Outline

- History and motivations
- Semiconductors physics
- Silicon radiation detectors
- Perspectives

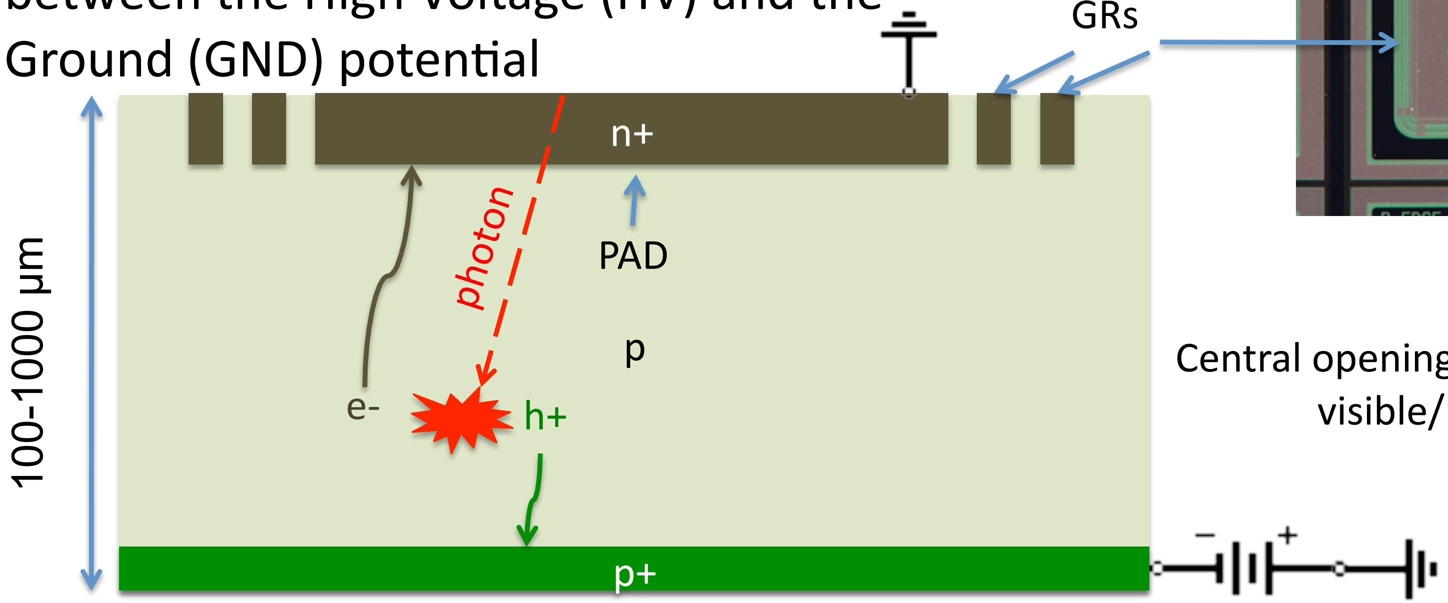
Silicon pad diode

A single p-n diode in reverse bias is the simplest silicon radiation detector

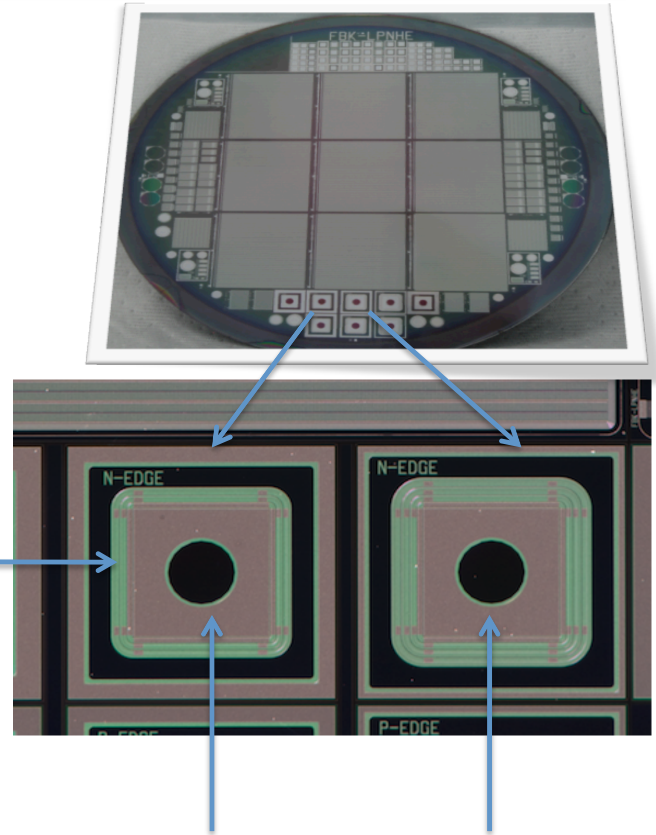
Often it is called pad diode

The size varies between few mm^2 to few cm^2

Guard Rings (GRs) assure a smooth transition between the High Voltage (HV) and the Ground (GND) potential

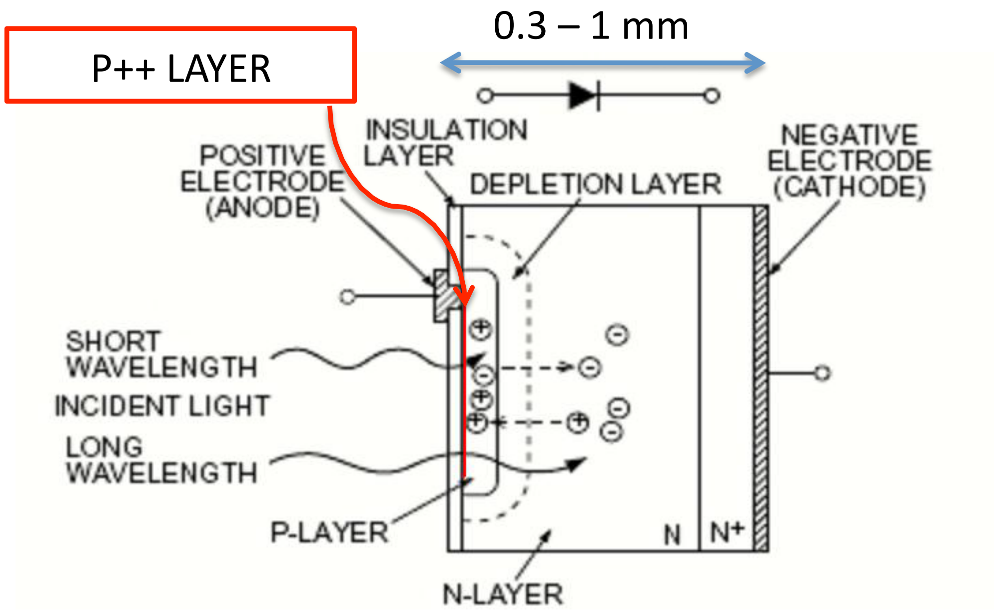


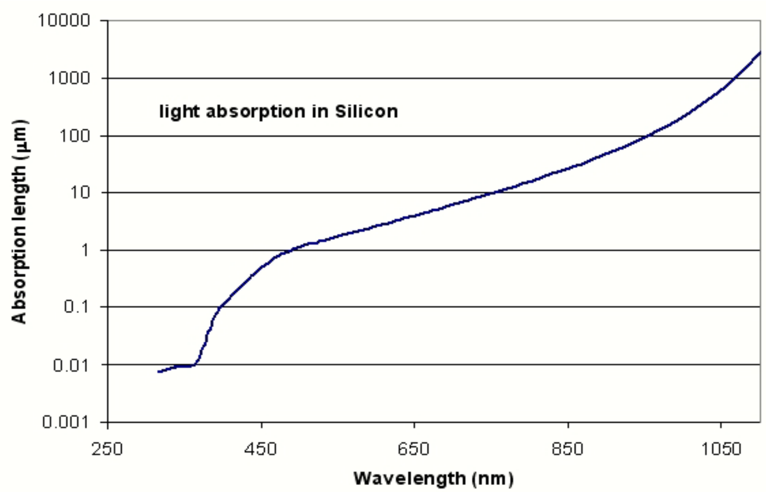
N-on-p production



Central openings in the aluminium layer for visible/IR photon detection

Detection of photons with silicon photodiodes





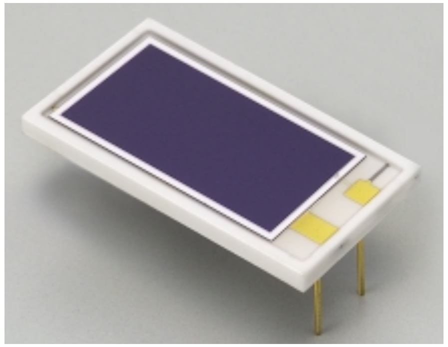
Photons can experience:

- Surface reflectivity losses
- Absorption losses in the top protection layer
- Conversion inside the top high conductive p++ layer with rapid recombination, mostly for UV light
- Conversion in the top p-layer (assumed to be depleted), mostly in the case of short wavelengths
- Conversion in the depleted n-layer, mostly in the case of longer wavelengths
- Conversion in the undepleted n-layer, mostly for IR light
- No absorption at all, mostly in the case of long wavelength IR light

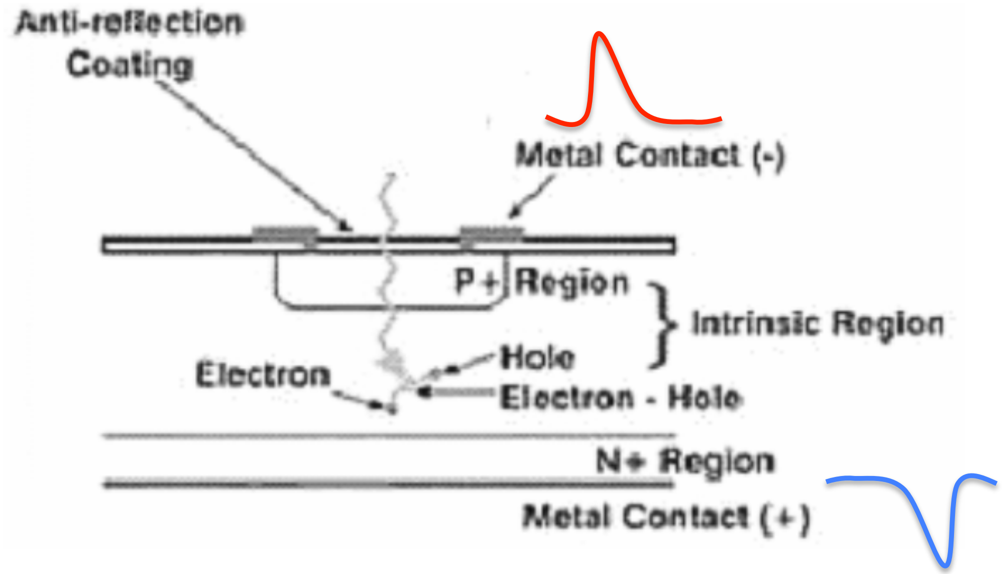
Silicon PIN diodes

- 'Sixties evolution: the p-i-n (PIN) photodiode
- Wavelength range of some 150 to 1100 nm, covering:
  - the emission wavelength of almost all organic and inorganic scintillators
  - Cherenkov radiators used in particle physics
- Very successful device
- Still used in
  - high energy physics (PMTs replacemet)
  - radiation detection
  - and medical imaging

Hamamatsu S2744-08



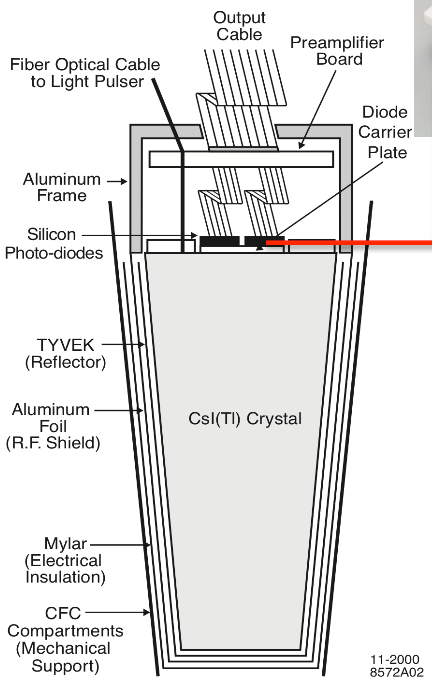
Silicon PIN photodiode



A piece of intrinsic high-ohmic silicon
Sandwiched between two heavily doped n+ and p+ regions

✓ Thick bulk: low capacitance (less noise) + sensible to longer wavelengths
✓ Undoped bulk: low depletion voltage; longer generation/recombination lifetime ➔ small charge losses, low leakage current

Si PIN diodes for a CsI(Tl) calorimeter (*BaBar*)



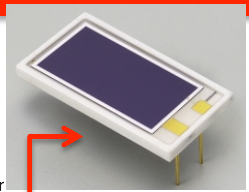
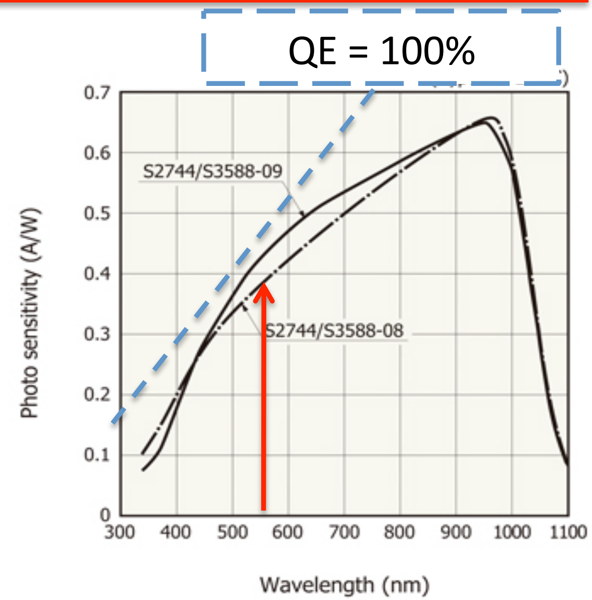


Table 2.6: Properties of CsI(Tl) .

Parameter	Values
Radiation Length	1.85 cm
Molière Radius	3.8 cm
Density	4.53 g/cm^3
Light Yield	50,000 γ/ MeV
Light Yield Temp. Coeff.	0.28%/°C
Peak Emission λ_{max}	565 nm
Refractive Index (λ_{max})	1.80
Signal Decay Time	680 ns (64%)
	3.34 μs (36%)

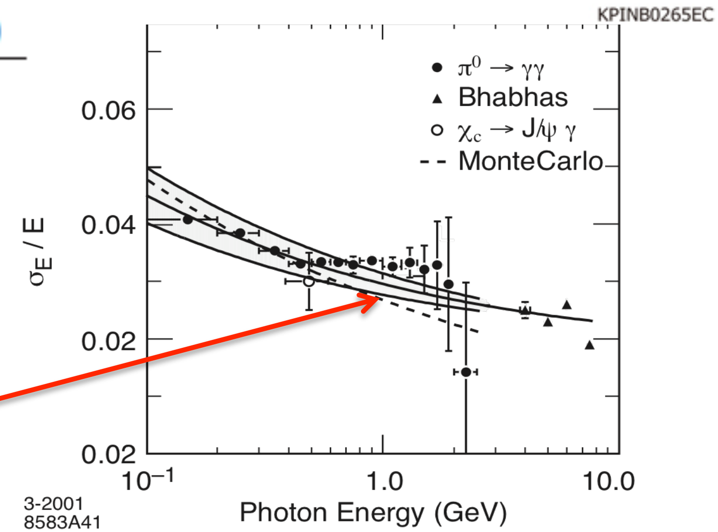


PIN diode: Vdepl ~ 70 V, I ~ 4nA, S~2cm^2

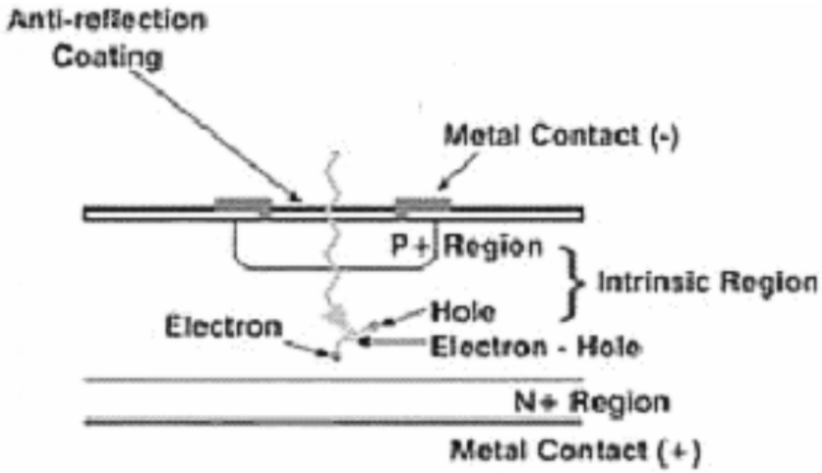
QE for peak emission close to 80%

PMTs only 10-15%

Photon energy resolution ~ 2-3% @ 1GeV



Si PIN diodes: pros and cons



✓ Simple and reliable
✓ Can operate in B
✓ Low voltage wrt PMTs

No internal gain:

✓ Output very stable

X Charge sensitive preamplifier is needed

X Low bandwidth filter is needed

- To cope with noise (leakage current + capacitance)

X Preamp & filter makes signal slow

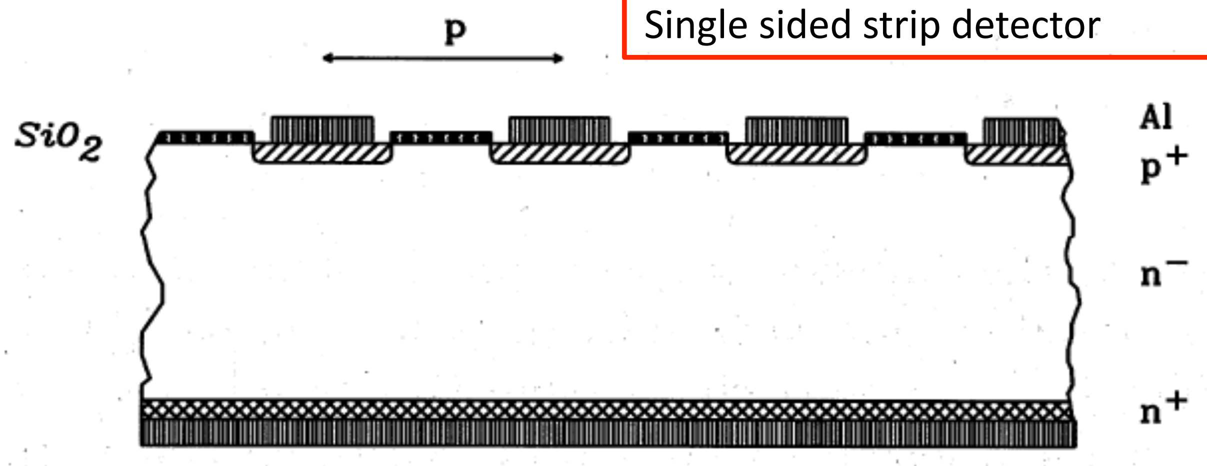
- E.g.: minimal detectable signal: O(100)/cm^2 photons with a filter time constant of few μs

Position measurement: Silicon microstrip detector

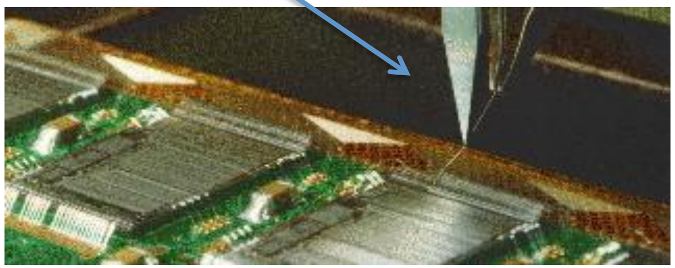
Segmentation of the collecting electrode, independent readout of them
➔position sensitive detector

Typical strip pitch 20-50 μm

Single sided strip detector



The connection between the strips and the readout chips is done via micro-bonding techniques (wires ~20 μm diameter)



Single sided microstrip detector
➔ Excellent position resolution in one dimension
Reminder:

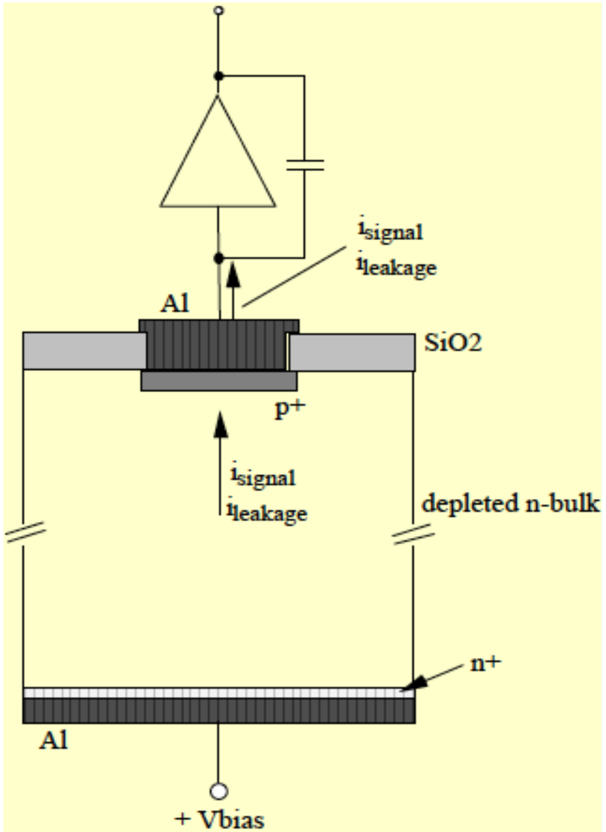
Binary r.o., single strip: $\sigma = p/\sqrt{12}$

Analogue r.o., 2 strips cluster: $x\ (C.O.G.) = (x_1h_1+x_2h_2)/(h_1+h_2)$, $\sigma \sim p/(SNR)$ (h_i=sign. amp.)

Microstrip detectors with AC-coupled readout

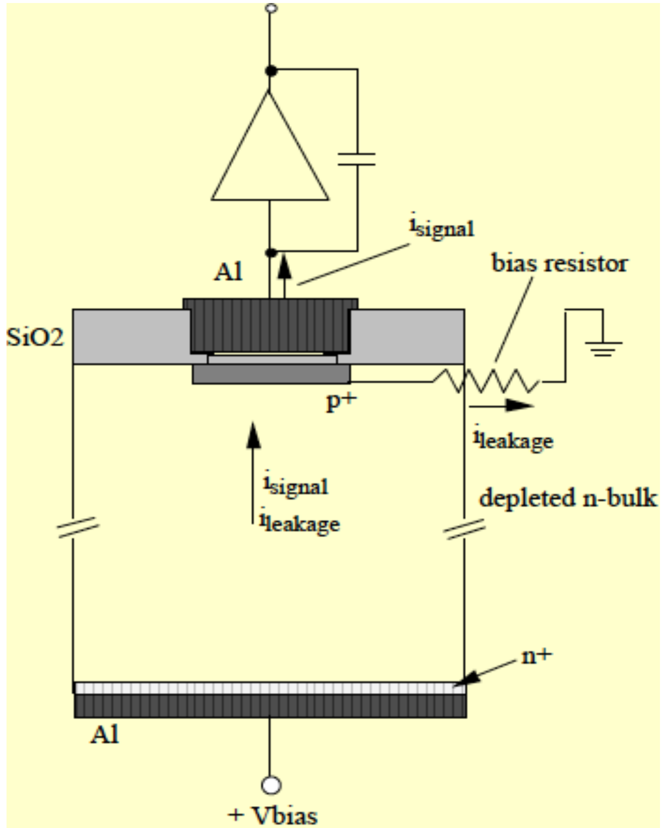
AC-coupling the detector with the electronics allows to avoid the DC detector leakage current to offset the working point of the preamplifier. Coupling capacitors of suitable value could be integrated in the detector itself (another benefit of the planar process)

DC-coupled detector



$C_C >> C_{S,tot}$

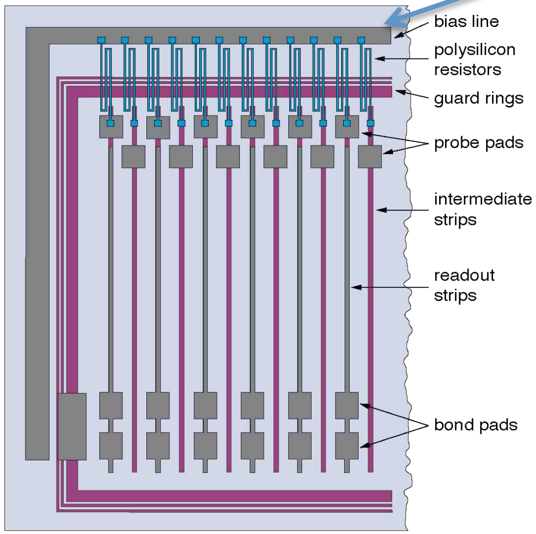
AC-coupled detector
with integrated coupling capacitance

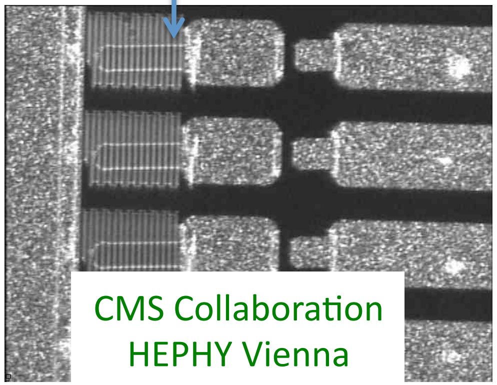


Biasing circuits

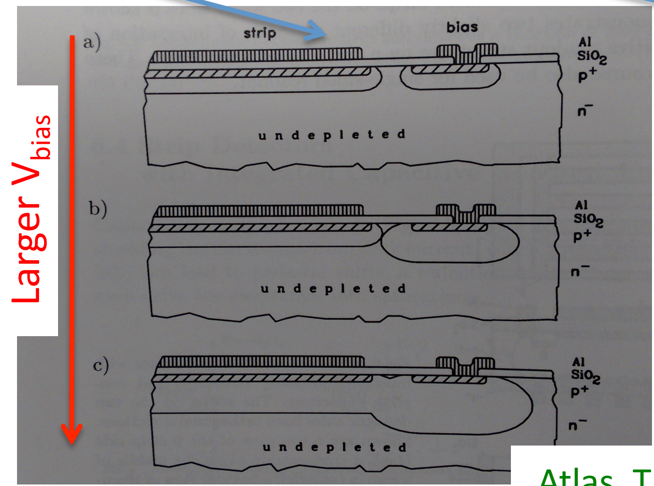
For an AC-coupled a DC path must be provided for the strip leakage currents

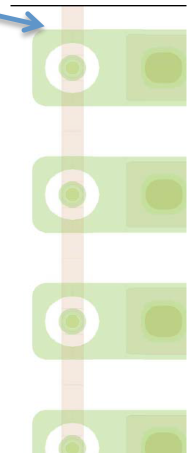
Two possible methods: via a resistor or by the punch-through method





CMS Collaboration HEPHY Vienna





Atlas, TU Dortmund & MPI-HLL

Deposition of polycristalline silicon between p+ implants and a common bias line

Drawback: Additional production steps and photo lithographic masks required.

Small potential difference between strip implant and the bias dot

This solution allows avoiding the technological steps required for polysilicon deposition in the detector processing; same technology DC and AC strips

Radiation damage?

Double-sided microstrip detectors (DSSD)

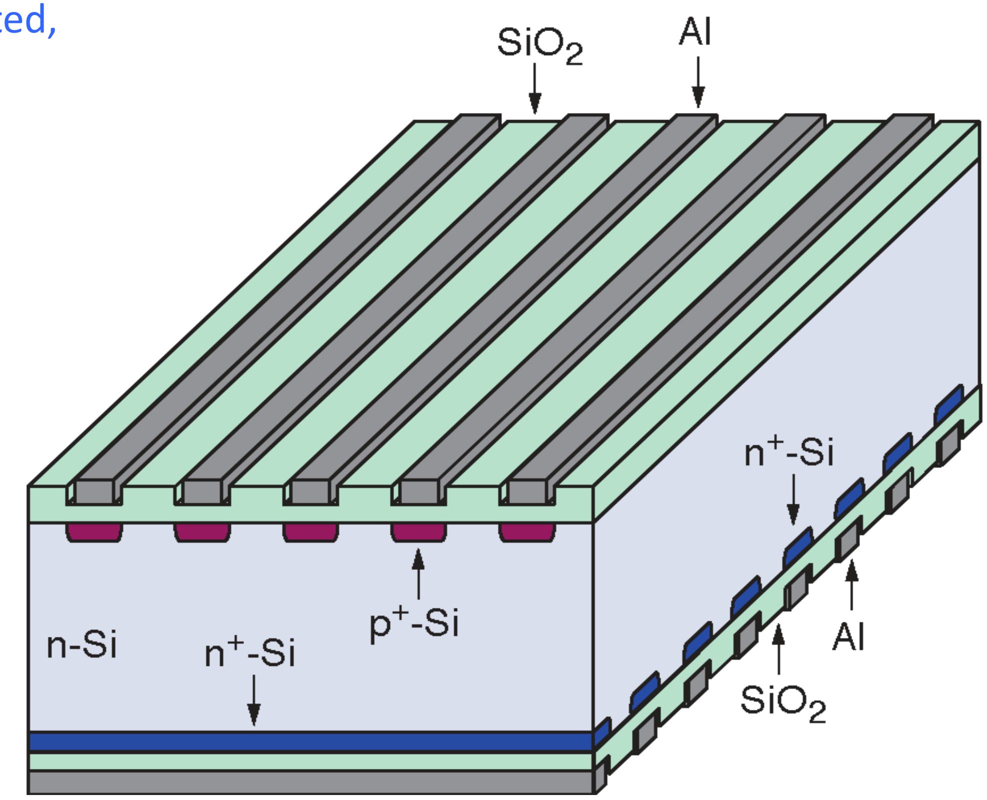
Single sided detector measures only one coordinate. To measure second coordinate requires second detector layer

Double sided strip detector measures two coordinates in one detector layer (minimizes material)

In n-type detector the n^+ backside becomes segmented, e.g. strips orthogonal to p^+ strips

Drawback: expensive as production, handling, and tests are more complicated

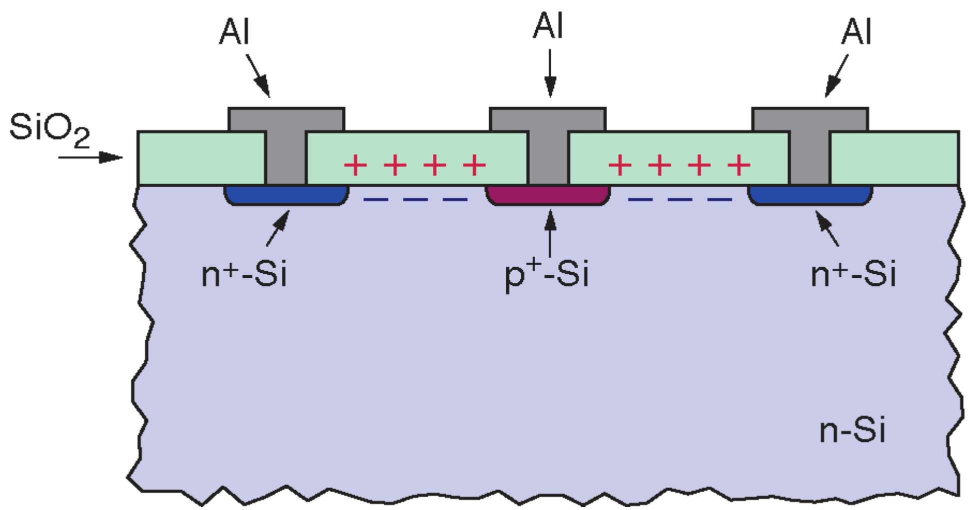
Scheme of a double sided strip detector (biasing structures not shown):



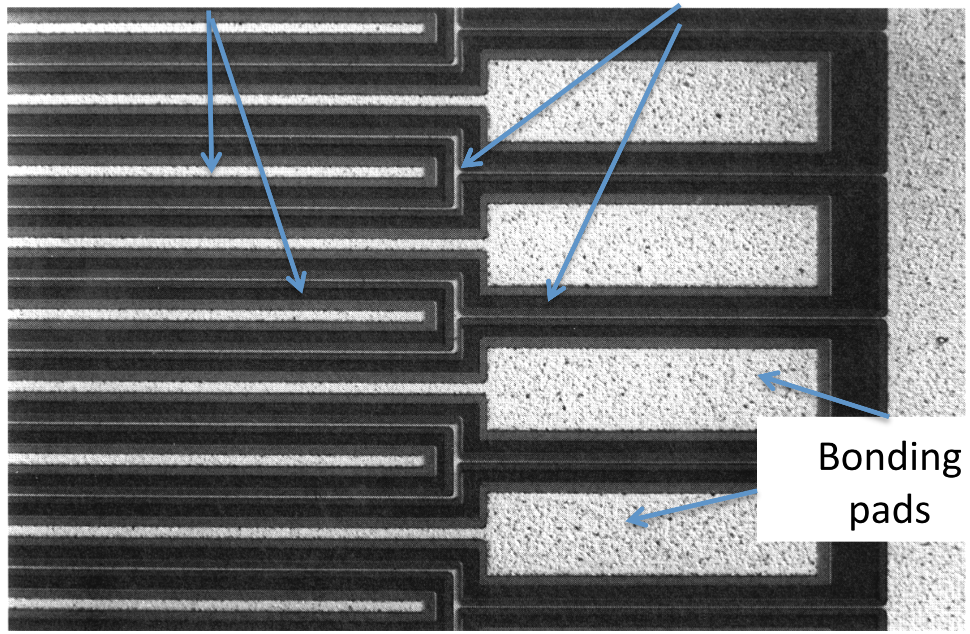
DSSD: p^+ stops

Problem with n+ segmentation: Static, positive oxide charges in the Si-SiO_2 interface
Shorting of n+ strips hence No position measurement possible

p^+-implants (p^+-stops, blocking electrodes) between n^+-strips interrupt the electron accumulation layer.
➔ Interstrip resistance reach again GΩ.

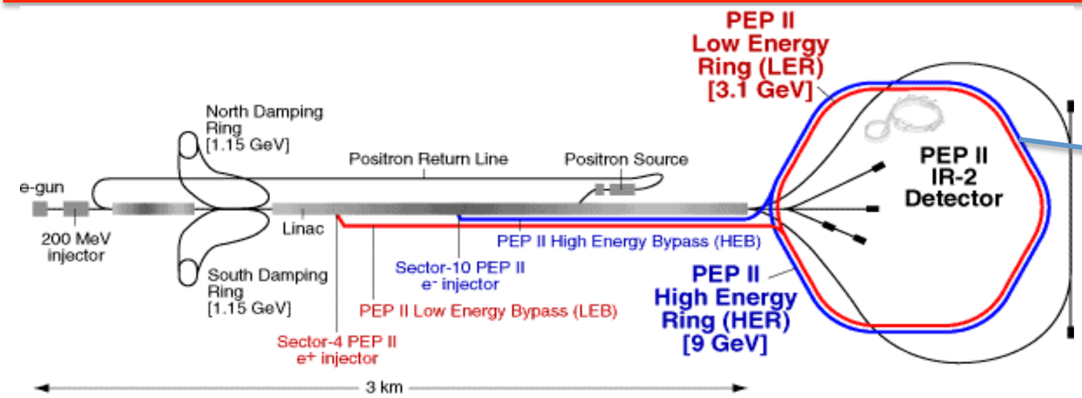


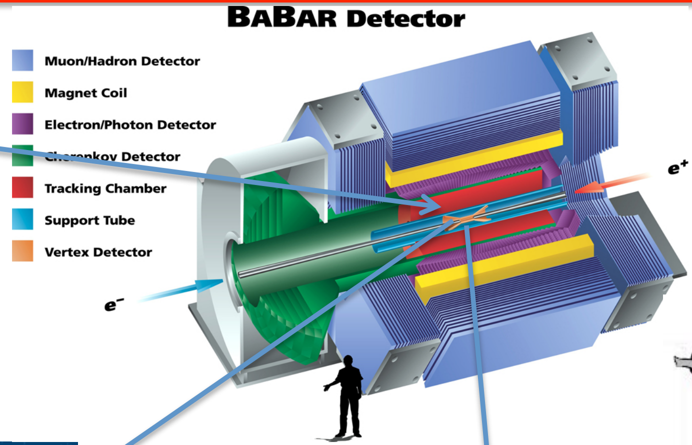
n+-side of a DSSD with p^+-stops

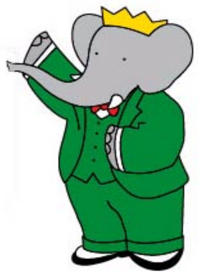


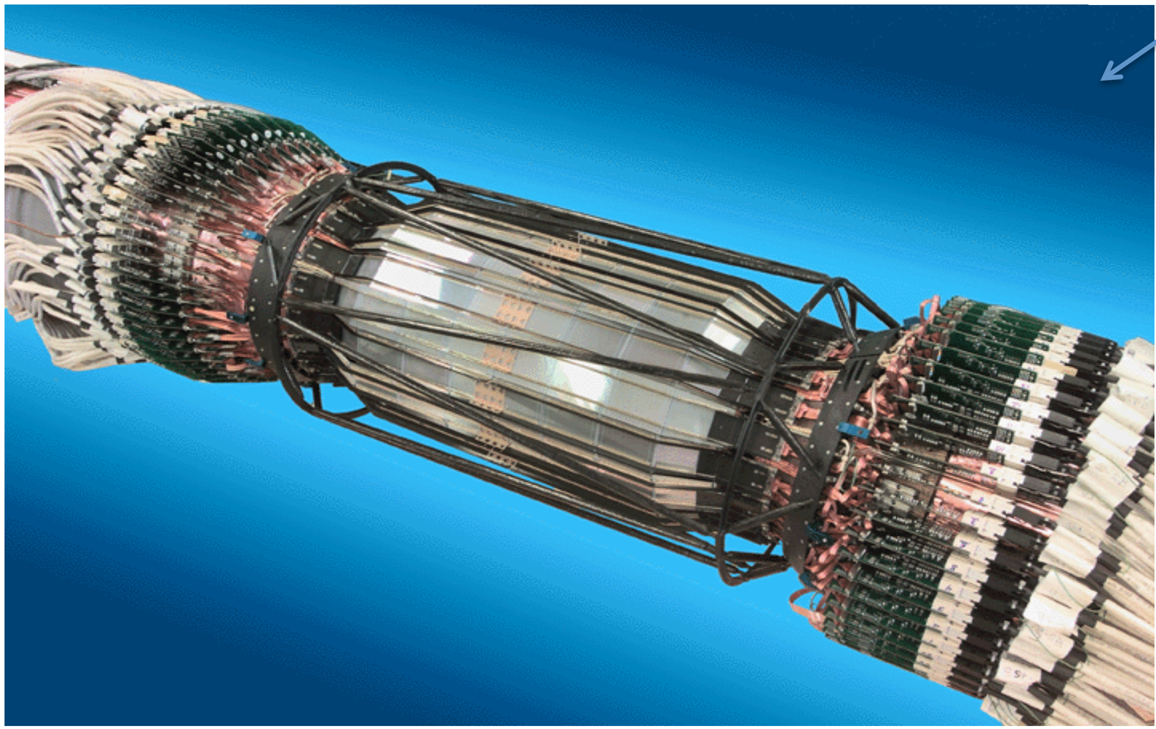
J. Kemmer and G. Lutz, New Structures for Position Sensitive Semiconductor Detectors, Nucl. Instr. Meth. A 273, 588 (1988)

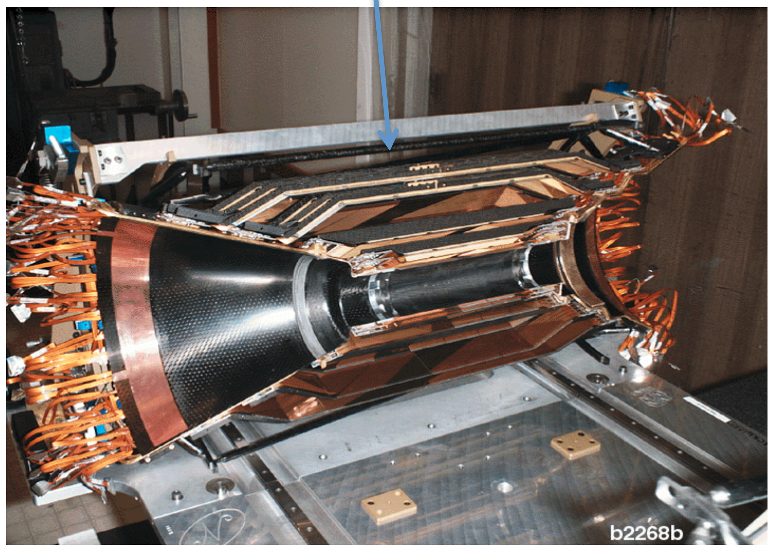
DSSD: the *BaBar* Silicon Vertex Tracker (SVT)







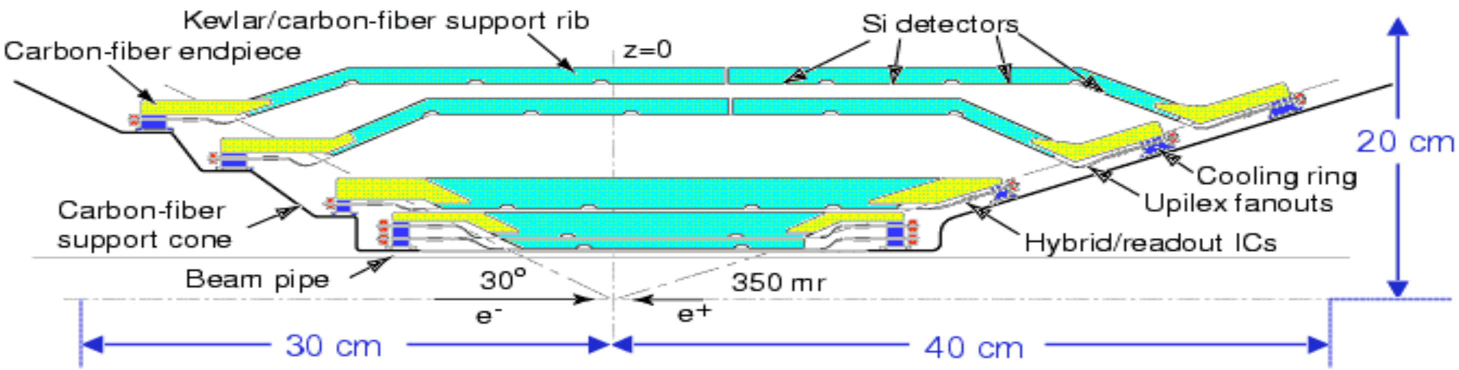




Babar SVT: physics requirements and layout

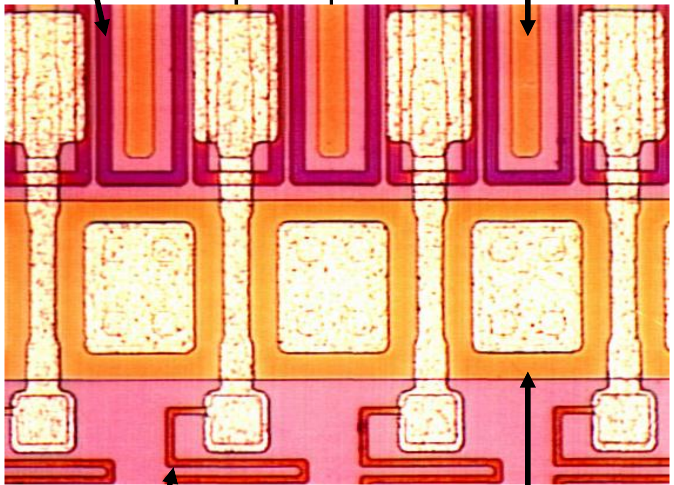
BaBar primary goal:
- Study of CP asymmetries in B decays
- Overconstrain CKM matrix parameters

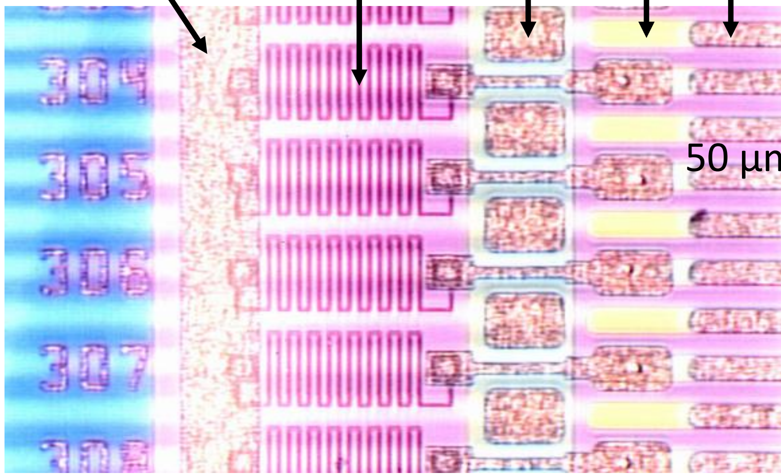
Main SVT physics requirements:
- SVT standalone tracking for p_t < 120 MeV/c with high efficiency
- Single vertex resolution along z-axis better than 80 μm (<Δz> of B mesons about 250 μm)



- Microstrip silicon detector; 5 double-sided layers
- Polar acceptance: 17.2° < θ < 150°
- Layer 1-3 (barrel-shaped) for a precise measurement of track impact parameter
- Layer 4-5 (arch shaped) for pattern recognition and low pt tracking
- X_0(Si) = 9cm: multiple scattering was the limiting factor to the resolution
- 150 k channels, 340 wafers (6 different models)

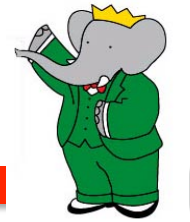
BaBar SVT sensors characteristics

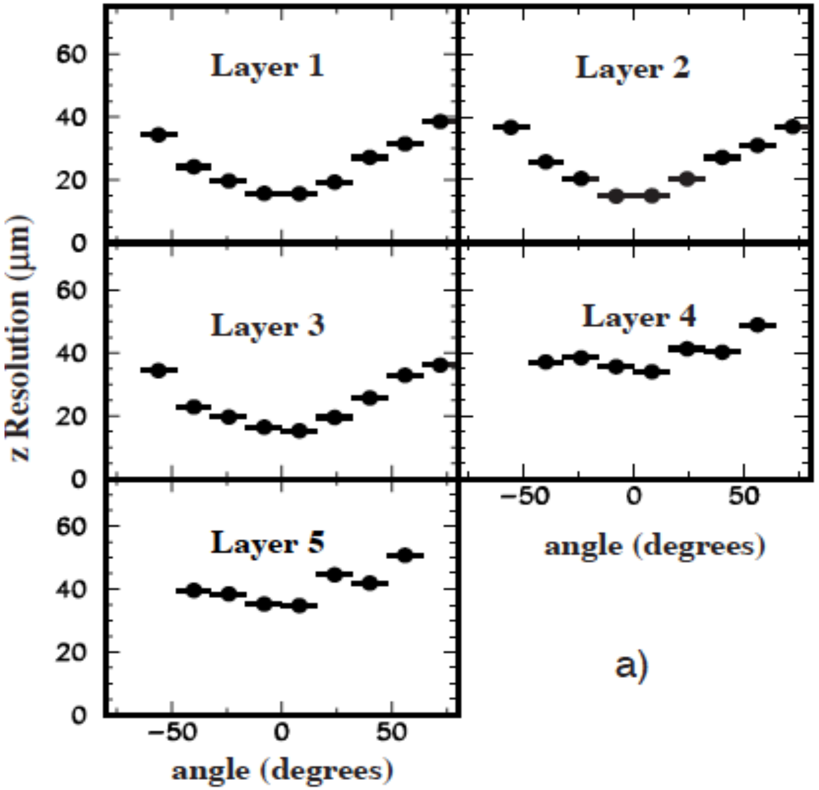


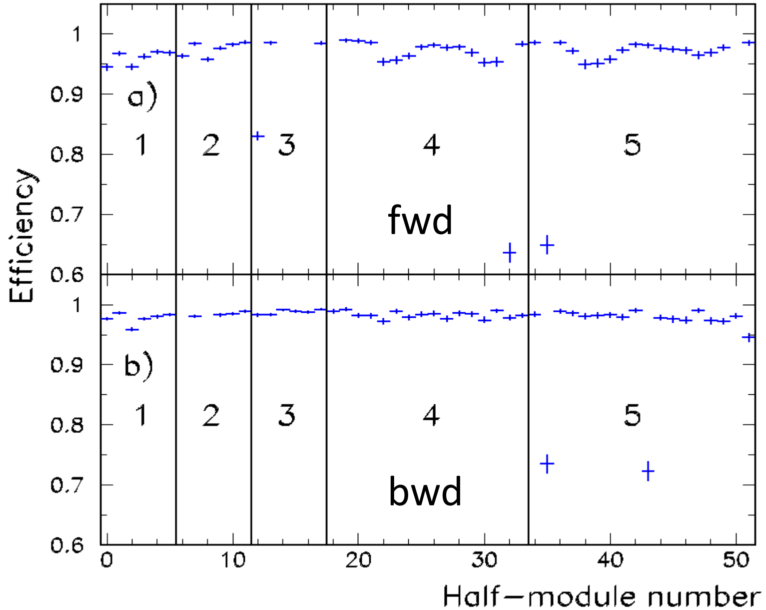


- Double-sided, AC-coupled Si
- Integrated polysilicon bias resistors
- 300 µm n-type (4-8 kΩcm)
- P^+ and n^+ strips perpendicular to each other

BaBar SVT performance







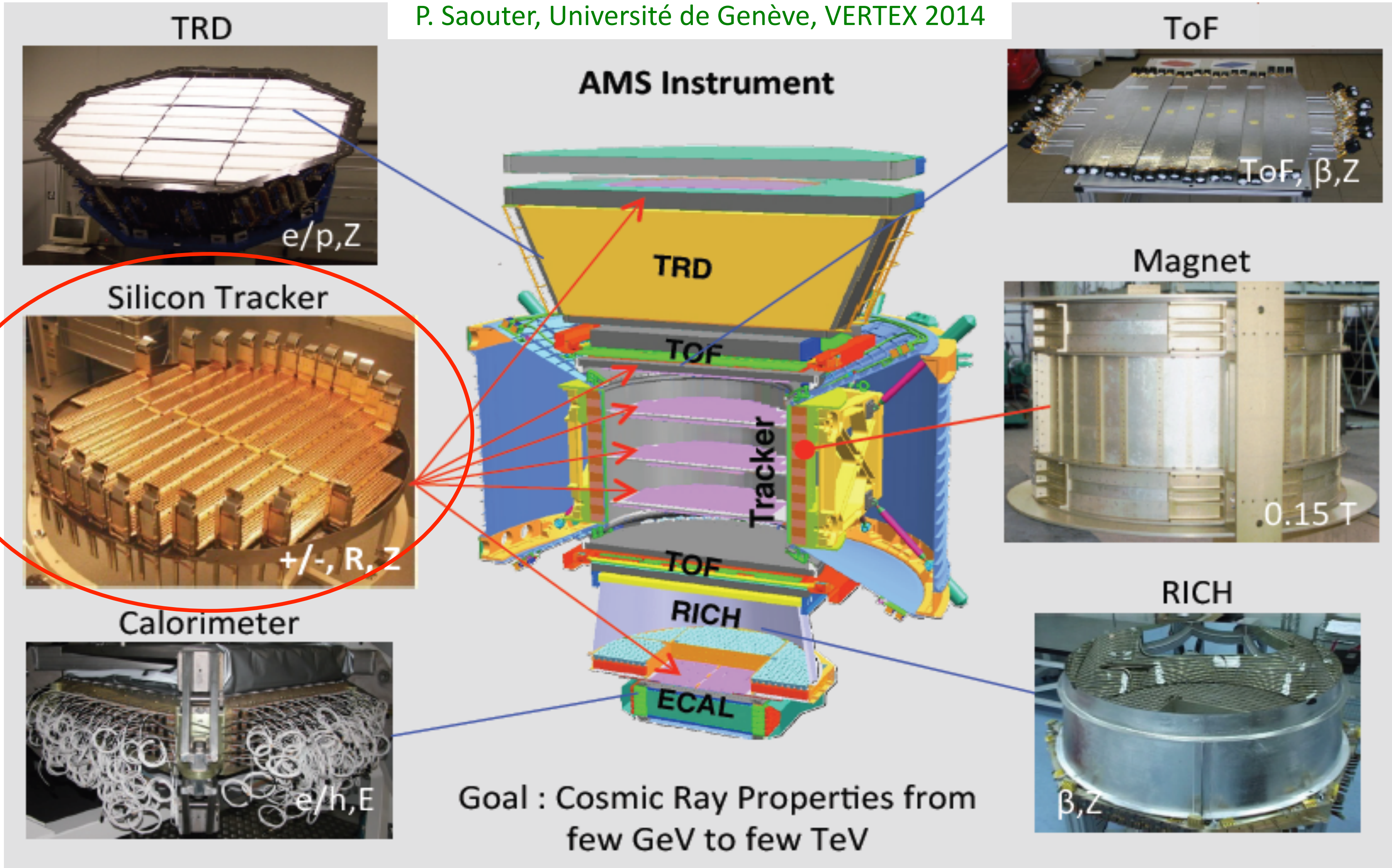
TDR target for perpendicular tracks p > 1 GeV:

Hit efficiency typically 98%

Layer 1-3 10-15 μm
Layer 4-5 30-40 μm

The BABAR Detector: Upgrades, Operation and Performance NIM A729 (2013) 615-701

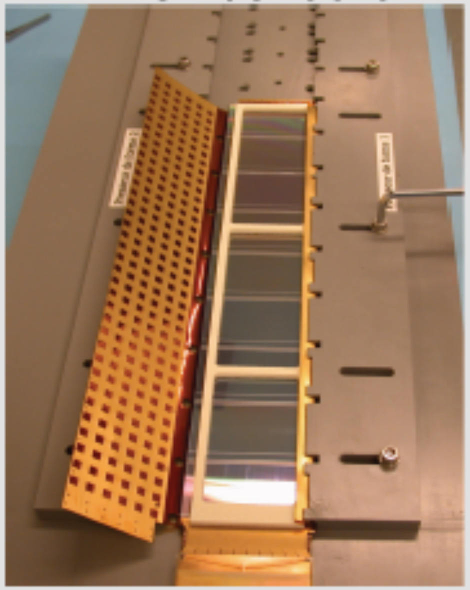
The AMS-02 Instrument



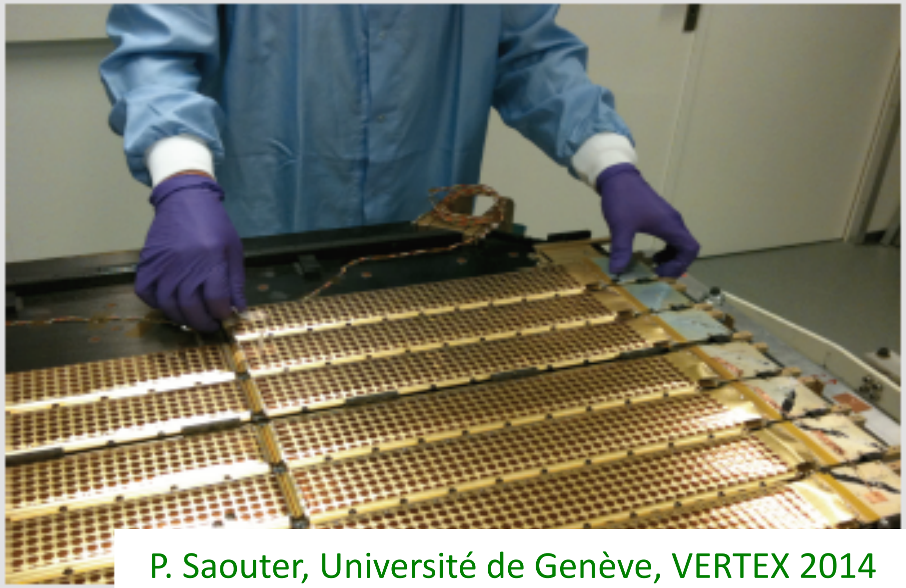
The AM-02 Silicon Tracker

- 2284, 300µm thick, double-sided silicon micro-strip sensors (p+-n-n+)
- 7 to 15 sensors arranged in basic functional units (ladders)
- Intrinsic position resolution : 10 (30) µm in y(x) bending (non-bending)
- 6 honeycomb carbon fiber planes (0.04 X_0)
- 196k channels → 192 Watts
- 126 Watts cooled by Tracker Thermal Control System (2 phase CO_2)
- Operational temperature range : -10°C to 25 °C.

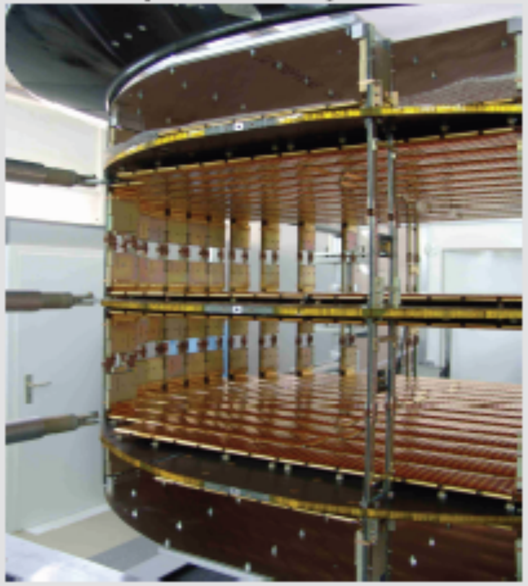
2284 sensors



192 ladders



9 layers in 6 planes

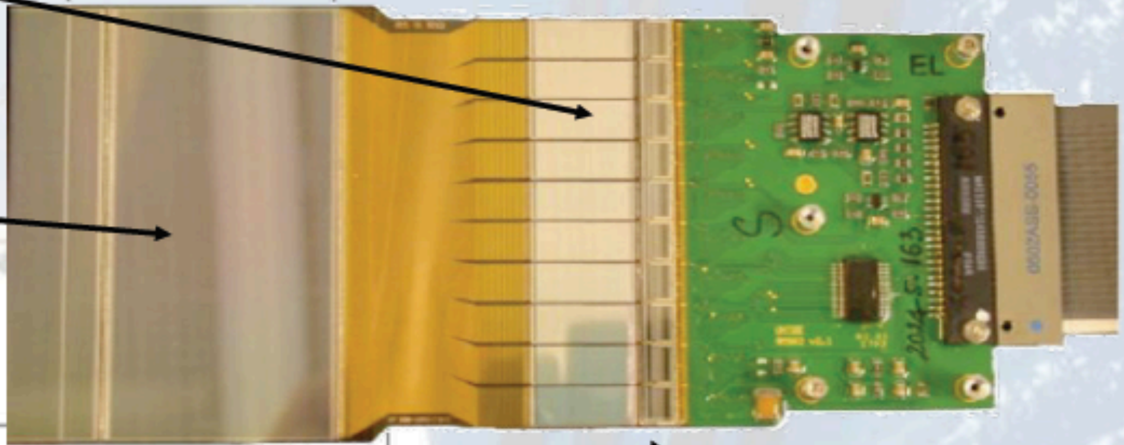


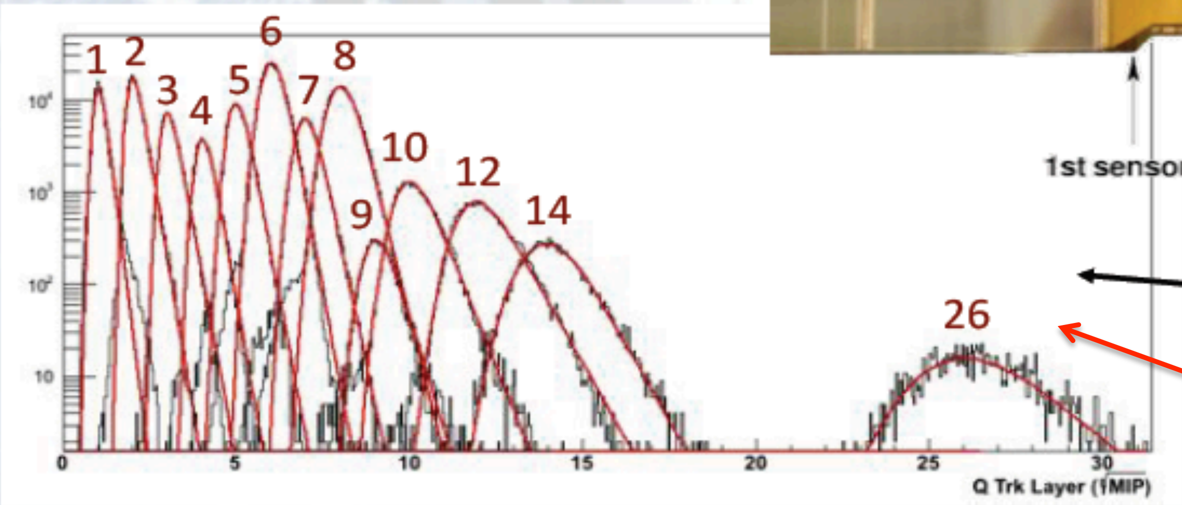
P. Saouter, Université de Genève, VERTEX 2014

Ladder components: junction (S, bending) side

700 pF coupling capacitances

double sided, DC coupled
300 μm thickness
7-15 sensors in a ladder
produced at:
- Colybris (CH)
- IRST (IT)





10 VA_hdr64a (IDEas, NO)
640 channels, 0.7 mW power each
CR-RC shaper and S&H 4 μs shaping time
100 MIP dynamic range

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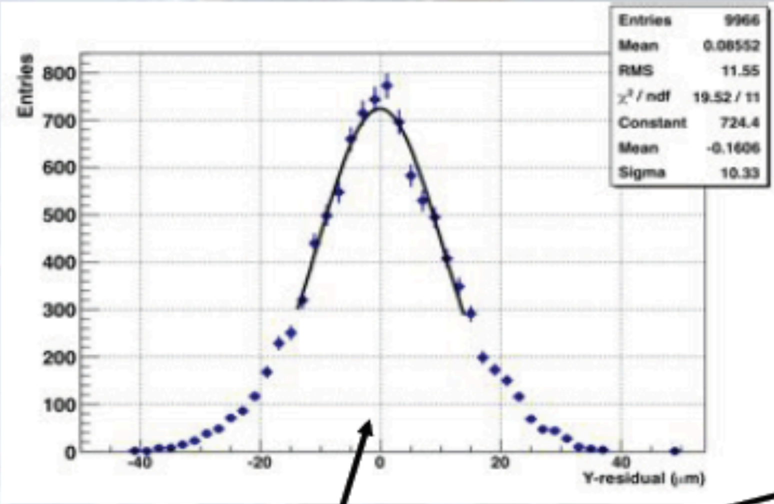
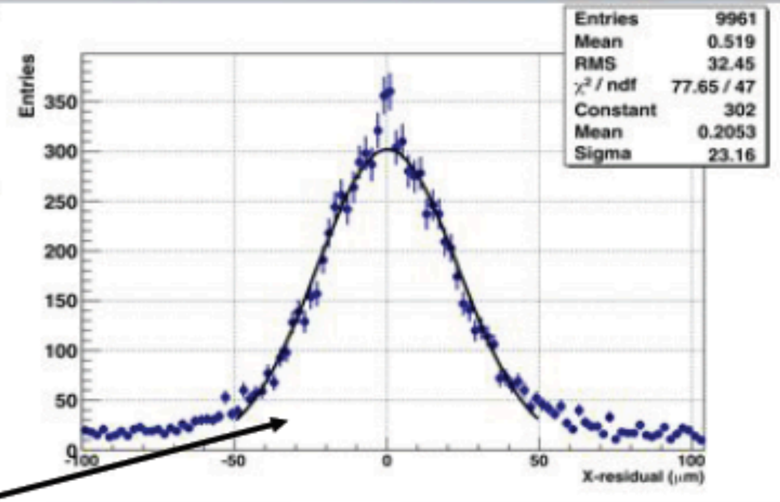
Spatial resolution performances

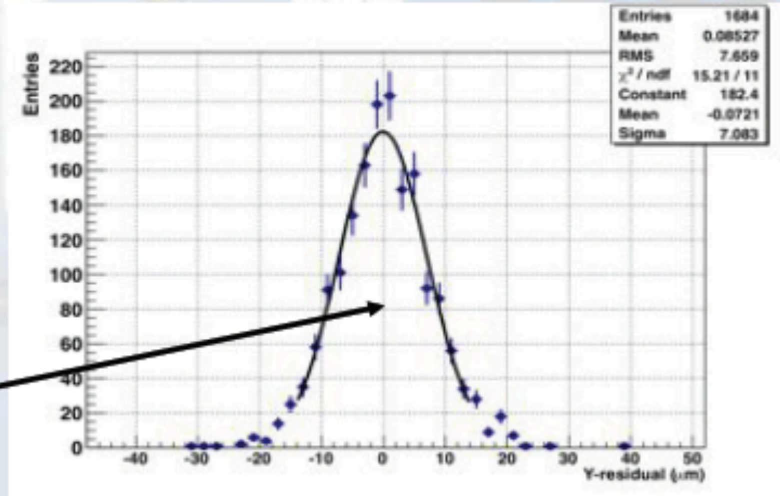




Protons (MIP)

Spatial resolution:

~ 10 (30) µm on Y/junction/bending (X/ohmic/not-bending), as expected



Helia

With Helia, thanks to higher S/N, the spatial resolution improves

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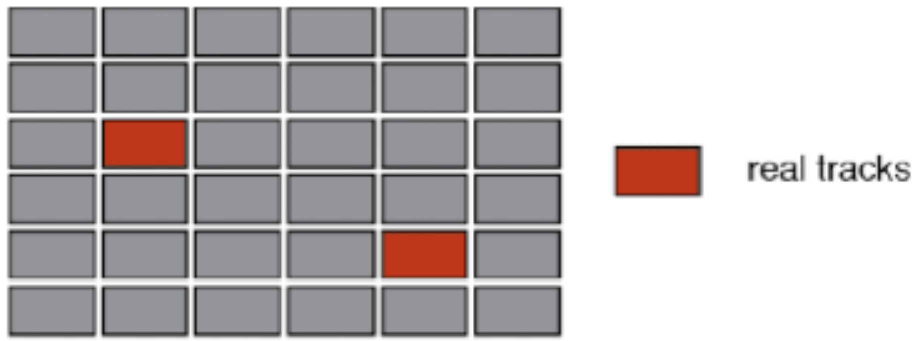
DSSD limitations

DSSD measure the 2 dimensional position of a particle track.
However, if more than one particle hits the strip detector the measured position is no longer unambiguous. “Ghost”-hits appear!

True hits and ghost hits in a double sided strip detector in case of two particles traversing the detector:

Pixel detectors produce unambiguous hits!

Measured hits in a pixel detector in case of two particles traversing the detector:



Hybrid Pixel Detectors

HPD: Typical size is (50-400) µm x 50 µm

If signal pulse height is not recorded, resolution is the digital resolution: $\sigma = p/\sqrt{12}$

e.g. σ = 14 µm for p = 50 µm

Reminder: better resolution is achieved with analogue readout

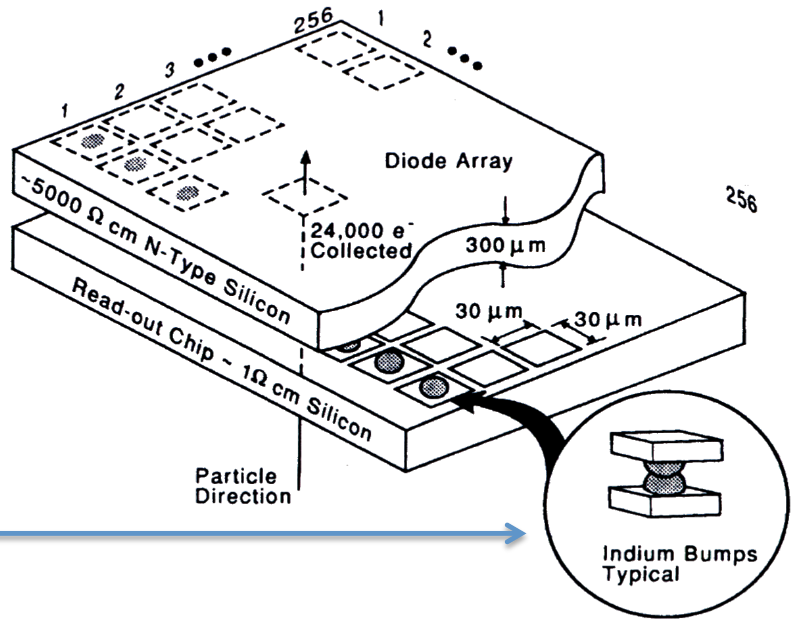
Small pixel area ➔ low detector capacitance (~ few fF/pixel) ➔ large SNR (>> 10)
Small pixel volume ➔ low leakage current (~ few pA/pixel)

Drawbacks of HPD: large number of readout channels

DSSD ~ 2n

HPD ~ n^2

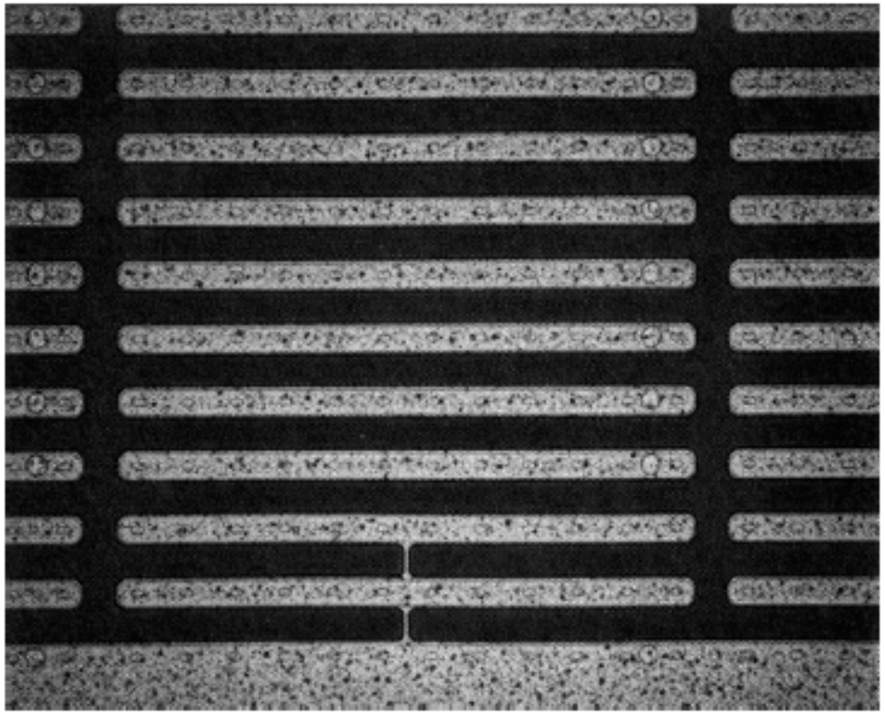
Large number of electrical connections in case of HPD
Large power consumptions of electronics

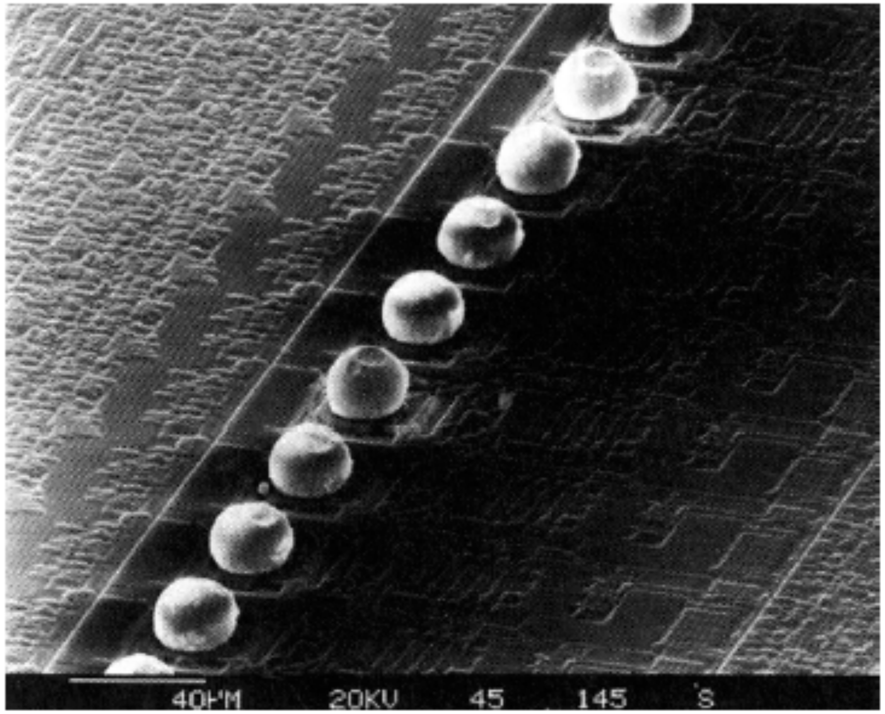


S.L. Shapiro et al., Si PIN Diode Array Hybrids for Charged Particle Detection, Nucl. Instr. Meth. A 275, 580 (1989)

HPD – bump bonding process

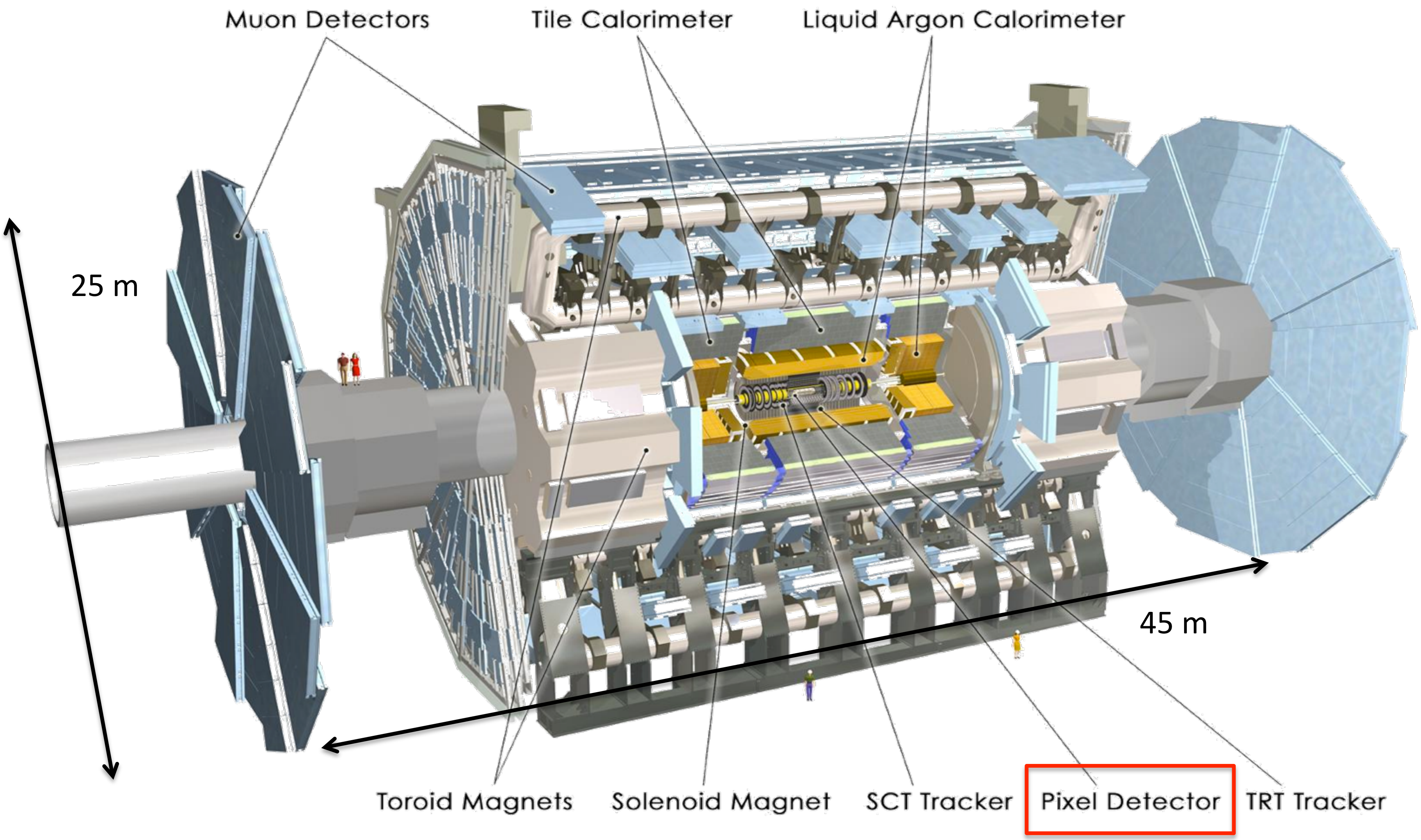
Electron microscope picture of pixel detector with long strip.
Left: Detector chip, right: readout chip with bump bonds applied.





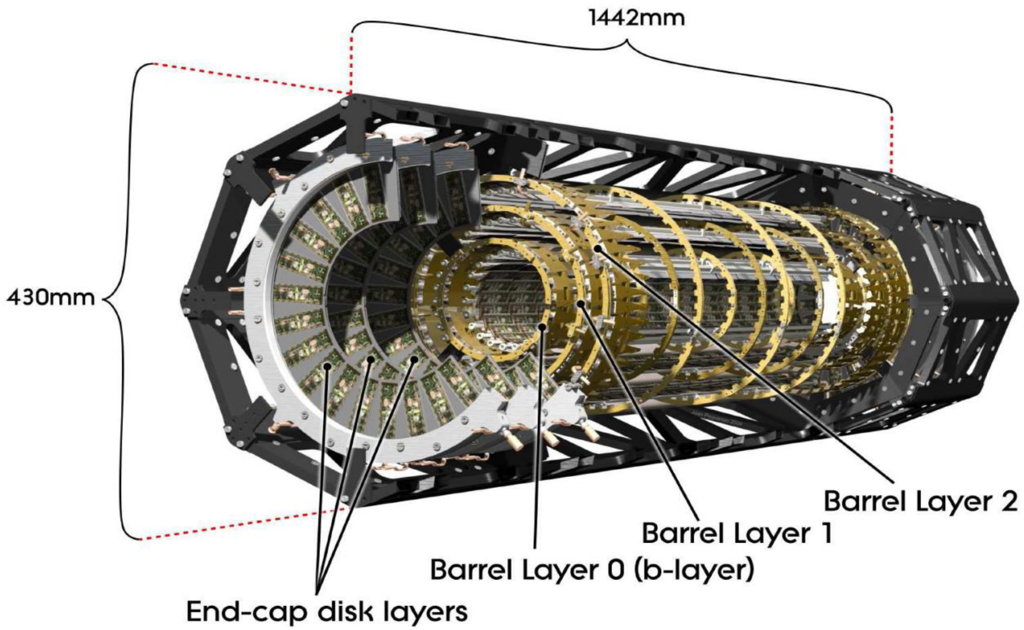
G. Lutz, *Semiconductor Radiation Detectors*, Springer-Verlag, 1999

Atlas Detector



Atlas Pixel System

M. Keil, TIPP 2011



- 3 hit-system for $|\eta| < 2.5$
  - •3 barrel layers
  - •2 x 3 endcap discs
- 1744 modules,
  80M readout channels
- Innermost barrel layer at 5 cm
- Radiation tolerance
  500 kGy / 10^{15} 1MeV n_{eq} cm^{-2}

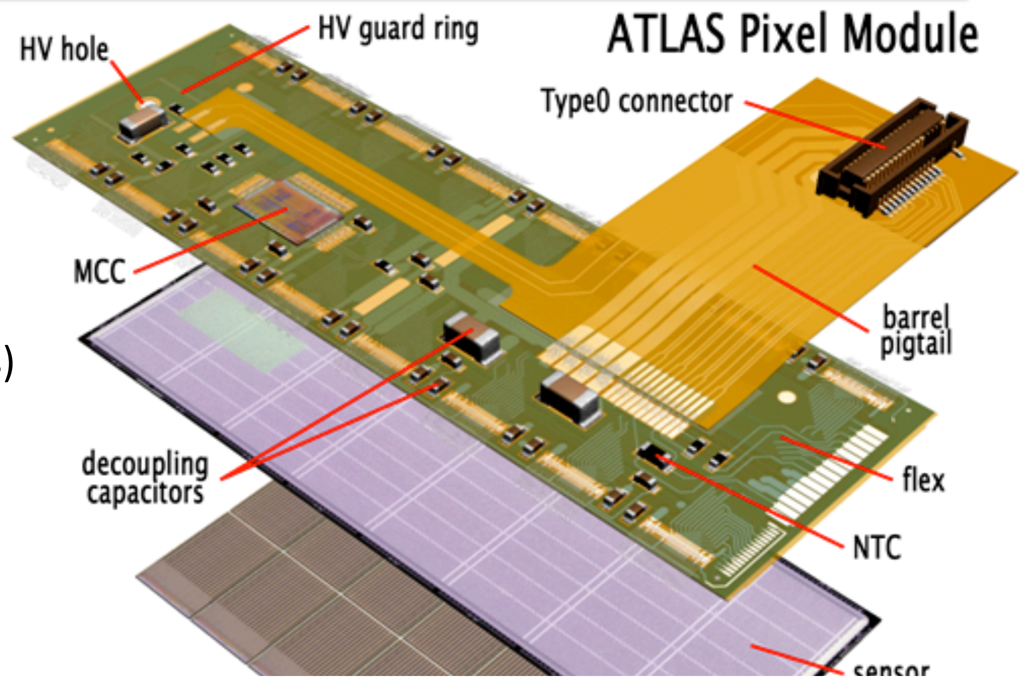
Requirements

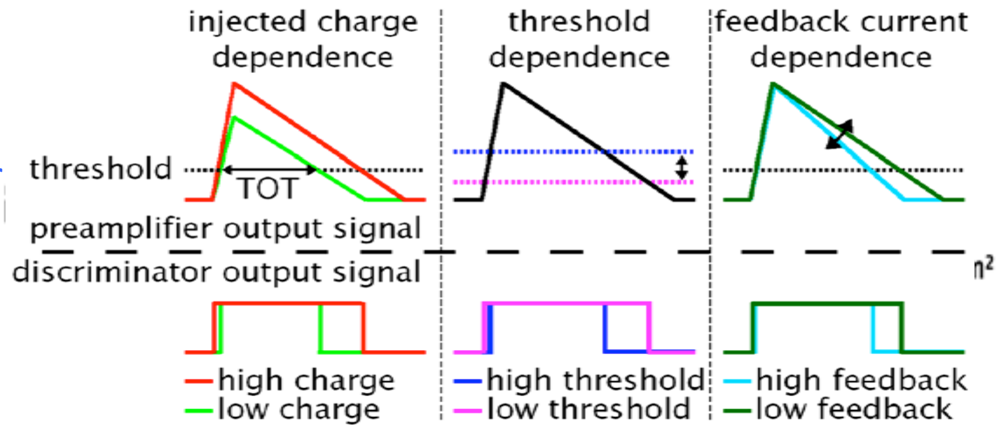
High space point resolution: 12 (90) μm in RΦ (z)
Pattern recognition: cope with ~ 25 interactions/crossing, tag heavy quarks at HLT
High hit-track efficiency

Atlas Pixel Module

M. Keil, TIPP 2011

- Sensor:
  - •250 µm thick n-on-n sensor
  - •47232 (328 x 144) pixels
  - •Typical pixel size 50 x 400 µm^2
    (50 x 600 µm^2 pixels in gaps between FE chips)
  - •Bias voltage 150 – 600 V
- Readout:
  - •16 FE chips, 2880 pixels each
  - •Zero suppression in the FE chip, MCC builds module event
  - •Pulse height measured by means of Time over Threshold

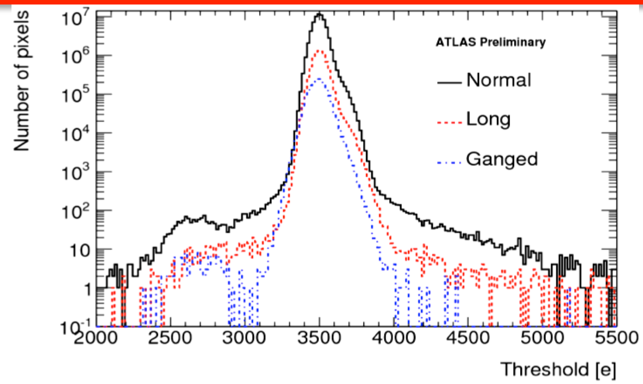




Atlas Pixels: Threshold and Noise

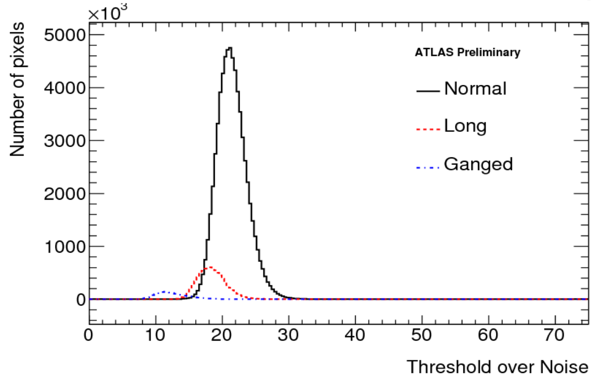
M. Keil, TIPP 2011

Typical threshold dispersion: σ ~ 40 e



Noise in normal pixels ~ 170 e

Figure of merit: Threshold-Over-Noise ~ 20



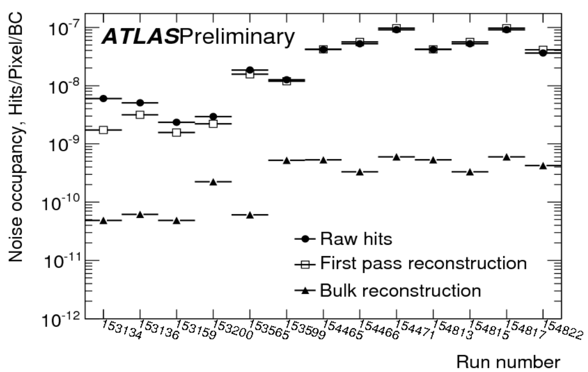
Pixels with hit rate higher than 10^{-5} are masked (0.1% @ 3500e)

After offline masking noise rate ~ 10^{-9}

➔less than 0.1 hit / event for 80M channels

(< 1 hit/event without offline masking)

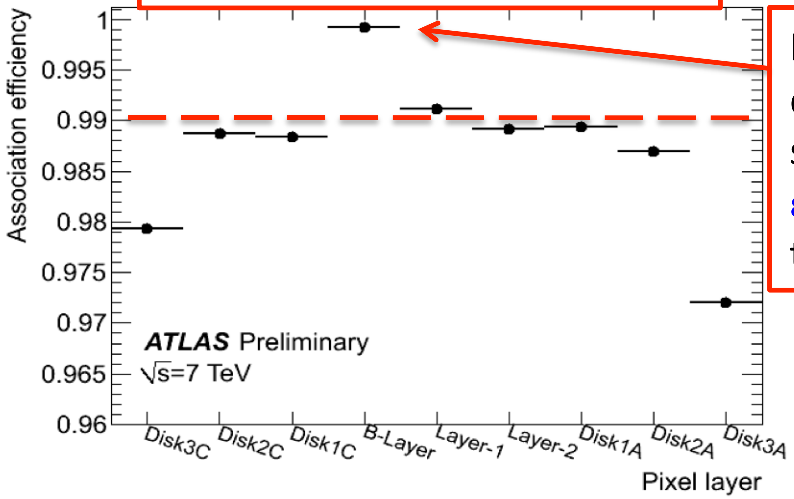
A very "quiet" detector"!



Atlas Pixels (Offline) Performance

M. Keil, TIPP 2011

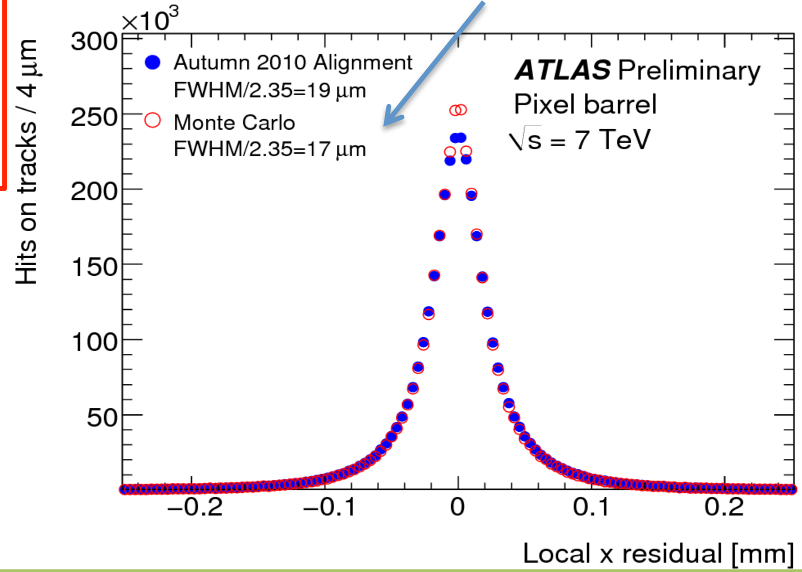
Hit-to-track association ε

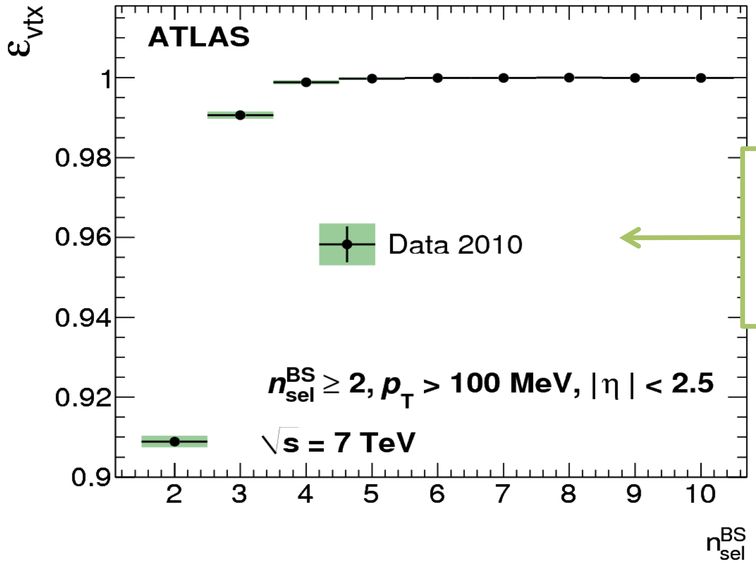


B-layer full efficient due to the track selection

ε ~ 99% for most of the modules

Width close to MC width for a perfectly aligned detector





Vertex reconstruction ε vs number of reconstructed tracks

For >= 4 tracks ε_{vtx} ~ 100%

Other Si Detector Structures

Silicon (PIN) diodes, Silicon Single and Double Sided Strip detectors and Hybrid Pixels detectors are mature technologies employed in almost every experiment in High Energy Physics

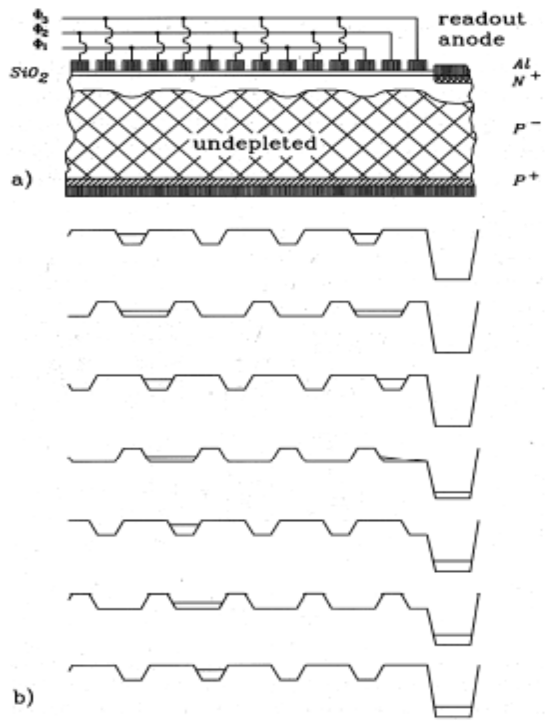
Let's now look at other interesting Silicon Detector Structures

- Charged Coupled Devices (CCD)
- Silicon Drift Detectors (SDD)
- Avalanche Photo Diode (APD)
- Silicon Photo Multipliers (SiPM – or Pixelized Photon Detector (PPD) or Multi-Pixel Photo Counters (MPPC))

MOS CCDs detectors

Invented in 1969, CCDs have been used for a long time as memories (storing and transfer of charge) and as optical sensors (image devices in video cameras)

Most important field of application as detectors: imaging in Astrophysics, from near infrared to X-rays.

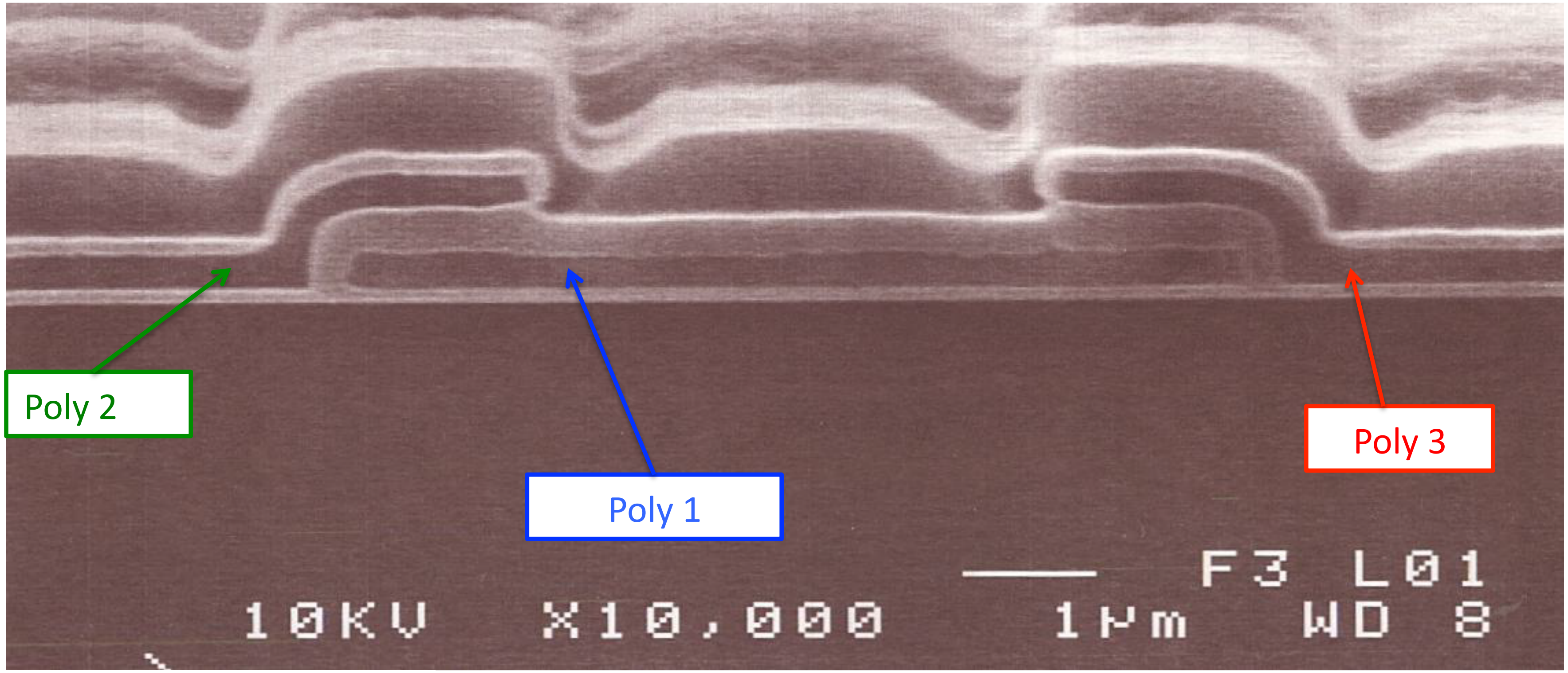


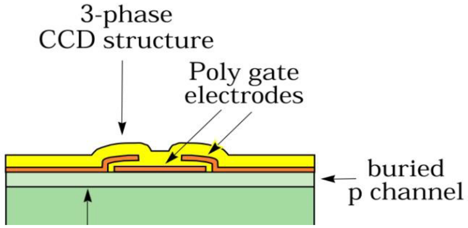
Conceptually: an array of MOS capacitors operated in overdepletion mode.
Electrons are created by ionization in the thin depleted region close to the silicon- oxide interface.
Charges are stored in the local energy minima at the Si-SiO_2 interface.
The charge can be moved towards the collecting electrode by periodically switching the voltages $\phi 1$, $\phi 2$ and $\phi 3$.

Slow device, hence not suitable for fast detectors
Problem: charge losses during transport are high because of the large density of trapping defects at the Si-SiO2 interface.

CCDs for astronomy and astrophysics today

Scientific CCDs typically use the same 3-phase clocking as in the original Boyle and Smith concept with overlapping polysilicon gate electrodes (triple poly)

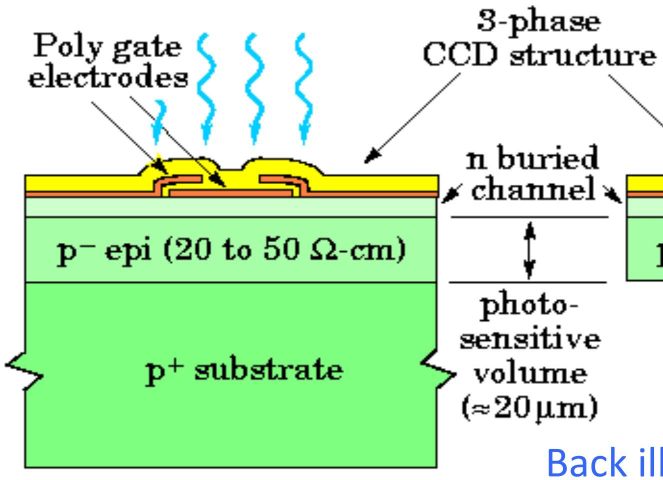




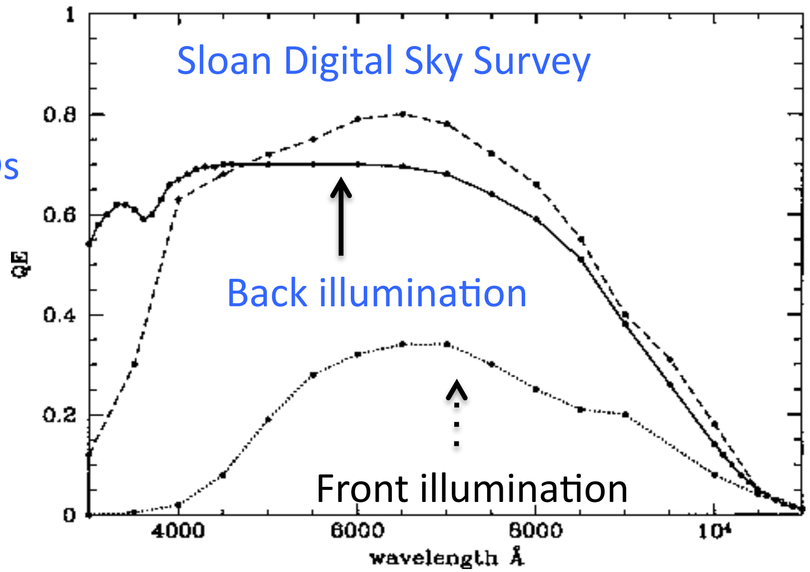
Scientific CCDs: front vs back illumination

Front illumination: Quantum efficiency loss from absorption in polysilicon gates
Reflections from complicated thin film stack

To overcome the problem of charge losses, the “buried channel” CCD (BCCD) has been developed.
An n-doping region shifts the electrons energy minimum from to the surface into the bulk



Back illumination of thinned CCDs
Remove p^+ substrate



http://www.astro.princeton.edu/PBOOK/camera/camera.htm

Scientific CCDs for Astronomy

Scientific charge-coupled devices are the detector of choice for astronomy

Wavelength range: λ ~ 350 nm to 1100 nm (from atmospheric cutoff to Silicon bandagap) ➔UV, visible and near-infrared wavelengths

Back illuminated: for high QE ➔ up to 90% at peak

Slow readout for low noise: less than 5 e- at 100 kpixels/s readout

Cryogenically cooled for low dark current: for -100 °C < t < -140 °C few e-/pixel/hour

Quite expensive (10MPixel ~ 100k€)

In the following some examples of astronomy cameras

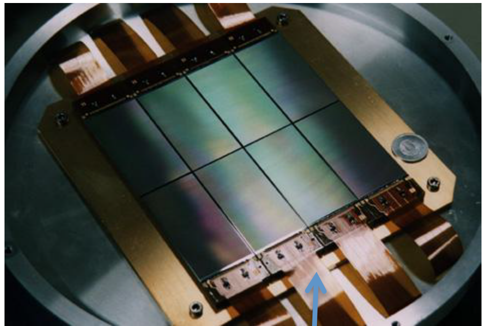
CCD cameras for astronomy

SDSS Photometric Camera –
30 2k x 2k, (24 μm)^2-pixel
Sloan Digital Sky Survey Telescope
2000 – 2008

120 MPixels

CCD: Thinned (10-20μm) partially depleted

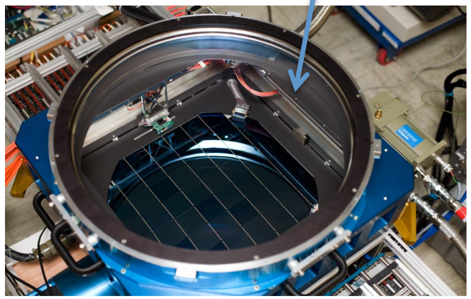
64 MPixels



SuprimeCam – 8 2k x 4k, (15 μm)^2-pixel CCDs
Subaru 8-m Telescope
(1998)

CCD: 40 μm thick, partially depleted

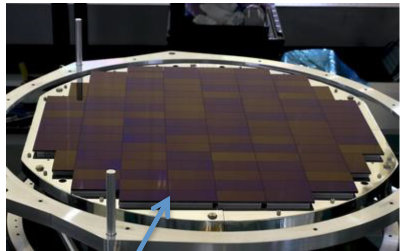
PS1 camera
60 4.8k x 4.8k, (10 μm)^2-pixel
Pan-STARRS telescope (2010)



1.4 GPixels

CCD: 75 μm thick, fully depleted

870 MPixels

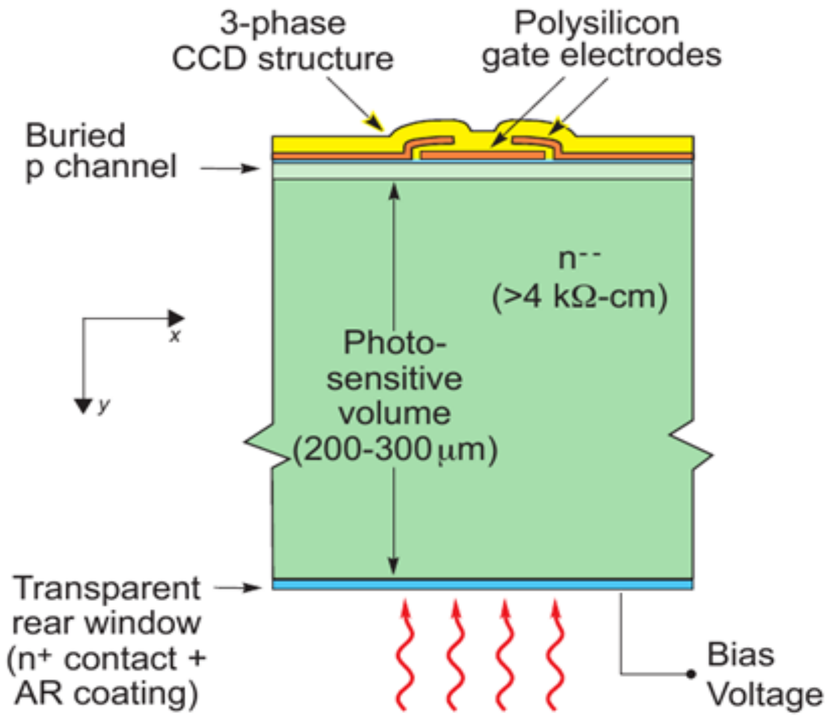


HyperSuprimeCam
116 2k x 4k, (15 μm)^2-pixel
Subaru 8-m Telescope
1st light achieved
28Aug2012

CCD: 200 μm thick, fully depleted

Trend: thick, full depleted CCDs

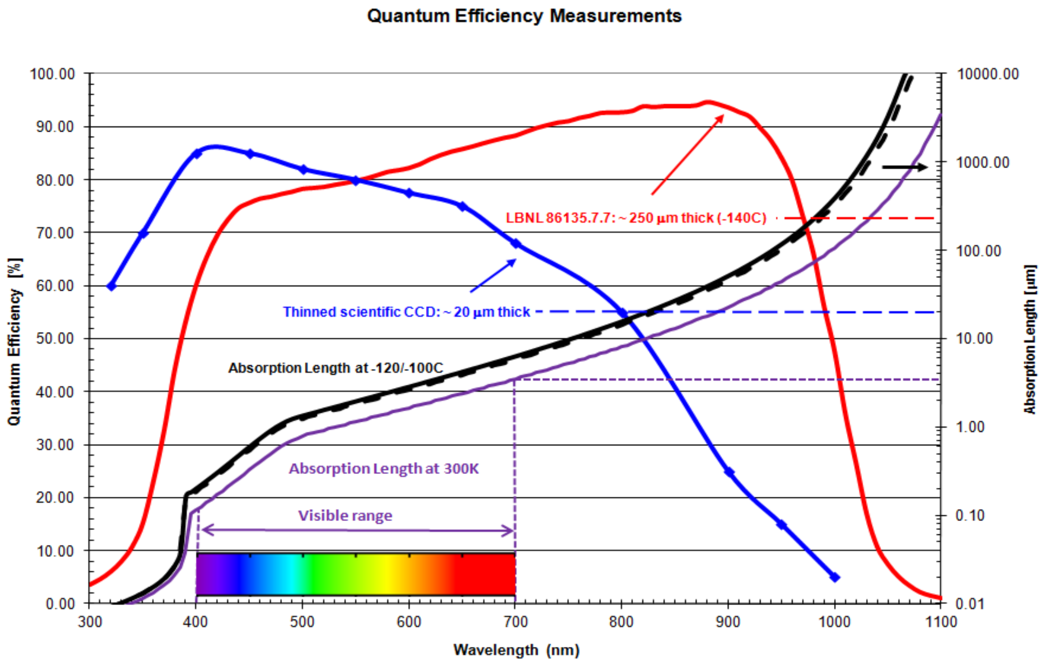
Thick, fully depleted CCDs



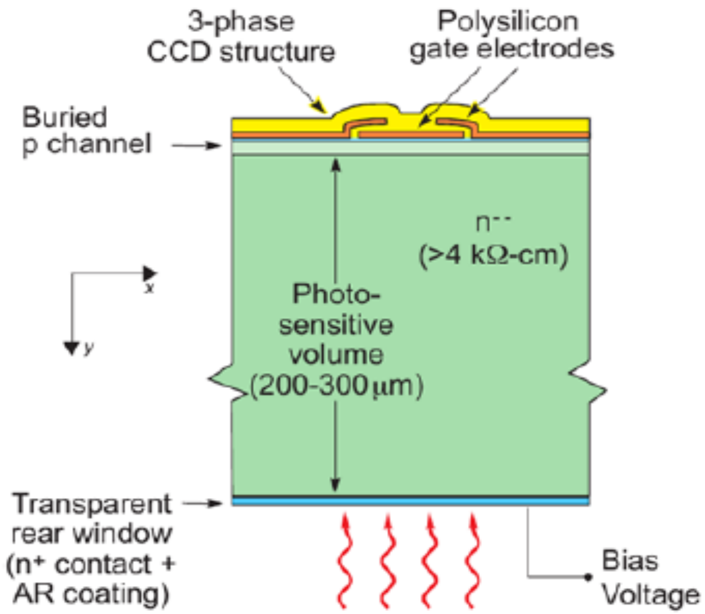
Fully Depleted, Back-Illuminated Charge-Coupled Devices Fabricated on High-Resistivity Silicon
Stephen E. Holland et al., IEEE TRANSACTIONS ON ELECTRON DEVICESVOL. 50, NO. 1 (2003) 225

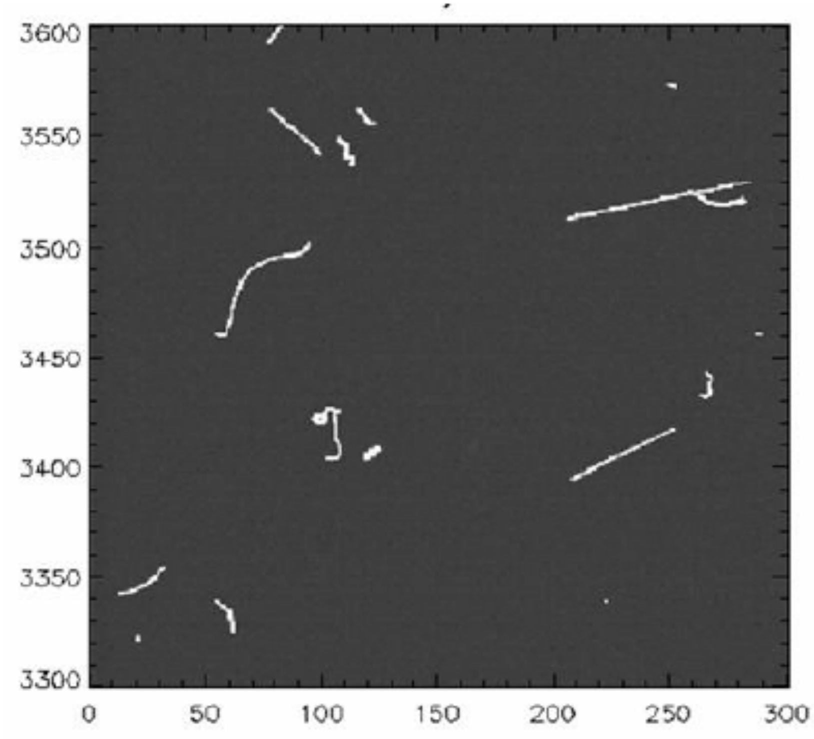
Merging of p-i-n and CCD technology:
A conventional CCD on a thick, high-resistivity Si substrate (> 4 kΩ-cm), fully depleted

The large thickness results in high near-infrared QE
The fully depleted operation results in the ability to control the spatial resolution



Drawbacks of thick, fully depleted CCDs





Cosmic rays and Compton electrons from background radiation leave long tracks

30 minute dark
200 μm thick CCD
Small sub-image

CCDs in your mobile

UNIVERSITY OF WISCONSIN–MADISON
NEWS

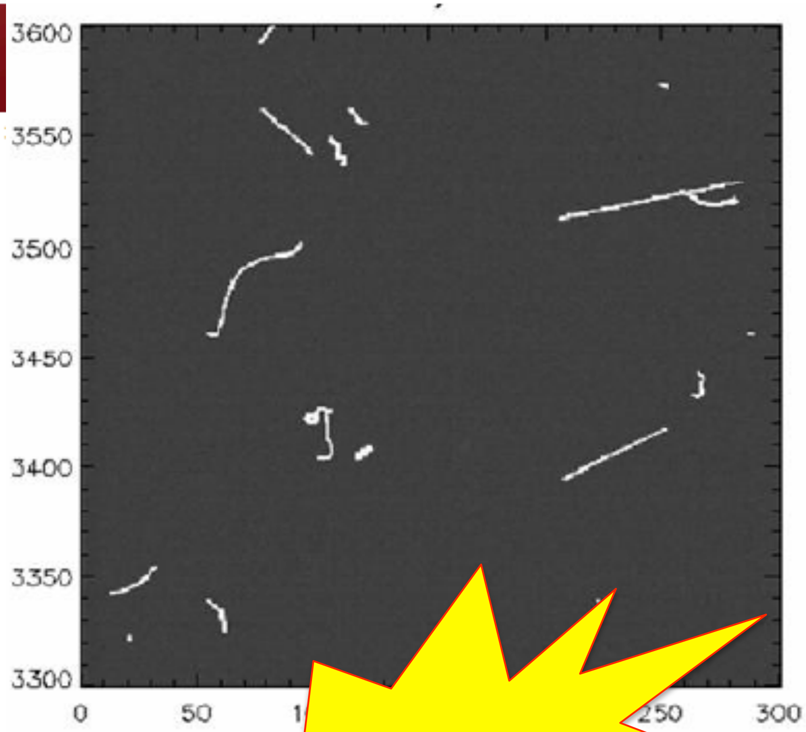
UW-Madison

http://www.news.wisc.edu/23166

Physicist turns smartphones into pocket cosmic ray detectors

Oct. 1, 2014 | by Terry Devitt

Email 30 Tweet 1348 Share 2757



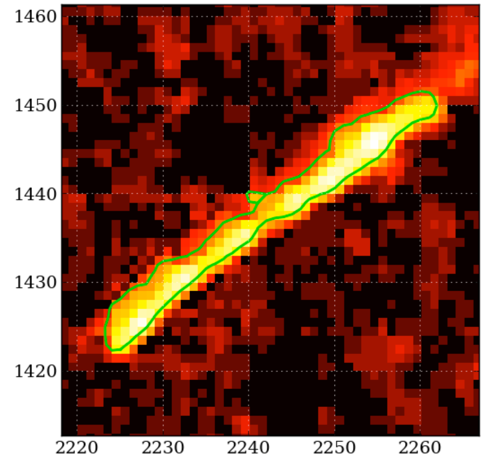
Try this at home!

CCDs in your mobile

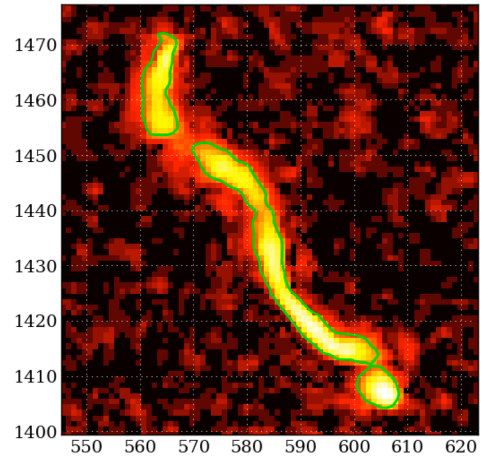
DECO

Distributed Electronic Cosmic-ray Observatory

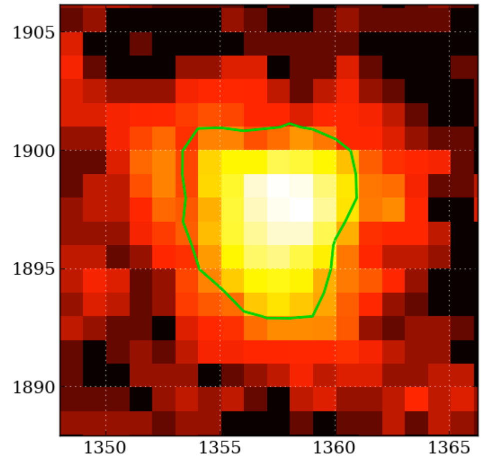
http://wipac.wisc.edu/deco



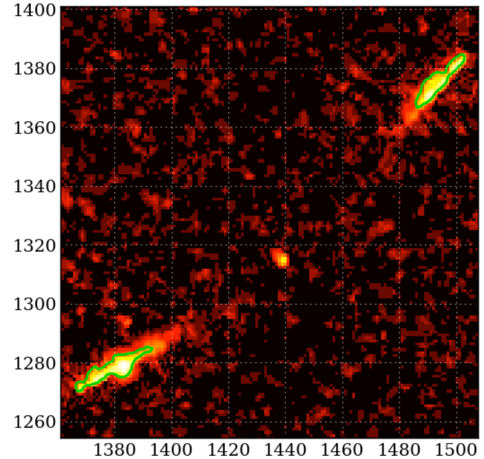
muon



e- from a radioactive decay



e-/gamma



???

LSST: Large Synoptic Survey Telescope

The Large Synoptic Survey Telescope (LSST) is a planned wide-field "survey” telescope

It will photograph the entire available sky every few nights

The telescope will be located in northern Chile

Science first light in 2021

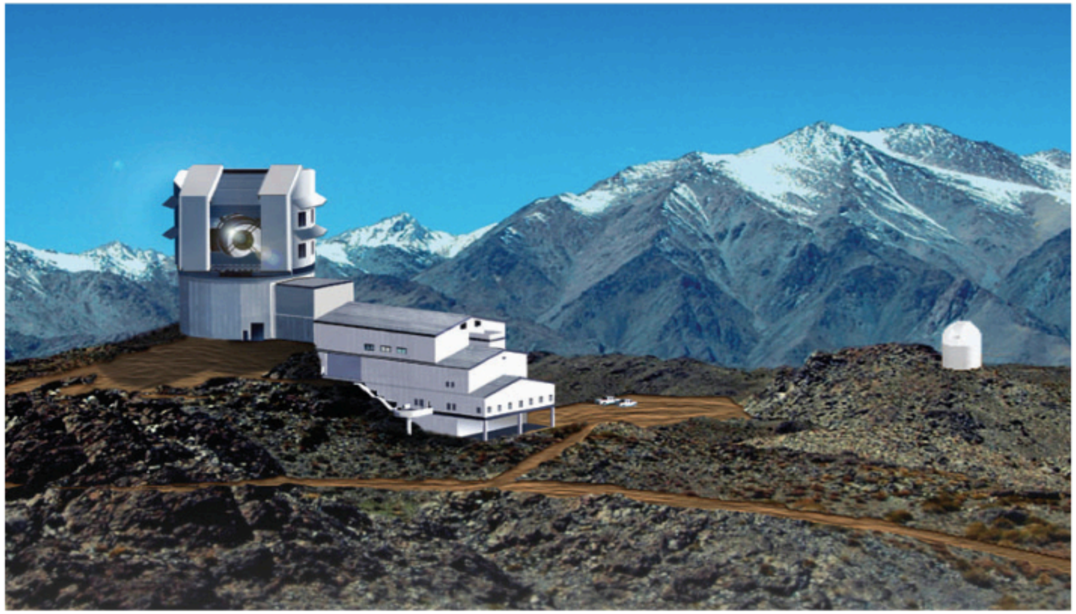
Some of the LSST Physics Goals

Measure gravitational lensing for DE/DM detection

Map small objects in Solar System

(Super)Novæ detection

Milky Way mapping



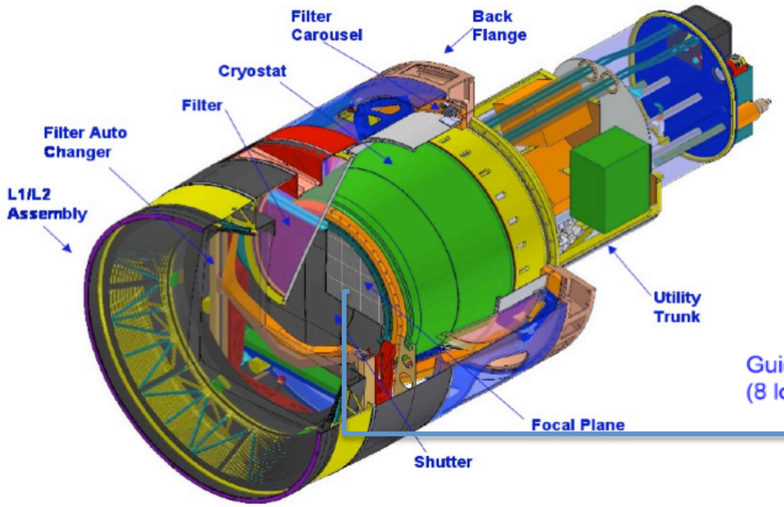
LSST Science Book
http://arxiv.org/pdf/0912.0201v1.pdf

LSST camera and CCDs

CCD sensors: deep depletion, back-illuminated devices

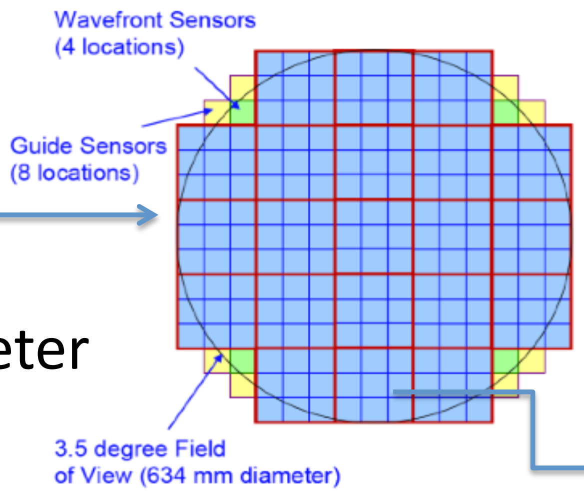
16 channels, r.o. in 2 seconds

t = -100 °C



Focal plane: 0.64 m in diameter

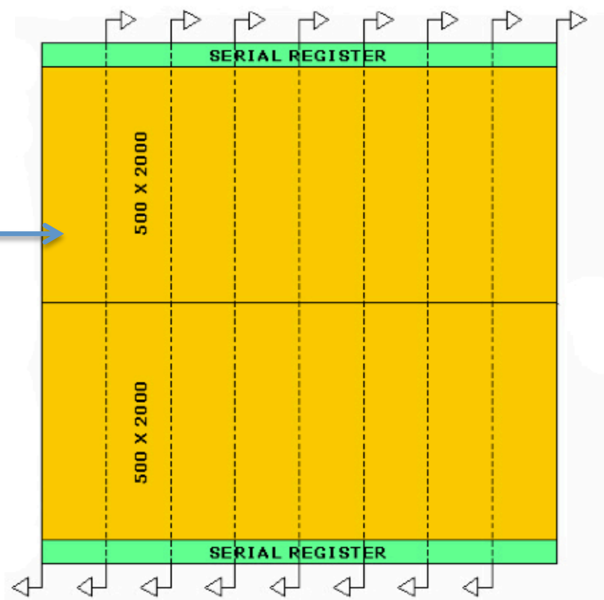
9.6 deg^2 filed-of-view



3.2 Gpixels comprised of

189 4k x 4k 10µm pixels

➔ plate scale of 0.2”/pixel

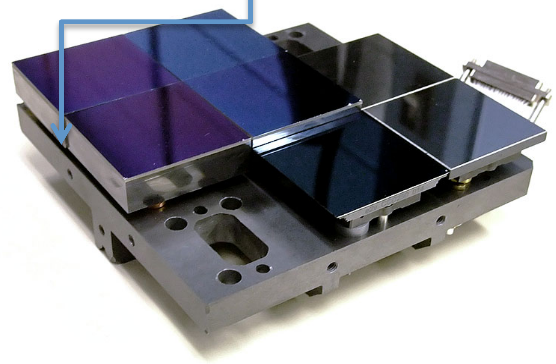


LSST sensor specifications

High quantum effciency from 320 to 1080 nm thanks to a large depletion depth (100 µm) and implementation of the sensor in a back-illuminated configuration

To reduce charge diffusion the sensor is fully depleted, and a high internal field is maintained within the depletion region. This is made possible by the use of high resistivity substrates and high applied voltages.

High Fill factor. A total of 189 4 K x 4 K sensors are required to cover the 3200 cm^2 focal plane. To maintain high throughput, the sensors are mounted in four-side buttable packages and are positioned in close proximity to one another with gaps of less than a few hundred µm. The resulting fill factor, *i.e.*, the fraction of the focal plane covered by pixels, is 93%.

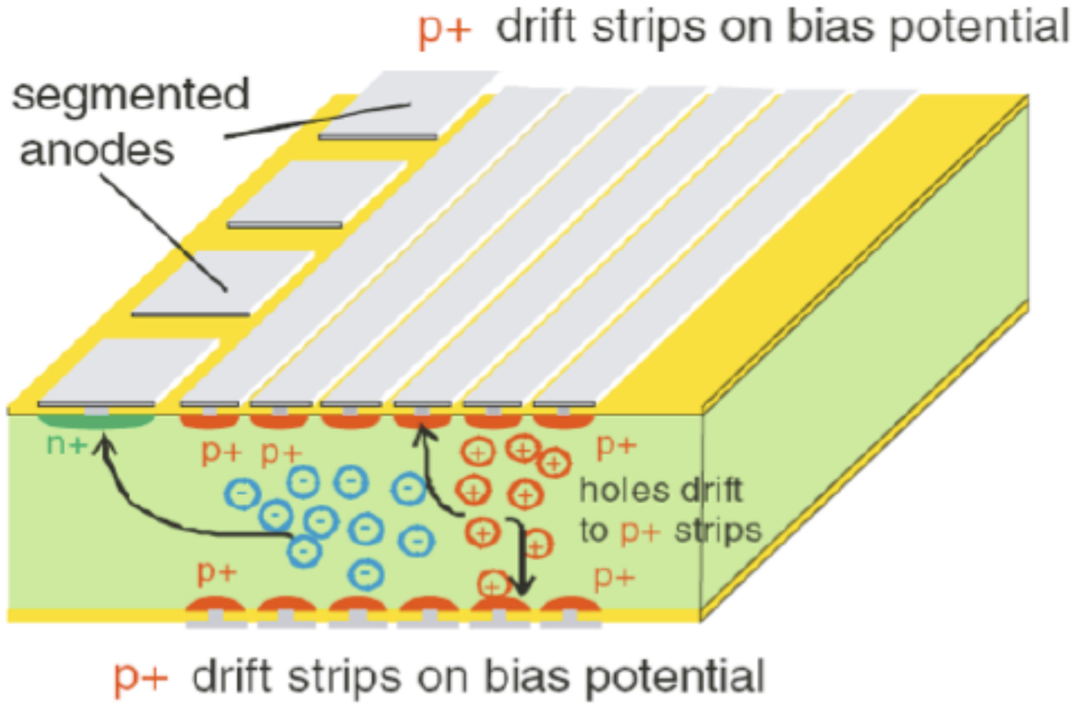


Prototype sensors mounted on a raft baseplate - http://www.lsst.org/News/enews/focal-plane-201101.html

Silicon Drift photon Detector (SDD)

In silicon drift detectors p^+ strips and the backplane p^+ implantation are used to fully deplete the bulk. A drift field transports the generated electrodes to the readout electrodes (n^+). One coordinate is measured by signals on strips, the second by the drift time.

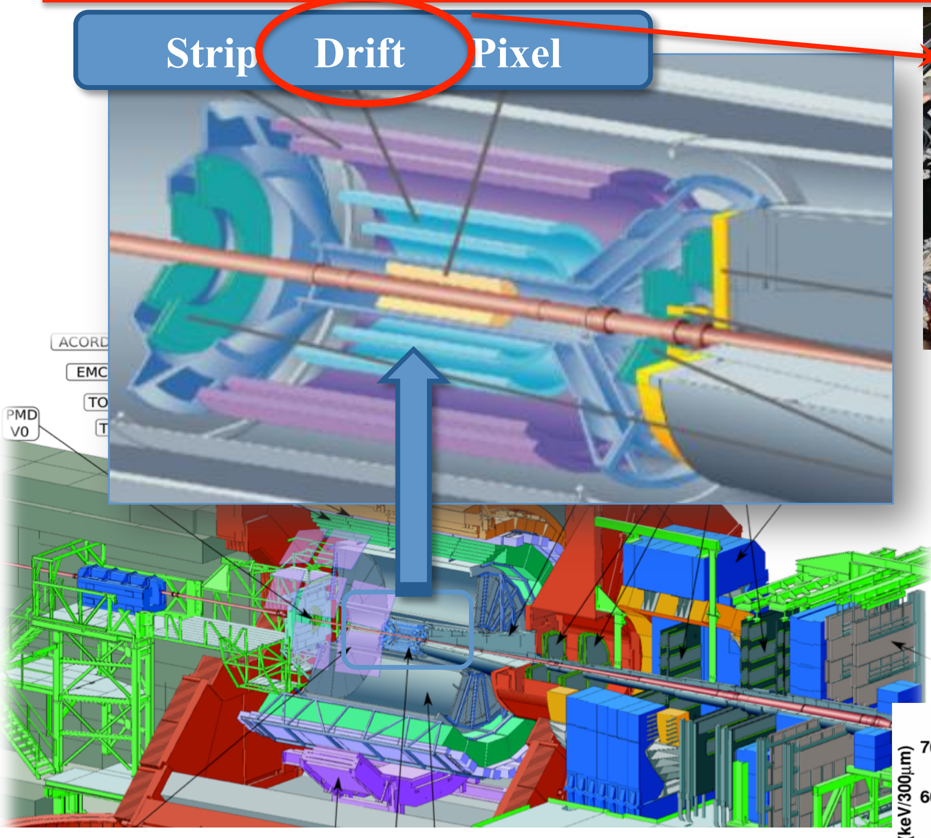
Evolution of Silicon Sensor Technology in Particle Physics, F. Hartmann, Springer Volume 231, 2009

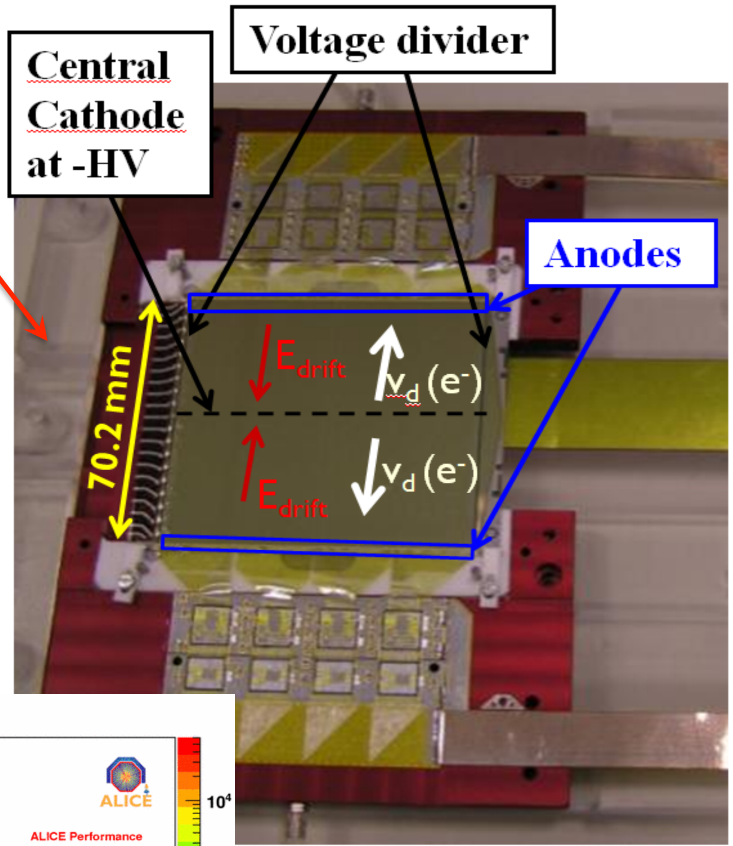


Used for example in the experiment ALICE (CERN)

The Alice Silicon Drift Detectors (SDD)

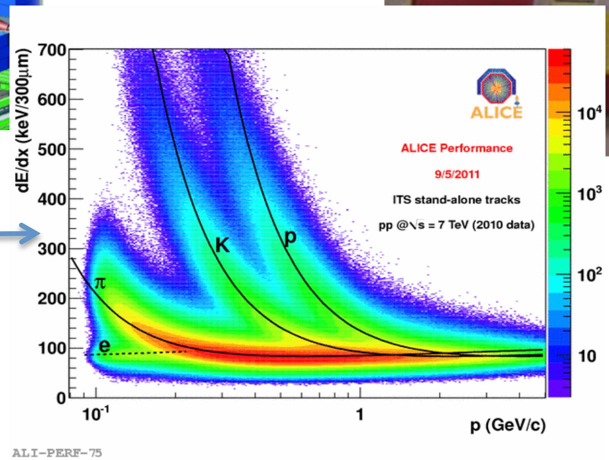
G. Contin PSD9





The PID performance:

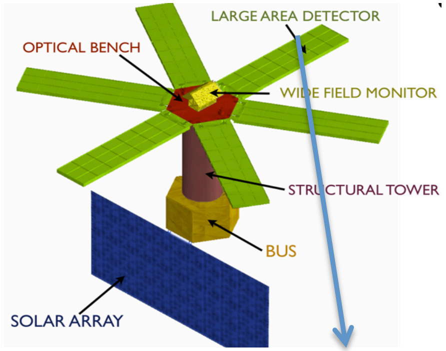
- dE/dx in SDD
- p-K separation up to 1 GeV/c
- K-π separation up to 450 MeV/c
- A resolution of about 10-15% is achieved

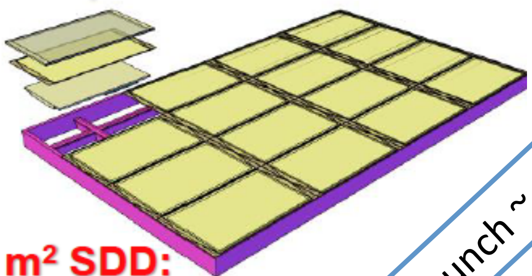


SDD: from X-rays to HEP and back

- Invented by Gatti and Rehak (1984) for X-ray spectroscopy
- Used for Tracking/PID in High Energy Physics
- Back to X-ray measurements: the LOFT experiment

Feroci et al., 2012



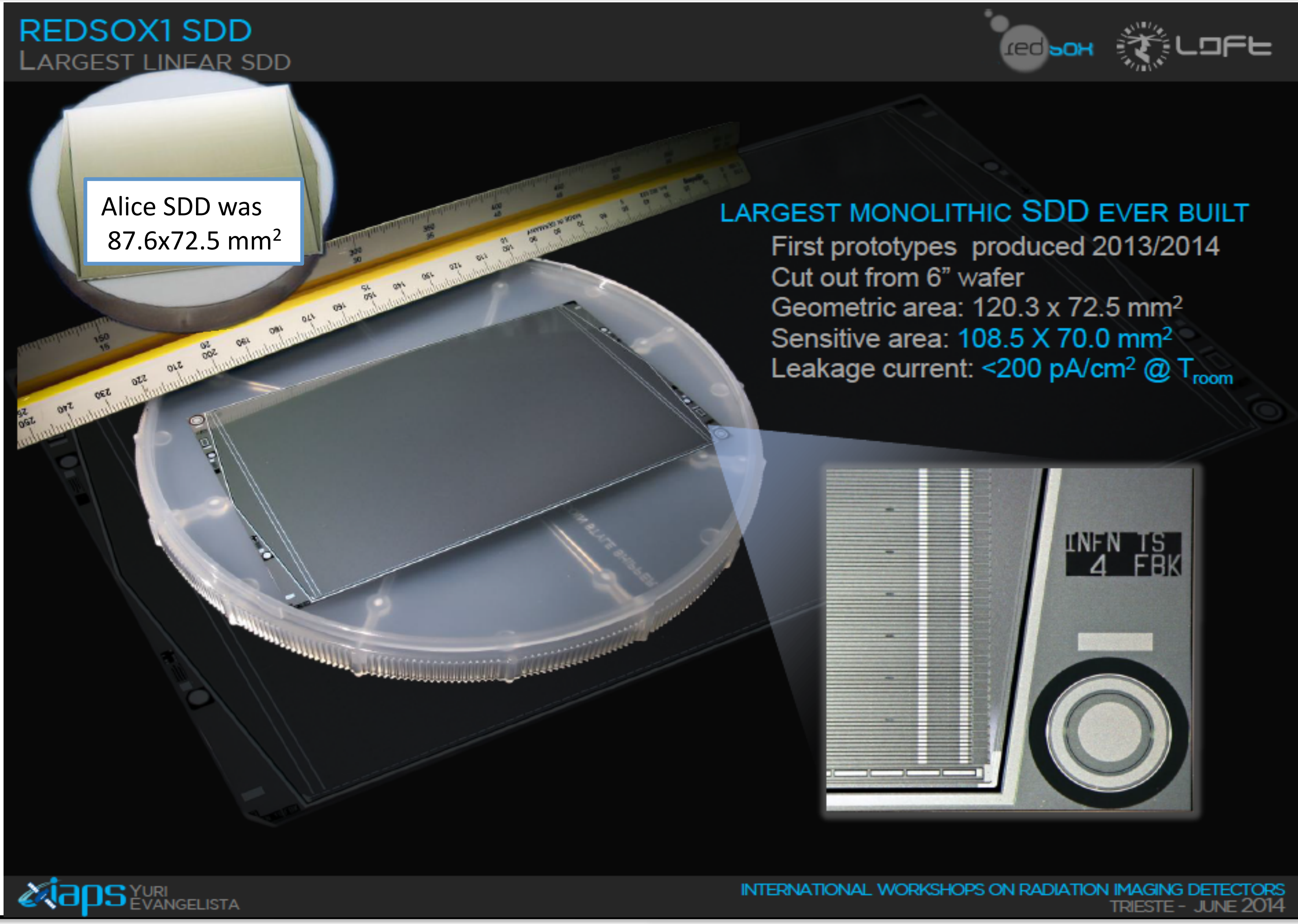


Launch ~ 2026 (?)

LAD with 15 m² SDD:
- **Heritage: ALICE at LHC**
- **Few channels/surface**
- **3D readout, HV along sensor**
- **Low input C, low noise**
- **Collimator MCP**

•The Large Observatory For x-ray Timing (LOFT) will investigate "matter under extreme conditions"
•Black Holes, Neutron Stars, etc. Through X-ray transients
•LAD: $15 m^2$ ~ 1.5 times larger than predecessor
➢Need for a light detector
➢Heritage: Alice SDD!
•~ 1 kg/m^2 (before up to 100)
➢More physics with less mass!

The largest linear SDD



LOFT SDD: specifications and performance

SUBSTRATE OPTIMIZATION FOR X-RAY DETECTION

- MATERIAL: NTD → FZ
- GEOMETRICA AREA (filling factor): 5” → 6” wafer <100>
- RESISTIVITY: 4 kΩ cm→ 9 kΩ cm
- THICKNESS (QE): 300 μm → 450 μm

2-50 keV energy range with spectral resolution below 260 eV @6 keV

Enhanced quantum efficiency at the low end of the energy range (thicker)

Possibility of X-ray spectroscopy timing on a ten microseconds scale.

The sensitive-to-total-area ratio is 87 %

Yuri Evangelista, Silvia Zane, Iworid2014

SDDs: pros and caveats

PROS

Non ambiguous 2D position information

Low number of channels with respect to DSSDs and especially pixels;

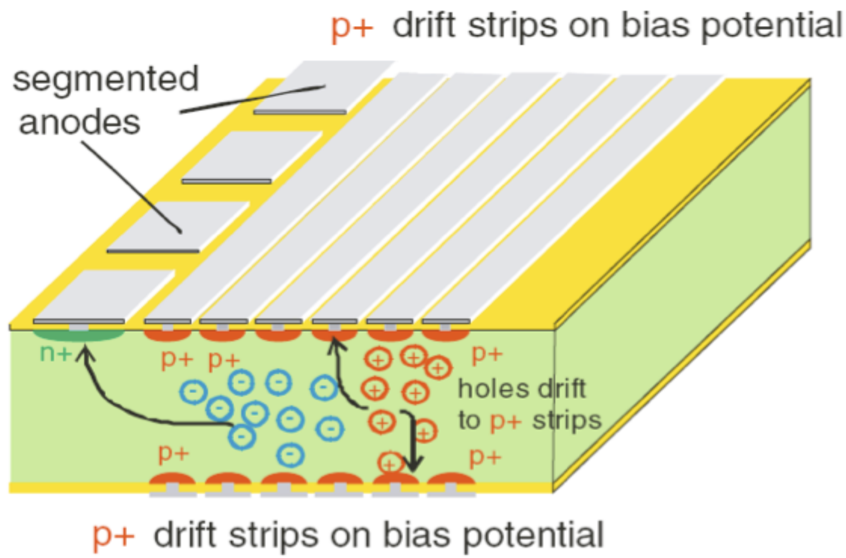
Excellent for spectroscopic applications (mono anode devices with radial drift)

CAVEATS

Strong dependence of mobility on temperature ➔ calibration needed!

Typical drift speeds ≈ 1 – 10 μm/ns (depending on the applied field)

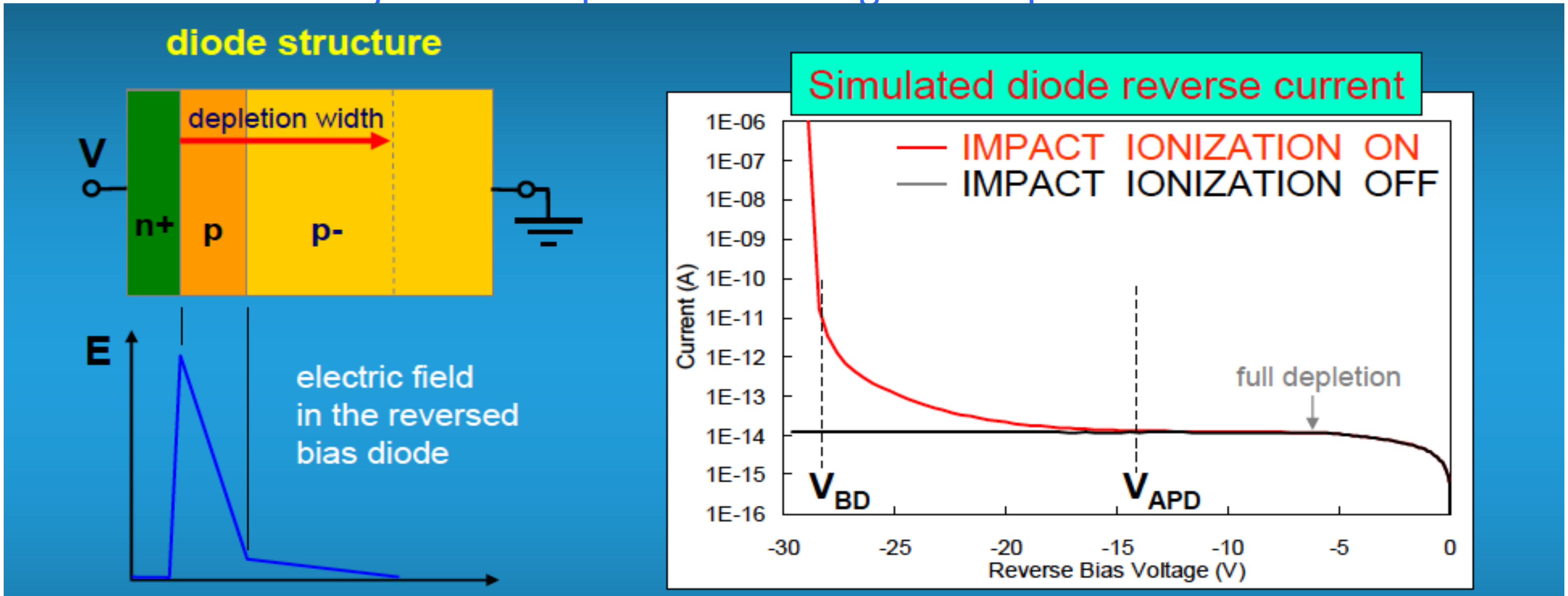
➔ it is a slow device.



Evolution of Silicon Sensor Technology in Particle Physics,
F. Hartmann, Springer Volume 231, 2009

Avalanche Photo Diodes (APDs)

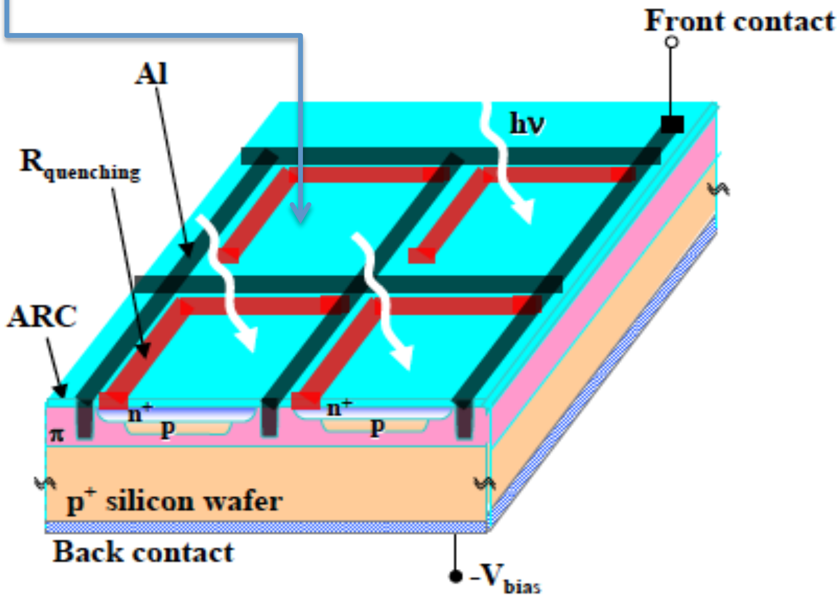
The avalanche photodiode (APD): p-n device with internal gain due to the high internal field at the junction of positive and negative doped silicon

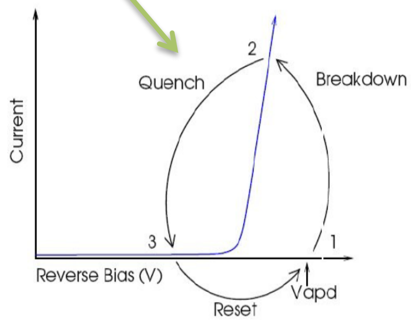


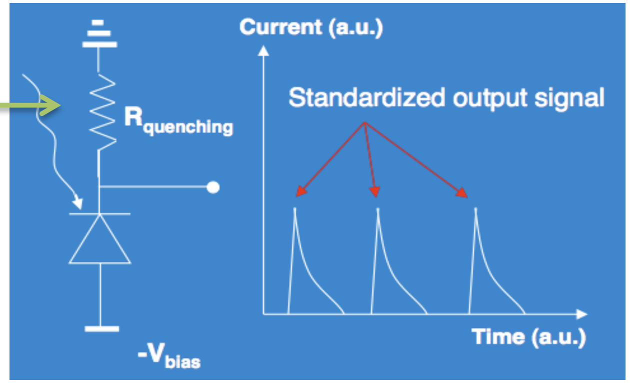
$V < V_{APD}$	⇒ photodiode	1	collected pair/generated pair
$V_{APD} < V < V_{BD}$	⇒ APD	<M>	collected pairs/generated pair
$V > V_{BD}$	⇒ Geiger-mode APD	∞	collected pairs/generated pair

Silicon Photo Multiplier (SiPM)

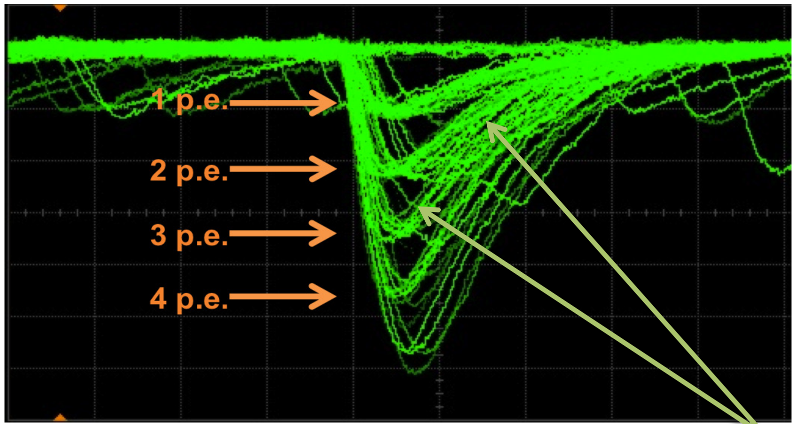
A Silicon Photo Multiplier is a matrix of n pixels connected in parallel (e.g. few hundreds /mm^2) on a common Si substrate
Each pixels is a GM-APD in series with R_{quench}







V.M. Golovin and A. Sadygov
(Russian patents 1996-2002)



A single GM-APD gives no information about light intensity ➔ in a SiPM the output charge is proportional to the number of triggered cells, that is (for PDE = 1) the number of photons

SiPM features

The characteristics of a SiPM are:

- possibility to detect single photons and give a signal proportional to the number of photons for low fluxes;
- extremely fast response (determined by avalanche spreading): in the order of few hundreds of ps.

Other features are:

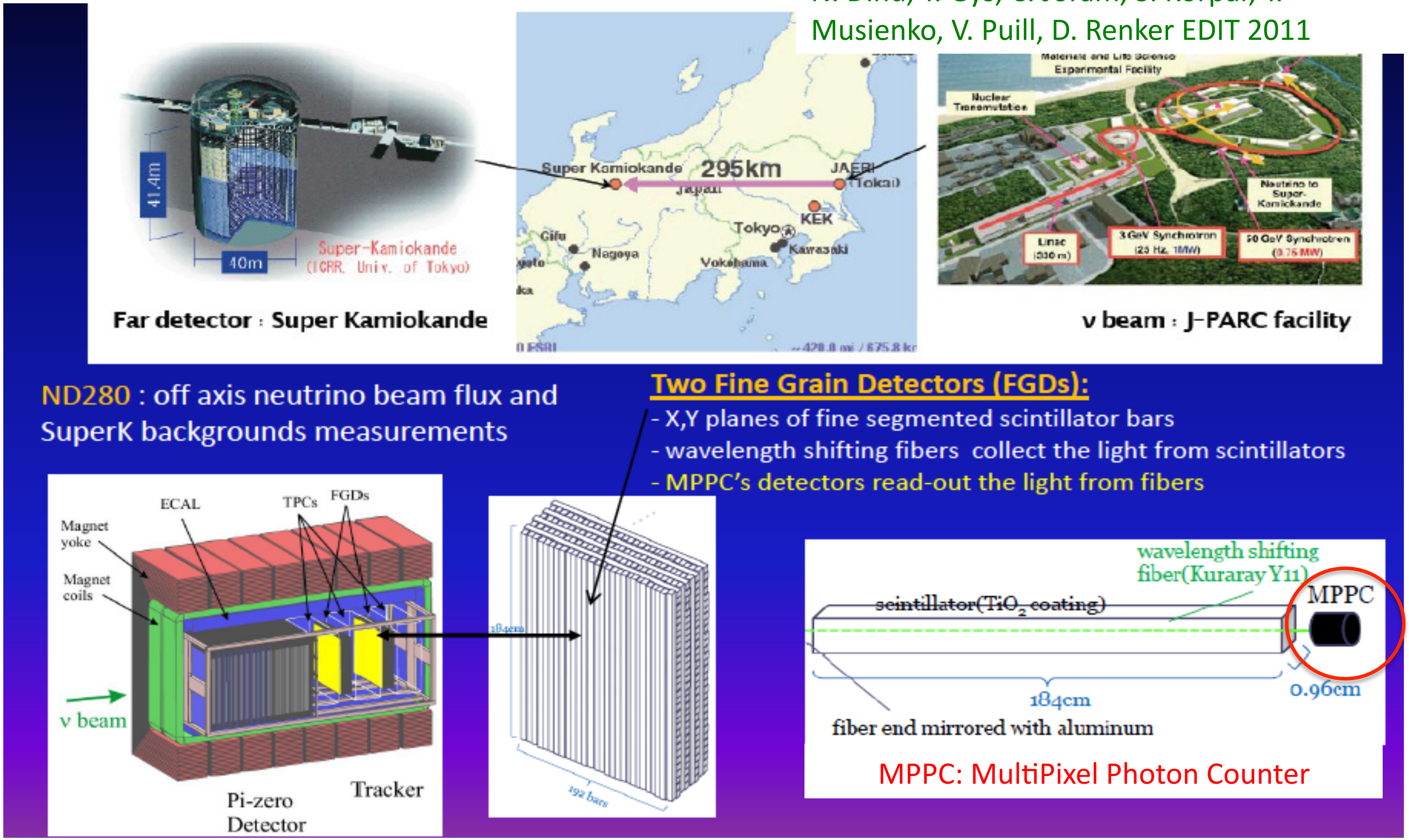
- Low bias voltage (20-60V)
- Low power consumption
- Insensitive to magnetic fields
- Compact and rugged

Possible applications are: scintillator read-out, PET, photon correlation studies, calorimetry…)

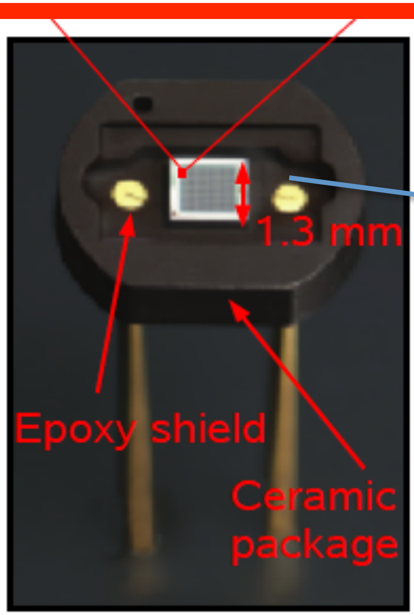
Example: T2K ND280 ECAL

T2K: Measure ν_μ disappearance and ν_e appearance

N. Dinu, T. Gys, C. Joram, S. Korpar, Y. Musienko, V. Puill, D. Renker EDIT 2011



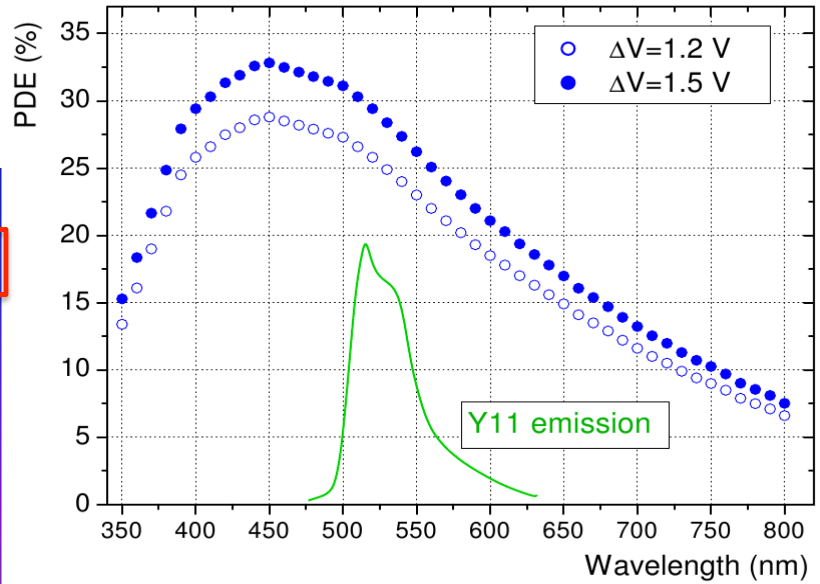
The T2K ND280 MultiPixel Photon Counter



R. Sacco, TIPP2011

Number of pixels	667
Active area	1.3 × 1.3 mm²
Pixel size	50 × 50 μm²
Operational voltage	68 – 71 V
Gain	~ 10^6

M. Haigh 2010



Total number of SiPMs in T2K = 56000
First large experiment to use this type of sensor.

System	Channels	Bad channels	Fraction
ECAL (DSECAL)	22336 (3400)	35 (11)	0.16% (0.32%)
SMRD	4016	7	0.17%
P0D	10400	7	0.07%
FGD	8448	20	0.24 %
INGRID	10796	18	0.17 %
Total	**55996**	**87**	**0.16 %**