A (Brief) History of Silicon Detectors for Particle Physics

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Prof. Dr. Erika Garutti
Universität Hamburg
MPG HLL Semiconductor Symposium, 8 Oct. 2024

A (Brief) History of Silicon Detectors for Particle Physics

or Excellent Detectors for Excellent Science

Outline:

- Pre-history: 1940 - 1980
- Evolution: 1980 - 2000
- Modern times: 2000 - Today
- Future

In this talk:

- I look back on some of the beautiful silicon detectors developed for astro particle- and particle physics, and reflect on the impact MPI-Physik and HLL had and still have on the field.
- These detectors have shaped and are shaping particle and astro-particle physics and also found numerous applications in other science fields and commercial products.
- I finally look into the future of the field with some considerations on the impact expected by the next generation of silicon detectors

Erika.Garutti @ uni-hamburg.de

Some Starting Remarks

and thank you words

All the HEP experiments always target for the **newest possible technology**.

Silicon areas need to be large, sensors and electronics must be radiation resistant, space requirements are tight.

Only specialized companies produce sensors in close collaboration with the HEP community.

The technology is similar but also sufficiently different to standard ASIC production,
light structures are preferred to robust ones.

High electrical fields need better material purity, well-defined doping profiles, voltage robust designs.

The HEP community encountered many problems along the way and succeeded in advancing many technological challenges. **Looking at the past always teaches useful lessons for the future.**

Many thanks to the inspiring books of Gerhard Lutz, Frank Hartmann, Norbert Wermes, and others; and to the many supporting discussions and material from Robert Klanner

The Very Early Days of Solid State Detectors

The pre-history: 1940-1980

Idea of solid state ionization chamber and first successful realisations:

1943: first usable semiconductor detector, P.J. von Heerden, Utrecht
"crystals (AgCl) could be sensitive to photoelectric effect, and also to β and α particles"

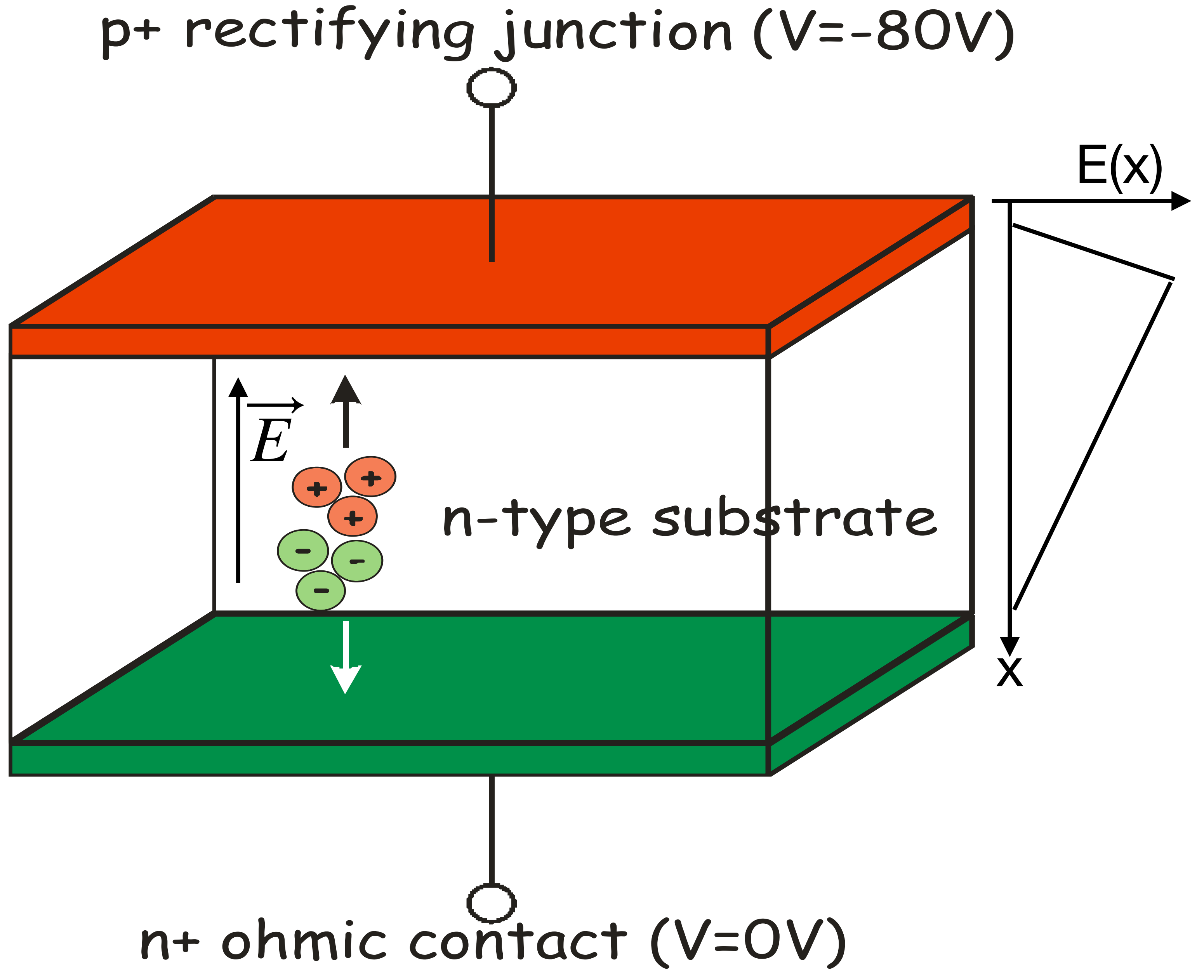
1949: first depleted detector, K.G. McKay, Bell (Ge – pn junction)

1955 – 1965: Si mono-crystals available
→ surface barrier at several labs. (Oak Ridge, Chalk River, CEA, ...)
→ gaseous diffusion of phosphorus
main motivation: excellent E resolution for nuclear physics spectrometers

1961: G. Dearnaley, Harwell: first segmented detector: a pixel detector !

1970: first strip detectors
Argonne, Fermilab, Karlsruhe, Southampton;
for nuclear physics and nuclear medicine

1970: W.S. Boyle and G.E. Smith, Bell CCD
pixels ~20x20 μm^2 and 1 cm^2 area (e.g. used as electrical storage devices, imaging e.g. in astronomy)



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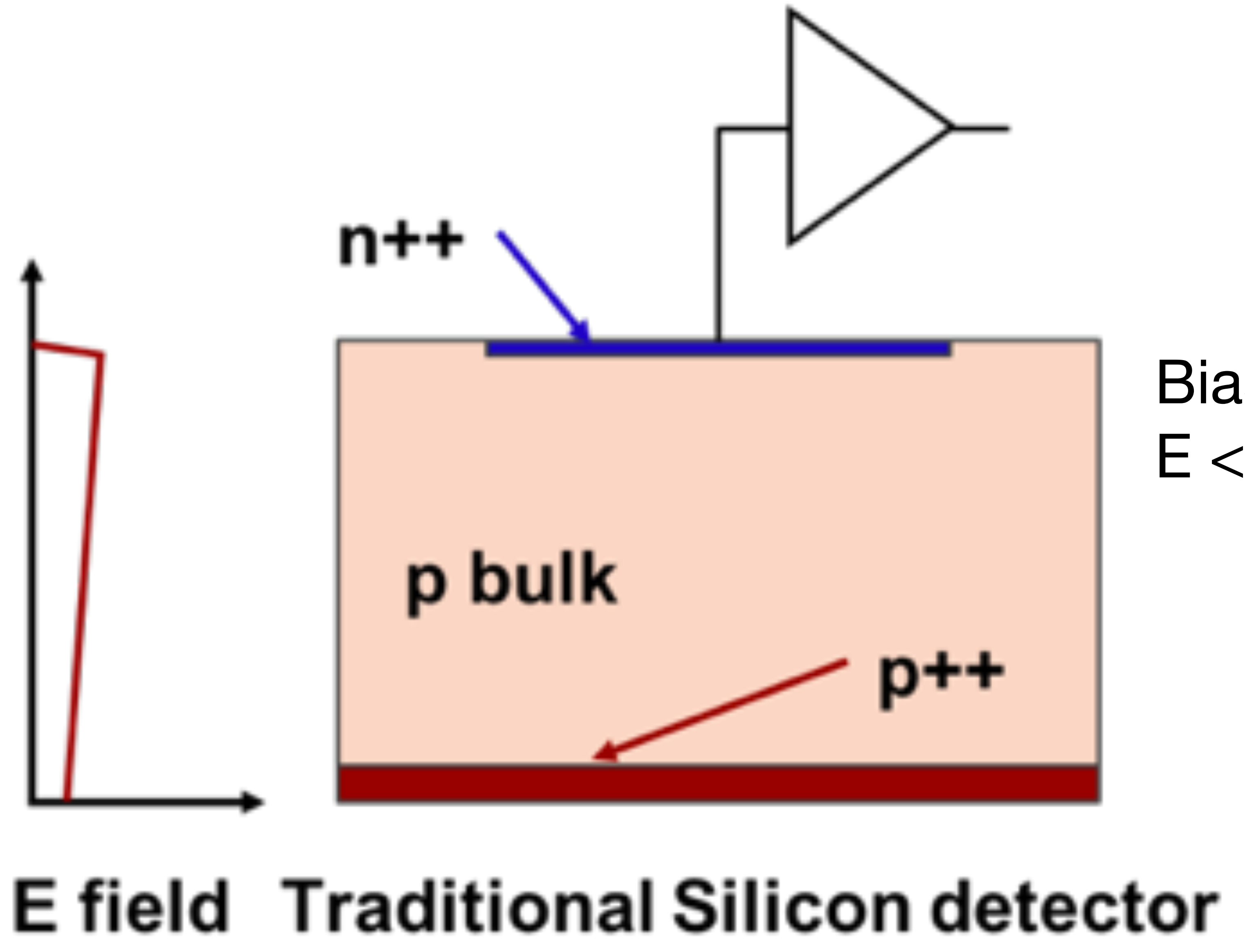
Detection on Silicon Sensors

The pre-history: 1940-1980

Silicon diode (pixel detectors)



Bias: 100 V / Thickness: 300 μm
E < 30 kV / cm

Typical values for Si:

- voltage 50 – 500 V
- thickness 0.05 – 1 mm
- collection time 5 – 50 ns
- diffusion few μm
- sensitive to light < ~1 μm,
  x-rays 0.2~20 keV
  charged particles

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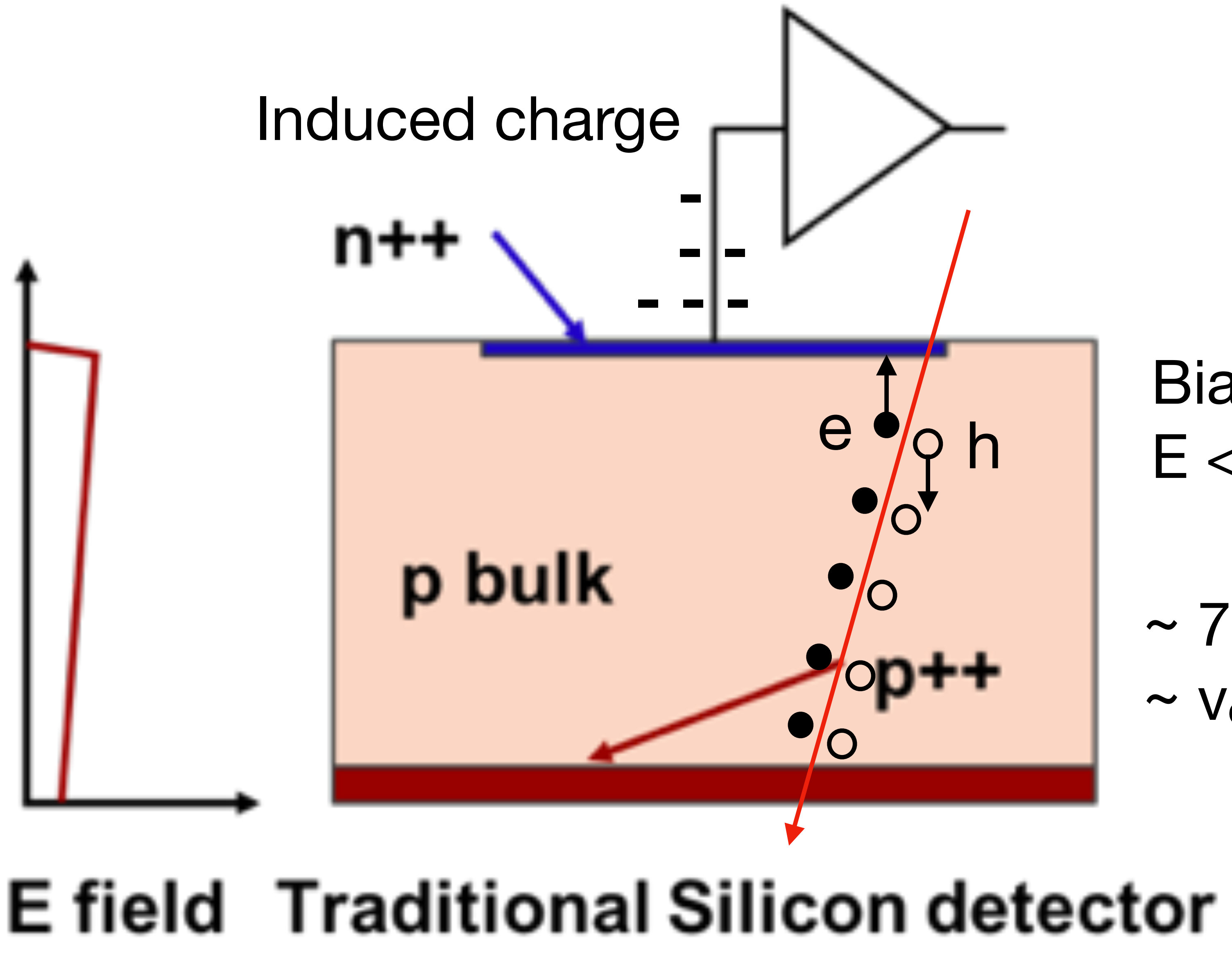


Bias: 100 V / Thickness: 300 μm
E < 30 kV / cm

~ 75 pairs / μm
~ v_d = 100 μm/ns (drift velocity)

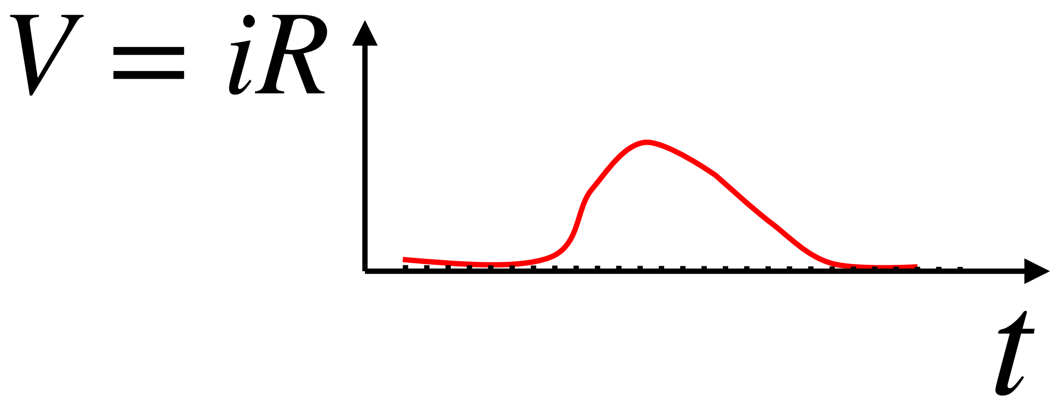
Signal pulse rise time ~ 1 ns
Time resolution ~ 150 -200 ps

Typical values for Si:

• voltage	50 – 500 V
• thickness	0.05 – 1 mm
• collection time	5 – 50 ns
• diffusion	few μm
• sensitive to light < ~1 μm,	
	x-rays 0.2~20 keV
	charged particles

- The charge carriers motion induces a current on the read-out electrode
- The signal ends when the charges are collected
- Signal shape calculated with Ramo's Theorem: $i \propto q v_d E_w$

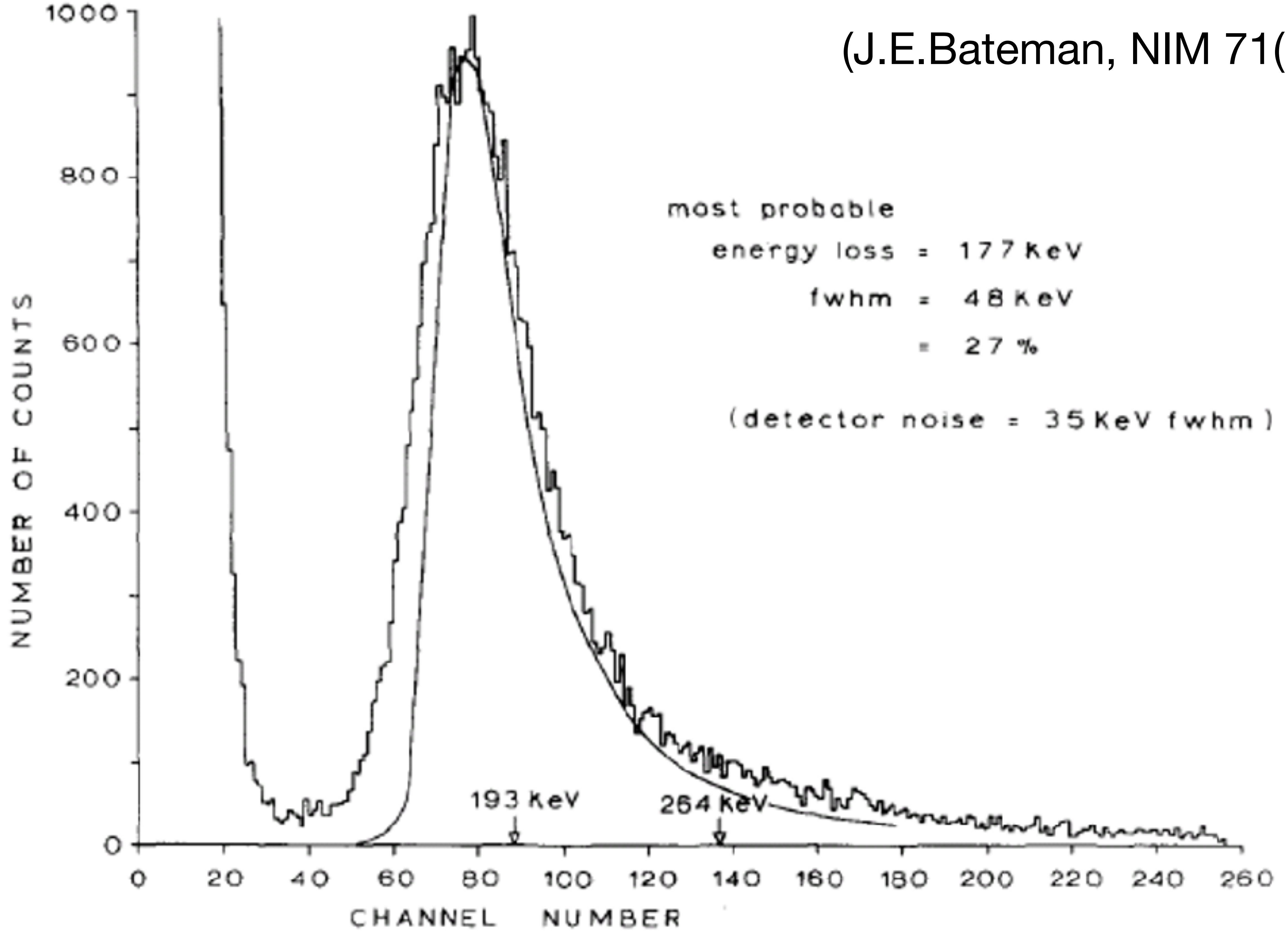
drift velocity weighting field



The Very Early Days of Solid State Detectors

The pre-history: 1940-1980

1969: Si-detectors can also be used to detect minimum ionizing particles !



(J.E.Bateman, NIM 71(1969)256)

Fig. 4. Energy distribution produced in C56 by electrons of energy 150 MeV (momentum resolution ≈ 2%). The solid curve is given by Landau's theory.

- signal 1e/h-pair / 3.6 eV
  → MIP: 42000 e/h / 0.5 mm
- noise ~ 4000 e (rms)

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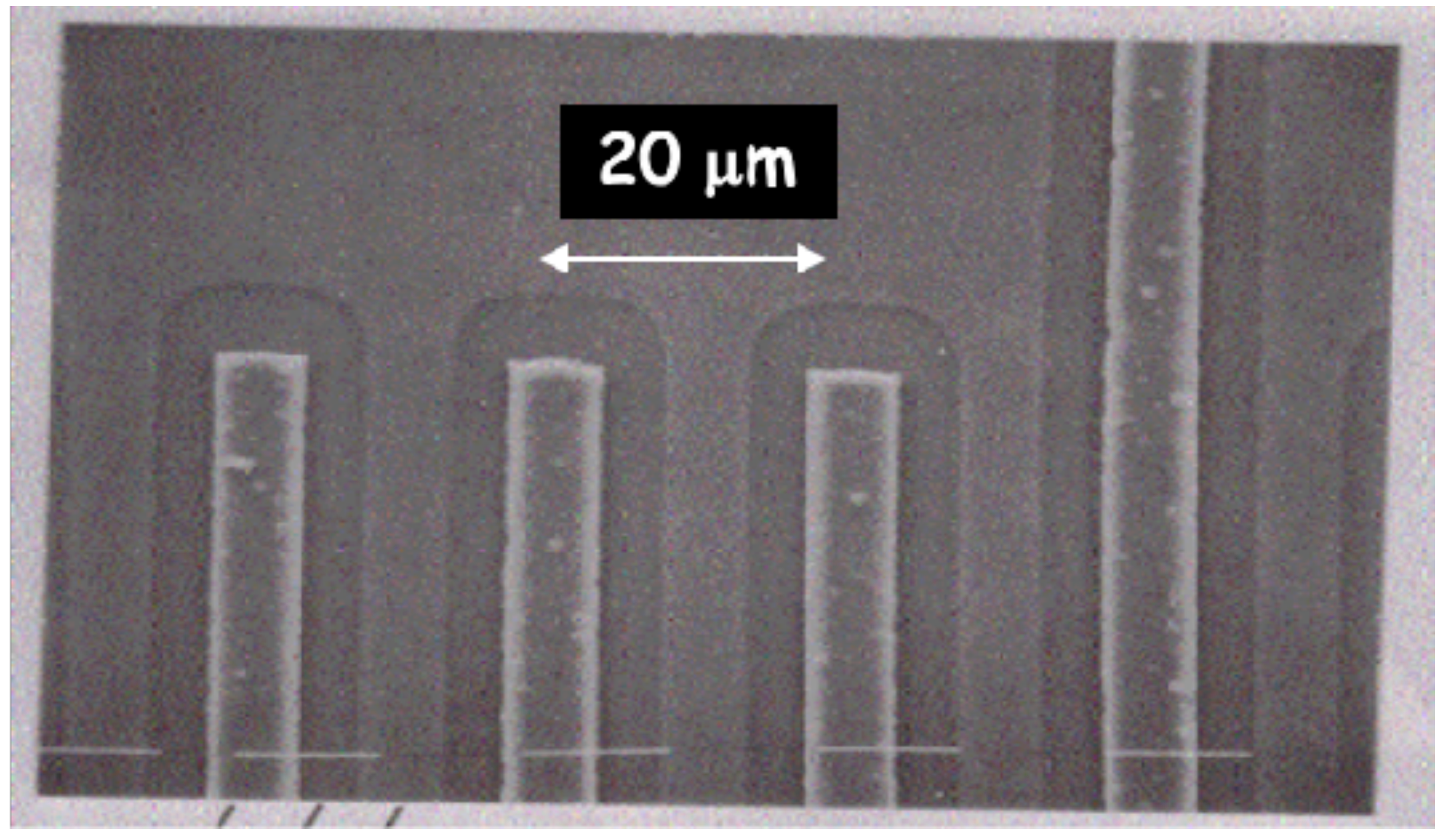
Transfer of the Planar Process to Detector Fabrication

The pre-history: 1940-1980

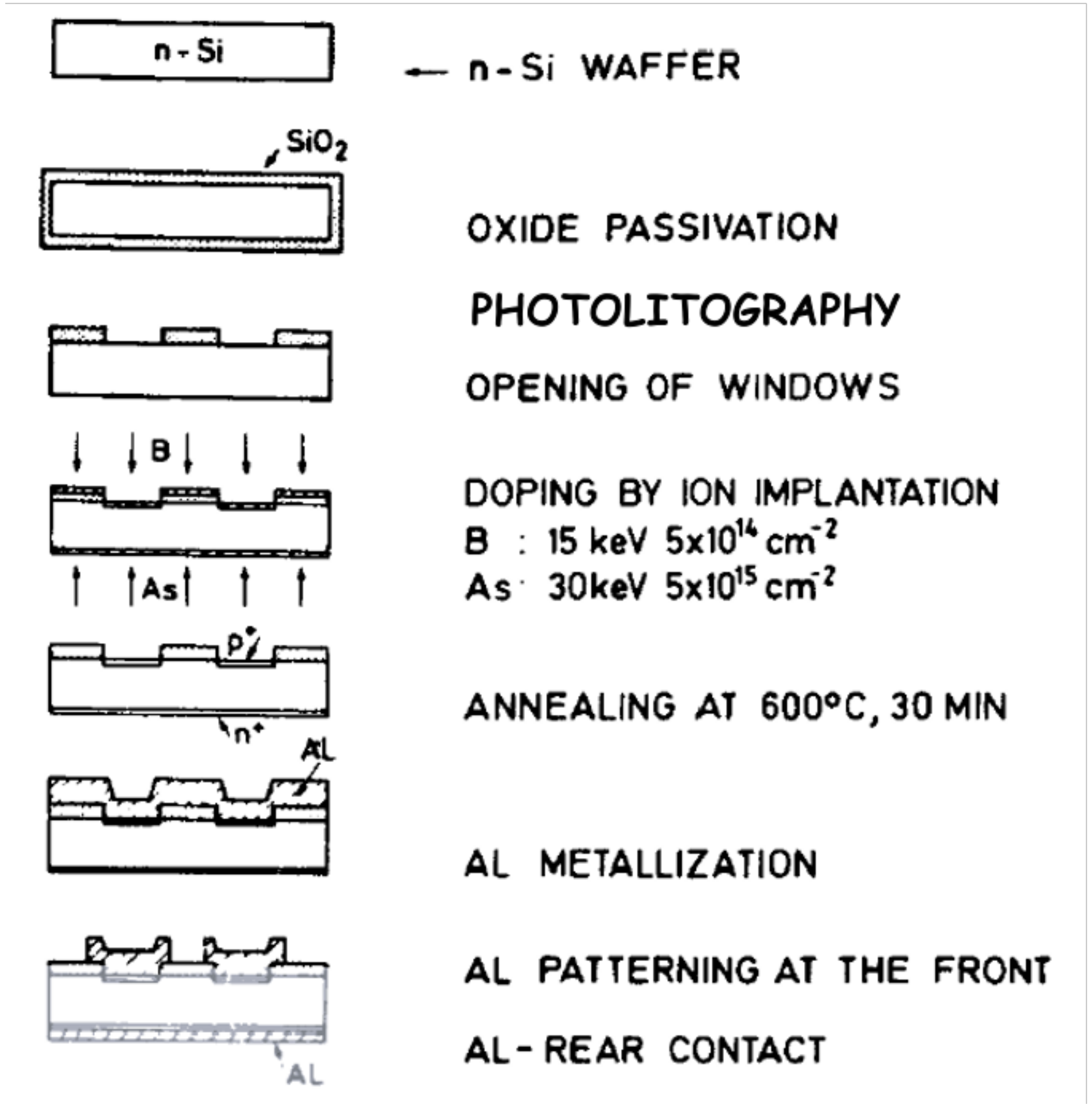
In 1975 several (> 7) companies in the US and Europe capable of surface barrier detectors fabrication — not suitable for fine segmentation

Josef Kemmer 1979,TU-Munich in Garching, transferred the highly developed Si-technology for electronics to detector fabrication + industry (P. Burger – Enertec/Canberra)

J. Kemmer, NIM 169(1980)499
NIM 226(1984)89



The planar process

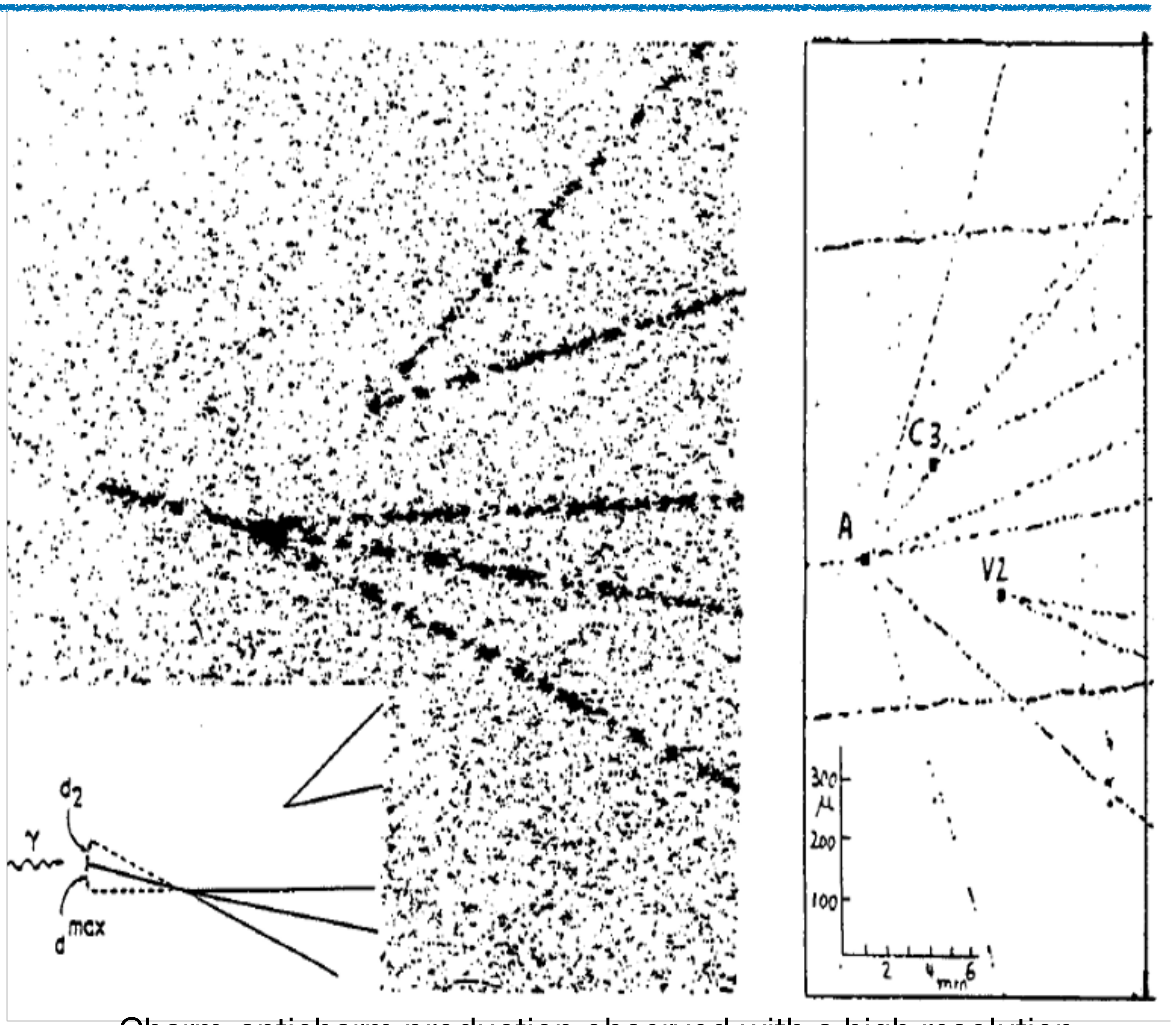


The First Silicon Detectors for HEP Experiments

The pre-history: 1940-1980

The November revolution and its aftermath

- discovery of particles with shorter lifetime then known ones (10^{-12}-10^{-13} s instead of 10^{-8}-10^{-10} s): J/ψ and the c-quark (1974), τ-lepton (1975), Υ and the b-quark (1977)
- decay length: $\gamma c\tau$ ~ 30 µm defines new **Requirements** on vertex detectors:



Charm-anticharm production observed with a high resolution bubble chambers at SLAC and CERN

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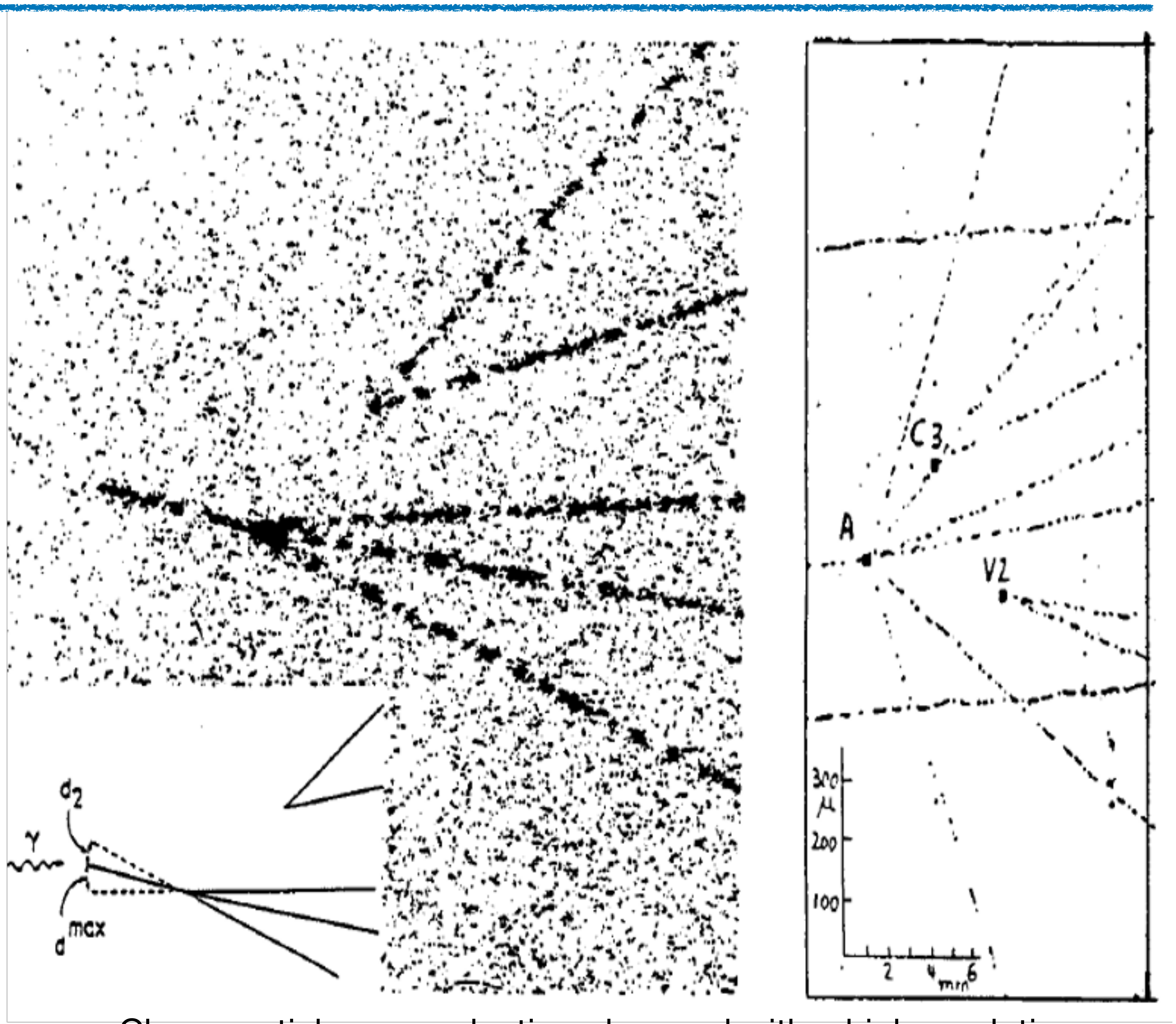
Requirements on vertex detectors:

- spatial resolution < 10 μm and good particle separation
- rate capability ~ 10^6 Hz
- low multiple scattering and photon conversion, i.e. thin sensors



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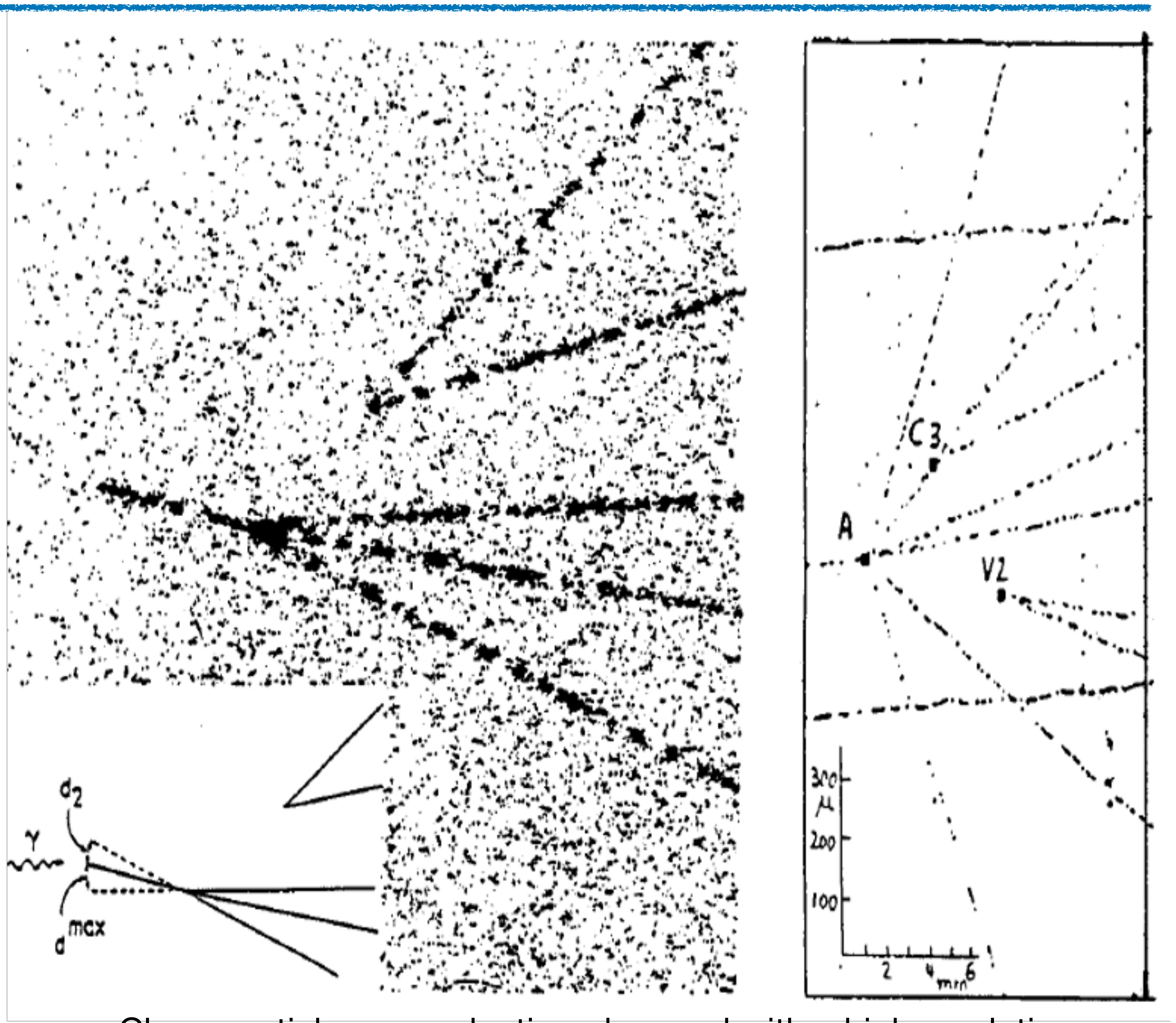


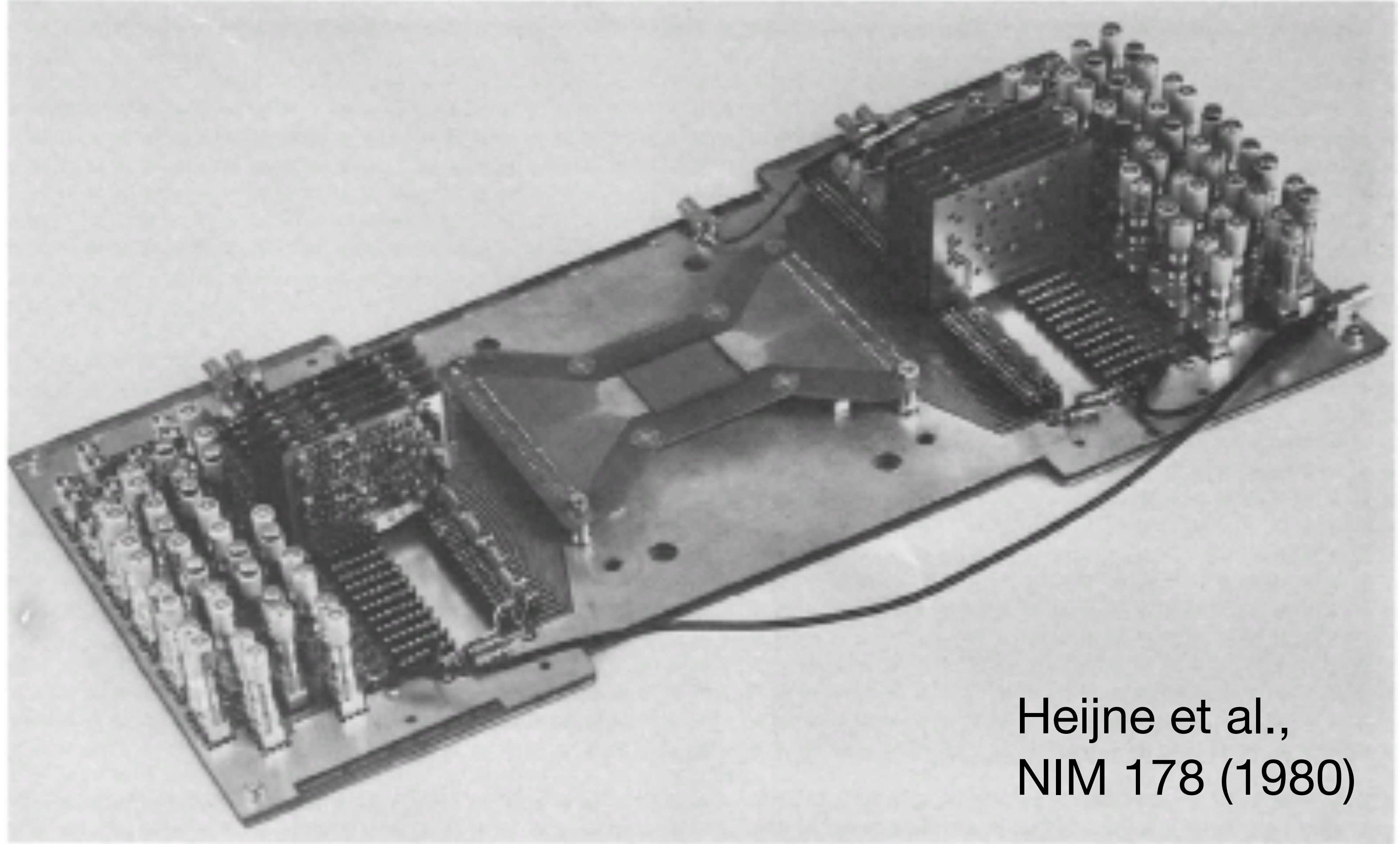
Charm-anticharm production observed with a high resolution bubble chambers at SLAC and CERN

The existing detectors (emulsions, high resolution bubble chambers, gas detectors) did not achieve the required overall performance

The First Silicon Detectors for HEP Experiments

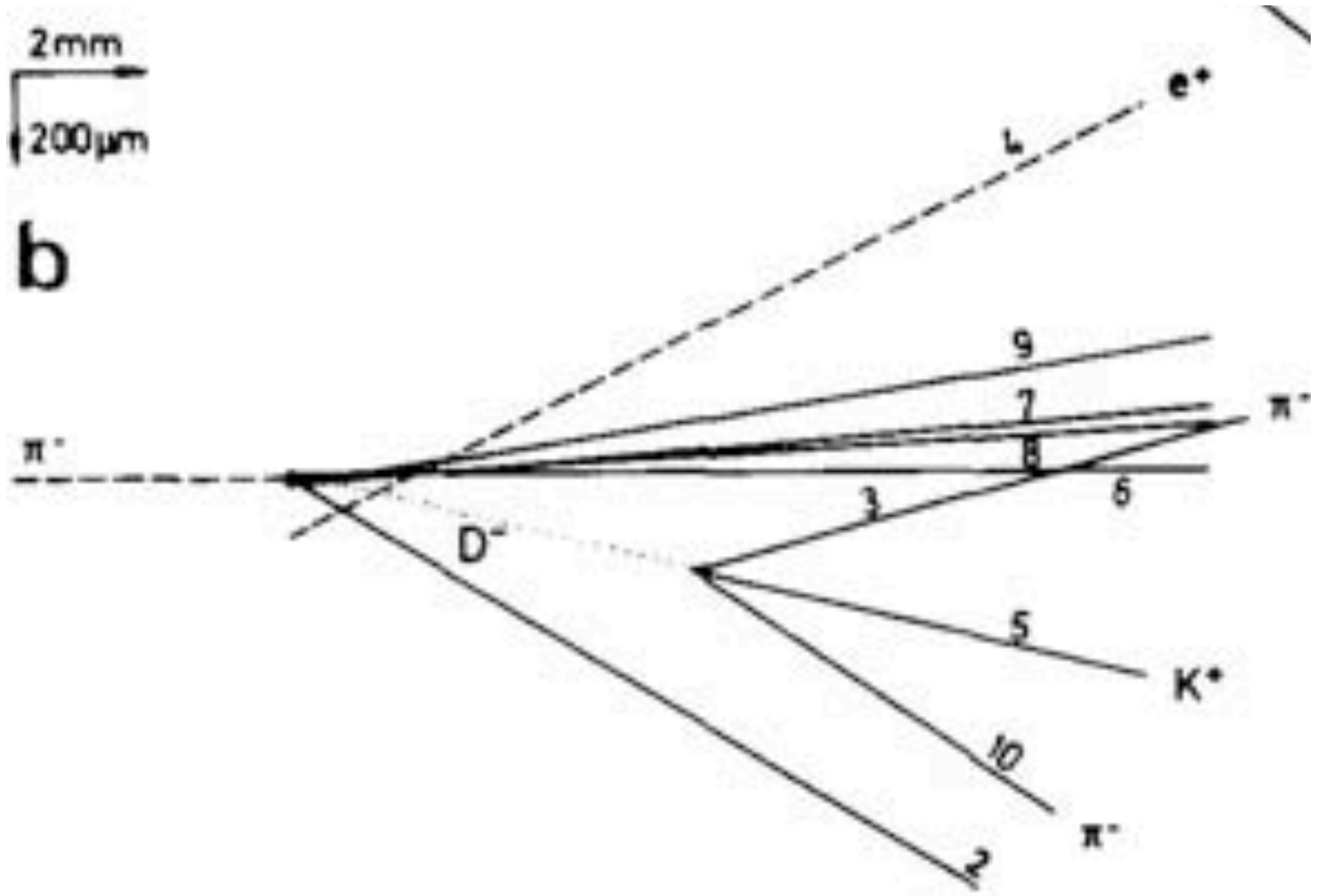
The pre-history: 1940-1980

Several HEP groups started to learn the art of silicon sensors and µ-electronics (in close collaboration with industry)



Heijne et al., NIM 178 (1980)

Fig. 6. The microstrip detector placed together with some amplifiers on the test board, which can be positioned in a beam.



CERN group (Heijne, Piuz, Jarron, Hyams et al. 1980)

- Si-strip sensor with 300 µm pitch
- Demonstrate vertex reconstruction within the NA-11 experiment
- Demonstrate capacitive charge division (thanks to broken channels)

Fundamental development in parallel to Si-detectors → very large scale integration (VLSI) readout chips e.g. CAMEX: Fraunhofer Institute in collaboration with Gerhard Lutz et al., TUM; Microplex: Hyams, Walker, Shapiro; …

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The First Silicon Detectors for HEP Experiments

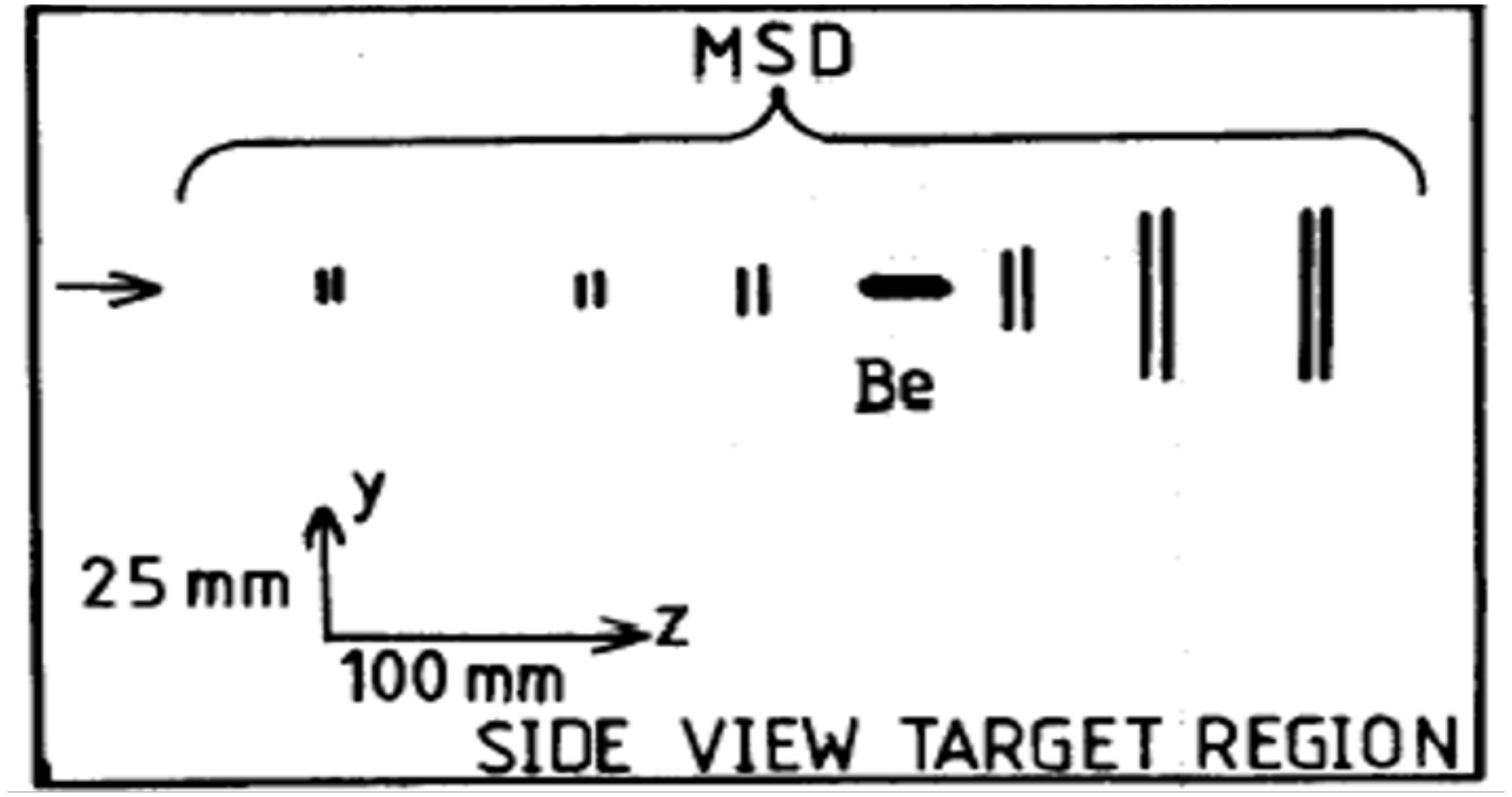
The quest of high precision resolution electronic detectors

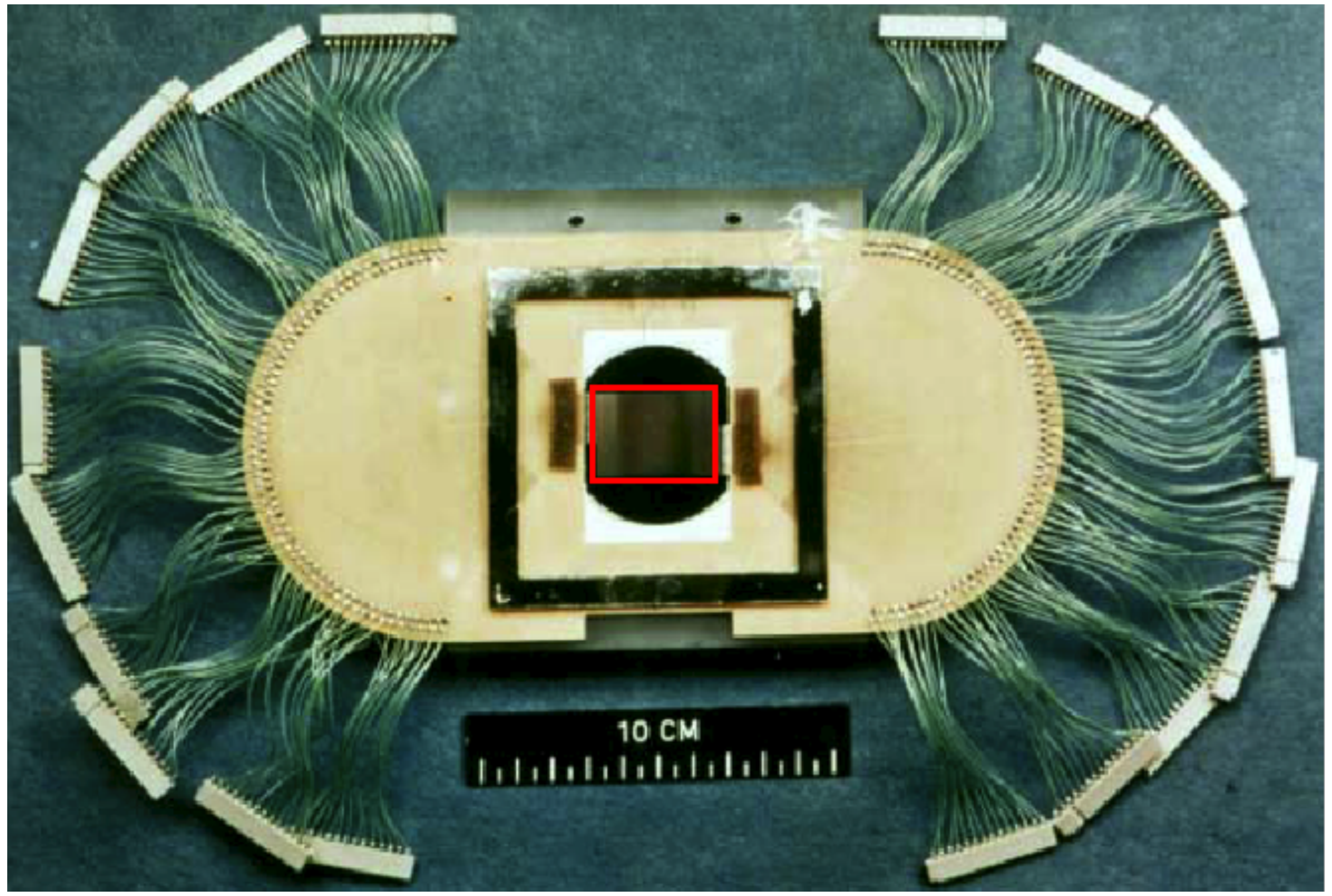
NA-11/ NA-32 experiment: spectrometer for hadron physics

lifetimes D^+, D_0, D_S,
observation and mass of D_S,
hadronic production of charm particles (QCD)

p Be → charm + X

1981: 6 planes Si-strip detectors





• area	24x36 mm^2
• strips/sensor	1200
• strip pitch	20 µm
• thickness	280 µm
• N of channels	< 2000

• efficiency	100%
• strip pitch	20 µm
• readout	capacitive charge division
• resolution with 60 µm readout	$\sigma = 5.4$ µm
• resolution with 120 µm readout	$\sigma = 7.8$ µm

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Getting Organized

The silicon detector community

~ 90 participants
> 11 from MPI

under MPE (Max-Planck Institut für Extraterrestrische Physik) director Joachim Trümper

1983: 3rd European Symposium on Semiconductor Detectors at Munich

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Getting Organized

The silicon detector community

Symposium Organizers:

R. Klanner (MPI) E. Heijne (CERN)

~ 90 participants

> 11 from MPI

G. Lutz (MPI)

co-founder in 1992 of the Max-Planck Halbleiterlabor (HLL) and co-director till 2004

under MPE (Max-Planck Institut für Extraterrestrische Physik) director Joachim Trümper

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See backup slide for the original photo and the list of names

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Silicon Vertex Detector for e+e- Colliders

The evolution: 1980-2000

The **next challenges**:

- Improve impact parameter resolution in Rϕ
- Add resolution in the third dimension: Rz
- Extend angular coverage

Impact parameter resolution:

$$\sigma_{d_0}^2 = \sigma_{MS}^2 + \sigma_{geom}^2$$

$$\sigma_{geom}^2 = \left(\frac{\sigma_1 r_2}{r_2 - r_1}\right)^2 + \left(\frac{\sigma_2 r_1}{r_2 - r_1}\right)^2$$ (simplified for only two layers)

$\sigma_{MS}^2 =$ Multiple Scattering contribution

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Silicon Vertex Detector for e^+e^- Colliders

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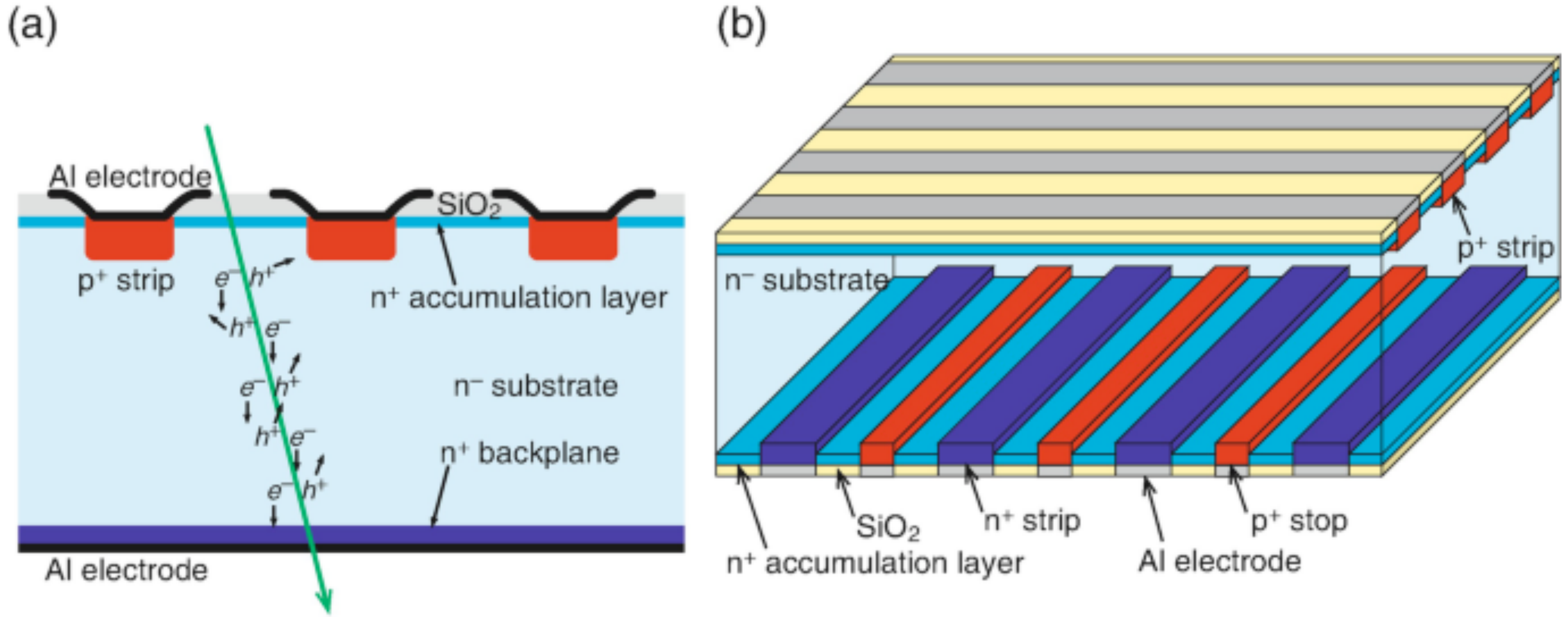
Optimisation steps:

- Double-sided sensors (minimise MS)



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Optimisation steps:

- Double-sided sensors (minimise MS)
- Strips parallel and orthogonal to the beam axis + routing lines on a second metal layer
- Strip, … microstrip, … pixels

Silicon Vertex Detector for e^+e^- Colliders

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Optimisation steps:

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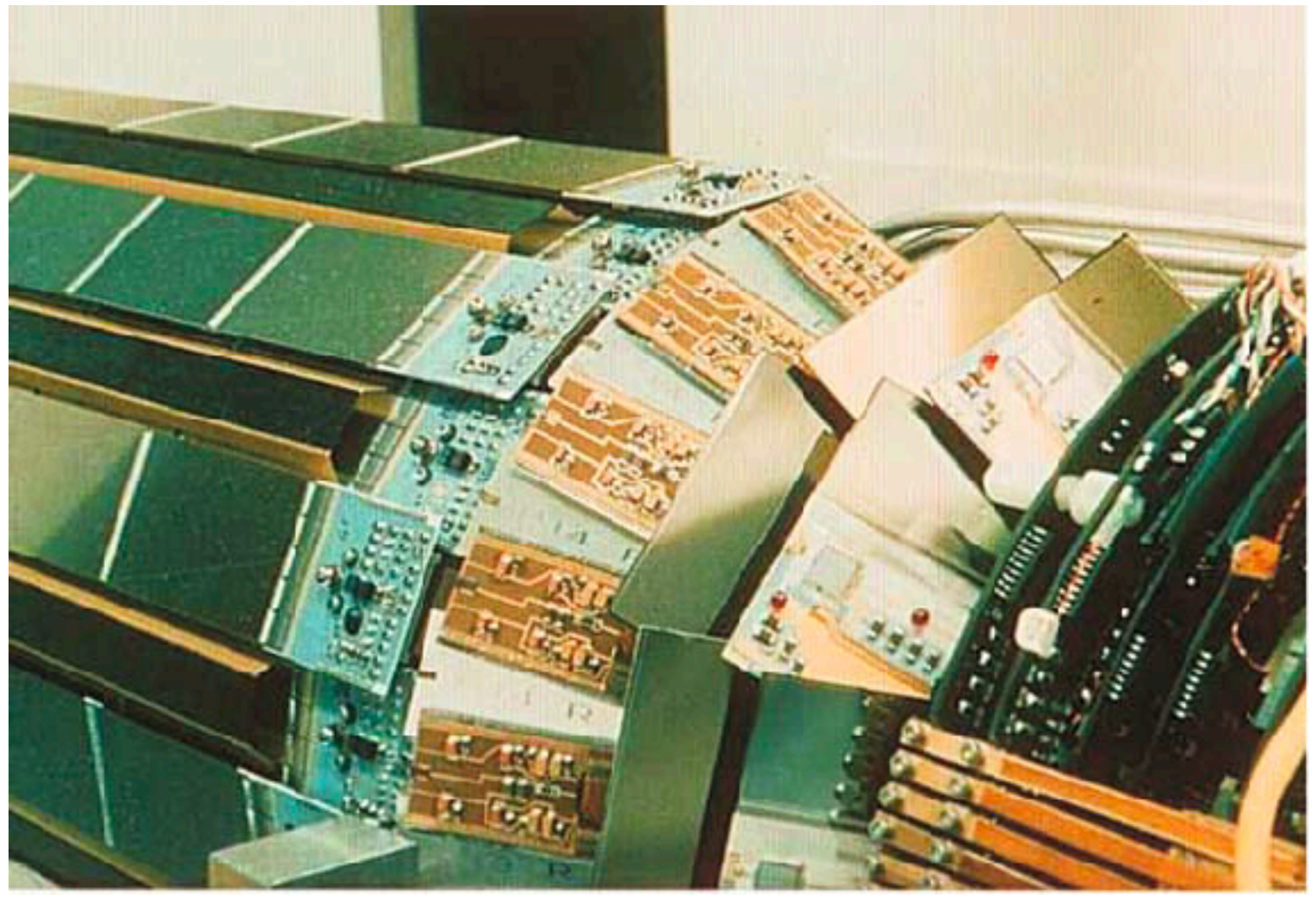
- Strips orthogonal to the beam axis + routing lines on second metal layer
- Strip, … microstrip, … pixels
- Dedicated forward detectors geometries



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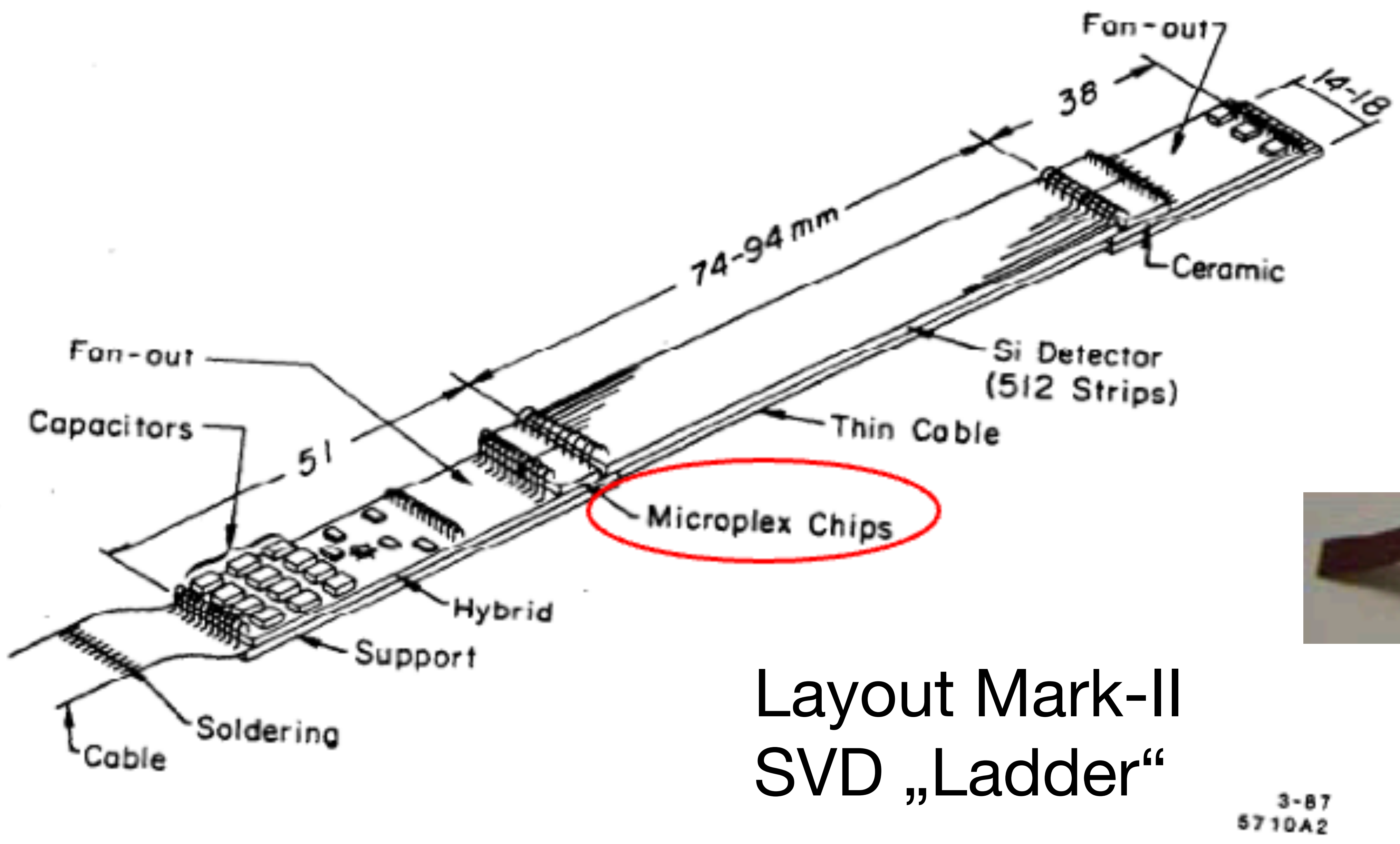
Silicon Vertex Detector for e^+e^- Colliders

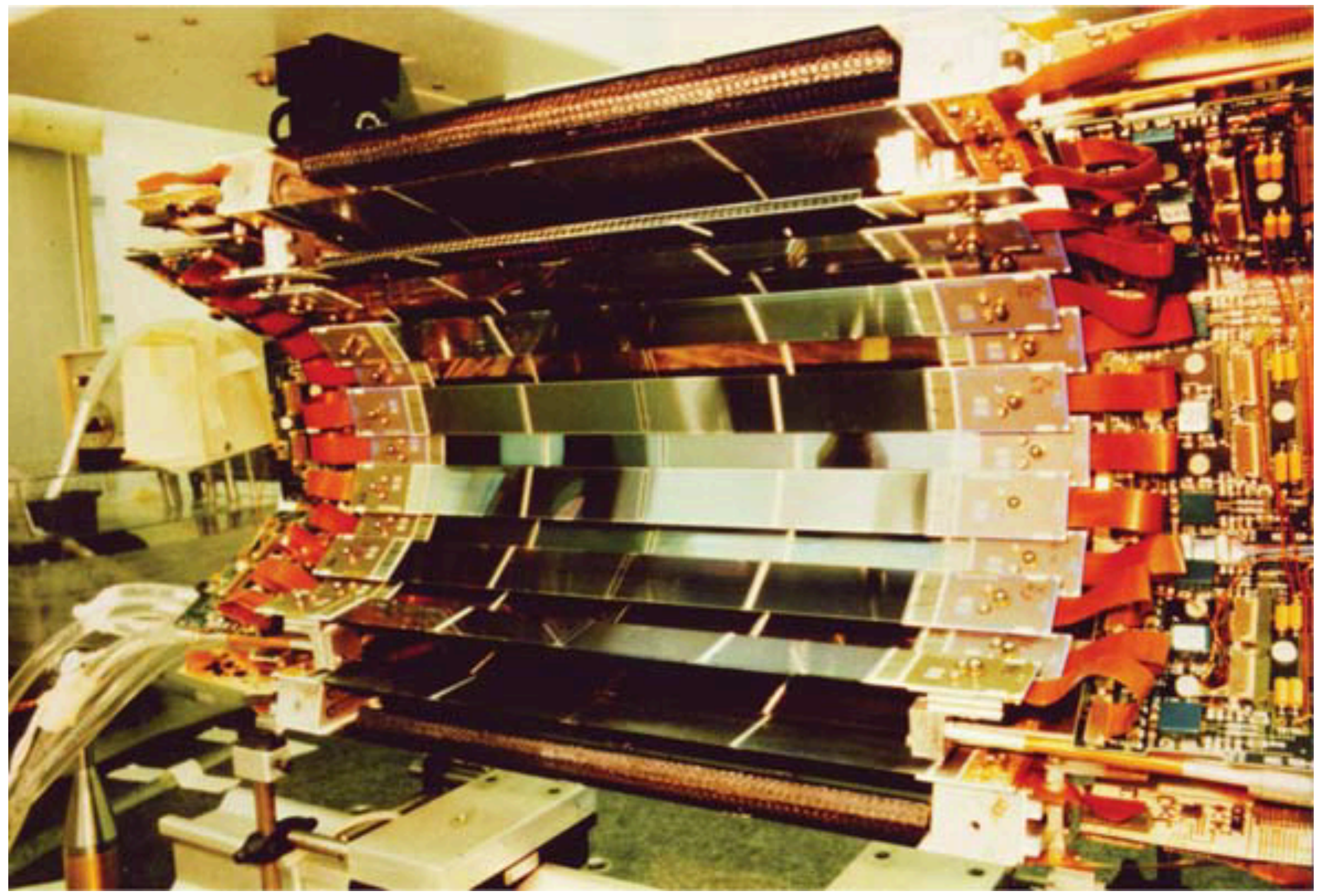
The evolution: 1980-2000

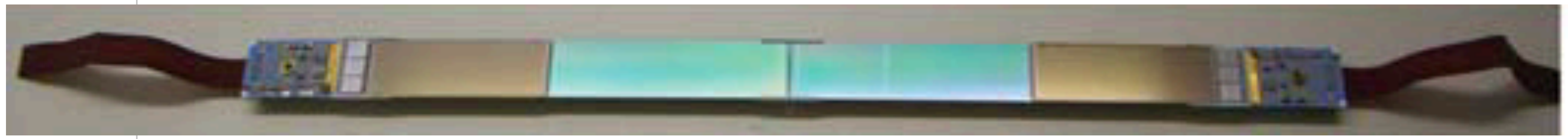
First generation of vertex detectors at colliders:

- 1985: Proposal to add Silicon Vertex Detector to Mark II @ SLAC (Adolphsen et al.)
  → impact parameter resolution ~20 µm
- 1996: DELPHI microvertex detector at LEP
  → tagging of b quarks down to low polar angles



Layout Mark-II
SVD „Ladder“





DELPHI inter tracker module
daisy chained strips via wire bonds

Silicon Vertex Detector for Hadron Colliders

The radiation hard era: >2000

Following the pioneering success of NA32 and Mark II → Si vertex detectors for all 4 LEP experiments, TeVatron, B-factories, HERA, RHIC and for all 4 LHC experiment

Silicon Vertex Detector for Hadron Colliders

The radiation hard era: >2000

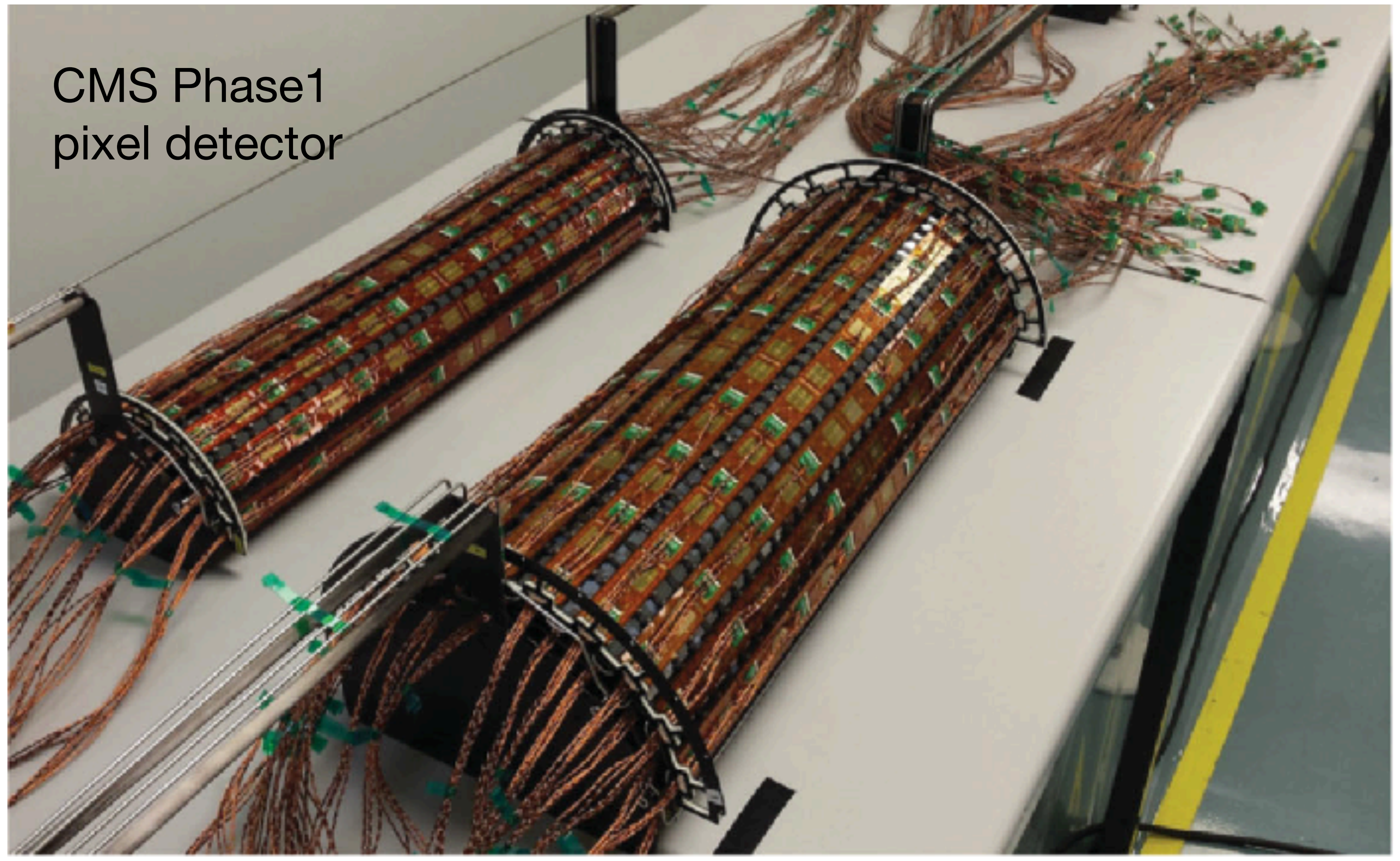
Following the pioneering success of NA32 and Mark II → Si vertex detectors for all 4 LEP experiments, TeVatron, B-factories, HERA, RHIC and for all 4 LHC experiment

The **next challenges**:

- Increasing luminosity = increasing particle fluence on detector → $\phi \sim 10^{16}$ n cm^{-2}
- High occupancy

Optimisation steps:

- Radiation hard sensors and electronics
- Small pixels pitch ~25-50 µm



Four layers of the tracker inner barrel inside the tracker outer barrel

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Silicon Vertex Detector for Hadron Colliders

The radiation hard era: >2000

Investigation of radiation damage in silicon and defect engineering for rad.hard. detectors

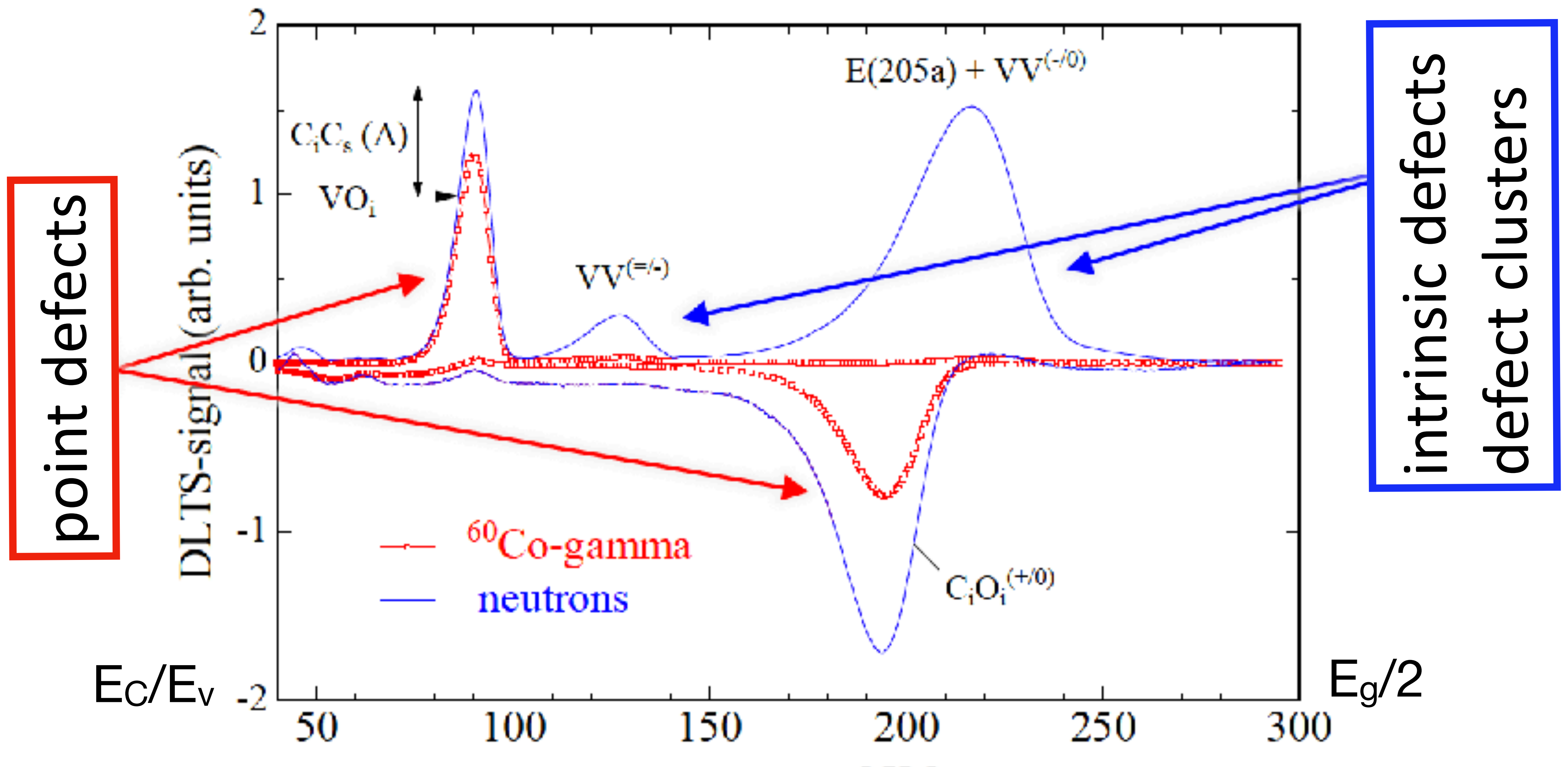
- RD48 (ROSE) collaboration: development of Oxygen enriched FZ silicon (DOFZ).

O-enrichment of about 2×10^{17} O/cm^3 in normal detector processing

- Hamburg model (Gunnar Lindström et al.) model the NIEL scaling of radiation damage

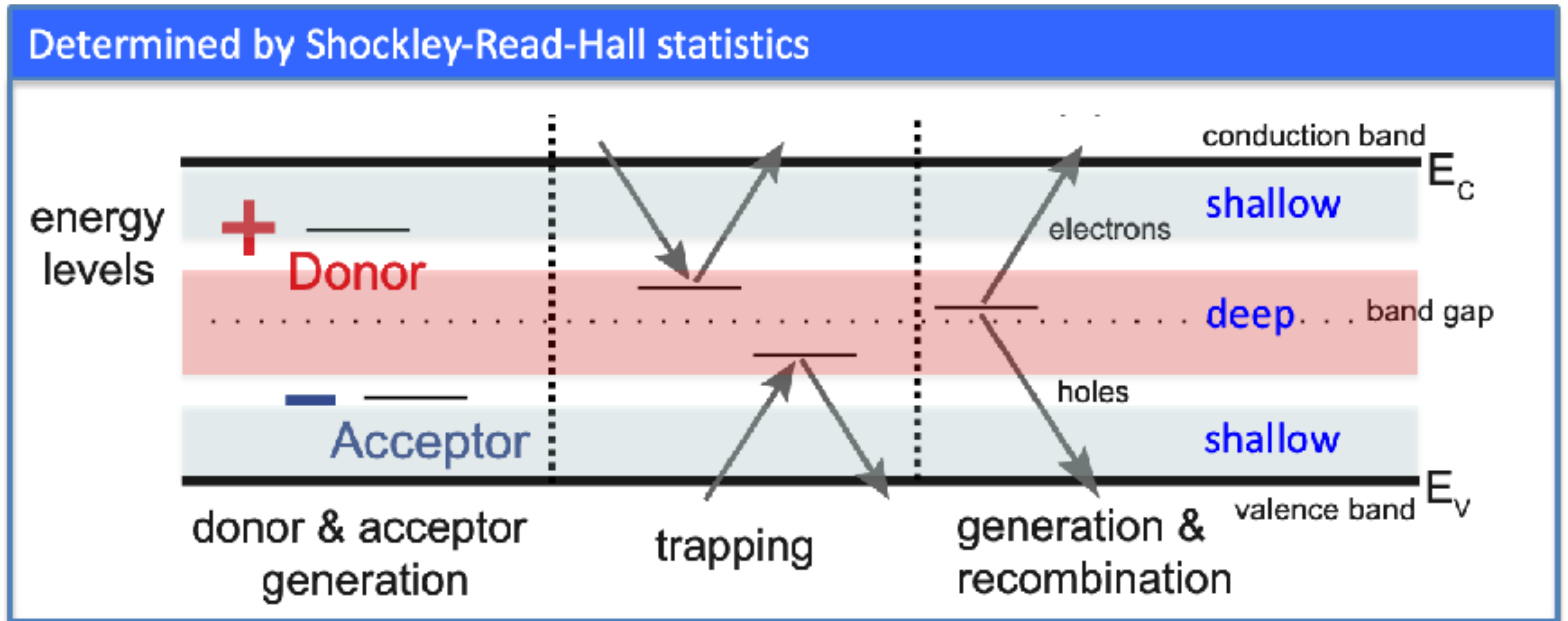
Gamma-irradiation ⇔ Neutron-irradiation

only point defects ⇔ cluster and point defects



M.Moll, PhD thesis, 1999

Determined by Shockley-Read-Hall statistics



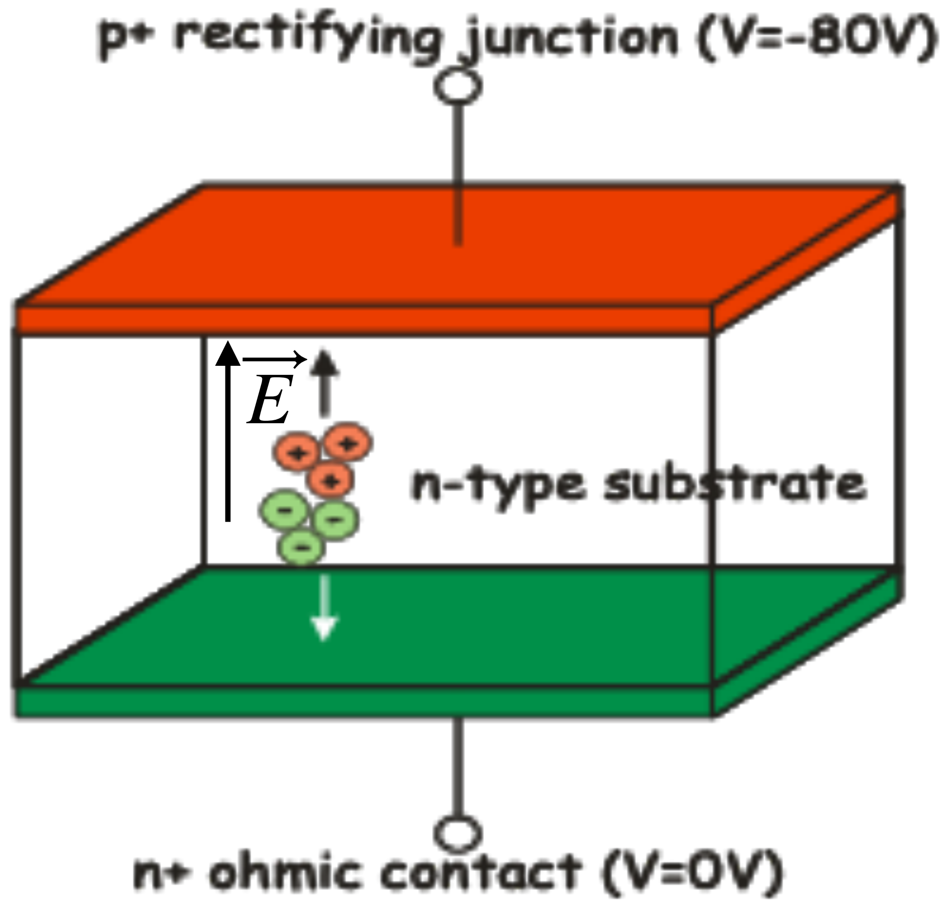
Charged defects (at RT)	Deep defects	Levels close to midgap
➔ change of E-field, V_{dep} (Acceptors in the lower half and donors in the upper half of the band gap)	➔ signal drop (Shallow defects do not contribute due to de-trapping)	➔ current increase ➔ Cooling during operation helps!

Beyond Planar Pad Sensors

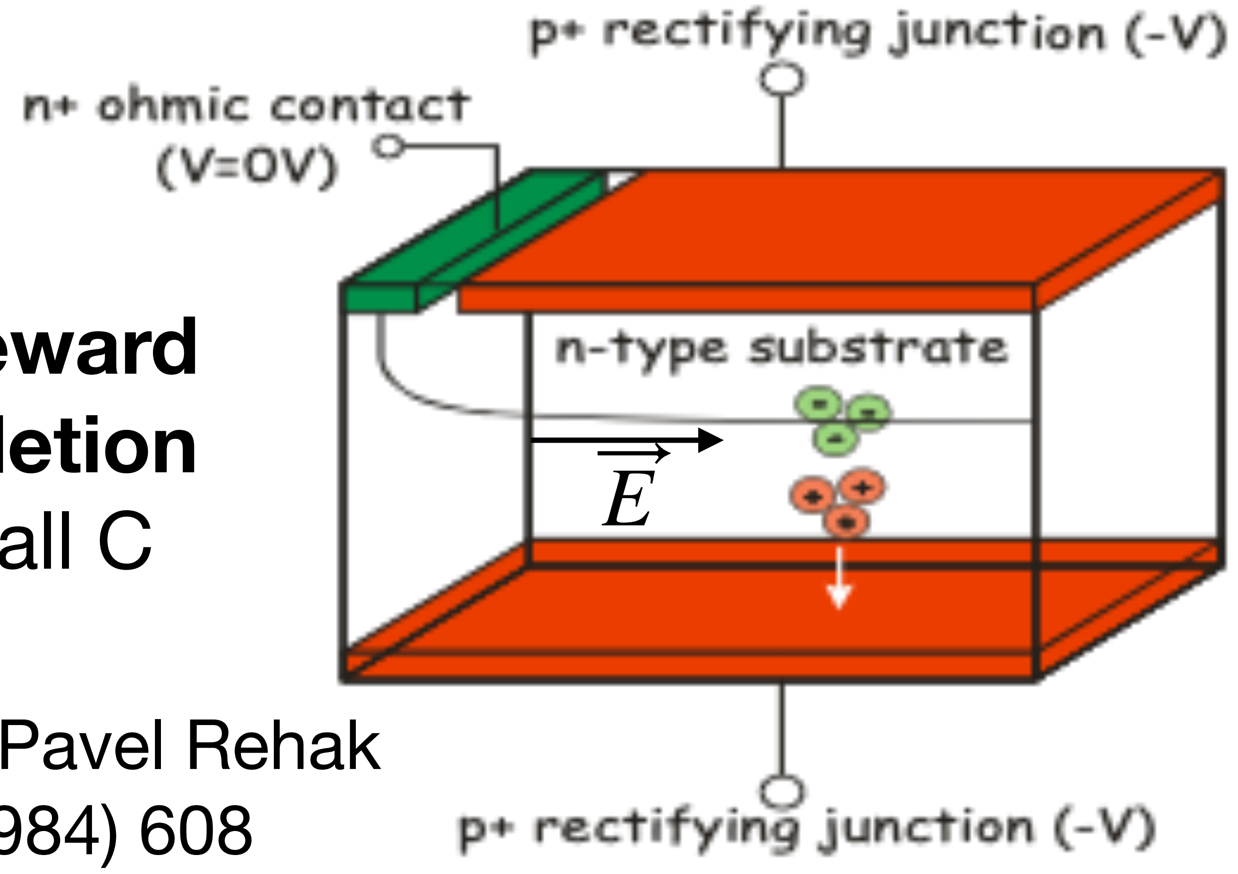
Silicon Drift Detectors

The Principle of Sideward Depletion

Planar pad diode
large C



Sideward depletion
small C



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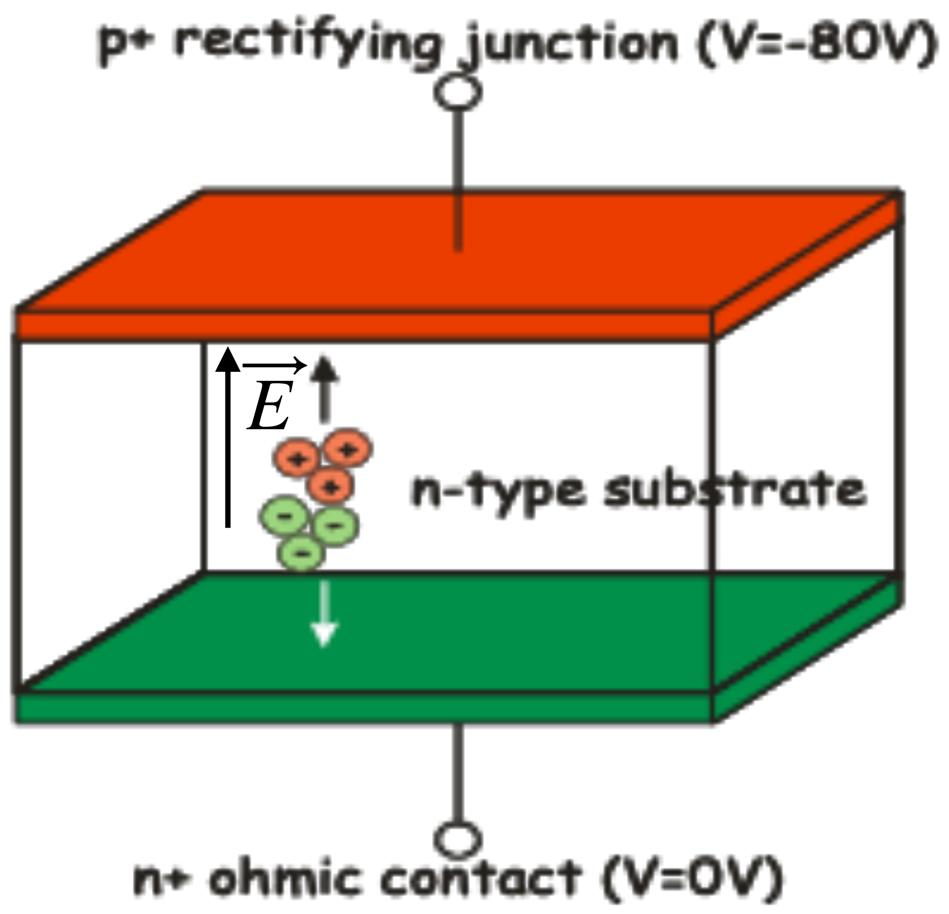
NIMA 226 (1984) 608

Silicon Drift Detectors

The Principle of Sideward Depletion

Planar pad diode
large C



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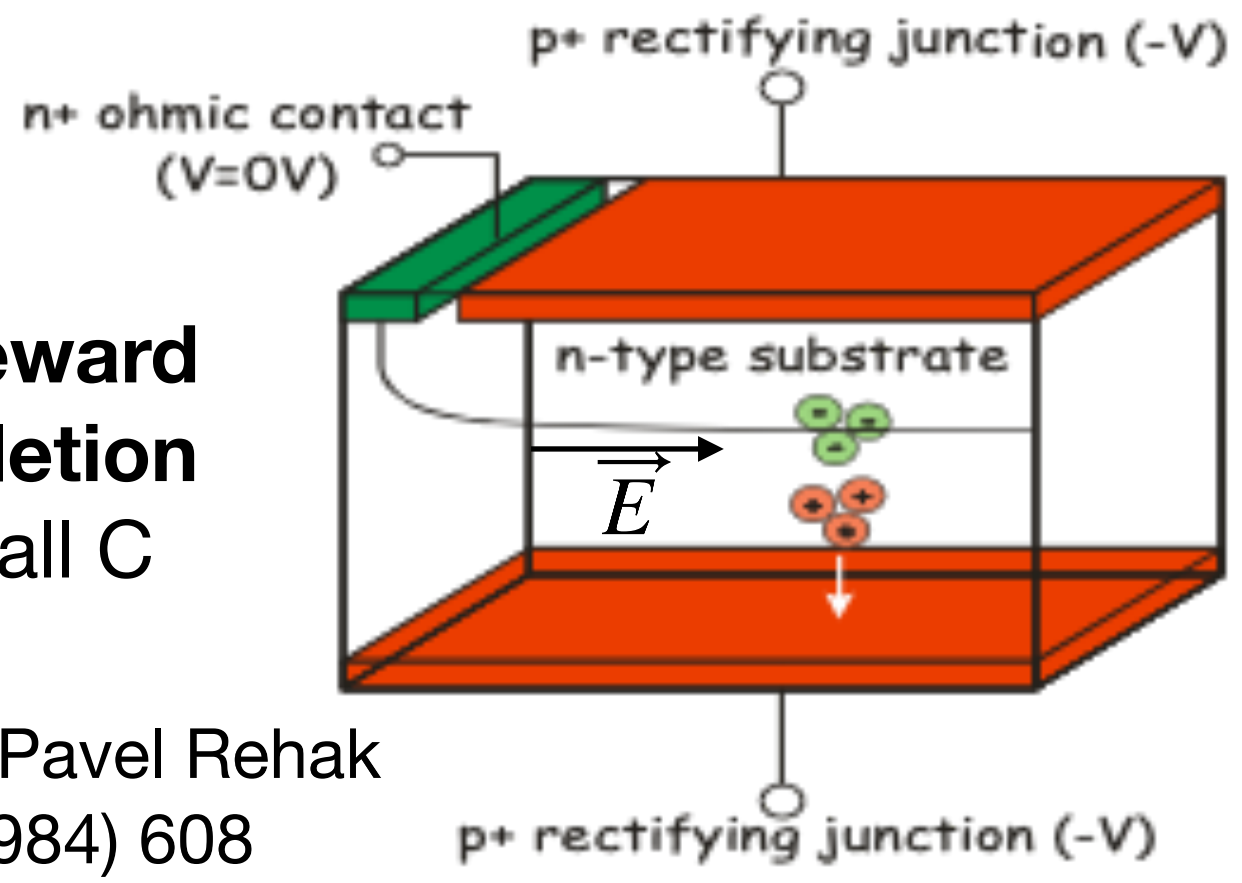

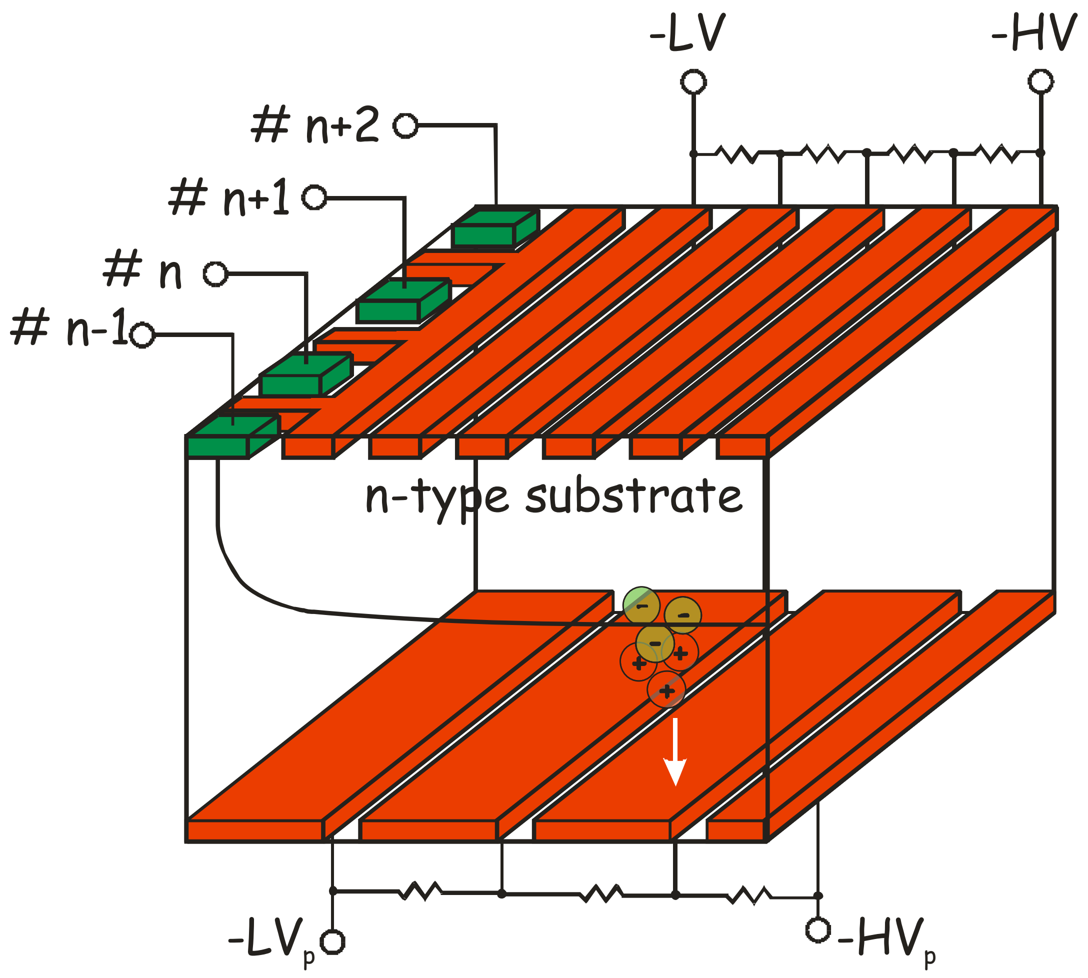

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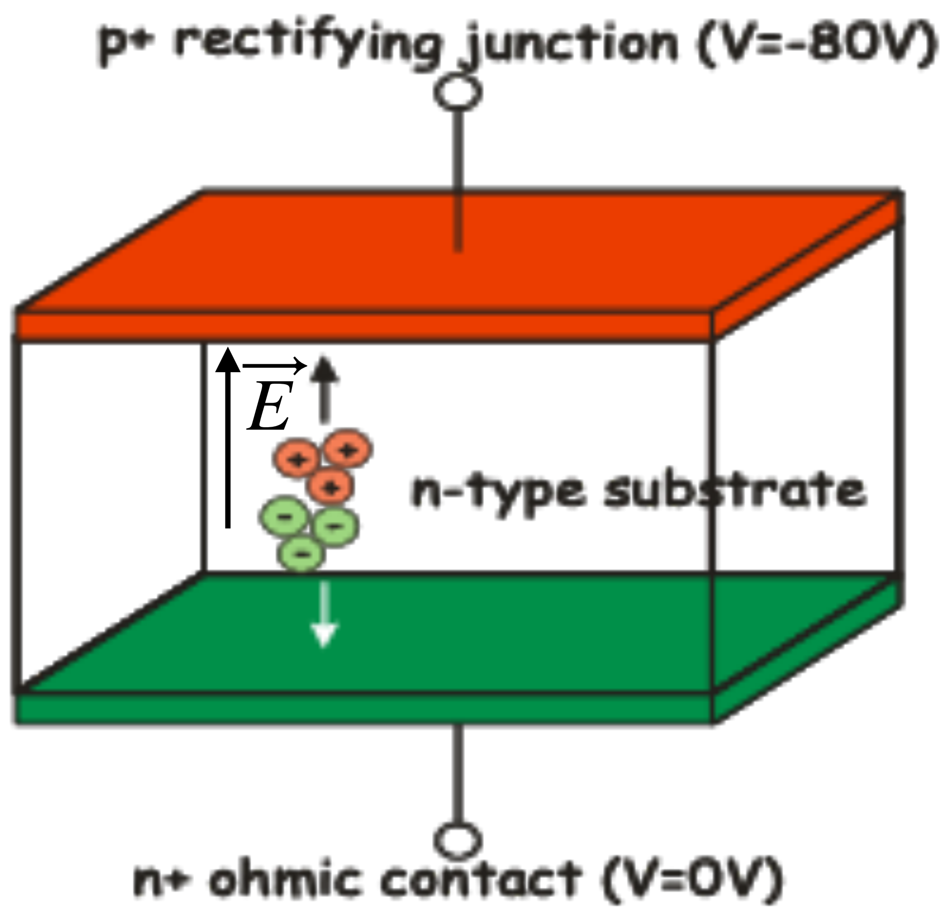
Silicon Drift Detectors

The Principle of Sideward Depletion

first silicon-drift chambers were built at TU/MPI-München and were characterized by MPI-München in the NA32 experiment

Planar pad diode
large C



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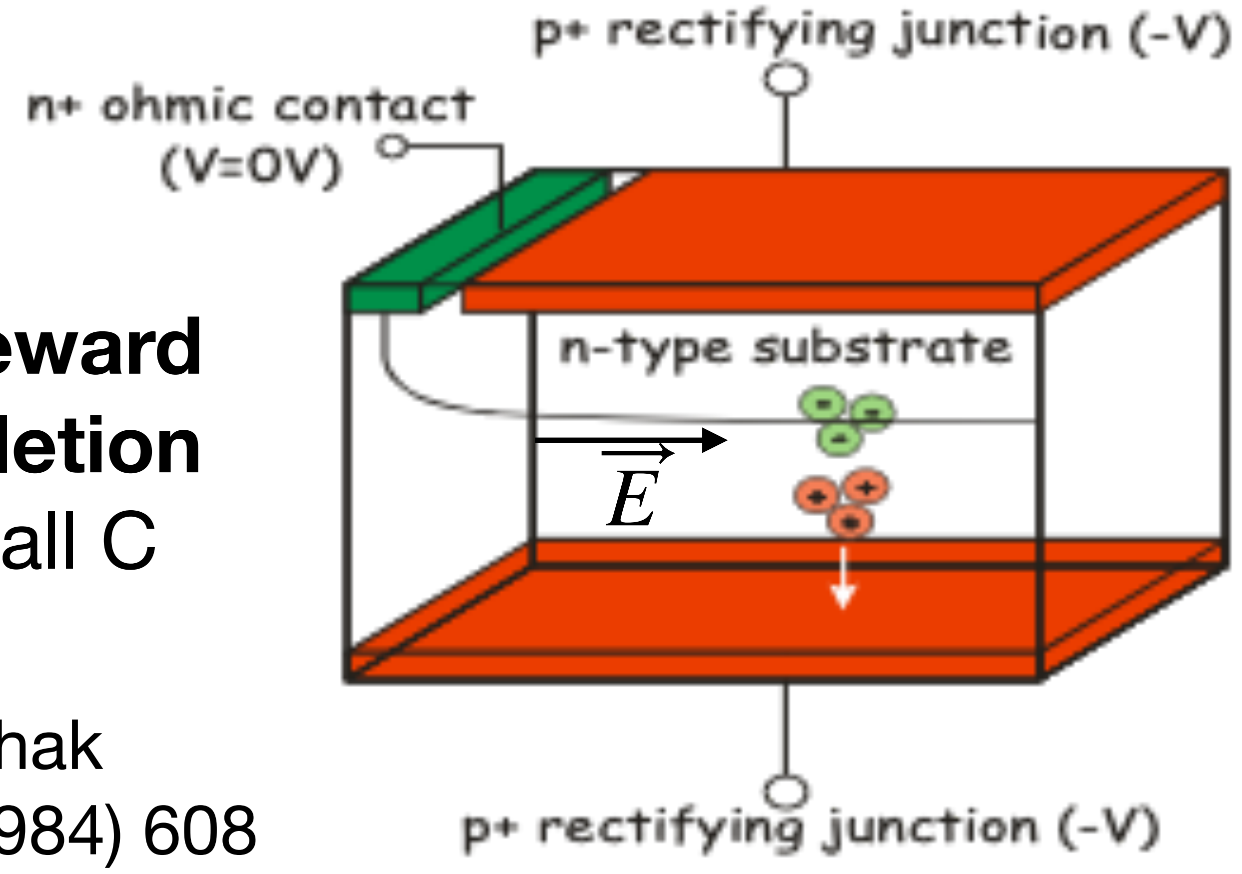

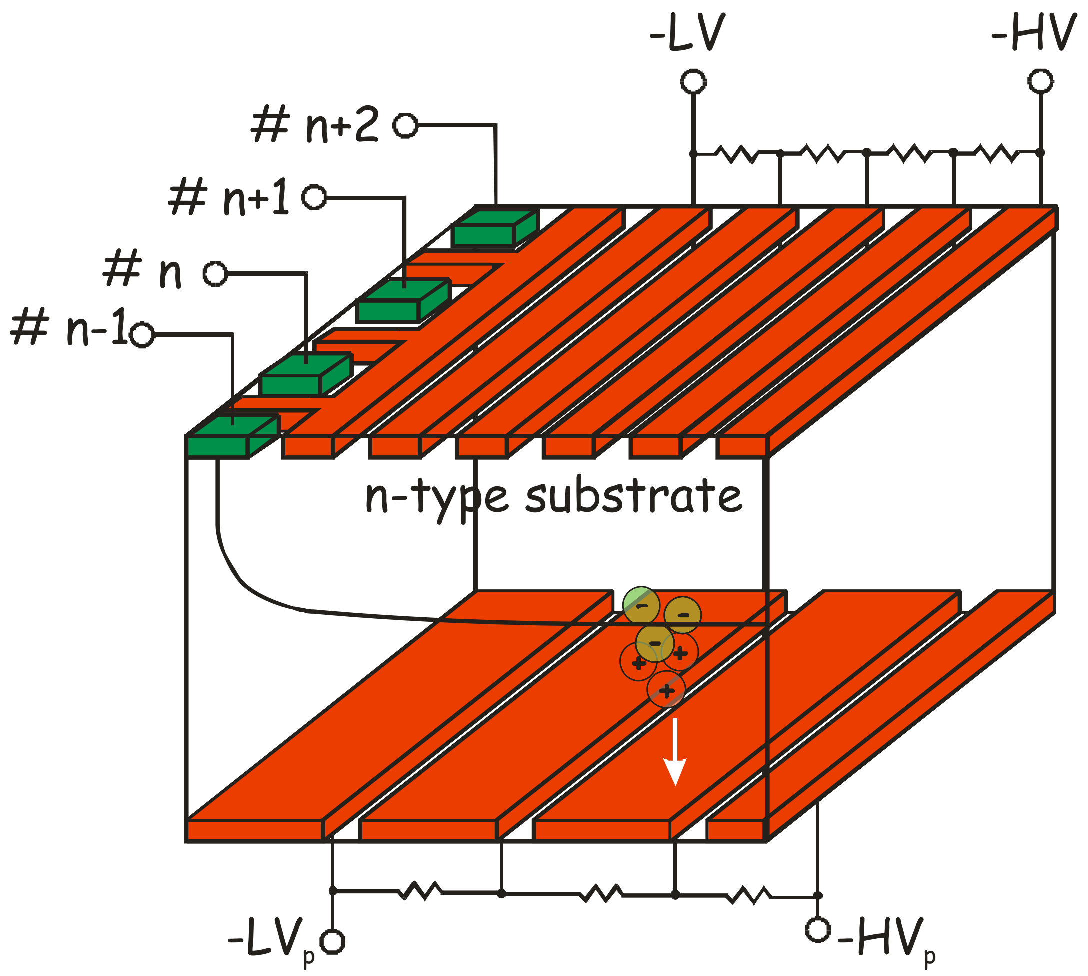

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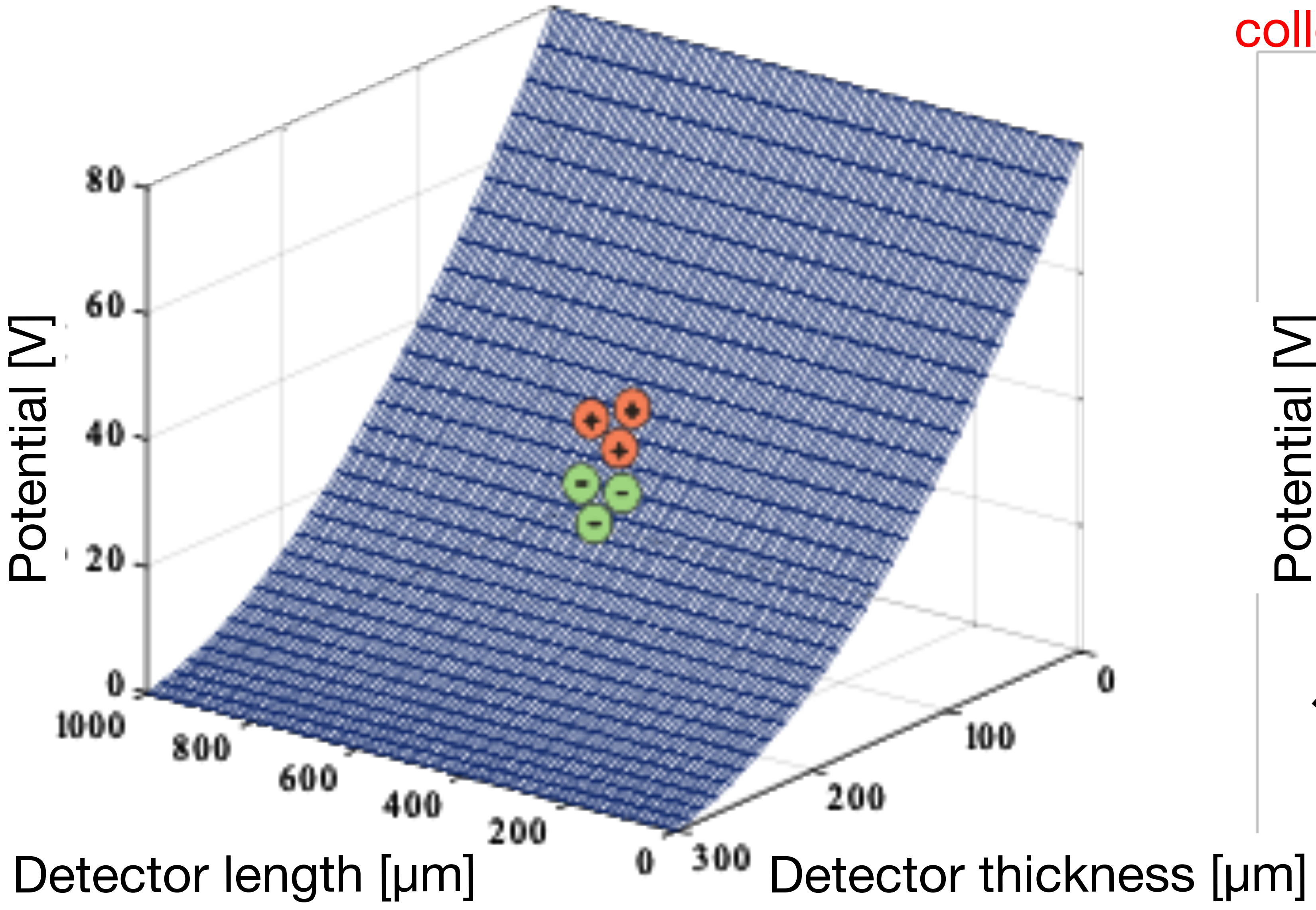
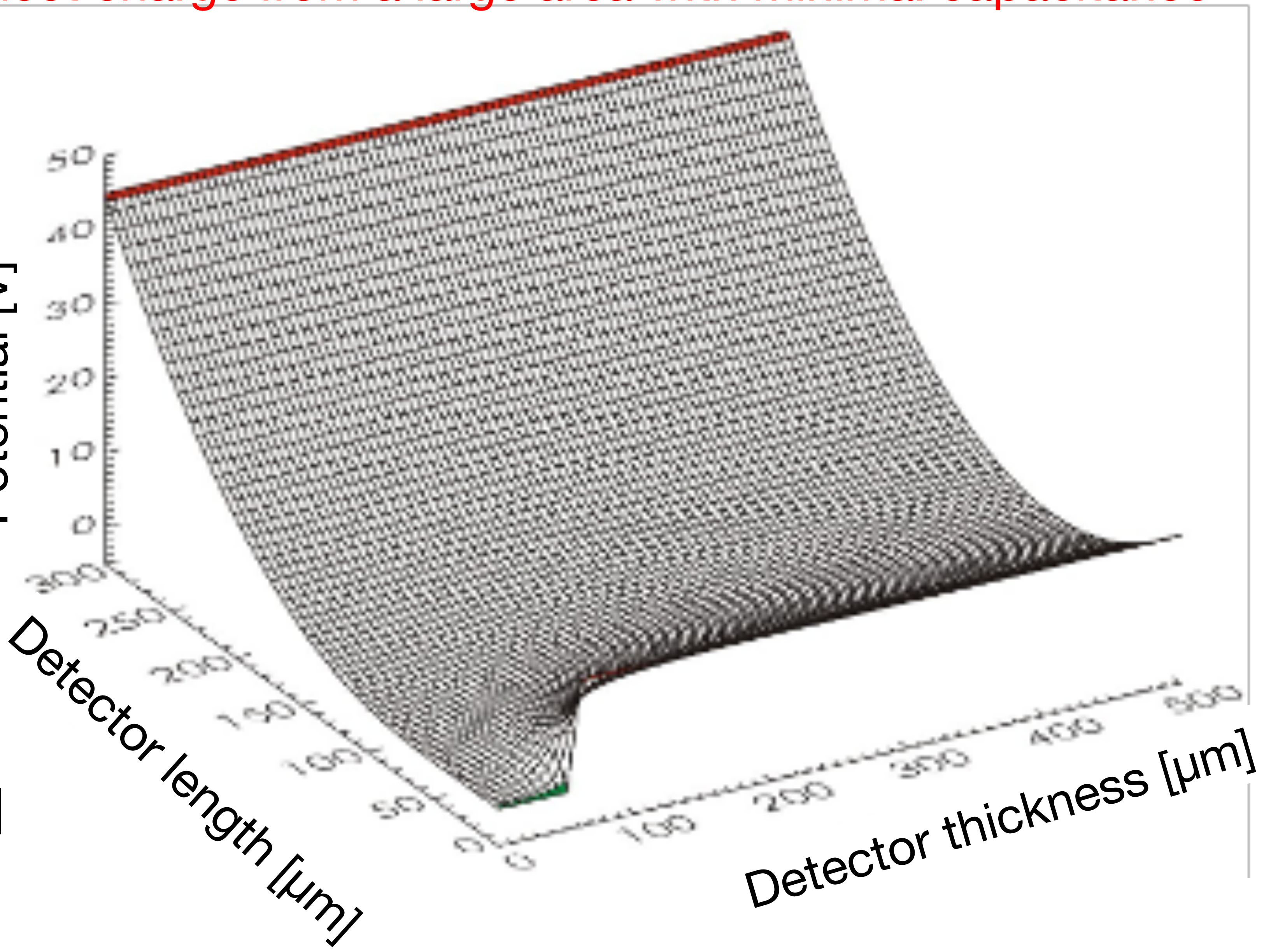
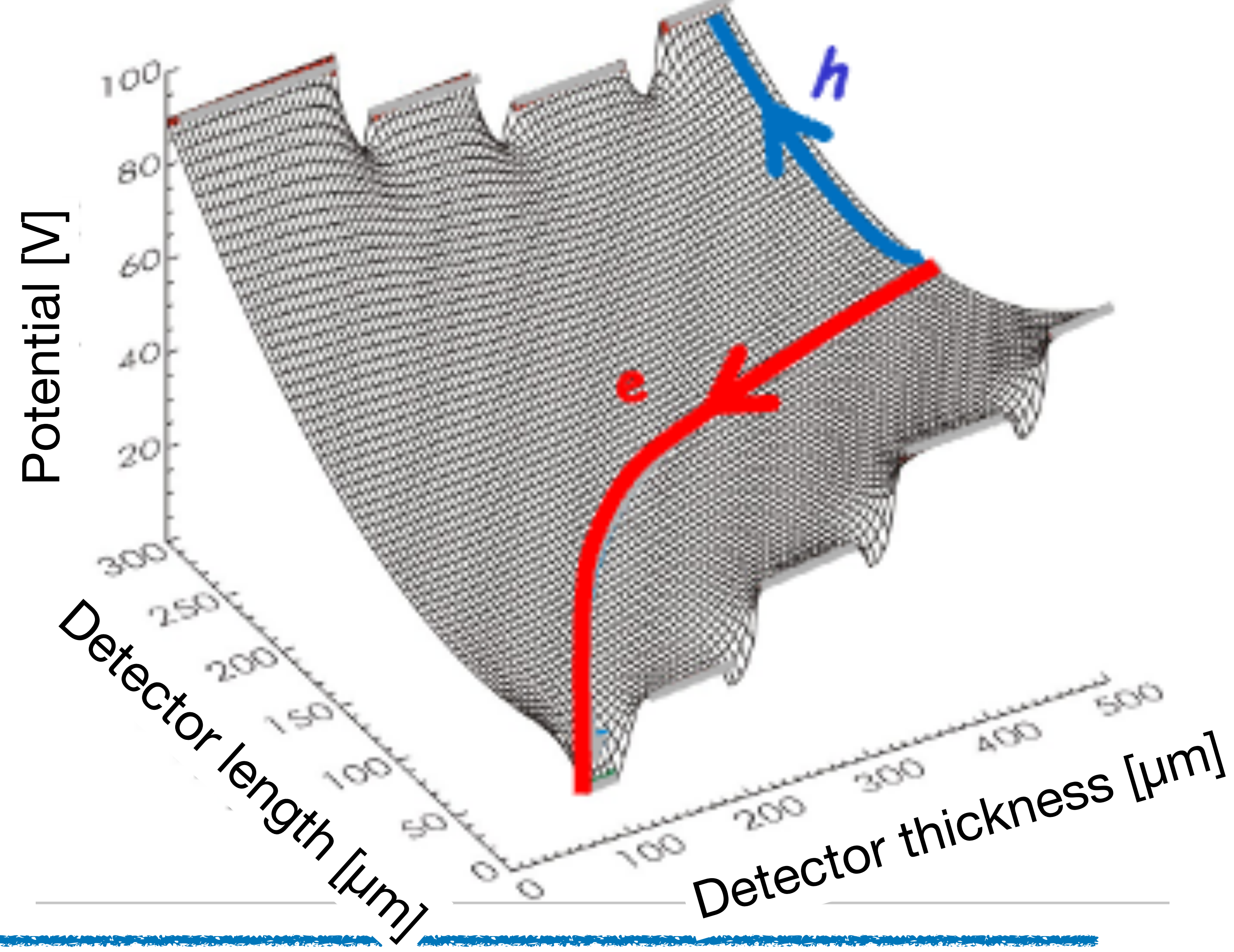
NIMA 226 (1984) 608

collect charge from a large area with minimal capacitance

segmented anode → transverse position
time-of-flight → longitudinal position



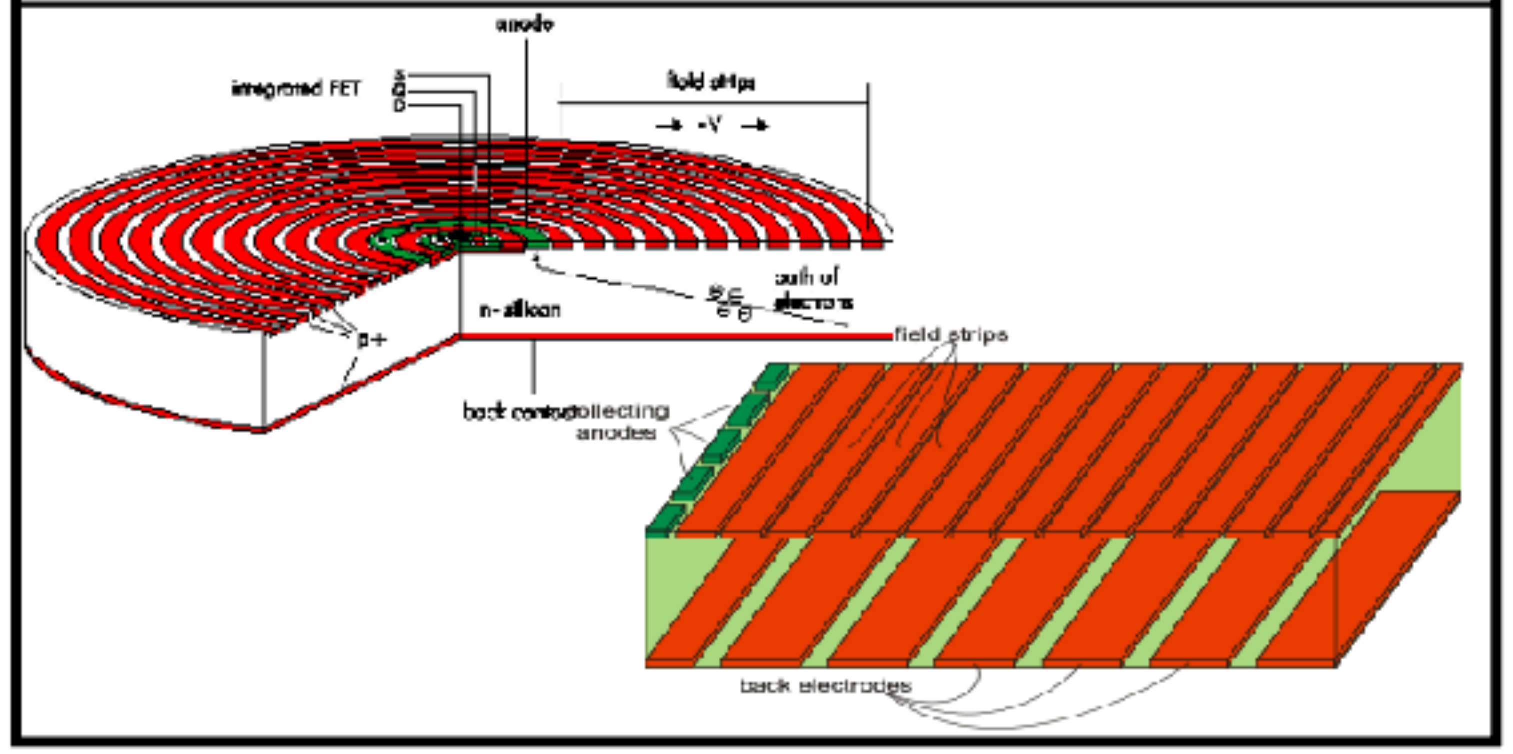




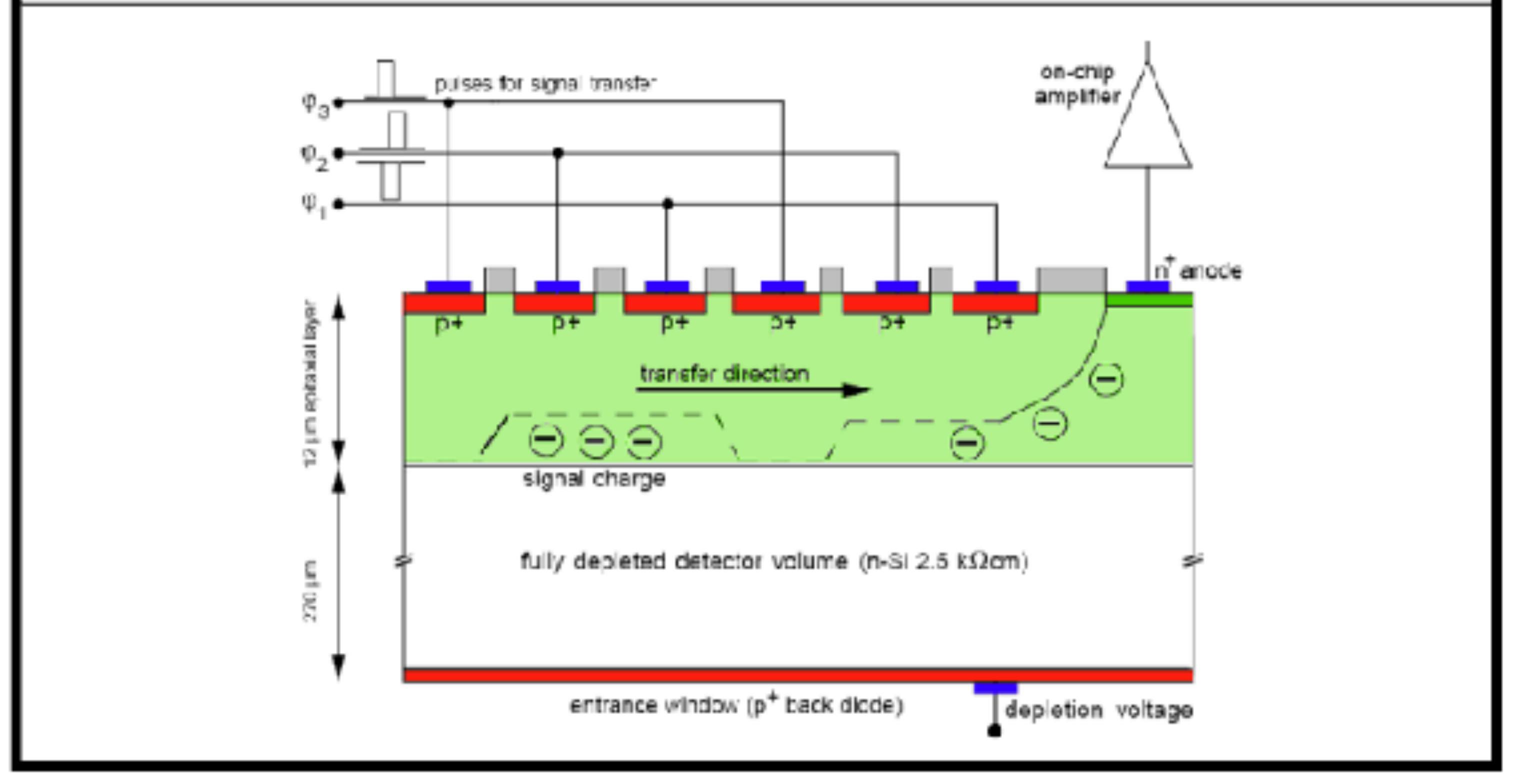
Silicon Drift Detectors

The Family of Detectors Based on Sideward Depletion

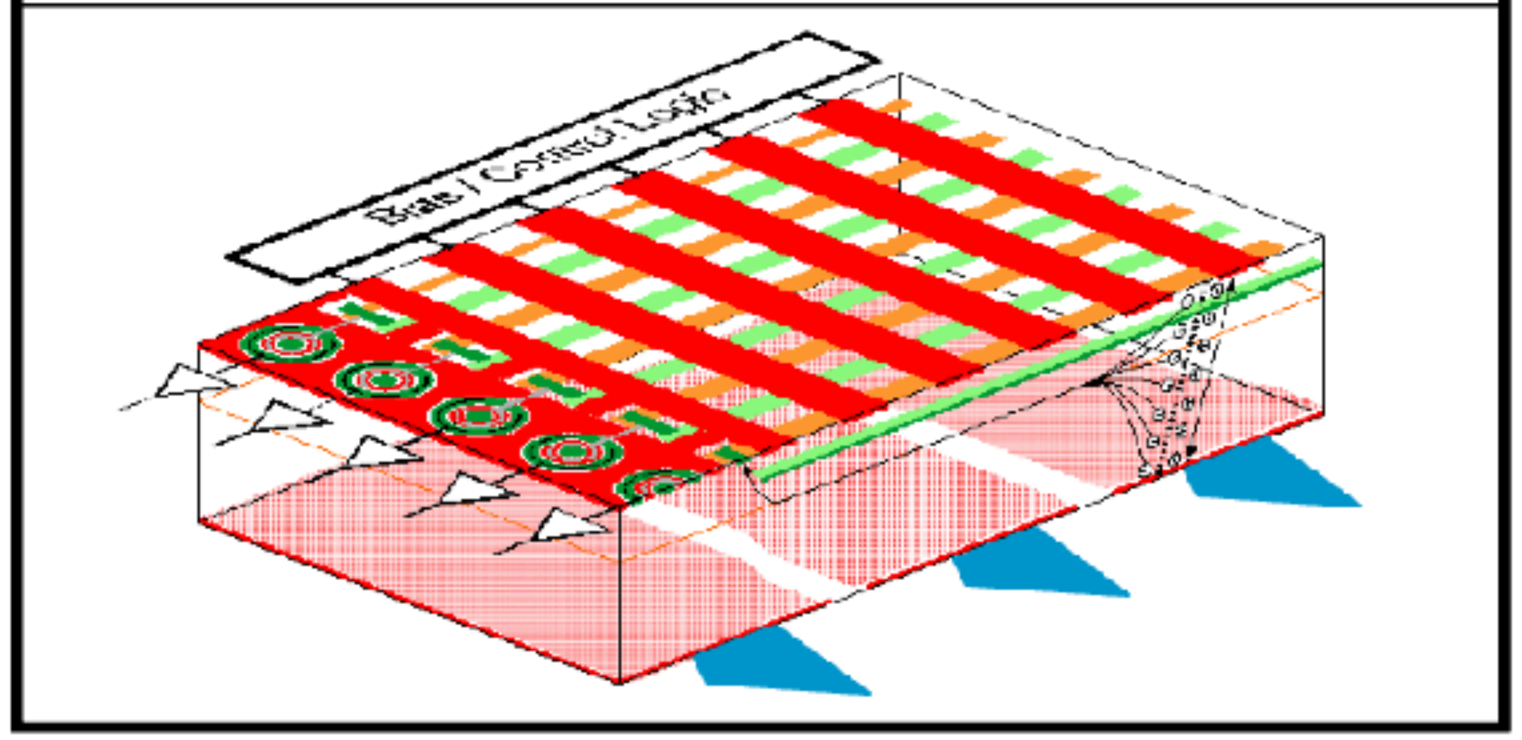
Silicon drift detector



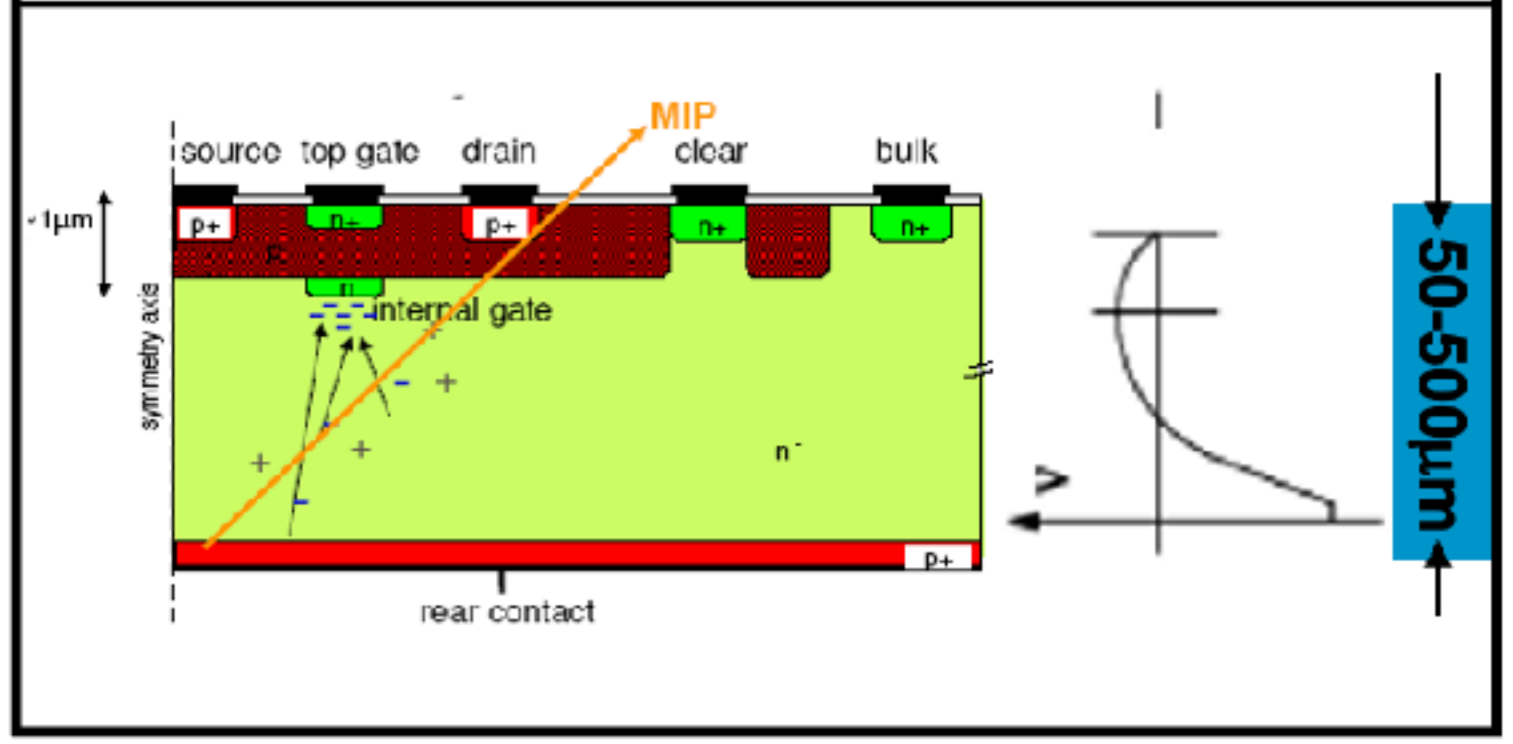
Fully depleted pnCCD



Controlled-drift detector



DEPFET



Large area low noise detectors became feasible

Many variations in the design

Main fields of application:

- X-ray detection
- Astro-particle physics
- Photon science

Talk from
Susanne Mertens

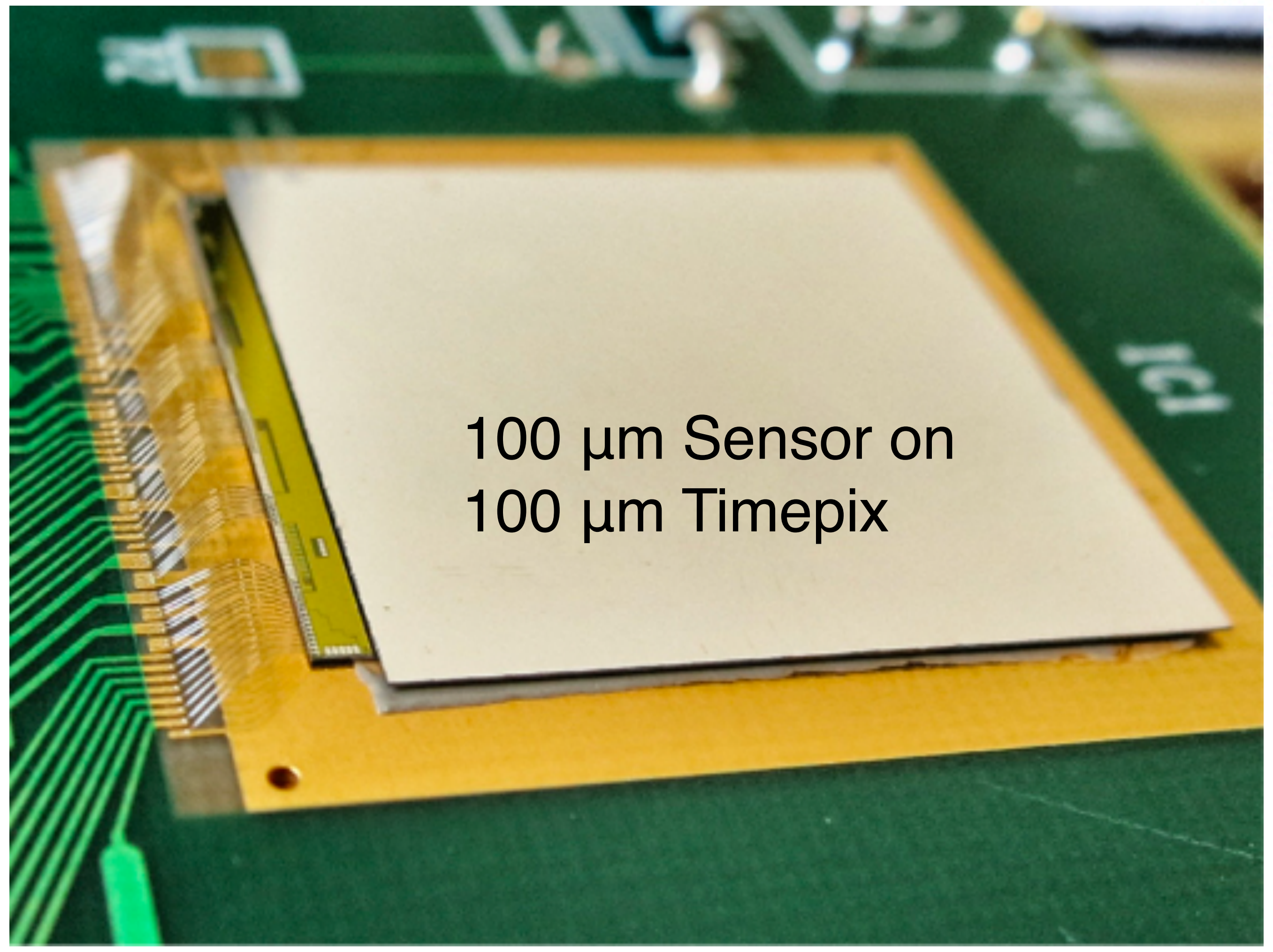
- Flavour physics @ Belle II

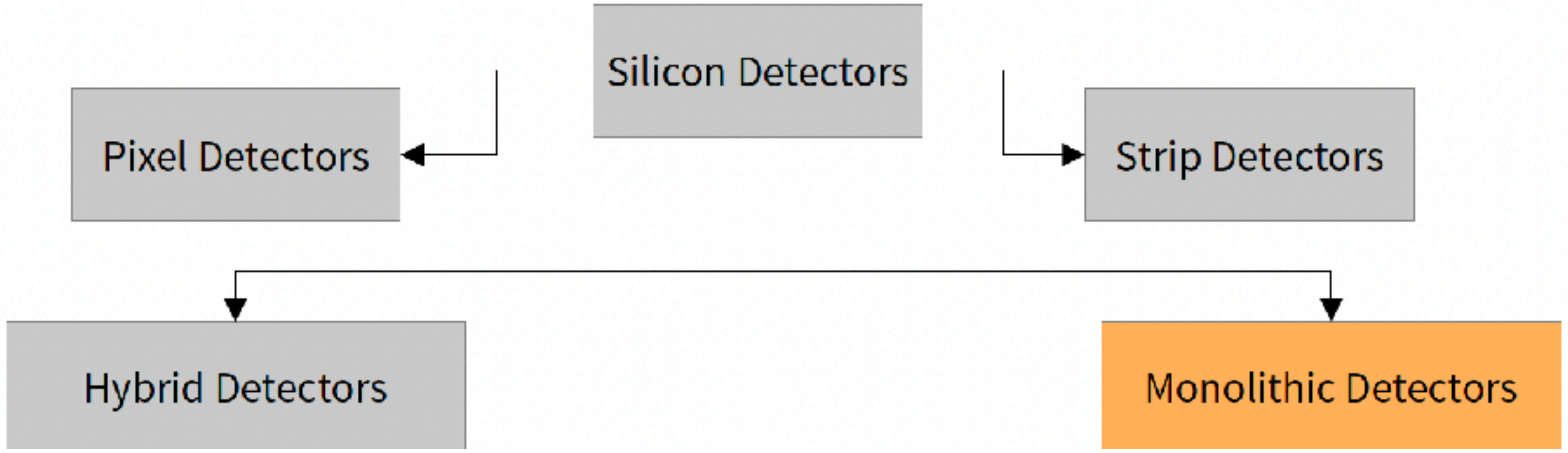
Talk from
Peter Križan

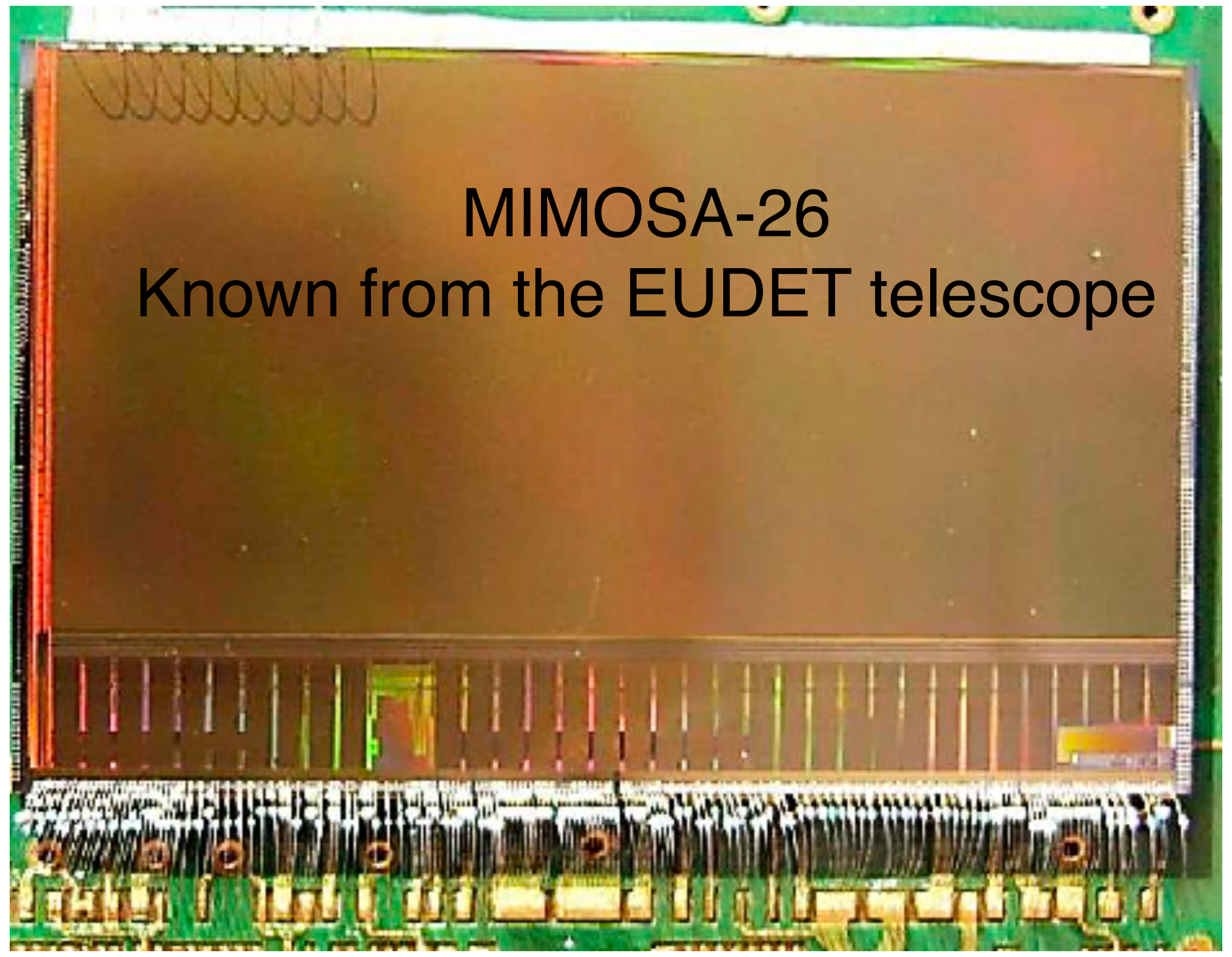
Erika.Garutti @ uni-hamburg.de

Segmented Silicon Detectors

various design concepts


100 µm Sensor on
100 µm Timepix



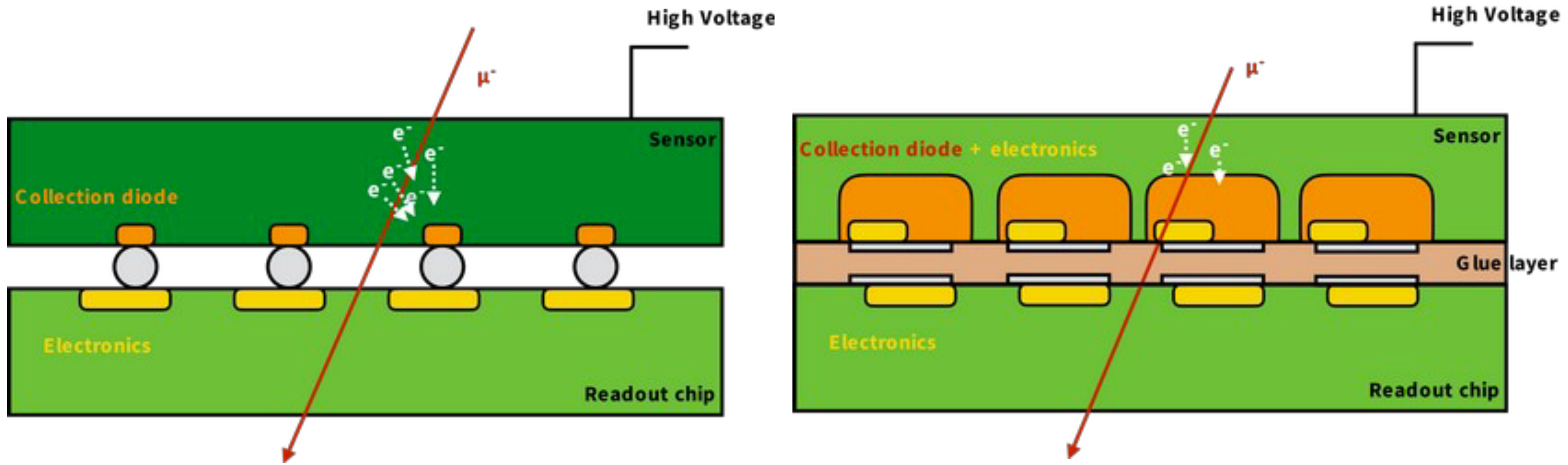

MIMOSA-26
Known from the EUDET telescope

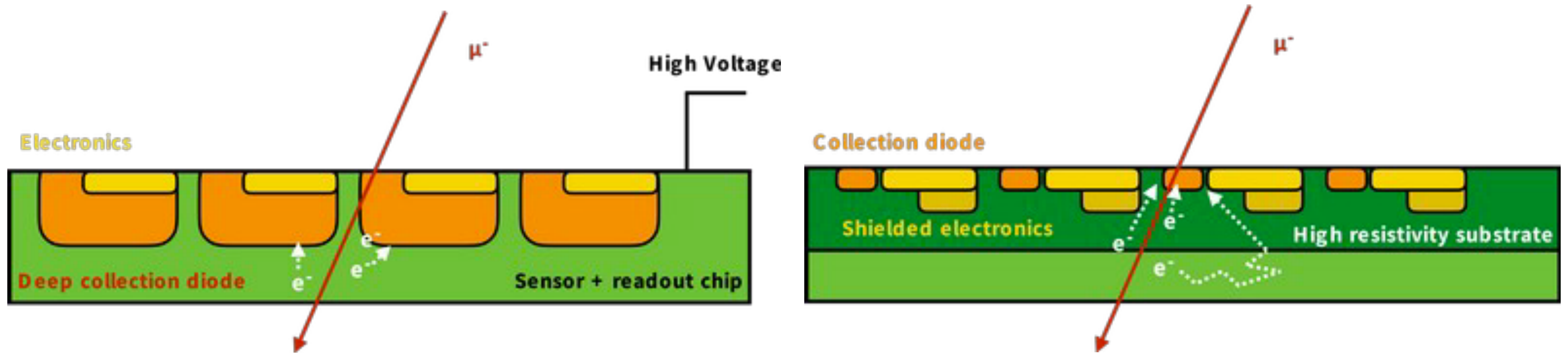
Sensor and readout chip separately optimised and tested before hybridisation

at LHC beginning (~2000)

	Hybrid pixels (2000)	**MAPS (2000)**
Single point resolution	~ 30 µm	~2 µm
Material budget	~ 500 µm Si	~ 50 µm Si
Time resolution	25 ns	~10 ms
Radiation hardness	~$10^{15}\ n_{eq}/cm^2$	$10^{12}\ n_{eq}/cm^2$

All-in-one approach:
sensing volume with intelligence

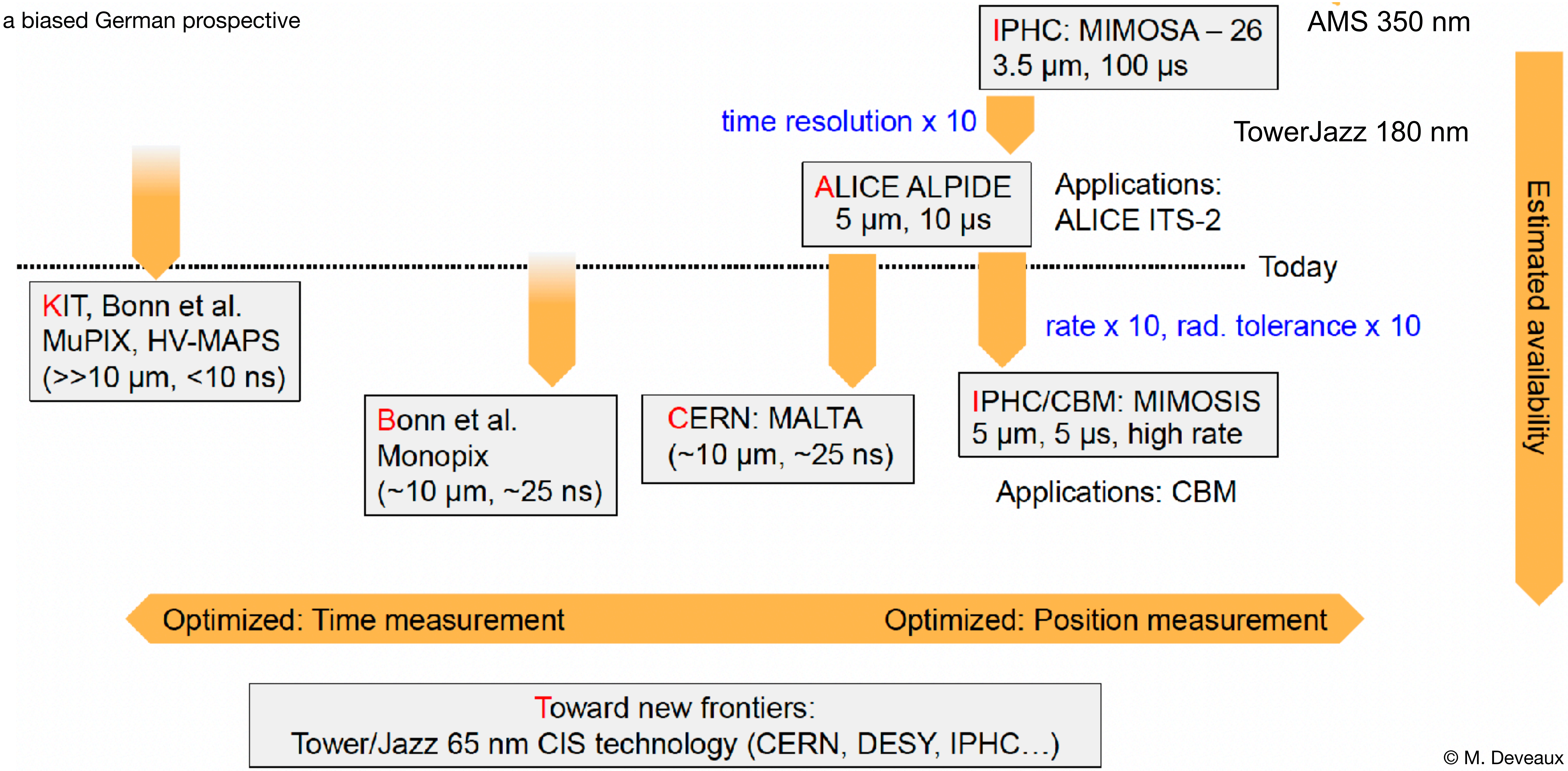




CMOS Monolithic Active Pixel Sensors

sensor and readout elements all-in-one

* a biased German prospective



IPHC: MIMOSA – 26
3.5 µm, 100 µs

AMS 350 nm

time resolution x 10

TowerJazz 180 nm

ALICE ALPIDE
5 µm, 10 µs

Applications:
ALICE ITS-2

Today

KIT, Bonn et al.
MuPIX, HV-MAPS
(>>10 µm, <10 ns)

Bonn et al.
Monopix
(~10 µm, ~25 ns)

CERN: MALTA
(~10 µm, ~25 ns)

rate x 10, rad. tolerance x 10

IPHC/CBM: MIMOSIS
5 µm, 5 µs, high rate

Applications: CBM

Estimated availability

Optimized: Time measurement

Optimized: Position measurement

Toward new frontiers:
Tower/Jazz 65 nm CIS technology (CERN, DESY, IPHC…)

© M. Deveaux

CMOS Monolithic Active Pixel Sensors

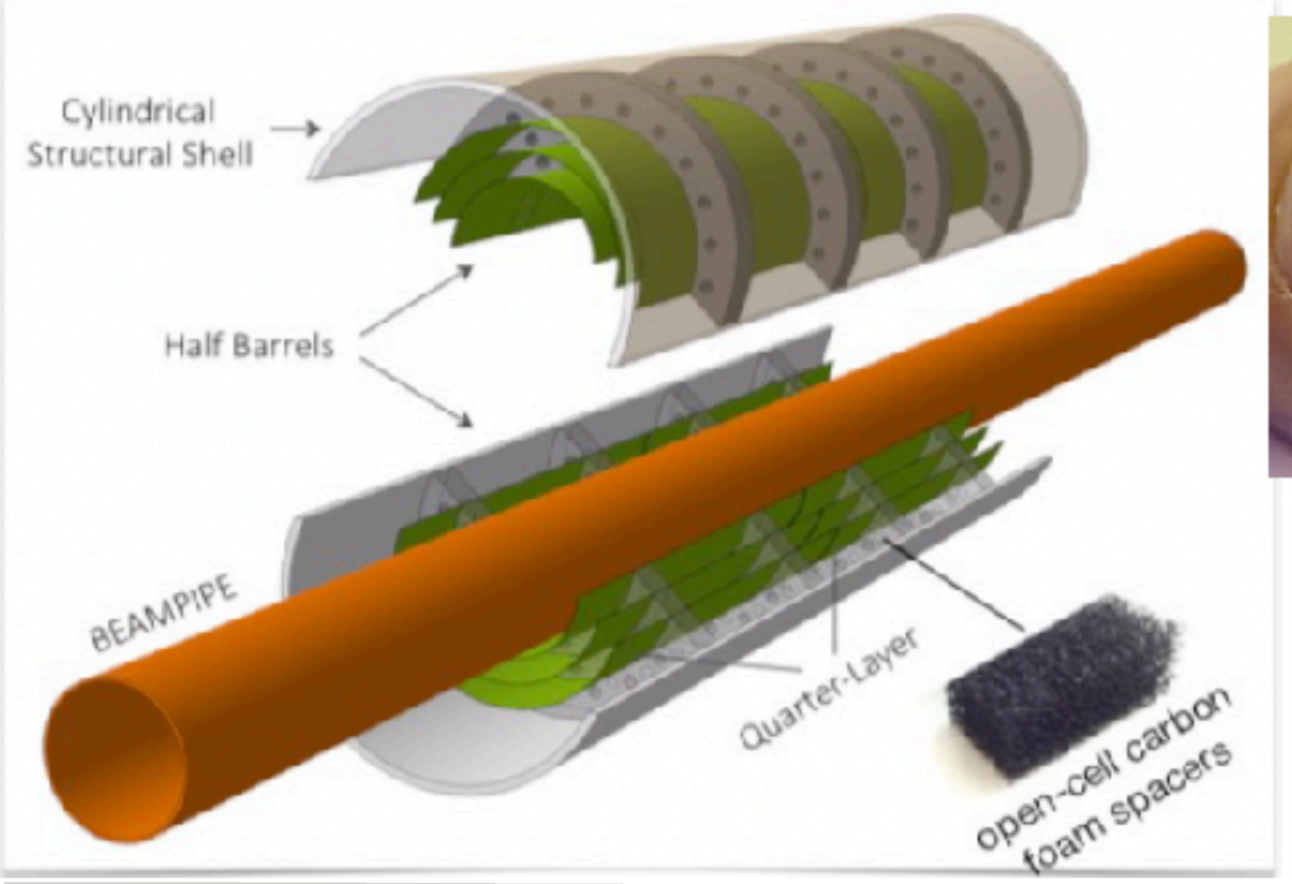
sensor and readout elements all-in-one

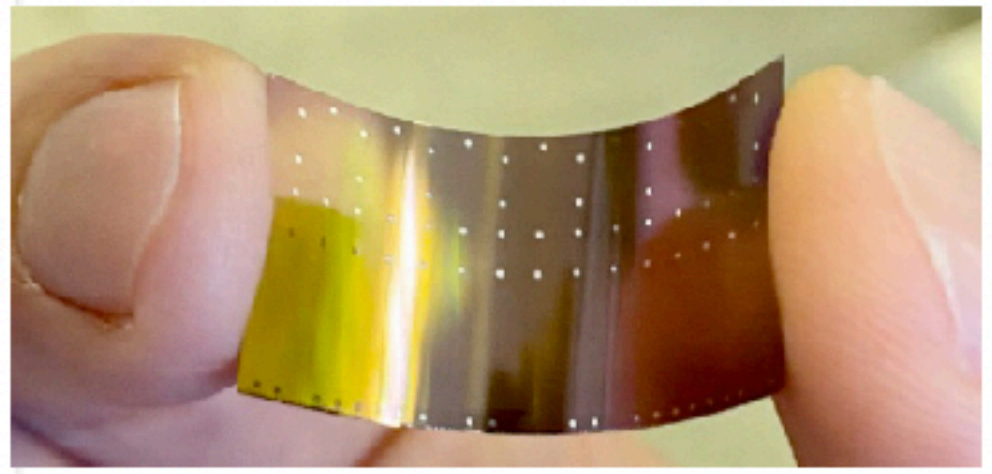
Monolithic Detectors

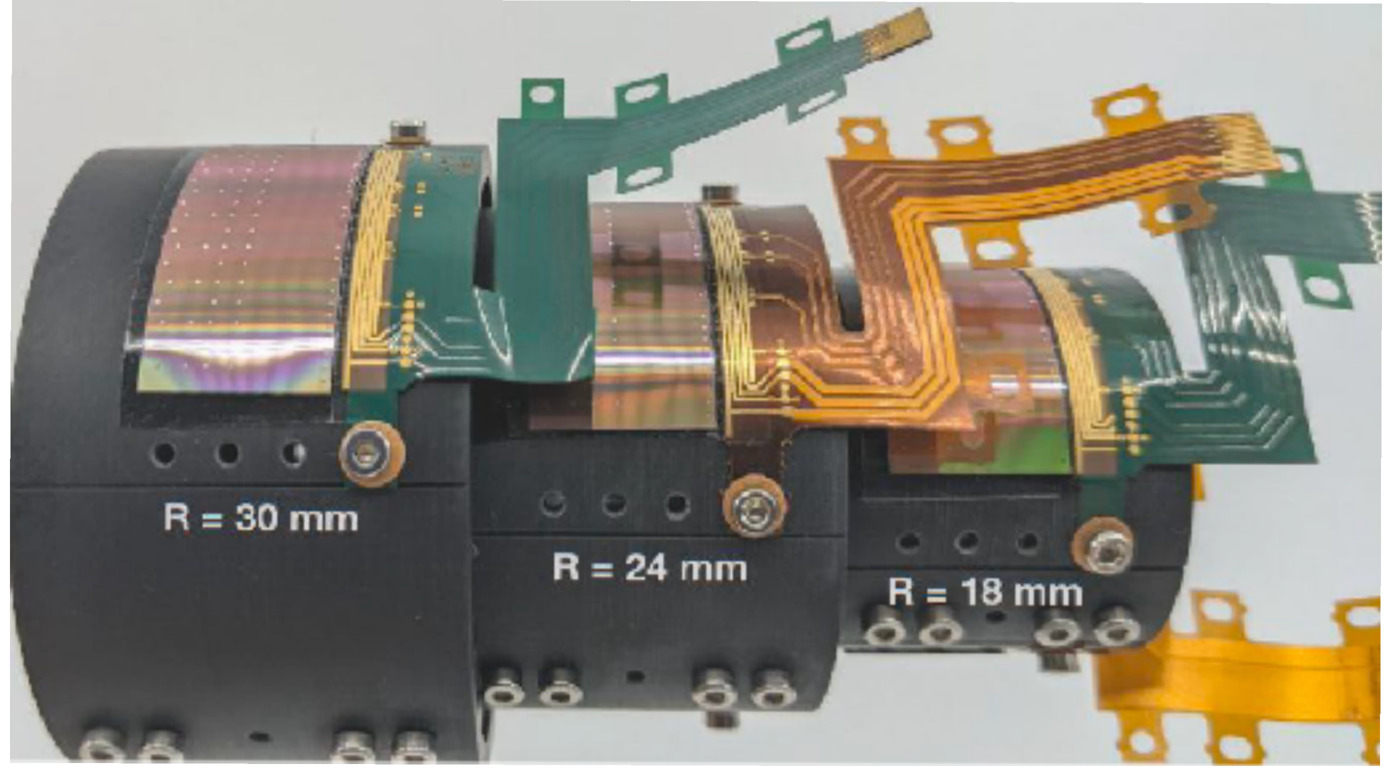
CMOS MAPS for ALICE ITS3 (Run 4):

(LOI: CERN-LHCC-2019-018, M. Mager)

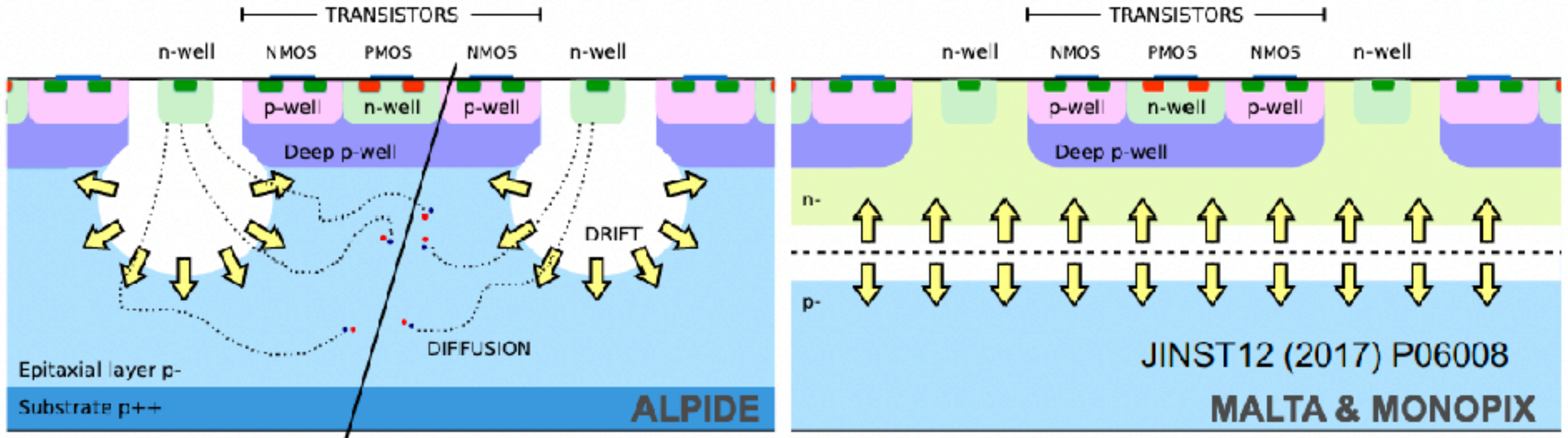
- Three fully cylindrical, wafer-sized layers based on curved ultra-thin sensors (20-40 µm), air flow cooling
- Very low mass, < 0.02-0.04% per layer







Radiation hardness of MAPS: From ALPIDE to MALTA/Monopix with modified Tower Jazz 180 nm process



TJ180nm Standard Process TJ180nm Modified Process

→ Up to 97% efficiency after fluence of $1 \times 10^{15}\ n_{eq}/cm^2$ H. Pernegger

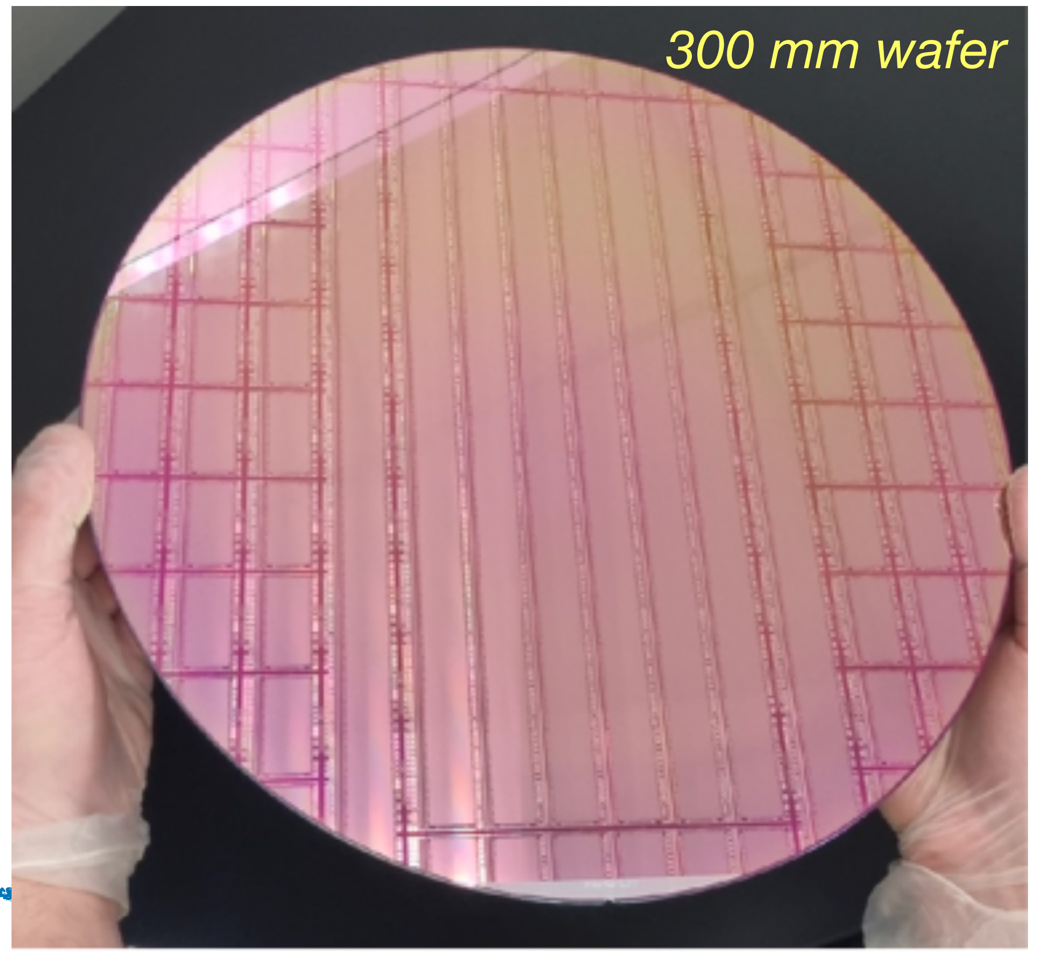
New CMOS TPSCo 65 nm technology

Validated on Digital and Analog Pixel Test Structures up to 10^{15} cm^{-2} and 100 kGy

Currently testing **stitching** for wafer scale sensors (now 26 x 1.4 cm^2)

A. Kotliarov

→ Efficiency > 99.9% independent on bending radius

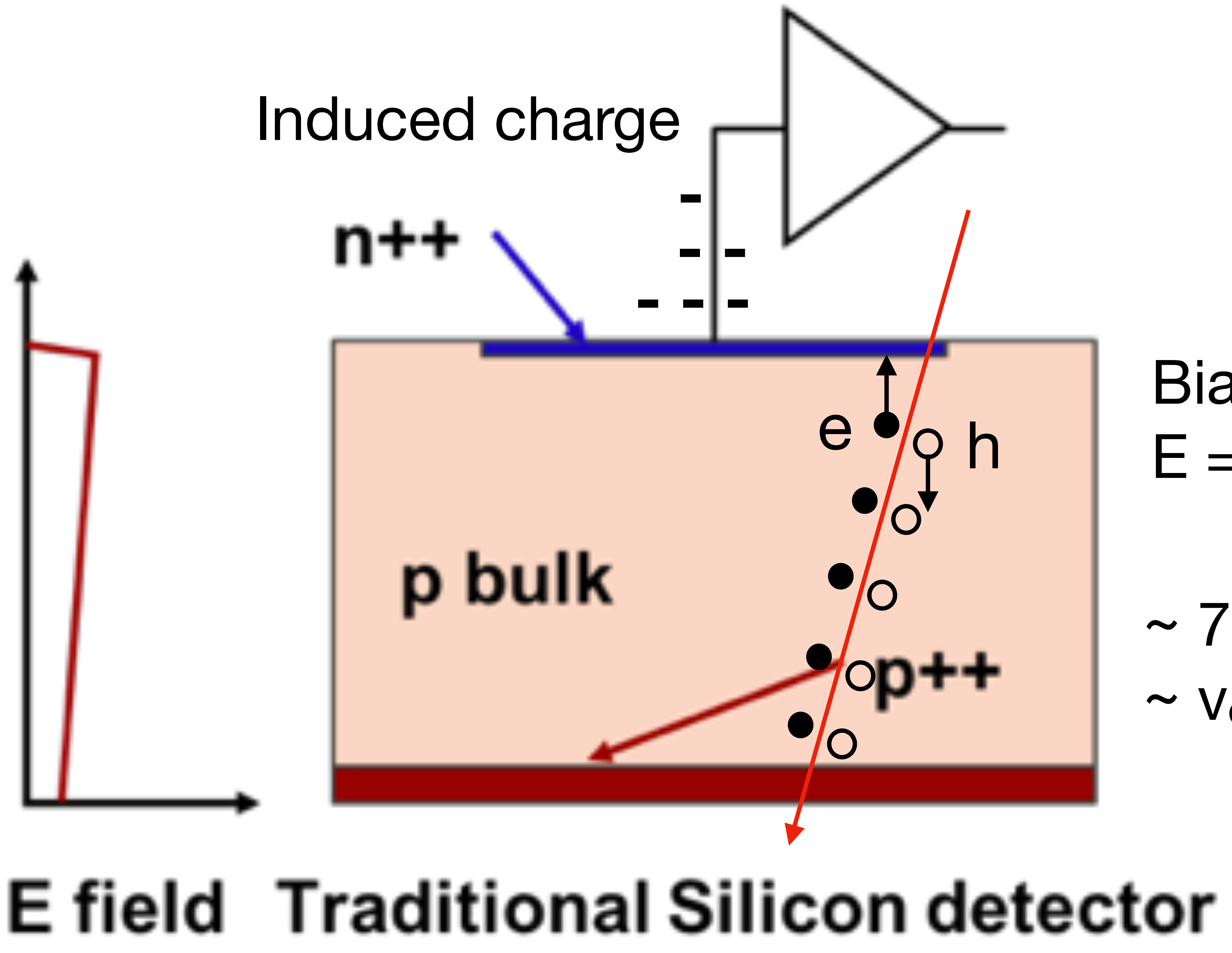


Silicon Detectors with Gain

fast timing

Silicon diode (pixel detectors)

Signal pulse rise time ~ 1 ns
Time resolution ~ 150 -200 ps

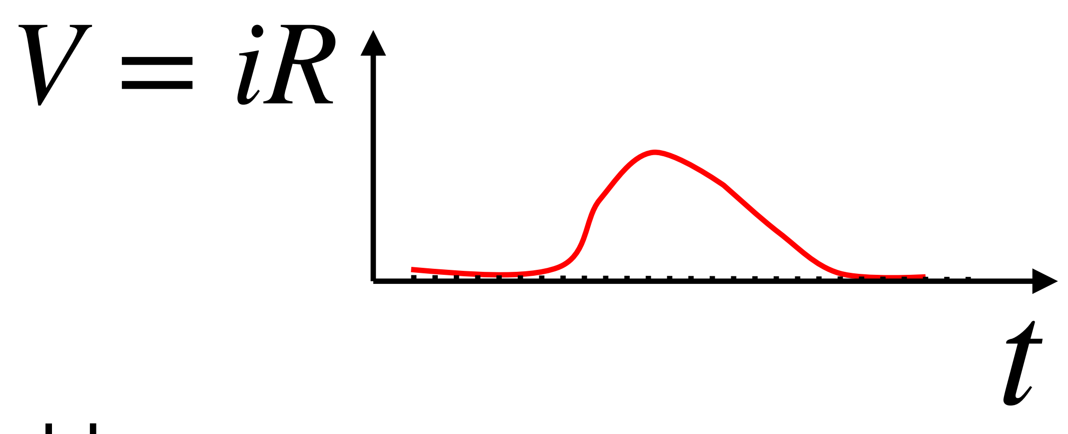


Bias: 100 V / Thickness: 300 µm
E = 30 kV / cm

~ 75 pairs / µm
~ v_d = 100 µm/ns (drift velocity)

- The charge carriers motion induces a current on the read-out electrode
- The signal ends when the charges are collected
- Signal shape is determined by Ramo's Theorem: $i \propto q v_d E_w$

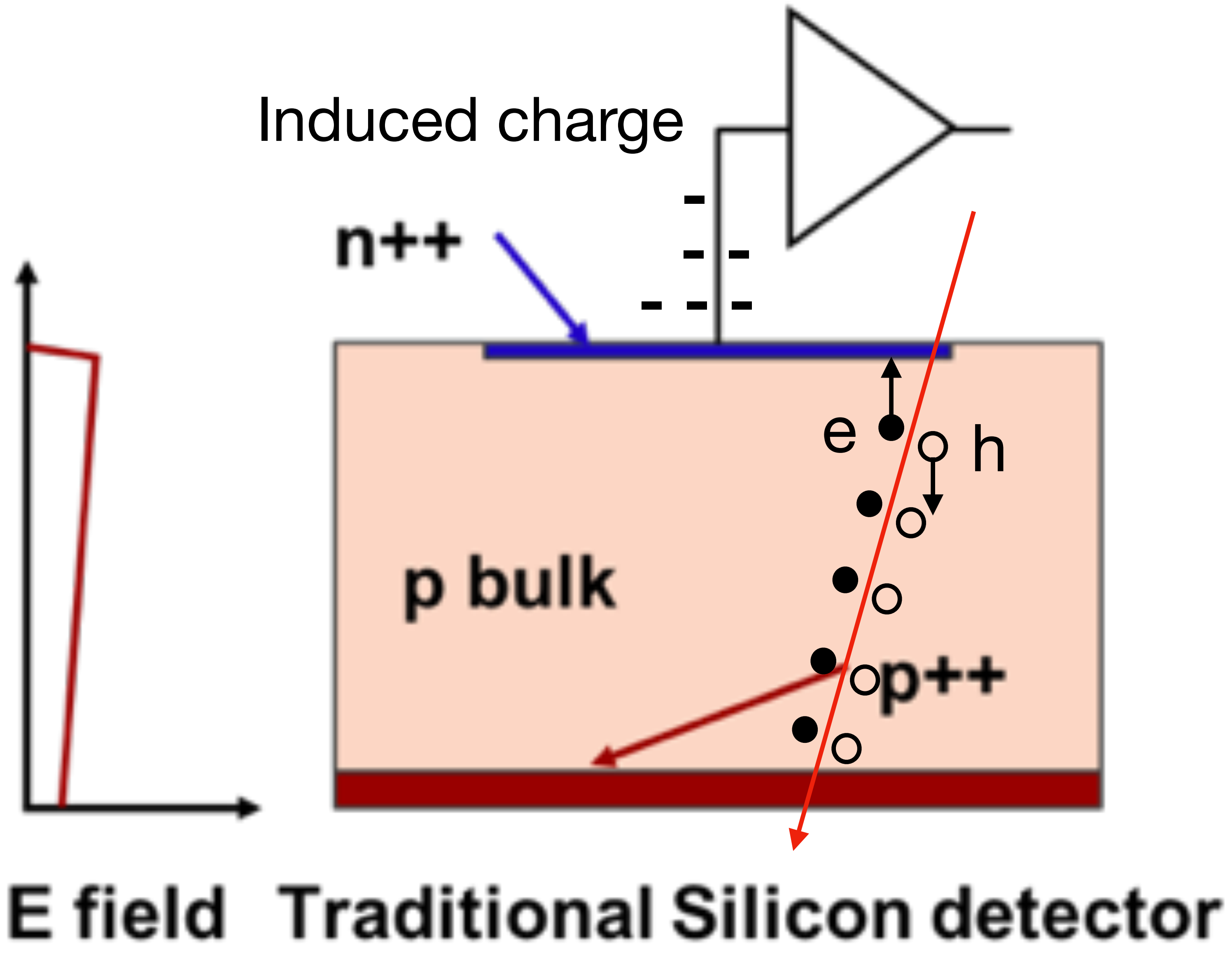
drift velocity   weighting field



Silicon Detectors with Gain

fast timing

Silicon diode (pixel detectors)



E field **Traditional Silicon detector**

Signal pulse rise time ~ 1 ns
Time resolution ~ 150 -200 ps

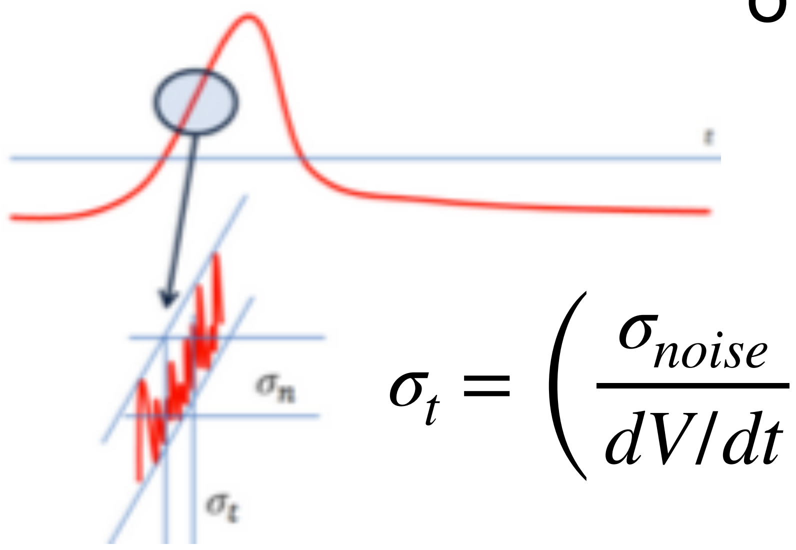
$$\sigma_t^2 = \left(\frac{\sigma_{noise}}{dV/dt}\right)^2 + (\Delta N_{e-h})^2 + (\Delta shape)^2 + (TDC, Clock, \ldots)^2$$

jitter

stochastic variation of N of e-h pairs

Signal shape negligible for good sensor design

electronics negligible



$$\sigma_t = \left(\frac{\sigma_{noise}}{dV/dt}\right)$$

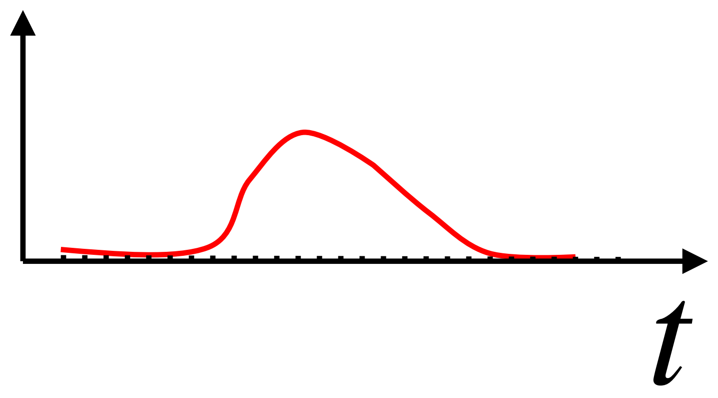
Need large dV/dt to suppress jitter
Need low internal gain

- The charge carriers motion induces a current on the read-out electrode
- The signal ends when the charges are collected
- Signal shape is determined by Ramo's Theorem: $i \propto q v_d E_w$

drift velocity

weighting field

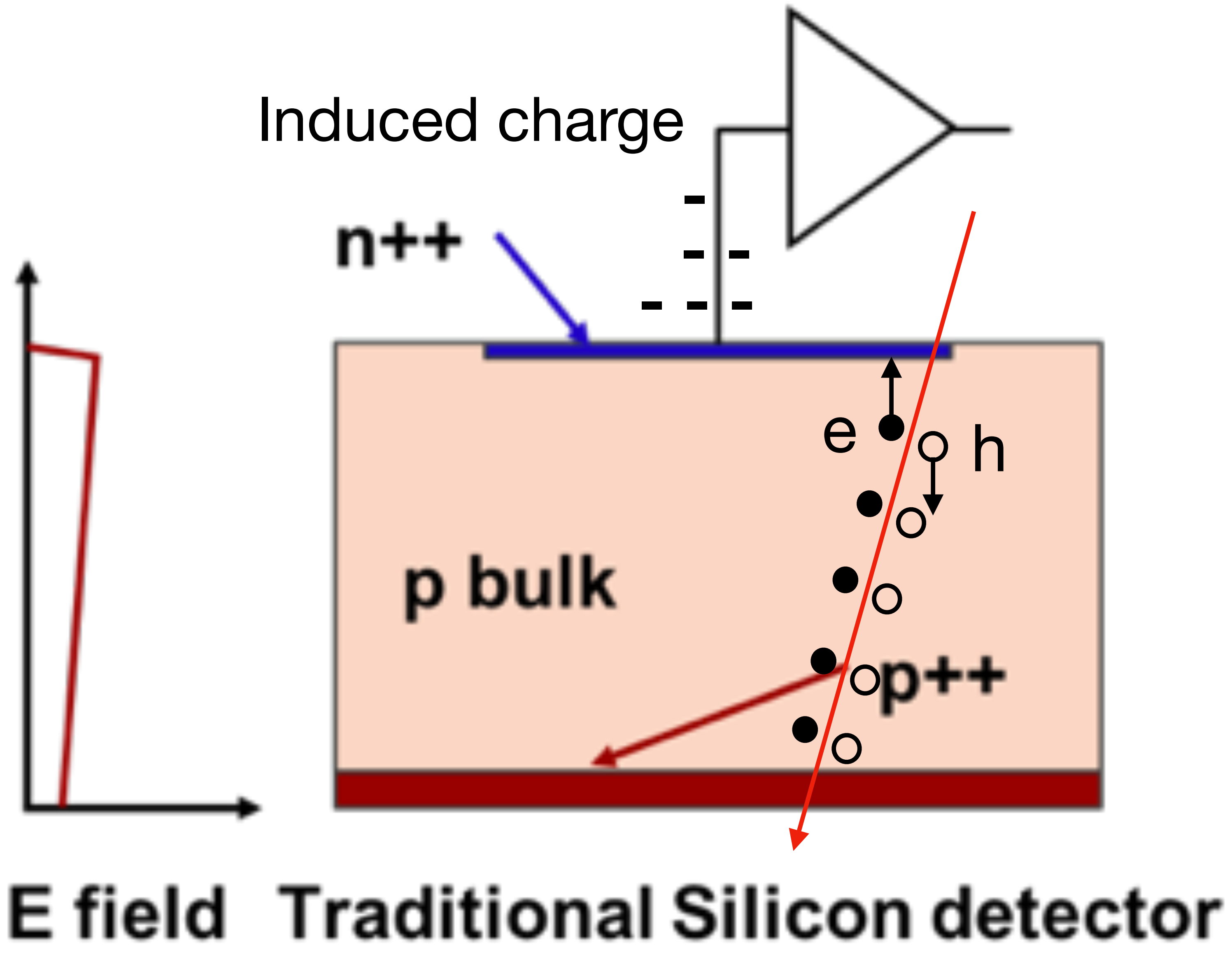
$V = iR$



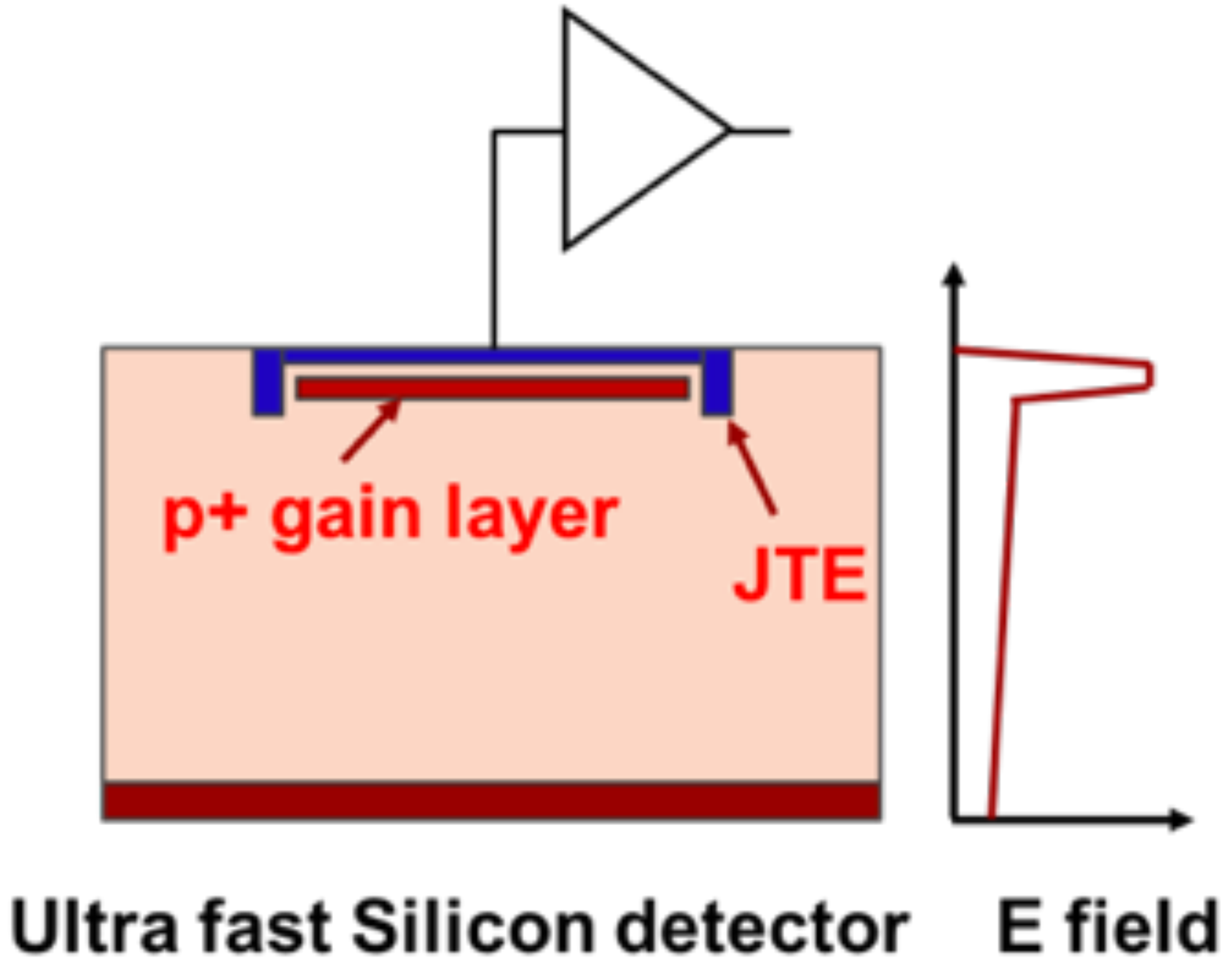
Silicon Detectors with Gain

fast timing

Silicon diode (pixel detectors)



Low **G**ain **A**valanche **D**etectors

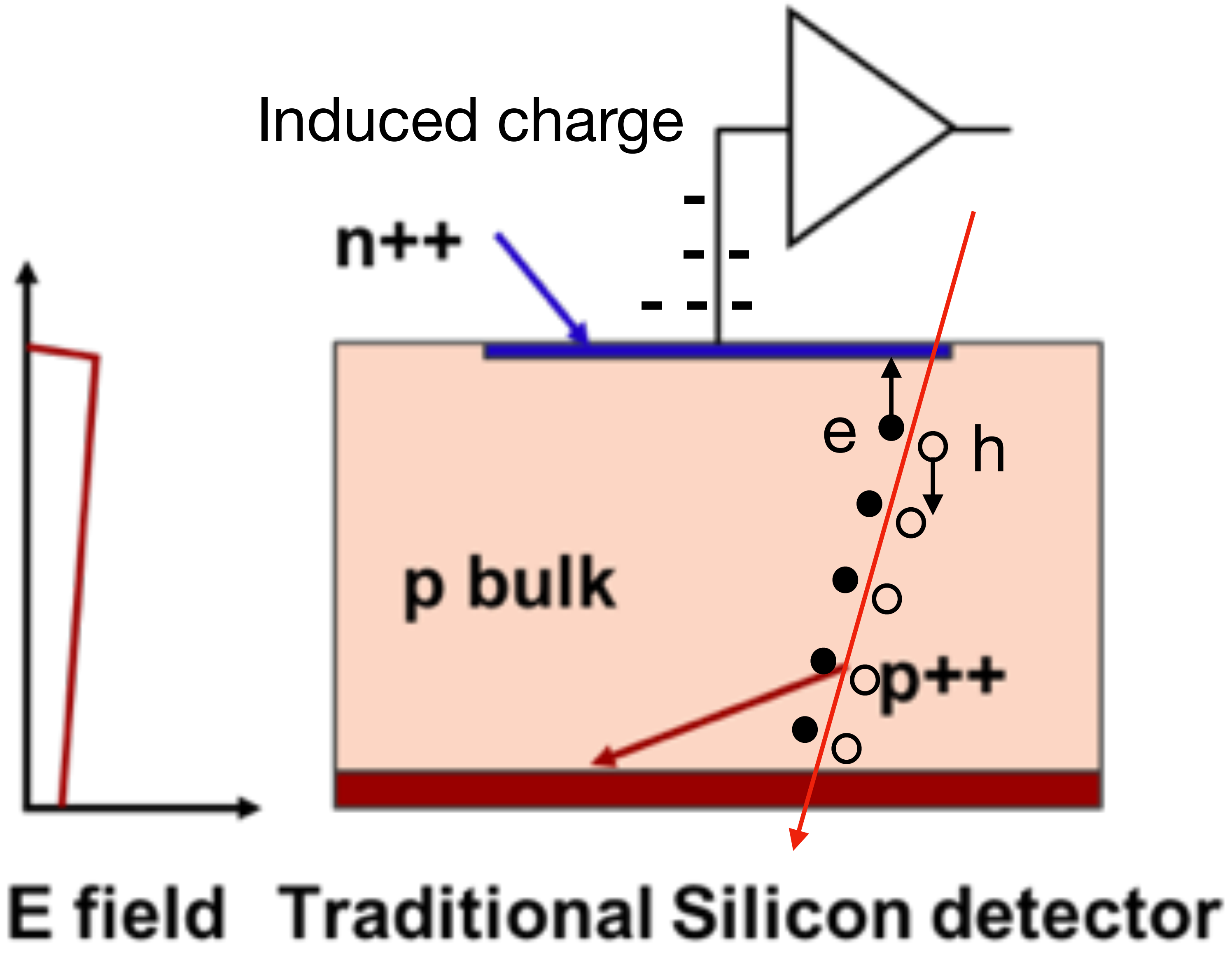


LGAD sensor first proposed and manufactured by CNM, Barcelona

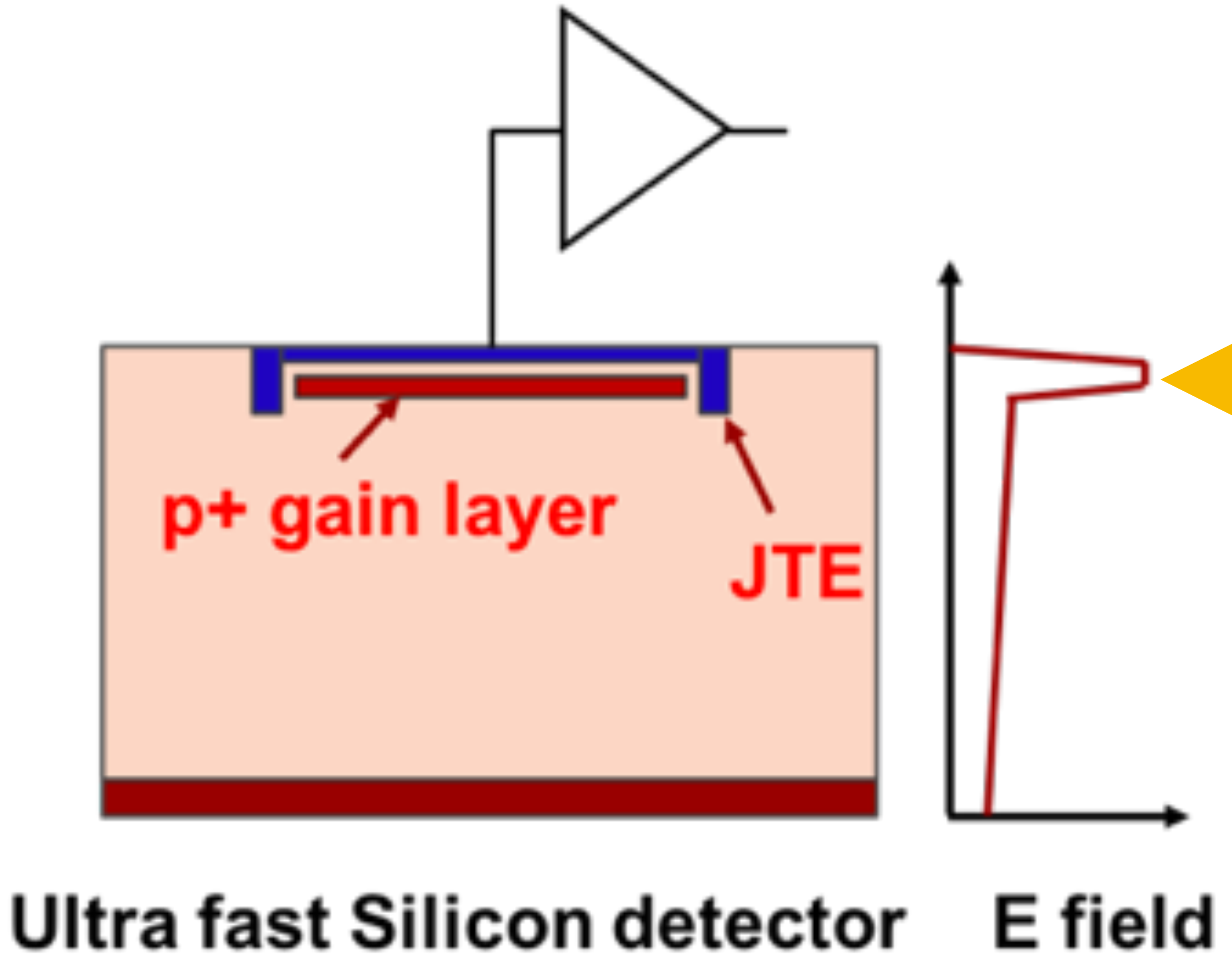
Silicon Detectors with Gain

fast timing

Silicon diode (pixel detectors)



Low **G**ain **A**valanche **D**etectors



Gain layer:
extra doping layer creates a parallel plate capacitor with high field: E ~ 300 kV/cm, closed to breakdown

LGAD sensor first proposed and manufactured by CNM, Barcelona

- Charge multiplication in high electric fields: $G =$ **Gain**

key ingredient for high temporal resolution

Silicon devices with gain:

LGAD: G = 10 — 20
APD: G = 50 — 500
SiPM: G ~ 10^5

Low Gain Avalange Detectors

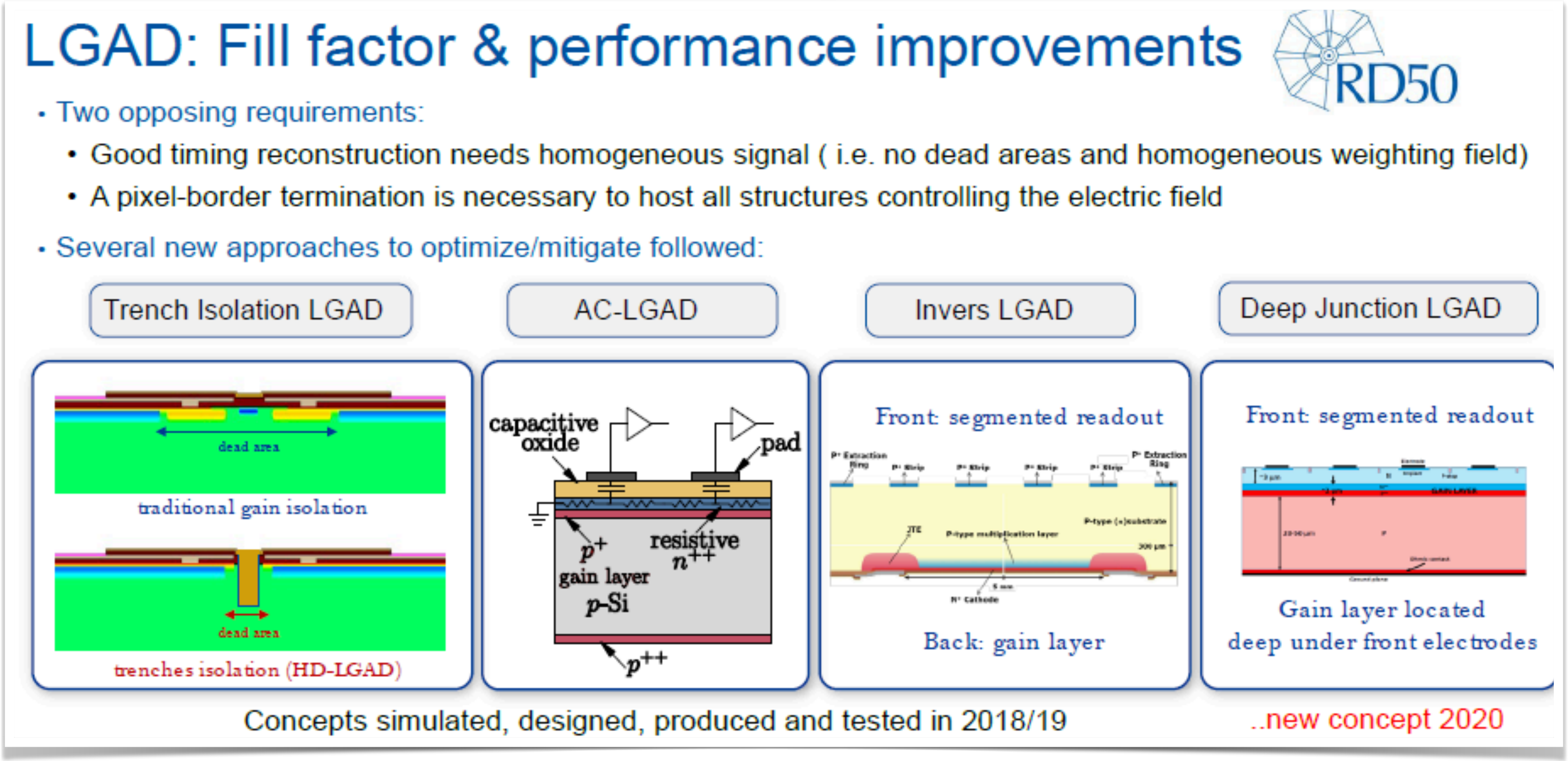
fast timing

Hybrid Detectors

Sensors for 4D-Tracking:

- Position resolution: ~ 10 µm
  ~ 5% of electrodes distance
- Time resolution: ~ 25 ps
  for 50 µm sensors

- Radiation Hardness up to
  ~ 2 x 10^{15} cm^{-2}



LGAD: Fill factor & performance improvements

- Two opposing requirements:
  - Good timing reconstruction needs homogeneous signal (i.e. no dead areas and homogeneous weighting field)
  - A pixel-border termination is necessary to host all structures controlling the electric field
- Several new approaches to optimize/mitigate followed:

Trench Isolation LGAD

AC-LGAD

Invers LGAD

Deep Junction LGAD

Concepts simulated, designed, produced and tested in 2018/19

..new concept 2020

Next employed in ATLAS / CMS fast timing layers

Ongoing:

- Improve fill factor and signal homogeneity

Erika.Garutti @ uni-hamburg.de

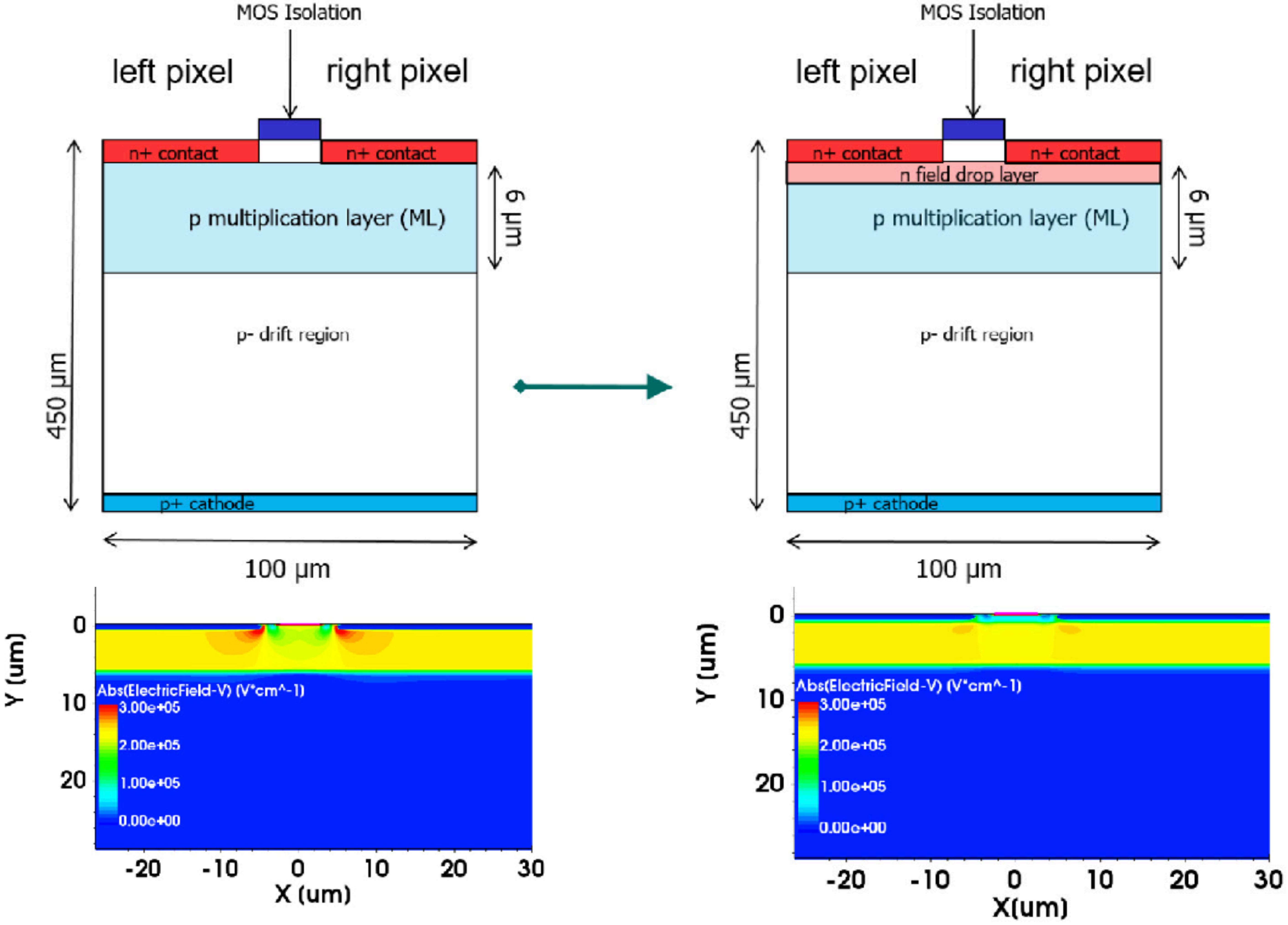
Low Gain Avalange Detectors

fast timing - with high fill factor

New LGAD development with 100% fill factor,
Rainer Richter (HLL)

MARTHA
Monolithic Array of Reach
THrough Avalanche photo diodes

The field drop layer under the n+ pixels, suppresses the peaks of the electric field at the pixel edges and thus the edge breakdown

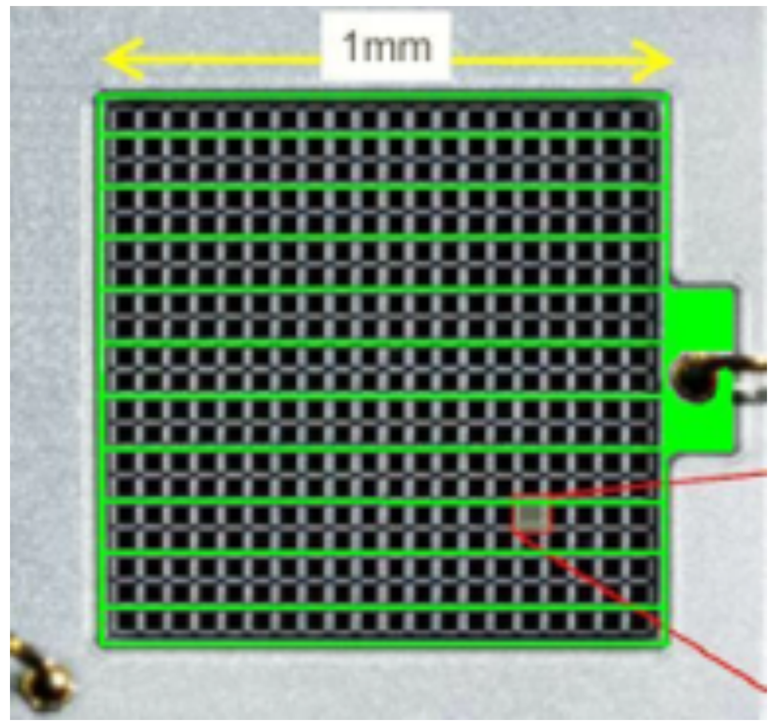


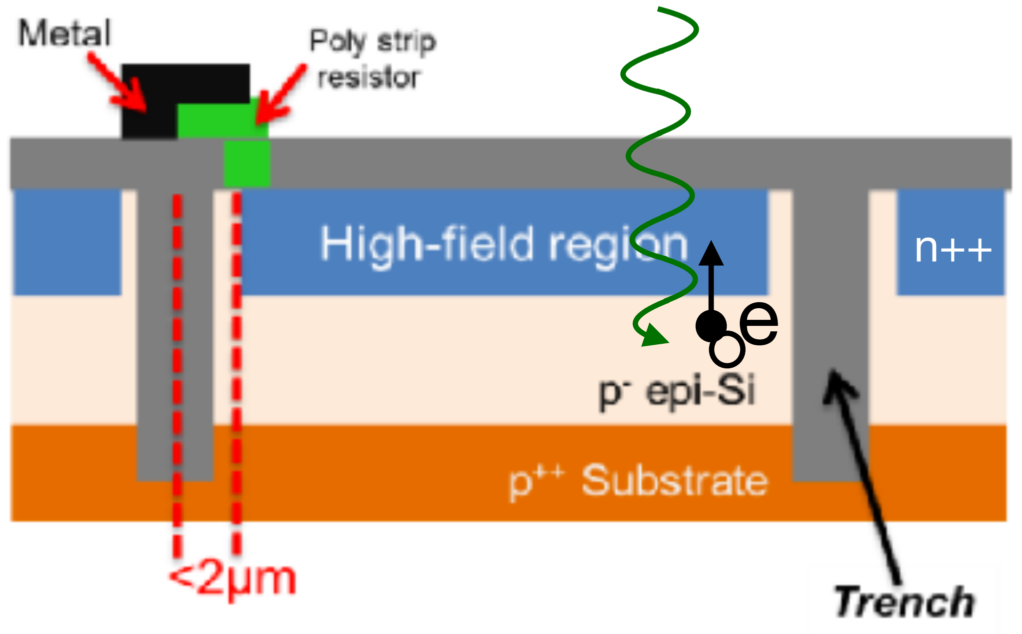
https://doi.org/10.1016/j.nima.2024.169761

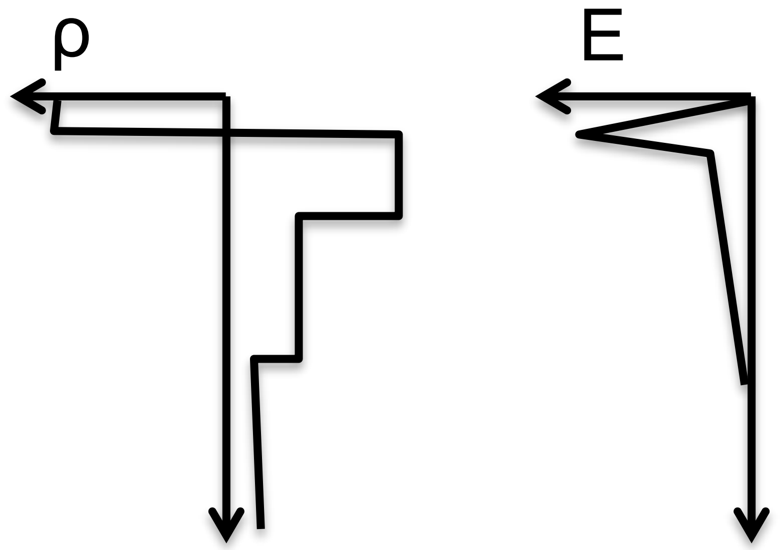
Silicon Photomultipliers

Single photon detection

SiPM







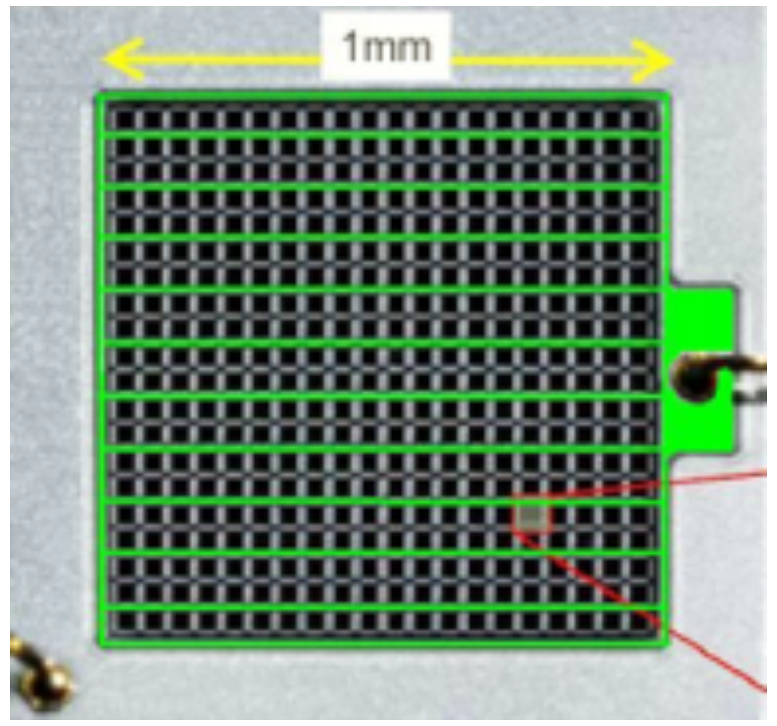
Si: ~ 5×10^{22} atoms/cm³
n++: ~ 10^{19} /cm³ (type V doped)
p+: ~ 10^{16} /cm³ (type III doped)

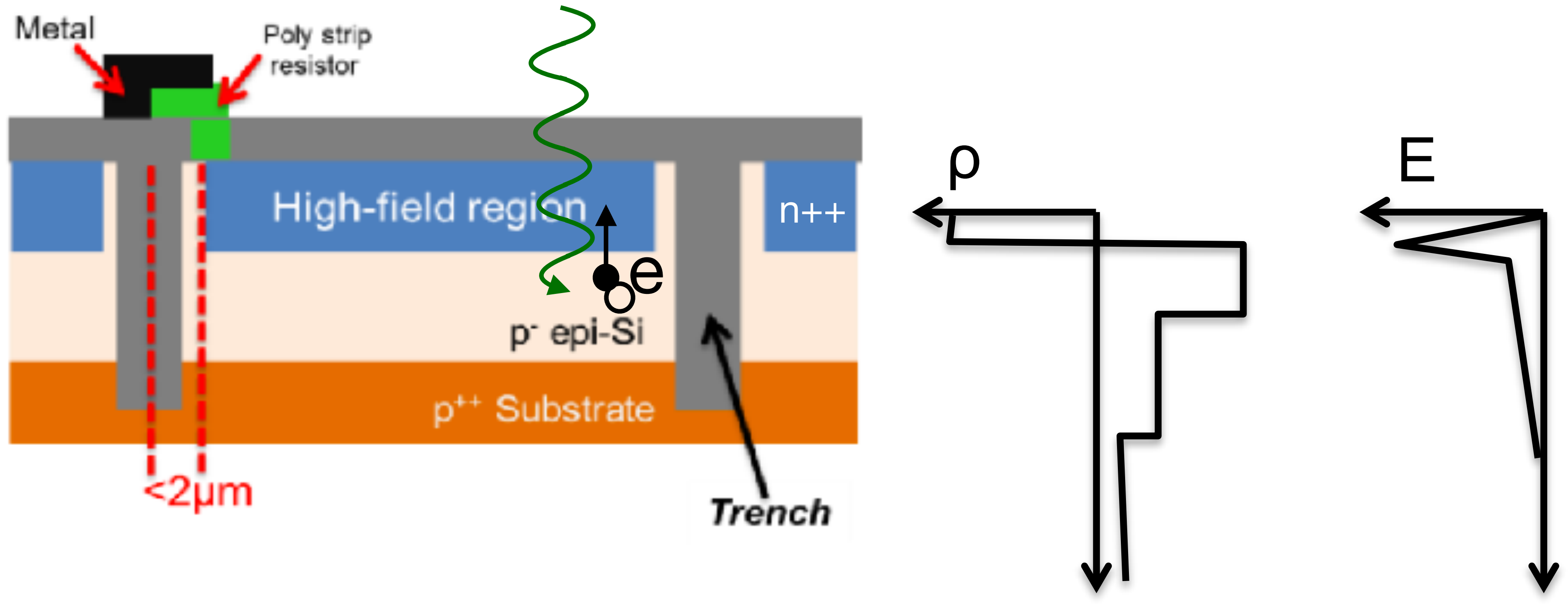
Bias: > 30 V / Thickness: ~ 1 µm
E > 300 kV / cm

Silicon Photomultipliers

Single photon detection

SiPM





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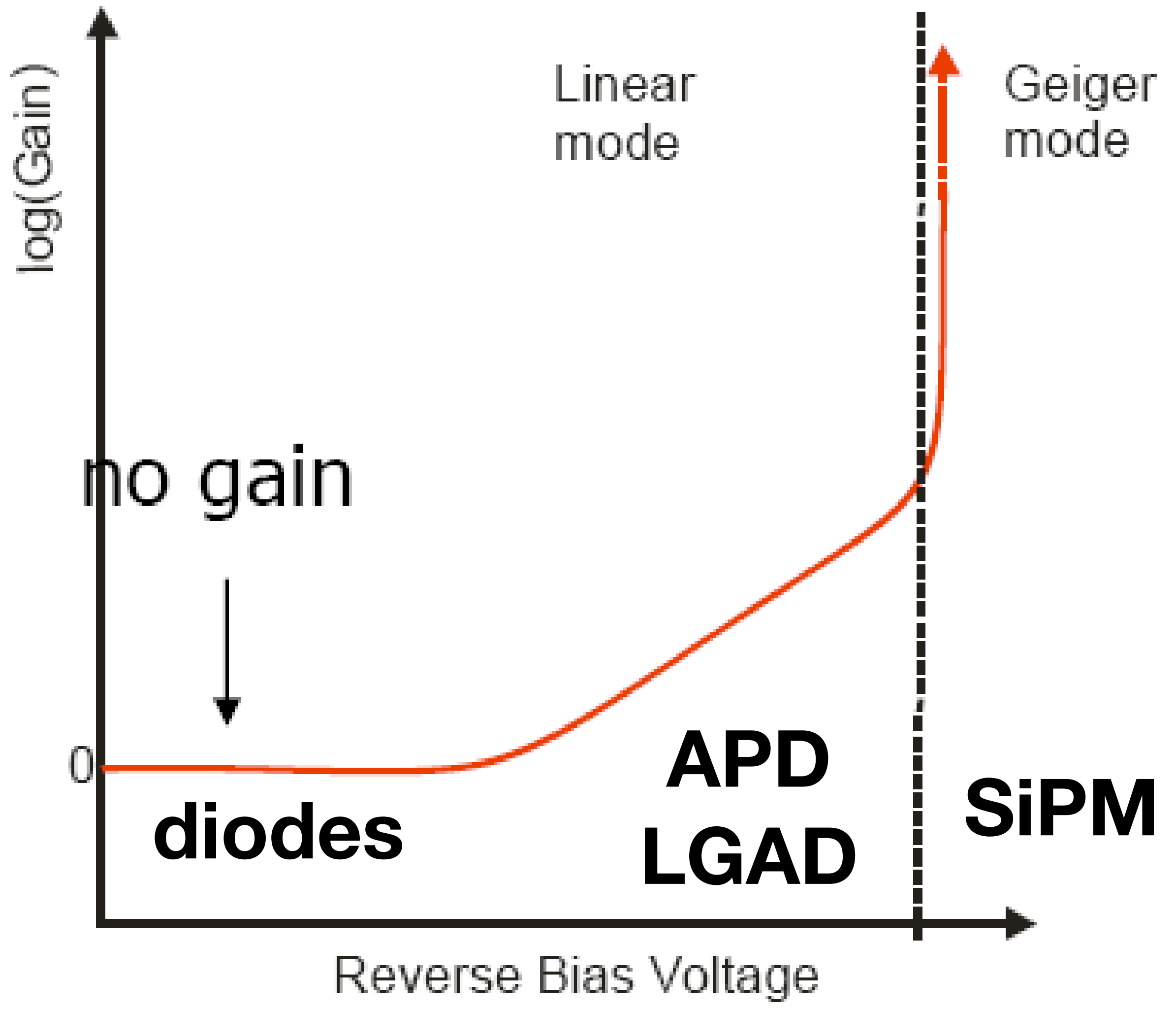
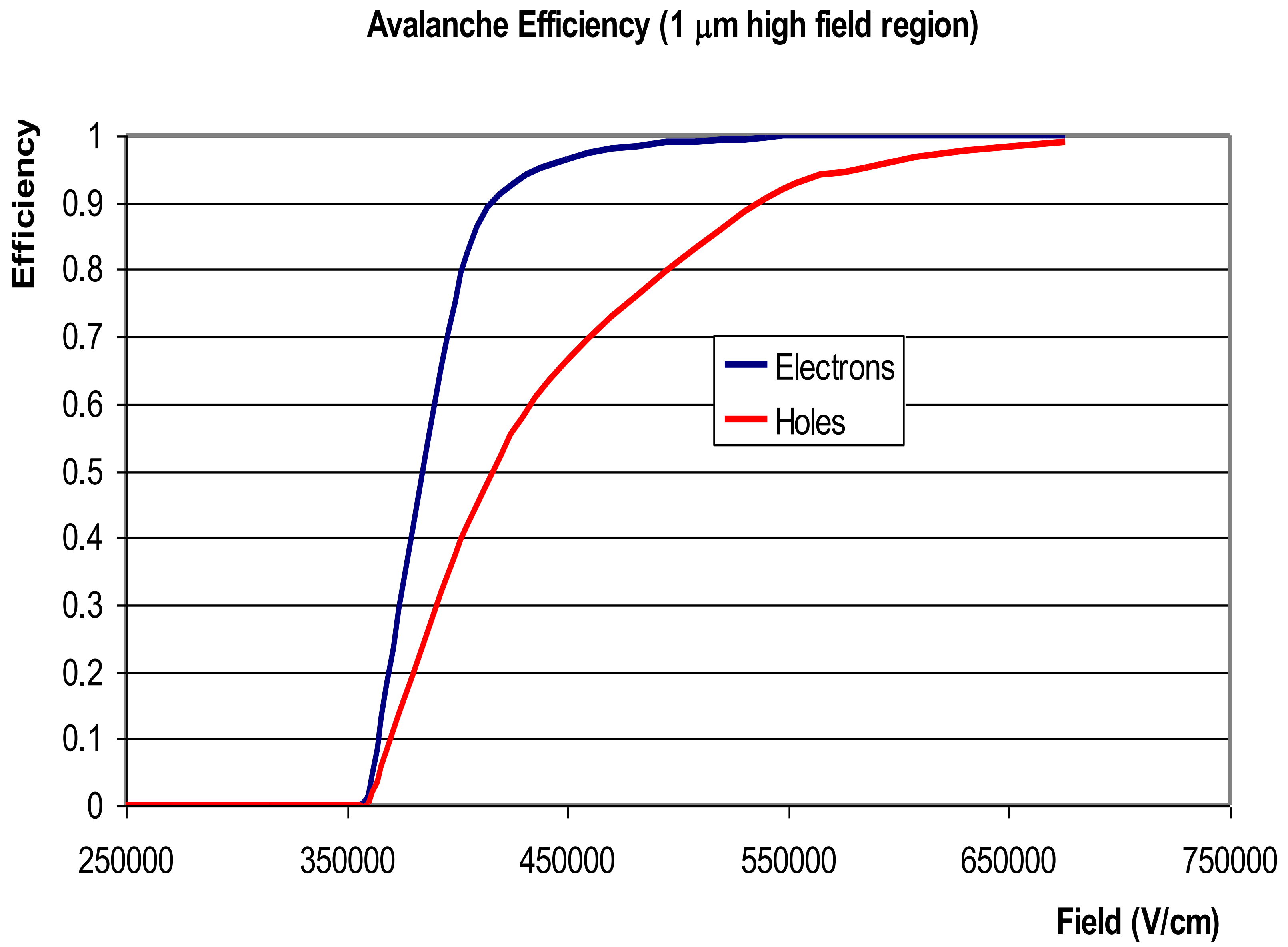
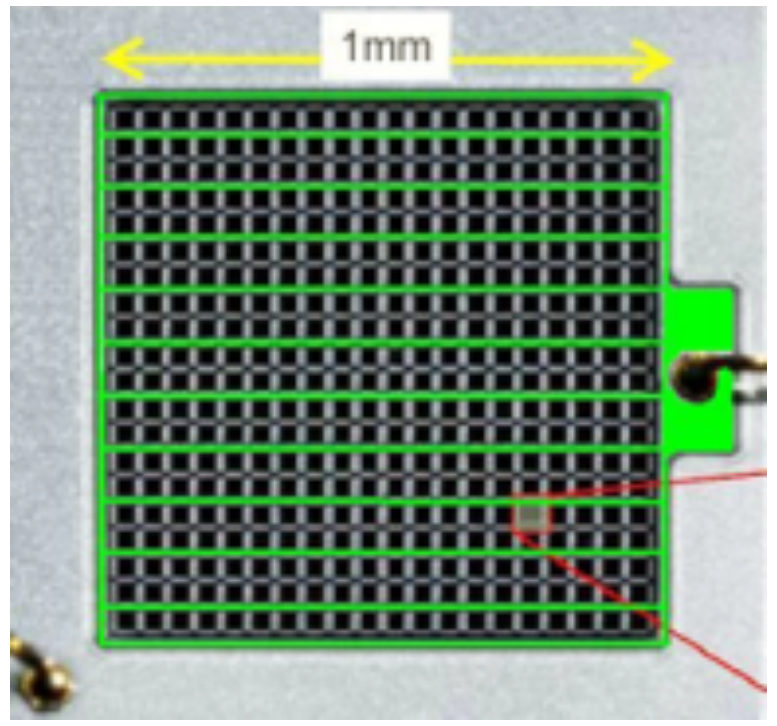


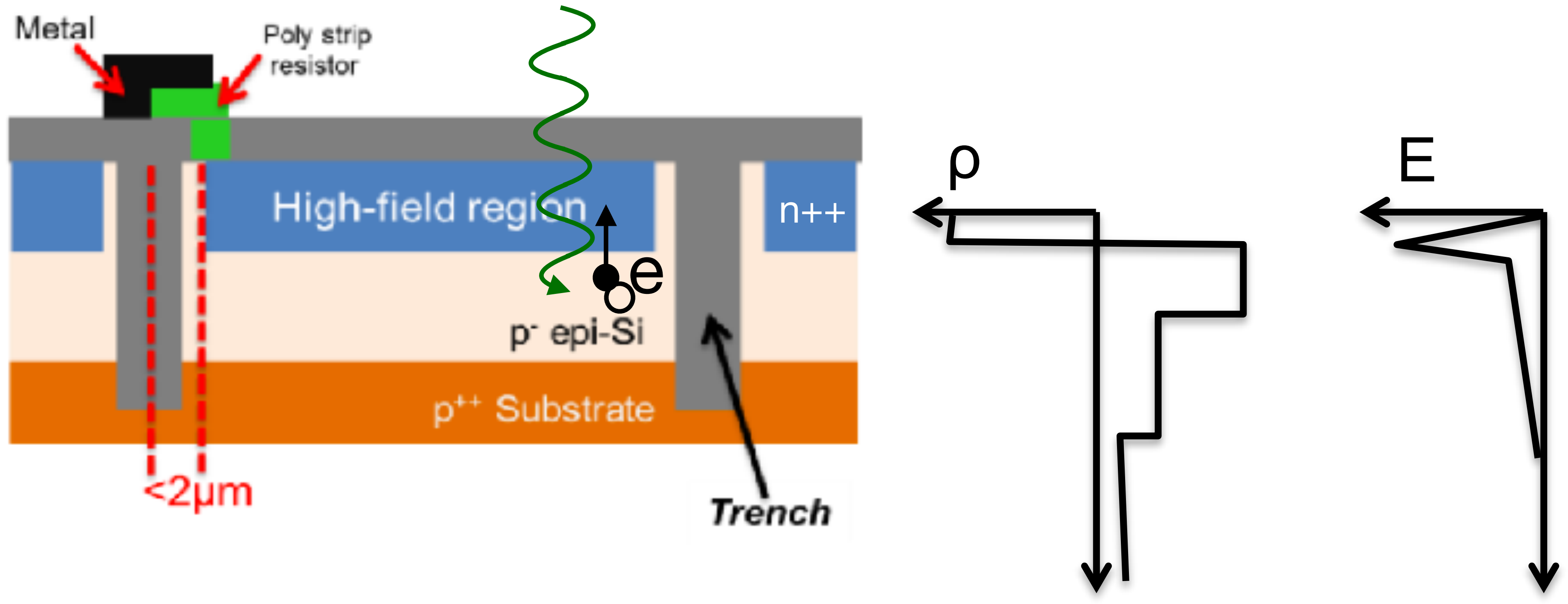


Silicon Photomultipliers

Single photon detection

SiPM





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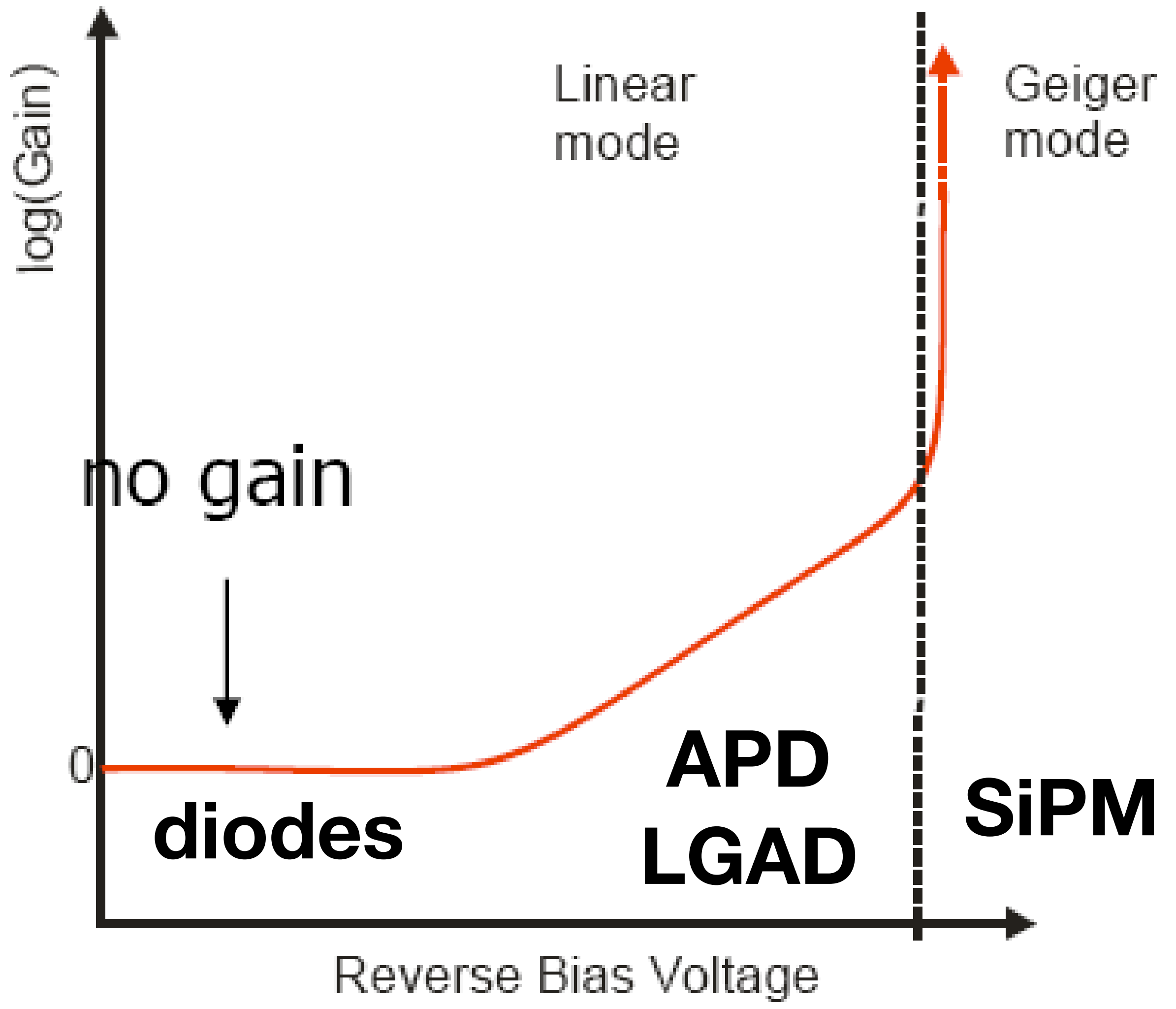
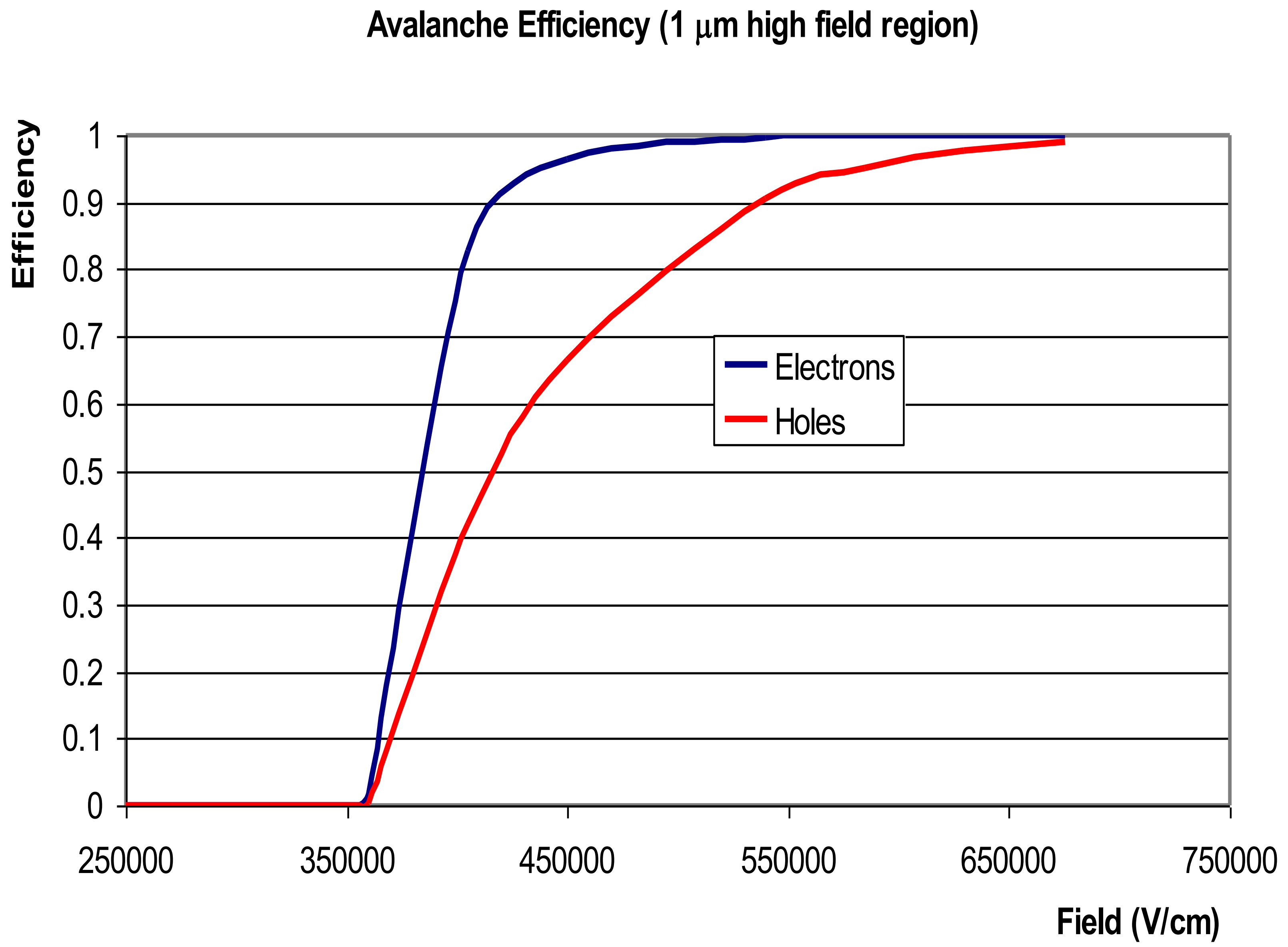
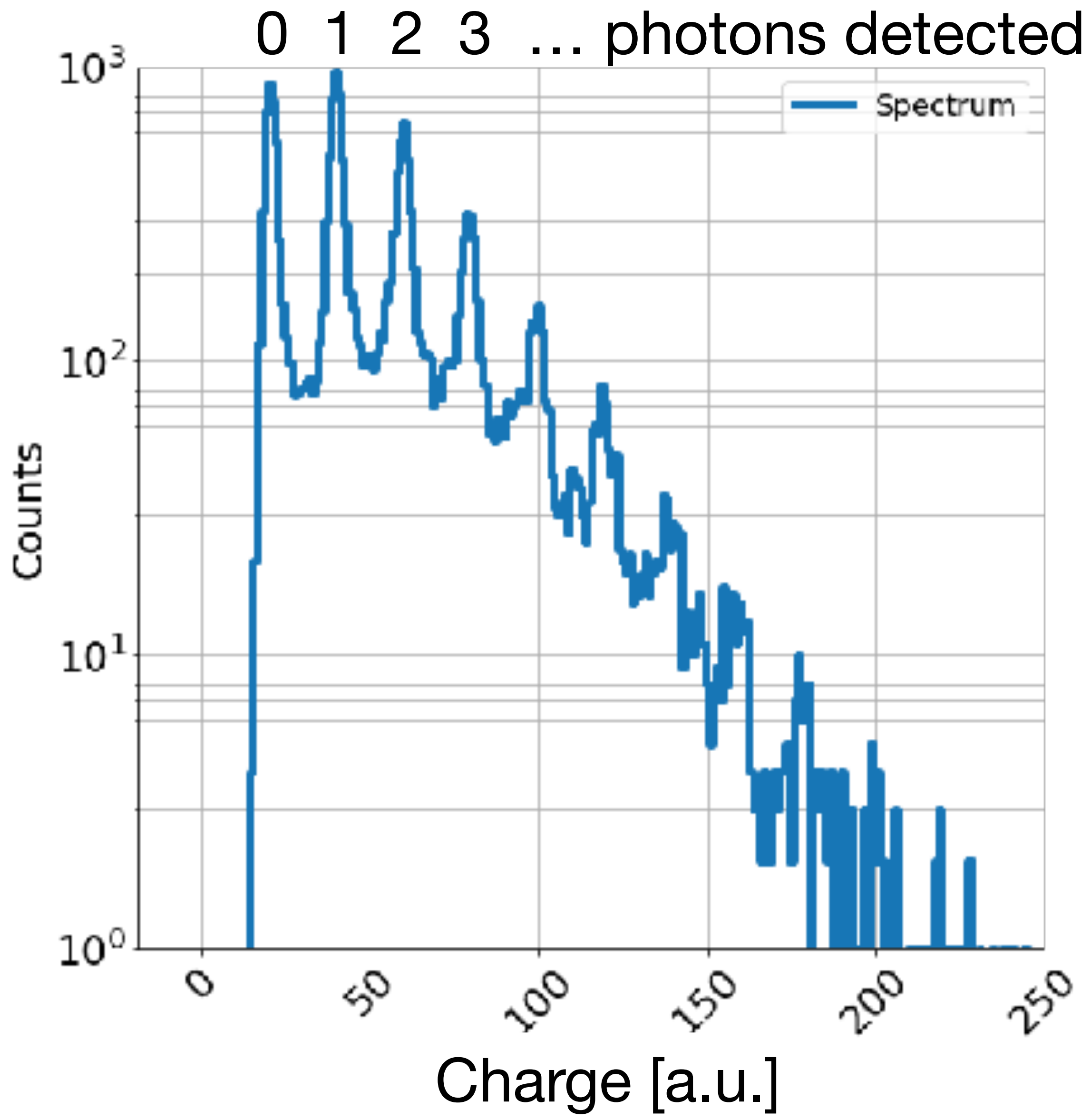


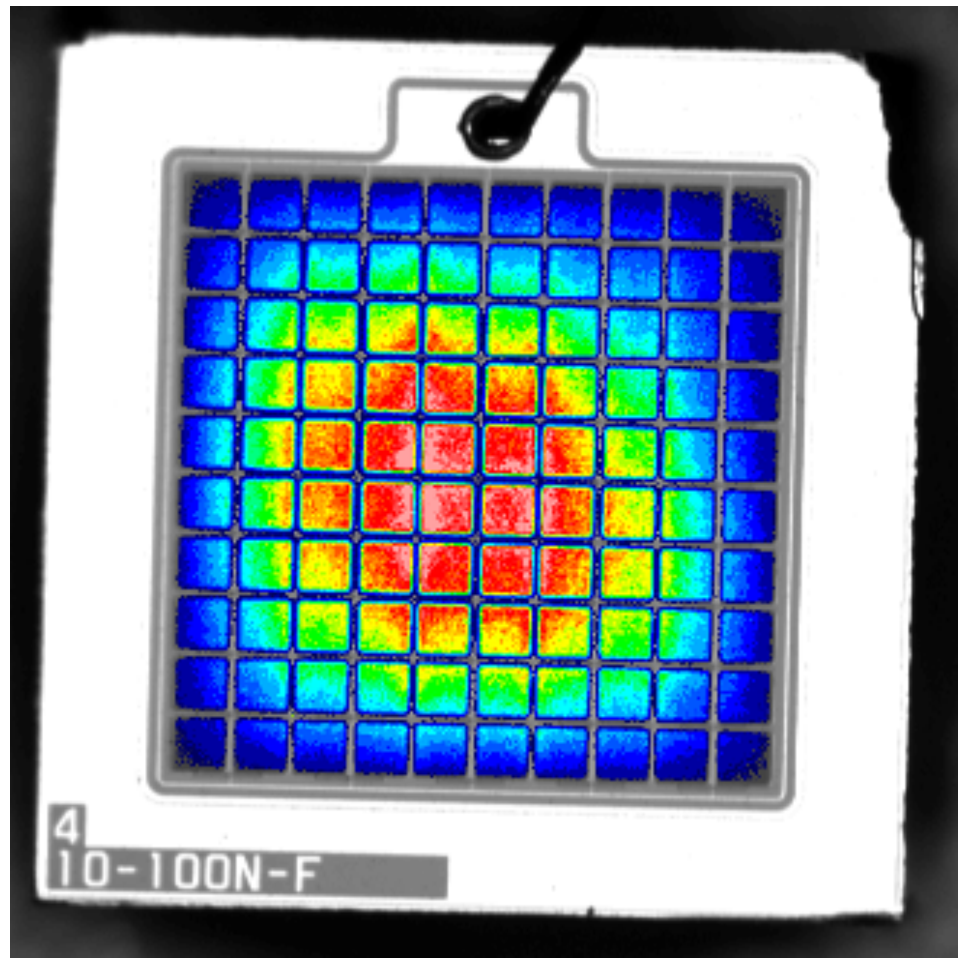




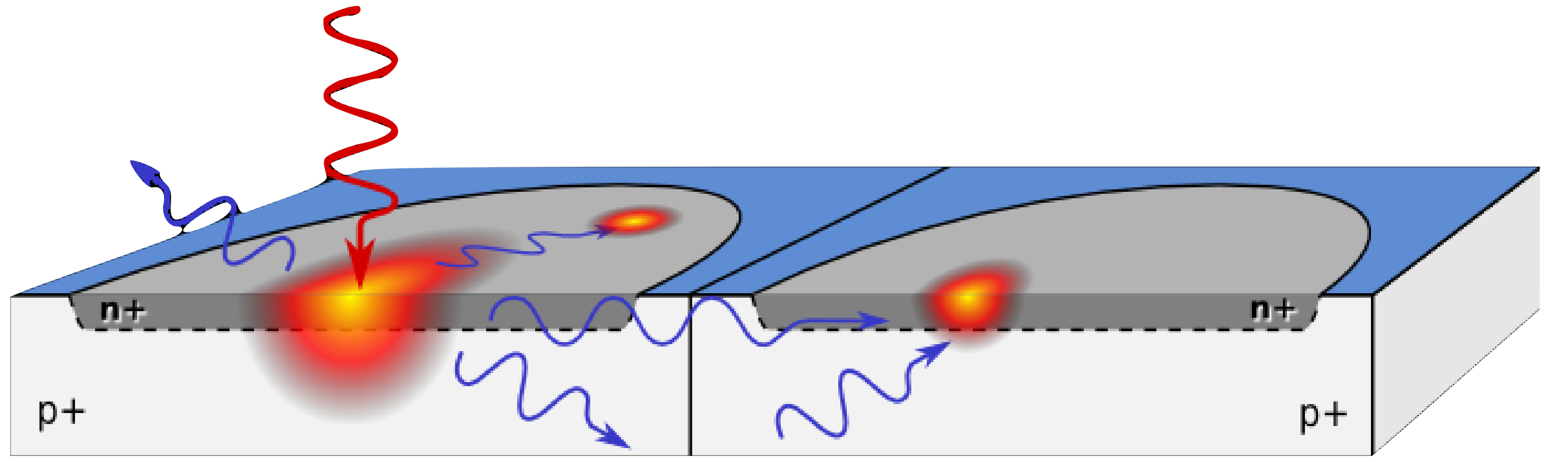
Erika.Garutti @ uni-hamburg.de

Silicon Photomultipliers

Single photon detection

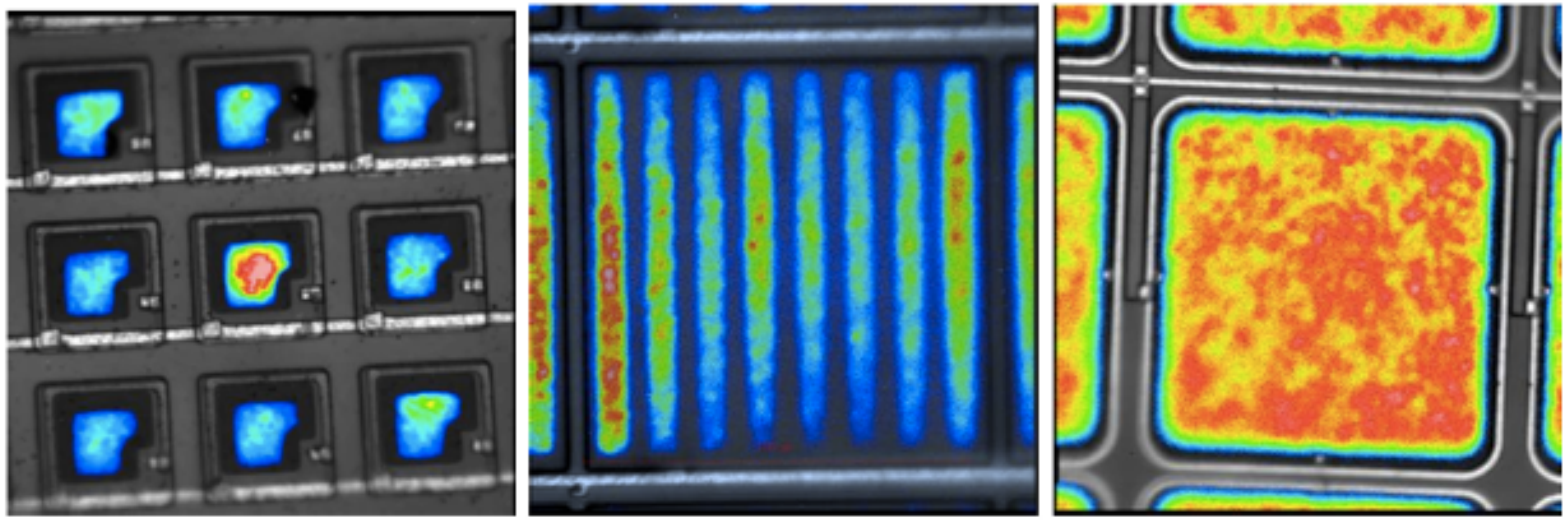


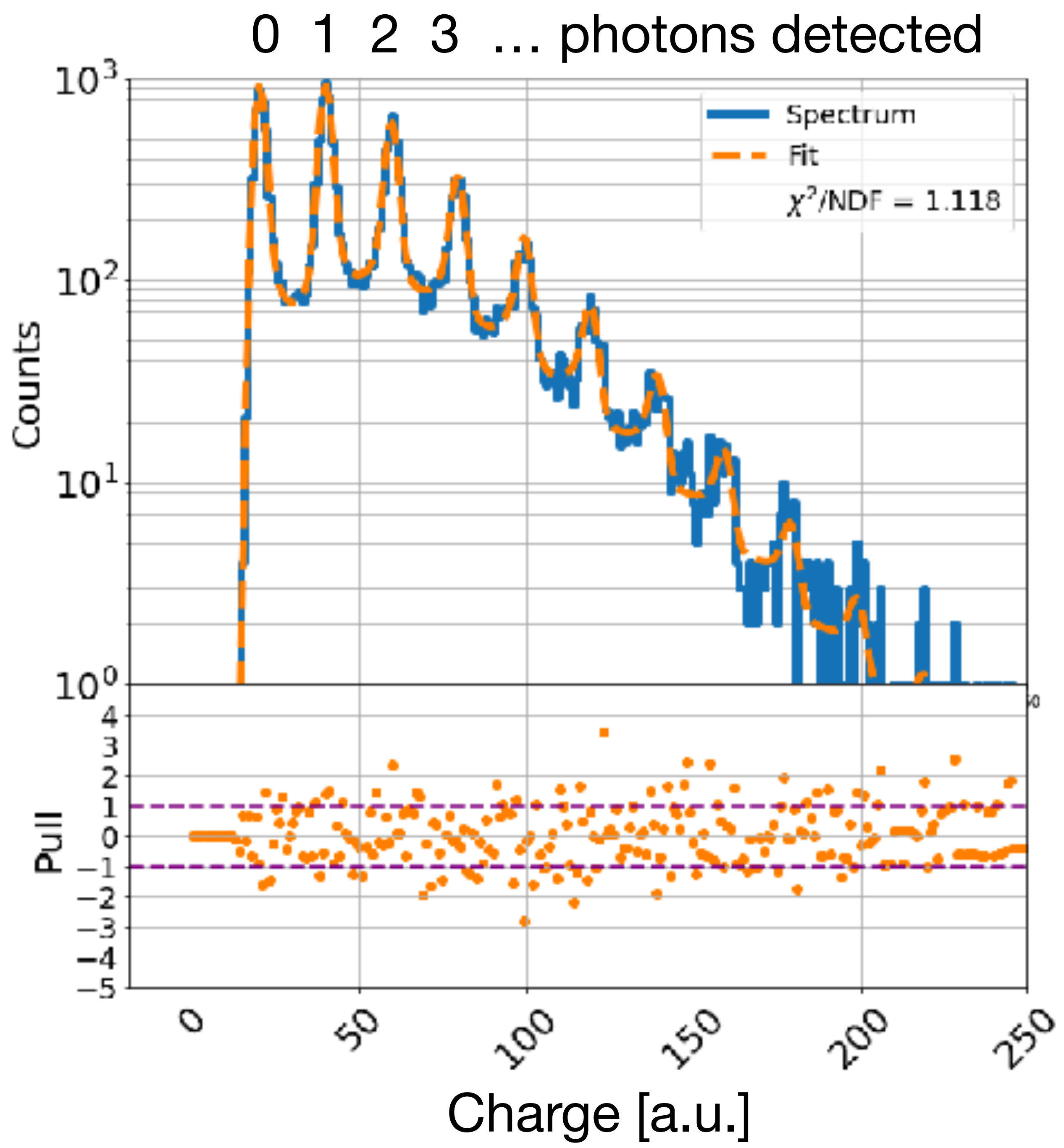
- Understanding of fundamental properties
- Nuisance characterisation
- Design optimization
- Control of production process



Seminal work on SiPMs at MPG HLL: Dolgoshein, Renker, Lorenz, Otte, Ninković and may others

Photoemission images of single pixels (J. Ninković, HLL)





PeakOTron: A Python Module for Fitting Charge Spectra of Silicon Photomultipliers
J. Rolph, E. Garutti, R. Klanner, T. Quadfasel, J. Schwandt

Silicon Photomultipliers

SiPMl - HLL

Idea:

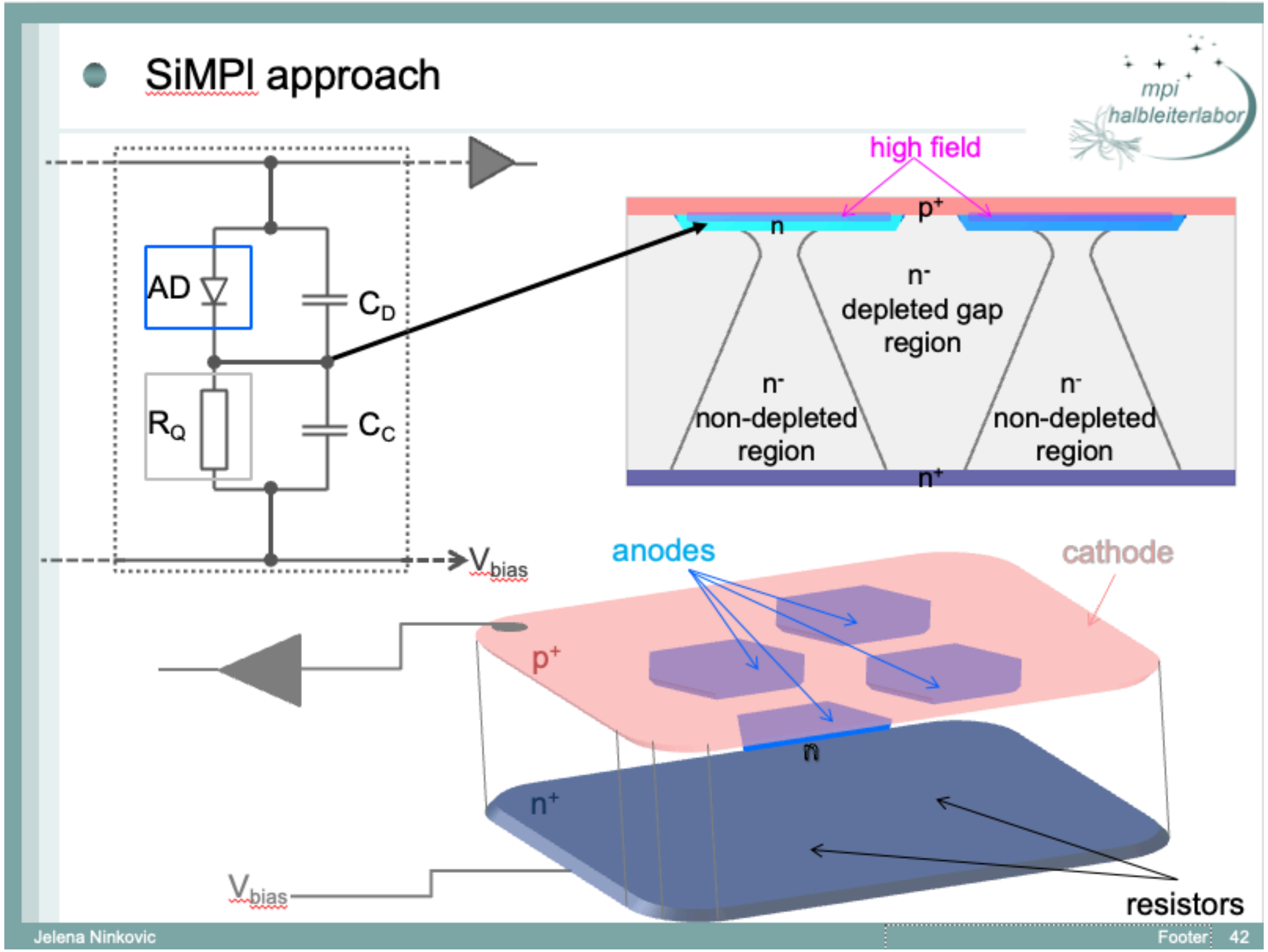
Obtain higher PDE removing polysilicon resistor

- simpler technology
- inherent diffusion barrier against minorities in the bulk → less optical cross talk

Drawbacks:

- Vertical resistor matching requires thin wafers

Jelena Ninković (HLL), 2014 IEEE-NSS Radiation Instrumentation Early Career Award for her contributions to developments of SiPMs with bulk-integrated quench resistors, and of DEPFET active pixel vertex detectors



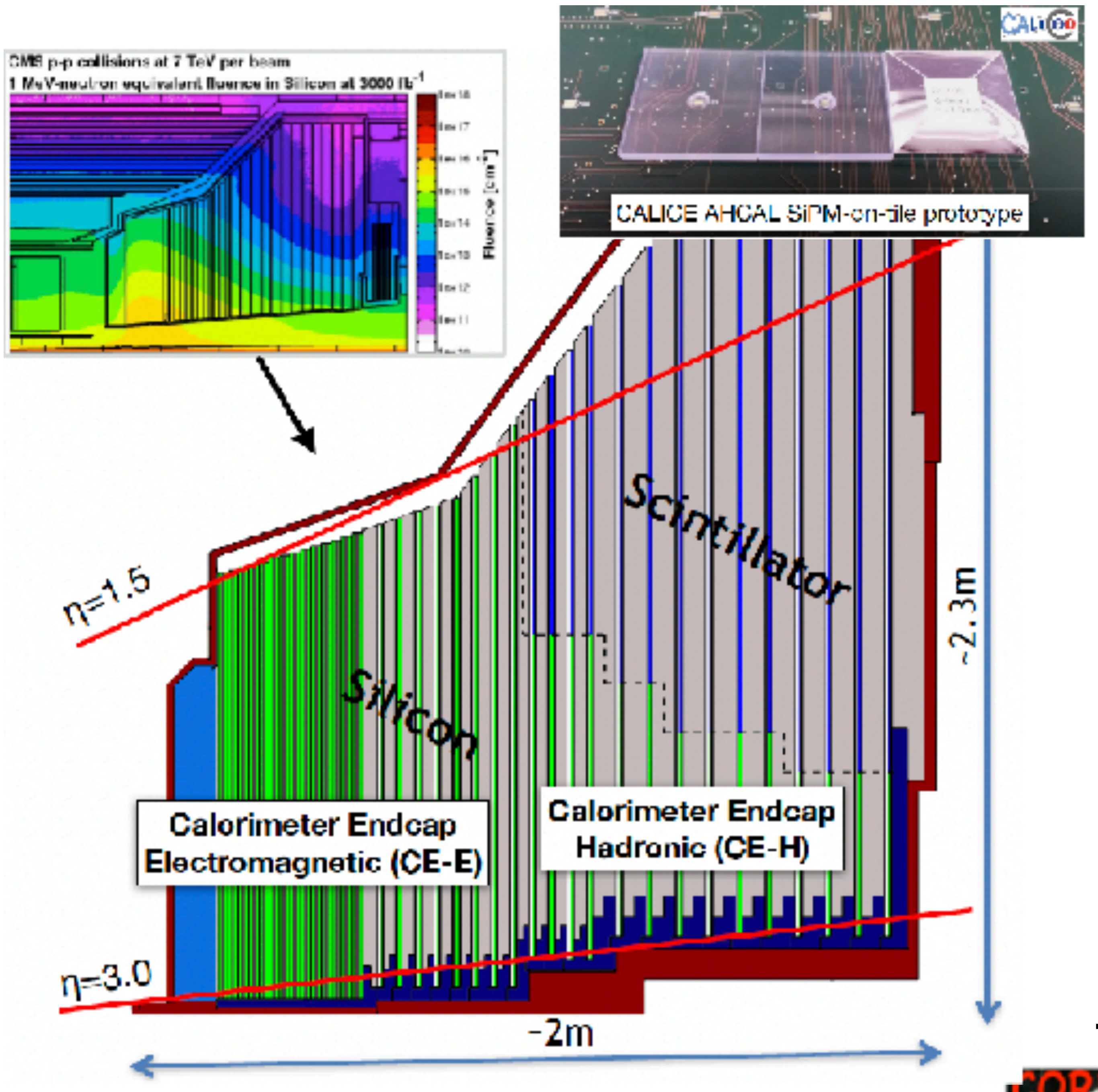
SiMPl approach

Jelena Ninkovic

Footer 42

Silicon Photomultipliers

Applications

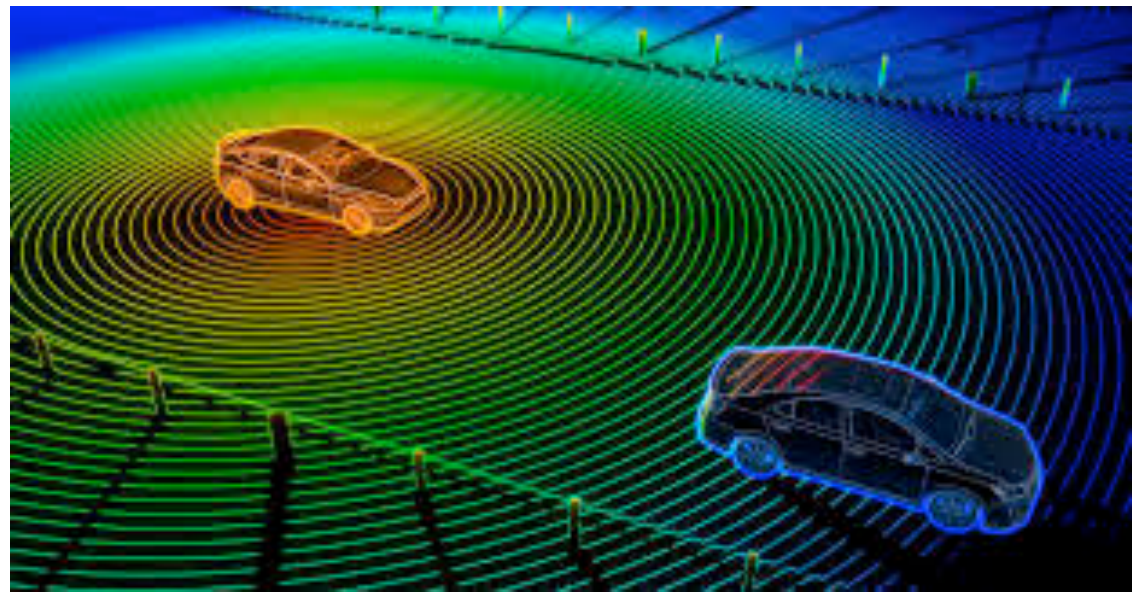


SiPM in particle physics experiments

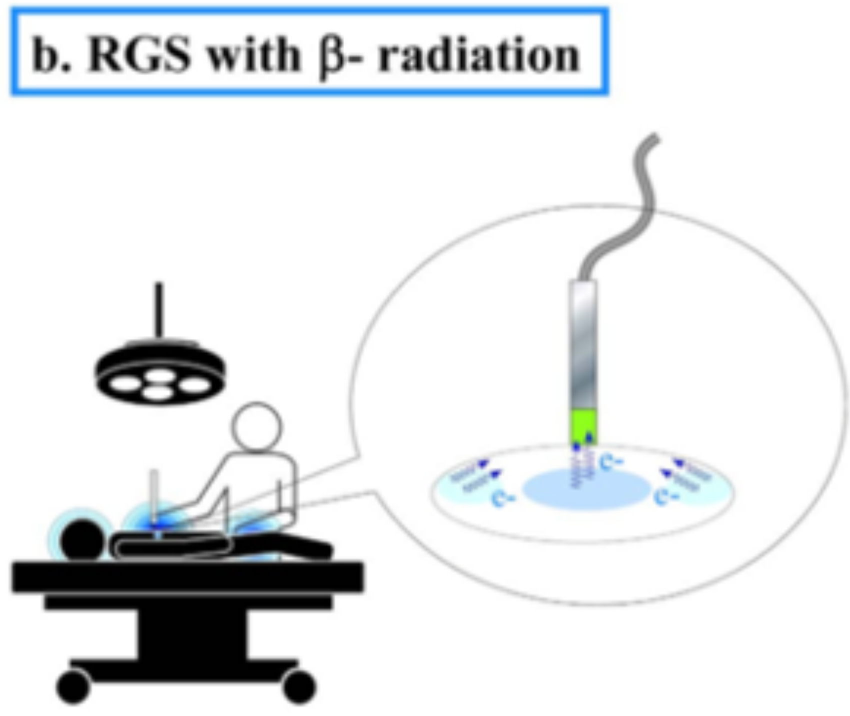
- in 20 years it became a ubiquitous detector

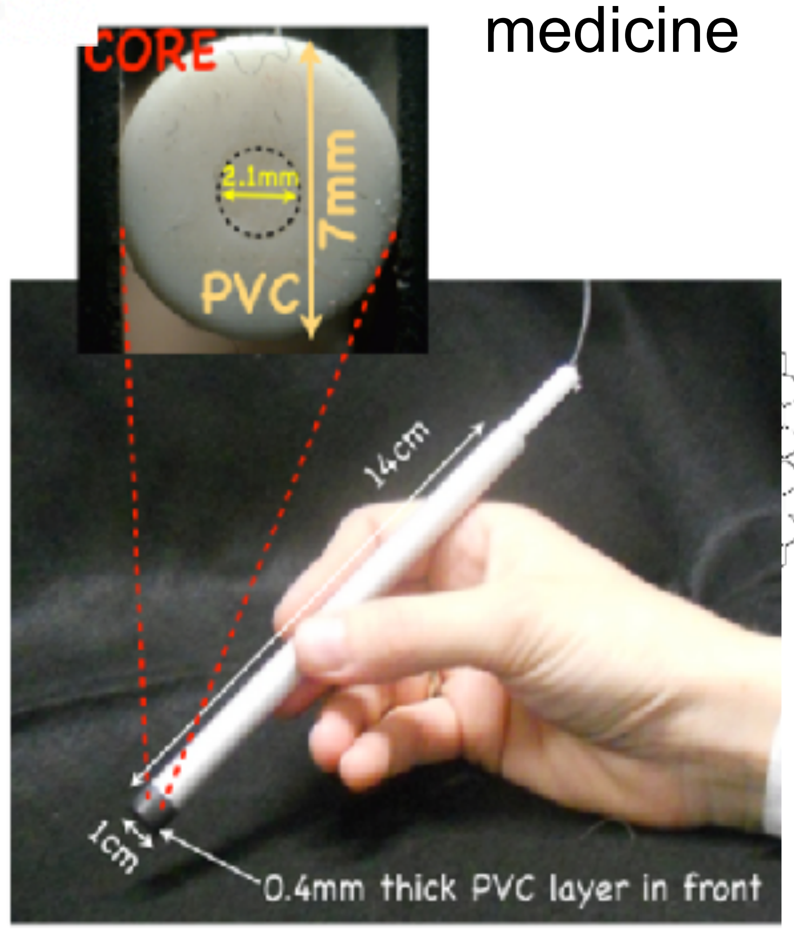
In radiation protection - gamma/neutron detector

SiPMs in automotive LiDAR technology



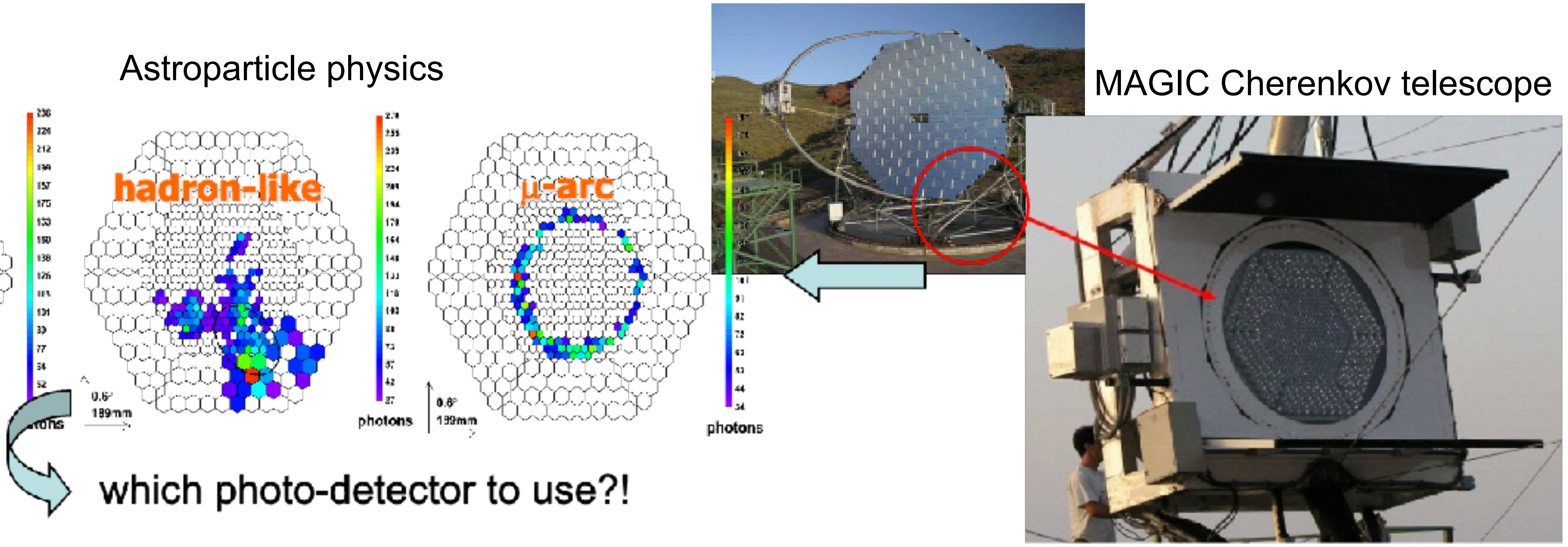
… and personalised medicine





Astroparticle physics

MAGIC Cherenkov telescope



which photo-detector to use?!

Outlook

A glance into the crystal ball

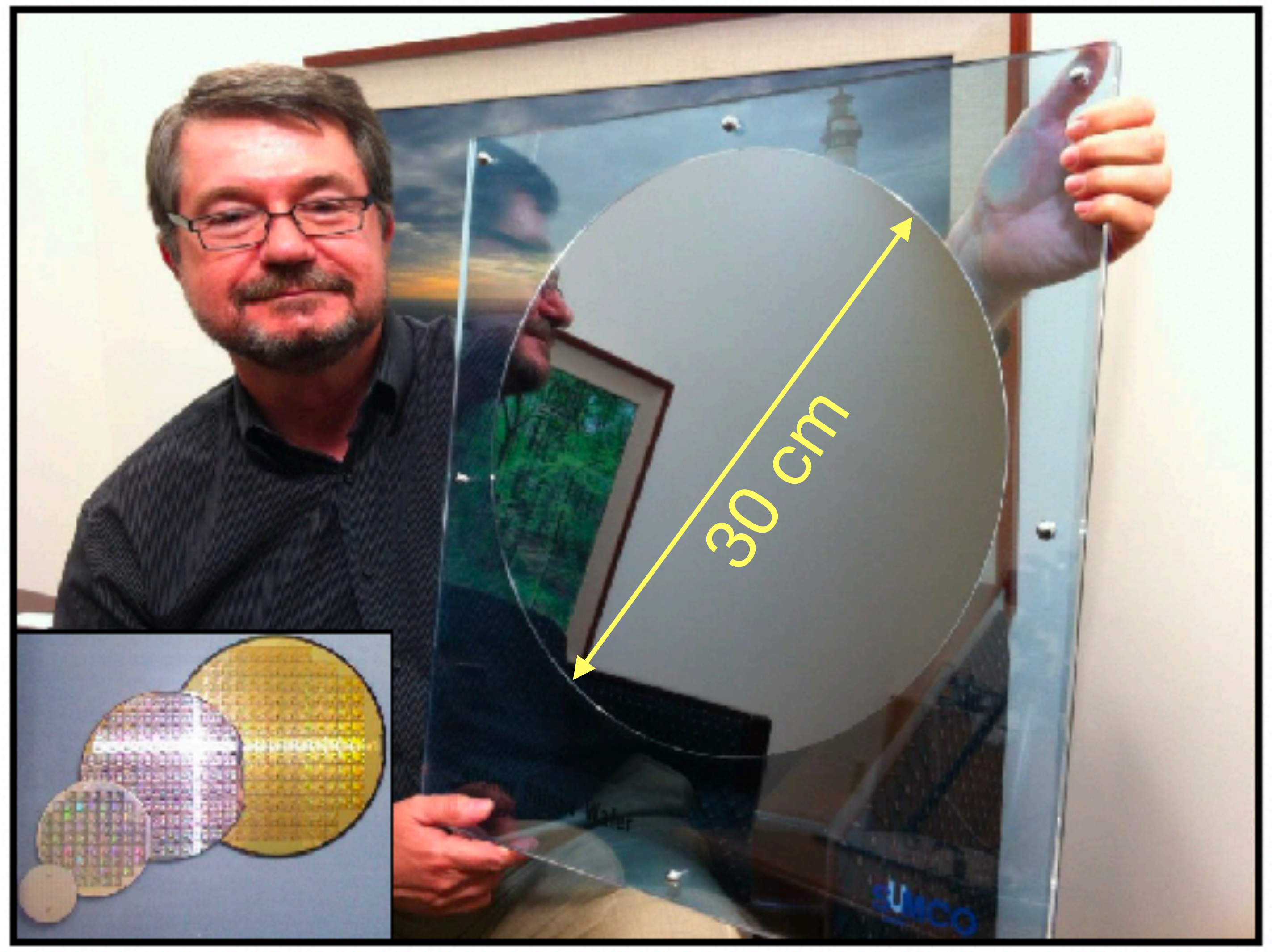
Silicon Detectors … still a “growing” field

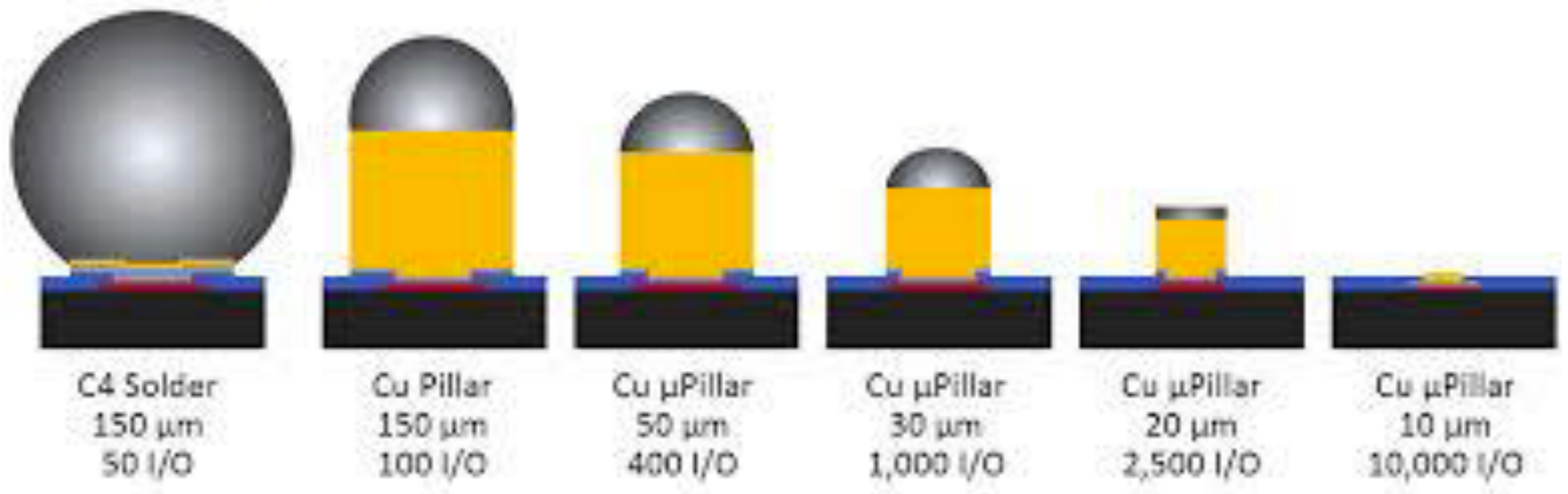
Silicon Detectors

a continuous growth

Tremendous technological improvements

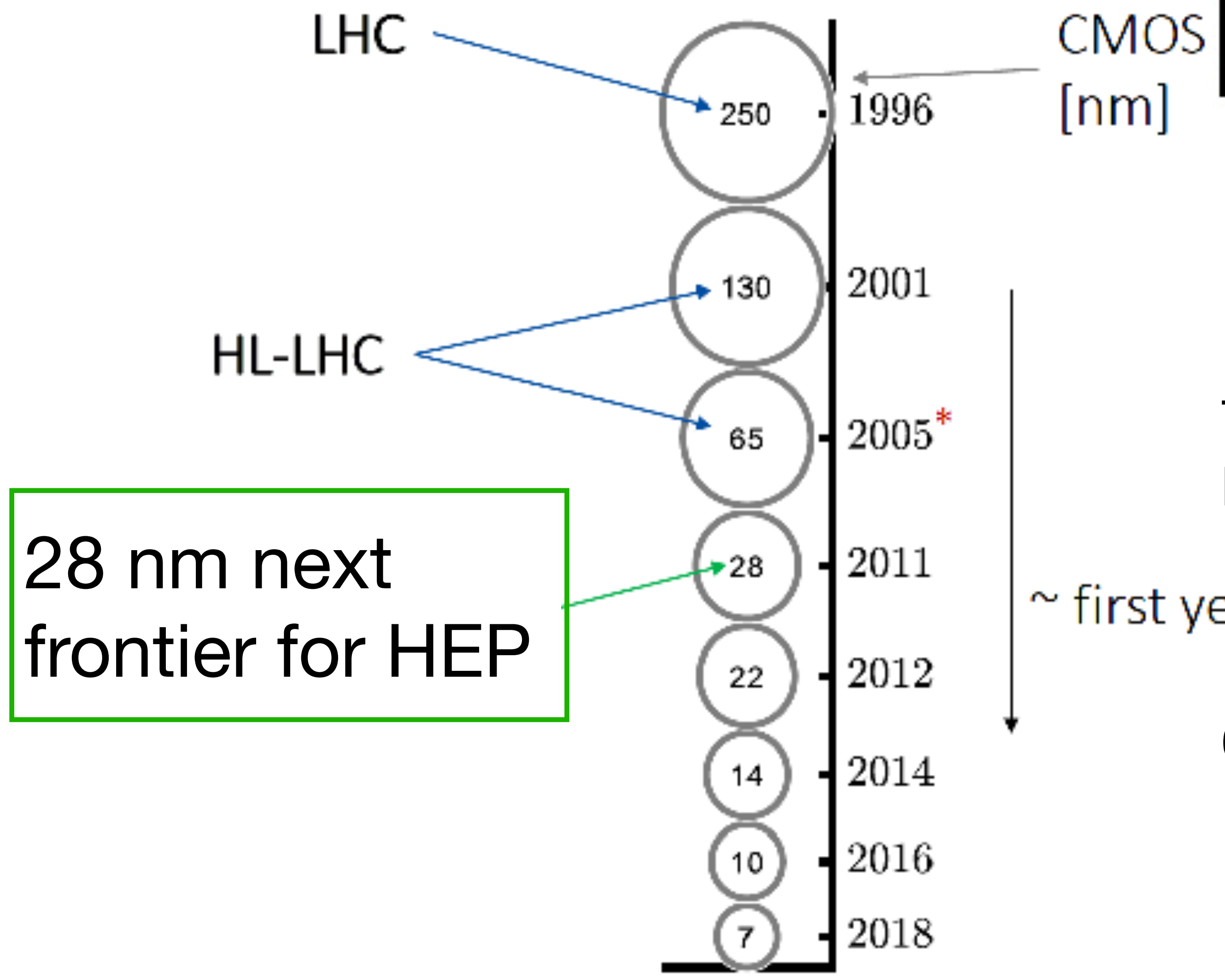
- The silicon **wafer size** increased from 2” to 12”
- The size of **bump bonds** decreased to < 10 µm and other technologies for hybridisation
- **Technology node** decreasing steadily, 65 nm in HEP





From metal solder sphere to micro-pillars

From solder bonding to bonding without Solder:
Gold µ-pillar Thermo-Compression Bonding



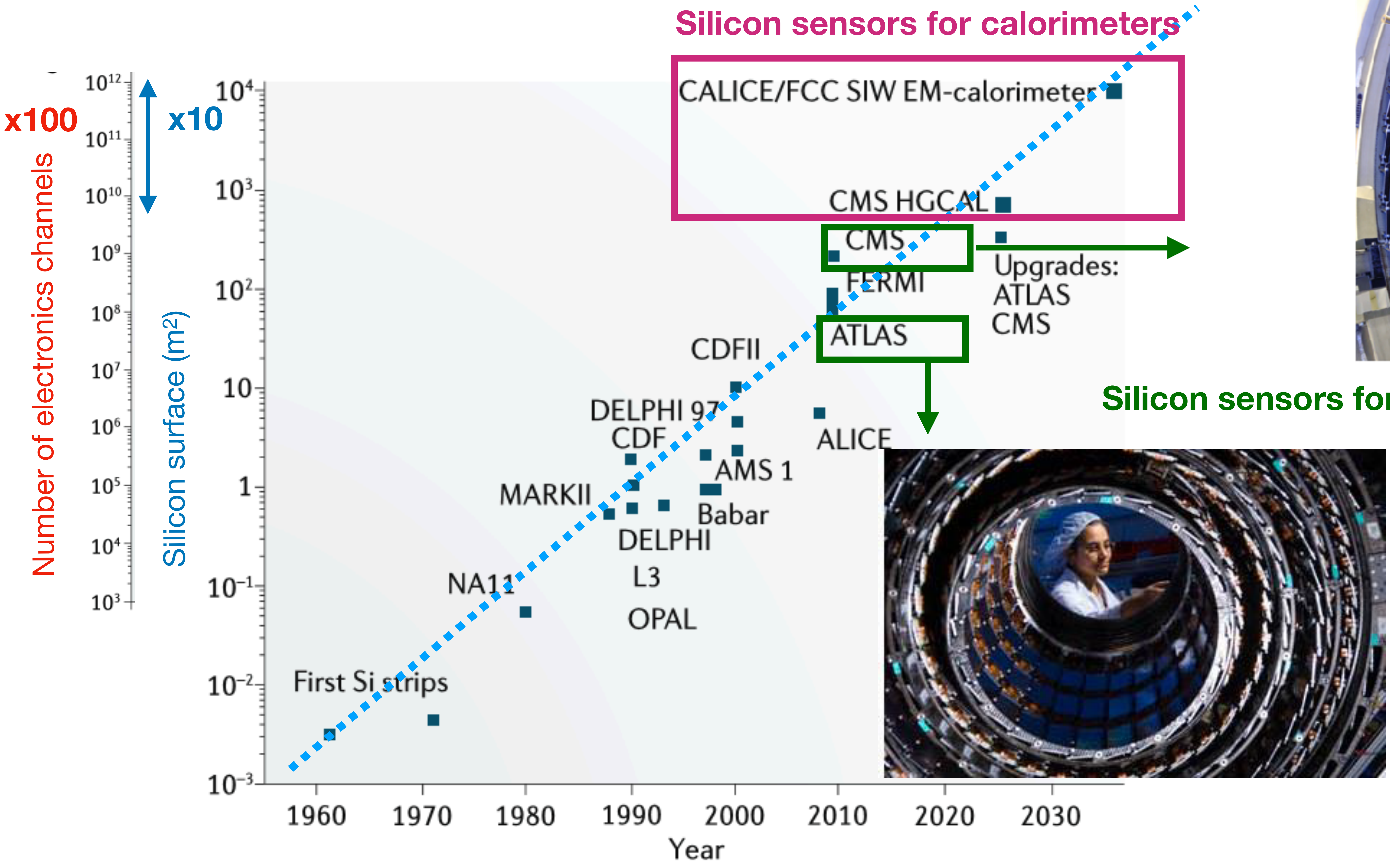
Feature size or “Node” refers to the size of different features of a transistor including gate length and half-pitch specific of a <u>semiconductor manufacturing process</u>

65 – 250 nm	(detector electronics in production in HEP)
28 nm	(detector electronics under preparation)
5 nm	~50 atom digital electronics of smart phones

After 28 nm → FinFETs have a completely different geometry, do not seem so promising in terms of radiation hardness

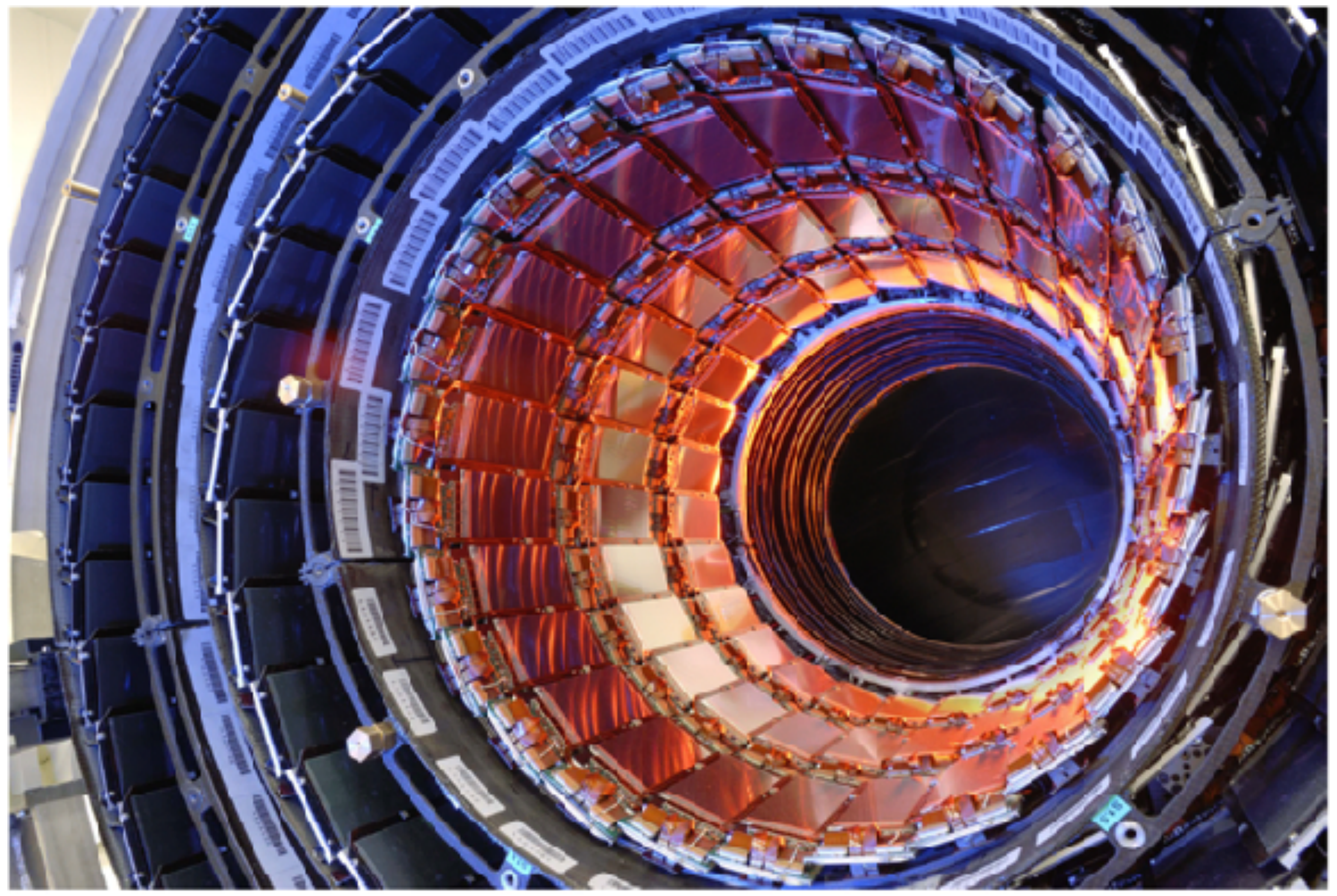
Historical Development

Silicon detectors are getting bigger



Silicon sensors for calorimeters

Silicon sensors for trackers

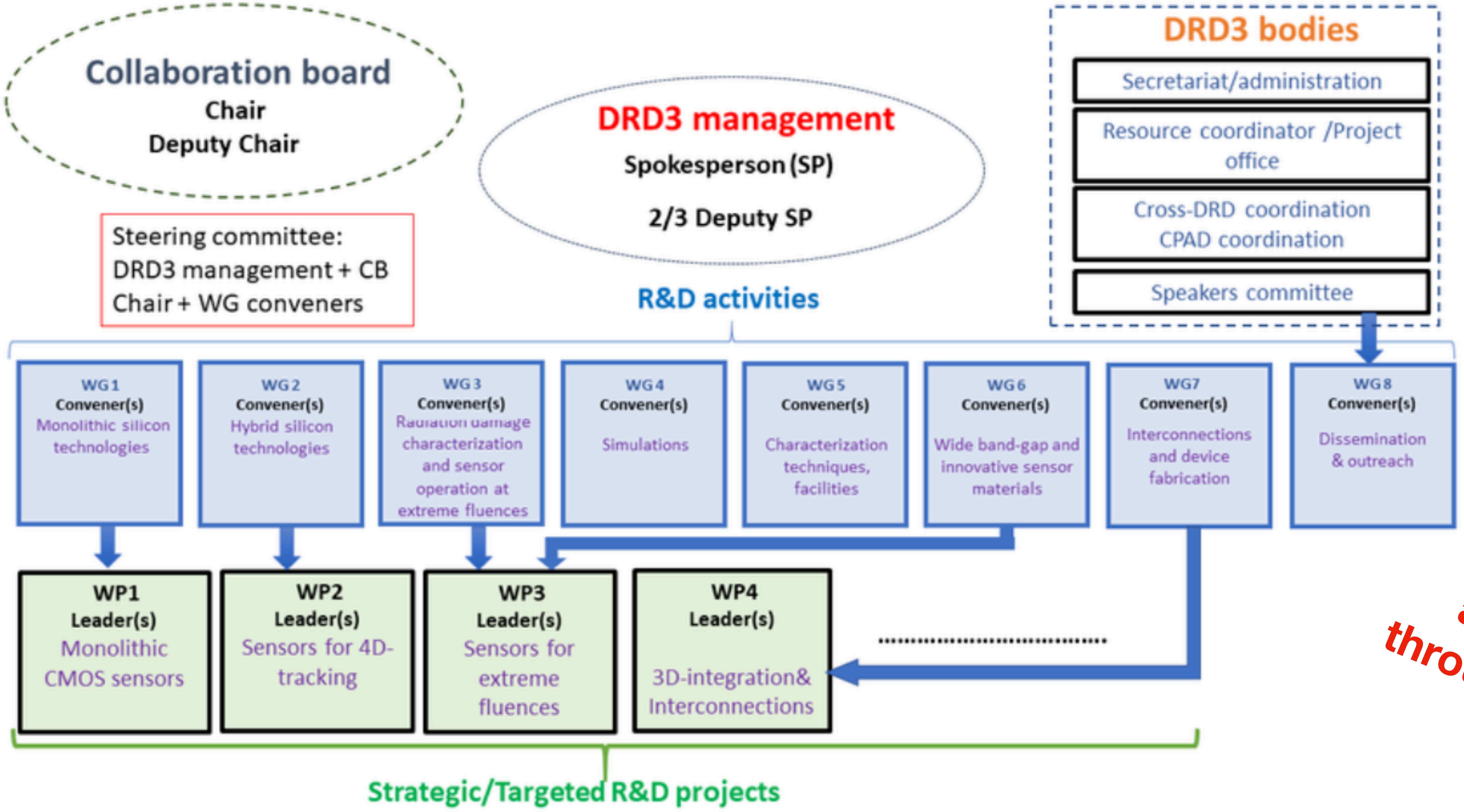


Remarkable: every decade the instrumented areas have increased by a factor of 10 while the numbers of channels in the largest arrays have increased by a factor of 100

Getting (even more) Organized

The silicon detector community — grows

Following the European Strategy for Particle Physics update in 2021 — European Detector Roadmap document — Definition of the Detector R&D Collaborations



Today 143 institutes are members throughout Europe

2024: The ECFA DRD3 Collaboration (Semiconductor Detectors)

Silicon Detectors for Particle Physics

a bright future ahead

- A (brief) history with many successes and important technological revolutions
- A bright prospective for more advancements in the future
- Excellence science needs excellent detectors: thinner, faster, smarter, harder, …

Erika.Garutti @ uni-hamburg.de

Silicon Detectors for Particle Physics

a bright future ahead

- A (brief) history with many successes and important technological revolutions
- A bright prospective for more advancements in the future
- Excellence science needs excellent detectors: thinner, faster, smarter, harder, …

- … which leads to the need of HLL

the furnace of great experts and creative minds with impressive equipment to invent the detectors for the future.

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BACKUP

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3rd Munich Symposium on Semiconductor detectors 1983

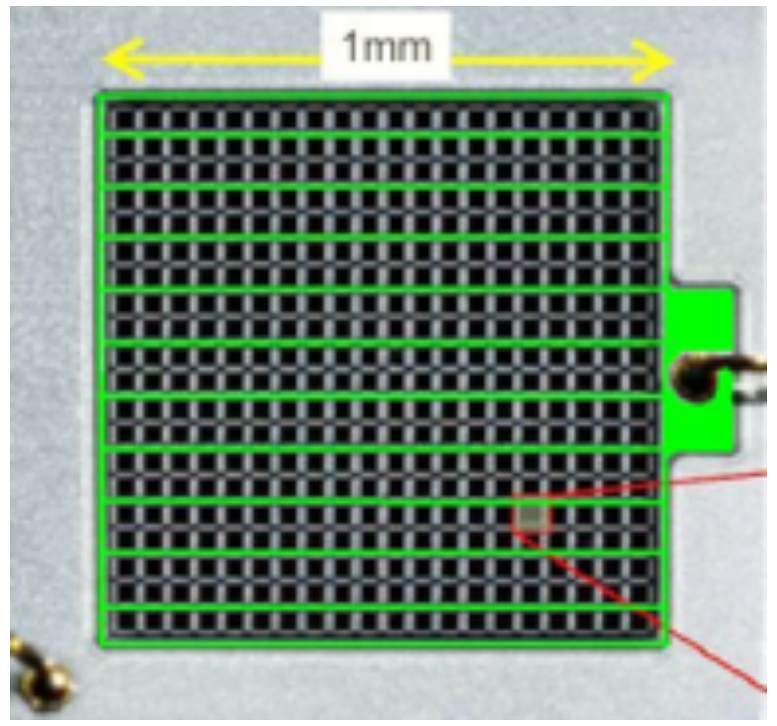
Erik H.M. HEIJNE
Pavia, 5 December 2016

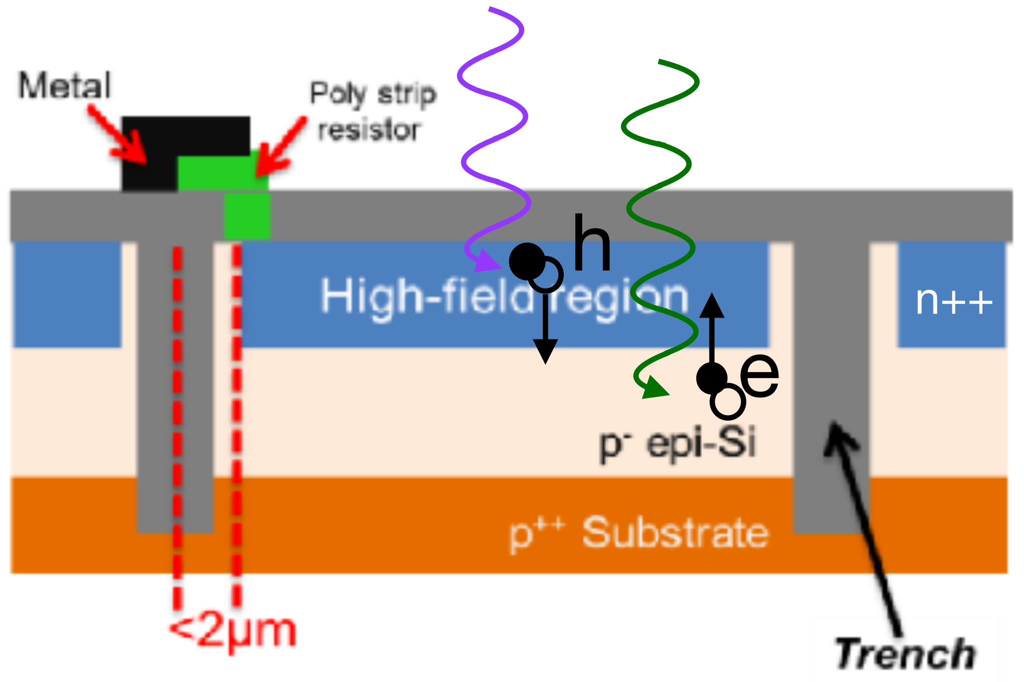
1	Pierre Jarron, CERN Genève	67	nn USA??
2	CdTe person USA?	68	Colin Wilburn, Micron Semiconductor, Southampton
3	? Wilfried von Ammon, Wacker?	69	Erik Heijne, CERN Genève
4	? Heinz Herzer, Wacker?	70	François Piuz, CERN Genève
5	CdTe person USA?	71	nn or Manfredotti ->19
6	Peter Glasow, Siemens Erlangen	72	Ettore Vittone, U Torino
7	Lothar Strüder, Max Planck, München	73	Makram Hage Ali, CNRS-PHASE Strasbourg
8	Jan van Rooijen, SRON Space Lab Utrecht	74	Marie-Odile Lampert, Enertec Strasbourg
9	Wim Mels, SRON Space Lab Utrecht	75	Hans-Günther Moser, Max Planck, München
10	Gerhard Lutz, Max Planck Institut, München	78	Heinz Filthuth
13	? Egbert Belau, Max Planck Institut, München	79	Robert Klanner, Max Planck, München
12	? nn, DESY Zeuthen?	82	Warner ten Kate, TU Delft
15	Herman Effing, Philips Elcoma SSP, Nijmegen	83	Wojciech Dulinski, LEPSI Strasbourg
16	?Prof Shiraishi Rikkyo Nagasaki Japan	85	Mrs Renata Ludwig, Max Planck Institut, München
17	? Walter Schoenmaekers, Metallurgy Hoboken	86	secr, Max Planck Institut, München
18	Roland Henck, Enertec Strasbourg	87	Emilio Gatti, Politecnico Milano
19	? Claudio Manfredotti, INFN, Torino	88	secr, Max Planck Institut, München
20	? H Seebrunner, MPI München	91	Henk Tiecke
23	Rob Hollander, IRI TU Delft	92	Y Kim
24	Leo Wiggers , Nikhef Amsterdam	93	Hans Dietl
25	François Lemeilleur, CERN	52	Ulrich Kötz, DESY Hamburg
26	Paul Karchin, Yale U, USA	53	Gert Viertel, CERN Genève (later ETHZ)
27	Pavel Rehak, BNL Brookhaven	**54**	Franco Manfredi, INFN & U Pavia
29	Paul Burger, Enertec Strasbourg	56	Antonio Longoni, Politecnico Milano
30	Thor-Erik Hansen, SINTEF Oslo	57	Prof Rolf Leiste, DESY Zeuthen
31	Ms Ariella Cattai, CERN Genève	58	nn, Polish? Hosticka?
32	Torleiv Buran, University of Oslo	59	nn, Max Planck, München
33	Bernard Hyams, CERN Genève	60	nn , Max Planck, München
34	Michal Turala, Max Planck, München (Krakow)	61	Guido Tonelli, INFN & U Pisa
35	Luciano Bosisio, INFN Pisa (?)	62	?? Xaverio d'Auria ??
36	Chris Damerell, Rutherford & U Oxford	63	Jean-Claude Muller, CNRS-PHASE Strasbourg
40	Veljko Radeka, BNL Brookhaven USA	64	Josef Kemmer, TU München
42	Tom Ludlam, BNL Brookhaven USA	65	Craig Woody, BNL Brookhaven
45	Walter Blum, Max Planck, München	66	Koei Yamamoto, Hamamatsu Japan

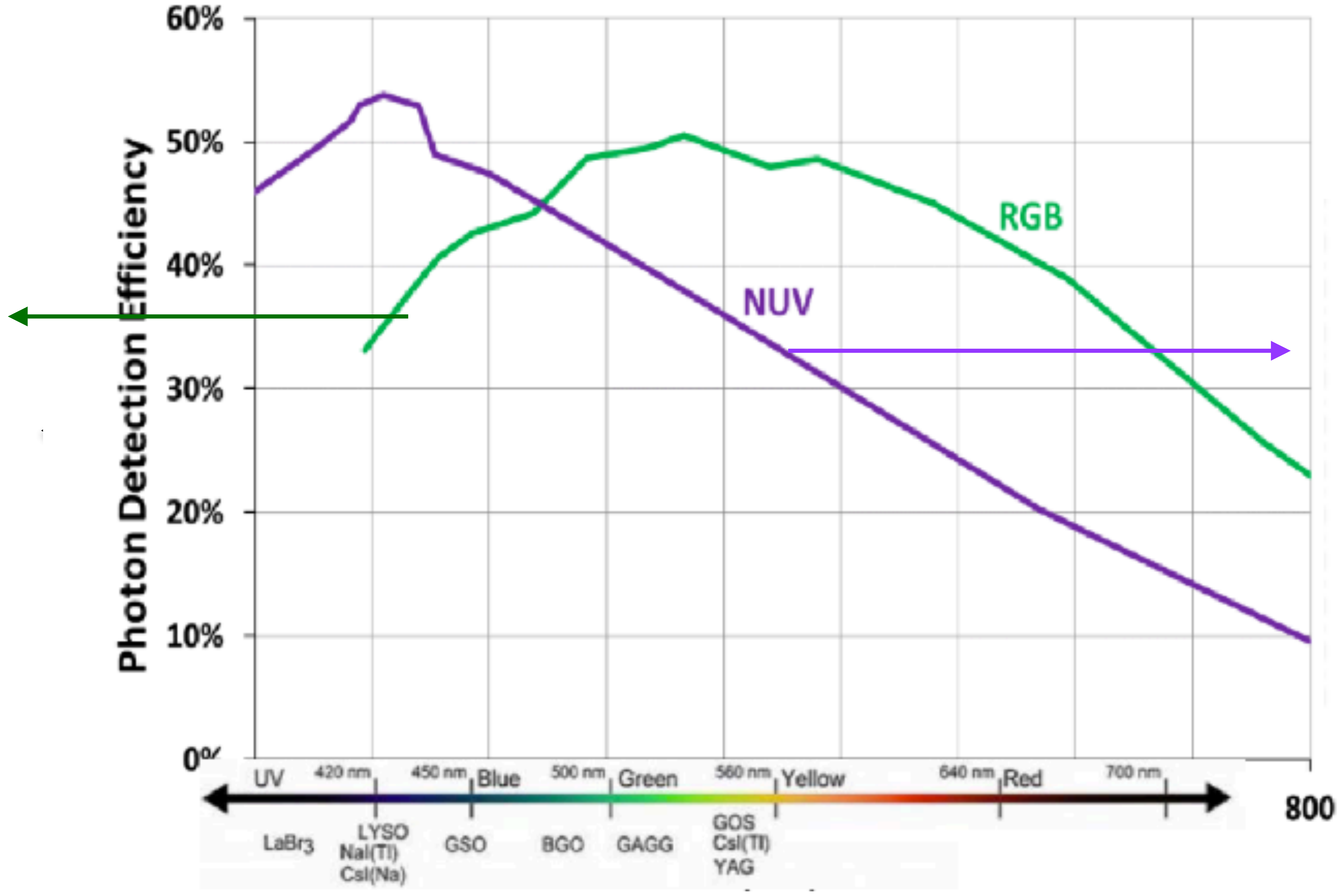
Silicon Photomultipliers

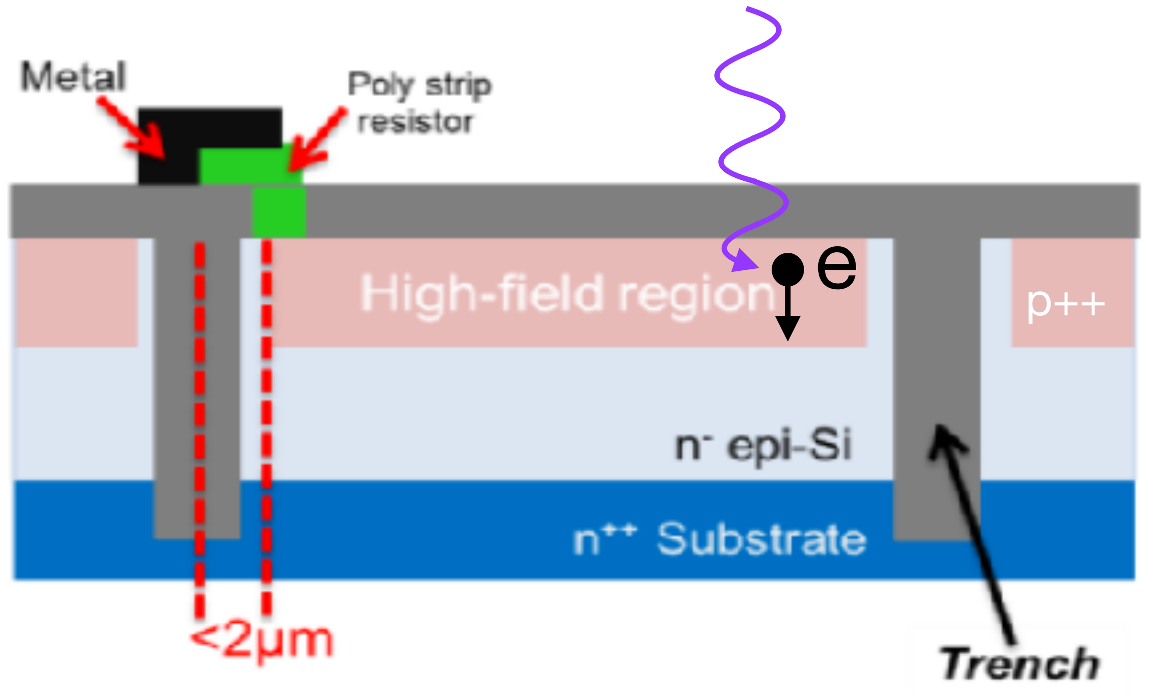
Single photon detection

SiPM







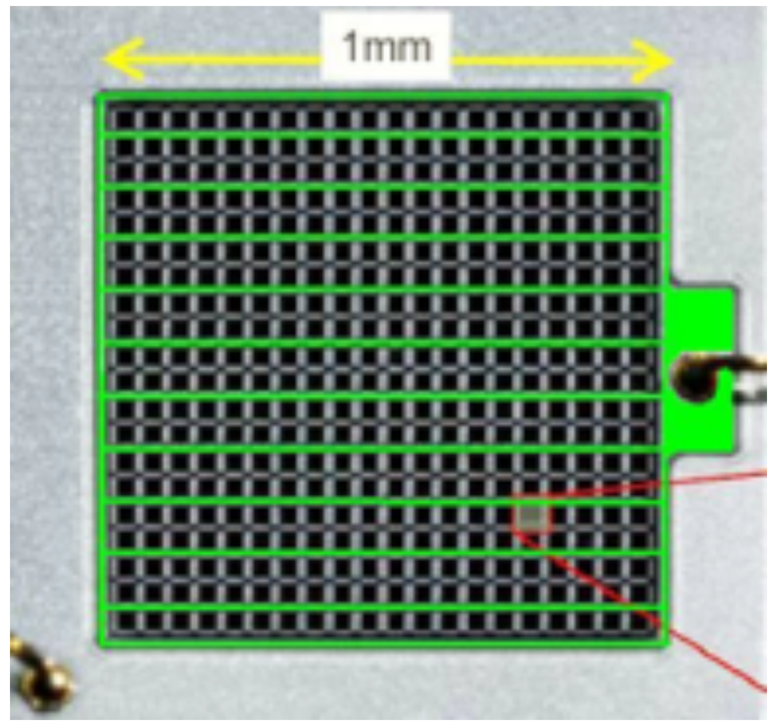


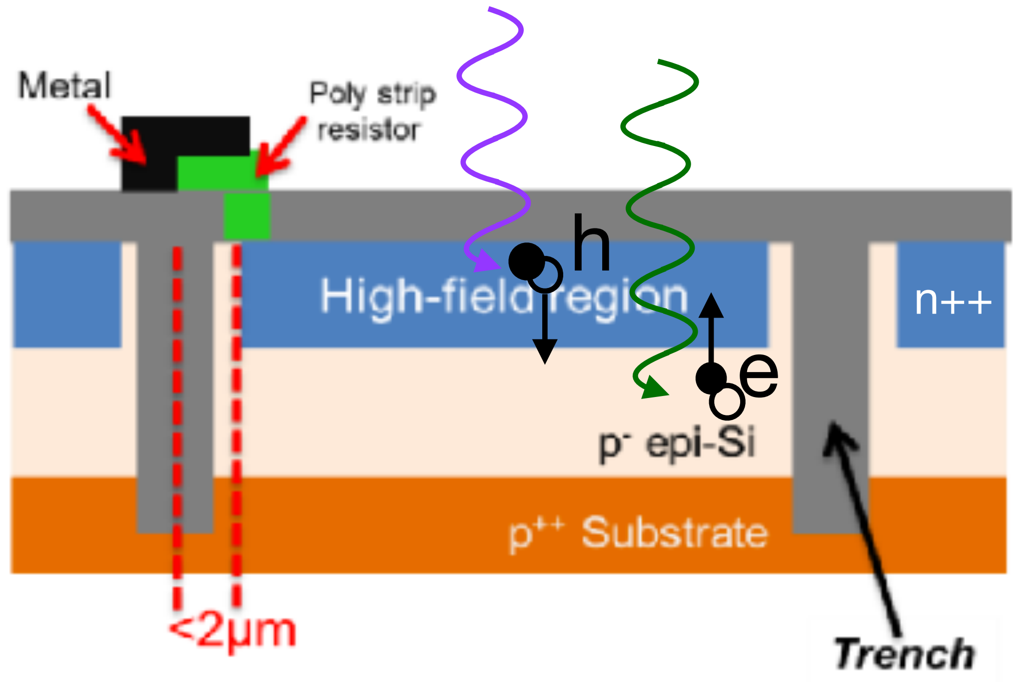
F. Acerbi, FBK

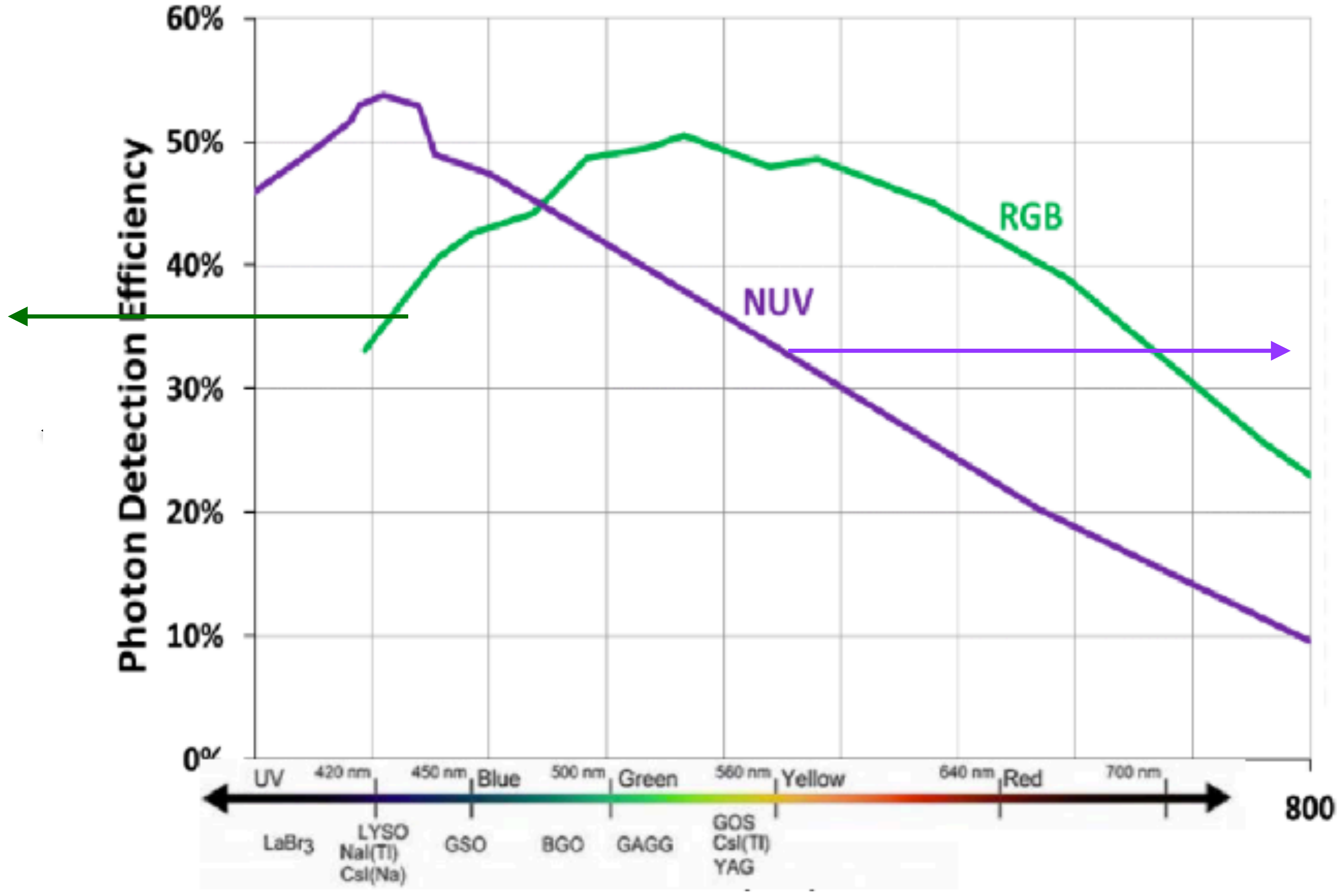
Silicon Photomultipliers

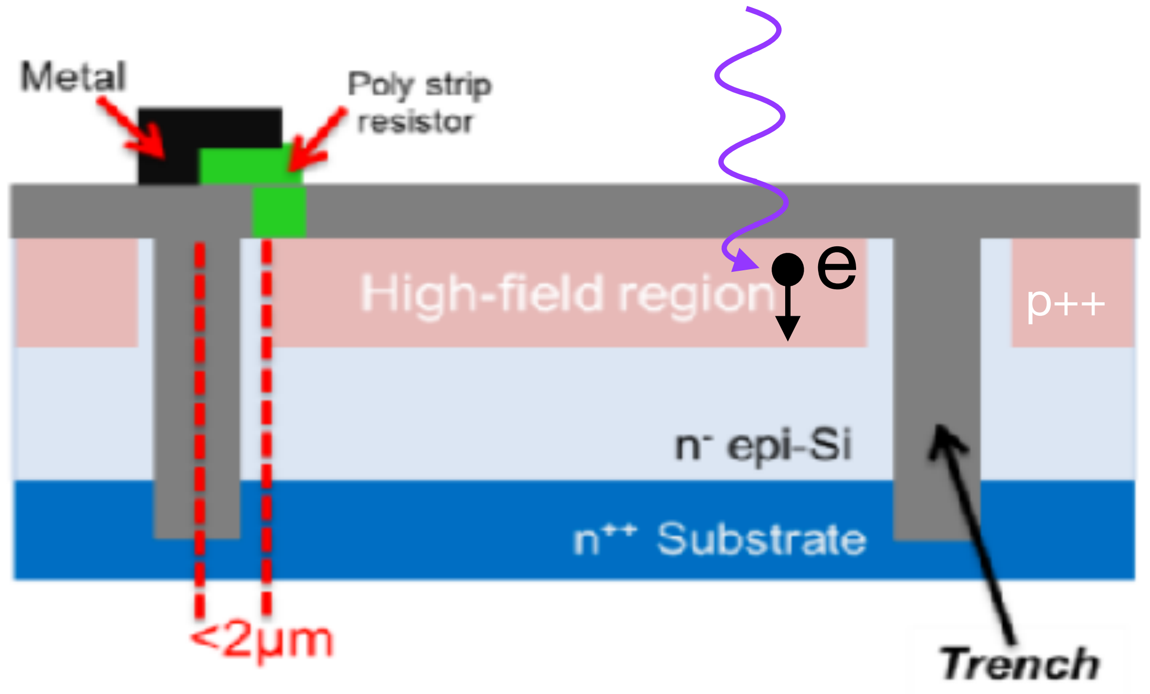
Single photon detection

SiPM

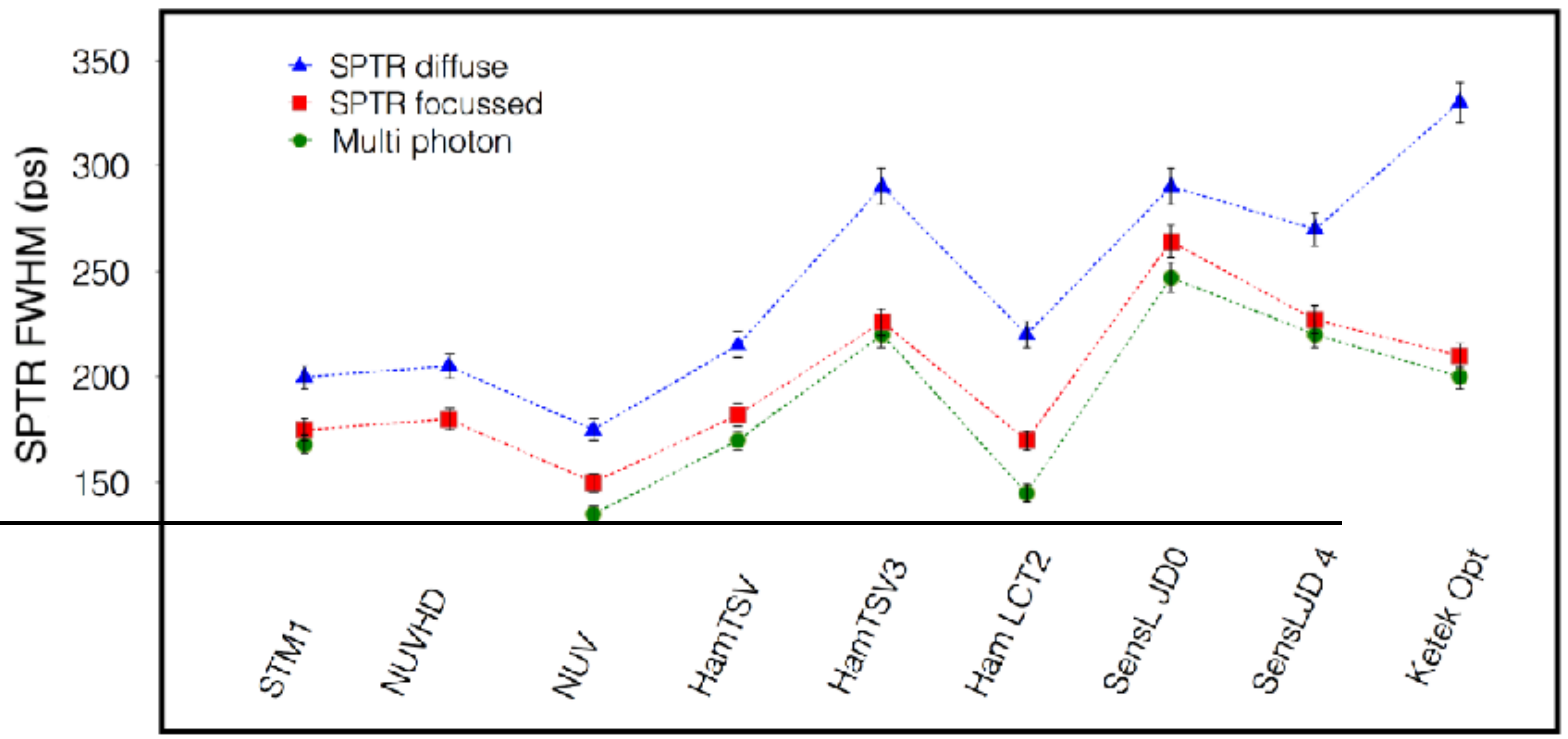








F. Acerbi, FBK



S. Gundacker et al, 2016 JINST 11 P10016

Single Photon Time Resolution (SPTR)
< 150 ps FWHM ($\sigma_{SPTR} = 65$ ps) reached

Note: $\sigma_t \propto \sigma_{SPTR} / \sqrt{N_{prompt}}$