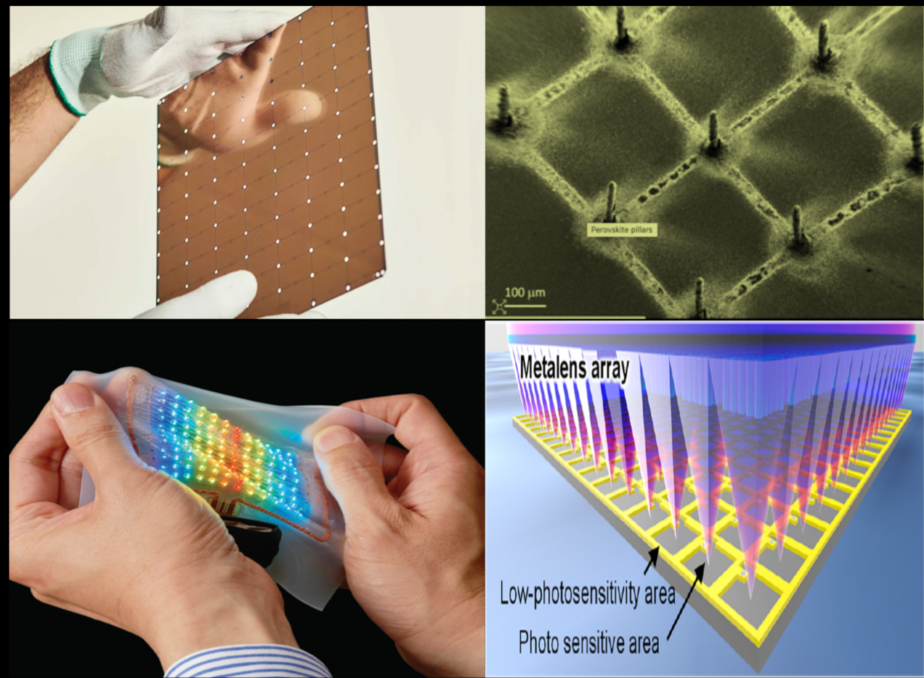
Radiation Detectors, Imaging What You Cannot See: Silicon and Advanced Techniques



Cinzia Da Vià

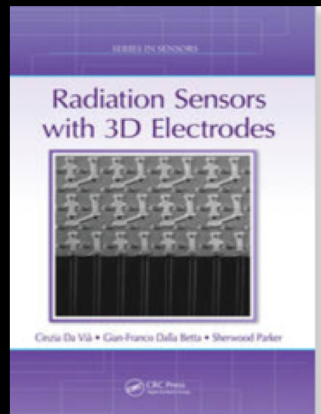
The University of Manchester, UK & Stony Brook University USA

Some Information about myself

- Professor at The University of Manchester (UK)
- Visiting Professor at the University of Stony Brook, New York, USA
- Member of the ATLAS Collaboration at CERN – LHC
- Chief editor Frontiers in Physics, Radiation Detectors and Imaging
- Co-Chair of the EU-ATTRACT Independent Committee
- IEEE WIE International Committee Member 2017-2022
- Member of the IEEE TAB Program on Climate Change
- Distinguished Lecturer and Organizer of the IEEE NPSS Instrumentation School

Scientific Interests:

- ➢ Radiation Detector development : silicon pixels, 3D silicon detectors, fast timing
- ➢ Radiation effects in silicon, "Lazarus effect"
- ➢ 3D printed detectors, Vertical integrated microsystems
- ➢ Quantum Imaging at X-Ray energies



This lecture

- Brief reminder: Radiation, Radiation interaction with Matter and Radiation Detectors
- Imaging Radiation with Silicon Detectors:

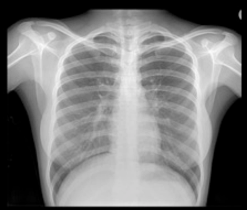
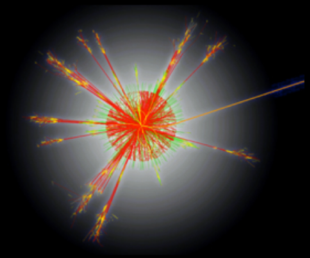
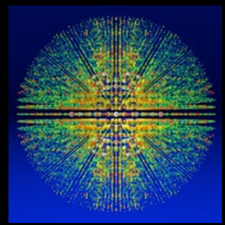
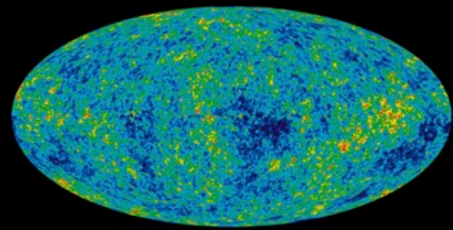
  Pixel sensors ←→ Monolithic and Hybrid

- Basics of Signal formation in silicon sensors
- ~~Basics of radiation effects in silicon sensors~~
- Examples of applications in High Energy Physics, medicine, Environmental Monitoring and Energy Harvesting
- A brief look at the future

Imaging radiation



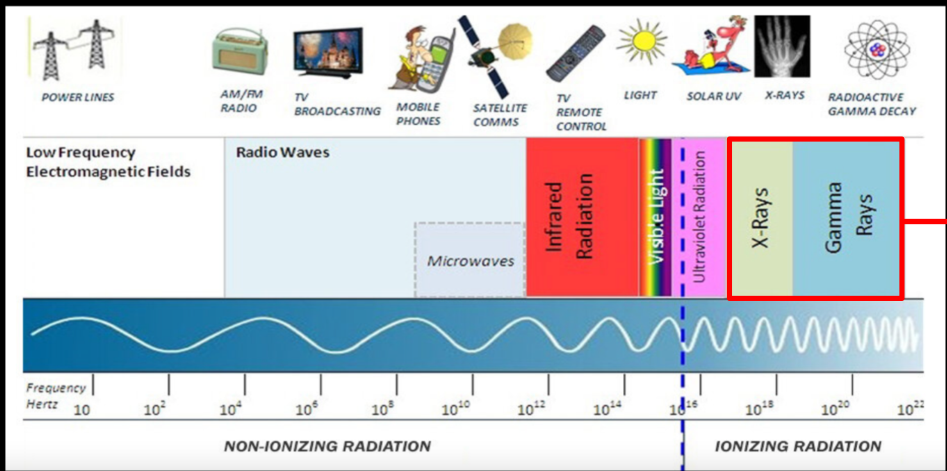
Web cams Smart phones photo cameras
machine vision, automotive, security etc...

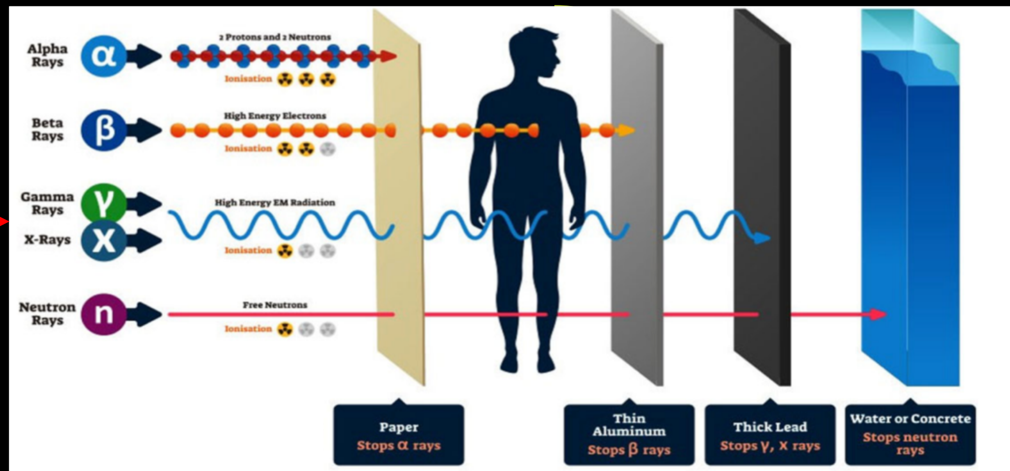





Medical imaging HEP x-ray crystallography cosmology
Quantum Imaging.....

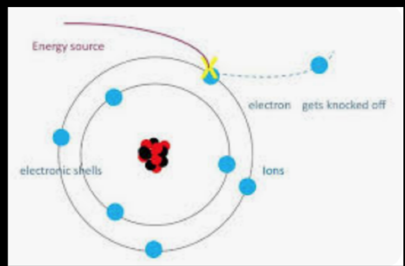
What is Radiation and its interaction with matter - recap

Radiation can be defined as the propagation of energy through space or matter in the form of electromagnetic waves or energetic particles.





Ionizing has enough energy to knock an electron from an atom



Non-ionizing does not have enough energy to ionize atoms but **generate heat** in the material it interacts with.

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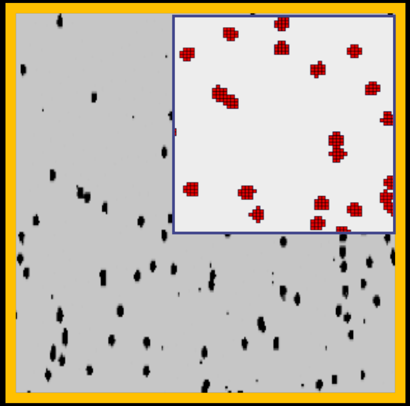
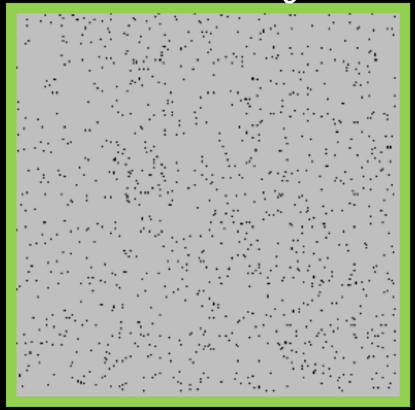
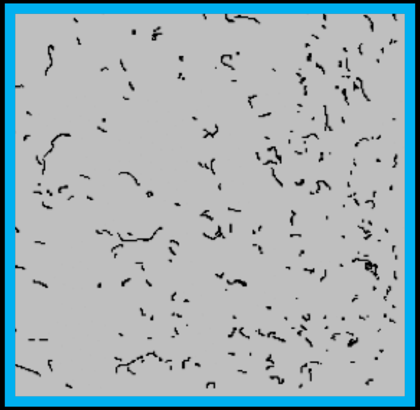
Particle "signatures" with the Timepix readout electronics

→ *See presentation from S. Pospisil*







- ^{241}Am alpha source gives clusters of ~5x5 pixels measured with the MEDIPIX-USB device and a 300 µm thick silicon sensor. The clusters are shown in detail in the inlet. The cluster sizes depend on particle energy and threshold setting.
- Signature of X-rays from a ^{55}Fe X-ray source. Photons yield single pixel hits or hits on 2 adjacent pixels due to charge sharing.
- A ^{90}Sr beta source produces "tracks" in the silicon detector.
- A pixel counter is used just to say "YES" if individual quantum of radiation generates in the pixel a charge above the pre-selected threshold

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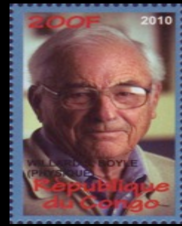
The semiconductor revolution 1947

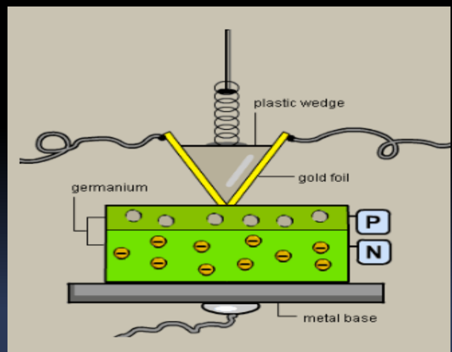


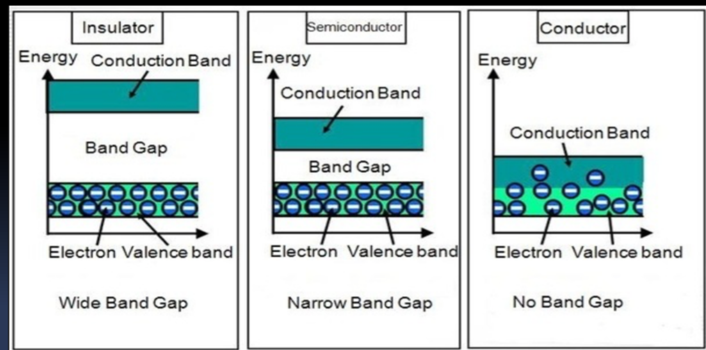
First transistor invented 1947 by William B. Shockley, John Bardeen and Walter Brattain (Nobel Prize 1956)

First semiconductor particle sensor: Pieter Jacobus Van Heerden, *The Crystalcounter: A New Instrument in Nuclear Physics.* University Math Naturwiss, Fak (1945).

CCD Nobel prize Boyle Smith 2009

Semiconductor a material that has a conductivity between a conductor and an insulator; electricity can pass through it, but not very easily



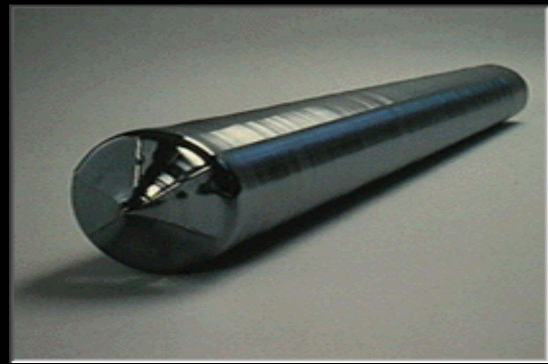


The point contact germanium transistor

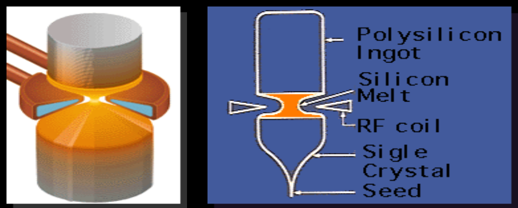
SILICON: from sand to wafer

Silicon (silicates) makes up 27.7% of the Earth's crust by mass and is the second most abundant element (oxygen is the first)

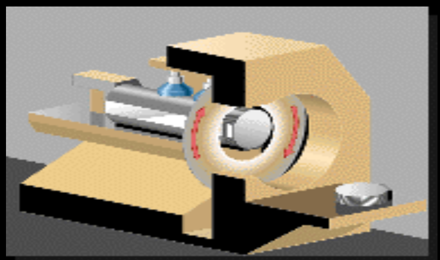
a) The sand is cleaned and further purified by chemical processes. It is then melted. Then a tiny concentration of phosphorus (boron) dopant is added to make n (p) type poly-crystalline ingots



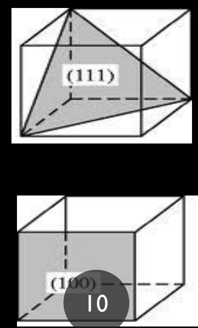
b) Single-crystal silicon is obtained by melting the vertically oriented poly-silicon cylinder onto a single crystal "seed" --- called "Float Zone-→ FZ"



c) Wafers of thickness 200- 500μm are cut with diamond encrusted wire or disc saws.



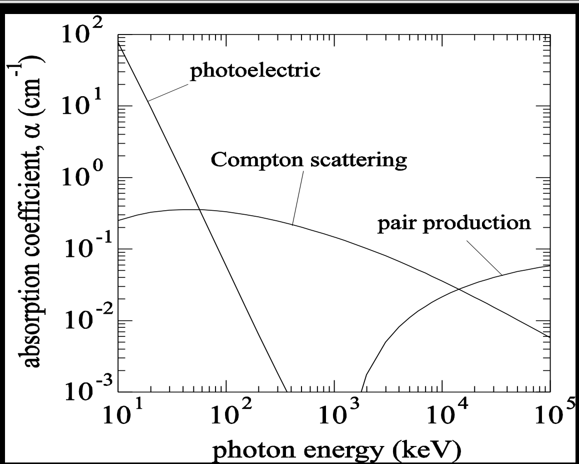
Note: the crystal orientation matters! <111> and <100> crystals can influence the detector properties eg. capacitance

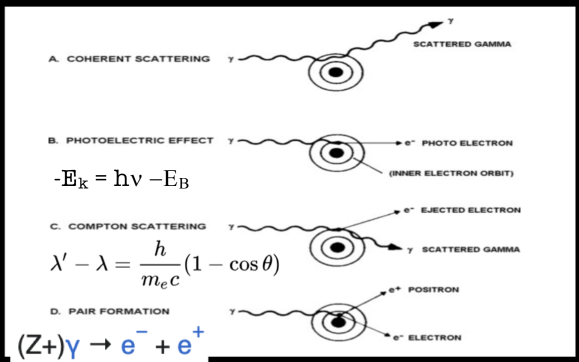


Interaction of radiation with silicon-

Quantum mechanics in action!!!!

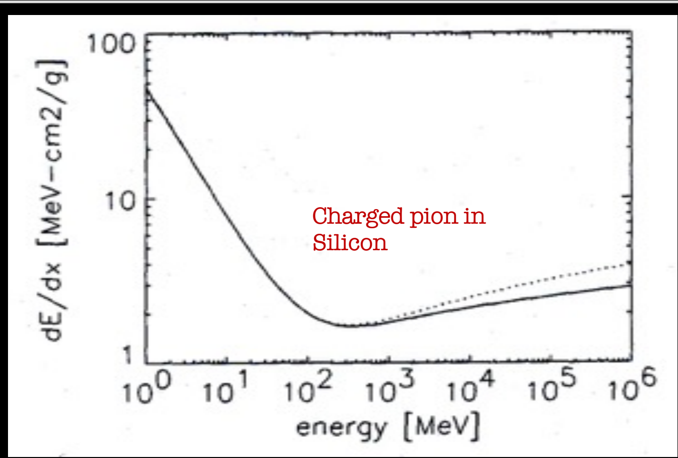
See presentation from A. Lyoussi





Photons:

-Photoelectric, Compton, pair production



Ionizing particles:

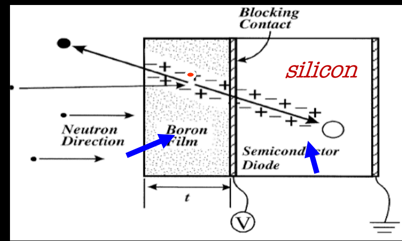
Bethe-Bloch equation:

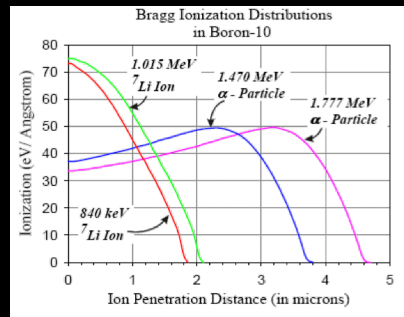
average/mean amount of energy lost due to ionization per unit of distance in the media)

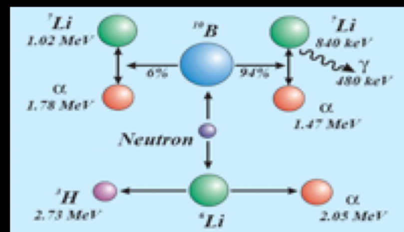
$$-\frac{dE}{dx} = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \cdot \left[\ln\left(\frac{2m_e c^2\beta^2}{I \cdot (1-\beta^2)}\right) - \beta^2\right]$$

$$n = \frac{N_A \cdot Z \cdot \rho}{A \cdot M_u}$$

Si bandgap=1.12 eV







Neutrons: Alpha Bragg peak

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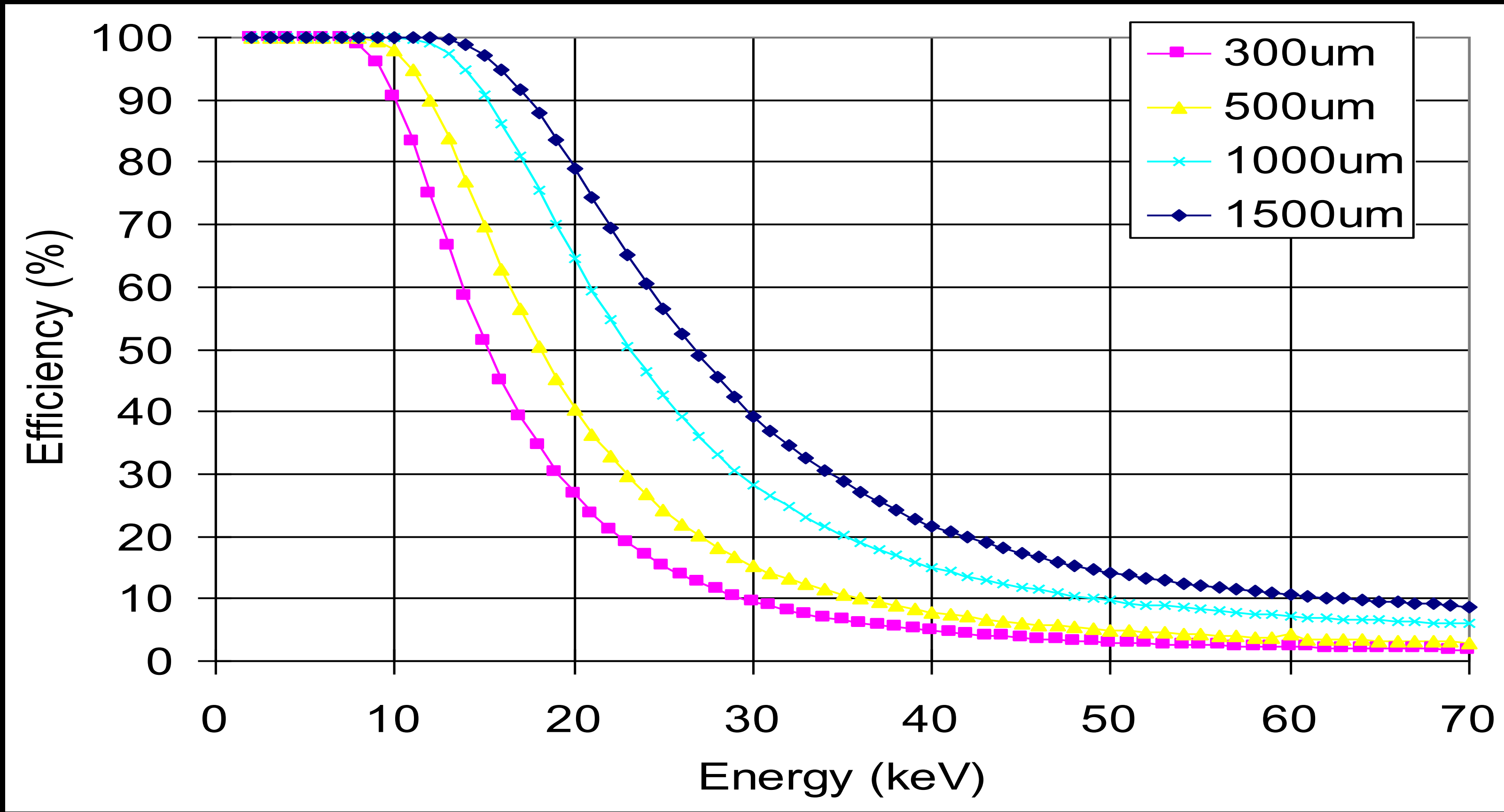
Photons

- Photons are the quantum particles carrying "electromagnetic energy"
- They have zero mass energy
- They travel at the speed of light
- Their energy is: $$E_{ph} = h\upsilon = hc/\lambda$$

(where h is the Planck's constant, 6.62×10^{-34} J·s)

- The most important forms of interaction with matter include:
  - Absorption
  - Refraction
  - Transmission/Reflection
  - Diffraction

X-ray absorption efficiency in Si



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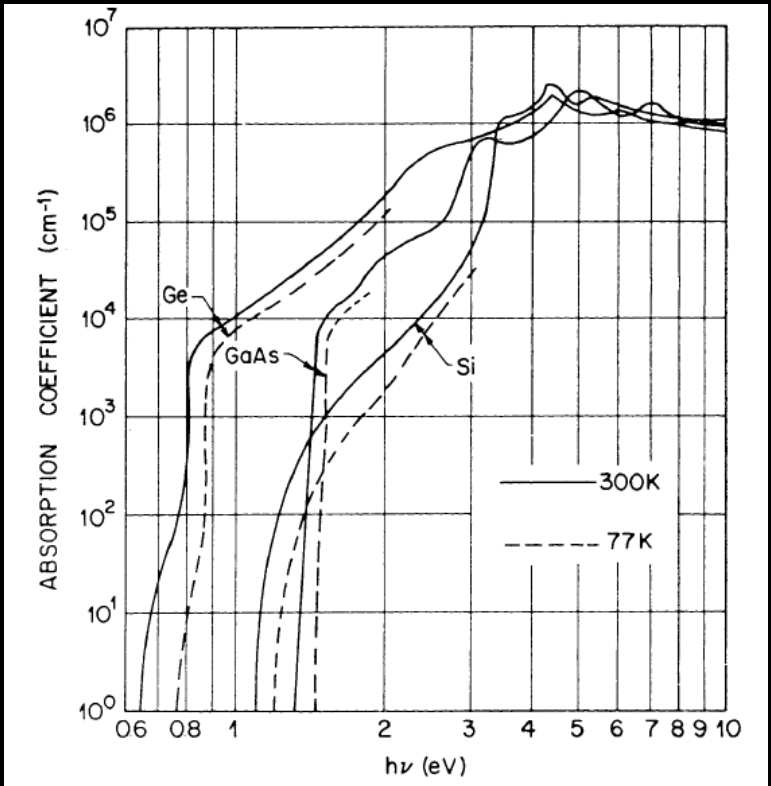
Absorption coefficient



- At low energy the most important parameter is the absorption coefficient α, that determines the probability of the photon to be absorbed
- α is strongly dependent on λ
- The attenuation of a light beam in the semiconductor is described by the Lambert-Beer's law:

$$\phi(x) = \phi_0 \cdot e^{-\alpha x}$$

Charged particles

- Charged particles continuously interact with electrons and protons in the nucleus via the long-range Coulomb force.
- Most interactions are elastic (Rutherford) scattering with atomic electrons.
- The basic theory has been developed by Bohr using classical arguments, and later in a quantum mechanical way by Bethe (1930), Bloch (1933) and Landau (1944).
- Since the time that the electrostatic force acts on the electron is inversely proportional to the velocity, the energy loss is inversely proportional to the square of the particle velocity.
- Minimum Ionizing Particle Energy Loss in Si: 3.87 MeV/cm.
- Ionizing Energy for e-h pair creation= 3.62eV

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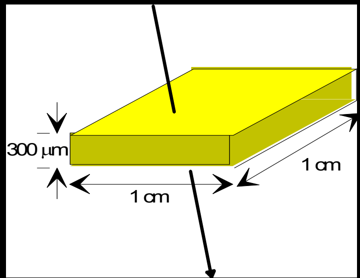
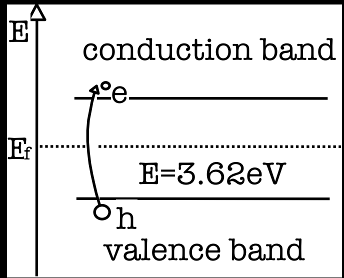
Problem: Getting a Signal from "pure" Silicon





Intrinsic semiconductor:

Pure (undoped) semiconductor the electron density n and hole density p are equal.

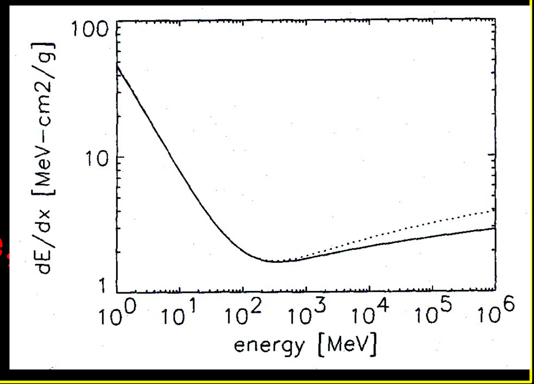
$$n = p = n_i$$

For Silicon: $n_i \approx 1.45 \cdot 10^{10}$ cm^{-3}

Signal generated by an Ionizing particle passing through 300 um intrinsic Silicon

- Ionization energy $I_0 = 3.62$ eV ,
- mean energy loss for a mip dE/dx = 3.87 MeV/cm →

  [dE/dx x d] /I_0 =[3.87 x 0.03]/3.62 = 3.2×10^4 e-h pairs



➢ $4.5 \cdot 10^8$ free charge carriers in 1cm x 1cm x 300um volume, but only $3.2 \cdot 10^4$ e-h pairs produced by a M.I.P.

➢ Need to reduce number of free carriers, hence deplete the detector

➢ Solution: Make use of reverse biased p-n junction (reverse biased diode)!!

Doping and p-n Junction

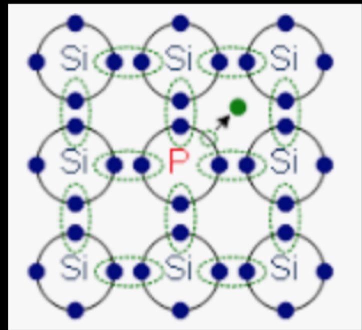
- Doping: n-type Silicon
  - add elements from V[th] group
    - donors (P, As,..)
  - electrons are majority carriers
- Doping: p-type Silicon
  - add elements from III[rd] group
    - acceptors (B,..)
  - holes are majority carriers

	detector grade	electronics grade
doping	≈ 10^{12} cm^{-3}	≈ 10^{17} cm^{-3}
resistivity ρ	≈ 5 kΩ·cm	≈1 Ω·cm

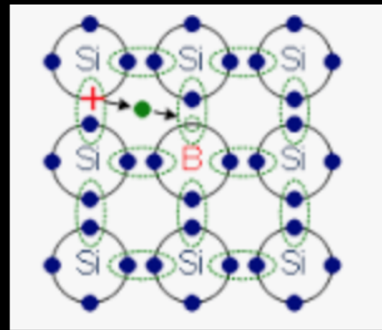
Resistivity

- carrier concentrations n, p
- carrier mobility μ_n, μ_p

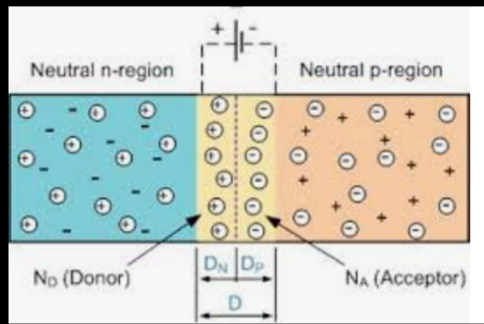
$$\rho = \frac{1}{q_0(\mu_n n + \mu_p p)}$$

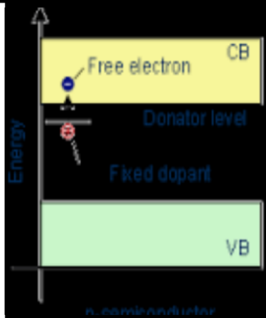


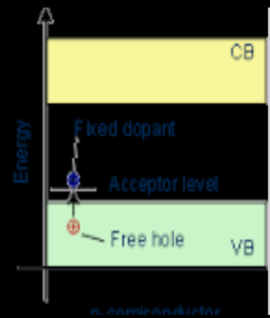
The P atom donated its 5th valence electron which becomes a free charge carrier



A free place in a B atom is filled with an electron therefore a new hole is generated







p-n junction

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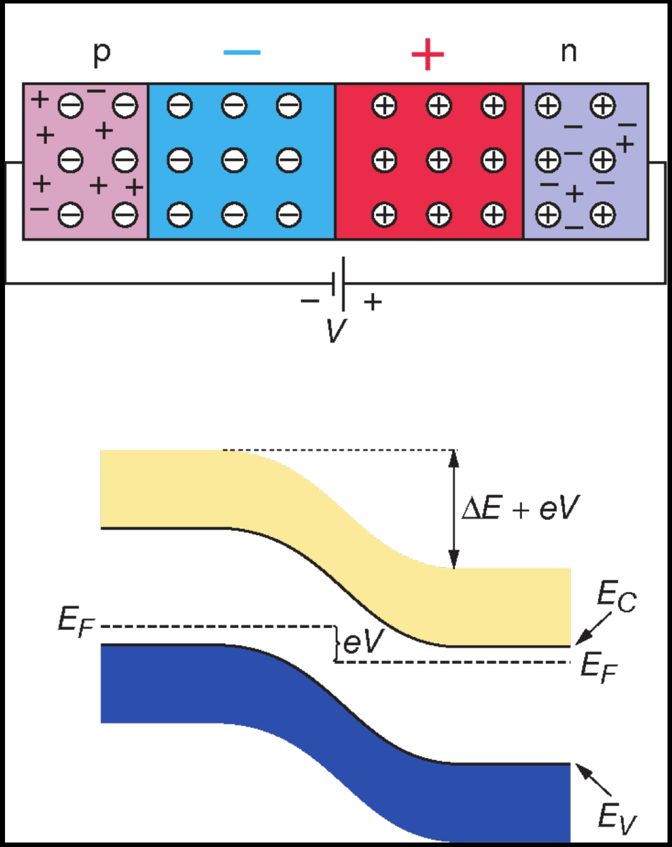
The depletion region

p-n junction with reverse bias

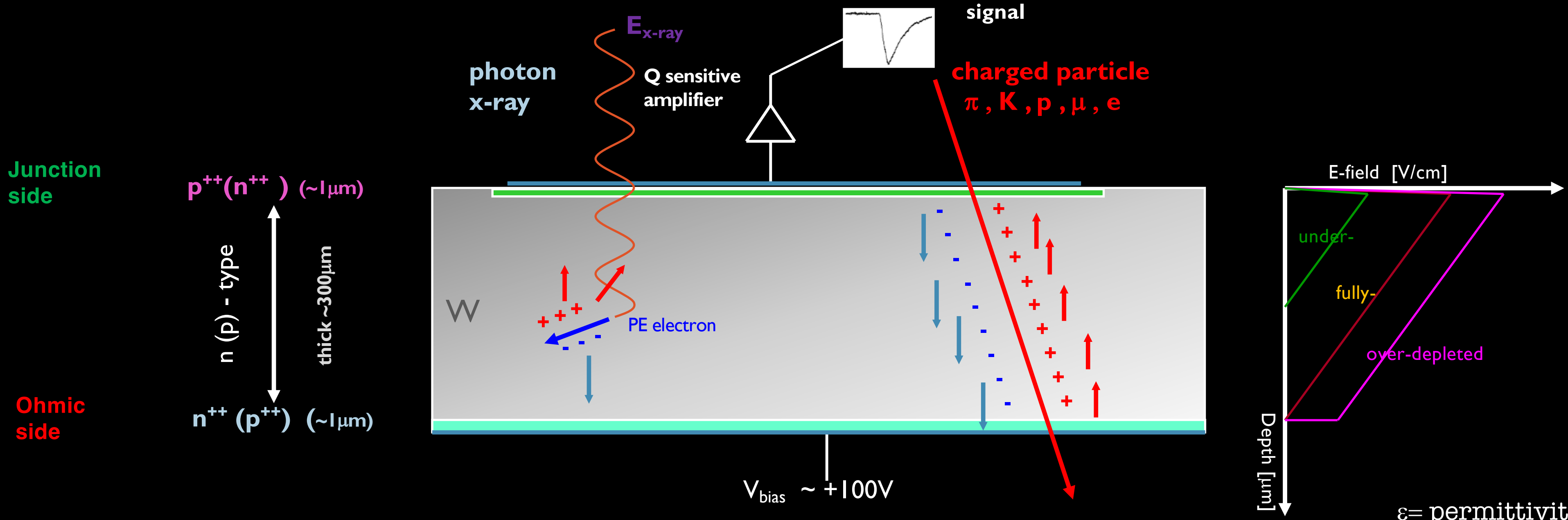
- At the interface of an n-type and p-type semiconductor the difference in the Fermi Levels (E_F) which is the energy level with a 50% probability of being occupied by an electron at any given time cause diffusion of surplus carries to the other material until thermal equilibrium is reached. At this point the fermi level is equal. The remaining ions create a space charge and an electric field stopping further diffusion.

- Operation with reverse bias
  - applying an external voltage V with the cathode to p and the anode to n
  - e and h are pulled out of the depletion zone. The depletion zone becomes larger.
  - The potential barrier becomes higher and diffusion across the junction is suppressed. The current across the junction is very small "leakage current".



Et voilà, that's the way we operate our semiconductor detectors!

p-n junction detector basic working principle

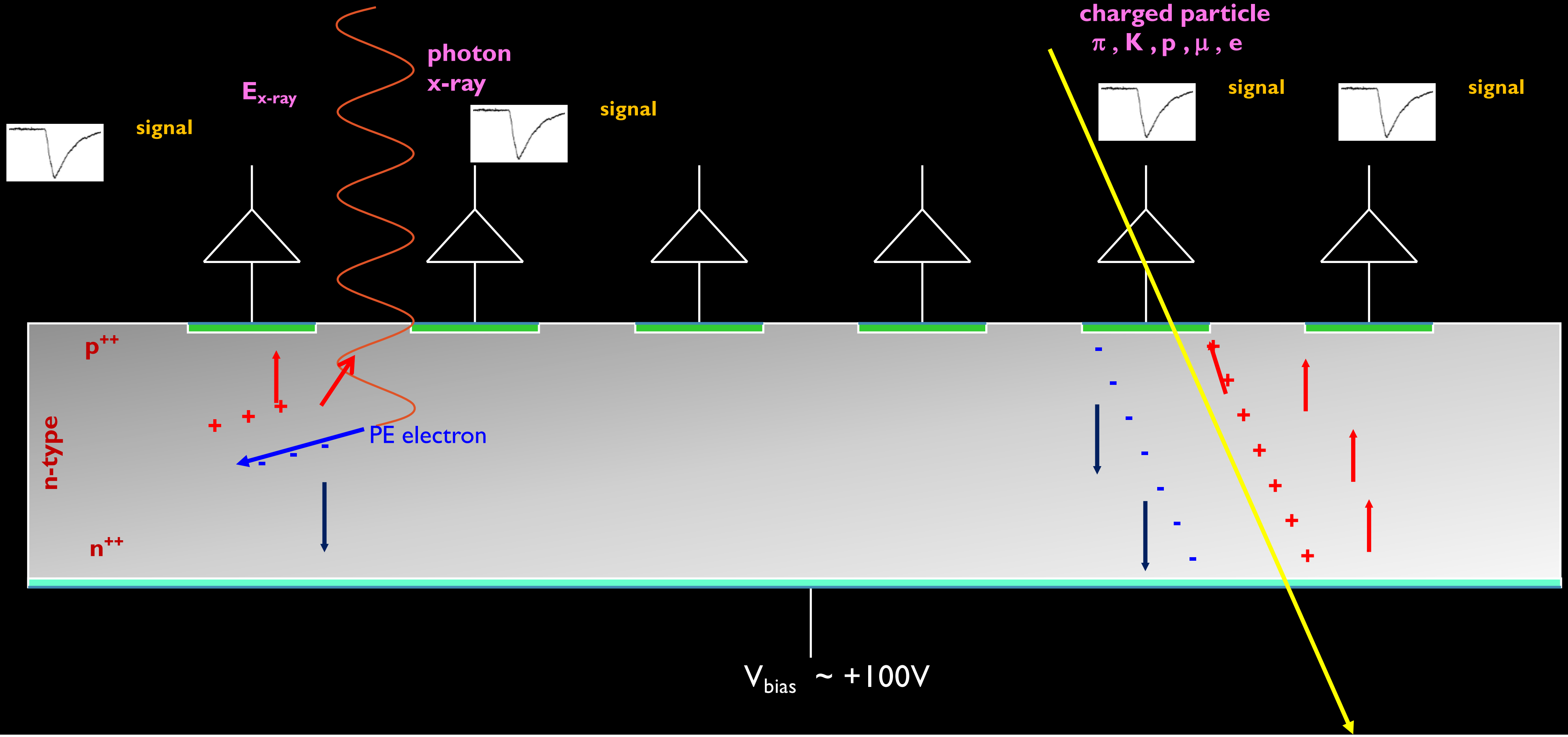


ε= permittivity

- n+ and p+ electrodes are implanted on the wafer's surfaces to form a p-i-n junction
- V_{bias} is the applied reverse bias voltage, W is the depletion region
- e-h pairs are created by the energy released by the impinging particle
- e-h drift towards the positive and negative electrode "inducing " a current pulse
- Charge collection time depends on the carrier mobility, bias voltage and carrier polarity

$$V_{bias} = \frac{(W)^2 \times e \times |N_{eff}|}{2\varepsilon_0 \varepsilon_{Si}}$$

Segmented Silicon Sensors for better position sensitivity ..“imaging”



Leakage Current

$$I_D = I_S\,(e^{qV_D/NkT} - 1)$$

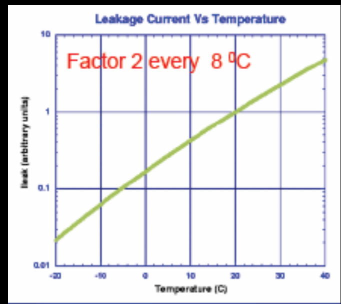
- **Generation Current:**

From “thermal” generation in the depleted region

$$j_{gen} \propto T^{3/2} \exp\left(\frac{1}{2kT}\right)$$

It’s minimal if the bulk is high resistivity
and with low impurities

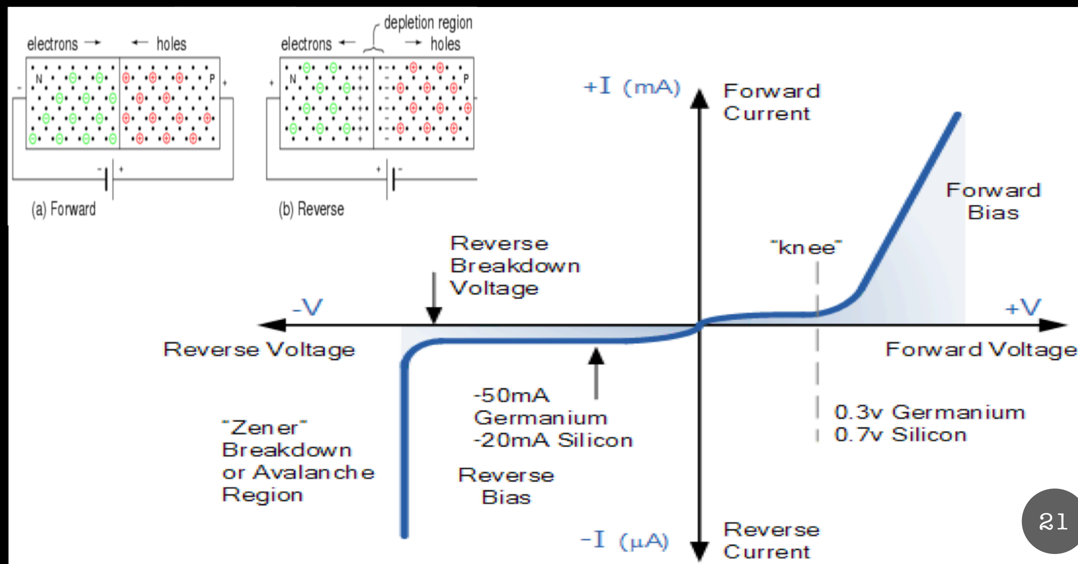
Doubles every 8°C



I_D = Diode current in amps
I_S = Saturation current in amps (typically 1 x 10^{-12} amps)
e = Euler’s constant (~ 2.718281828)
q = charge of electron (1.6 x 10^{-19} coulombs)
V_D = Voltage applied across diode in volts
N = "Nonideality" or "emission" coefficient (typically between 1 and 2)
k = Boltzmann’s constant (1.38 x 10^{-23})
T = Junction temperature in Kelvins

- **Diffusion Current:**

Carriers from the ‘un-depleted’ region
Diffusing into the depleted region



Signal to Noise and Landau distribution

SIGNAL if there is a PARTICLE

→ Signal formed no matter what

→ Detection efficiency

NO SIGNAL if NO PARTICLE

→Noise under control

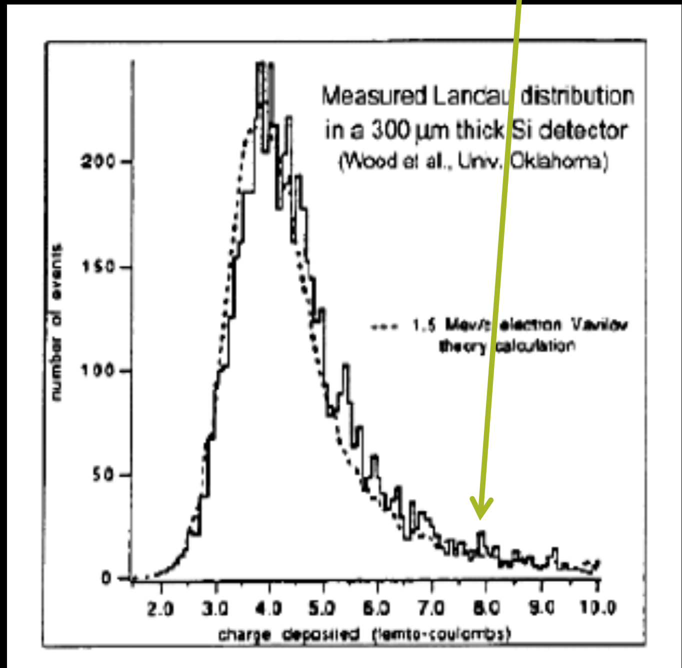
→Discrimination

Mean (dE/dx) Si = 3.88 MeV/cm
⇒116 keV for 300 μm thick Si (~75e/um)

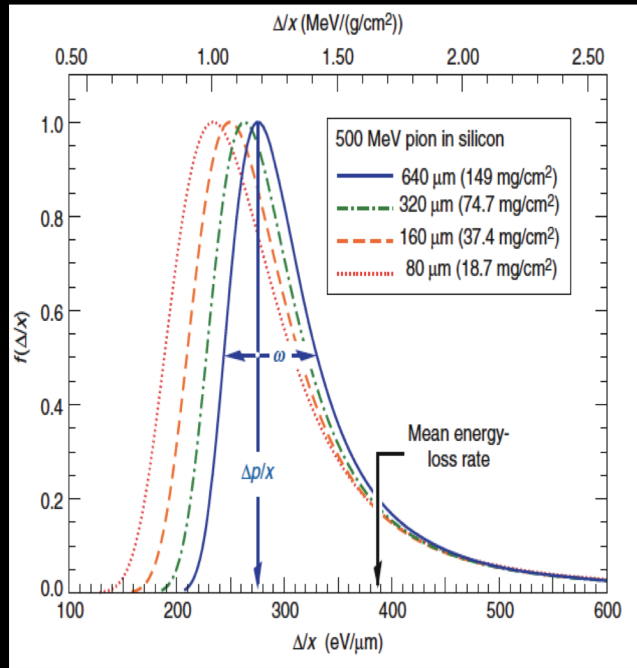
Most probable loss = 81 keV for 300μm Si
Since 3.6eV needed to make e-h pair
⇒ charge in 300 μm= 22500 e- (=3.6 fC) (75e/um)

Mean charge = Most probable charge ≈ 0.7× mean

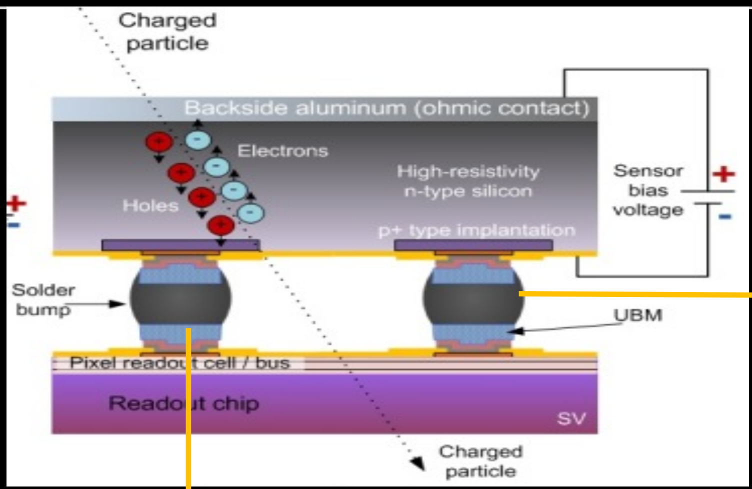
High energy tail
From delta rays

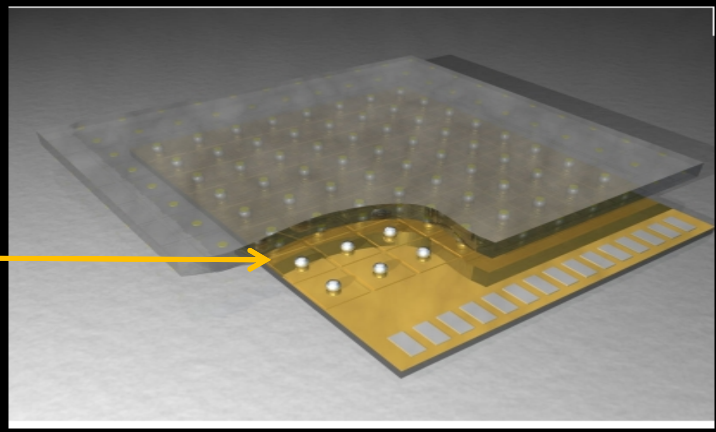


Width depends on
Substrate thickness

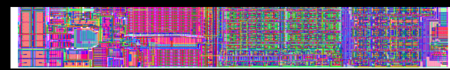


Two-dimensional segmentation. Pixel Detectors “Hybrid”

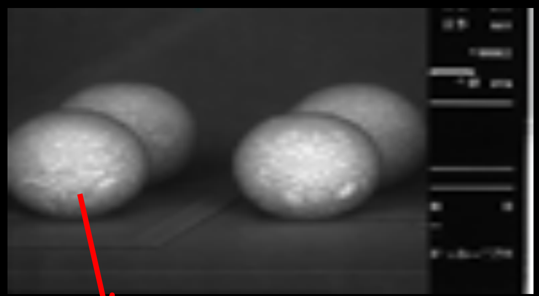




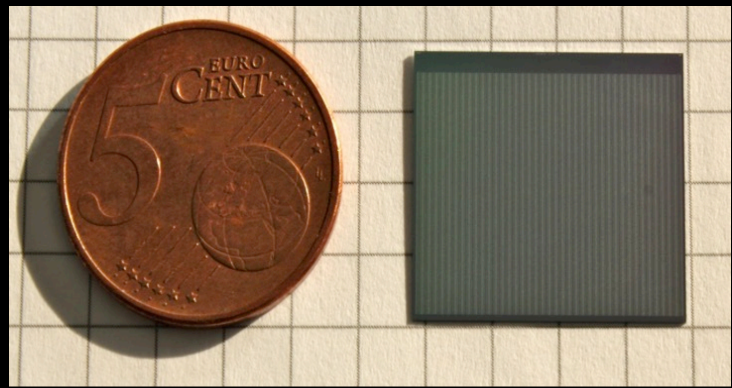
FE-I4
80x336
=26 880 pixels
125 x 50 um^2



solder



50 microns (25um In, <10um Au)



ATLAS FE-I4~4cm^2

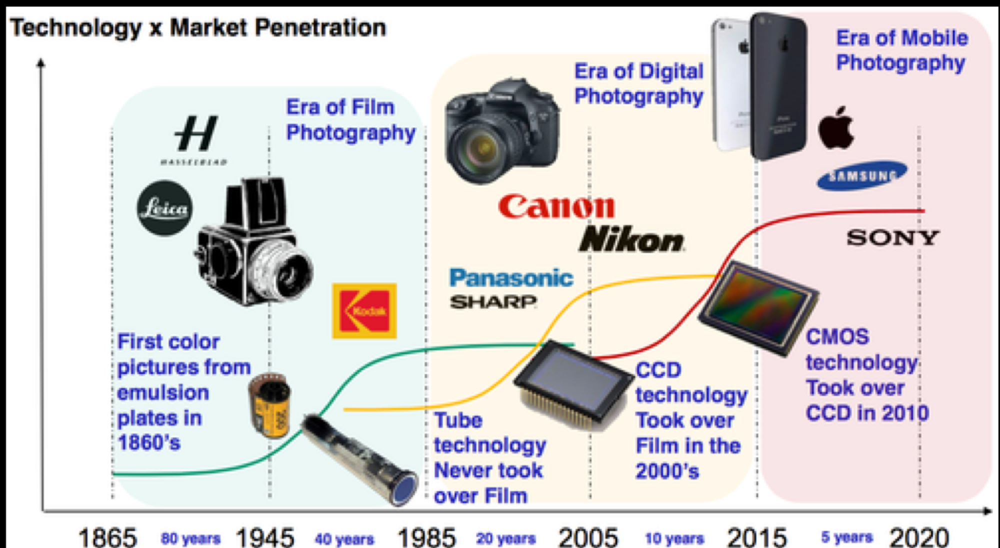
IEEE TNS Vol: 56, Issue: 3, 2009

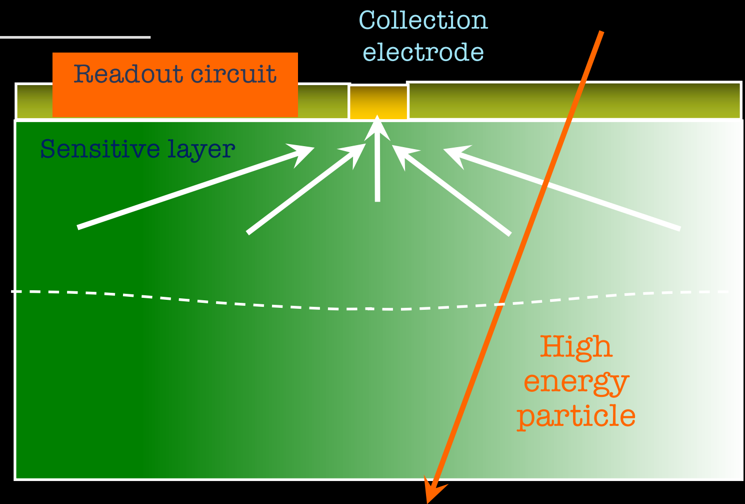
Pixel detectors "Monolithic"

Integrate the readout circuitry together with the detector in 'one piece ' of silicon

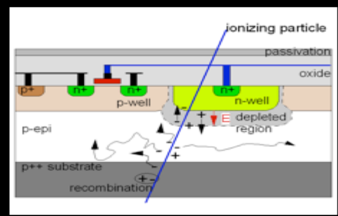
The charge generated by a particle is collected on a defined collection electrode either by diffusion or by the application of an E-field

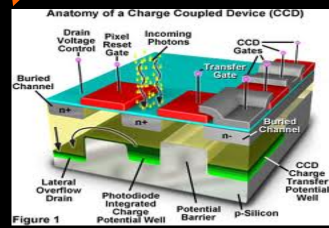
Small pixel size and thin effective detection thickness





MAPS





Pixel size :
20 x 20 micron
Thickness
20-50 um

Used in the
EUDET telescope And at
STAR at RICH

CCD
Charge coupled
Device
Various
dimensions

Many uses in
Different fields

Pixels detectors

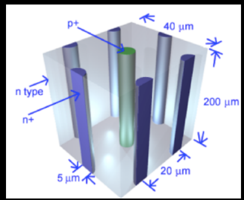
Hybrid

Radiation Hardness

Granularity, low mass

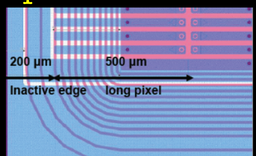
Monolithic

3D sensors

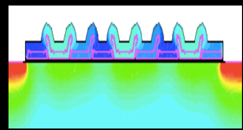


diamond

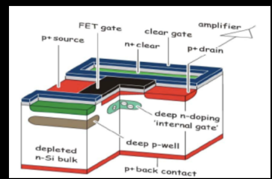
n-in-n, n-in-p-
planar



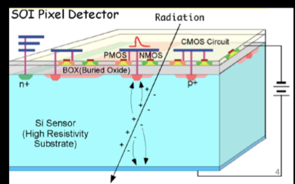
CCD



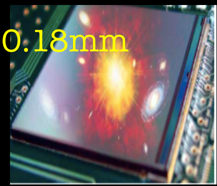
DEPFET

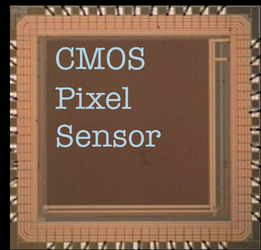


SOI

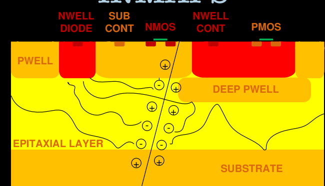


Mimosa

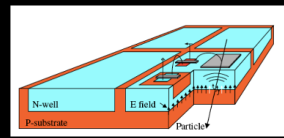




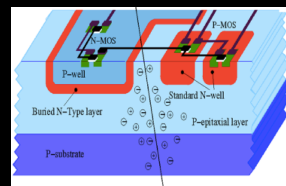
INMAPS



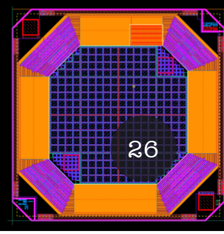
HV-MAPS



deepNwell



LePiX

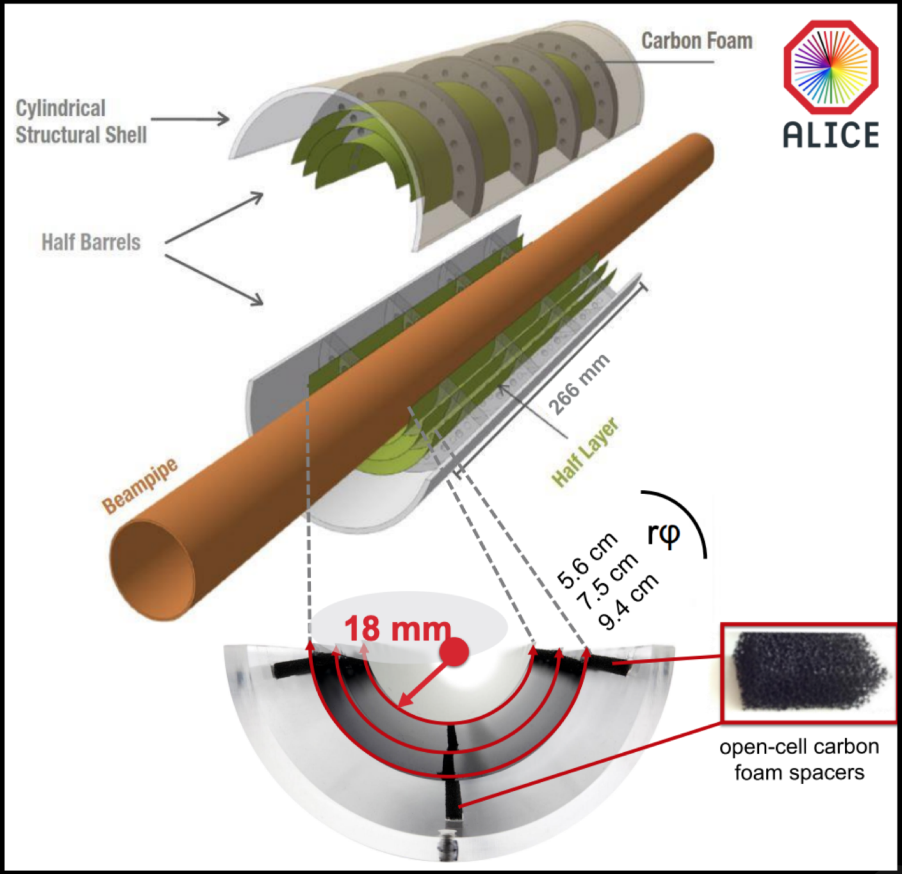


Cinzia Da Via, Stony Brook USA and The University of Manchester, UK– 2024

ALICE ITS3: a bent stitched MAPS-based vertex detector

Using special properties of silicon
– Wafer-scale sensor ASICs – Fabricated with stitching
– All electrical signals and power routed on-chip
– Ultra-thin and bendable: 50 μm
– 266 mm (Z) x variable width* (rϕ)
– CMOS MAPS • 65 nm technology
– Open-cell carbon foam spacers

Key benefits
– Extremely lightweight
• Material budget: 0.35% X0* => 0.05% X0
– Uniformly distributed material
– Closer to interaction point
• Beam pipe radius: 18.2 mm => 16 mm
• Radial position: 24 mm => 18 mm



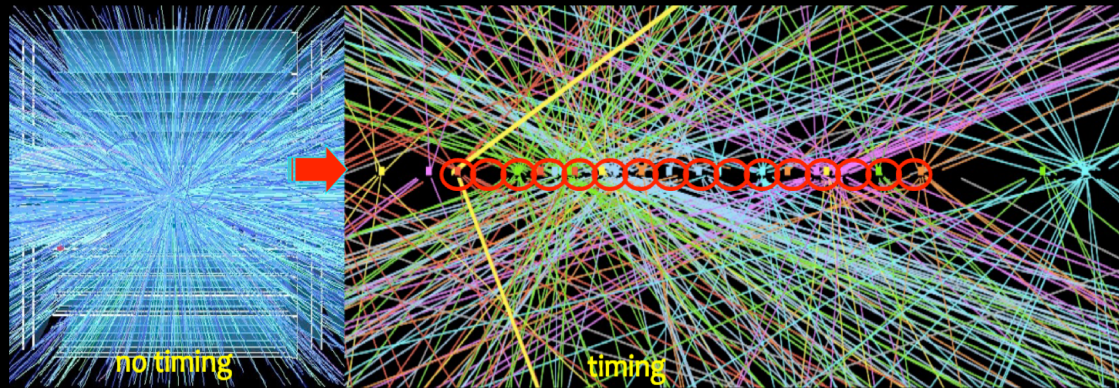
*X0 (radiation length)=the mean length (in cm) into the material at which the energy of an electron is reduced by the factor 1/e

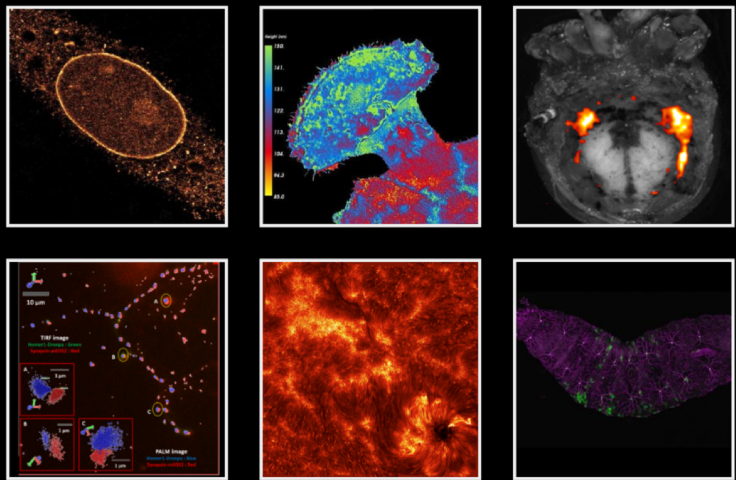
Slide from From Ola Groettvik

High Precision Imaging in space and time

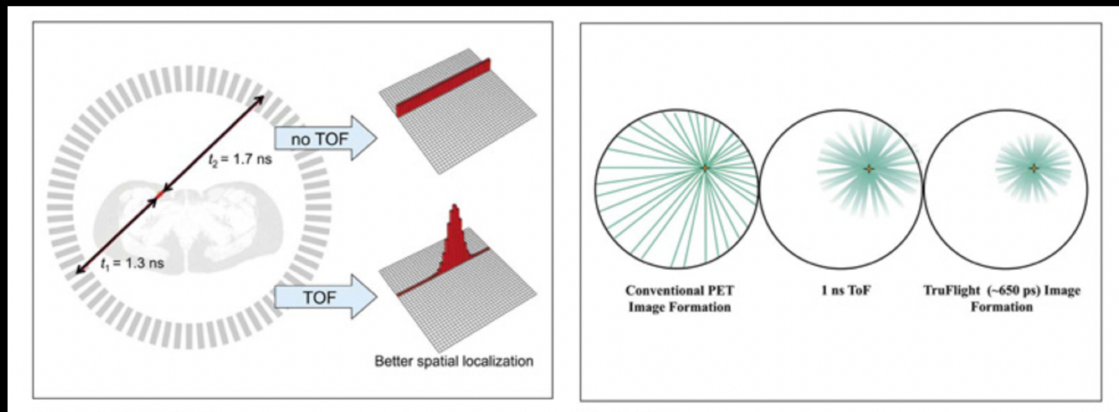
Cinzia Da Via, Stony Brook USA and The University of Manchester, UK– 2024

Fundamental Science





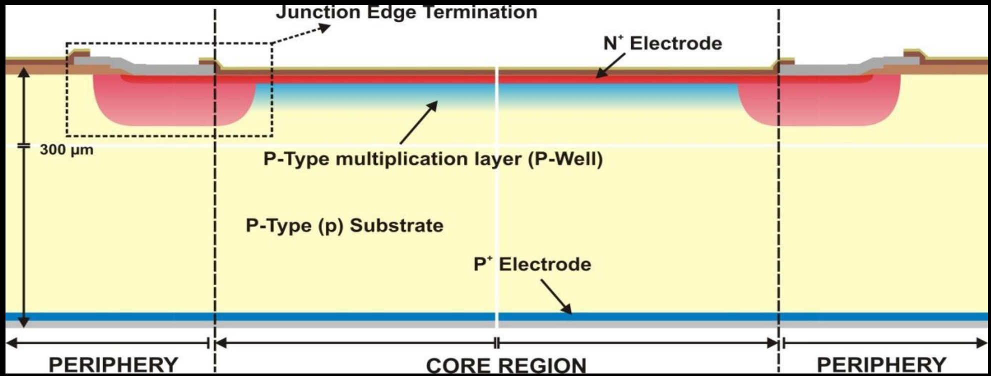
Biology

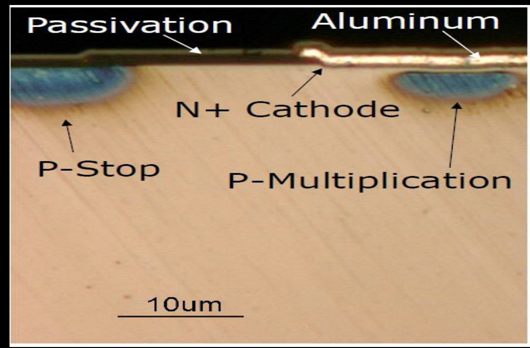


Medical Imaging

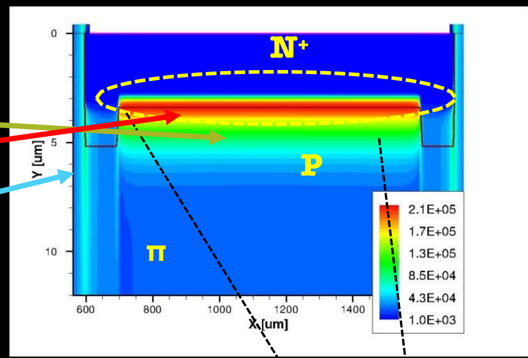
LGAD Basics. Low Gain Detector

G. Pellegrini, Low Gain Avalanche Detectors

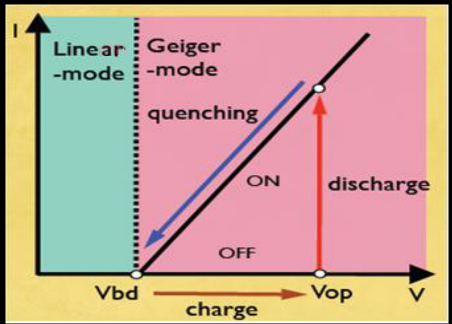


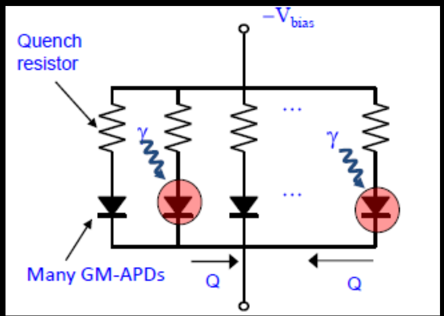


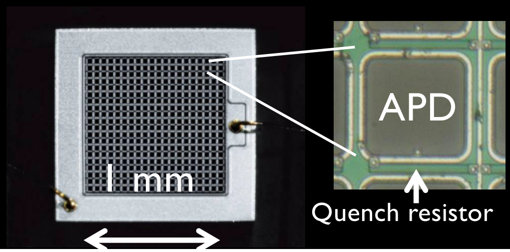
- Core Region
  - ✓ Uniform electric field, high enough to activate mechanism of impact ionization (multiplication)
- Termination
  - ✓ High electric field confined in the core region
- Periphery
  - ✓ Dead region. Charges should not be collected. Reduction of the surface leakage currents



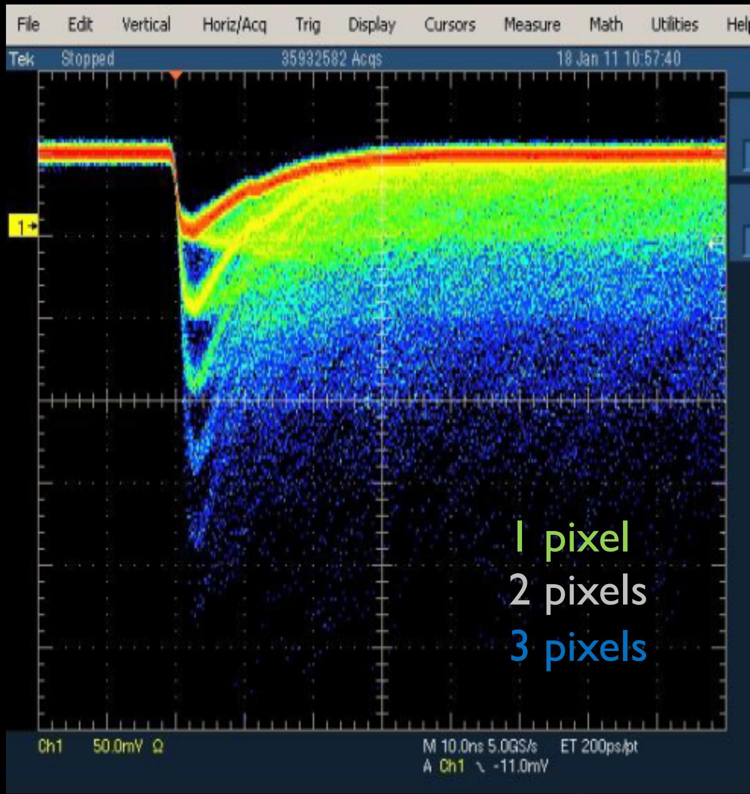
Silicon Photomultipliers (SiPm)





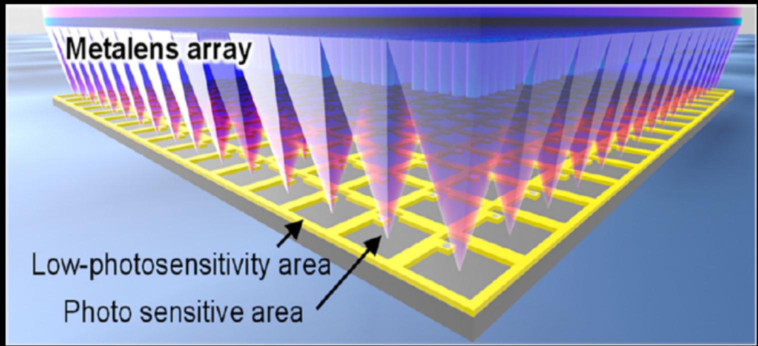


- SiPm requires a special doping profile to allow a high internal field (>10^5 V/cm) which generates avalanche multiplication
- APD cell operates in Geiger mode (= full discharge), however with (passive/active) quenching.
- The avalanche formation is intrinsically very fast (100ps), because confined to a small space.
- High Gain G ~ 10^5 -10^6 at rel. low bias voltage (<100 V)
- G is Sensitive to temperature and voltage variations
- Fill factor still low due to quench resistor on the surface (but work in progress to solve this)



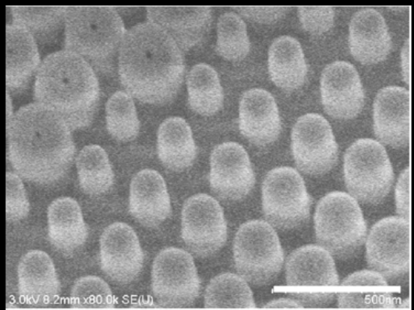
40 x 40 Metalens Array for Improved Hamamatzu Silicon Photomultiplier Performance

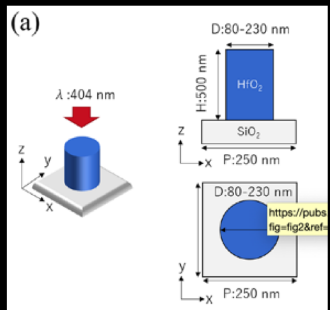
Soh Uenoyama and Ryosuke Ota ACS Photonics 2021, 8, 1548–1555*



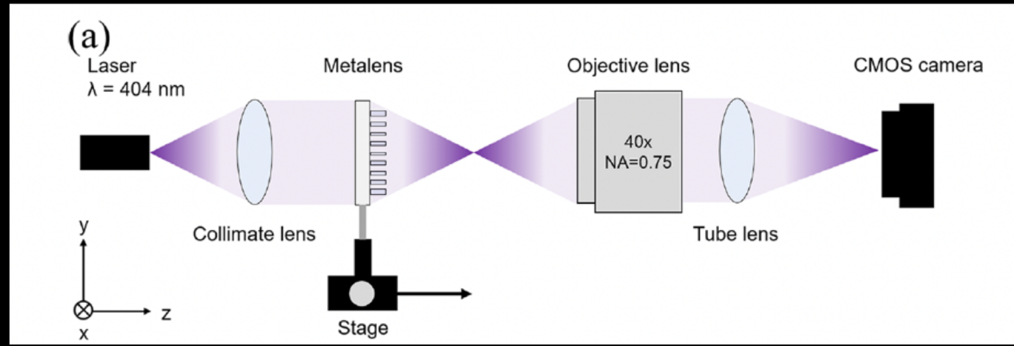
3x3mm^2
75um

~82%
Fill factor
(~50%)

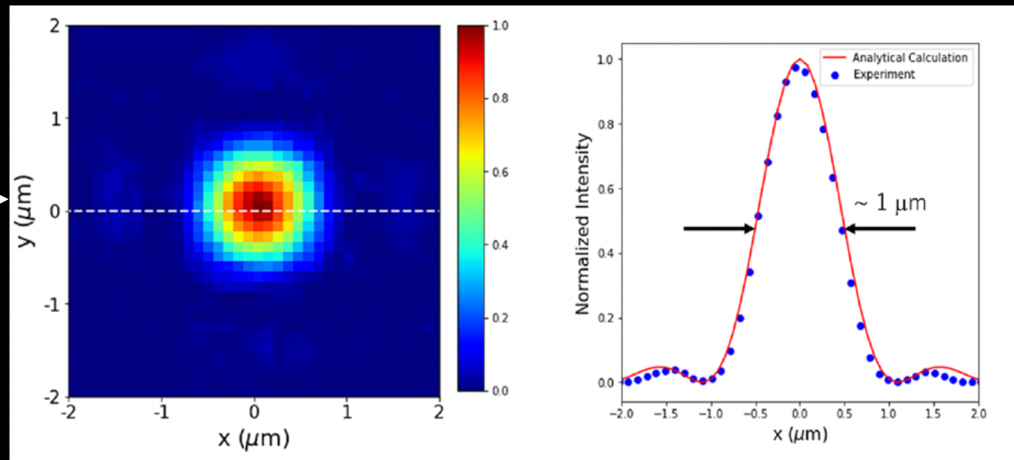




Hafnium oxide (HfO2) nanopillars on a 300 µm thick glass substrate to minimise absorption in the Near UV

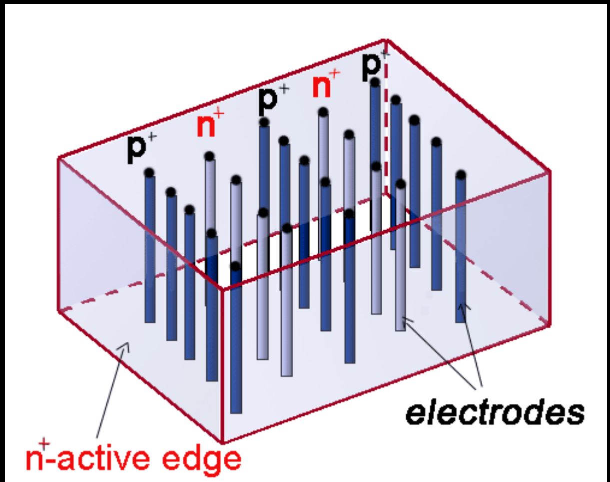


Focal Point
~14.5um Outside focal point



circular transmission nanopillar varies the locally effective index by changing the diameter of the metasurface and does not depend on incident polarization.

3D radiation sensors



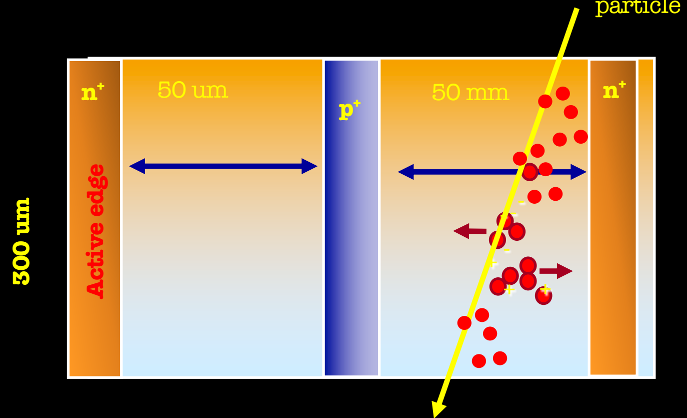
3D silicon detectors were proposed in 1995 by S. Parker, and active edges in 1997 by C. Kenney.

Combine traditional electronics processing and MEMS (Micro Electro Mechanical Systems)
technology.

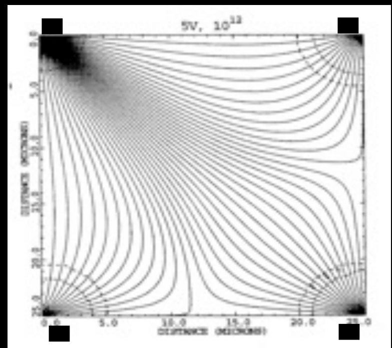
Electrodes are processed inside the detector bulk instead of being implanted on the Wafer's surface.

The edge is an electrode! Dead volume at the Edge < 5 microns!

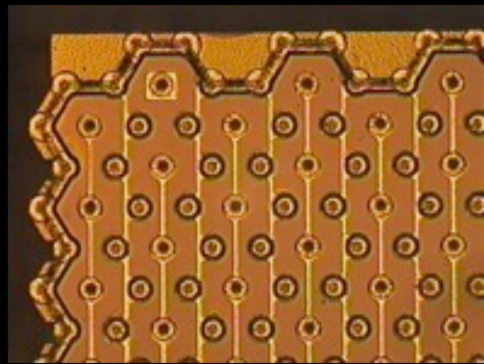
The electric field is parallel to wafer's surface: and smaller inter-electrode spacing: low bias voltage, low power, reduced charge sharing and high speed – for the same wafer thickness



V=7V
Before
irradiation



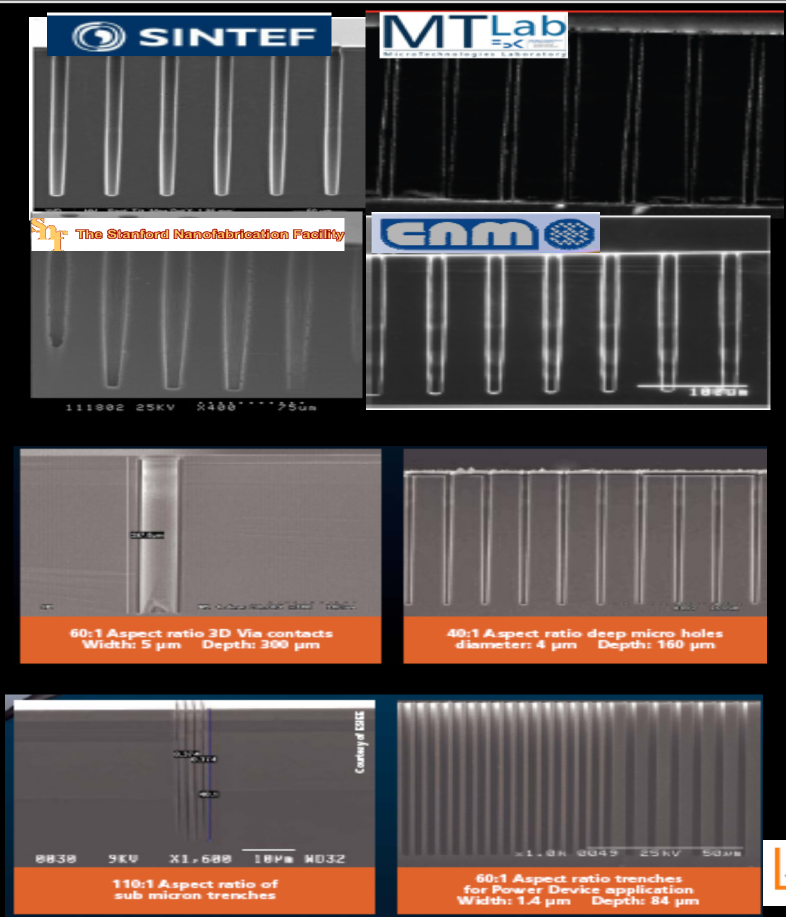
Drift lines parallel to the surface



Precision in space and time Developments in Bulk Micro-Fabrication

NATURE https://doi.org/10.1038/s41598-020-79560-z

Deep Reative Ion Etching



11:1
1997

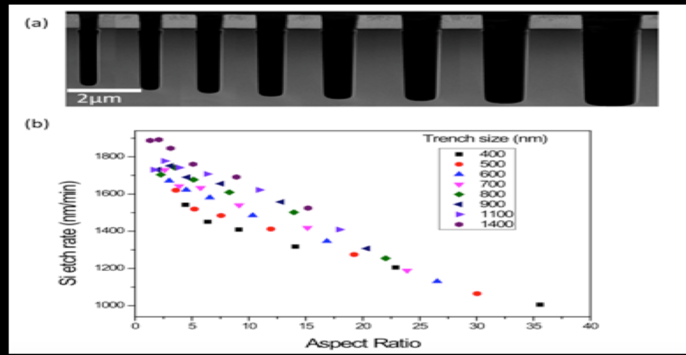
24:1
today

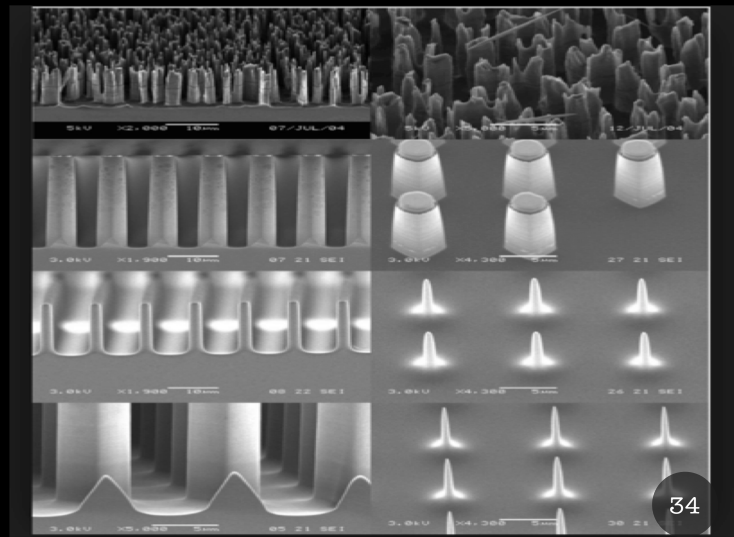
40-60:1

110:1!!!

ALCATEL Micro Machining Systems

Cryo-etching Atomic Level Etching (ALE)





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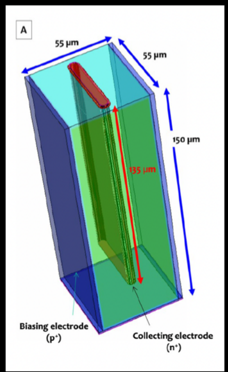
Fast response and Radiation hardness of 3D sensors

A. Lampis 23rd International Workshop on Radiation Imaging Detectors Riva del Garda, June30th 2022

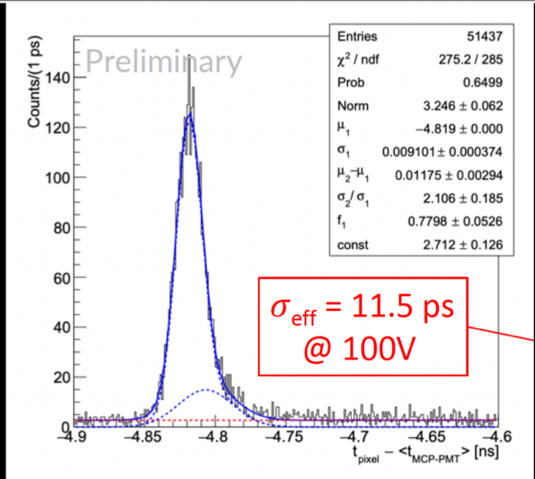
M. Manna et al. NIMA 979 (2020) 164468

3D Trench

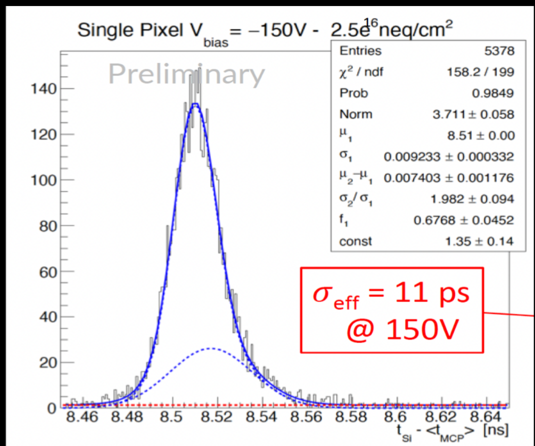


TimeSPOT

180 GeV/c π+beam

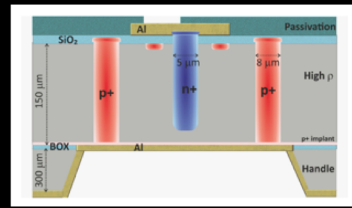


Timing resolution Before irradiation



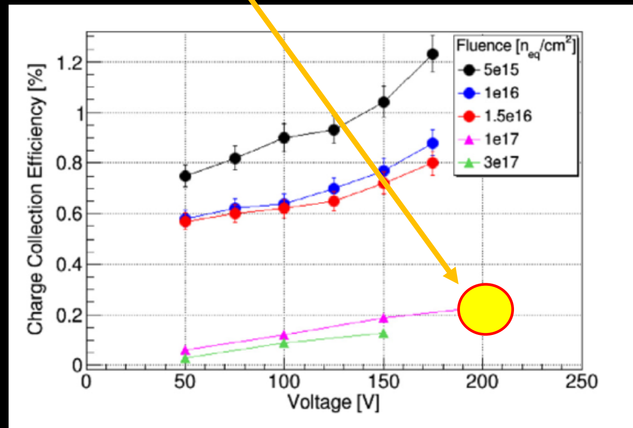
Timing resolution after irradiation

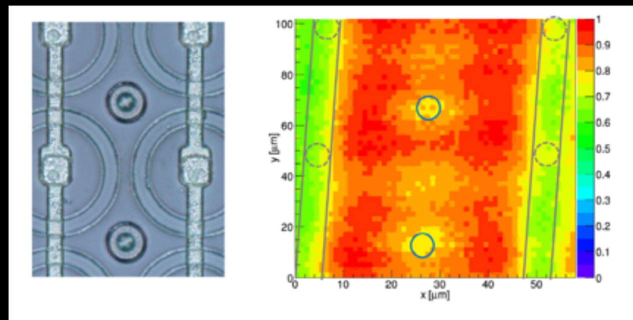
IES 35um



$1\times10^{17} neq/cm^2$ at 250 V (T= −16°C)

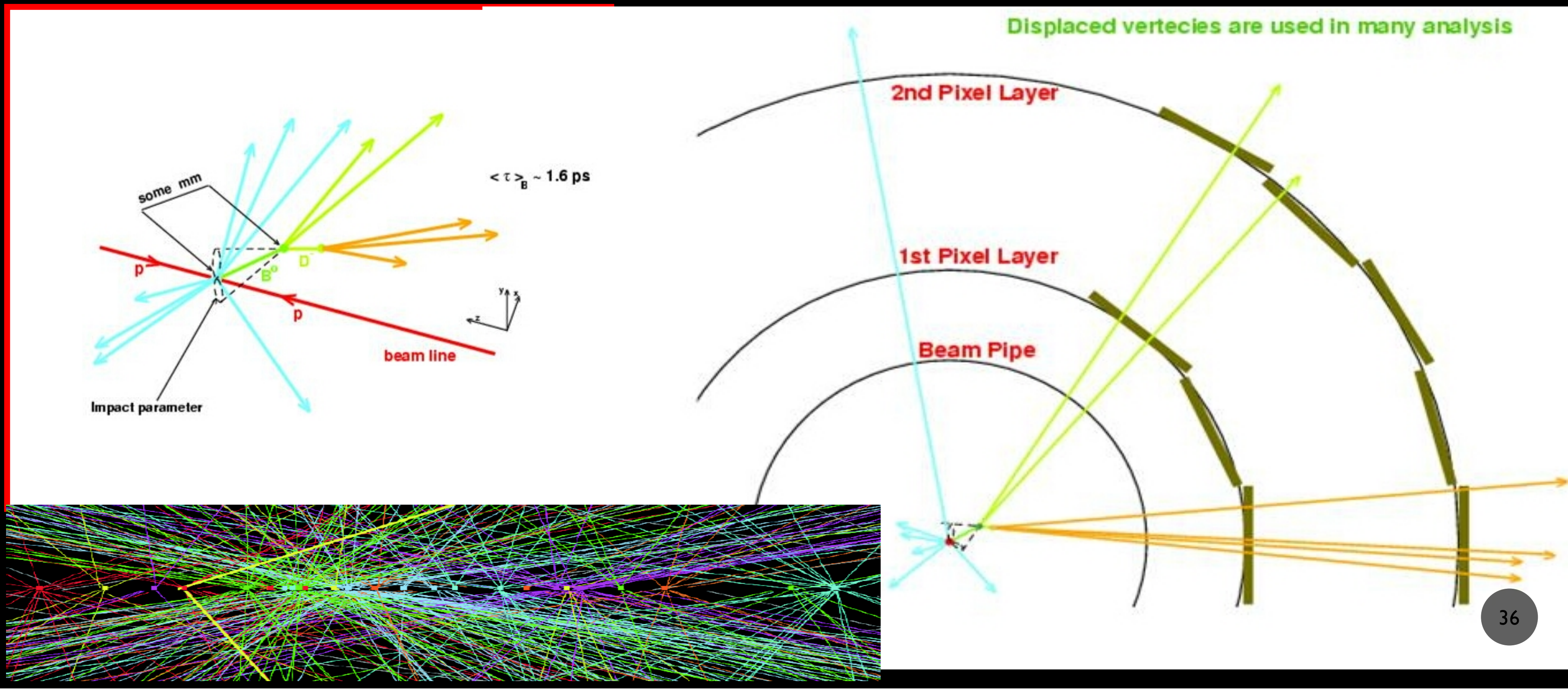
with top IR illumination

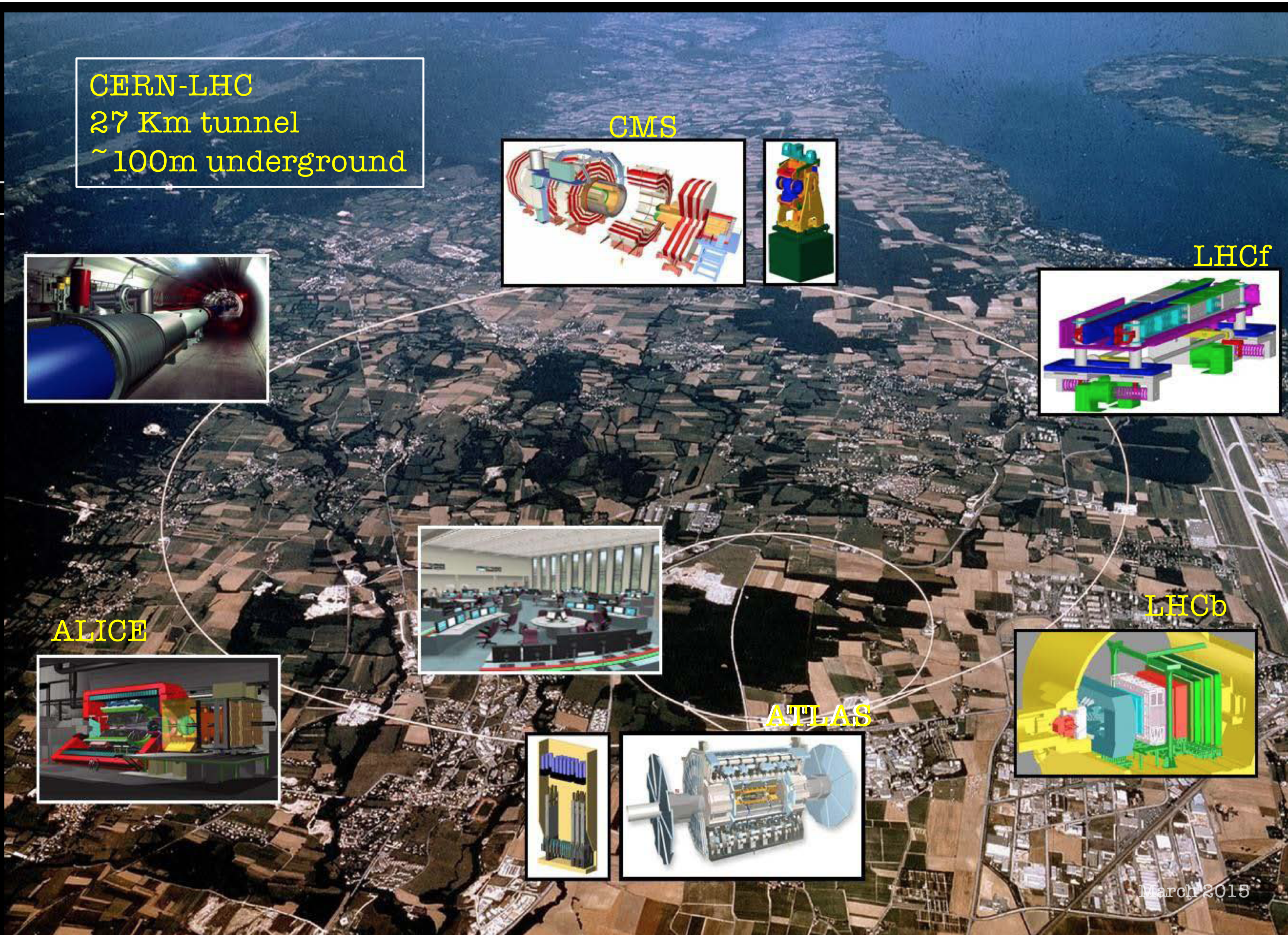




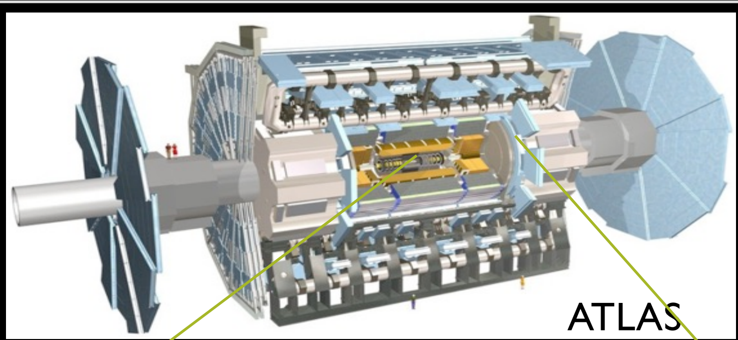
Example: Tracking Identification of Event Vertices

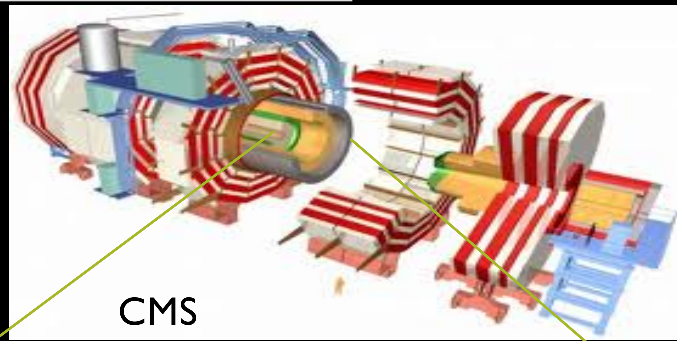
- primary event vertex reconstruction crucial in multiple collision events
- secondary vertices for live time tagging
- b- jet tagging

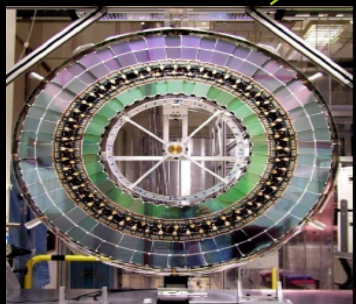



CERN-LHC
27 Km tunnel
~100m underground
CMS
LHCf
LHCb
ALICE
ATLAS
March 2015

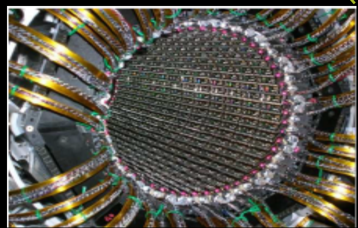
ATLAS and CMS use alone more that 250m² of Silicon Strips to “image” charged particles



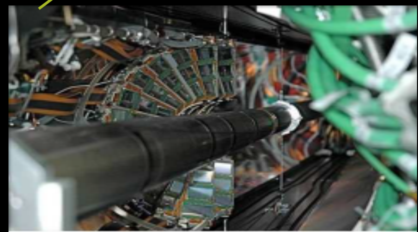




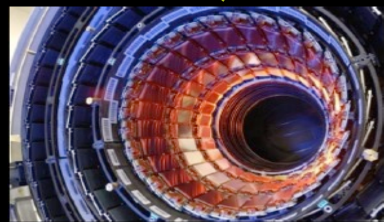
Strips
$61m^2$ of silicon.
6.2million channels 4 barrel layers + 9 disks per endcap
30cm < R < 52cm



Pixels
3 Barrel layers
(r=5,9,12 cm)
2 end caps each with 3 disks
80Mpixels 50x400um2
Digital I/O



Pixels
3 barrel layers
2 end caps each with 2 disks
66 Mpixels 150 x 100um2
Analog I/O



Strips
198 m^2 of silicon,
9.3 million channels
Inner : 4 barrel layers,
3 end-cap disks
Outer: 6 barrel layers,
9 weels
22cm < R < 120cm

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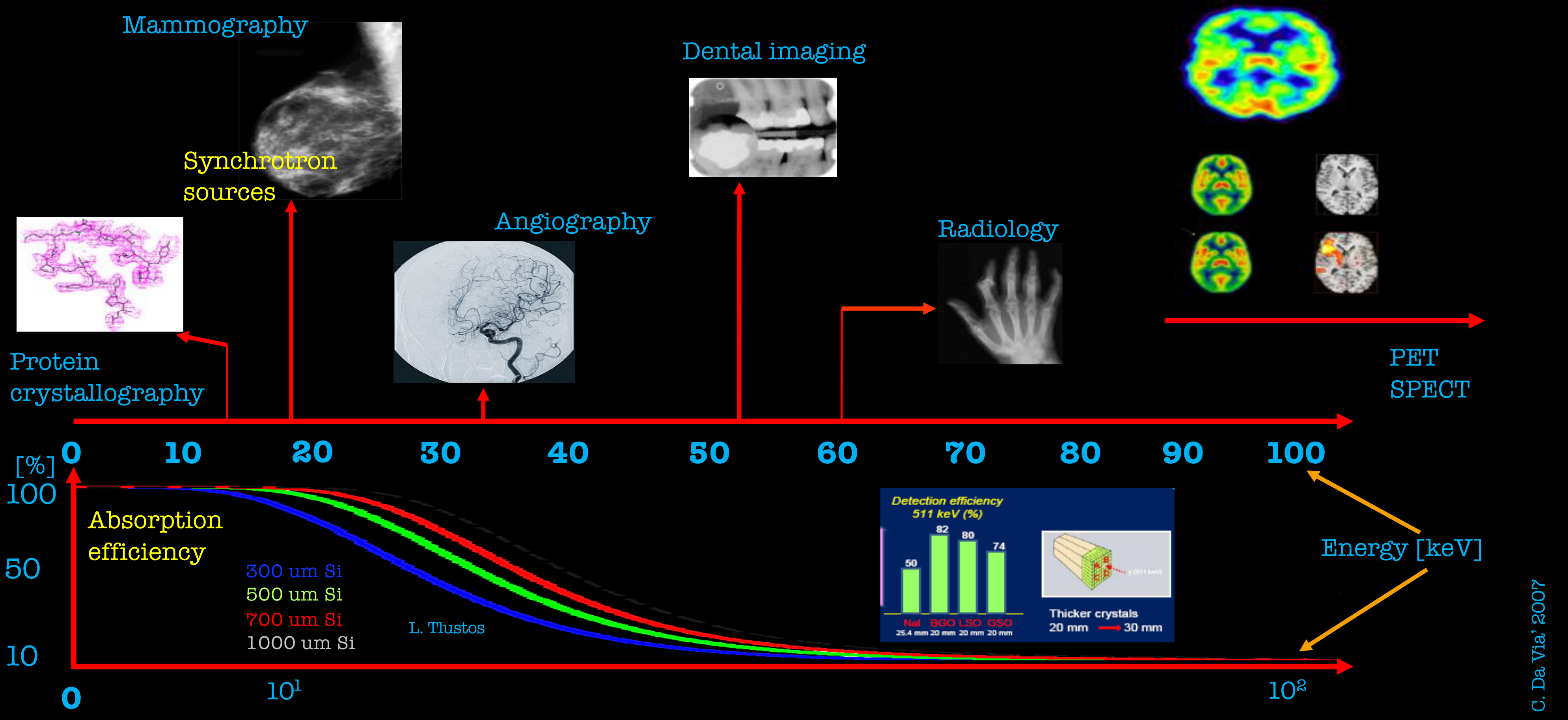
X-ray energy of the most common medical and biological applications



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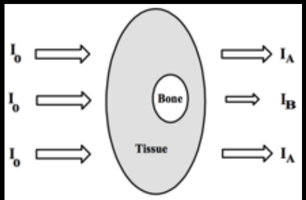
Direct/indirect conversion

Contrast



I_A/I_B

Resolution
pixel dimension-x

Signal to noise ratio
S/N

Dose to the patient

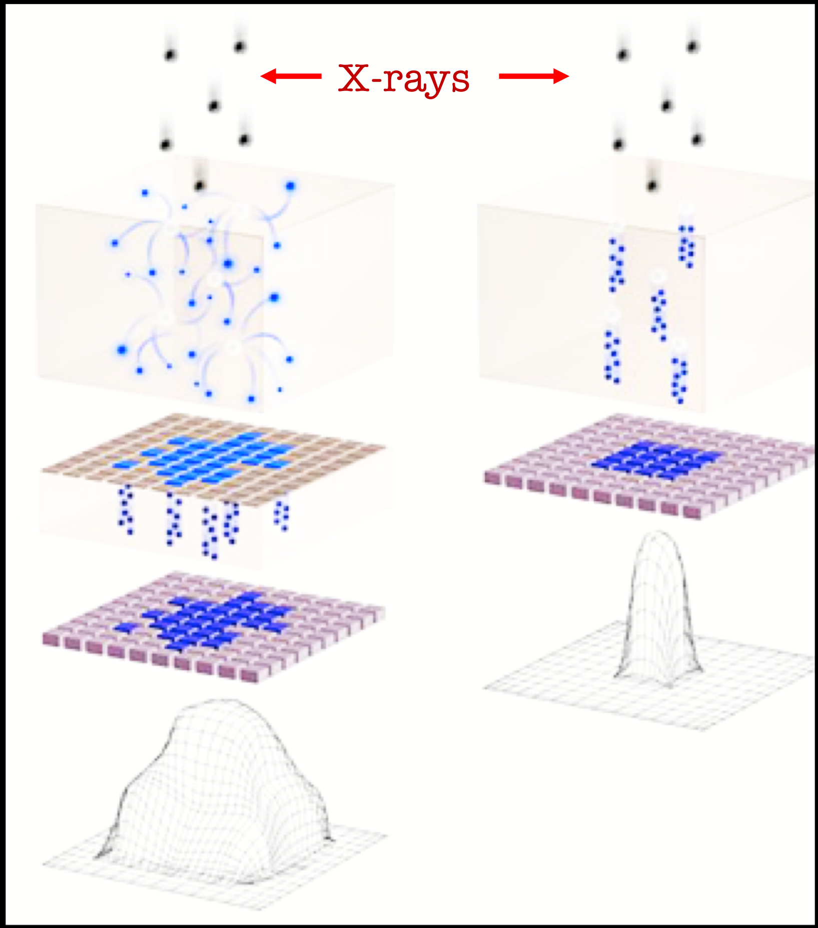
Organ	dose skin mGy	effective dose mSv
Thorax, face	0,2 - 0,5	0,015 - 0,15
Lumbar region	4 – 28	1,5
Urography	40 – 60	3
Brain scan	7 – 78	1
Whole Body scan	30 – 60	4 – 10
Mammography	7 – 25	0,5 - 1

Scintillator
Gadox, YAG CsI
(high Z)

Photodiode/ CCD

electronics

Sampled
image



Direct
conversion
Si, Ge, CdTe,
GaAs, Se

electronics

Sampled
image

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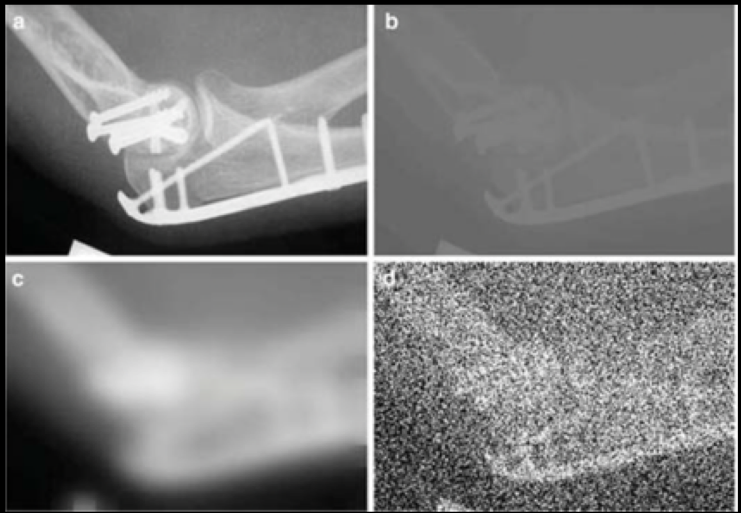
Comparison of different image qualities

Optimum image quality has adequate resolution and contrast, and a low noise level

This image has high spatial resolution and low noise, but it has almost zero contrast.



This mage has low noise and high contrast, but very poor spatial resolution.

This image has high spatial resolution but very high noise level which destroyed the image contrast

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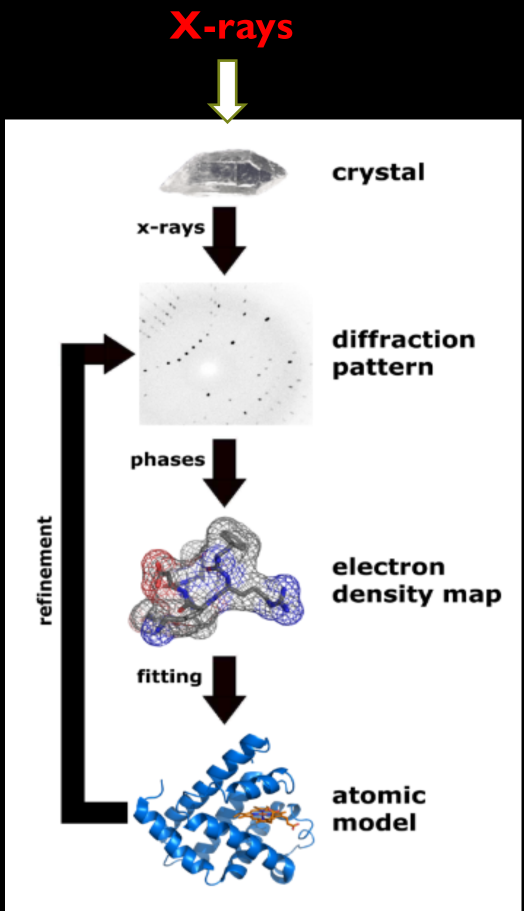
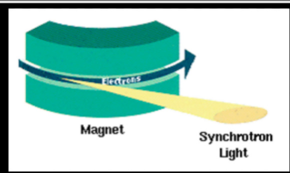
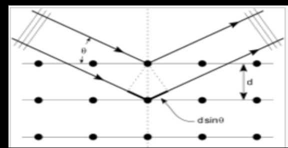
Synchrotron Radiation: Diffraction Protein crystallography 12 KeV

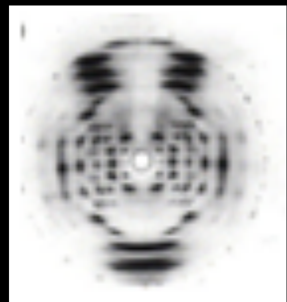


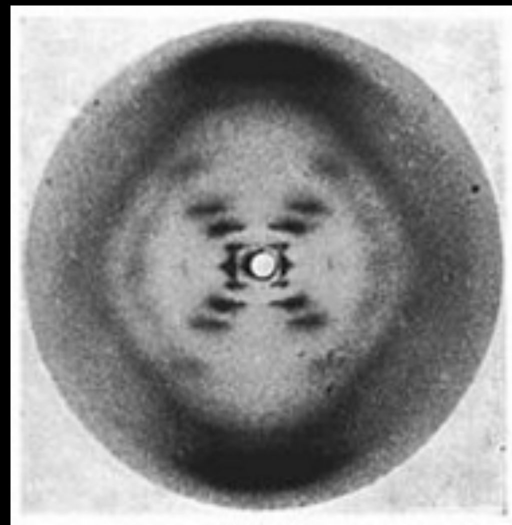
$$2d\sin\theta = n\lambda$$

Bragg Law





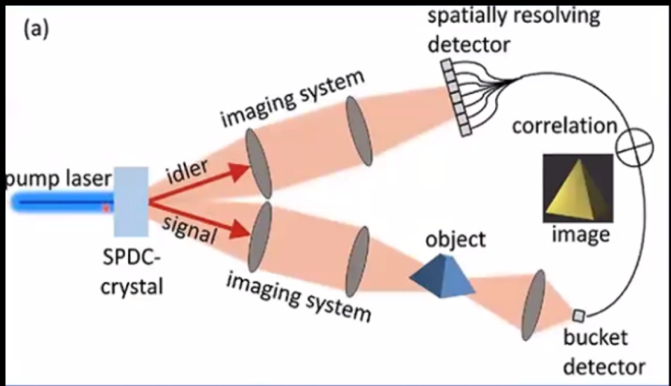




X-ray diffracted Photographic image of the double helix taken in 1952 by Rosalind Franklin and Raymond Gosling. The DNA sample was fibrous DNA

Ghost Imaging of undetected photons

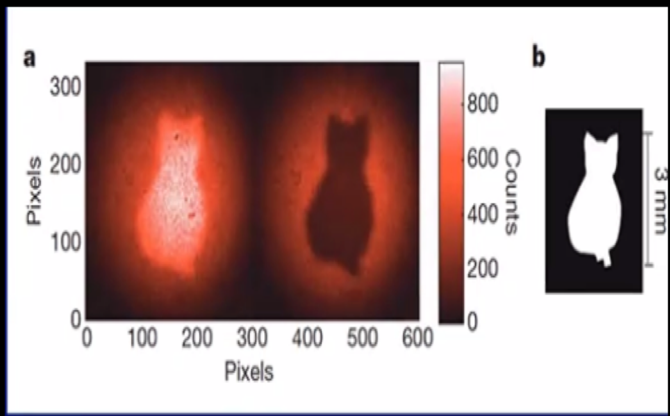
•https://doi.org/10.1364/QIM.2014.QTu1A.1



Uses Quantum Entanglement – Non-local correlation, superposition states

Entangled Photons generated in Non –Linear medium

SPDC=Spontaneous Parametric Down Conversion



Bucket detector=No-segmentation placed on the line of the object. Just detects the arrival of a photon, but without position information

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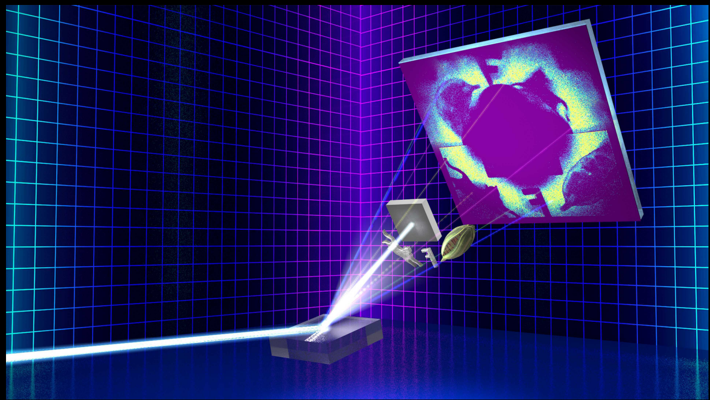
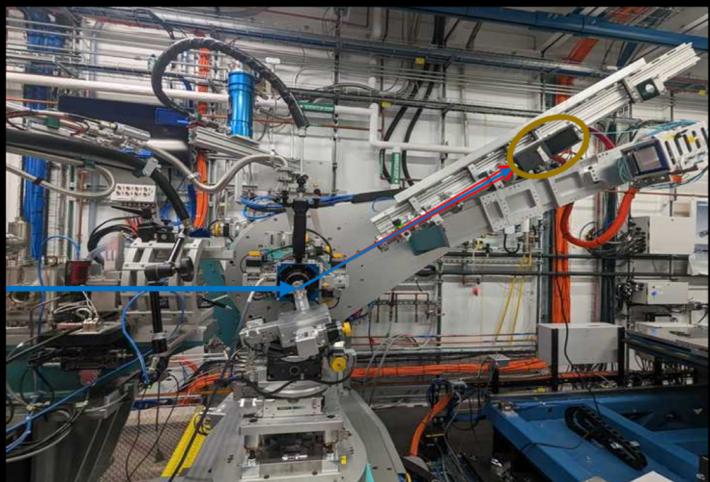
Ghost Imaging with Xrays

Quantum enhanced microscope collaboration





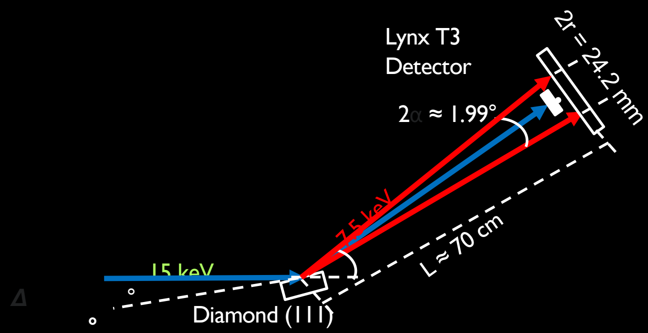
The effect of parametric down conversion (PDC) is the spontaneous decay of a photon of frequency w_p into two of frequencies w_i and w_s in an optically non-linear medium

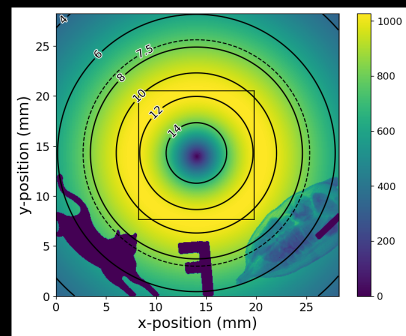
Energy conservation,

$w_p = w_i + w_s$

Momentum conservation

- $k_p = k_i + k_s$





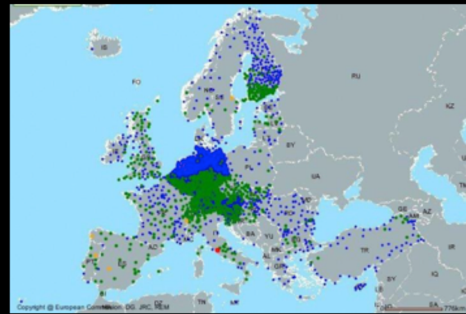
U. Stöhlker

Environmental Radiation Monitoring

Gamma Dose Rate (GDR) networks in Europe

German Network
1800 GDR stations
to perform gamma
Spectrometry and
Create contamination
Map for long -lived
radionuclides

Inter-calibration facility (INTERCAL) on Schauinsland mountain (1200 m) since 2007



European countries established GDR networks during the cold war period and improved these networks after the Chernobyl accident in 1986.

Monitoring of:
nuclear facilities
atomic bomb scenarios
terroristic attacs

Detecting Solar Radiation for Energy Harvesting Photovoltaic

A solar cell is basically a p-n-diode where current, voltage and resistance – vary when exposed to light

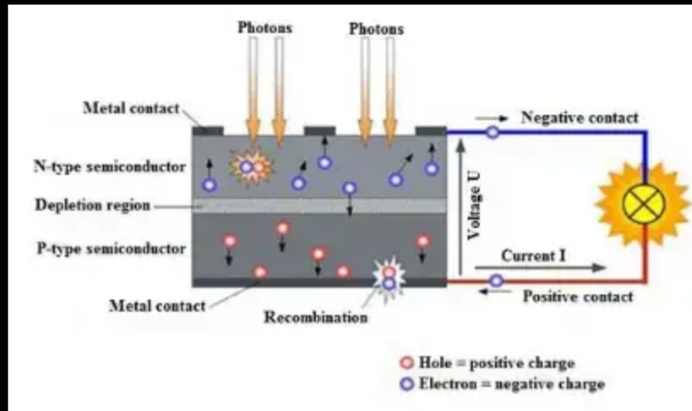
Solar cell Efficiency (Maximum):-

$$\eta_{max} = \frac{P_{max}}{E * A_c} \times 100\ \%$$

P_{max} = Maximum Power Output (in W)

E = incident radiation flux (in W/m^2)

A_c = Area of Collector (in m^2)



- The Earth receives 174 petawatts (10^{15}) (PW) of incoming solar radiation (insolation) at the upper atmosphere.

- About 30% is reflected back to space wh[illegible] PW, is absorbed by clouds, oceans and land masses.
- In 2022 solar photovoltaic PV generated 4.5% (1284 TWh) of the world's electricity compared to 1% (253 TWh) in 2015. Wind and solar generated over 12% of the world's electricity in 2022

Land Coverage

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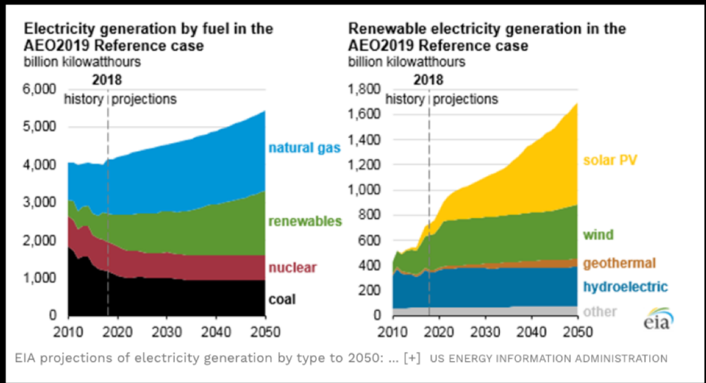
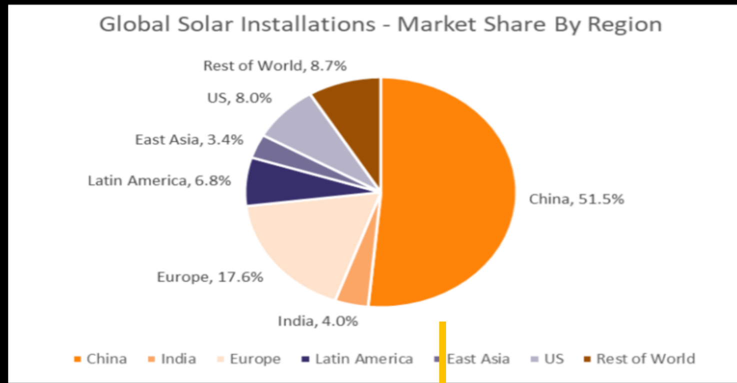
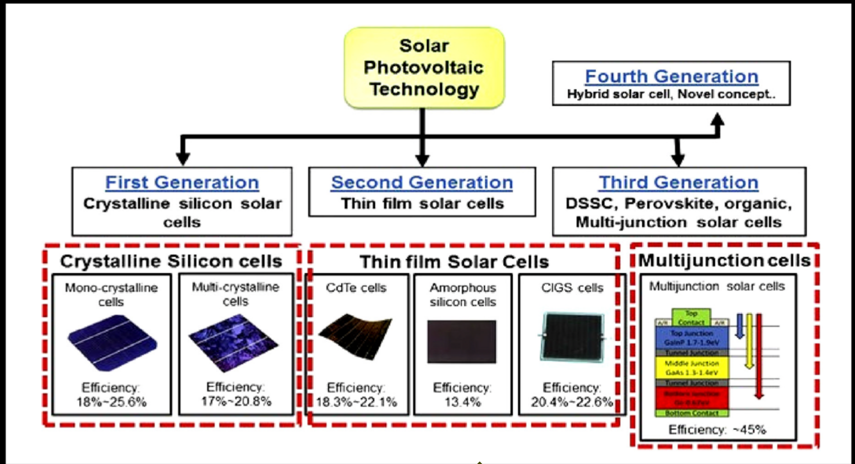
Harvesting UV Radiation from the Sun in 2023

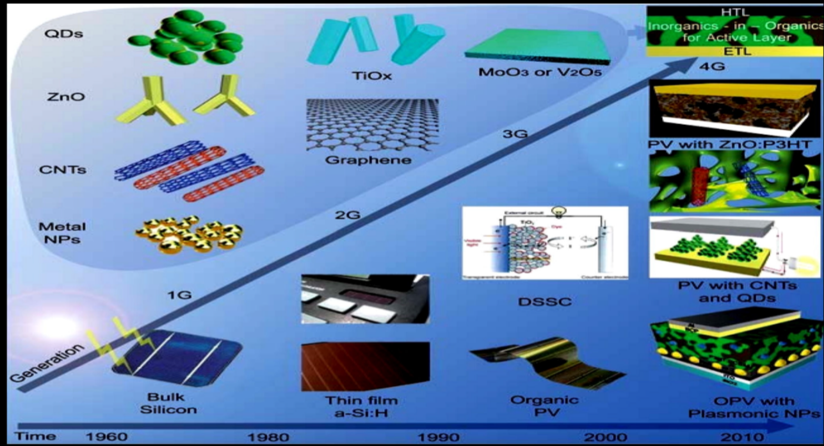




The Sustainable City in Dubai, United Arab Emirates Produce 87% of its needed energy over 114-acre

Solar Photovoltaic Technologies



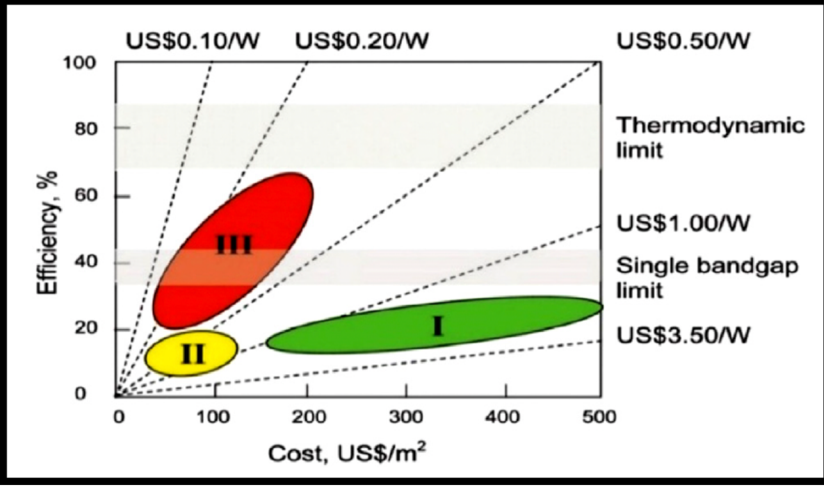


Generations

Efficiency

Evolution

Cost



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Conclusions

The development of radiation detectors and imaging technologies has always been a crucial component in scientific discoveries. Silicon being one of the most abundant element on earth still has a great potential in being a big player in sustainable solutions for the future.

By making the unseen “visible”, these detectors not only expand our understanding of the natural world but also pave the way for innovations that improve and advance human life.

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