# Silicon is for physics what carbon is for life

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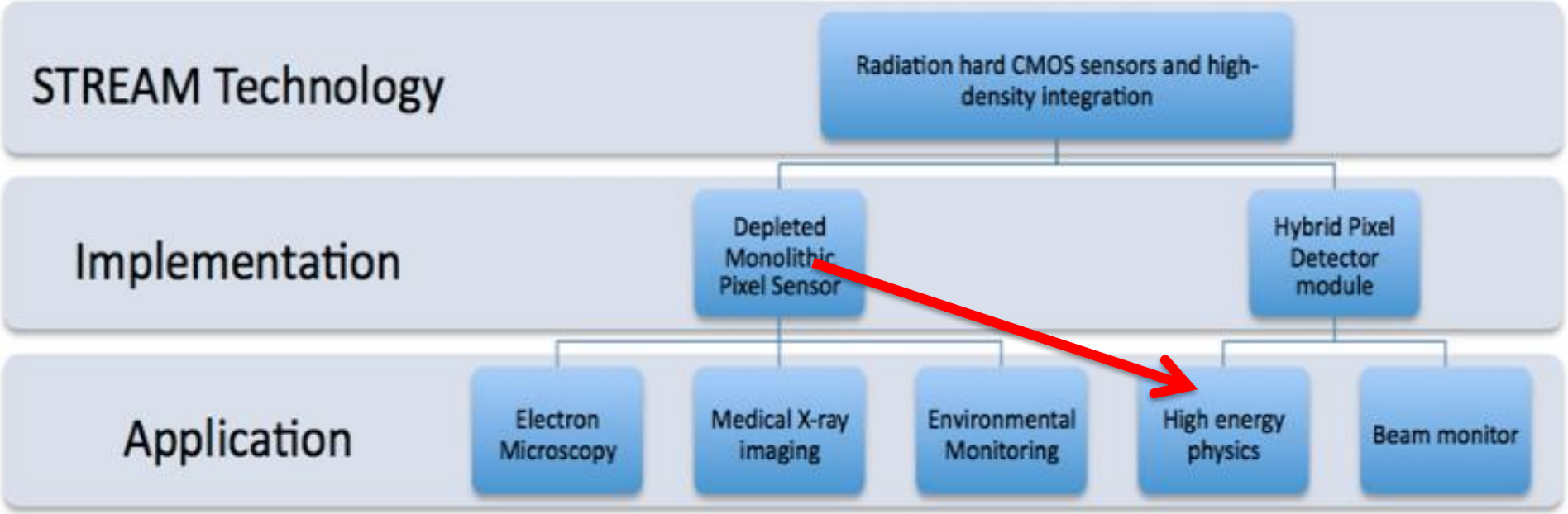
# STREAM Summer School




1990 in RD19 we started with both monolithic and hybrid,
but hybrid proved much easier for quick results and ~1995 we abandoned monolithic

today, monolithic may fulfill even ATLAS needs, if pixels can be made sufficiently small

but note that consumer imagers move to hybrid ...!!!  BSI on CMOS is expensive

# STREAM Summer School

Advanced radiation detectors + long-term reliability

Why semiconductors? Why silicon? Historical perspectives

The sensor and the associated signal+information processing

From 0- to 1- to 2-D Now towards 3D detection with Si

existed already in gas or liquid detectors

Monolithic/3D CMOS detectors with fully integrated processing

Reliability & radiation hardness of sensors & integrated circuits

First thing: what is going on elsewhere, and where best to look?

# STREAM Summer School

Measurement is the basis for understanding

at least since Galilei and van Leeuwenhoek

Technology is the basis for measurement

Instead of evolutionary, progress may be disruptive

Reconsider prejudices:  your own,  and those of others

What was impossible 5 years ago, may have become feasible

Thousands of scientists work in all corners of the planet

My own activities were guided by visits at other labs, conferences by IEEE (NSS, NSREC, IEDM, ISSCC,..) and workshops Many visits and personal contacts in industry

# Some potentially controversial points

note that I am semiconductor , not particle physicist

## UPGRADE SHOULD BE AMBITIOUS

NO TRIGGER, READ ALL ?? as intended by LHCb

## INVESTIGATE VECTOR DETECTOR

SEMICONDUCTOR or GASEOUS after all

## INTEGRATE TRACKING and CALORIMETRY

FLOW APPROACH, FULLY RESOLVE JETs

## USE INDUSTRY TRENDS in Si towards '3D'

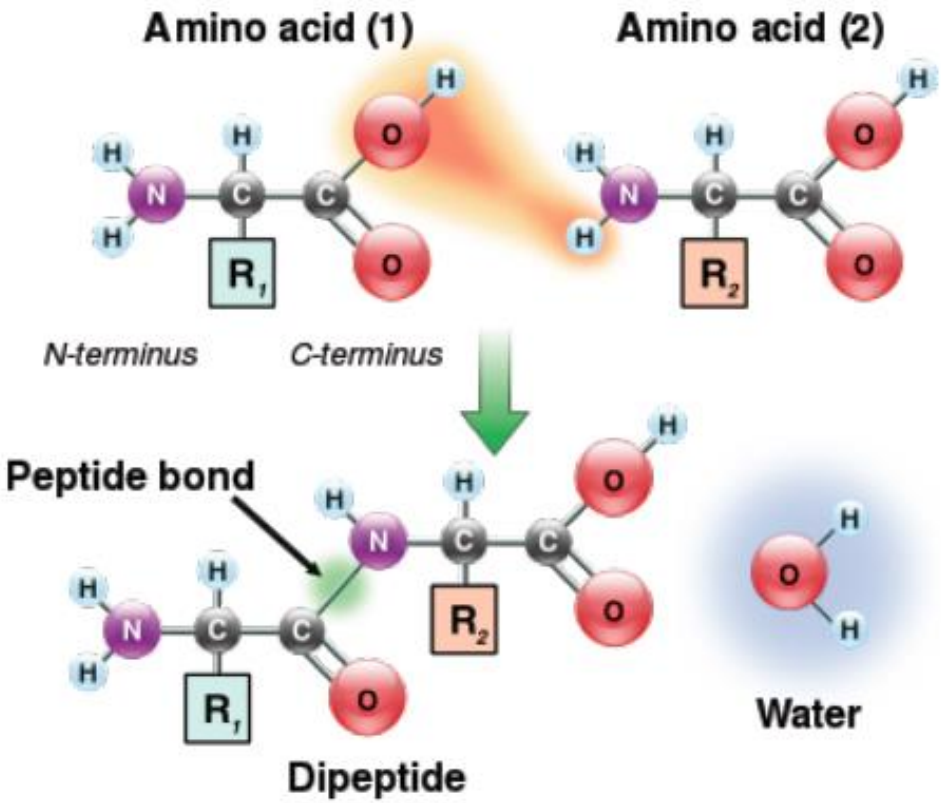
THICK Si TRACKIng & IMAGING

## R&D MUST INCLUDE SYSTEM ASPECTS

HARDWARE but also SOFTWARE & ANALYSIS TIME

on earth silicon is more abundant
but carbon has been more successful

versatility and lower binding energies



# Mendeleev <1900

# Periodic Table of Elements

ELEMENTAL

COMPOUNDS

**also: $HgI_2$ (AgCl) etc.**

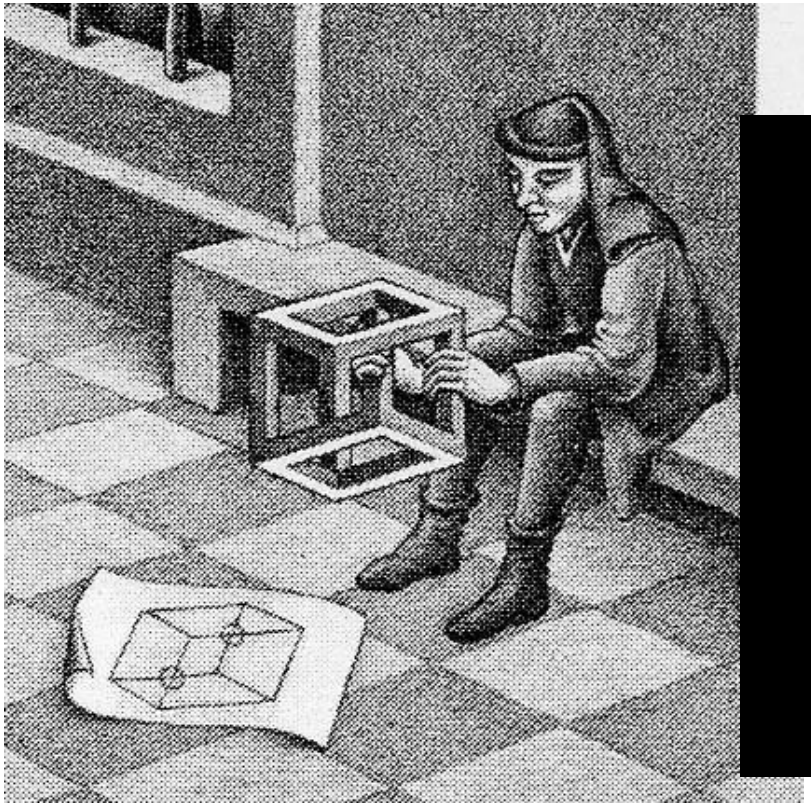
| | IA | IIA | IIIB | IVB | VB | VIB | VIIB | VII | IB | IB | IIIA | IVA | VA | VIA | VIIA | 0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 H | | | | | | | | | | | | | | | 2 He |
| 2 | 3 Li | 4 Be | | | | | | | | | 5 B | 6 C | 7 N | 8 O | 9 F | 10 Ne |
| 3 | 11 Na | 12 Mg | | | | | | | | | 13 Al | 14 Si | 15 P | 16 S | 17 Cl | 18 Ar |
| 4 | 19 K | 20 Ca | 21 Sc | 22 Ti | 23 V | 24 Cr | 25 Mn | 26 Fe | 27 Co | 28 Ni | 29 Cu | 30 Zn | 31 Ga | 32 Ge | 33 As | 34 Se | 35 Br | 36 Kr |
| 5 | 37 Rb | 38 Sr | 39 Y | 40 Zr | 41 Nb | 42 Mo | 43 Tc | 44 Ru | 45 Rh | 46 Pd | 47 Ag | 48 Cd | 49 In | 50 Sn | 51 Sb | 52 Te | 53 I | 54 Xe |
| 6 | 55 Cs | 56 Ba | 57 *La | 72 Hf | 73 Ta | 74 W | 75 Re | 76 Os | 77 Ir | 78 Pt | 79 Au | 80 Hg | 81 Tl | 82 Pb | 83 Bi | 84 Po | 85 At | 86 Rn |
| 7 | 87 Fr | 88 Ra | 89 +Ac | 104 Rf | 105 Ha | 106 106 | 107 107 | 108 108 | 109 109 | 110 110 | | | | | | | | |

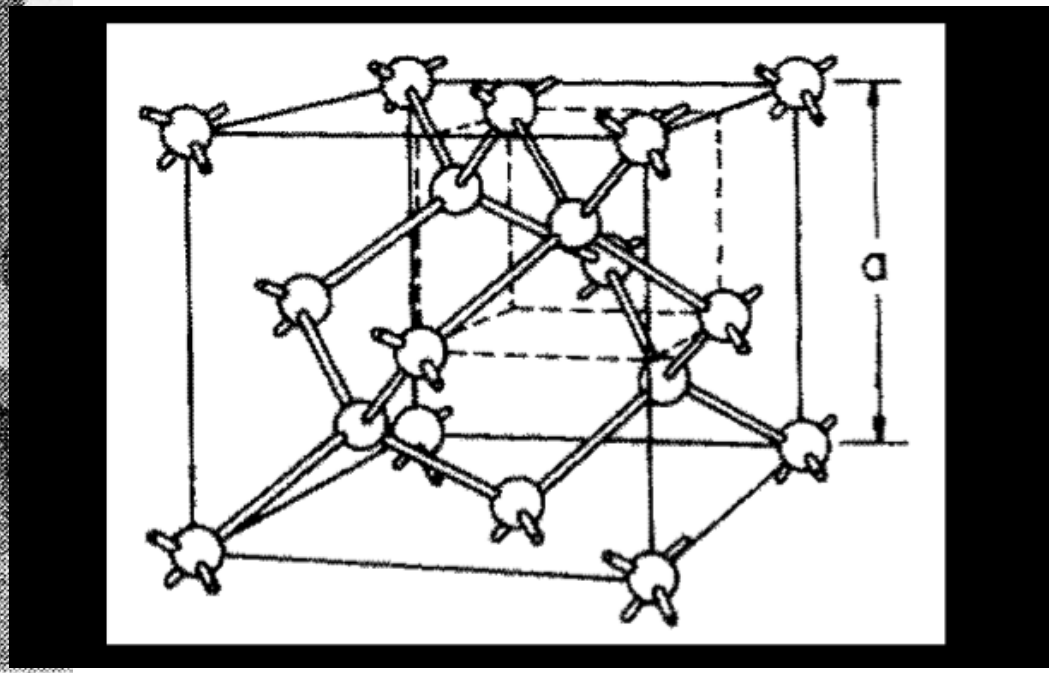
| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| * Lanthanide Series | 58 Ce | 59 Pr | 60 Nd | 61 Pm | 62 Sm | 63 Eu | 64 Gd | 65 Tb | 66 Dy | 67 Ho | 68 Er | 69 Tm | 70 Yb | 71 Lu |
| + Actinide Series | 90 Th | 91 Pa | 92 U | 93 Np | 94 Pu | 95 Am | 96 Cm | 97 Bk | 98 Cf | 99 Es | 100 Fm | 101 Md | 102 No | 103 Lr |

**Legend - click to find out more...**

| | | | |
|---|---|---|---|
| H - gas | Li - solid | Br - liquid | Tc - synthetic |
| Non-Metals | Transition Metals | Rare Earth Metals | Halogens |
| Alkali Metals | Alkali Earth Metals | Other Metals | Inert Elements |

# Mono-crystalline semiconductors






silicon single crystal
Imagination and Innovation

- sensitive to visible light (CCD, CMOS camera)
- also all other sorts of radiation (>1.12 eV bandgap)

LOW Z, not efficient for $\gamma$ >10keV

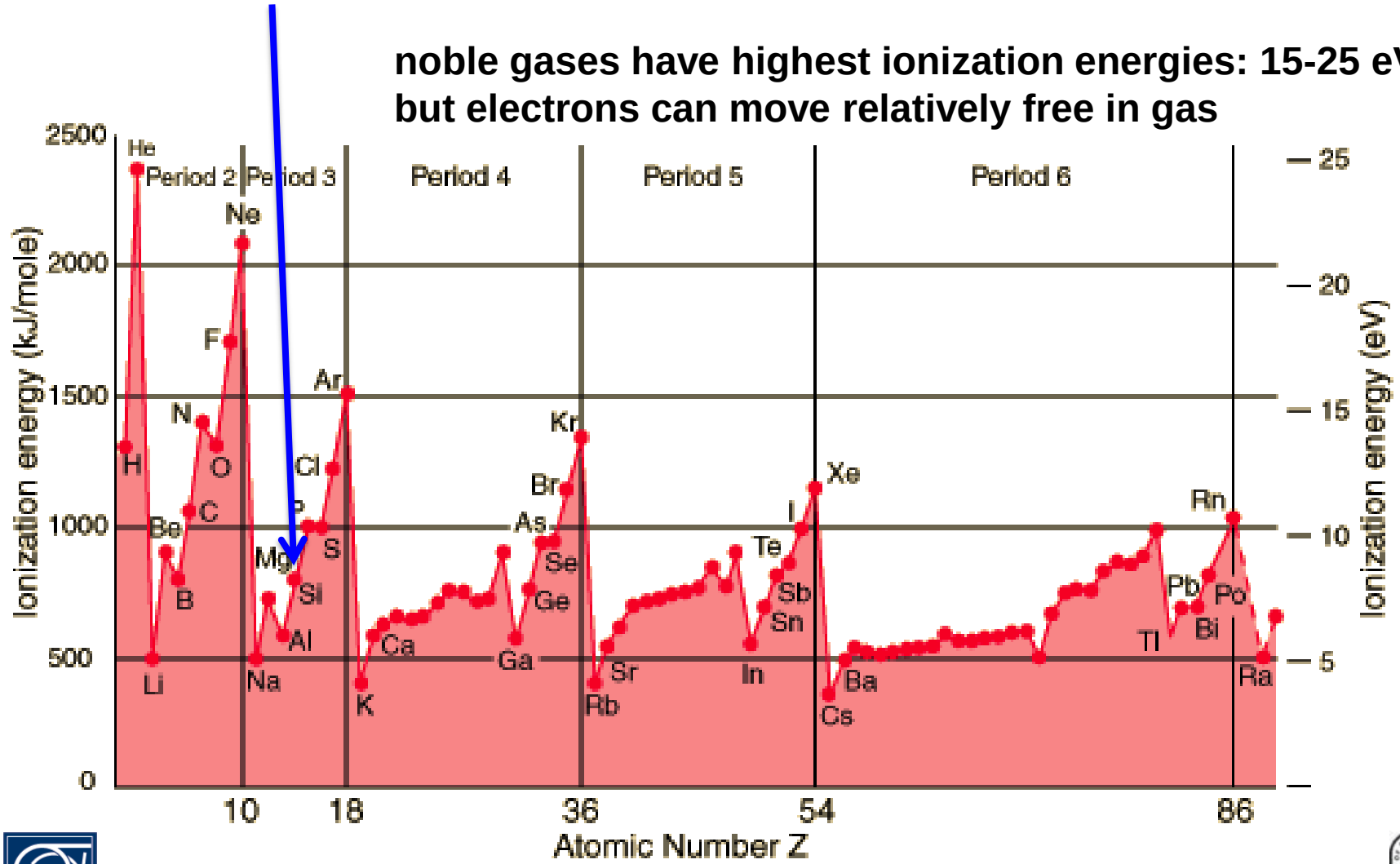
- conductivity adjustable over 10 orders ($10^{10}$-$10^{20}$)
- surface oxide provides high impedance isolation

~1955 Bell,1959 Planar(Hoerni-Fairchild),1970 LOCOS ( Kooi, Philips)

# Ionization energy of atoms

**ionization energy of isolated Si atom 8.15 eV**

**noble gases have highest ionization energies: 15-25 eV**
**but electrons can move relatively free in gas**



# Semiconducting single crystal is different

## Overlapping electron waves:

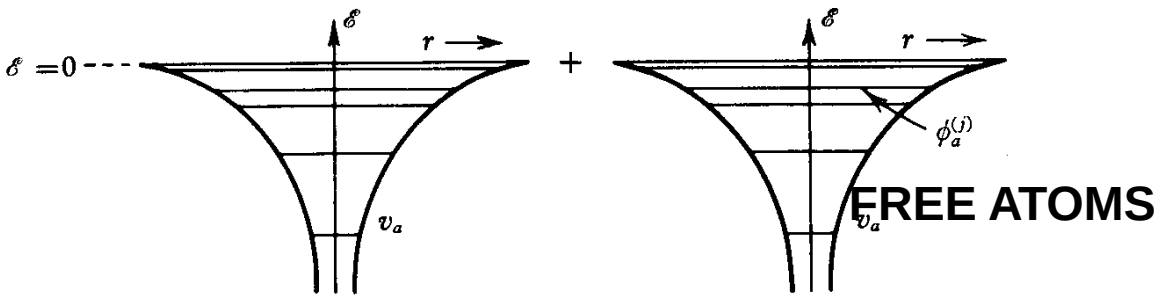
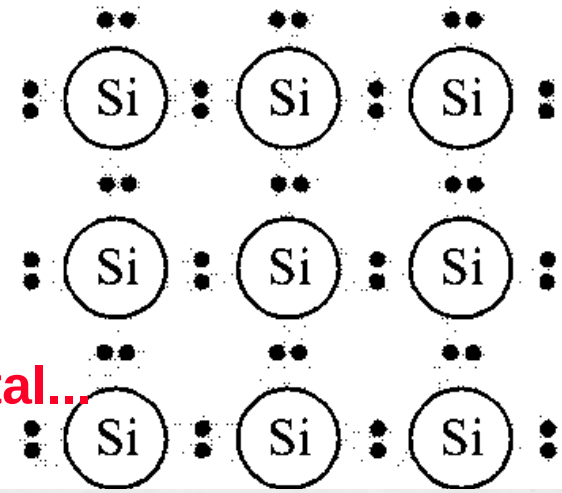



Fig. 54. Bound atomic orbitals of free atoms.




**Electrons are shared throughout whole crystal...**

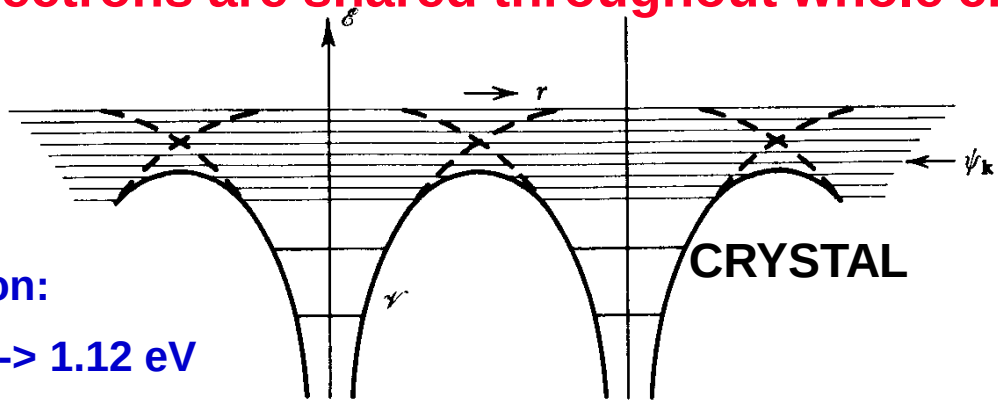
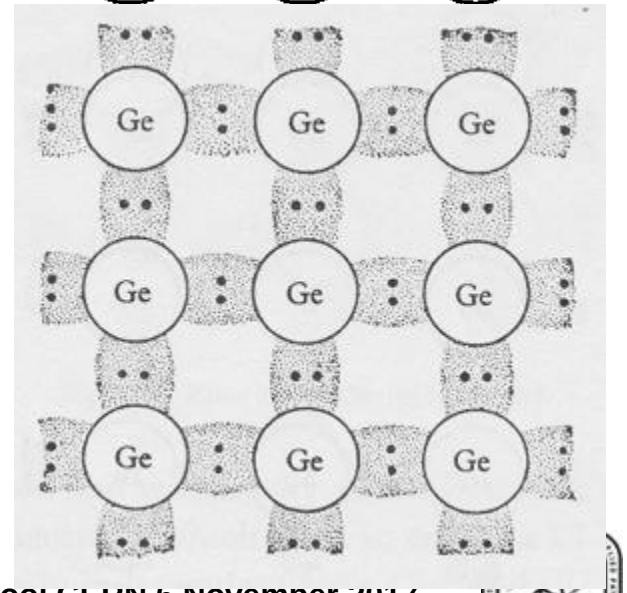



Fig. 55. Bloch states of crystal.




**ionization:**

**8.15eV --> 1.12 eV**

**e-h pair 3.64 eV**

**Exclusion principle applies to a whole crystal**
**--> filling of energy bands**

# silicon is 2nd most common element (28%) in earth crust

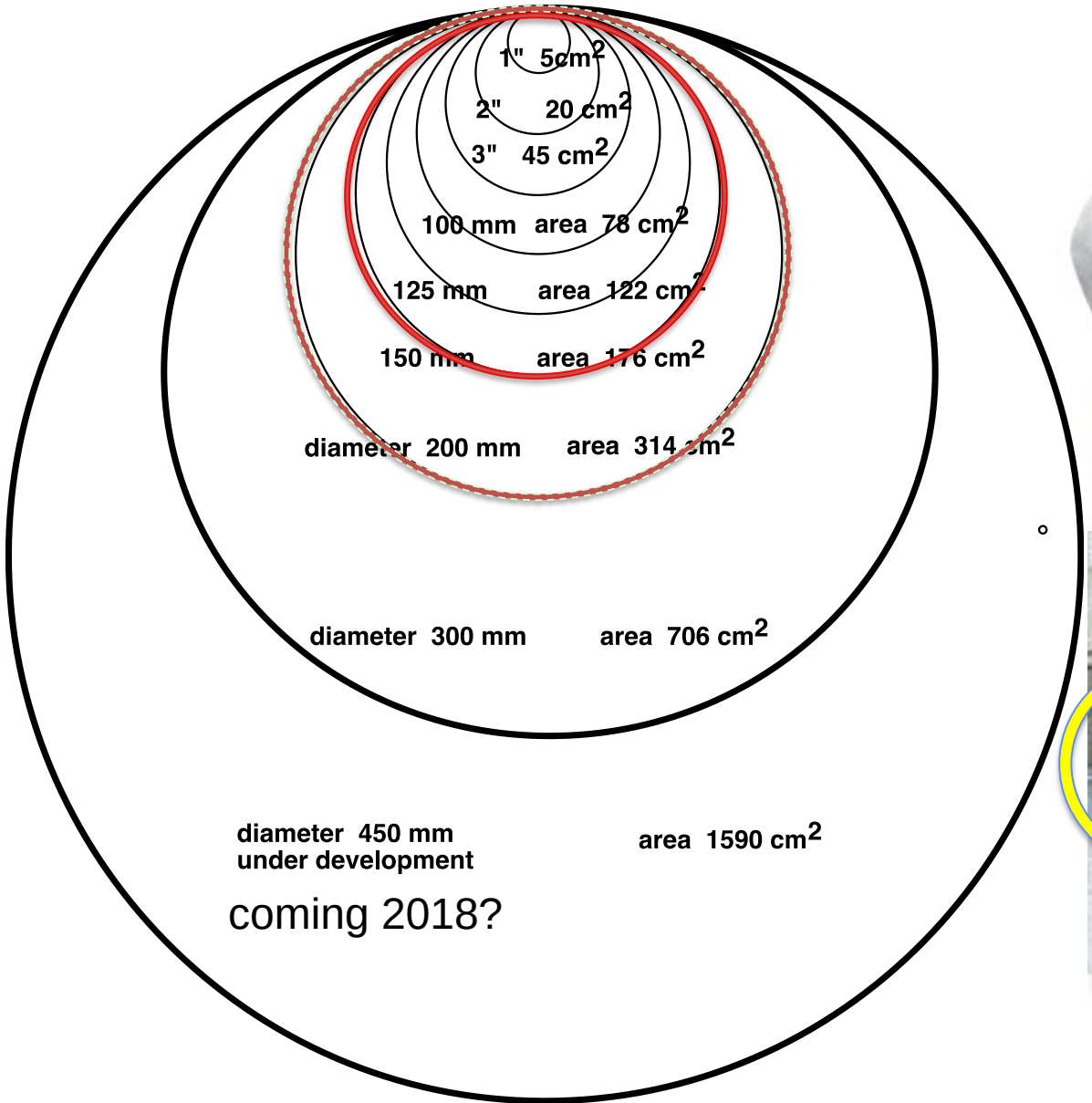
## quartz ($SiO_2$)

## sand - mostly $SiO_2$

# Silicon single crystal growing

**1955-2017** **Wafer sizes**

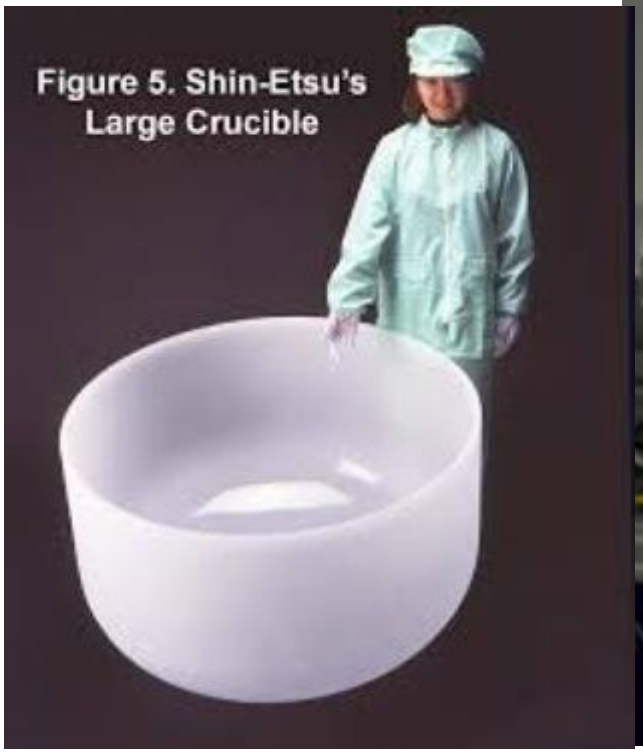
**Increase of wafer diameter 3/4” - 450mm**

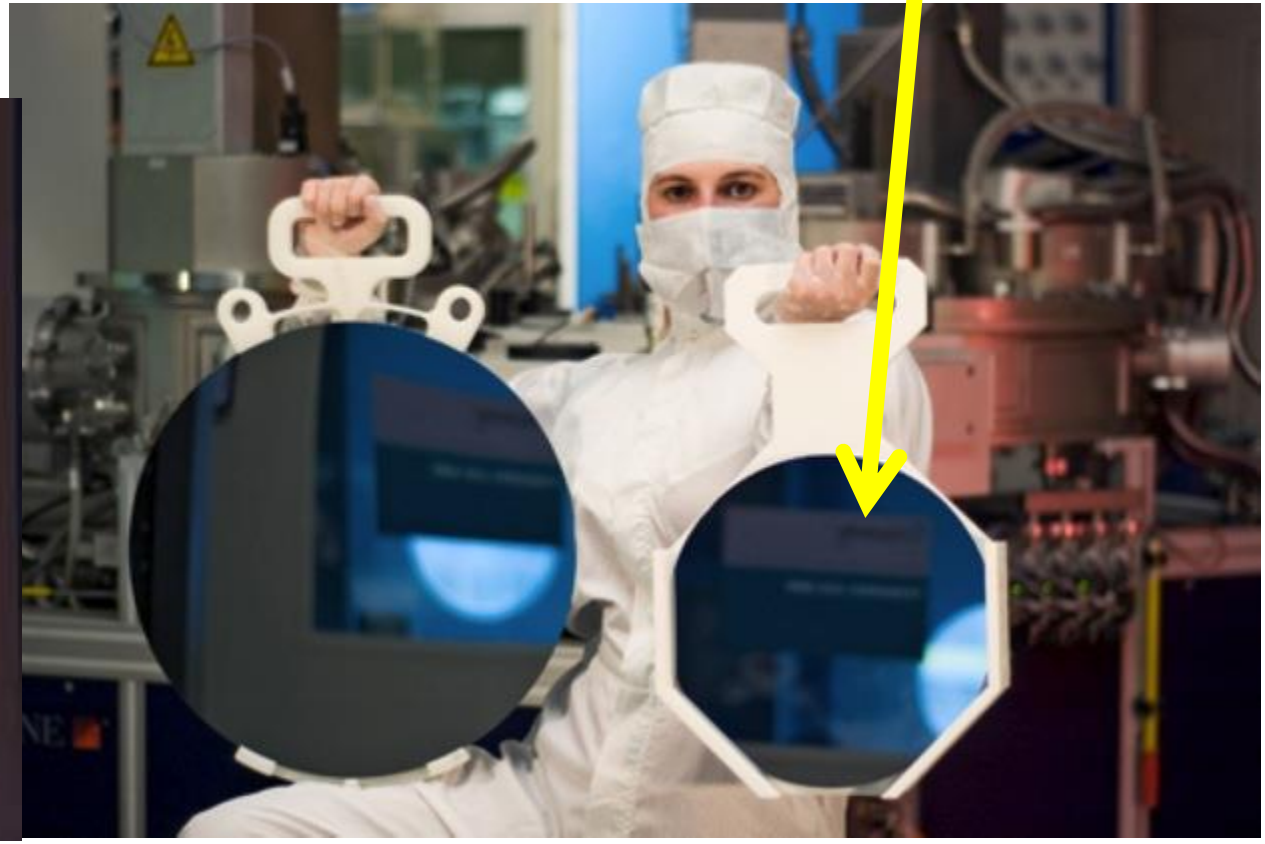



Very large silicon single crystal Ø 45 cm

450mm still not widely accepted as next standard.

CMOS foundries worldwide use Ø 30 cm



# Silicon single crystal growing

Some approximate economics, just to get a feel:

Worldwide production of Si wafers 2015 was $67 \times 10^9$ $cm^2$ (6.7 $km^2$ )
corresponds to 96 million wafers of 300mm diameter (700 $cm^2$)
Revenue in Si was only 7.2 B$, amounts to average of 10.7 cents per $cm^2$
or 75$ for a polished 300mm wafer

High resistivity Si much more expensive, available up to Ø150mm (200mm?)

Typical wafers processed in major foundry: some thousands/day, 1M/year

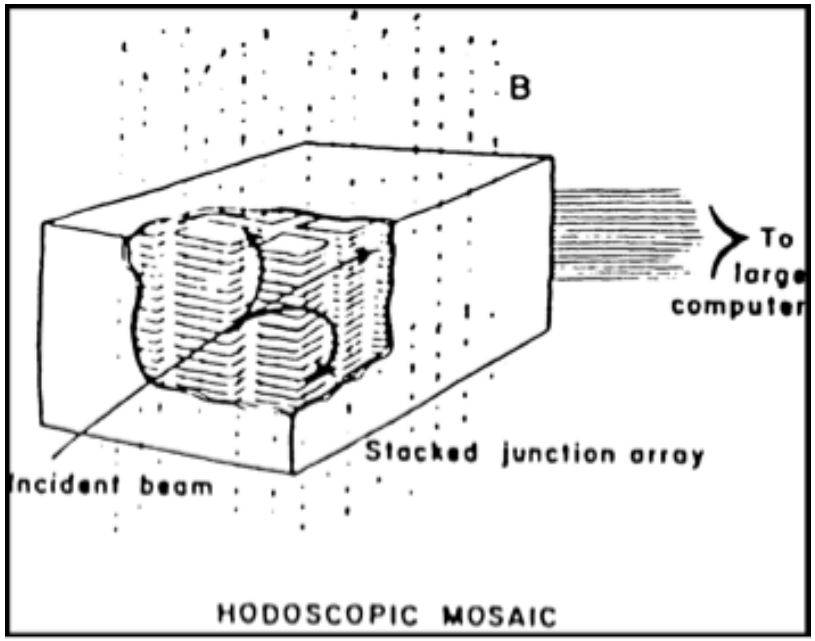
Worlwide sales of semiconductor devices in 2015
revenue 333.7 B$ if all Si area were used --> 5$ per $cm^2$
the raw Si enters for <u>only 2.1%</u> in the cost of the devices

expected revenue in 2017 378 B$ with growth 12% to 2016

data from SEMI website

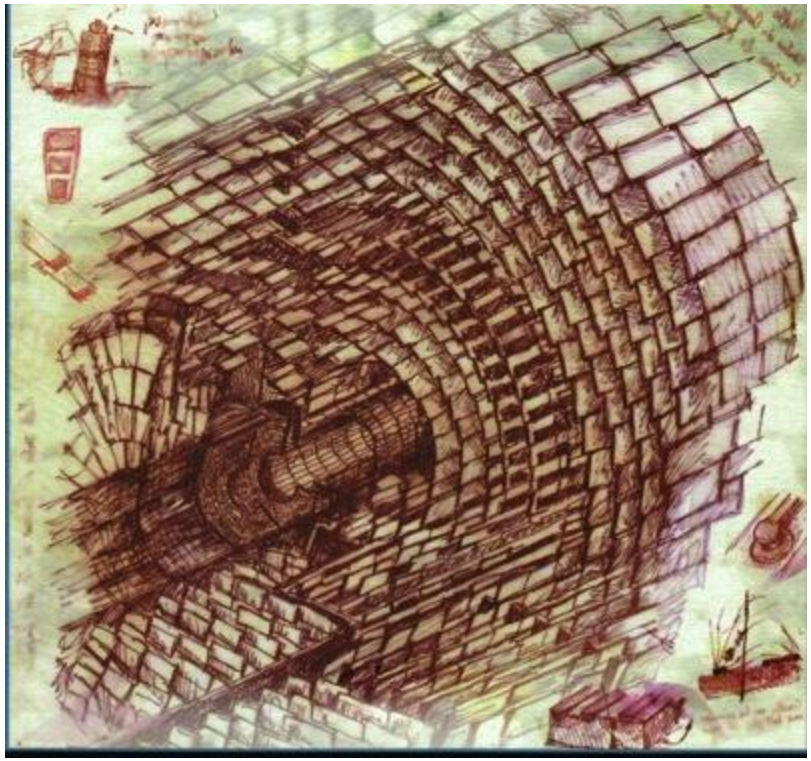
# Plans for Si particle tracking systems

## 1960




~1959 proposal of diode array suggested at Hughes Aircraft by Friedmann and Mayer reported by Bromley in Asheville

## 1998



1998 artistic concept in CMS Technical Design Report for the inner Si tracker

# The 1980 revolution in Si detectors

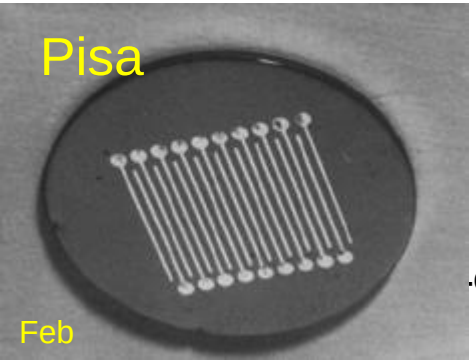
**In 1980 several 'revolutionary' innovations took place, that were to shape silicon detectors for future applications in particle physics and other fields**

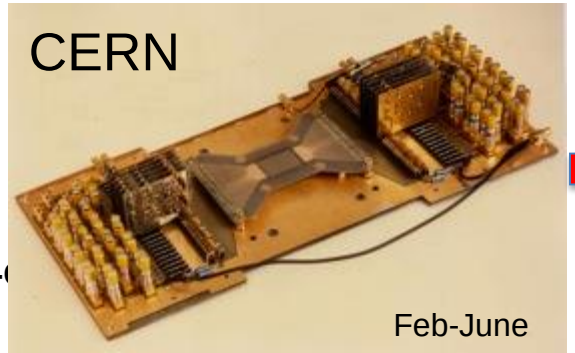
1. **Segmented surface barrier detector,19 strips, pitch 0.6mm made in Pisa.**
   **NIM 176 (1980) 457, Amendolia et al. (Menzione, Bosisio,..) readout 2-ch, in beam at CERN**

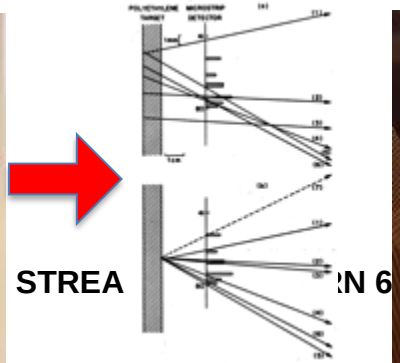
2. **Si microstrip detectors, 100 strips, pitch 0.2mm, Heijne, Burger, Jarron, CERN made at Enertec, Strasbourg; tested May at CERN, with full readout and a first vertex reconstruction by Jos Vermeulen and Andrew Wylie: NIM 178**

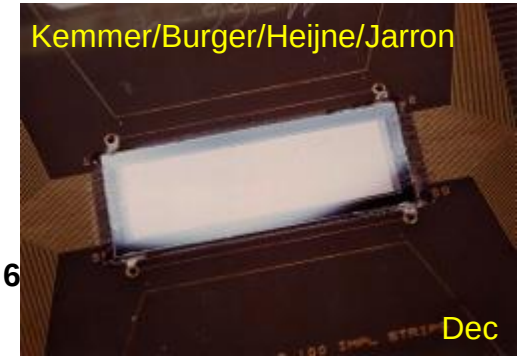
3. **Publication NIM 169 of planar passivated Si diodes with low noise/current by Josef Kemmer, Techn. Univ. München (~nA/cm$^{-2}$, see before).**
   **Process commercialized by Enertec/Strasbourg from 1981.**

4. **December 1980, first Si microstrip by planar process made by Kemmer, in collaboration with Heijne/Burger; simultaneously with Klanner/Lutz of MPI**
   **IEEE Trans.Nucl.Sci. 29 (1982) 733 (Kemmer, Burger, Henck, Heijne at Nucl Science Symp 1981**



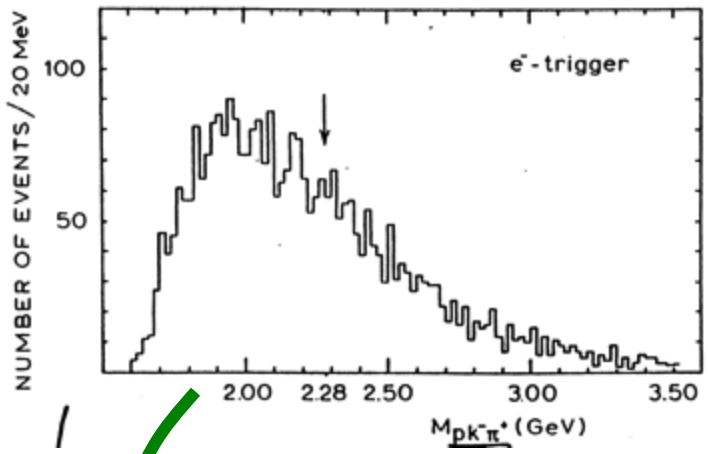



# Charmed particle 2nd vertex recognition

## NA11 CHARM EXP

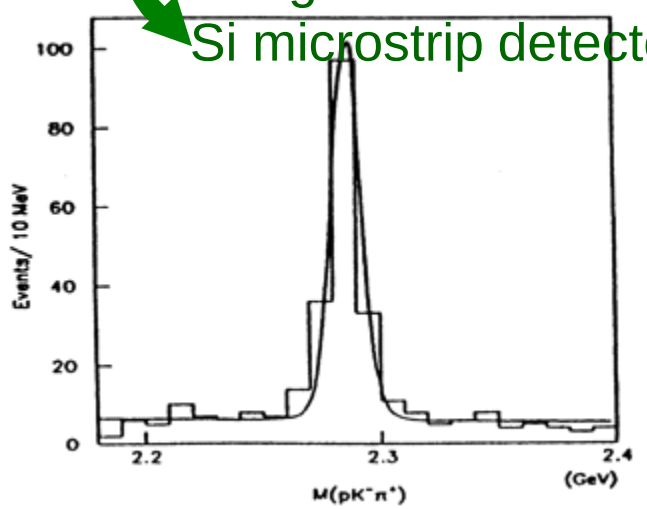
$\Lambda_c$ --> $p\,K^-\pi^+$




Invariant mass distribution of Lambda
with wirechamber spectrometer only
in spite of large statistics, 'NO' selectivity

using new technology :
Si microstrip detectors + CCD  2D helps much more

CCD by Damerell cs.

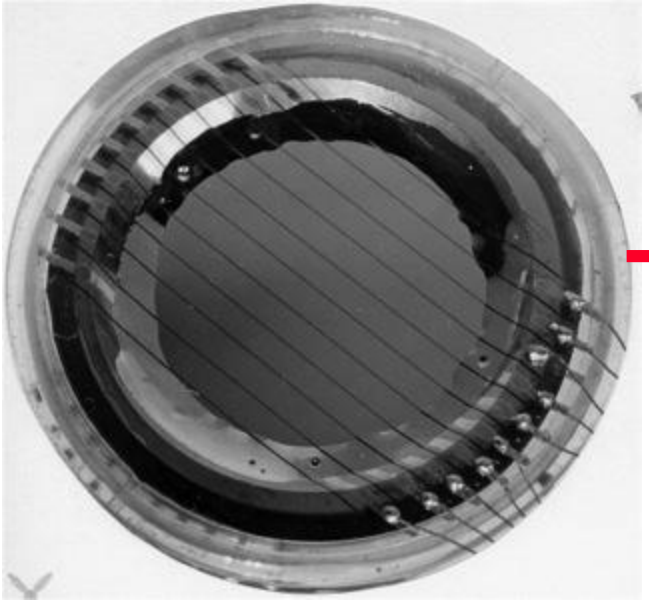



much less background events
much improved sensitivity
NA11 can run at reduced beam intensity

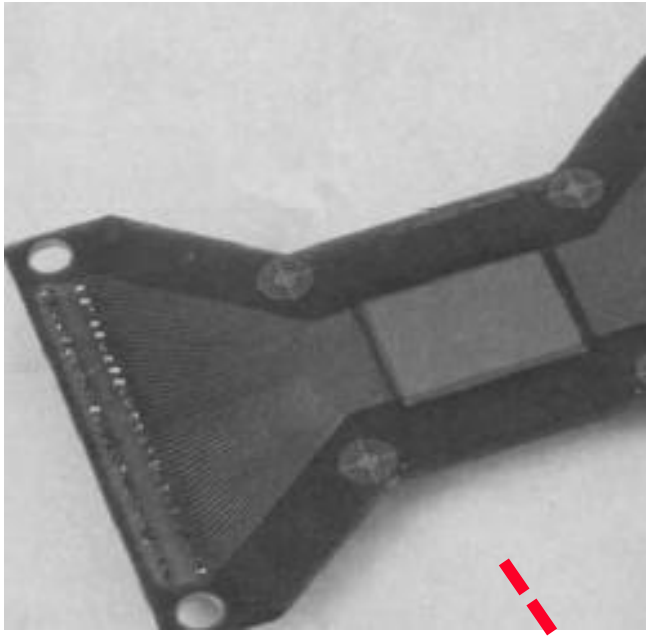
DRAMATIC IMPROVEMENT !

# Segmented silicon detectors

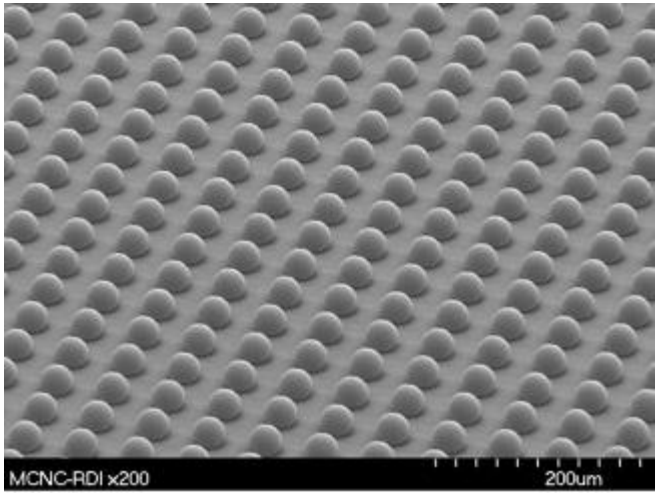
progressively smaller elements



**~1965**
**PHILIPS-Amsterdam**
**100 x 1370µm x 1370µm**
Ammerlaan, van Dantzig, Visschers



**1980 CERN / ENERTEC Strasbourg**
**100 x 4000µm x 200µm**
**Jarron, Burger, CSEM, Kemmer**




**1989-2000**
**Pixel detectors developed at CERN**
**smallest pixel side ~50µm**
**Campbell, Snoeys, LAA, IMEC, ETHZ, EPFL, RD19, Omega, Medipix**

# Early <1990 readout chips for segmented Si detectors

Chips NOT to scale

## SLAC/(DELPHI)

Microplex 1983

Walker, Parker, Hyams, Shapiro

NIM A226 (1984) 200

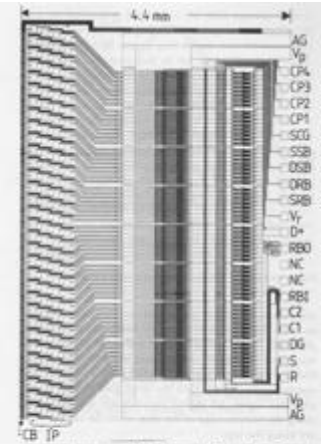



Fig. 3. Enlarged view of chip layout; AG = Analog Ground; D+ = Digital +5; $V_p$ = Analog +5 (Pulsed); RBO = Read Bit Out; CP4 = Calibrate Pulse 4; NC = No Connection; CP3 = Calibrate Pulse 3; RBI = Read Bit In; CP2-Calibrate Pulse 2; C2 = Clock 2; CP1-Calibrate Pulse 1; C1 = Clock 1; SCG = Storage Cap Ground; DG = Digital Ground; SSB = Source, Signal Bus; S = Store; DSB = Drain Signal Bus; R = Reset; DRB = Drain, Ref Bus; IP = Input Pads; SRB = Source, Ref Bus; CB = Calibrate Buses; $V_T$ = $V_{ref}$

## RAL/DELPHI

MX1 MX2 1987

Seller, Allport, Tyndel

IEEE TNS 35(1988) 176

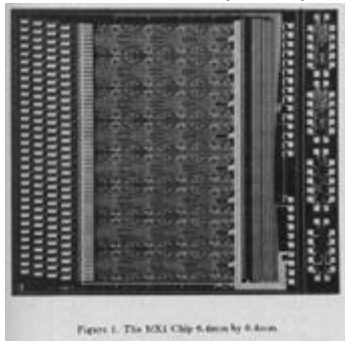


Figure 1. The MX1 Chip 6.4mm by 6.4mm.

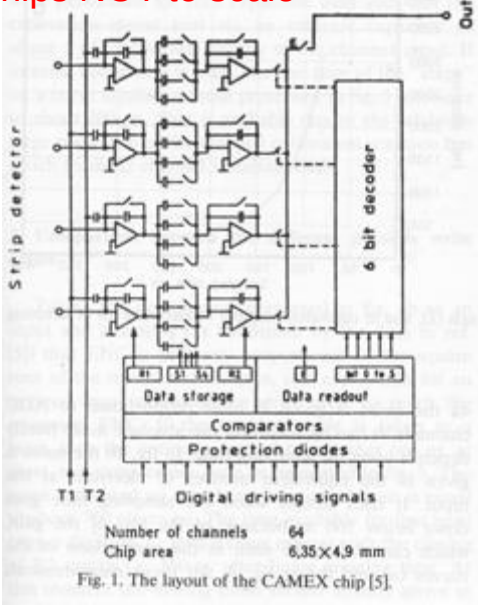



Fig. 1. The layout of the CAMEX chip [5].

## CAMEX64/ALEPH-MPI

Buttler, Lutz, Hosticka

Becker et al. IEEE TNS 36(1989) 246

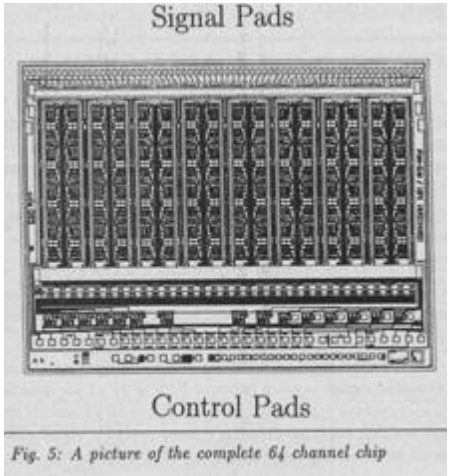
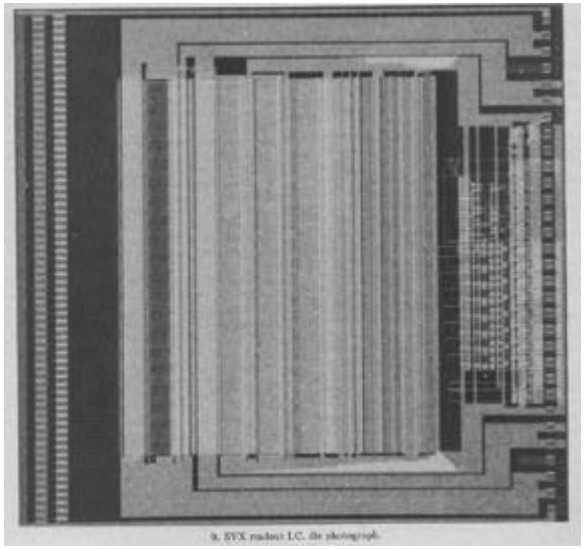


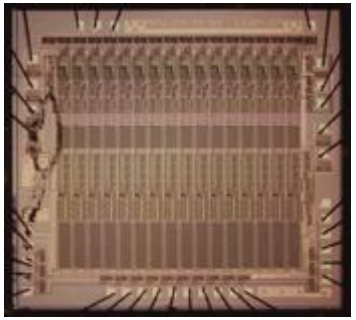

*Fig. 5: A picture of the complete 64 channel chip*



9. SVX readout I.C. die photograph.

## CDF-SVX Kleinfelder 1988

Kleinfelder et al. IEEE TNS 35(1988) 171



## AMPLEX (UA2)

Pierre Jarron 1987

classical, continuous feedback

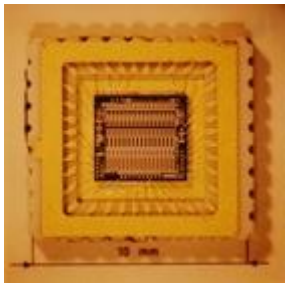
actually the first in a collider:1988

Beuville et al. NIM A288 (1990) 157

# Hermetic Si pad detector for UA2

Cylindrical detector array
collaboration with
Claus Gößling and Alan Clark
U. Dortmund, U. Genève

FIRST Si barrel detector
in collider experiment
FIRST Si array with
IC chip readout

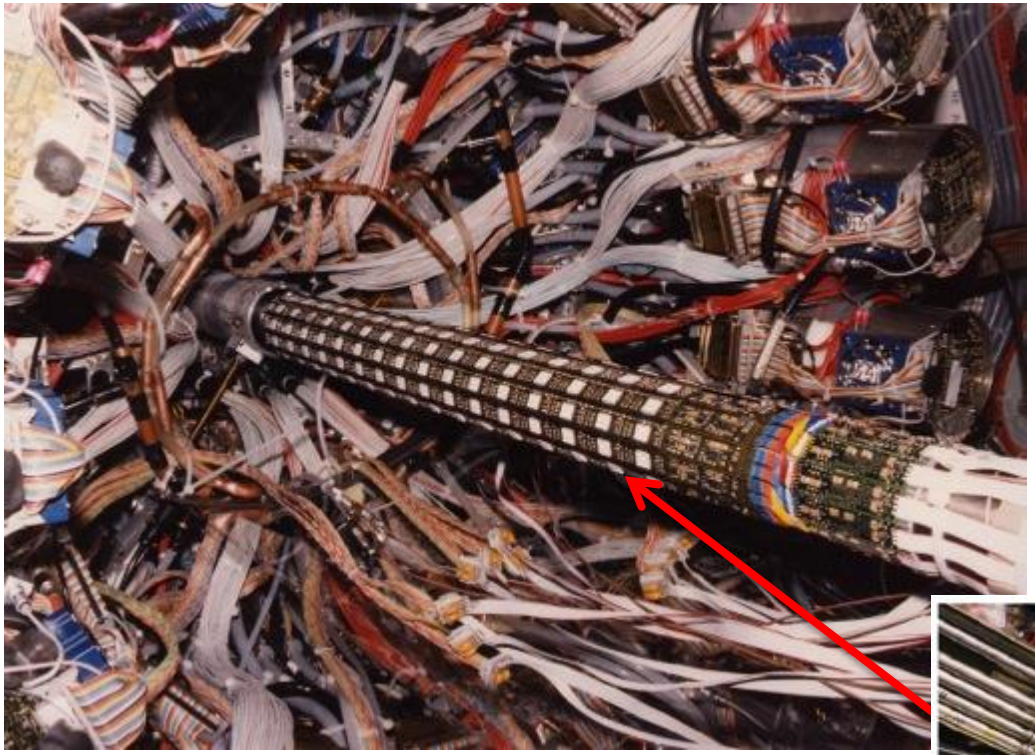


**~5 mm thin CILINDER around beam pipe**
**ONLY POSSIBLE using "AMPLEX" chip**
**16-channel circuit design Pierre Jarron**

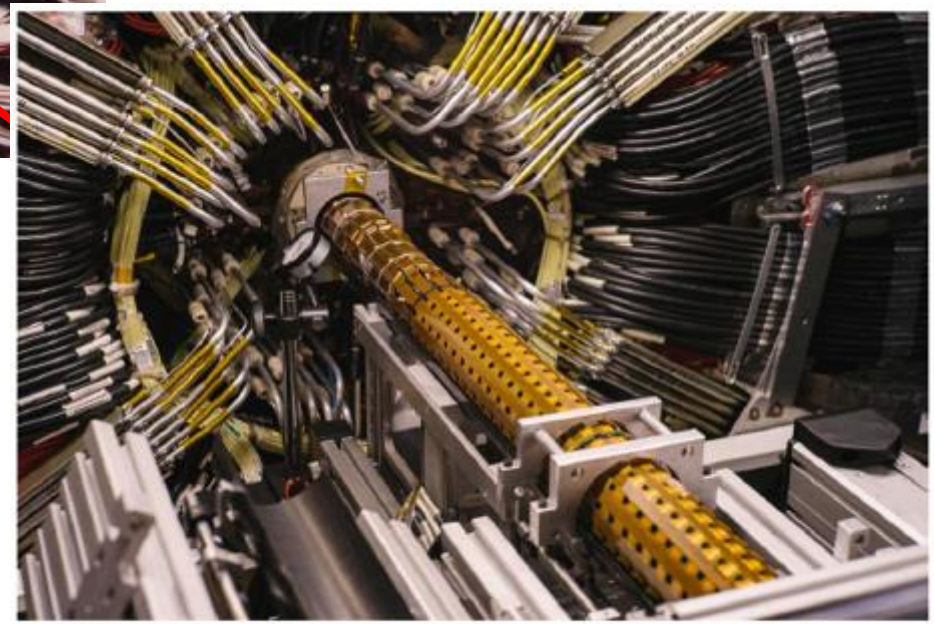
R. Ansari et al. NIMA279(1989) 388

1986 – 1988 in LAA microelectronics project

# Hermetic Si pad detector for UA2



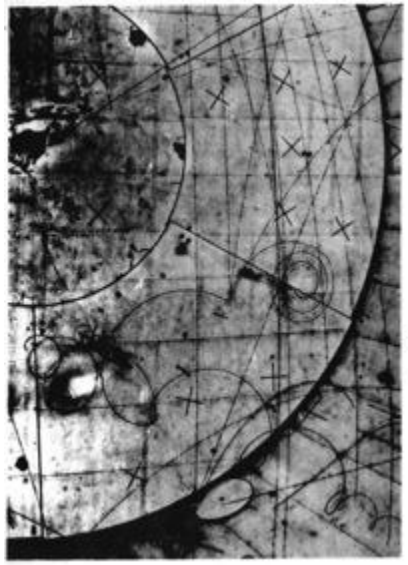
2nd Generation Insertion

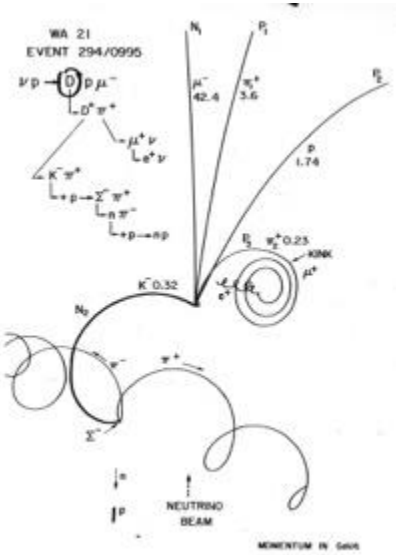


2015 Inner-B-Layer ATLAS IBL

**Figure 1:** Picture of IBL insertion into the ATLAS detector.

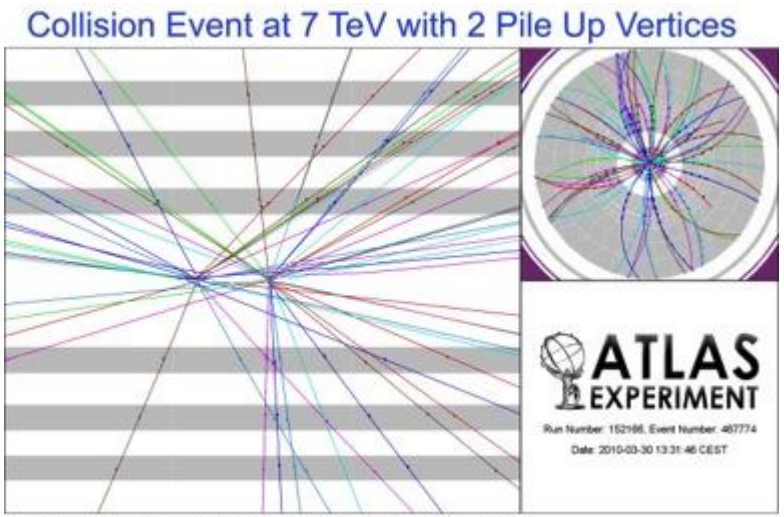
# from Bubble Chambers to fully Electronic Silicon Imagers



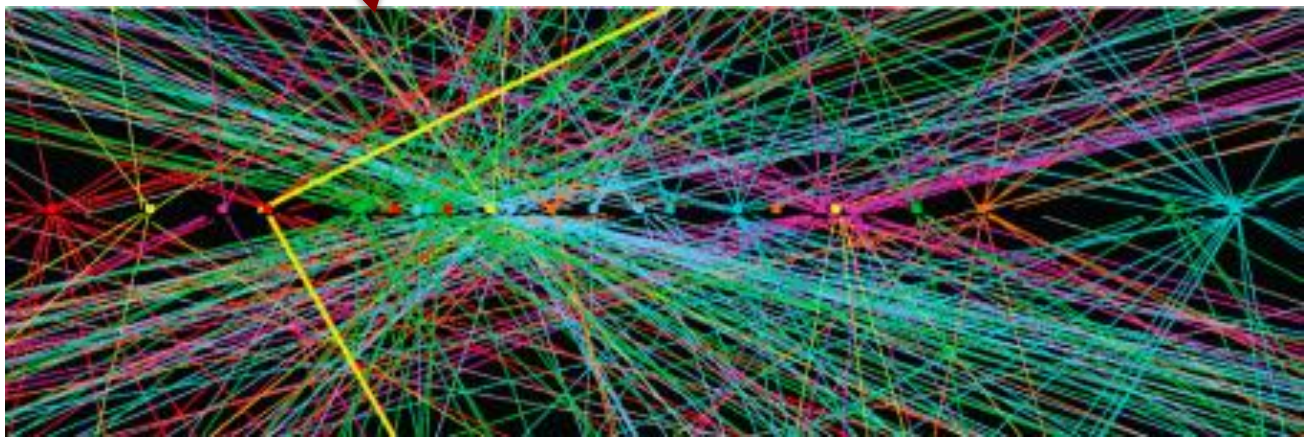



**BEBC 1981**
**photo every ~1s**

## ATLAS experiment 2012




http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html



**LHC 2016**
**40 million**
**records per s**

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

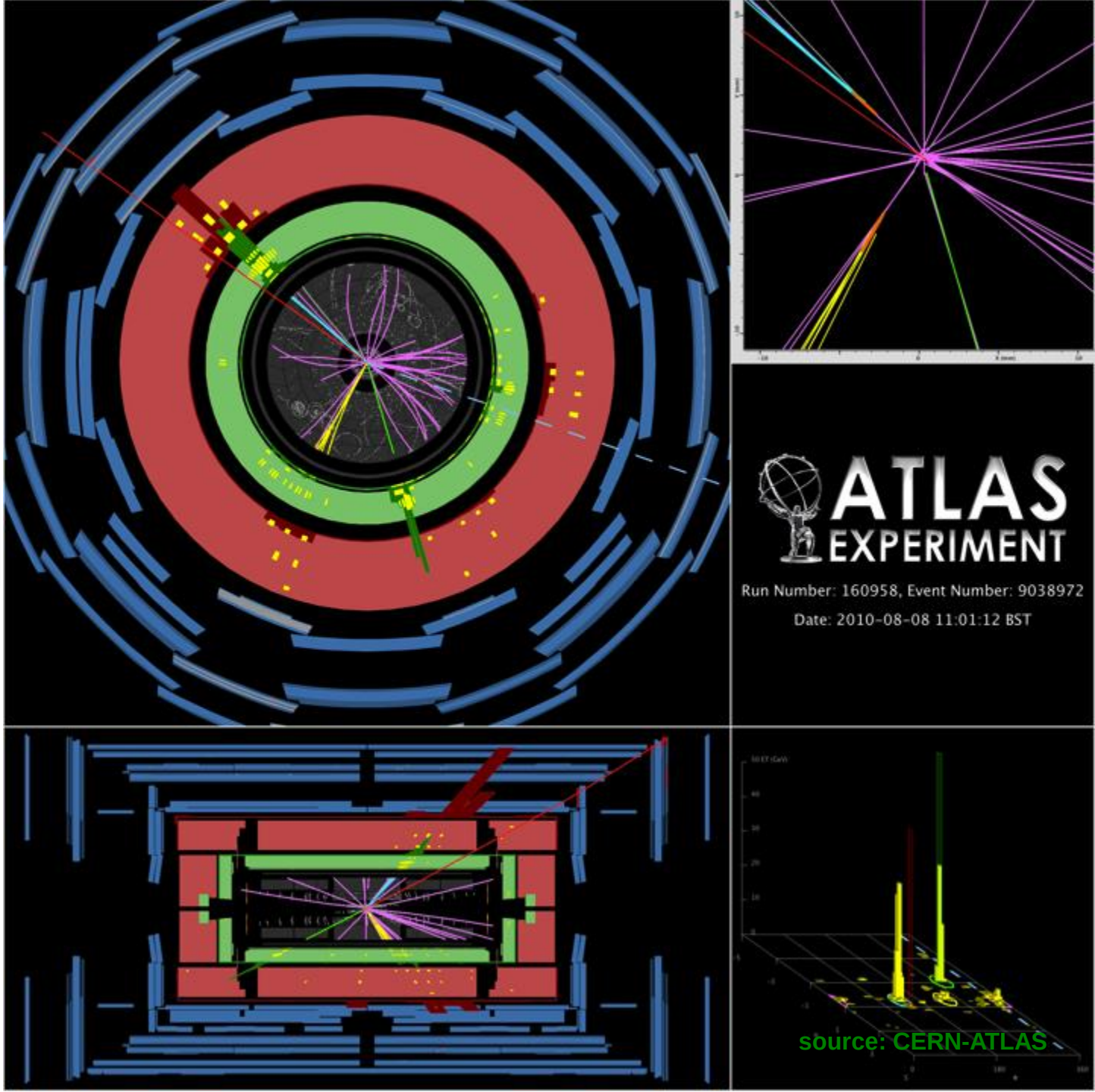
**Imaging Now All Electronic with 3-D Reconstruction**

**Many Tracks + here 2 "Jets"**

**40 million / sec**

**Second Vertex: a short-lifetime particle is a messenger for new phenomena**

**next: blow-up**



# ATLAS

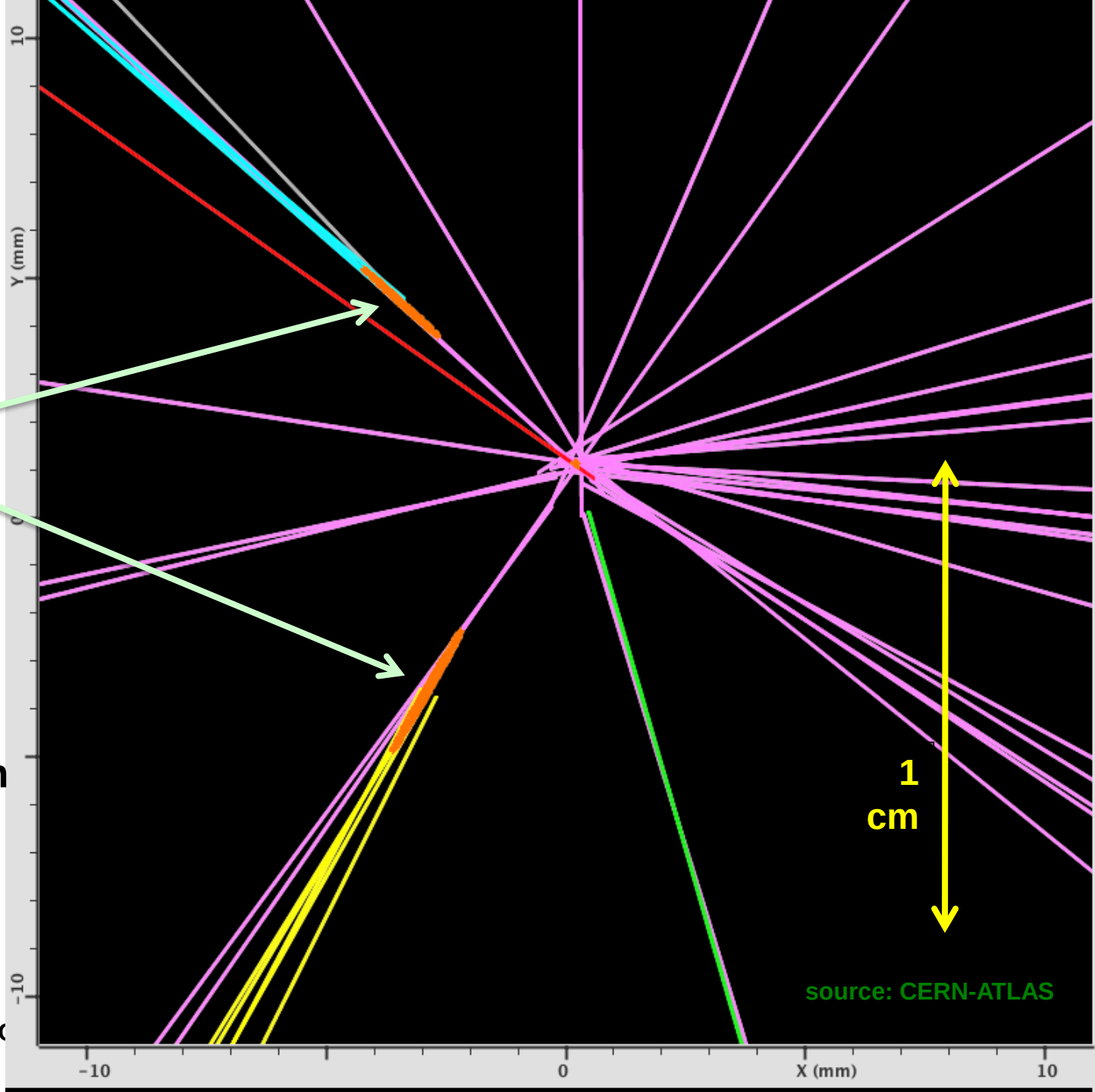
## Details around Primary Vertex

Two Secondary Vertices: “messengers”

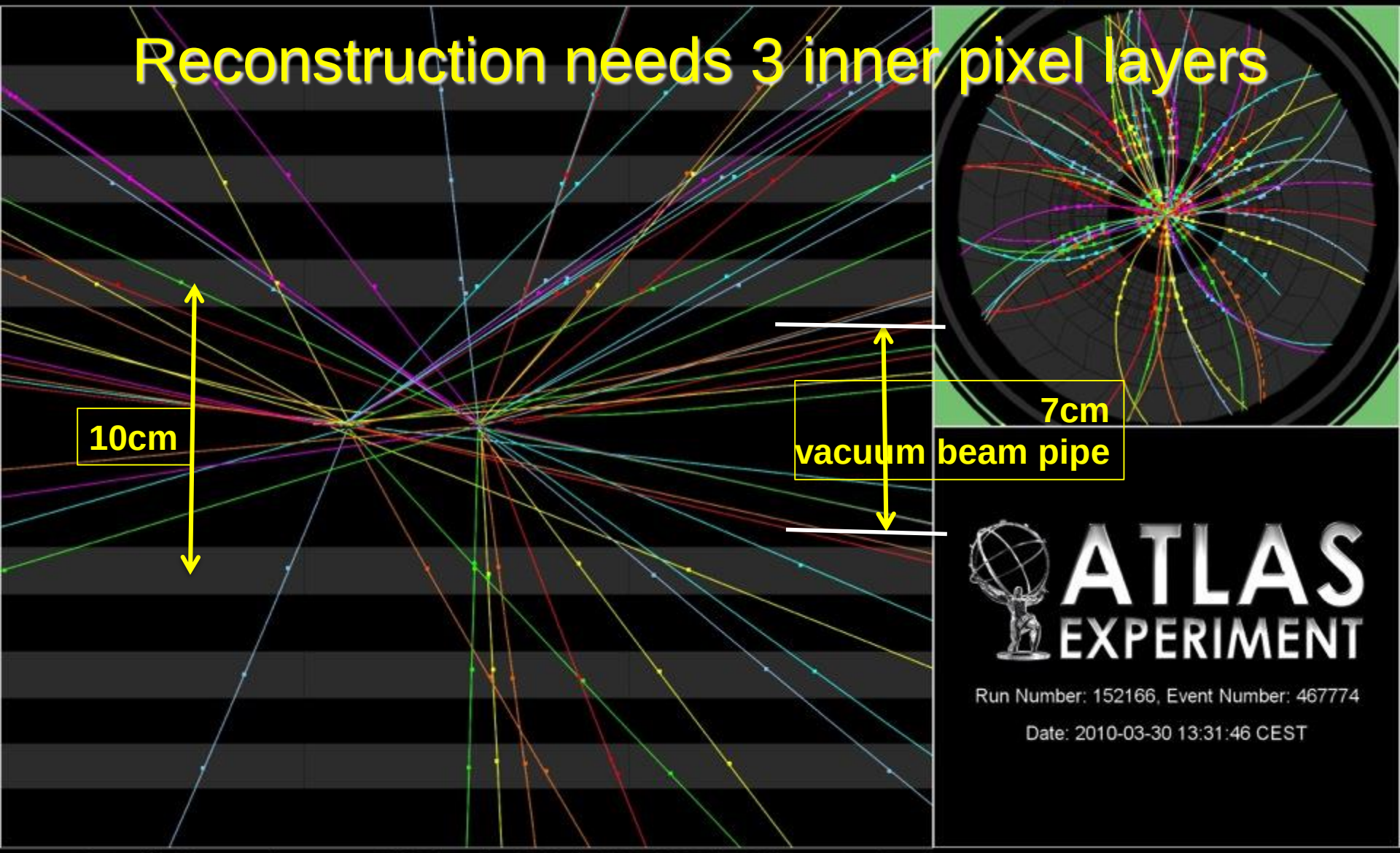
**Note scale**

1cm

all this is INSIDE beam pipe ∅ 7cm



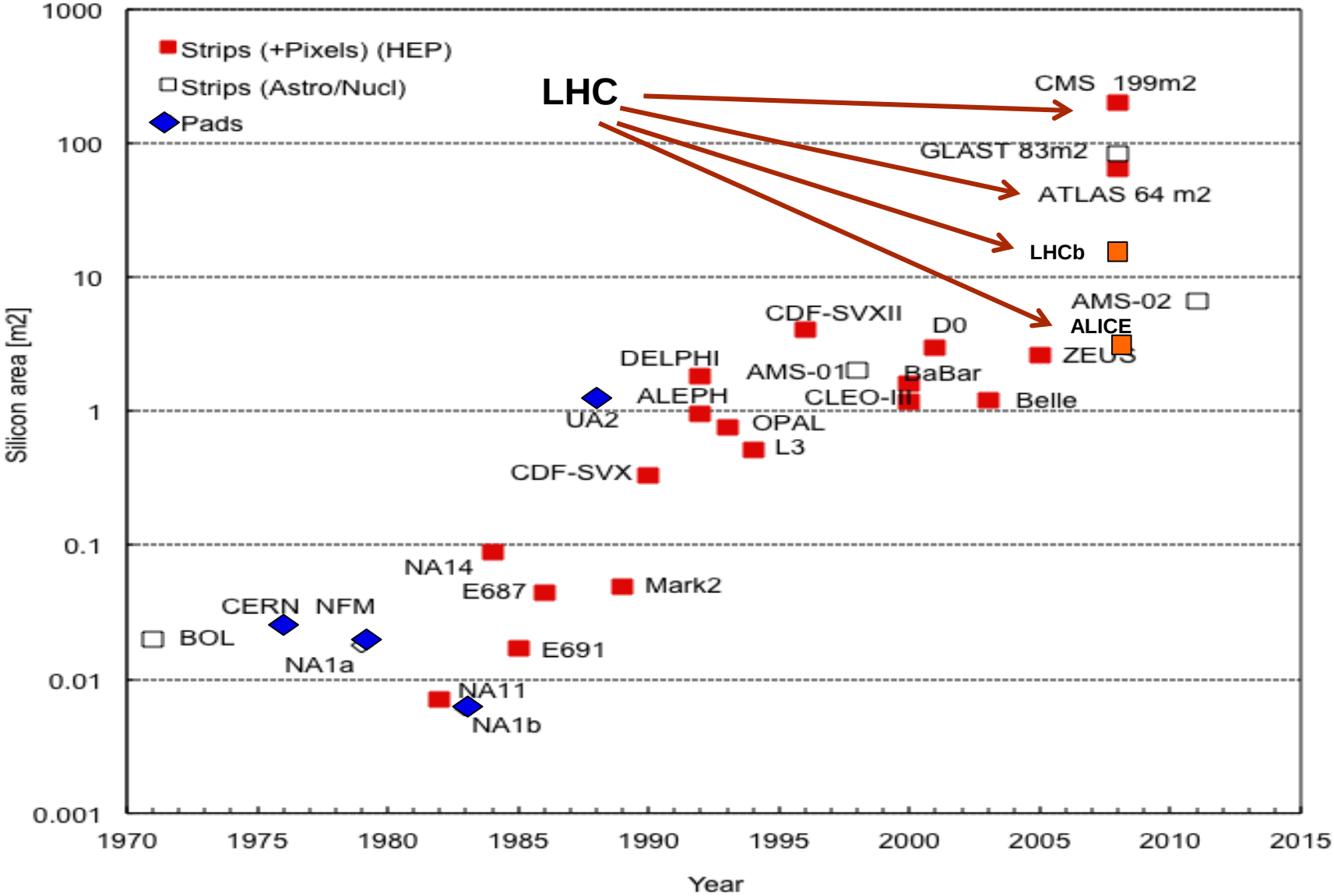
# Collision Event at 7 TeV with 2 Pile Up Vertices




http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

source: CERN- ATLAS

# Increase of the size of silicon detector systems
## in all LHC experiments and in many others



# Innovation in radiation hardness for Si chips and sensors

**Radiation effects in equipment have been an issue for spacecraft since Telstar**

**Dose levels even much higher inside collider experiments: krad -> Mrad**
**~1988 only 'iron-ball' experiment looked possible, what to do?**

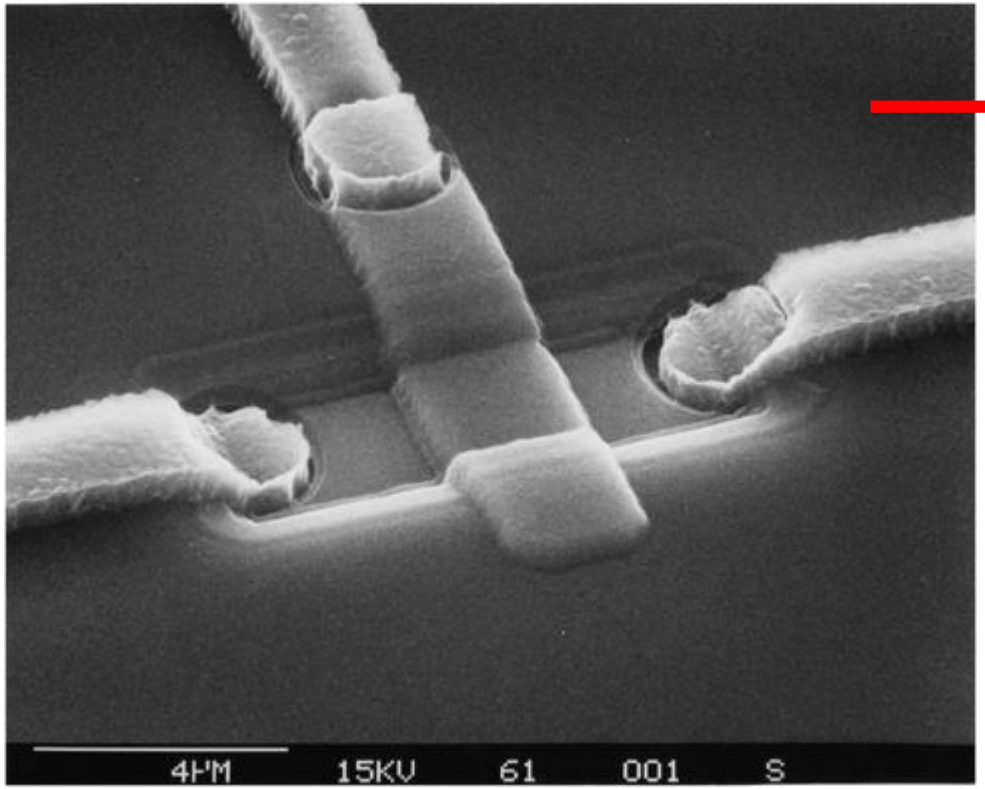
**Understanding of the particle interactions in Si and Si-oxide + beam testing**

**The 3 main radiation effects require 3 main solutions:**
**oxide threshold shift disappears due to tunneling, if oxide <5nm**
**suggestion based on work Nelson Saks, NRL Washington**
**edge leakage current under thick oxide avoided by enclosed layout**
**solution implemented ~1978 at RCA Princeton by Ron Smeltzer**
**single event effects (upset, burnout,..) avoided by triplication**
**standard approach in avionics, visit by Eugene Normand Boeing**
**These 'innovations' allowed financially acceptable radiation hard chips**

**A serious situation avoided by learning from specialists 1984-1997**

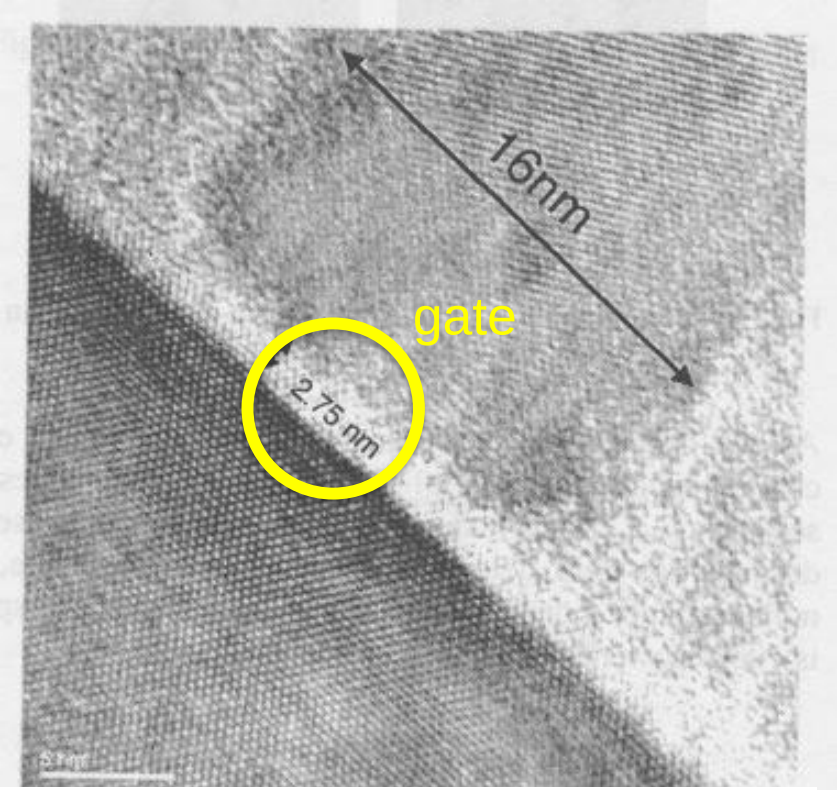
**Radiation hardness improvement of sensors has also been achieved**
**segmentation helps for dark current and signal loss**

# Integrated electronics is key: silicon MOS transistor




**continuous scaling/**miniaturization

**2015**




**2 µm TECHNOLOGY**

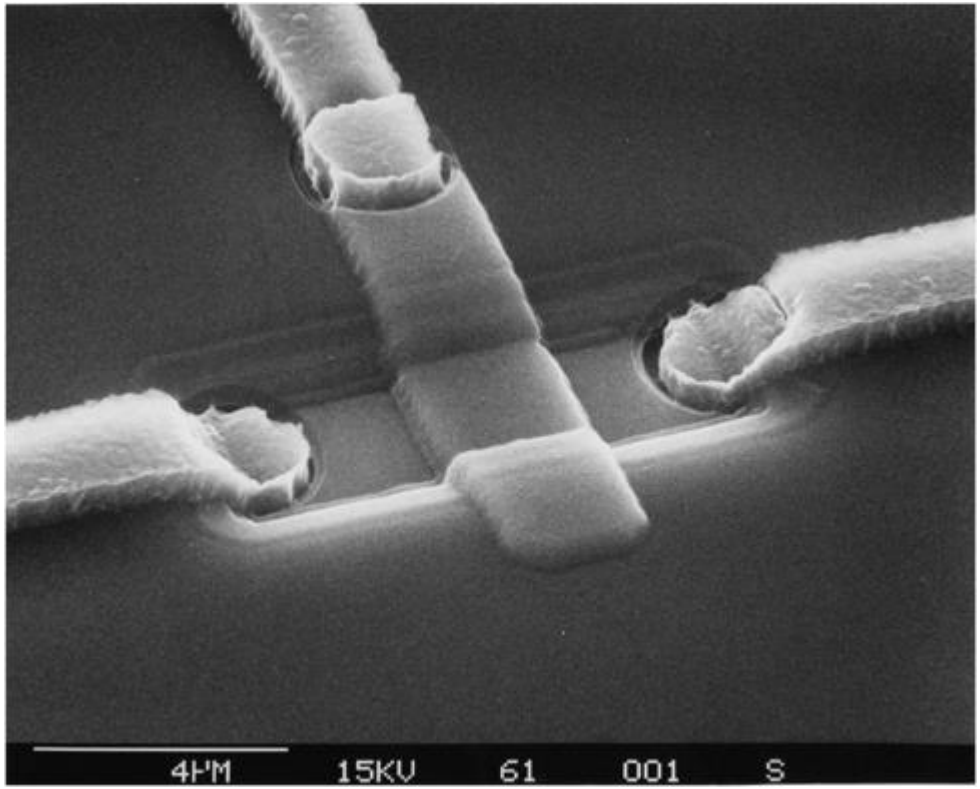
**1985**

HEP was 2 generations behind industry

**gate length .016 µm**

**$SiO_2$ gate thickness 2.75 nm**

# Integrated electronics is key: silicon MOS transistor




**on the same scale**

ongoing miniaturization

**$SiO_2$ gate 2.75 nm**
**thin gate is radhard**

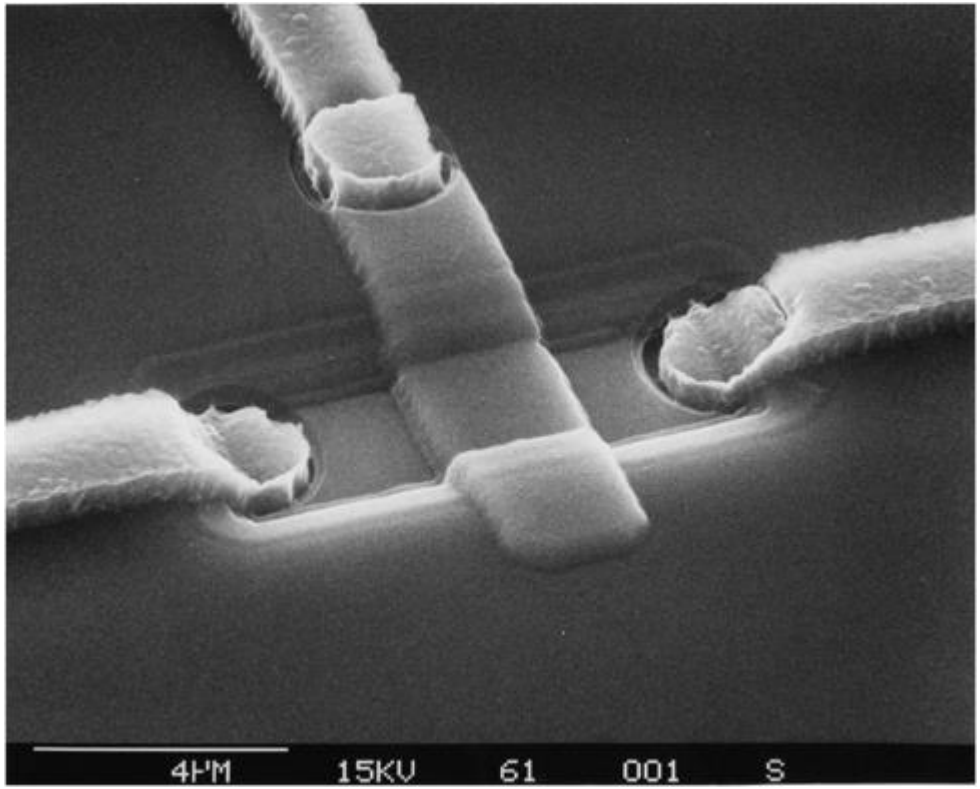
**2 μm TECHNOLOGY**
**1985**

HEP was 2 generations behind industry

**0.016 μm**
**2015**

now HEP is 8 generations behind

# Integrated electronics is key: silicon MOS transistor




**continuous scaling/**miniaturization

**2015**

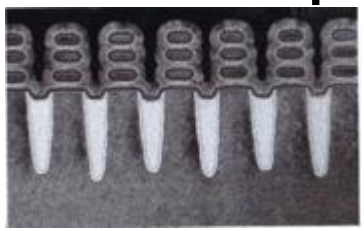
**same scale**

**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

# Ever more advanced (smaller) nm CMOS

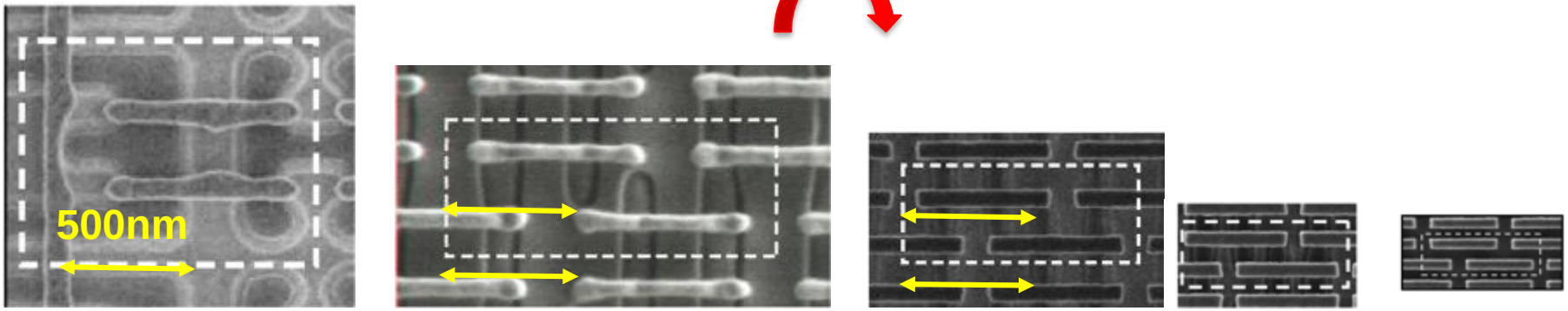
## INTEL : large improvement in lithography ≤45 nm

**example: minimal SRAM cell**

**~ TO SCALE**

**Several characteristics also have been improved, well beyond expectations**

**90 nm** **65 nm** **45 nm** **32 nm** **22 nm**




**1.0 µm²**
**1cells/ µm²**

**0.57 µm²**
**1.7cells/ µm²**

**0.346 µm²**
**2.9cells/ µm²**

**5.8cells/ µm²**

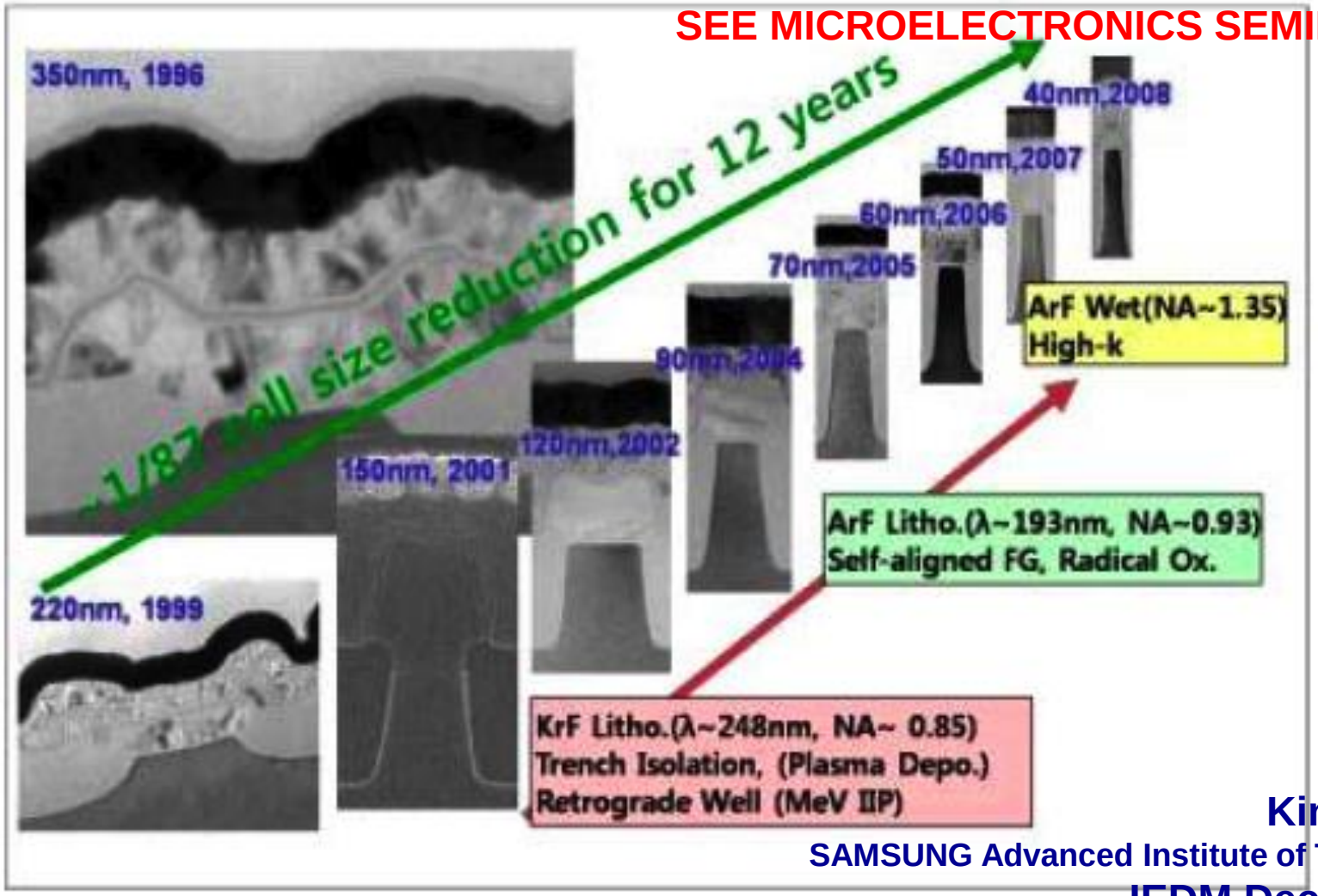
**10.8cells/ µm²**

**linear scale 4x smaller; area 10.8 x smaller**

**Mrs Kelin KUHN**
**IEEE IEDM 2007 & 2010**

# 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**

# Microelectronics essential for experiments
# vice versa: CMOS chips impossible without accelerators

major tools for CMOS manufacturing:
- ion implanters
- analysis equipment: X-ray, RBS, fluorescence, e-beam scanning SEM/TEM

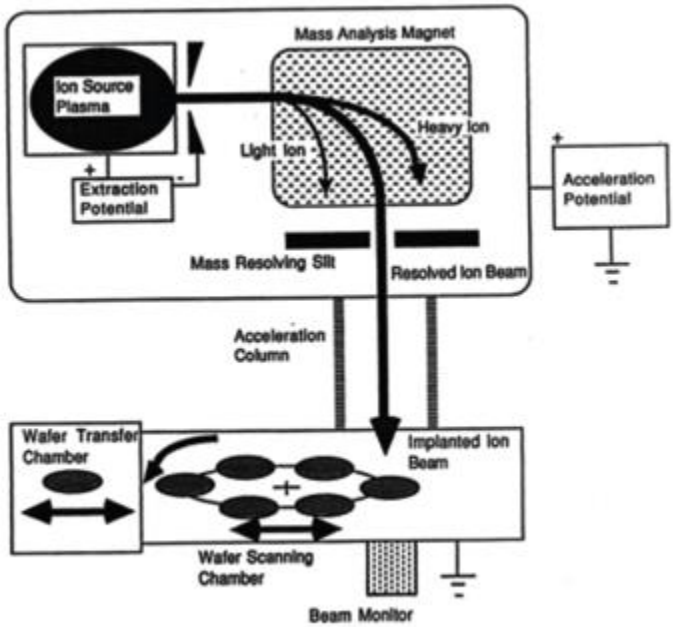
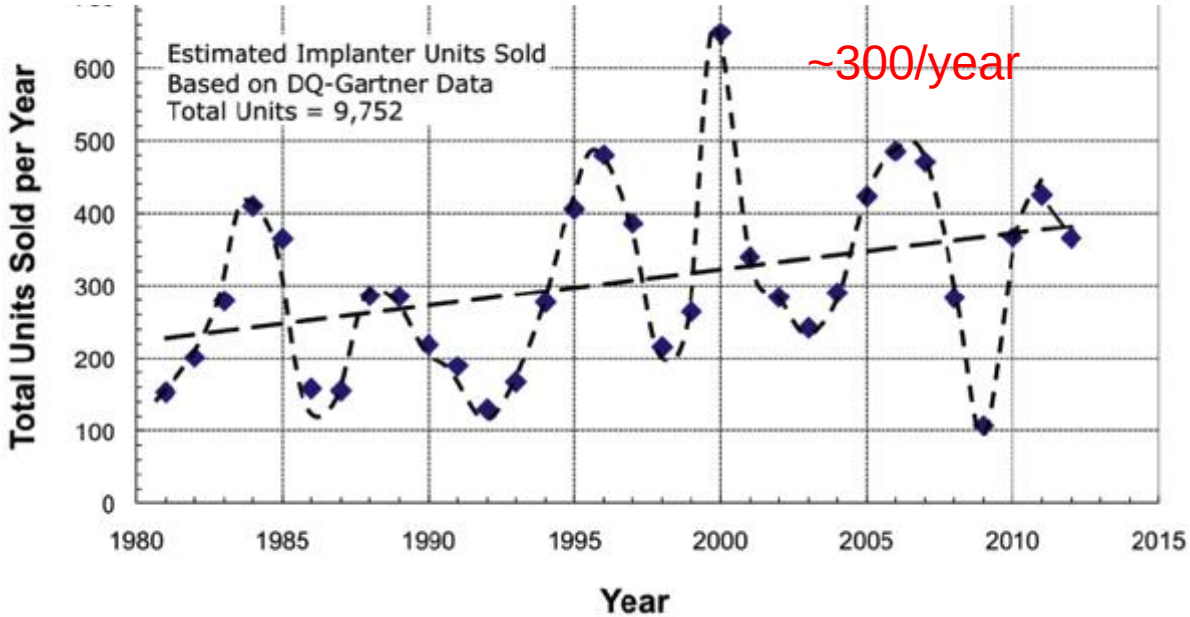



Figure 4: Major ion implantation beamline components.

WEYB2 Proceedings of PAC2013, Pasadena, CA USA

## ION IMPLANTATION FOR SEMICONDUCTOR DEVICES: THE LARGEST USE OF INDUSTRIAL ACCELERATORS

S.B. Felch, Susan Felch Consulting, Los Altos Hills, CA 94022, USA
M.I. Current, Current Scientific, San Jose, CA 95124, USA
M.C. Taylor, Taylor Consulting, Lake Oswego, OR 97034, USA



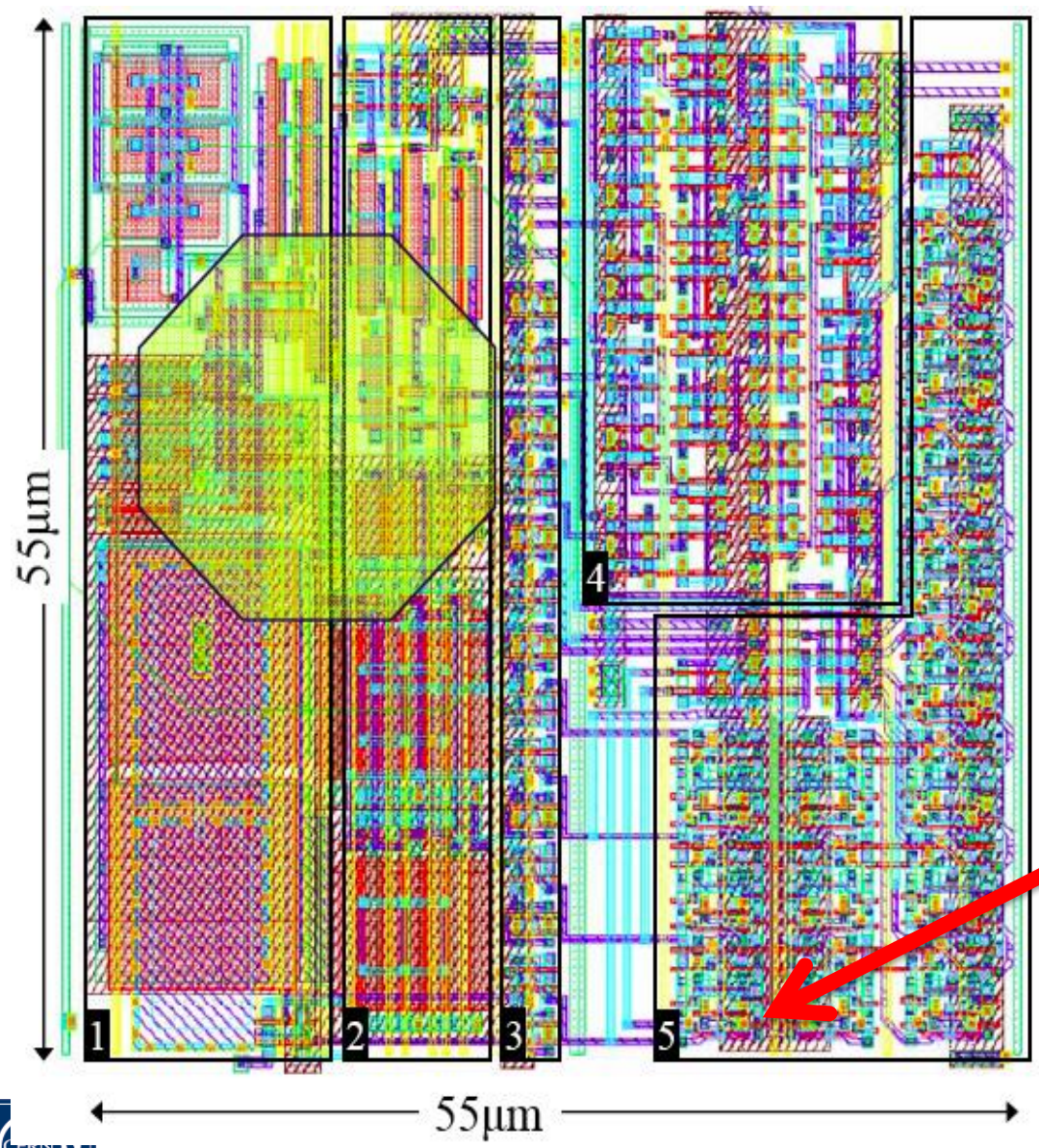
# Silicon 2D pixel detectors from 1989

can handle hundreds of simultaneous particles

smaller cells allow improved signal/noise S/N

example: Timepix development,
now prototype for LHCb Velopix vertex upgrade

# TIMEPIX original cell layout

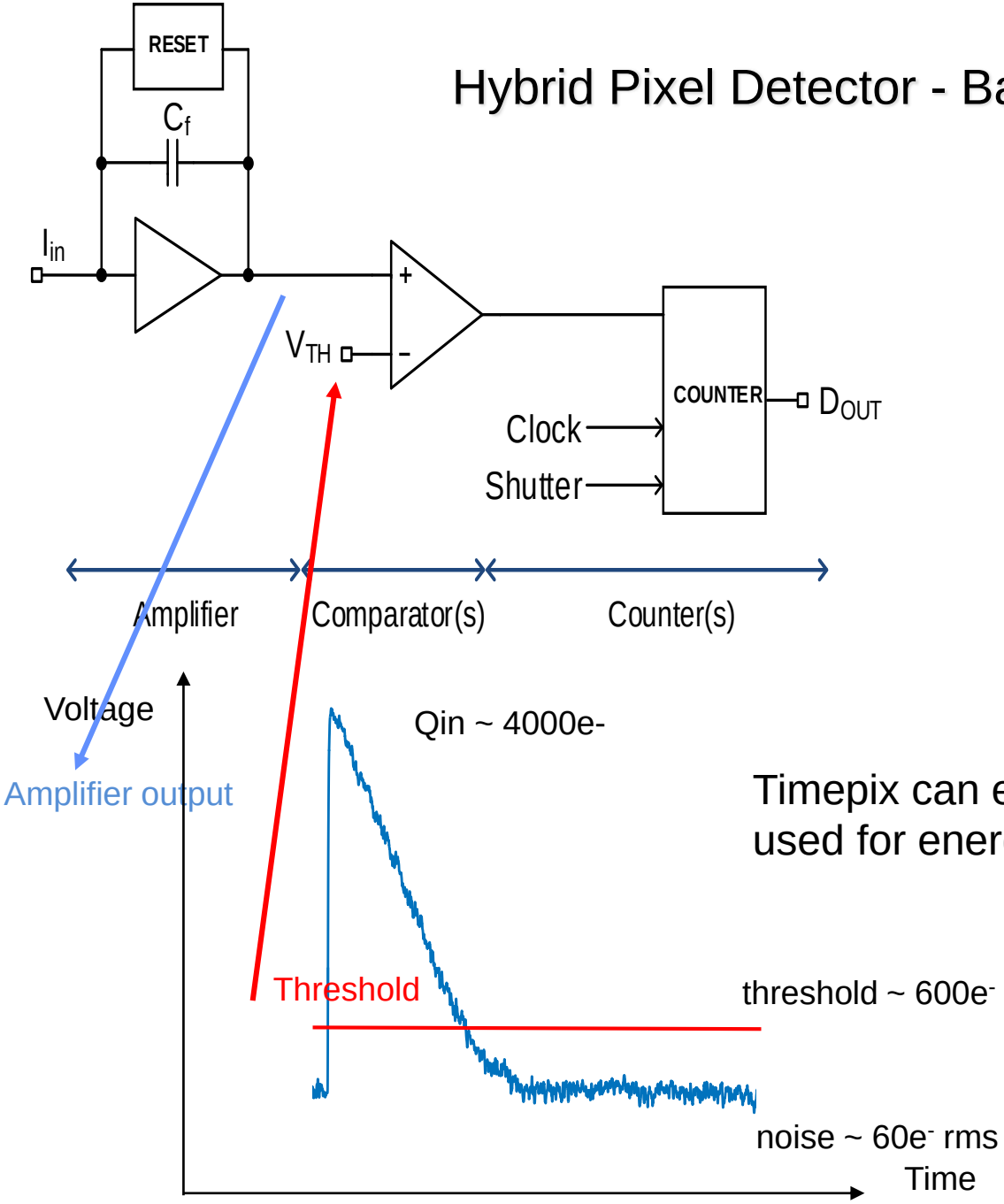



design by
Xavier Llopart
and colleagues
PhD Thesis p. 107
CERN 2007

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

includes Time-Over-Threshold
signal amplitude digitizer
in each pixel

# Hybrid Pixel Detector - Basic Circuit

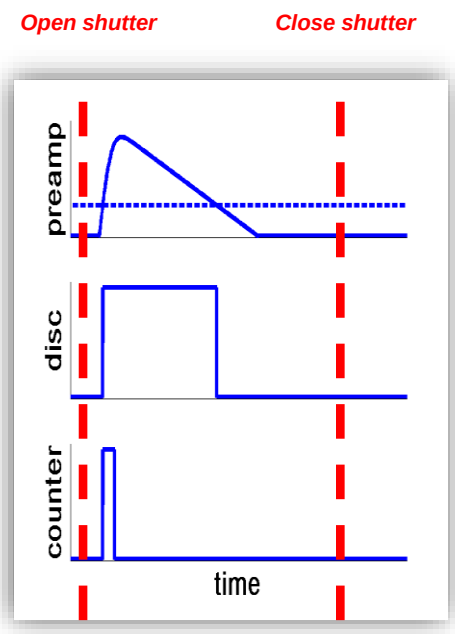



Timepix can easily distinguish $Fe^{55}$ line used for energy calibration in-pixel ToT

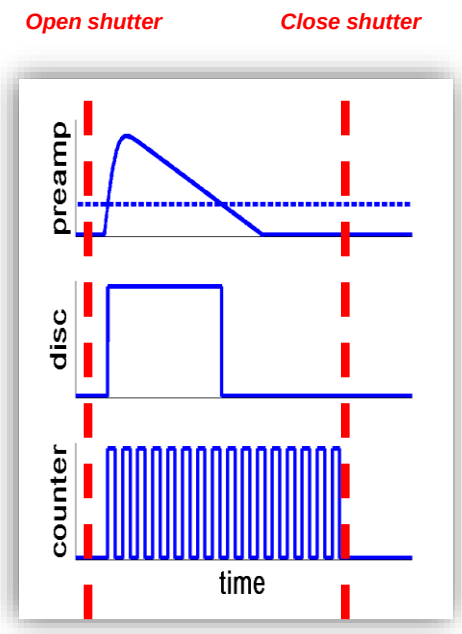
→ imaging free of noise

# Timepix Pixel Operation Modes

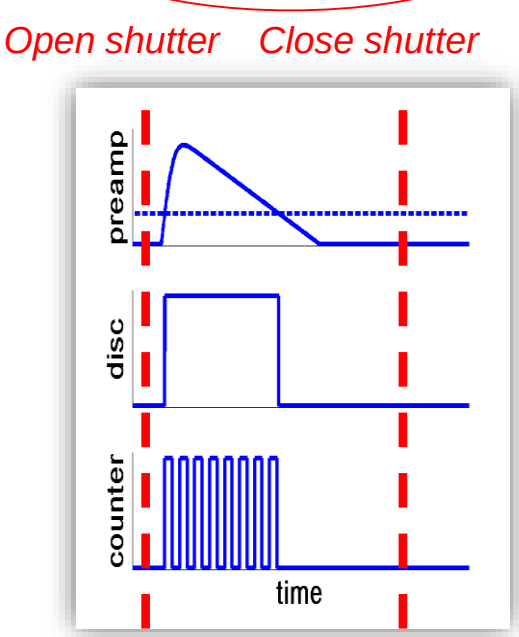
Particle counting




Arrival Time*




Time over threshold



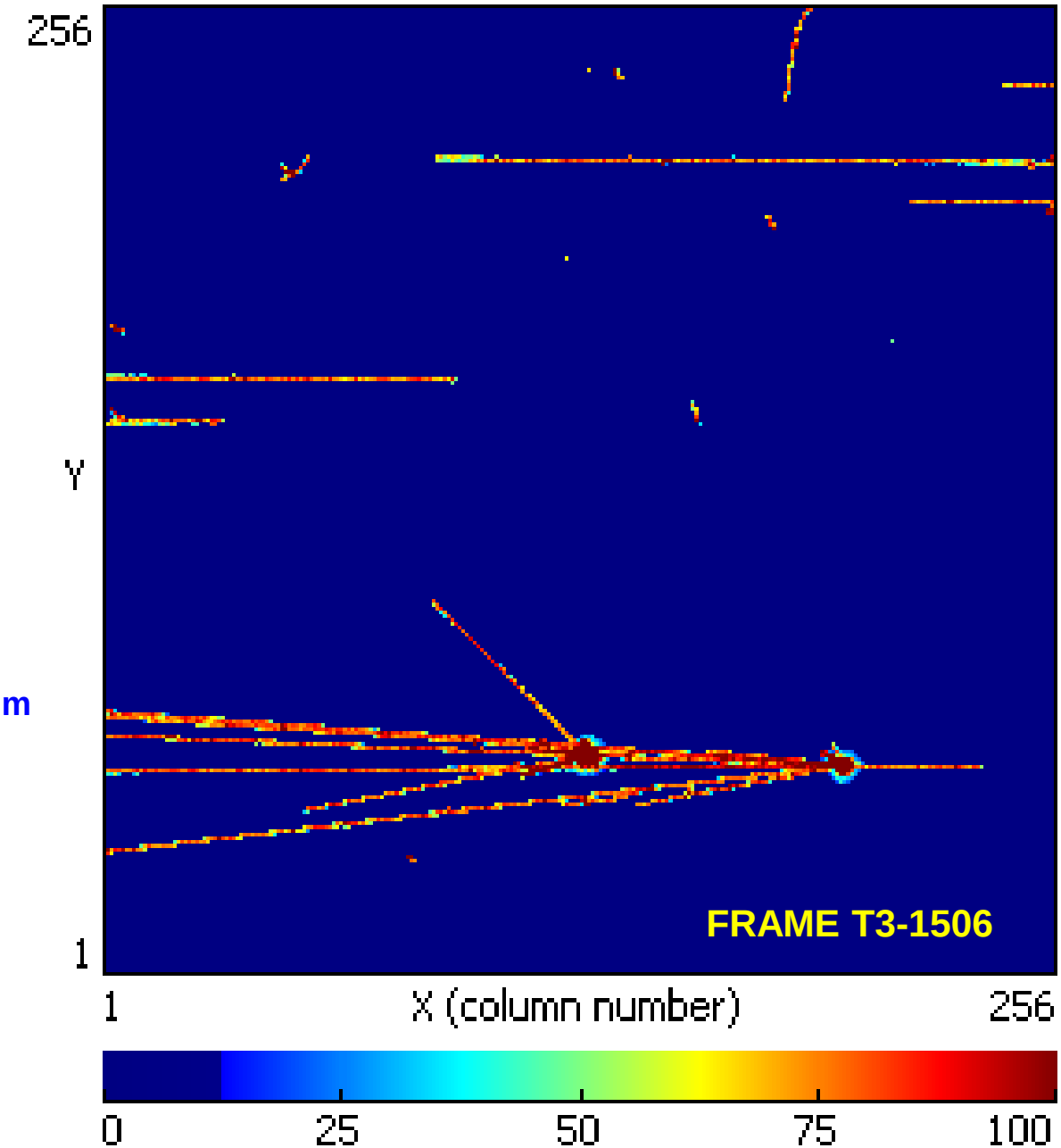

* originally implemented at the request of the EUDet Collaboration for use in gas-TPC

# TIMEPIX silicon ’emulsion’/portable ‘bubble chamber’

**H6 120 GeV p/ π beam 2007**

**incident from the right**

**Beam**




**pion interacts with Si,**
**one secondary pion again, after ~3mm**

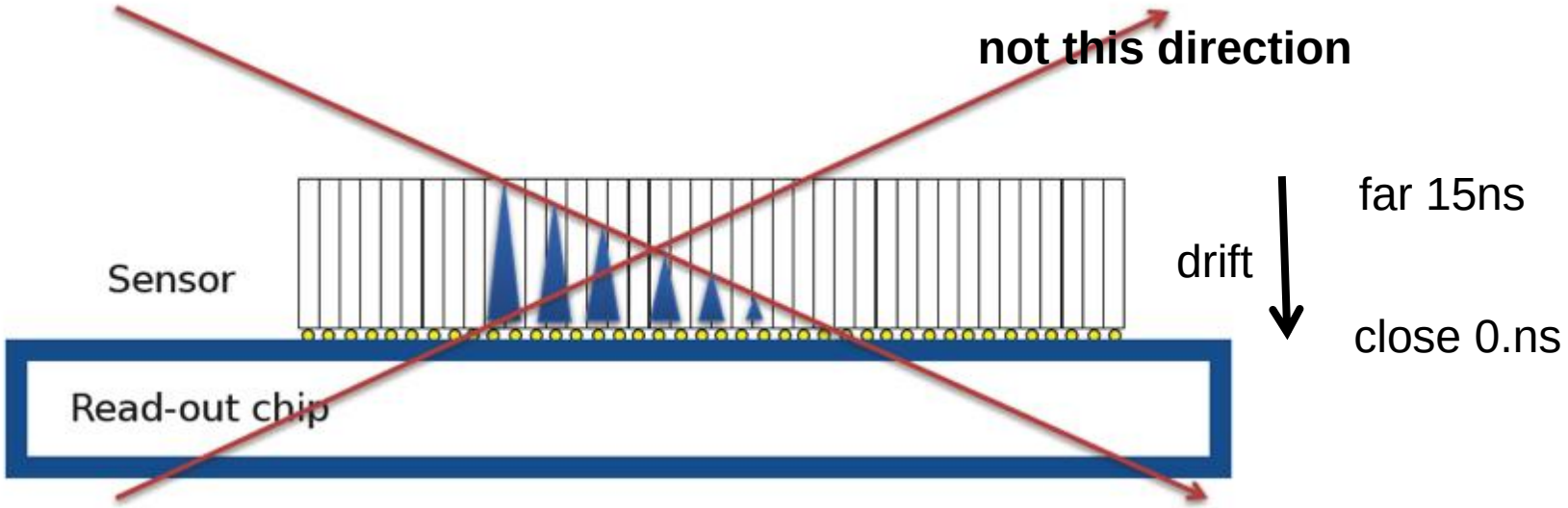
Trails to the front or to the back ?
ambiguity can be solved if
2 adjacent planes are used
-> stack of pixel detectors
or: see hereafter, new Timepix3

beam test with help of
John Idarraga / then Montréal

# Timepix3 track entry point & direction

carrier drift time in z-coordinate is always recorded in each pixel : 0 to ~15ns
currently with 1.2ns precision
future chip intends to achieve well below 1 ns

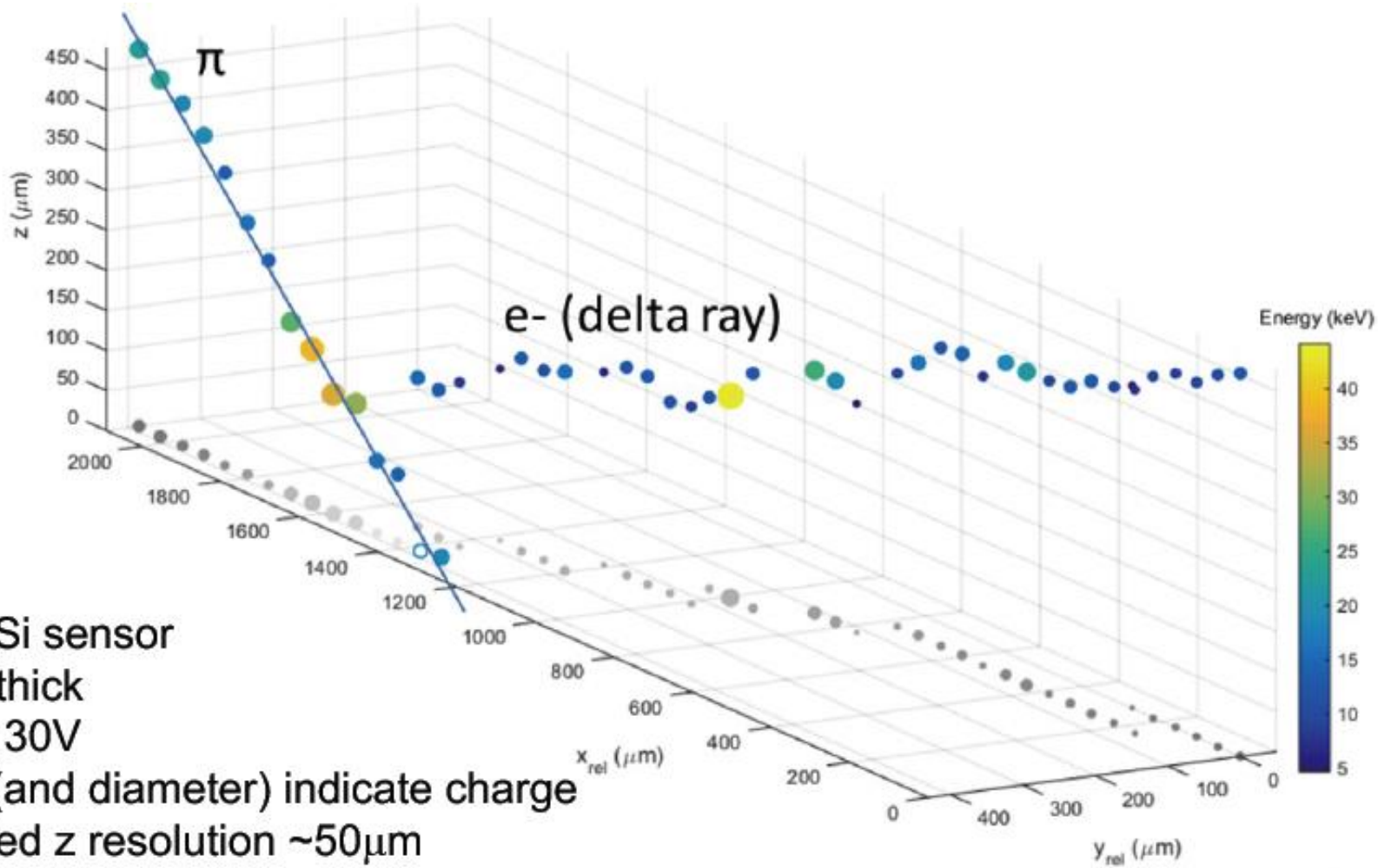
ambiguity is resolved and entry point is precisely known




useful for high-energy electrons at ~low intensity in microscope
500µm thick sensor can stop electrons ~350keV; little radiation damage

# Timepix3 3D track reconstruction

**120 GeV $\pi$**




60 deg
p+ in n Si sensor
500μm thick
$V_{bias}$ = 130V
Colour (and diameter) indicate charge
Measured z resolution ~50μm

Slide courtesy of B. Bergmann, S. Pospisil, IEAP, CTU, Prague

# Photosensitive Emulsion, a slow 3D Detector

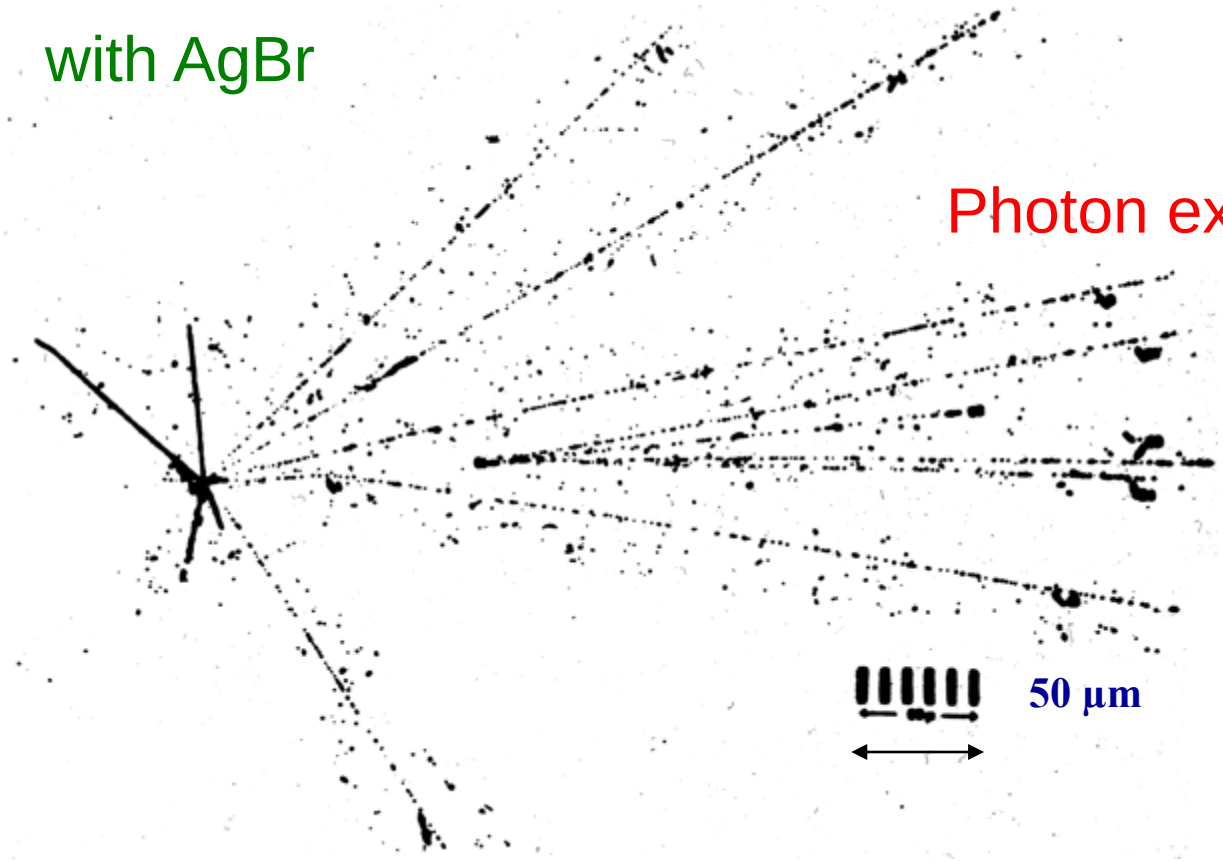
Thick gelatine film

with AgBr

3D, sub µm precision

CHARM DECAY

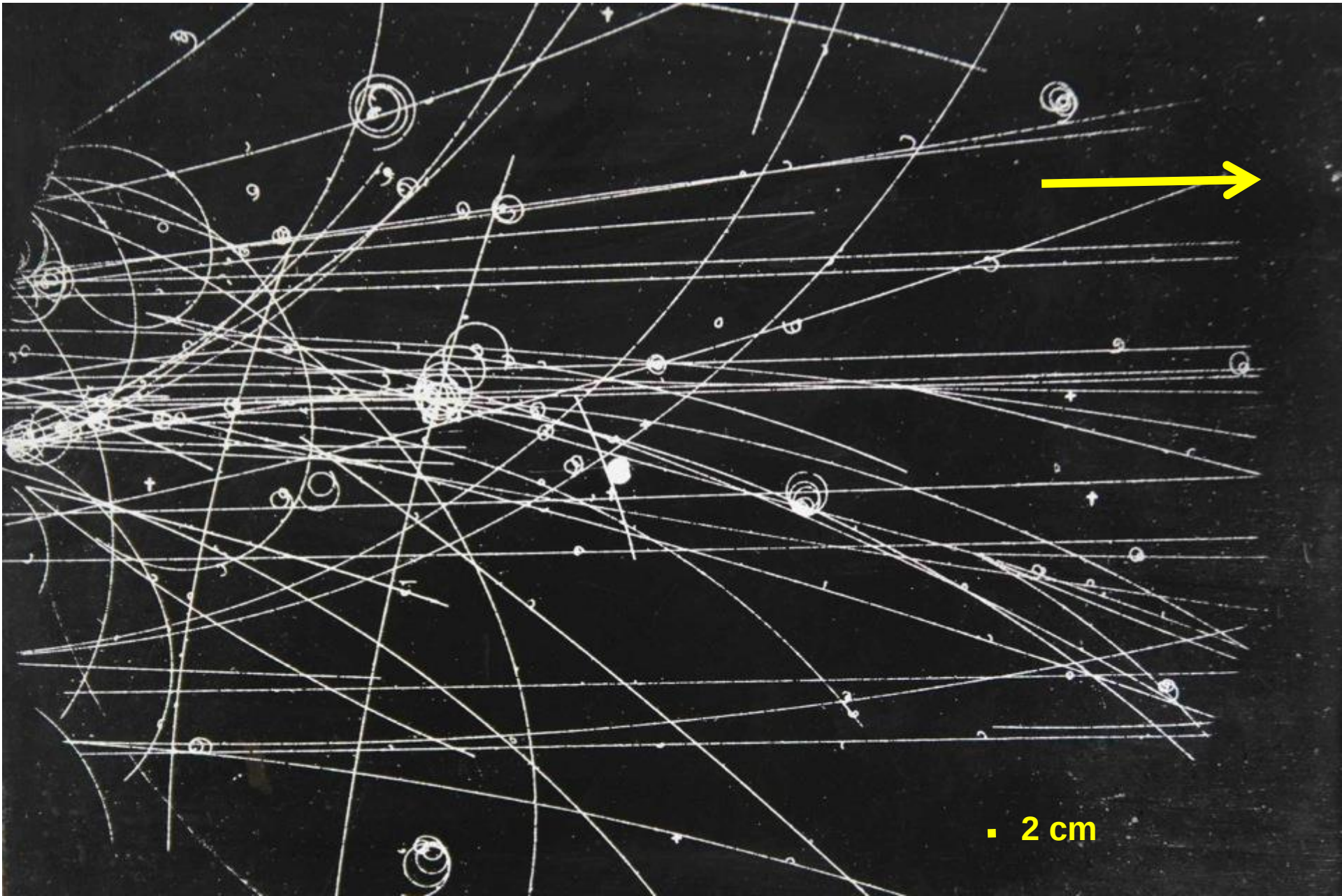
Photon exp.WA59 ~ 1985

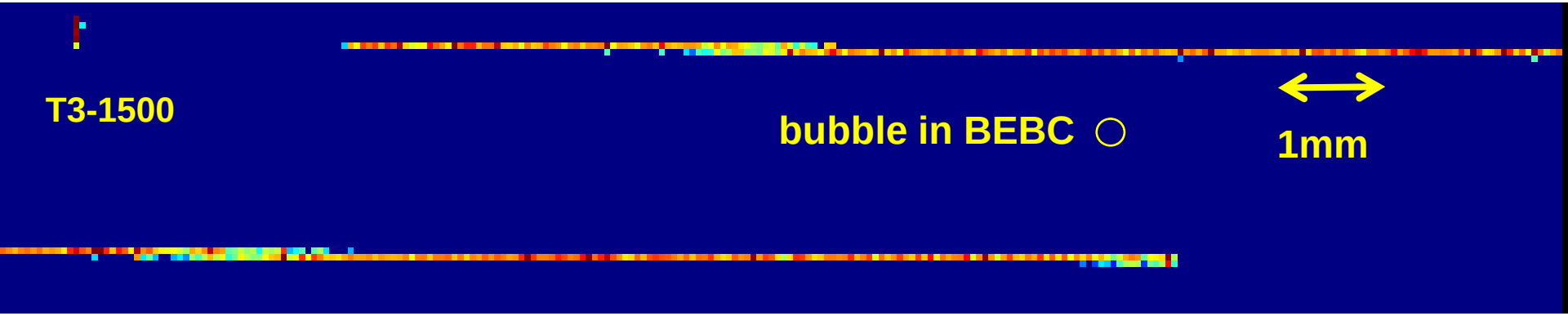



Successive ionizing energy transfers (~5keV) to grains create latent image

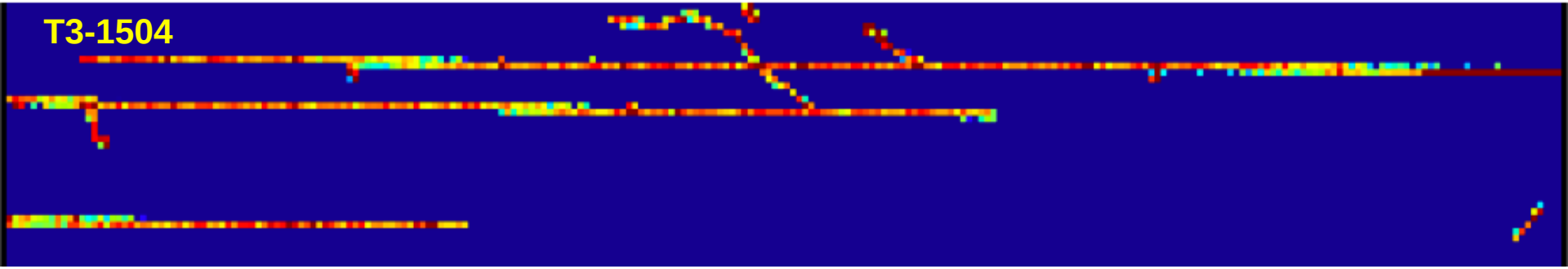
500 µm

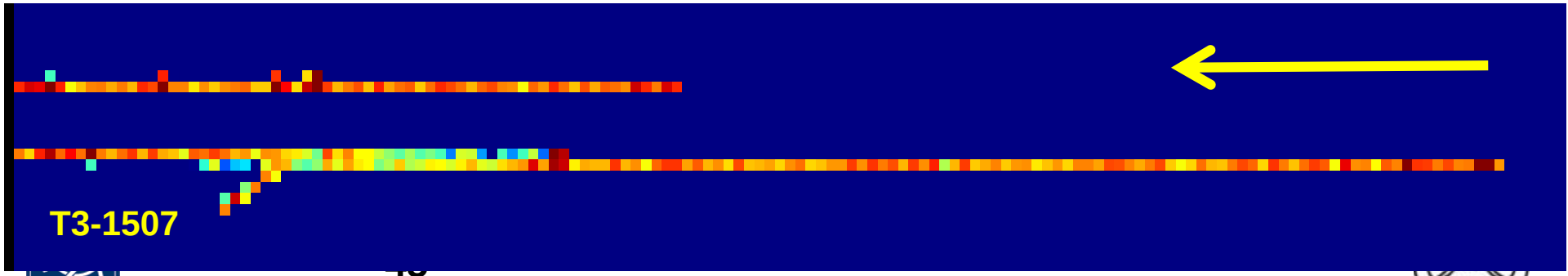
# Particle Physics Old Times (2m Chamber CERN)






# Typical Muon Trails in Timepix ...



# Arguments for imaging detector

Tracking with many pixels (15-30) improves precision

allows to exclude points corrupted by a d-ray

possible to reach precision <0.1μm

Reduction of ambiguities in reconstruction process

recent 2-point stubs design helps, imaging goes further

Additional information on type of particle: improved dE/dx

Specific features help to identify energetic leptons (e , μ)

transverse momentum, delta rays, lateral scattering

Sensitivity for exotic things

e.g. clusters from neutrals, interactions at very low energy

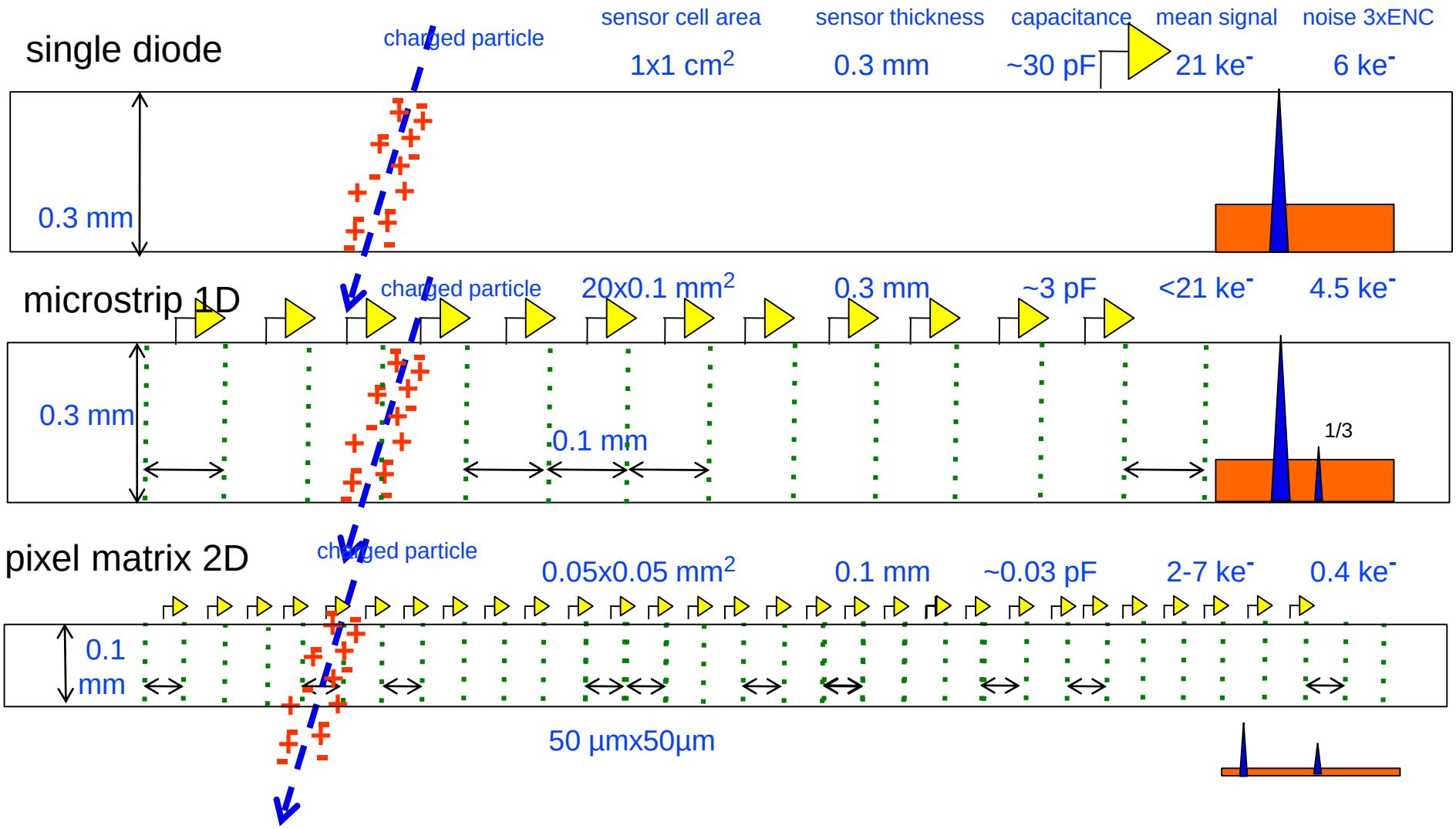
# Towards 3D voxel/vector detector 5µm x 5µm x 5µm

# monolithic, stacked

nm technology
cabling
cooling
mechanics

# The main innovation

## Segmentation of the sensor area into ever smaller cells

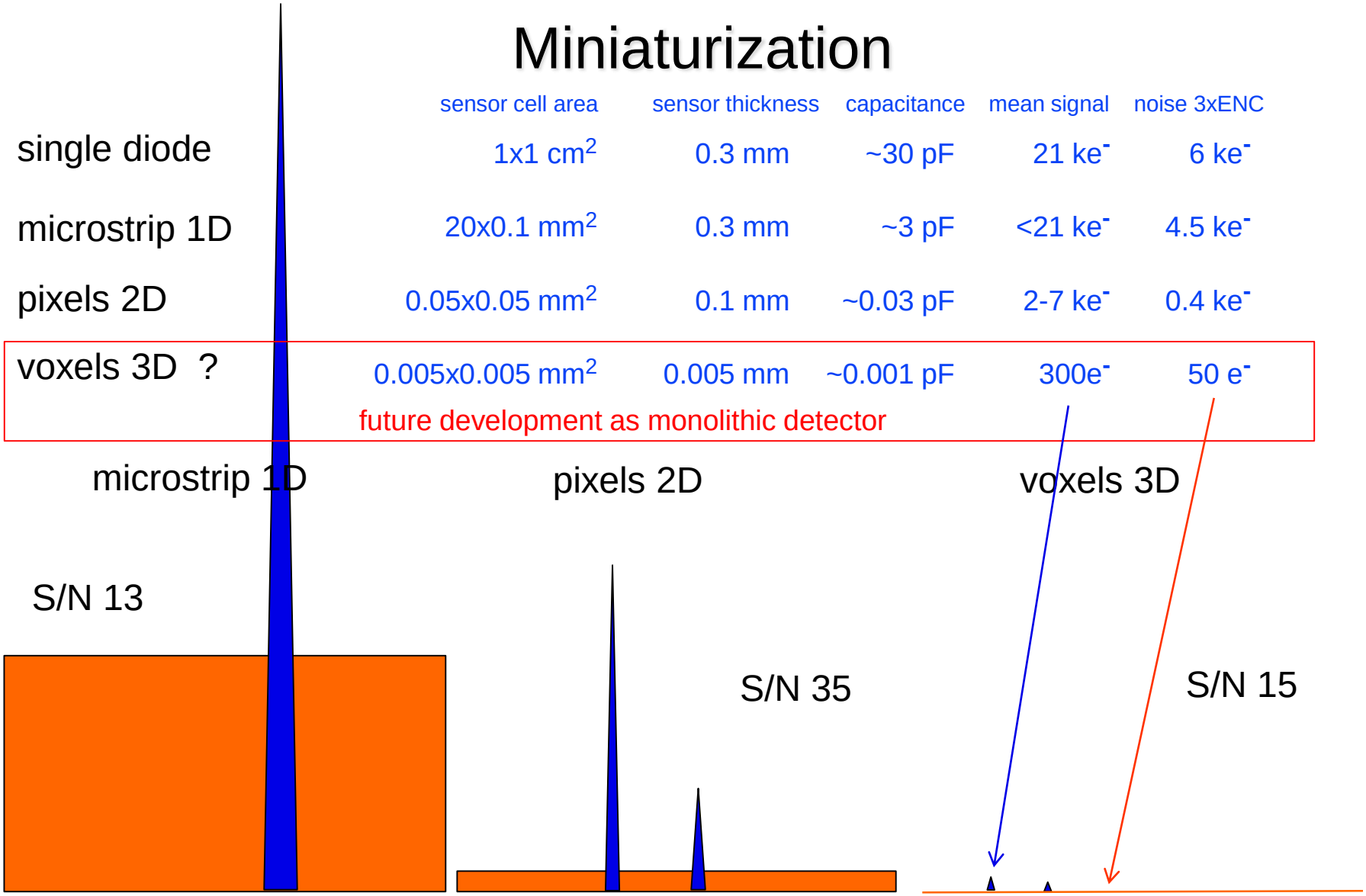



Improvement of signal/noise allows thinner sensor: < 100µm

# Miniaturization

| | sensor cell area | sensor thickness | capacitance | mean signal | noise 3xENC |
|---|---|---|---|---|---|
| single diode | 1x1 $cm^2$ | 0.3 mm | ~30 pF | 21 $ke^-$ | 6 $ke^-$ |
| microstrip 1D | 20x0.1 $mm^2$ | 0.3 mm | ~3 pF | <21 $ke^-$ | 4.5 $ke^-$ |
| pixels 2D | 0.05x0.05 $mm^2$ | 0.1 mm | ~0.03 pF | 2-7 $ke^-$ | 0.4 $ke^-$ |
| voxels 3D ? | 0.005x0.005 $mm^2$ | 0.005 mm | ~0.001 pF | 300$e^-$ | 50 $e^-$ |

future development as monolithic detector




voxel electronics requires advanced technology of a few nanometer dimensions

# Matrix with smaller cells performs better in noise and power

$$\frac{S}{N} \sim \frac{Q/C}{\sqrt{gm}} \sim \frac{Q}{C}\sqrt[m]{I} \sim \frac{Q}{C}\sqrt[m]{P} \text{ with } 2 \leq m \leq 4$$

or

$$P \sim \left\{\frac{\frac{S}{N}}{\frac{Q}{C}}\right\}^{m} \text{ with } 2 \leq m \leq 4$$

For constant S/N:

$$P \sim \left[\frac{Q}{C}\right]^{-m} \text{ with } 2 \leq m \leq 4$$

Signal charge/detector capacitance (Q/C) is the figure of merit for the sensor determining the analog performance/power consumption

m = 2 for weak inversion up to 4 for strong inversion

# small changes all

mosquito 5 mg

$5\ 10^{-3} \times 6\ 10^{23} \sim 3\ 10^{21}$ nucleons

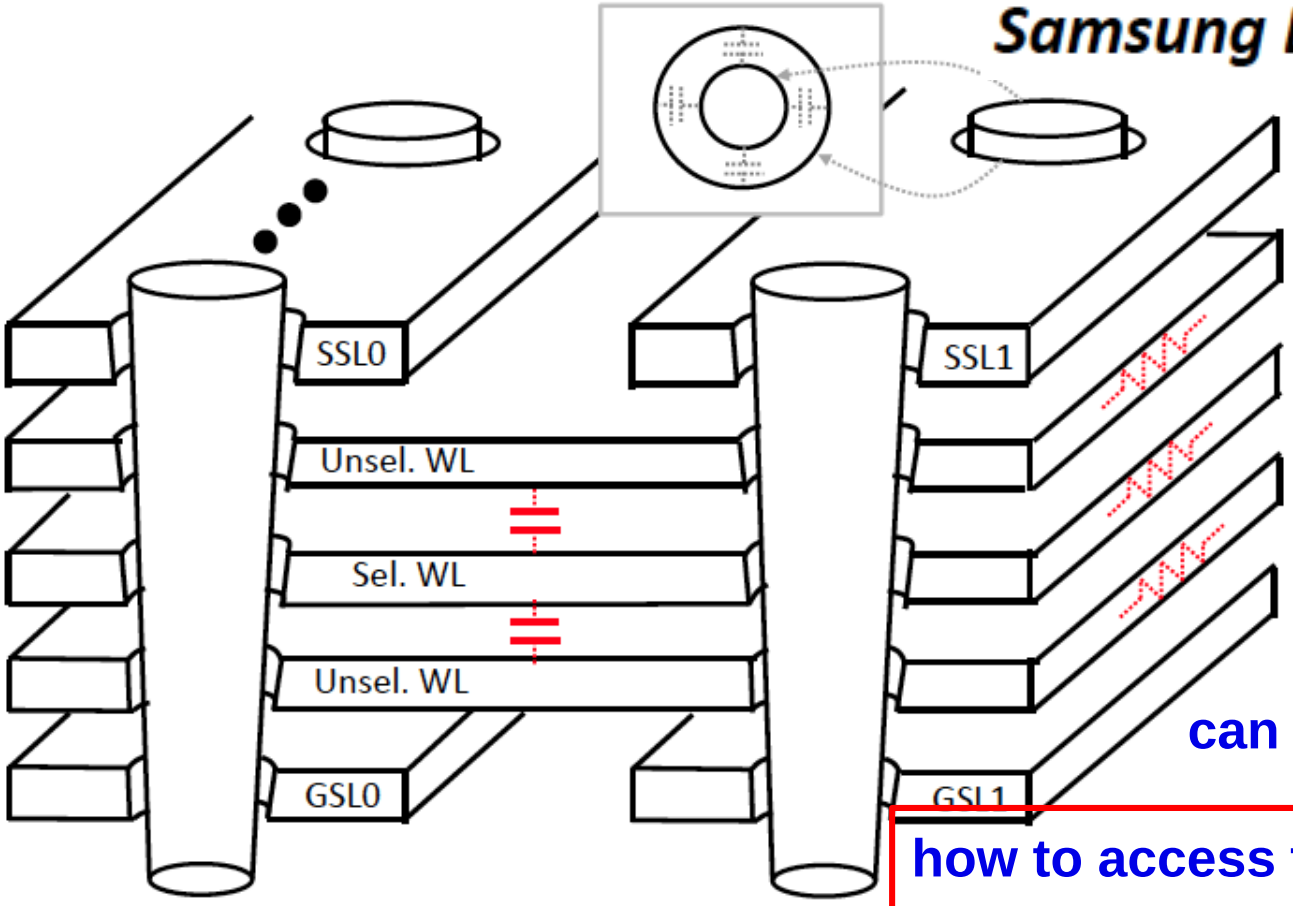
walks upside down as well

represents same energy as LHC proton, but not concentrated

# 3-D Stacked Si for flash memory
# 256 Gb 48 layers -- 2016

**now in 2017 64 layers, 512 Gb**

***Samsung Electronics, Korea***

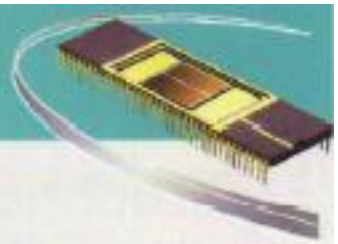



**can store 3 bits per cell**

**how to access this for science???**

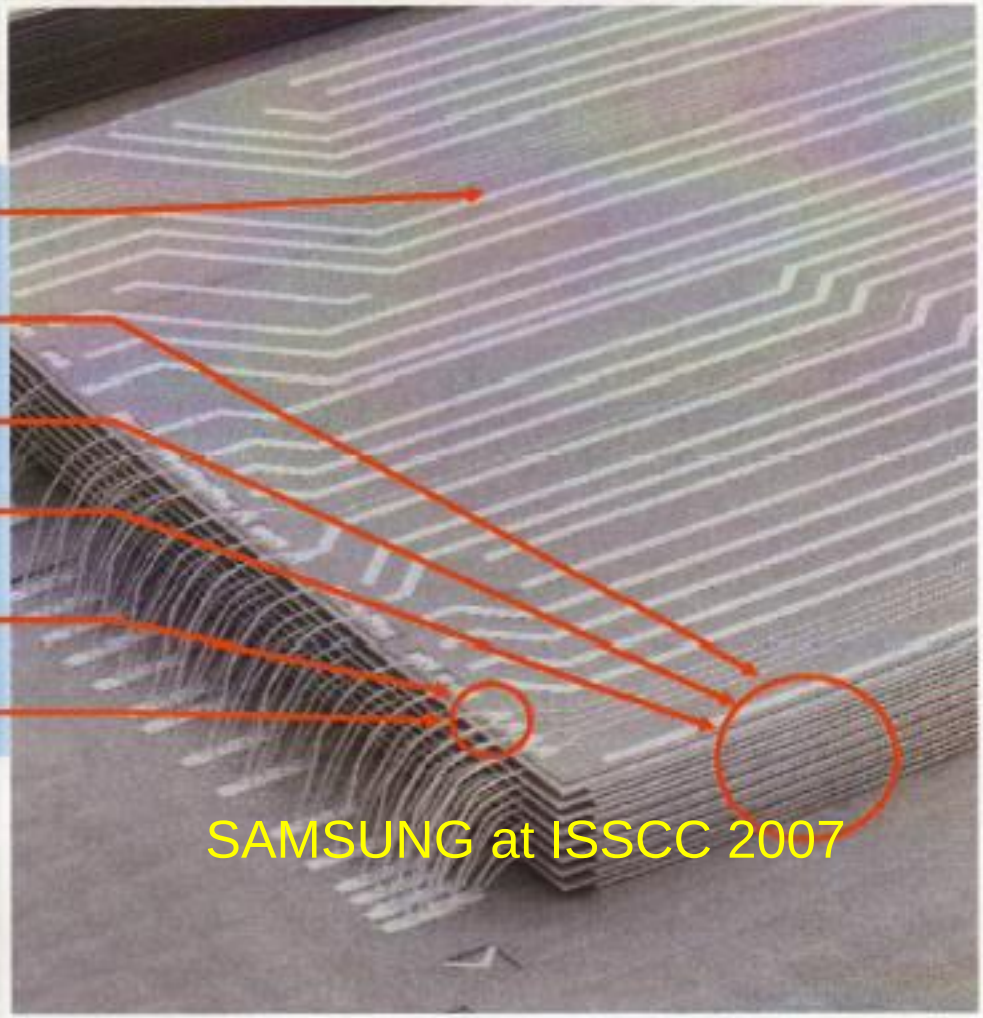
‘old’ example of 3D memory stacking; 48 layers in 2016

# 16 Chip Stacking Technology

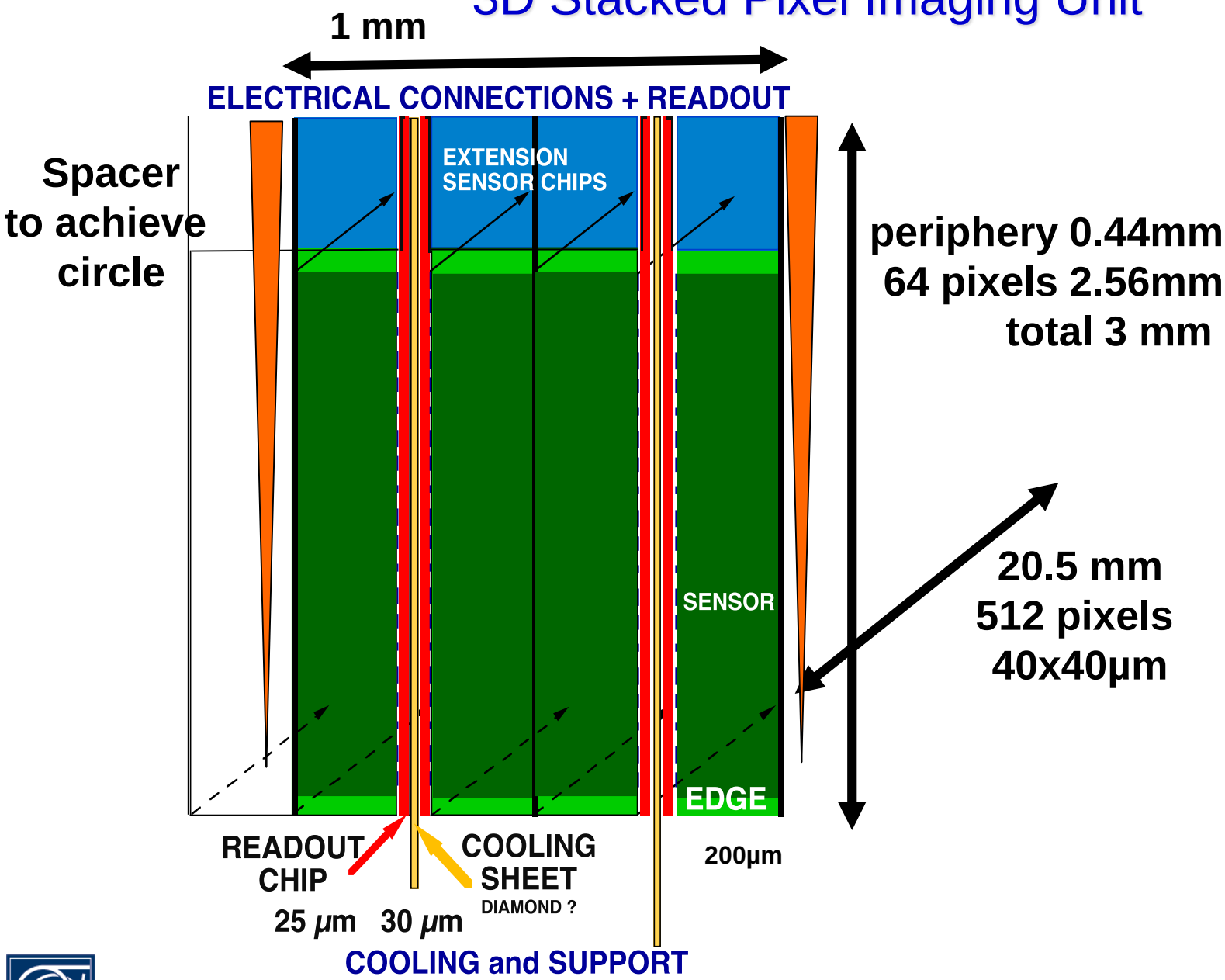


- 16 Same Die Stack Package Development

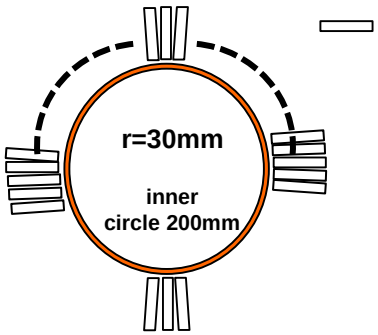
- Pad Relocation using WLI
- 30 um Wafer Thinning
- Laser Sawing
- Damage-less Die Pick-up
- 250um Overhang
- 50um Loop Height



# 3D Stacked Pixel Imaging Unit



# Speculative design for a thick tracker




Full Pixel System of 20 rings, 40cm long:

Number of chips 20x200x4 =16 000

16 000 x 32768 = 525 000 000 pixels

Overall layer structure:

Basic Unit has 4x512 pixels of 200µmx40µm

coverage is 200 x 2064 = 400 000 pixels per layer

occupancy ~1% for 1000 interactions/average multiplicity 40

20% Insensitive area from readout chips and spacers,

remedy could be to incline basic units

64 layers deep along the radius

Operational:

Ultra-LHC 1000 collisons/crossing

40 000 tracks x 64 pixels generate 1010 carriers/10ns

continuous signal current ~0.1A

dark current ~equal 16 000 x 10µA = 0.16 A

**Highly speculative indeed, many mechanical and electrical issues....**
**What could be physics gains for such a system?**

silicon is catching up on carbon
scientific applications abound

carried by high volume in consumer field

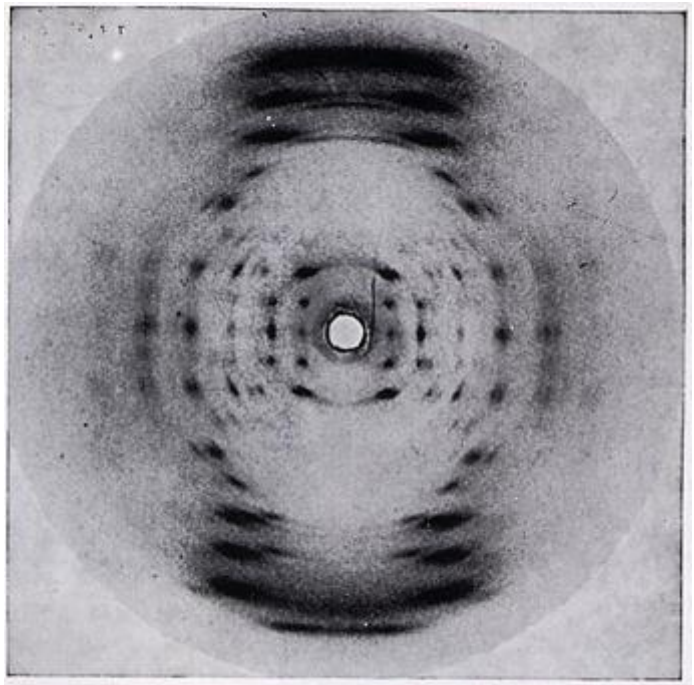
disruptive and new applications

# a few scientific silicon device applications outside particle physics

# silicon for DNA analysis

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

limited structural analysis

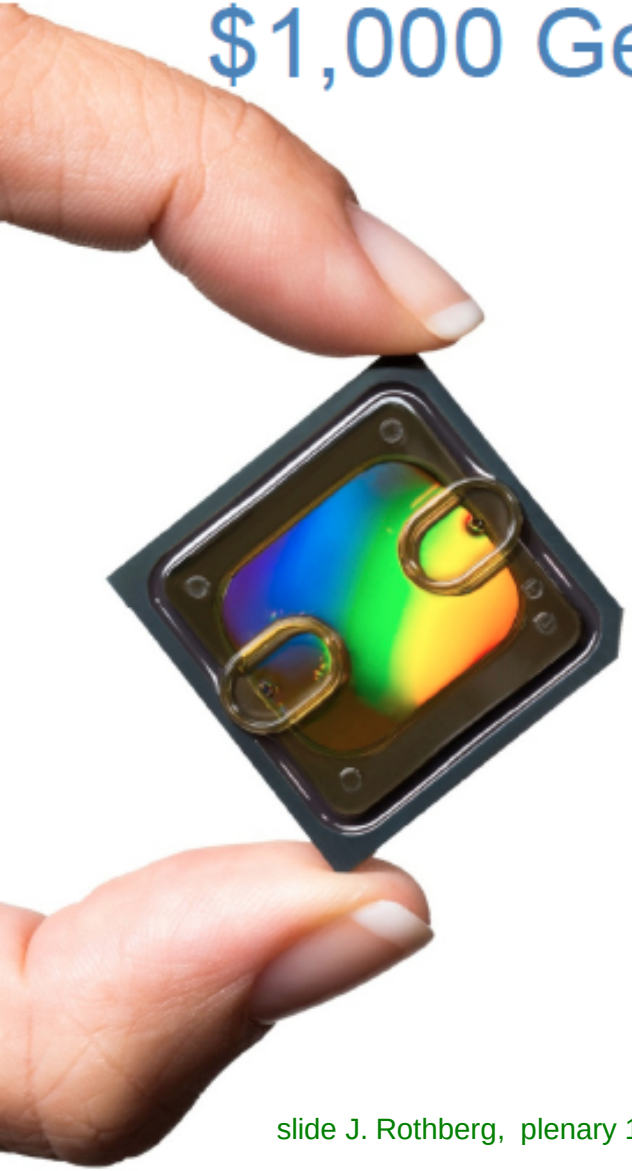


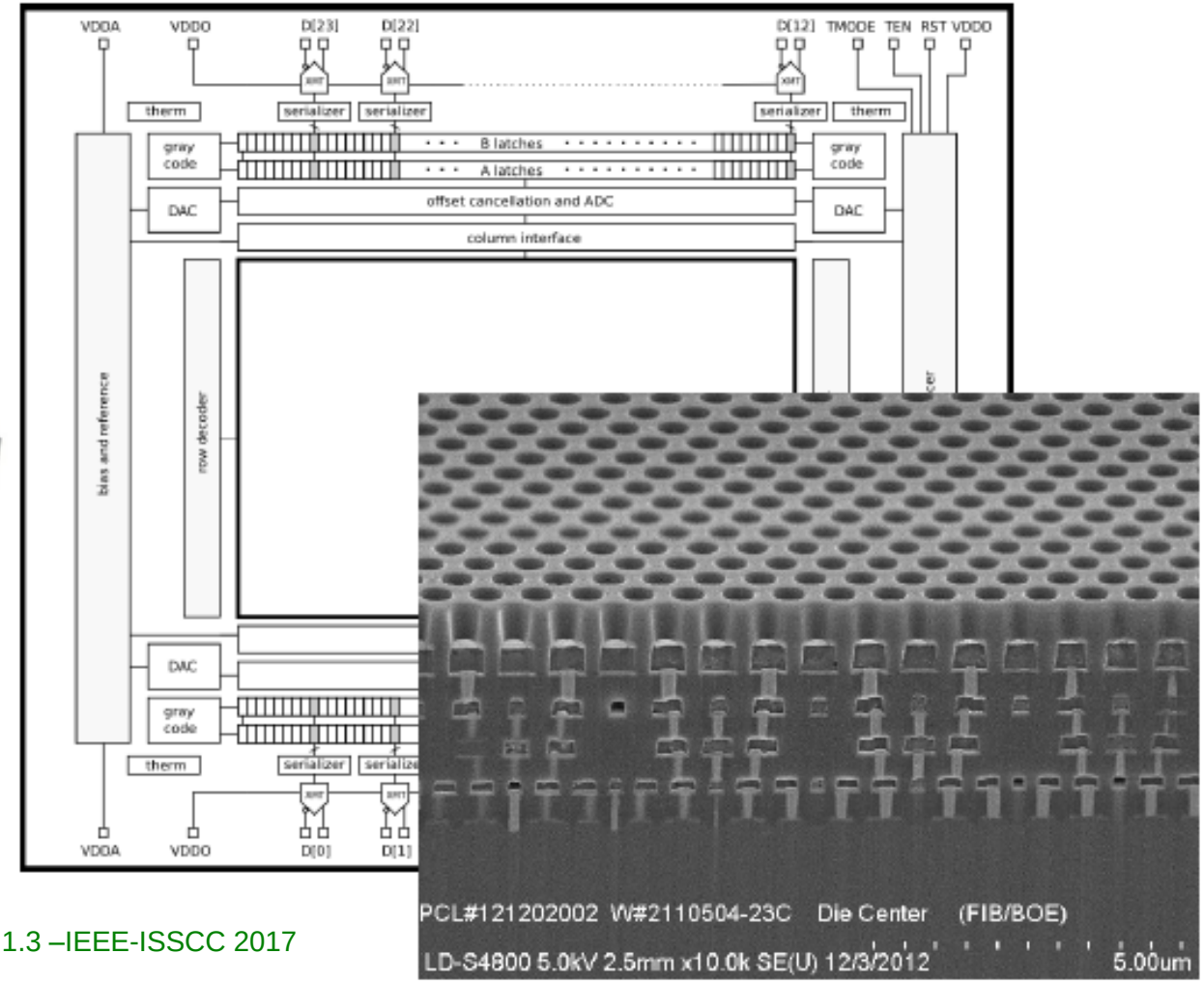
*An X-ray photograph of crystalline DNA in the A form.*

nano CMOS technology using ion-sensitive FET:

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

# DNA sequencing in USB device


Oxford NANOPORE Technologies®

**see**
**https://www.nanoporetech.com/**


single molecule analysis

e.g. protein or DNA

via ‘nano’ hole in polymer foil

on top of a Si readout chip

# 1970 ISFET by P. Bergveld

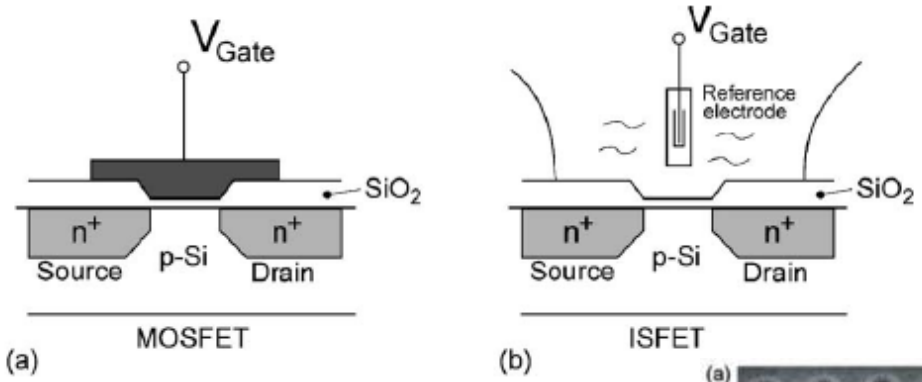
1973 PhD Thesis
Piet Bergveld
U. Twente NL

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 --> $H^+$



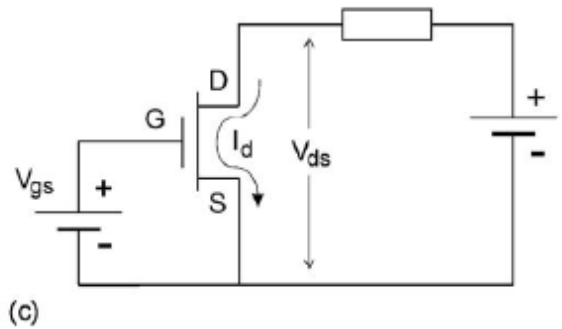
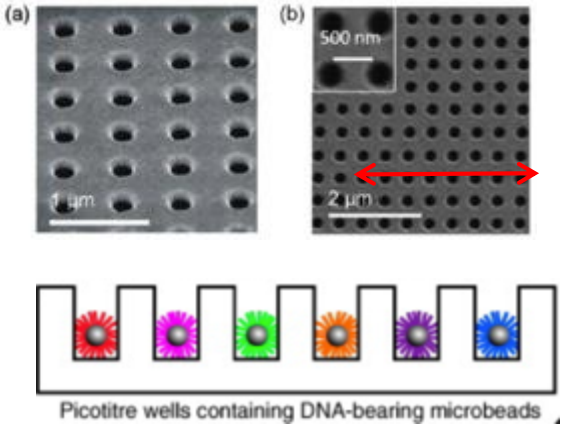




Fig. 3. Schematic representation of MOSFET (a), ISFET (b), and electronic diagram (c).

0.2 µm pores
4µm




Heather and Chain, Genomics 107 (2016)

## 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

# silicon imagers in astronomy

photographic recording in astronomy has nearly completely disappeared since the introduction of high quality silicon imagers

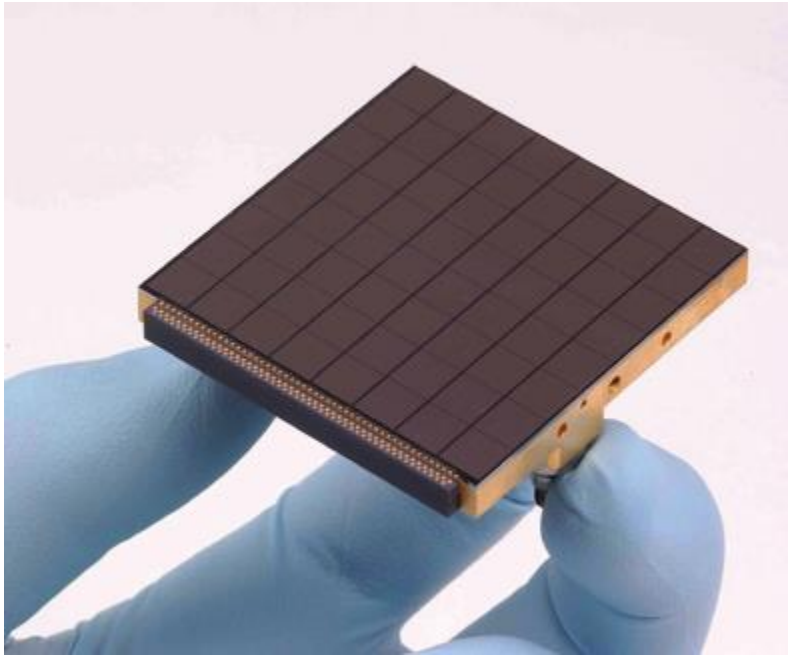
long exposures now can be made in separate steps

various on-line processing methods

electronic processing of spectra into (false) colors

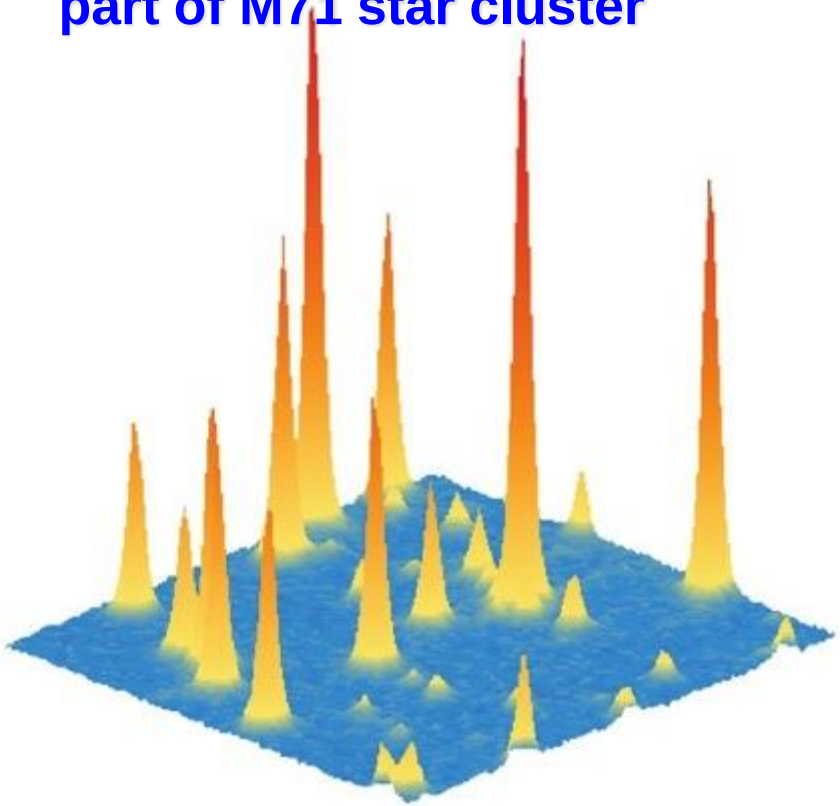
# silicon CCD in astronomy

## Orthogonal Transfer CCD can internally compensate for distortions



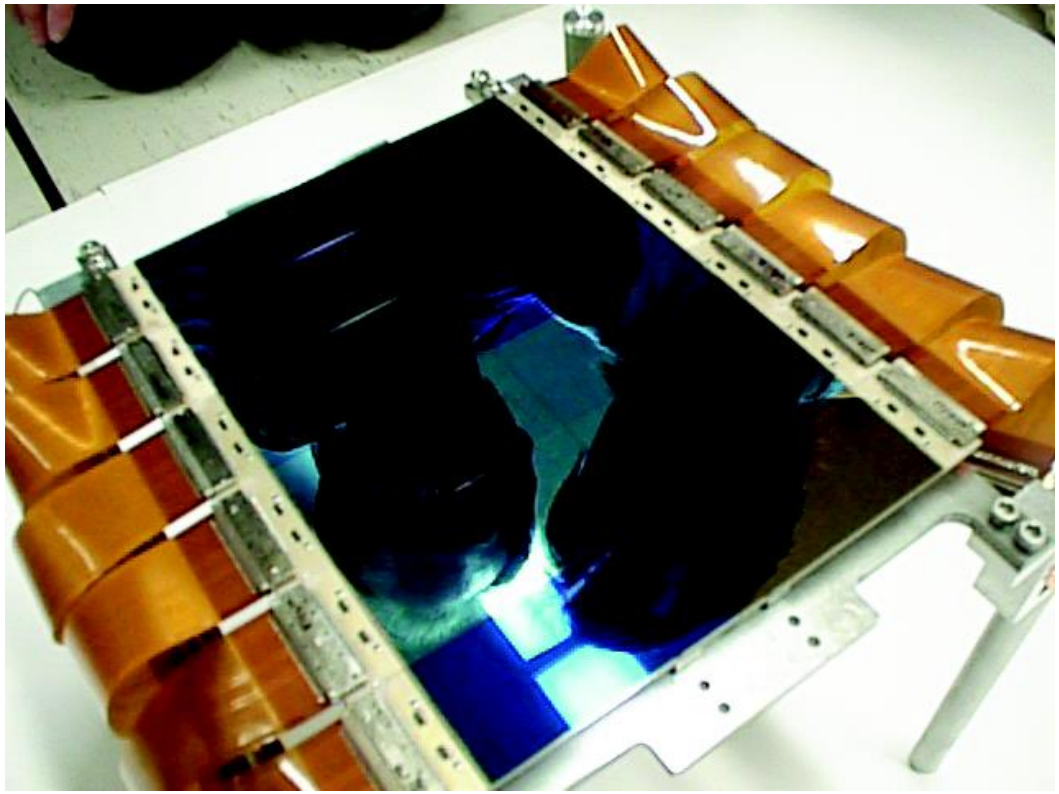
5x5 cm OTCCD array with backside incidence
1995-2000 Lincoln Lab MIT

**part of M71 star cluster**



images from Burke et al. - Lincoln Lab Journal 16 (2007) 393-412

# silicon CCD in astronomy

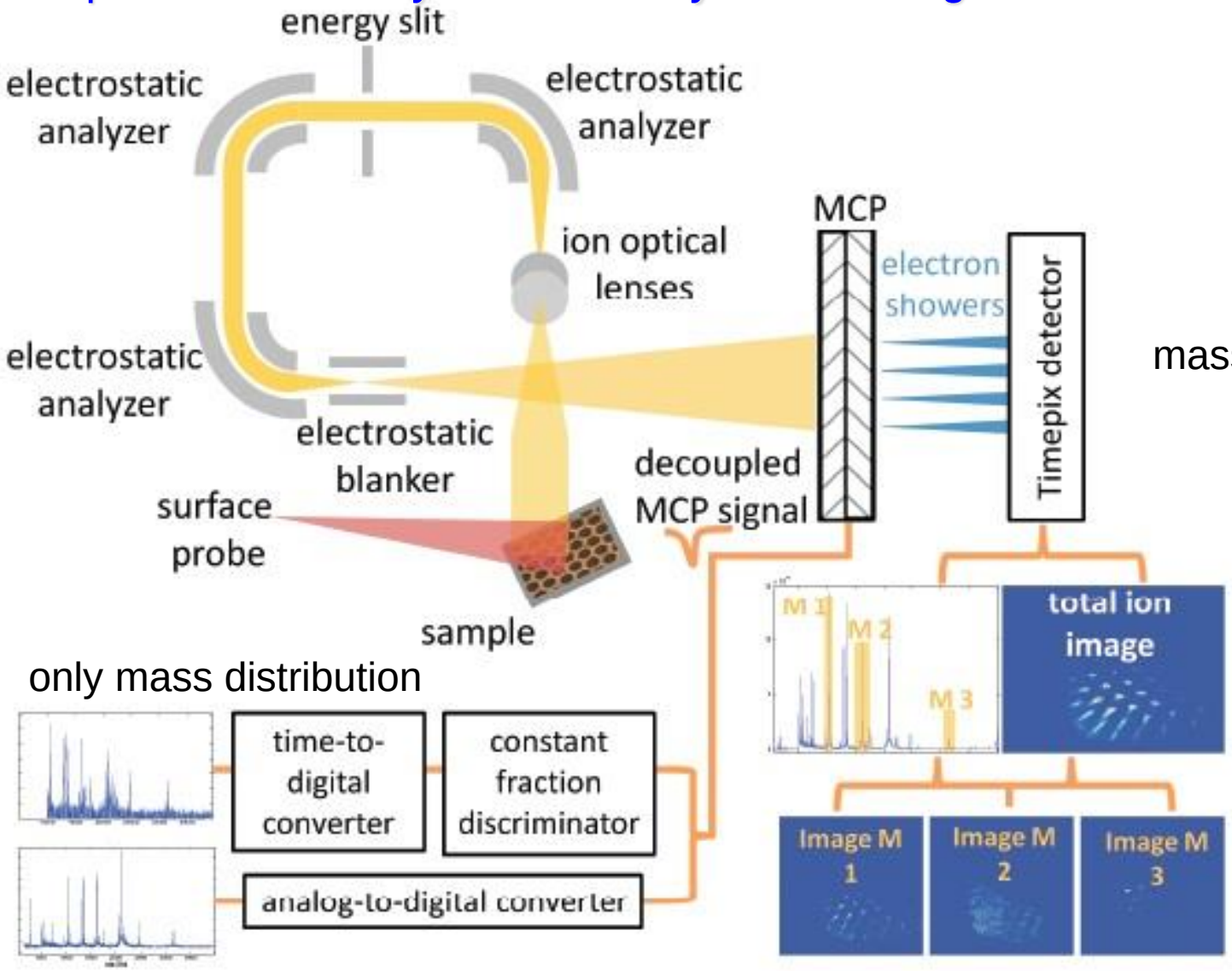


CFH Canada-France-Hawaii
CCD array of 12 units, Lincoln Lab
$10^8$ pixels 15µm --> 228 $cm^2$
Mauna Kea 1998

Burke et al. - Lincoln Lab Journal 16 (2007) 393-412

# Silicon Timepix for mass spectroscopy

## Separation of heavy molecules by Time-of-Flight




mass distrubution also image

only mass distribution

figure from J. Jungmann – PhD Thesis Univ Utrecht (2011) p. 96

# Timepix for mass spectroscopy

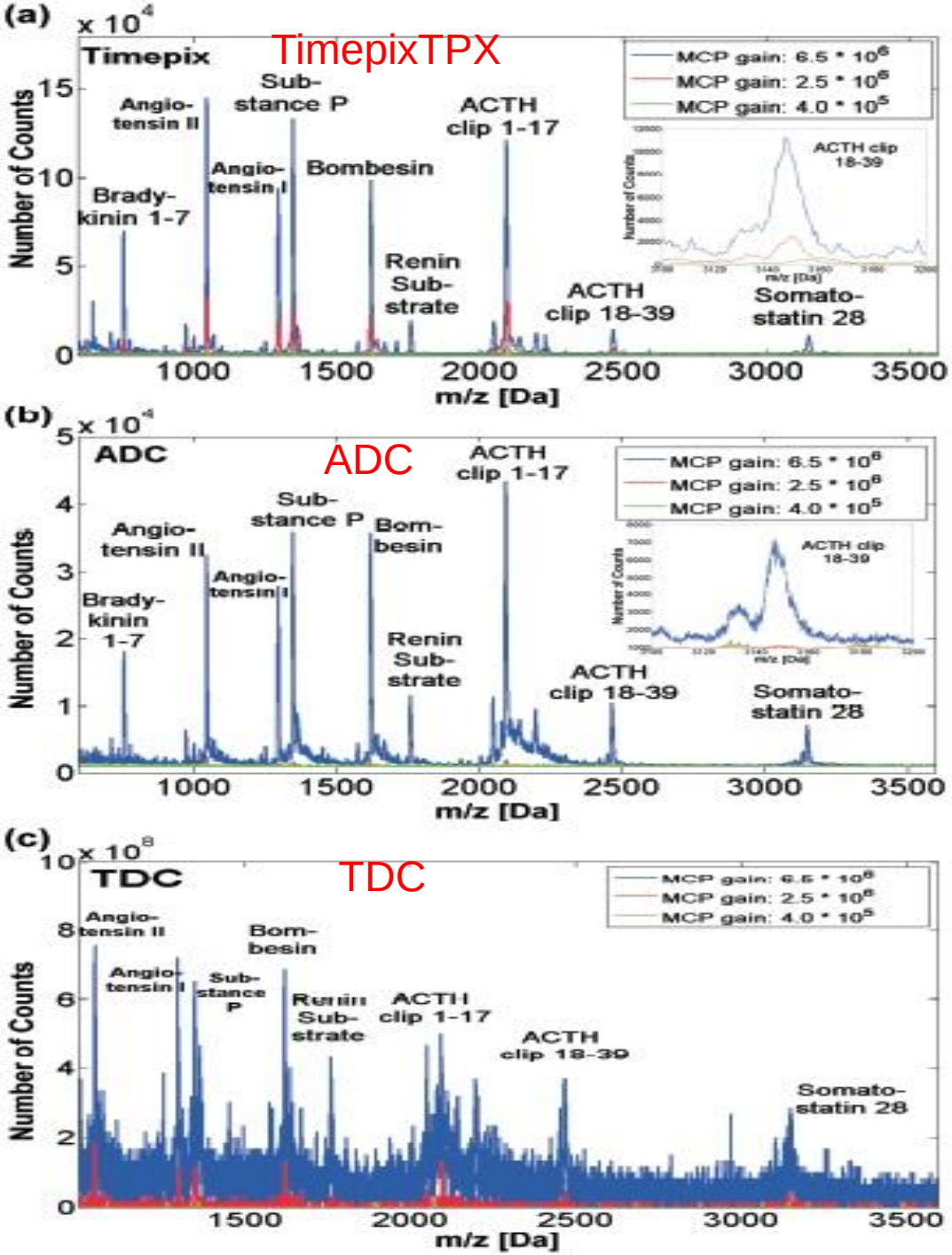
Comparison of the mass spectra by 3 different methods

and 3 gains in MicroChannelPlate

Timepix spectrum less noise

better resolution

+ image of sample




figures from J. Jungmann – PhD Thesis
Univ Utrecht (2011) p. 97-103

# Radiation imagers for schools and amateurs

with educational kit

IEAP/CTU, Prague

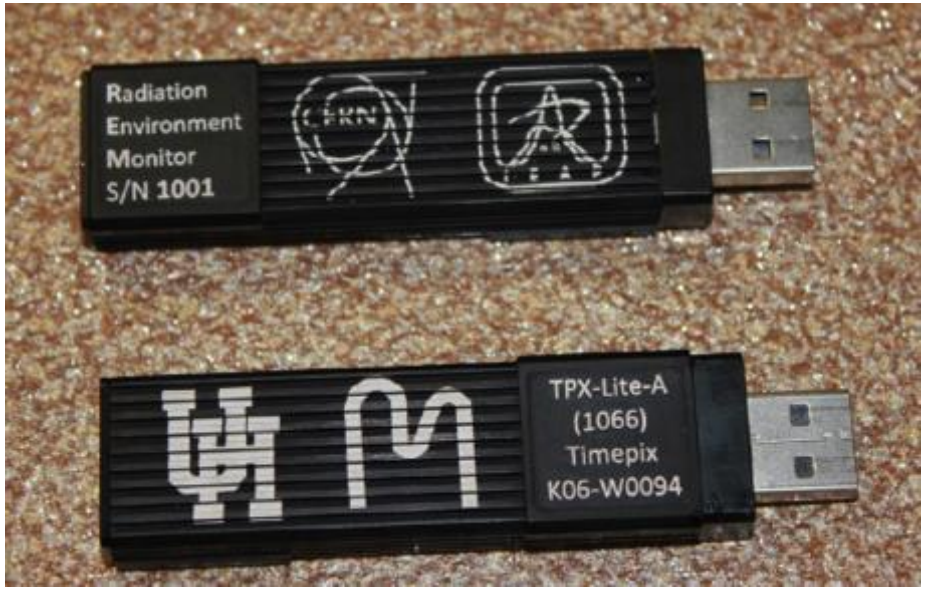

Jablotron &
IEAP/CTU, Prague


AdvaCam &
IEAP/CTU, Prague

CERN Timepix imager inside

**http://ardent.web.cern.ch/ardent/ardent.php**

# Timepix for dosimetry in Int Space Station ISS

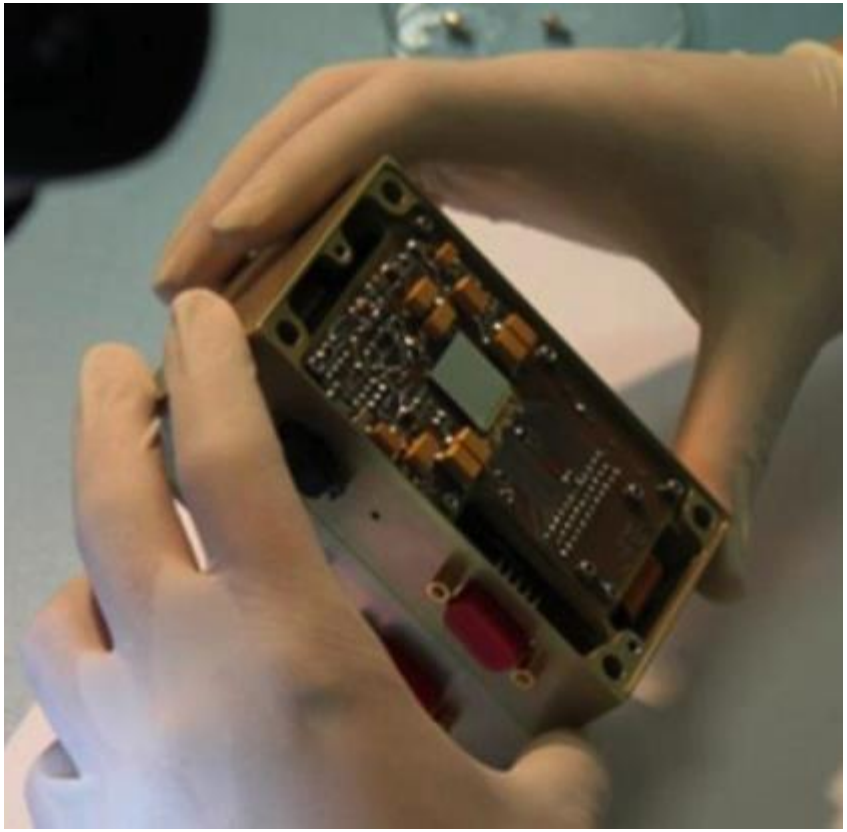




AMS largest space experiment....
Pixel chip maybe smallest

# Timepix SATRAM on PROBA V at 820km

**Space Application Timepix Radiation Monitor**

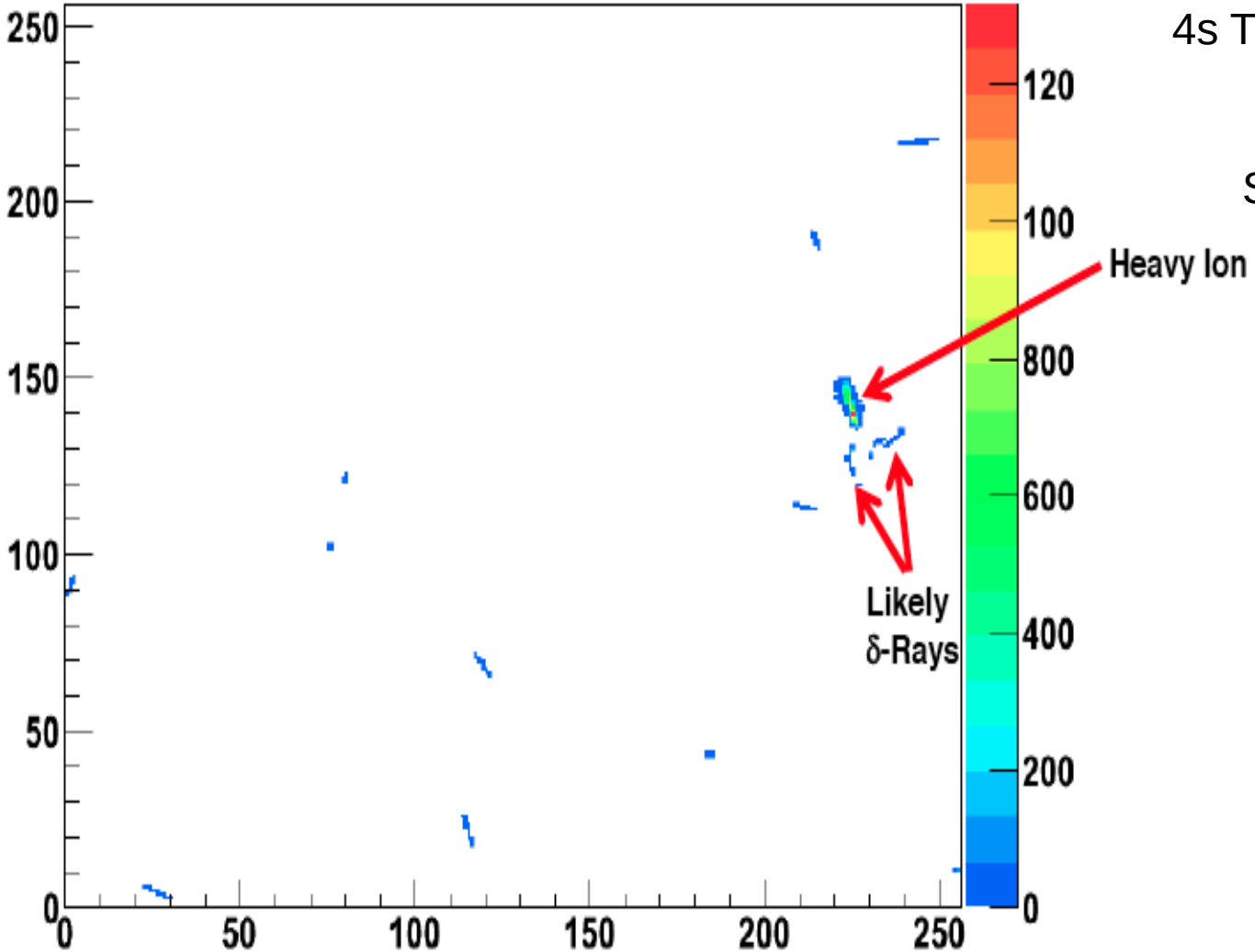



**Launched 7 March 2013**
**Altitude ~820km (Low Earth Orbit)**

**Carlos Granja**
**from talk EPS Ravenna Workshop**

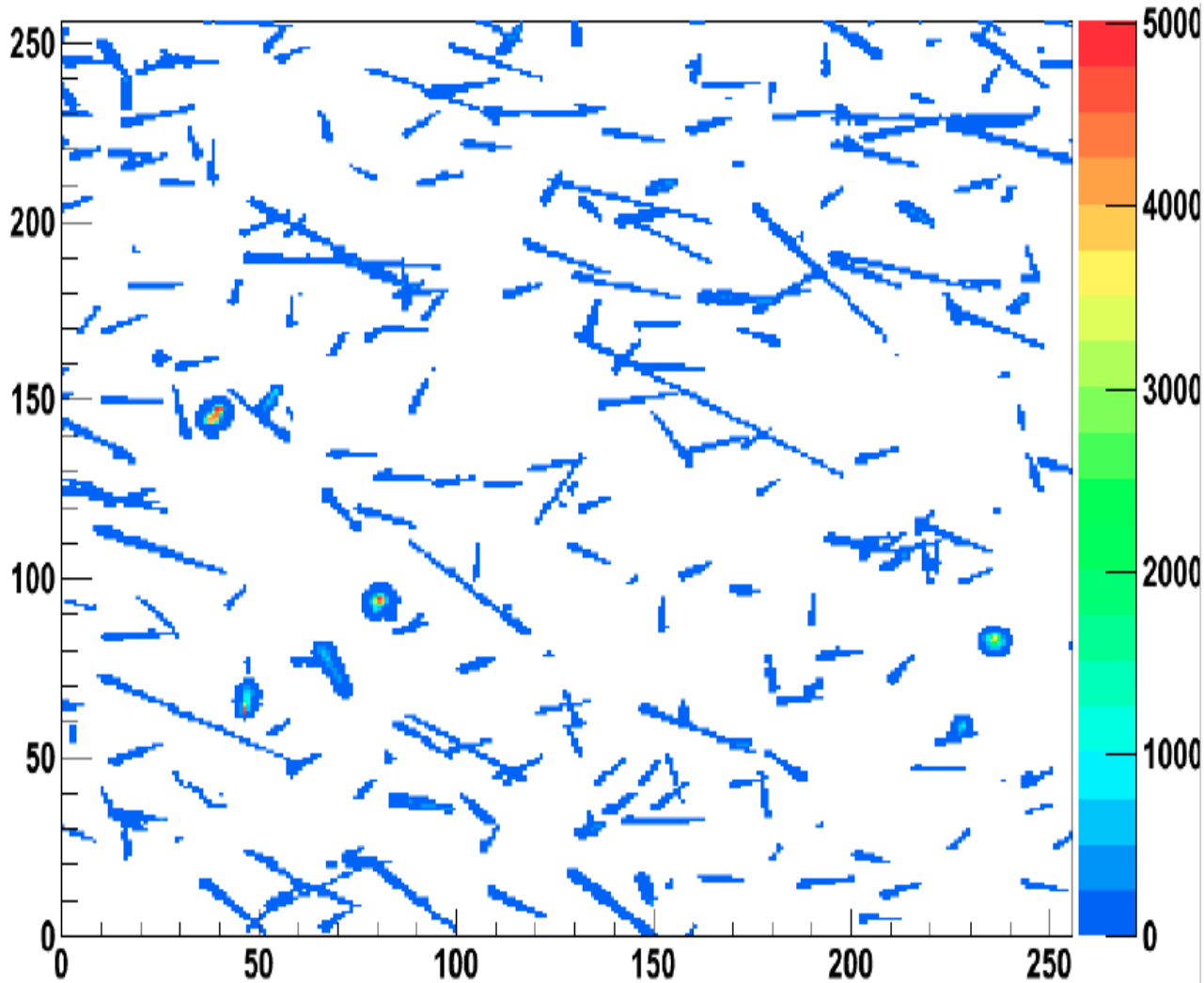
**Erik HEIJNE IEAP-CTU & CERN EP Department**

# Timepix dosimetry at the Int Space Station ISS




4s Timepix exposure taken in ISS passingover South China Sea

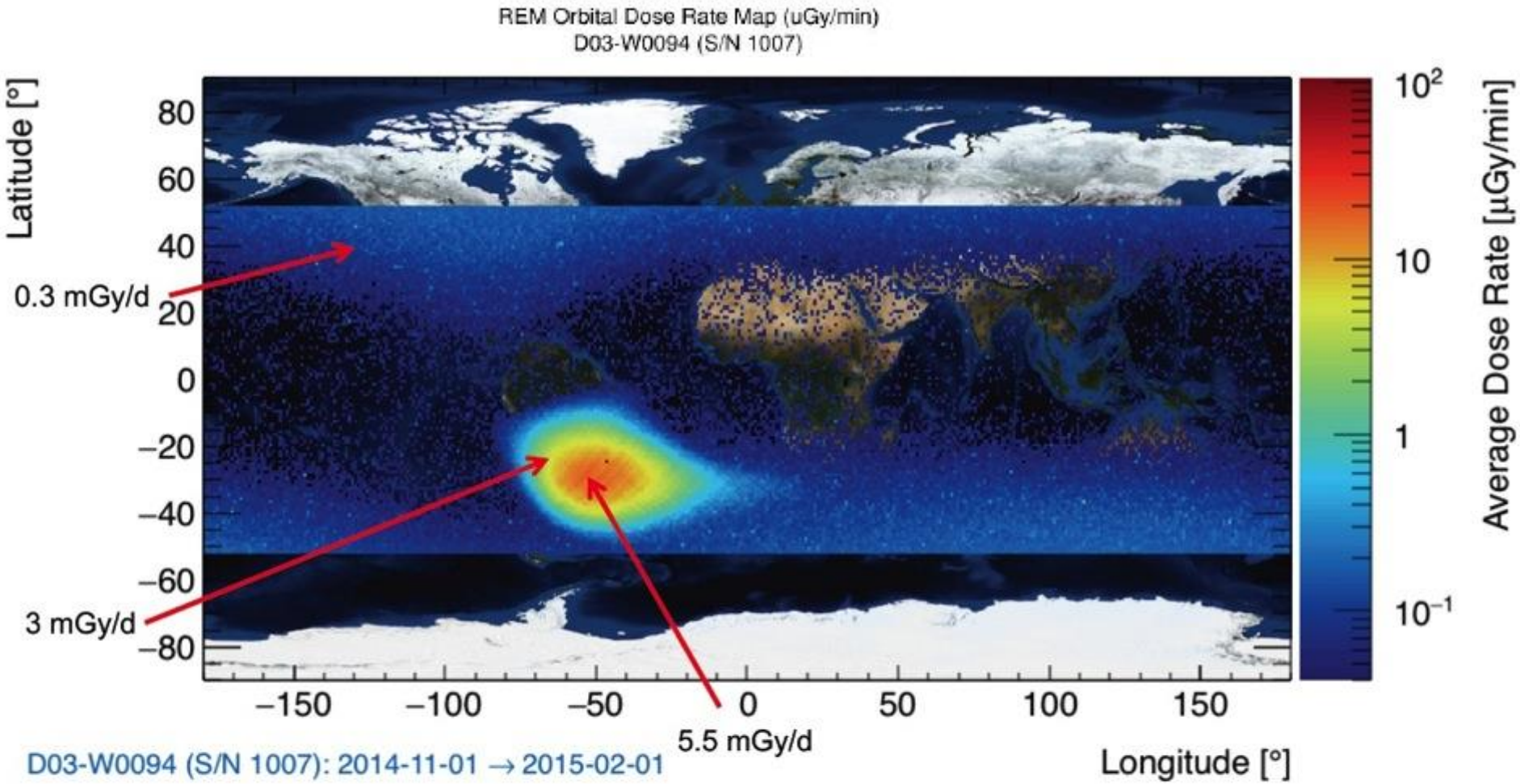
# Timepix dosimetry at the Int Space Station ISS



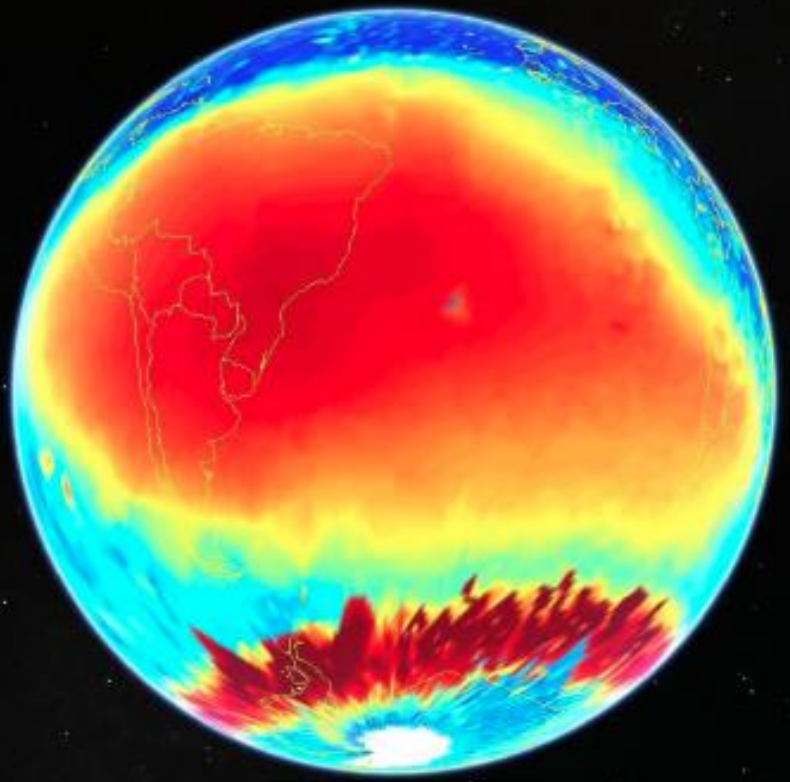

4s Timepix exposure taken in ISS passing through SAA South America Anomaly

various types of quanta can be identified and accounted for in personal dosimetry

# Timepix dosimetry at the Int Space Station ISS



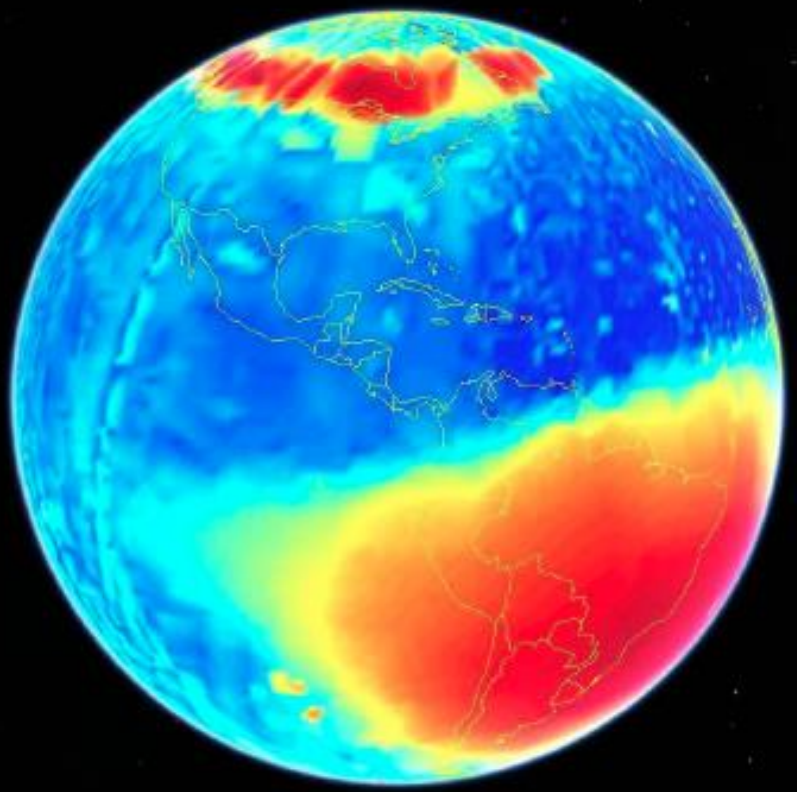

University of Houston, IEAP Prague, NASA



South America, Antarctica, South Atlantic Anomaly SAA

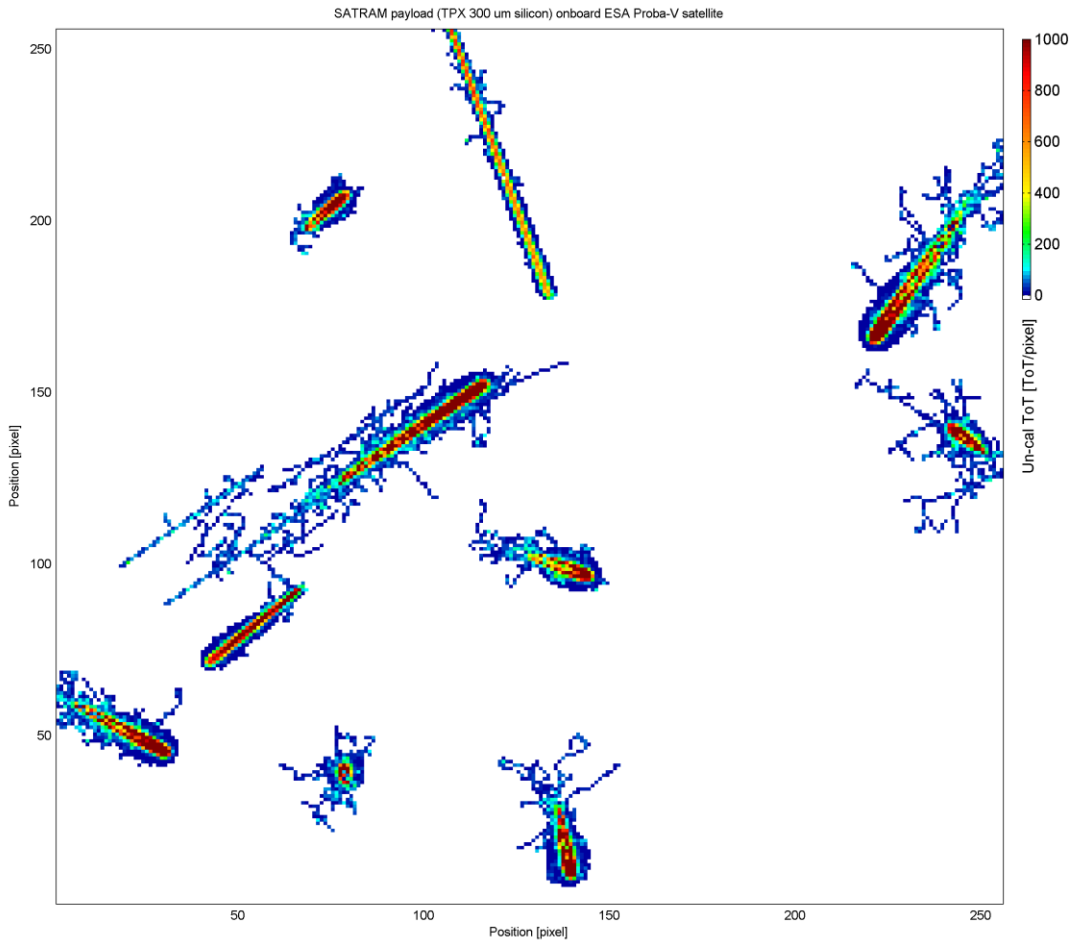
# Timepix on ProbaV 'SATRAM'

The Americas



Radiation field Earth map spatial distributions measured by Timepix onboard ESA Proba-V satellite LEO orbit 820 km altitude displaying all radiation components integrated over 5.5 months

# Observe exotic phenomena already in space ?




**Clusters observed with Timepix pixel detector at 850km altitude in ESA Proba V mission SATRAM experiment 2013-2014**

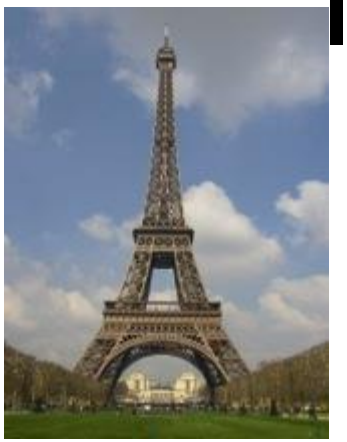
**Most of these clusters (from several frames) can be explained as energetic heavy ions**

**sometimes come from nuclear interaction in upstream material**

STONE AGE

BRONZE AGE

IRON AGE



SILICON AGE

# Main points

how to innovate

silicon for science and technology =
= similar to carbon for evolution of life

sensor design depends closely on signal circuits

silicon is disruptive in society and in science

miniaturization basis for better measurements

examples of silicon in other science fields
using our pixel detectors or other

**Science discovery → New technology → Applications**
**Biology, Medicine, Informatics at quantum level**
**.....**

# End of the beginning

# Find alternatives to enable triggers in Ultra-LHC (1000 collisions/crossing) if muons and calorimetry run out

2025-2035 Horizon

increase of intensity probably the main option
for long-term operation of LHC

as long as radiation levels can be supportable

hints for TeV-energy physics may be found in space

virtual particles in high-precision LHCb ?

Physics experiments should exploit recent industrial Si technology (<20nm) and achieve:

- lower power for same functions
- ps timing
- more on-chip memory
- multilayer information processing
- economy of scale
- ....
- higher rates, better data
- new physics?

# Future ???

CMOS readout circuits in 32nm, 14nm, .,via & 3D stacking

More recent nanoCMOS technology also for sensors

Monolithic detector chips in CMOS instead of hybrid .....

more on-chip **memory**

Smaller pixel capacitance: 100 $e^-$ on 0.1 fF -> 160mV

**ultrapixels** of ~2x2µm$^2$ need charge from ~3µm Si --> 32nm CMOS +fast

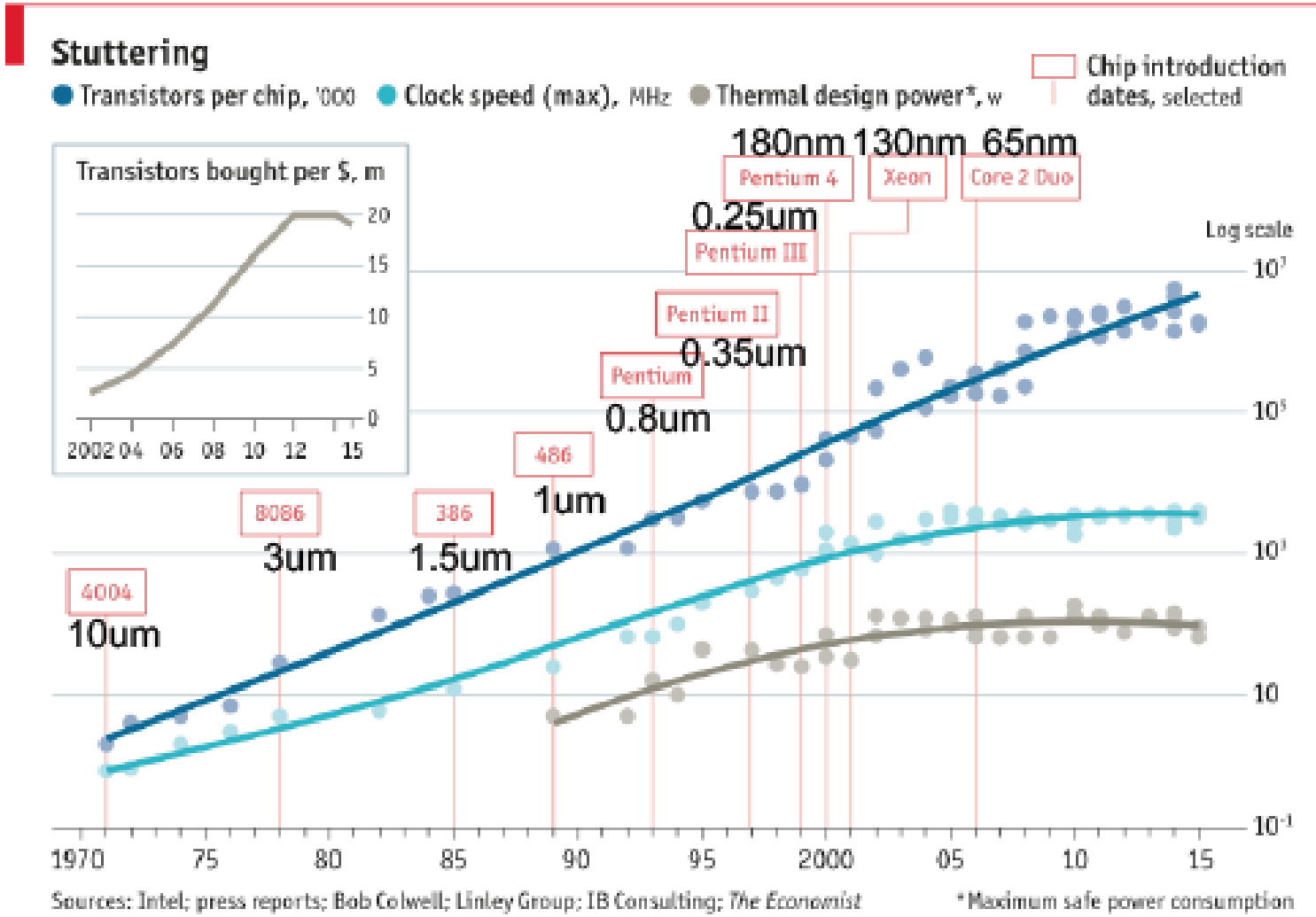
Larger wafersize can be used if smaller pixels

Faster signals allow timestamps 'inside-crossing' <20ps?

# Moore's uncertain future

saturation since 2000
still more transistors
power improves

slide by
Michael Campbell
from Economist article



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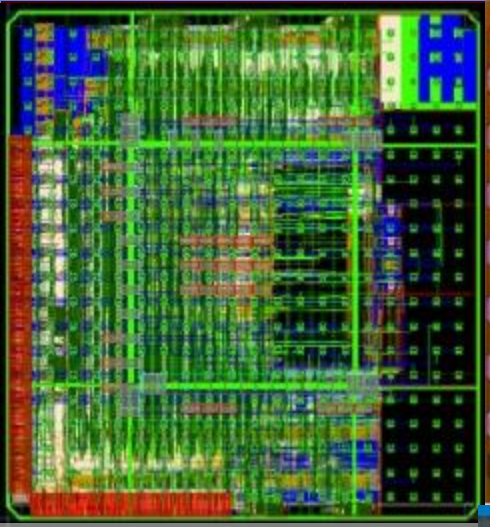
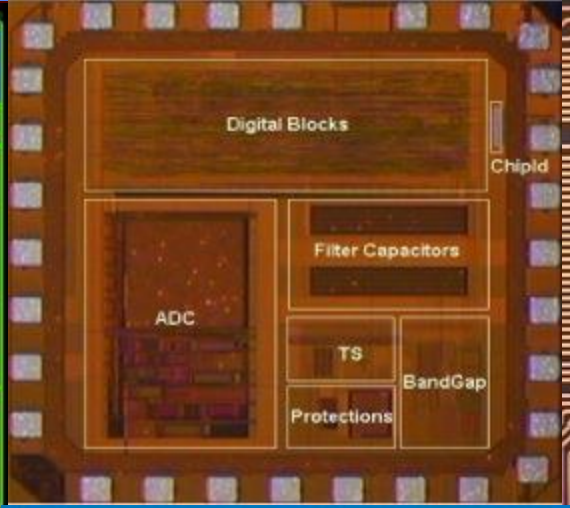
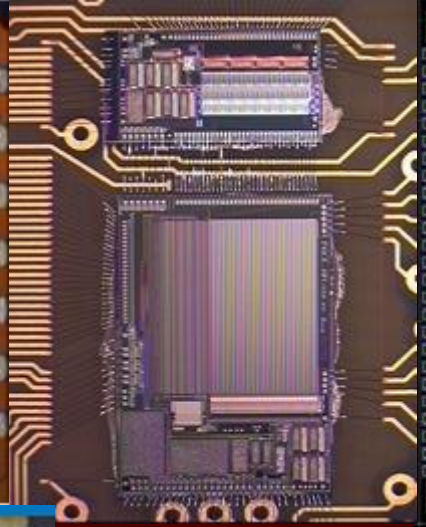
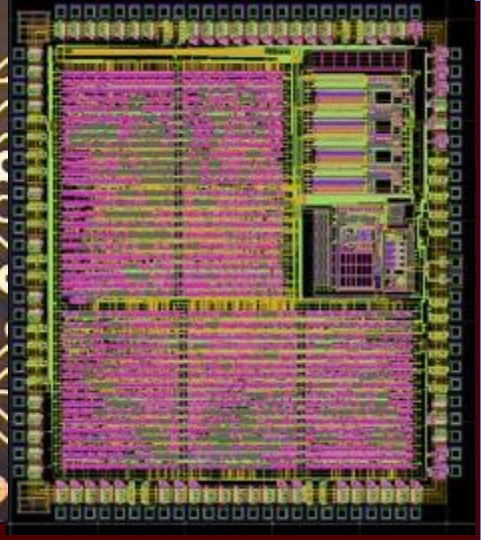
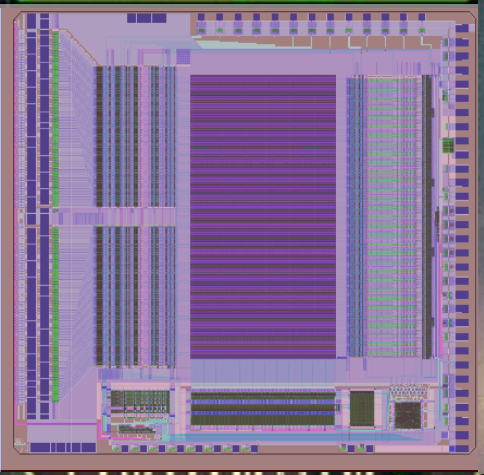


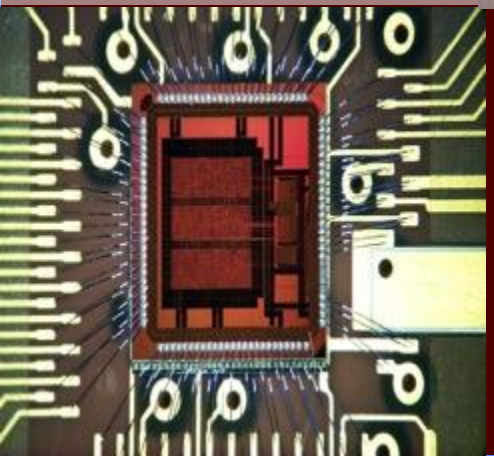







# Silicon for Science

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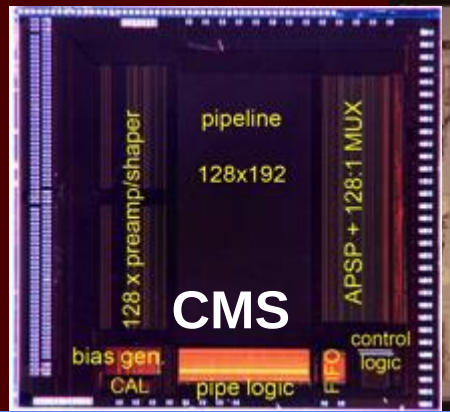
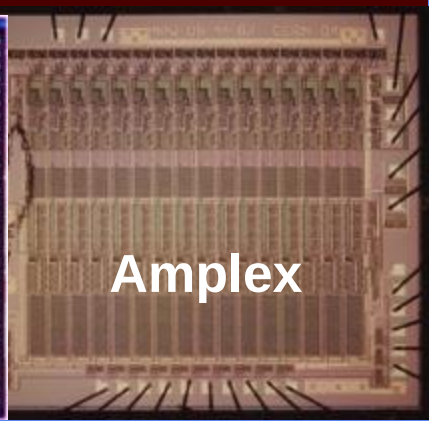
**Erik.Heijne@cern.ch**

Future HEP experiments will rely on newest electronics

need timely R&D efforts, expertise and resources

worldwide collaboration & tens of millions to do it right