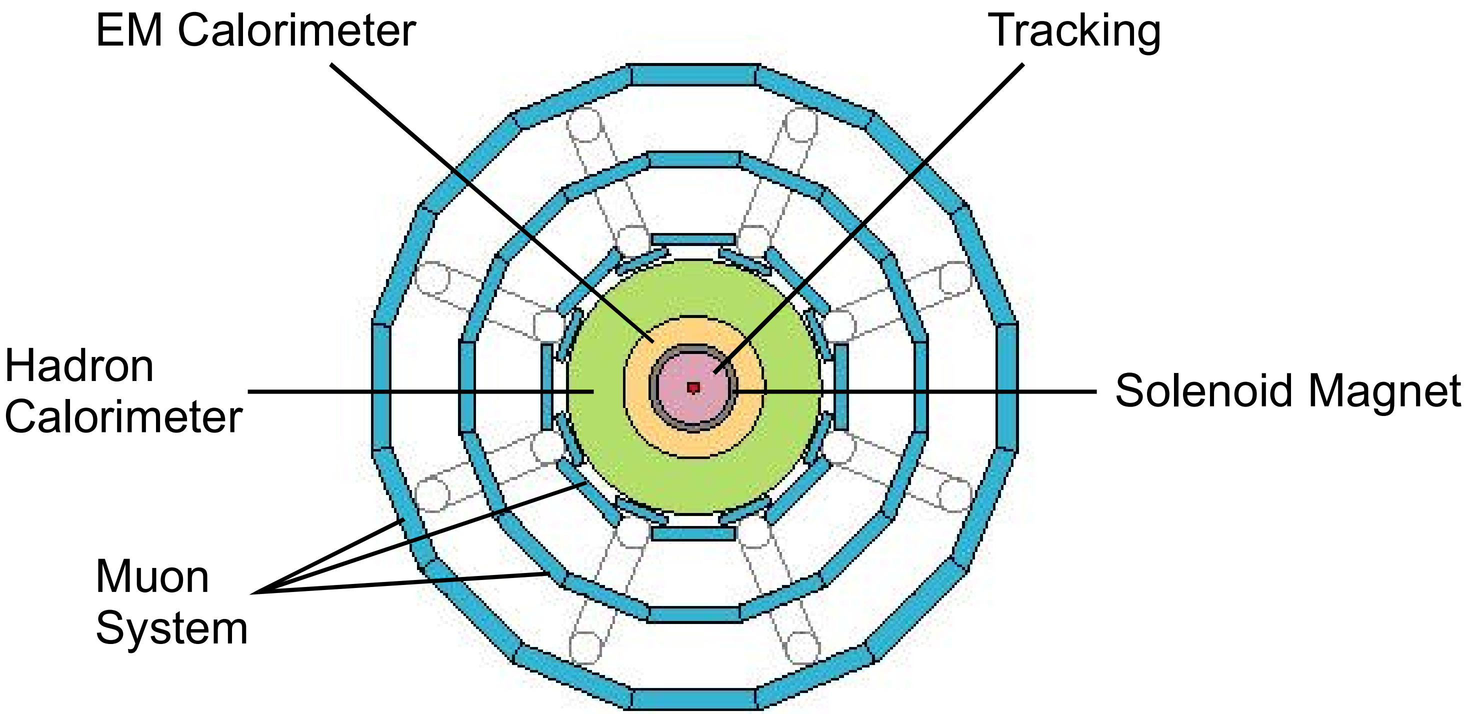
(measurement taken before the introduction of unleaded gasoline).



4. A High Energy Physics Detector (ATLAS)



Schematic End-View



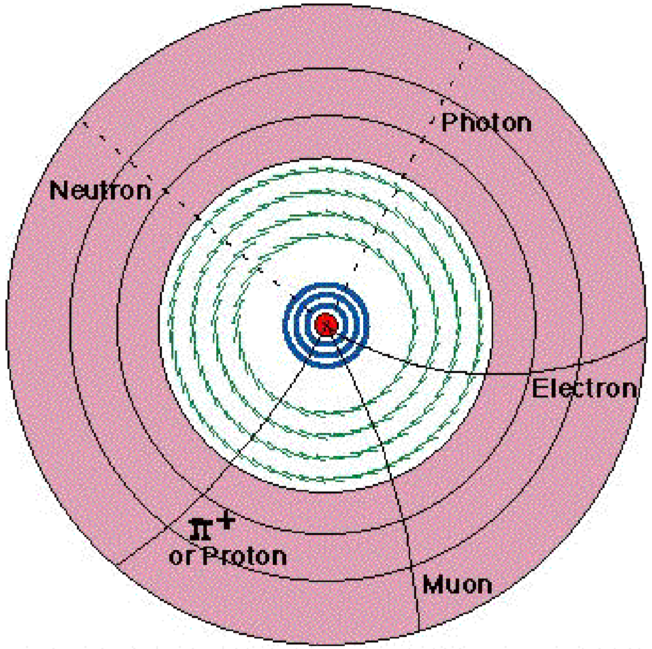
Tracking in 2T magnetic field

Separate particles by

sign of charge

magnetic rigidity q/m

$\Rightarrow$ position measurement layer by layer to reconstruct tracks



Inner layers: Silicon pixel and strip detectors

Measure presence of hit

Outer layers: “straw” drift chambers

timing provides position information (see muon system)

Calorimetry

Particles generate showers in calorimeters

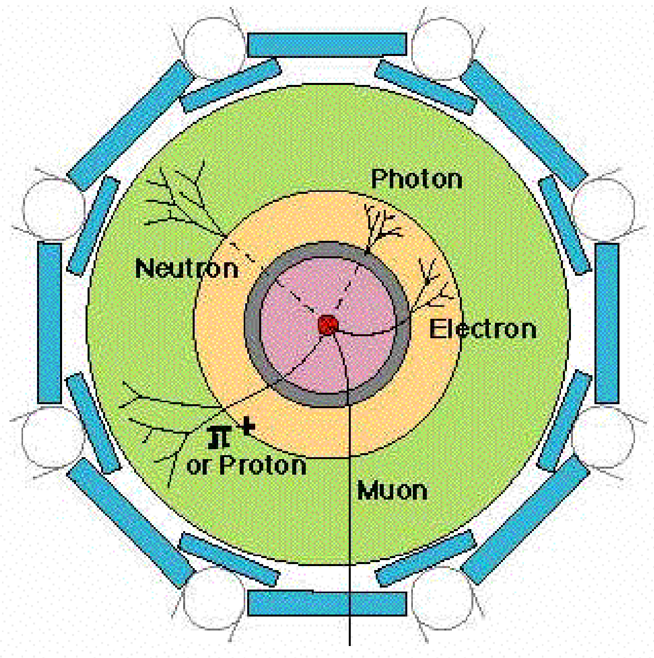
Electromagnetic Calorimeter (yellow):

Absorbs and measures the energies of all electrons, photons

Hadronic Calorimeter (green)

Absorbs and measures the energies of hadrons, including protons and neutrons, pions and kaons

(electrons and photons have been absorbed in EM calorimeter)



⇒ amplitude measurement

position information provided by segmentation

Muon System

Muons are the only charged particle that can travel through all of the calorimeter material and reach the outer layer.

muons with energy above, say, 5 GeV will penetrate about 5 meters of steel, whereas hadrons of almost any energy are completely absorbed in about 1.5 meters of steel.

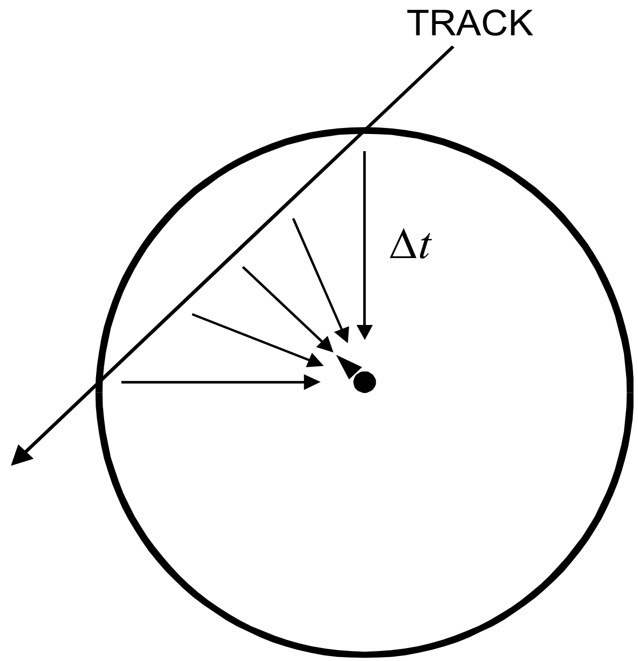
The muon sensors are gas proportional drift chambers: 3 cm in diameter, ~ 1 – 6 m long.

Electrons formed along the track drift towards the central wire.

The first electron to reach the high-field region initiates the avalanche, which is used to derive the timing pulse.

Since the initiation of the avalanche is delayed by the transit time of the charge from the track to the wire, the time of the avalanche can be used to determine the radial position.

Principle also used in straw tracker – need fast timing electronics



5. Failure Detection in Integrated Circuits

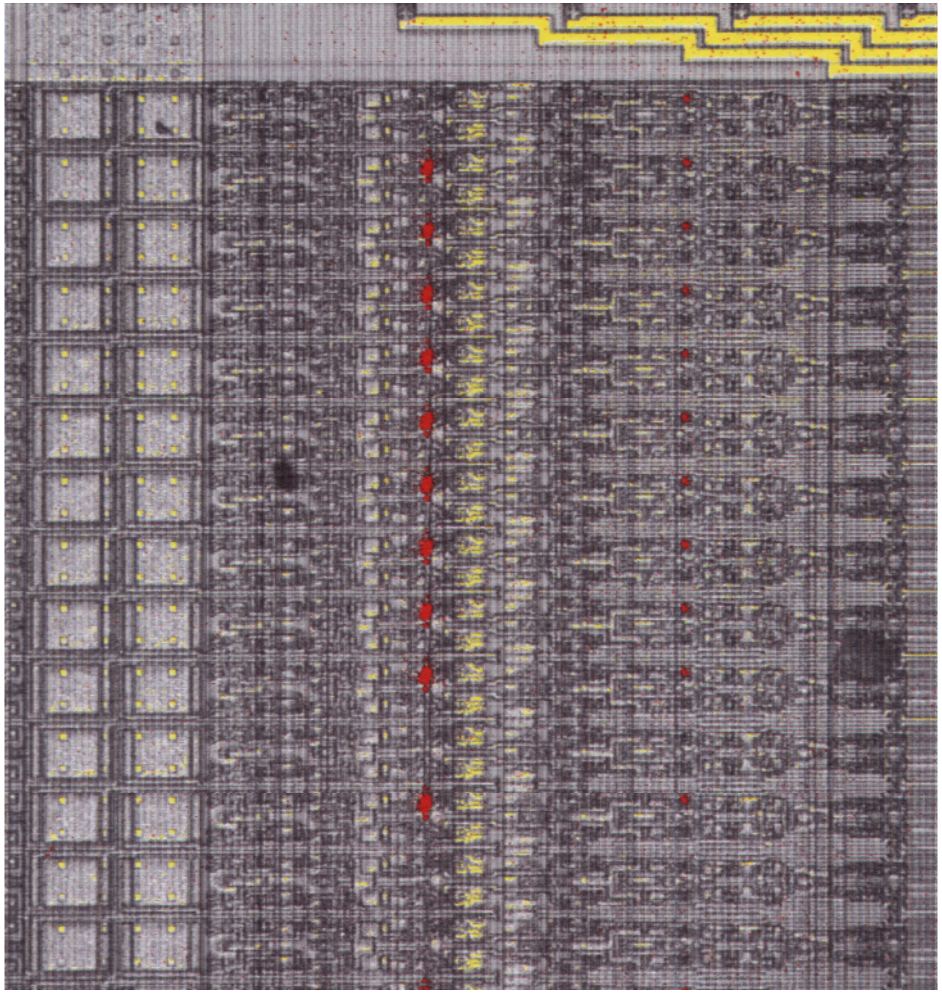
In the course of developing the front-end ICs for the ATLAS SCT, poor fabrication yields led us to an extensive program of failure analysis.

One tool is to view IR images of chips. Defects can form localized high-field regions that allow electrons to acquire sufficient energy while traversing their mean free path to excite atomic transitions. Emission from these defect sites can be “seen” with appropriate position-sensitive sensors.

Data taken with T. Ohsugi at Hiroshima University.

1.2 x 1.5 mm^2 view of chip

Image at λ= 1 μm (red) superimposed on visual image (gray/yellow)

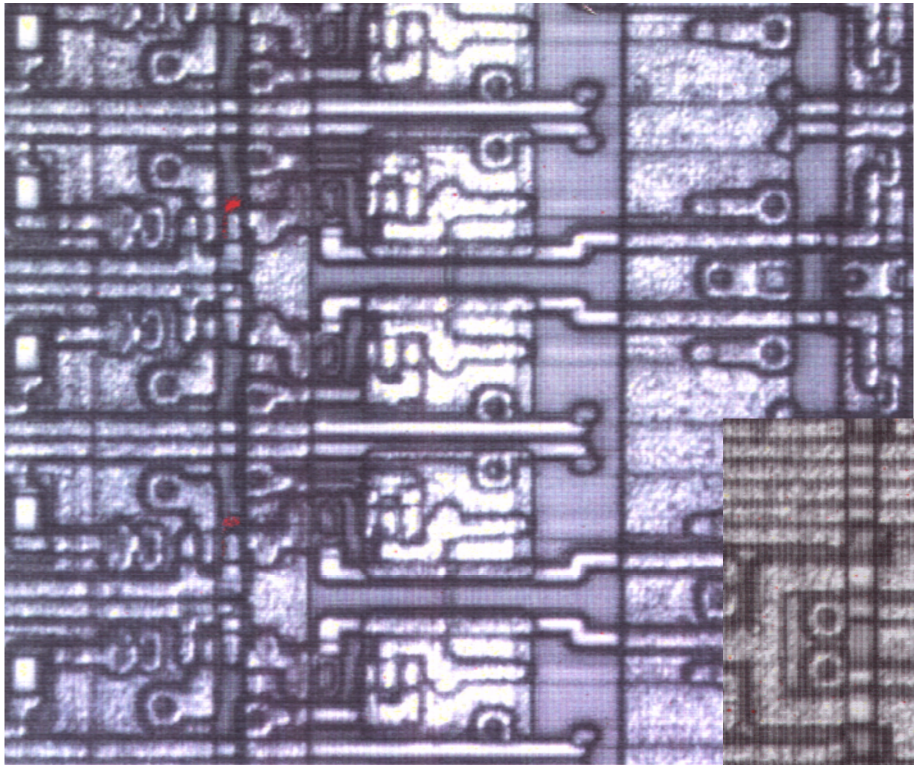


↑ ↑

red spots indicate IR emission

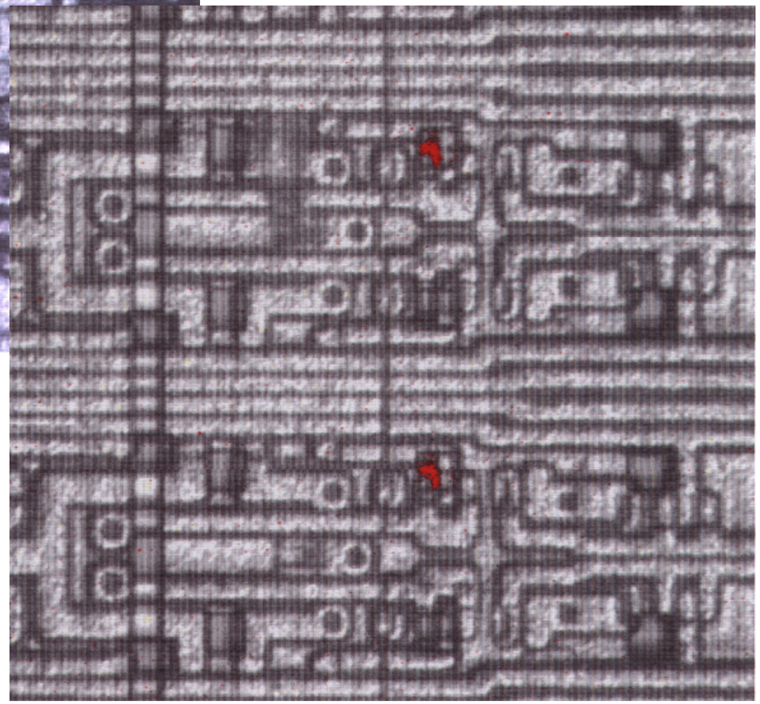
Viewing the emission sites at higher resolution allows the identification of individual transistors.

Left row



~ 30 μm

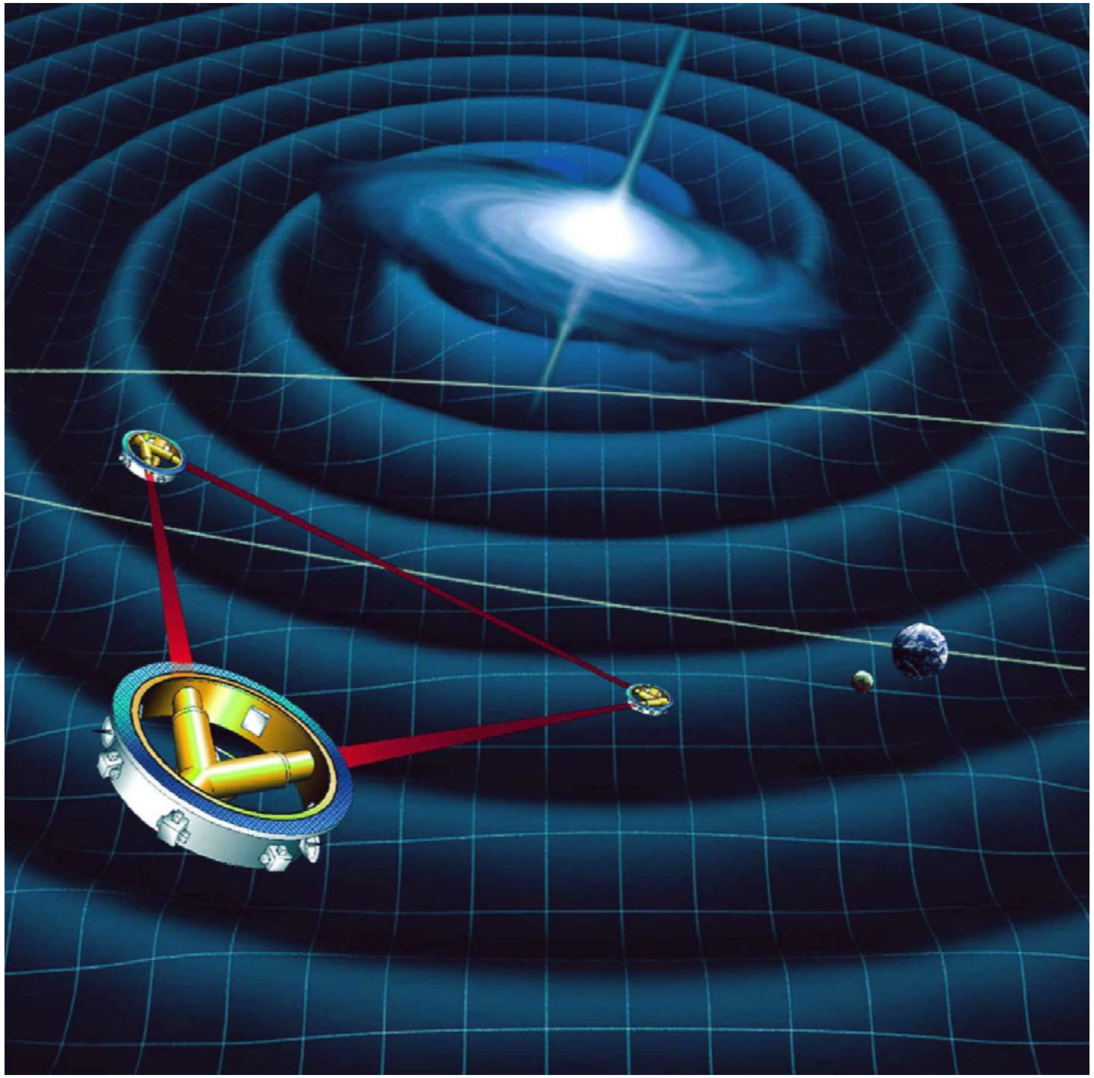
Right row



Since the aluminum metallization is opaque at 1 μm, the emission appears to “go around the corner”.

6. Detection of Gravity Waves

LISA is a next-generation space-based gravity wave detector.



Proposed as a joint ESA/NASA project the projected launch date is 2011.

Designed to complement ground-based experiments such as LIGO that are sensitive in the range 10 to 10^3 Hz, LISA will extend cover the range 10^{-4} to 10^{-1} Hz, with possible extensions down to 10^{-6} Hz.

Artist's view of LISA, embedded in gravity wave field from a binary pulsar.

LISA consists of three proof masses at the three corners of an equilateral triangle.

The sides of the triangle are $5{\cdot}10^6$ km long; laser interferometry will control the spacing to 50 μm.

The proof masses reside in individual spacecraft and are in free fall.

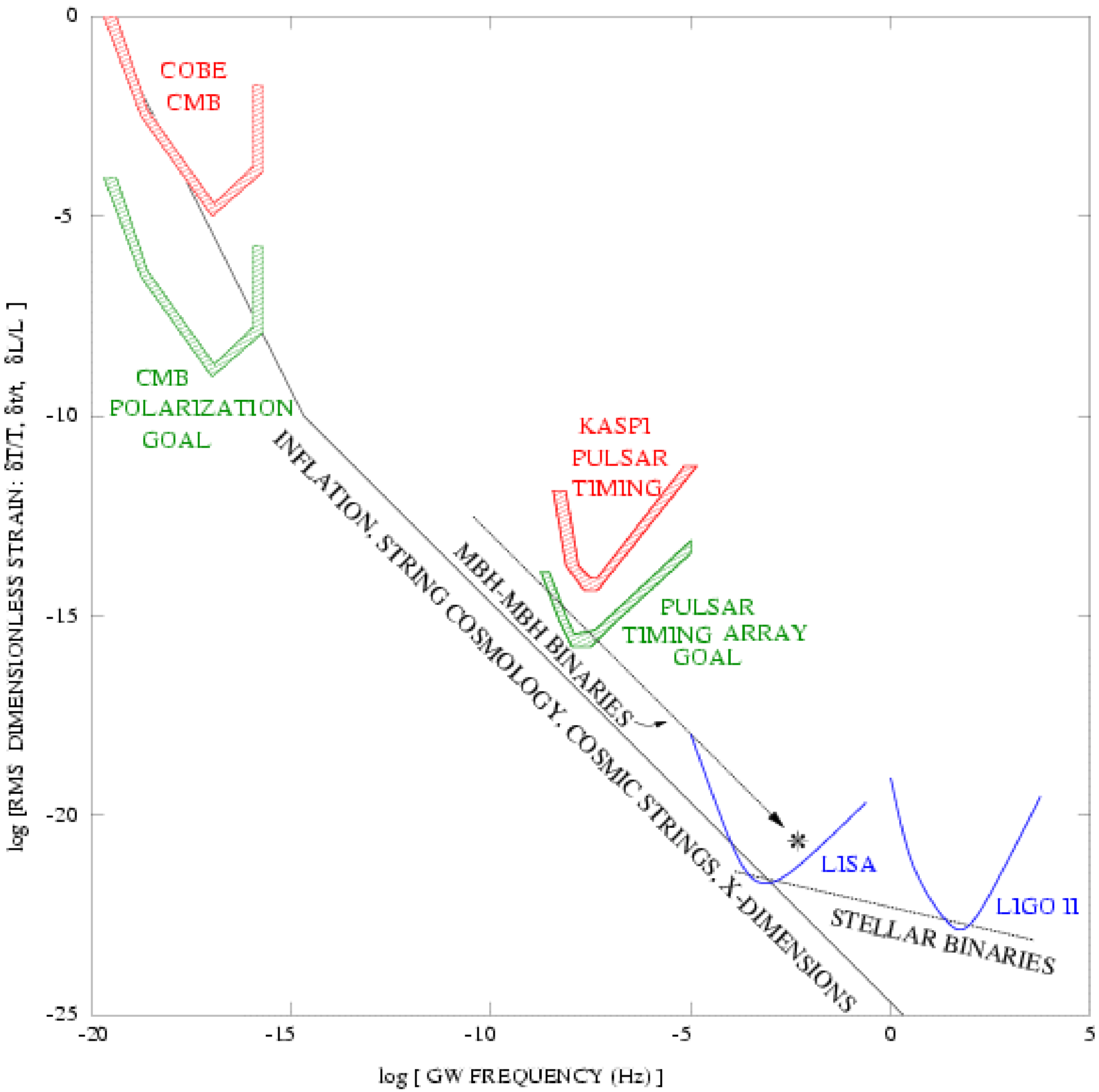
Gravity waves will displace the proof masses.

Coincident motion and the relative phase are indicators of the presence and source of gravity waves.

In the current design, capacitive sensors measure the displacement.

Extensions to lower frequencies will probably require more sophisticated position sensing.

CMB polarization experiments extend gravity wave measurements to the range $10^{-16} – 10^{-19}$ Hz.



Summary of Measured Quantities

Although the various detector systems look very different, they all follow the same principles.

Sensors must determine

1. presence of a particle (or signal)
2. magnitude of the signal
3. time of arrival

Some measurements depend on sensitivity, i.e. detection threshold.

example: silicon tracker, to detect presence of a particle in a given electrode

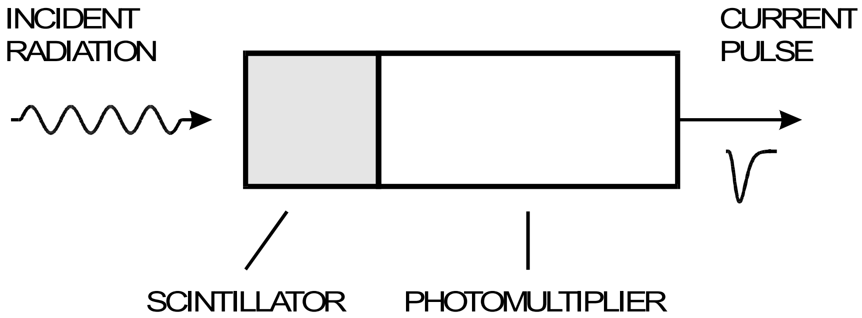
Others seek to determine a quantity very accurately, i.e. resolution

example: x-ray or gamma spectroscopy
calorimeter – magnitude of absorbed energy
time-of-flight measurements (e.g. mass spectroscopy)
muon chambers – time measurement yields position

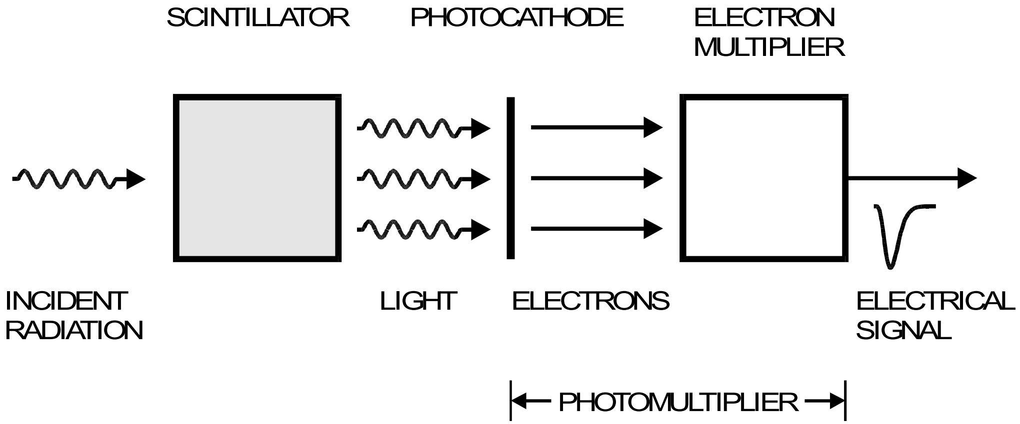
All have in common that they are sensitive to

1. signal magnitude
2. fluctuations

A Typical Detector System – Scintillation Detector



Processes in Scintillator – Photomultiplier



number of photons
$\propto$ absorbed energy

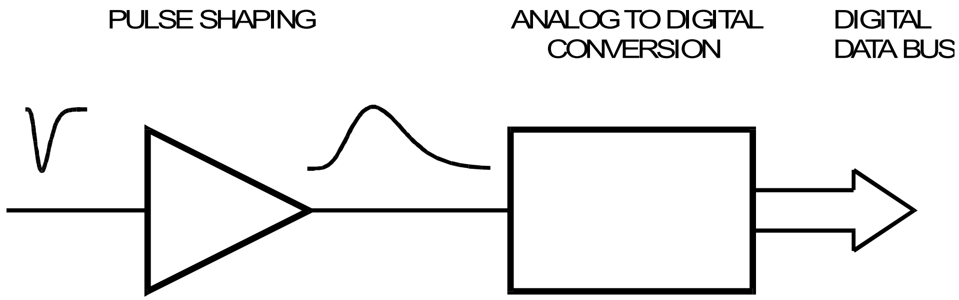
number of photoelectrons
$\propto$ absorbed energy

charge in pulse
$\propto$ abs. energy

Signal Processing

charge in pulse
$\propto$ abs. energy

pulse height
$\propto$ absorbed energy



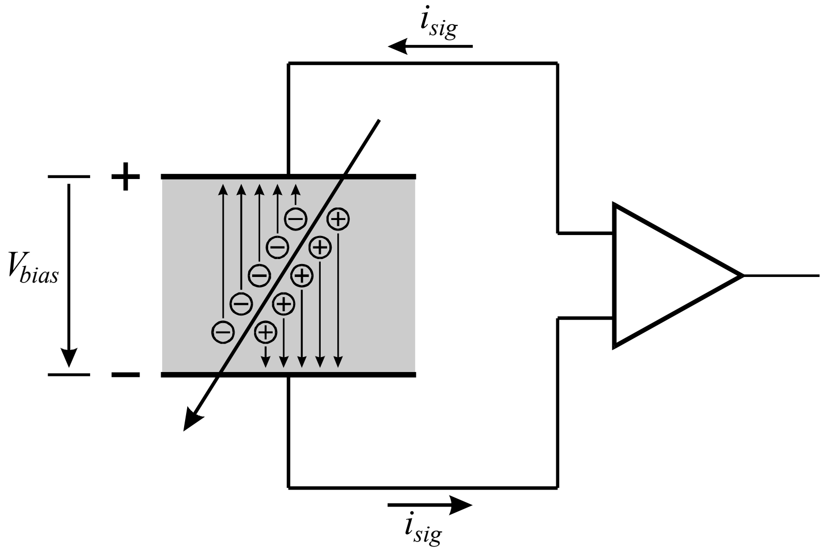
Ionization Chamber

All ionization chambers utilize the same principle:

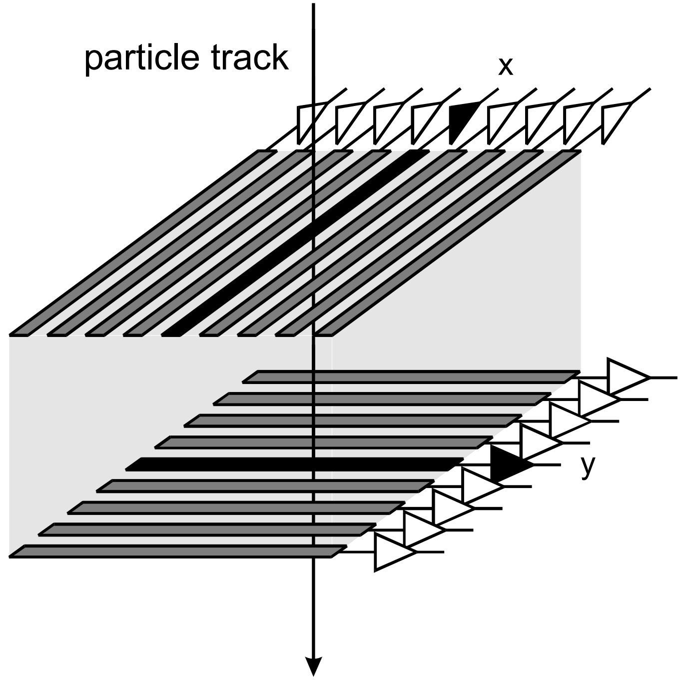
1. Particles deposit energy in an absorber and create mobile charge carriers (positive and negative charge pairs).

   in solids, liquids: electrons and holes
   in gases: electrons and ions

2. Electric field applied to detector volume sweeps charge carriers towards electrodes and induces a signal current



Segmented electrodes yield position.



Purpose of pulse processing and analysis systems

1. Acquire electrical signal from detector

   typically a short current pulse

2. Tailor the time response (i.e. “shape” the output pulse) of the system to optimize

   - minimum detectable signal (detect hit/no hit)
   - energy measurement (magnitude of signal)
   - event rate
   - time of arrival (timing measurement)
   - insensitivity to detector pulse shape
   - some combination of the above

   Generally, these cannot be optimized simultaneously

   $\Rightarrow$ compromises

   Position-sensitive detectors use presence of hit, amplitude measurement or timing.

   $\Rightarrow$ same problem

3. digitize the signal and store for subsequent analysis

Additional requirements, depending on specific application, e.g.

- radiation resistance
- low power
  - portable systems
  - large detector arrays, e.g. in HEP
- robustness
- cost

2. The Signal

Any form of elementary excitation can be used to detect the radiation signal.

$$\text{Magnitude of signal} = \frac{\text{absorbed energy}}{\text{excitation energy}}$$

An electrical signal can be formed directly by ionization.

Incident radiation quanta impart sufficient energy to individual atomic electrons to form electron-ion pairs (in gases) or electron-hole pairs (in semiconductors and metals).

Other detection mechanisms are

Excitation of optical states (scintillators) $\rightarrow$ light intensity

Excitation of lattice vibrations (phonons) $\rightarrow$ temperature

Breakup of Cooper pairs in superconductors

Formation of superheated droplets in superfluid He

Typical excitation energies:	Ionization in gases	~30 eV
	Ionization in semiconductors	1 – 10 eV
	Scintillation	20 - 500 eV
	Phonons	meV
	Breakup of Cooper Pairs	meV

Precision of signal magnitude is limited by fluctuations

Two types of fluctuations

1. Fluctuations in signal charge for a given energy absorption in detector

   Signal formed by many elementary excitations

$$\text{Average number of signal quanta} = \frac{\text{absorbed energy}}{\text{excitation energy}} \quad \Rightarrow \quad N = \frac{E}{E_i}$$

   Number of signal quanta fluctuates statistically. $\Delta N = \sqrt{FN}$

   where F is the Fano factor (0.1 in Si, for example), so the energy resolution

$$\Delta E = E_i \Delta N = \sqrt{FEE_i} \quad \text{r.m.s.}$$

$$\Delta E_{FWHM} = 2.35 \times \Delta E_{rms}$$

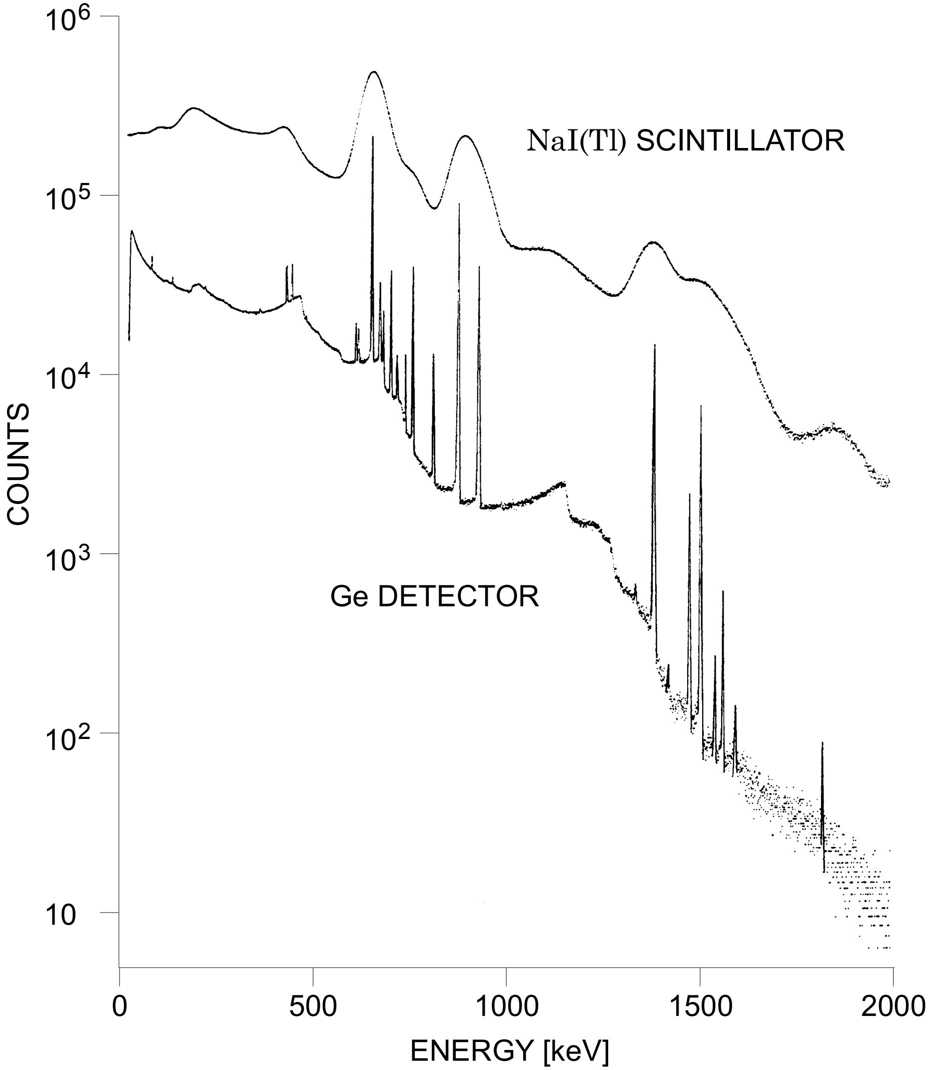
2. Baseline fluctuations in the electronics: “electronic noise”

The overall resolution is often the result of several contributions. Individual resolutions add in quadrature, for example

$$\Delta E = \sqrt{\Delta E_{fluc}^2 + \Delta E_{elec}^2}$$

If one contribution is 20% of the other, the overall resolution is increased by 10%.

Resolution of NaI(Tl) and Ge detectors



NaI(Tl) scintillation detector:

signal fluctuations

Ge detector:

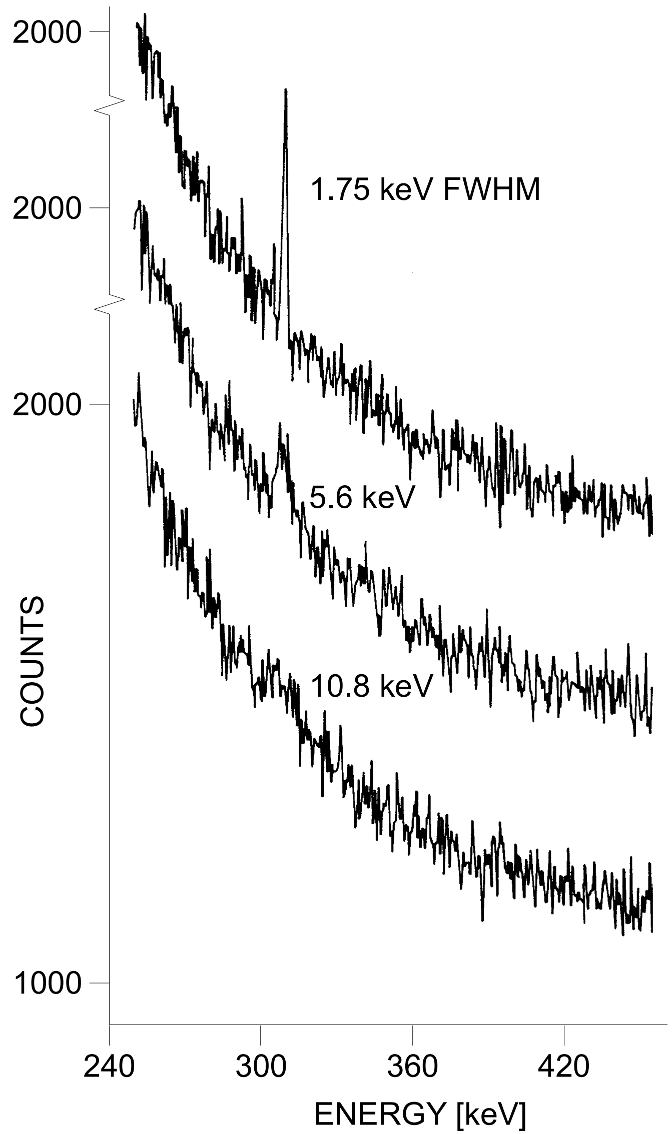
predominantly electronic noise

(J.Cl. Philippot,
IEEE Trans. Nucl. Sci. **NS-17/3** (1970) 446)

Resolution improves sensitivity

Signal to background ratio improves with better resolution

(narrow peak competes with fewer background counts)



G.A. Armantrout, *et al.*, IEEE Trans. Nucl. Sci. **NS-19/1** (1972) 107

Signal Fluctuations in a Scintillation Detector

Example:

a typical NaI(Tl) system (from Derenzo)

511 keV gamma ray

$\Downarrow$

25000 photons in scintillator

$\Downarrow$

15000 photons at photocathode

$\Downarrow$

3000 photoelectrons at first dynode

$\Downarrow$

$3 \cdot 10^9$ electrons at anode

2 mA peak current

Resolution of energy measurement determined by statistical variance of produced signal quanta.

$$\frac{\Delta E}{E} = \frac{\Delta N}{N} = \frac{\sqrt{N}}{N} = \frac{1}{\sqrt{N}}$$

Resolution determined by smallest number of quanta in chain, i.e. number of photoelectrons arriving at first dynode.

$$\frac{\Delta E}{E} = \frac{1}{\sqrt{3000}} = 2\% \text{ r.m.s.} = 5\% \text{ FWHM}$$

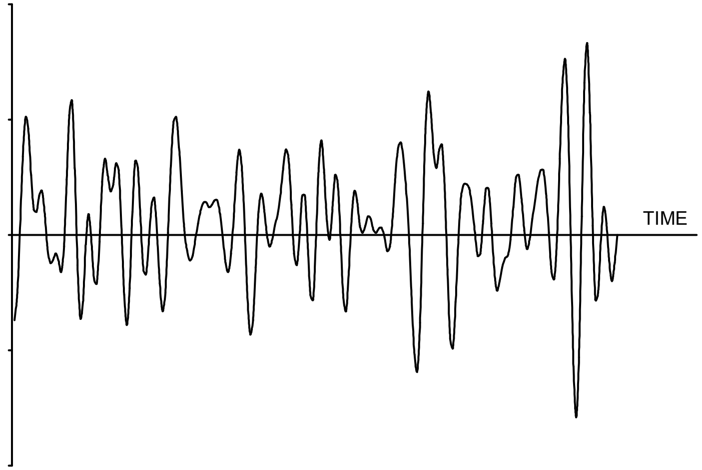
In this example

Typically 7 – 8% obtained, due to non-uniformity of light collection and gain.

Baseline Fluctuations (Electronic Noise)

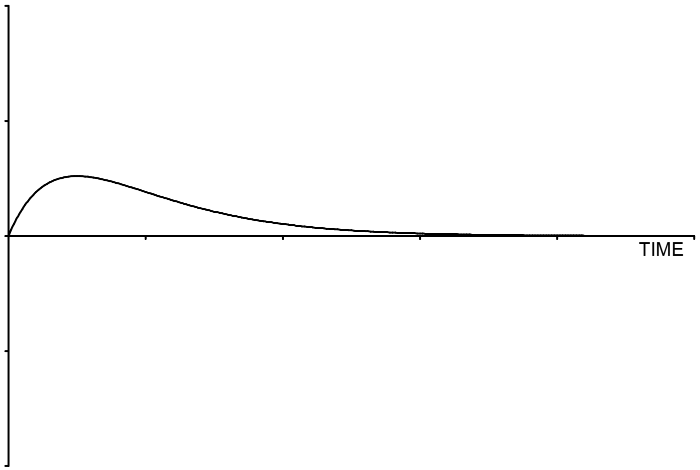
Choose a time when no signal is present.

Amplifier's quiescent output level (baseline):

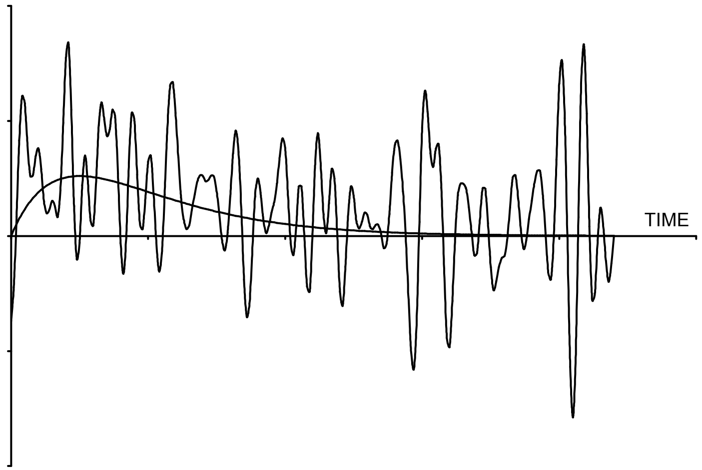


In the presence of a signal, noise + signal add.

Signal:



Signal+Noise (S/N = 1)



Measurement of peak amplitude yields signal amplitude + noise fluctuation

The preceding example could imply that the fluctuations tend to increase the measured amplitude, since the noise fluctuations vary more rapidly than the signal.

In an optimized system, the time scale of the fluctuation is comparable to the signal peaking time.

Then the measured amplitude fluctuates positive and negative relative to the ideal signal.

Measurements taken at 4 different times:

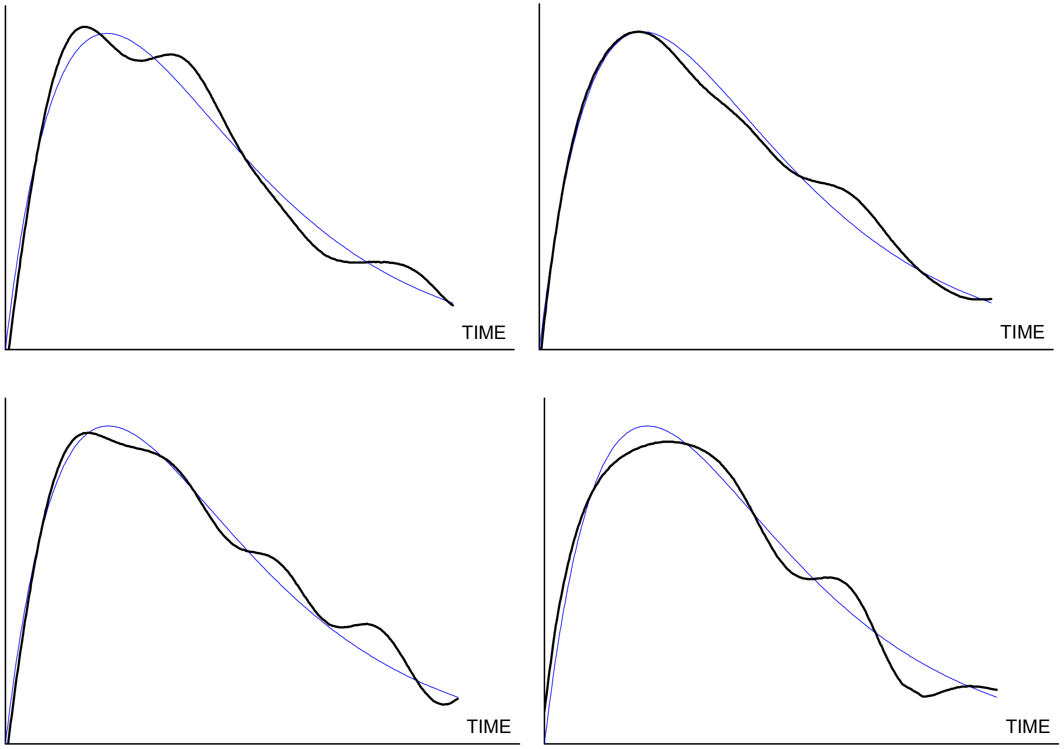
noiseless signal superimposed for comparison

S/N = 20

Noise affects

Peak signal

Time distribution



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3. The Problem

Radiation impinges on a sensor and creates an electrical signal.

The signal level is low and must be amplified to allow digitization and storage.

Both the sensor and amplifiers introduce signal fluctuations – noise.

1. Fluctuations in signal introduced by sensor

2. Noise from electronics superimposed on signal

The detection limit and measurement accuracy are determined by the signal-to-noise ratio.

Electronic noise affects all measurements:

1. Detect presence of hit:
   Noise level determines minimum threshold.
   If threshold too low, output dominated by noise hits.

2. Energy measurement:
   noise "smears" signal amplitude

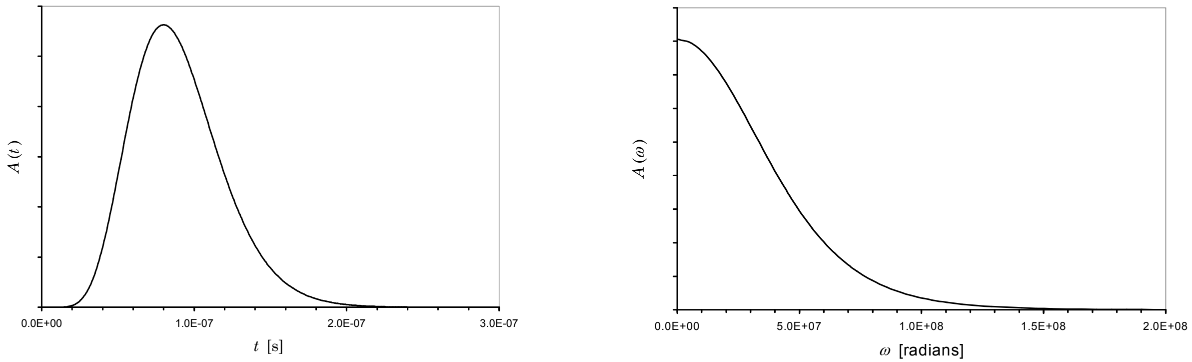
3. Time measurement
   noise alters time dependence of signal pulse

How to optimize the signal-to-noise ratio?
1. Increase signal and reduce noise
2. For a given sensor and signal: reduce electronic noise

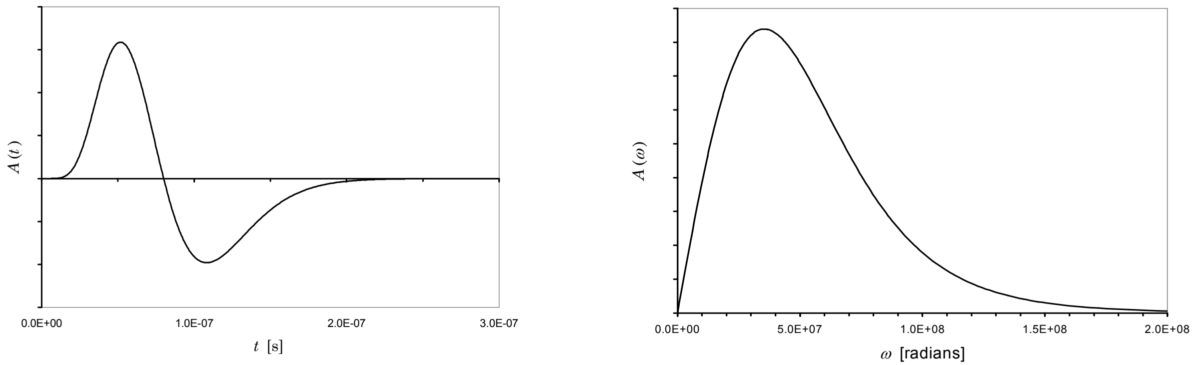
Assume that the signal is a pulse.

The time distribution of the signal corresponds to a frequency spectrum (Fourier transform).

Examples: Time Domain Frequency Domain



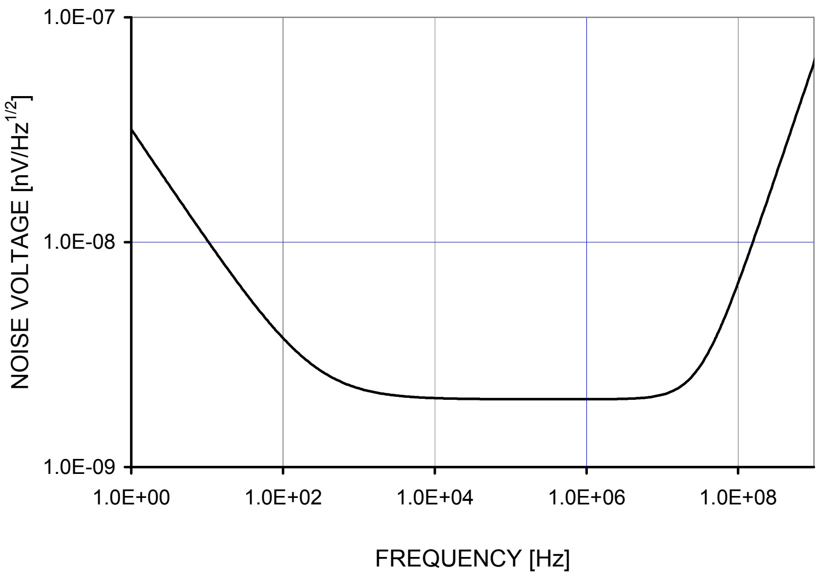
The pulse is unipolar, so it has a DC component and the frequency spectrum extends down to 0.



This bipolar pulse carries no net charge, so the frequency spectrum falls to zero at low frequencies.

The noise spectrum generally not the same as the signal spectrum.

Typical Noise Spectrum:



$\Rightarrow$ tailor frequency response of measurement system to optimize signal-to-noise ratio.

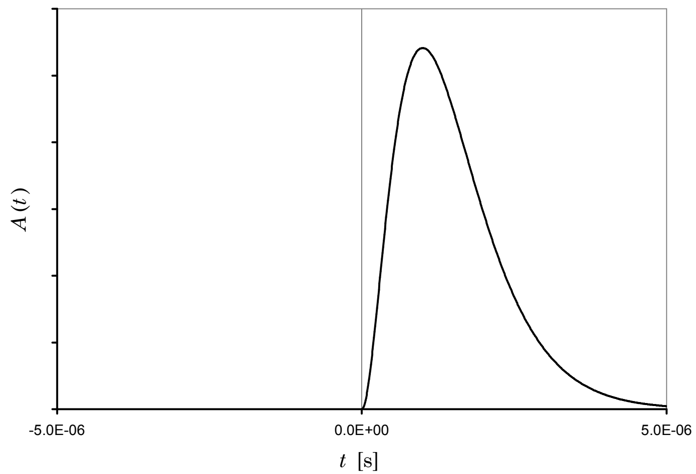
Frequency response of measurement system affects both

- signal amplitude and
- noise.

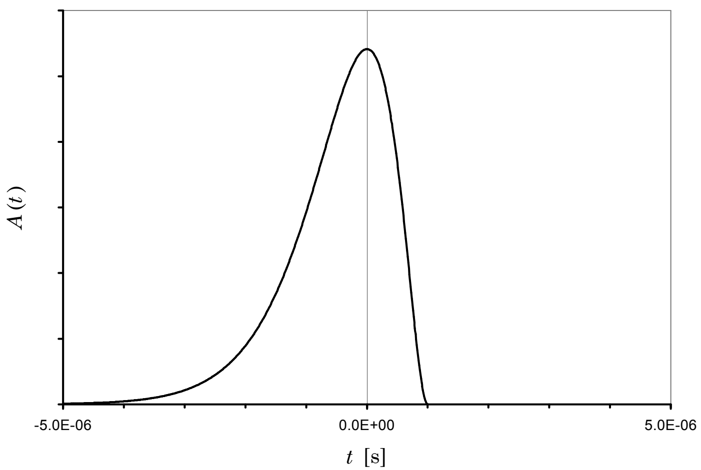
There is a general solution to this problem:

Apply a filter to make the noise spectrum white (constant over frequency). Then the optimum filter has an impulse response that is the signal pulse *mirrored in time* and shifted by the measurement time.

For example, if the signal pulse shape is:



The response of the optimum filter:



This is an “acausal” filter, i.e. it must act before the signal appears.

⇒ only useful if the time of arrival is known in advance.

Not good for random events
need time delay buffer memory

⇒ complexity!

Does that mean our problem is solved (and the lecture can end)?

1. The “optimum filter” preserves all information in signal, i.e. magnitude, timing, structure.

   Usually, we need only subset of the information content, i.e.
   area (charge) or time-of-arrival.

   Then the raw detector signal is not of the optimum form for the information that is required.

      For example, a short detector pulse would imply a fast filter function. This retains both amplitude and timing information.
      If only charge information is required, a slower filter is better, as will be shown later.

2. The optimum filter is often difficult or impractical to implement

      Digital signal processing would seem to remove this restriction, but this approach is not practical for very fast signals or systems that require low power.

4. Simpler filters often will do nearly as well

5. Even a digital system requires continuous (“analog”) pre-processing.

6. It’s often useful to understand what you’re doing, so we’ll spend some more time to bring out the physical background of signal formation and processing.

4. Signal processing systems

Large detector systems may consist of several subsystems especially designed to perform specific functions, for example

- position sensing (tracking)
- energy measurement (spectroscopy, calorimeters)
- timing
- particle identification

Functions

Although these subsystems may look very different and use radically differing technologies, they all tend to comprise the same basic functions:

1. Radiation deposits energy in a detecting medium.

   The medium may be gas, solid or liquid.

   In a tracking detector one wishes to detect the presence of a particle without affecting its trajectory, so the medium will be chosen to minimize energy loss and particle scattering.

   Conversely, if one wishes to measure the total energy (energy spectrometry or calorimetry), the absorber will be chosen to optimize energy loss (high density, high Z).

2. Energy is converted into an electrical signal, either directly or indirectly. Each detected particle will appear as a pulse of electric charge.

   Direct conversion:
      incident radiation ionizes atoms/molecules in absorber, creating mobile charges that are detected. (ionization chambers)

   Indirect conversion:
      incident radiation excites atomic/molecular states that decay by emission of light, which in a second step is converted into charge. (scintillation detectors)

- The primary signal charge is proportional to the energy absorbed.

  Some typical values of energy required to form a signal charge of 1 electron:

gases	30 eV
semiconductors	1 to 10 eV
scintillators	20 to 500 eV

  In neither of these schemes is the signal charge available instantaneously.

  Scintillation detector: The pulse duration is determined by the decay time of the optical transitions.

  Ionization chamber: The charges must move to the electrodes to obtain the full signal.

  Typical pulse durations: 1 ns – 10 μs

3. The electrical signal is amplified.

a) electronic circuitry

b) gain by secondary multiplication

Primary charge is accelerated to sufficient energy for it to liberate additional charge carriers by impact ionization.

Examples: proportional chambers
avalanche photodiodes
photomultiplier

Both techniques may introduce significant random fluctuations (electronic noise, avalanche noise).

Ideally, a gain stage would increase only the magnitude of the detector pulse, without affecting its time dependence.

This ideal behavior is never strictly realized in practice, as it would require amplifiers with infinite bandwidth.

However, this is not a severe limitation, as in many applications it is quite acceptable and even desirable to change the pulse shape.

4. Pulse shaping

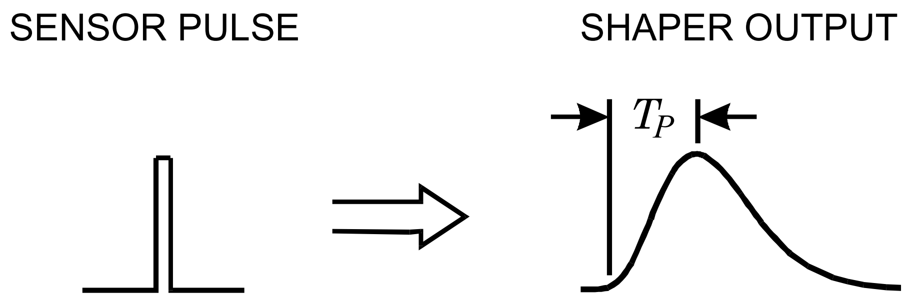
(not always necessary, but always present in some form)

The time response of the system is tailored to optimize the measurement of signal magnitude or time and the rate of signal detection.

The output of the signal chain is a pulse (current or voltage) whose area is proportional to the original signal charge, i.e. the energy deposited in the detector.

Typically, the pulse shaper transforms a narrow detector current pulse to

- a broader pulse
  (to reduce electronic noise),
- with a gradually rounded maximum at the peaking time T_P
  (to facilitate measurement of the amplitude)



However, to measure pulses in rapid succession, the duration of the pulse must be limited to avoid overlapping signals.

If the shape of the pulse does not change with signal level, the peak amplitude is also a measure of the energy, so one often speaks of pulse-height measurements or analysis.

The pulse height spectrum is the energy spectrum.

5. Digitization

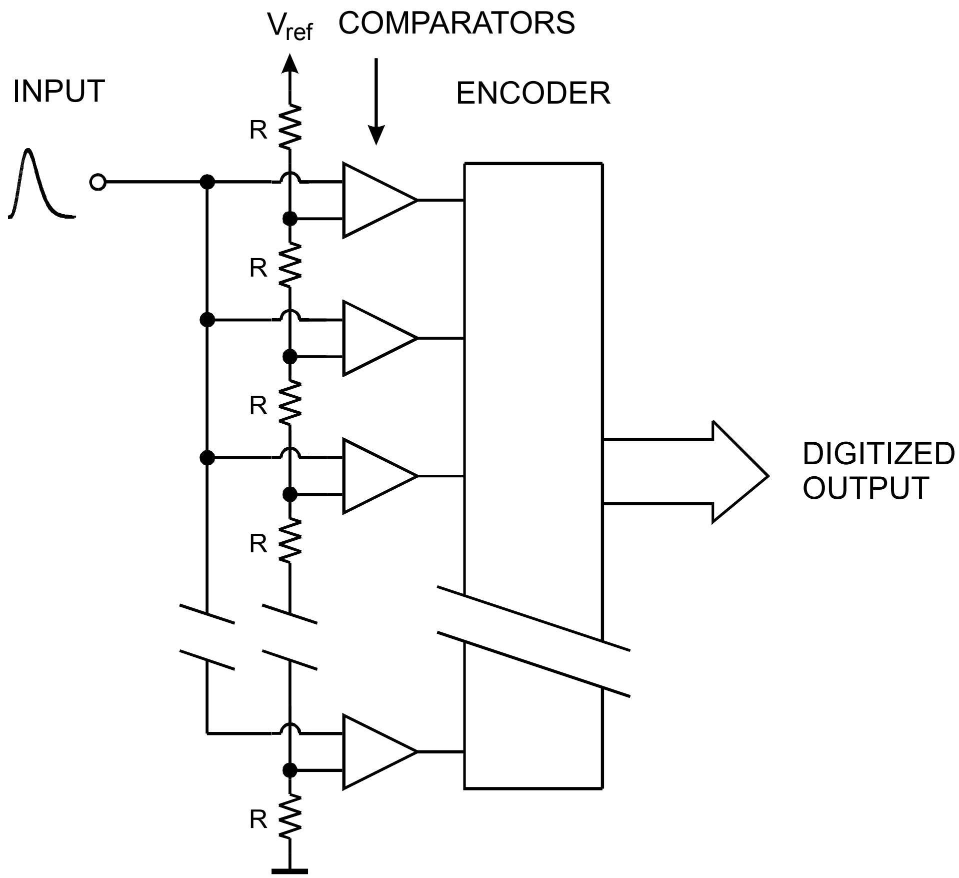
5.1 Signal Magnitude
(analog-to-digital converter, viz. ADC or A/D)

Example: Flash ADC

The input signal is applied to n comparators in parallel. The switching thresholds are set by a resistor chain, such that the voltage difference between individual taps is equal to the desired measurement resolution.

In the presence of a signal all comparators with threshold levels less than the signal amplitude will fire. A decoder converts the parallel bit pattern into a more efficient form, for example binary code.

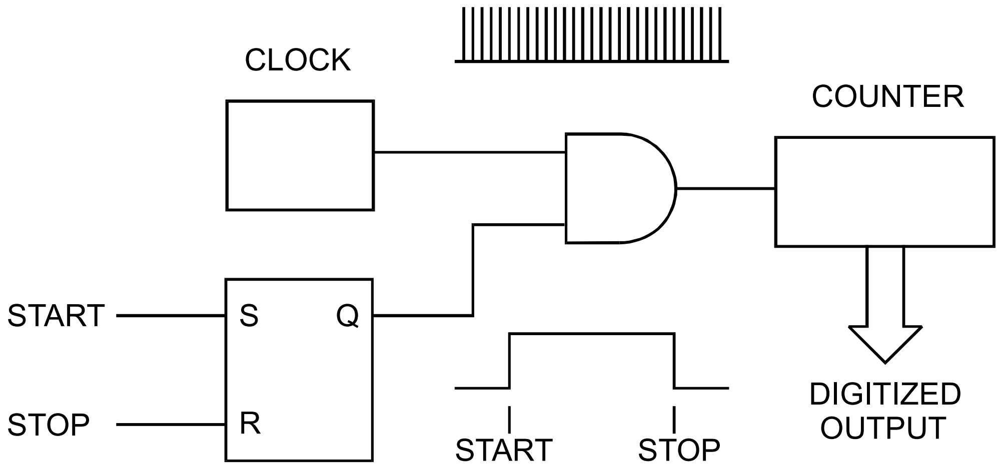
This type of ADC is fast, but requires as many comparators as measurement bins. Other converter types provide higher resolution and simpler circuitry at the expense of speed.



5.2 Time difference between the detected signal and a reference signal (time-to-digital converter, TDC)

The reference signal can be derived from another detector or from a common system clock, the crossing time of colliding beams, for example.

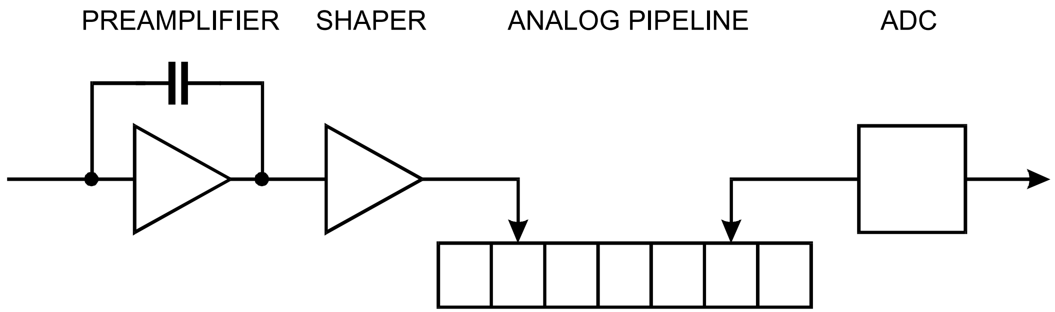
Circuit implementations include schemes that count “clock ticks” in fully digital circuitry or combine time-to-amplitude and amplitude-to-digital conversion in mixed analog-digital arrangements.

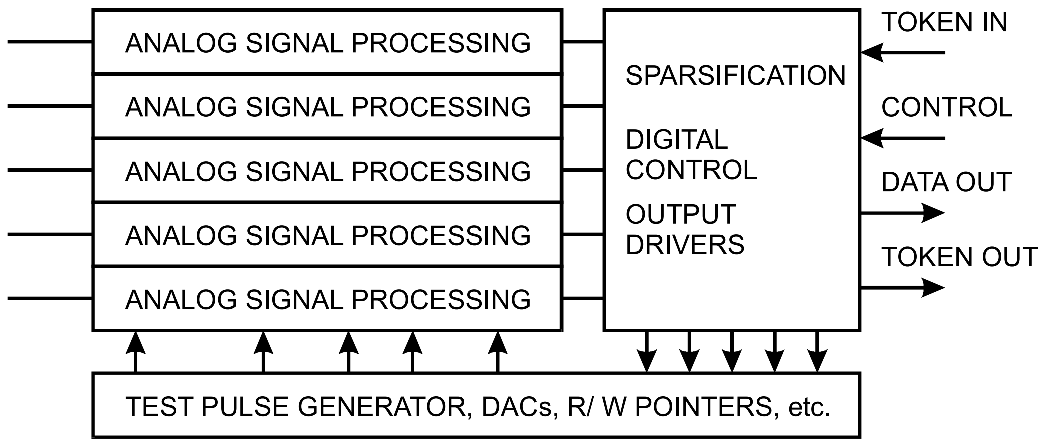


6. Data Readout

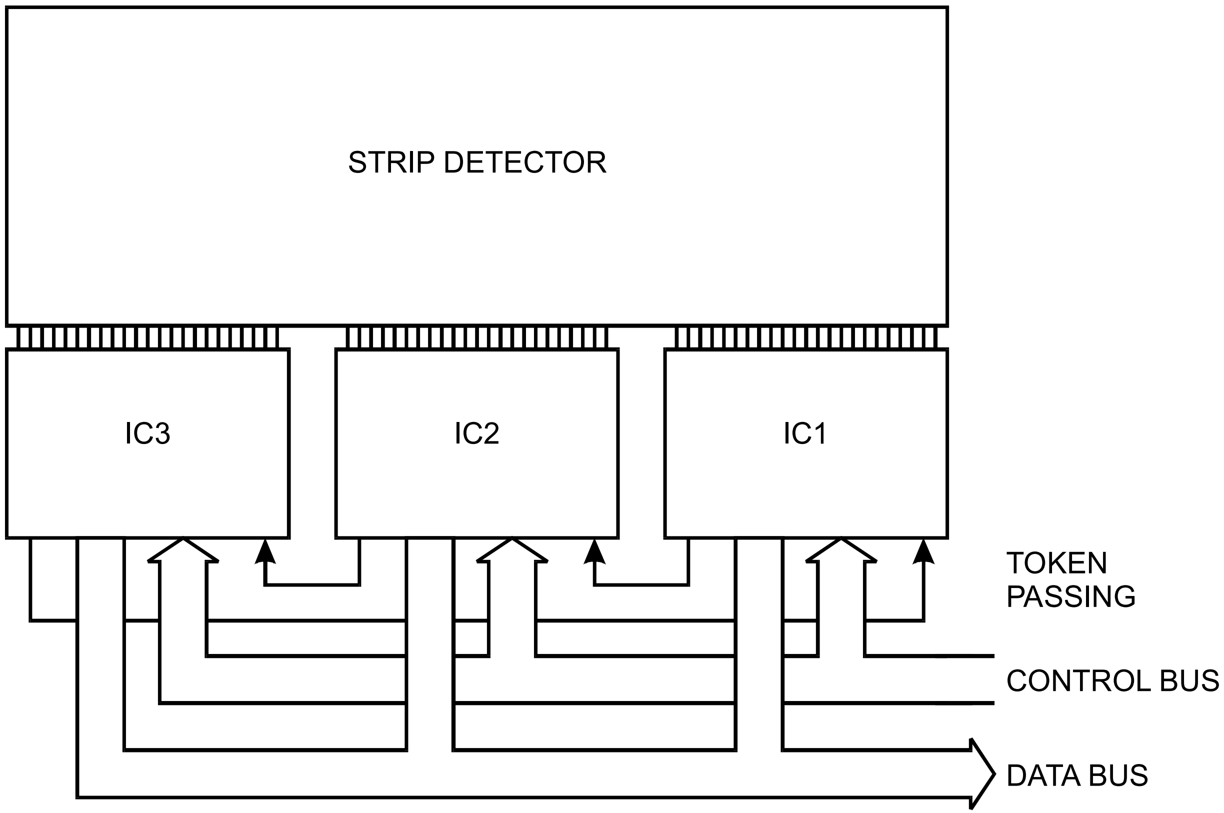
In complex detector systems the individual digitized outputs may require rather complex circuitry to combine the signal associated with a specific event and "package" them for efficient transfer.

Example: Multi-channel strip detector readout IC





A detector module must combine outputs from multiple readout ICs



Readout is organized by a token-passing scheme.
The right-most chip IC1 is the master. A command on the control bus initiates the readout. When IC1 has written all of its data it passes the token to IC2. When IC2 has finished it passes the token to IC3, which in turn returns the token to the master IC1.

Example: Silicon-Strip Detector Module

Strip electrodes (left) connected to readout ICs through wire bonds and pitch adapters.

Each IC includes 128 channels on 50 μm pitch of low-noise preamplification, pulse shaping, analog-to-digital conversion, and zero-suppressed data readout (only struck channels read out)