X-ray detectors
How do they work ?
How are they characterized ?

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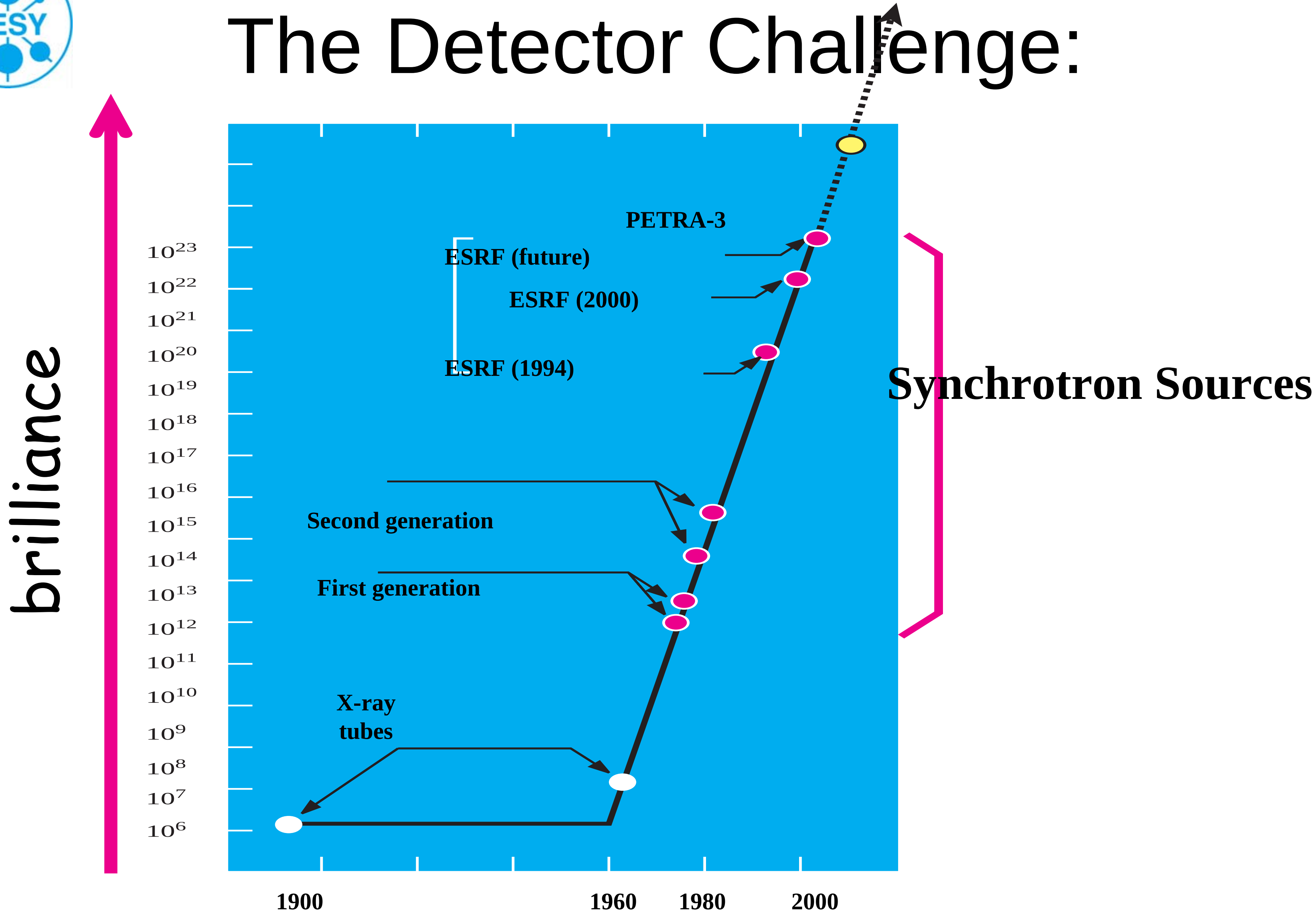
The Detector Challenge:



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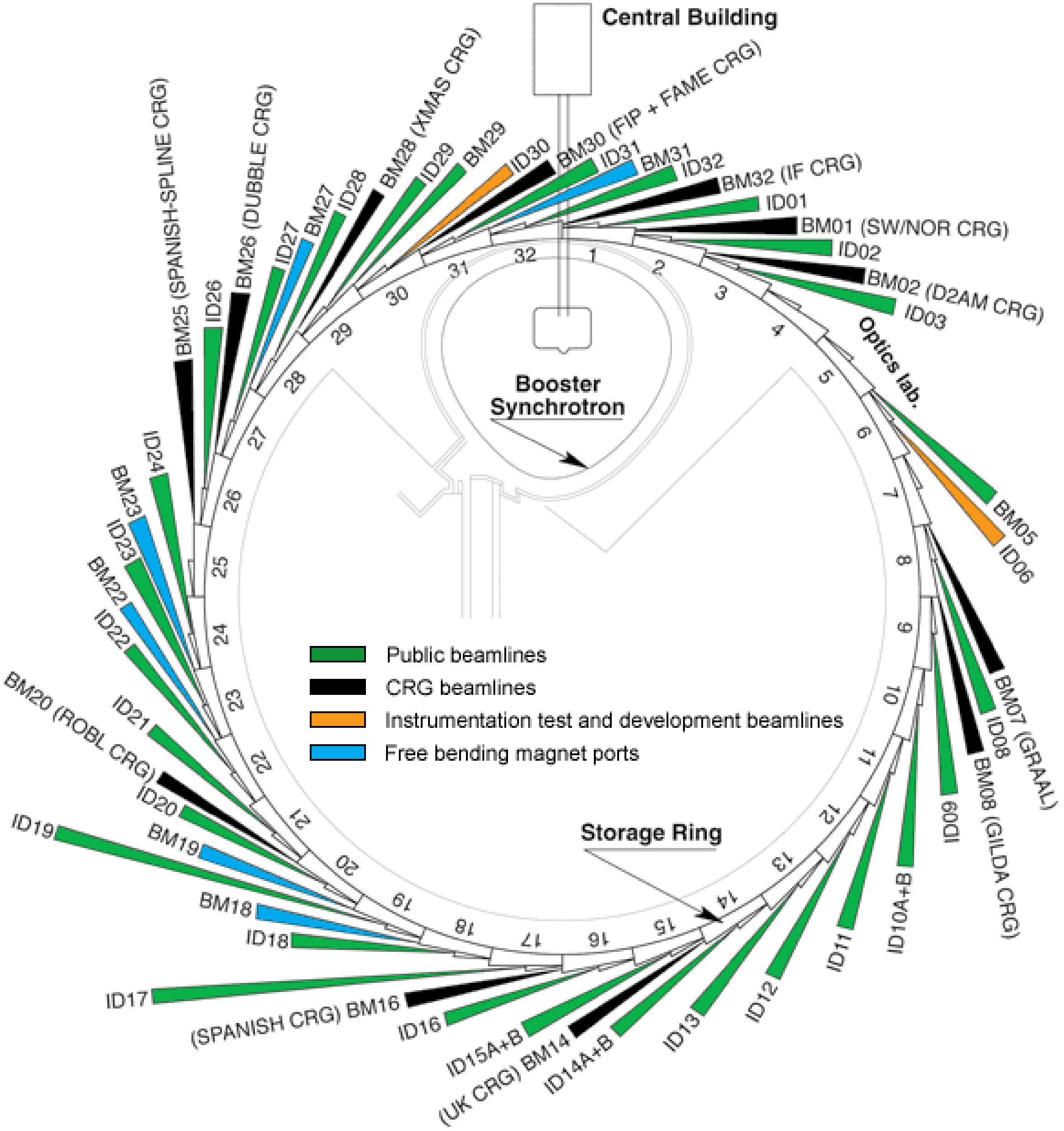


16/03/2009

The Detector Challenge:

- **Spectroscopy** (determine energy of the X-rays):
  - meV – 1 keV resolution
  - time resolved (100 psec) – static
- **Imaging** (determine intensity distribution)
  - Micro-meter – millimeter resolution
  - Tomographic
  - Time resolved
- **Scattering** (determine intensity as function momentum transfer = angle)
  - Small angel – protein crystallography
  - Diffuse – Bragg
  - Crystals - liquids

What are the basic principles ?

1. X-ray light is quantized (photons)
2. In order to detect you have to transfer energy from the particle to the detector
3. A photon is either fully absorbed or not at all (no track like for MIPs)
4. The energy absorbed is transferred into an electrical signal and then into a number (digitized).

Signal Generation → Needs transfer of Energy

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

Ionization (gas, liquids, solids)

Excitation of optical states (scintillators)

Excitation of lattice vibrations (phonons)

Breakup of Cooper pairs in superconductors

Typical excitation energies:

Ionization in semiconductors:	1 – 5 eV
Scintillation:	appr. 20 eV
Phonons:	meV
Breakup of Cooper pairs:	meV

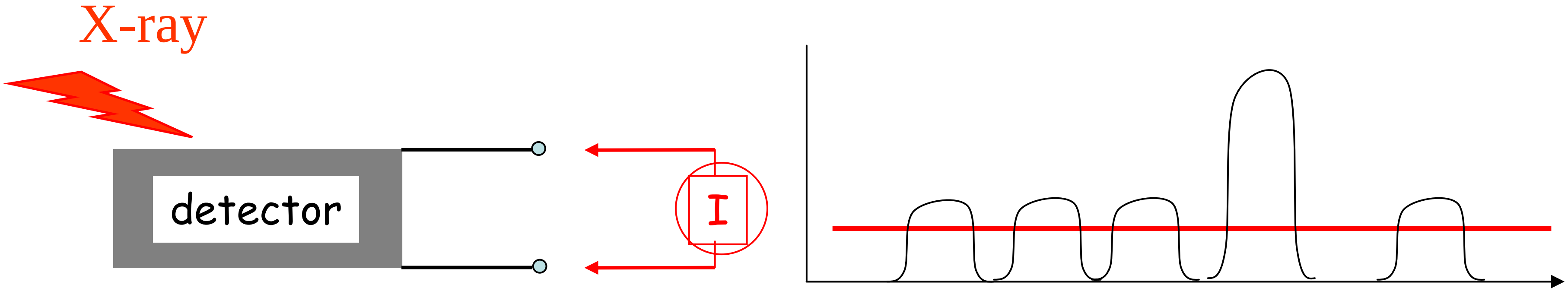
What would you like to know about your X-rays?

1. Intensity or flux (photons/sec)
2. Energy (wavelength)
3. Position (or mostly angles)
4. Arrival time (time resolved experiments)
5. Polarization

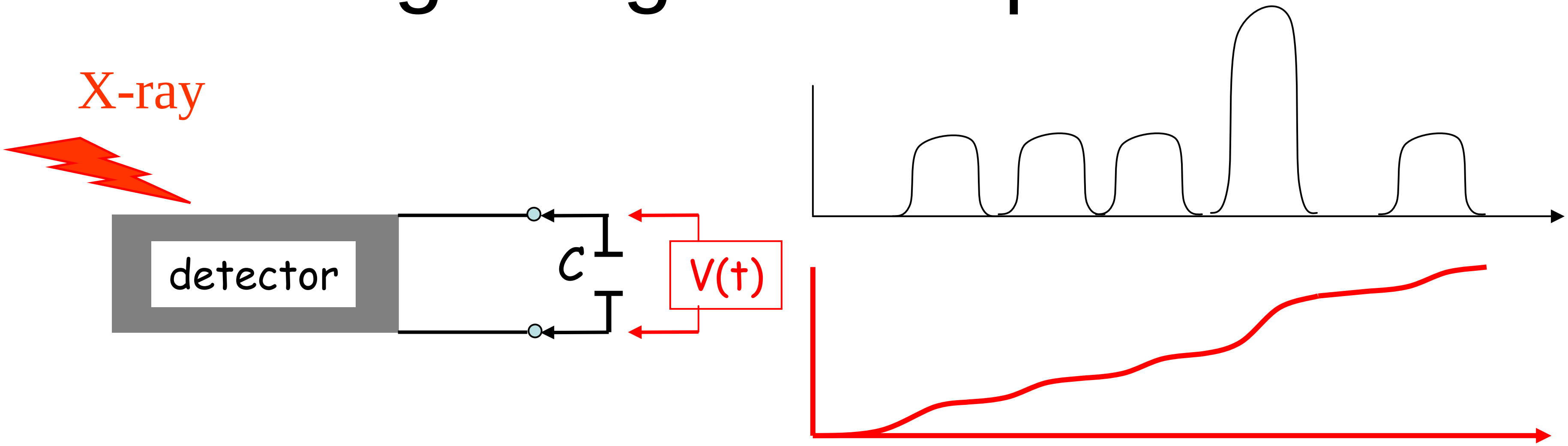
3 modes of detection

1. Current (=flux) mode operation
2. Integration mode operation
3. Photon counting mode operation
4. Energy dispersive mode operation

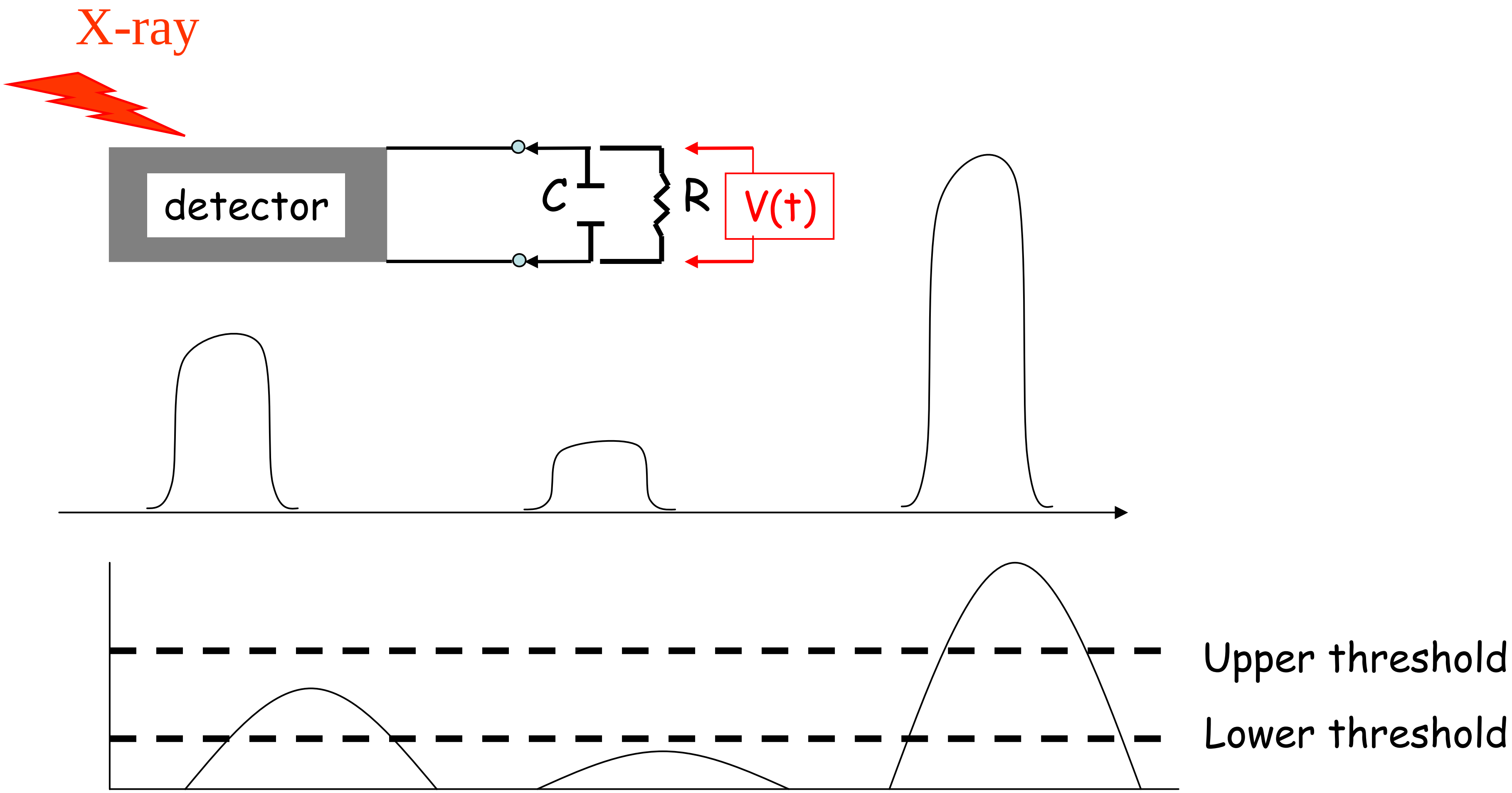
Current mode operation



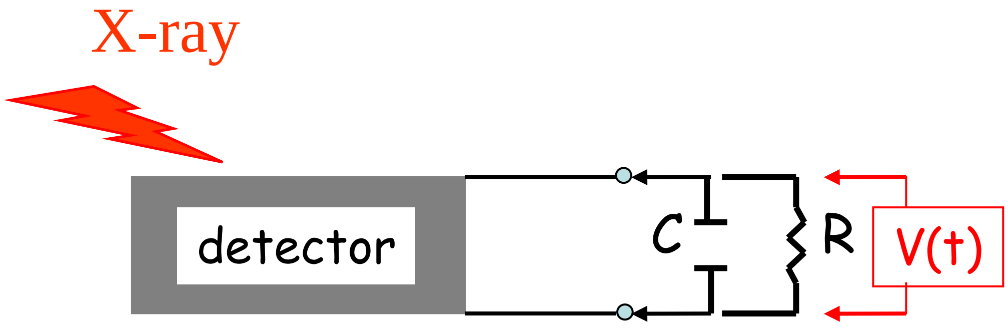
Integrating mode operation

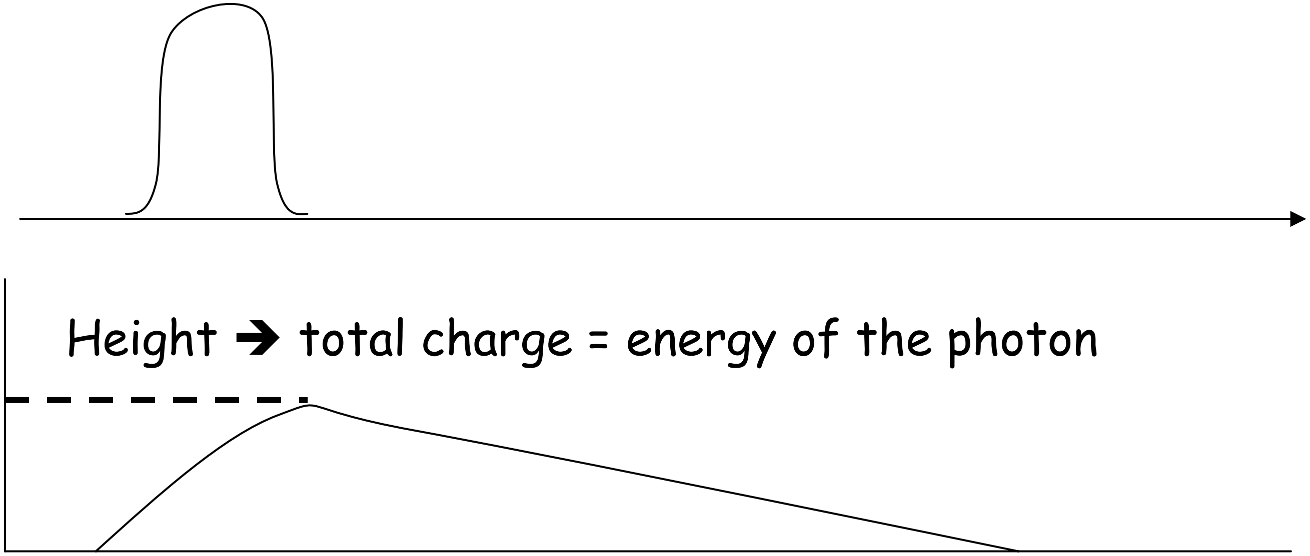


Photon counting mode



Energy dispersive mode





Height ➔ total charge = energy of the photon

Some general detector parameters

- **QE** = quantum efficiency = fraction of incoming photons detected (<1.0). You want this to be as high as possible.
- **DQE** = detective quantum efficiency =

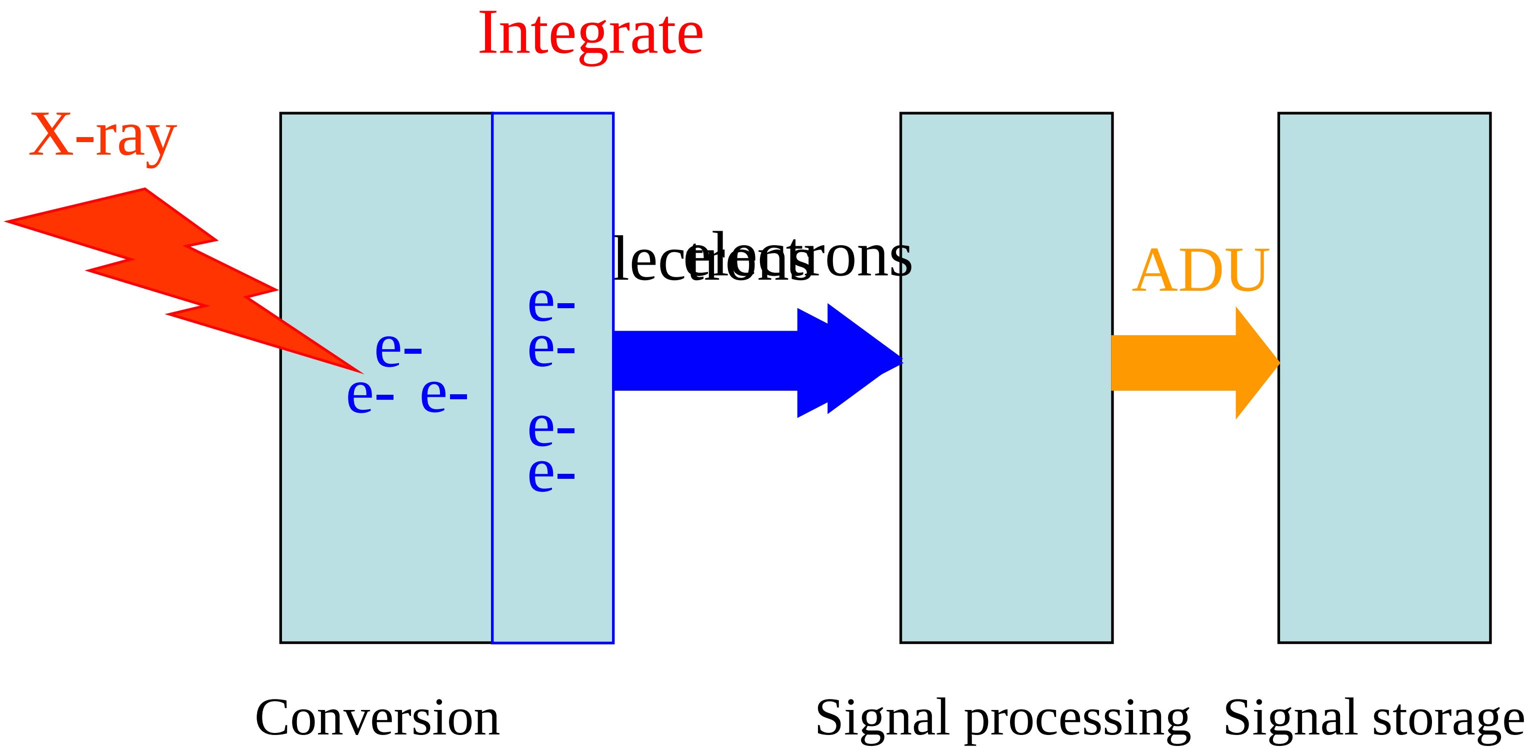
  $$\frac{(signal/noise)_{out}}{(signal/noise)_{in}} \leq 1.0$$

  You can never increase signal, nor decrease noise! So signal to noise will always degrade in the detector. (NB: **signal to noise is the most important parameter** when you measure something!)
- **Gain** = relation between your signal strength (V, A, ADU) and the number of photons.

2-Dimensional X-ray Detectors

- Workhorses at synchrotron sources ➔ make the best use of the available photons.
- Integrating versus counting
- Direct versus indirect detections

Counting versus Integrating



Integrate

X-ray

e-
e- e-

e-
e-
e-
e-

lectrons
electrons

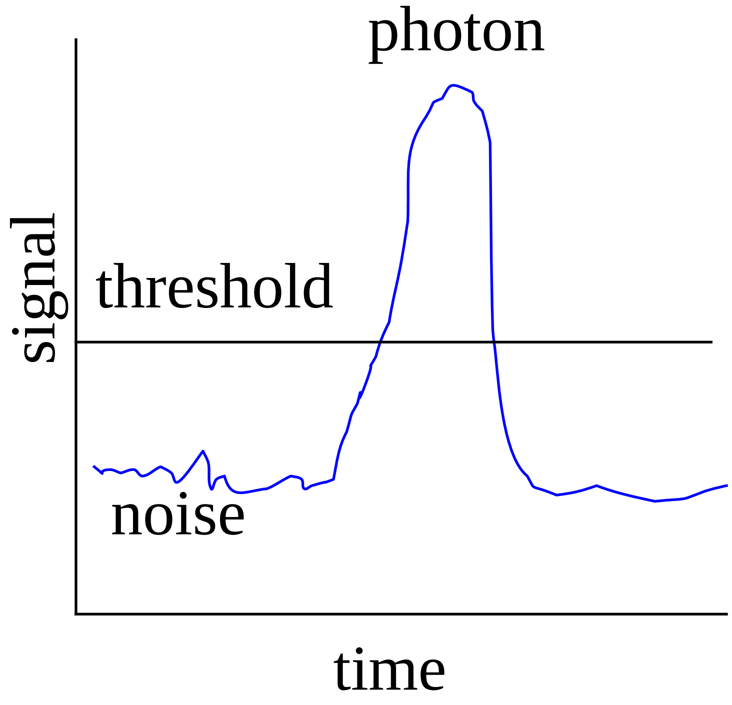
ADU

Conversion

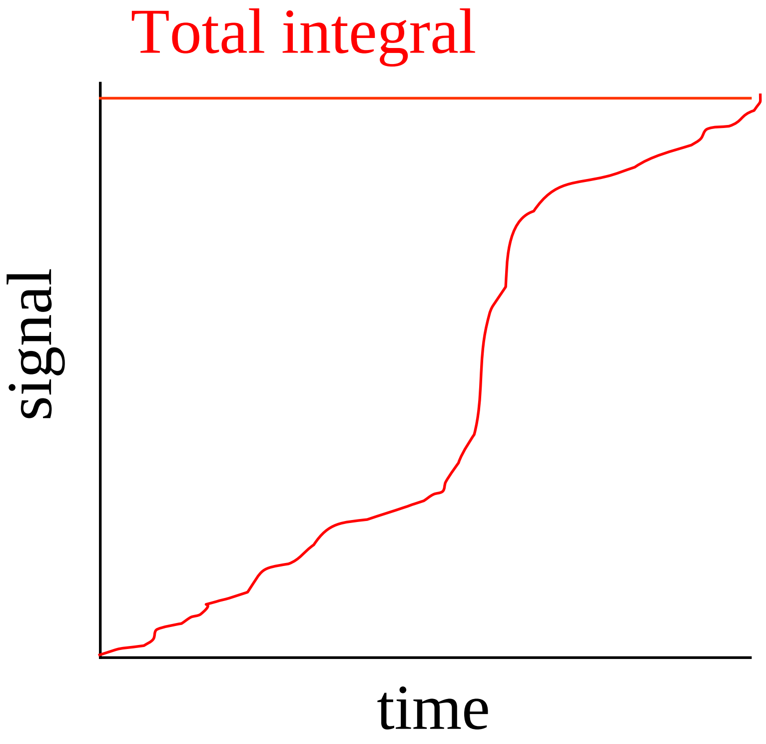
Signal processing

Signal storage

Counting versus Integrating



Low noise

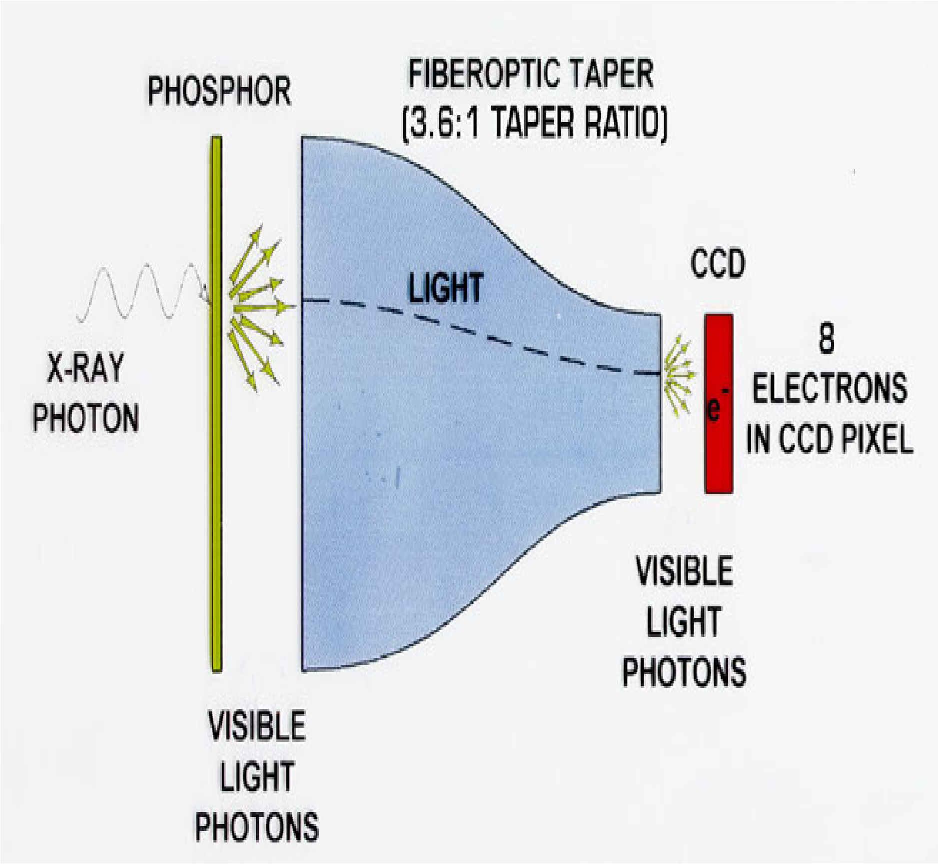


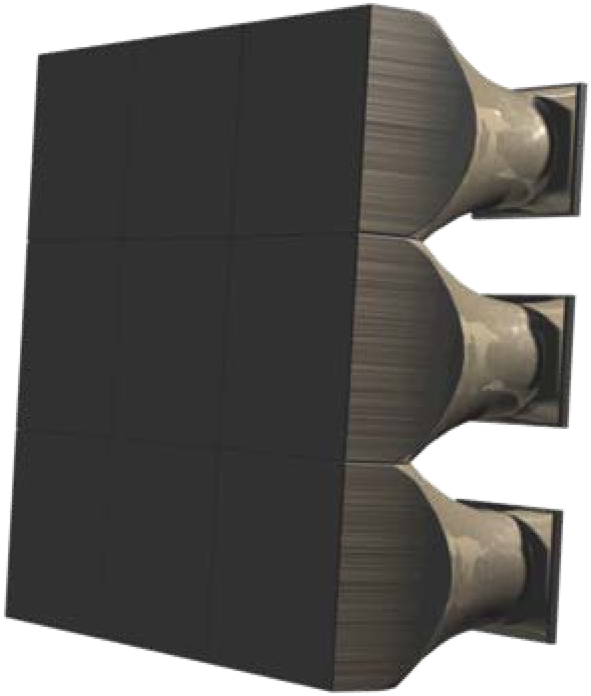
Fast

CCD = Charge Coupled Devices

- Very thin silicon layer that transfers photons into electrons ➔ not good for X-rays ➔ use intermediate scintillator/phosphor.
- Storage wells that store generated charge; including thermally induced charge = dark current ➔ fast but noisy
- Readout of signal through one readout node; transfer charge from one pixel to the next towards readout node ➔ long readout times
- Small pixels: 10 – 30 micrometer.
- Commercial product for large market ➔ perfect

Large area CCD systems, mainly for PX





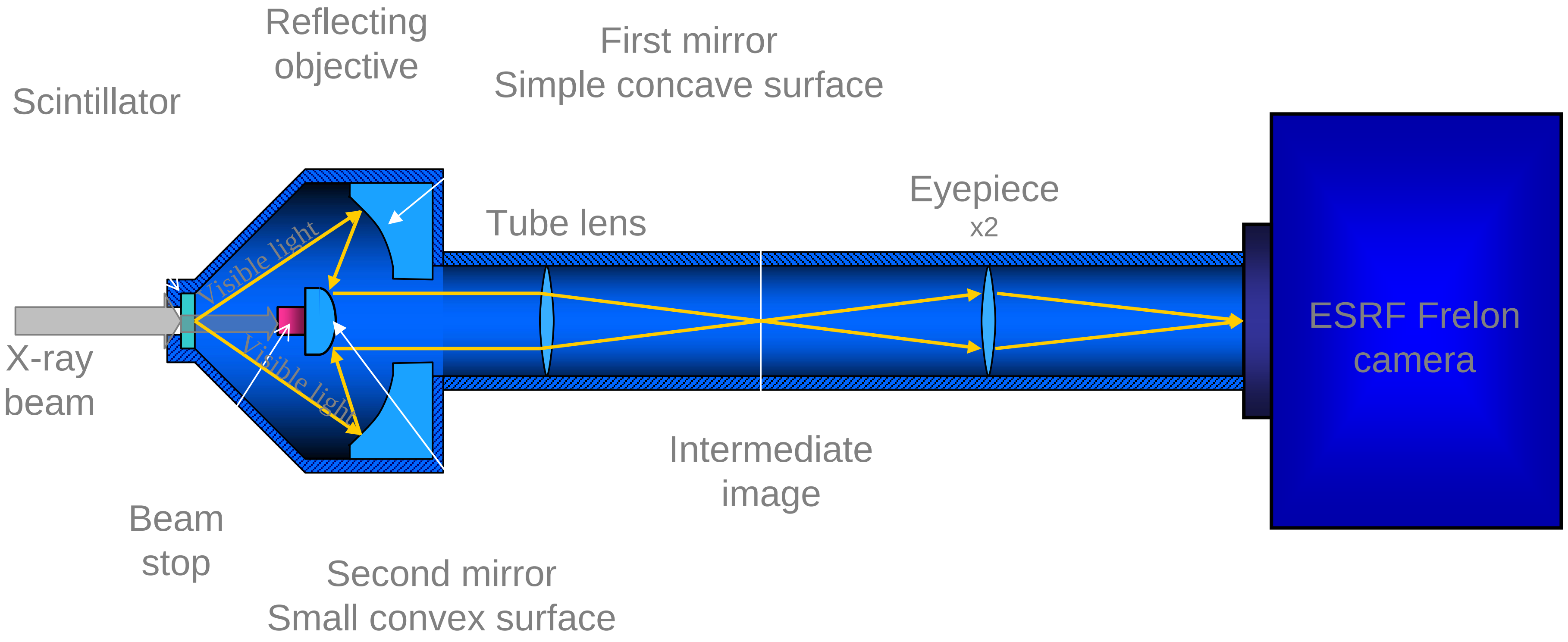
– Indirect detection

==> losses & spreading

– Integrating detector

==> noise & information loss

High resolution imaging with CCD's



Scintillator is very inefficient

Full tomo dataset in < 1 sec.

Signal Generation → Needs transfer of Energy

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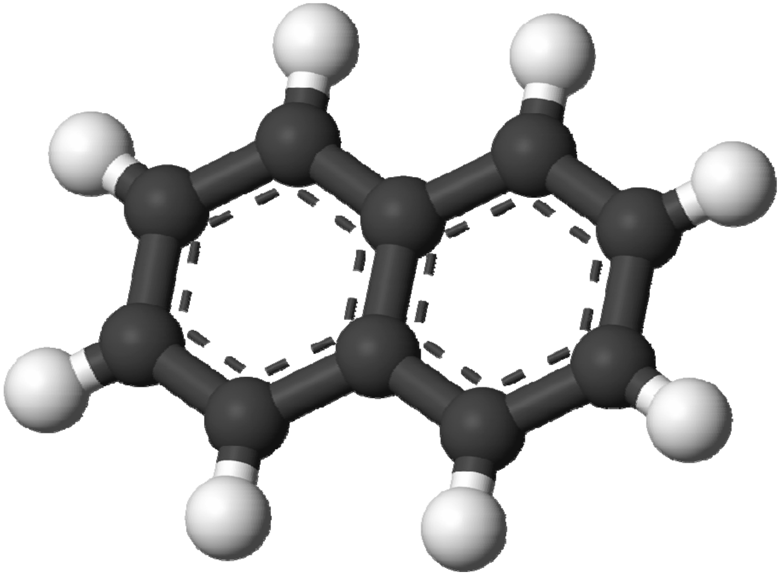
A) Organic (molecular) scintillators



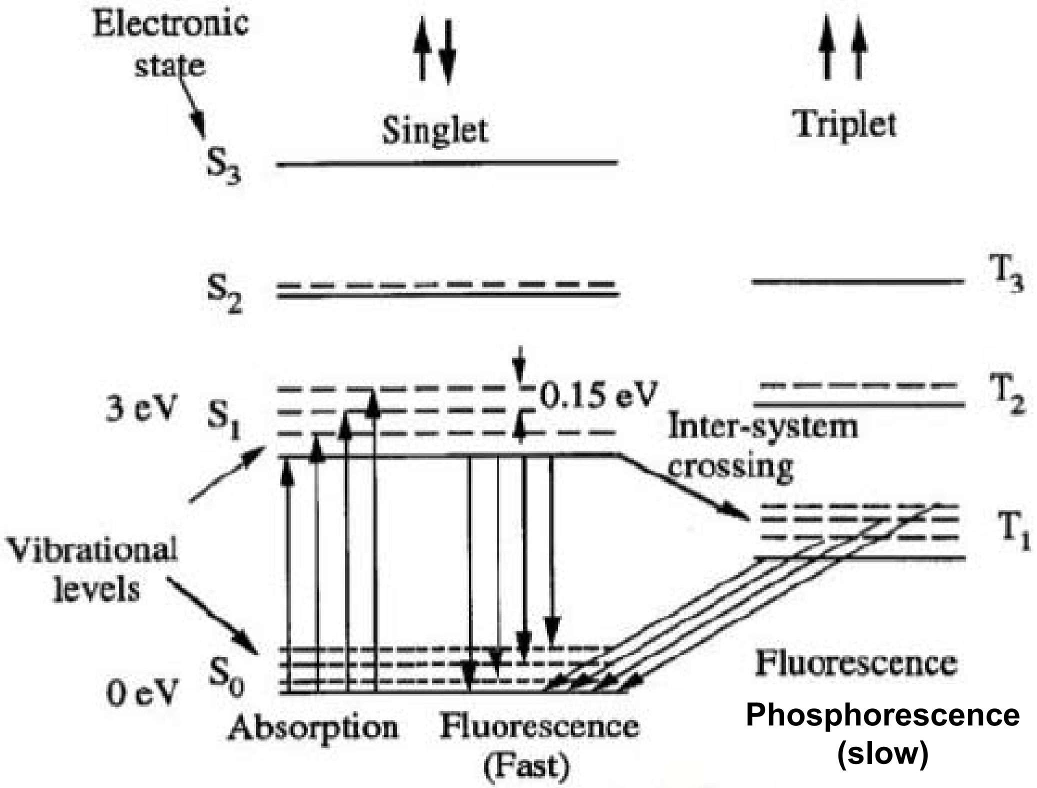
Naphtalene:
π-electron system

<u>Advantages:</u>
- Fast
- No need for Xtals

➔liquids, glasses, …

<u>Disadvantages:</u>
- inefficient
- Non-linear (quenching)
- not good for γ's

The electronic levels:



„Stokes-Shift" => Transparenz

1) Prompt fluorescence
2) Phosphorescence
3) Delayed fluorescence

➔ Complicated time structure

b) Inorganic crystalline scintillators (NaI:Tl)

Origin does not stem from molecular energy levels but from band-structure levels.

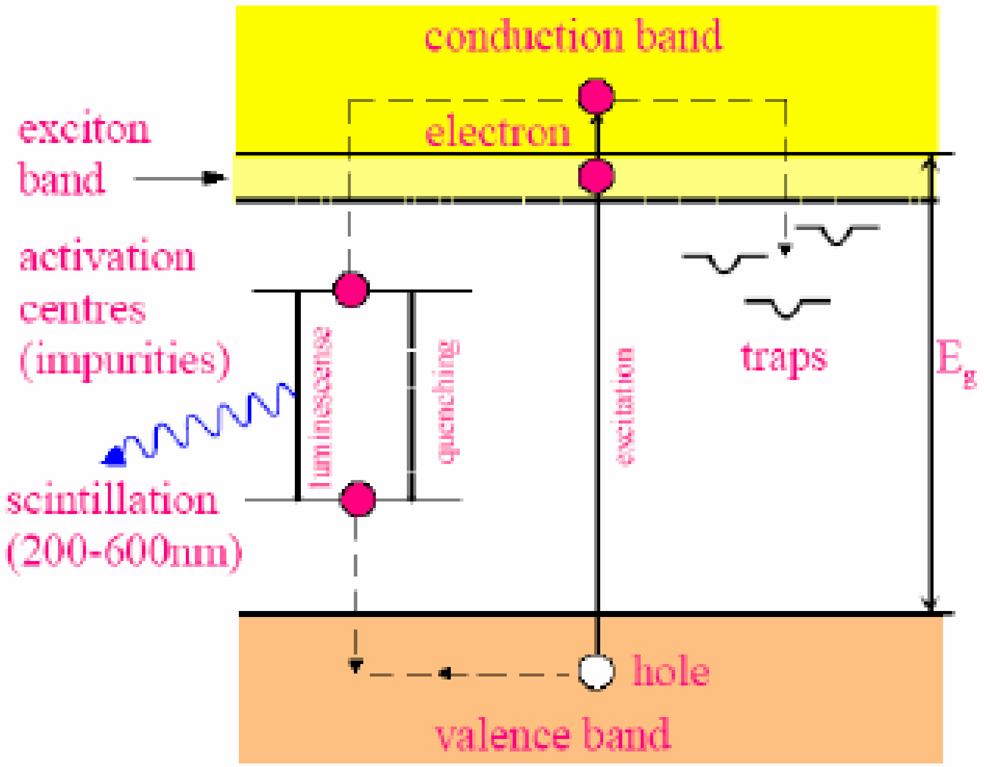
Advantages:

- Good efficiency
- Good linearity
- Radiation tolerance

Disadvantages:

- Relatively slow
- Crystal structure needed (small and expensive)

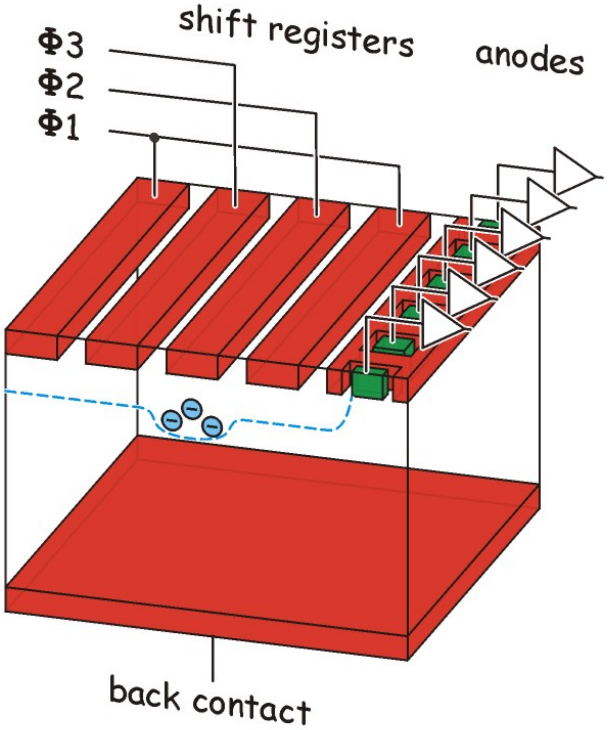
Three different scintillation mechanisms (crystals like NaI, CsI, BGO, BaF_2, ...)

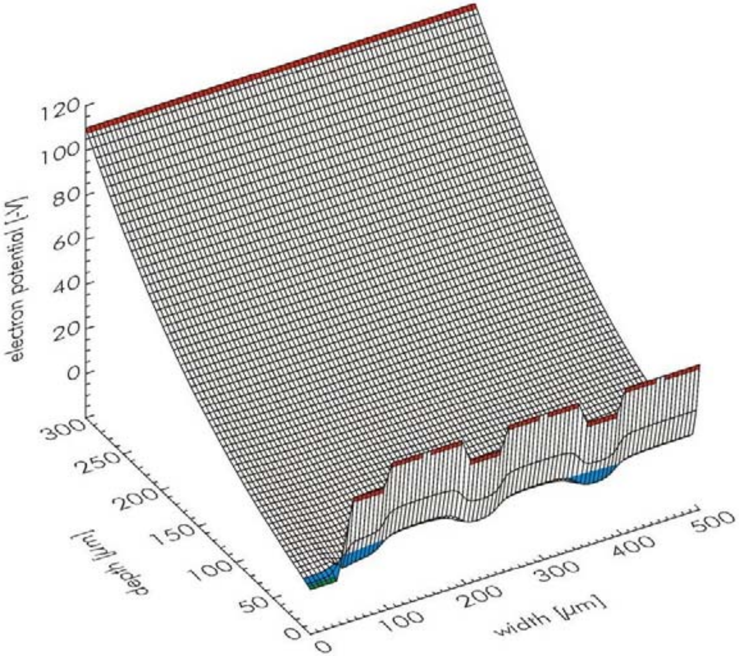


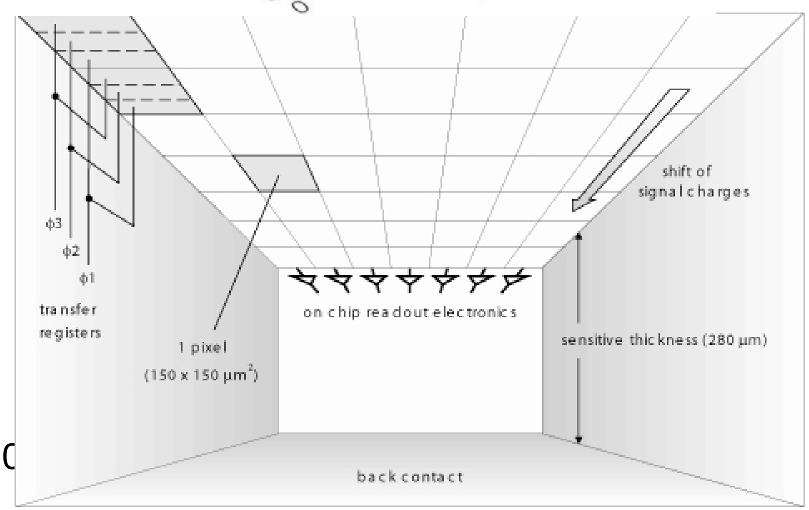
→ > 1 decay time constants

- **fast** recombination (ns ... µs) from activation centres
- **slow** recombination due to trapping (~100ms)

Direct detection pnCCD



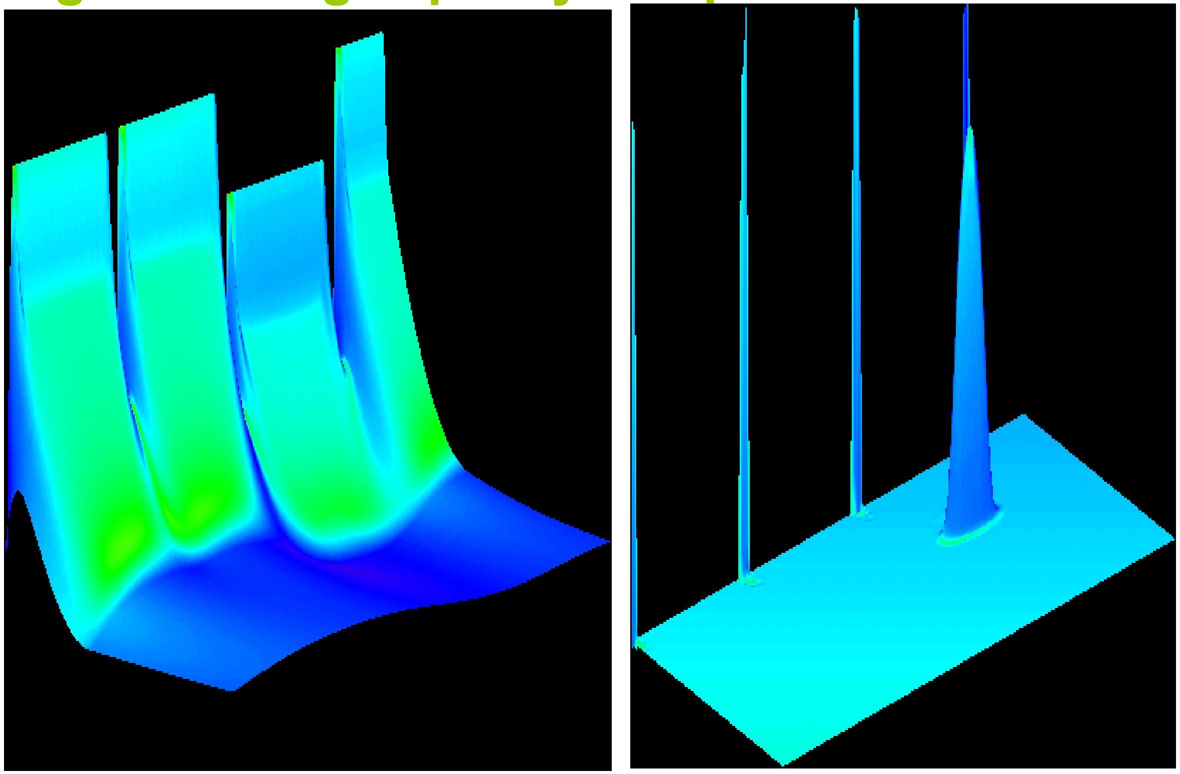




- **full depletion (50 µm to 500 µm)**
- **back side illumination**
- **high readout speed**
- **pixel sizes from 36 µm to 650 µm**
- **charge handling: more than 10^6 e^-/pixel**
- **high quantum efficiency**

How many charges can be stored in one pixel ?

What determines the charge handling capacity in a pixel ?



pixel volume:
20x40x12 μm³ ≈ 1x10⁴μm³

Doping: 10² P per μm³

CHC = 1 x 10⁶ per pixel

can be **increased** by **doping**

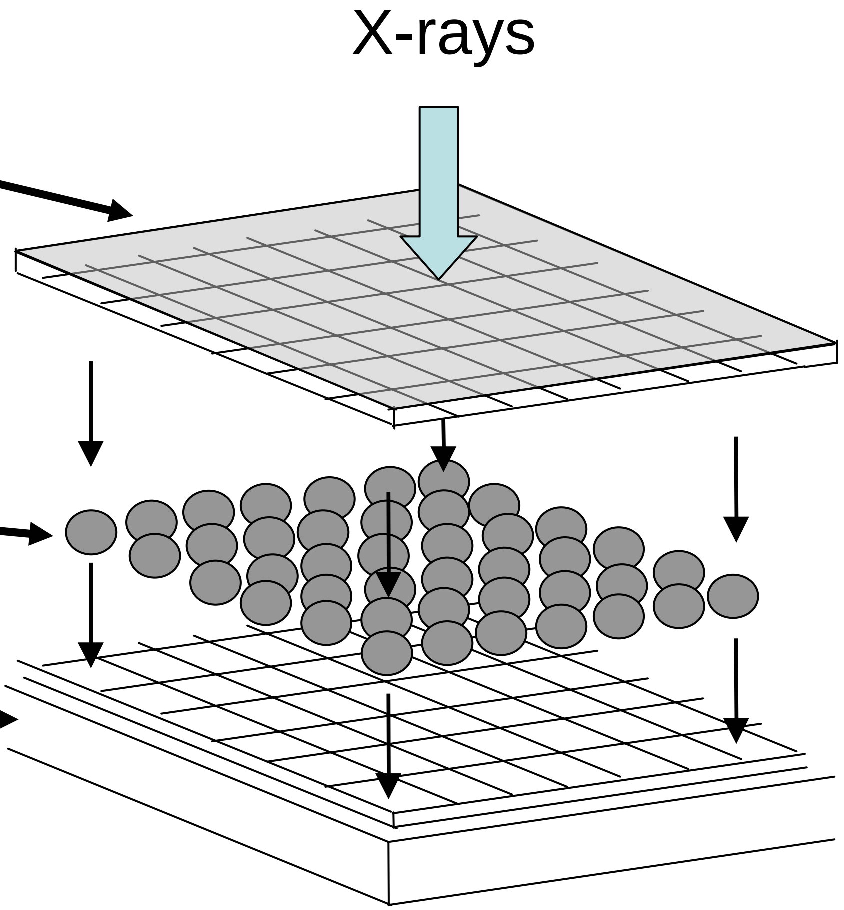
The new generation 2D detectors: Hybrid Pixel Array Detectors

What are they?

and

why are they so good?

Hybrid Pixel Array Detector (HPAD)



Diode Detection Layer

- **Fully depleted, high resistivity**
- **Direct x-ray conversion**
- **Silicon, GaAs, CdTe, etc.**

Connecting Bumps

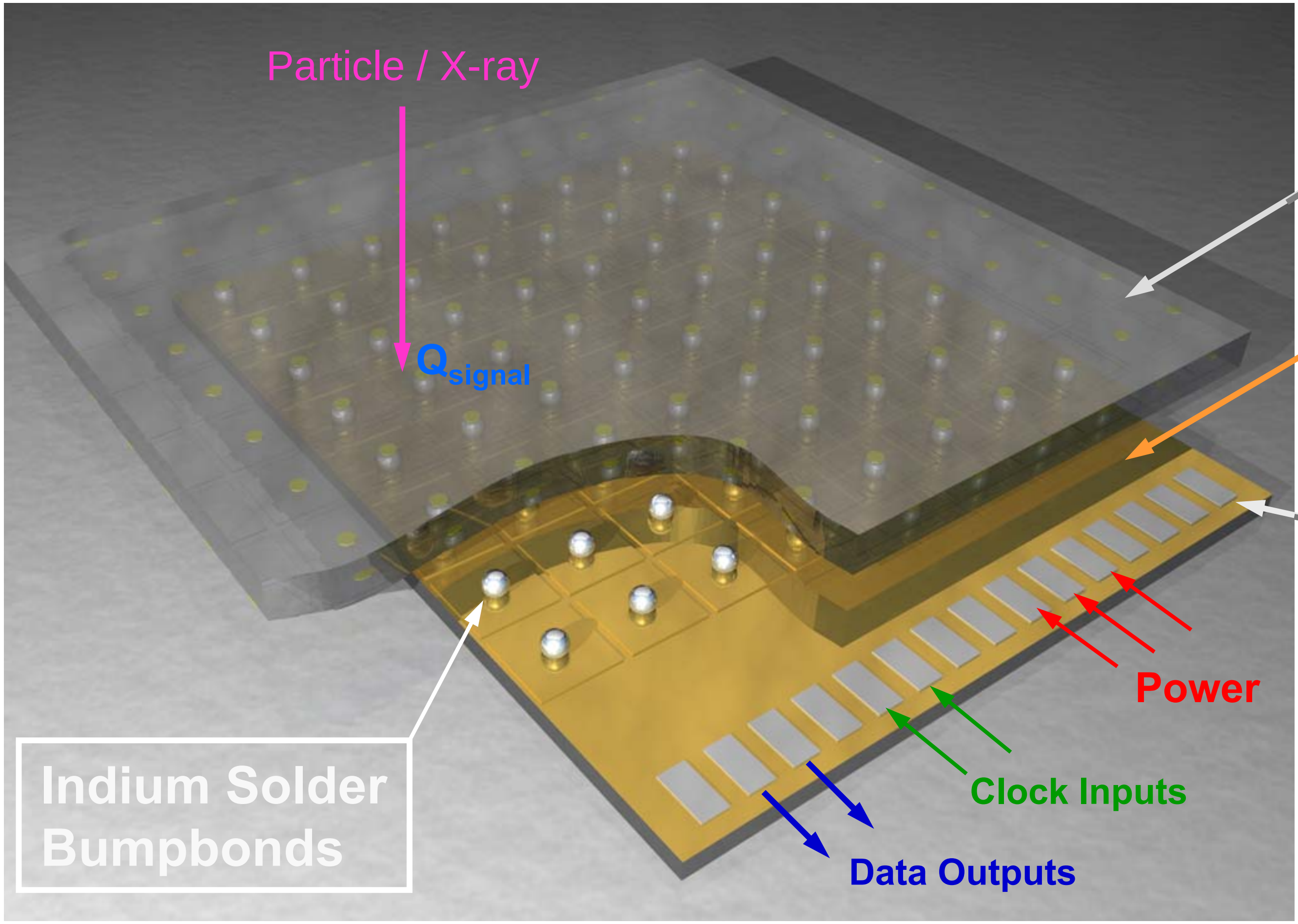
- **Solder or indium**
- **1 per pixel**

CMOS Layer

- **Signal processing**
- **Signal storage & output**

Gives enormous flexibility!

Hybrid Pixel Detectors



Pixelated Particle Sensor

Amplifier & Readout Chip CMOS

Connection wire pads
- Power
- Inputs
- Outputs

Particle / X-ray → Signal Charge → Electr. Amplifier → Readout → Digital Data

Signal Generation → Needs transfer of Energy

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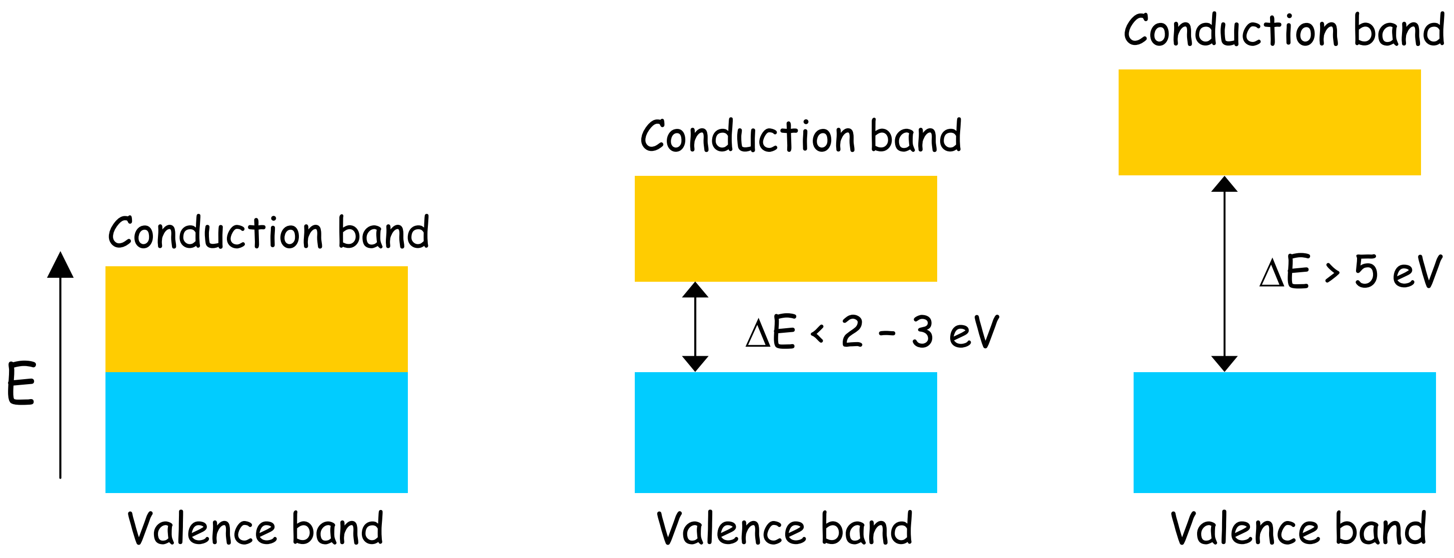
Classification of Conductivity



Conductor

Semiconductor

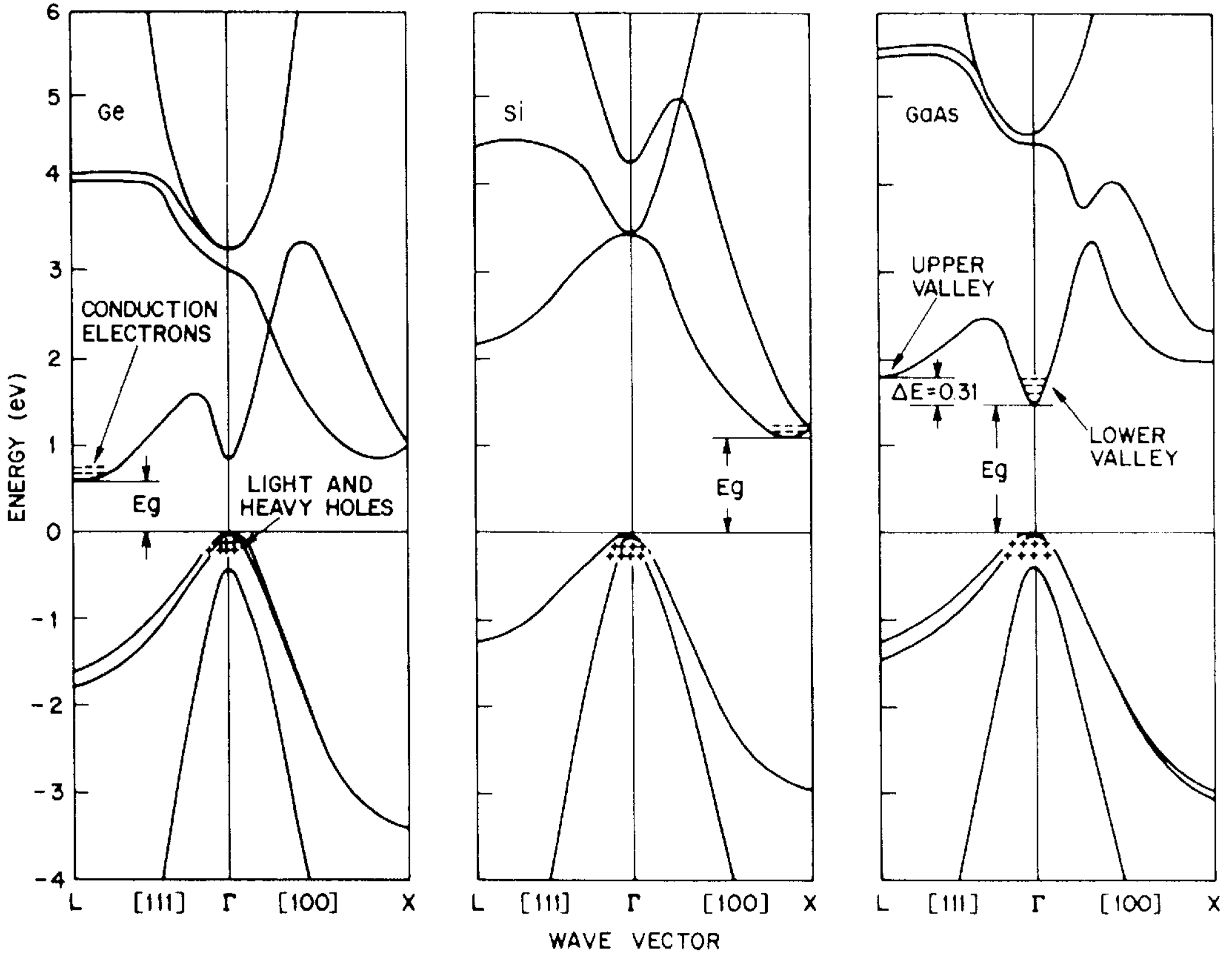
Insulator

Si, Ge

Diamond

Band structure (3)

Ge Si GaAs

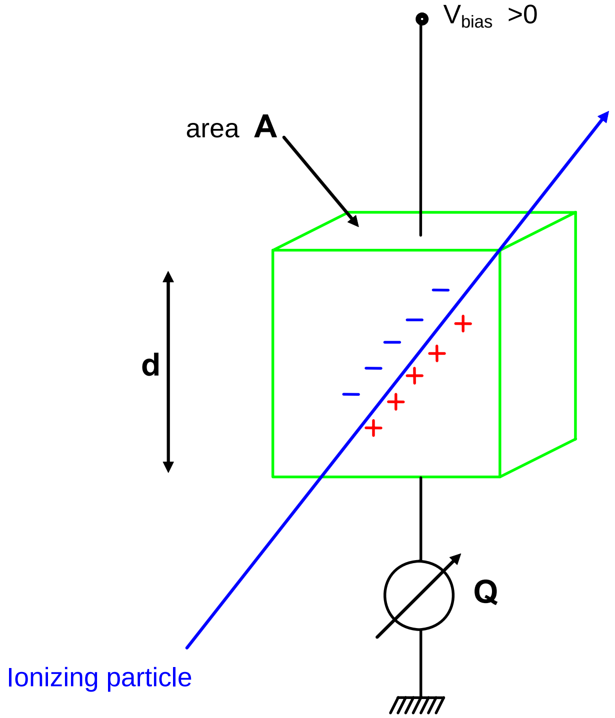


E_g = 0.7 eV E_g = 1.1 eV E_g = 1.4 eV

Indirect band gap Direct band gap

„Ohmic“ Particle Detector

Ohmic material : Resistivity ρ e.g. intrinsic semiconductor



- **E-field** :

  $E = V_{bias} / d$

- **Carrier velocity** :

  $v = \mu E = \mu (V_{bias} / d)$

- **Signal collection time** :

  $\tau = d / v = d^2 / (\mu \; V_{bias})$

- **Resistance** :

  $R = \rho \; (d / A)$

- **„leakage current“** :

  $i_{leak} = V_{bias} / R = (V_{bias} A) / (\rho \, d)$

- **„leakage charge“** :

  $Q_{leak} = i_{leak} \, \tau = d \, A / \rho \, \mu$

  $Q_{leak} = \text{Volume} / \rho \, \mu$

Example : Silicon ρ = 20 kΩcm

d = 300mm , Signal charge = 4fClb = 24’000 e

- Pad detector : A = 1 cm^2

  Q_{leak} = 10^{-9} Clb ---> σ ~ 80'000 e ---> S/N ~ 0.3

- Pixel detector : 100μm x 100μm ---> A = 10^{-4} cm^2

  Q_{leak} = 10^{-13} Clb ---> σ ~ 800 e ---> S/N ~ 30 !!!!

The operation of semiconductor materials in a “ohmic” regime works fine for:

- Silicon ($\Delta E_{bandgap}$ = 1.16eV) at low temperature
- High bandgap semiconductors (GaAs, Diamond) at room temperature

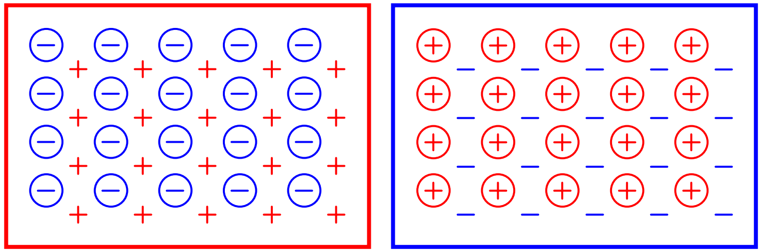
However, for Silicon at room temperature need another trick !

p-n-junction and space charge region

fixed charges : ⊖ ⊕

mobile charges: + −

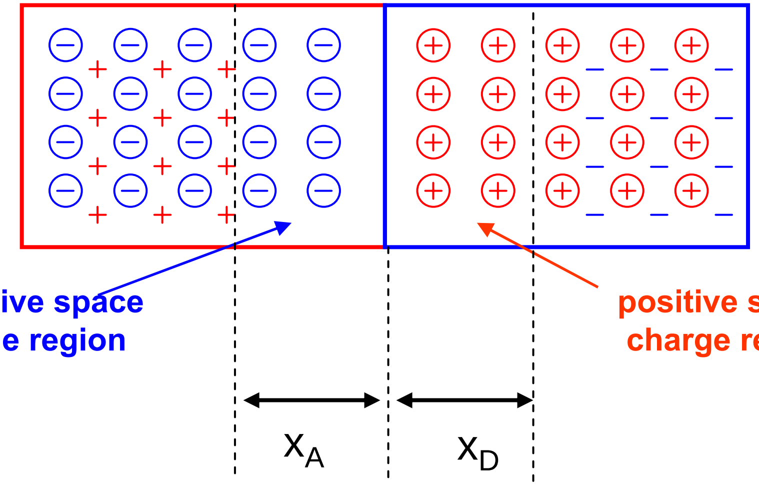
p-type n-type



p-n-junction **before** equalization of Fermi levels

acceptor density $\mathbf{N_A}$

donor density $\mathbf{N_D}$



p-n-junction **after** equalization of Fermi levels

negative space charge region

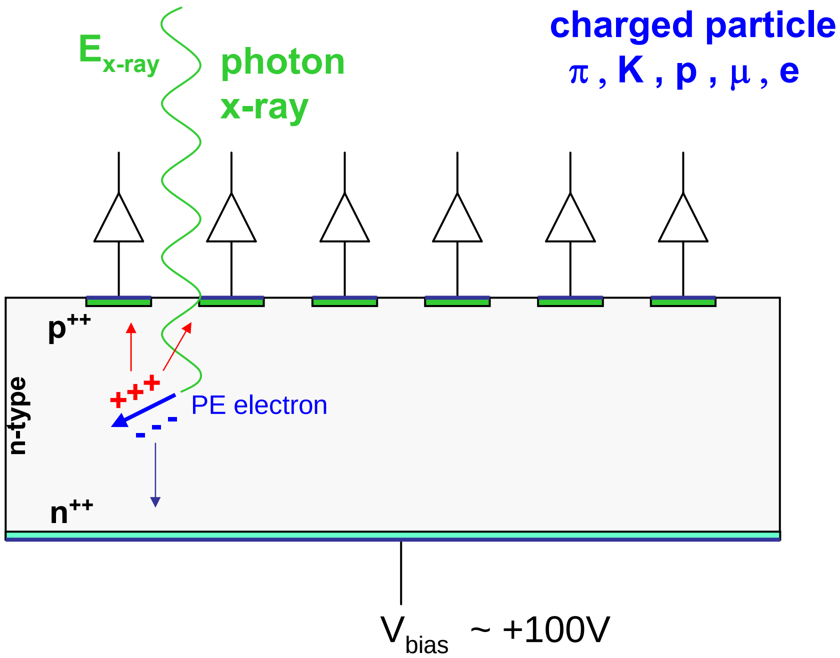
positive space charge region

charge neutrality →

$$\boxed{N_A \cdot x_A = N_D \cdot x_D}$$

region free of mobile carriers ! → no leakage current !

Segmented Silicon Diode Sensors for Particle Detection



Shared Charge collection on segmented electrodes due to:

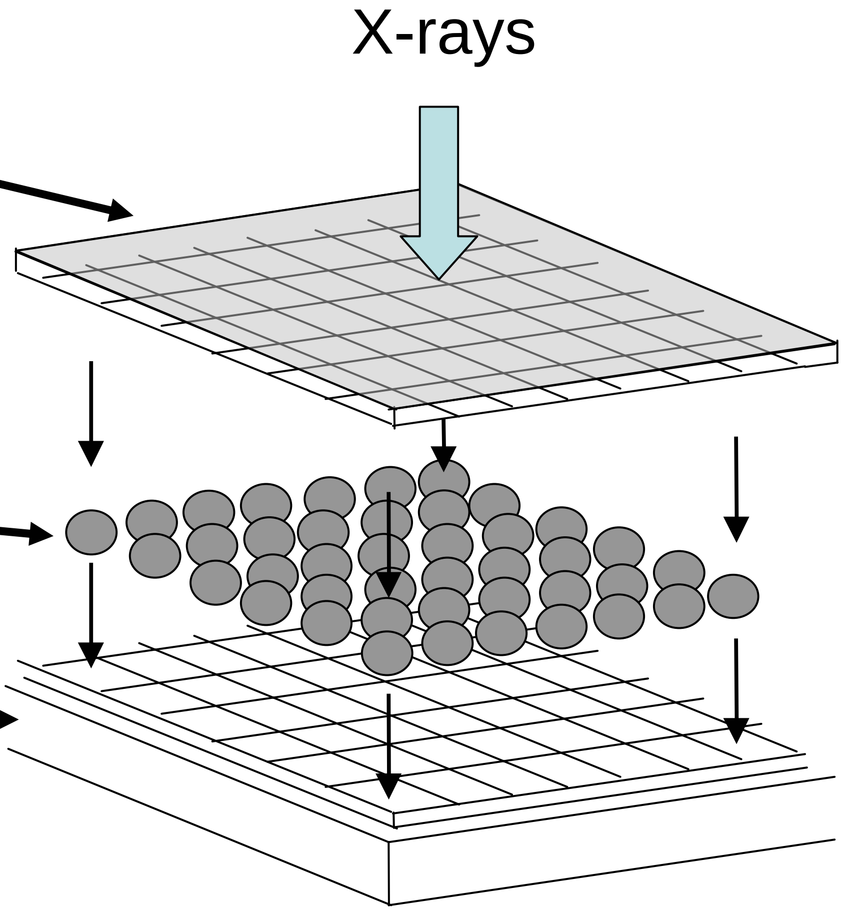
- Diffusion during drift time
- Lorentzangle due to presence of B-field
- Tilted tracks

Individual readout of charge signal on electrodes allows **position interpolation** that is better than pitch of segmentation.

Silicon microstrip detectors in HEP:

Strip pitch = 50μm
Position resolution ~1.5 μm achieved

Hybrid Pixel Array Detector (HPAD)



Diode Detection Layer

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- Silicon, GaAs, CdTe, etc.

Connecting Bumps

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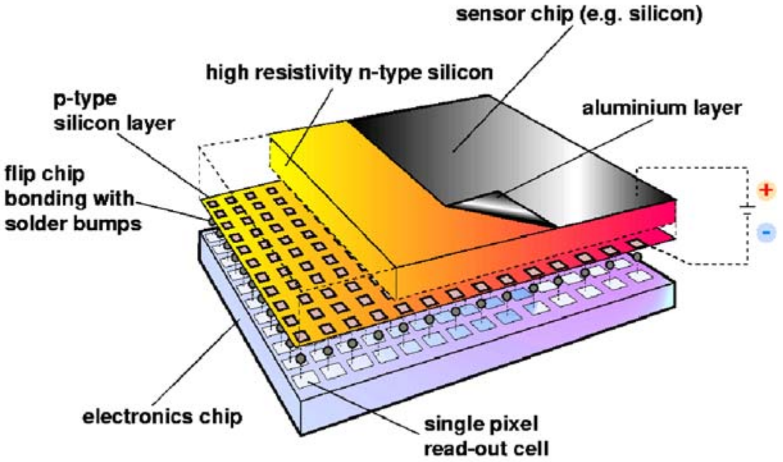
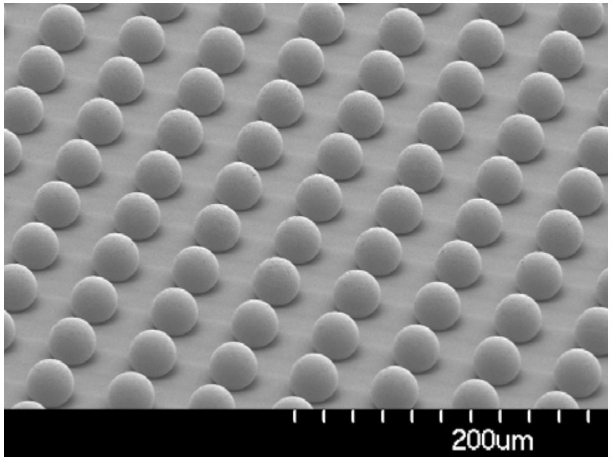
CMOS Layer

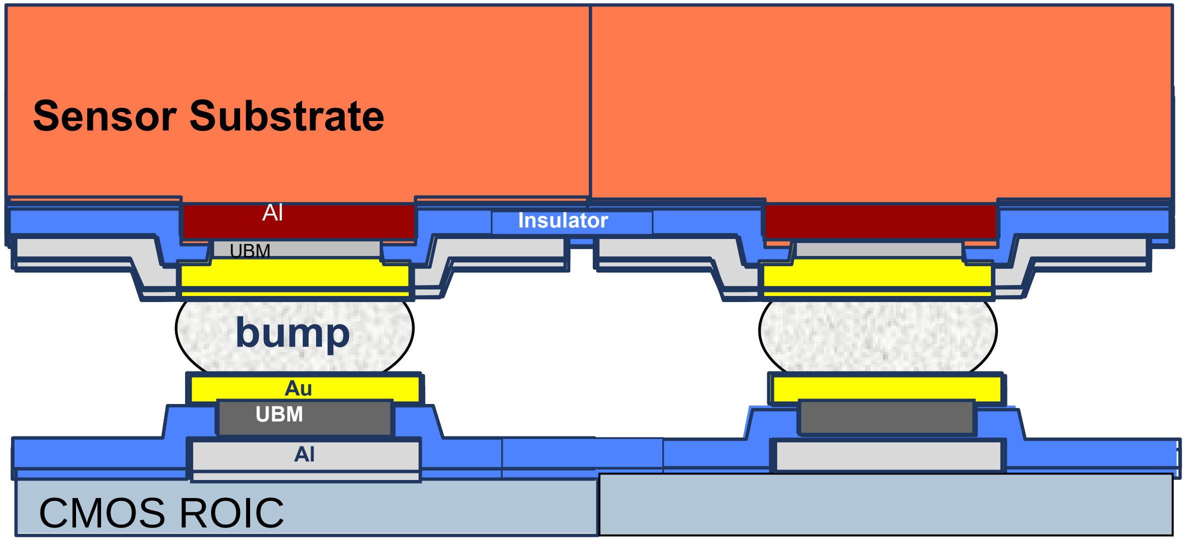
- Signal processing
- Signal storage & output

Gives enormous flexibility!

The new generation: Medipix et al.

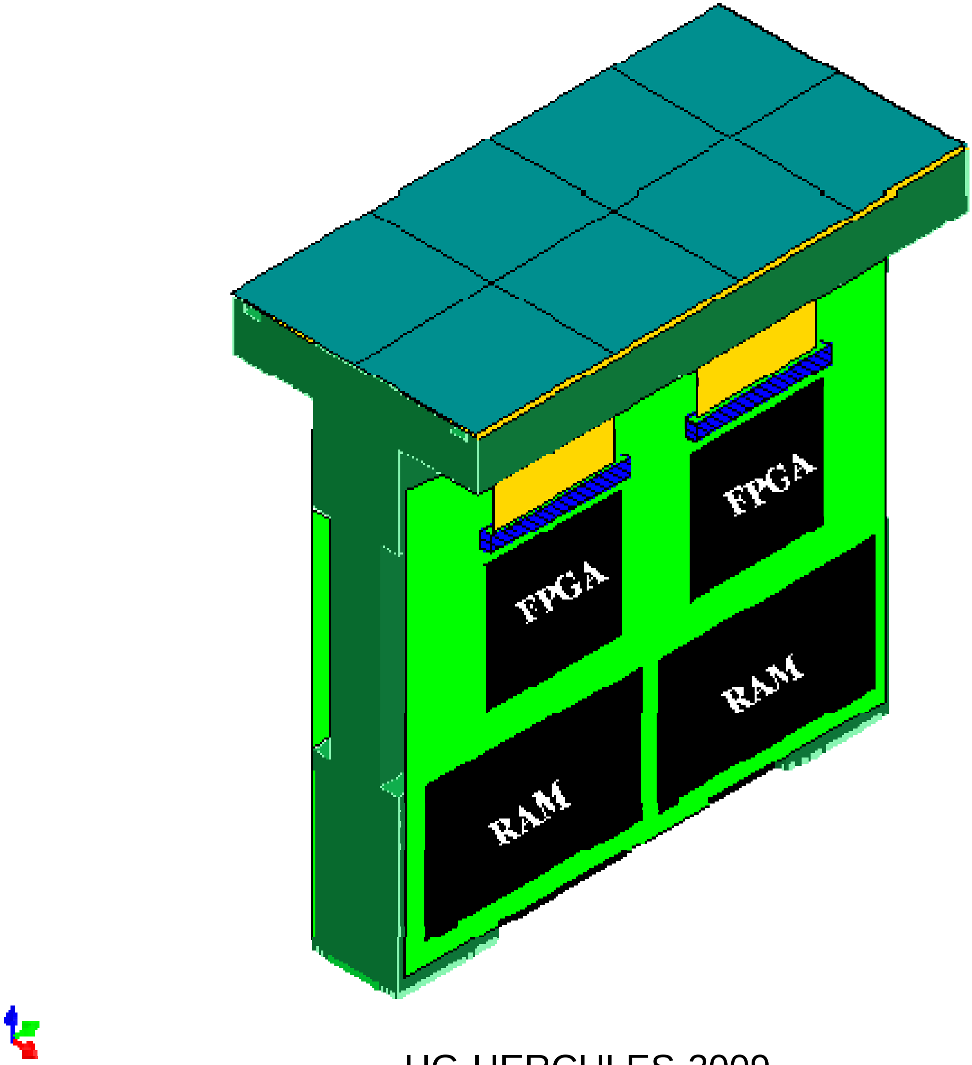




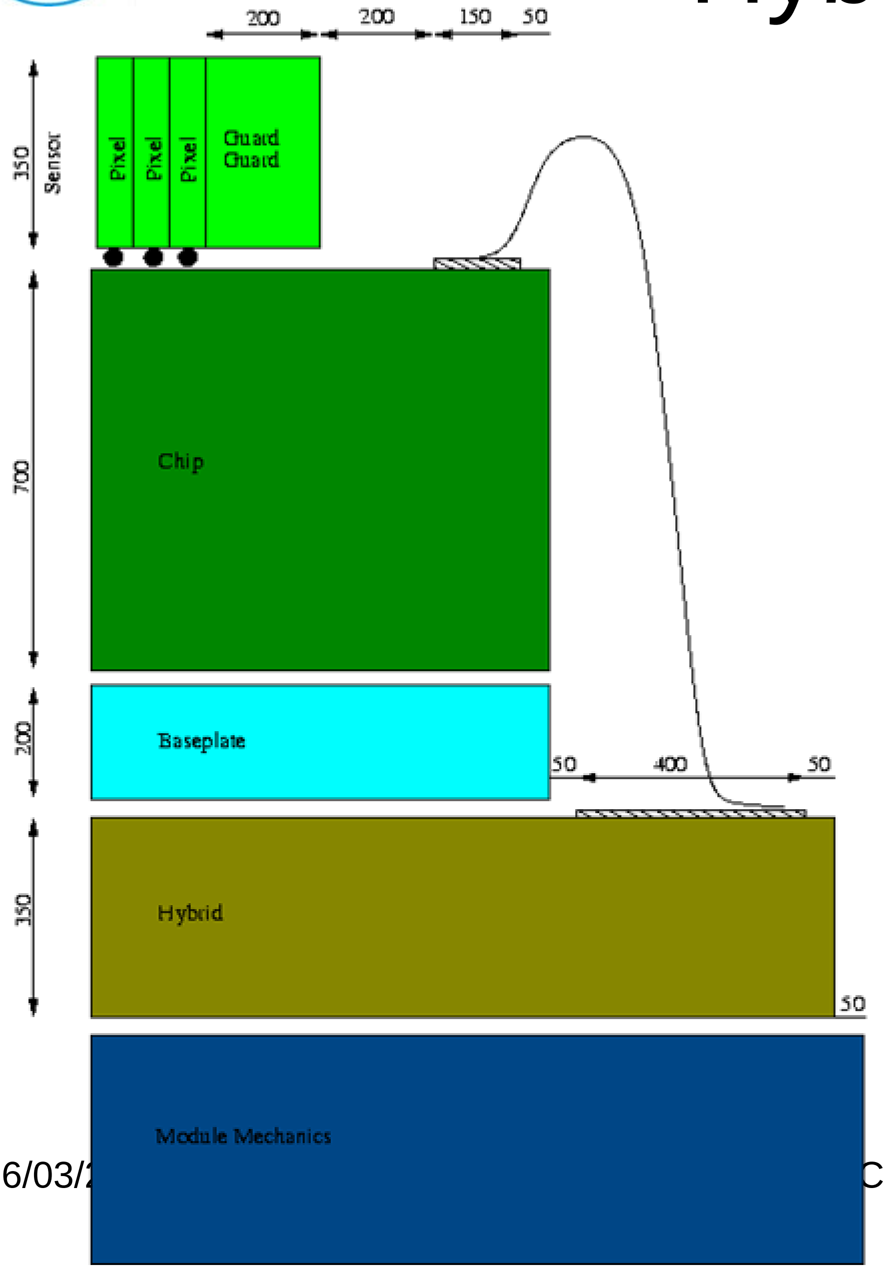


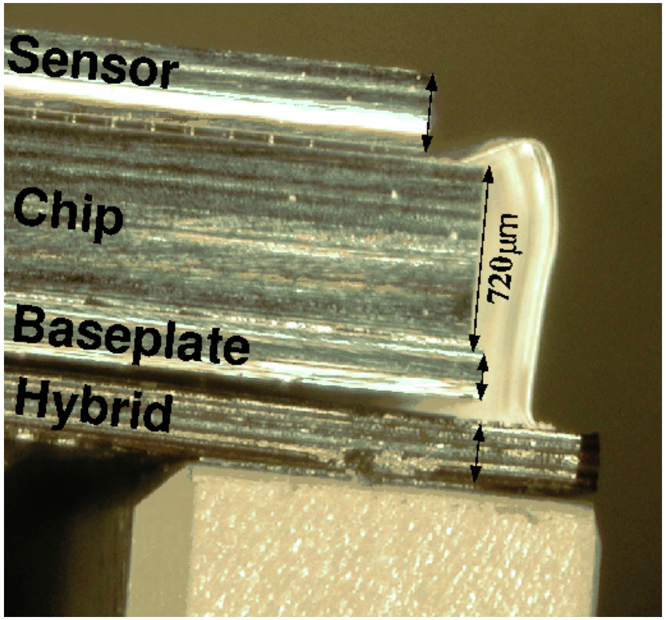
XFS Module Specification: PSI/SLS

Operate **2x4 (8)** Chips per Module. **~78 x 39 mm^2**

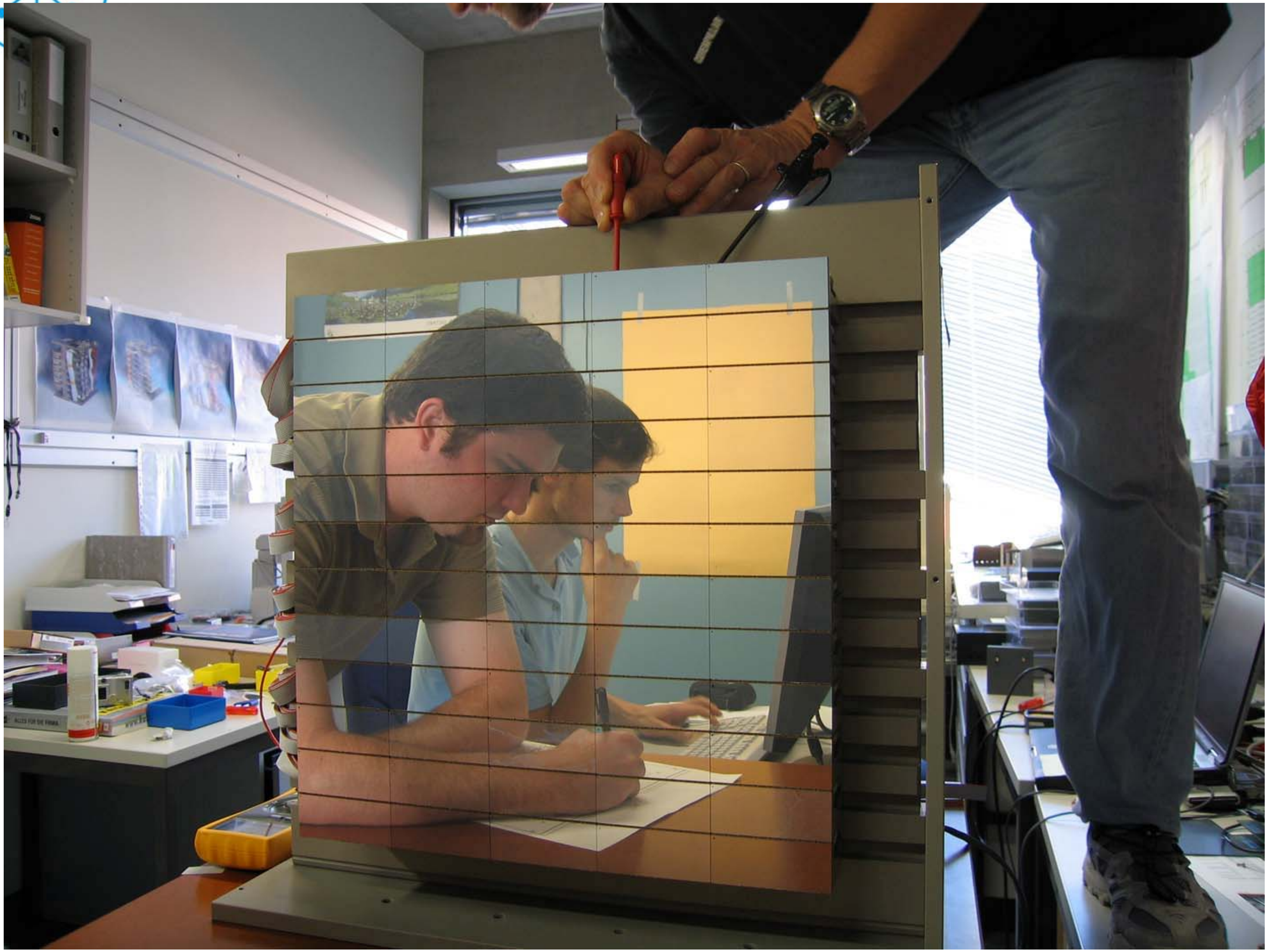


Hybridization





- Cut the sensor as close as possible
- Use thinned readout chips
- Stay within the exact n-fold pixel pitch

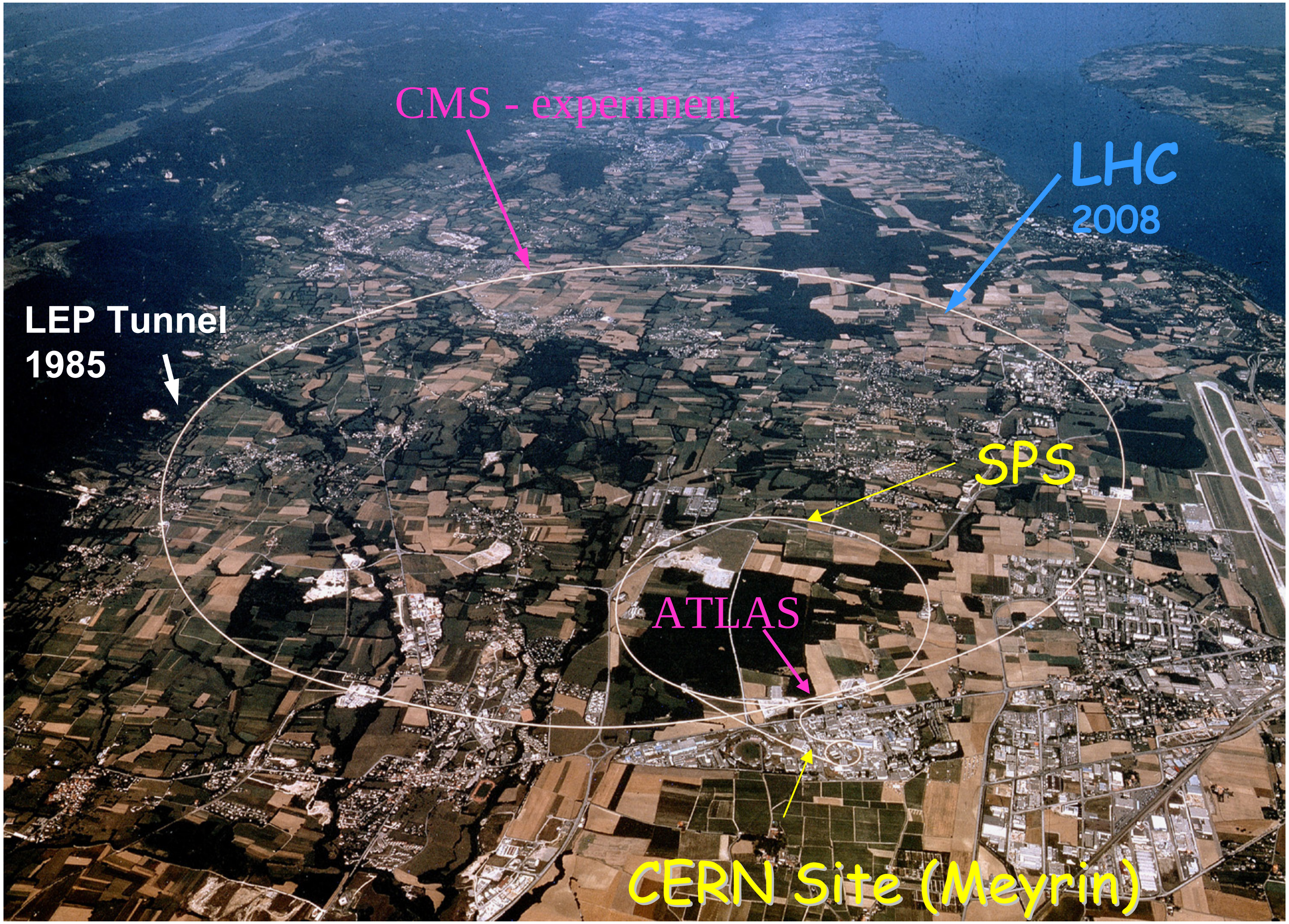


Courtesy: Ch. Brönnimann, PSI SLS Detector Group

Why are HPADs so popular ?

- Custom design of functionality: you design your readout chip specific for your application (unlike CCDs).
- Can do photon counting ➔ “no” noise.
- Direct detection ➔ good spatial resolution
- Massive parallel detection ➔ high flux
- But: development takes long and is expensive.

Large Hadron Collider LHC at CERN

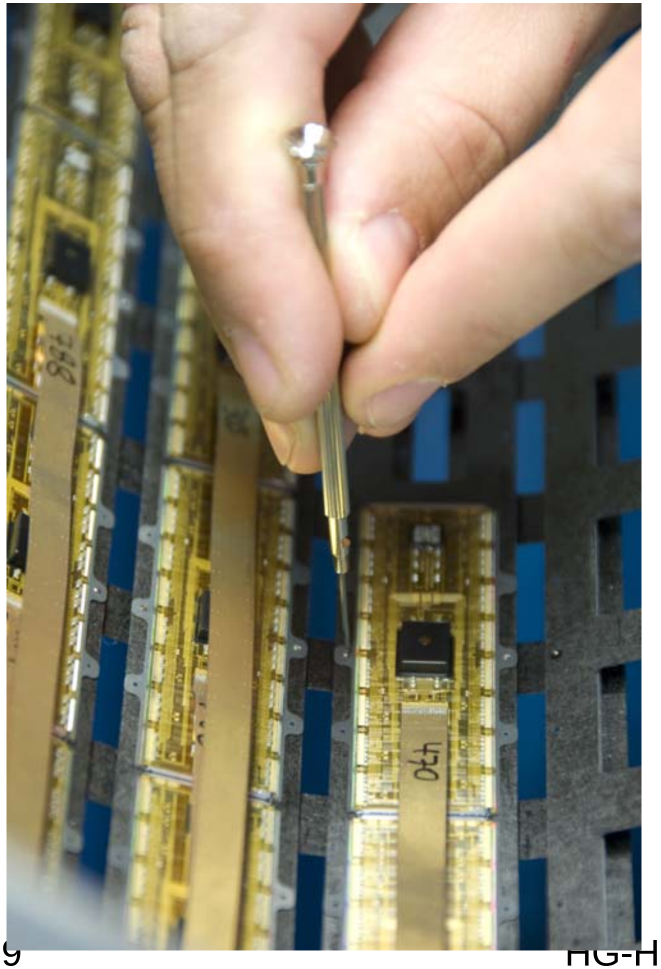


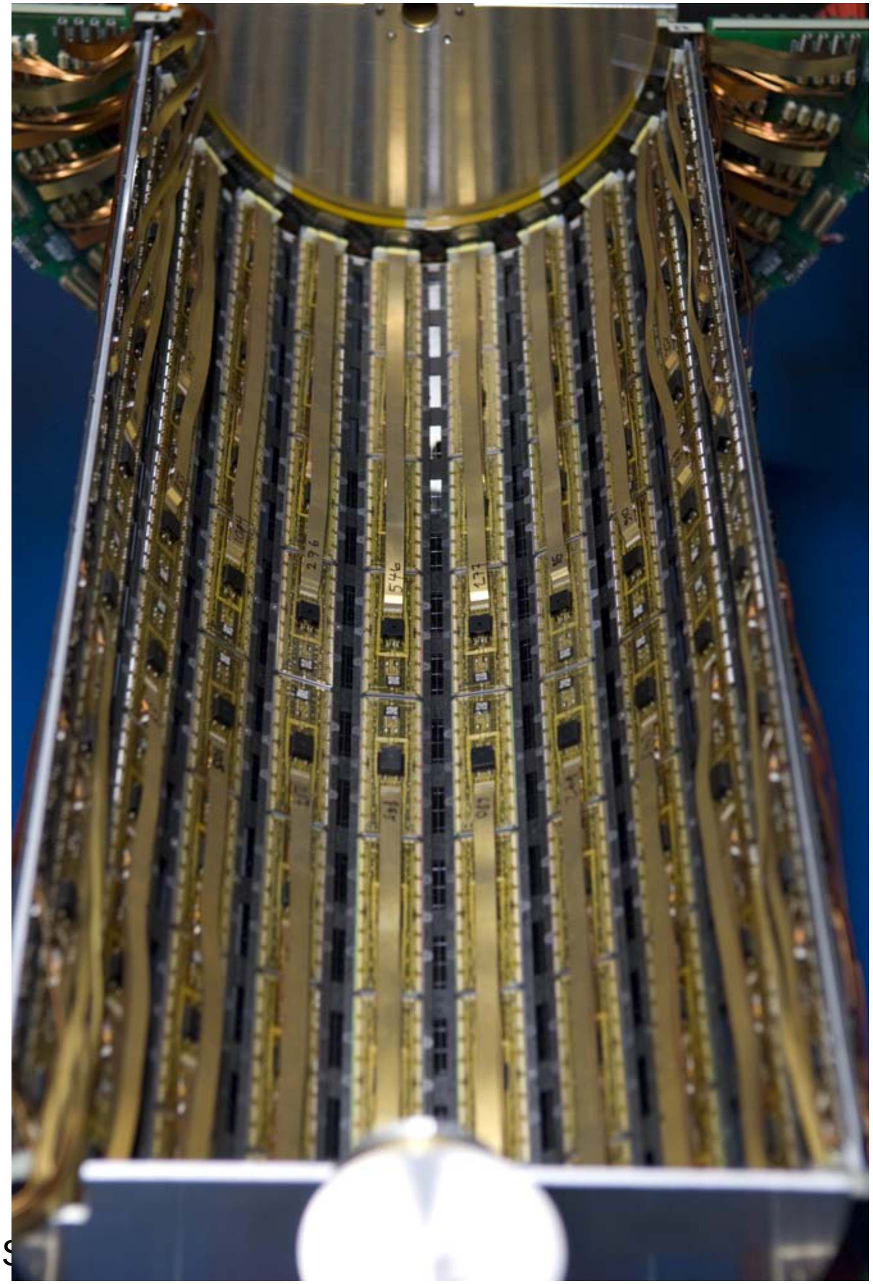
Proton – Proton collisions at 14 TeV → Higgs & SUSY search

CMS Pixel Detector

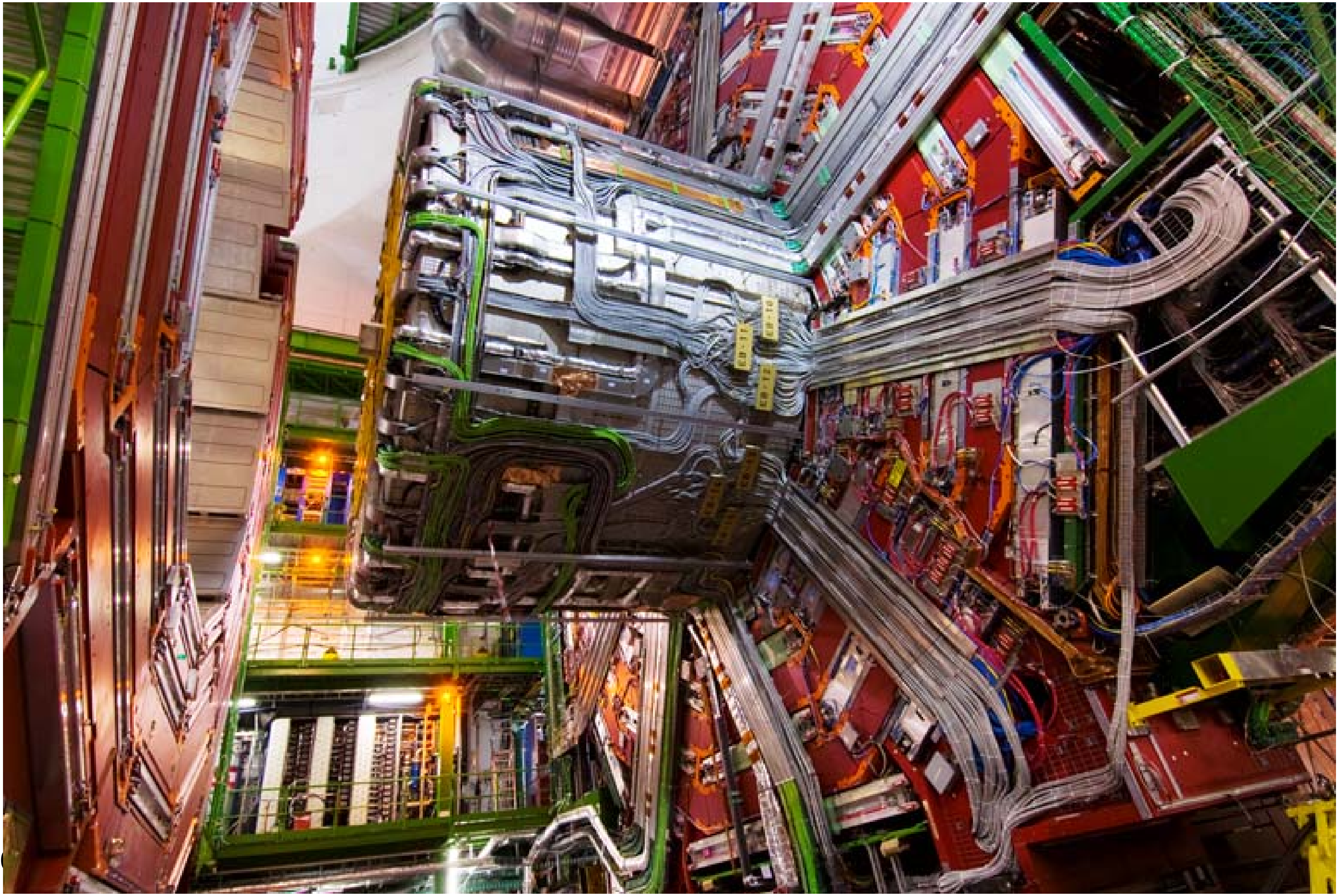
for the Large Hadron Collider

768 pixel modules ~ 0.75 m^2

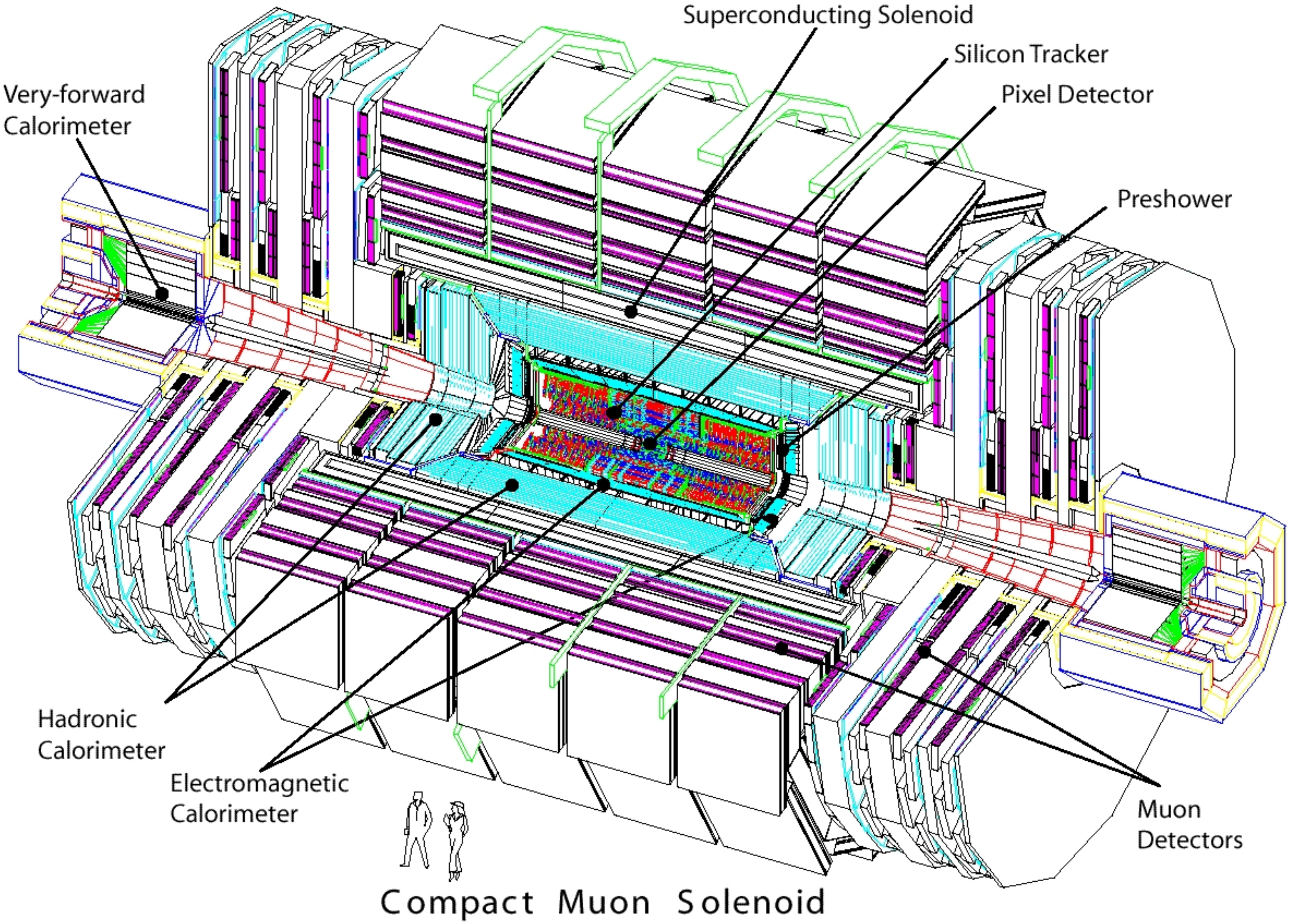




After 13 years of R&D and construction we install the Pixel Detector into CMS



Compact Muon Solenoid



Some more parameters for 2D systems

- Point Spread Function (PSF) (Line spread function (LSF) or spatial resolution):

  A very small beam (smaller than the pixel size) will produce a spot with a certain size and shape. Very important are the FWHM; and the tails of the PSF.

  This is experimentally difficult ➔ use sharp edge and LSF

  Note: pixel size is not spatial resolution! (but should be close to it in an optimal design).

Some more parameters for 2D systems

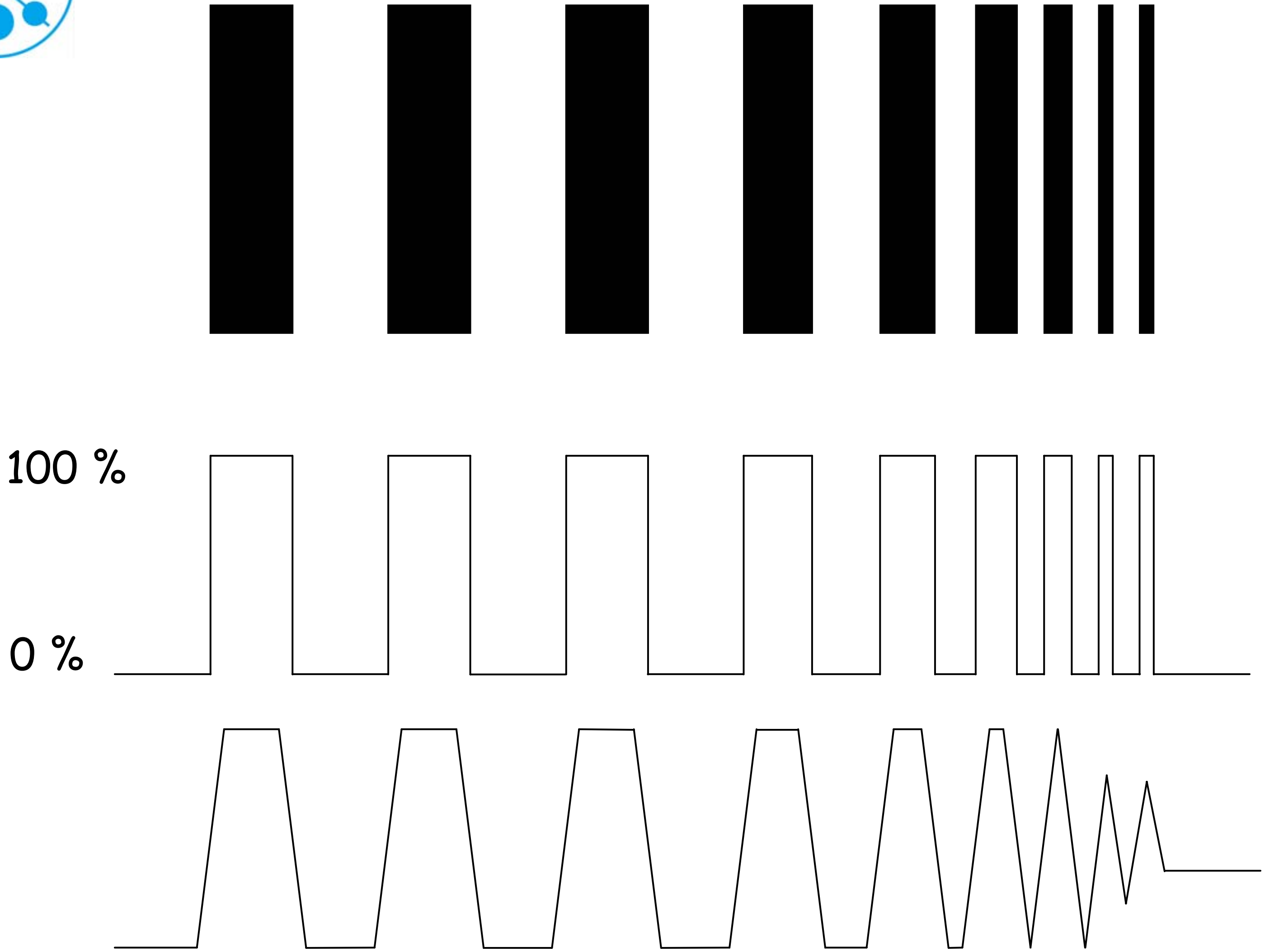
- Modulation Transfer Function (MTF):

  How is a spatially modulated signal (line pattern) recorded (transferred) by the detector?

$$Modulation \equiv contrast \equiv \frac{Max - Min}{Max + Min}$$

This depends on the frequency.

Is directly related to the LSF and the DQE


100 %
0 %

Some more parameters for 2D systems

- Modulation Transfer Function (MTF) Example

Ideal: $$contrast \equiv \frac{100-0}{100+0} = 1.0$$

Effect of noise: $$contrast \equiv \frac{150-50}{150+50} = 0.5$$

Effect of PSF: $$contrast \equiv \frac{75-25}{75+25} = 0.5$$

Summary Detectors

- Signal-to-noise ratio most fundamental parameter in measurements.
- A detector is always a compromise (ex. speed vs. noise). Application determines what you compromise.
- Never take a detector as a “perfect black box”, be aware of limitations.
- Understanding your detector is part of understanding your science.