23rd Workshop on Radiation Imaging Detectors - iWoRiD 2022
Riva del Garda, Italy, 26 – 30 June 2022

# Semiconductor Drift Detectors:
## history, present and future


Giuseppe Bertuccio

Politecnico di Milano

Department of Electronic, Information and Bioengineering
and
National Institute of Nuclear Physics (INFN)
Milan, Italy

# Thank you!

## Scientific Committee

**Matthieu Boone**, University of Ghent, Belgium
**Cinzia Da Via**, University of Manchester, United Kingdom
**Roelof de Vries**, PANalytical B.V., The Netherlands
**Joaquim Dos Santos**, Universidade de Coimbra, Portugal
**Wasi Faruqi**, MRC LMB, United Kingdom
**Christer Fröjdh**, Mid Sweden University, Sweden
**Heinz Graafsma**, DESY, Germany
**Renata Longo**, University of Trieste, Italy; INFN, Italy
**Ralf Hendrik Menk,** Elettra Sincrotrone, Italy
**Thilo Michel**, Friedrich-Alexander-Universität, Germany
**Seppo Nenonen**, Oxford Instruments Technologies Oy, Finland
**Valeria Rosso**, University of Pisa, Italy; INFN Pisa, Italy
**Bernd Schmitt**, PSI, Switzerland
**Val O´Shea**, University of Glasgow, United Kingdom

## Local Organizing Committee

**Gian-Franco Dalla Betta**, University of Trento (Chair)
**Lucio Pancheri**, University of Trento
**Alberto Quaranta**, University of Trento
**Coralie Neubüser**, TIFPA- INFN
**Nicola Massari**, Fondazione Bruno Kessler
**Giovanni Paternoster**, Fondazione Bruno Kessler
**Roberto Iuppa**, University of Trento

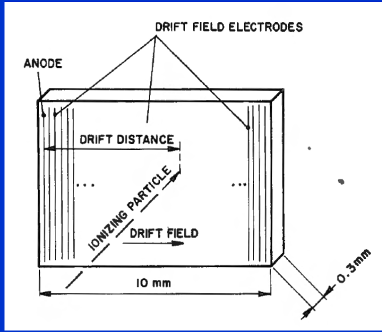
# Preface

2022…a significant year
for
Silicon Drift Detectors (SDDs)

Twofold anniversary

100th of *Emilio Gatti* birthday (1922)

40th of SDD's conception (1982)



# Outline

Semiconductor Drift Detectors

- History
  - the context
  - conception and evolution
- Present
  - state of the art
  - running R&D
- Future
  - Where SDDs can go
  - What we could expect

# History of SDD
# …a preface…

# Historical overview ?

**Historical aspects in Science and Tecnology (S&T) are generally neglected**

(Psycological) reasons:

- Old is outdated
- New makes Old obsolete
- S&T look at the future, past doesn't care

Drawback of the above vision:

- The time-dimension of S&T is lost
- S&T become anonymous

Actually…S&T is made by women and men in an historical context!

# What History in S&T can offer us…

To grow a consciousness on:

- How discoveries or ideation were born…and can born
- How much new devices improve from the first prototypes!

In addition…

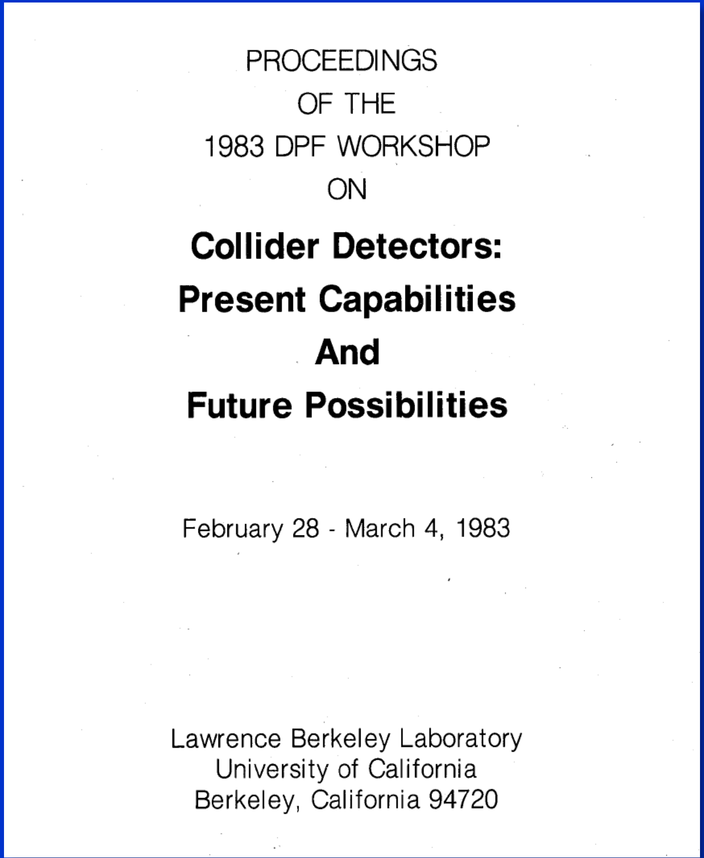
to know men and women who have allowed the current scientific context

- …is fascinating
- …young Researchers can acquire confidence and motivation in their work

it would be great if every conference had a historical talk!

# The birth of the Semiconductor Drift Detectors

# 1983: the SDD concept is published

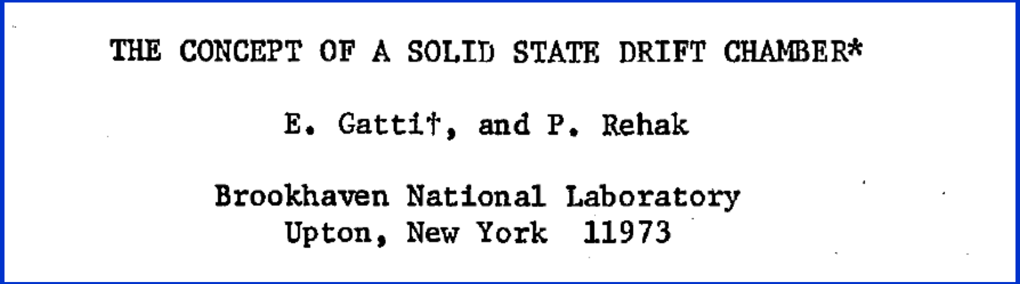


PROCEEDINGS
OF THE
1983 DPF WORKSHOP
ON

**Collider Detectors:**
**Present Capabilities**
**And**
**Future Possibilities**

February 28 - March 4, 1983

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720



THE CONCEPT OF A SOLID STATE DRIFT CHAMBER*

E. Gatti†, and P. Rehak

Brookhaven National Laboratory
Upton, New York 11973

# Pavel Rehak

1945 - 2009

| | |
|---|---|
| 1969 | Ph.D. in natural sciences, University of Prague, Czechoslovakia |
| 1972 | 2nd Ph.D. in high-energy physics, Scuola Normale Superiore, Pisa, Italy |
| 1973 | Kernforschungszentrum, Karlsruhe, Germany |
| 1975 | Yale University and CERN |
| 1976 | Brookhaven National Laboratory, Physics Department |
| 1994 | Brookhaven National Laboratory, Instrumentation Division |

# Emilio Gatti

1922 - 2016

| | |
|---|---|
| 1946 | Industrial Electrical Engineering, University of Padua, Italy |
| 1946 - ‘48 | Electrical Communication specialization, Galileo Ferraris Institute, Turin, Italy |
| 1948 - ’57 | C.I.S.E (Nuclear Science Research Centre), Milan, Italy |
| 1951 - ’97 | Politecnico di Milano, professor of Physics, professor of Electronics |
| 1998 - 2016 | Politecnico di Milano Emeritus professor |

# Emilio Gatti: main inventions and contribution

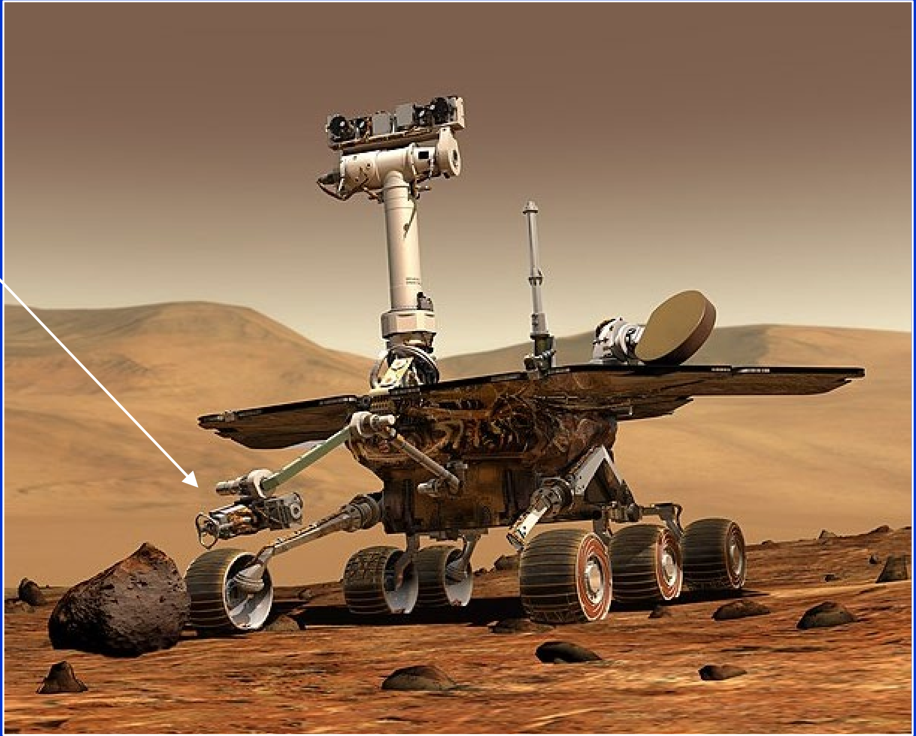
1922 - 2016

| | |
|---|---|
| 1953 | Added step method for single channel discriminators |
| 1955 | Charge Sensitive Preamplifier |
| 1956 | Vernier method to improve the event timing |
| 1962 | Optimum filters for radiation detectors |
| 1962 | Spectrum expander |
| 1963 | The Light Chamber |
| 1963 | Sliding scale method for A/D Conversion |
| 1964 | Statistical theory of scintillation counters |
| 1983 | The Solid State Drift Detector |

# E. Gatti ideas on Mars planet exploration

Alpha Particle X-ray Spectrometer (APXS)

- Silicon Drift Detector
- Charge Sensitive Preamplifier
- Sliding Scale ADC



# Emilio Gatti - awards

1922 - 2016

| | |
|---|---|
| 1953 | Bianchi Prize – Italian Electrical Engineering Society |
| 1968 | National Prize for Physics – Angelo della Riccia Foundation |
| 1971 | Richi Prize – Italian Electrical and Electronic Engineering Society |
| 1972 | Gold Medal for School, Culture and Art – President of the Republic |
| 1973 | Fellow of IEEE |
| 1982 | Publication Prize - Italian Electrical Engineering Society |
| 1984 | IEEE Centennial Medal |
| 1988 | Annual Merit Award - Nuclear & Plasma Sciences Society |
| 1995 | Laurea Honoris Causa in Physics – University of Milan |
| 1996 | International Prize Gerolamo Cardano – Rotary and University of Pavia |
| 2003 | IEEE Radiation Instrumentation Outstanding Achievement Award |

# 1983: the concept published

PROCEEDINGS
OF THE
1983 DPF WORKSHOP
ON
**Collider Detectors:**
**Present Capabilities**
**And**
**Future Possibilities**

February 28 - March 4, 1983

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

**THE CONCEPT OF A SOLID STATE DRIFT CHAMBER***

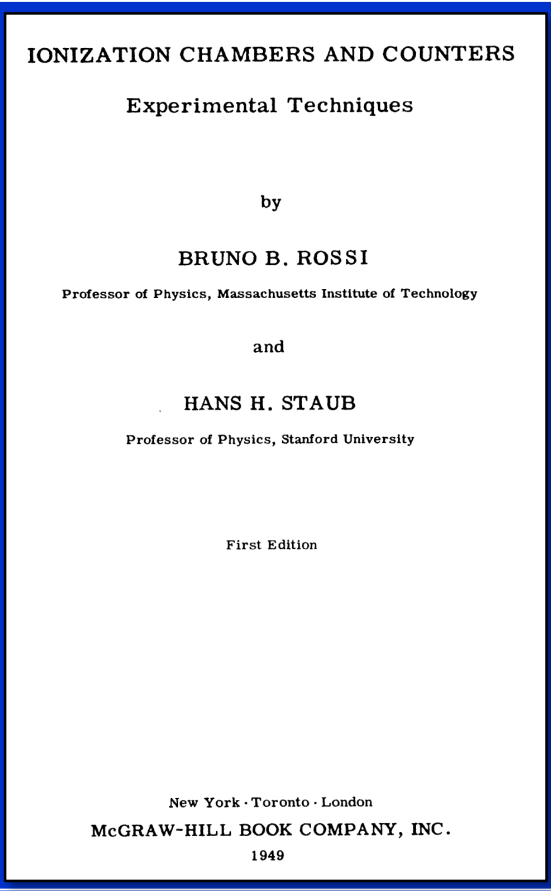

E. Gatti†, and P. Rehak

Brookhaven National Laboratory
Upton, New York 11973


# When and why
# an invention can born

## the case of SDD's

# from 1908 to '70: Ionisation Chambers


IONIZATION CHAMBERS AND COUNTERS

Experimental Techniques

by

BRUNO B. ROSSI

Professor of Physics, Massachusetts Institute of Technology

and

HANS H. STAUB

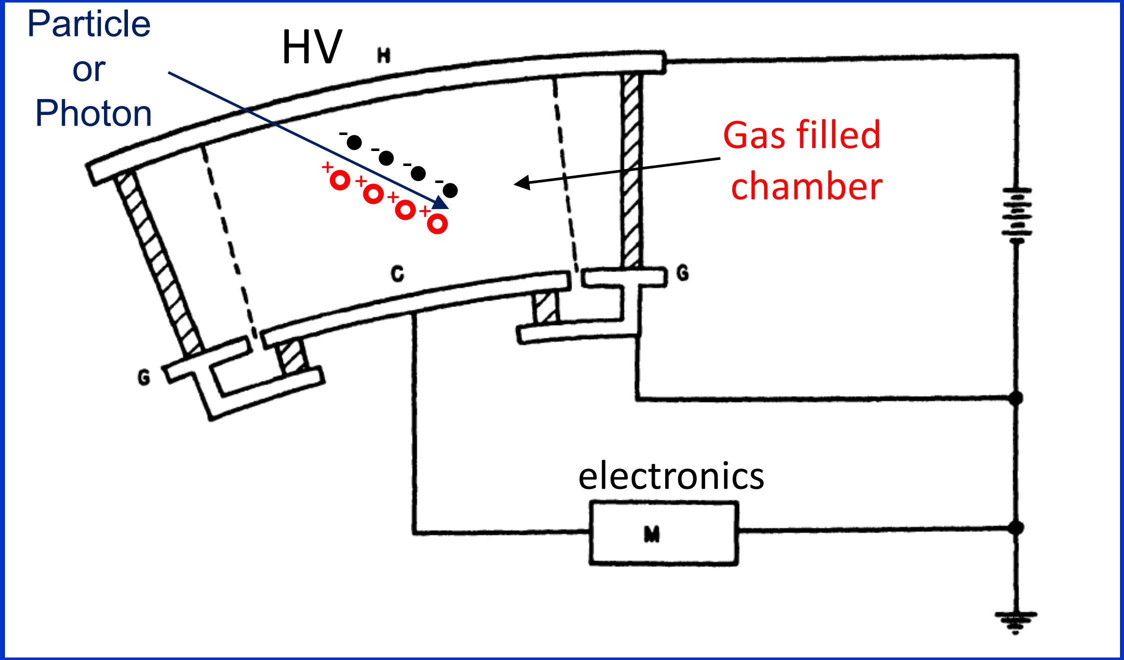
Professor of Physics, Stanford University

First Edition

New York · Toronto · London

McGRAW-HILL BOOK COMPANY, INC.

1949



# 1960: something new appears…

PROCEEDINGS OF THE

SEVENTH SCINTILLATION COUNTER SYMPOSIUM

Washington, D. C.

February 25–26, 1960

IRE Transactions

ON NUCLEAR SCIENCE

Volume NS-7 JUNE–SEPTEMBER, 1960 Number 2–3

PROCEEDINGS OF THE

SEVENTH SCINTILLATION COUNTER SYMPOSIUM

Washington, D. C.

February 25–26, 1960

Sponsored Jointly by
American Institute of Electrical Engineers
Institute of Radio Engineers
Atomic Energy Commission
National Bureau of Standards

PUBLISHED BY THE

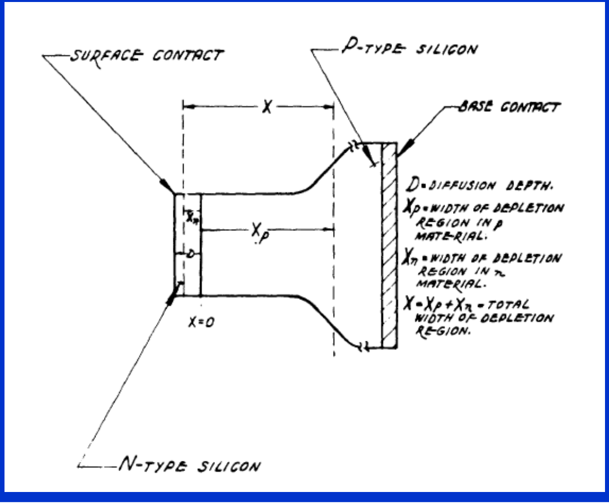
PROFESSIONAL GROUP ON NUCLEAR SCIENCE

# 1960: from *gases* to *semiconductors*

# The Solid-State Ionization Chamber*

S. S. FRIEDLAND,† J. W. MAYER,‡
AND J. S. WIGGINS‡

†Solid State Radiations, Inc., Culver City, Calif.
‡Huges Aircraft Co., Los Angeles, Calif.




Diffused
pn junction

*THE SOLID-STATE IONIZATION CHAMBER*

## The Solid-State Ionization Chamber*

S. S. FRIEDLAND,† J. W. MAYER,‡
AND J. S. WIGGINS‡

*Summary*—Shallow diffused silicon *p-n* junction detectors have been used as room-temperature particle spectrometers for protons, alpha particles, heavy ions, and fission fragments. By the use of high base resistivity devices operated at high reverse biases (> 200 volts), the width of the sensitive volume has been extended beyond 0.5 mm, permitting linear response to protons up to 9 mev. Improved diffusion techniques have resulted in more shallow diffusion depths so that the "window effect" is reduced, extending the low energy response to below 200 kev for alpha particles. Use of low-noise amplifiers has permitted observation of half-widths of the pulse height-distribution equivalent to 18 kev.

Use of shallow diffused silicon *p-n* junctions as charged particle detectors has been extensively investigated at Hughes Aircraft Company and other laboratories.[1] As was mentioned in the preceding paper, the units can be made to respond linearly to energy lost by an ionizing particle within the sensitive volume of the junction. Essentially, the high field region within the device determines the sensitive volume of the detector, a concept which follows closely the action of a conventional ionization chamber.

A discussion of the principles of operation of a solid-state ionization chamber will be aided by referring to Fig. 1. A *p-n* junction is formed close to one surface of a slab of high resistivity *p*-type silicon by a shallow diffusion of phosphorous. A reverse bias is

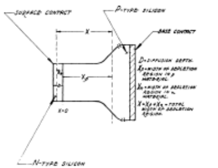



Fig. 1—Schematic diagram of a *p-n* junction under reverse bias.

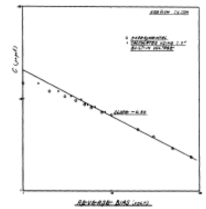


Fig. 2—Capacity vs reverse bias relation of a shallow-diffused *p-n* junction.

established across the junction, which in turn establishes a depletion region (space-charge region) on both sides of the junction. The width of the depletion region from the junction into the *p*-type material is $X_p$, from the junction into the *n* region $X_n$, and the total depletion width is given by $X$ where

$$X = X_p + X_n.$$

The magnitude of $X_n$ or $X_p$ is given approximately by

$$X = \left(\frac{\varepsilon V}{2\pi q N_I}\right)^{1/2}$$

where $V$ is the total potential drop across the depletion region in question, $\varepsilon$ is the dielectric constant of the silicon, $q$ is the electronic charge, and $N_I$ is the concentration of ionized impurity centers.

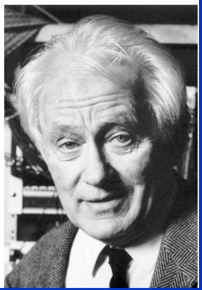
In a diffused junction, as shown in Fig. 1, $X_p/X_n = (\sigma_n/\sigma_p)^{1/2}$ may typically have a value of $10^3$, where $\sigma_n$ and $\sigma_p$ are the conductivities of the *n*- and *p*-type regions, respectively. Thus, the major portion of the depletion region exists beyond the junction into the bulk of the *p*-type silicon, and only a small region exists in front of the junction approaching the surface.

It can be seen from these relations that the width of the depletion region or sensitive volume of the device is proportional to $(\mu\rho V_b)^{1/2}$ where $\rho$ is the re-

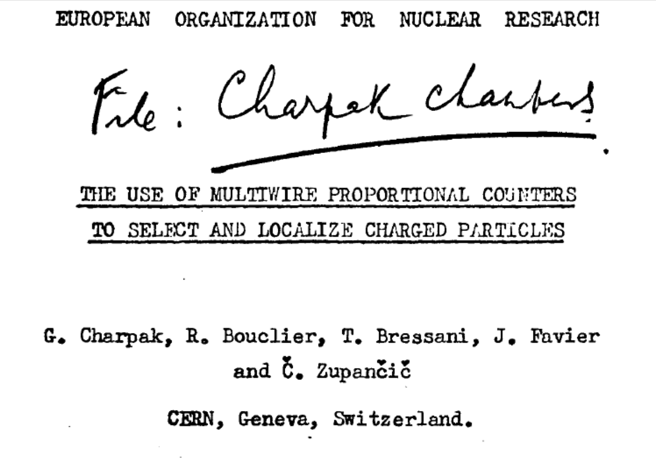
*This work has been supported in part by the Defense Atomic Support Agency under Contract DA-49-146-XZ-016.
†Solid State Radiations, Inc., Culver City, Calif.
‡Huges Aircraft Co., Los Angeles, Calif.
[1] See, for example, S. S. Friedland, J. W. Mayer, and J. S. Wiggins, "Tiny semiconductor is fast, linear detector," *Nucleonics*, vol. 18, pp. 54–59; February, 1960.

181

# 1968: The Multiwire Chamber



Georges Charpak
(1924-2010)



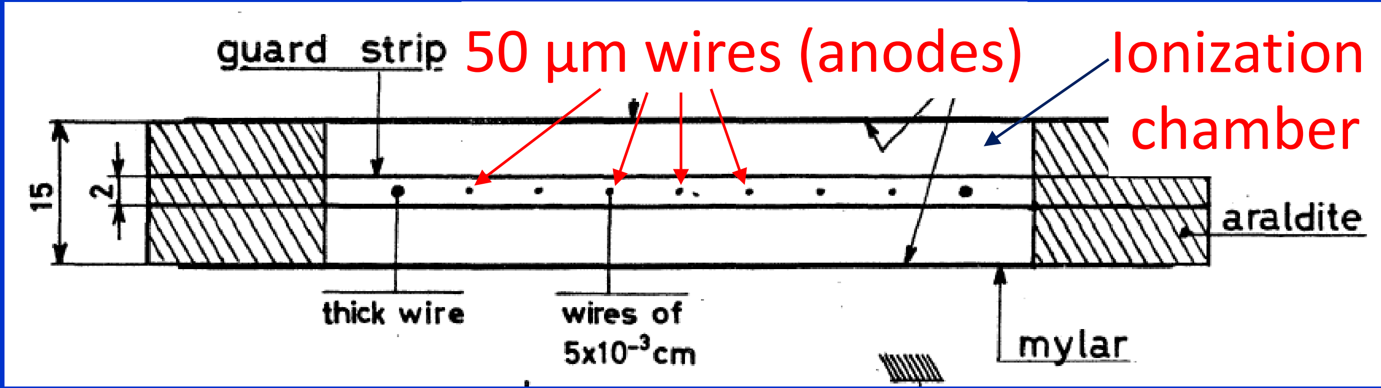
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

File: Charpak chambers

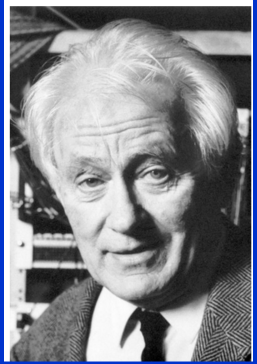
THE USE OF MULTIWIRE PROPORTIONAL COUNTERS
TO SELECT AND LOCALIZE CHARGED PARTICLES

G. Charpak, R. Bouclier, T. Bressani, J. Favier
and Č. Zupančič

CERN, Geneva, Switzerland.



# 1969: The (gas) Drift Chamber



Georges Charpak
(1924-2010)

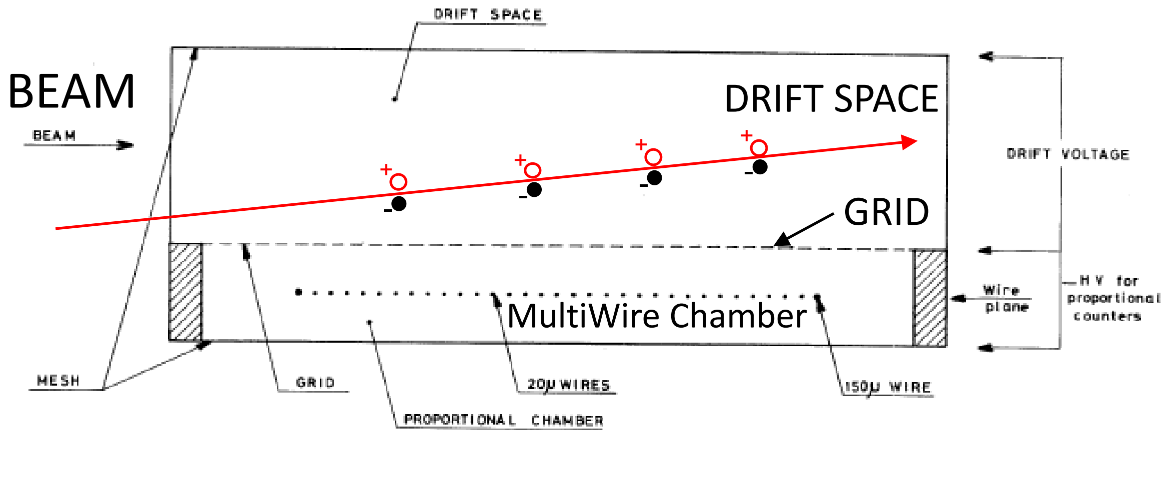
**Nobel Prize in Physics 1992**

"for his invention and development of particle detectors, in particular the multiwire proportional chamber"

TRACK LOCALIZATION BY MEANS OF A DRIFT CHAMBER*)

T. Bressani, G. Charpak, D. Rahm**), Č. Zupančič

CERN, Geneva, Switzerland




DRIFT CHAMBER

# BNL 1978-'81: Rehak works on ionization chambers

IEEE Transactions on Nuclear Science, Vol.NS-25, No.1, February 1978

SECOND COORDINATE READOUT IN
DRIFT CHAMBERS BY CHARGE DIVISION*

V. Radeka and P. Rehak

Brookhaven National Laboratory
Upton, New York 11973

IEEE Transactions on Nuclear Science, Vol. NS-28, No. 1, February 1981

SIGNAL SHAPING AND TAIL CANCELLATION FOR GAS
PROPORTIONAL DETECTORS AT HIGH COUNTING RATES*

R. A. Boie, A. T. Hrisoho,† and P. Rehak

Brookhaven National Laboratory
Upton, New York 11973

# Milano, 1978-’79: Gatti works on ionization chambers

IEEE Transactions on Nuclear Science, Vol.NS-25, No.1, February 1978

OPTIMUM FILTERS WITH TIME WIDTH CONSTRAINTS
FOR LIQUID ARGON TOTAL-ABSORPTION DETECTORS*

Emilio Gatti

Istituto di Fisica Politecnico Milano
Milano, Italy

and

Veljko Radeka

Brookhaven National Laboratory
Upton, New York 11973

IEEE Transactions on Nuclear Science, Vol. NS-26, No. 2, April 1979

CONSIDERATIONS FOR THE DESIGN OF A TIME
PROJECTION LIQUID ARGON IONIZATION CHAMBER*

E. Gatti, G. Padovini, L. Quartapelle†

and

N. E. Greenlaw and V. Radeka‡

in collaboration with
Veliko Radeka (BNL)

# 1979: a Breakthrough in semiconductor detectors

Joseph Kemmer

Univ. Munich

NUCLEAR INSTRUMENTS AND METHODS 169 (1980) 499-502.

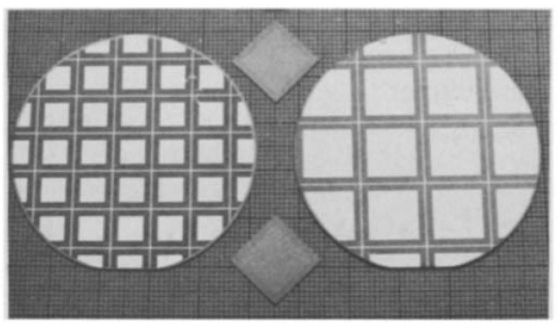
**FABRICATION OF LOW NOISE SILICON RADIATION DETECTORS BY THE PLANAR PROCESS**

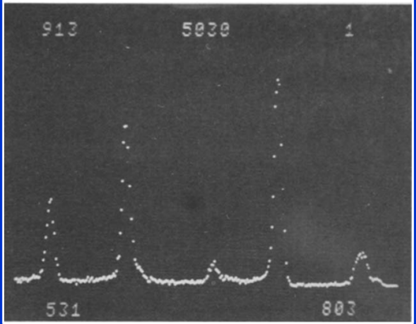
J KEMMER

*Fachbereich Physik der Technischen Universitat Munchen, 8046 Garching, Germany*

Received 30 July 1979 and in revised form 22 October 1979

*Dedicated to Prof Dr H -J Born on the occasion of his 70th birthday*





# 1982: first Si Microstrip Detector with planar technology

Joseph Kemmer
Univ. Munich

Paul Burger
Enertec company

Erik Heijne
CERN

IEEE Transactions on Nuclear Science, Vol. NS-29, No. 1, February 1982

PERFORMANCE AND APPLICATIONS OF PASSIVATED
ION-IMPLANTED SILICON DETECTORS

J. KEMMER
Fakultät für Physik der Technischen Universität München
8046 GARCHING, Germany
P. BURGER and R. HENCK
ENERTEC-SCHLUMBERGER, 1, Parc des Tanneries
67380 STRASBOURG Lingolsheim, France
E. HEIJNE
CERN, European Organisation for Nuclear Research
1211 GENEVA 23, Switzerland

Microstrip Detector
(first with planar technology)

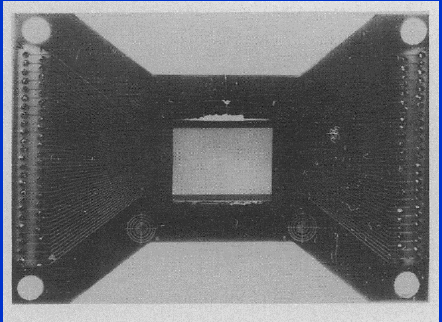


Fig. 8 : Silicon microstrip detector

It could be called
**the Solid State Multiwire Chamber**

Are time and conditions ready
for a Solid State Drift Chamber?

# 1982: Gatti and Rehak studied $E_{field}$ in MCP

IEEE Transactions on Nuclear Science, Vol. NS-30, No. 1, February 1983

## Study of the Electric Field Inside Microchannel Plate Multipliers[a)]

E. Gatti[b)], K. Oba[c)] and P. Rehak
Brookhaven National Laboratory
Upton, New York 11973

$$u(x,y,z,s) = \frac{Q_o}{4\pi\varepsilon_r\sqrt{\gamma(r-r_o)^2+(z-z_o)^2}} \frac{1}{\sqrt{1/\tau_r+s}} \frac{1}{\sqrt{b+s}} \quad (20)$$

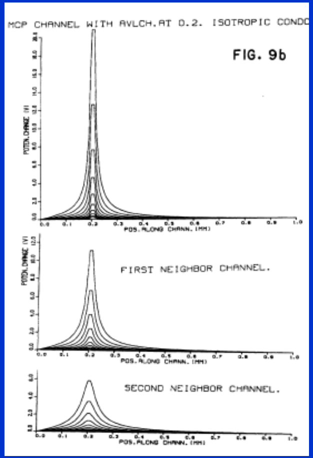
where $\gamma = \varepsilon_z/\varepsilon_r$; $\tau_r = \varepsilon_r/\sigma_r$; $\tau_z = \varepsilon_z/\sigma_z$;

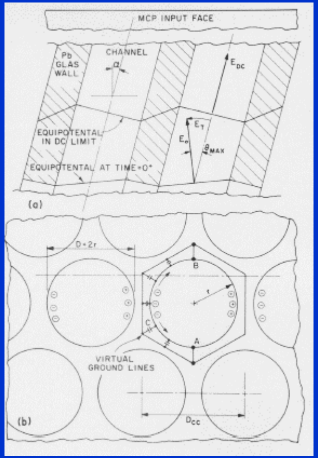
$$(r-r_o)^2 = (x-x_o)^2 + (y-y_o)^2$$

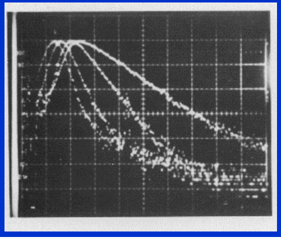
and $$b = \frac{\gamma(r-r_o)^2/\tau_z+(z-z_o)^2/\tau_r}{\gamma(r-r_o)^2+(z-z_o)^2}.$$

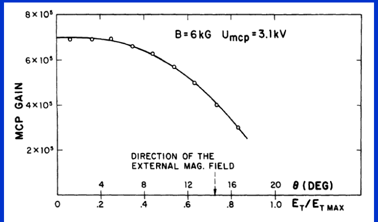
The form of equation (20) has a known Laplace inverse-transform which is:

$$U(x,y,z,t) = \frac{Q_o}{4\pi E_r\sqrt{\gamma(r-r_o)^2+(z-z_o)^2}} \cdot \exp\left[-\frac{1}{2}(b+1/\tau_r)t\right] \cdot I_o\left(\frac{1}{2}(b-1/\tau_r)t\right) . \quad (21)$$



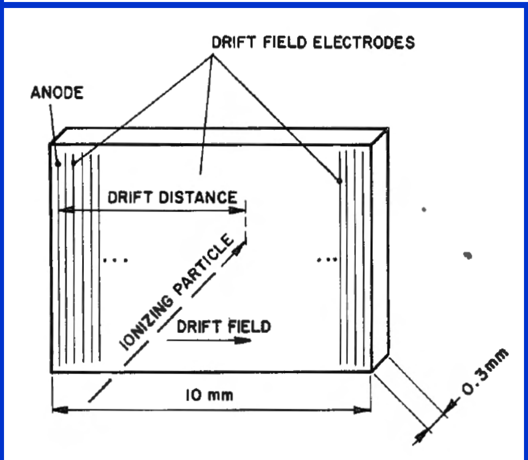


# 1983: the SSD concept published

THE CONCEPT OF A SOLID STATE DRIFT CHAMBER*

E. Gatti†, and P. Rehak

Brookhaven National Laboratory
Upton, New York 11973

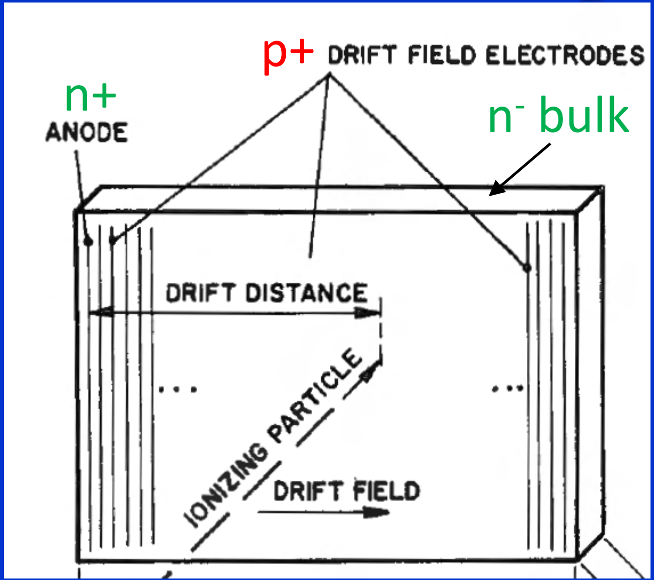



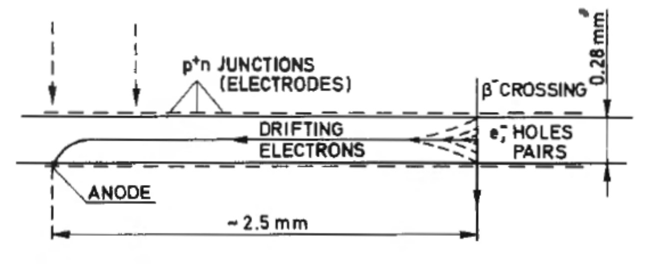

advantages w.r.t. Gas Drift Chambers:

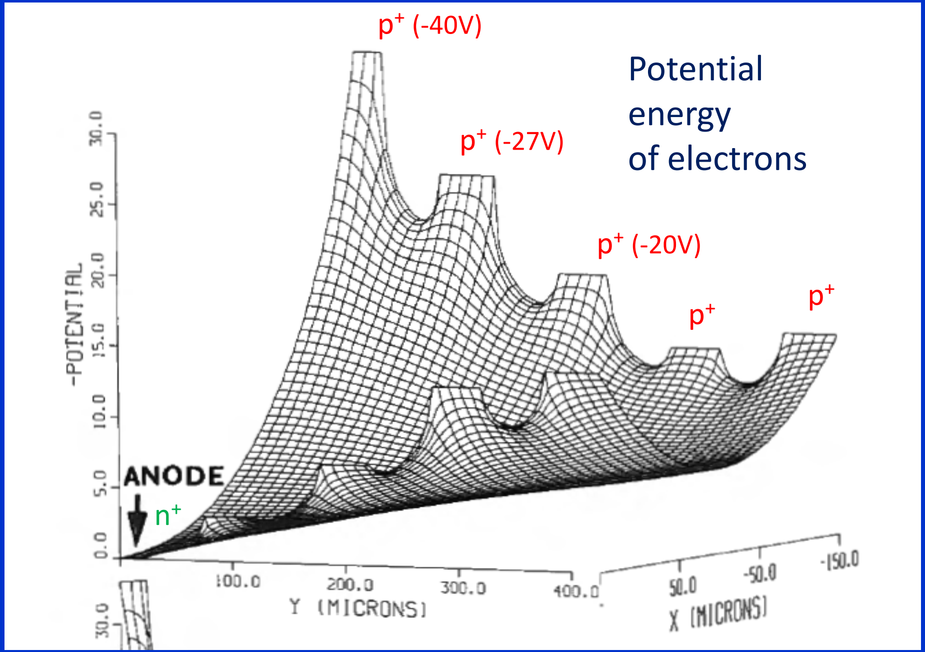
reduced δ-rays

reduced ionization density fluctuation

# SDD: principle of operation




Drift time gives a coordinate

# 1984: first SDD realized

Nuclear Instruments and Methods in Physics Research 226 (1984) 129–141

**SILICON DRIFT CHAMBERS – FIRST RESULTS AND OPTIMUM PROCESSING OF SIGNALS ***

Emilio GATTI

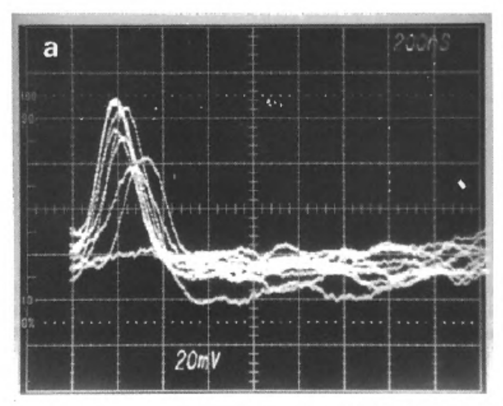
*Dipartimento di Elettronica, Politecnico di Milano, Piazza Leonardo da Vinci 32, Milano, Italy*

Pavel REHAK

*Brookhaven National Laboratory, Upton, New York 11973, USA*

Jack T. WALTON

*Lawrence Berkeley Laboratory, Berkeley, California 94720, USA*




Fabricated at: Lawrence Berkeley Laboratory, CA, USA
Tested at: Brookhaven National Laboratory, NY, USA

# 1985: BNL, PoliMI, Univ. Munich, LBL

IEEE Transactions on Nuclear Science, Vol. NS-32, No. 2, April 1985

SEMICONDUCTOR DRIFT CHAMBERS

E. Gatti*°, P. Rehak*, A. Longoni°
*Brookhaven National Laboratory, Upton, N.Y., USA
°Politecnico di Milano, Milano, Italy

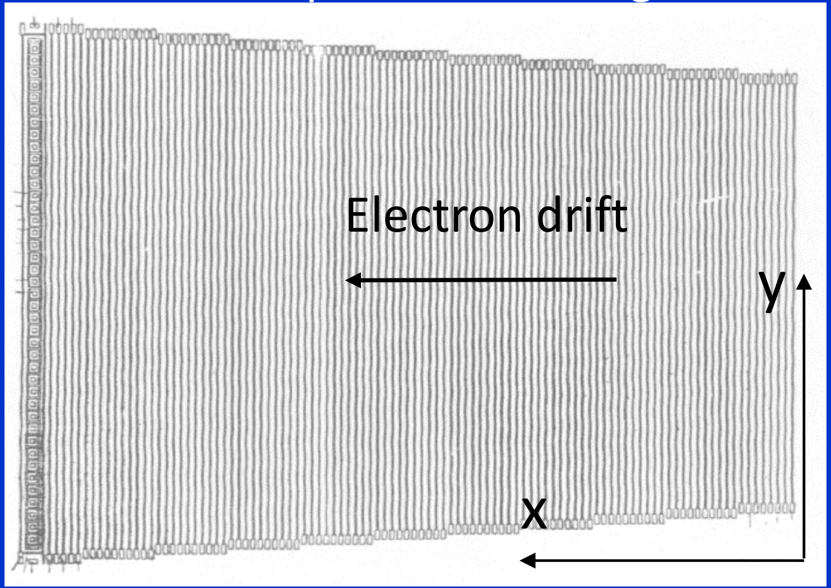
J. Kemmer
Fakultät für Physik der Technischen Universität, München, FRG

P. Holl, R. Klanner, G. Lutz and A. Wylie
Max Planck Institut für Physik und Astrophysik, München, FRG

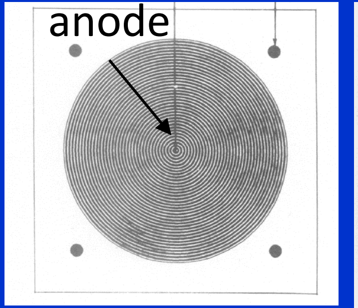
F. Goulding, P.N. Luke, N.W. Madden, J. Walton
Lawrence Berkeley Laboratory, California, USA

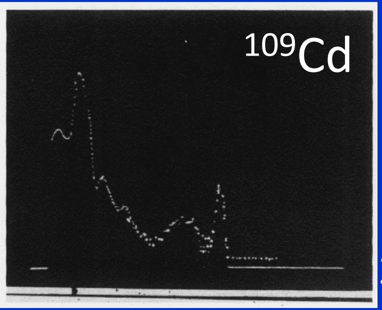
Multi-anodes SDD
for 2D-position sensing

41 anodes




Circular SDD
for X-rays




300 e- r.m.s.
2.6 keV FWHM

# SDD in particle colliders

## 1995

ALICE SDD

CERN – LHC

Silicon Vertex Tracker (SVT)

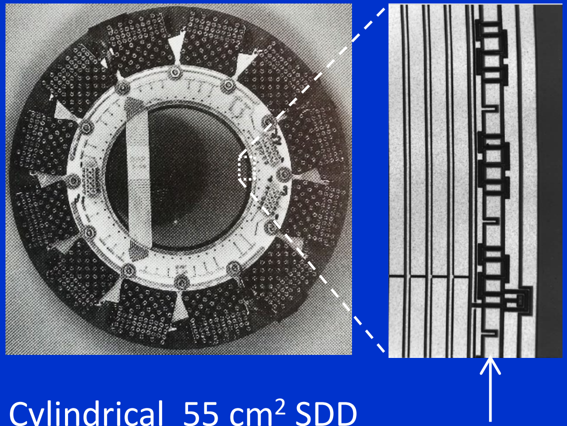
260 x 52 $cm^2$ Linear SDDs
in 2 layers
2 x 256 anodes/SDD

## 1996

AZTEC SDD

CERN – NA45/WA98

Microvertex detector



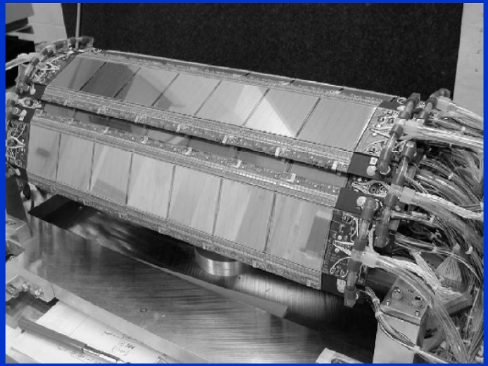

Cylindrical 55 $cm^2$ SDD
Radial drift: 700 V/cm
360 anodes

## 2001

STAR SDD

BNL – RHIC

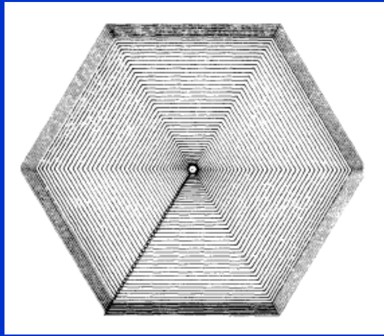
Silicon Drift Tracker (SDT)



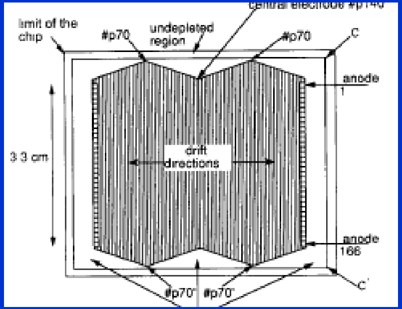
216 x 40 $cm^2$ Linear SDDs
in 3 Cylindrical layers
2 x 240 anodes/SDD

# Development of SDD's

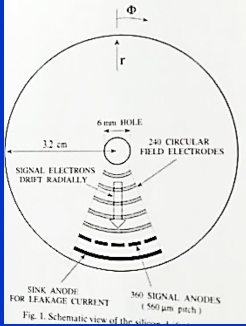
Spiral (1989)



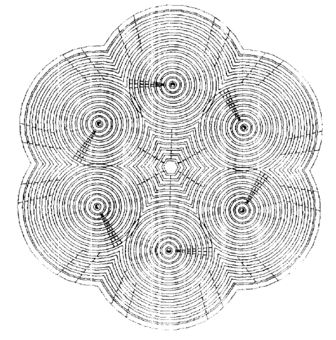
Large Area (1991)
4 x 4 cm



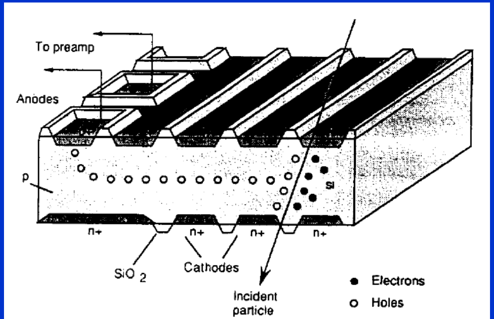

3'' wafer cylindrical (1992)
360 anodes



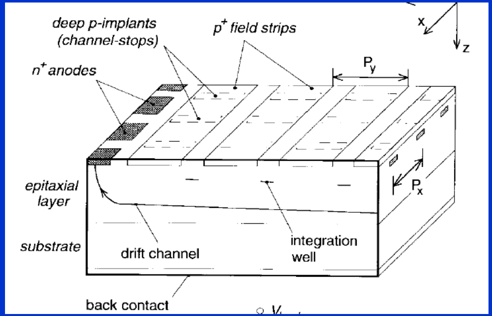

SDD Array (1994)



P-type SDD (1995)




Controlled Drift (1997)




Droplet SDD (2004)

# Ge and Compound SDD

## 1987: Ge Drift Detector

**GERMANIUM DRIFT DETECTOR: A NEW TOMOGRAPHIC DEVICE PROVIDING INFORMATION ON THE CHEMICAL PROPERTIES OF A BODY SECTION*,****

Emilio GATTI[+] and Pavel REHAK
*Brookhaven National Laboratory, Upton, NY 11973, USA*

Josef KEMMER
*Faculty of Physics, Munich Technical University, D-8048 Garching, FRG*

## 1996: $HgI_2$ Drift Detector

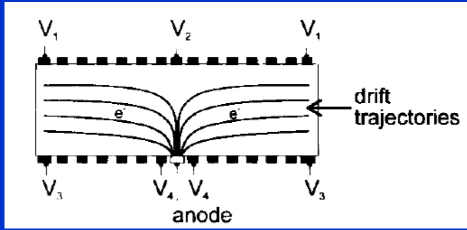
New gamma-ray detector structures for electron only charge carrier collection utilizing high-*Z* compound semiconductors

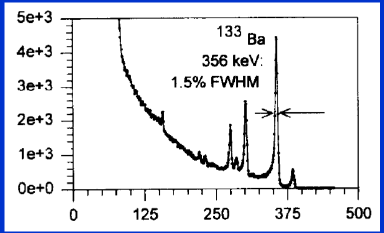
B.E. Patt*, J.S. Iwanczyk, G. Vilkelis, Y.J. Wang
*Xsirius, Inc., 1220-A Avenida Acaso, Camarillo, CA 93012,* USA

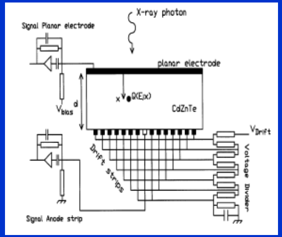
## 1998: CdZnTe Drift Detector

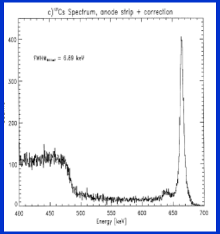
CdZnTe drift detector with correction for hole trapping

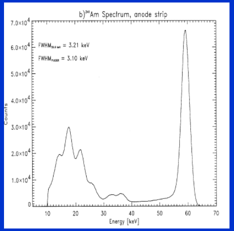
M.A.J. van Pamelen, C. Budtz-Jørgensen*
*Danish Space Research Institute, Juliane Maries Vej 30, 2100 København Ø, Denmark*





A key point of Drift Detector: single charge carrier induction

# Key features of SDD's

| | Planar Junction | SDD |
|---|---|---|
| DC output current $I_{DET}$ | ÷ Detector's Volume | ÷ Detector's Volume |
| Output capacitance $C_{DET}$ | ÷ Detector's Area<br>≈ 35 pF/cm$^2$ (300 μm thick) | Independent of Area<br>< 100 fF |

$C_{IL}$ : Load capacitance at Preamp. input $C_{IL} = C_{DET} + C_{connection} + C_{feedback/test}$

$C_G$ : Preamp. input FET capacitance

Minimum noise for capacitive matching: $C_G = C_{IL}$

Minimum ENC: $ENC_{min} \div (I_{DET})^n (C_{IL})^m$

Optimum shaping time: $\tau_{opt} \div \frac{(C_{IL})^m}{(I_{DET})^n}$

$C_{IL} \downarrow \Rightarrow$

Lower ENC
@
Shorter shaping time
⇓
Higher resolution
@
Higher photon/particle rate

# Key features of SDD's

| | Planar Junction | SDD |
|---|---|---|
| DC output current $I_{DET}$ | ÷ Detector's Volume | ÷ Detector's Volume |
| Output capacitance $C_{DET}$ | ÷ Detector's Area<br>≈ 35 pF/cm² (300 μm thick) | Independent of Area<br>< 100 fF |

$C_{IL}$ : Load capacitance at Preamp. input $C_{IL} = C_{DET} + C_{connection} + C_{feedback/test}$

$C_G$ : Preamp. input FET capacitance

Minimum noise for capacitive matching: $C_G = C_{IL}$

Minimum ENC: $ENC_{min} \div (I_{DET})^n (C_{IL})^m$

Optimum shaping time: $\tau_{opt} \div \frac{(C_{IL})^m}{(I_{DET})^n}$

$C_{IL} \downarrow \Rightarrow$

Lower ENC
@
Shorter shaping time
⇓
Higher resolution
@
Higher photon/particle rate

# The development of the Front-End Electronics for SDD's

# 1987-'89: JFET and Preamp. integrated

## Brookhaven – Milan – Munich collaboration

JOURNAL DE PHYSIQUE
Colloque C4, supplément au n°9, Tome 49, septembre 1988

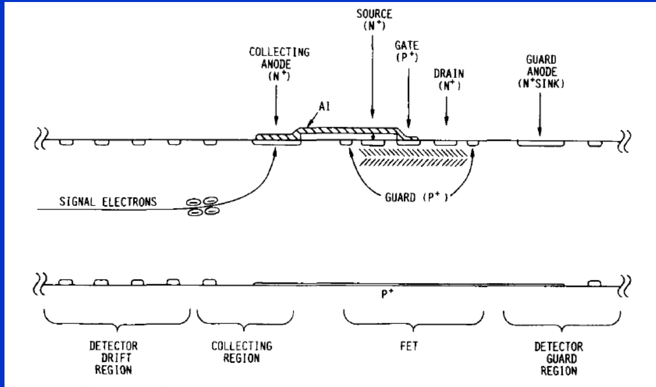
JFET FOR COMPLETELY DEPLETED HIGH RESISTIVITY SILICON

V. RADEKA, P. REHAK, S. RESCIA, E. GATTI*, A. LONGONI*, M. SAMPIETRO*, G. BERTUCCIO*, P. HOLL**, L. STRUDER** and J. KEMMER***

IEEE ELECTRON DEVICE LETTERS, VOL. 10, NO. 2, FEBRUARY 1989 91

Implanted Silicon JFET on Completely Depleted High-Resistivity Devices

VELJKO RADEKA, FELLOW, IEEE, PAVEL REHAK, MEMBER, IEEE, S. RESCIA, EMILIO GATTI, FELLOW, IEEE, A. LONGONI, M. SAMPIETRO, G. BERTUCCIO, P. HOLL, L. STRÜDER, AND J. KEMMER




CHARGE-SENSITIVE PREAMPLIFIER FOR INTEGRATION ON SILICON RADIATION DETECTORS: FIRST EXPERIMENTAL RESULTS

P. REHAK *13th June 1989*
S. RESCIA
V. RADEKA

*Brookhaven National Laboratory*
*Upton, NY 11973, USA*

E. GATTI
A. LONGONI
M. SAMPIETRO
G. BERTUCCIO

*Istituto di Fisica*
*Politecnico di Milano*
*CEQSE-CNR*
*Piazza Leonardo da Vinci 32, 20133 Milano, Italy*

J. KEMMER
U. PRECHTEL
T. ZIEMANN

*MBB GmbH*
*Postfach 801149, 8000 Munchen 80, Federal Republic of Germany*

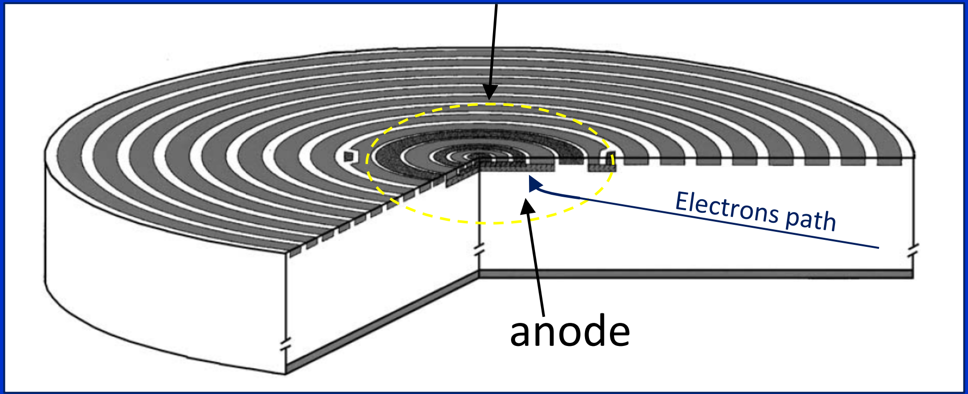
# 1994: SDD with integrated JFET

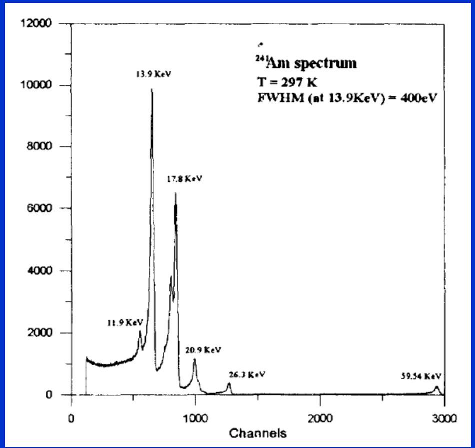
**Design and test at room temperature of the first Silicon Drift Detector with on-chip electronics**

R. Hartmann, D. Hauff, S. Krisch, P. Lechner, G. Lutz, R. H. Richter, H. Seitz and L. Strüder
MPI Halbleiterlabor, Paul-Gerhardt-Allee 42, 81245 München, Germany

G. Bertuccio, L. Fasoli, C. Fiorini, E. Gatti, A. Longoni, E. Pinotti and M. Sampietro
Politecnico di Milano, Dipartimento di Elettronica e Informazione, Piazza L. da Vinci 32, 20133 Milano, Italy

JFET




SDD used area
2 mm$^2$

@ +24°C
41 e- rms
(356 eV FWHM)

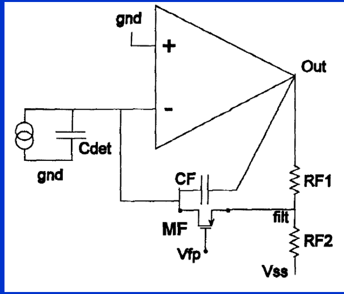
Proceedings of IEDM 94-545

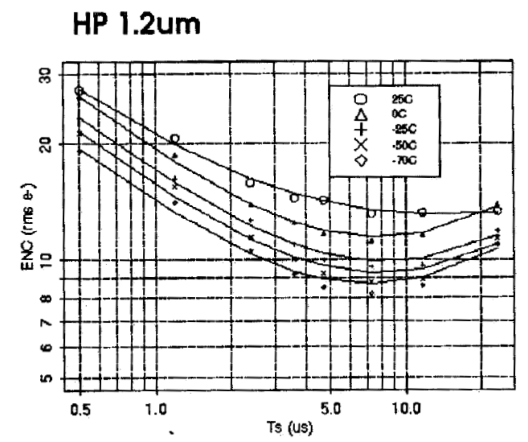
# 1997: SDD and CMOS preamplifier

**CMOS Preamplifier with High Linearity and Ultra Low Noise for X-Ray Spectroscopy**

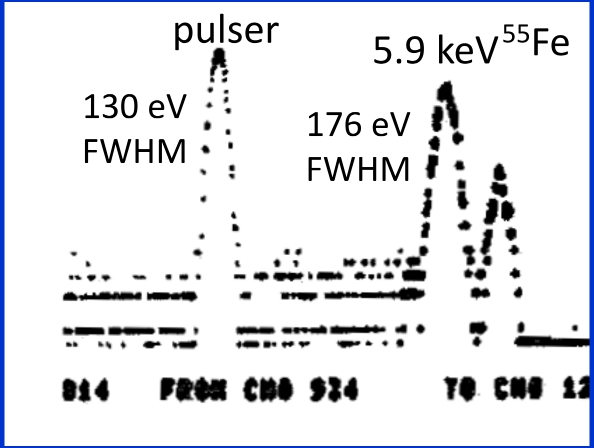
P. O'Connor*, P. Rehak*, G. Gramegna[+], F. Corsi[+], C. Marzocca[+]
* Brookhaven National Laboratory, Upton, NY 11973 USA
[+]Politecnico di Bari, Dipartimento di Elettrotecnica ed Elettronica, via E. Orabona 4, 70125 Bari, Italy

HP CMOS 1.2 µm
AMS CMOS 1.2µm



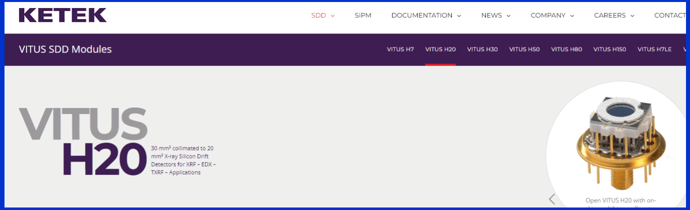

Intrinsic ENC = 9 e- rms
@ +25°C

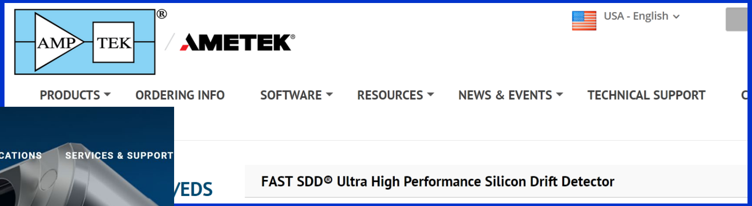



With SDD: ENC = 16 e- rms
@ -70°C

# Present & Future
# of
# Solid State Drift Detectors

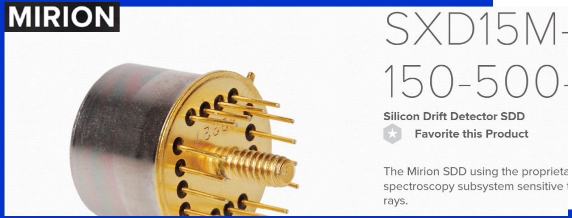
# Present: many commercial SDDs available

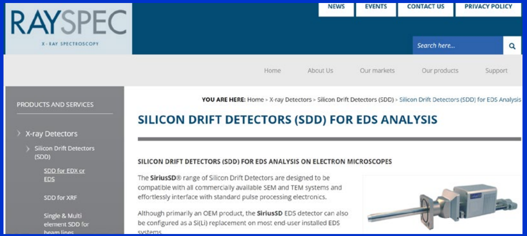


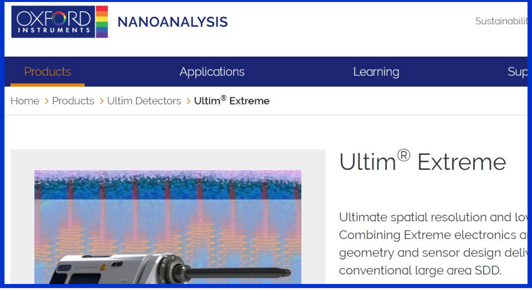










Geometry: cylindrical

Area : 5 mm$^2$ to 150 mm$^2$

Applications: Analysis with X-rays

FWHM <130 eV @ 5.9 keV, - 35 °C

# What about today SDD R&D?

## just an example…

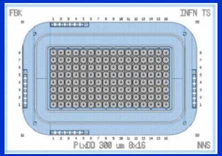
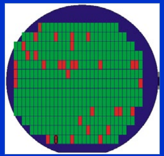
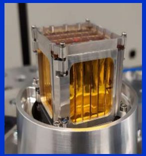
# REDSOX: R&D collaboration on SDDs

RESEARCH DRIFT FOR SOFT X-RAYS redsox

P.I. Andrea Vacchi, University of Udine

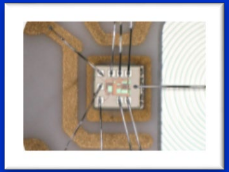
| | | | | |
|---|---|---|---|---|
| Bologna Univ.<br>G. Baldazzi | ELETTRA - Trieste<br>G. Cautero | FBK - Trento<br>P. Bellutti | KIT - Karlsruhe<br>M. Caselle | Bologna, Roma<br>C. Labanti, M. Feroci |
| INFN Bologna, Milano, Roma, Trento, Trieste | Pavia University<br>P. Malcovati | Politecnico di Milano Univ.<br>G. Bertuccio | Udine University<br>A. Vacchi | |

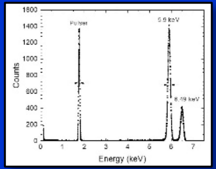
# REDSOX: a complete flow of activities

| SDD Design | ASICs Design & Test | SDD Manufacturing | SDD Electrical Test | System Assembly and Test |
|---|---|---|---|---|
|  |  |  |   |   |
| INFN Trieste, Udine<br>FBK - Trento | Politecnico di Milano<br>University of Pavia | FBK - Trento | FBK, TIFPA - Trento | INAF Bologna, Roma, Trieste, Udine, PoliMi |

## from Design to Application

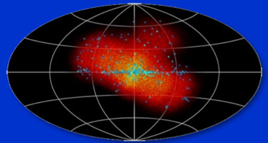
### High-End Prototypes



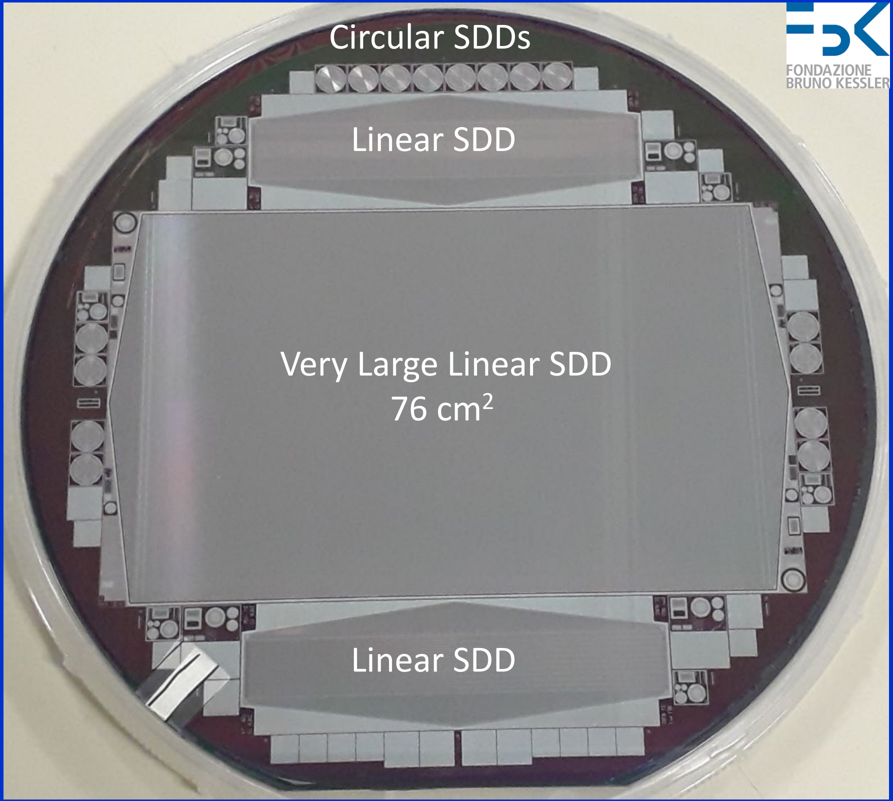


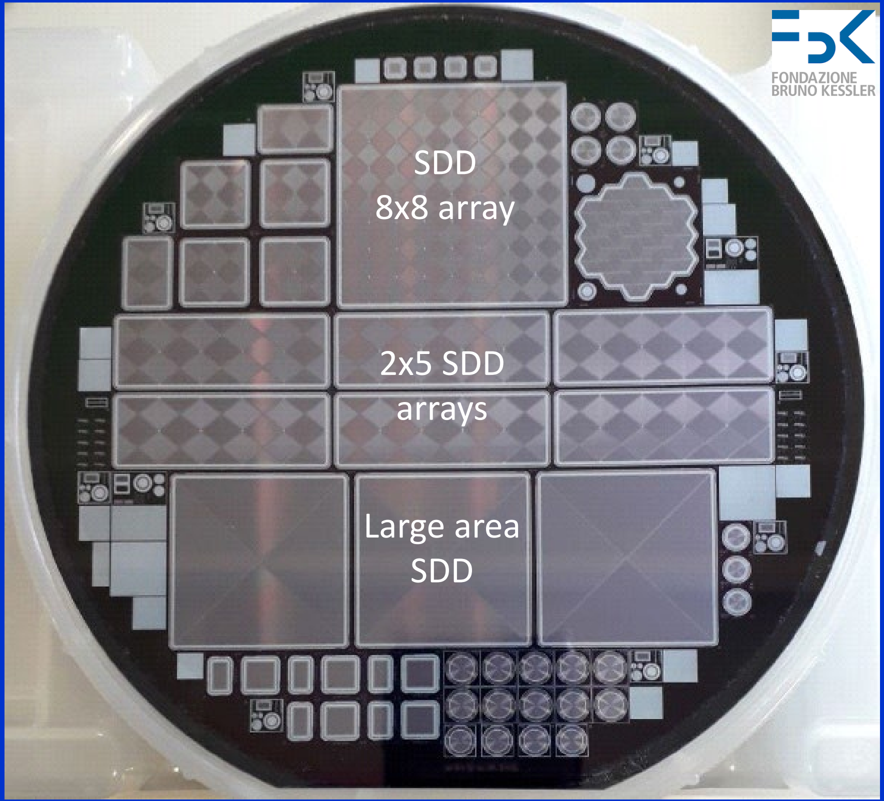

### Synchrotron System

### Space X-γ Telescopes

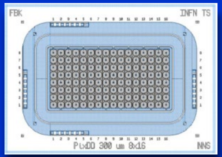
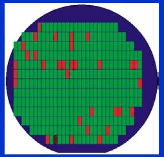
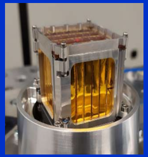


# SDD's wafers


FONDAZIONE BRUNO KESSLER
Circular SDDs
Linear SDD
Very Large Linear SDD
76 cm²
Linear SDD

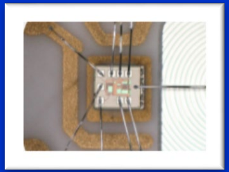

FONDAZIONE BRUNO KESSLER
SDD
8x8 array
2x5 SDD
arrays
Large area
SDD

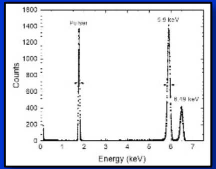
# REDSOX: a complete flow of activities

| SDD Design | ASICs Design & Test | SDD Manufacturing | SDD Electrical Test | System Assembly and Test |
|---|---|---|---|---|
|  |  |  |   |   |
| INFN Trieste, Udine<br>FBK - Trento | Politecnico di Milano<br>University of Pavia | FBK - Trento | FBK, TIFPA - Trento | INAF Bologna, Roma,<br>Trieste, Udine, PoliMi |

## from Design to Application

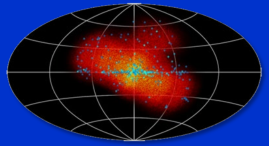
### High-End Prototypes






### Synchrotron System

### Space X-γ Telescopes

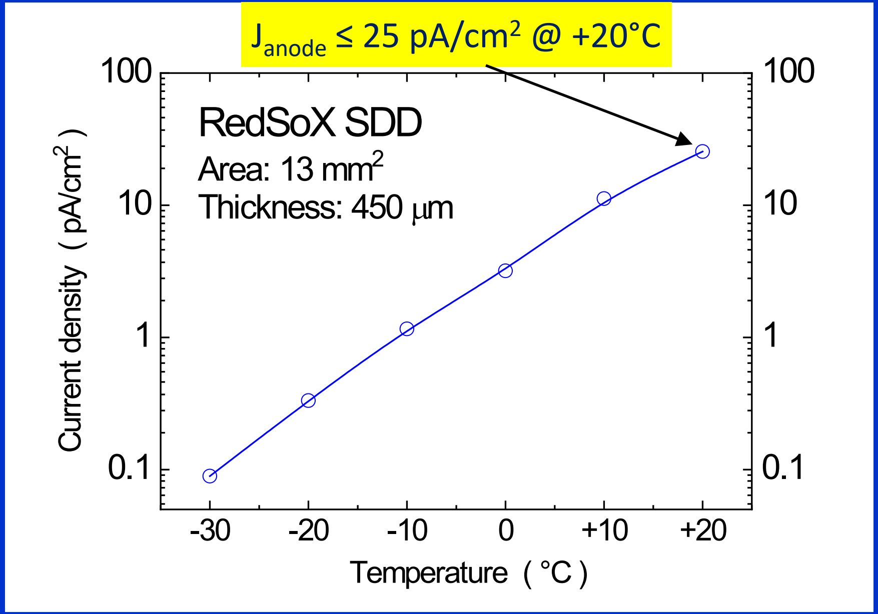


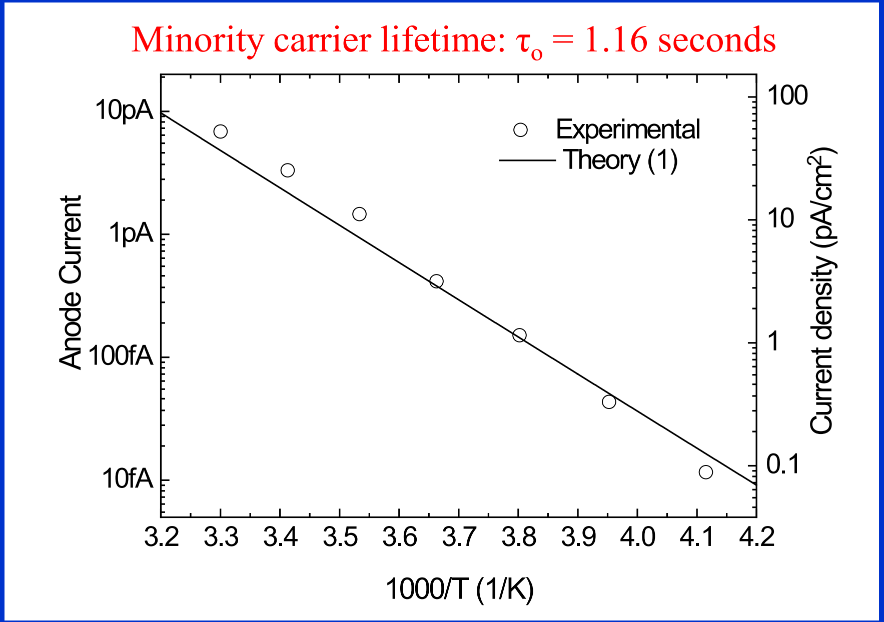
# Advances in SDD: ultra low anode current

Nominal values for most processes: 100 ÷ 200 pA/cm$^2$

$$I_{anode} = AW\frac{n_i}{2\tau_o} = \frac{AW}{2\tau_o}\sqrt{N_{Co}N_{Vo}}\left(\frac{T}{T_o}\right)^{3/2} e^{-\frac{E_g}{2kT}}$$

SDD current at anode



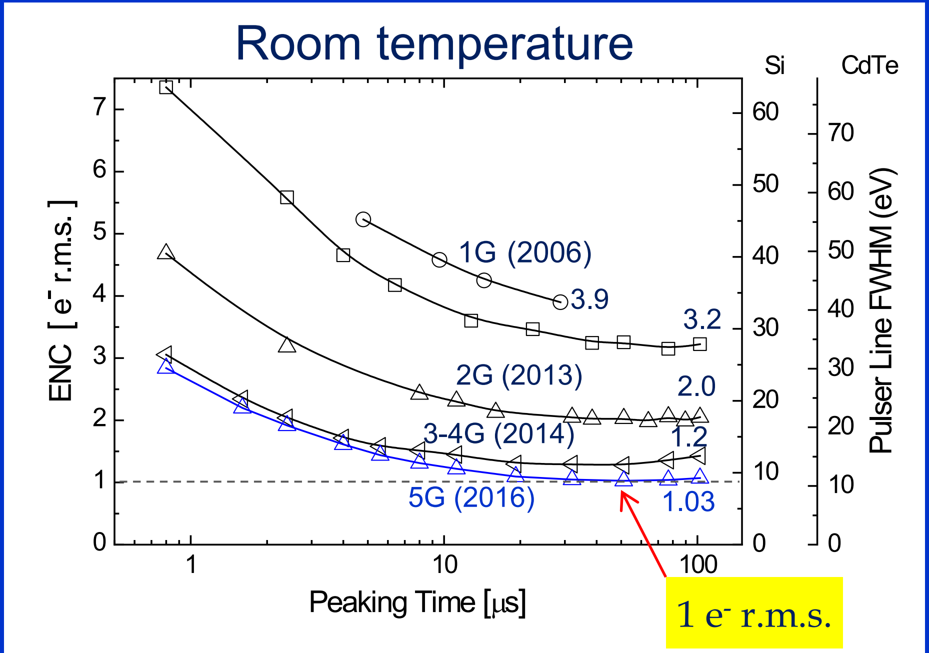
# Advanced in Front-End: SIRIO Charge Preamplifier

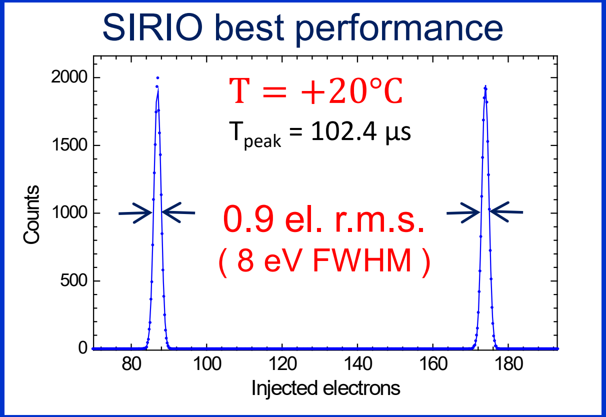
Nuclear Instruments and Methods in Physics Research A 579 (2007) 243–246

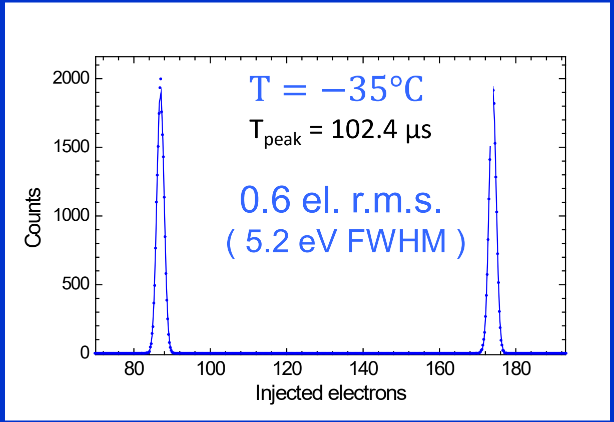
Progress in ultra-low-noise ASICs for radiation detectors

Giuseppe Bertuccio[a,b,*], Stefano Caccia[a,b]

[a]Politecnico di Milano, Department of Electronics Engineering and Information Science, P.za L. da Vinci 32, 20133 Milano, Italy
[b]National Institute of Nuclear Physics, INFN sez., Milano, Italy

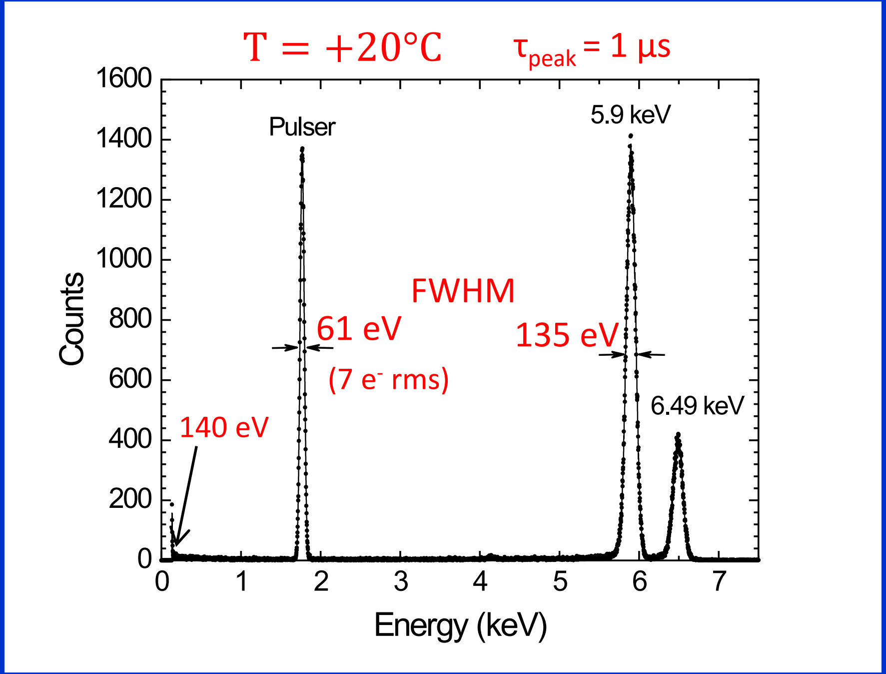


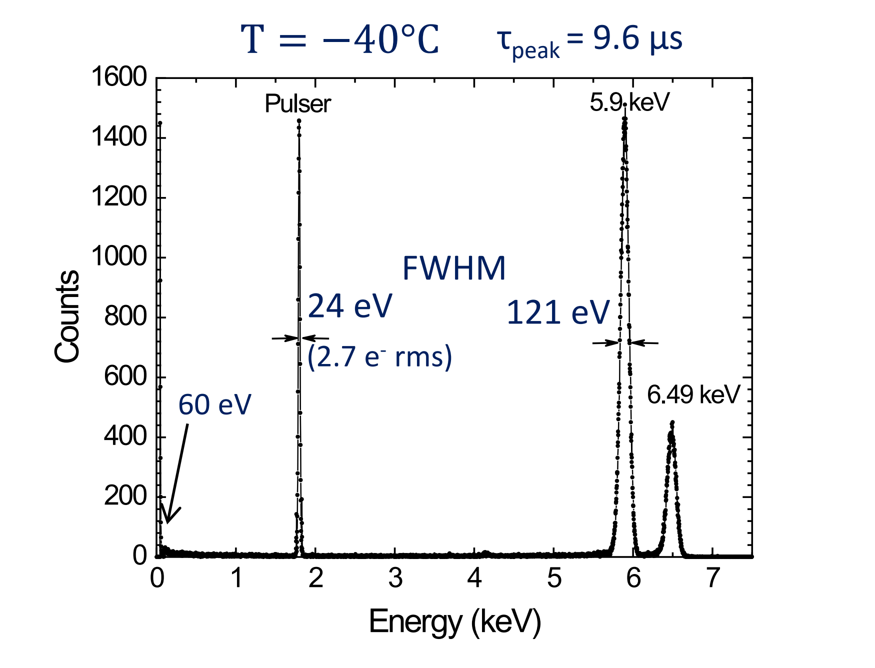



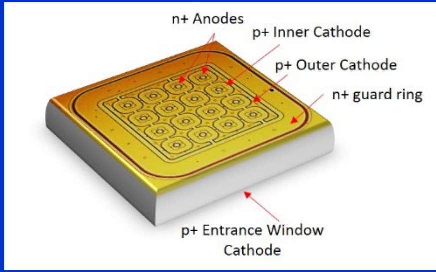
# Advances in energy resolution

## Cylindrical SDD (13 mm$^2$) coupled to SIRIO-3 Preamplifier

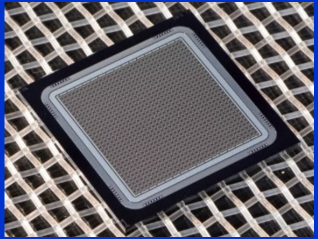


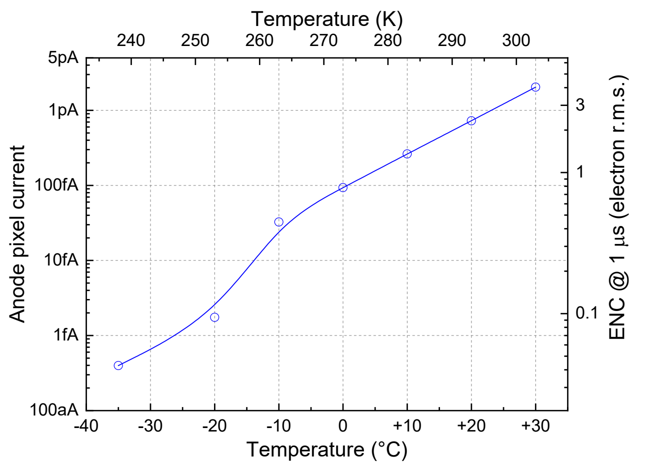
# PixDD: Pixel drift detector



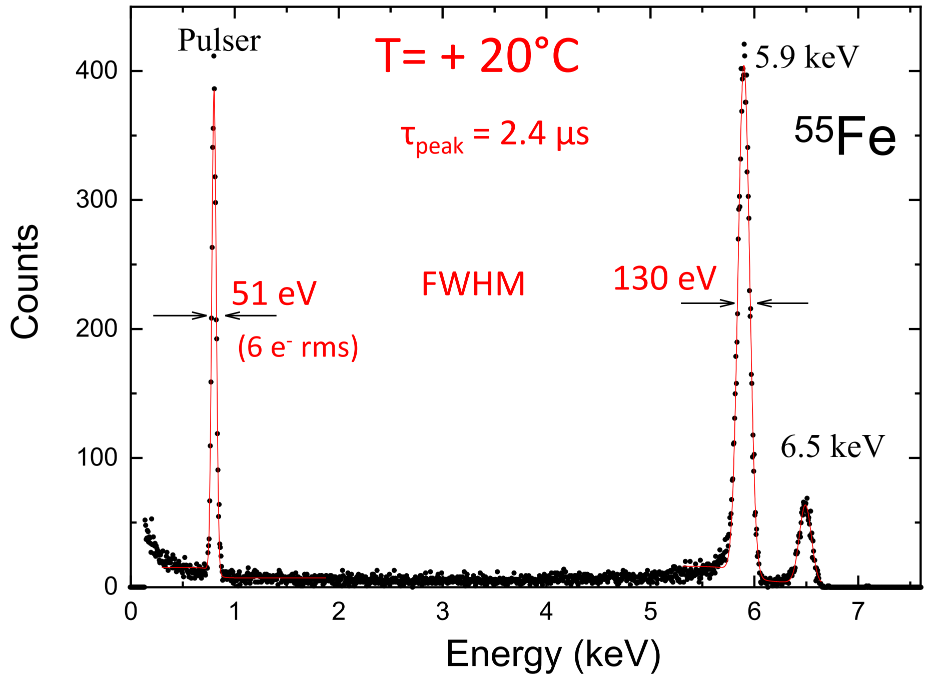

32x32 PixDD



Pixel area: 300 µm x 300 µm




At Room Temperature with SIRIO preamp.



# Conventional vs. Drift Pixel

## Conventional Pixel

$Area: 300\ \mu m\ \times 300\ \mu m$

$I_{leakage}\ \lesssim$ 1 pA @ 20°C

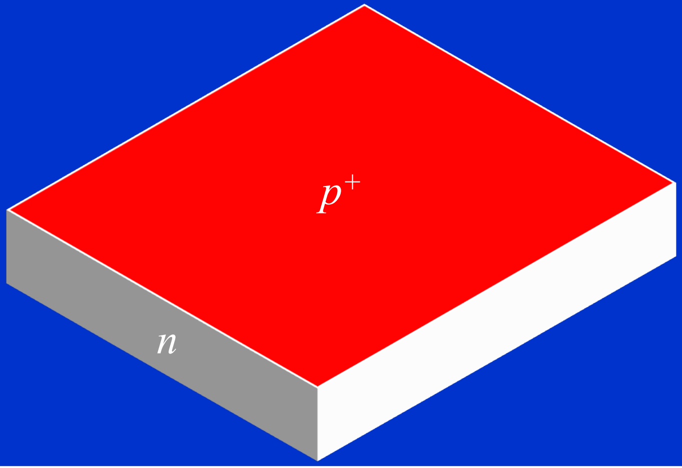
$C_{junction} \cong tens\ of\ fF$

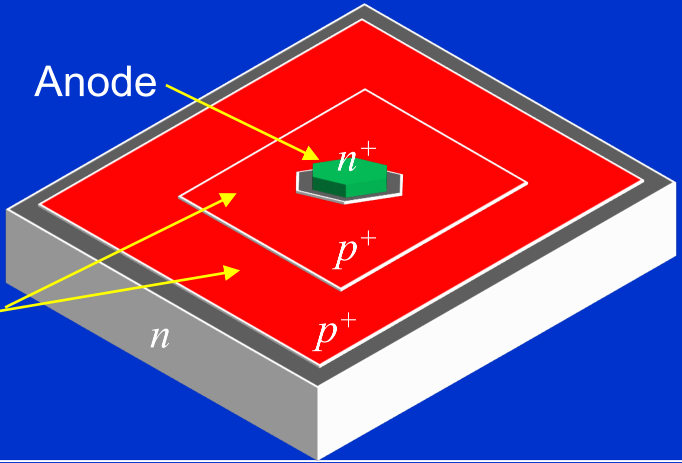
## Drift Pixel

$I_{leakage}\ \lesssim$ 1 pA @ 20°C

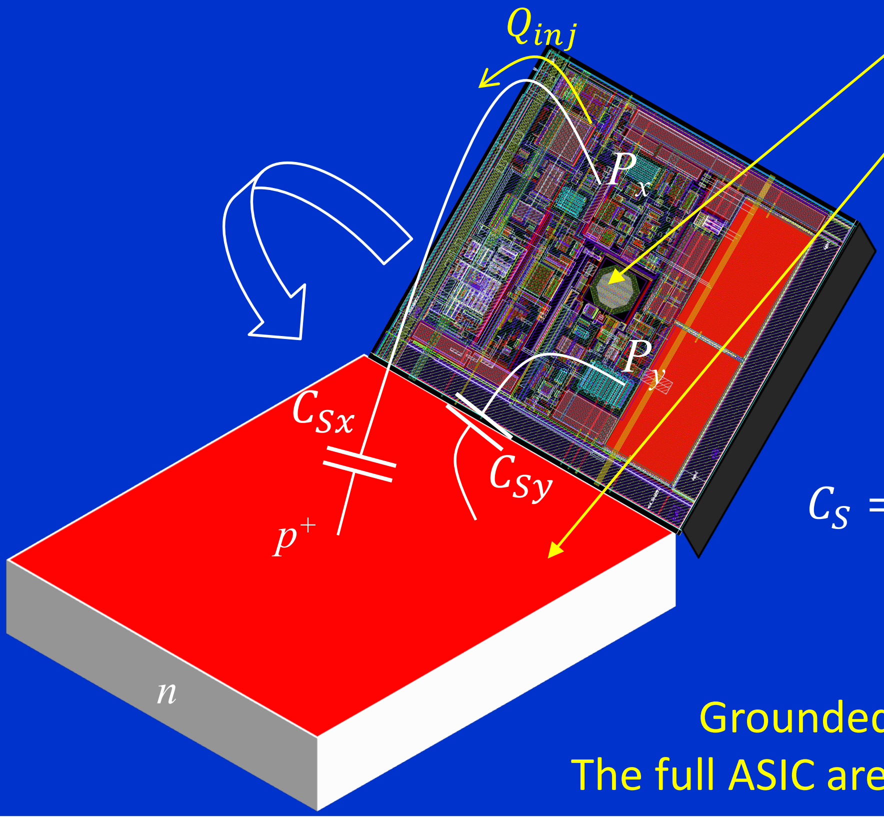
$C_{anode} \cong tens\ of\ fF$

Is there any advantage with Drift Pixels?



# Conventional Pixel




ASIC input
≡
pixel electrode

The whole pixel electrode
becomes
the ASIC input

$$Q_{injected(j)} = C_{Sj} \cdot V_{signal(P_j)}$$

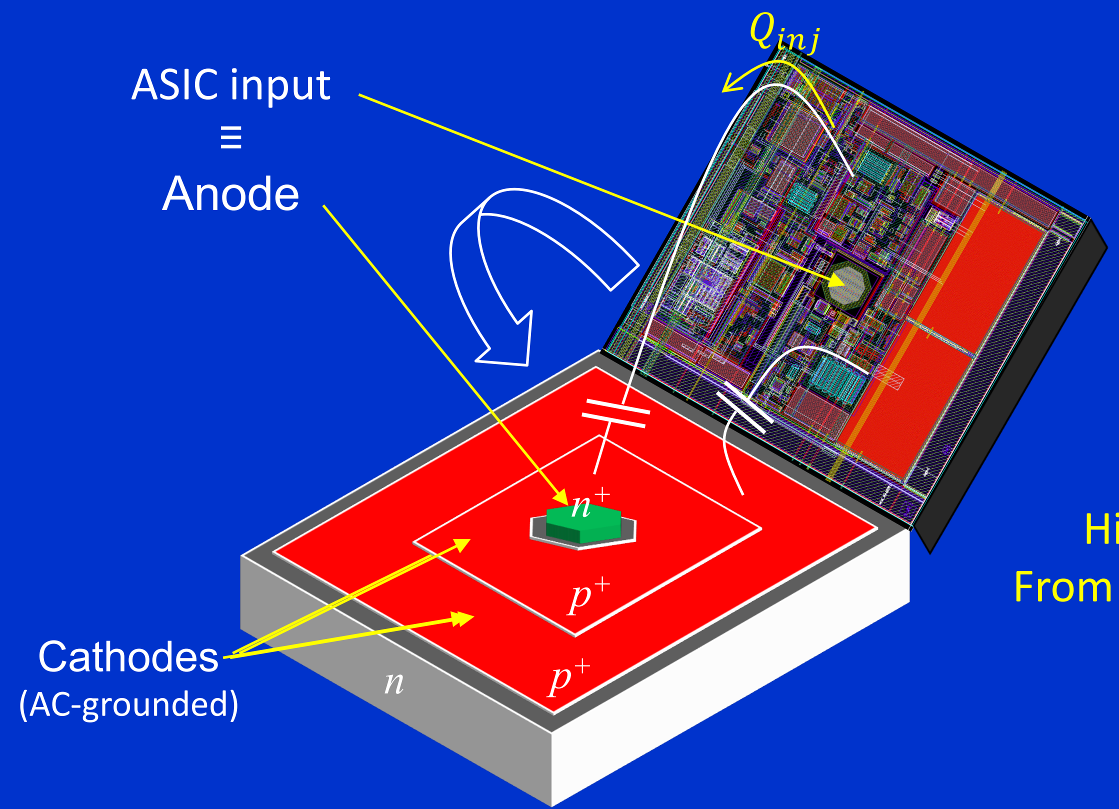
$$V_{signal(P_j)}: mV\ to\ Volts$$

$$C_S = 0.1fF \quad \Longrightarrow \quad \frac{Q_{injected(j)}}{V_{signal(P_j)}} = 10^{-16}\frac{C}{Volt}$$

$$10^3 electrons/Volt\ (3.6\ keV/Volt)$$

Grounded metal shields on ASIC are needed
The full ASIC area is a ground plane at tens µm from pixel

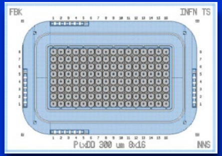
# Drift Pixel




High Immunity
From charge injection!

# REDSOX: a complete flow of activities

**SDD Design**



INFN
Trieste, Udine
FBK - Trento

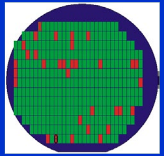
**ASICs Design & Test**

Politecnico di Milano
University of Pavia

**SDD Manufacturing**

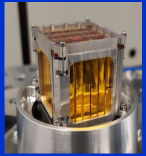
FBK - Trento

**SDD Electrical Test**



FBK, TIFPA - Trento

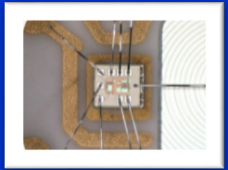
**System Assembly and Test**

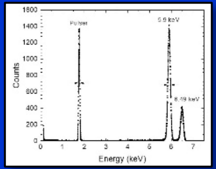


INAF Bologna, Roma,
Trieste, Udine, PoliMi

## from Design to Application

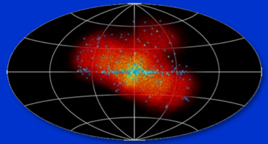
### High-End Prototypes






### Synchrotron System

### Space X-γ Telescopes

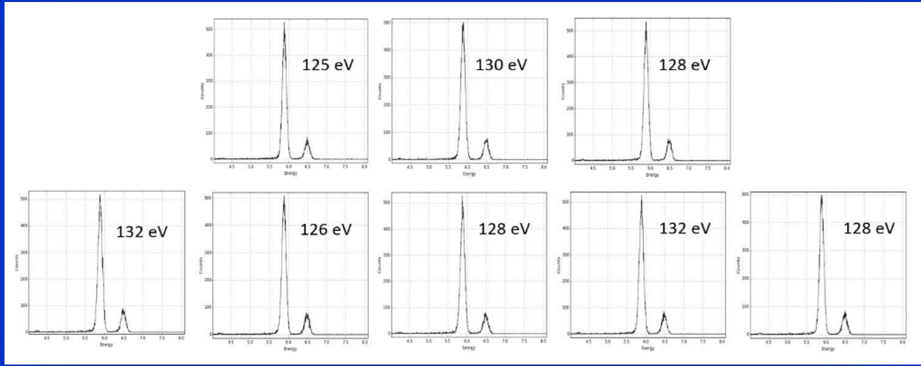


# SDDs at TwinMiC – ELETTRA Synchrotron

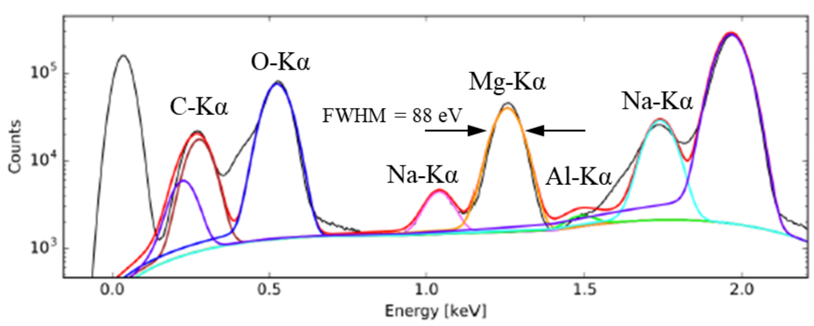
Total active area ~12 cm$^2$

8 elements SDD with SIRIO preamp.

Best results: 125 - 132 eV FWHM @ 5.9 keV

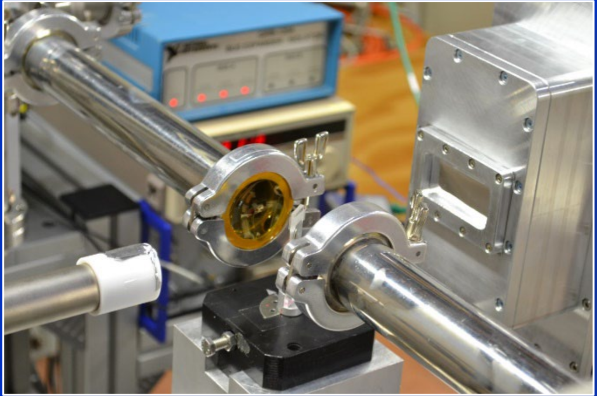



Lightweight elements spectroscopy

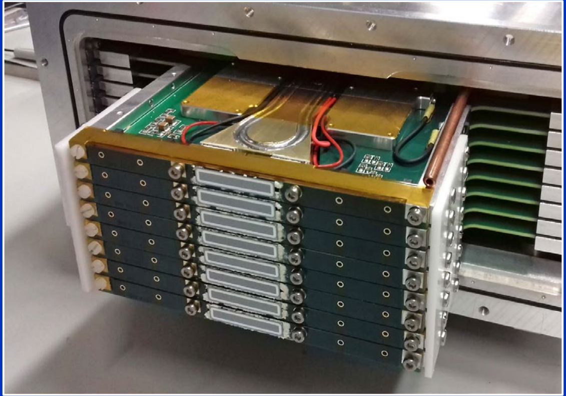


# SESAME Synchrotron (Allan, Jordan)

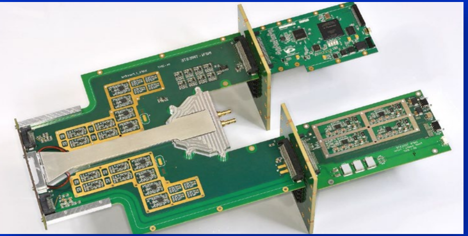

## XRF-XAFS beamline



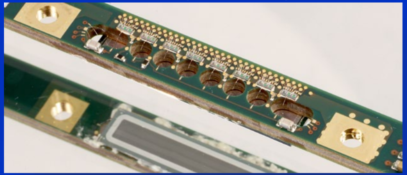
## 8 x 8 SDDs total area 5.7 cm$^2$



Single module

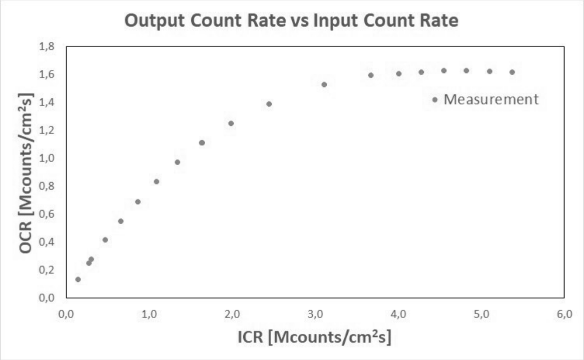


SIRIO preamp.



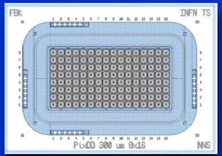
< 180 eV FWHM at 5.9 keV and +23°C

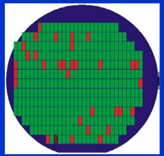

Output Count Rate: 1.6 Mcps/cm$^2$

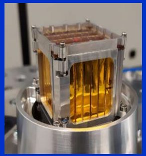


# REDSOX: a complete flow of activities

| SDD Design | ASICs Design & Test | SDD Manufacturing | SDD Electrical Test | System Assembly and Test |
|---|---|---|---|---|



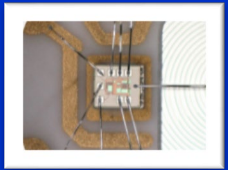



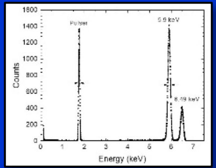


| SDD Design | ASICs Design & Test | SDD Manufacturing | SDD Electrical Test | System Assembly and Test |
|---|---|---|---|---|
| INFN Trieste, Udine<br>FBK - Trento | Politecnico di Milano<br>University of Pavia | FBK - Trento | FBK, TIFPA - Trento | INAF Bologna, Roma,<br>Trieste, Udine, PoliMi |

## from Design to Application

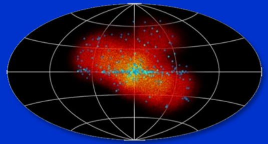
### High-End Prototypes



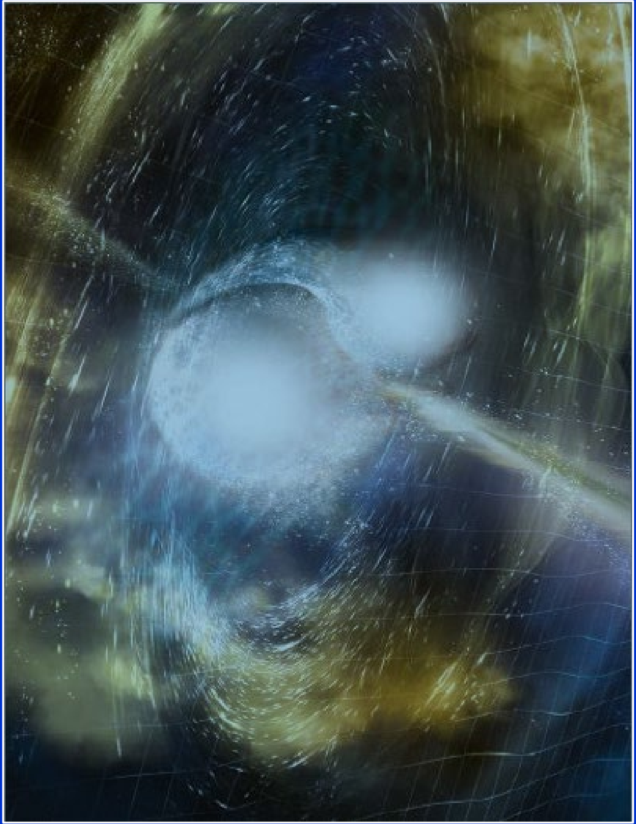



### Synchrotron System

### Space X-γ Telescopes

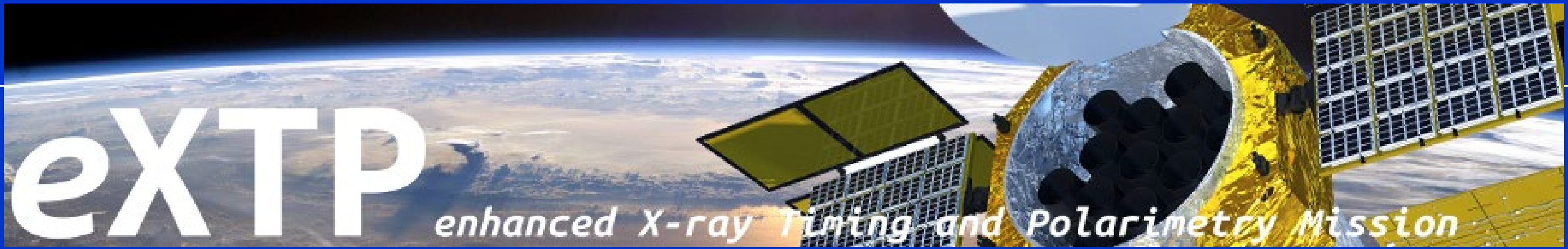


# Semiconductor Detectors for Space Telescopes



Requirements:

- Operation on satellite
- Spectroscopic capability
- Imaging capability
- Timing capability
- Energy range: from keV to MeV
- Total sensitive area: > 1 $m^2$




spectral, timing and polarimetry observations

Launch date: 2027, Mission duration: 8 years

**China**

P.I. Prof. Shuang Zhang

IHEP/CAS – Beijing

CAS, CNSA, IHEP, Tsinghua Univ., Tongji Univ., CAST, Microsat

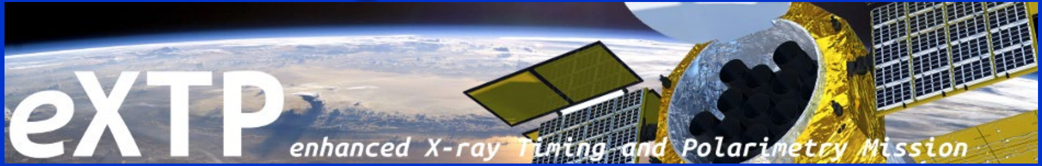
**Europe**

P.I. Dr. Marco Feroci

INAF IAPS Roma

Italy, Spain, Germany, France, Switzerland, Czech Republic, Poland, Denmark, The Netherlands, Austria, Turkey

# eXTP Space Mission

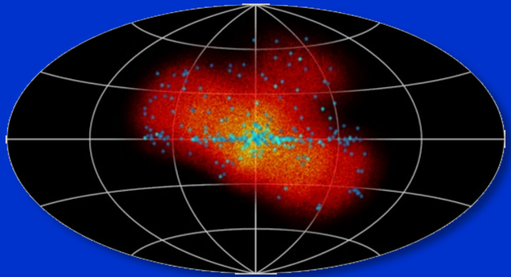



Study of matter under extreme conditions of gravity, density and magnetism

For the first time: simultaneous, high-throughput spectral, timing and polarimetry observations

- Accretion physics in the strong-field regime of gravity and tests of General Relativity in neutron stars and black holes over the mass scale.

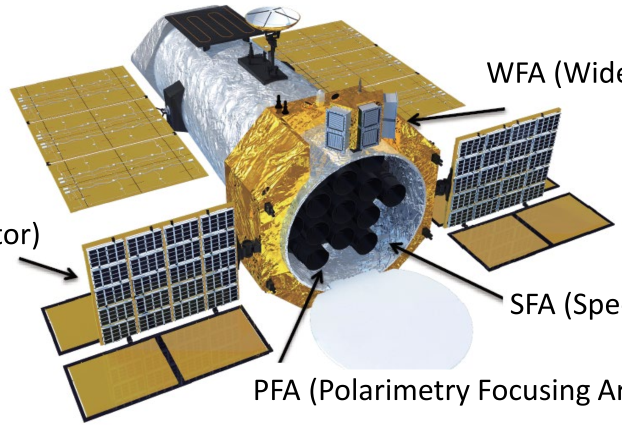
- Physics of light and matter in the presence of ultra-strong magnetic fields in magnetars and X-ray pulsars.



- Multi-purpose observatory and wide-field monitoring for transients (and e.m. counterparts of GWs). Rapid follow-up.

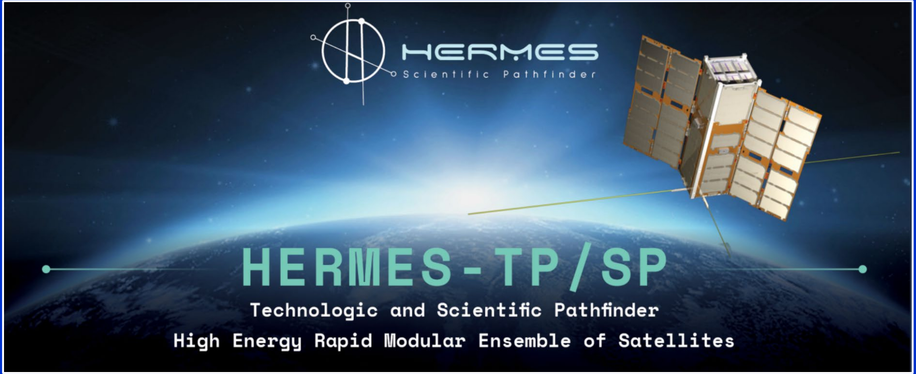
http://www.isdc.unige.ch/extp/

# eXTP Imaging System on satellite

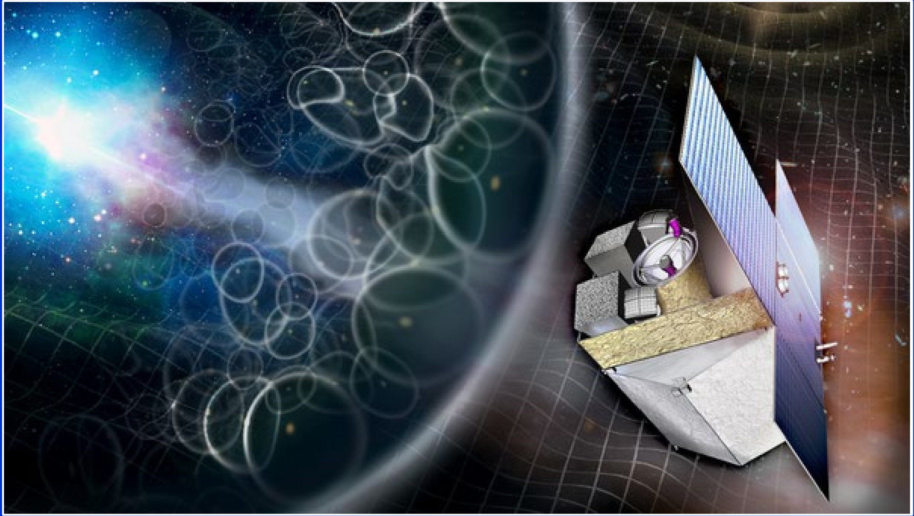



| Payload | Configuration | Optics | Detector | Effective Area | Energy range (keV) |
|---|---|---|---|---|---|
| SFA | 9 Telescopes | Nickel replica ⇨ | **SDD** | 0.5 – 0.70 $m^2$ | 0.5 - 10 |
| LAD | 40 Modules | MCP Collimator ⇨ | **SDD** | 3.4 $m^2$ | 2 - 30 |
| PFA | 4 Telescopes | Nickel replica | Gas Pixel Detector | 900 $cm^2$ | 2 - 10 |
| WFM | 6 Cameras | 1.5 Coded Mask ⇨ | **SDD** | FOV > 4sr | 2 - 50 |

# Two Missions for Gamma Ray Burst Study





PI : Dr. Fabrizio Fiore

National Institute of Astrophysics (INAF)

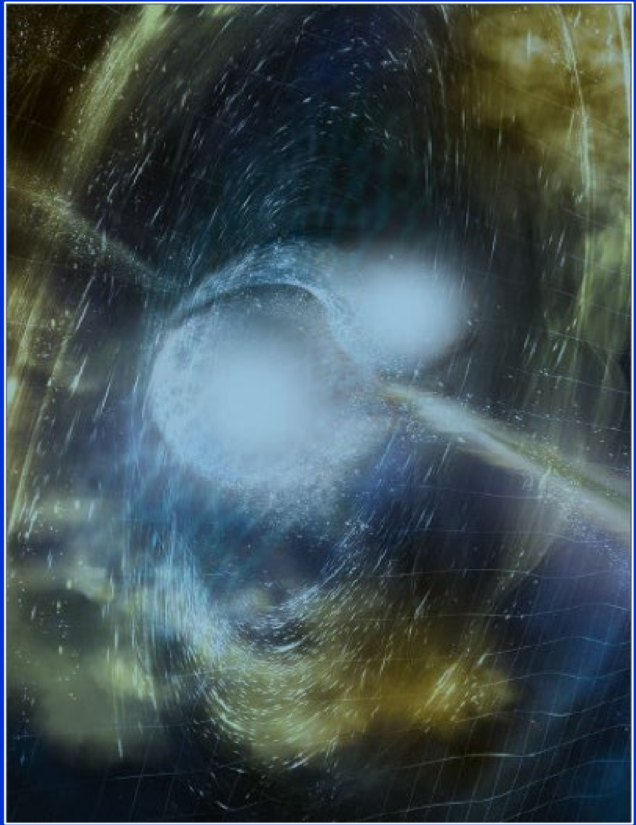
Trieste, Italy

PI : Dr. Lorenzo Amati

National Institute of Astrophysics (INAF)

Bologna, Italy

# Gamma Ray Burst (GRB)



hot topic in Astrophysics

Sudden and unpredictable burst of Soft γ / hard-X rays

Photon energy band: keV to MeV

Total energy: $10^{45}$ J ( $10^{14}$ TeV)

Time duration: 0.1-100 s

Huge energy flux: up to 1 GeV/cm$^2$/s

Extragalactic origin: neutron stars merging
black hole formation

# HERMES project

High Energy Rapid Modular Ensemble of Satellites

PI : Dr. Fabrizio Fiore - INAF-OATS, Trieste, Italy

Scientific goal: Gamma-Ray Burst study
- localization (arc-min accuracy)
- timing (μs resolution)

Detection apparatus: 3U CubeSats

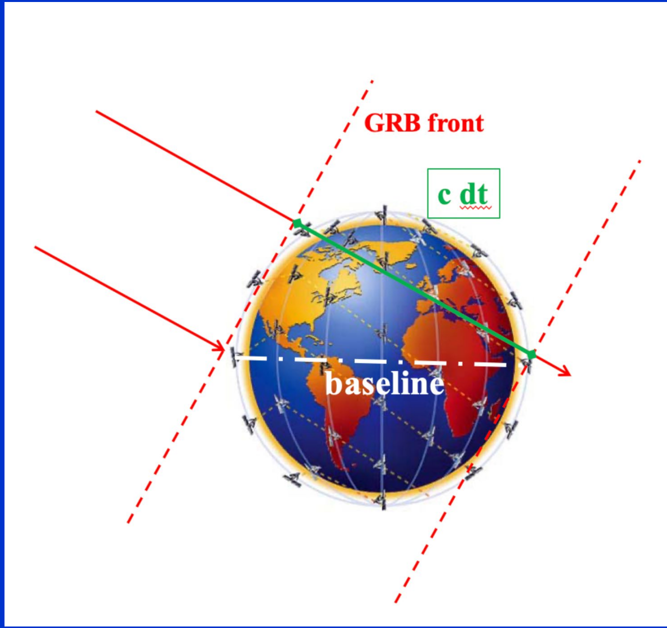
Orbit: equatorial 525 km altitude

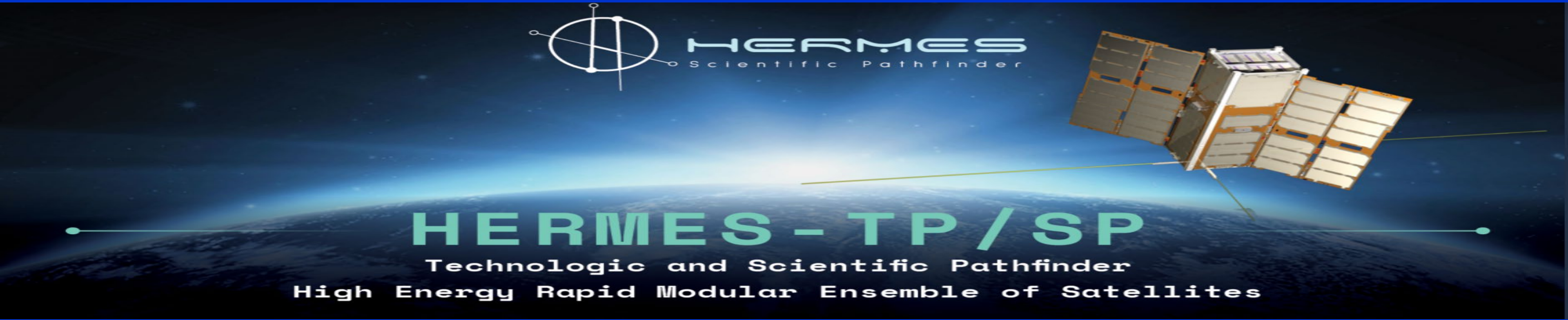
Detectors: Scintillators (GAGG:Ce) + SDDs

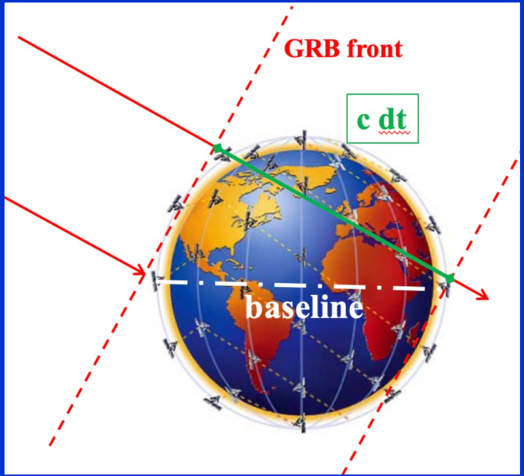
GRB localization: triangulation

Launch: first 6 CubeSats in 2023

Peculiarities: modularity, all sky coverage, low cost

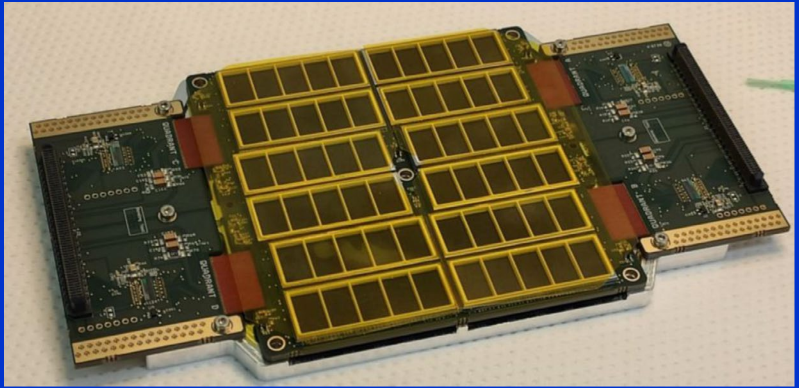





Cubesat
for GRB localization

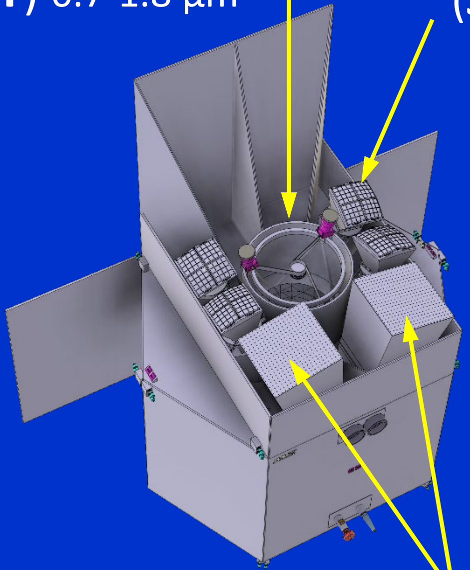
CubeSat 3U
10 x 10 x 30 $cm^3$



Energy band: 50 – 300 keV
60 GAGG read by 2 SDDs
120 SDDs organized in 12 arrays (53 $cm^2$)
Array: 2x5 SDDs 7.4x6 $mm^2$ (4.4 $cm^2$)

InfraRed Telescope
(**IRT**) 0.7-1.8 µm

4x Soft X-ray Imagers
(**SXI**) 300 eV – 5 keV

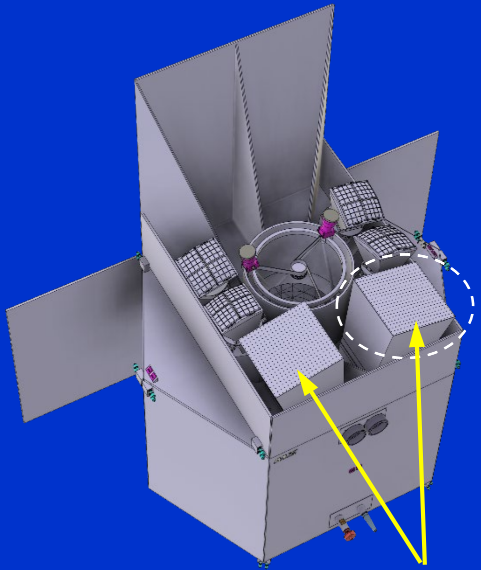


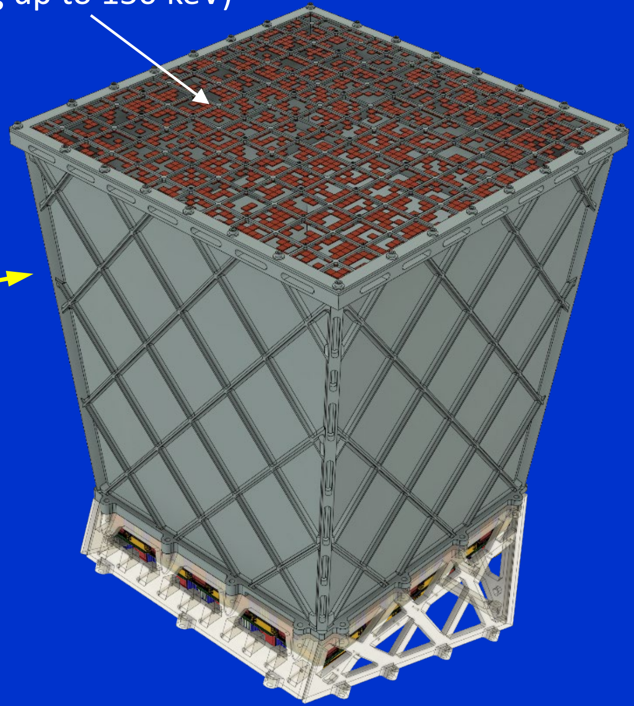
theseus
TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR

2x X-Gamma Ray Imaging
Spectrometers (**XGIS**)
2 keV – 10 MeV

# THESEUS: the X-Gamma Ray Imaging Spectrometer


Coded mask (60x 60 cm$^2$)
(imaging up to 150 keV)

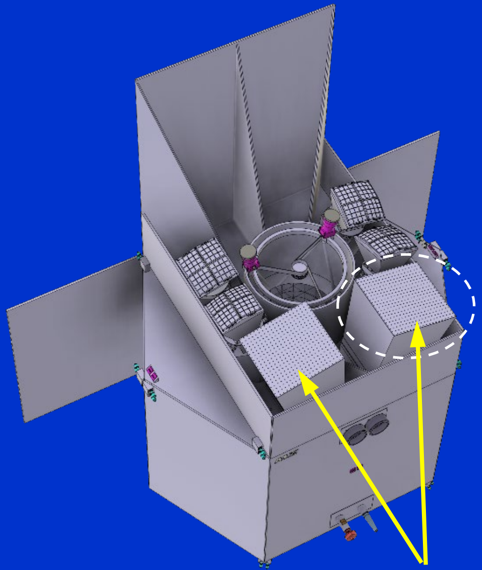




2x X-Gamma Ray Imaging Spectrometers (**XGIS**)
2 keV – 10 MeV

# THESEUS: the X-Gamma Ray Imaging Spectrometer

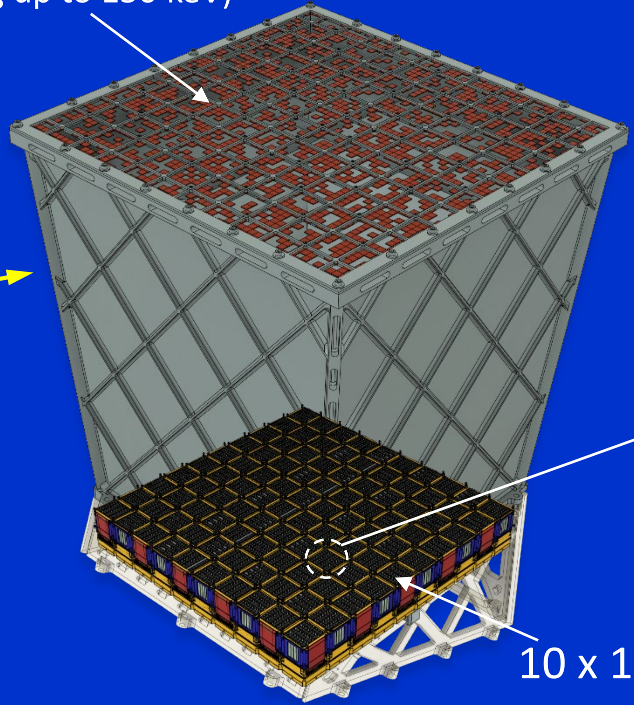
theseus
TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR



2x X-Gamma Ray Imaging Spectrometers (**XGIS**)

2 keV – 10 MeV

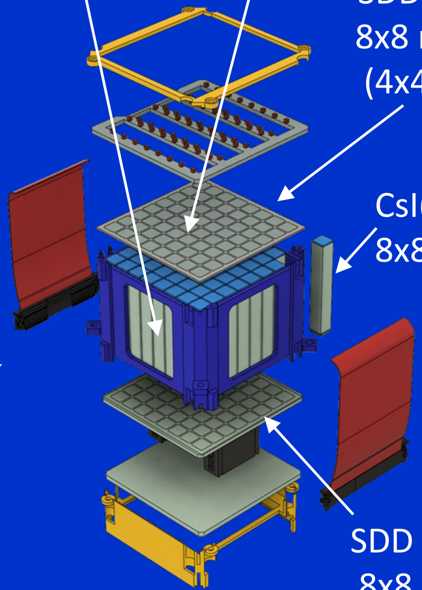
Coded mask (60x 60 cm$^2$)
(imaging up to 150 keV)



10 x 10 modules

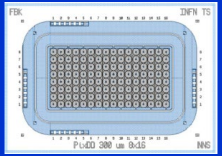
12800 SDDs (each SDD: 5x5mm$^2$)

module



# REDSOX: a complete flow of activities

**SDD Design**




INFN
Trieste, Udine
FBK - Trento

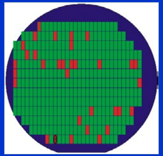
**ASICs Design & Test**

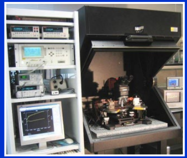
Politecnico di Milano
University of Pavia

**SDD Manufacturing**

FBK - Trento

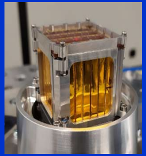
**SDD Electrical Test**





FBK, TIFPA - Trento

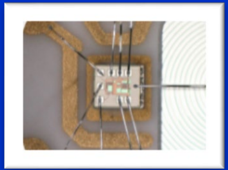
**System Assembly and Test**

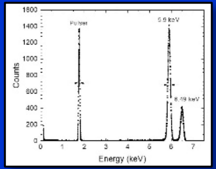


INAF Bologna, Roma,
Trieste, Udine, PoliMi

## from Design to Application

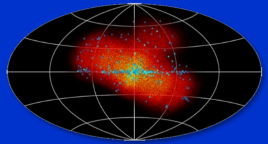
### High-End Prototypes

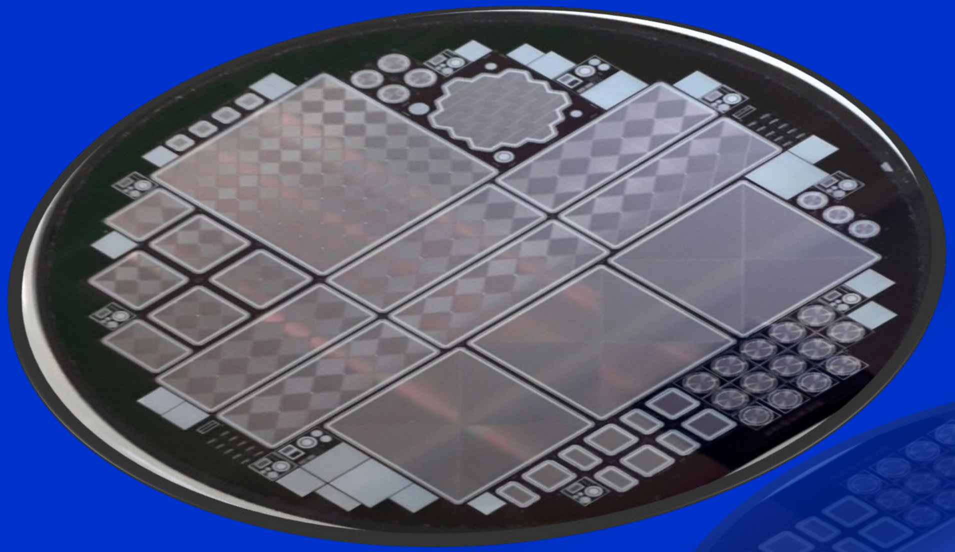





### Synchrotron System

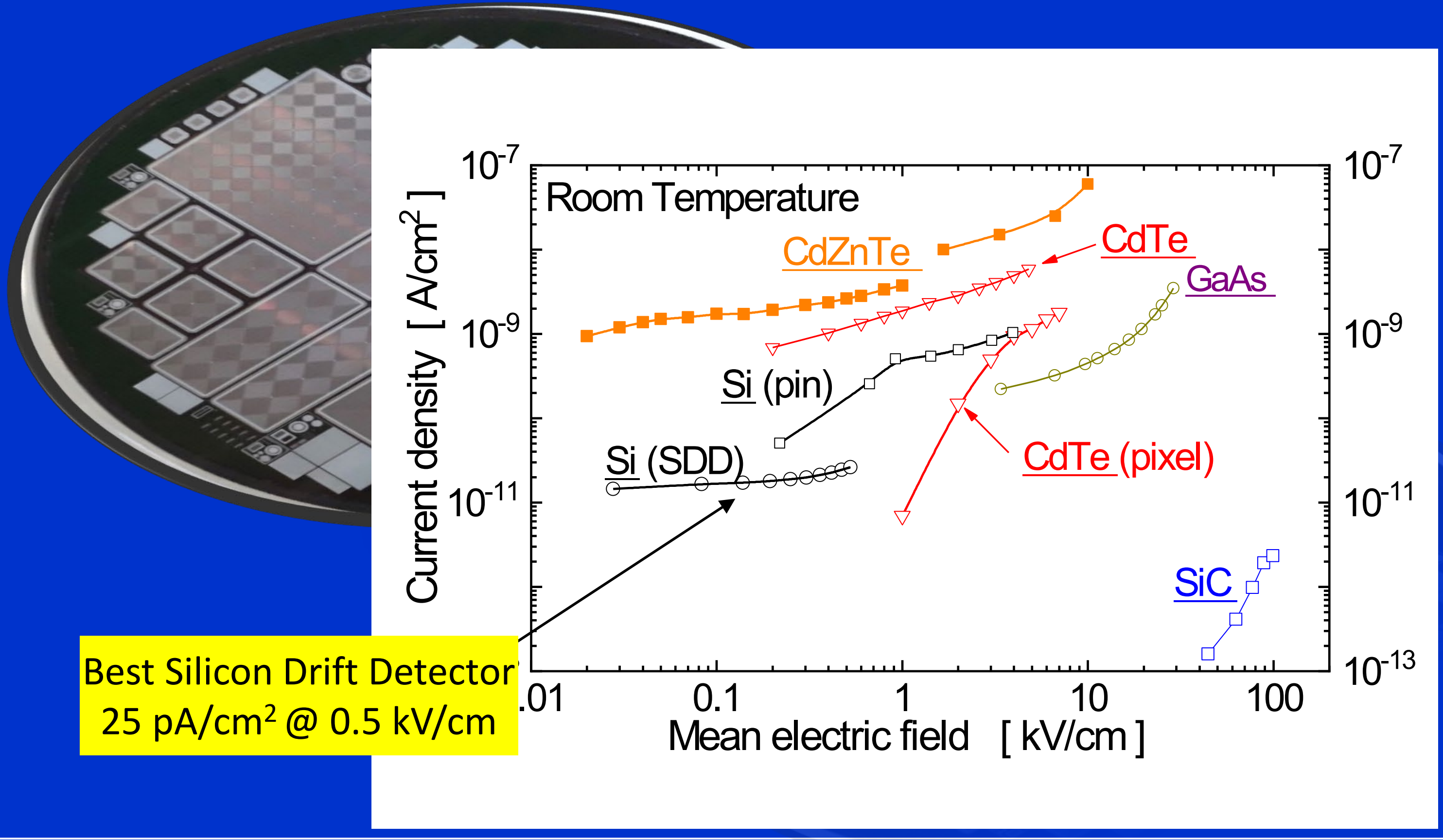
### Space X-γ Telescopes





# SDD's future
## where to go?
## what we should expect?

# Ultra low noise SDD



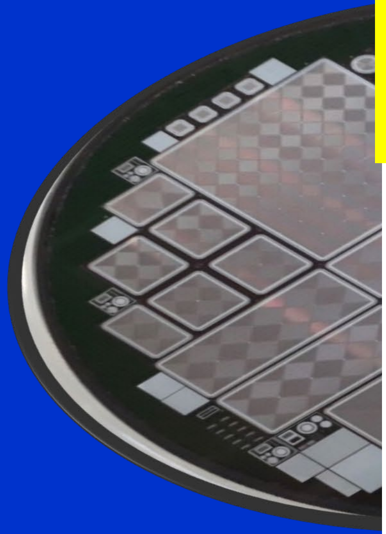

Best Silicon Drift Detector
25 pA/cm$^2$ @ 0.5 kV/cm

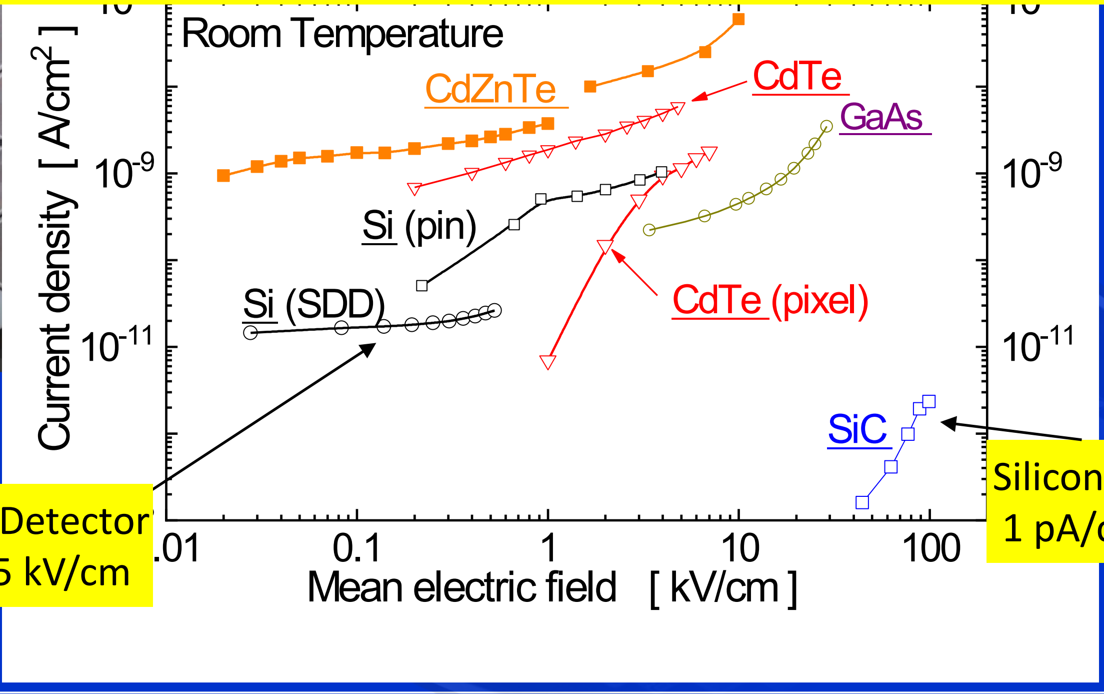
# Ultra low noise SDD

## SiC Drift Detectors

Ultra low noise (low $I_{DET}$, low $C_{DET}$)

Ultra Fast (operation close to electron saturation velocity)






Best Silicon Drift Detector
25 pA/cm² @ 0.5 kV/cm

Silicon Carbide Detector
1 pA/cm² @ 100 kV/cm

# Conclusion

Solid State Drift Detectors

a great idea…

a fascinating story…

a still amazing adventure…

Thanks to Emilio Gatti and Pavel Rehak

and to each one who is continuing their passion