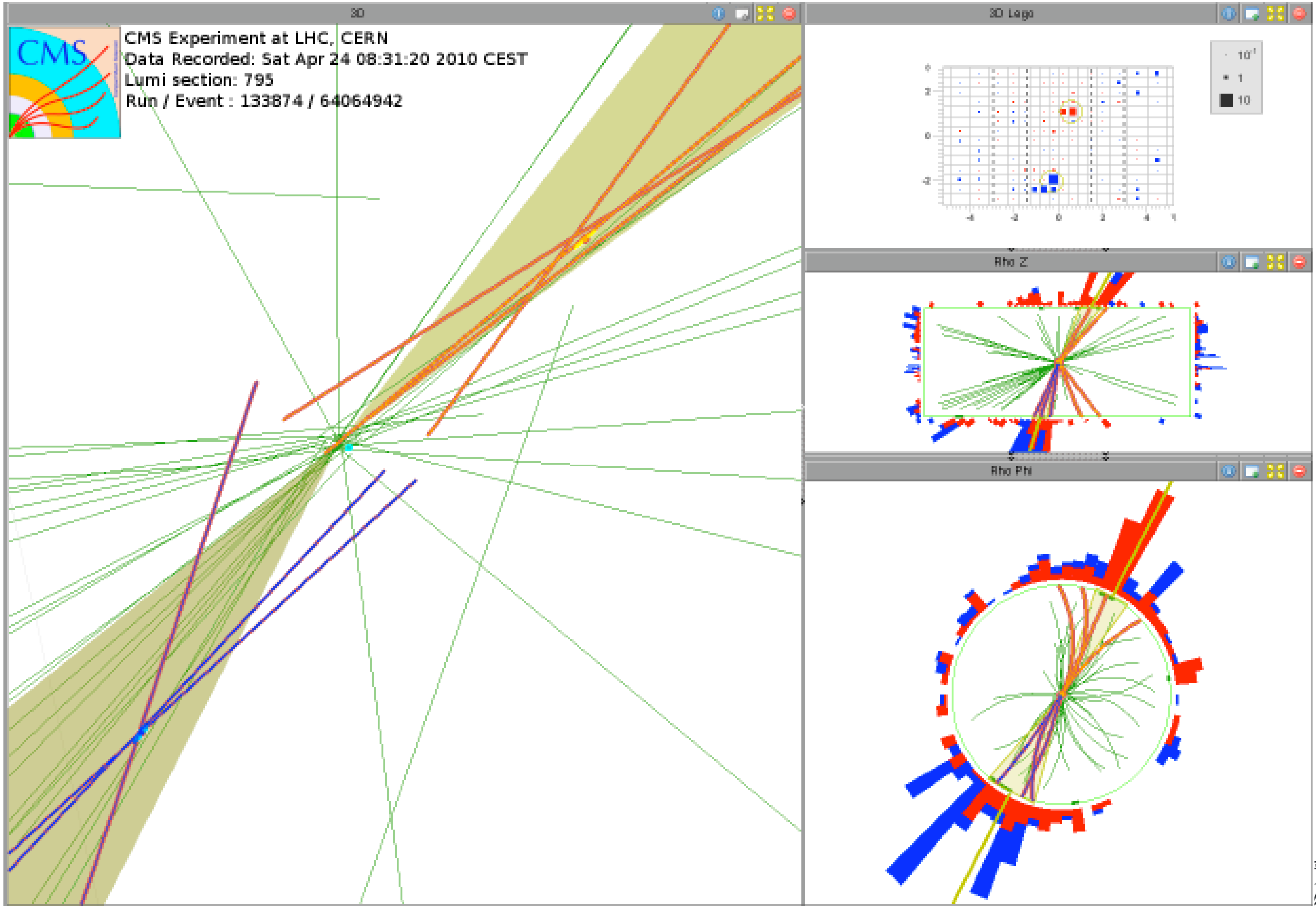
INTEGRATED SEMICONDUCTOR DETECTORS for TRACKING and ENERGY MEASUREMENT: HOW TO USE NEW TECHNOLOGIES

ERIK H.M. HEIJNE

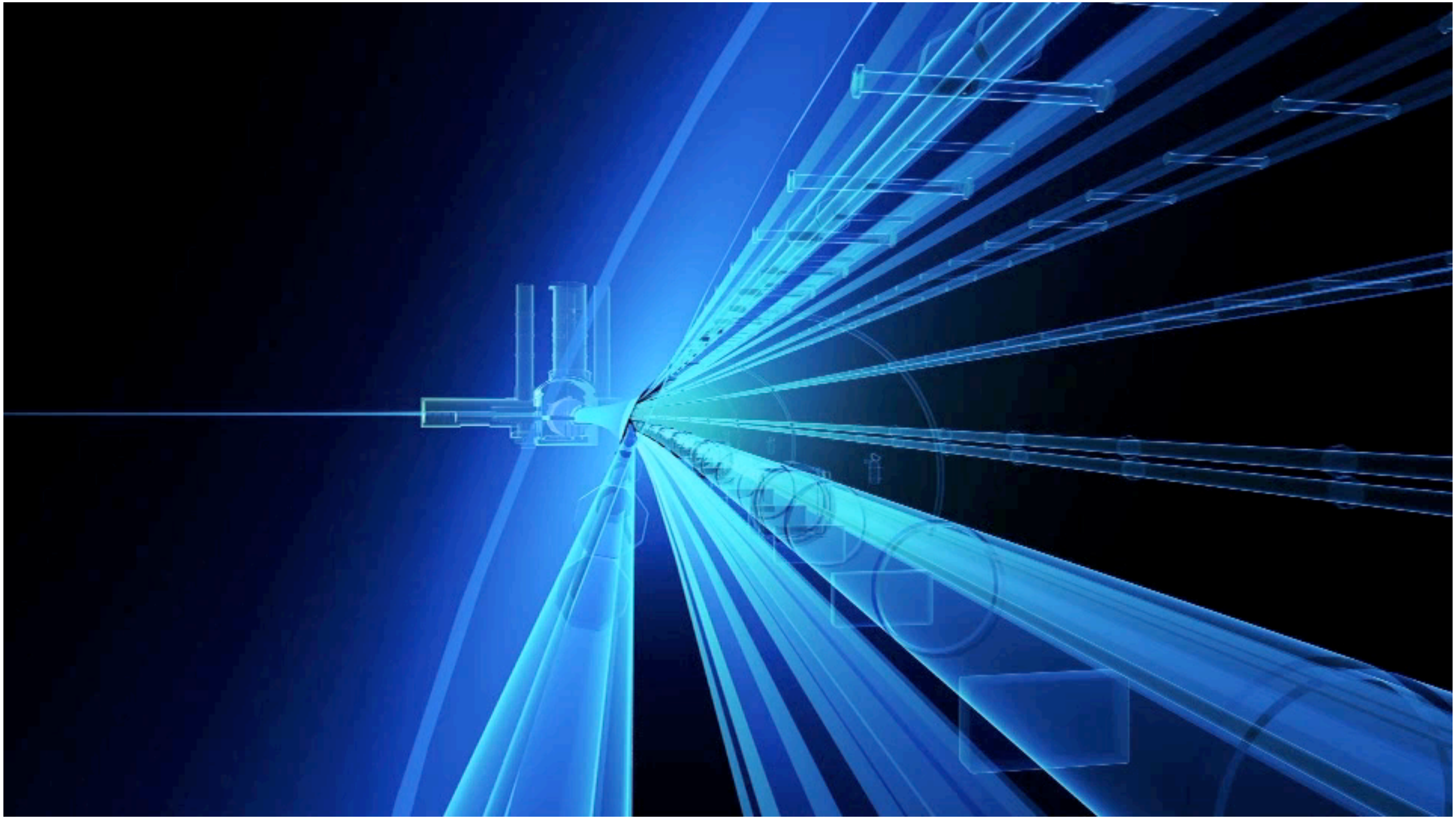
CERN EDIT School

Geneva 31 January 2011

CMS double B jet CANDIDATE



ATLAS ANIMATION of REAL INTERACTION



THANKS for HELP Michael Hauschild   Pippa Wells will talk Saturday on vertexing

NEW MATERIALS

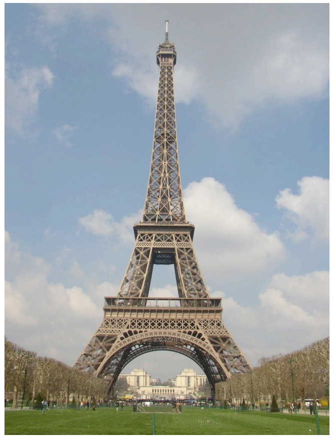
NEW TOOLS

NEW DISCOVERIES

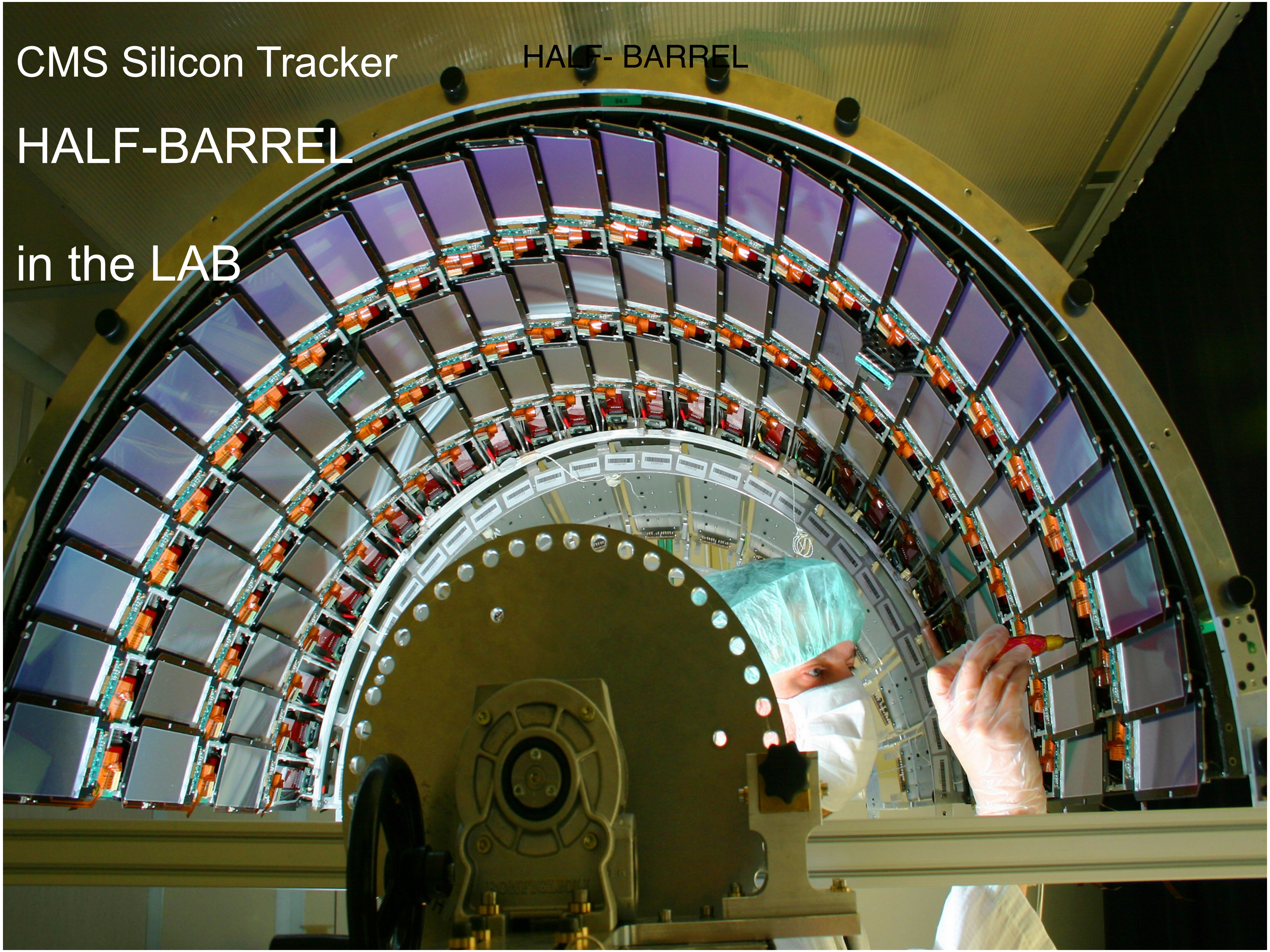
STONE AGE

BRONZE AGE

IRON AGE



SILICON AGE


CMS Silicon Tracker
HALF- BARREL
HALF-BARREL
in the LAB

OUTLINE

USE of TECHNOLOGY TRENDS

SILICON & MICROELECTRONICS; GRAPHENE; 3D

HISTORICAL STEPS

FROM BUBBLE CHAMBER to ATTOSCOPE : PRODUCTIVITY

A FEW BASIC POINTS

ENERGY LOSS; SIGNALS; NOISE; SEGMENTATION;
SPEED & DEADTIME; MANUFACTURABILITY

FUTURE DIRECTIONS

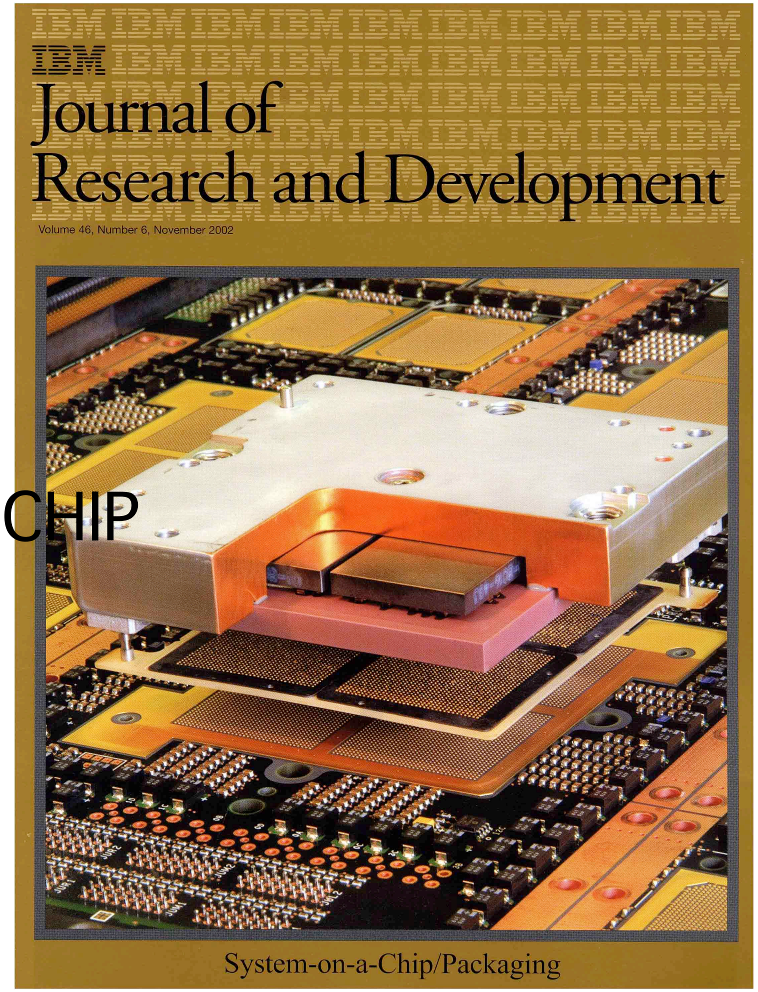
HIGH RATE & OCCUPANCY; OTHER APPLICATIONS

CONCLUSION

KEEP GOING: TOOLS <-> DISCOVERIES

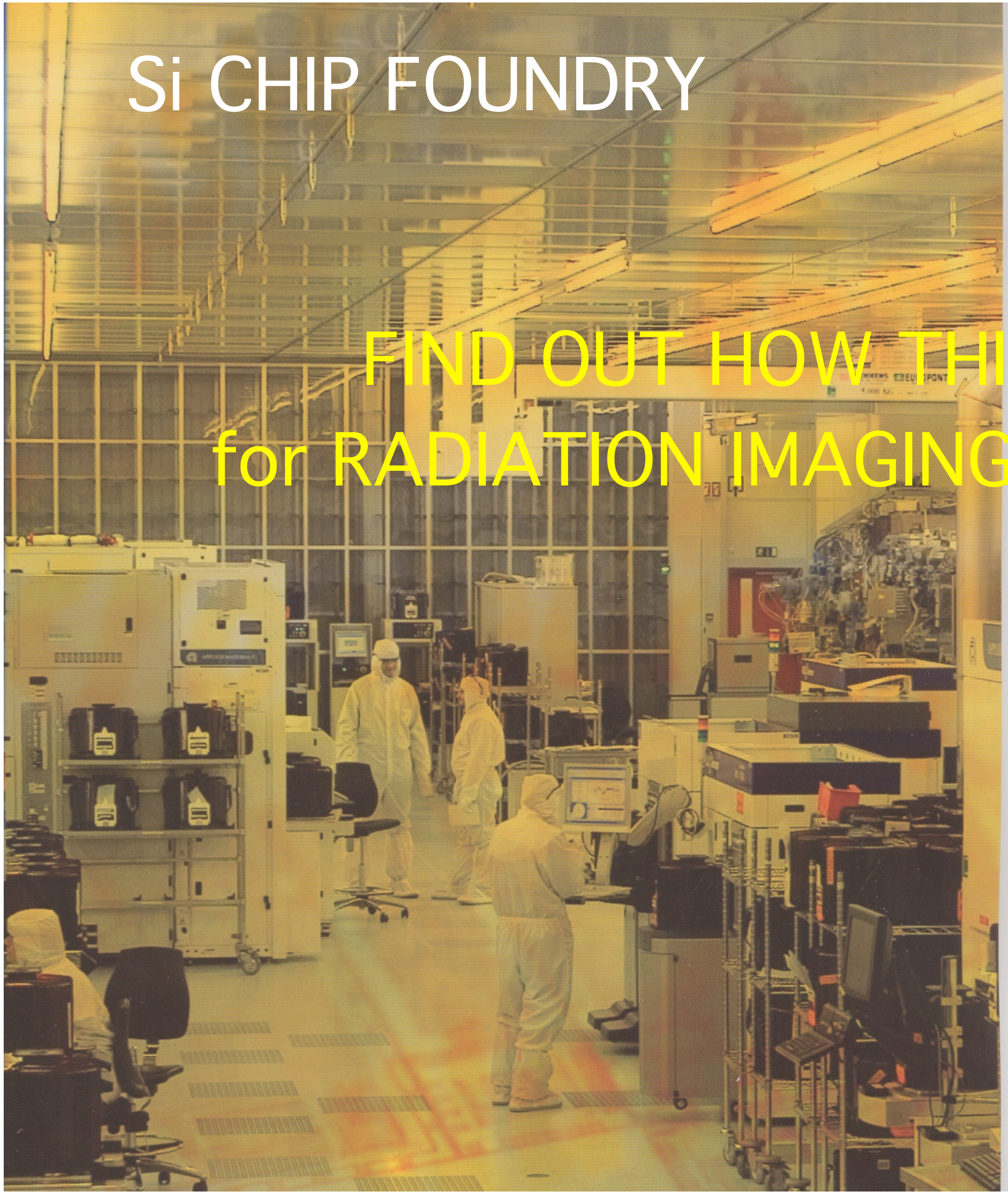
NEW APPROACHES USING Si TECHNOLOGY

SYSTEM-on-CHIP



3-D CERAMIC MODULE PACKAGE IBM

Si CHIP FOUNDRY



FIND OUT HOW THIS CAN BE USED for RADIATION IMAGING APPLICATIONS

TYPICAL INVESTMENT 3B$

DAILY PRODUCTION
1000-3000 WAFERS

TURNOVER 10M$ / DAY

CAN WE ACCESS THIS ?

MOS TECHNOLOGY
METAL – OXIDE - SILICON

FUNDAMENTAL COMPONENTS

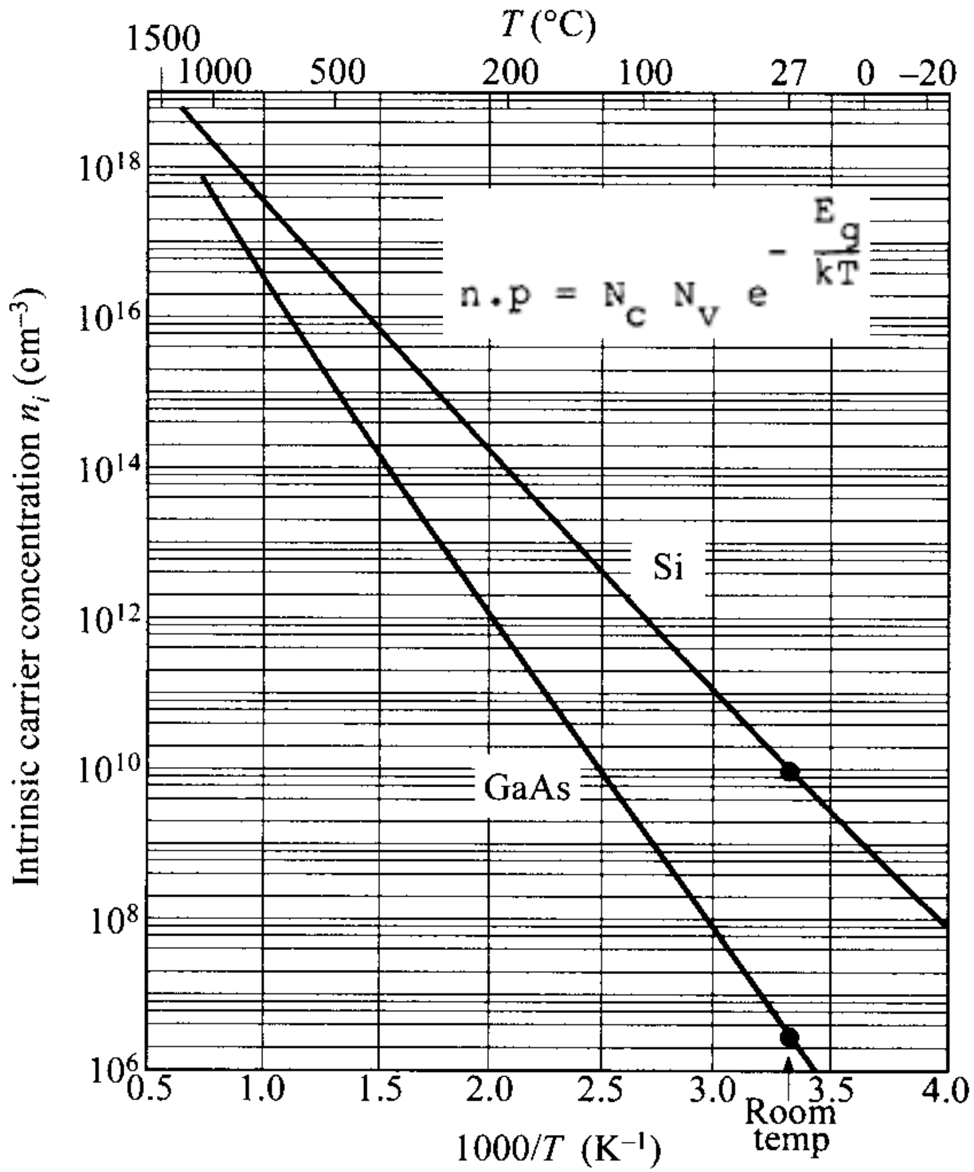
* MOS CAPACITOR — CCD IMAGER MATRIX

* p – n DIODE — CMOS IMAGER MATRIX

* VARIOUS TRANSISTORS

SMALL RESISTORS in THIN METAL LAYERS

INTRINSIC CARRIER CONCENTRATION



n_i^2= n.p= constant

e.g. if slightly doped
n=10^{13}cm^{-3}
then p=10^{7}cm^{-3} only

at Room Temp
Si n_i^2=10^{20}cm^{-3}

GaAs much lower

CARRIERS in SEMICONDUCTORS

MAJORITY CARRIERS

MOVE RAPIDLY TO MAINTAIN
OVERALL CHARGE NEUTRALITY
TYPICALLY WITHIN DIELECTRIC RELAXATION TIME

SCREENING with CHARACTERISTIC DISTANCE 'DEBYE LENGTH'

MINORITY CARRIERS

MOVE AS LONG & AS FAR AS 'LIFETIME' PERMITS : CAN BE ms

TYPICAL DISTANCE (NO FIELD) 'DIFFUSION LENGTH' ~mm

TRAPPING CENTERS

TAKE CARRIERS AWAY

seminars on radiation damage
Michael Moll and others

CARRIER MOBILITY

FREE CHARGE CARRIERS : ELECTRONS - HOLES

$v_e = \mu_e E$ μ_e electron MOBILITY

IN MOST SEMICONDUCTORS electrons MOVE FASTER than HOLES

in PURE Si $\mu_e = 1430\ cm^2\ V^{-1}\ s^{-1}$ $\mu_h = 480\ cm^2\ V^{-1}\ s^{-1}$

in HIGHLY DOPED Si $\mu_e = 60\ cm^2\ V^{-1}\ s^{-1}$ $\mu_h = 35\ cm^2\ V^{-1}\ s^{-1}$

SUCH as in DEEP SUBMICRON CMOS : TRANSISTORS are SLOWER

LATER : CARRIER MOBILITY in GRAPHENE ~ 100 000 !!!!

SEMICONDUCTOR MATERIALS

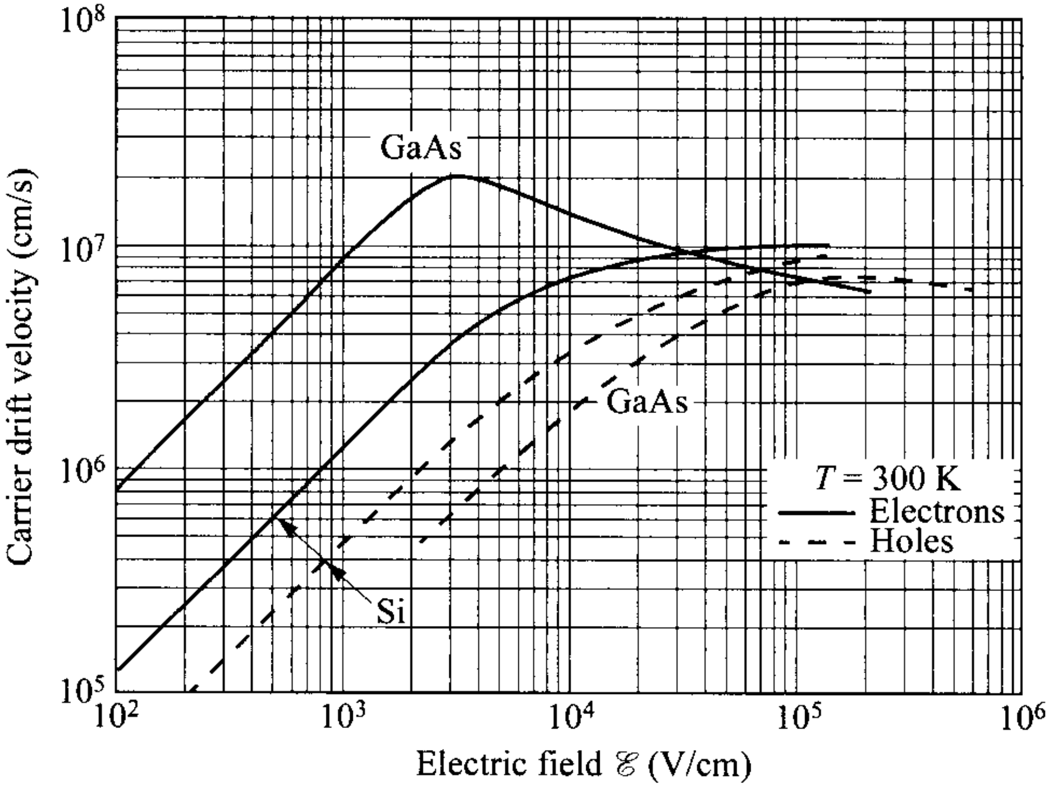
RELEVANT for DETECTORS

Element	Symbol	Z	density ρ gcm^{-3}	ni cm^{-3}	band gap eV	e-h pair eV	carrier lifetime τ	mobility 300 K μe $cm^2V^{-1}s^{-1}$	mobility 300 K μh $cm^2V^{-1}s^{-1}$	rad length X_0 cm
ELEMENTAL										
diamond	C	6	3.5	$\sim 10^3$	5.6	13.25	some ns	2400	2100	12.2
silicon	Si	14	2.33	$1.1\ 10^{1}$[illegible]	1.12	3.61	>5 ms	1430	480	9.36
amorphous Si	Si-H	14	2.1		~1.9	3.4-6.0	few ns	~1	.004	10.4
germanium	Ge	32	5.32	$2.41 0^{13}$	0.67	2.98	>5 ms	3900	1900	2.30
COMPOUNDS										
IV - IV	SiC	14-6	3.2		3.00			400	50	
III - V	GaAs	31-33	5.3	$1.8\ 10^6$	1.43	4.2	few ns	8500	400 40	2.3
III - V	InP	49-15		$2.\ 10^8$	1.25	4.0		4600	150	
III - V	InSb	49-51		$2.\ 10^{17}$	0.17	1.0		78000	750	
II - VI	CdTe	48-52	6.1		1.47	4.43	μs	1100	100 80	1.46
Compensated	CdZn Te 10 %	31-34	4.5		1.6	5. ?	1 μs	$\mu\tau\ 3.10^{-3}$	80	
III - VI	GaSe	av 62	6.4		2.03	4.5		75	45	1.16
Ternary	HgI_2	49.1	6.		2.15	4.15	100 μs	$\mu\tau<10^{-2}$	6	

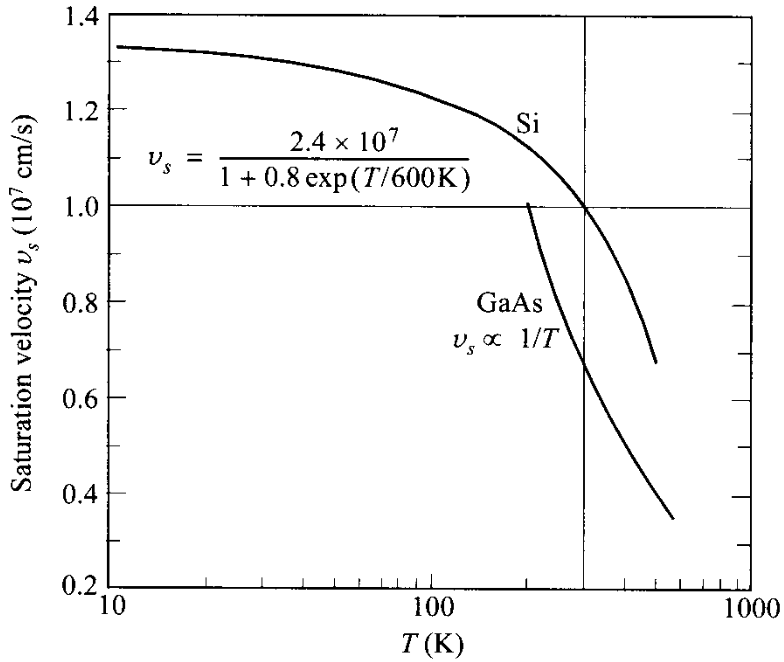
e & h MOBILITY GRAPHENE ~ 100 000

CARRIER TRANSPORT in Si and GaAs

CARRIER DRIFT VELOCITY vs FIELD



SATURATION vs TEMP



MOBILITY is a function of doping, temp, field..

SEMICONDUCTOR DETECTORS ARE INHERENTLY FAST : 5 - 20 ns

SILICON DIODE

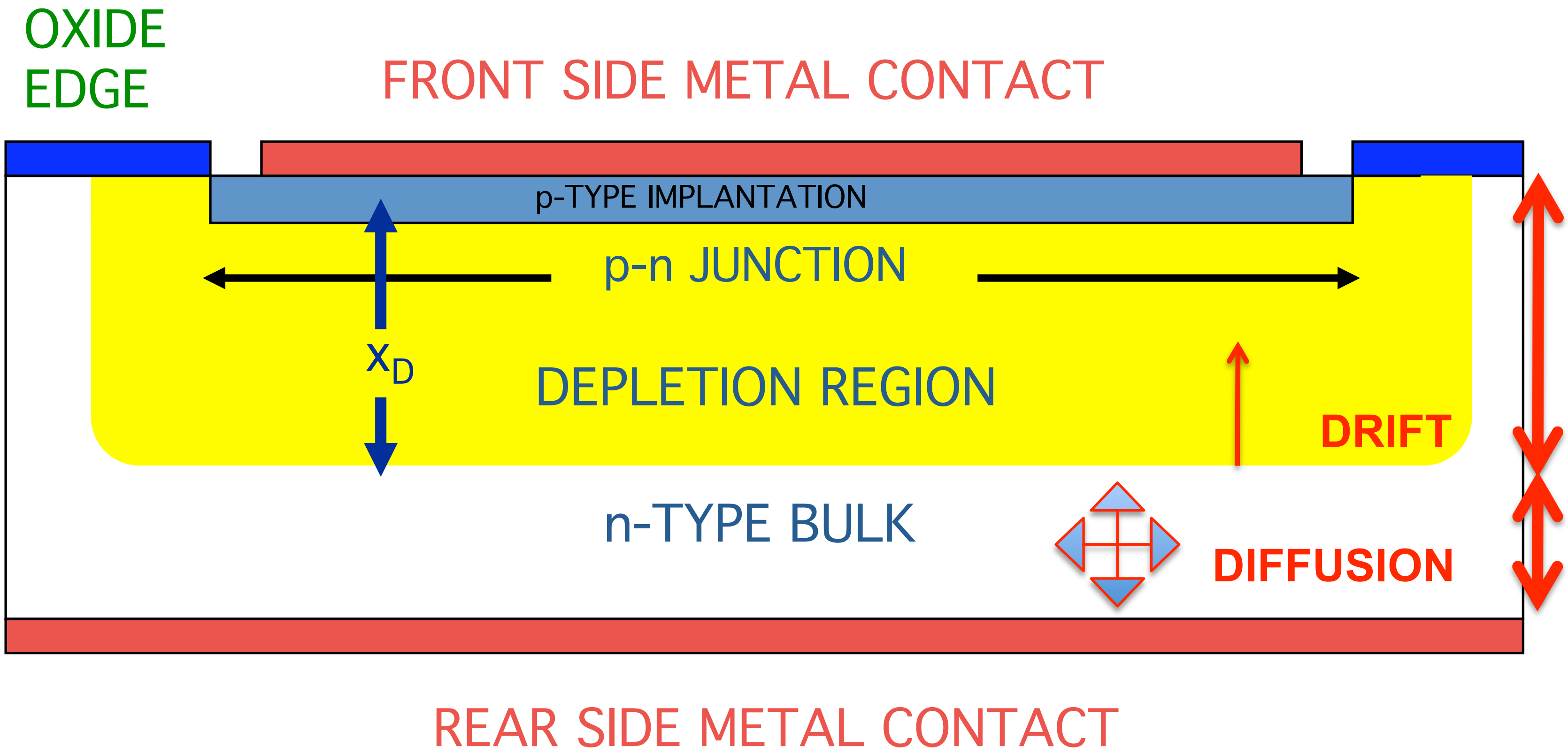
FIELD and POTENTIAL : CHARGE EQUILIBRIUM
IONIZED ATOMS at EITHER SIDE of the JUNCTION

ACTUAL NUMBER of CHARGES IS QUITE SMALL :

PIXEL VOLUME 0.5 x 0.3 x 0.05 = 0.0075 mm^3 = 7.5 million μm^3
contains ~ 2 million unit charges on average 1 charge per 3 μm^3

TO BE COMPARED WITH :
SIGNAL from 5 MeV alpha PARTICLE: 1.4 million unit charges

SCHEMATIC of DIODE



$$x_D = \sqrt{\frac{2\ \varepsilon}{q\ \ n}(V_0 + V_B)} = \sqrt{2\varepsilon\mu_e\rho\ (V_0 + V_B)}$$

x_D CAN BE LARGE, BECAUSE HIGH RESISTIVITY of BULK Si

SPECIAL FEATURES of Si DETECTOR DIODES

BULK VOLUME is USED, THIN CONTACT LAYER

CMOS ONLY SURFACE DEVICES

SUBSTRATE MUST BE GOOD QUALITY

UNUSUAL RESISTIVITY, VERY LOW DOPING

NEEDED for TOTAL DEPLETION and LOW LEAKAGE CURRENT

SOME STRANGE CONSEQUENCES

REAR CONTACT IMPLANTED SOMETIMES PATTERNED

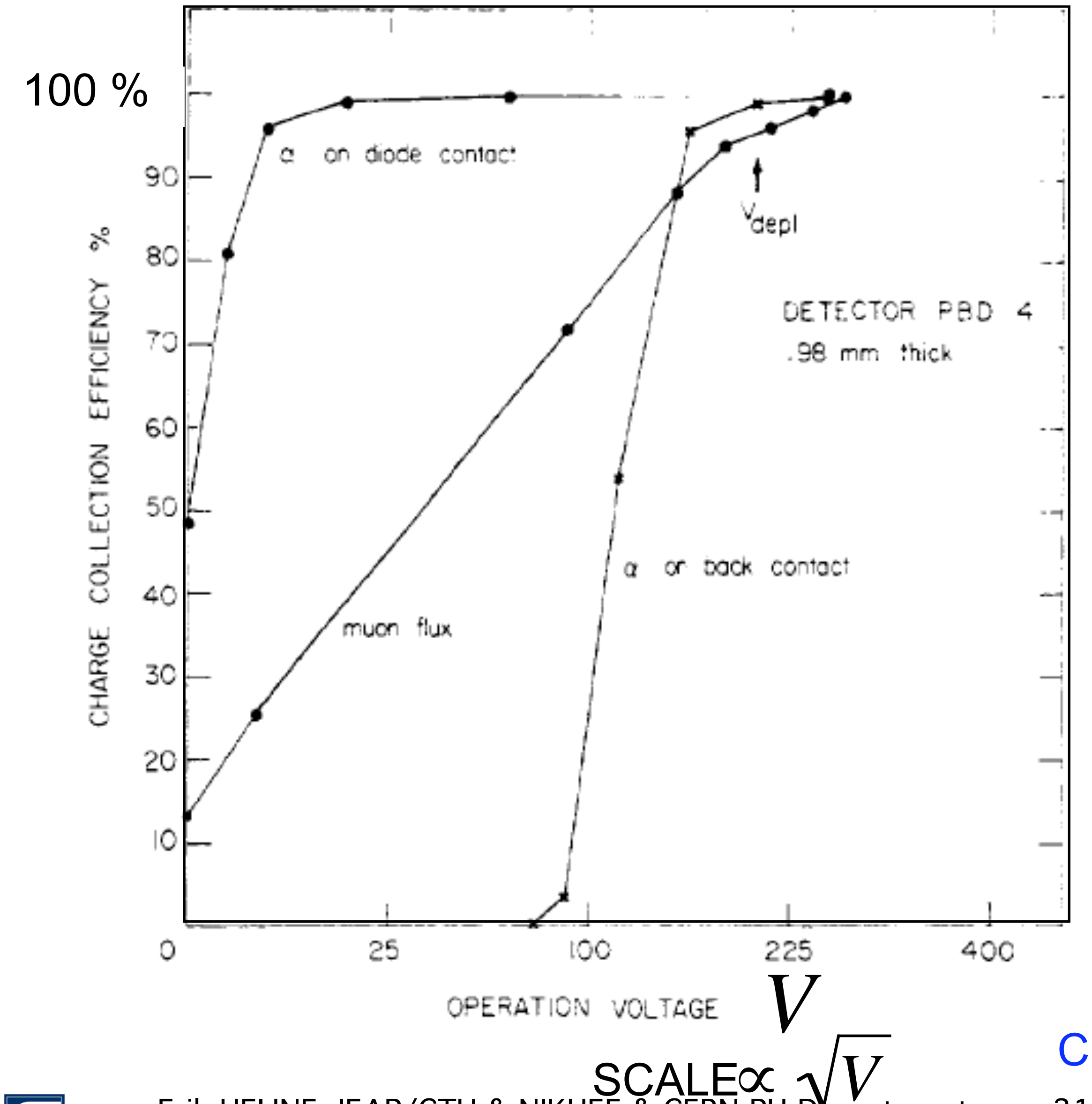
HI-LO JUNCTION, AVOID MINORITY CARRIER INJECTION

KILL CARRIER CONCENTRATION and LIFETIME

CUSTOM / SMALL SERIES PRODUCTION

HIGH COST PER DEVICE

TOTAL DEPLETION of DIODE



CHARGE SIGNAL
(in VACUUM) for
α PARTICLES
on FRONT DIODE
or BACK SIDE CONTACT

SIGNAL for TRAVERSING
MUONS is
~PROPORTIONAL $\propto \sqrt{V}$

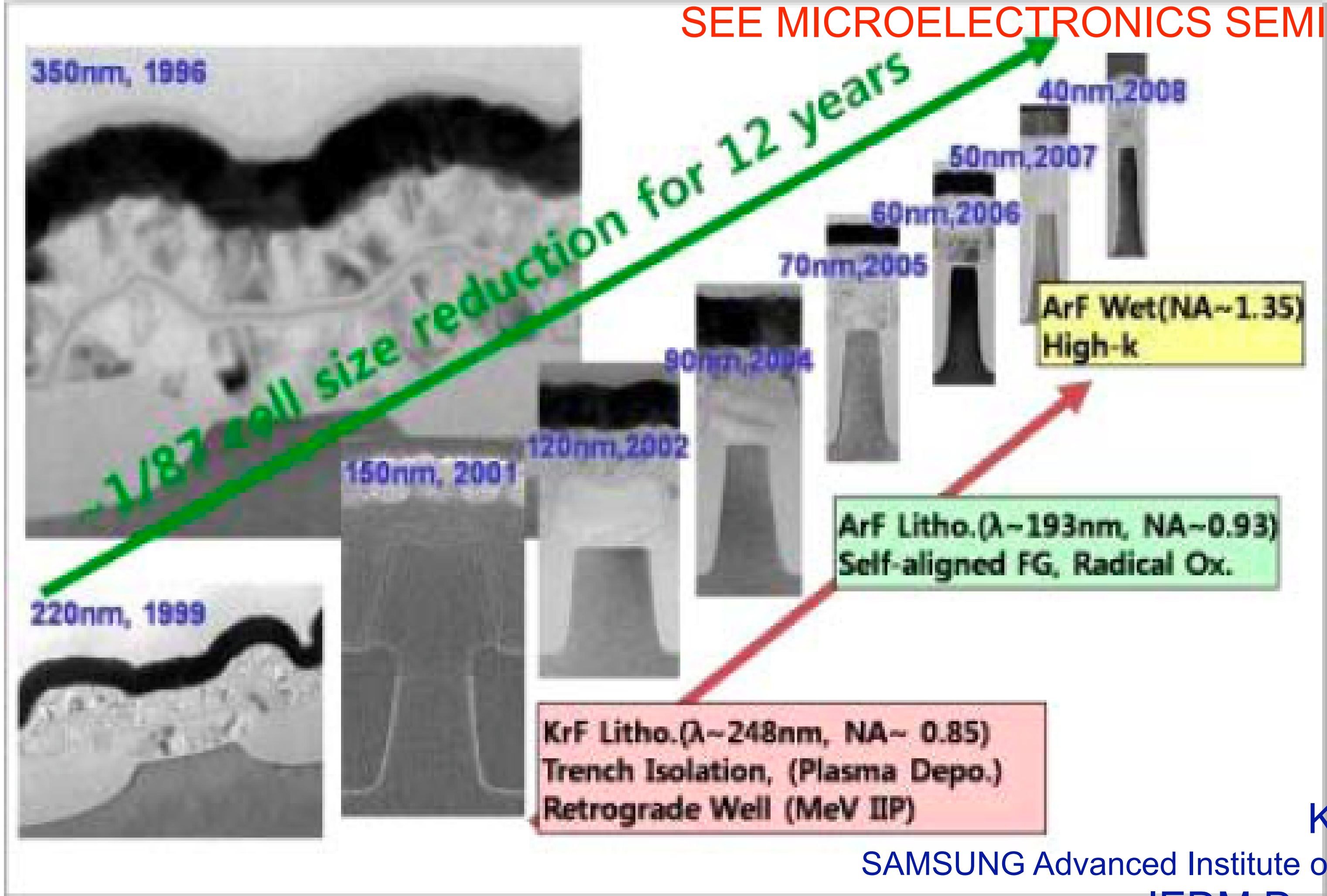
CERN Yellow Report 83-6, p.76

MICROELECTRONICS TECHNOLOGY TRENDS

SEMINARS & EXERCISES in 'BASIC & ADVANCED ELECTRONICS'
coordinator Alessandro MARCHIORO

SAMSUNG : Trend in NAND memory cell 1996-2008

SEE MICROELECTRONICS SEMINARS



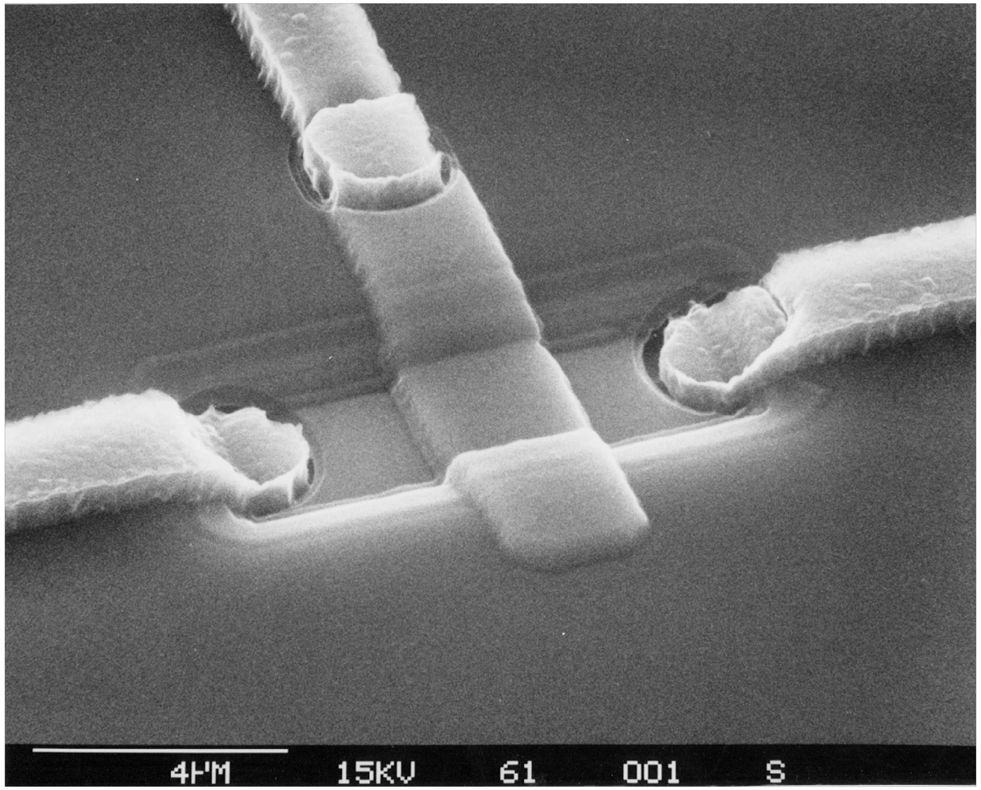
Kinam KIM
SAMSUNG Advanced Institute of Technology
IEDM Dec 2010 1.1

Fig. 3 NAND cell dimensional scaling and related technology evolution

FLASH UNIT CELL 0.00375 um2 -> 260 cells/um2

TREND in TRANSISTORS

SILICON MOS TRANSISTOR



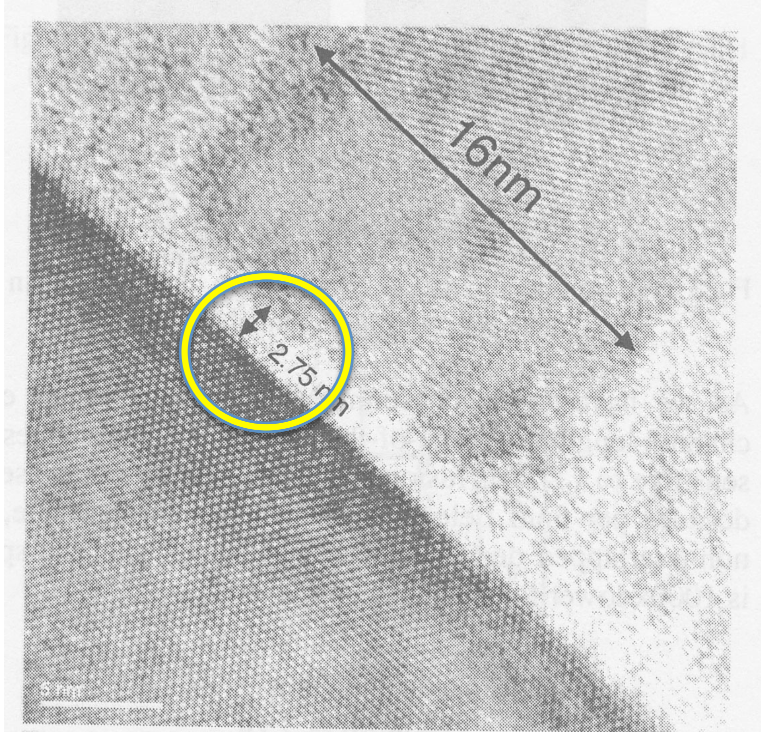
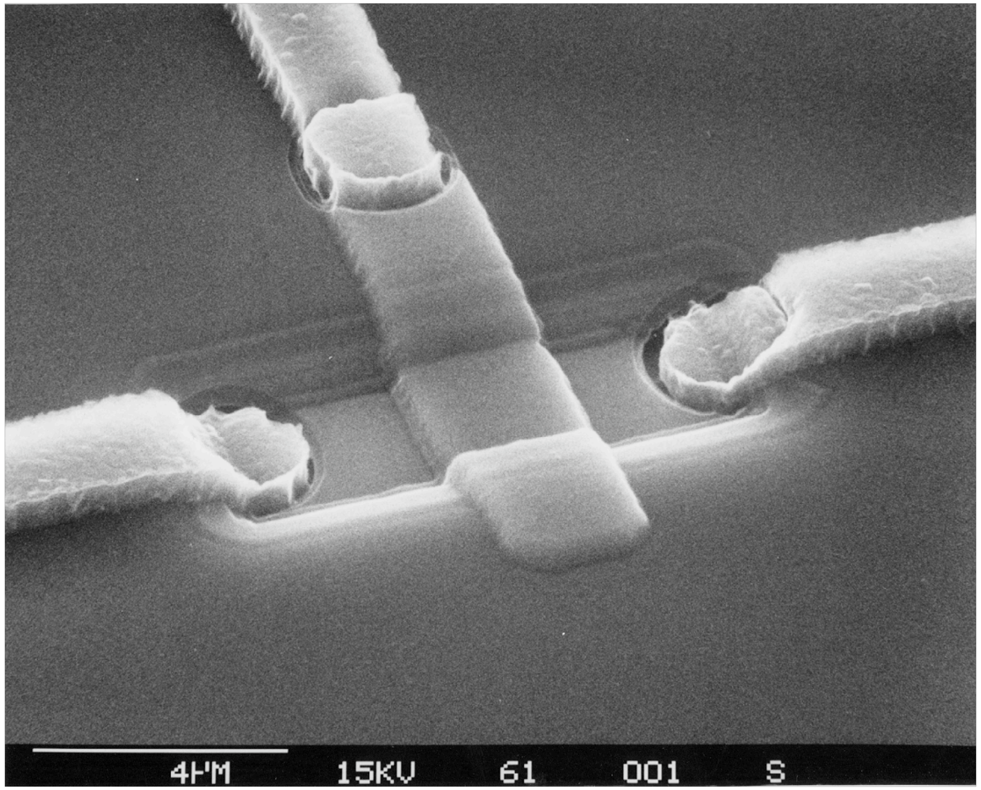


Fig. 1 : Hi-Res Cross section of the 16nm NMOS

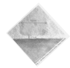
SiO_2 gate 2.75 nm

2 μm TECHNOLOGY 1982 0.016 μm 2007

SILICON MOS TRANSISTOR



CORRECT SCALE



SiO_2 gate 2.75 nm

2 μm TECHNOLOGY 1982 0.016 μm 2007

SOI TRANSISTORS LETI (Grenoble)

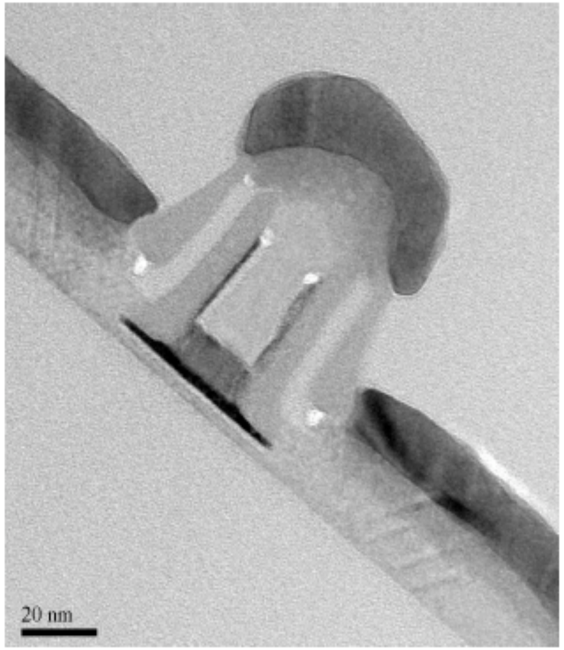
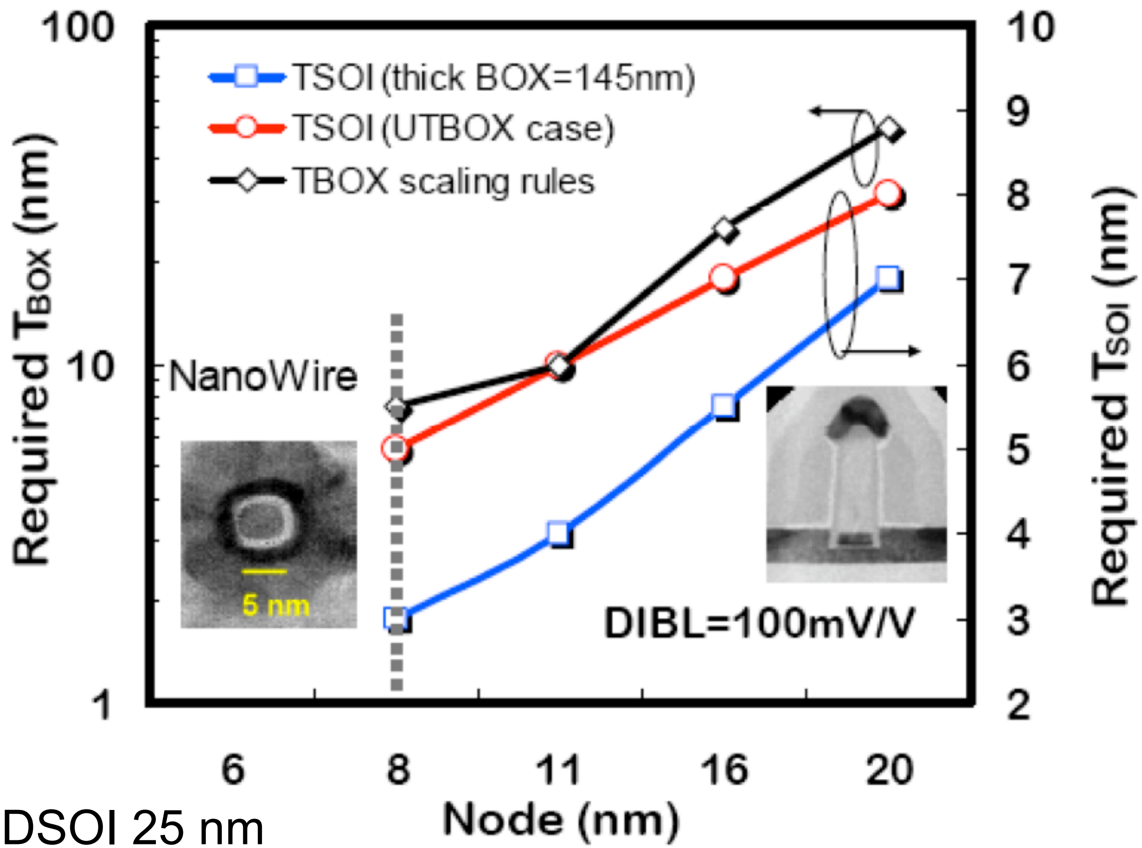


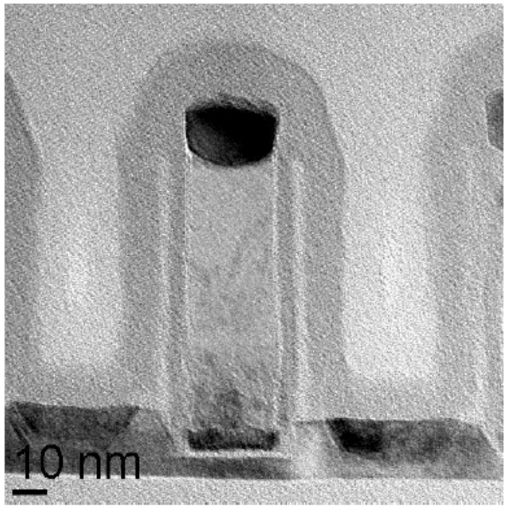
Fig. 1- TEM cross section of 18nm gate length n-sSOI MOSFET.

LETI-SOITEC 3.4

SOI TRANSISTOR 18 nm

NANOWIRE TRANSISTOR 8 nm





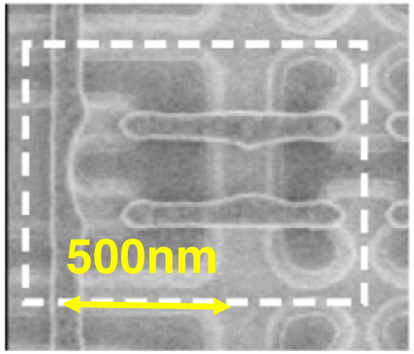
FDSOI 25 nm

INTEL : IMPROVED LITHOGRAPHY ≤45 nm

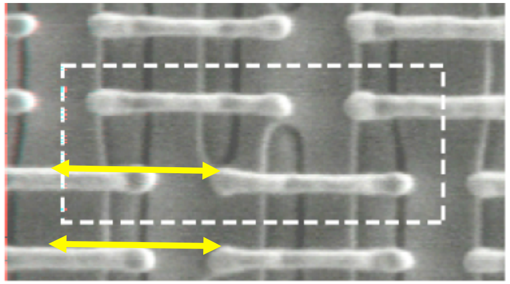
MINIMAL SRAM CELL

ALSO, SEVERAL CHARACTERISTICS IMPROVED BEYOND EXPECTATIONS

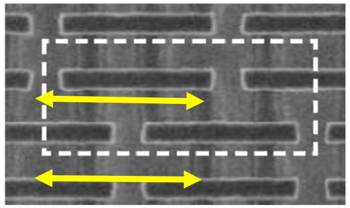
90 nm



65 nm



45 nm



~ TO SCALE

Mrs Kelin KUHN, IEEE IEDM 2007

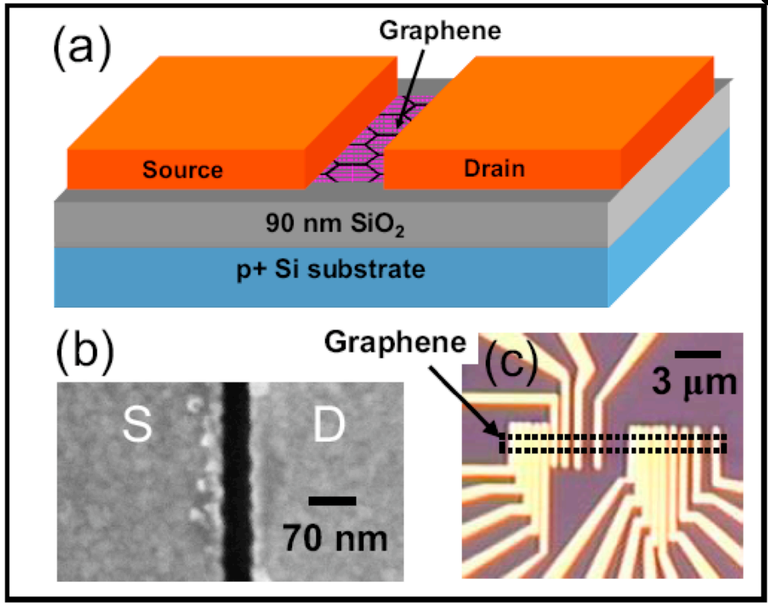
LATEST CHALLENGER for SPEED

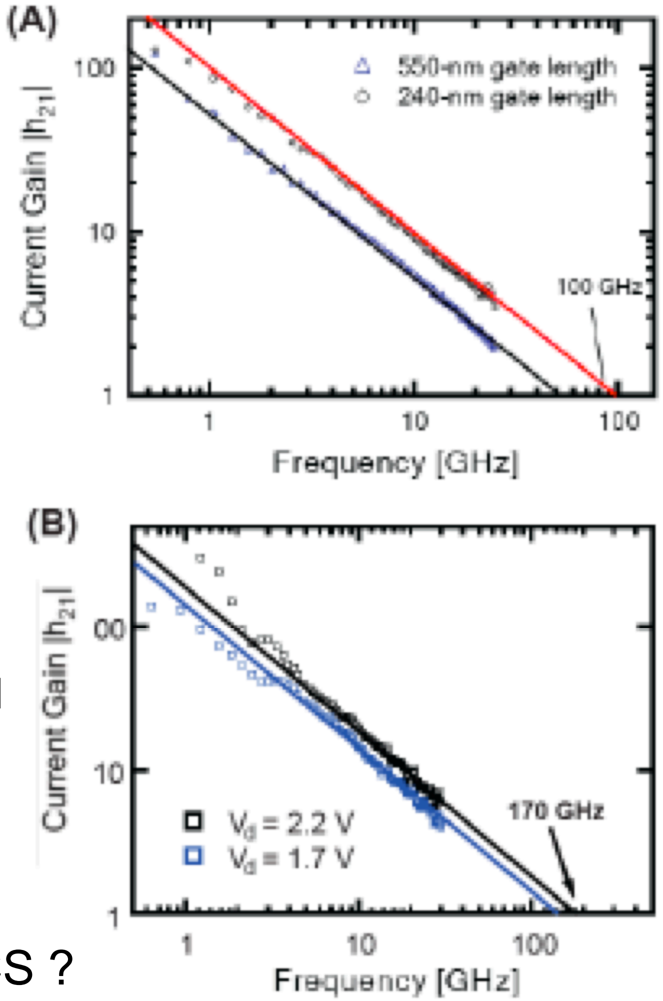
GRAPHENE

SINGLE ATOMIC LAYER of C ATOMS

MAJOR EFFORTS in
UNIVERSITIES & INDUSTRY

GRAPHENE





(a) Schematic view of a back-gated graphene FET
(b) SEM image of metal contacts of a 70nm device and
(c) optical image of the fabricated devices.

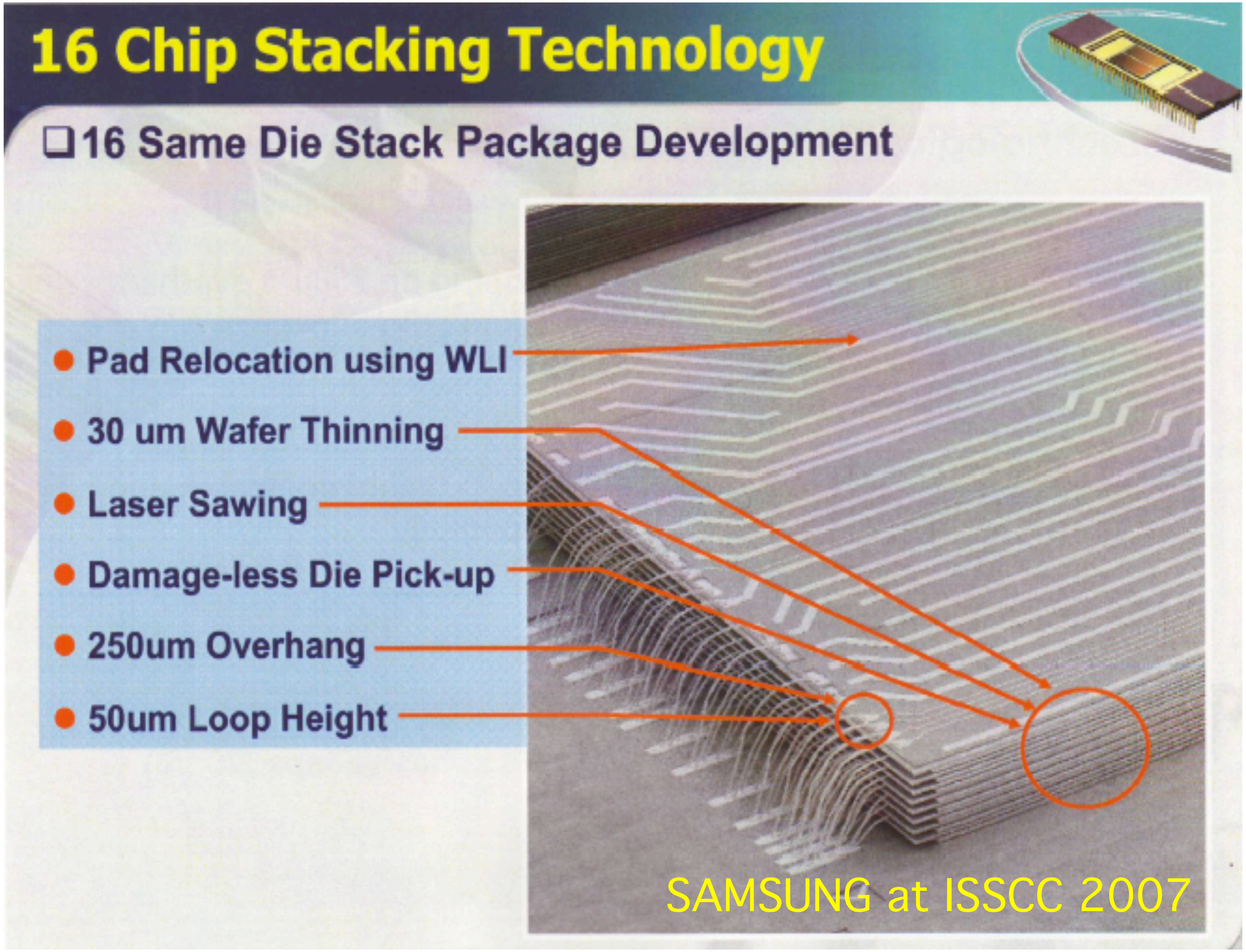
VERY HIGH e & h MOBILITY -> THz ?

PHOTOSENSITIVE: FAST OPTOELECTRONICS ?

Figure 2. (A) Current gain (h_{21}) versus frequency plot of two RF transistors with gate lengths of 550nm and 240nm showing cutoff frequencies (f_T) of 53GHz and 100GHz, respectively [8]. (B) The characteristics of a 90nm gate length, 160 nm source-drain separation transistor. The f_T is 170 GHz.

IBM Dec 2010 IEDM 23.1

3D STACKING TECHNOLOGY



3D STACKING with Through Si Vias

more on this LATER

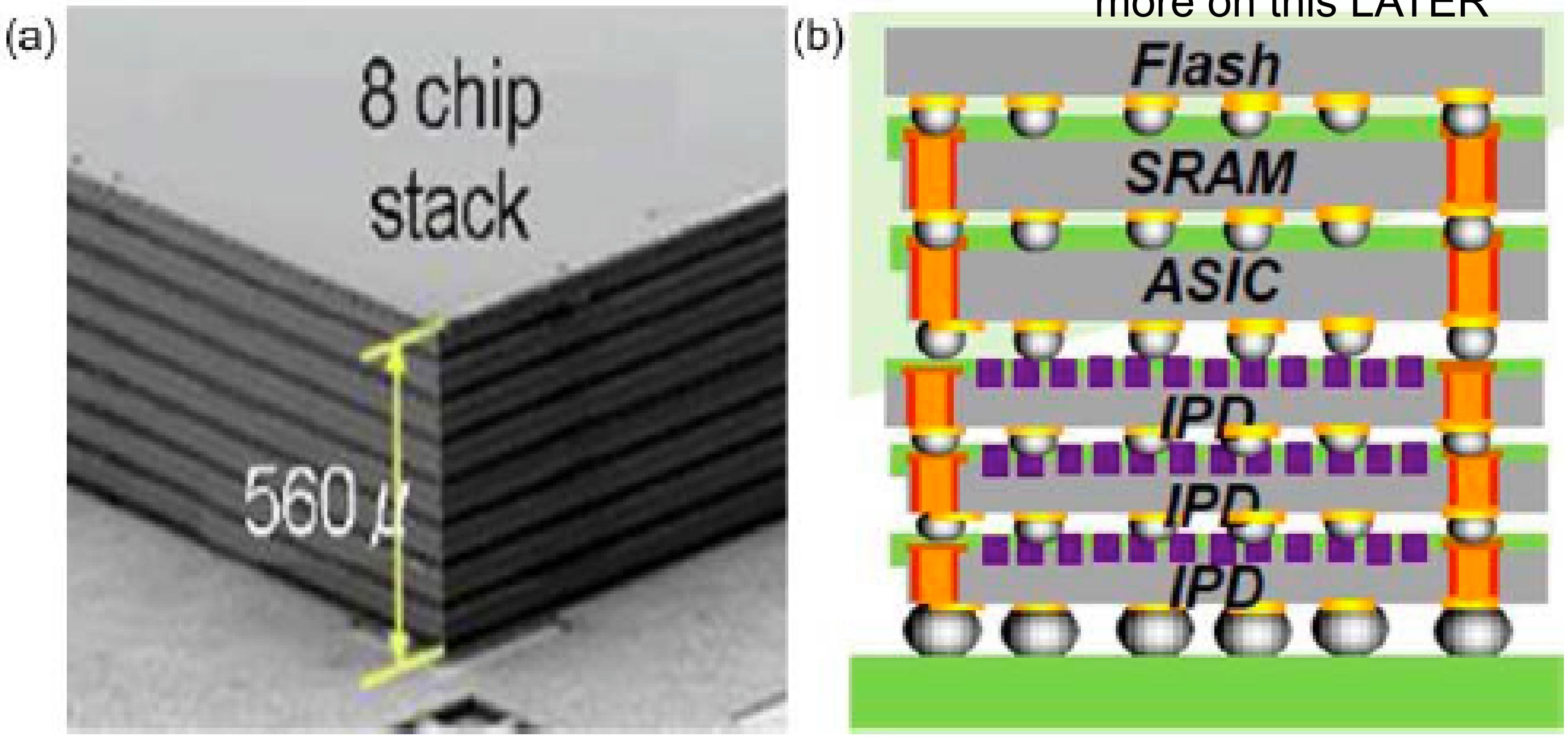


Fig. 11 (a) Photograph of a 3D IC chip stack, (b) Conceptual drawing of a 3D integrated device for medical application enabled by TSVs and Si interposers. (Image source: 2009 Yole report on 3D IC integration & TSV interconnects)

Heinz GRAAFSMA SEMINAR on FUTURE SENSORS: 3D

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MICRO ELECTRONICS

↓

NANO ELECTRONICS

↓

ATTO PHYSICS

ATTO

MILLI

MICRO

GIGA NANO

TERA PICO

PETA FEMTO

10^{+18} EXA ATTO 10^{-18}

10^{+21} ZETTA ZEPTO

10^{+24} YOTTA YOCTO 10^{-24}

ATLAS & CMS: ATTOSCOPES study 10^{-18} m

COURTESY W. van DONINCK

FIRST OBSERVATION of PION

Nuclear capture of pion

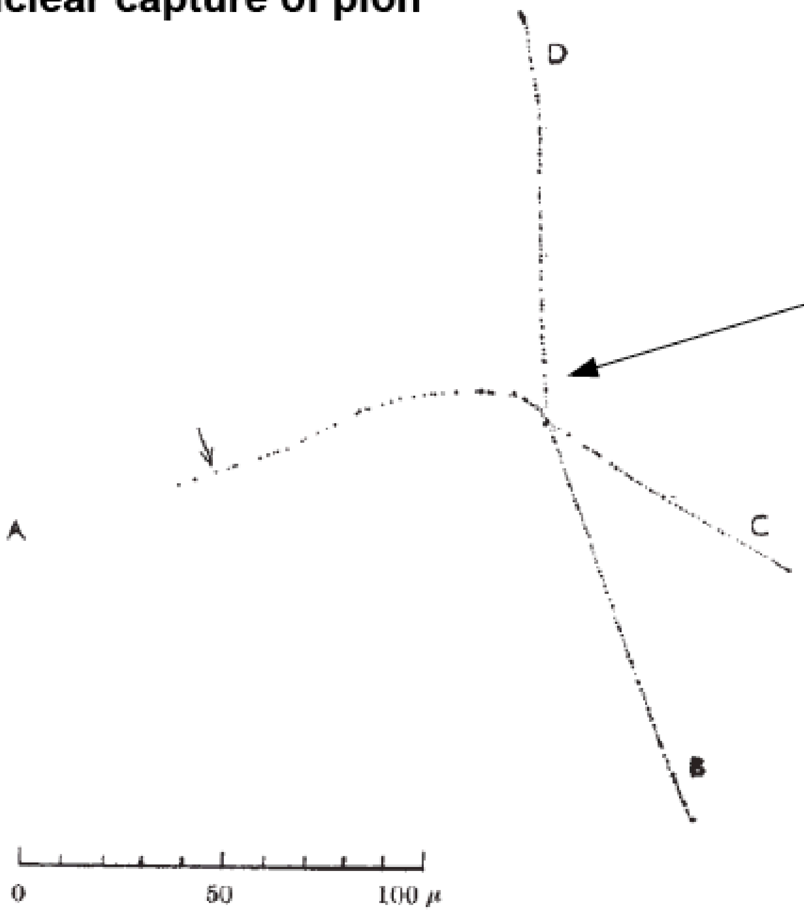
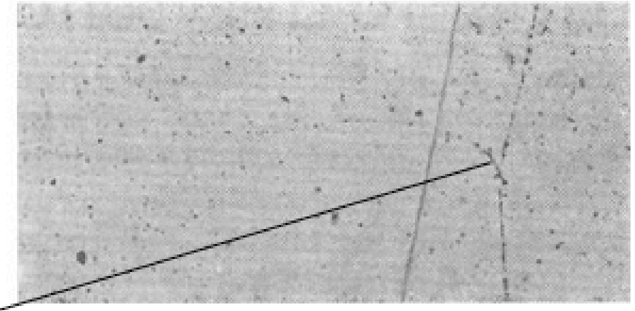


Fig. 1 *b*. TRACE OF COMPLETE STAR ON SCREEN OF PROJECTION MICROSCOPE, SHOWING PROJECTION OF THE TRACKS IN THE PLANE OF THE EMULSION. TRACK *A* CANNOT BE TRACED WITH CERTAINTY BEYOND THE ARROW



g. 1 *a*. PHOTOMICROGRAPH OF CENTRE OF STAR, SHOWING TRACK OF ISON PRODUCING DISINTEGRATION. (LEITZ 2 MM. OIL-IMMERSION OBJECTIVE. × 500)

- **A is the new meson**
- **B,D,C are likely protons**
- **Track C goes into the page**

Why A is a new meson:
electron: range too large
proton: scattering too large
muon: frequent nuclear interaction

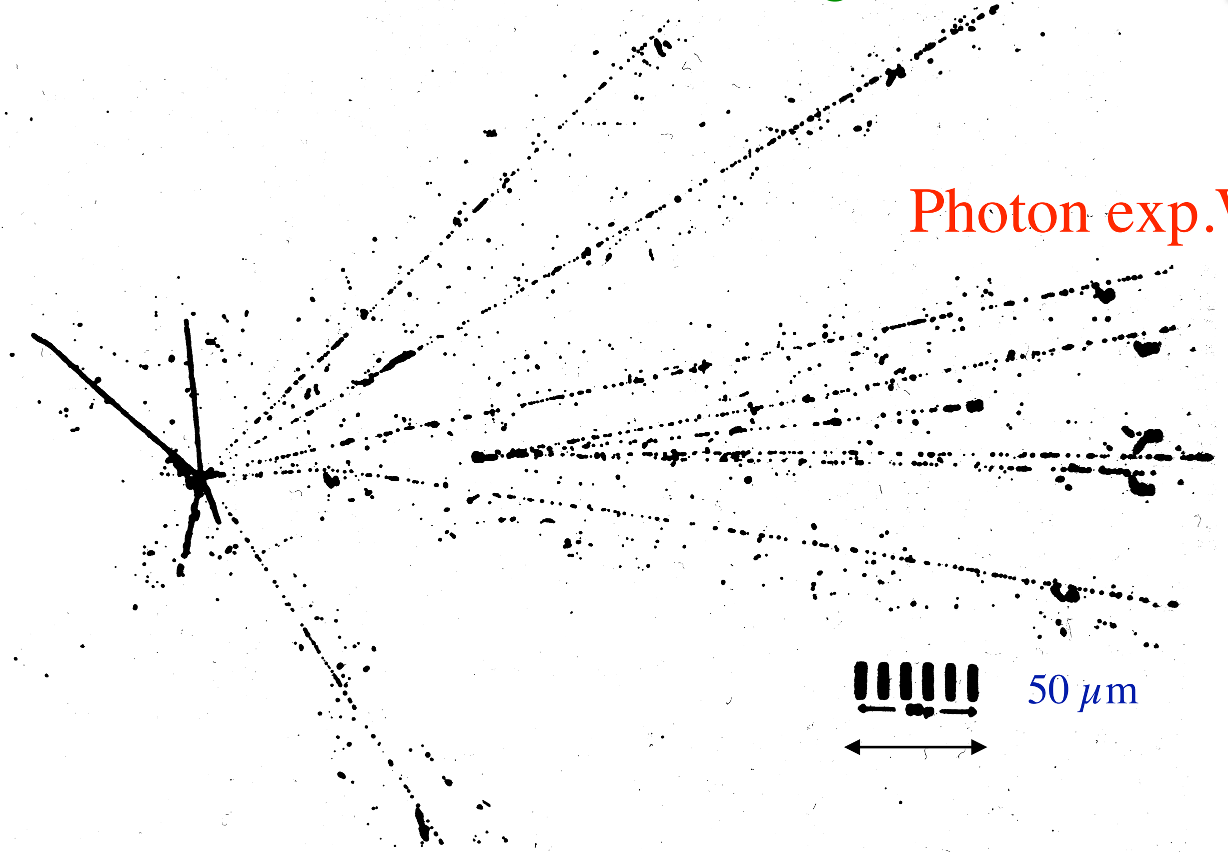
from PDF by Kapliy, 2008

11

(Jan 1947, observed by D. Perkins)

NUCLEAR EMULSION

SPECIAL, THICK FILM AgBr 3D, sub μm PRECISION



SUCCESSIVE IONIZING ENERGY TRANSFERS TO GRAINS
MAKE LATENT IMAGE

500 μm

SOME HISTORICAL STEPS

1943 - 2010

PHOTOGRAPHIC FILM and
GAS-FILLED 'Geiger' COUNTER are oldest

SEMICONDUCTOR DETECTORS
ALLOW PRECISE ENERGY MEASUREMENT

AgCl CRYSTAL FIRST DETECTOR in 1943

FIRST WORKING SEMICONDUCTOR DETECTOR

THE CRYSTALCOUNTER
A NEW INSTRUMENT IN NUCLEAR PHYSICS

PROEFSCHRIFT
TER VERKRIJGING VAN DEN GRAAD VAN DOCTOR IN DE WIS- EN NATUURKUNDE AAN DE RIJKSUNIVERSITEIT TE UTRECHT, OP GEZAG VAN DEN RECTOR MAGNIFICUS, J. BOEKE, HOOGLEERAAR IN DE FACULTEIT DER GENEESKUNDE, VOLGENS BESLUIT VAN DEN SENAAT DER UNIVERSITEIT TEGEN DE BEDENKINGEN VAN DE FACULTEIT DER WIS- EN NATUURKUNDE TE VERDEDIGEN OP 30 JULI TE 3 UUR,

DOOR

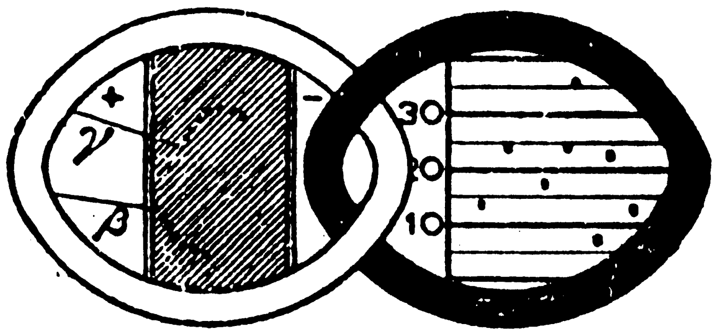
PIETER JACOBUS VAN HEERDEN
GEBOREN TE UTRECHT

AMSTERDAM
N.V. NOORD-HOLLANDSCHE UITGEVERS MAATSCHAPPIJ
1945

AgCl CRYSTAL
is SEMICONDUCTOR
USED at LIQUID AIR temp

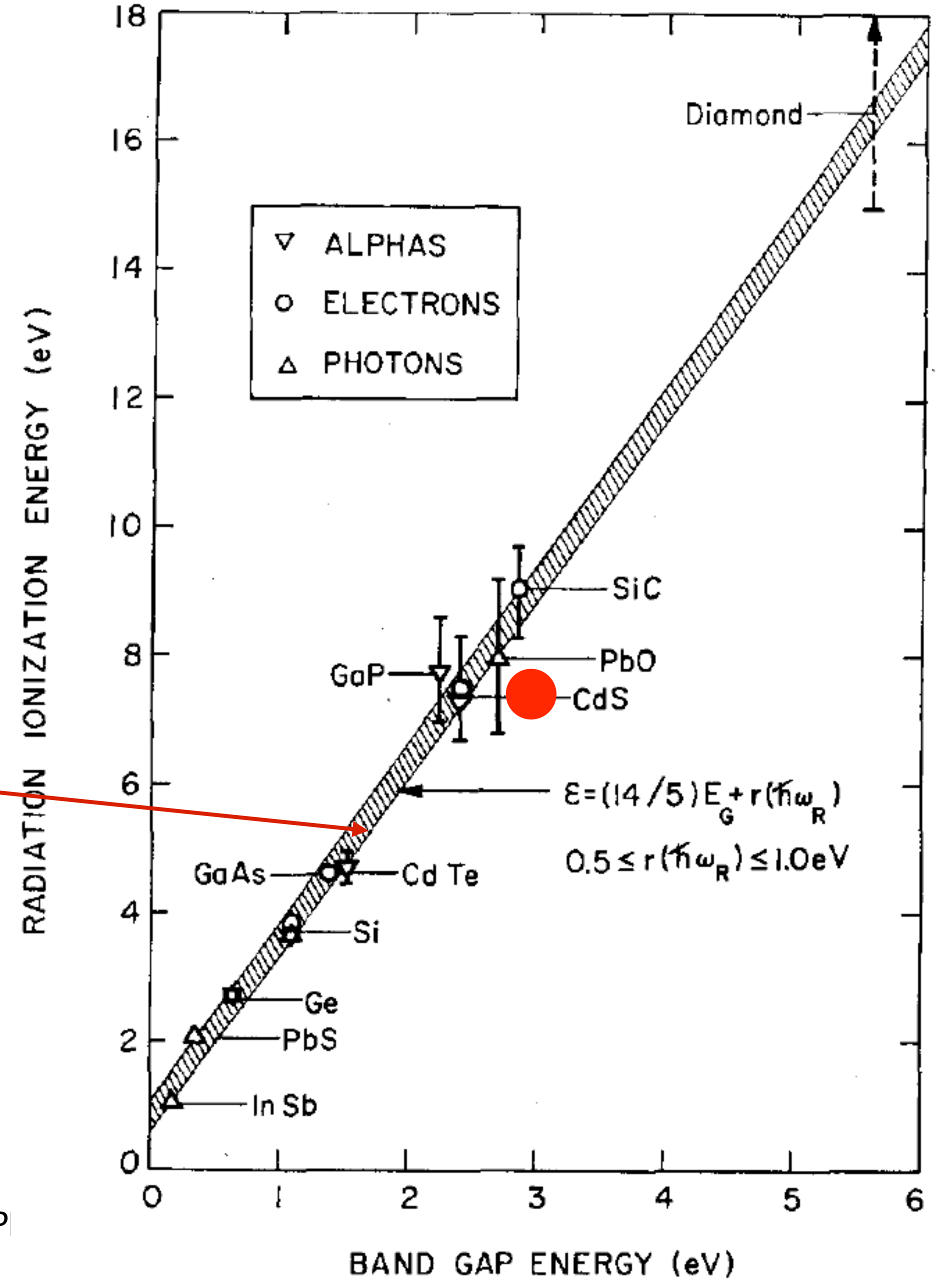
CONDUCTIVE @ RT,
CONTACTS INJECTING

PhD 30 July 1945, Utrecht



ε vs SEMICONDUCTOR BANDGAP

EARLIEST DETECTOR:
AgCl CRYSTAL
bandgap 3.2 eV
ε 7.6 eV

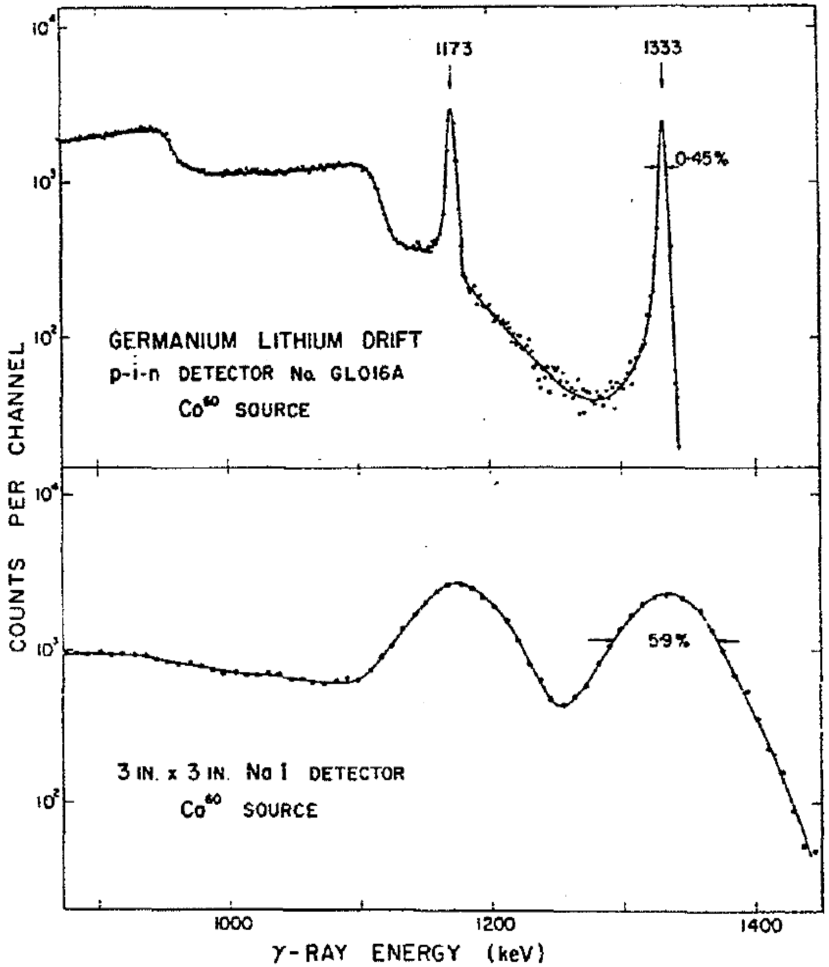


TYPICAL
RELATIONSHIP *a ~ 2.83*

From: C.A. Klein

J. Appl.Phys. 39(1968) 2029

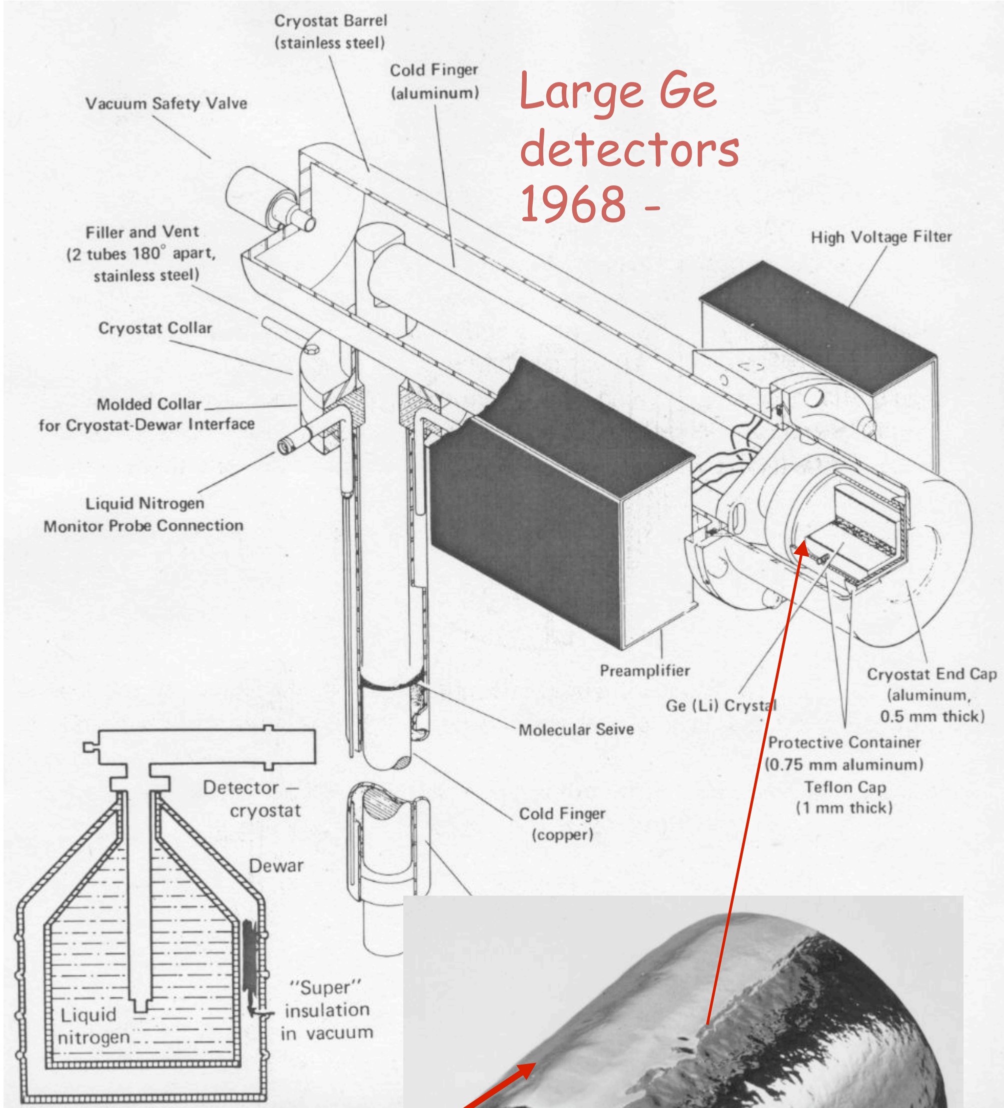
1963 Germanium Detector Breakthrough

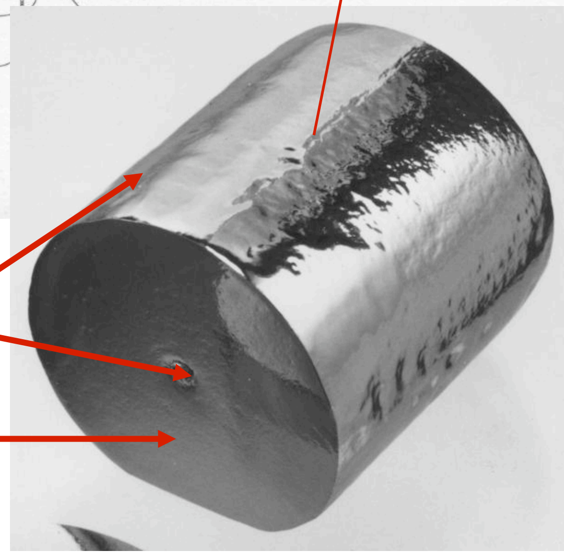


From: A.J. Tavendale

PRESENTATION Veljko RADEKA
DESY WORKSHOP Oct 2008

Large Ge detectors 1968 -

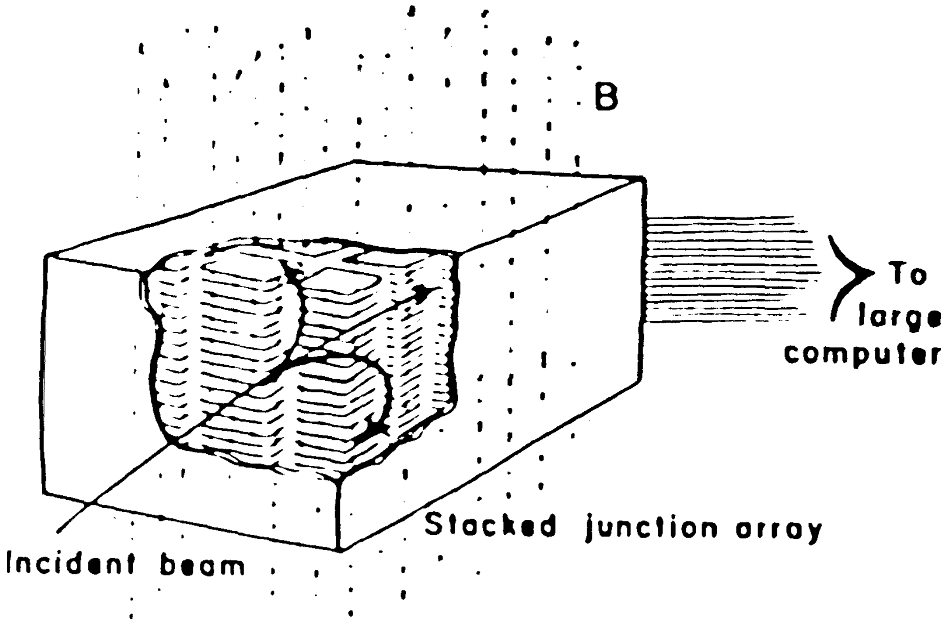




Coaxial det.contacts

Ge-crystal ~50-100 cm^3

Si ‘CLOUD’ CHAMBER 1963



HODOSCOPIC MOSAIC

EARLY PROPOSAL (USA)
for SEMICONDUCTOR TRACKER

WAS NEVER MADE

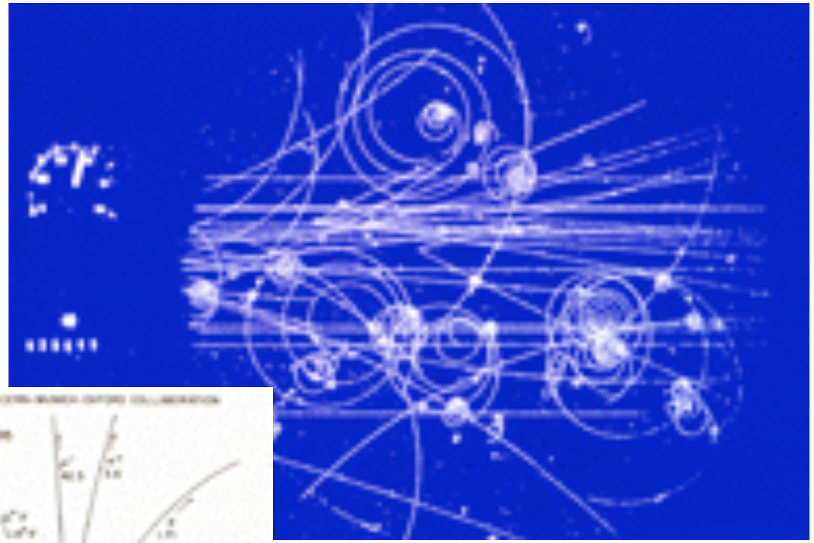
PRECEDED BREAKTHROUGH
of BUBBLE CHAMBERS ~ 1965

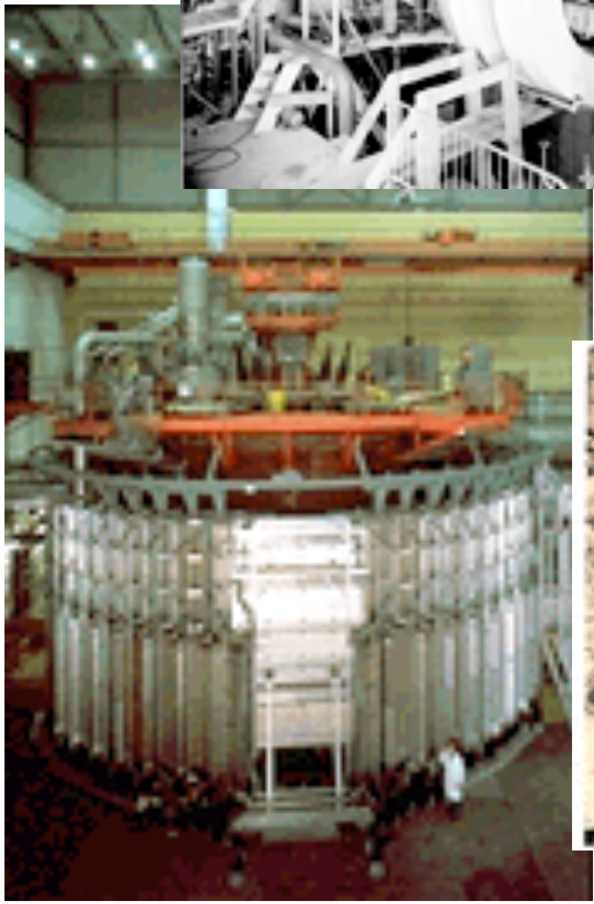
- CONNECTIONS NOT SOLVED
- READOUT ELECTRONICS UNDERESTIMATED
- SEGMENTATION NEEDED to REDUCE NOISE

BUBBLE CHAMBERS: IMAGING ELEMENTARY PARTICLES

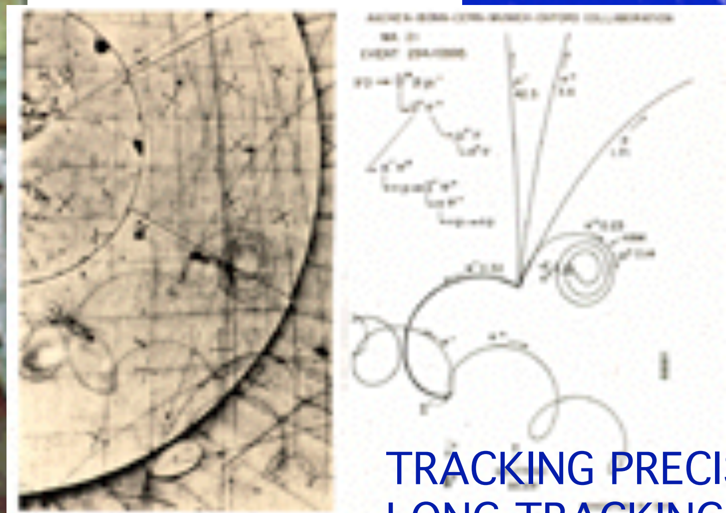
GARGAMELLE : LIQ PROPANE
~1973
NEUTRAL CURRENTS

PHOTO from
2m CHAMBER
LIQ HYDROGEN



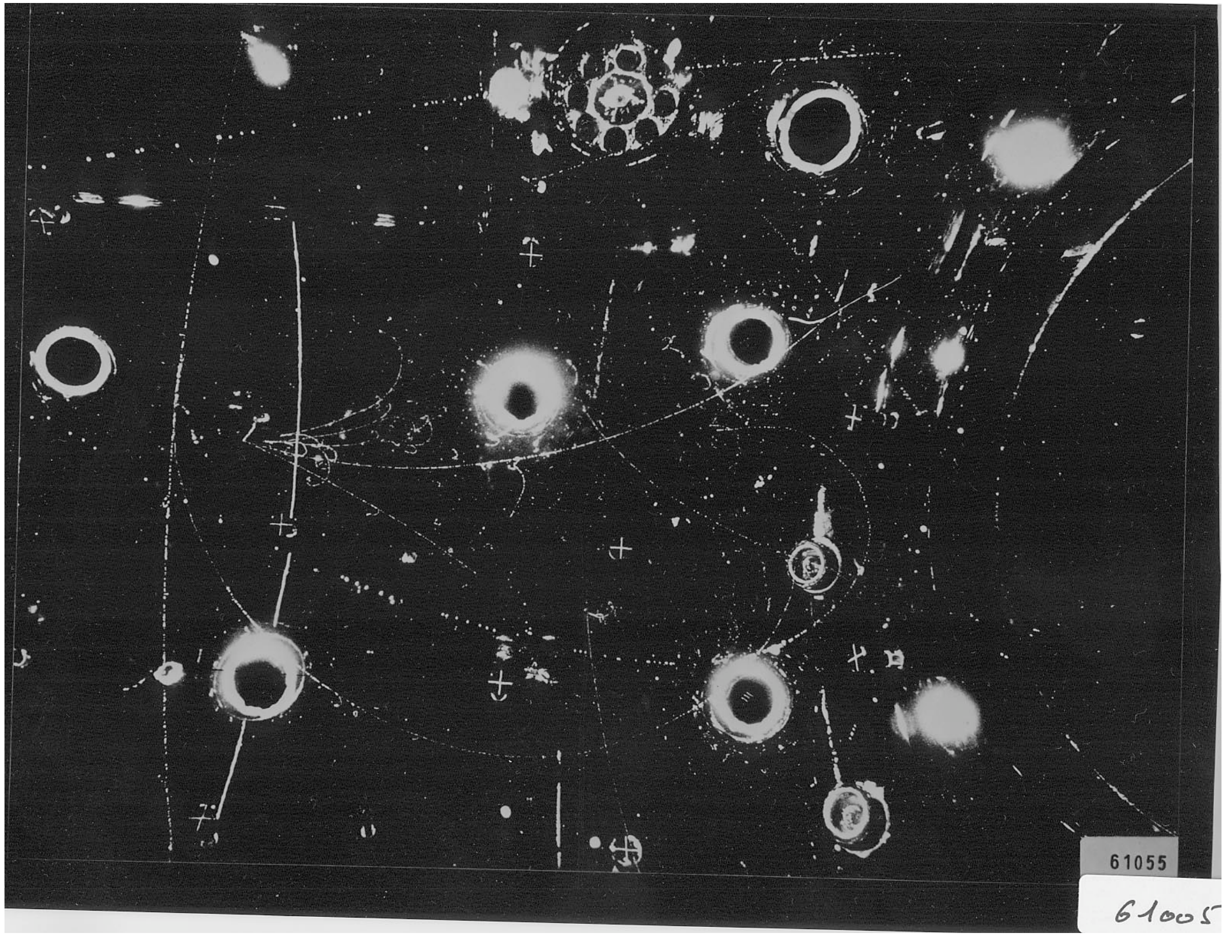


BEBC
Neutrino interaction



TRACKING PRECISION ~ 1mm
LONG TRACKING DISTANCES -> MOMENTUM
USED ~ 1960 - 1985

GGM CHAMBER with ν INTERACTION



NEUTRINO INTERACTION
IN HEAVY LIQUID
GARGAMELLE

SEVERAL LOW MOMENTUM 'DELTA' ELECTRONS
CAN BE SEEN AS 'BLOBS' ALONG TRACKS

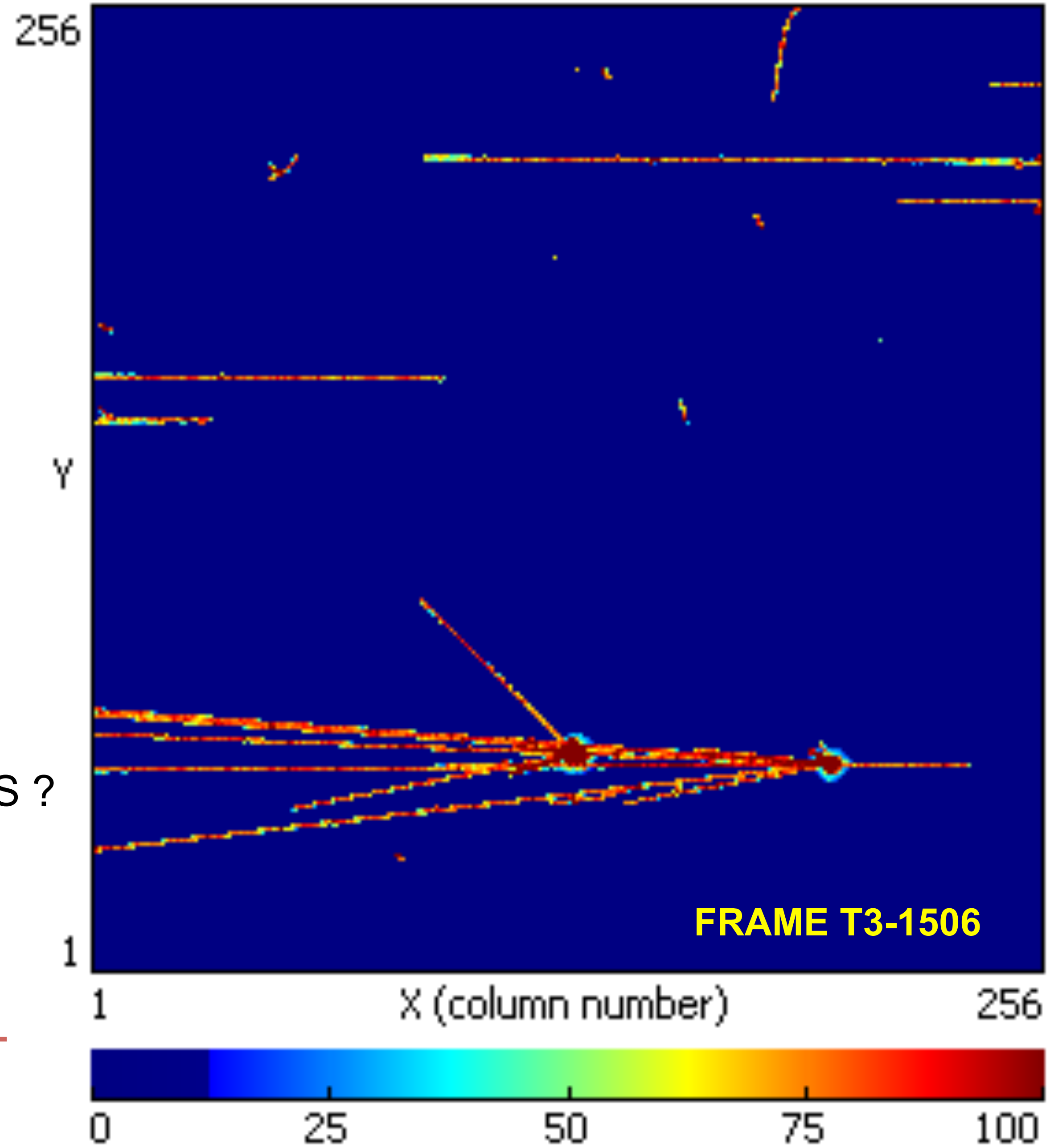
TIMEPIX CHIP as SILICON 'EMULSION' or 'BUBBLE CHAMBER'

H6 PION BEAM 2007

INCIDENT from RIGHT

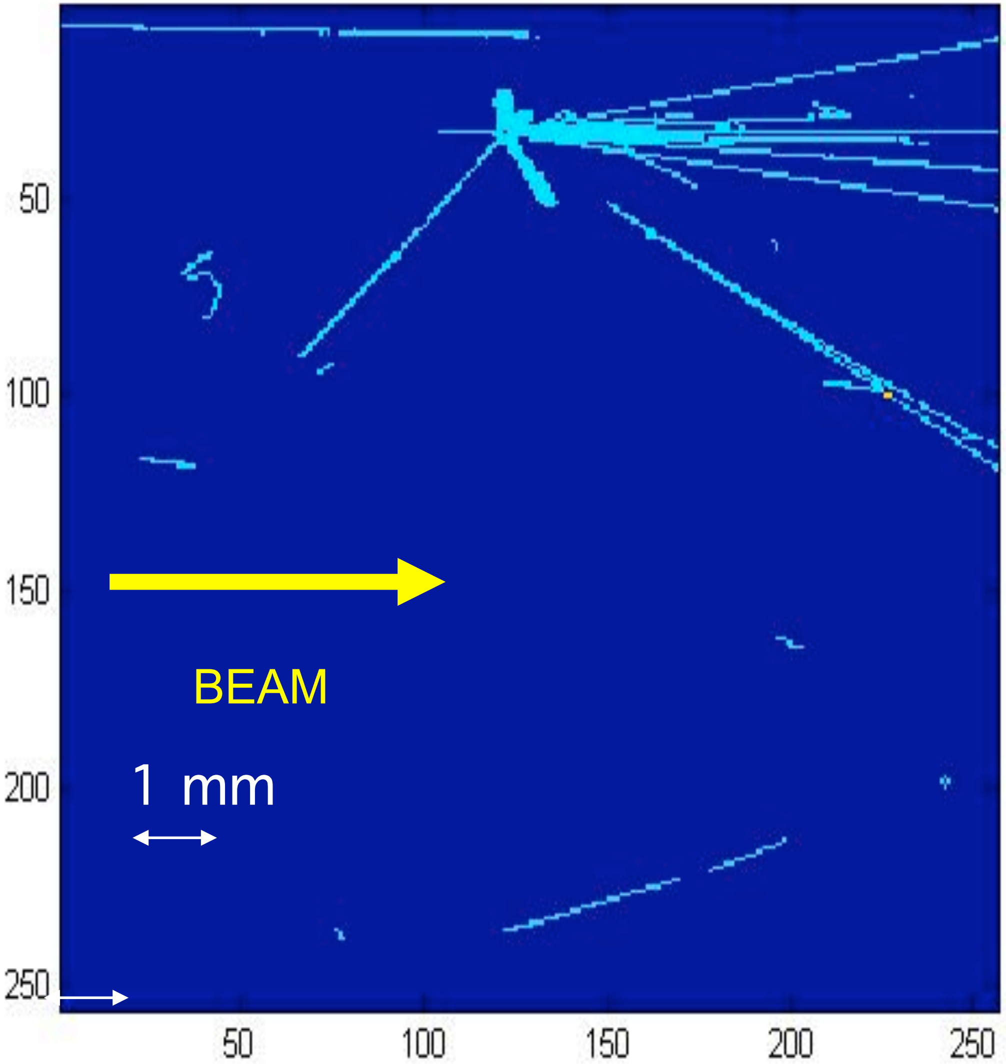
BEAM ←

WHICH DIRECTION of TRAILS ?



with John Idarraga / Montréal
now LAL

120 GeV PIONS in Si IMAGER : MEDIPIX



INTERACTION in
Medipix DETECTOR
Si 'BUBBLE CHAMBER'

DECAY of K_0 ?

↔ 500 μm

July 2006 Parallel Medipix P-05-0583

INTEGRATED DETECTOR

ELECTRONIC 'INTEGRATED CIRCUIT'

DIFFERENT FUNCTIONS TOGETHER

HYBRID; MONOLITHIC; IN-PACKAGE

SIMILAR for 'INTEGRATED DETECTOR'

SENSOR FUNCTION
SIGNAL PROCESSING
TRIGGER SELECTION
BUFFER / STORAGE
TRANSMISSION
MONITORING etc.

MASSIVE USE of CUSTOM CIRCUITS

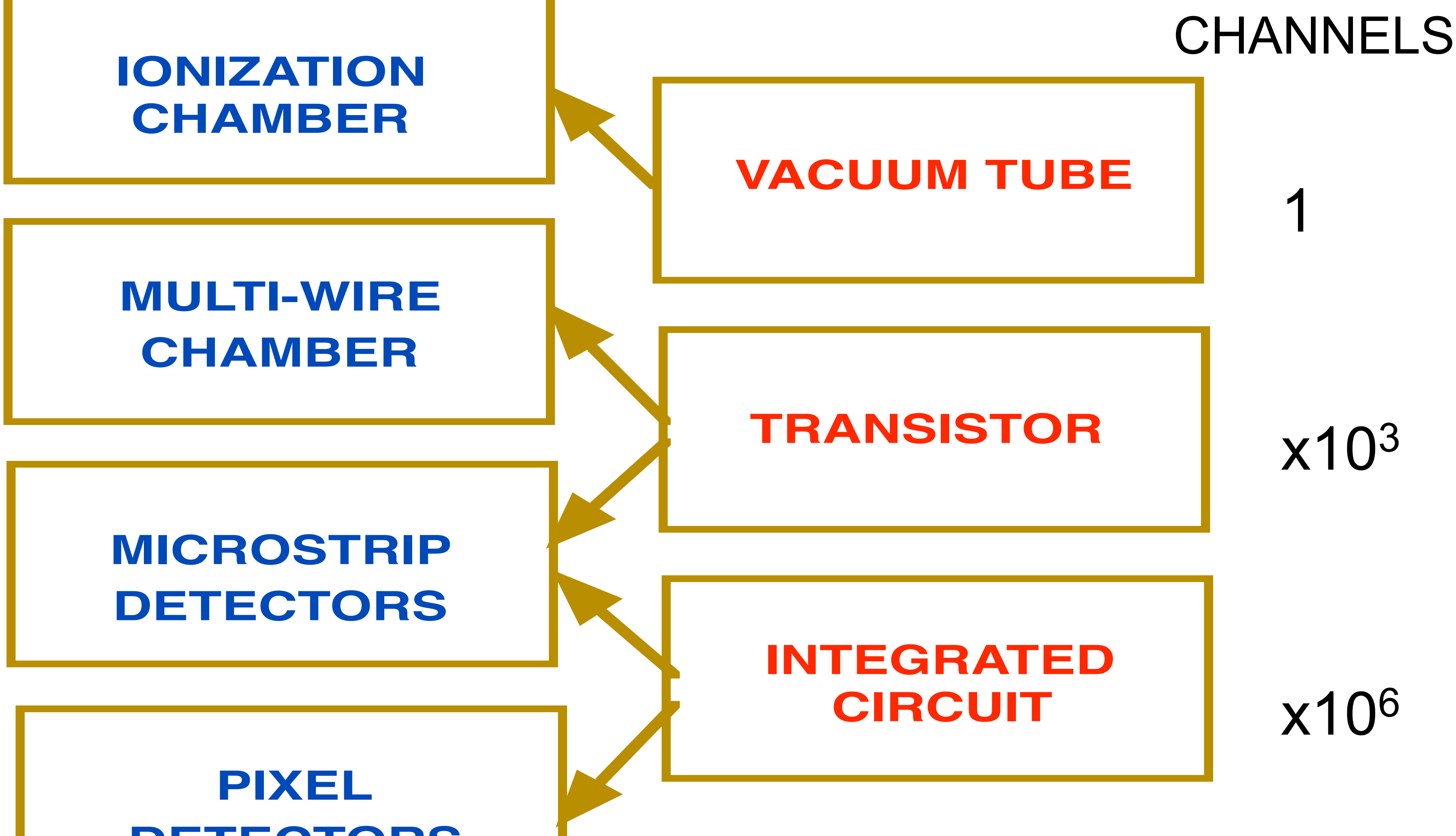
PROGRESS in Si SENSORS

HAND-in-HAND with AVAILABLE INDUSTRIAL TECHNOLOGY

0-D	**SINGLE DIODE**	**1955**
1-D	**SEGMENTED DIODE mm**	**1960**
QUASI 2-D	**DOUBLE-SIDED STRIPS**	**1965**
TRUE 2-D	**CCD/MOS MATRIX**	**1971**
	PIXELS MONOLITHIC or HYBRID	**1989**
	PILLARS '3D'	**1998**
TRUE 3-D	**VOXELS next step ?**	

Segmentation

ELECTRONICS Miniaturization



SYMBIOSIS of SENSORS&READOUT

mip SIGNAL in Si DETECTOR

MANY DETAILS in LATER SEMINARS

CURRENT SIGNAL INDUCED on CONTACTS by MOVING CARRIERS
→SIGNAL CURRENT DECREASES WHILE CARRIERS ARE COLLECTED

MAXIMAL CURRENT SIGNAL in BEGINNING

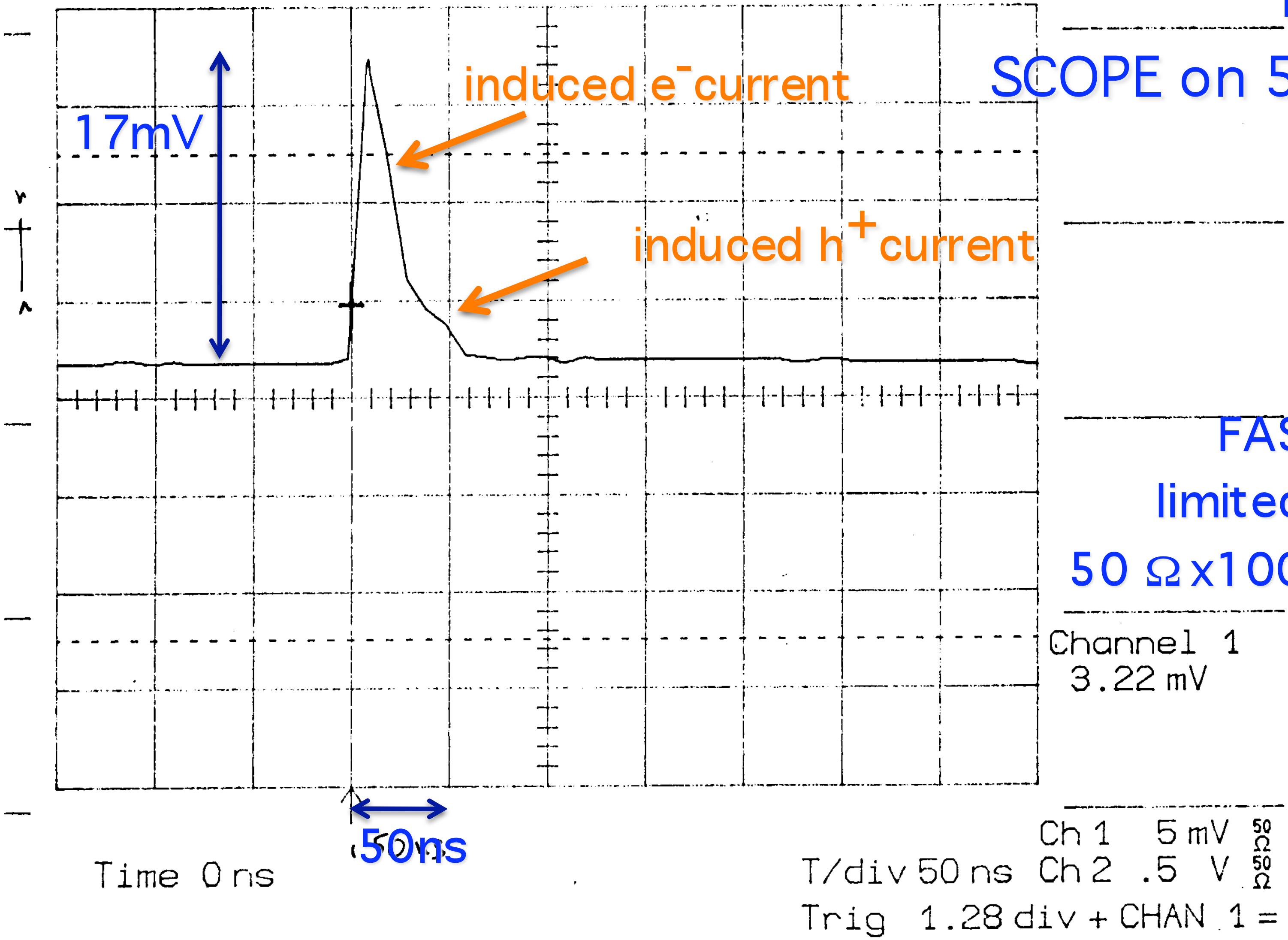
REMEMBER $Q = C \times V$ → MAXIMAL SIGNAL at SMALL CAPACITANCE
1000 e^-= 10^{-16}C gives 0.1V on 1 fF

and $i = dQ/dt$ → FAST SIGNAL gives HIGH CURRENT
1000 e^- in 1ns gives 0.1μA

Si SIGNAL SPEED

SIGNAL CURRENT from Pb ION in 200μm Si DETECTOR

SCOPE on 50 Ω ONLY

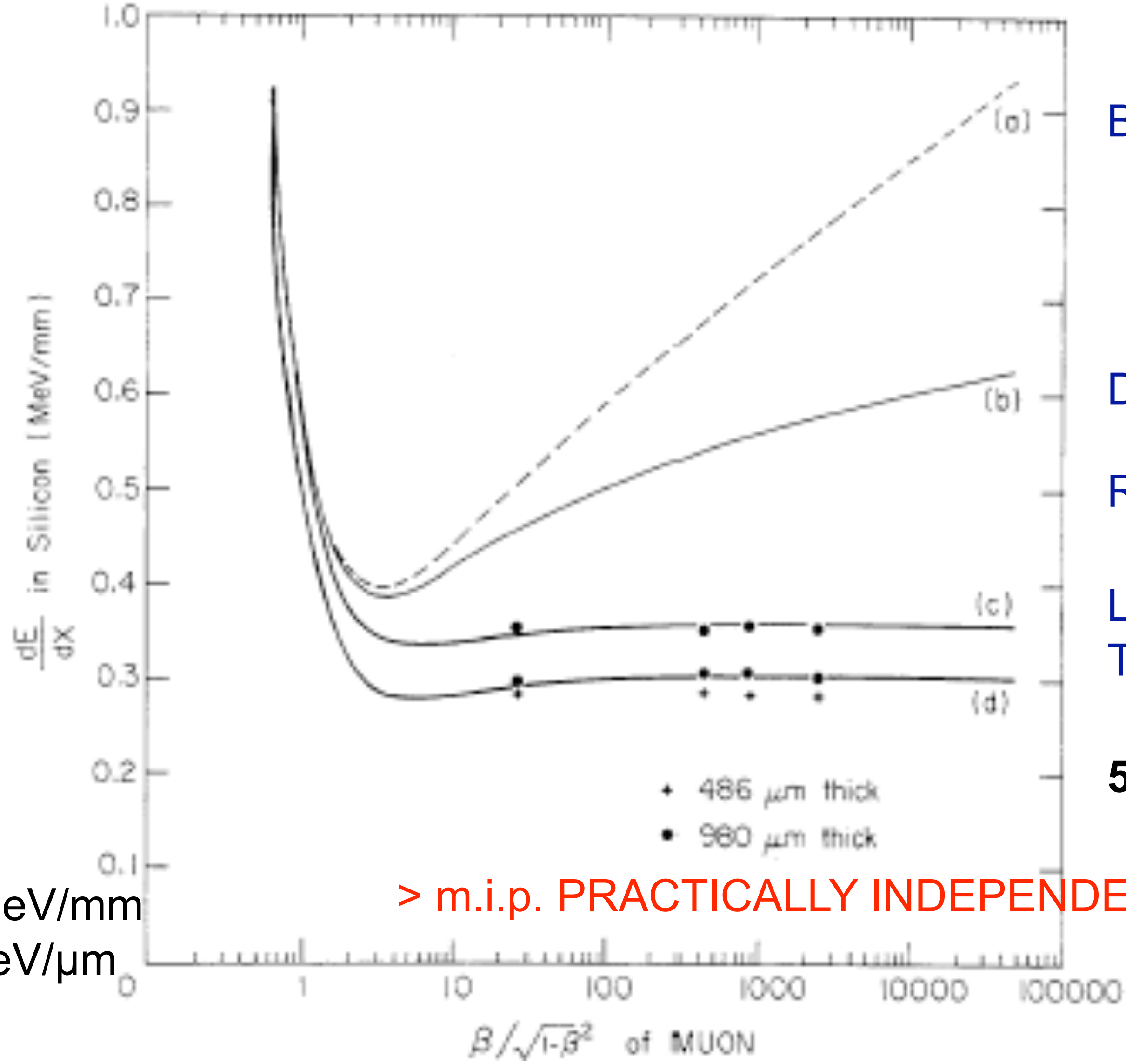


FAST RISE TIME

limited by RC time

50 Ω x100pF=5x10^{-9}s

ENERGY LOSS in SILICON



BETHE-BLOCH

DENSITY EFFECT

RESTRICTED NOT PLOTTED

LANDAU PEAK
THICKNESS DEPENDENT

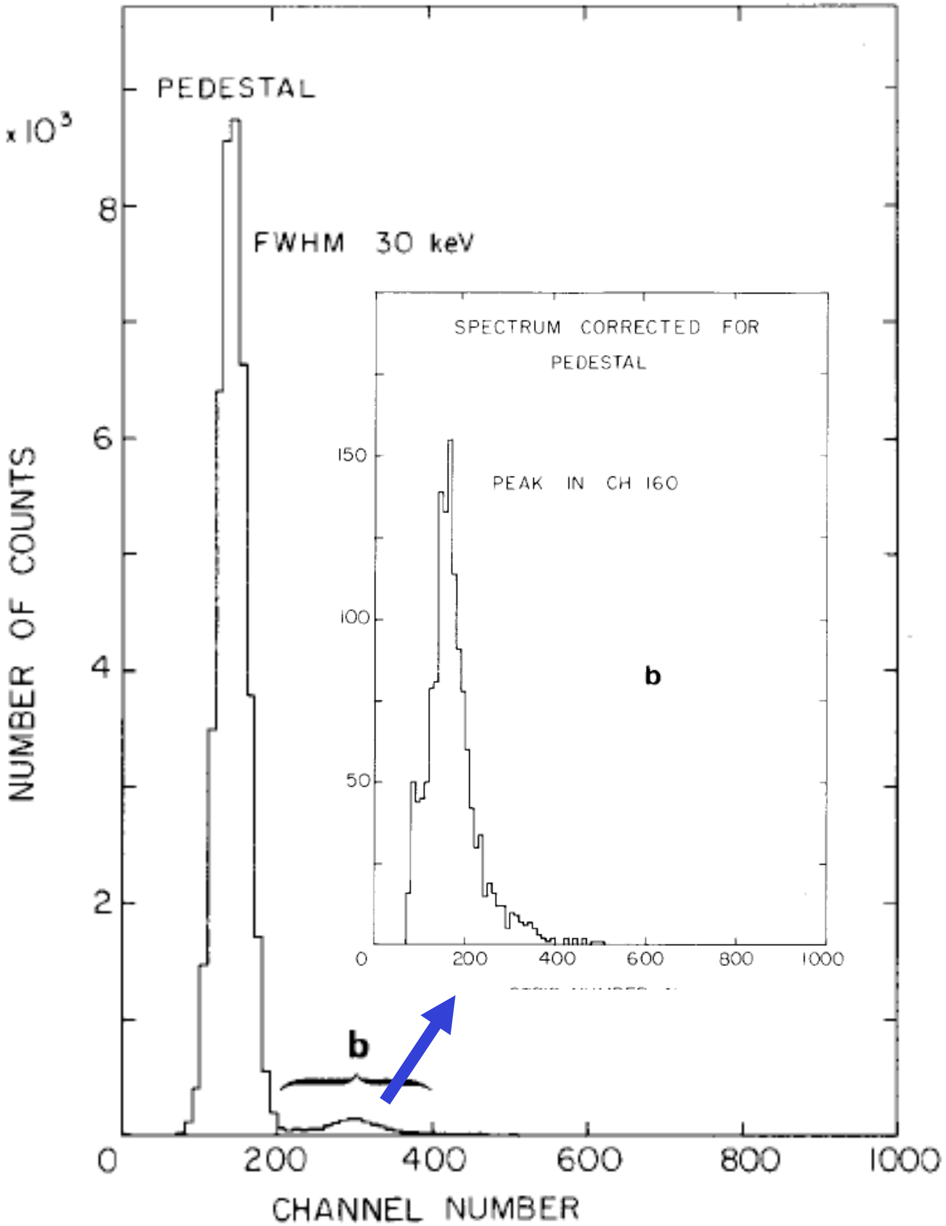
500keV e^- goes ~1mm in Si

MeV/mm
keV/µm

> m.i.p. PRACTICALLY INDEPENDENT of MOMENTUM

MEASUREMENTS
HEIJNE CERN Report 83-06

SIGNALS in Si MICROSTRIP



SIGNAL DISTRIBUTION
10 GeV PIONS
in 400 μm Si ~110 keV or ~30ke$^-$

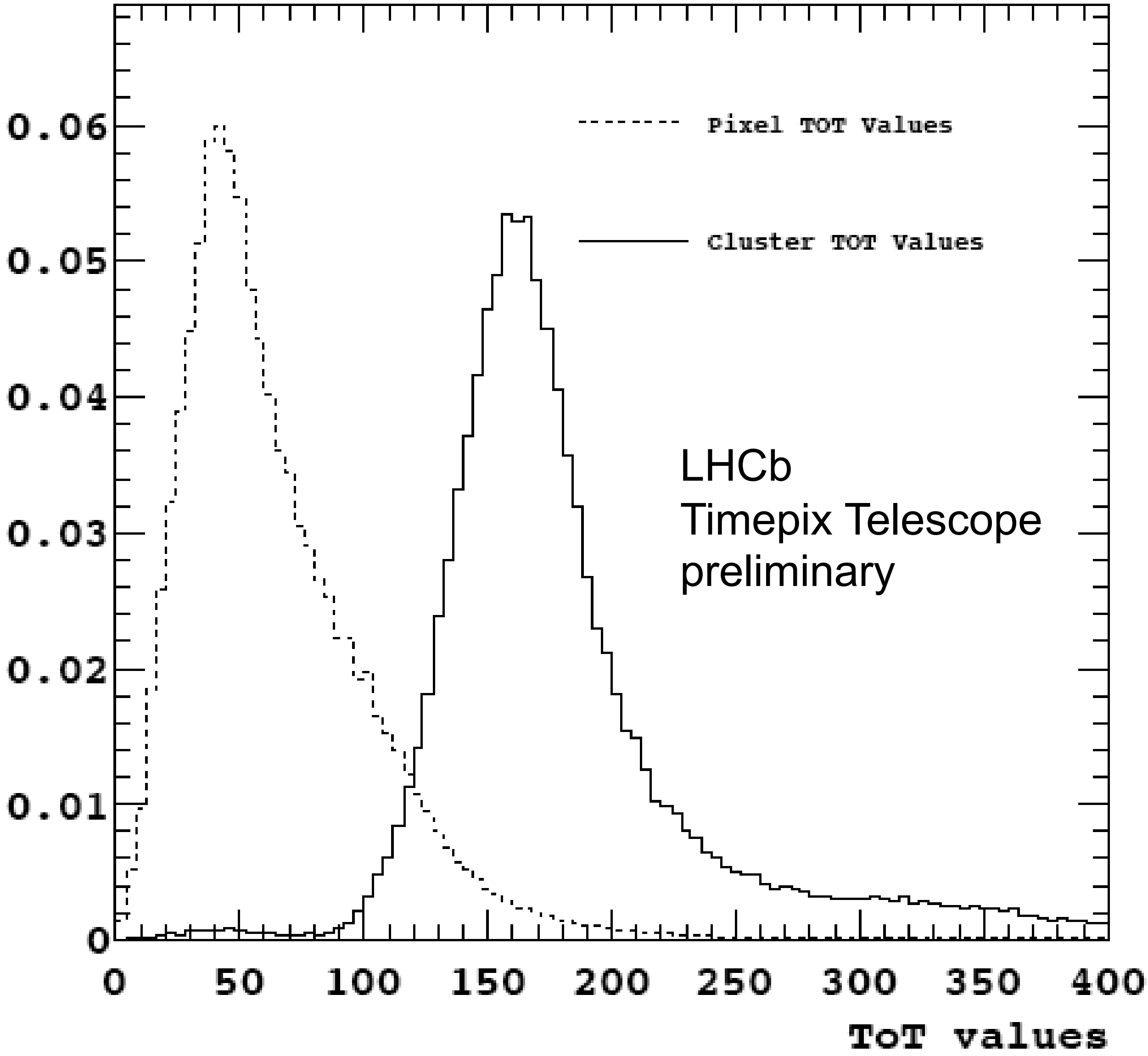
NOISE DISTRIBUTION
AROUND 'ZERO' PEDESTAL
FWHM 30 keV s=12.7 keV
3500 e$^-$ rms

DETECTOR READOUT WAS
60ns GATED INTEGRATION
AFTER BEAM TRIGGERS

LOW ENERGY TAIL !!!
- DOUBLE HITS
- OVERLAP from NOISE PEAK

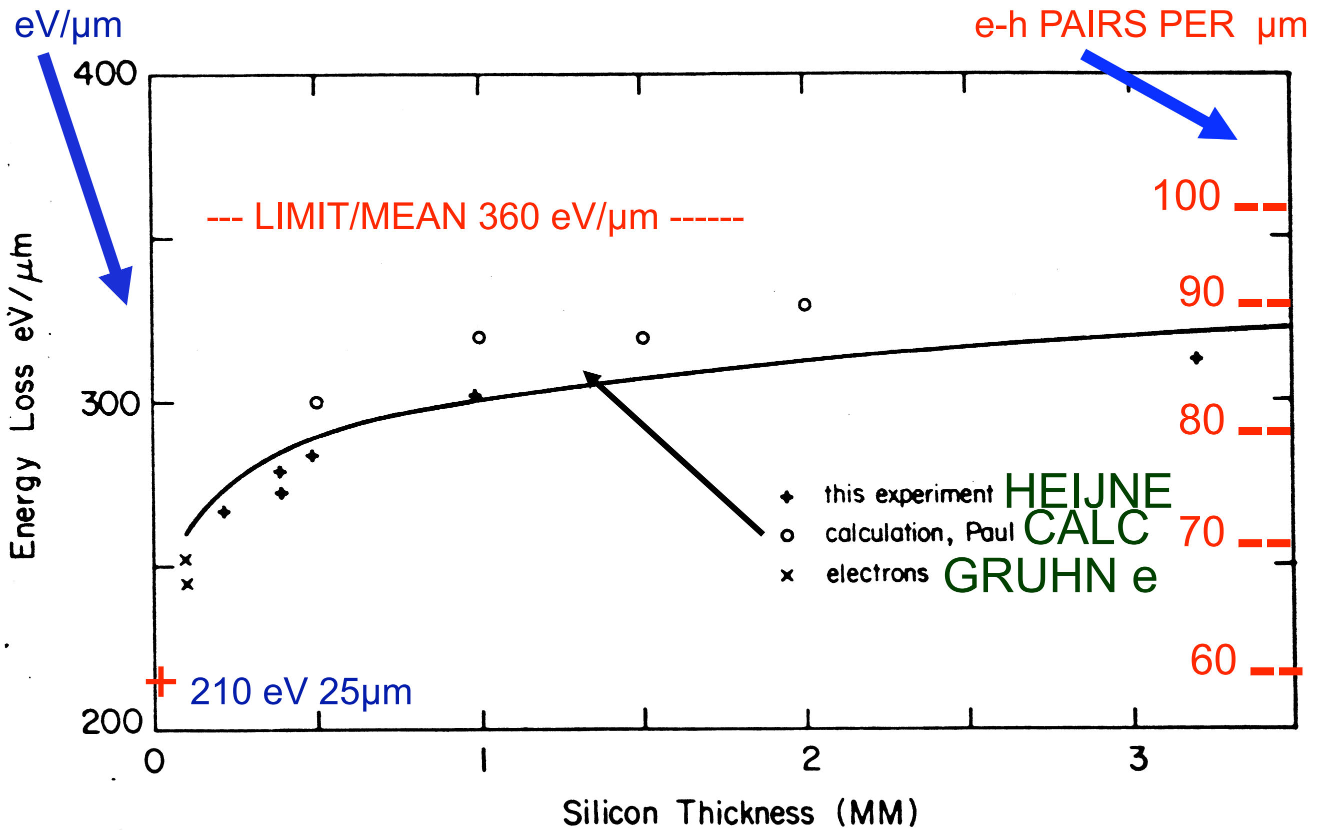
FIRST MICROSTRIP DETECTOR
NIM 178 (1980) 331

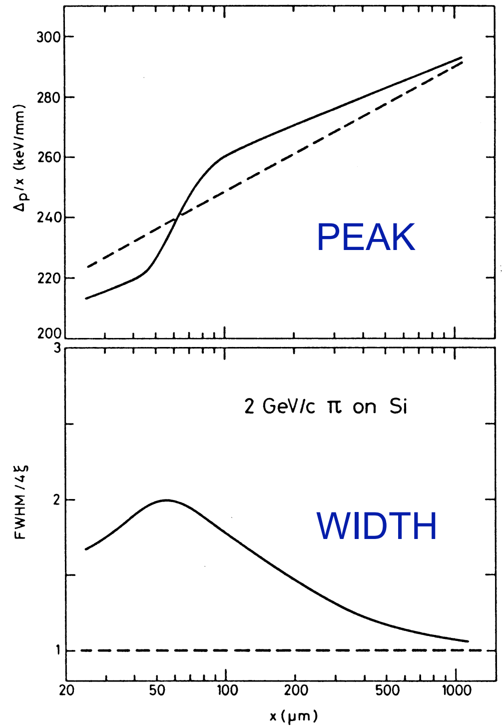
SIGNALS in Si PIXEL



ENERGY DEPOSITION in THIN Si

LOSS / µm DECREASES





Heijne CERN 83-06 (1983) 30

< 1mm BINDING of ELECTRONS causes
DEVIATIONS from LANDAU

Bak et al.
Nucl. Phys. B288 (1987) 681

BASICS of a DETECTOR

SIGNAL if there is PARTICLE

→ DETECTION EFFICIENCY

NO SIGNAL if NO PARTICLE

MORE DIFFICULT : NOISE

POSITION/ TRAJECTORY/ ORIGIN of PARTICLE
WHICH TYPE of PARTICLE
ENERGY of PARTICLE

DETECTORS and READOUT

- HISTORICAL PERSPECTIVE
  SMALLER and SMALLER :   MICRO, NANO, ATTO,..
  from MICROSCOPE to ATTOSCOPE

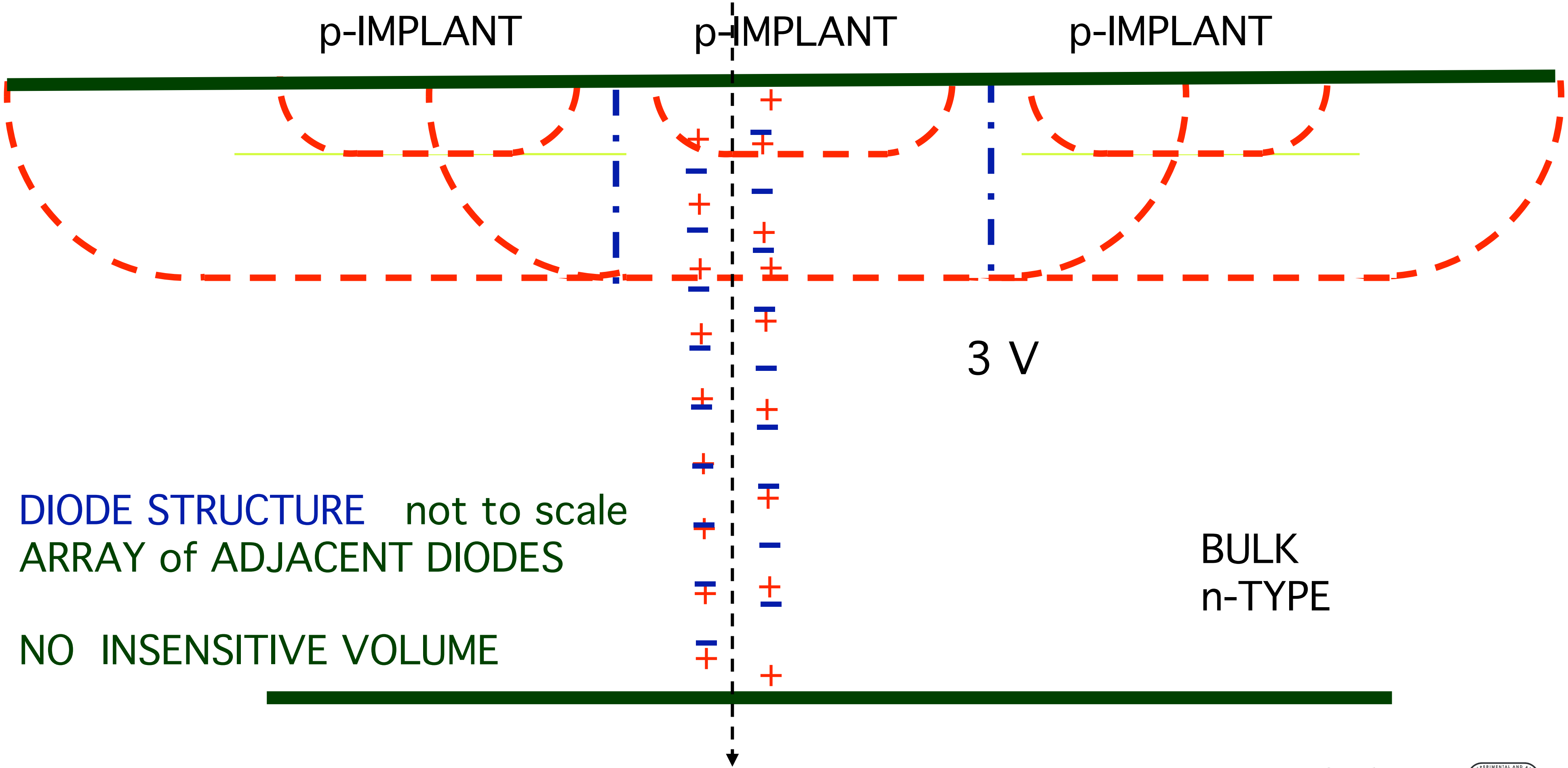
-PARTICLE PHYSICS EXPERIMENTS at the LHC

- VARIETY of SENSORS
  MOMENTUM via TRACKING POINTS
  TOTAL PARTICLE ENERGY (via CHARGE or LIGHT)
  ENVIRONMENT (POSITIONS, TEMP, RADIATION DOSE, ..)

-A LOT of ELECTRONICS
  CUSTOM DESIGN FRONT- END CHIPS
  DATA TRANSMISSION to CONTROL ROOM
  WORLD-WIDE DISTRIBUTION and CONTROL   (on/off line)

SILICON DIODE DETECTORS

IONIZING PARTICLE
LOCALIZED SIGNAL



DIODE STRUCTURE not to scale
ARRAY of ADJACENT DIODES

NO INSENSITIVE VOLUME

(RE) INVENTIONS of MONOLITHIC SEGMENTED DIODE

1. HARWELL: STRUCTURES on 1" SLICE
   1958 not continuous 1960 continuous

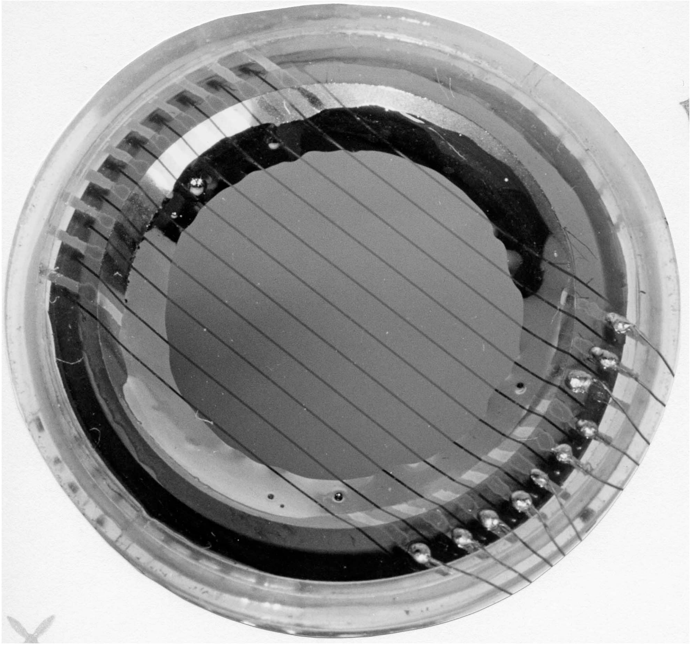
2. SACLAY: A FEW CONTINUOUS DIODES
   1963 full charge collection

3. IKO/PHILIPS: FRONT/REAR STRIPS 1.2 mm (Hofker)
   1965 projected 2-D US patent 1971

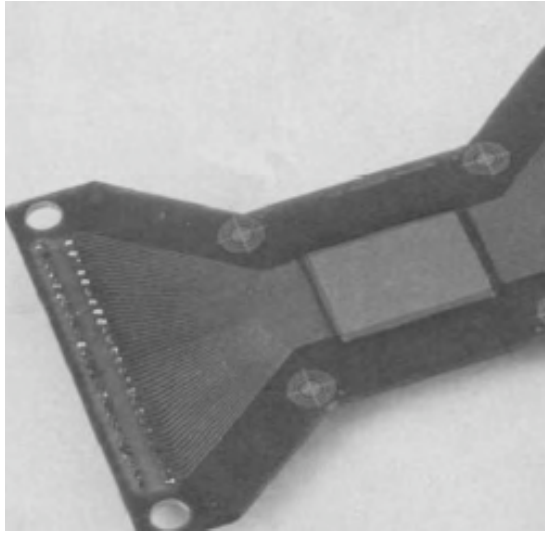
SEVERAL PROJECTS 1970 - 1980, but ELECTRONICS is LIMITATION

4. CERN + ENERTEC, MUNICH TU + MPI, several others
   1980 smaller dimensions 200 um, 50 um
   ion implantation (Kemmer, Burger), clean processing
   matched (micro) electronics !!!!

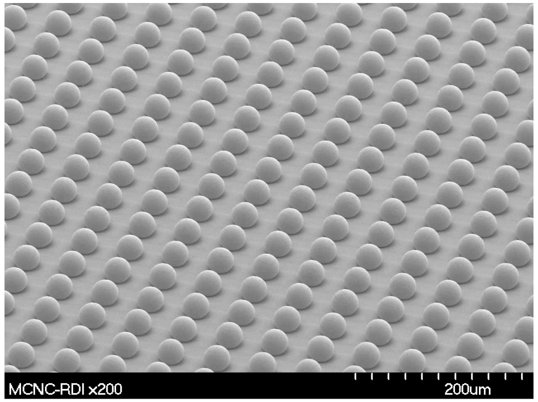
DIODE SEGMENTATION



~1965
PHILIPS
100 x 1370umx1370um



1980
CERN / ENERTEC
100 x 4000umx200um



~2000
CERN / MEDIPIX
65000 x 55umx55um

NOMENCLATURE for SEGMENTED SILICON DETECTORS

Table 2 Segmented silicon detectors - Naming convention based on cell dimensions

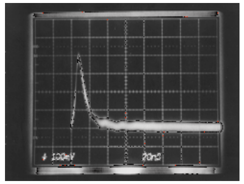
Detector Type	**Coordinate**	**Long Edge**	**Short Edge**	**Associated Chip**
Pad Detector	2D	≥ 1mm	≥ 1mm	16 to 64 channels
Microstrip Detector	1D	≥ 1mm	< 1mm	128 channels
Hybrid Pixel Detector	2D	< 1mm	< 1mm	2048 to 65 536 ch
Monolithic Pixel Chip	2D	< 30μm	< 30μm	>250 000 cells

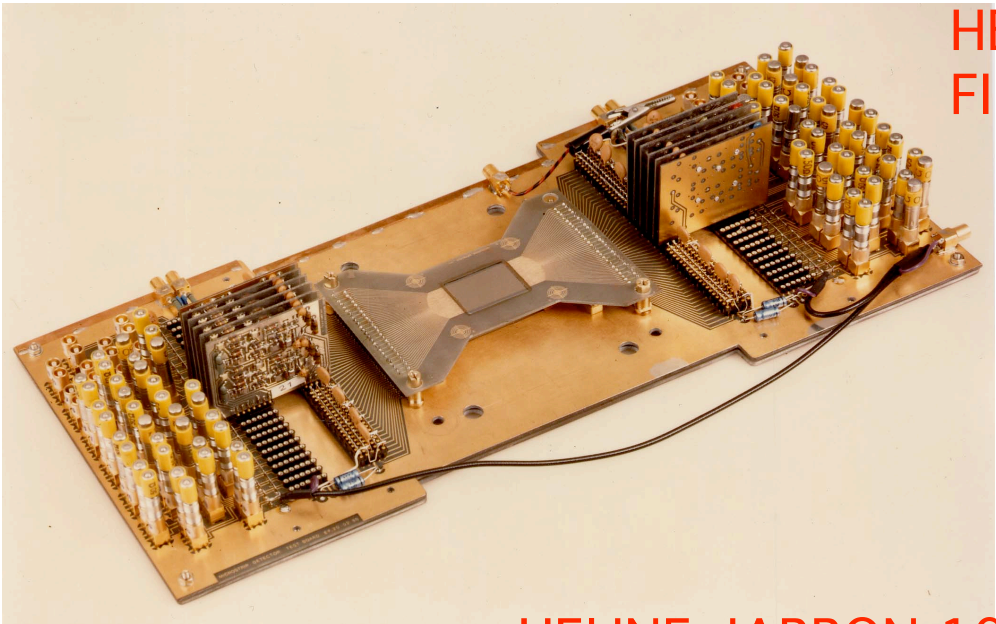
1 mm used as CRITICAL DIMENSION

CERN MICROSTRIP DETECTORS

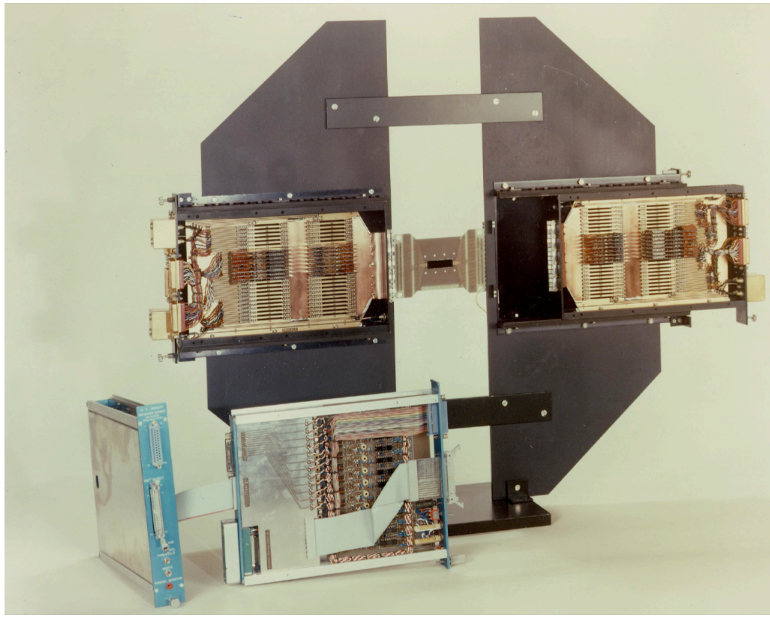
DESIGN OF MATCHED READOUT

1980 DISCRETE COMPONENTS on DUAL CARDS
1984 HYBRID QUADS on CERAMIC THICK FILM
1987 AMPLEX CHIP CERN, MICROPLEX SLAC





HEIJNE-JARRON 1980
FIRST BEAM TEST 100 x 200 μm

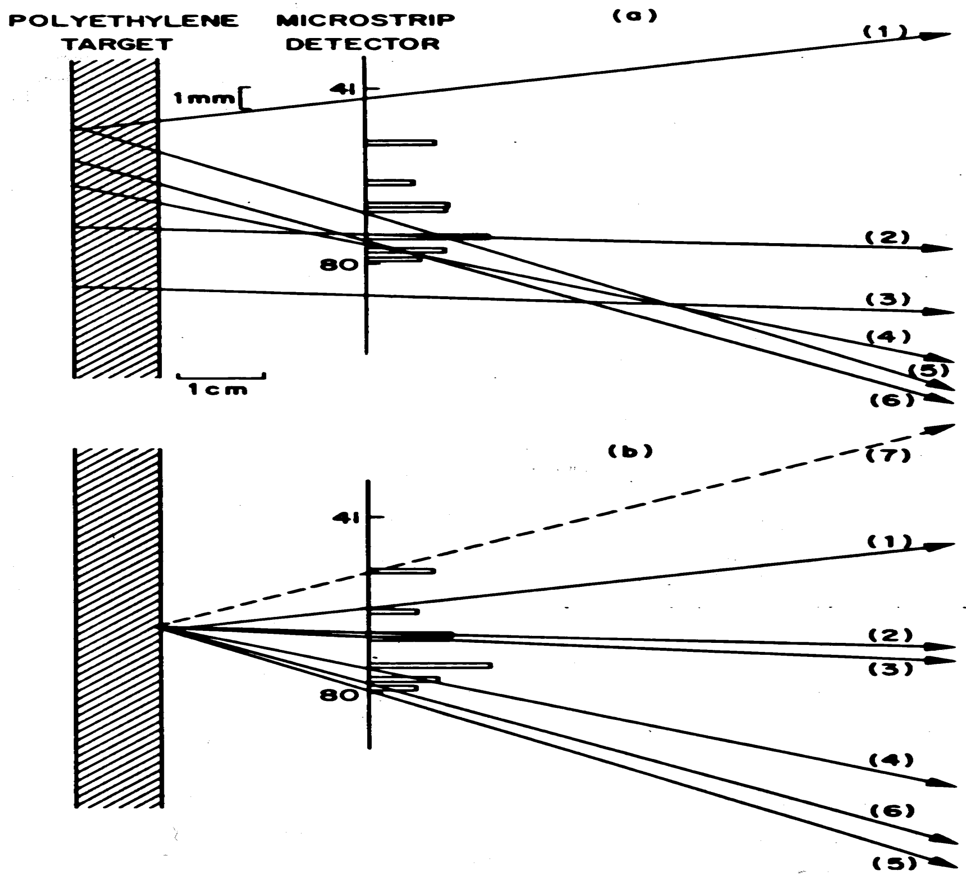


HEIJNE-JARRON 1981
NA11 SETUP
SENSOR 100 x 50 μm

SILICON MICROSTRIP DETECTOR

FIRST PRECISE TEST: RECONSTRUCTION of TRACKS DIRECTLY BEHIND TARGET NA11

JUNE 1980



TRACKS AS SEEN BY SPECTROMETER USING WIRECHAMBERS

TRACKS ORDERED USING SILICON HITS
+ ONE NEW (7)

PRIMARY VERTEX IMPROVED

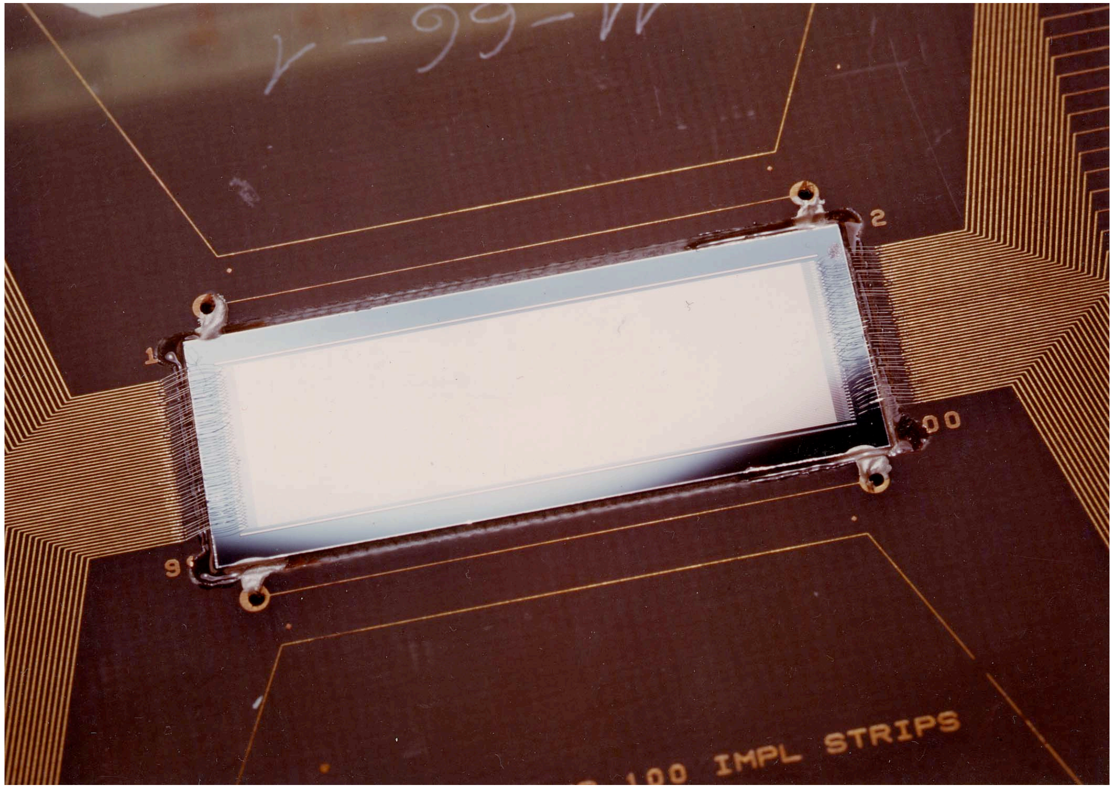
Heijne, Jarron
Hyams, Vermeulen, Wickens

SILICON MICROSTRIP DETECTOR

CERN : THIRD GENERATION 1981

ION-IMPLANTED, 100 μm PITCH

COLLABORATION ENERTEC+KEMMER

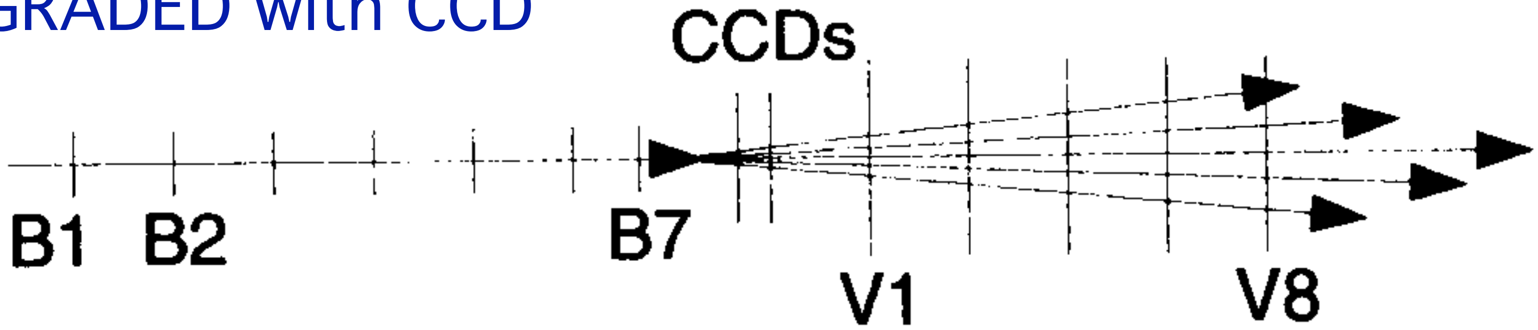


ULTRASONIC WIREBONDING

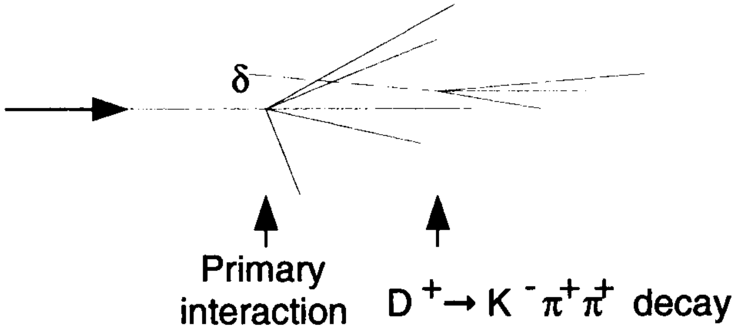
MOUNTING as 1980 SURFACE BARRIER

NEW DETECTORS for CHARM and B

NA11
UPGRADED with CCD



ORIGINAL PROPOSAL USED WIRECHAMBERS
FIRST UPGRADE Si MICROSTRIP DETECTORS
CERN & MPI (Kemmer, Klanner, Lutz, Heijne, Jarron, Burger, ..)
SECOND UPGRADE CCD RAL (Damerell, Watts)

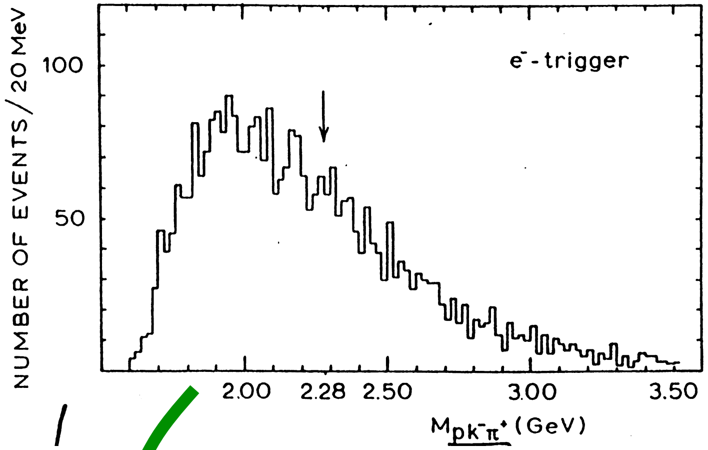


SELECTIVITY through TRACKING
and SECONDARY VERTEX

CHARMED PARTICLE RECOGNITION

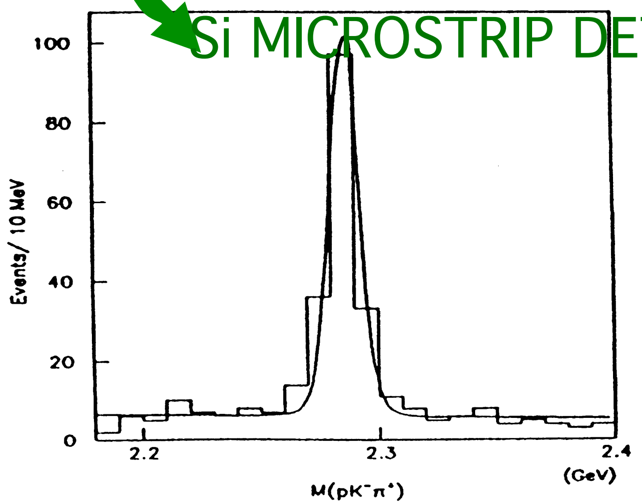
NA11 CHARM EXP

$\Lambda_c \rightarrow p K^- \pi^+$



INVARIANT MASS DISTRIBUTION
LARGE STATISTICS / 'NO' SELECTIVITY

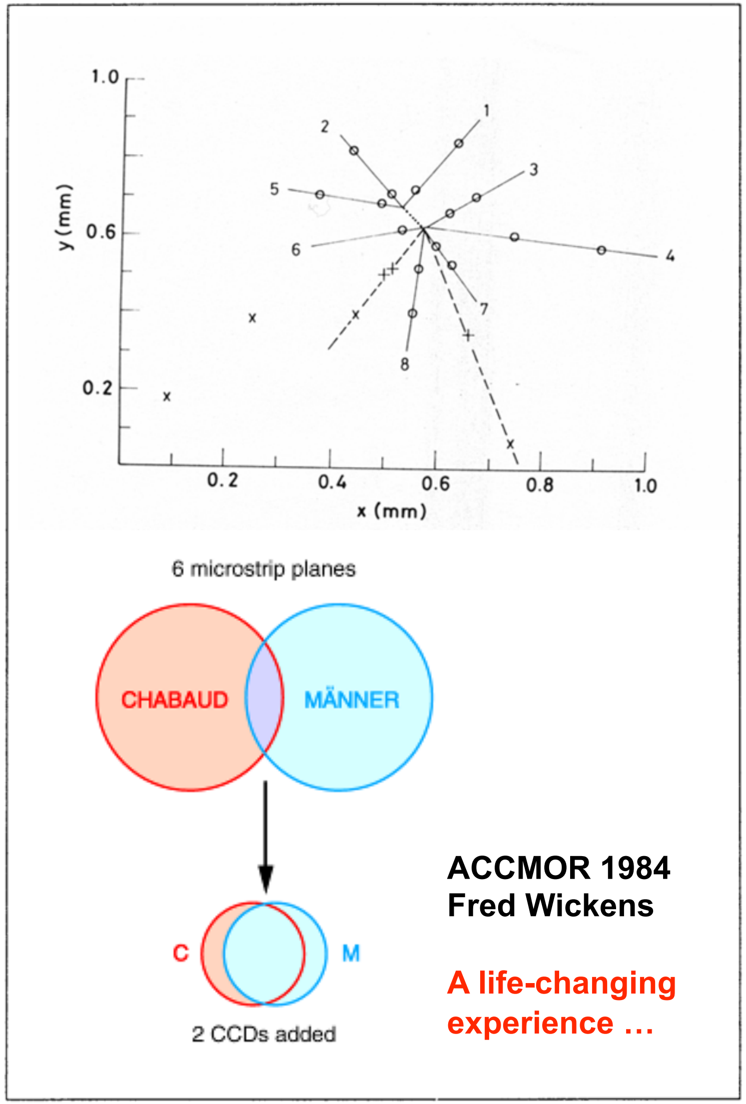
NEW TECHNOLOGY :
Si MICROSTRIP DETECTORS + CCD



REDUCED BACKGROUND
MUCH HIGHER SENSITIVITY
CAN RUN at LOWER BEAM INTENSITY

DRAMATIC IMPROVEMENT !

CHARMED PARTICLE RECOGNITION



NA11 CHARM EXP

ANOTHER TECHNOLOGY IMPROVEMENT : CCD

TRUE 2D MEASUREMENTS

'LIFE-CHANGING'
Chris DAMERELL,

ILC Silicon Pixel Tracker – Chris Damerell – Dec 2010

MONOLITHIC VERTEX DETECTORS

CCD by Damerell et al. in NA11 1981.......

SOI in RD19 : Franz Pengg, Bart Dierickx (IMEC)

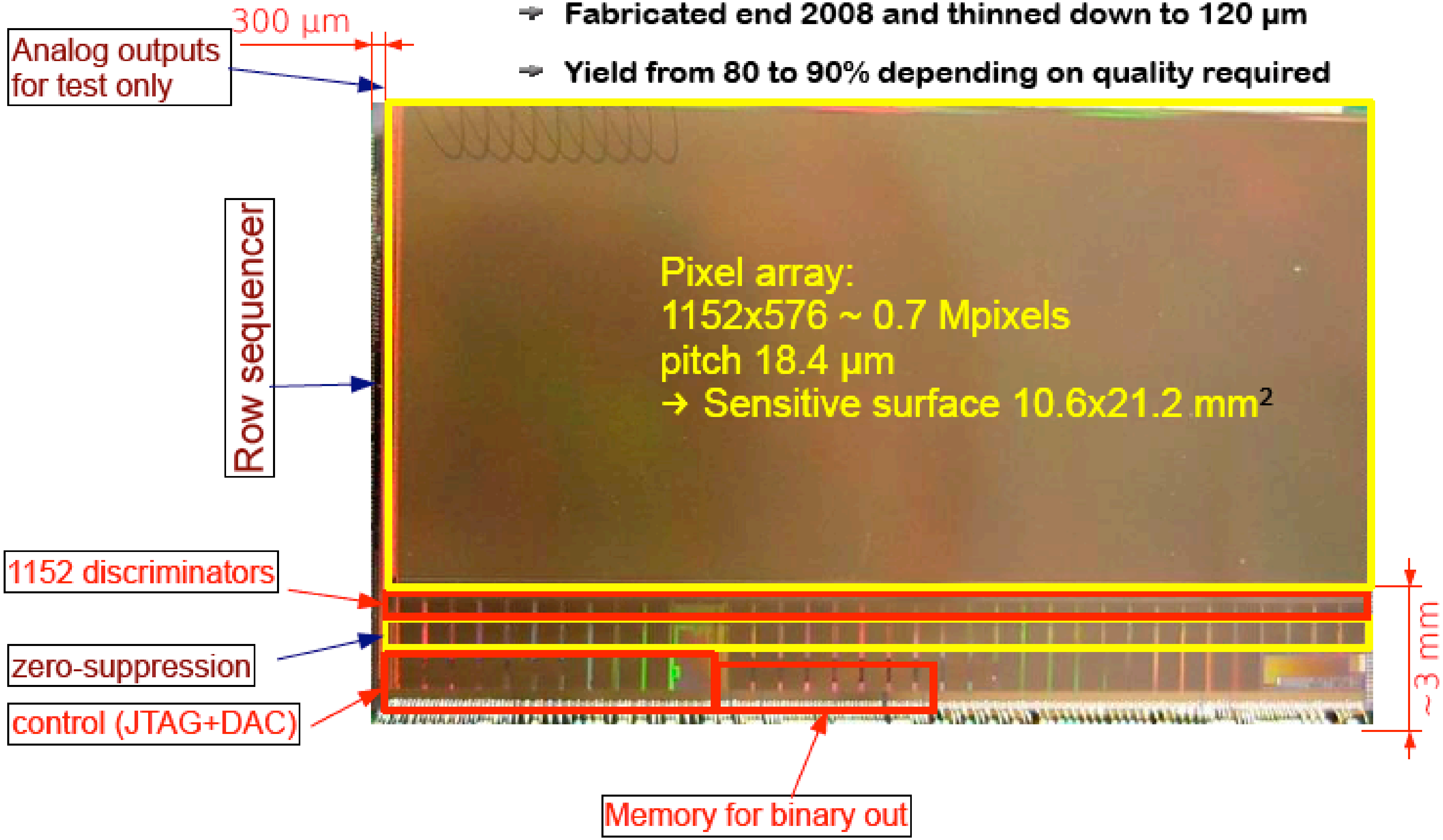
now SEVERAL R&D PROJECTS :

- CMOS
- CCD
- SOI – 3D

details will be presented in the School

Generic architecture validation

- **Full size : MIMOSA 26 (EUDET final sensor)**
  - Process AMS 0.35 µm OPTO
  - Fabricated end 2008 and thinned down to 120 µm
  - Yield from 80 to 90% depending on quality required



DIRECT γ-RAY CONVERSION in IMAGING CCD

CONVERSION DIRECTLY IN THE SENSOR

^{55}Fe SOURCE

ENERGY DEPOSIT --> FREE CARRIERS in ONE or SEVERAL PIXELS

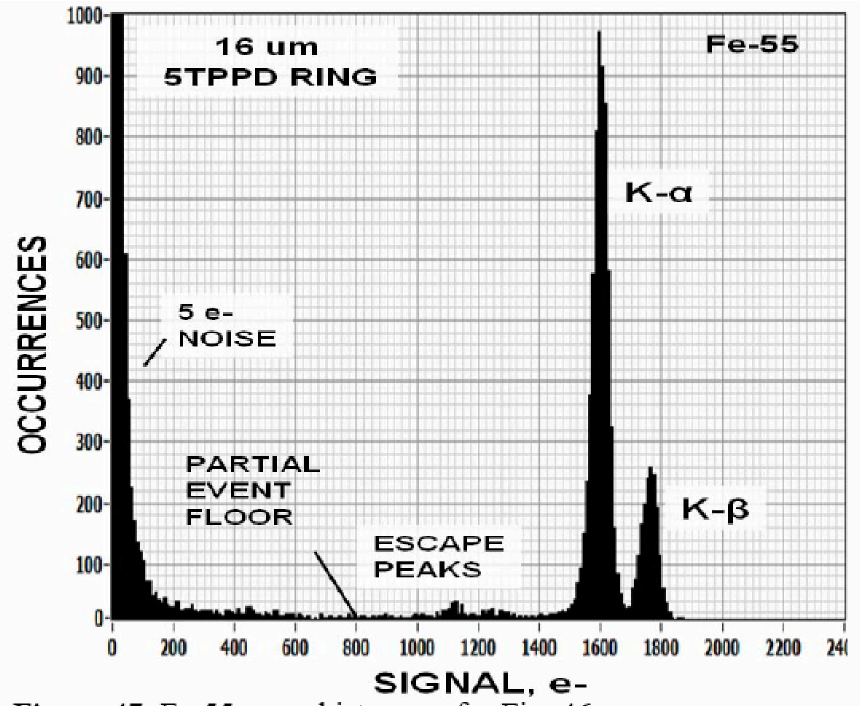


Figure 47. Fe-55 x-ray histogram for Fig. 46.

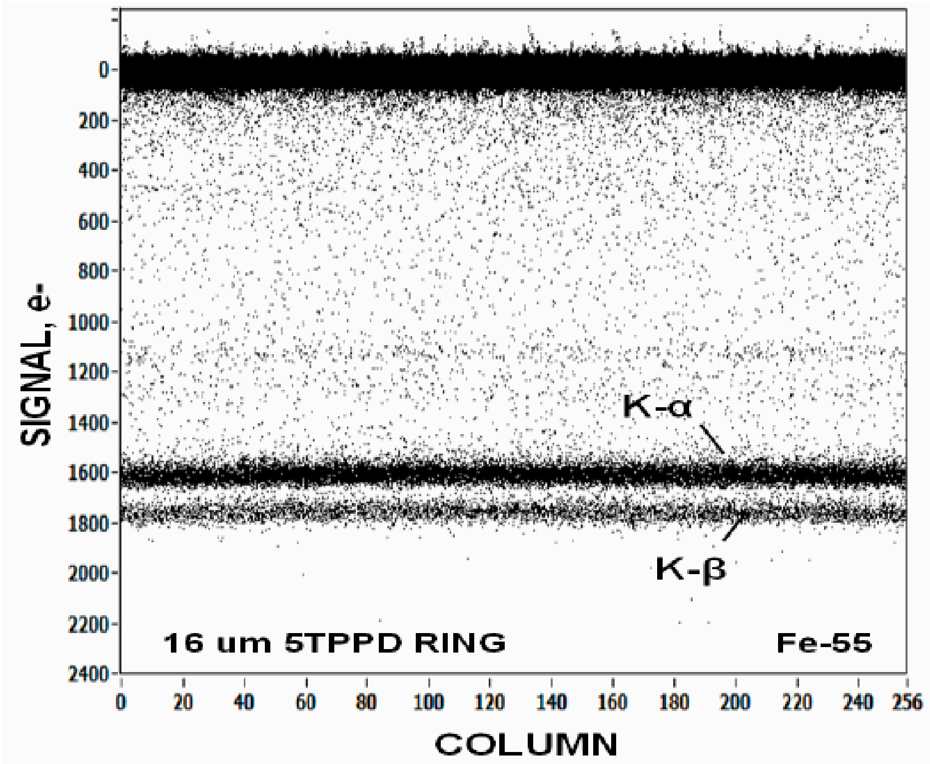


Figure 46. Fe-55 response for a 16 um 5TPPD pixel.

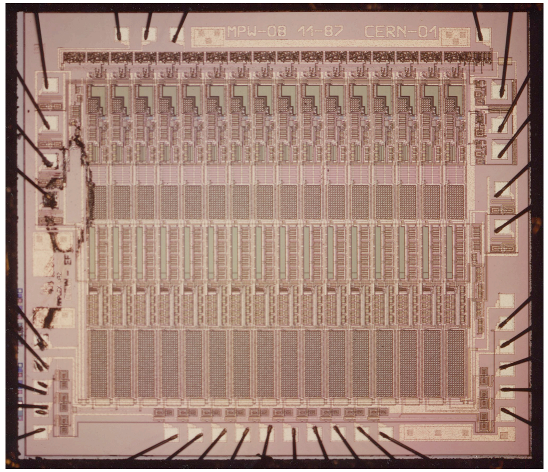
TRANSISTORS in EACH PIXEL
Janesick et al, SPIE 2010
CMOS-CCD 256x256 pixels
cooled

2010

SINGLE PIXEL EVENTS -> SPECTRUM

HERMETIC PAD DETECTORS UA2

DETECTOR CYLINDER
CURRENTLY
IN U. DORTMUND by
Claus Gößling



16 CHANNELS
COLLABORATION
IMEC LEUVEN

~5 mm THICK CILINDER

ONLY POSSIBLE with "AMPLEX" CHIP
DESIGN Pierre Jarron

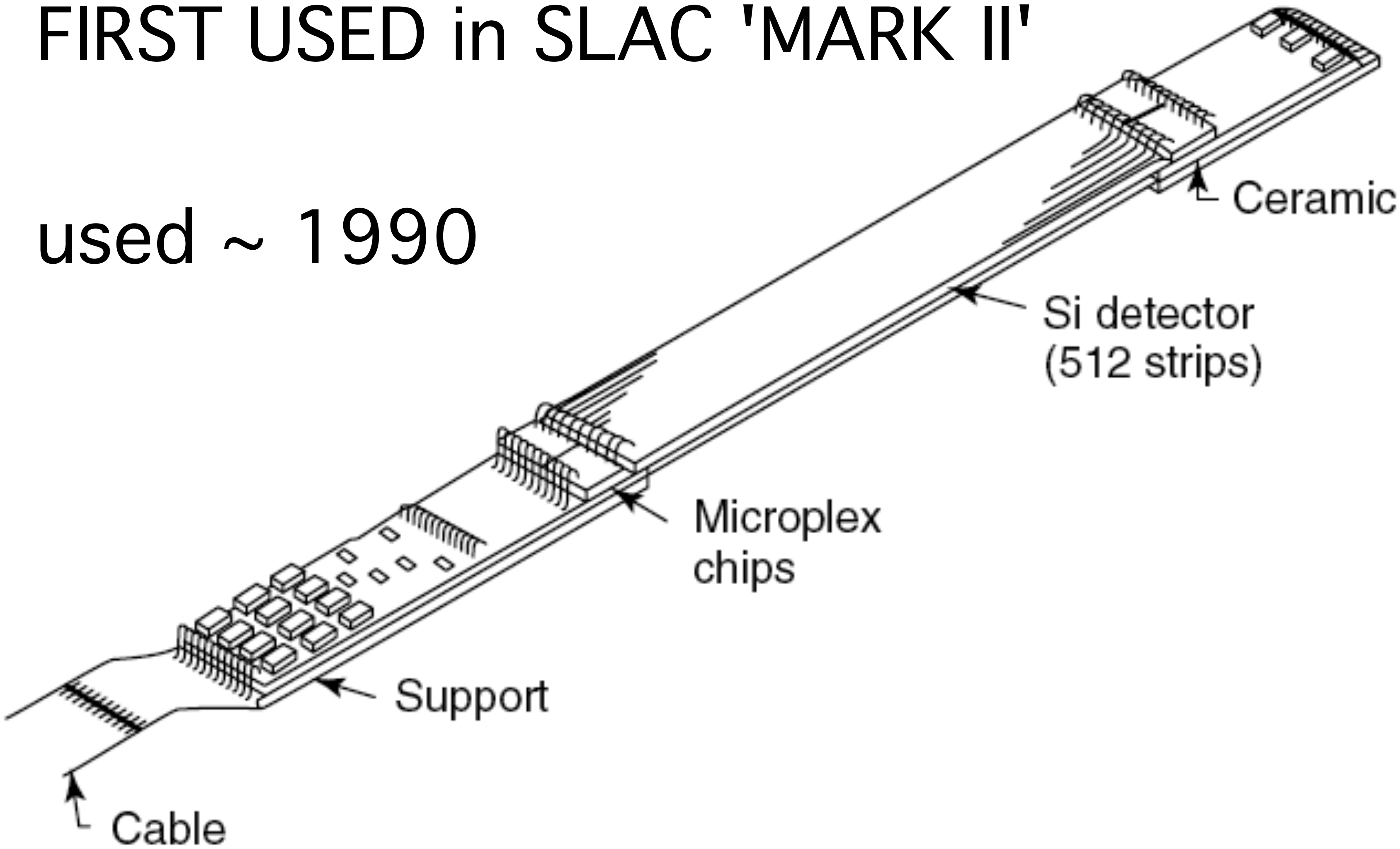
1986 – 1988

FIRST Si DETECTOR
in COLLIDER
FIRST operating Si DETECTOR
with IC CHIP READOUT

Si DETECTOR 'LADDER'

FIRST USED in SLAC 'MARK II'

used ~ 1990



Si TRACKING in LEP

ULTIMATELY all LEP EXPERIMENTS
USED a Si TRACKER

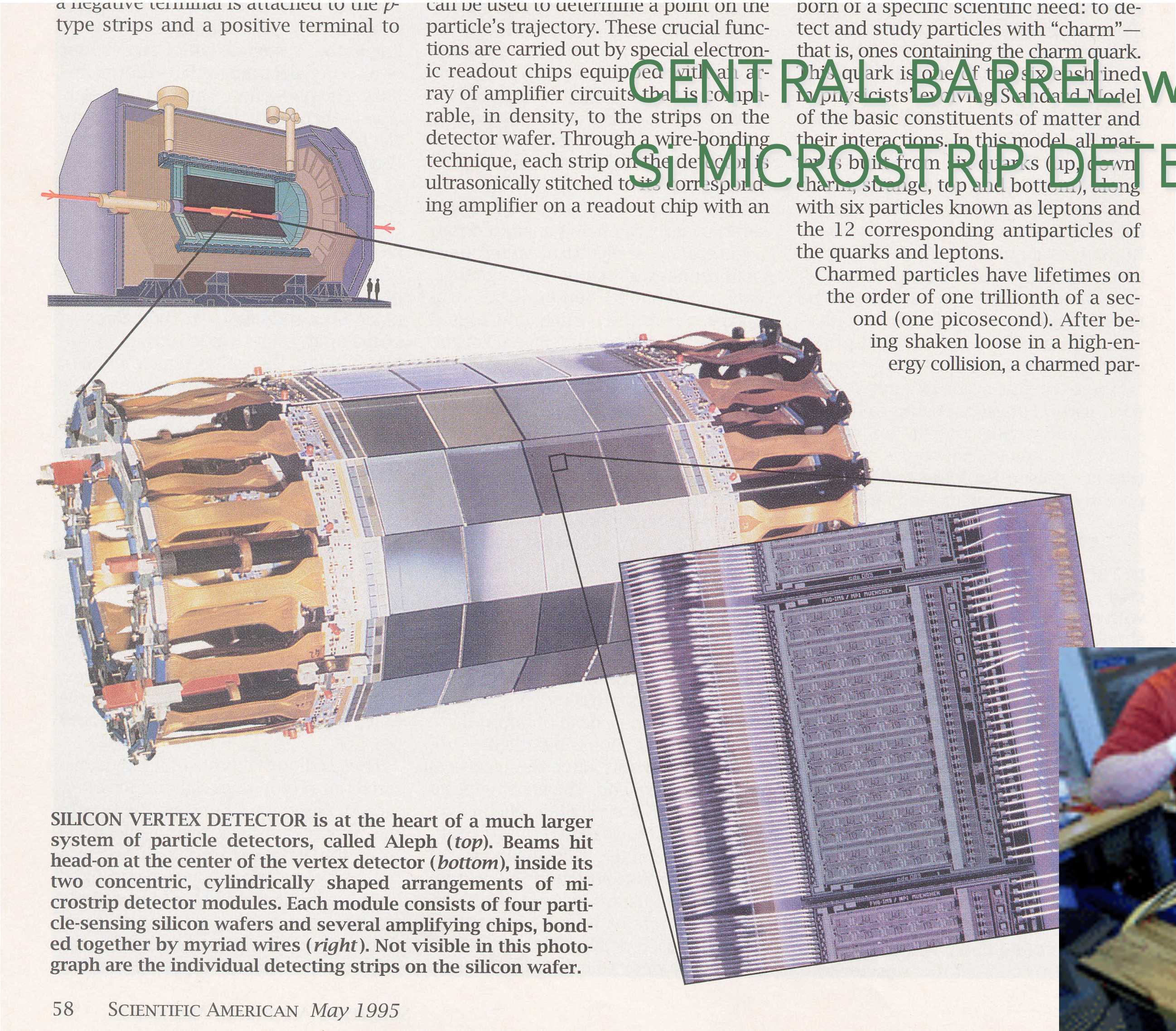
Si MICROSTRIPS WELL-ADAPTED

MODERATE MULTIPLICITY

SLOW SHAPING OK (RATE ~ μs)

SEGMENT CAPACITANCE ~50 pF

ALEPH Si TRACKER



a negative terminal is attached to the p-type strips and a positive terminal to

can be used to determine a point on the particle's trajectory. These crucial functions are carried out by special electronic readout chips equipped with an array of amplifier circuits that is comparable, in density, to the strips on the detector wafer. Through a wire-bonding technique, each strip on the detector is ultrasonically stitched to its corresponding amplifier on a readout chip with an

born of a specific scientific need: to detect and study particles with "charm"—that is, ones containing the charm quark. This quark is one of the six enshrined in physicists' evolving Standard Model of the basic constituents of matter and their interactions. In this model, all matter is built from six quarks (up, down, charm, strange, top and bottom), along with six particles known as leptons and the 12 corresponding antiparticles of the quarks and leptons.

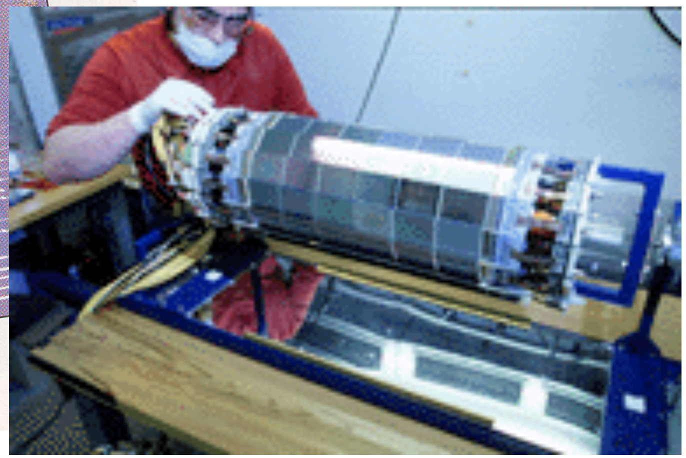
Charmed particles have lifetimes on the order of one trillionth of a second (one picosecond). After being shaken loose in a high-energy collision, a charmed par-

SILICON VERTEX DETECTOR is at the heart of a much larger system of particle detectors, called Aleph (*top*). Beams hit head-on at the center of the vertex detector (*bottom*), inside its two concentric, cylindrically shaped arrangements of microstrip detector modules. Each module consists of four particle-sensing silicon wafers and several amplifying chips, bonded together by myriad wires (*right*). Not visible in this photograph are the individual detecting strips on the silicon wafer.

58 SCIENTIFIC AMERICAN *May 1995*

CENTRAL BARREL with 3 LAYERS of Si MICROSTRIP DETECTORS

FULL ASSEMBLY
BEFORE INSERTION



SCIENTIFIC AMERICAN, 1995

ALEPH B - event

TRACKS IDENTIFIED WITH Si MICROSTRIP PLANES :

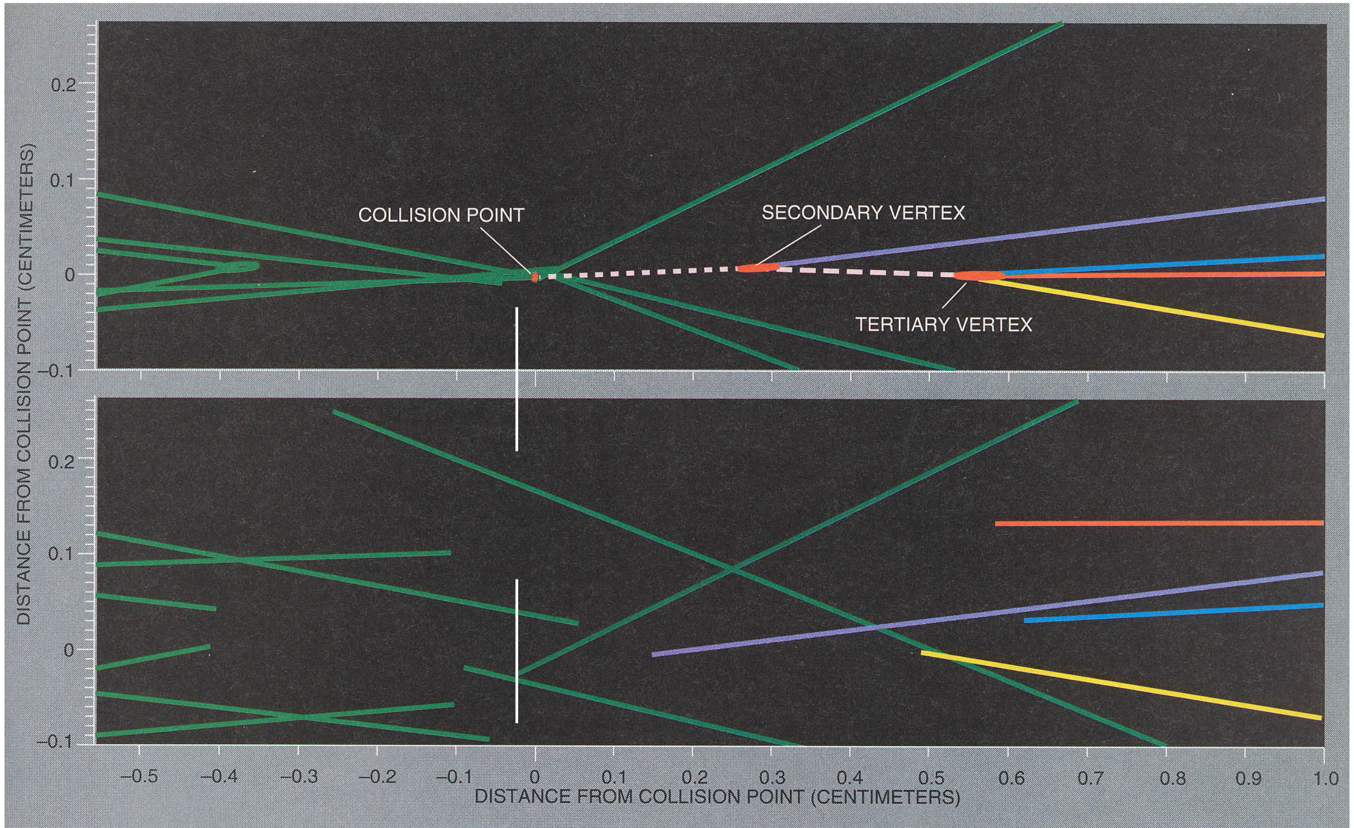
SECONDARY and TERTIARY VERTEX

BECOME APPARENT --> Bottom Particle

B – EVENTS 'MESSENGER'

-> $e^- \nu_e$ then -> $\phi\ \pi^+$ $\phi \rightarrow K^+K^-$

also allows LIFETIME MEASUREMENT



Si OFF-LINE DISPLAY

GAS TPC ALONE :

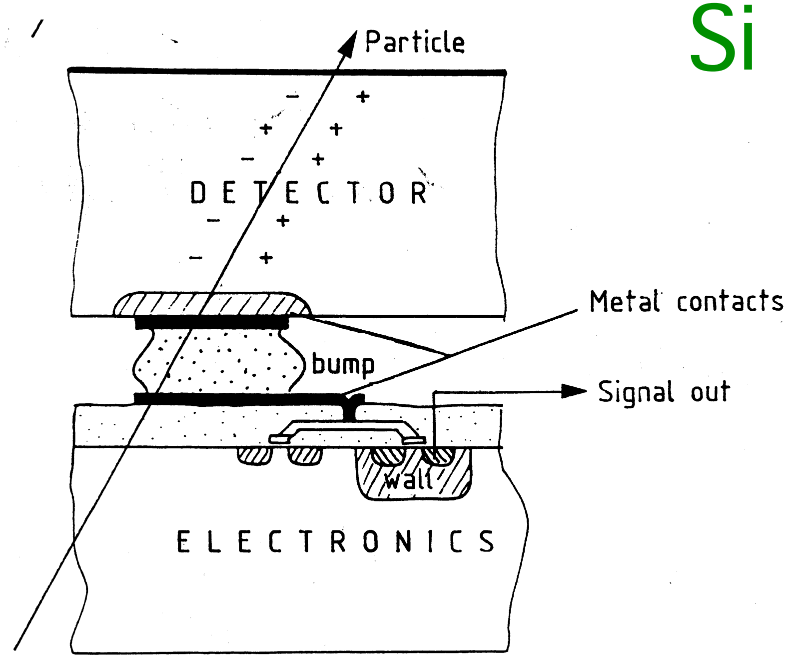
NOT ENOUGH INFORMATION TO FIND SECONDARY VERTEX

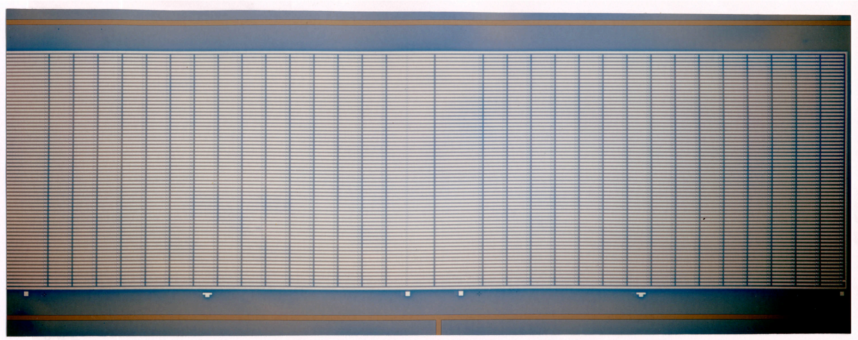
HYBRID Si PIXEL SENSOR 1991

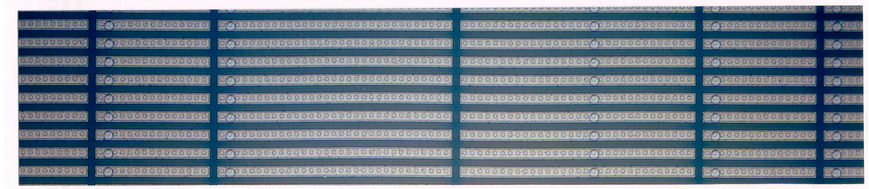
CERN : CAMPBELL, HEIJNE

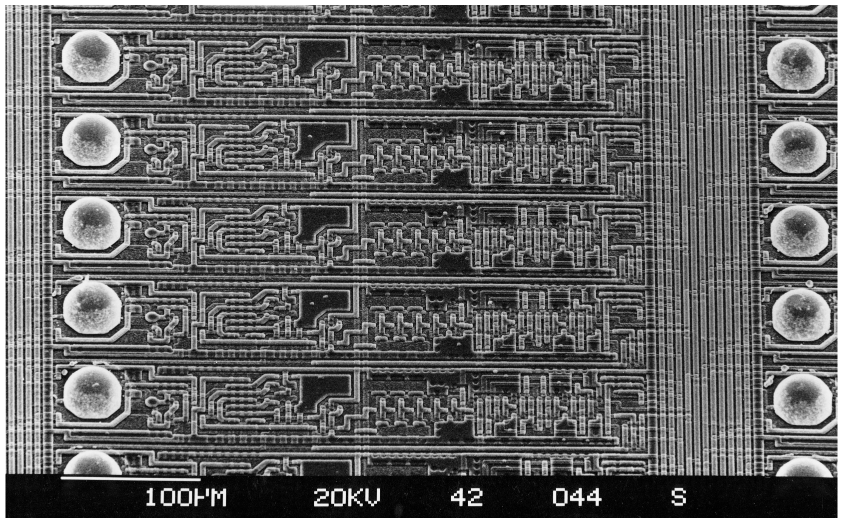
SENSOR MATRIX TRUE 2 - D

Si







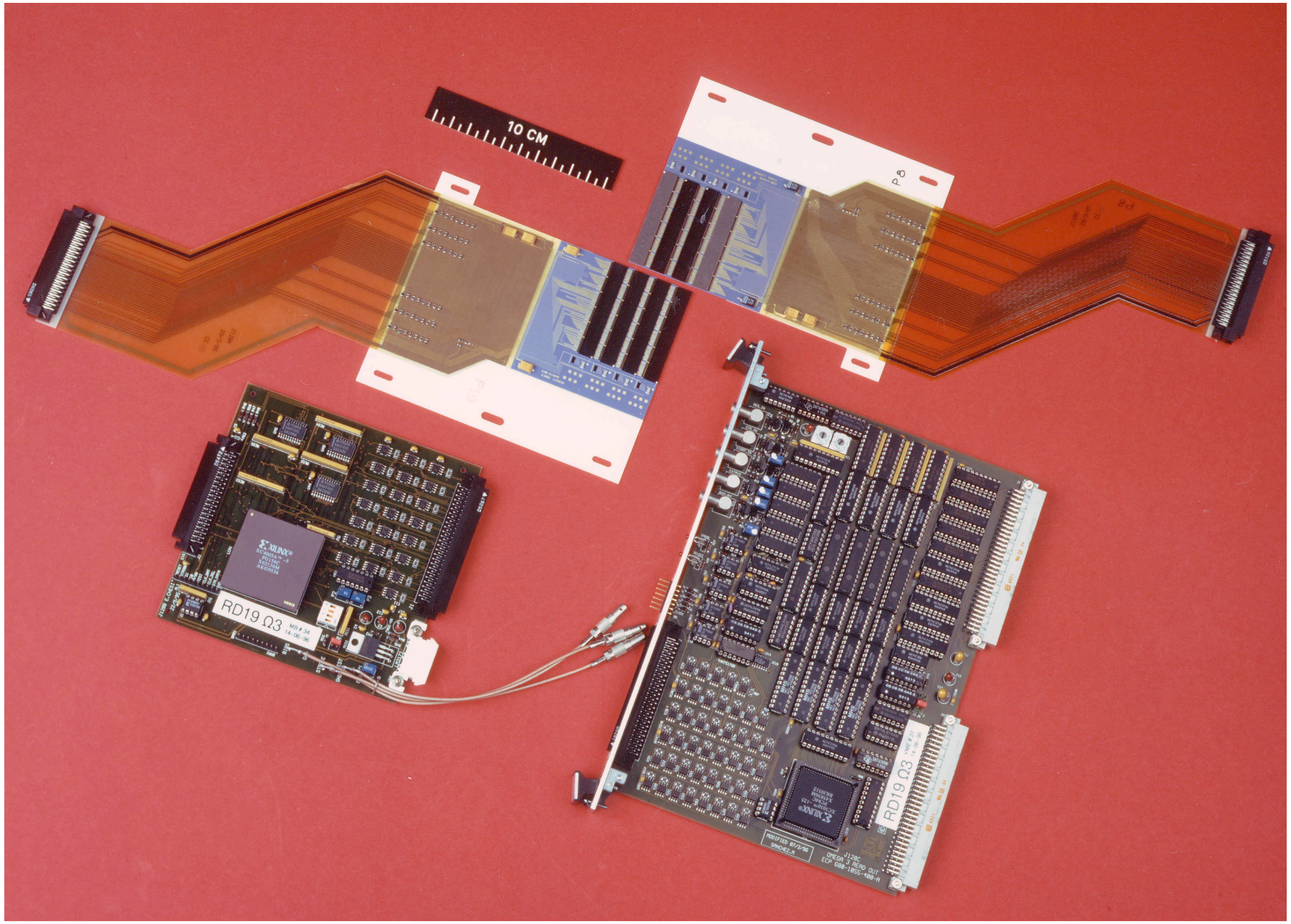


BUMPS

+

READOUT ELECTRONICS

LHC1 PIXEL ARRAYS ~ 1995



2 x 4 LADDERS
with OVERLAP
COVER 5 x 5 cm^2

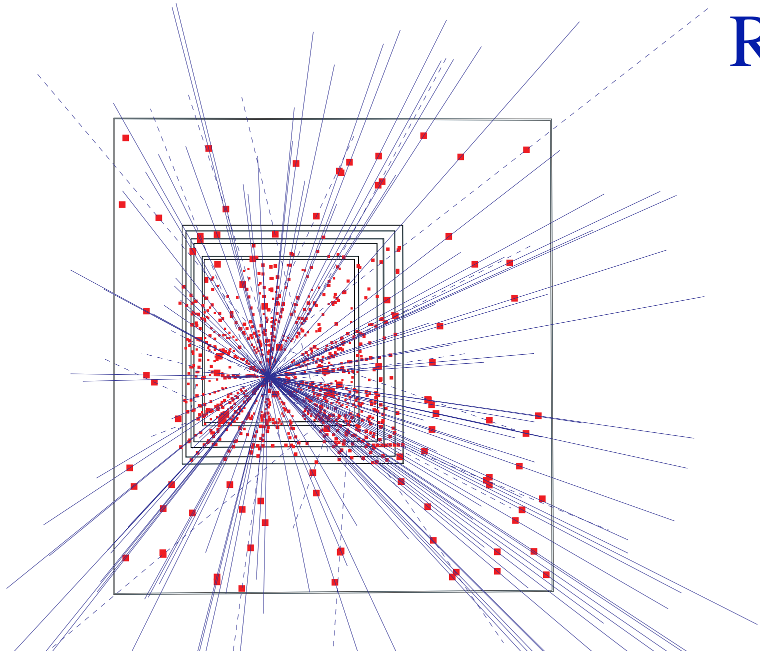
14 PLANES
BUILT 1992 - 97

PIXEL TELESCOPE USED in CERN
RD19 DEVELOPMENT for LHC

TRACKING with PIXELS at CERN

1995

WA97



RD19

7 PLANES
1.1 M pixels

153 tracks

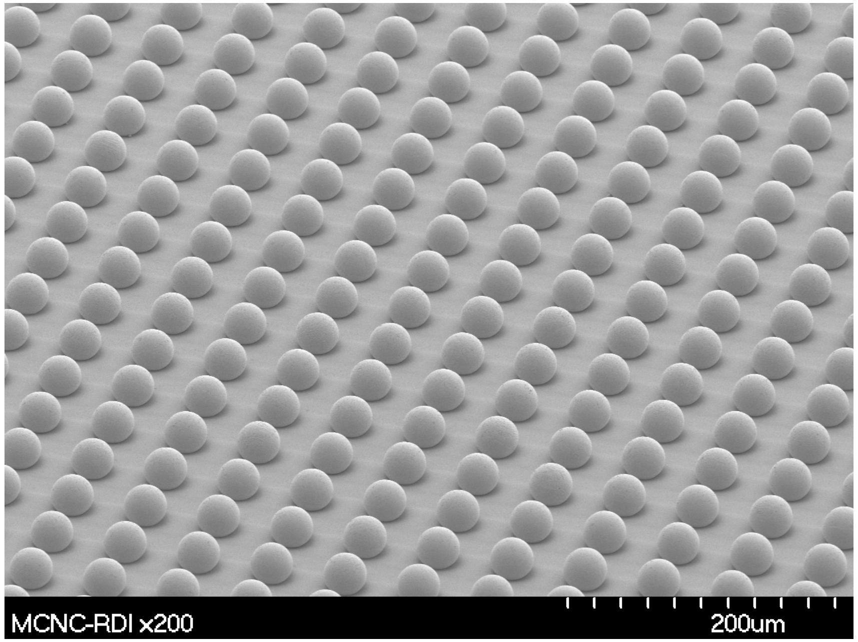
B-field OFF

^{208}Pb ion at 158 A GeV/c on Pb target

Millions of EVENTS ANALYZED

SPACE POINTS
NOISE-FREE

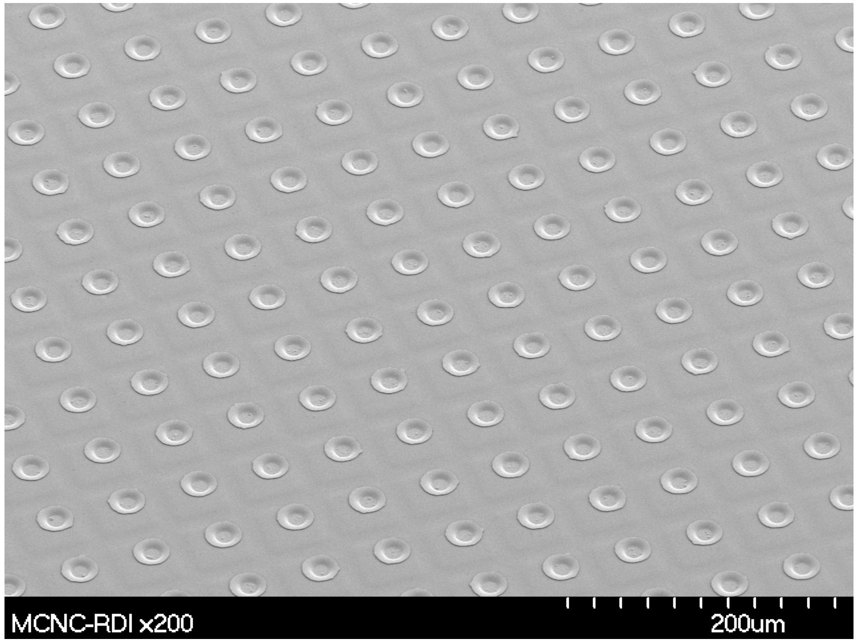
HYBRID PIXEL DETECTOR Medipix2



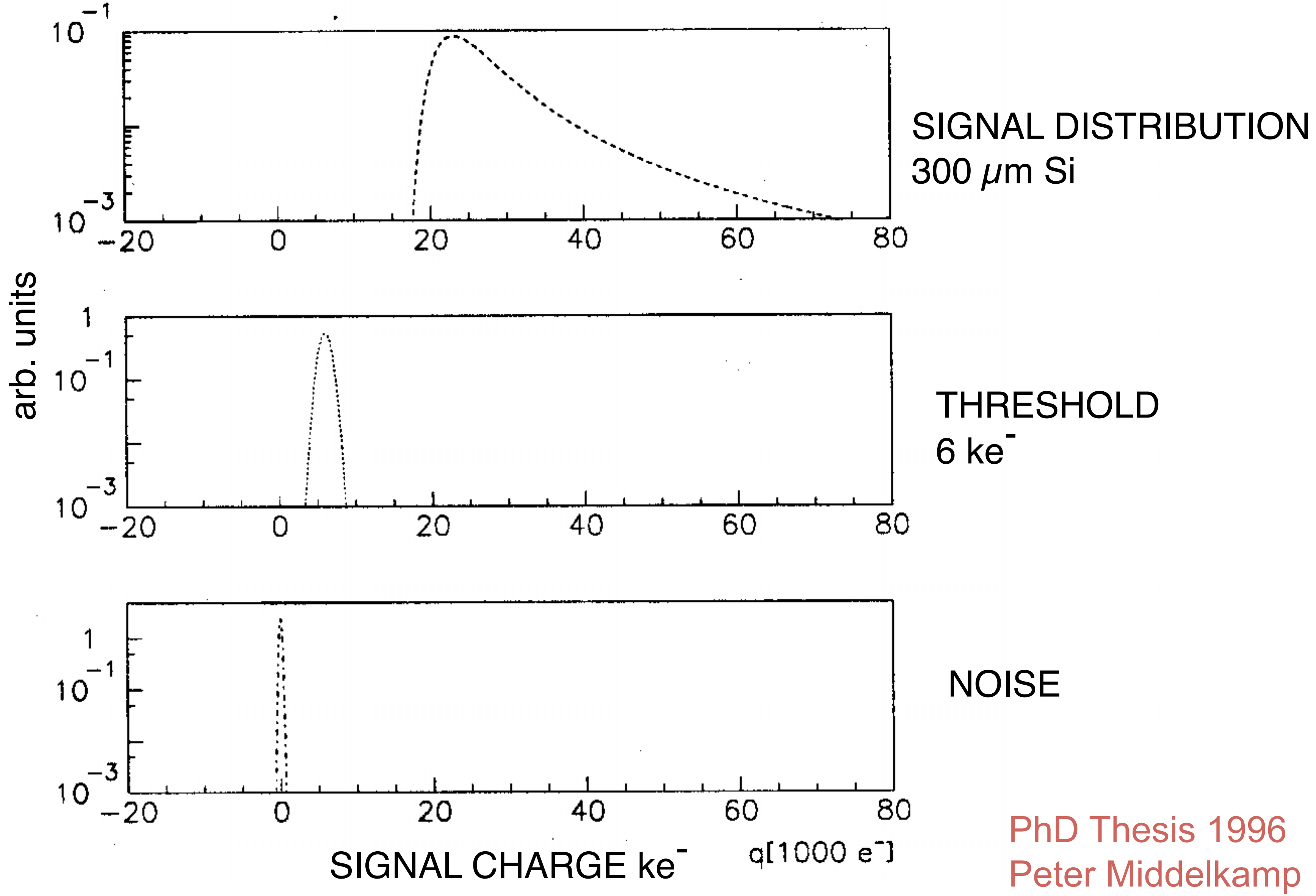
SEM PHOTOS
COURTESY MCNC-RDI DURHAM NC

PITCH 55 µm

MEDIPIX2   CERN 2001
CAMPBELL & LLOPART
256 COLUMNS x 256 ROWS
pixel 55µm x 55 µm



CHARACTERISTICS for BINARY PIXEL SYSTEM



PhD Thesis 1996
Peter Middelkamp
fig.36

TIMEPIX CHIP 2007

MODIFICATION of MEDIPIX2

CLOCK up to 100 MHz to EACH PIXEL

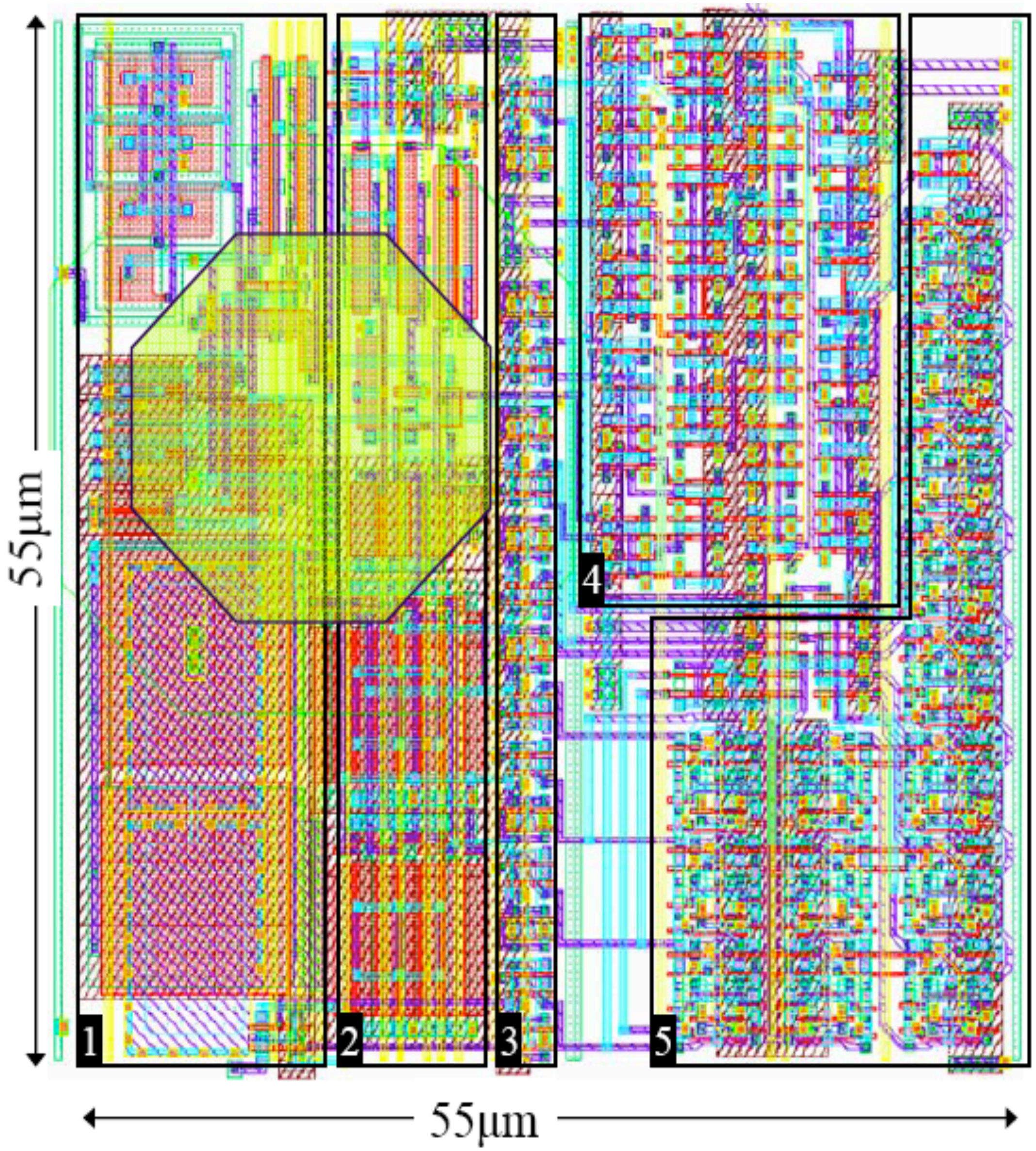
ADDED MODES:

ENCODING of ARRIVAL TIME of PULSE

ENCODING TOTAL 'TIME OVER THRESHOLD'

TIMEPIX CHIP was DESIGNED for GASEOUS TPC READOUT under DEVELOPMENT for ILC by EUDET COLLABORATION

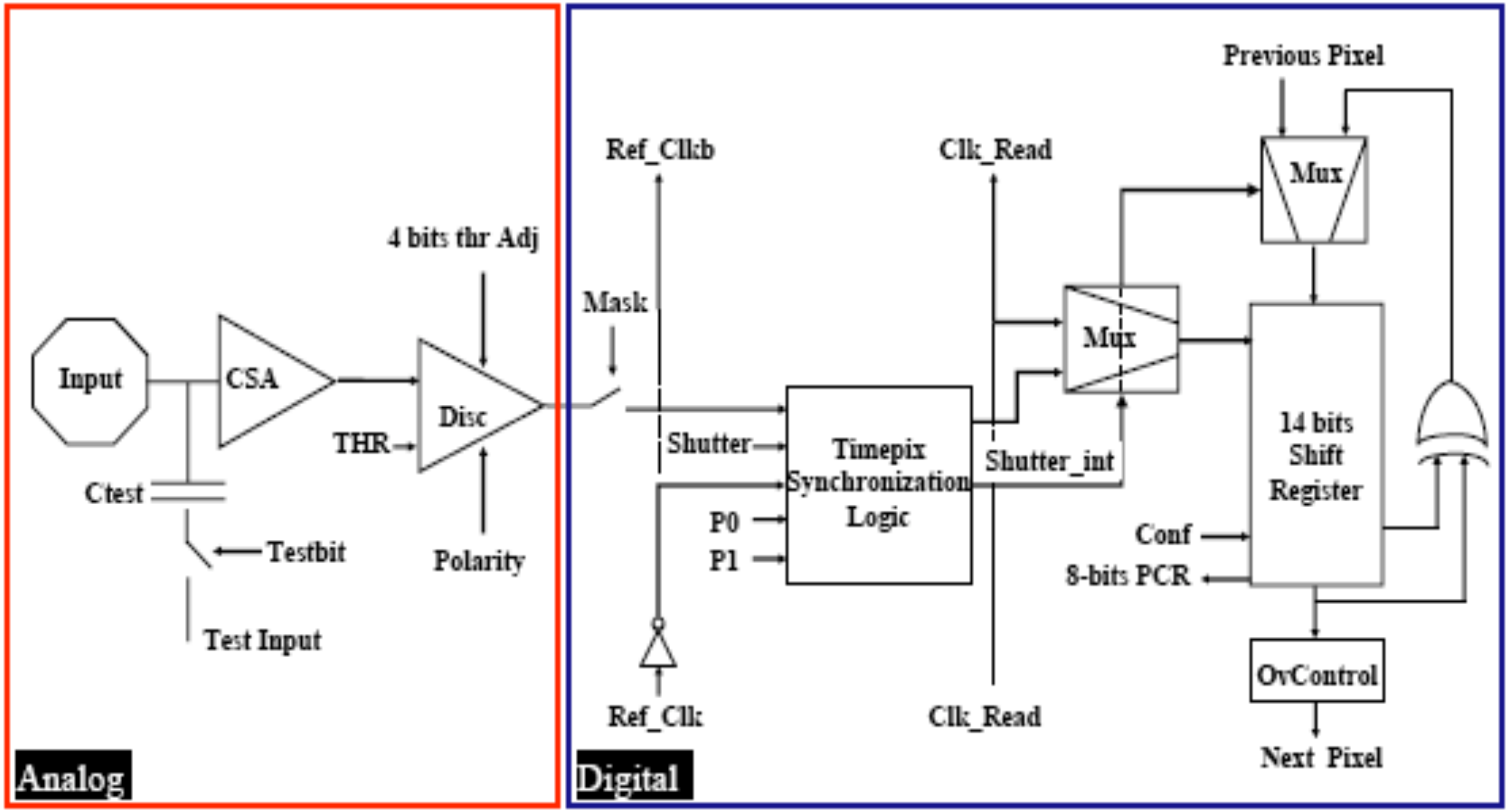
TIMEPIX CELL LAYOUT



DESIGNER
Xavier LLOPART
CERN
PhD Thesis p. 107

1. PREAMPLIFIER CSA
2. THRESHOLD, 4-BIT TUNING
3. 8-BIT CONF REGISTER
4. REF_CLK & SYNCHR LOGIC
5. 14-BIT COUNTER

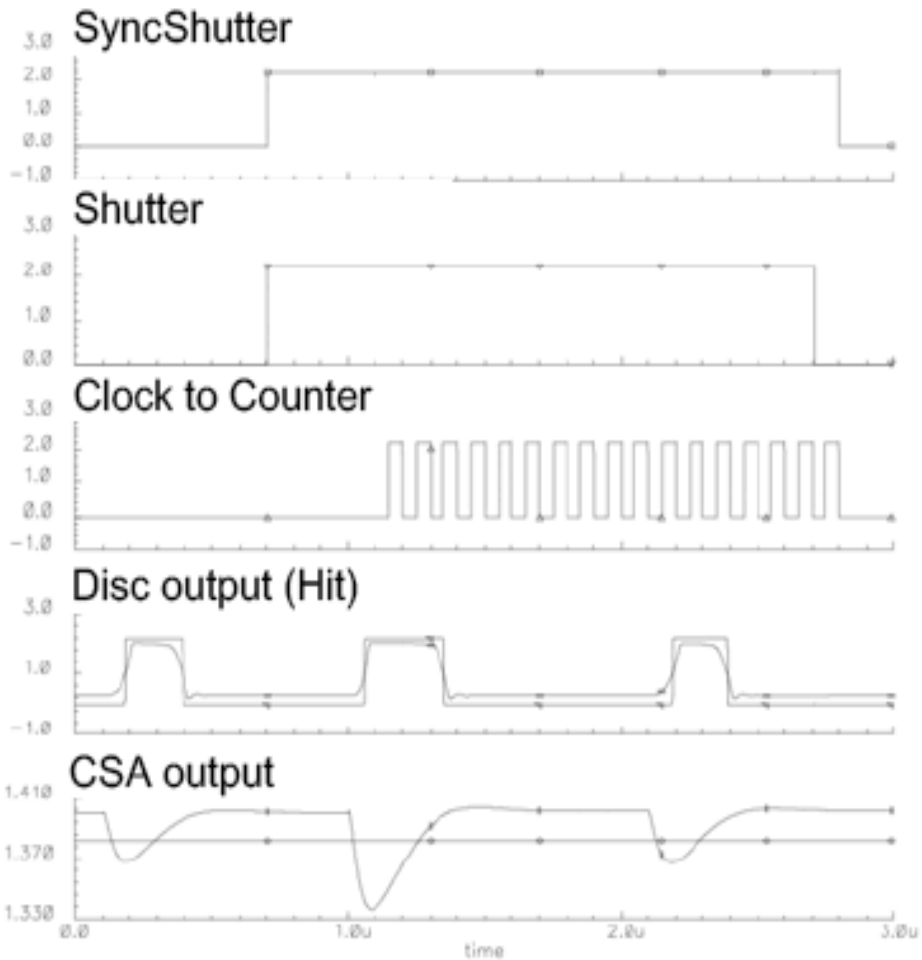
TIMEPIX SCHEMATIC



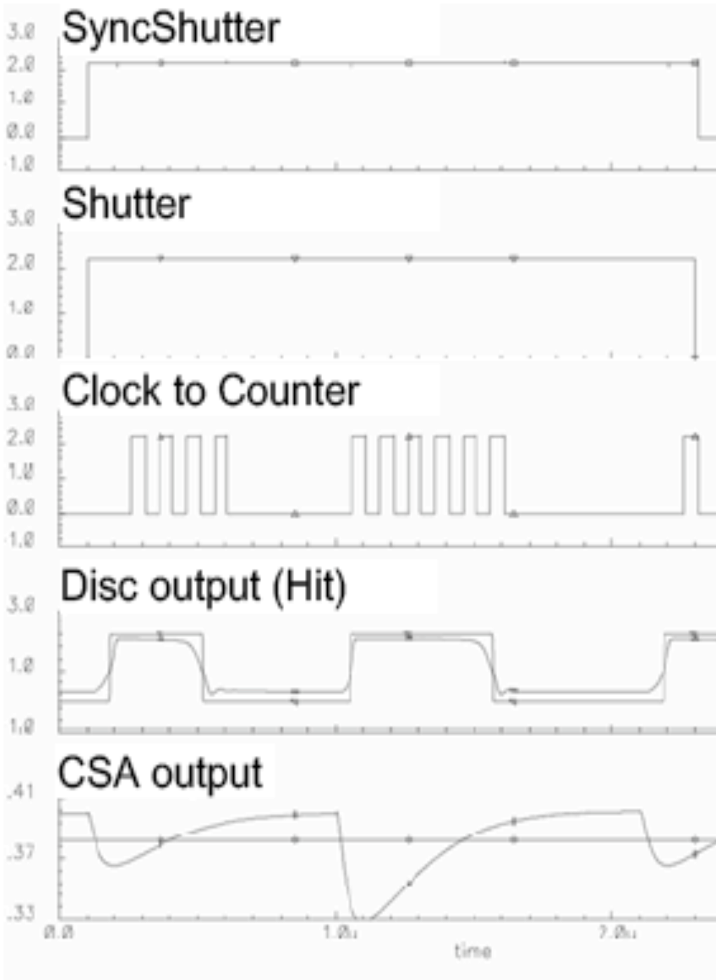
BASED on MPX2-MXR

ADDED REF_CLK -> 100 MHz

TIMEPIX OPERATION MODES



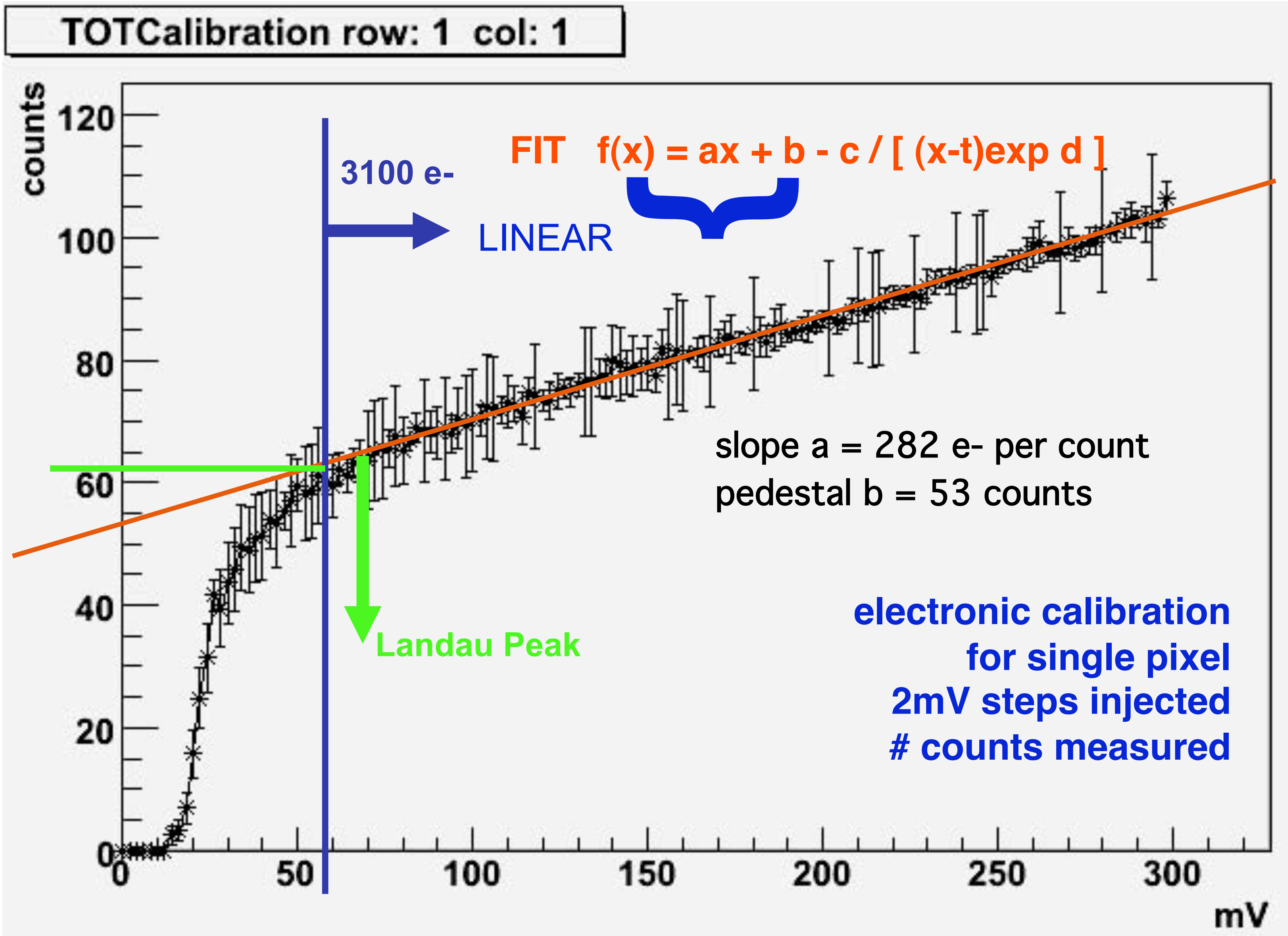
MODE : ARRIVAL TIME



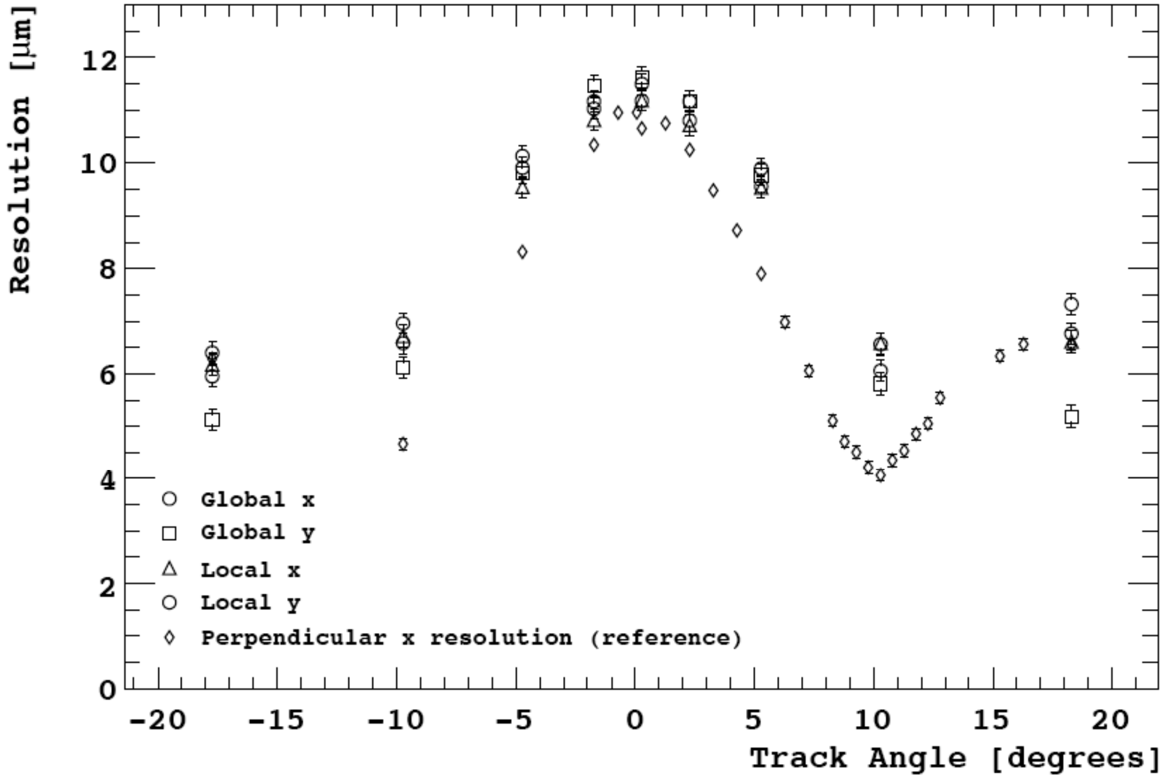
100 MHz

MODE : TOT 'TIME over THRESHOLD'

PIXEL CALIBRATION TOT (1,1)



TRACKING PRECISION in Si with Timepix



RECENT MEASUREMENTS
LHCb using
TIMEPIX TELESCOPE

4µm at 10°

1µm PRECISION CLAIMED
some YEARS AGO

PRACTICAL VALUES ~5-15µm

Figure 28: The resolution in the diagonal and normal directions as a function of track angle variation in the diagonal direction.

ANALOG MEASUREMENTS with Si TIMEPIX

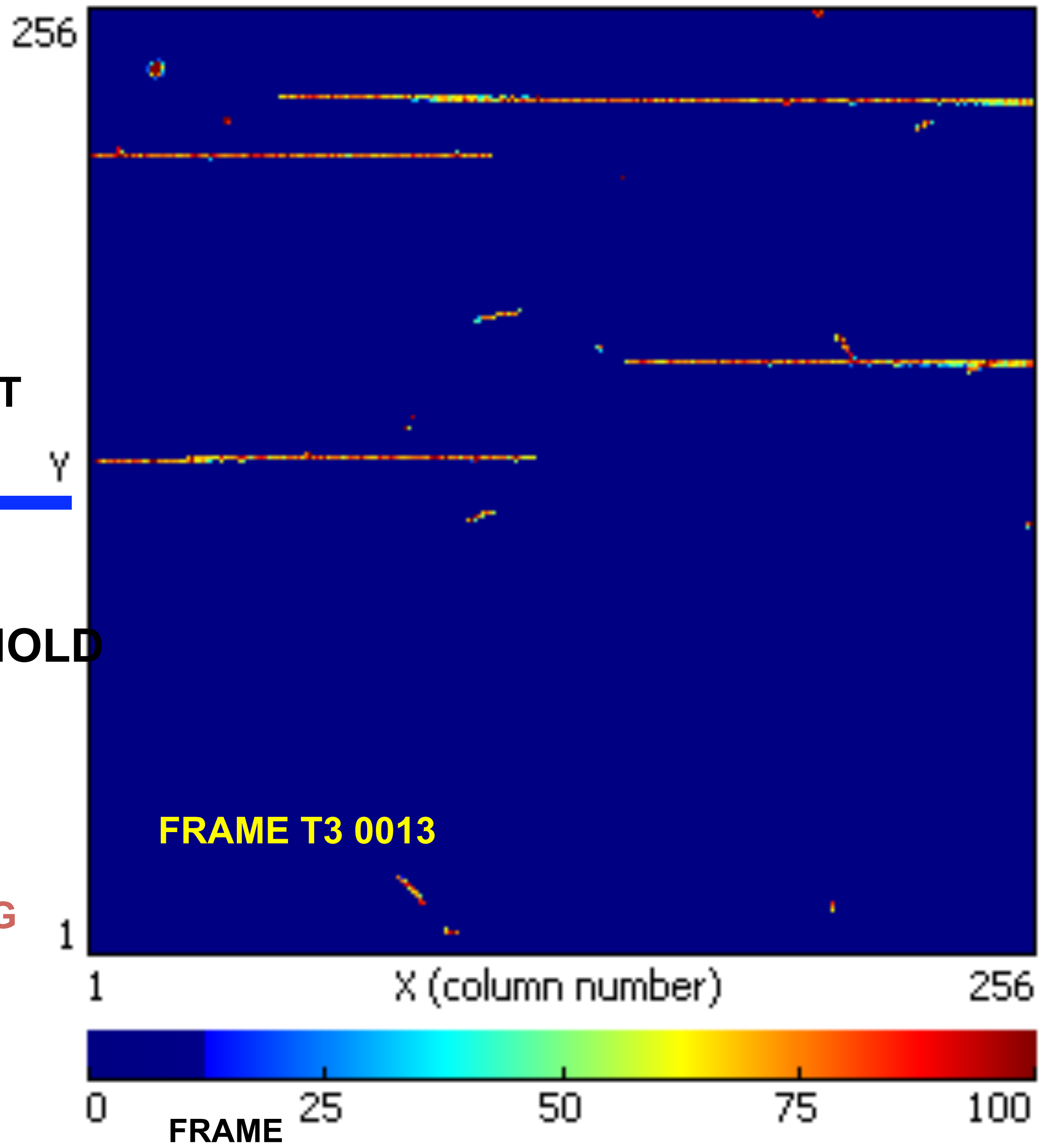
MUONS / PIONS
H6 in EHN1

June 2007

INCIDENT from RIGHT

BEAM

TIME-OVER-THRESHOLD in # COUNTS
MIP PEAK ~ 65



JOHN IDARRAGA
DOMINIC GREIFFENBERG
ERIK HEIJNE

MEASUREMENTS with MIPs in Si TIMEPIX (2007)

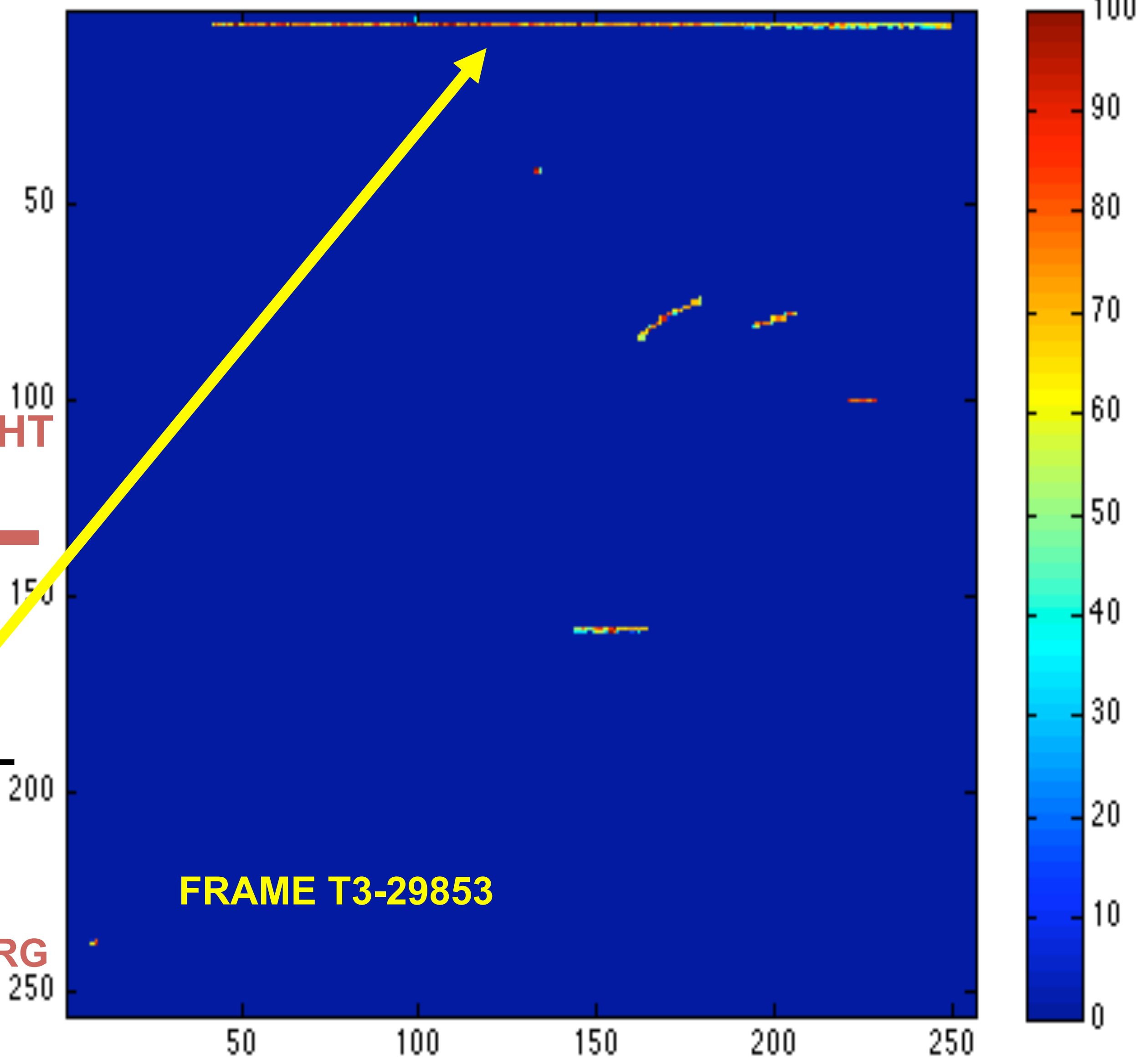
MUONS
H6 in EHN1

June 2007

INCIDENT from RIGHT

BEAM

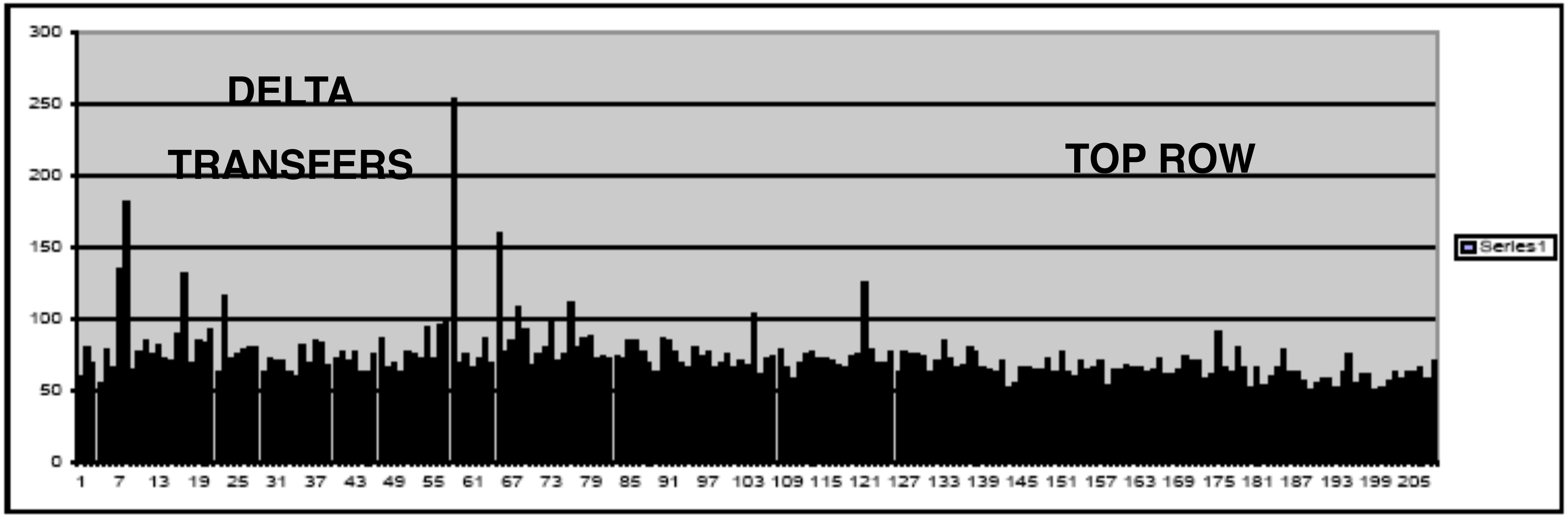
ANALYZED TRAIL



JOHN IDARRAGA
DOMINIC GREIFFENBERG
ERIK HEIJNE

M.I.P. TYPICALLY DEPOSITS 200 - 300 eV per um
11- 16.5 keV in PIXEL TOT RANGE 70-95 (1 keV~6 COUNTS)

TRAIL ANALYSIS FRAME 29853

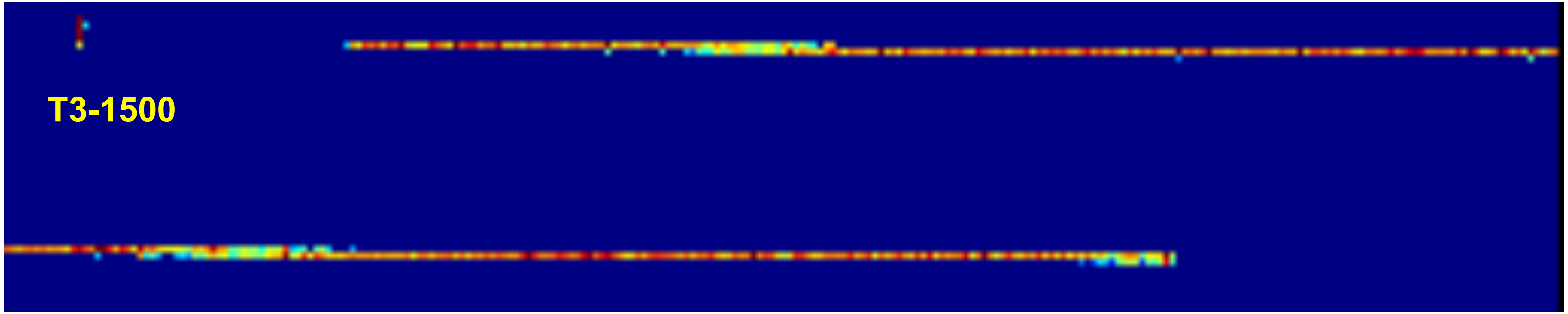


SHOWS   4 ENERGETIC DELTA δ e- TRANSFERS

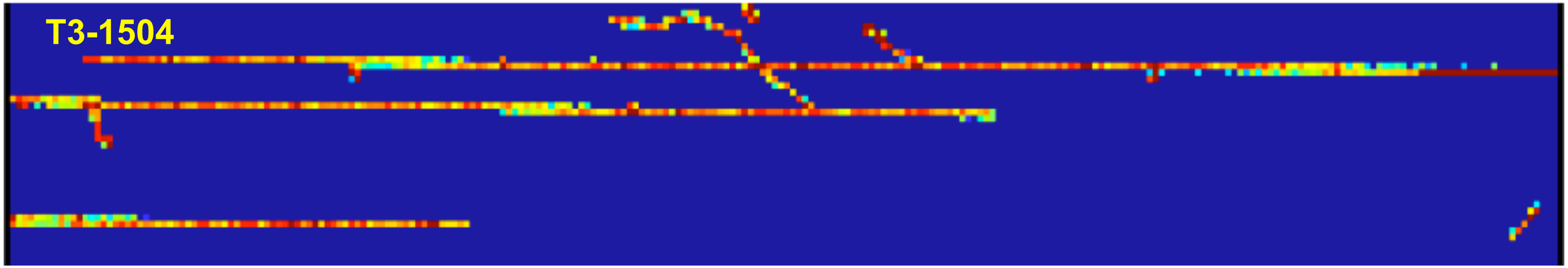
EVEN IF THESE REMAIN WITHIN THE PIXEL

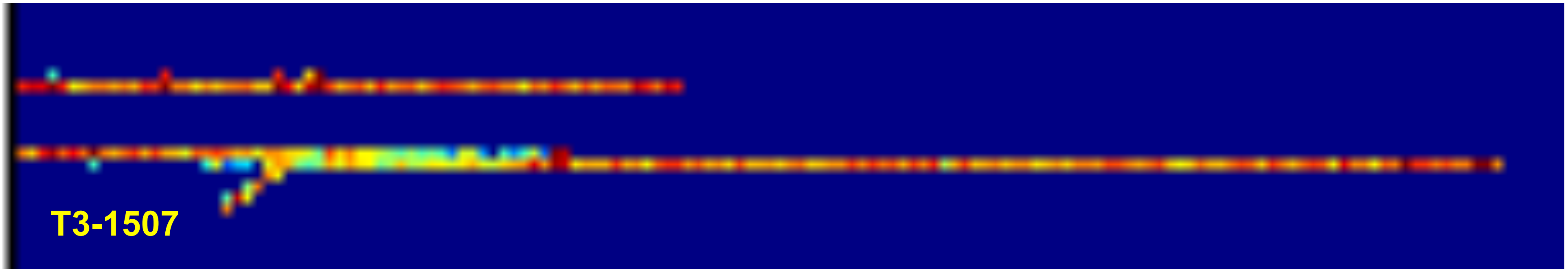
SOMETIMES SUCH ENERGETIC ELECTRONS TRAVEL THROUGH SEVERAL PIXELS

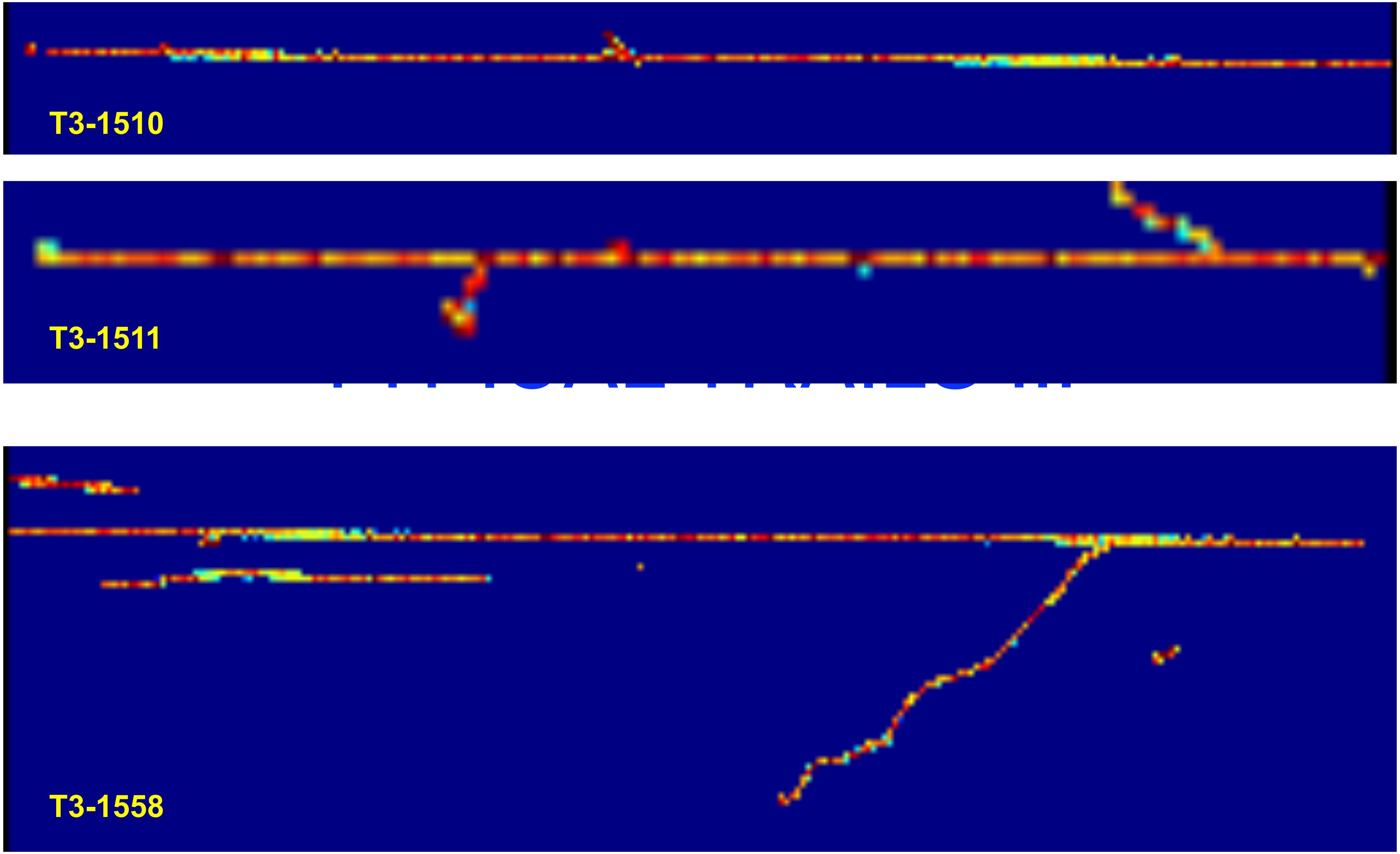
(CORRUPTED MEASUREMENT POINTS)



TYPICAL TRAILS ...






T3-1510
T3-1511
T3-1558

RATE / RESPONSE TIME
is a MAIN REQUIREMENT for DETECTOR

EMULSION	'STATIC'	
SCINTILLATOR + PM	ns	→ FIBERS
BUBBLE CHAMBER	s	
WIRE CHAMBER	μs	→ GAS DRIFT
Si DETECTOR	ns	

NOISE and RISETIME (τ_s 'speed') in PREAMPLIFIER

Series Noise: $$ENC_d^{\,2} \propto \frac{C_t^{\,2}}{g_m \tau_s}$$ Capacitance, Speed

Parallel noise: $$ENC_o^{\,2} \propto I_o \tau_s$$ Dark current I_0

Preamp rise time: $$t_r \propto \frac{C_t}{g_m} \frac{(C_L + C_f)}{C_f}$$

In general C_t should be as low as possible and g_m high, but more g_m implies more power

PRESENTATION Michael CAMPBELL

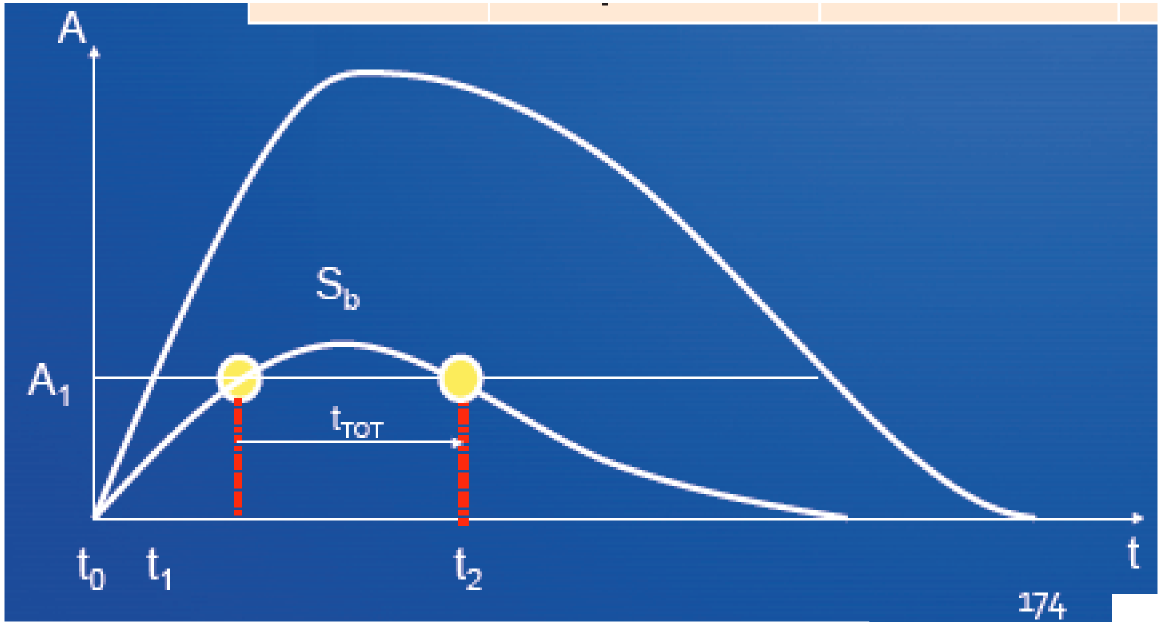
FAST TIMING 70ps Gigatracker NA62

200μm Si DETECTOR

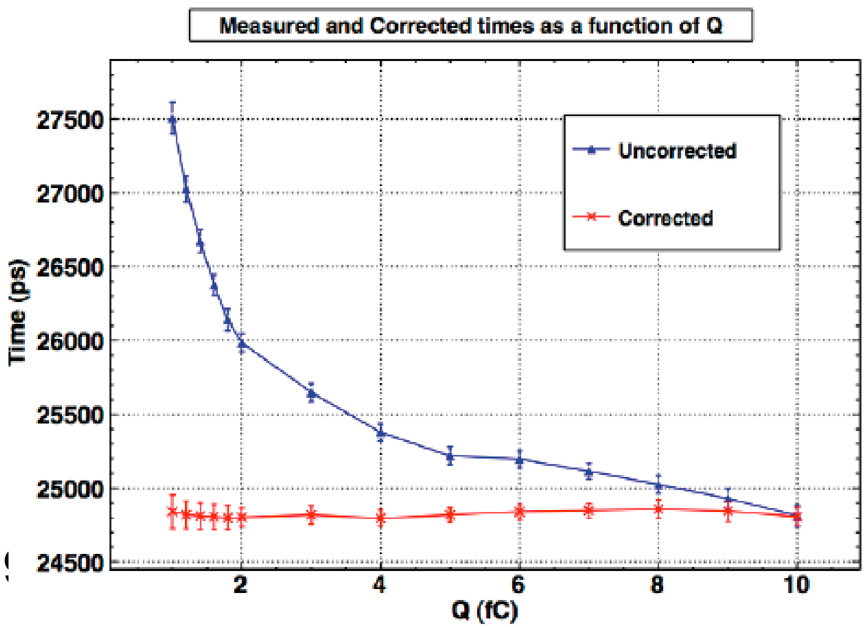
pixels 300μmx300μm

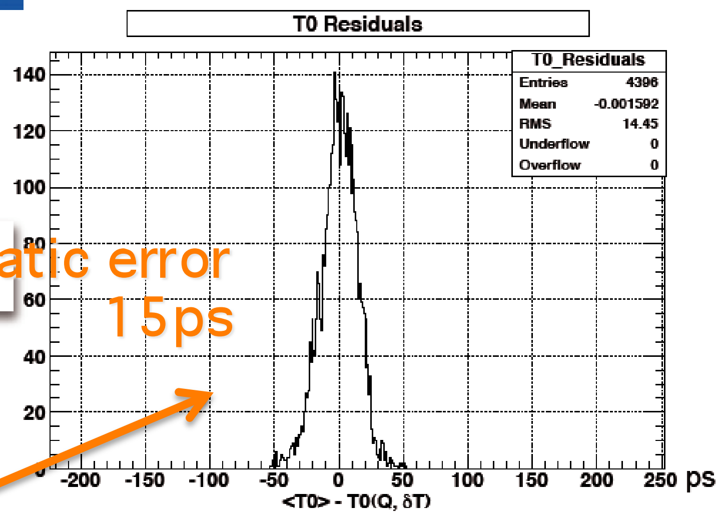
CORRECT TIMEWALK

in READOUT CHIP



measure TOT of shaped signals from LASER



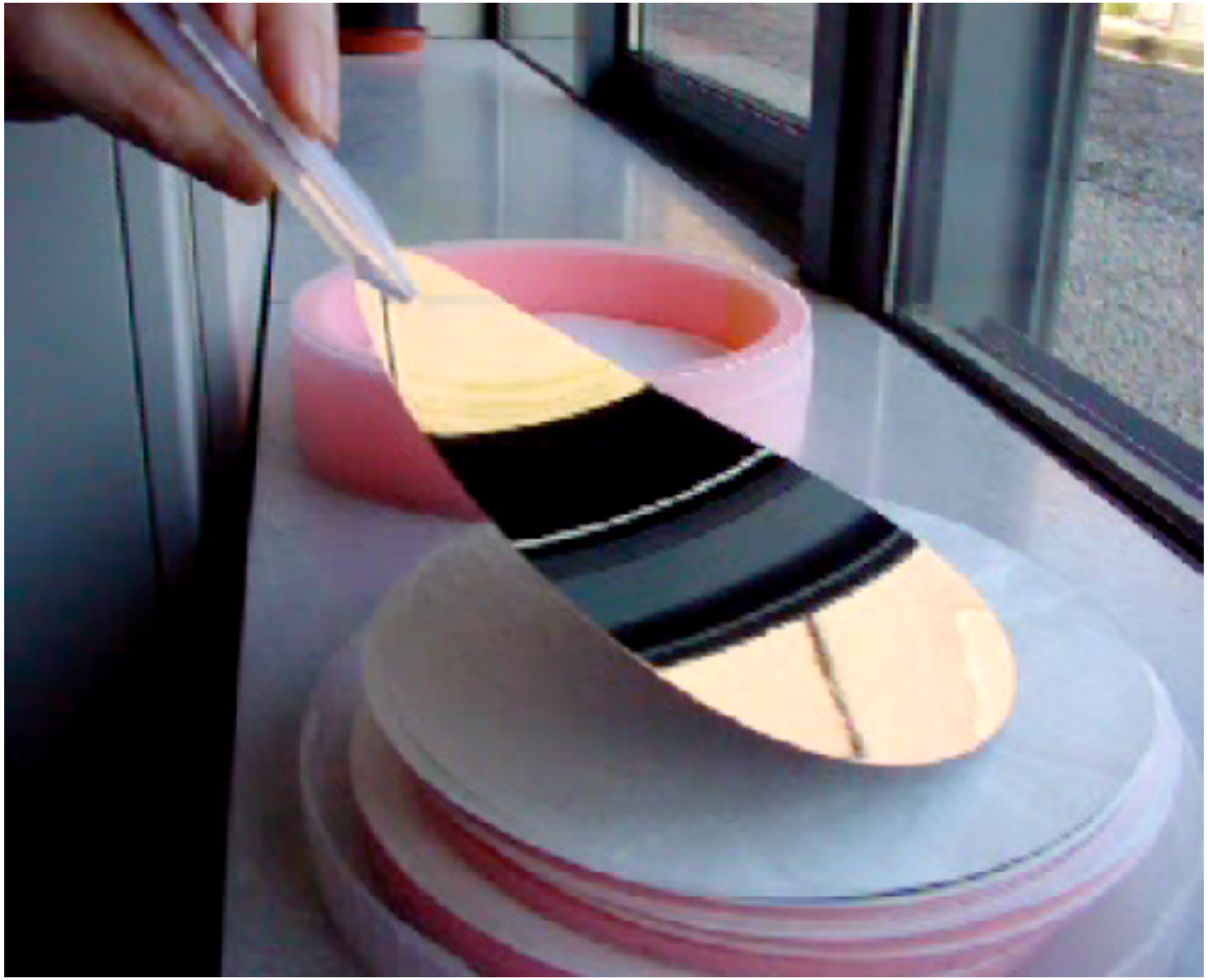


systematic error 15ps

GTK team NA62

3 DIMENSIONS
and
THINNING

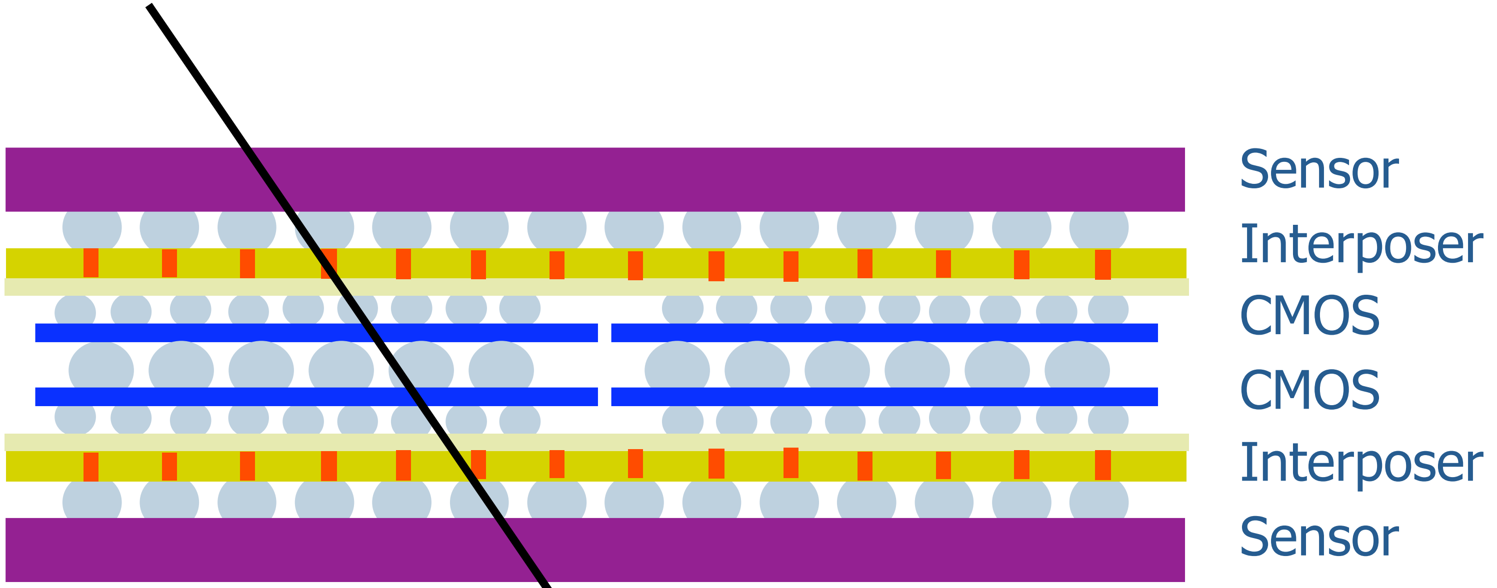
THIN WAFERS and THROUGH VIA for 3D STACKS



IMEC
Leuven

TRACK VECTOR DETECTOR

3D MULTILAYER ASSEMBLY



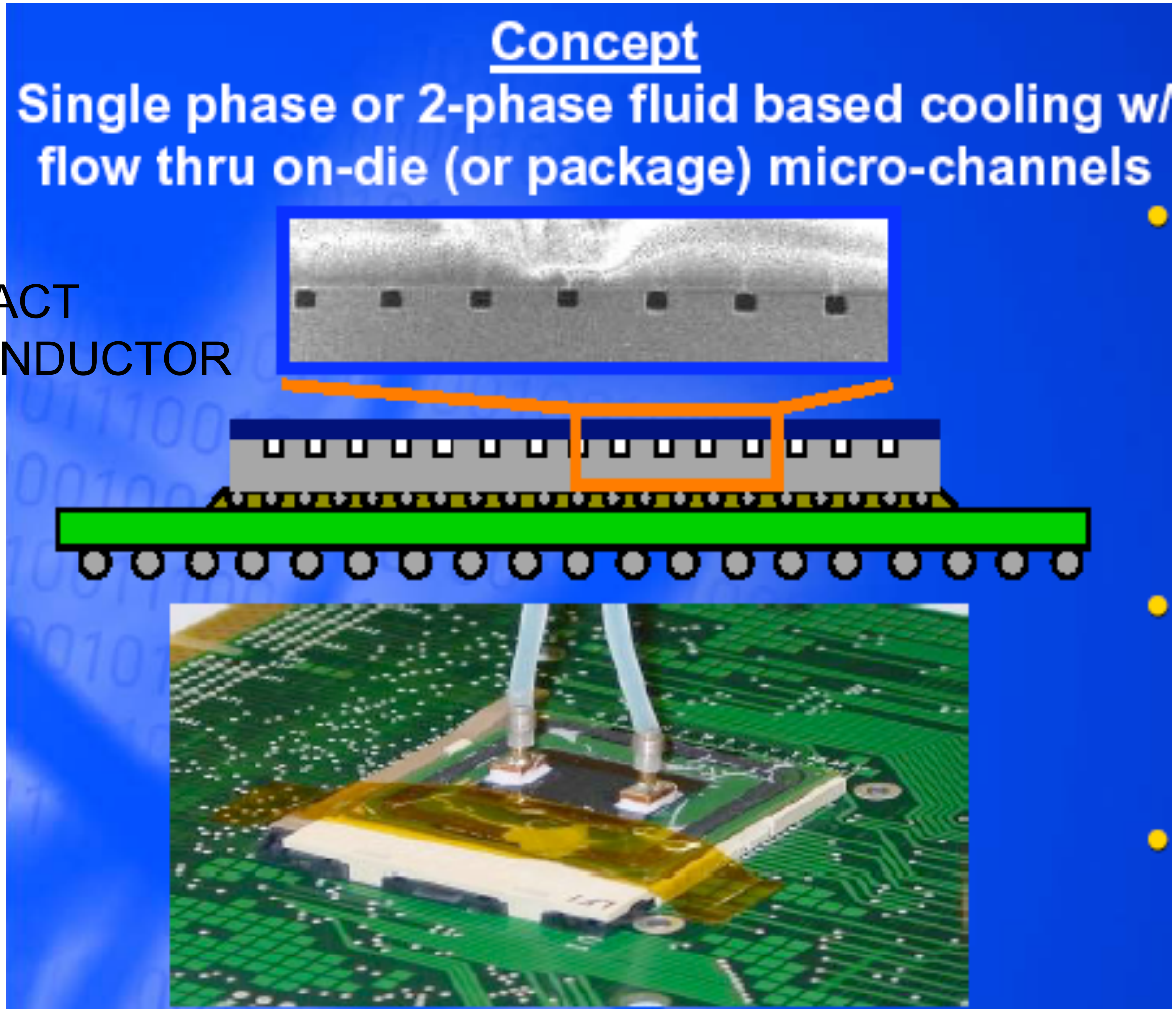
PROVIDES X , Y , Θ_X , Θ_Y

intersecting position + angular direction

RECENT APPROACH for CHIP COOLING

WAFERS are FUSED after ETCHING CHANNEL

DIRECT CONTACT
Si is GOOD CONDUCTOR



IMPROVING VERTEX TRACKING DETECTORS ?

COPING with SLHC DENSITY & EVENT RATE

INVESTIGATE DIFFERENT APPROACHES

DETERMINE MULTIPLICITIES & ENERGY-RELATED INFORMATION

ENERGY FLOW SEMINAR Patrick Janot on Saturday

DETERMINE QUICKLY THE RELEVANT PRIMARY VERTEX

REDUCE AMBIGUITIES

IMPROVE PATTERN RECOGNITION

VECTOR COORDINATES for TRAILS

USE MORE POINTS ON TRAIL

RESPECT LIMITATIONS on POWER & COST

WHICH PROBLEMS from NEW PHYSICS ?

FINAL

INTEGRATION of MICROELECTRONICS and DETECTOR

OPTIMIZATION in view of FINDINGS in EXPERIMENT

RATE CAPABILITY

TRACKING PRECISION

TRIGGER SELECTIVITY

RADIATION HARDNESS

RELIABILITY

TRY 'IMPOSSIBLE' APPROACH
at least EVERY 10 YEARS AGAIN

TECHNOLOGY may have CHANGED

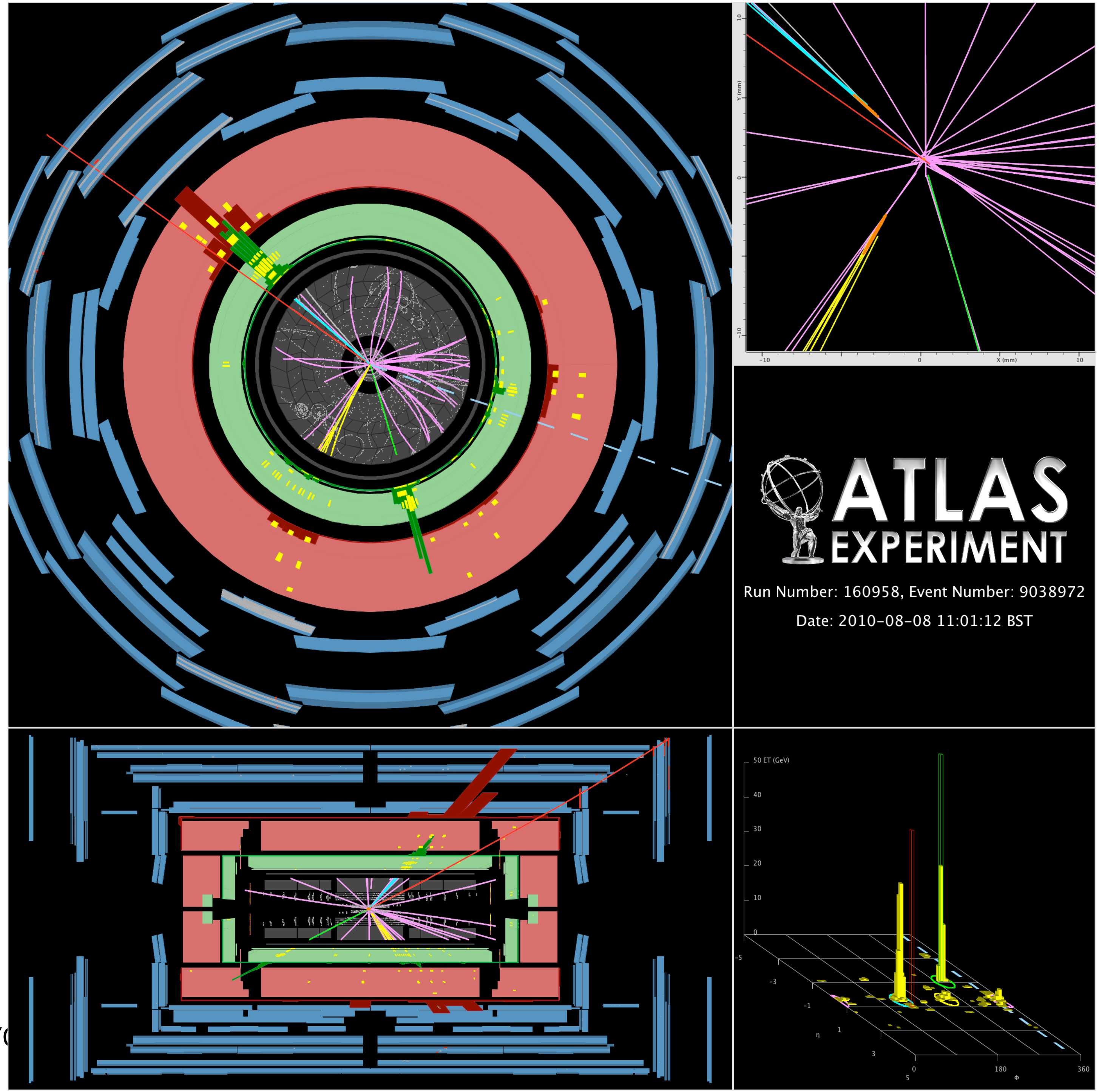
INVESTIGATE TRADE-OFFS in NEW APPROACHES

LONG-TERM DEVELOPMENT

ECONOMICS NOT TRIVIAL

2 JETS

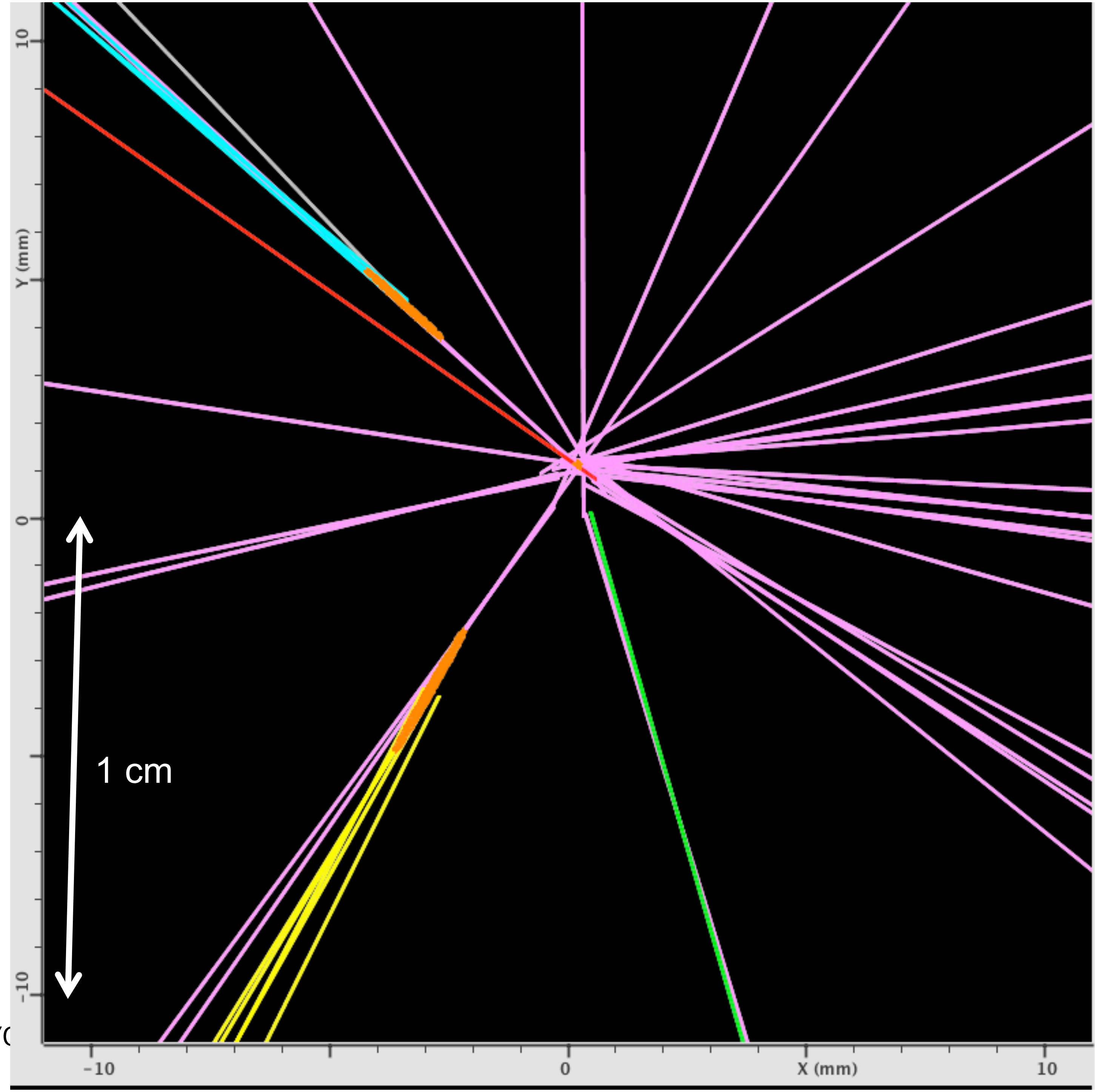
SECONDARY VERTICES



DETAILS
near PRIMARY
VERTEX

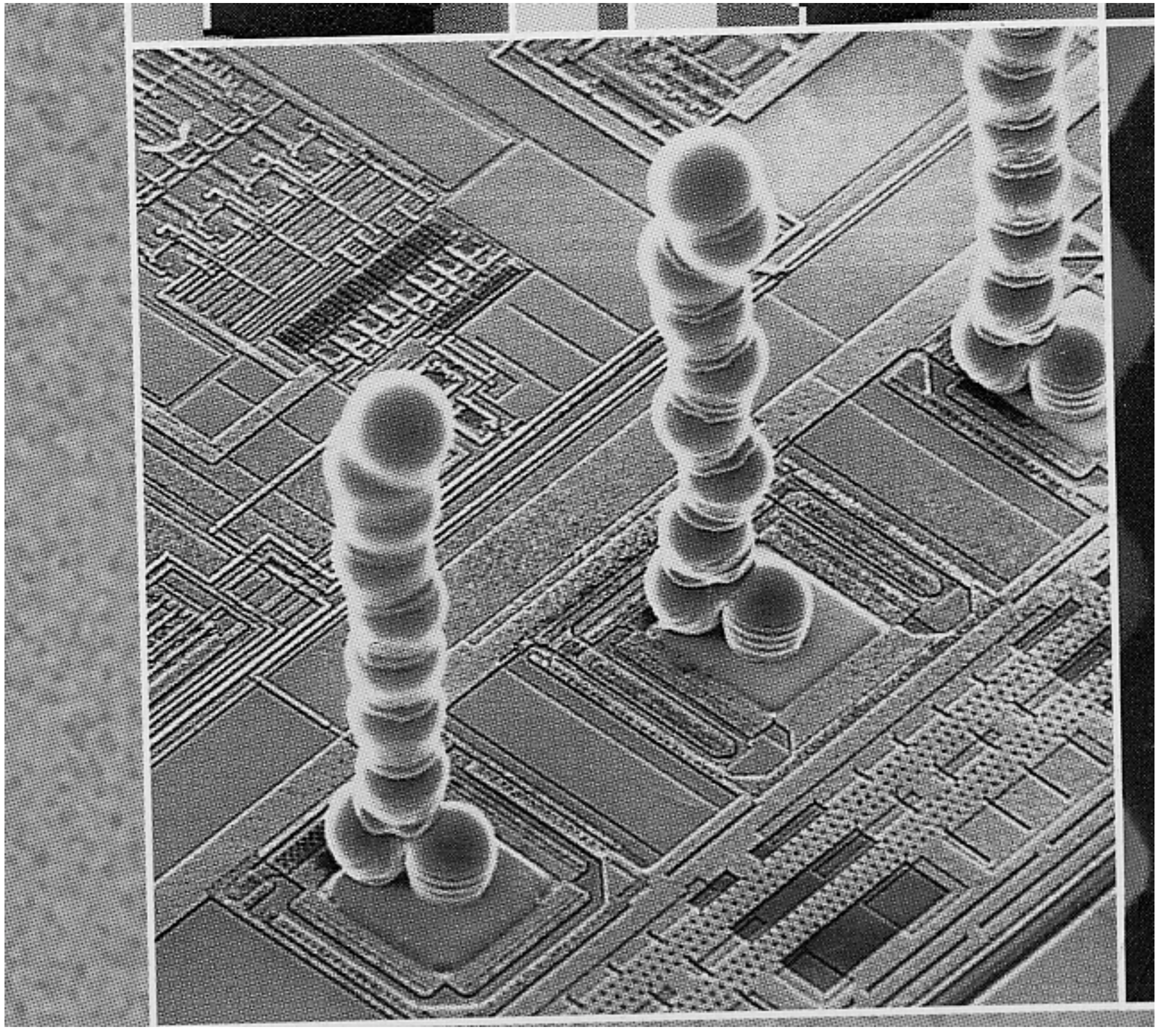
SECONDARY
VERTICES with
UNCERTAINTY
ELLIPSES (orange)

NOTE SCALE:
ALL THIS is INSIDE
BEAM PIPE



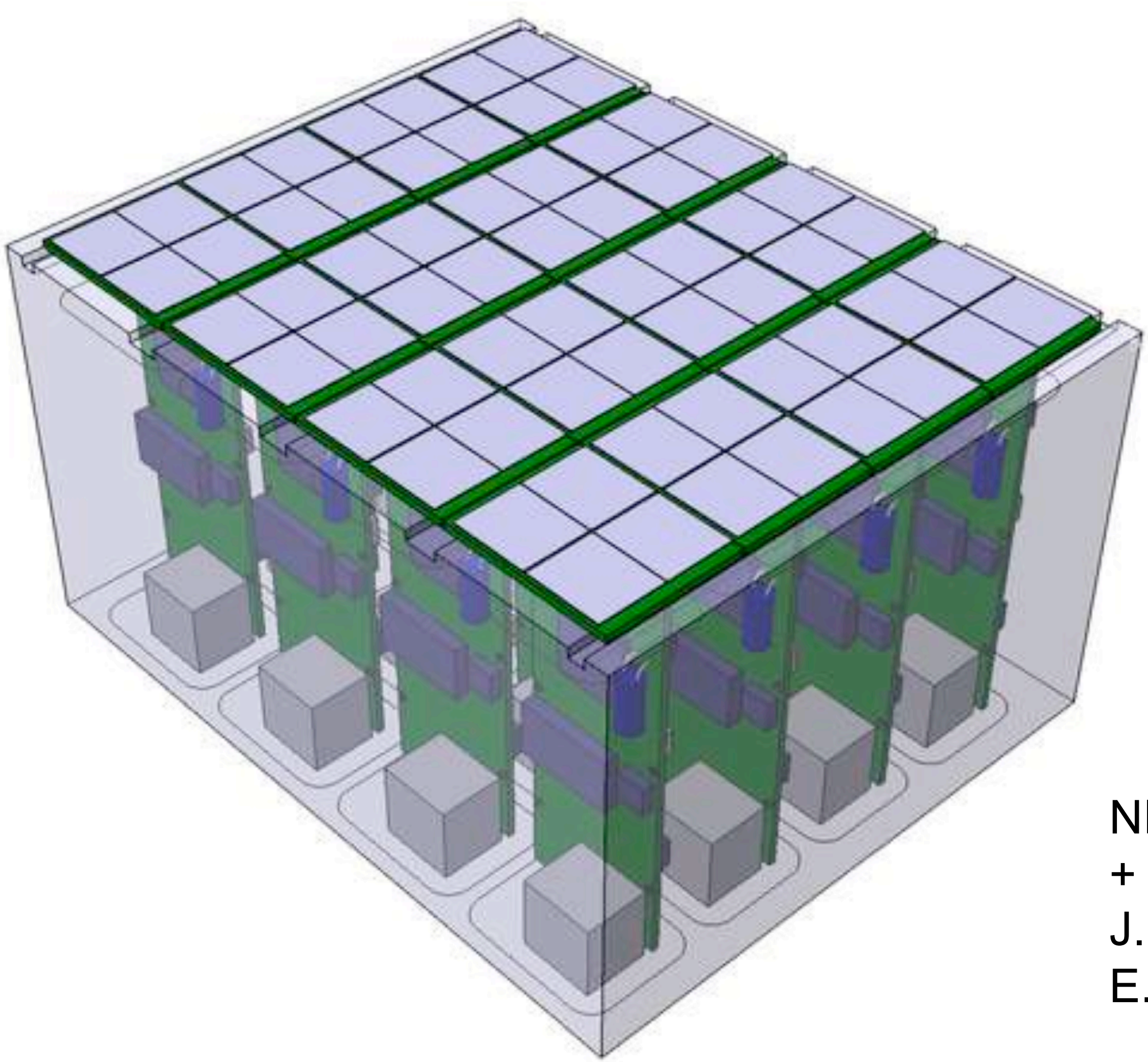
END

VARIOUS WAYS of BUMP BONDING



APPLICATIONS

MEDIPIX ARRAY DESIGN



EXPECTED
END 2010

NIKHEF + PANALYTICAL
+ MEDIPIX / CERN
J. Visschers, K.Bethke,
E. Heijne cs.

SPIN-OFF to PANALYTICAL

PIXCEL DETECTOR for X-RAY DIFFRACTION

ALMELO, NL PANalytical

COSMIC PARTICLES in MXR Si PIXEL

256 x 256 PIXELS
300 µm THICK

CAN BE
RADIATION
DOSE METER

IDENTIFY SPECIFIC QUANTA
- ELECTRONS
- PHOTONS
- MIPs
- NEUTRONS -> ALPHAs

ADJUSTABLE EXPOSURE
ms - minutes GIVES
LARGE DYNAMIC RANGE

Frame CTU Prague