Semiconductors reveal the world

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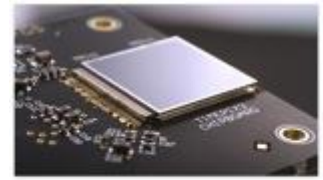
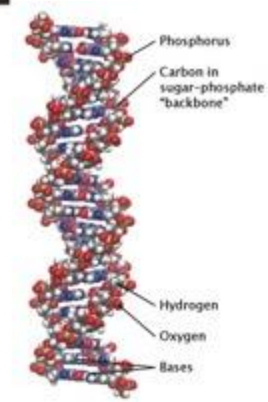
Czech Technical University, Prague
CERN EP Department, Geneva
Nikhef, Amsterdam

24 October 2023   Workshop "Days of Detection"- Padova

Semiconductors reveal the world

Flint-silex-SiO_2
7cm on spear
12 000 y ago





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24 October 2023 Workshop "Days of Detection"- Padova

A million years of humanity

progress characterized by use of materials and tools

Stone Age : paleo/meso/neolithic

tools of flint (silex = 'dirty' quartz-SiO_2)

Pottery Age

art, ceramic vessels allow cooking and storing food

Bronze Age

processing metals: weapons and art

Iron Age

heavy tools, constructions and transportation

Silicon Age ('anthropocene', 'Crawfordian')

information processors, primarily based on Si & SiO_2

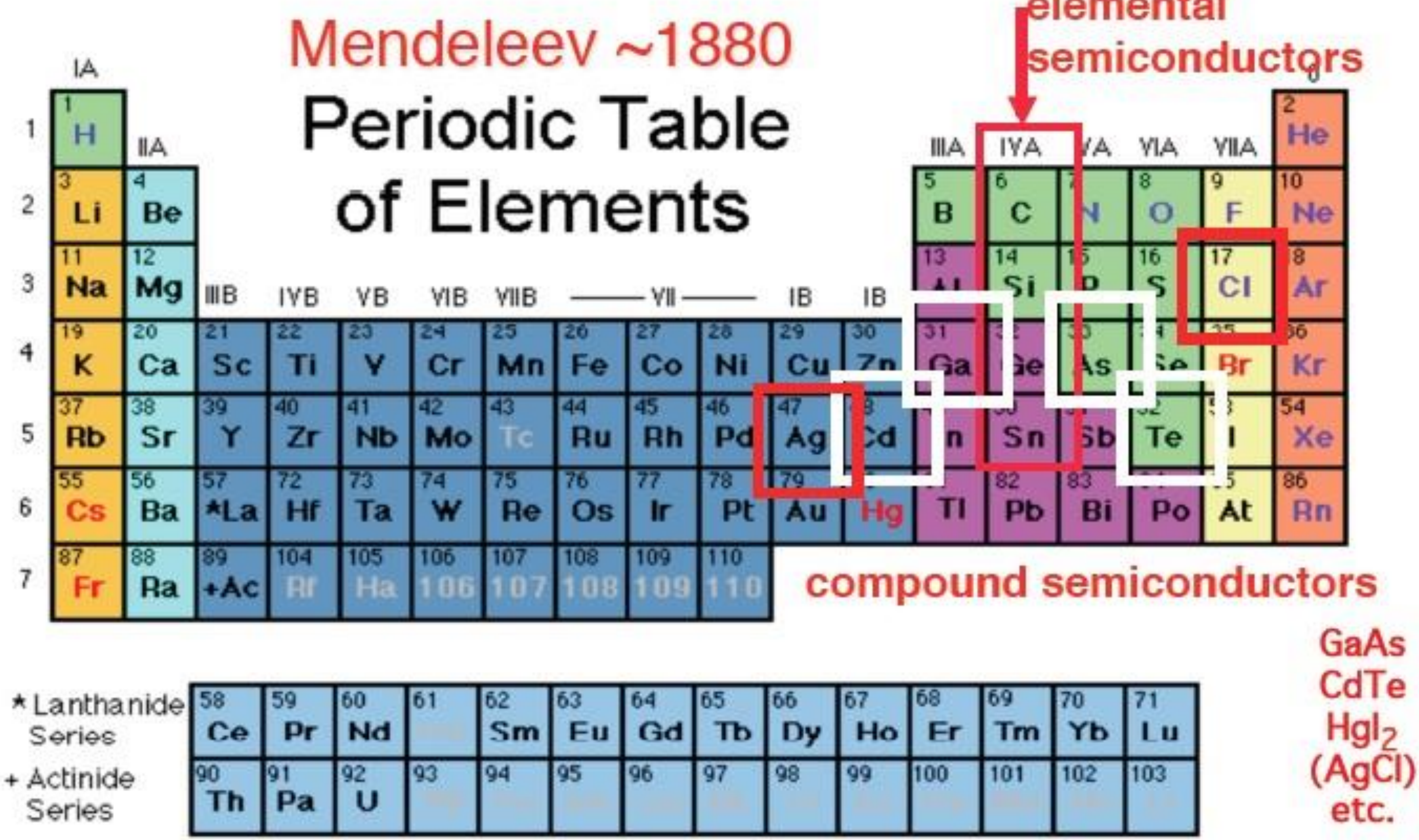
elementary particle physics

our expertise is with analysis of individual quanta

periodic system of atoms   92 natural elements

proposed by Mendeleev 150 years ago

Semiconductors



➔ **in Si crystal the conductivity can range over 10 orders (x10^{10})**

elementary particle physics

our expertise is with analysis of individual quanta

periodic system of atoms 92 natural elements

proposed by Mendeleev 150 years ago

model of the atom by Niels Bohrs protons+electrons

just 100 years ago

natural isotopes, radioactive decay neutrons

Chadwick 91 years ago

successively more particles positron, muon, pion,...Higgs

photographic plates, cloud chamber, bubble chamber,<80 years ago

microelectronics now enables much enhanced detection rate:

earlier ~1 interaction image per day or per second

recent electronic recording >10^9 per second

nuclear/particle physics instruments

started with photographic recording

emulsions, cloud chamber, bubble chamber

progressively moved to electrical Geiger counter, photomultiplier, spark- and wire- chamber,..

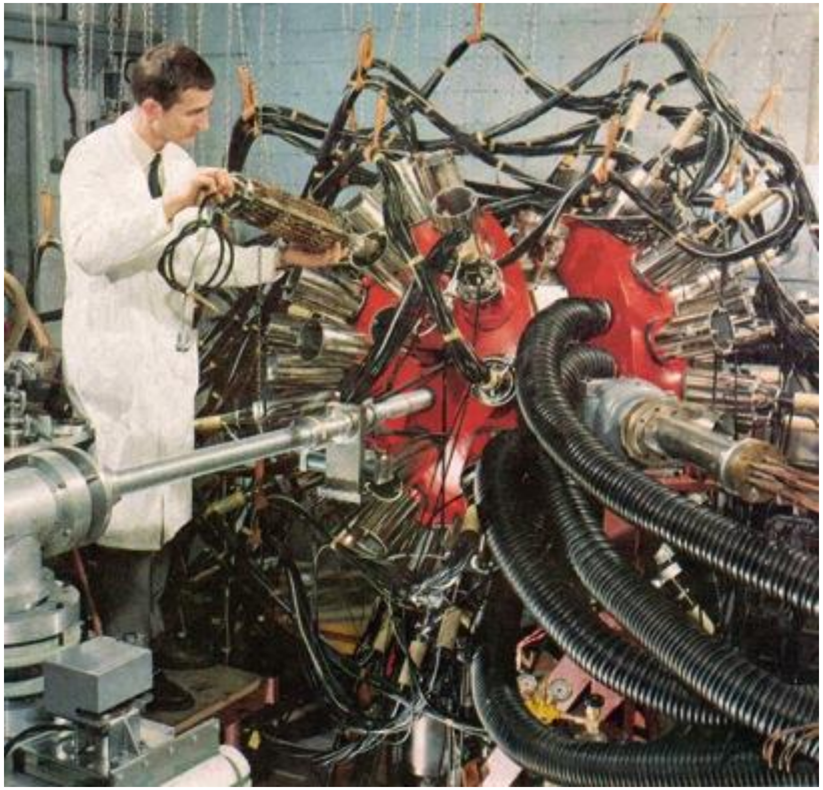
then fully electronic techniques: Time Projection Chamber, Si microstrip, Si pixels

ASIC design introduced at CERN ~1987

now 'Big Data' Petabytes

Experiments exploit electronics

1967



BOL experiment at IKO, Amsterdam, operational ~1966-73

2008

insertion of the CMS Si tracker; a few people stand by, operational 2008-now

~1967: Integrated Si telescope for 'BOL'

178

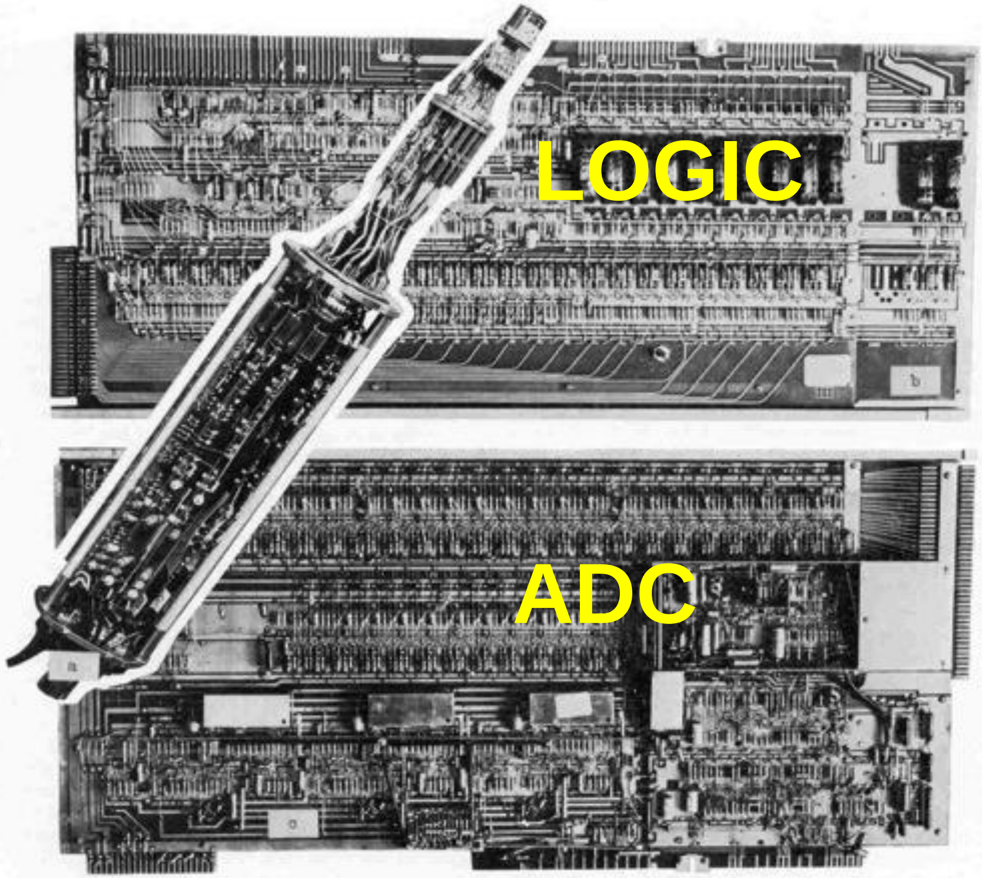


Fig. 1. Composition of the electronic parts of a complete detection channel: a) detection unit; b) logic unit; c) ADC unit.

one, indicating whether the left or the right partner of the pair was hit. Including the edges, this yields a 7-signal position code for each side of the detector (6 pairs of strips and edges + left/right indication). For the generation of this code, the bipolar 30 ns position indication signals from the transformers secondaries are amplified, used to extract a left-indication signal from one polarity and then rectified. To reduce the number of bits of the location code, the edge signal is then encoded as if three innermost pairs of strips were simultaneously activated. The 12 location signal lines are connected to the logic unit. Each line has got its own lower level adjustable discriminator. Remote control of the lower level discriminators is possible in the range from 0.3 MeV to 2 MeV. With the discriminators set to their most sensitive values, 50 MeV protons can be detected[3]). Set to an intermediate value, 25 MeV alpha particles (just stopping in the Checkerboard detector) do not cause significant cross talk between the position indication channels.

13-bit ADC 100MHz
& 8-bit ADC 6 MHz

only 2 ADC per board

0.5 x 1 m^2

64 such sets were used

NIM 92 (1971)

Oberski et al.

the 'normal' elementary particles

protons

neutrons

electrons

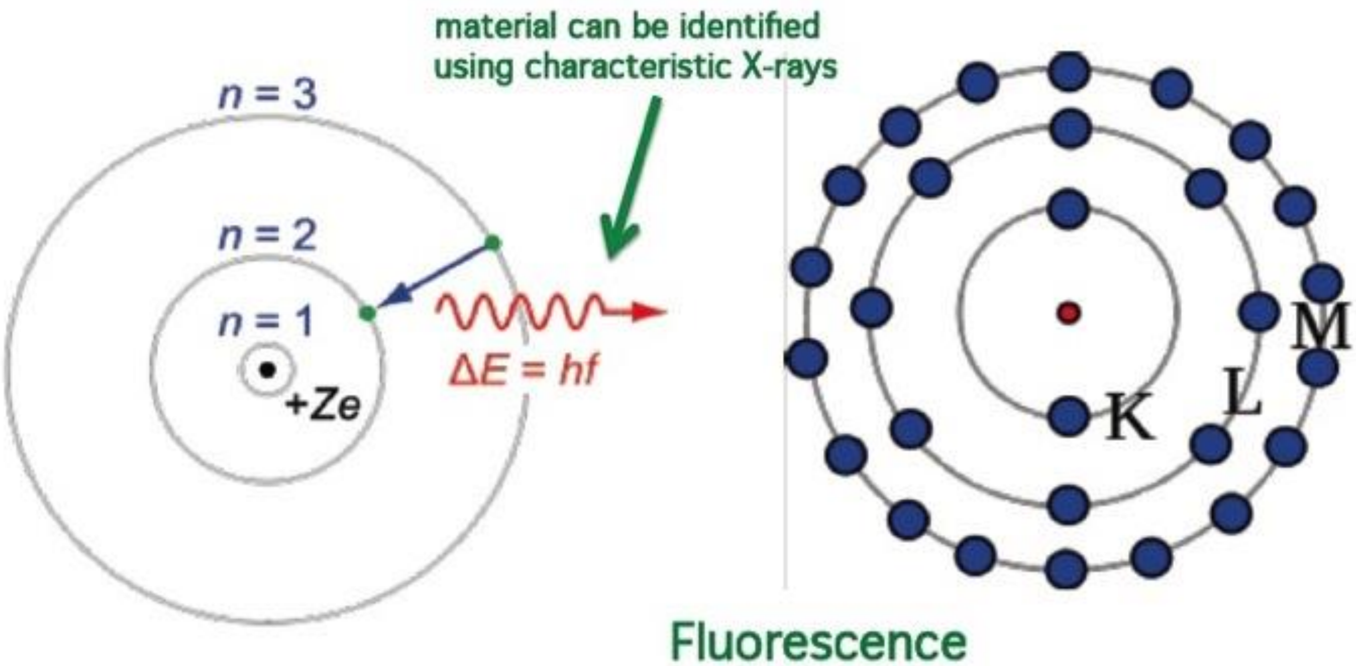
make up (nearly) everything around us

electrons are the most relevant

electrons determine size and properties of atoms
collective behaviour with band structure in (poly)crystals
energy absorption/emission lines identify the elements
precise measurements use Ge or Si detectors

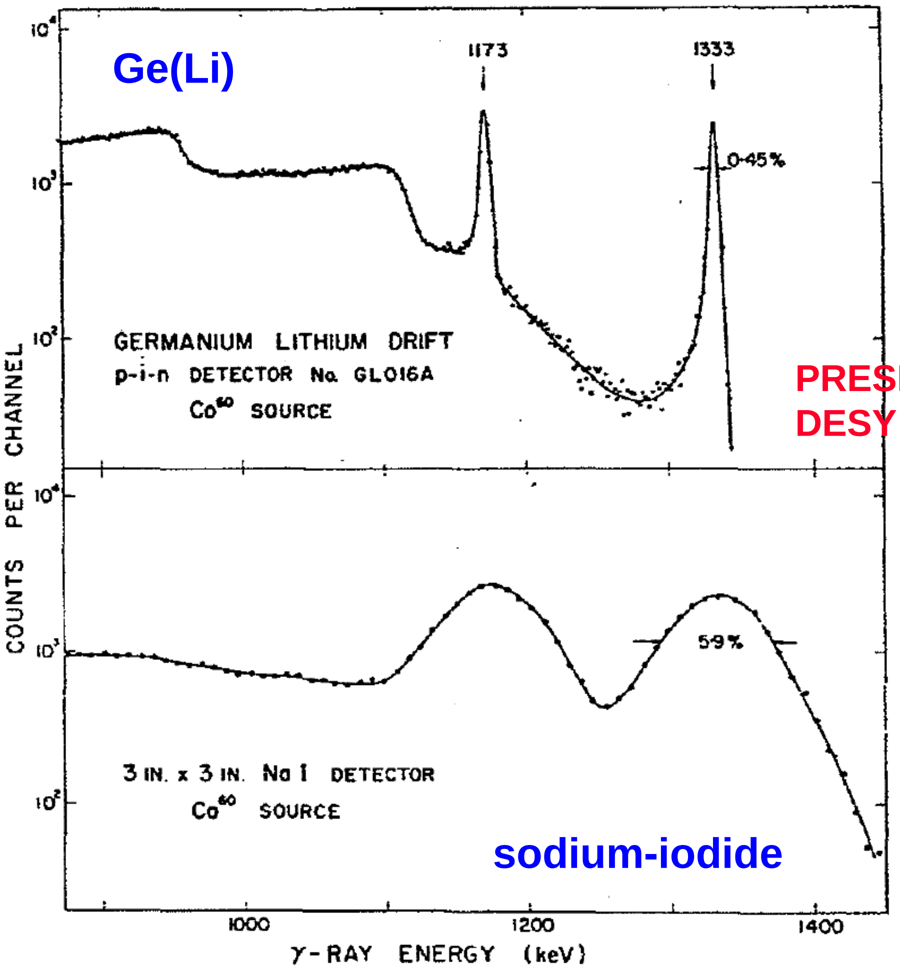
identification of materials with X-rays or e-microscopes

electrons can be steered through solids
now also imaging with segmented matrix detectors



identification of materials using energy of the fluorescence photons

1963 Germanium Detector Breakthrough

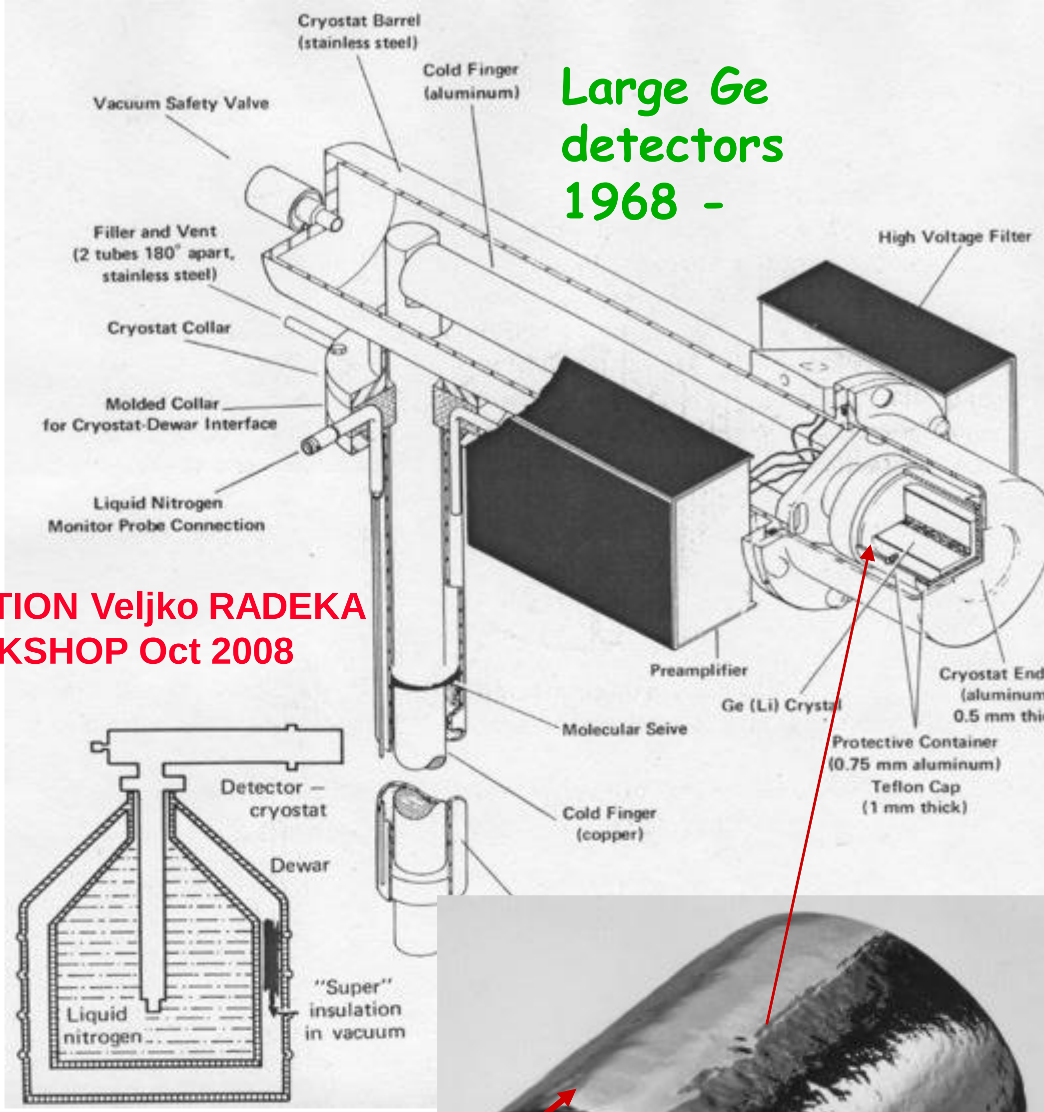


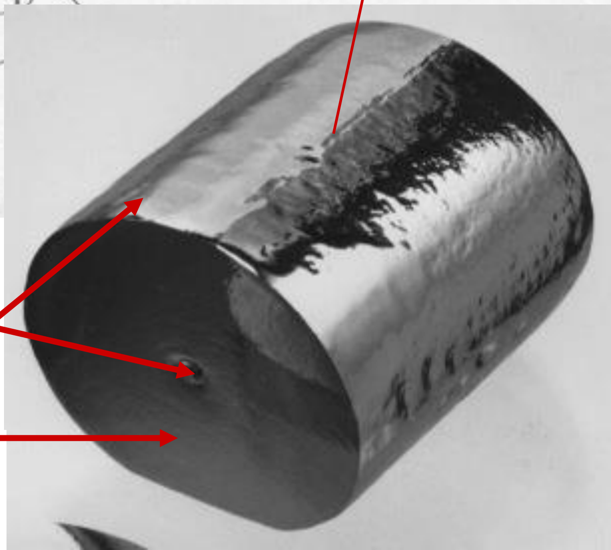
From: A.J. Tavendale and G.T. Ewan

Nucl.Instr.Meth. 25 (1963)185-187

PRESENTATION Veljko RADEKA DESY WORKSHOP Oct 2008

Large Ge detectors 1968 -





Coaxial det.contacts

Ge-crystal ~50-100 cm^3

detectors revealing things

rivelatore better implies discovery and analysis of elementary components and processes of matter

using detectors for single quantum imaging/analysis
leads to innovations for old & new instruments

electron microscopes   nm dimensions

X-ray imaging   many applications

neutron imaging

nuclear magnetic resonance   mri especially in medical analysis

ion backscattering

DNA analysis with micropores   DNA developed over millions of years

etc.

semiconductor crystals excellent quantum detectors

high stopping power, low ionization energy compared to gas or liquid

overview of seminar

history, materials and tools

particle physics instrumentation

→ semiconductors - silicon in particular

semiconductor detectors for quantum particles

applications beyond particle physics

thoughts - difficulties – final remarks

semiconductor silicon

Si as element identified in materials research ~1820

Si mono-crystals made for radar 1940-1950

commercial Si crystal growth: Montecatini, Italy ~ 1955

first Si transistor 1954: Morris Tanenbaum Bell Labs

only 69 years ago

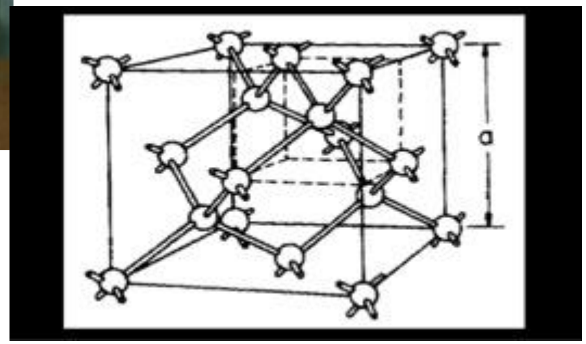
Si oxidation discovered accidentally 1955 Bell Labs

<1970 most labs/companies made their own crystals

electronics pre-history

Laben-Milano ~1955

nuclear pre-amplifier



Si crystal model

a=0.54 nm

real atoms muuuuuuch smaller

Si monocrystal 1"
Montecatini (IT) ~1955
-> Monsanto

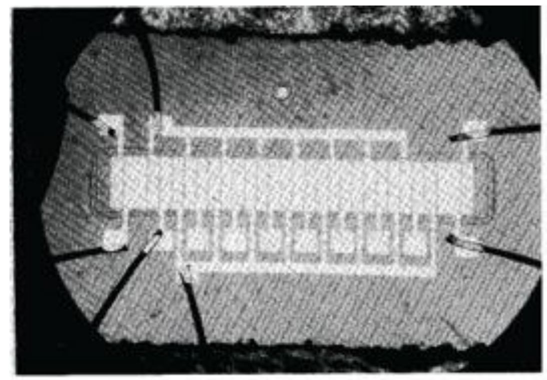
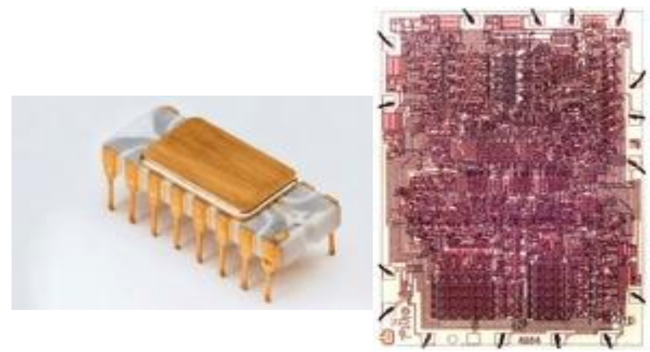


Fig. 3. The first 8-bit fully integrated device with diode inputs and outputs.

first CCD
Bell Labs 1969
.Boyle & Smith



1971 Intel 4004 10μm nMOS

electronics pre-history

1920 – 1965

electronics based on electrodes in vacuum tubes

radio also uses 'crystal oscillator' as frequency reference

1940 – 1960

study of semiconductors & growth of monocrystals

selenium, GaAs, then Ge, but Si was difficult and came later

1943

AgCl crystal is first semiconductor detector (electrons)

Utrecht, P. van Heerden   recorded electron energy spectrum

1960 – 1970

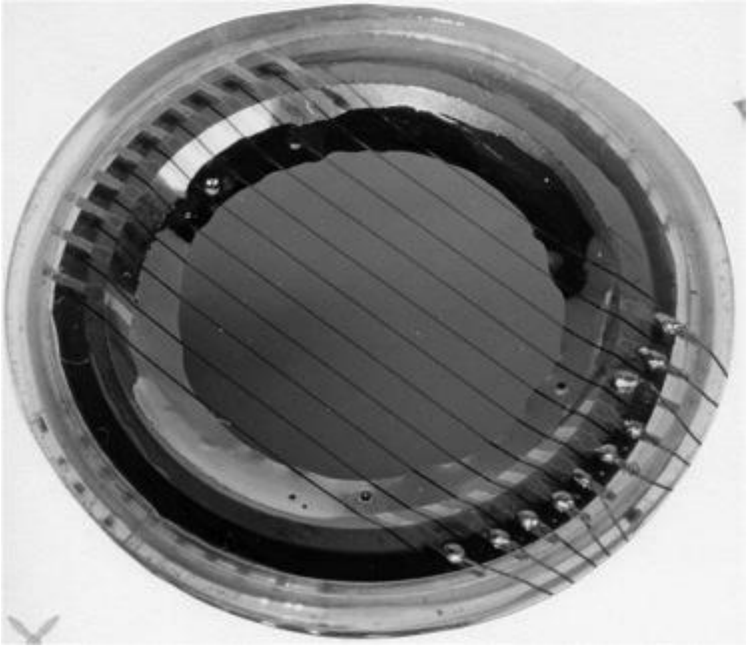
first complex integrated circuits;   Moore's law 1965

R&D worldwide (Kooi, Philips,1966 LOCOS), stronger manufacturing in USA

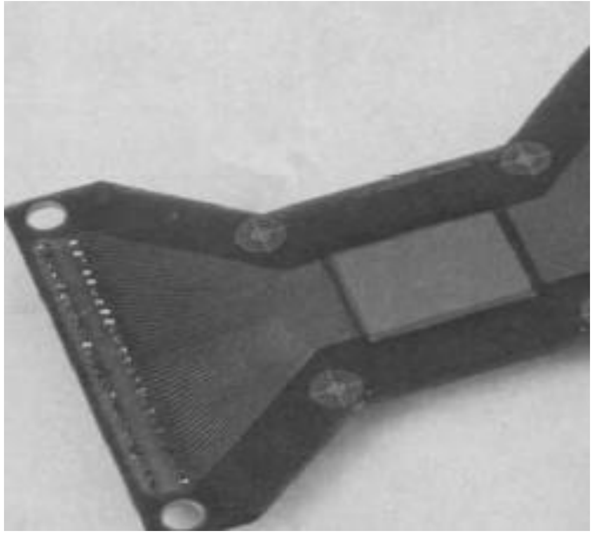
East: IBM, BellLabs, Texas, RCA,..   West: Fairchild, Intel,...

Si sensors/detectors and electronics

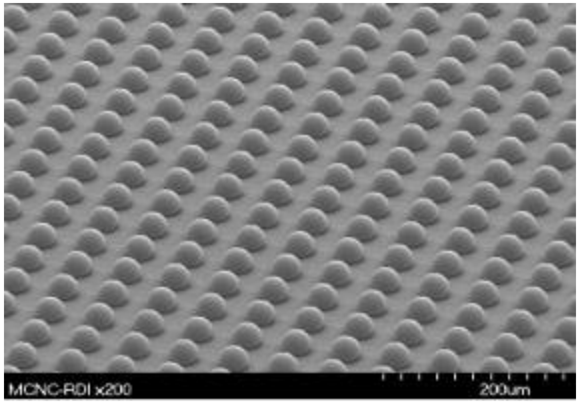
Si first used as nuclear detector, soon also segmented ~1955 Oak Ridge → Ortec



~1965
PHILIPS / IKO Amsterdam
80 squares 1370umx1370um



1980
CERN / ENERTEC Strasbourg
100 strips x 4000umx200um



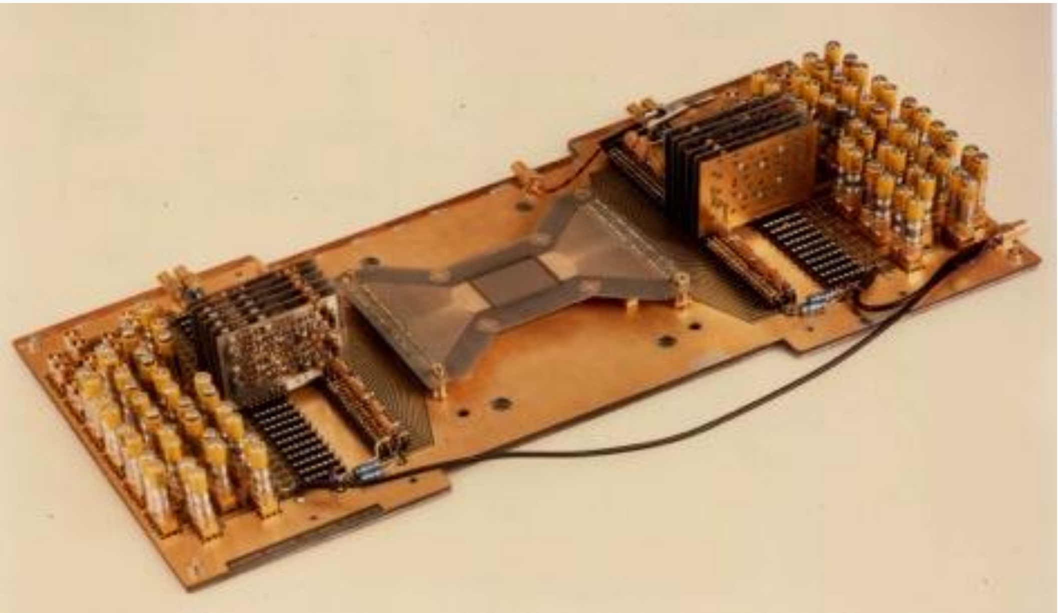
2000
CERN / MEDIPIX
65000pixels x 55umx55um

Si Microstrip detector

segmentation, full signal processing connected to each element
including ADC, memory and transmission

conceived at 1979 IEEE-Nuclear Science Symposium in San Francisco
implemented in collaboration at Enertec, Strasbourg, February 1980

first test setup CERN May 1980



2009 VELO tracker in LHCb

Special features Si microstrip detectors

can record energetic quanta/particles: from few keV → GeV

visible indirectly possible   visible+photocathode+microchannelplate MCP

segmentation with contiguous elements → charge sharing

detection efficiency is 100%   visible+photocathode+MCP is less

signal processing for each element, including thresholding

threshold adjustment enables noise-free recording

energy/'color' of each electron/photon can be recorded

allows position measurement better than the pitch

all this equally true for 'pixel detectors'

segmented Si detectors need readout chips ~1985

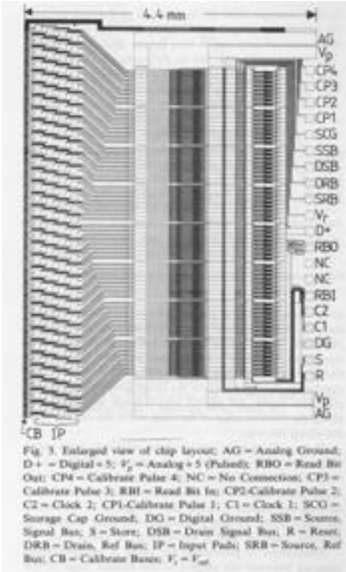
Chips NOT to scale

SLAC/(DELPHI)

Microplex 1983

Walker, Parker, Hyams, Shapiro

NIM A226 (1984) 200

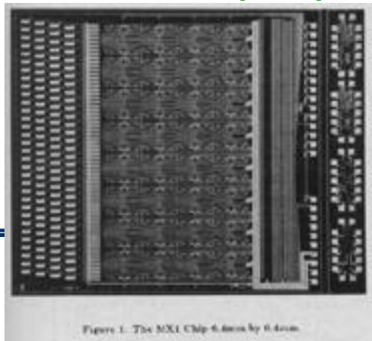


RAL/DELPHI

MX1 MX2 1987

Seller, Allport, Tyndel

IEEE TNS 35(1988) 176



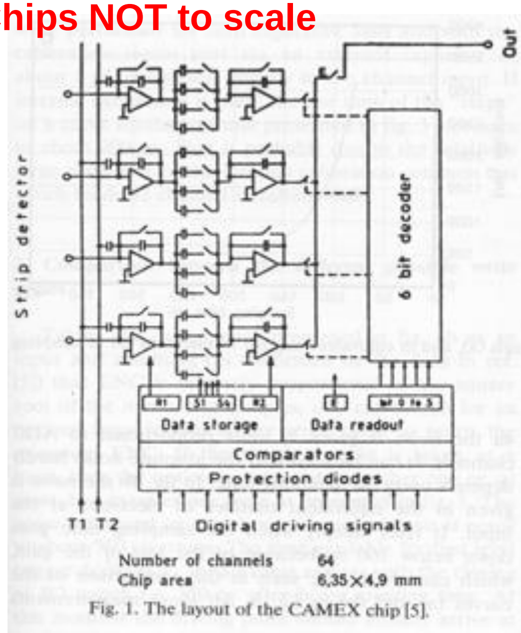


Fig. 1. The layout of the CAMEX chip [5].

CAMEX64/ALEPH-MPI

Buttler, Lutz, Hosticka

Becker et al. IEEE TNS 36(1989) 246

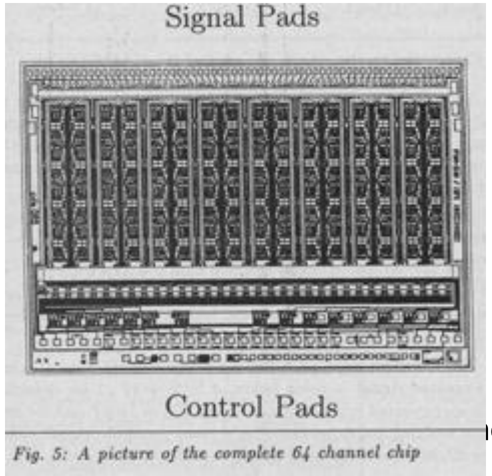
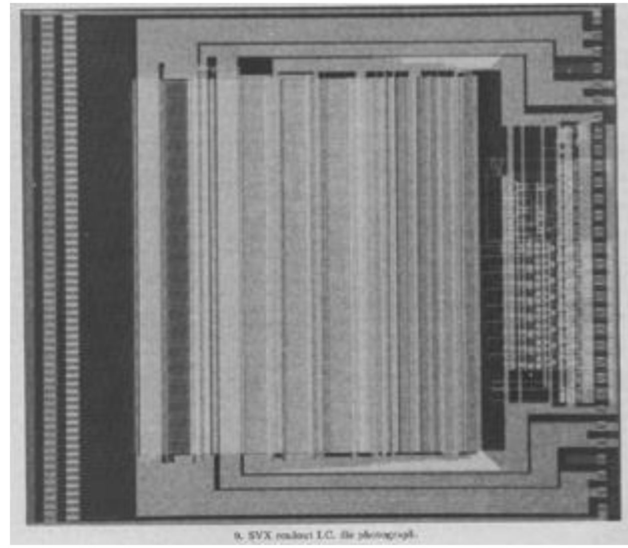


Fig. 5: A picture of the complete 64 channel chip



CDF-SVX Kleinfelder 1988

Kleinfelder et al. IEEE TNS 35(1988) 171

AMPLEX (UA2)

Pierre Jarron 1987

classical, continuous feedback

actually the first in a collider:1988

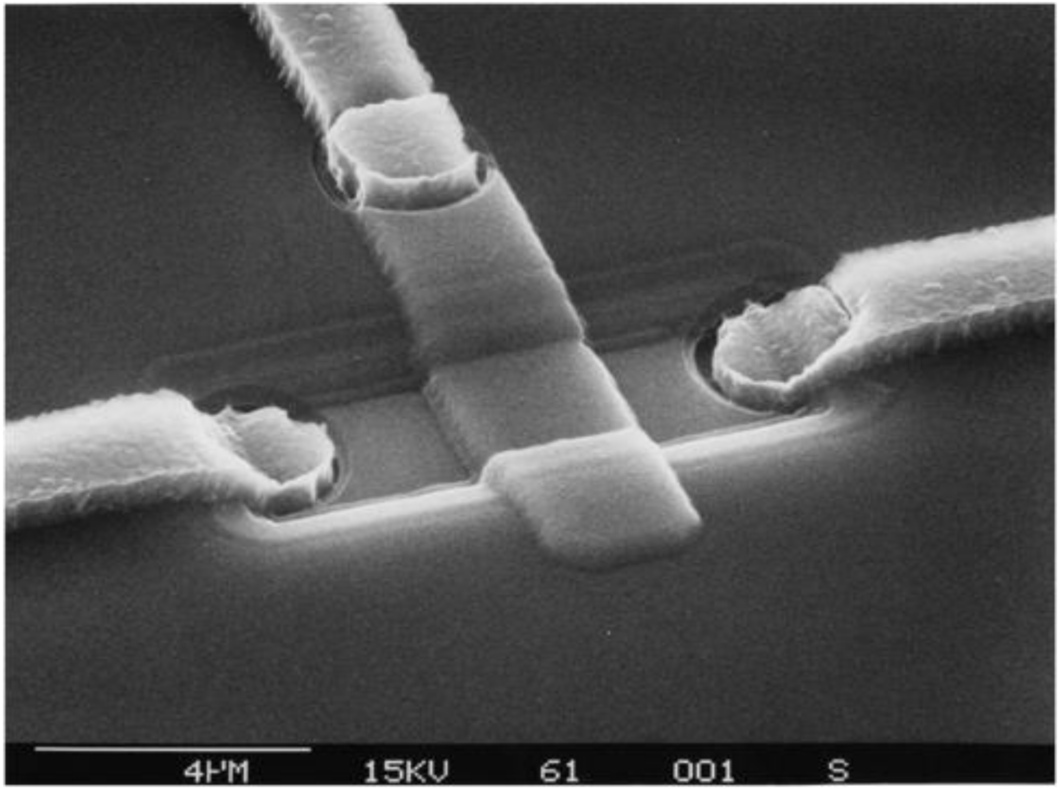
Beuville et al. NIM **A288 (1990) 157**

IC technology becomes accessible after 'Mead-Conway revolution' 1979

particle physics community learns how to design and implement Si IC

profit from continuous progress in Si CMOS

Silicon MOS transistor



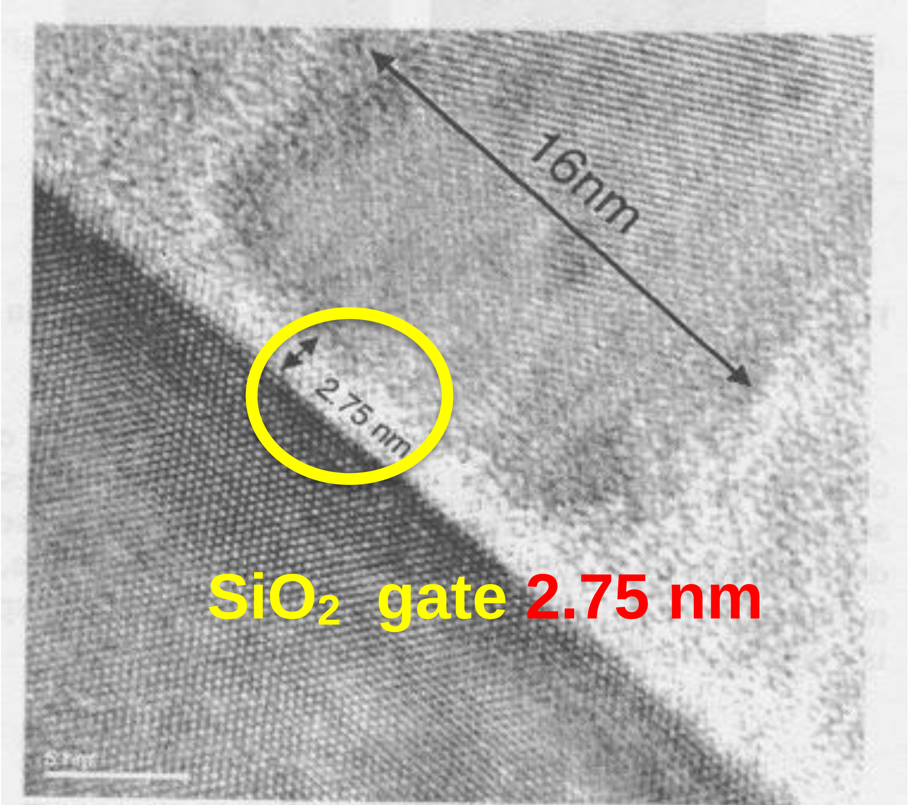


Fig. 1 : Hi-Res Cross section of the 16nm NMOS

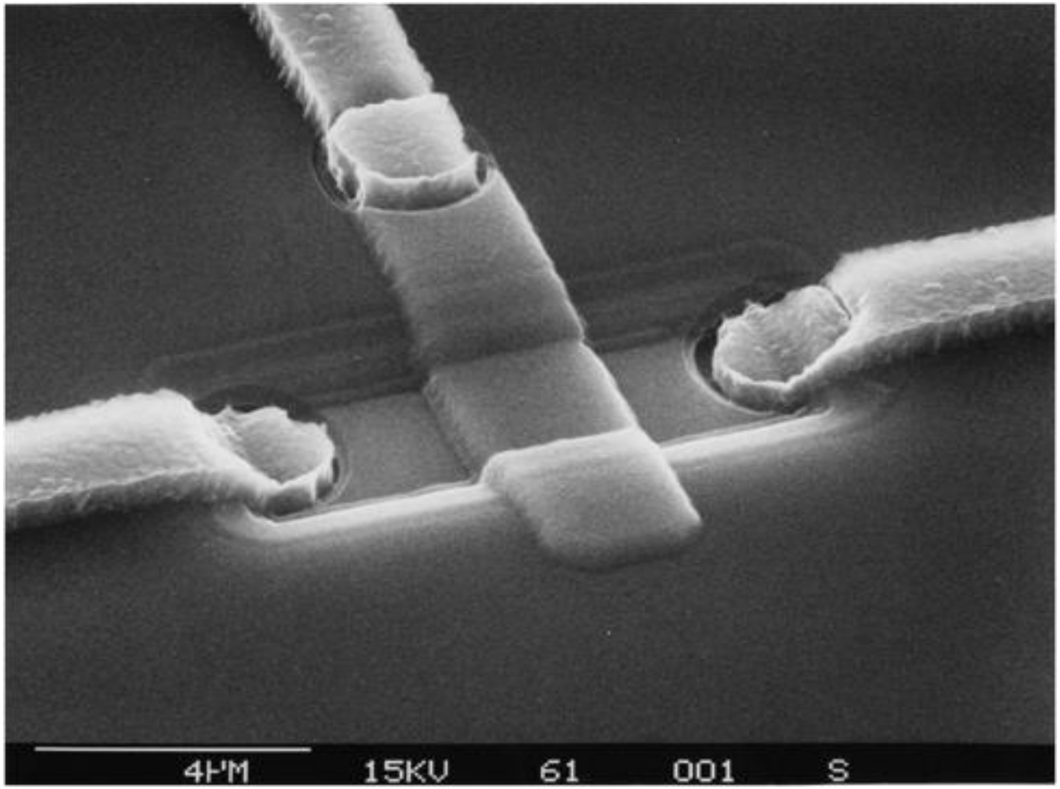
2 µm TECHNOLOGY **0.016 µm**

1985 **2015**

HEP was 2 generations behind industry

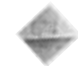
2015 HEP is 8 generations behind

Integrated electronics is key: silicon MOS transistor



continuous scaling/miniaturization

2015



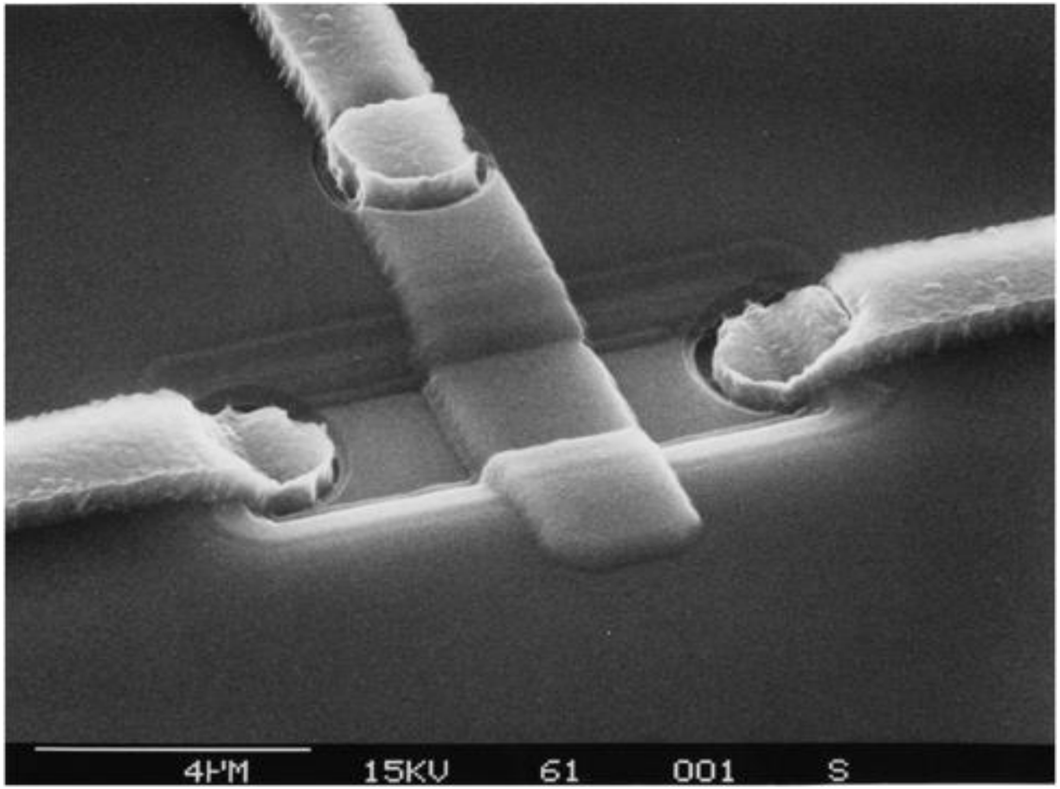
same scale

2 µm TECHNOLOGY 0.

1985

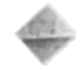
HEP was 2 generations behind industry

Integrated electronics is key: silicon MOS transistor



continuous scaling/miniaturization

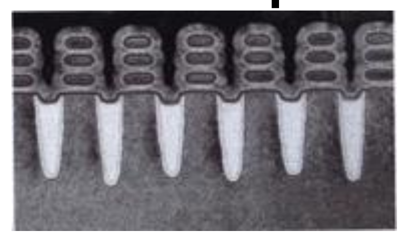
2015



same scale

gate length .016 µm
SiO_2 gate thickness 2.75 nm
thin gate usually radhard

2017 development at IBM



gate-all-around
source IBM

not same scale

2 µm TECHNOLOGY

1985

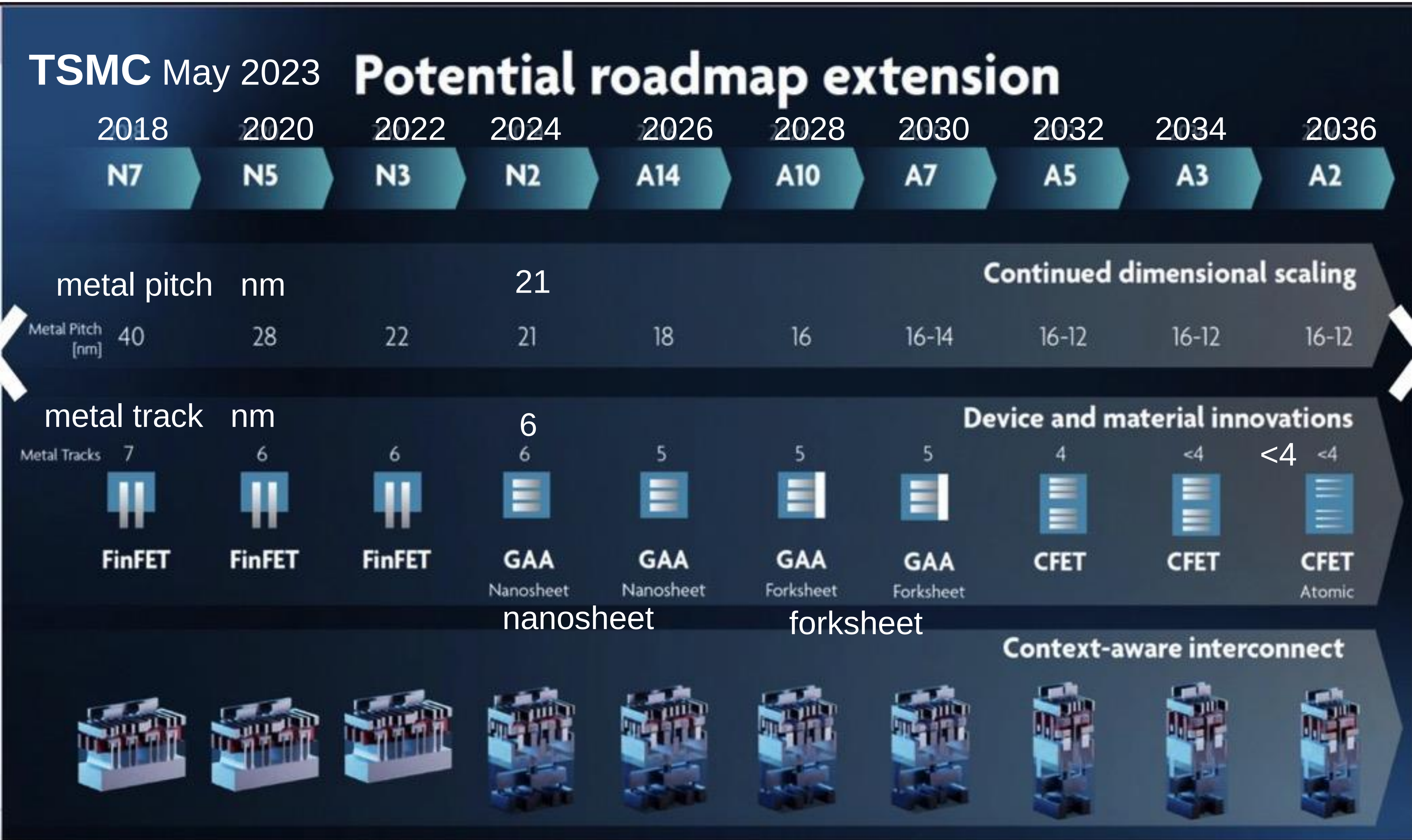
HEP was 2 generations behind industry

0.005 µm

2017

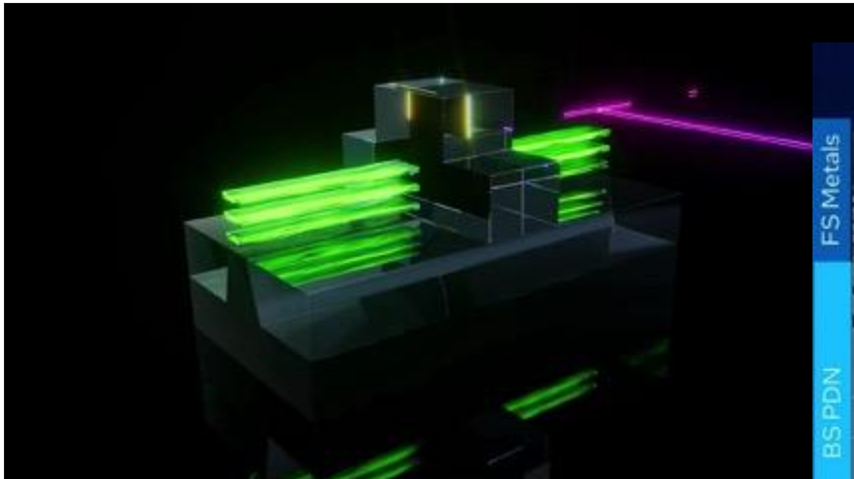
now HEP is 8 generations behind

Si technology 2023+

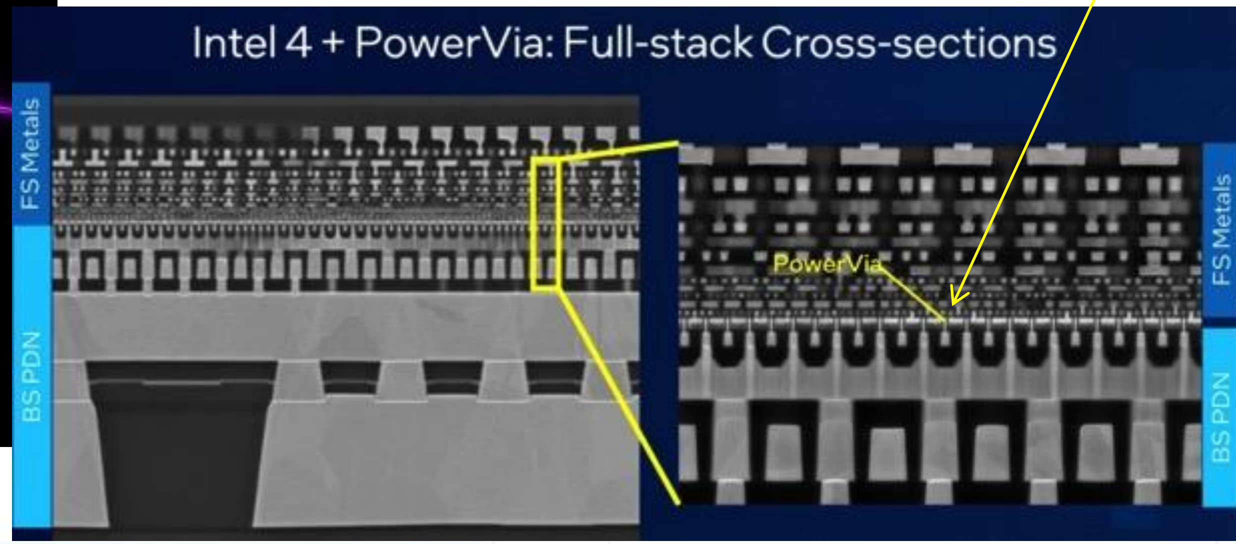


Si technology 2023+

nanosheet transistor TSMC

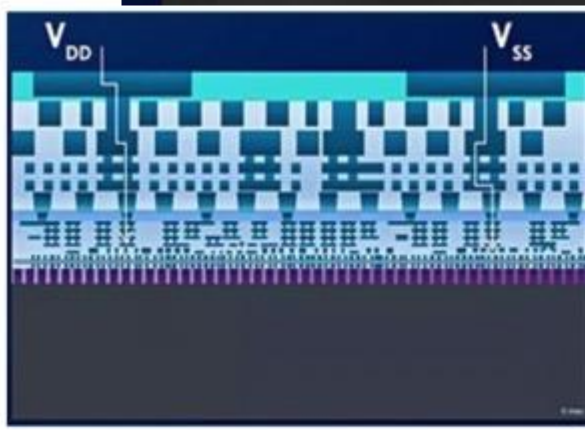


INTEL power supplies
both front and back, with via

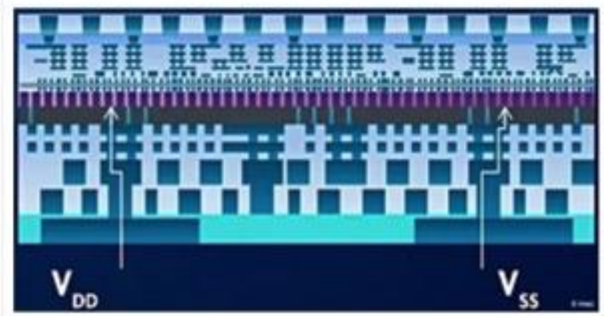


improves power distribution
shorter lines
more area available to
solve congestion

needs thin Si & nano – via's



TSMC power supplies
traditionally on front



V_{DD} V_{SS}

now from back side

Innovative Electronics developed in Nuclear/Particle Physics

Analog-to-Digital Converters ADC

1948 Wilkinson & Gatti, etc.

fast analog signal amplifiers

even operating at -200 ° C for Ge detectors
radiation spectroscopy

modular systems for signal/data processing

NIM, Camac, Fastbus, ... (Worldwide Web..)

ASIC design for analog and digital processing

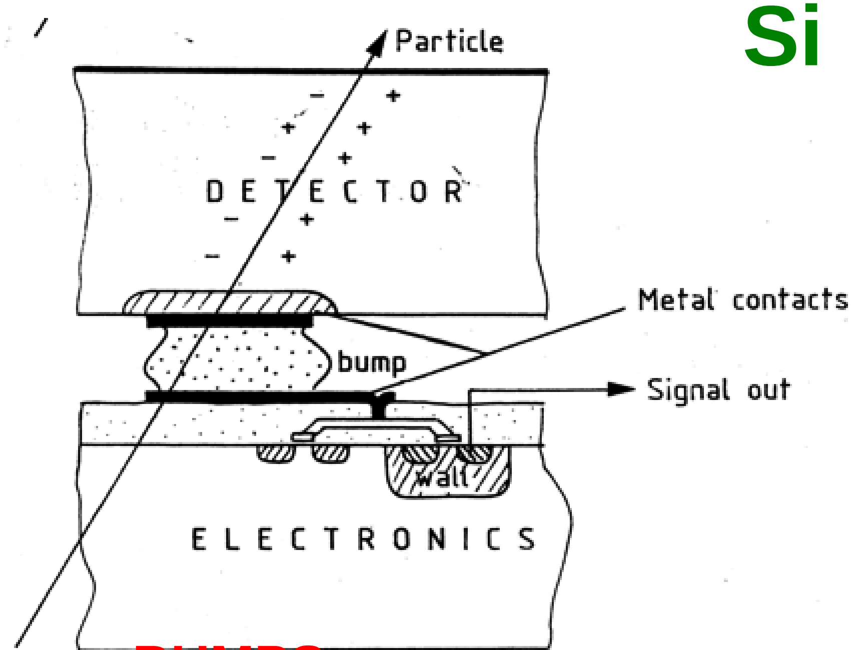
2D sensing/imaging instruments

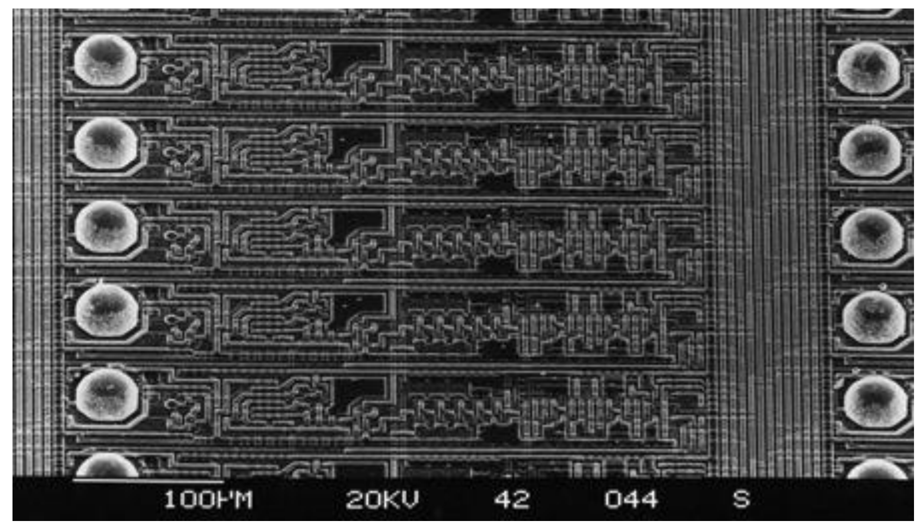
HYBRID Si PIXEL SENSOR 1991

CERN : CAMPBELL, HEIJNE

SENSOR MATRIX TRUE 2 - D

Si

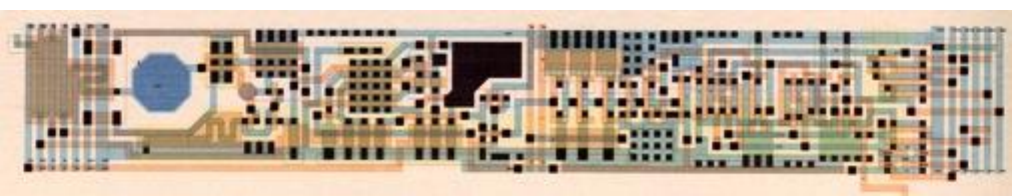




BUMPS

+

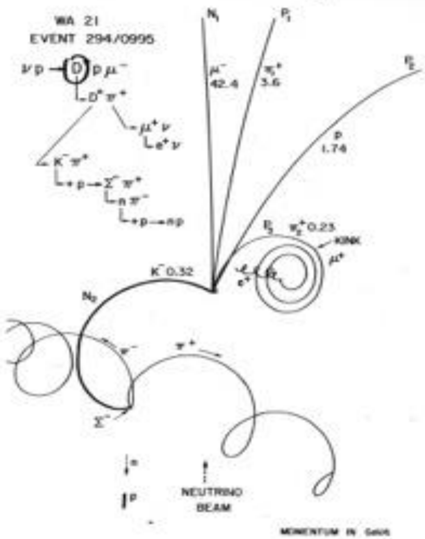
READOUT ELECTRONICS



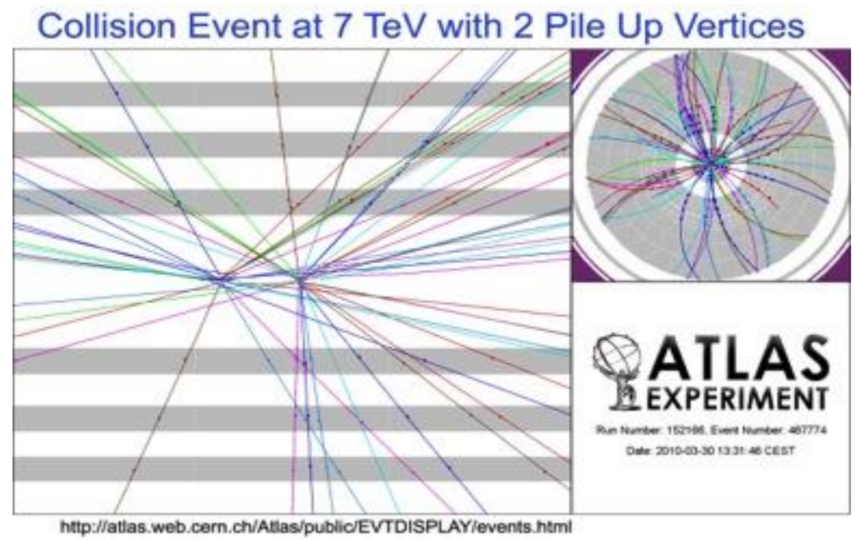
applied in ATLAS & CMS innermost Si pixel layer

source: CERN- ATLAS

Study of elementary particles: from Bubble Chambers to fully Electronic Imagers



ATLAS experiment 2012



BEBC 1981
photo every ~1s

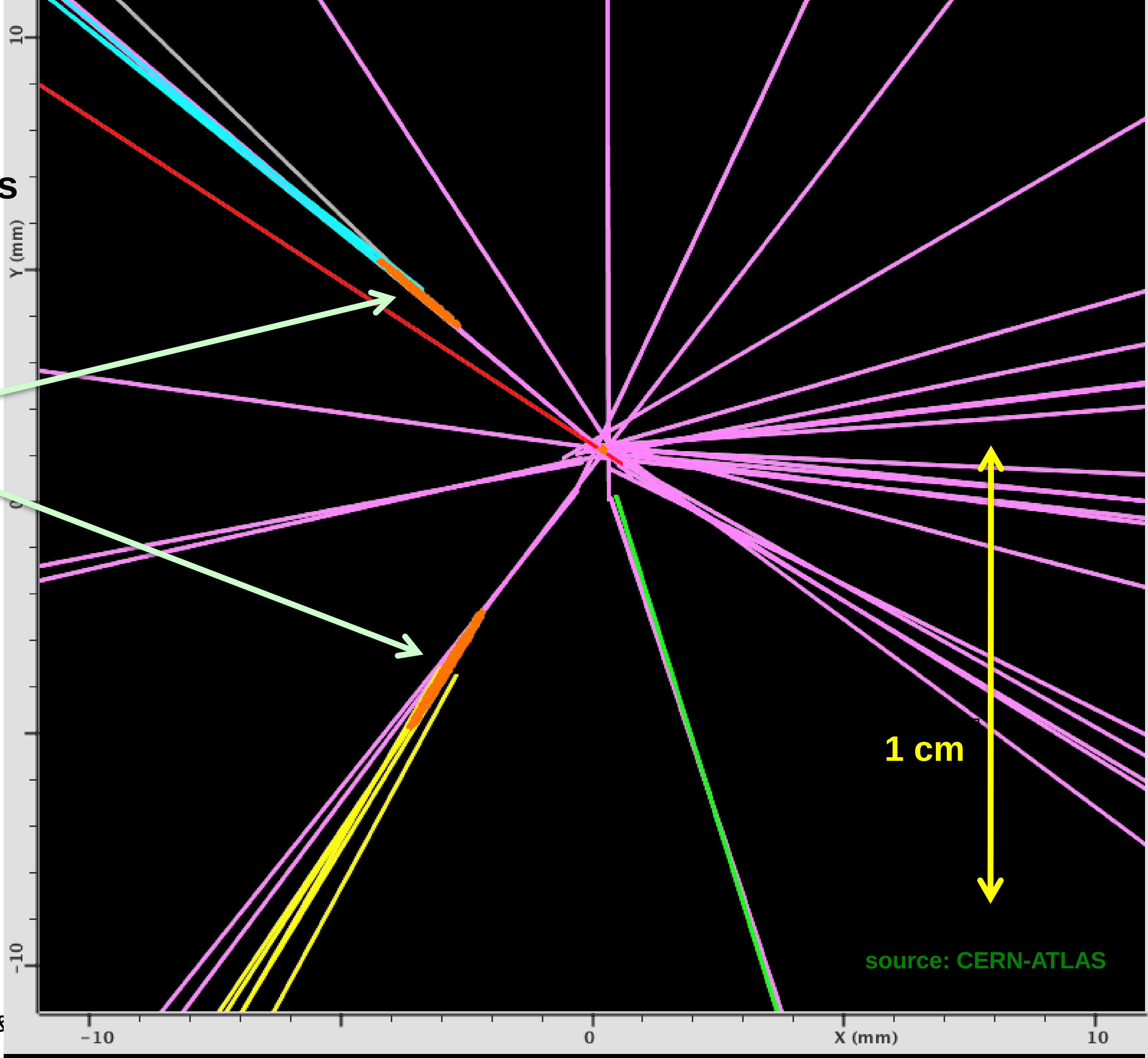
40 million records per s

Liquid H → silicon for vertexing **(but image information is lost)**

ATLAS exp at LHC

pixel system allows reconstruction primary vertex
+
two secondary vertices:
“messengers” for interesting interaction

Note scale
1cm
all this is INSIDE beam pipe ∅ 7cm



~2000 Medipix hybrid detector identifies particles

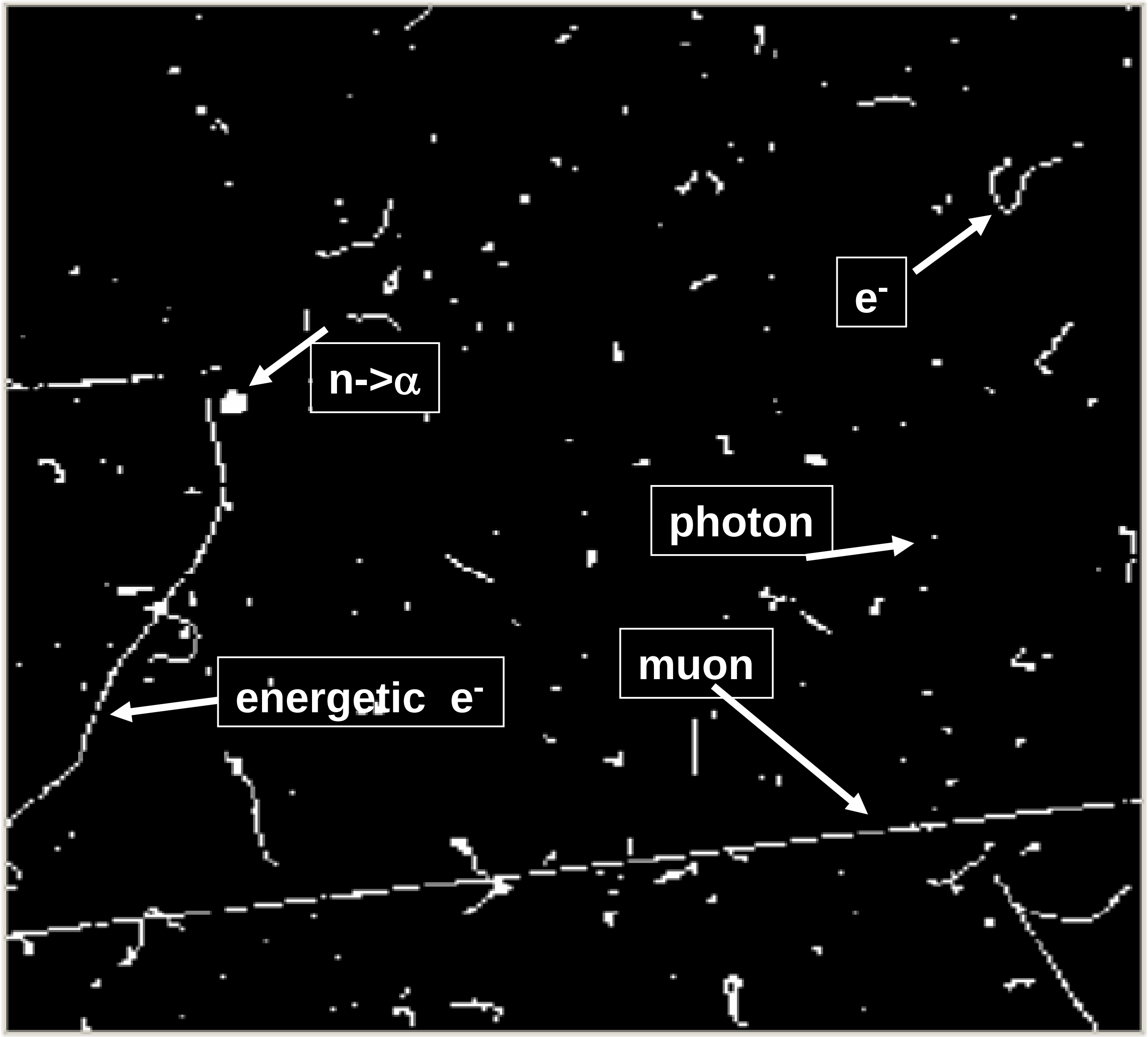
256 x 256 pixels
sensor matrix 300 µm
pixels just count 'hits'

can be used as radiaton dosimeter

IDENTIFY SPECIFIC QUANTA
- **electrons**
- **photons**
- **MIPs**

neutron -> interaction -> alpha
- **alpha's from decay**

pixel records up to 16k hits
in adjustable exposure time
ms – minutes - days
flux over large dynamic range



frame from IEAP CTU Prague

Timepix version in ‘USB’ stick

IEAP/CTU, Prague
Advacam : miniPix

new features implemented in each pixel:

signal amplitude – in-pixel ADC ToT

recording time-of-arrival of quantum ToA

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

H6 PION BEAM 2007

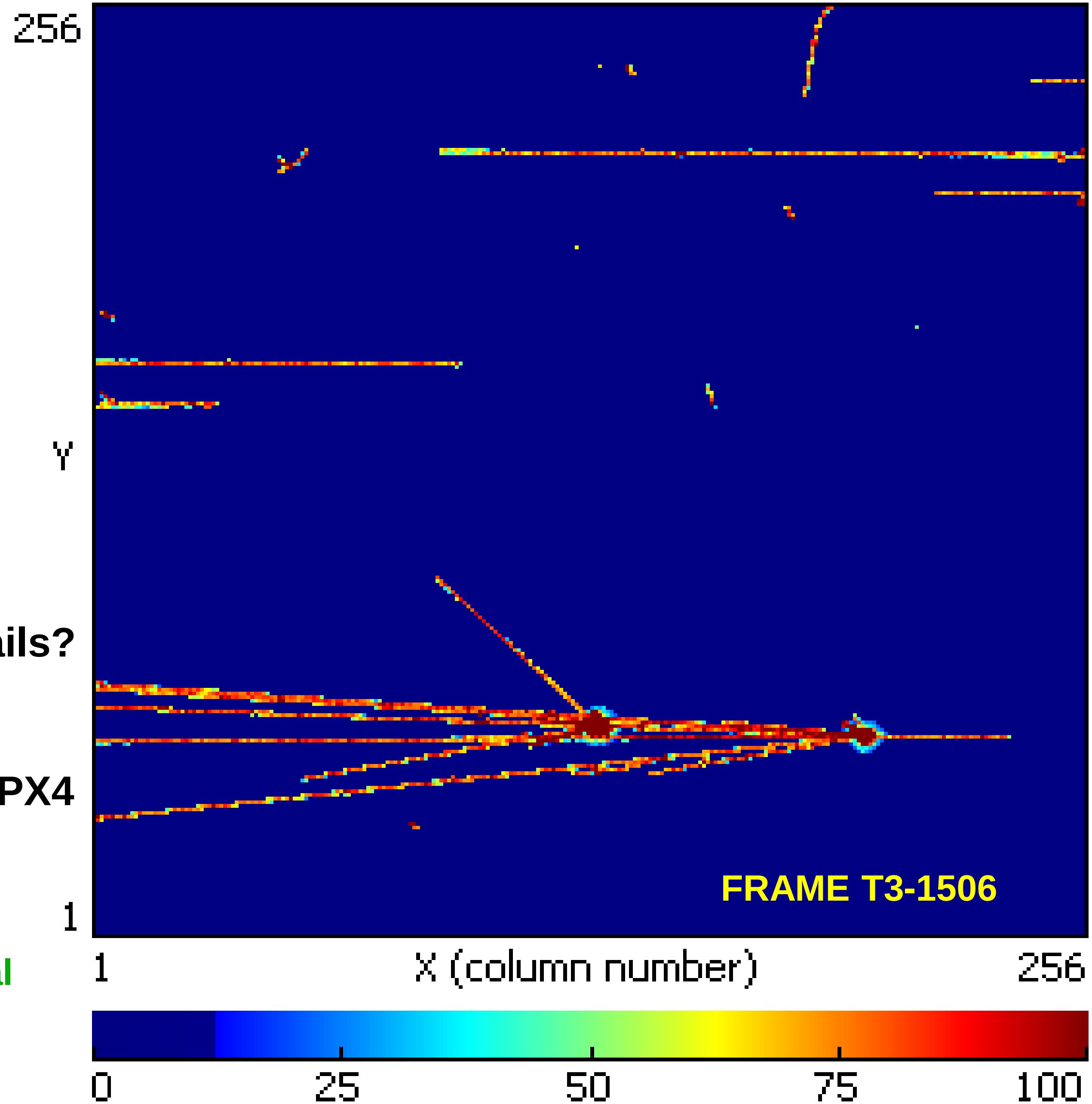
INCIDENT from RIGHT

BEAM

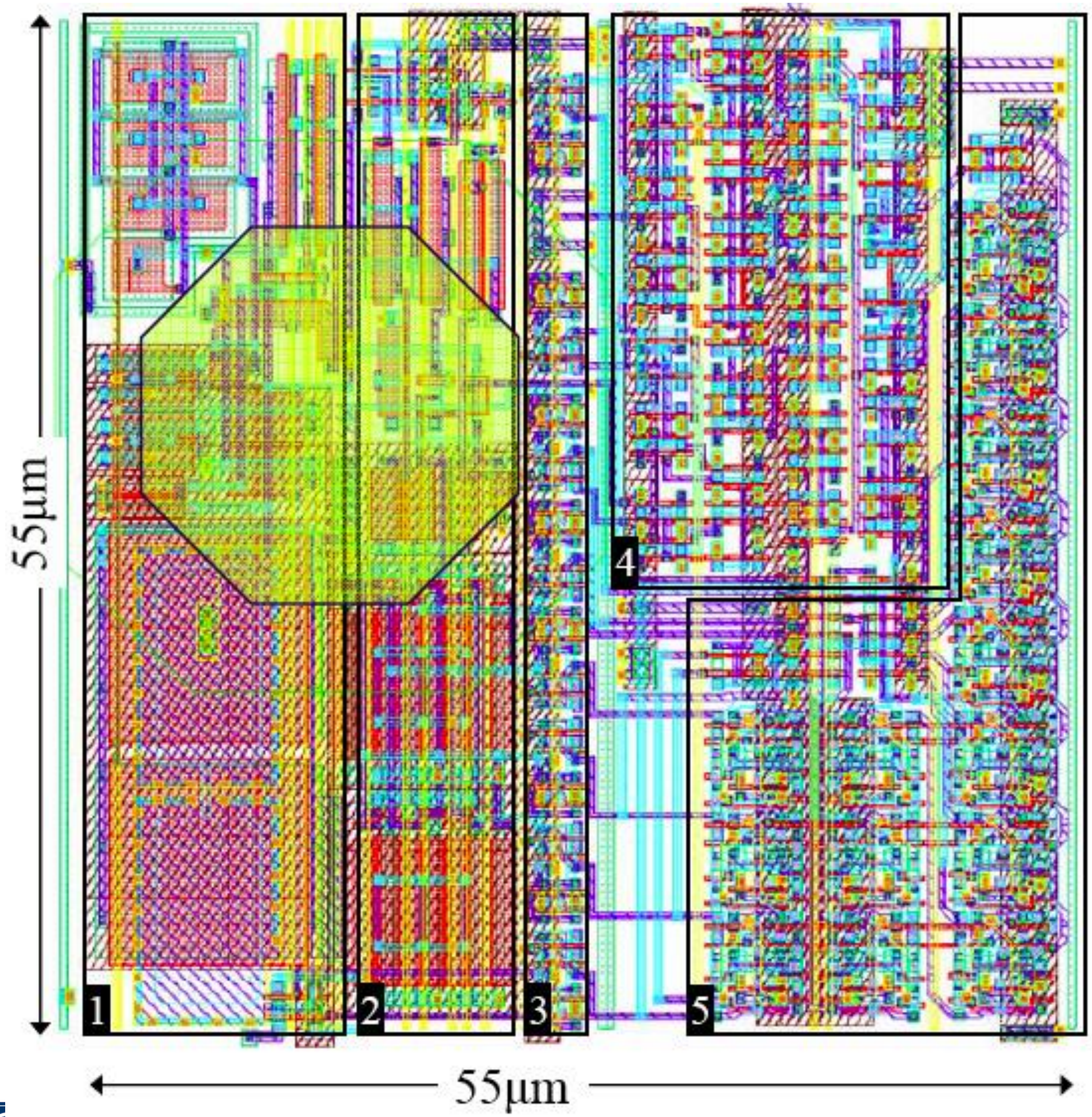
in which directions move the trails?

need simultaneous ToT & ToA implemented in TPX3, TPX2 & TPX4

Heijne with John Idarraga / Montréal



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

Timepix4 ready 2021

JINST 17 (2022) C01044

Timepix4, a large area pixel detector readout chip which can be tiled on 4 sides providing sub-200 ps timestamp binning

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[c] *Nikhef, Science Park 105, 1098 XG Amsterdam, The Netherlands*

[d] *IEAP Institute for Experimental and Applies Physics, Czech Technical University in Prague, Husova 240/5, 110 000 Prague 1, Czech Republic*

Timepix4 30x24.7 mm^2 connected to 4 Si sensors

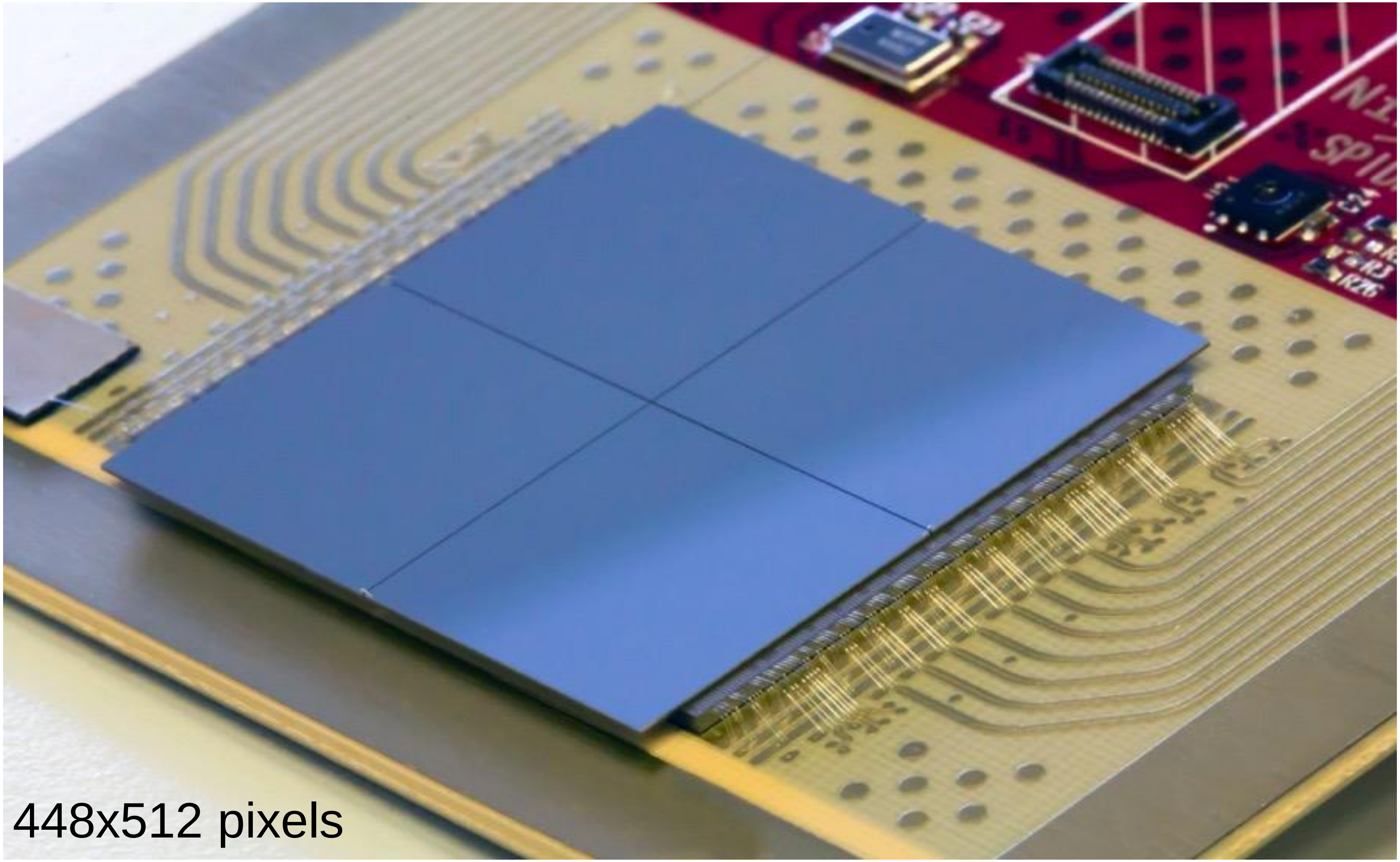
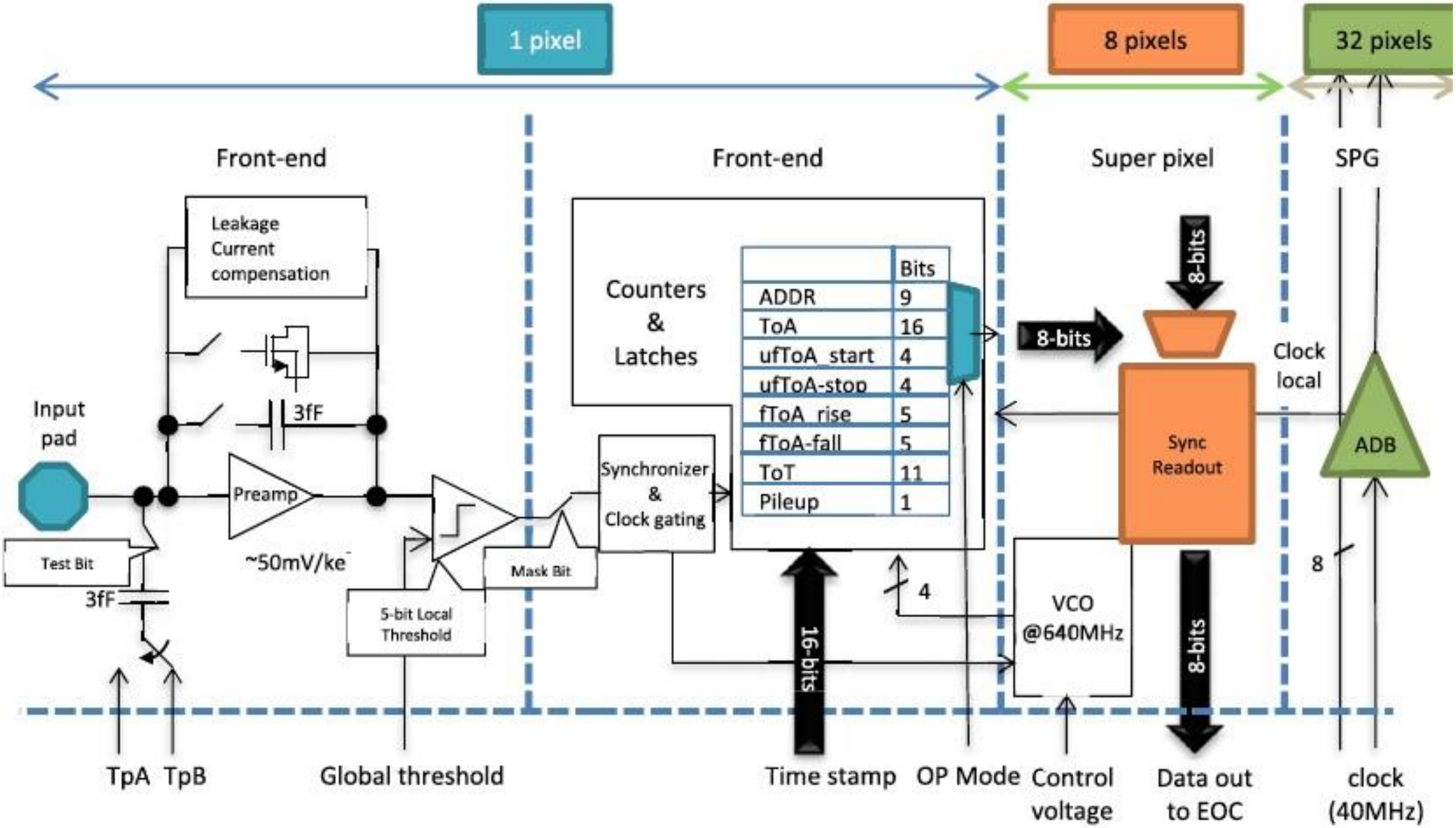


Photo M. Fransen, Nikhef

Timepix4 Pixel Schematic final

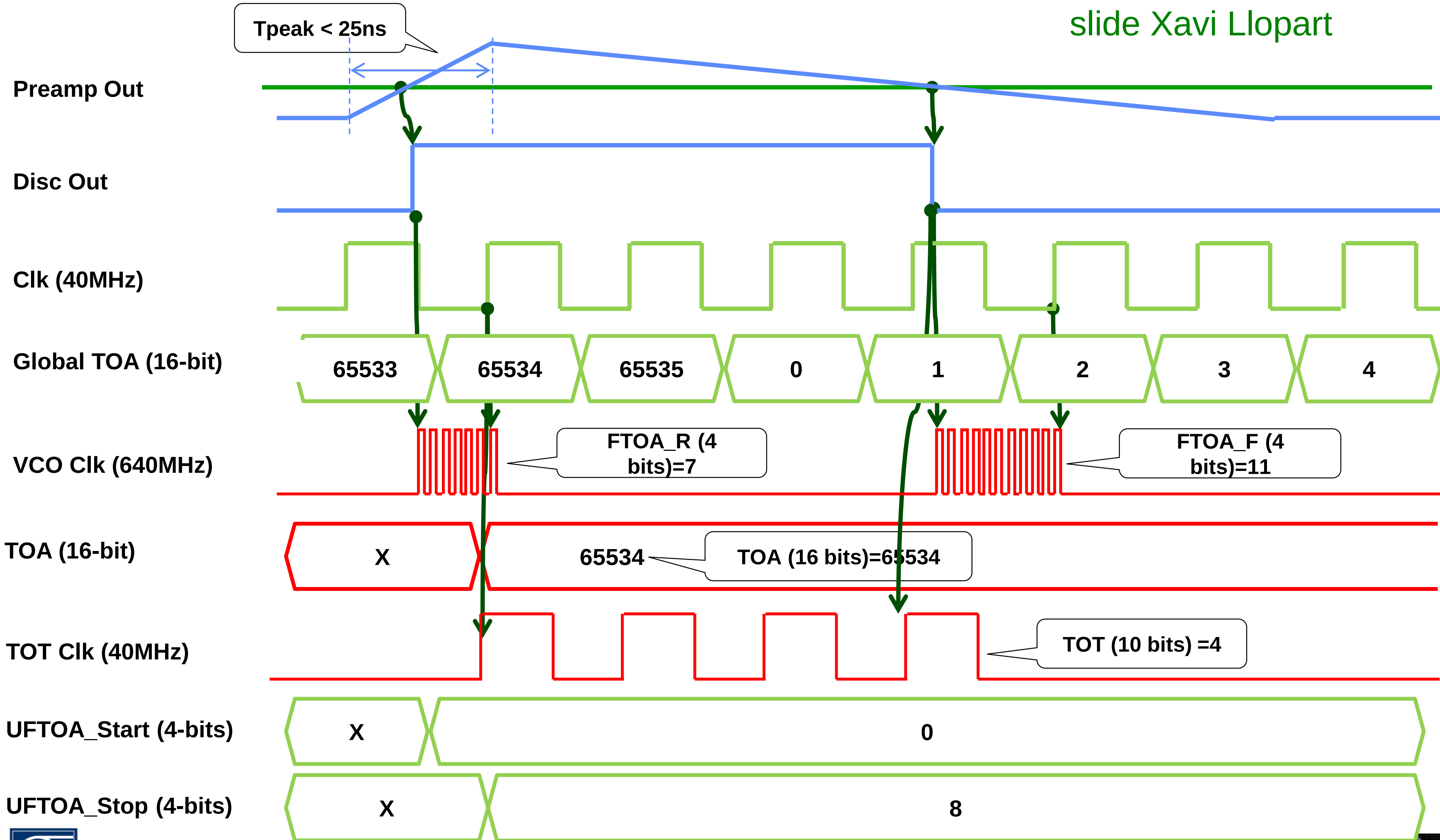
slide Xavi Llopart



medipix collaboration

TPX4 Pixel Operation in ToA & ToT, data-driven

slide Xavi Llopart



Timepix4 FE performance summary

slide Xavi Llopart

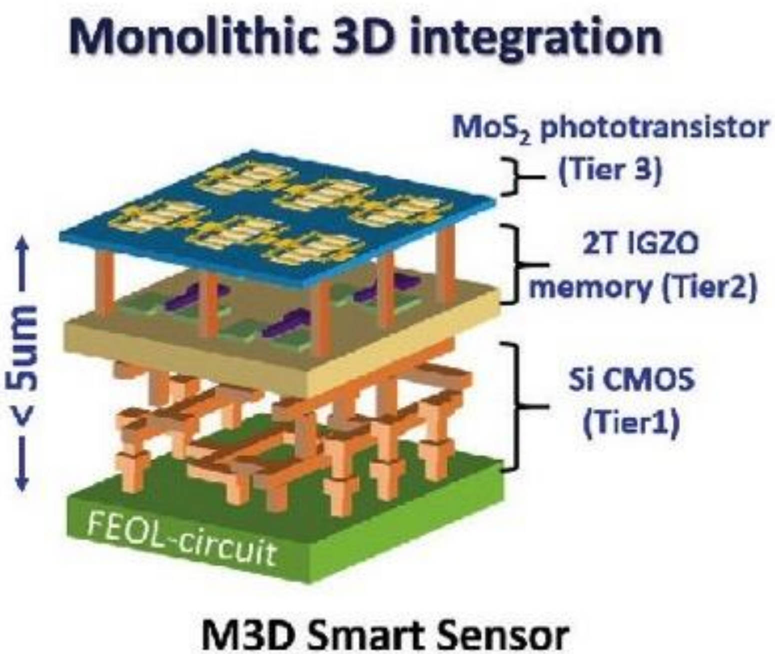
	e^- collection	h^+ collection	h^+ collection (log gain)
Gain	~50 mV/ke-	~50 mV/ke-	~25 mV/ke-
ENC (@Cin=50fF)	~60 $e-_{rms}$	~60 $e-_{rms}$	~65 mV/ke-
Minimum threshold	< 400 e-	< 400 e-	< 450 e-
TOA Jitter	<40 ps $_{rms}$ Qin > 10Ke-		
TOT linearity	< 250 ke-	< 200 ke-	< 800 ke-
Pixel analog power	<7.5uA (@1.2V, 9 µW)		

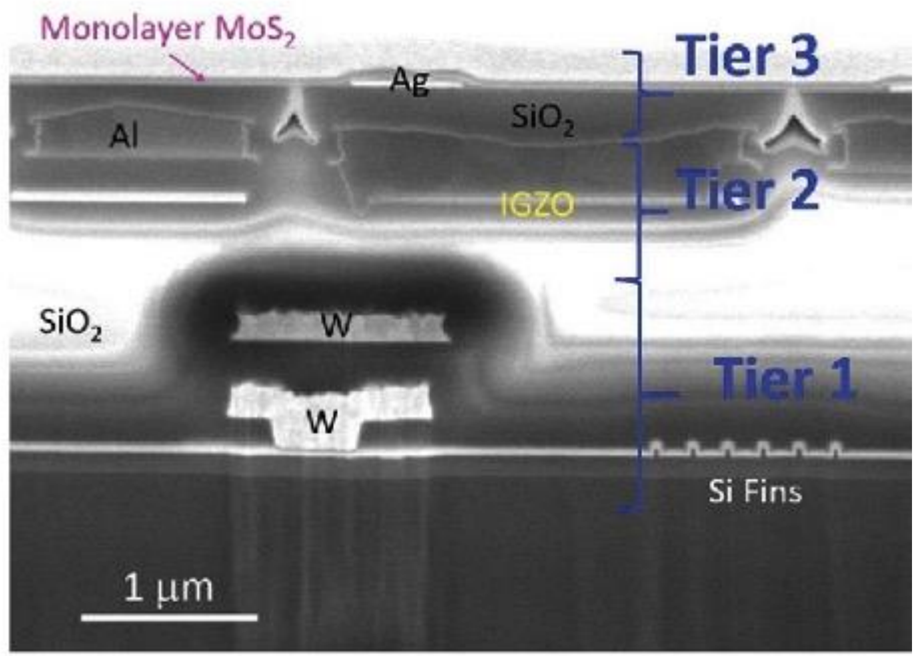
ENC vs Cin slope ~0.3 e^-/fF

ENC vs Ileak slope ~4 e^-/nA

bump-bonded imagers now quite 'obsolete'

this 1965 technology replaced by
3D multi-layer structures
using Cu-Cu interconnects & nano TSV





Samsung, 3-layer'monolithic' imager circuit
to be published IEDM 2023 **image from Semiconductor Digest Oct**

'Spin-off' outside particle physics

applications with single quantum imaging

'color' X-ray computed tomography

recognize organ composition, cheaper than MRI

analysis space radiation environment : ISS, ProbaV, .

see separate components, better dose value

atomic/molecular mass spectrometry

real-time counting of components

synchrotron X-ray diffraction

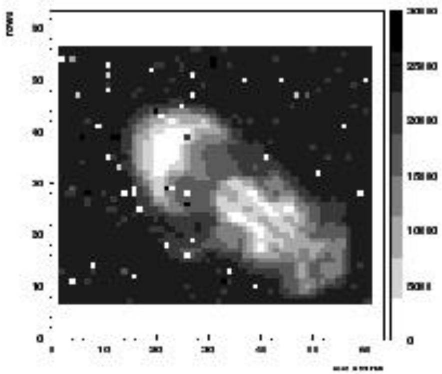
real-time instead of photographic film

DNA analysis also uses nanoscopic integrated circuits

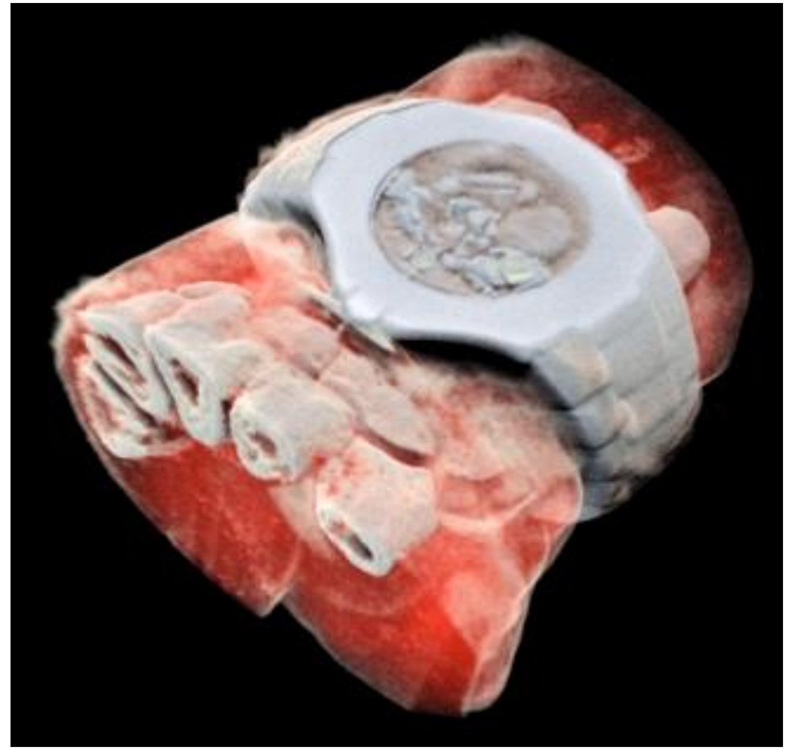
electron microscopy, etc.

spares

progress in X-ray images of objects: 1998 - 2019



Lukas Tlustos ~2001
with first PCC



MARS Bio imaging Canterbury
X-ray CT with Medipix3 2019

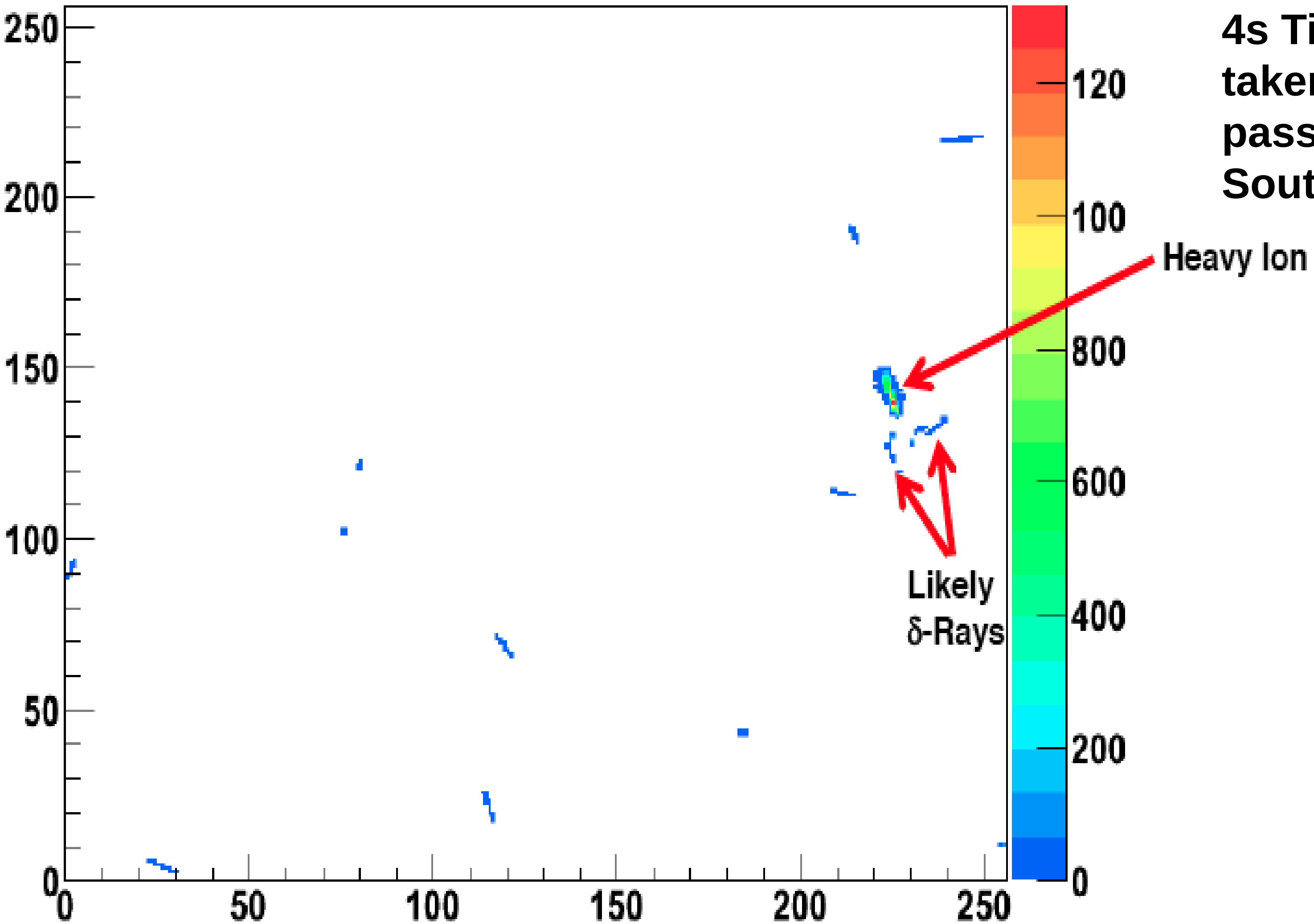
advances in processing of single photons

full potential finally <u>begins</u> to be exploited

Pixel chips for dosimetry in Int Space Station ISS

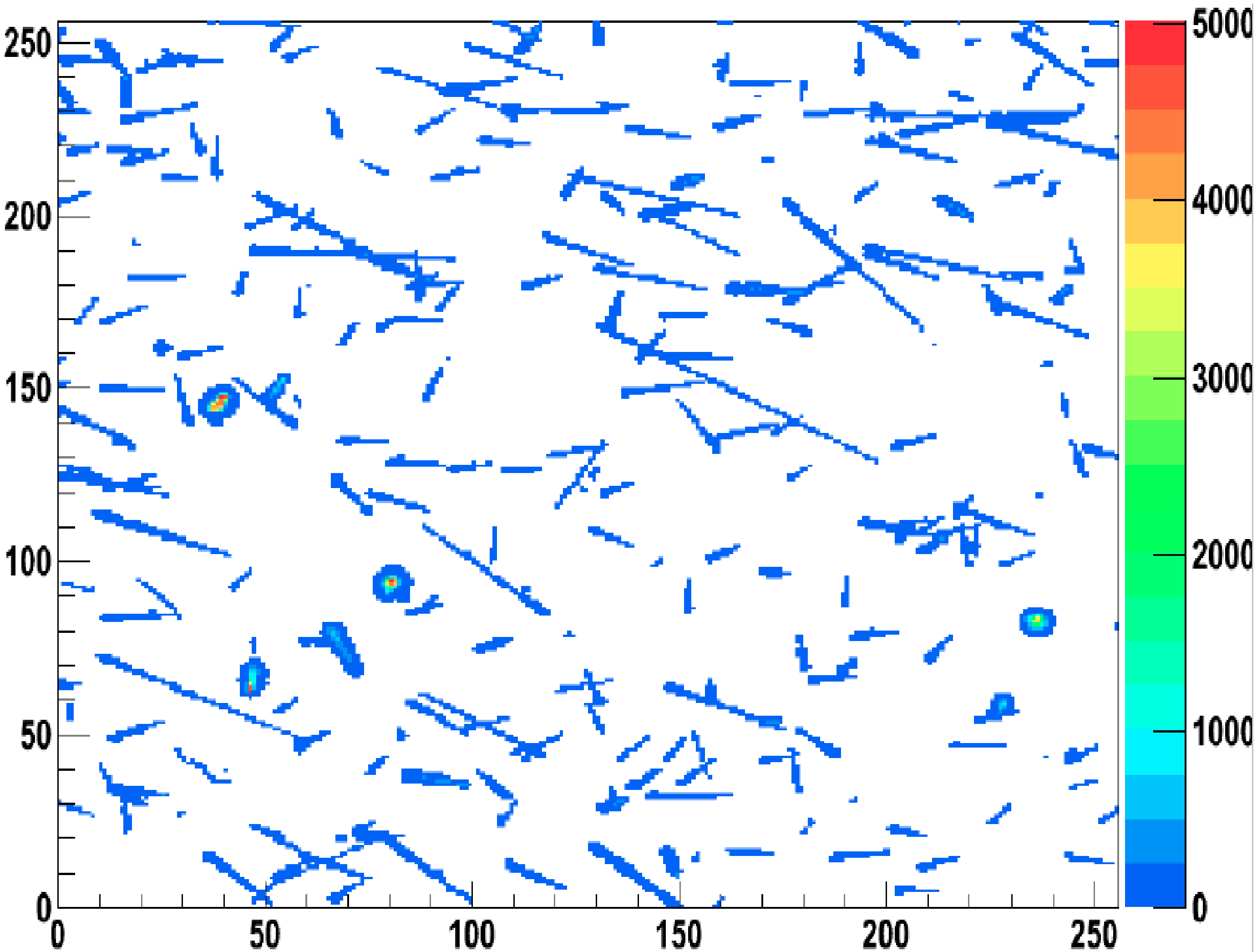
AMS largest experiment....
Pixel chip maybe smallest

Dosimetry at the Int Space Station ISS



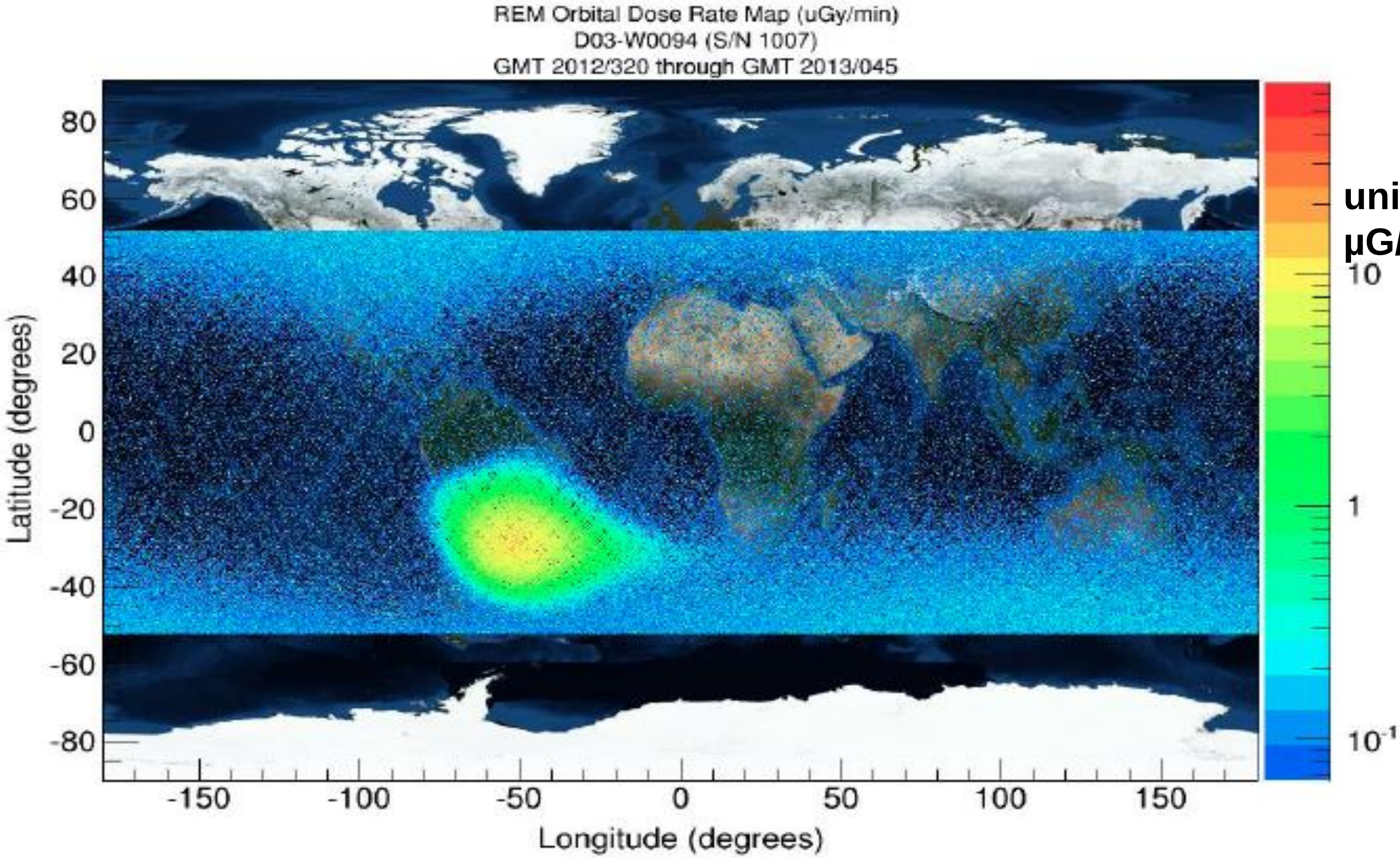
4s Timepix exposure taken in ISS passingover South China Sea

Dosimetry at the Int Space Station ISS



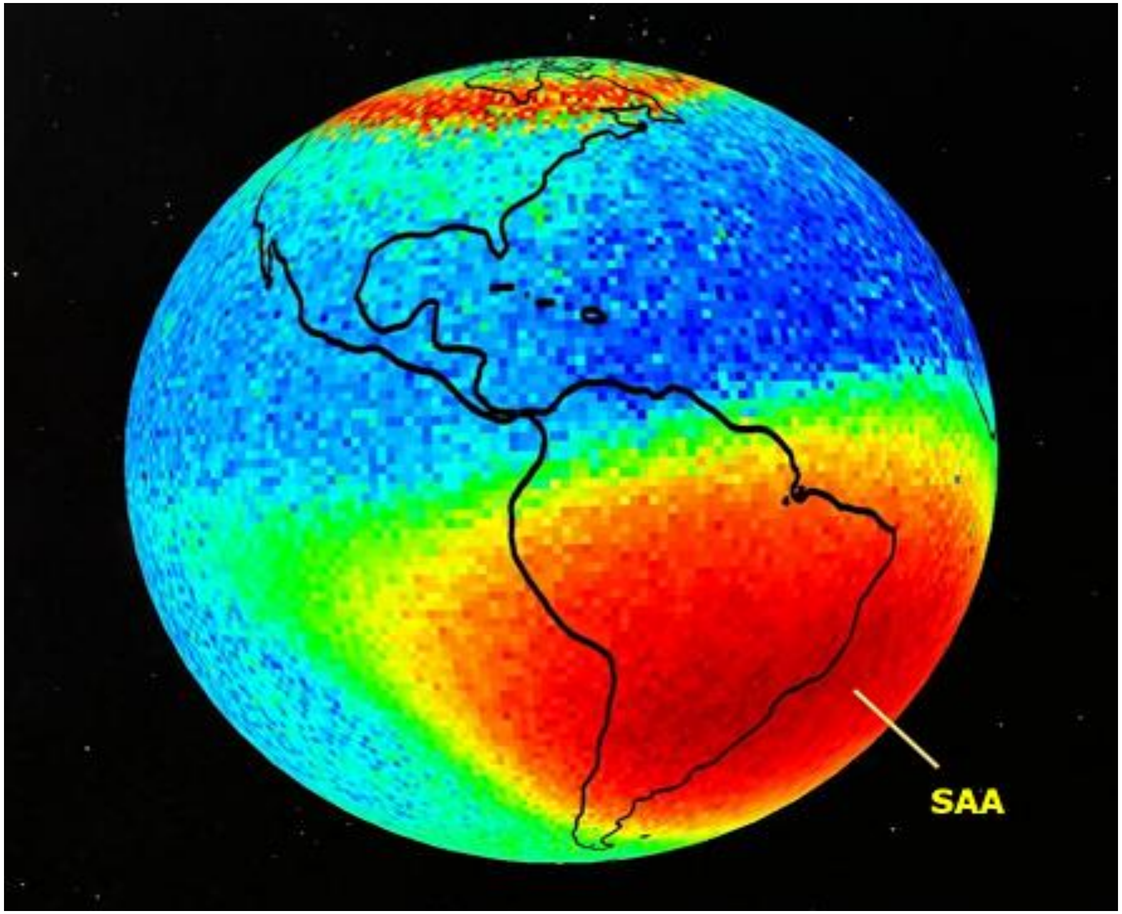
4s Timepix exposure taken in ISS passing through SAA South America Anomaly

Dosimetry at the Int Space Station ISS

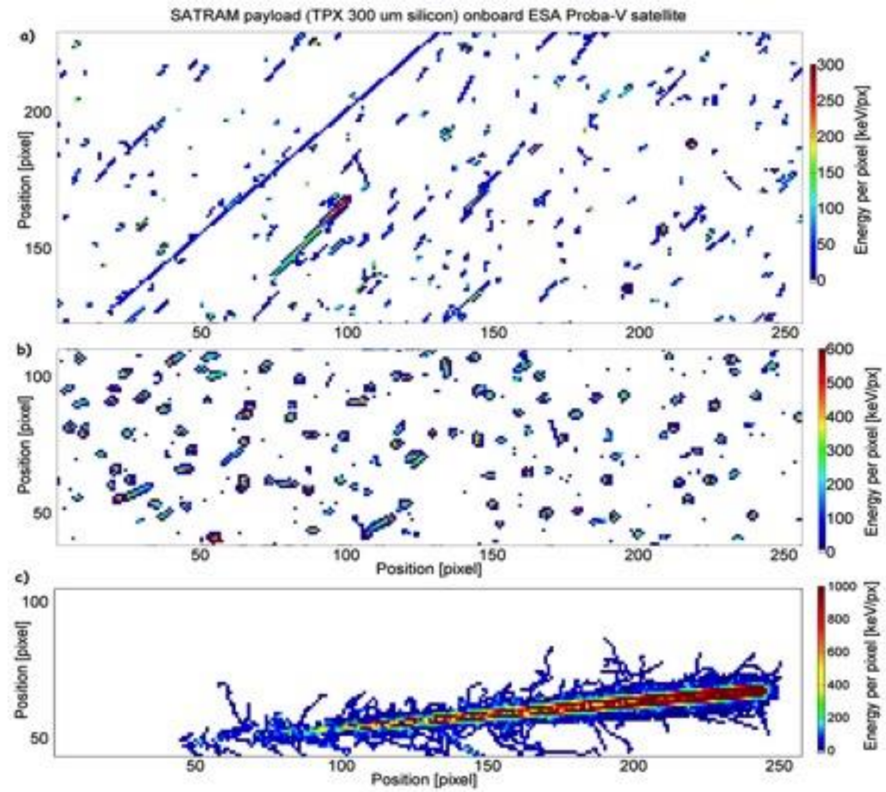


units μG/min

dosimetry with TPX on ESA satellite Proba-V



frames in LEO orbit ~800km, different positions



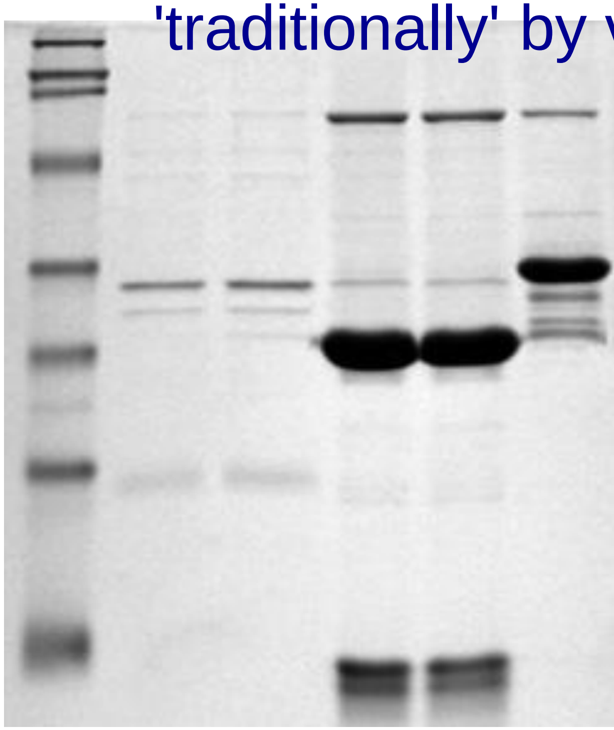
courtesy Carlos Granja IEAP-CTU (2015)

ion track with ∂ electrons

Timepix to replace'classical' methods

molecular mass spectrometry

'traditionally' by very slow gel-electrophoresis

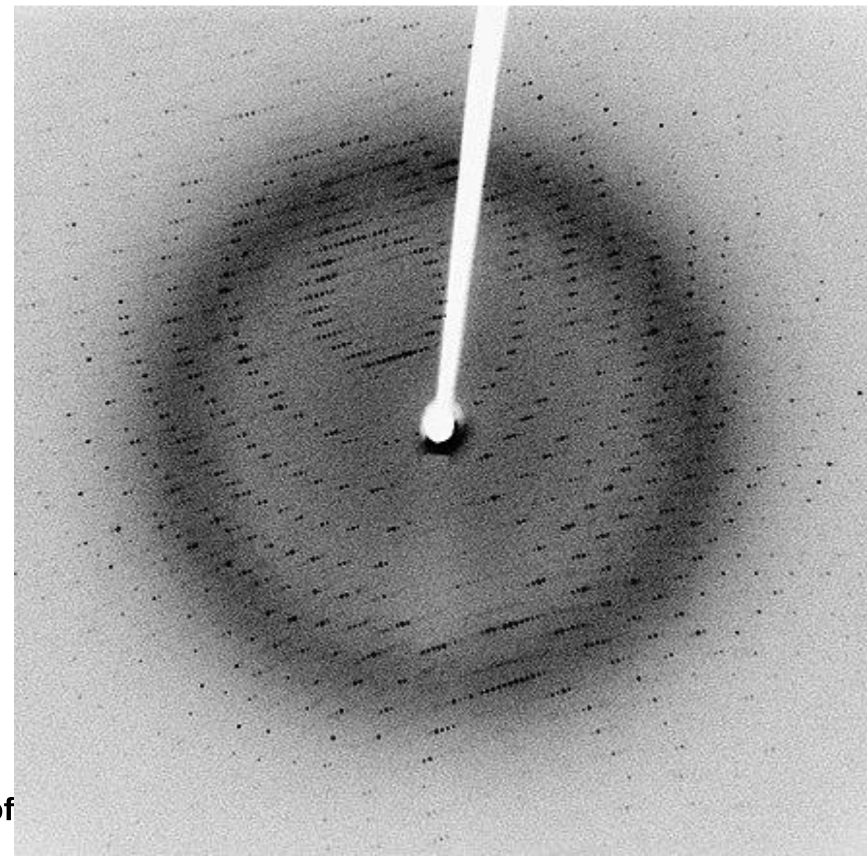


synchrotron X-ray diffraction

'traditionally' by photography

real-time recording

can follow sample degradation



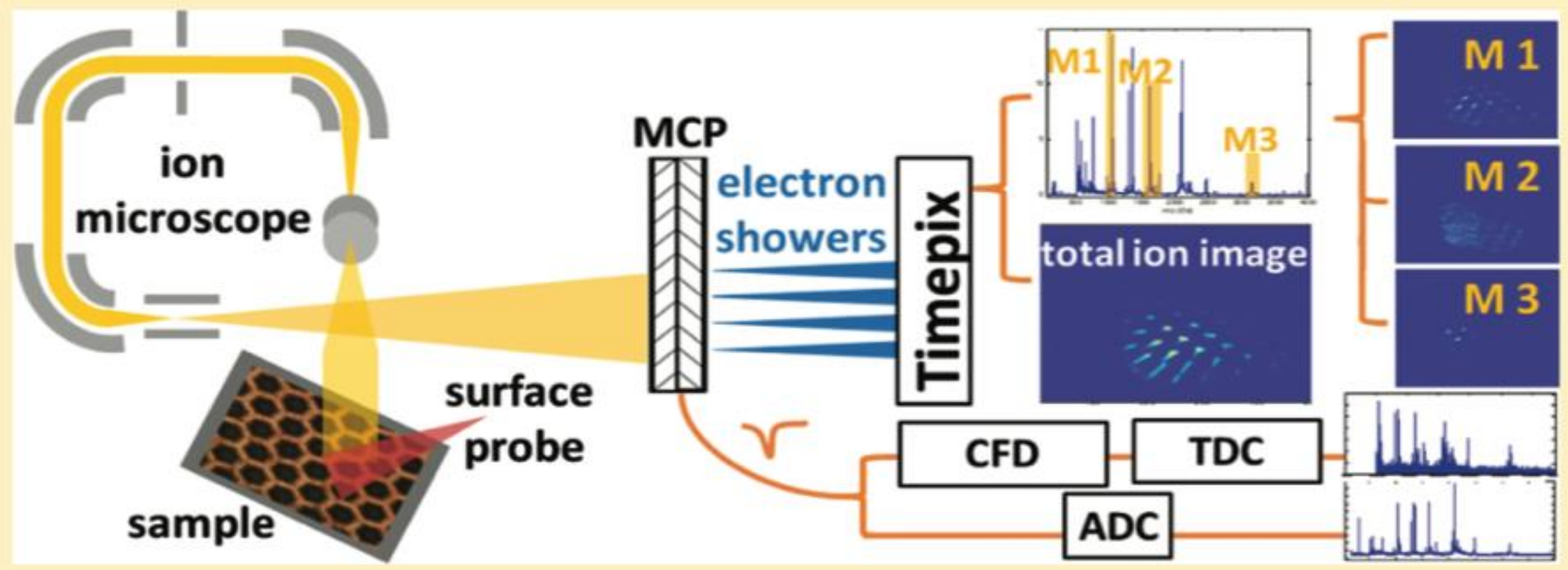
ToF Mass Spectrometry Imaging

FOM Institute AMOLF

Novel detection capability for large biomolecules in time-of-flight (TOF) based mass spectrometry imaging (MSI)

Using a Timepix quad (512x512) assembly combined with a chevron microchannel plates (MCP) captures time-resolved images of several m/z species in a single measurement

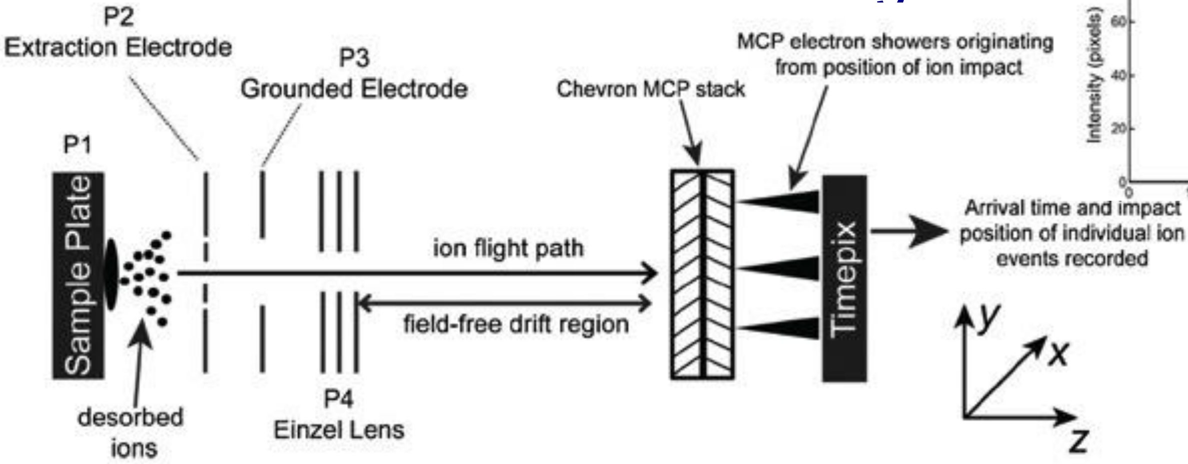
Timepix delivers an order of magnitude greater detectable range than an ADC and returns mass spectra for MCP gains from 4×10^5 to 6.5×10^6

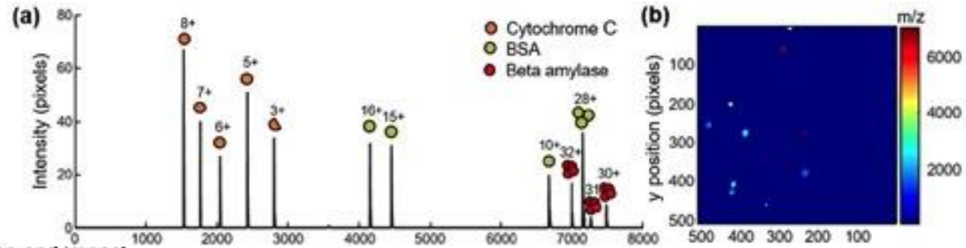


Timepix to replace'classical' methods

molecular mass spectrometry

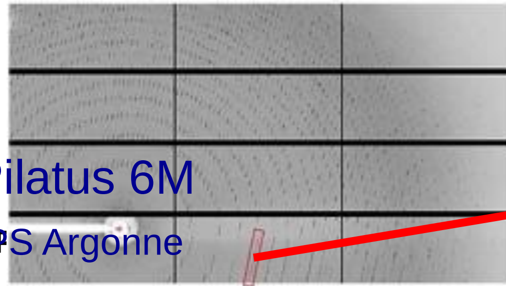
now vacuum 'time-of-flight'





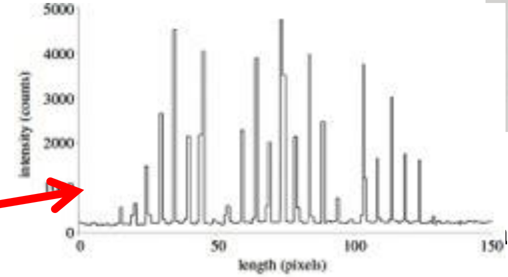
synchrotron X-ray diffraction

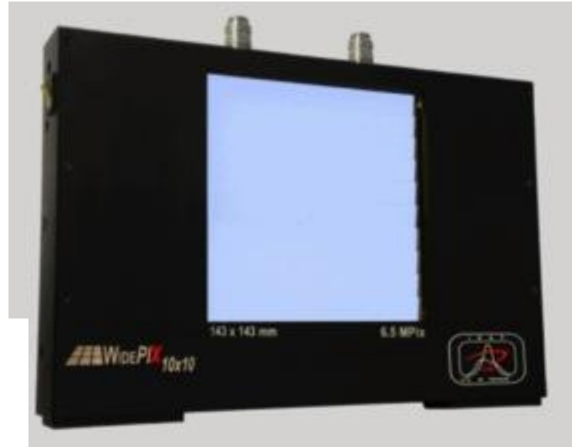
now photon counting Si imagers



Pilatus 6M

APS Argonne





WIDEPIX 10X10

revealing the earth

nuclear methods, accelerators and detectors:

innovation for scientific & practical applications:

an example: absolute geochronology

relative isotope content U-Pb, Pb-Pb, K-Ar ratio's in rock → Ga

isotope ratio mass spectrometry could use Timepix detector

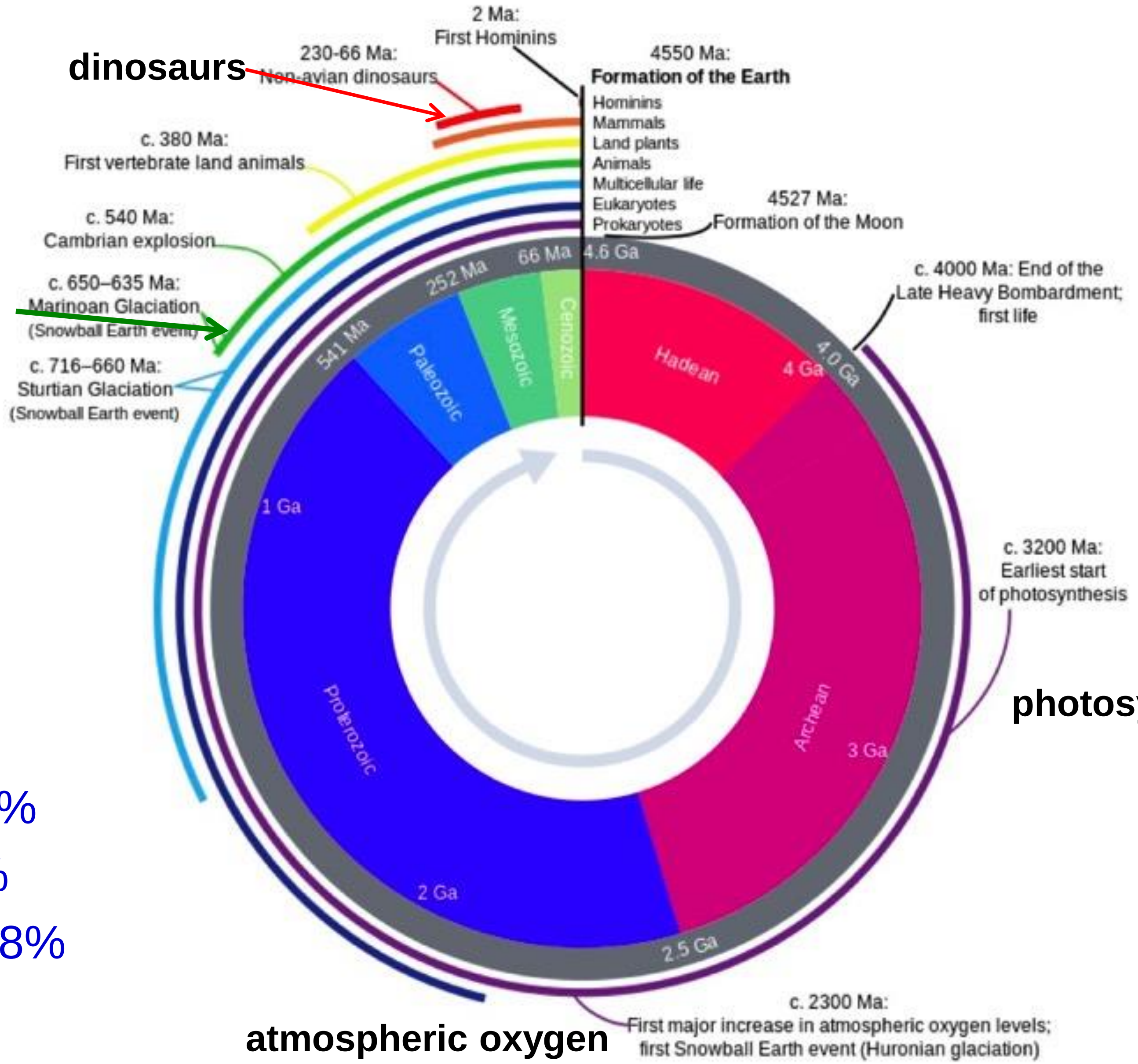
radiocarbon 14 dating characterizes bio materials over millenia ~60ka

atomic/molecular mass spectroscopy ionToF replacing electrophoresis

detectors always need clever electronic circuits

this Workshop....

The earth developed over 4550 million years



Earth's history with time-spans of the eons to scale

diagram
Wikipedia

earth crust :

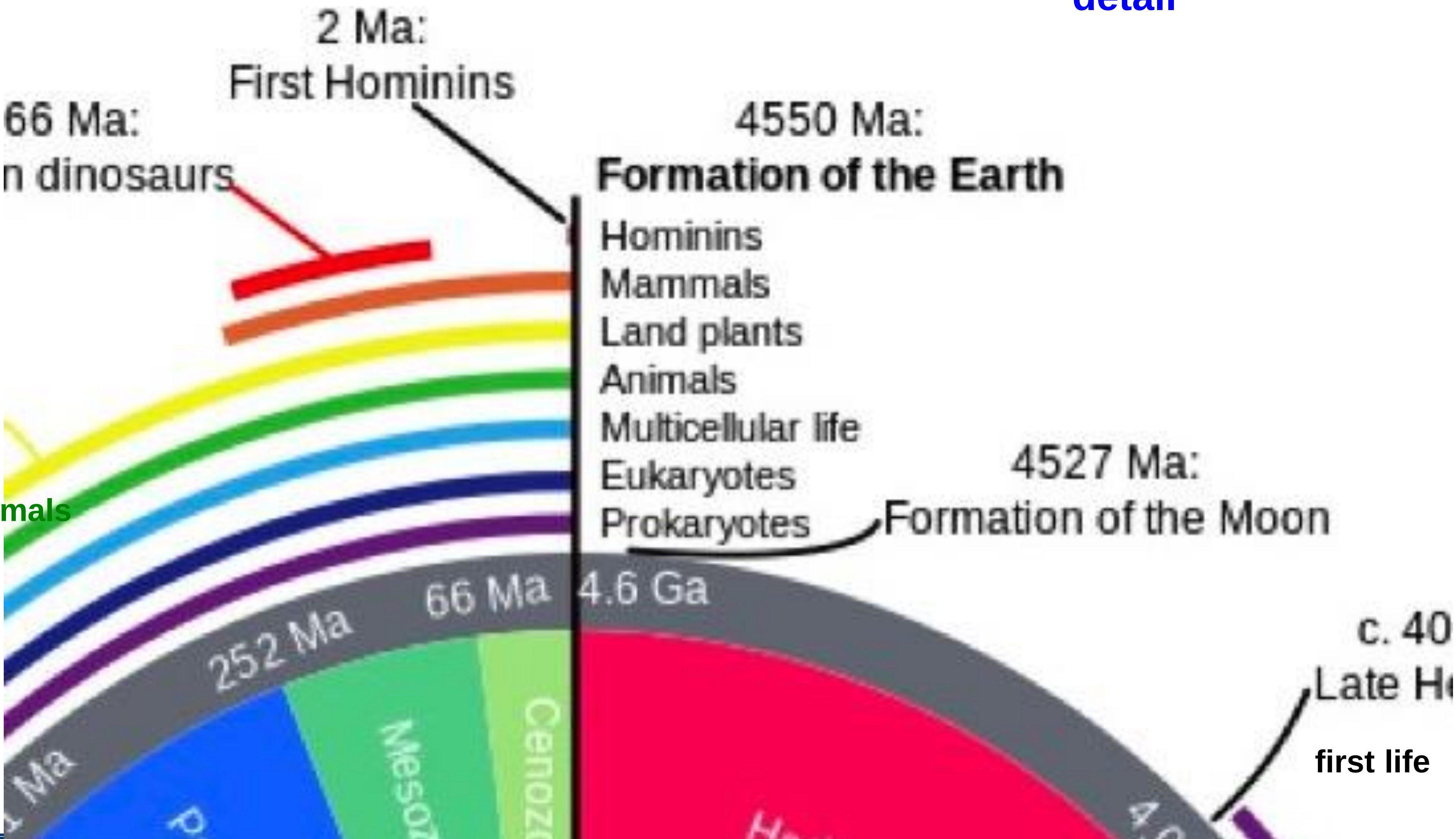
O oxygen 46%

Si silicon 28%

C carbon 0.08%

The earth developed over 4550 million years

detail



animals

first life

thoughts about some difficulties

collective behaviour of electrons/holes in crystal

unique energy levels & bandgap for charge carriers

other quantum effects in chips at nm dimensions?

particle/wave duality observed/used in chips ?

use of entangled photons or electrons ?

A few comments at the end

Use everything that the incoming quantum can tell you

its type/mass, E, dE/dx, position, direction, time of incidence, ..

also polarization, light emission,??? future

Sensor material and thickness can be optimized

thin for timing, thin+low Z for particle tracking

thick + high Z for X-ray imaging

Segmentation depends on area-need processing electronics

large pixels can give better energy value, avoid summing

small pixels give characteric clusters, improved positions

the smaller the better?   dynamic sizing of pixels?

Electronics must aim at lowest power and noise

Integration using 3D technologies for better overall system

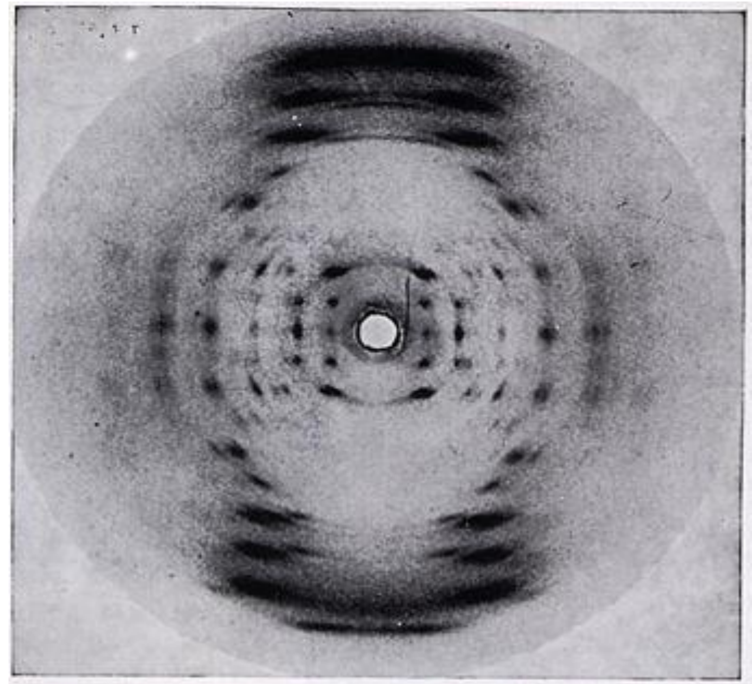
Thank You

Spares

silicon for DNA analysis

Crick & Watson used DNA single crystal and X-ray diffraction photography

limited structural analysis

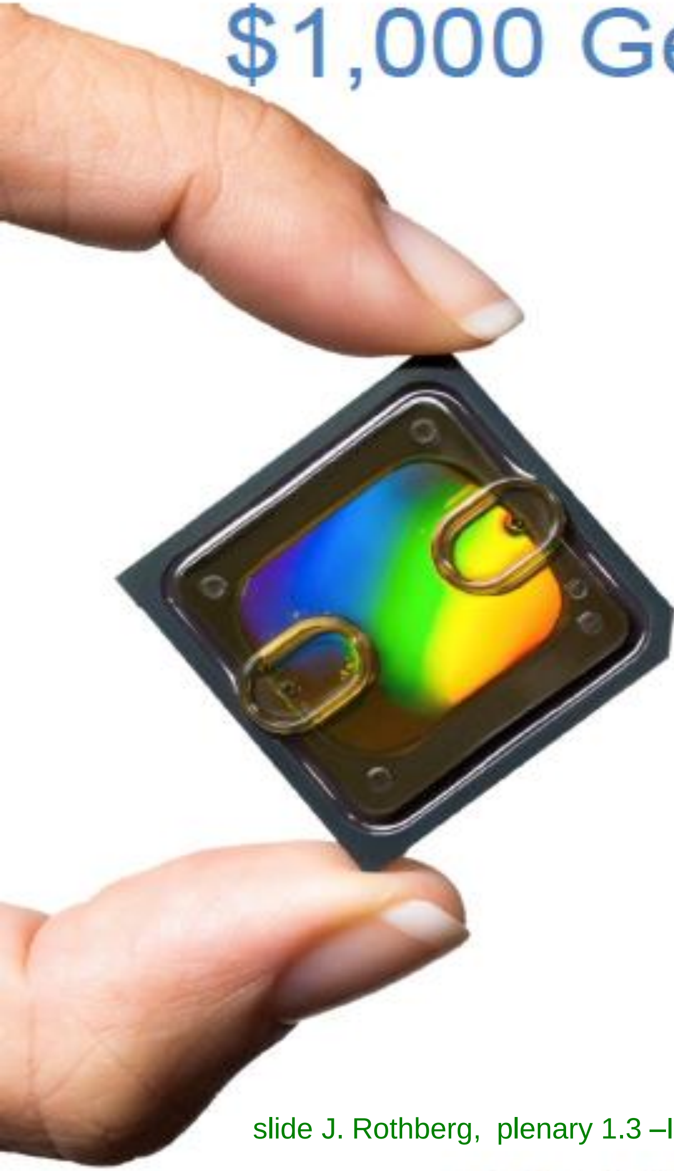


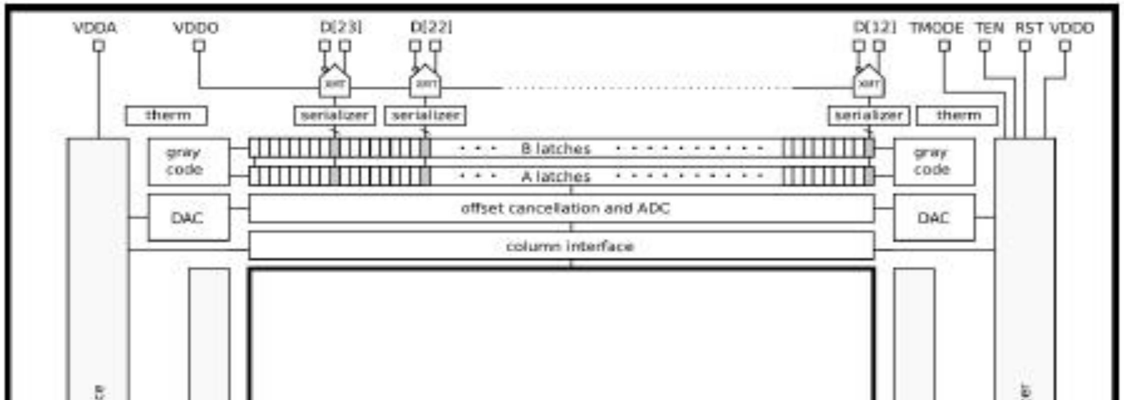
An X-ray photograph of crystalline DNA in the A form.

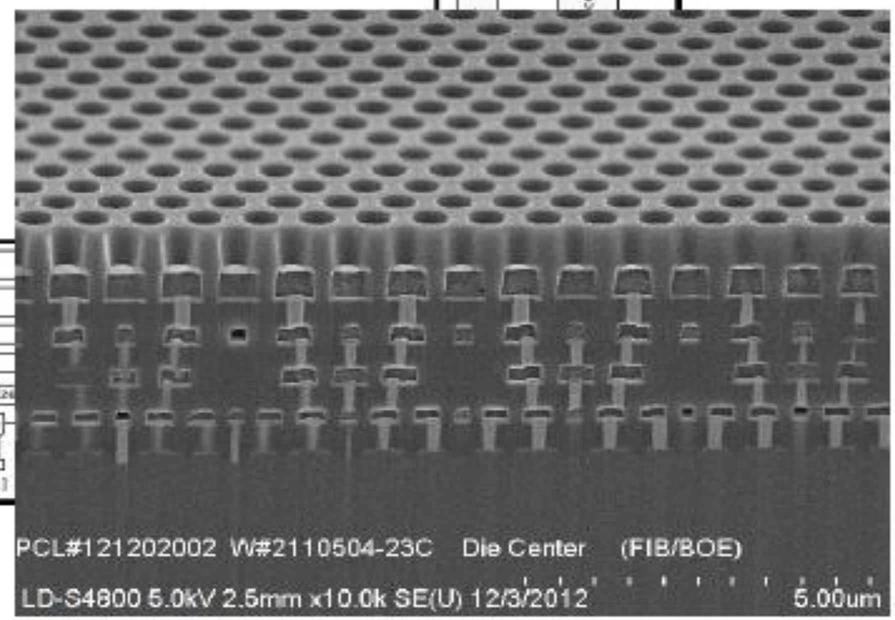
nano CMOS technology using ion-sensitive FET:

now the "lab-on-silicon-chip" changes everything

$1,000 Genome Machine on a Chip







slide J. Rothberg, plenary 1.3 –IEEE-ISSCC 2017

660 Million Sequencing Reactions

-14,000 on the End of a Human Hair

1970 ISFET by P. Bergveld

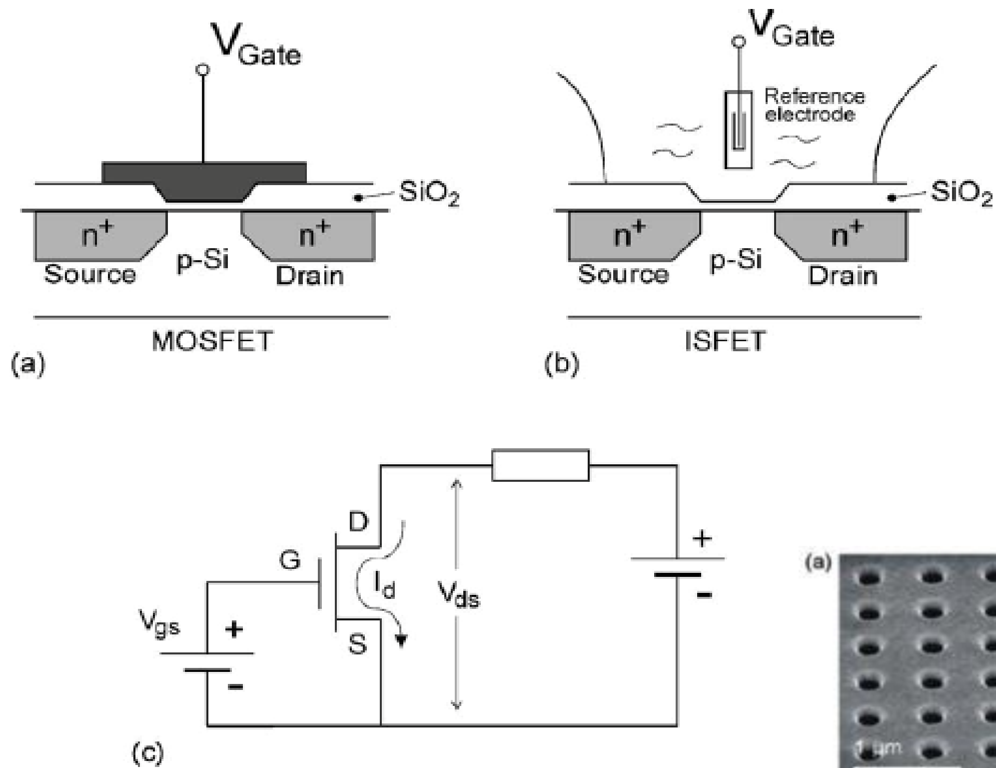
1973 PhD Thesis
Piet Bergveld
U. Twente NL

detects chemical process
that changes pH of liquid

much more sensitive if
the transistor is very small

then large array possible
with nano-pores

a fragment couples to
known DNA in pore --> H^+



0.2 µm pores
4µm

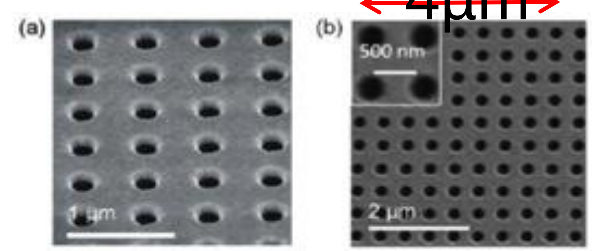


Fig. 3. Schematic representation of MOSFET (a), ISFET (b), and electronic diagram (c).

The Ion Sensitive Transistor

1.3: The Development of High-Speed DNA Sequencing: Jurassic Park, Watson, Neanderthal, Moore and You.

basic slide J. Rothberg, plenary 1.3 –IEEE-ISSCC 2017

'Pre-History' of Imagers

1970 – 1975

delay lines BBD (Philips) – CCD (Bell Labs) become imagers

Sangster and Teer, IEEE SC4(1969) 131-136 **Boyle and Smith,review IEEE ED33(1976) 661-663**

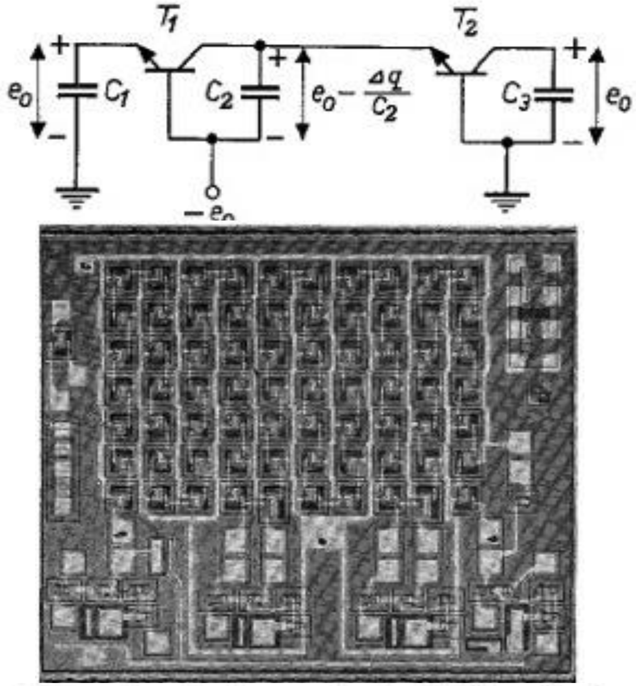


Fig. 10. An integrated 70-bucket series delay line including sampling, amplifying, and output stages (chip size 2 × 2.25 mm²).

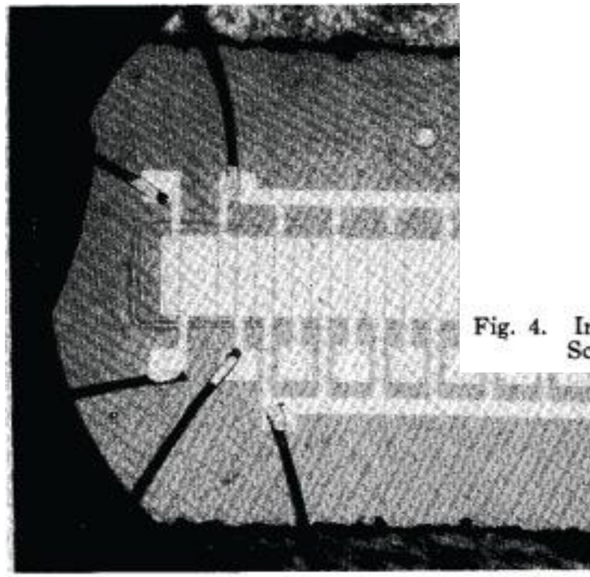


Fig. 3. The first 8-bit fully integrated device wit outputs.

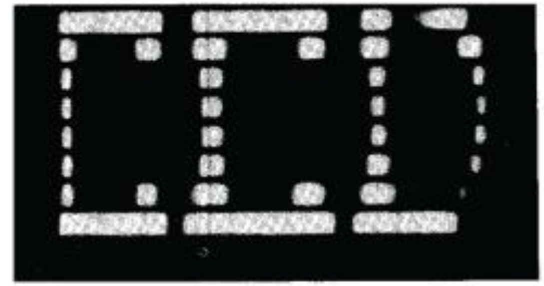


Fig. 4. Image produced by an 8-bit linear array of CCD elements. Scanning from left to right was obtained mechanically.

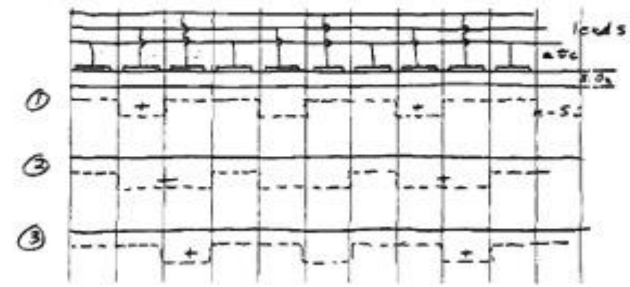


Fig. 1. Reproduction of the notebook sketch of the first three-phase charge-coupled device.

1980 – 1990

CCD primarily in science and industry

soon CCD also with IR-sensing matrix & solder bump-bonds
using ~1965 IBM C4 chip contact bump technology

the 4 early 2D particle imager projects

CCD Damerell et al.

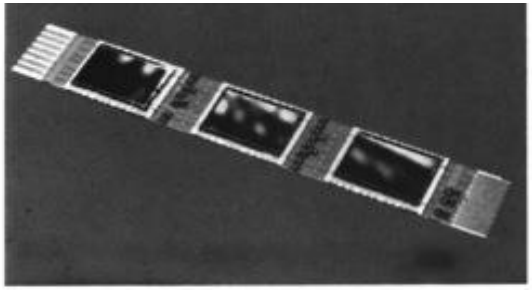


Fig. 3. Photograph of a partly assembled ladder. The 3 upper CCDs have been mounted on the ceramic mother card. The ladder would be completed by mounting 2 further CCDs on the underside, giving continuous coverage over the ladder length of 5 chips.

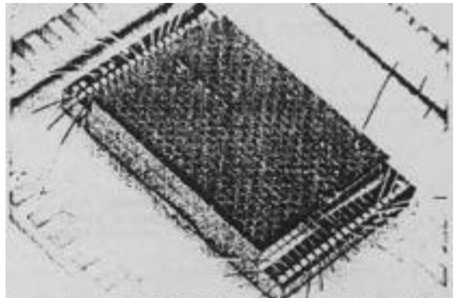


Fig. 2. Typical planar hybrid sensor chips

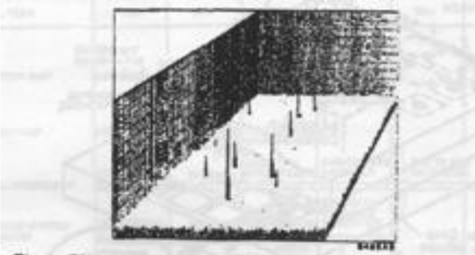
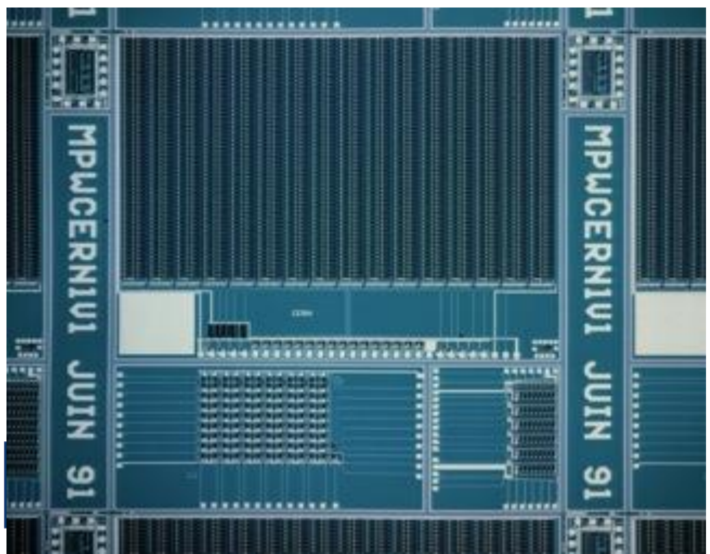
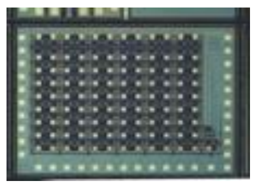


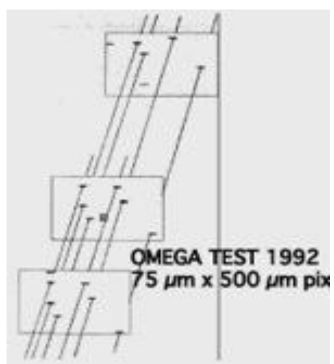
Fig. 4. Plot of 250 GeV/c pions being detected as they traverse a 256 x 256 array illustrating the strengths of two-dimensional readout to aid in pattern recognition.

Gaalema Hybrid SLAC-SSC Shapiro et al.

Hybrid Heijne, Jarron, Campbell ++







HR-Si Snoeys et al. 1991

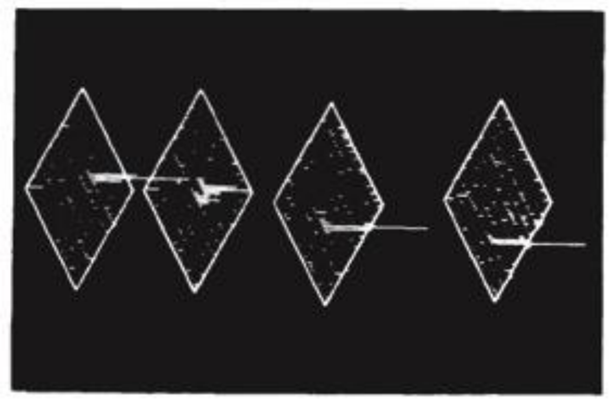
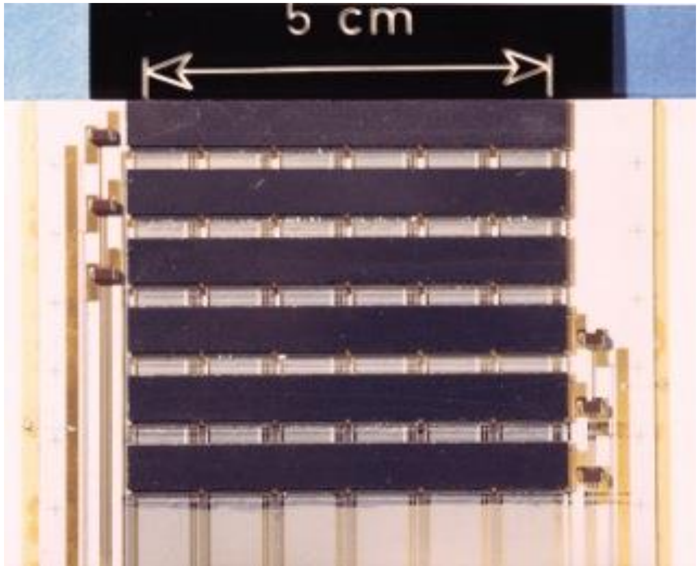
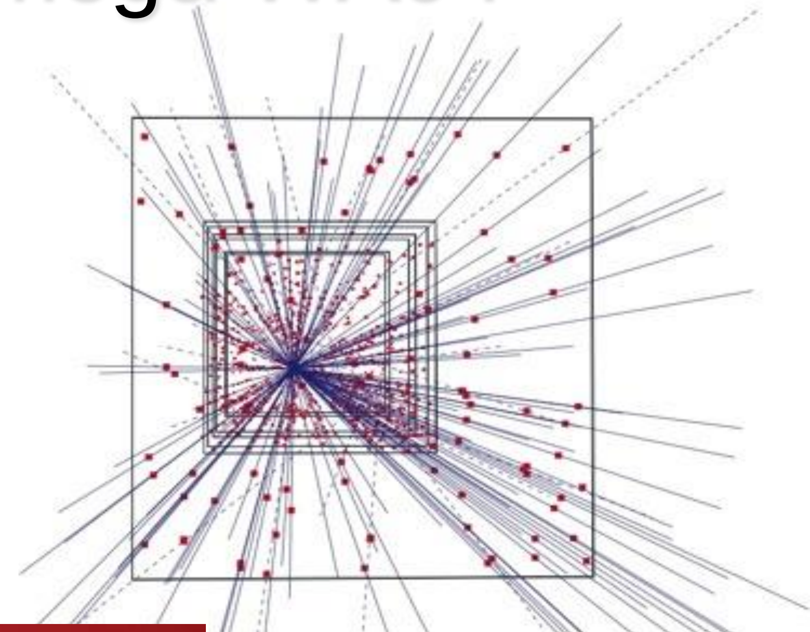
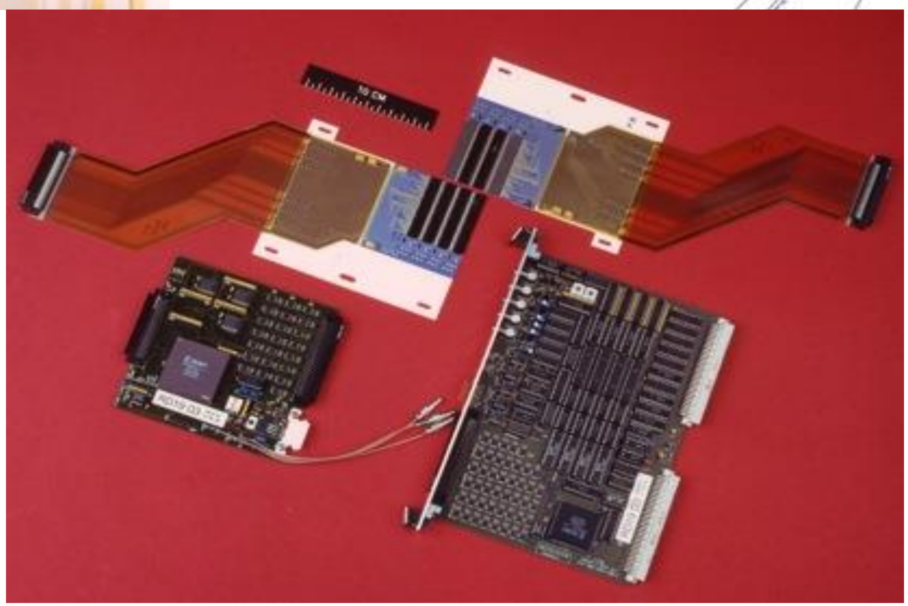


Fig. 15. Display of a high energy particle track through the telescope. The negative pulse heights (noise) are not plotted but are of comparable magnitude.

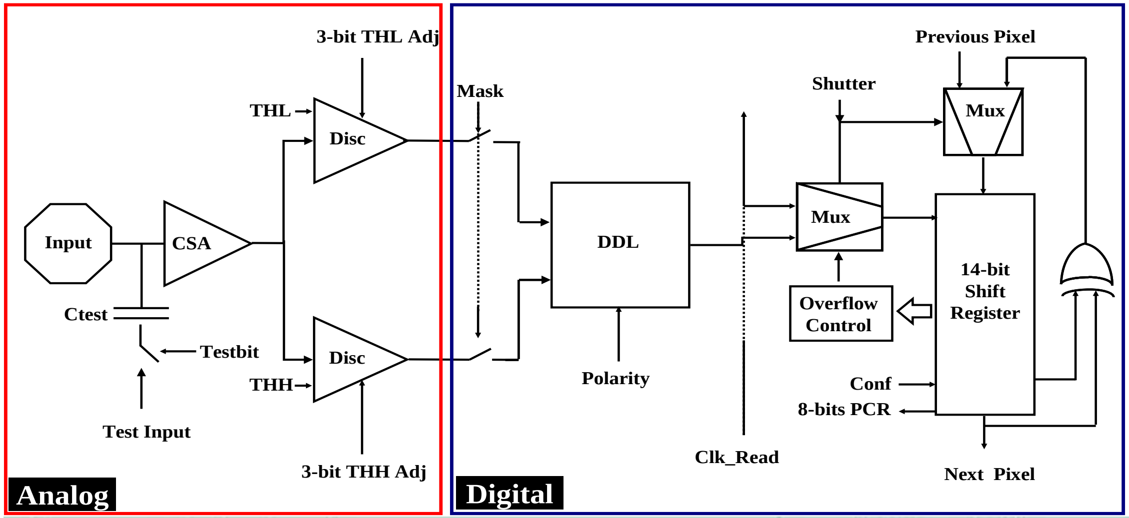
RD19 telescope in Omega WA94



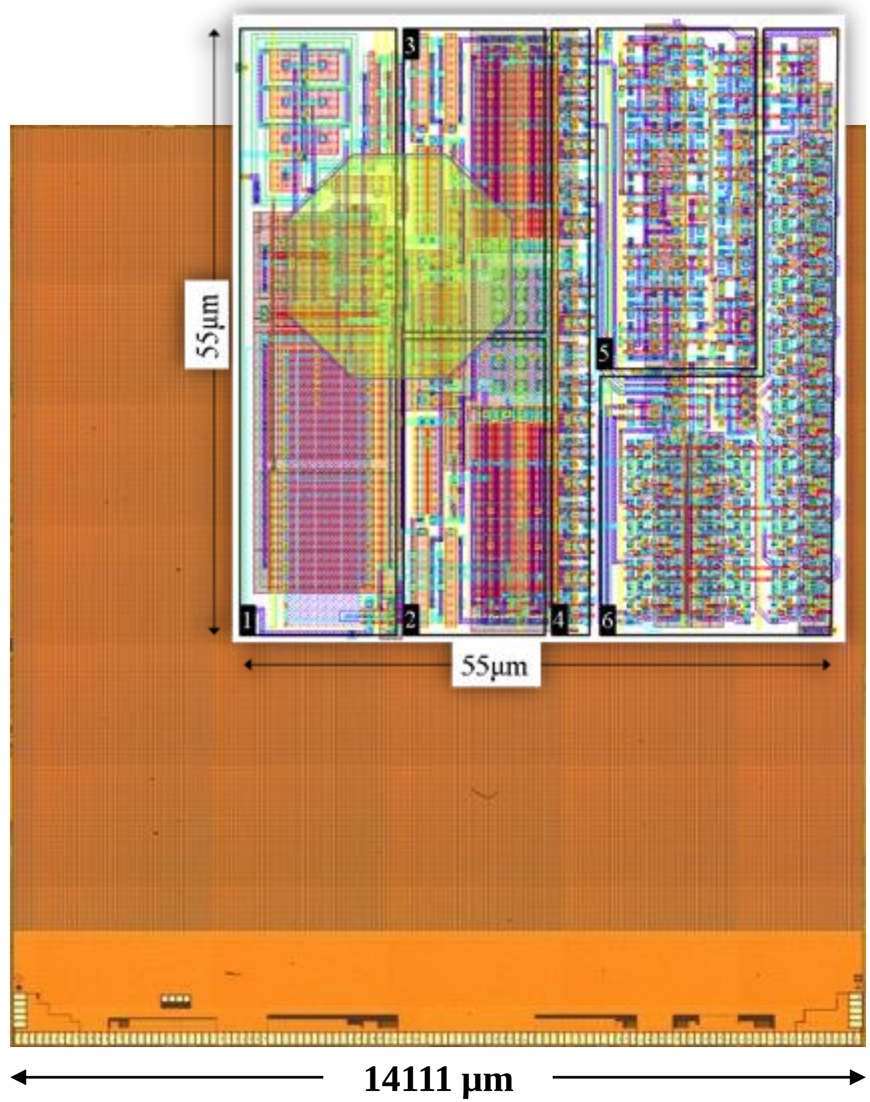




Medipix2: Mpix2MXR20 (2005)



Measured pixel gain	10.7 mV/ke-
Measured ENC	~110 e- rms
Threshold dispersion before equalization	~400 e- rms
Threshold dispersion after equalization	~95 e- rms
Minimum detectable charge	~900 e-
On-chip threshold DAC step	~413 μV or ~40 e-
On-chip threshold DAC INL over the full range	<2 LSB (80 e-)
Voltage DACs Temperature dependence	5.6 e-/°C
Pixel counter depth-Overflow control	11810-Yes
Maximum serial readout clock	~180 MHz
Pixel static power consumption	~8 μW



Photographic emulsion

1935 – 1965 Illford Ltd Kodak "nuclear emulsion"

Cecil Powell : 1946 pion discovery Nobel 1950

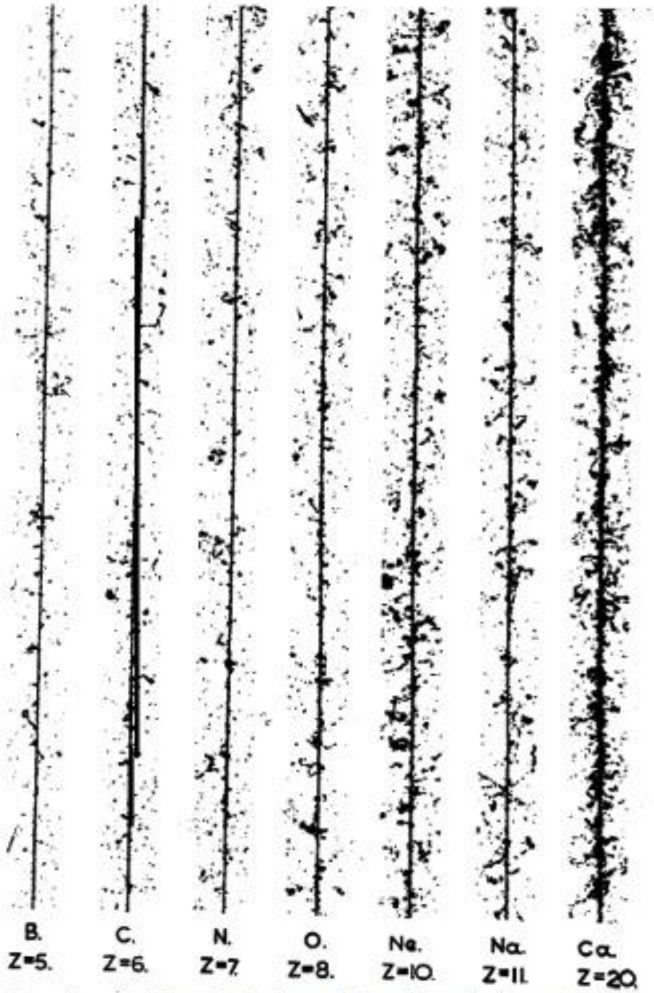
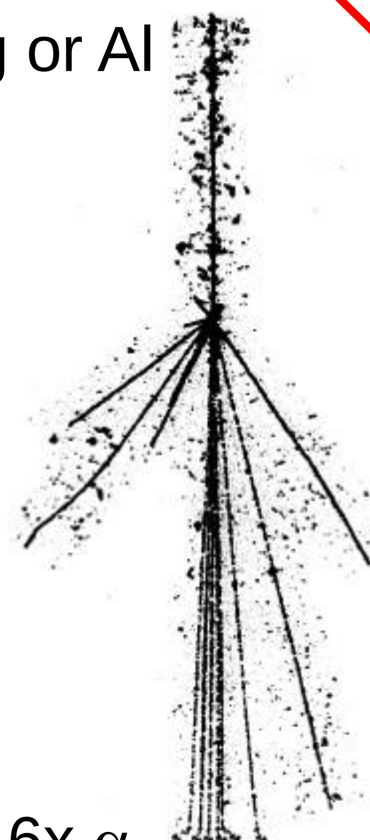


Fig. 2. Examples of the tracks in photographic emulsions of primary nuclei of the cosmic radiation moving at relativistic velocities.

Mg or Al



6x α

Fig. 3. A nucleus of magnesium or aluminium moving with great velocity, collides with another nucleus in a photographic emulsion. The incident nucleus splits up into six α-particles of the same speed and the struck nucleus is shattered.

π-μ-e