Imaging and imagination, the scene of nuclear and particle physics

Erik H.M. HEIJNE

Contribution in Memory of
P. Franco Manfredi
Pavia, 5 December 2016

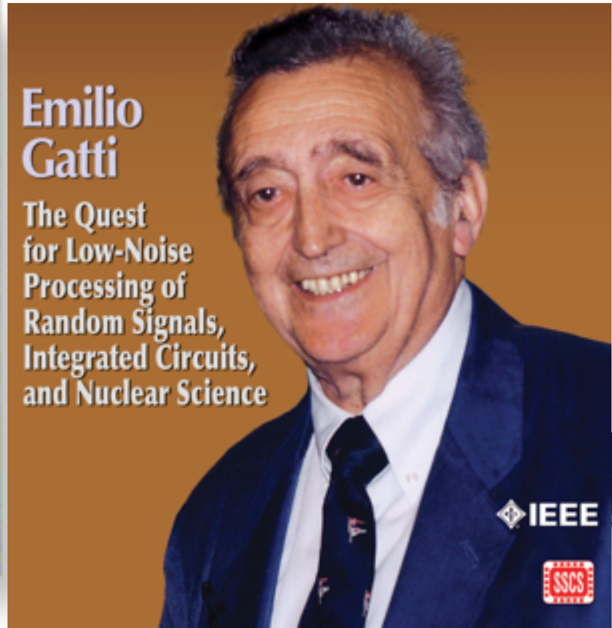
Introduction

Imaging and imagination,
P. Franco Manfredi and the scene of nuclear and particle physics

The early discoveries in nuclear and particle physics were made to a large extent by using visible imaging media, such as photographic emulsions, cloud or bubble chambers. However, soon major progress only was possible by introducing low-noise electronic tools, especially for measuring energy levels with adequate precision, and for coping with high interaction rates.

Dr Pier Franco Manfredi has been one of the key people in this field. Through the contributions by him, and colleagues world-wide, electronics became progressively more and more important. A transition took place from the visual-image based devices to purely electronic instruments. Silicon-based instruments appear to be the ultimate example. But in the newest silicon devices the two distinct approaches begin to re-merge again. Expected performance of future particle sensors will feature high rate and high multiplicity capability, yet improved precision and shorter timing. It may be essential also to recover a true imaging capability. This might allow new discoveries in elementary particle physics as well as in other fields where ionizing radiation interacts with materials .

Pier Franco Manfredi - Emilio Gatti
a life-long tandem, >55 years



Politecnico
October 2012

We lost both, within one year

Some History

IEEE Nuclear Science Symposium 1977 San Francisco

Discussing preamplifier feedback with stabilized 'cold' resistance
for the NA1 FRAMM experiment (see later)

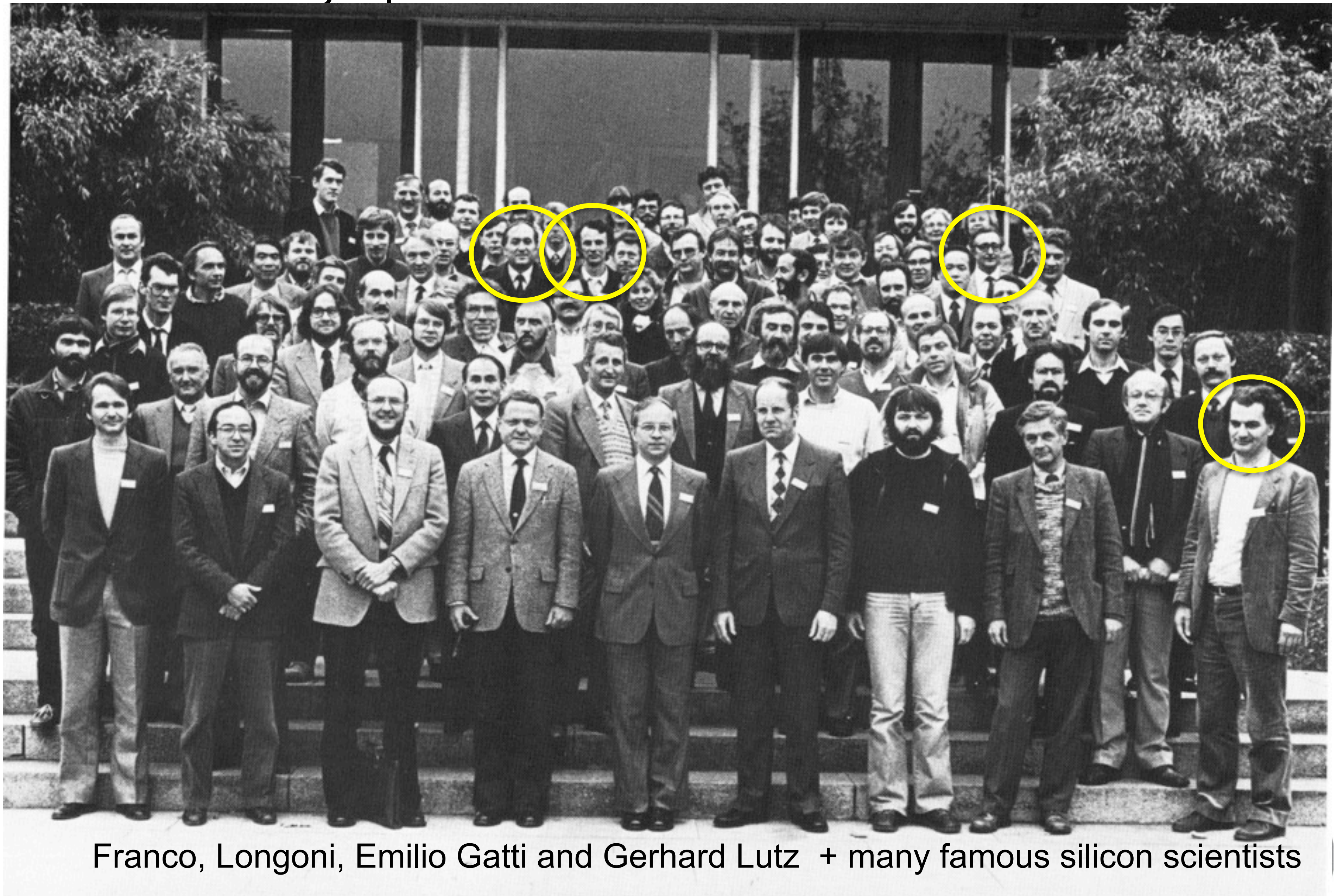
Amplifier for silicon microstrip detector, design by Pierre Jarron
was discussed with Franco during many CERN visits

Important milestone: 3rd Munich Semiconductor Symposium 1983
(see photo)

Numerous interactions 1980 – 2000, also at IEEE NS Symposia

2012 IEEE SSCS Magazine Emilio Gatti: close work with Franco

3rd Munich Symposium on Semiconductor detectors 1983



Franco, Longoni, Emilio Gatti and Gerhard Lutz + many famous silicon scientists

First pion

Nuclear capture of pion

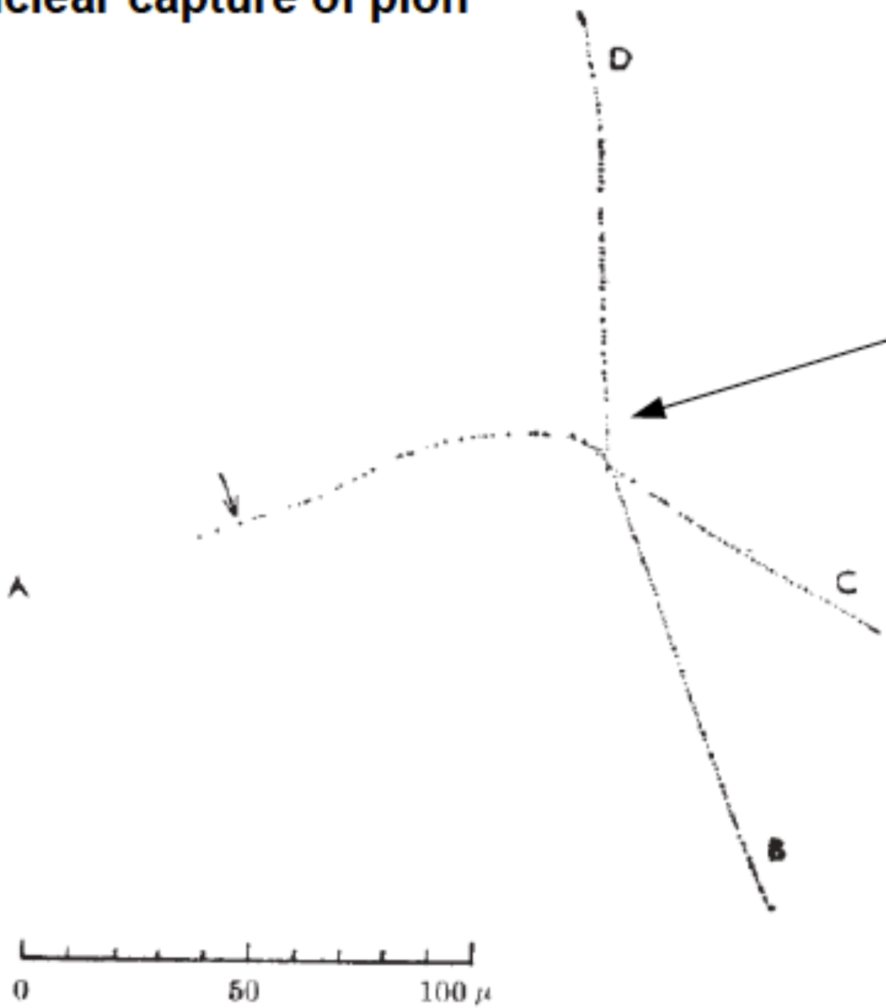
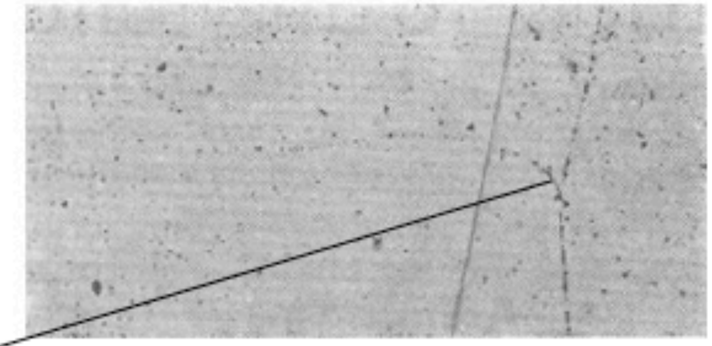


Fig. 1 *b*. TRACE OF COMPLETE STAR ON SCREEN OF PROJECTION MICROSCOPE, SHOWING PROJECTION OF THE TRACKS IN THE PLANE OF THE EMULSION. TRACK *A* CANNOT BE TRACED WITH CERTAINTY BEYOND THE ARROW



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

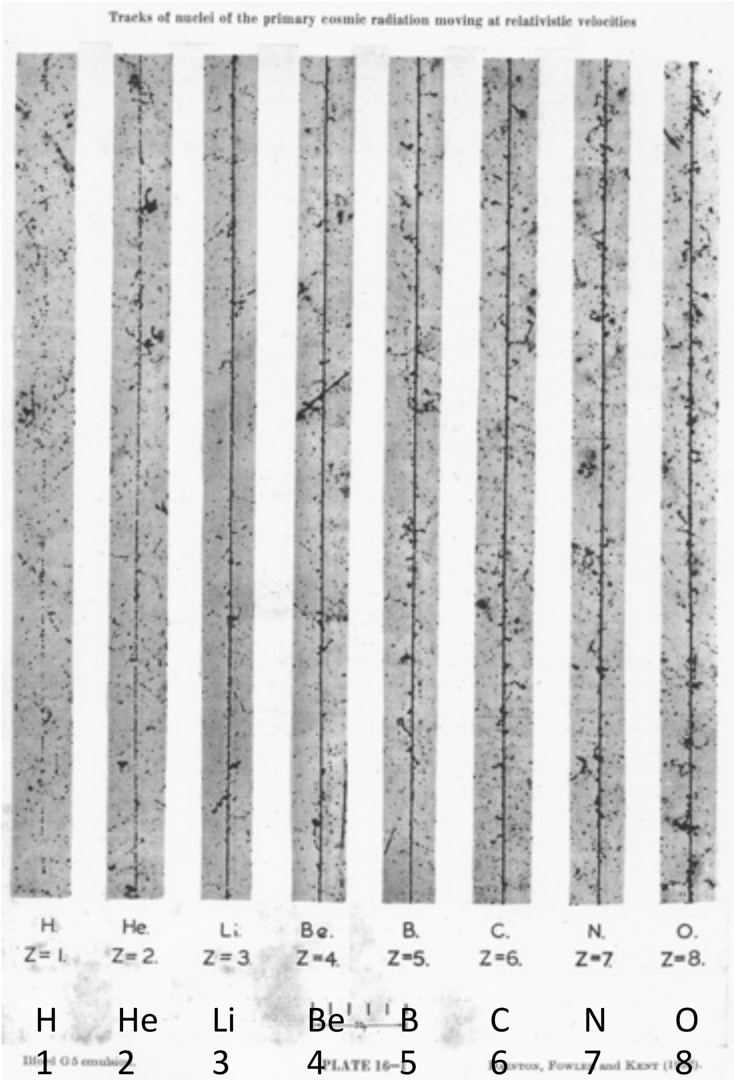
Why A is a new meson:
electron: range too large
proton: scattering too large
muon: frequent nuclear interaction

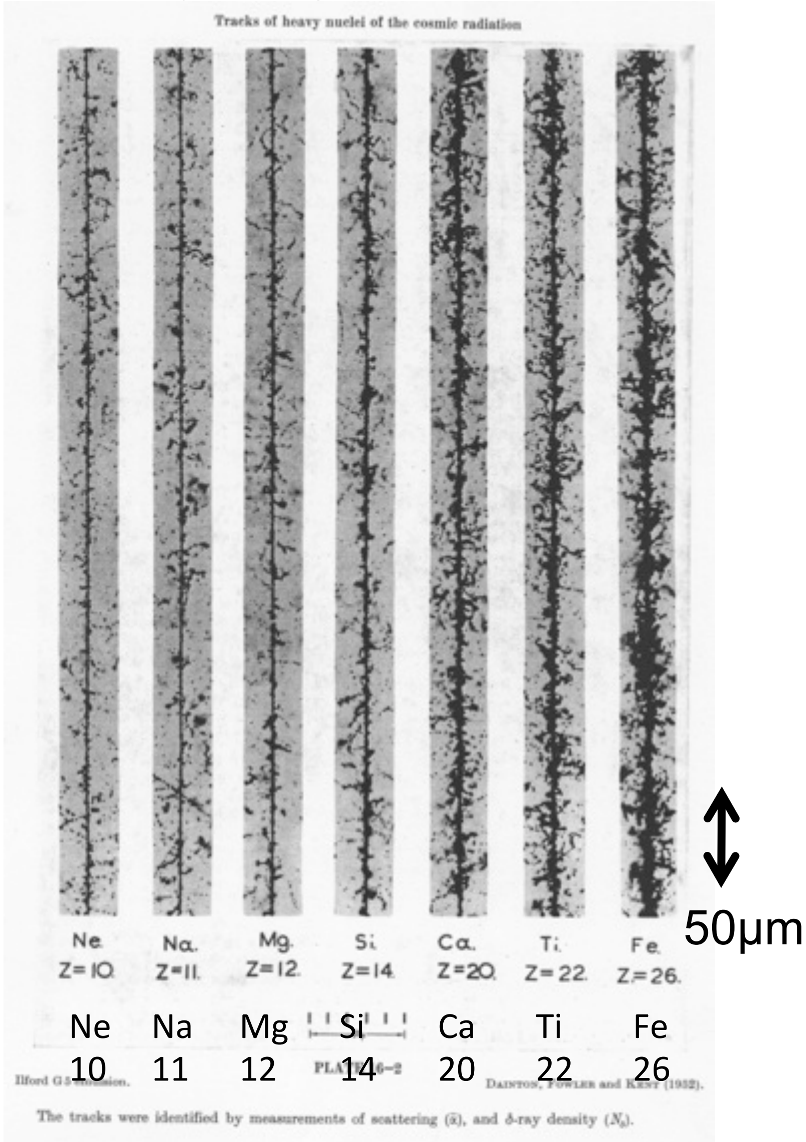
from a presentation Anton Kapliy, 2008
http://hep.uchicago.edu/cdf/frisch/p363/particles_kapliy.pdf

(Jan 1947, observed by D. Perkins)

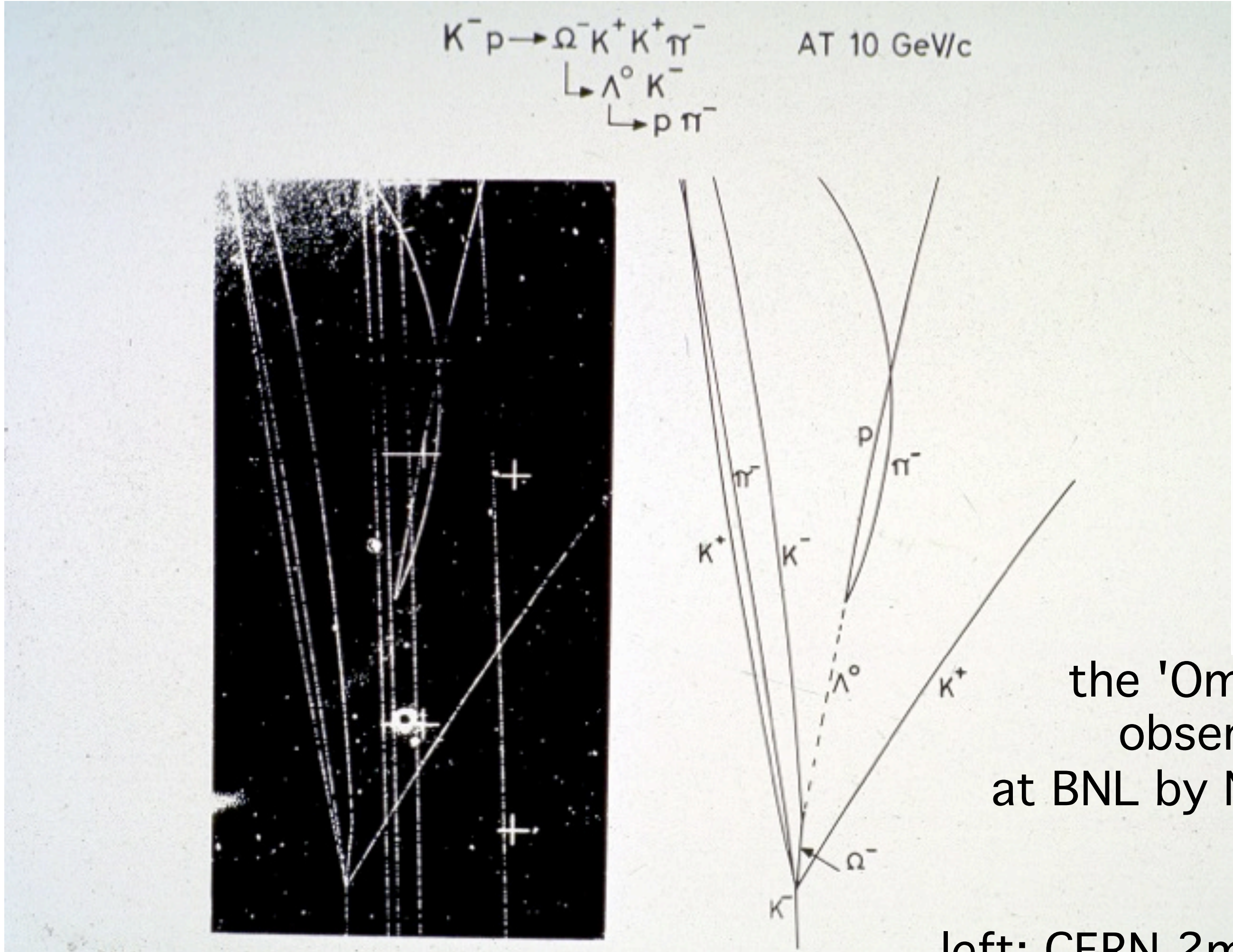
Sequence of Ions Z=1...26 in Emulsion

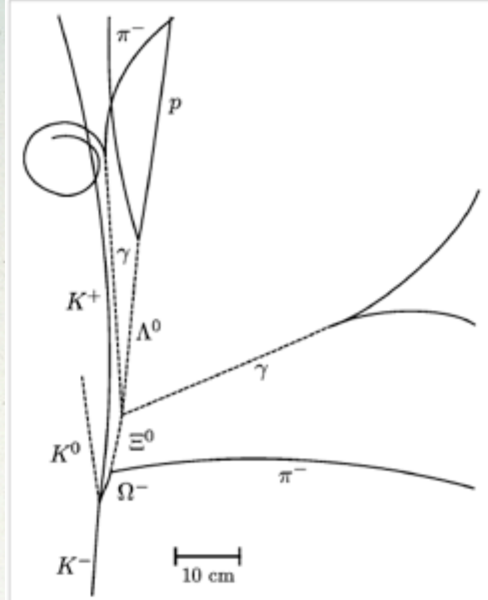
Energy deposit and also the delta ray frequency along the track proportional to Z^2





Imaging needed to unravel particle characteristics





Bubble chamber trace of the first observed Ω baryon event at Brookhaven National Laboratory.

the 'Omega' Ω particle
observed first in 1964
at BNL by Nick Samios et al.
drawing right

left: CERN 2m bubble chamber
photo + reconstruction

CERN-EX-41769
CERN 2-m bubble chamber ~1970

Imaging was chemical and/or mechanical, slow and mostly not electronic

Nuclear Physics – Particle Physics

Most early discoveries have been made with imaging devices such as photographic film, Wilson cloud chamber or bubble chamber

Ionization chamber, Geiger-Müller counter and scintillator+PM delivered electrical signals, timing & coincidence

but not quite proportional to energy

Energy spectrometry essential for understanding nuclear structures

For elementary particles: decay modes and lifetime more of interest

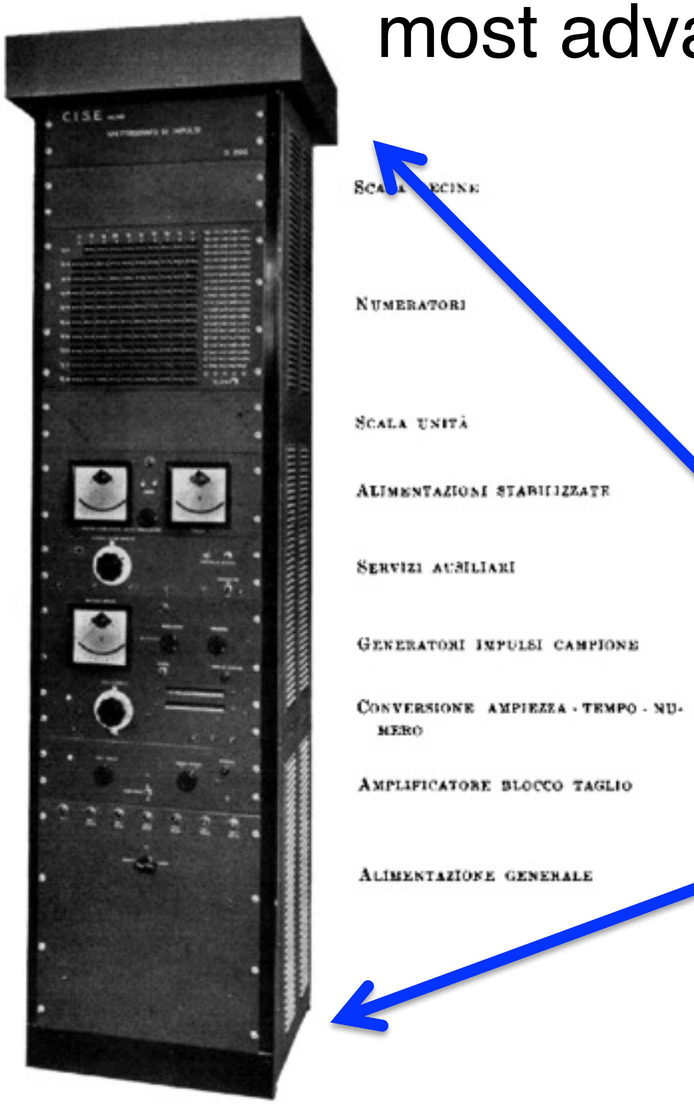
minimum ionization at speed of light

Early focus of electronic development in nuclear studies

Emphasis on visual methods in elementary particle research

mass/energy >>GeV accelerators

ADC: nuclear and particle physics experiments need most advanced technologies for progress



In 1948 Wilkinson introduced signal digitization for nuclear spectrometry

D.H. Wilkinson Proc.Cambridge Phil.Soc.46(1950) 508

Emilio Gatti improved it further (1949)

using 2 telephone registers

→ 99 channel digitizer

E. Gatti Nuovo Cimento 7(1950) 655-673

One rack, one ADC !!

F.Anghinolfi and E. Heijne IEEE-Sol.St Circ Mag.4-3(2012) 24
history of ADC

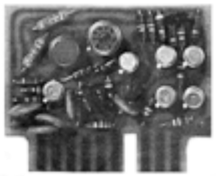
iPHONE
>30 ADCs

Major innovations in/for silicon detectors

1957 alloyed or diffused n-p and later p-n junctions
(Chalk River, others)
~1959 Gold surface barrier rectifying structure allows preservation of high resistivity
(J. Blankenship, Oak Ridge)
~1960 ¾" and 1" Si crystals commercially available (Monsanto, Wacker, Montecatini)

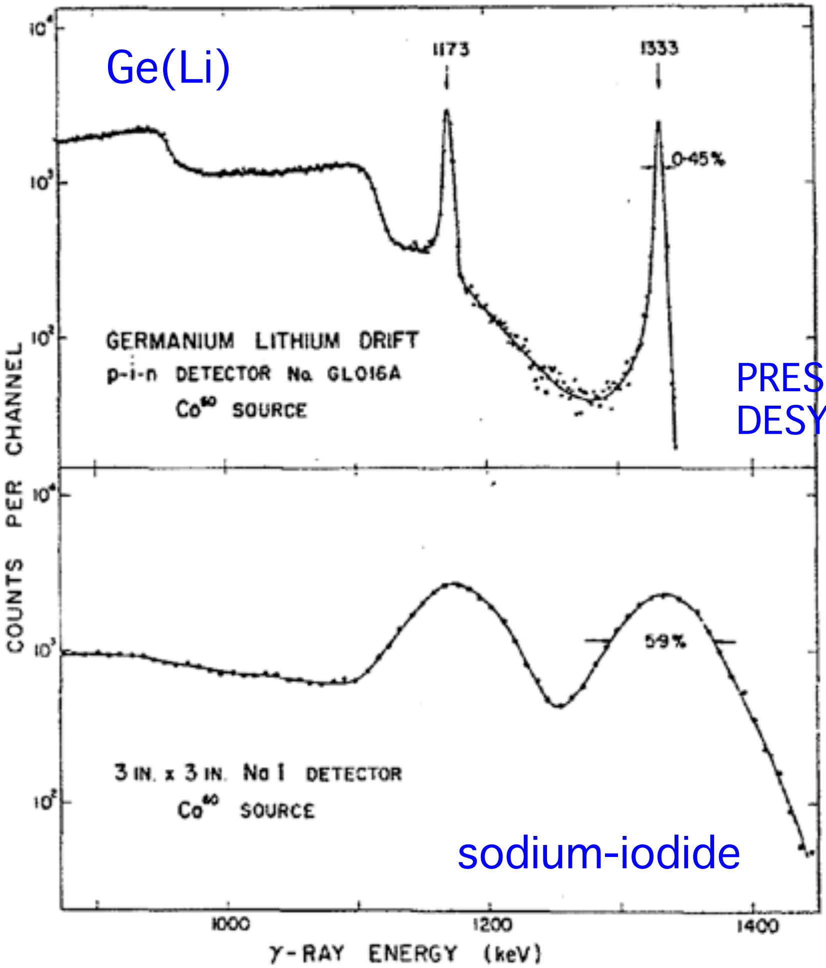
1960 Lithium drift for very thick depletion volume (>5mm, needs 77K cryo LN)
(E. Pell, General Electric)
1963 Si JFET (cooled 77K) in place of tube-preamp, for lower noise (Radeka, BNL)

CSP Laben ~1960 from review Bertuccio SSCM



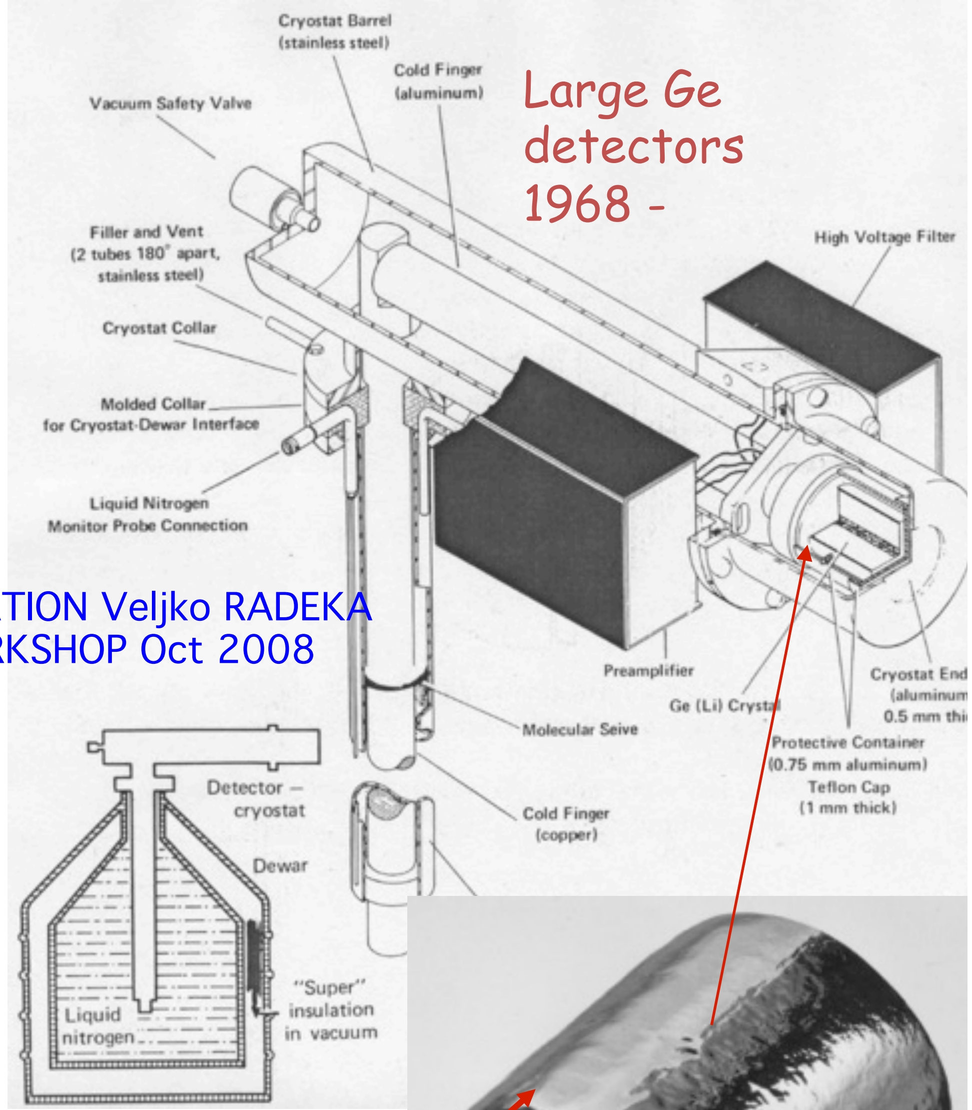
https://upload.wikimedia.org/wikipedia/commons/8/85/Discrete_opamp.png

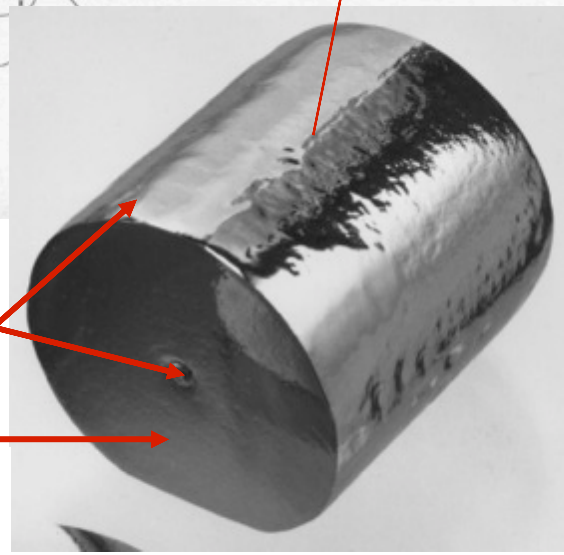
1963 Germanium Detector Breakthrough



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

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



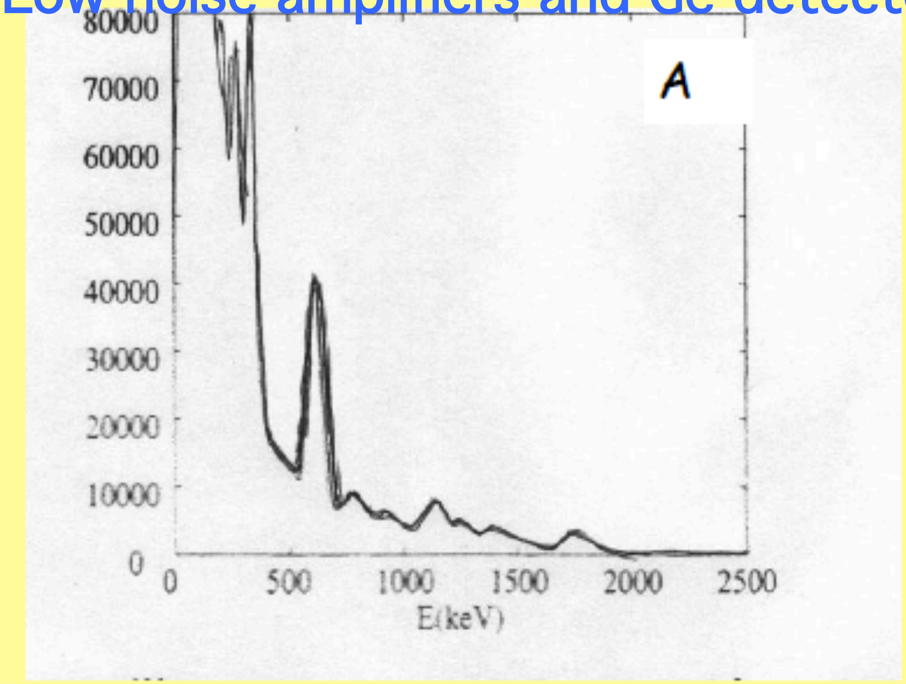


Coaxial det.contacts

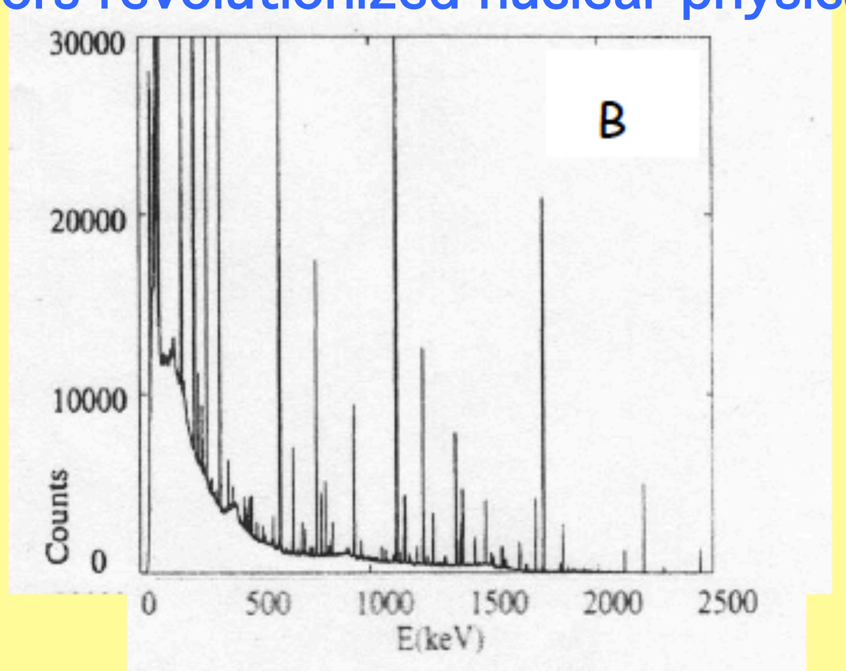
Ge-crystal ~50-100 cm^3

Prior to the advent of semiconductor detectors, gamma-ray spectrometry relied on NaI and CsI scintillation detectors. The energy resolution was poor, being limited by the statistics in the scintillation and charge multiplication processes.

Low noise amplifiers and Ge detectors revolutionized nuclear physics



^{226}Ra gamma-ray spectrum from a 309 cm^3 NaI detector



^{226}Ra gamma-ray spectrum from a 240 cm^3 coaxial germanium detector

The germanium detectors, initially Ge(Li), later HPGe, brought about a dramatic improvement in the resolution of γ-ray spectrometry, as it can be inferred by comparing figures A and B.

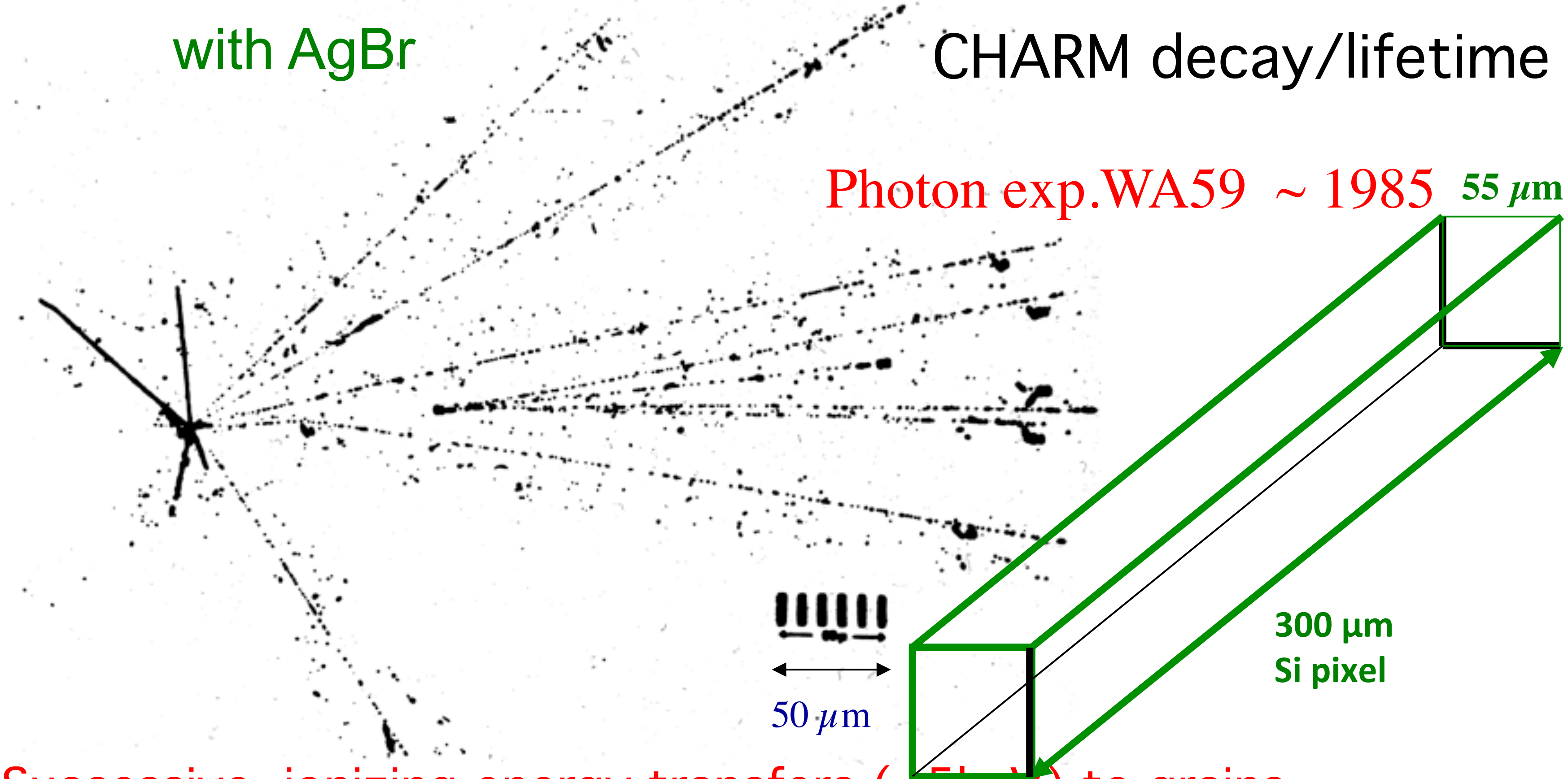
Photosensitive Emulsion as Detector

Thick gelatine film

3D, sub µm precision

with AgBr

CHARM decay/lifetime

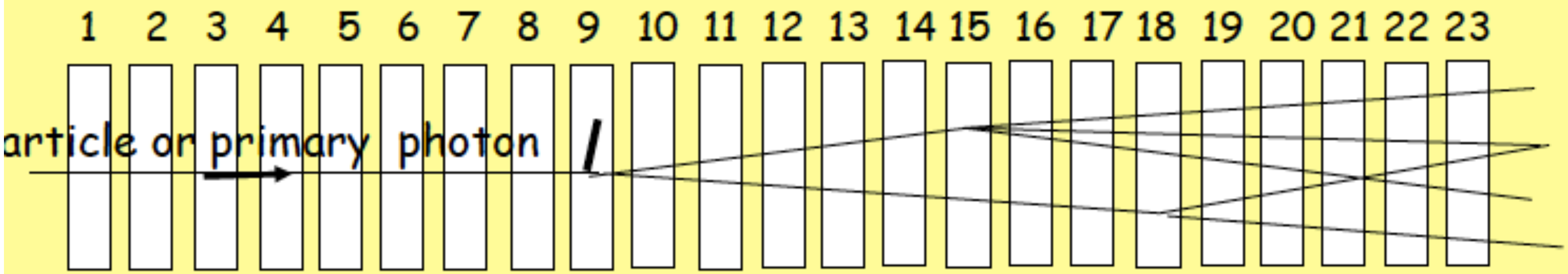


Successive ionizing energy transfers (~5keV) to grains
create the latent image

500 µm

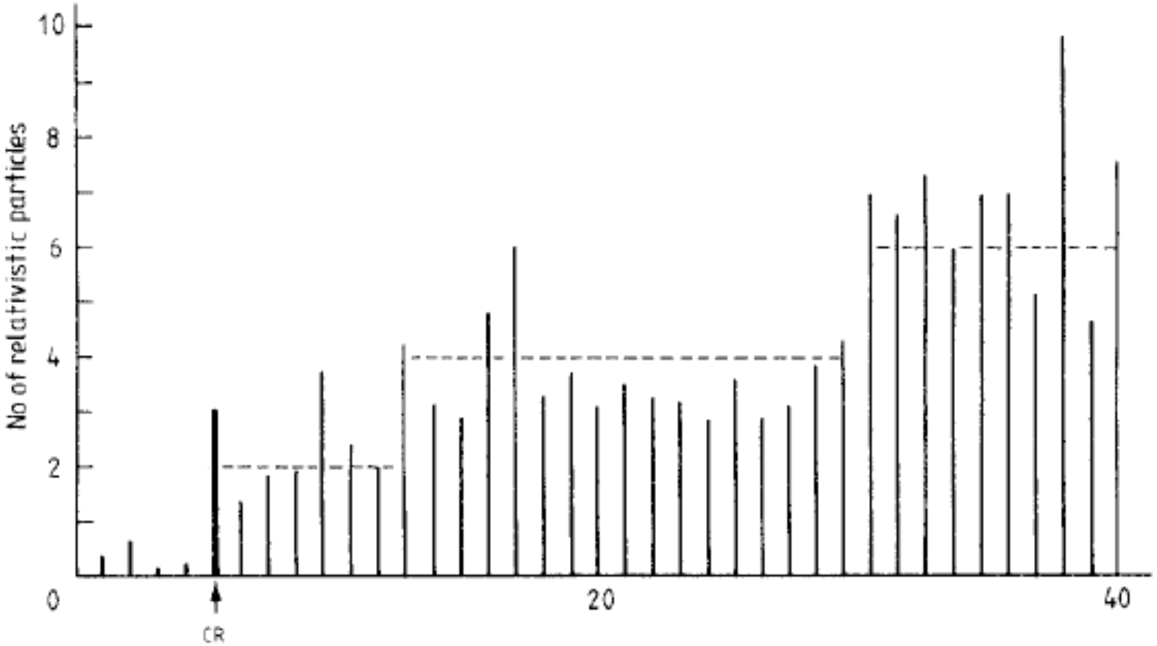
Charm lifetime measurement in CERN NA1 using telescope of 40 thin Si detectors

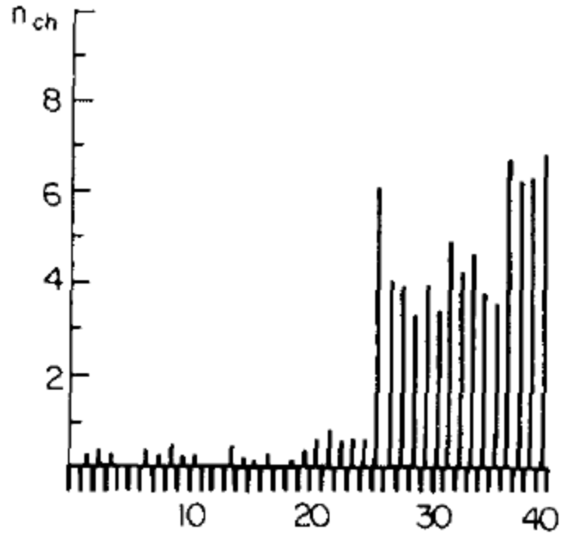
describing a particular class of position-sensing detectors, the so called active targets that have been employed in some fixed-target experiments about two-to three decades ago. An active target is shown below.

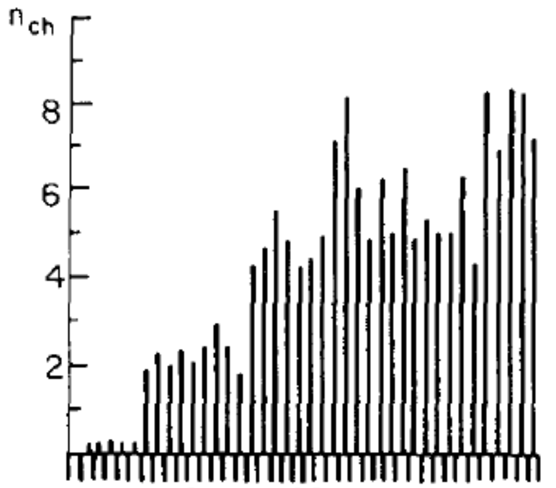


The active target is a telescope of silicon detectors which implements a twofold function. Besides providing the target material it samples the specific energy loss dE/dx in the beam direction. The silicon active target of FRAMM experiment at CERN (late seventies-early eighties) employed 40 silicon layers.

Some NA1/FRAMM measurements







Feedback for large capacitance diodes

The silicon telescopes brought about the noise limitations arising from the large detector capacitances, hundreds of pF, associated with the short values of t_p needed to comply with the high event rates during the accelerator spill. The optimization of the silicon active targets through three experiments was extremely instructive for the reasons listed below.

❖ In their first intervention (CERN SPS, 1968) it was noticed that they offered an interesting niche for the bipolar transistor as a front-end device and this is connected with **their comparatively small high-frequency noise at low currents.**

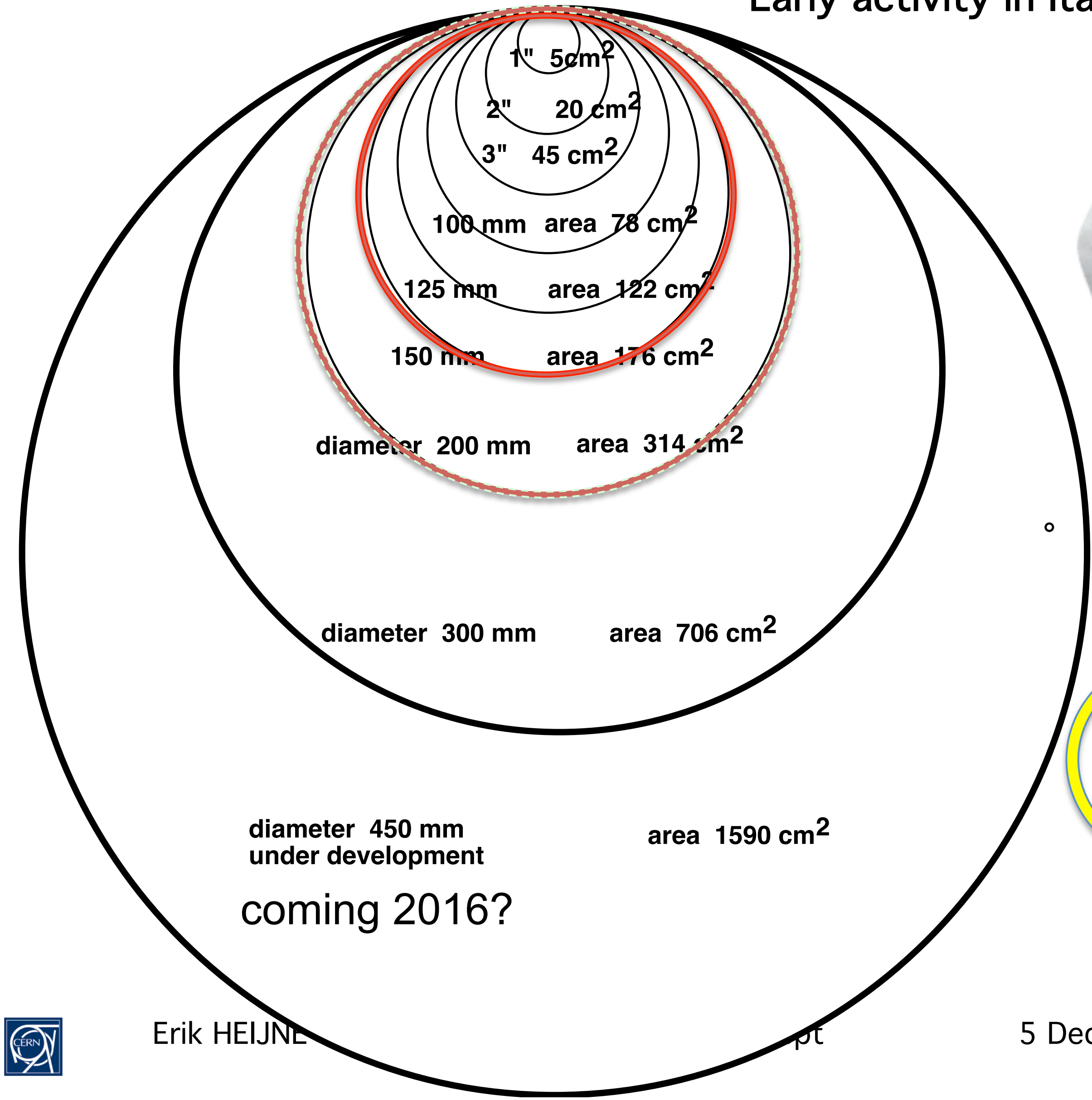
❖ Next came the remark that, being the detectors employed in the totally depleted mode, their association with a preamplifier featuring a *stabilized cold resistance* at the input, the time constant determined by the product of the detector capacitance and the cold resistance could be employed as a part of the shaping process. This solution was employed in the silicon active target of FRAMM experiment (CERN SPS, 1979-1983).

Silicon single crystal growing

1955-2015 **Wafer sizes**

Increase of wafer diameter 3/4" - 450mm

Early activity in Italy: Montecatini



Single Crystal Silicon Ingot

CZ Crystal Pullers
(Mitsubishi Materials Silicon)

Silicon moved instrumentation completely into electronics

Surface barrier diodes and the ‘Checker board’ detector

Ion-implanted diodes: the Kemmer patent

Silicon microstrip detector and parallel signal processing

CCD as particle detector

Silicon drift chamber

Introduction of CMOS integrated circuits for readout

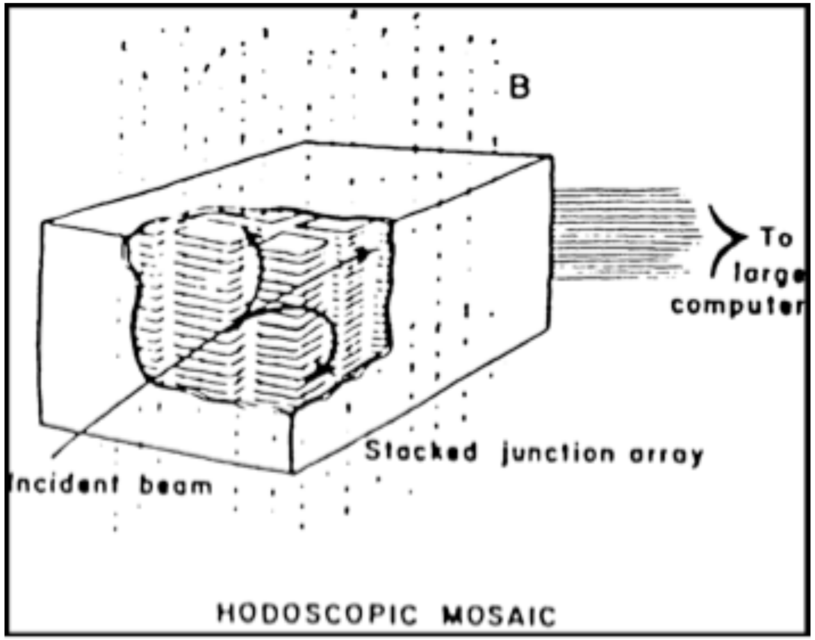
Hybrid pixel detector

3D ‘pillar’ diode matrix and 3D stacked detectors

Monolithic/3D CMOS detectors with fully integrated processing

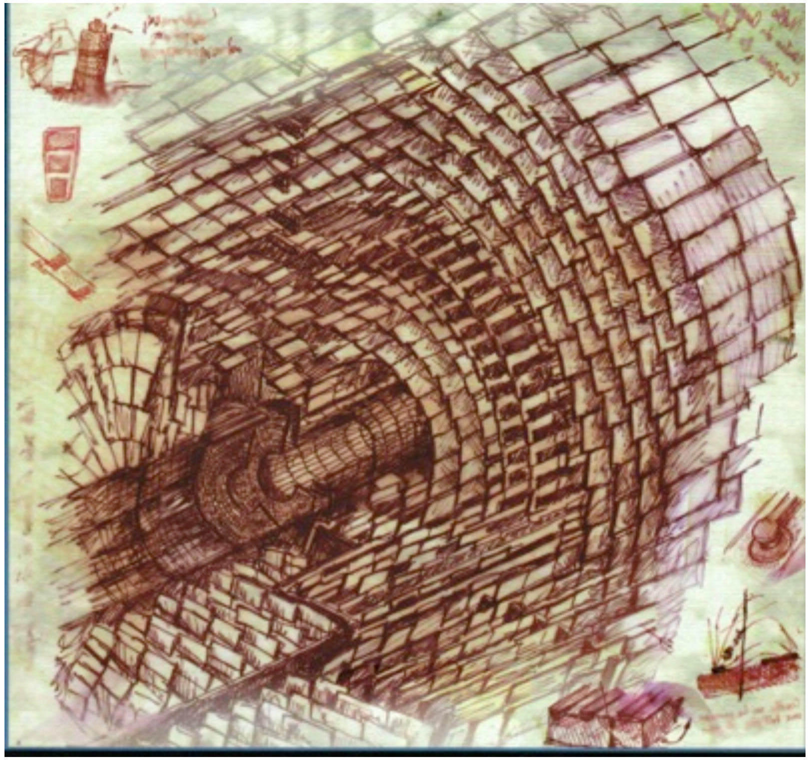
Plans for Si particle tracking systems

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

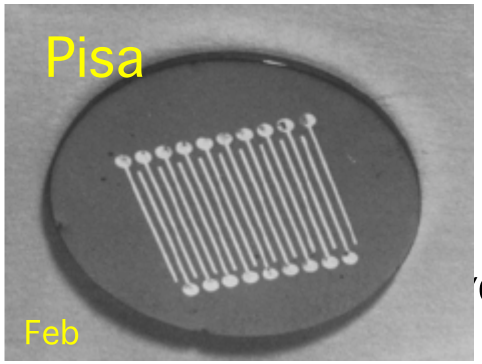
In 1980 several 'revolutionary' innovations took place, that were to shape silicon detectors for future applications in particle physics and other fields

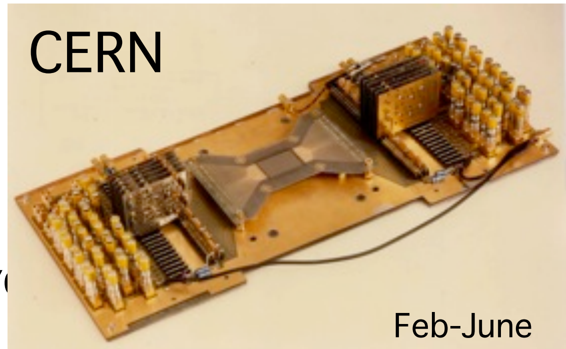
1. Segmented surface barrier detector,19 strips, pitch 0.6mm made in Pisa.
   NIM 176 (1980) 457, Amendolia et al. (Menzione, Bosisio,..) readout 2-ch, in beam at CERN

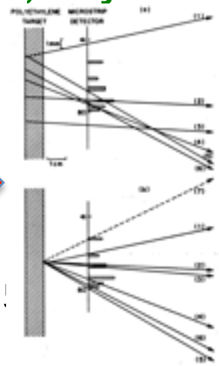
2. Si microstrip detectors, 100 strips, pitch 0.2mm, Heijne, Burger, Jarron, CERN made at Enertec, Strasbourg; tested May at CERN, with full readout and a first vertex reconstruction by Jos Vermeulen and Andrew Wylie, NIM 178

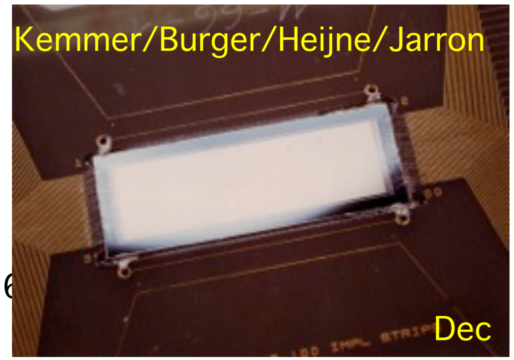
3. Publication in NIM 169 of planar passivated Si diodes with low noise/current by Josef Kemmer, Techn. Univ. München (~nA/cm^{-2}, see before). Process commercialized by Enertec/Strasbourg in 1981.

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





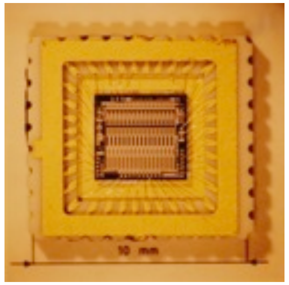




Hermetic Si pad detector for UA2

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

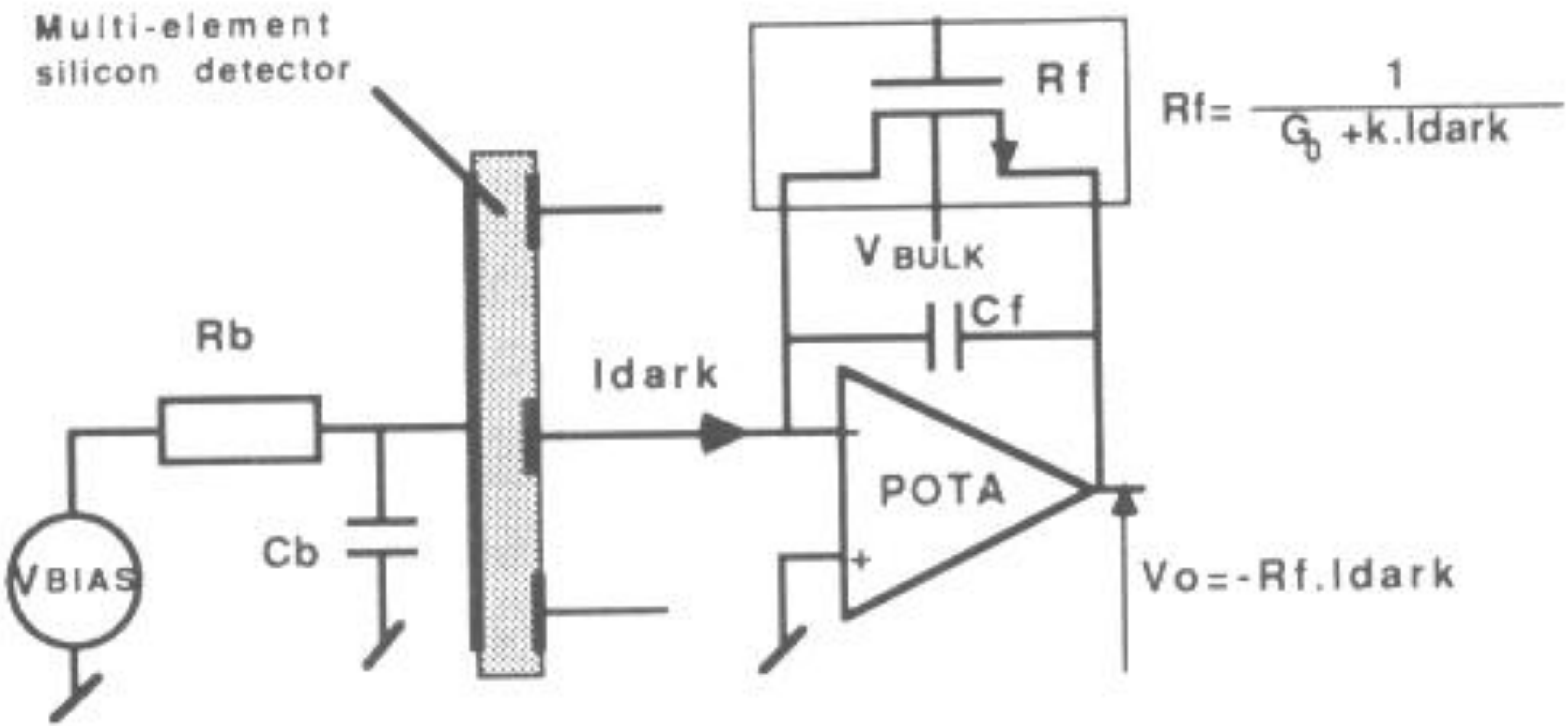


~5 mm thin CILINDER around beam pipe
ONLY POSSIBLE using "AMPLEX" chip
16-channel circuit design Pierre Jarron

R. Ansari et al. NIMA279(1989) 388

1986 – 1988 in LAA microelectronics project

LEAKAGE CURRENT COMPENSATION JARRON 1986



AMPLEX CHIP COMPENSATES CURRENT UP TO ~ 800nA per CHANNEL

From 1-D to 2-D

CCD, Pixels, Drift

Reducing noise, improving S/N

reducing capacitance is main aspect

also have to deal with dark current/baseline

LHC vertexing
in ATLAS
3 pixel layers
are indicated

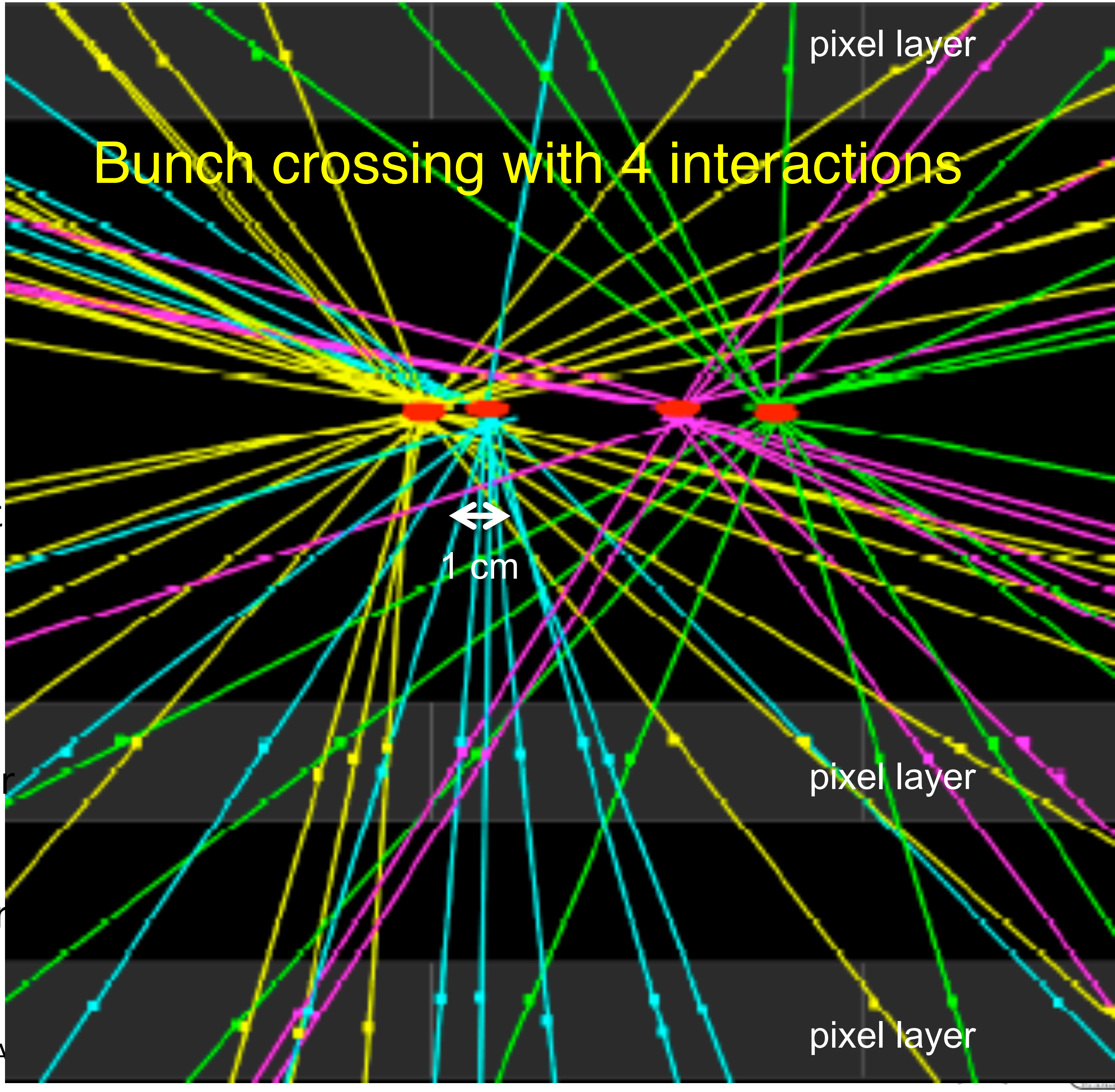
4 primary
vertices with
uncertainty
ellipses (orange)

Yellow event 32 t

Blue event 15 tr

Purple event 15 tr

Green event 18 tr



now towards ps timing

discriminate within bunch crossing

time-of-flight particle identification

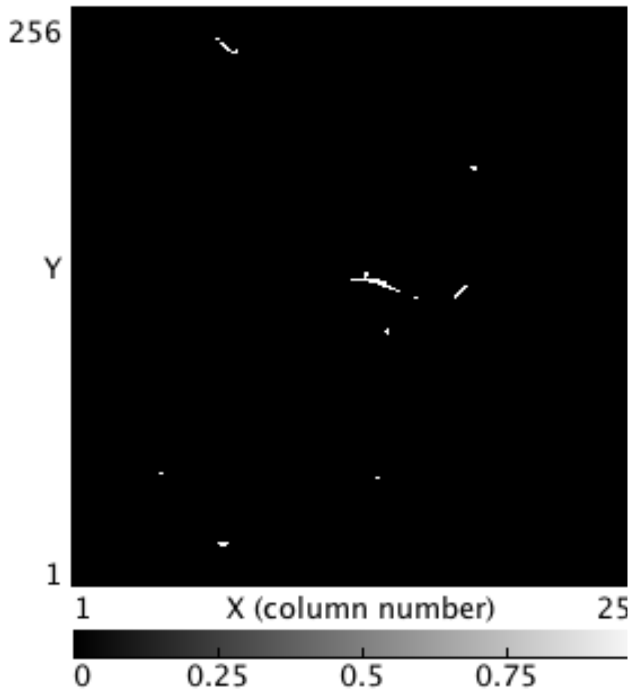
need correction for comparator timewalk

need faster sensors : SiC or Si avalanche ?

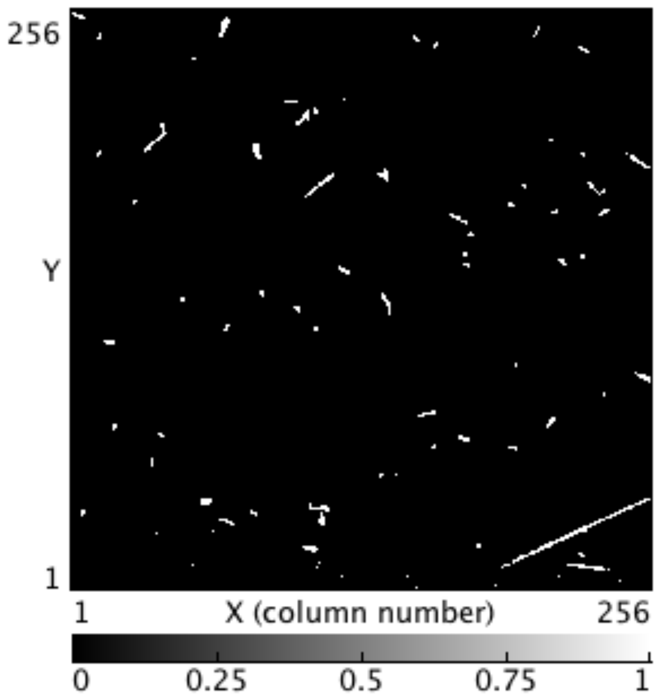
outside particle physics: fully integrated USB package

Single Quanta around us

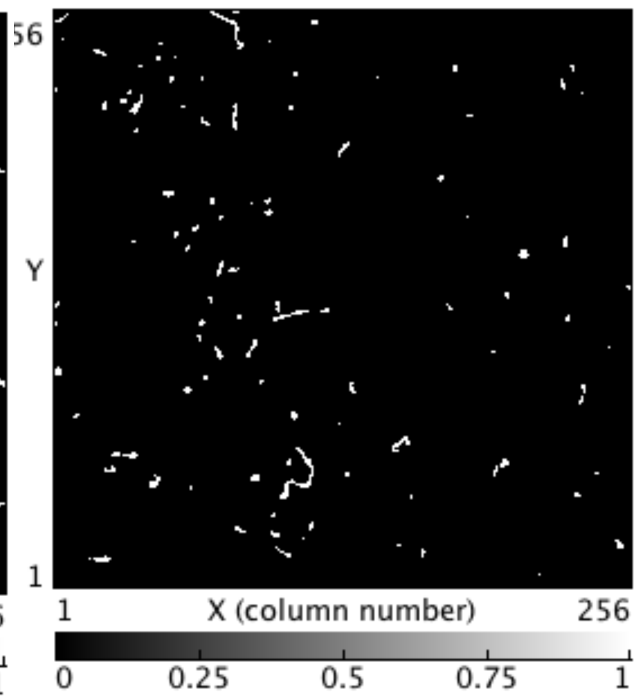
60s Exposure at ground level



60s Exposure in plane at 24 000 feet

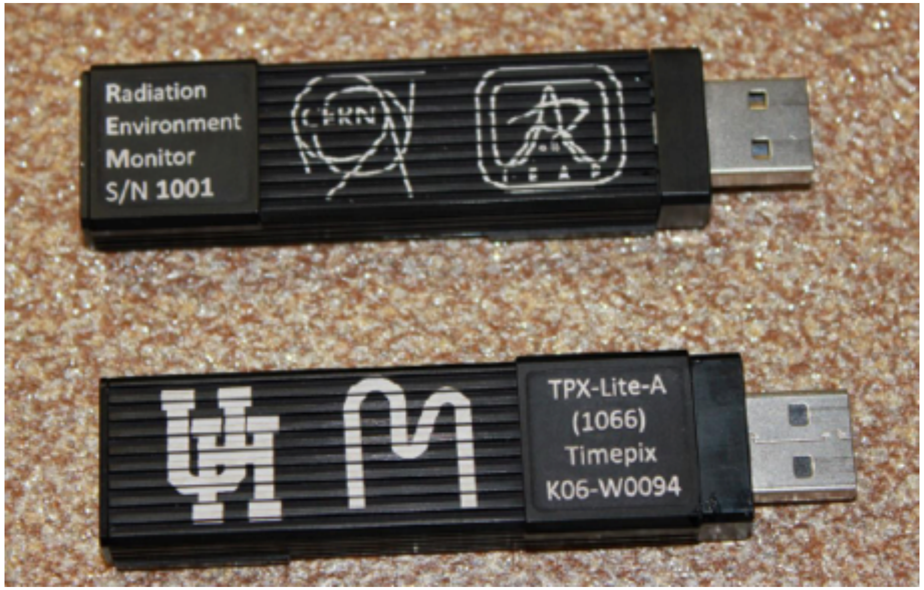


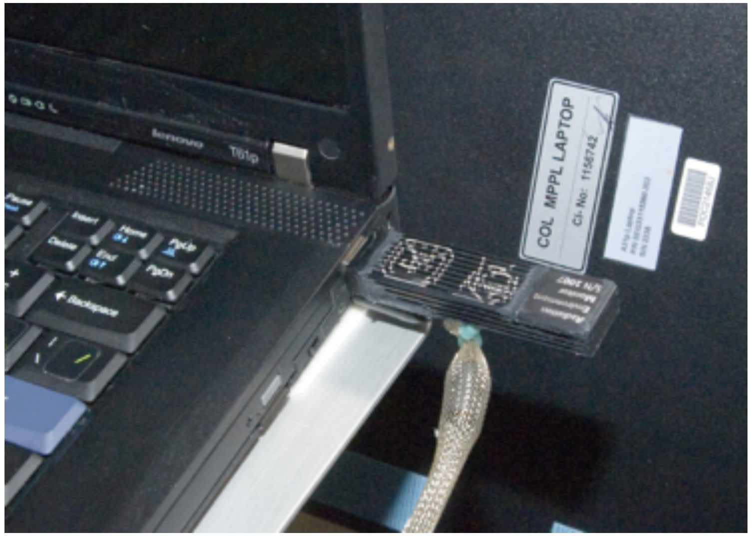
6s Exposure with old wristwatch (radium)



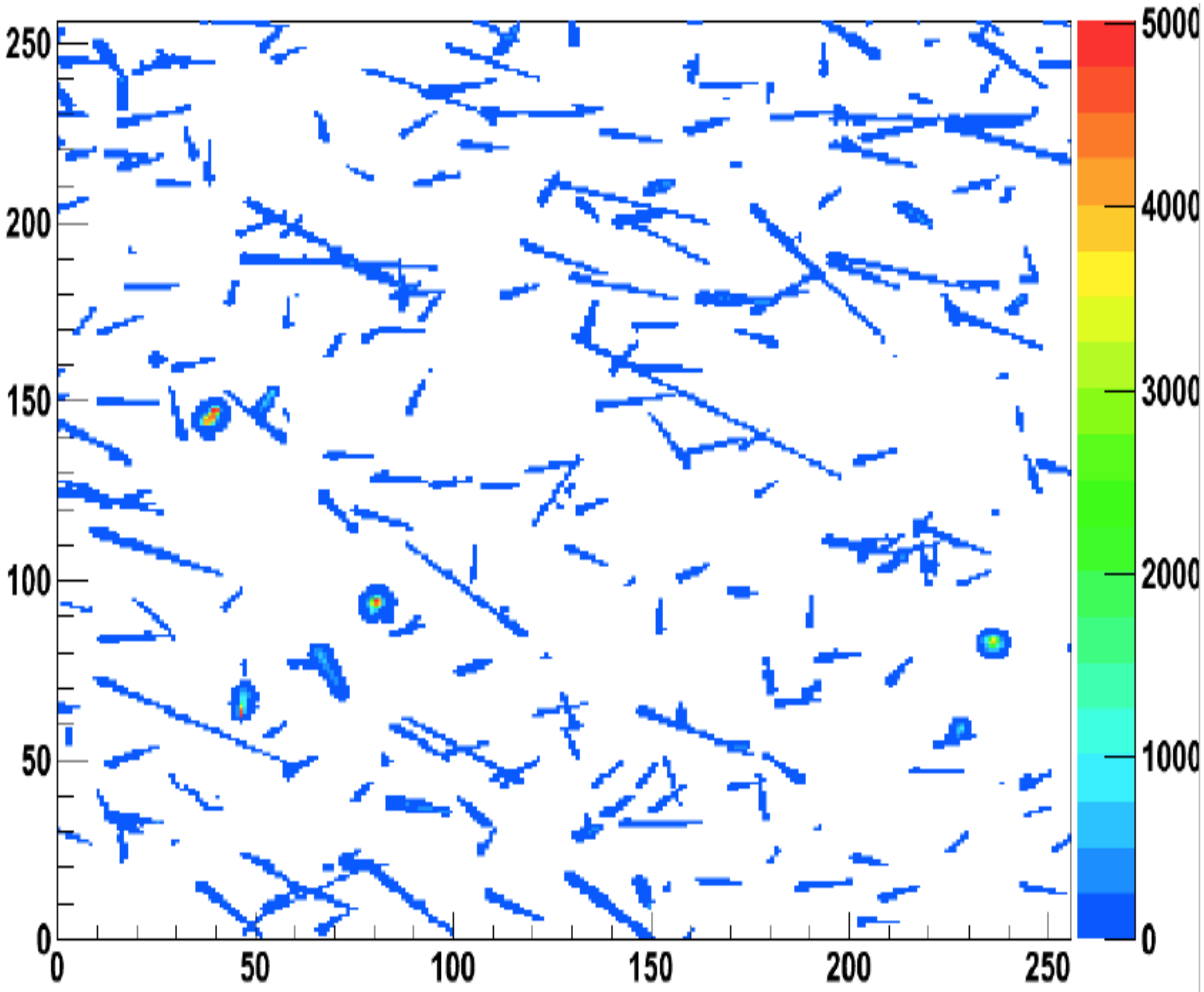
Dose levels well within safety zone

Pixel chips for dosimetry in Int Space Station ISS

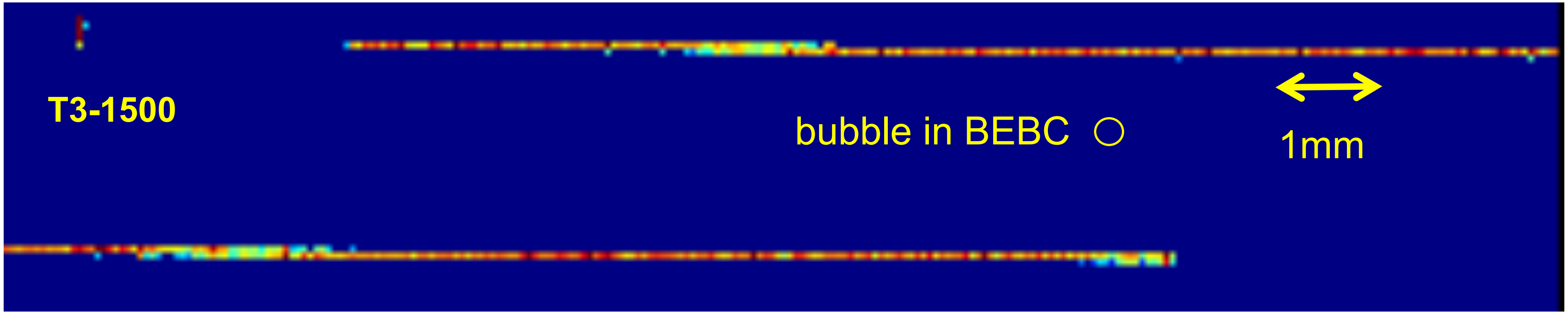




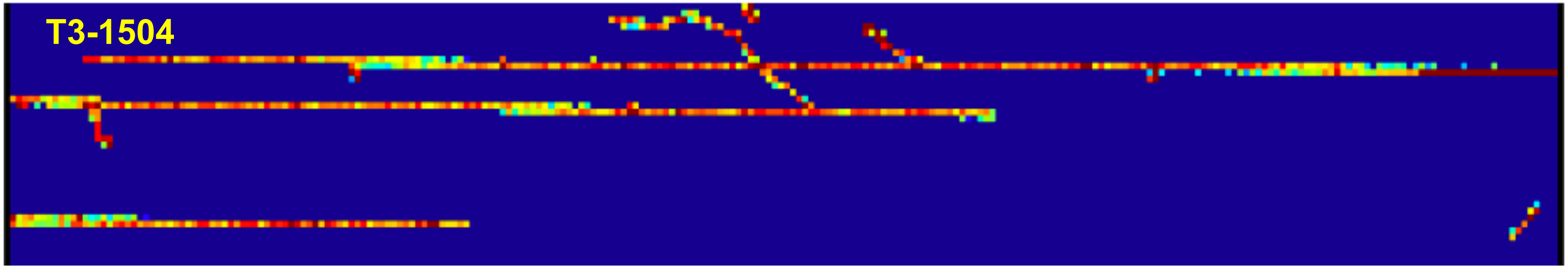
Dosimetry at the Int Space Station ISS

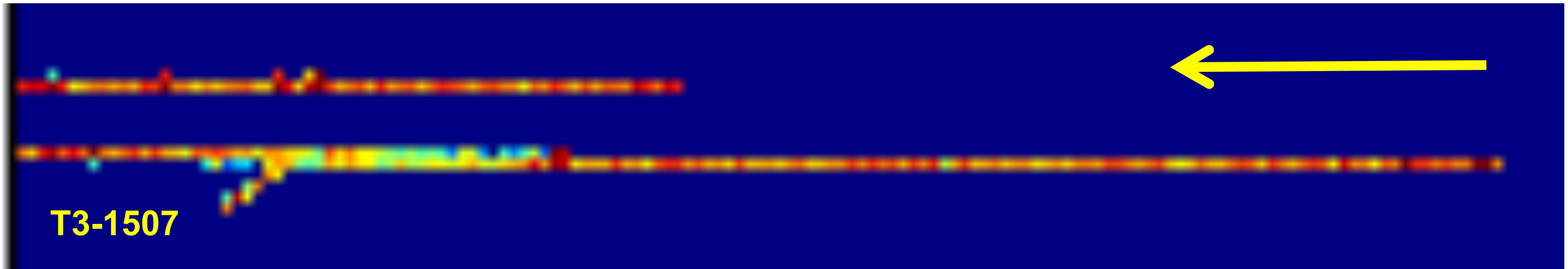


4s Timepix exposure taken in ISS passing through SAA South America Anomaly but can be used in physics beams as well...

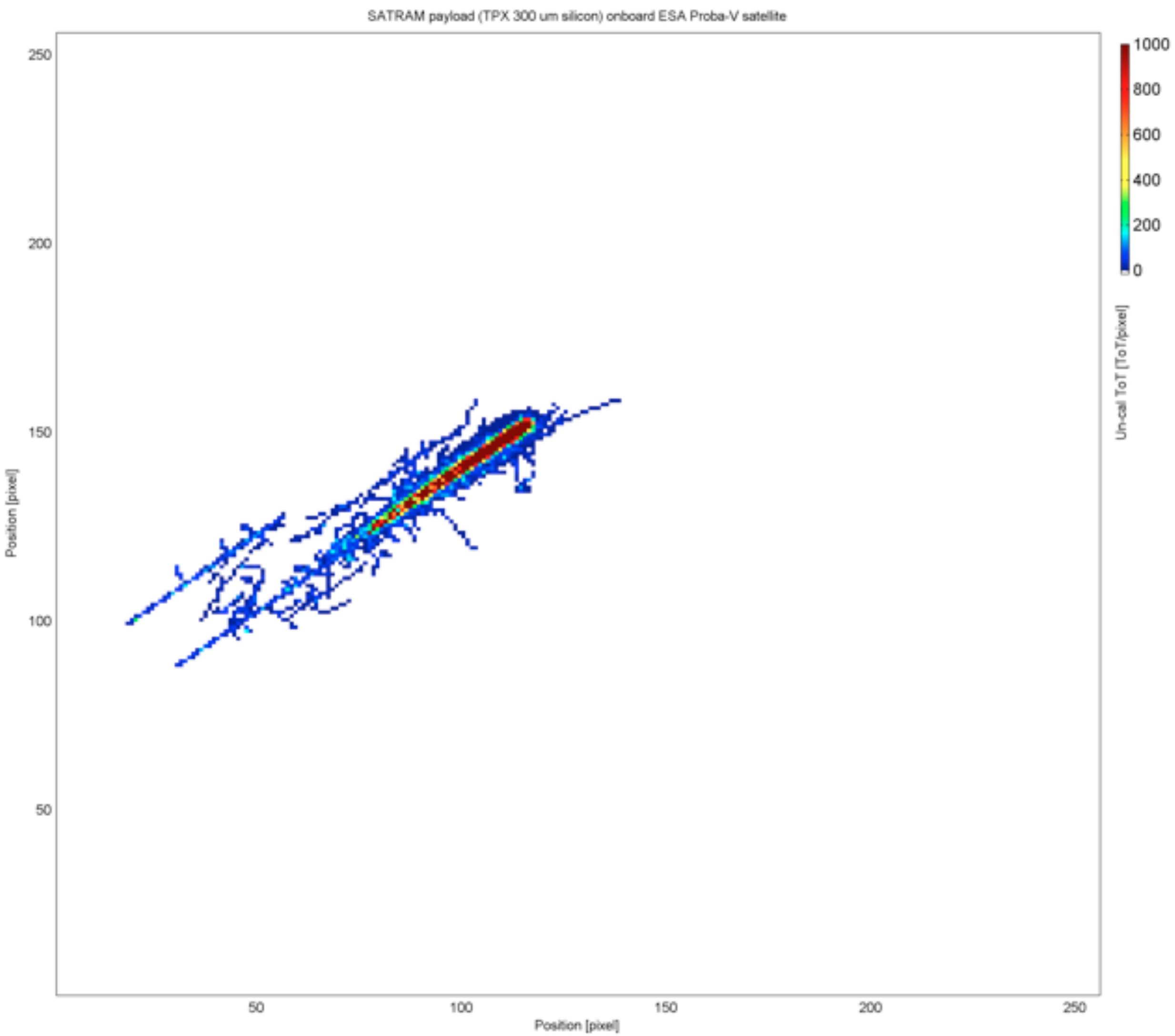


Typical Muon Trails in Timepix ...





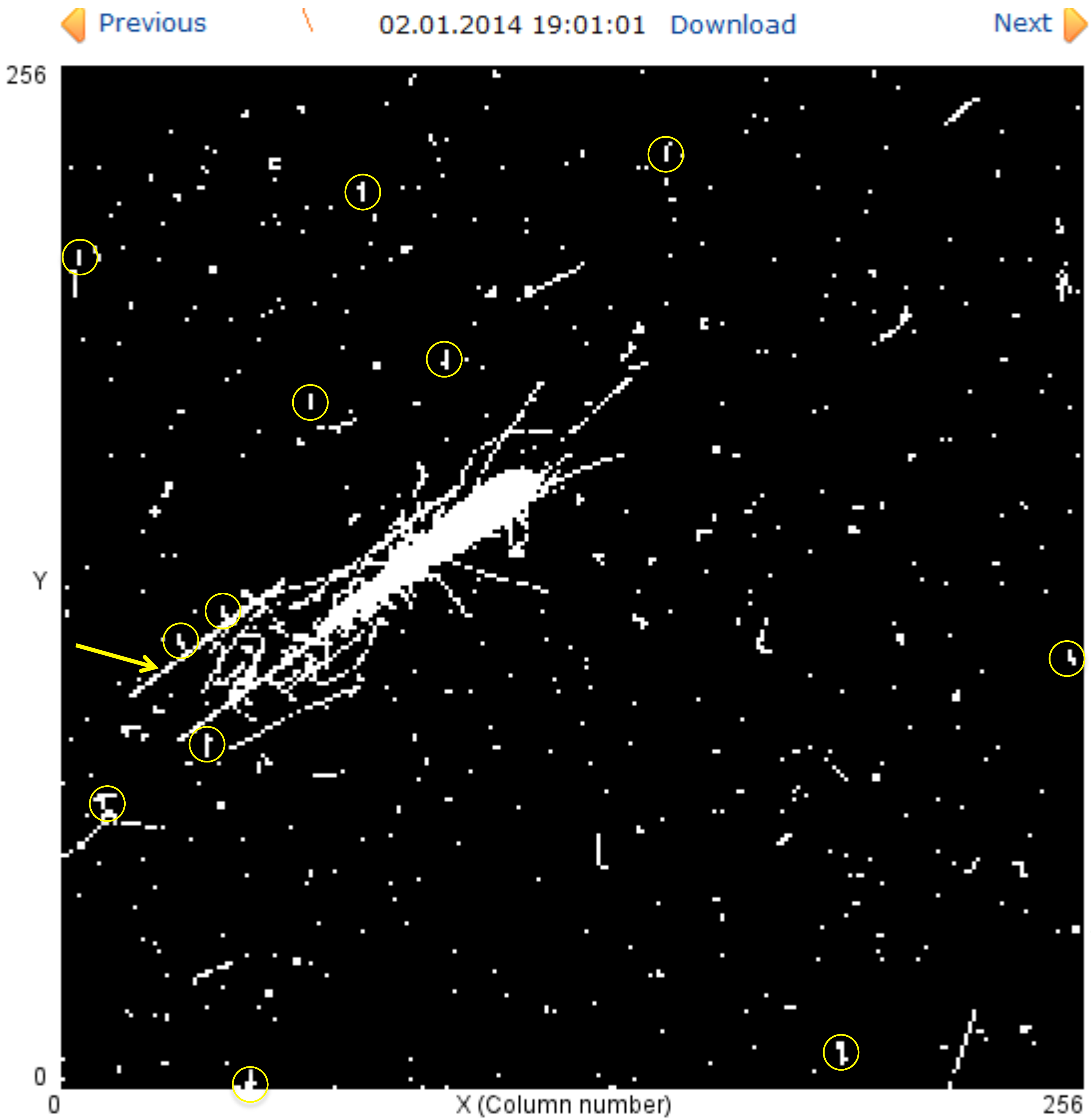
Space, at 850 km altitude, ProbaV satellite ESA
Satram Cluster/Event with Trail and δ electrons



only part of a
full frame exposure

must be highly ionized heavy ion

what is accompanying m.i.p. track (left) with so many delta rays?



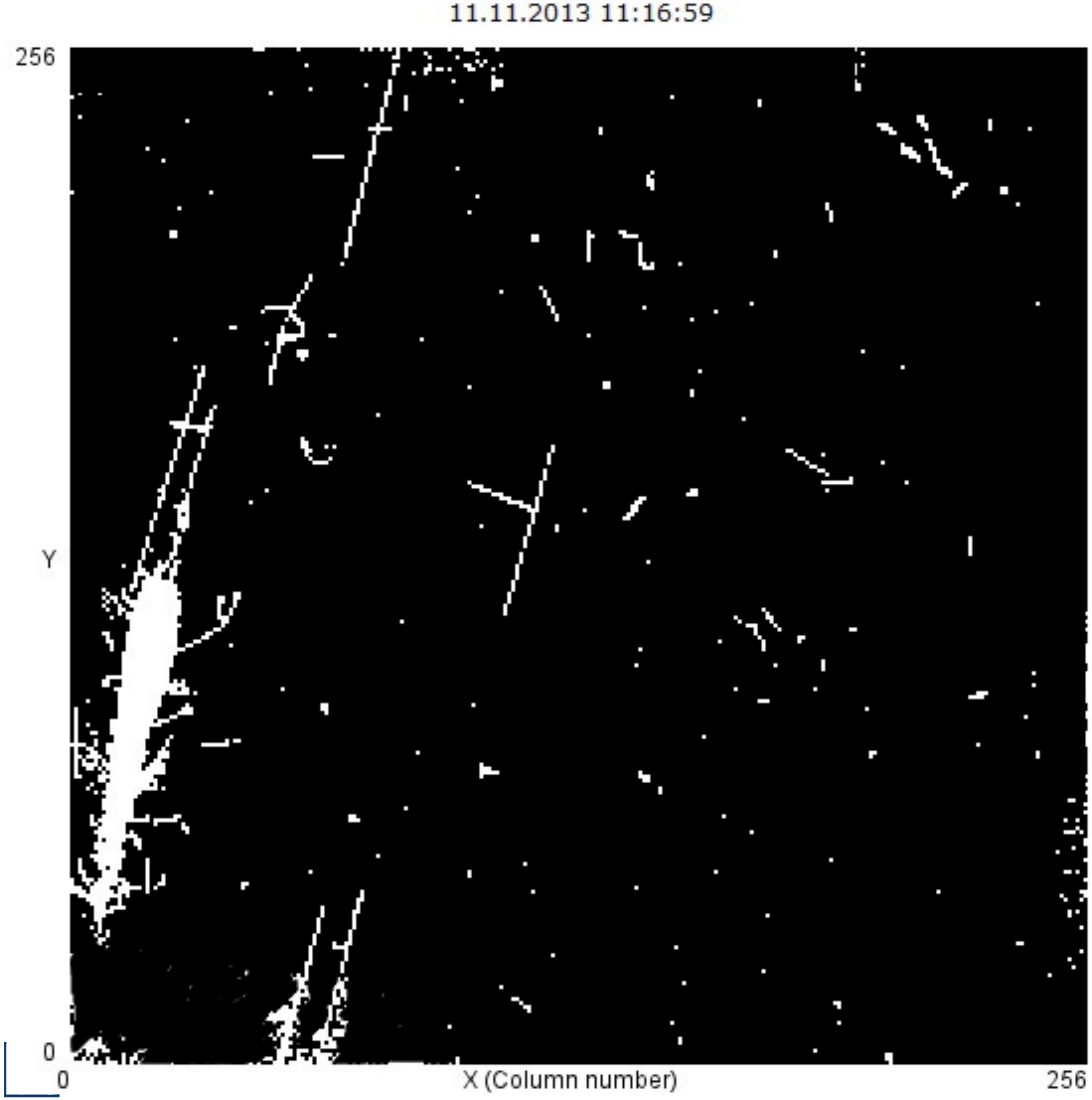
Delta's in Si

Same frame,
now fully shown

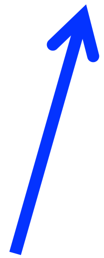
two of these
'apparent' deltas
may be in fact
'out-of-time'
short m.i.p. s
that overlap on
the long track
indicated with
the arrow

data from IEAP-CTU Prague
Medipix Monitoring web site

Another Satram Frame: November 2013



6 m.i.p. + ion
coming out
from satellite

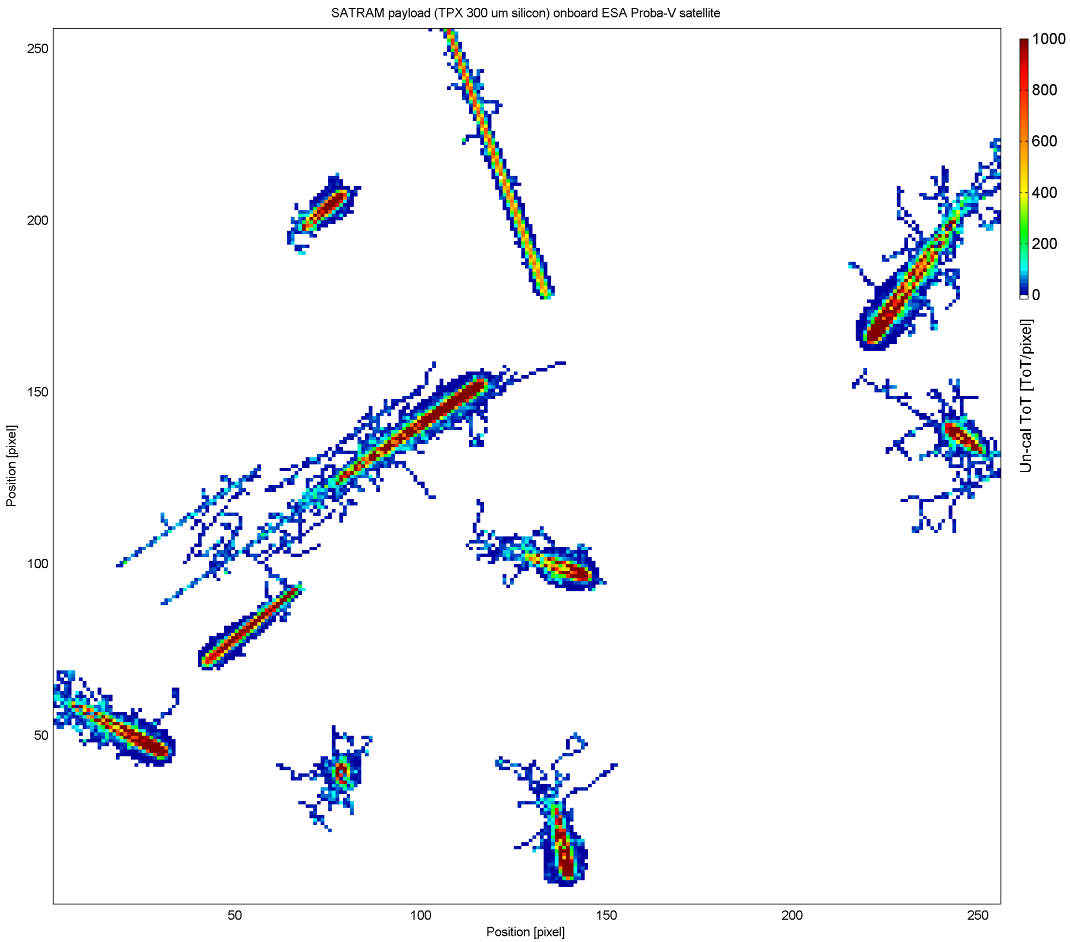


wide charge deposit by ion
at rear of sensor
due to diffusion

delta's point towards rear

data from IEAP-CTU
Medipix Monitoring web site

Is there a danger that we can miss new phenomena?

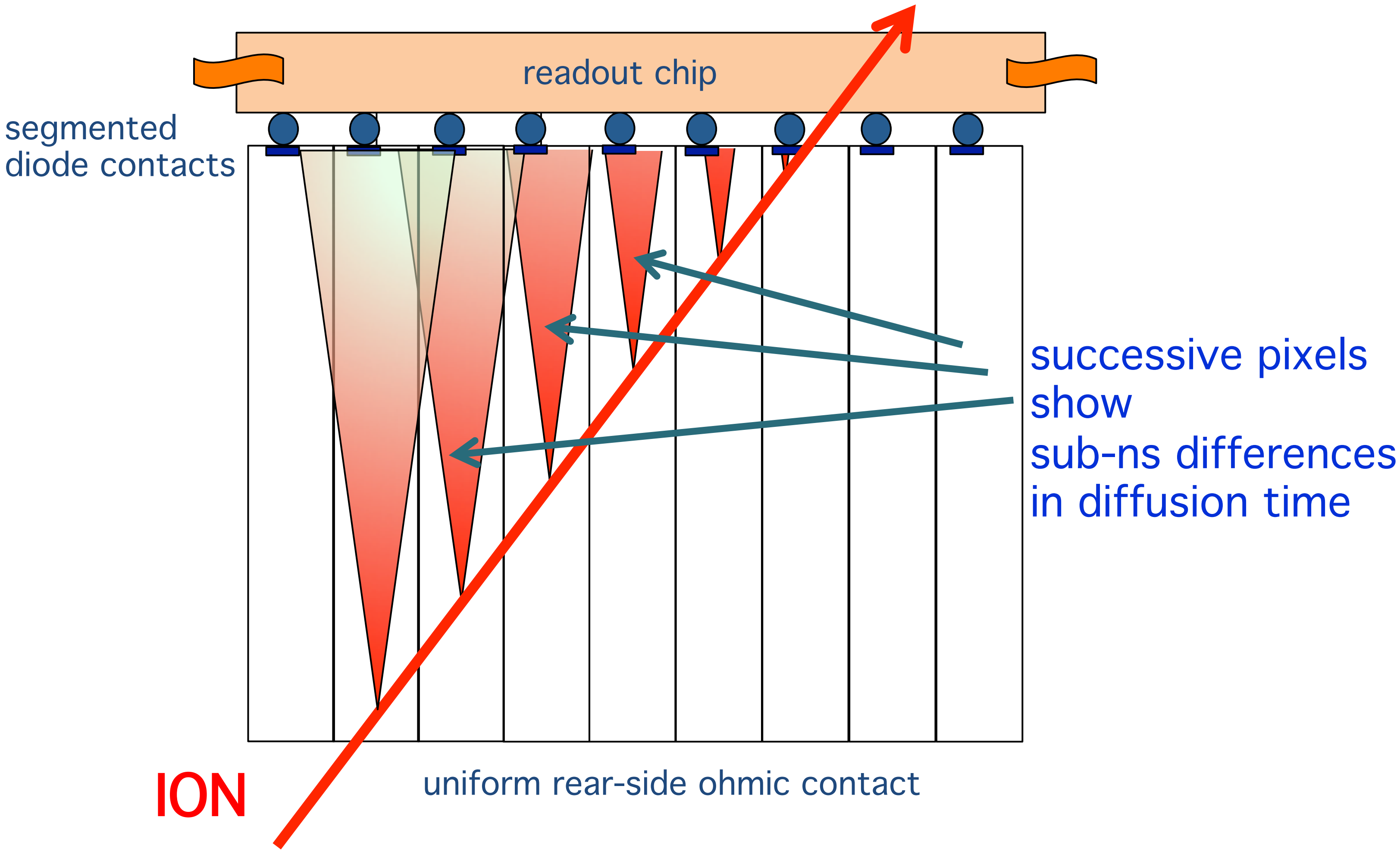


Clusters observed with Timepix pixel detector at 850km altitude in ESA Proba V mission SATRAM experiment 2013-2014

Most of these clusters can be explained as energetic heavy ions

sometimes part of a nuclear interaction in upstream material

IonTrails and charge collection



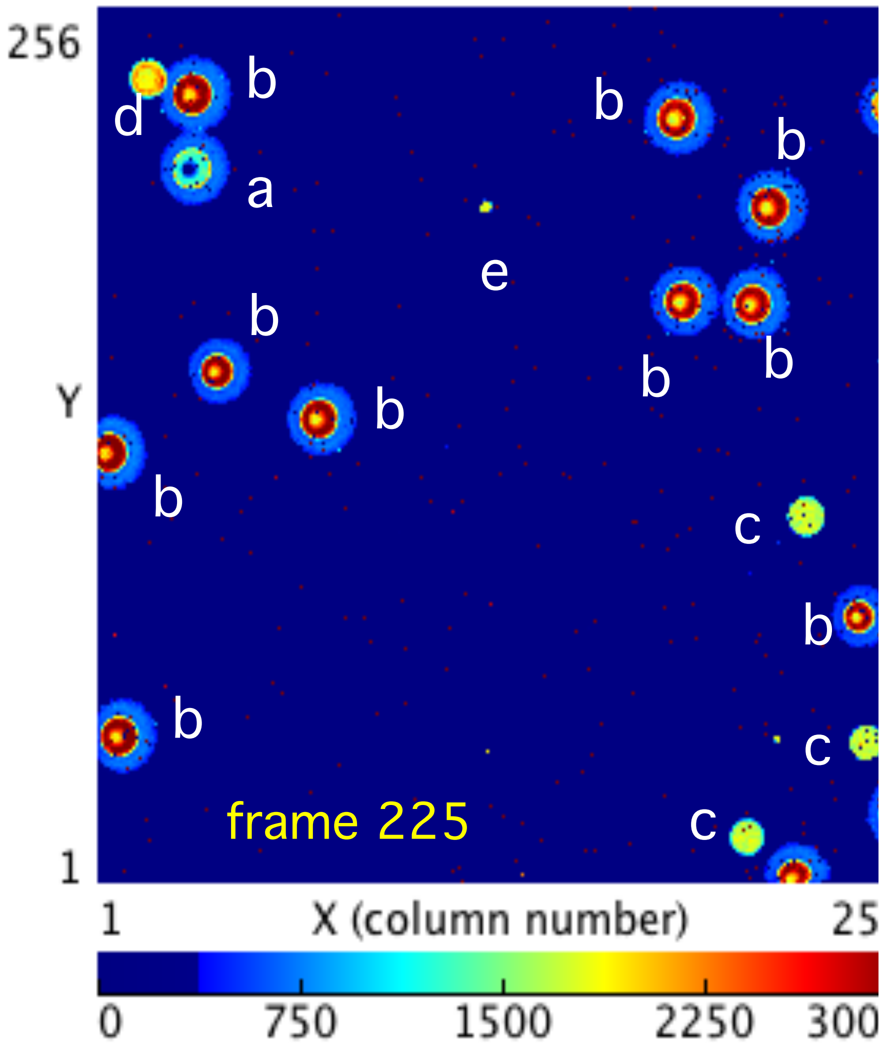
rear-side glancing angular incidence (e.g.4.1 degree)

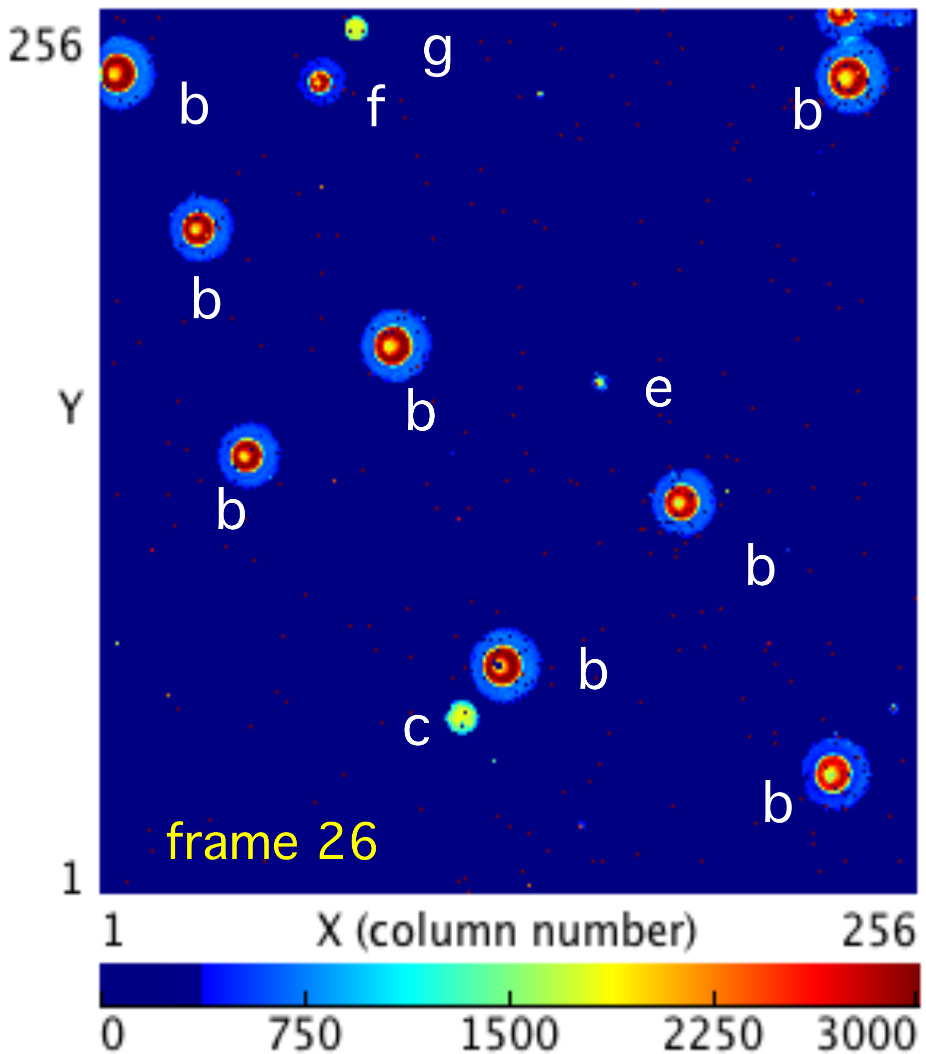
Imaging at future LHC just around the Vertex

Some different (but ancient) ideas for future Detectors

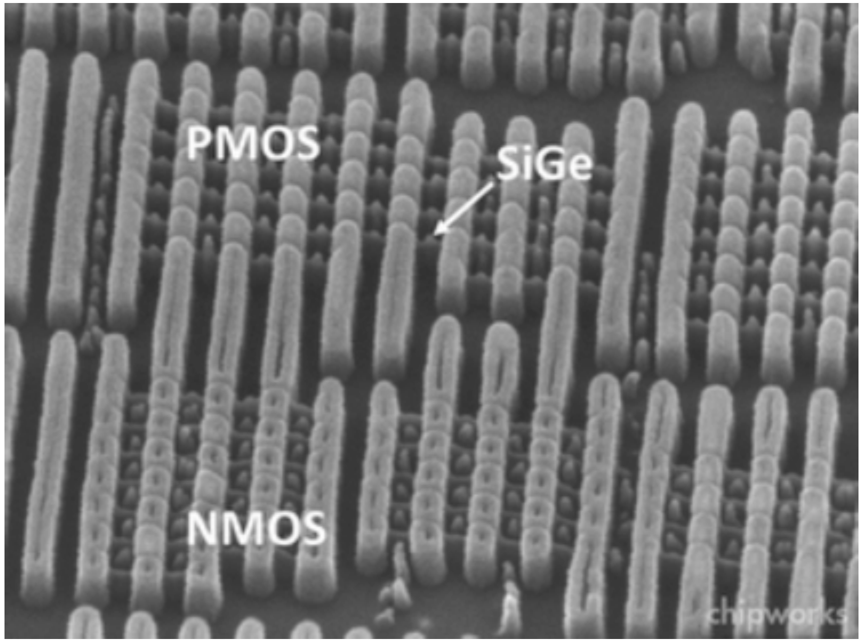
keep in mind nanometer electronics and 3D developments

Heavy ions, mixed beam, CERN fixed target
frames with ~perpendicular incidence (1mm sensor bias 2V)



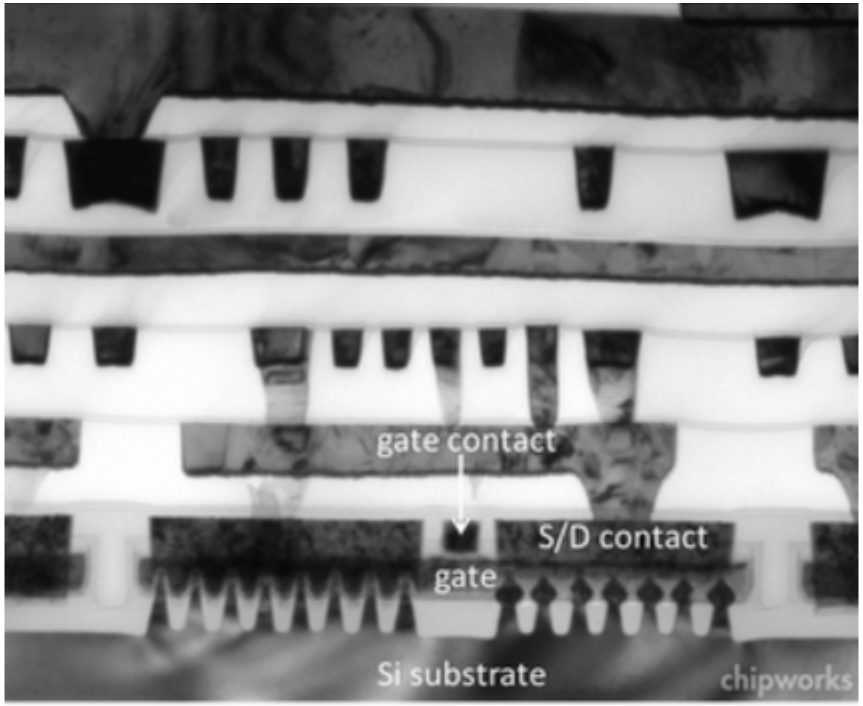


22nm transistors on XEON chip, INTEL



analyzed by Dick James,Chipworks
April 2012
using FEI Osiris TEM

transistors have this 'unexpected' slope



Stacking of memory chips

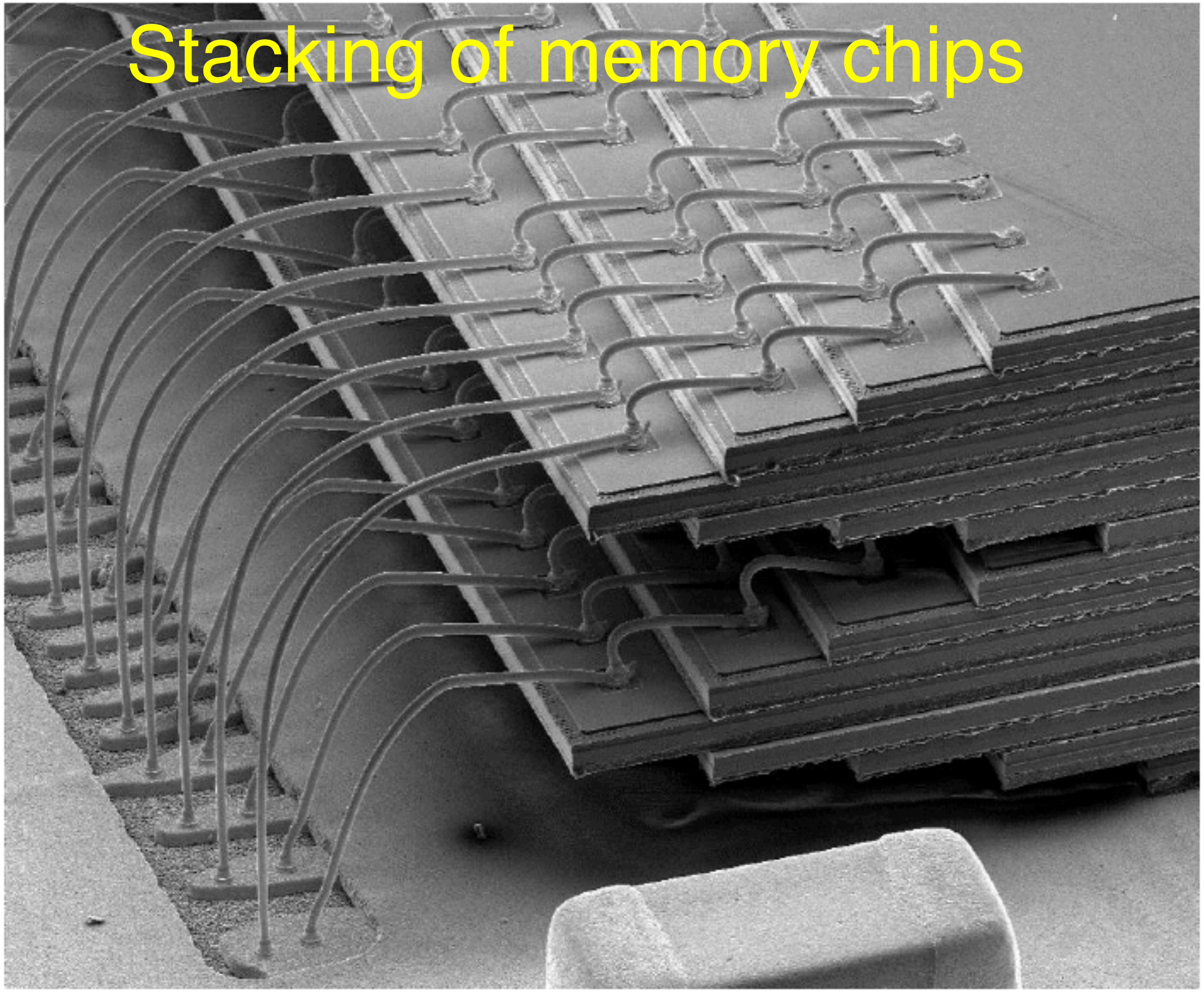
64Gb
SANDisk
2012

MicroSD
16 layers.
thinned

flat
wirebonds

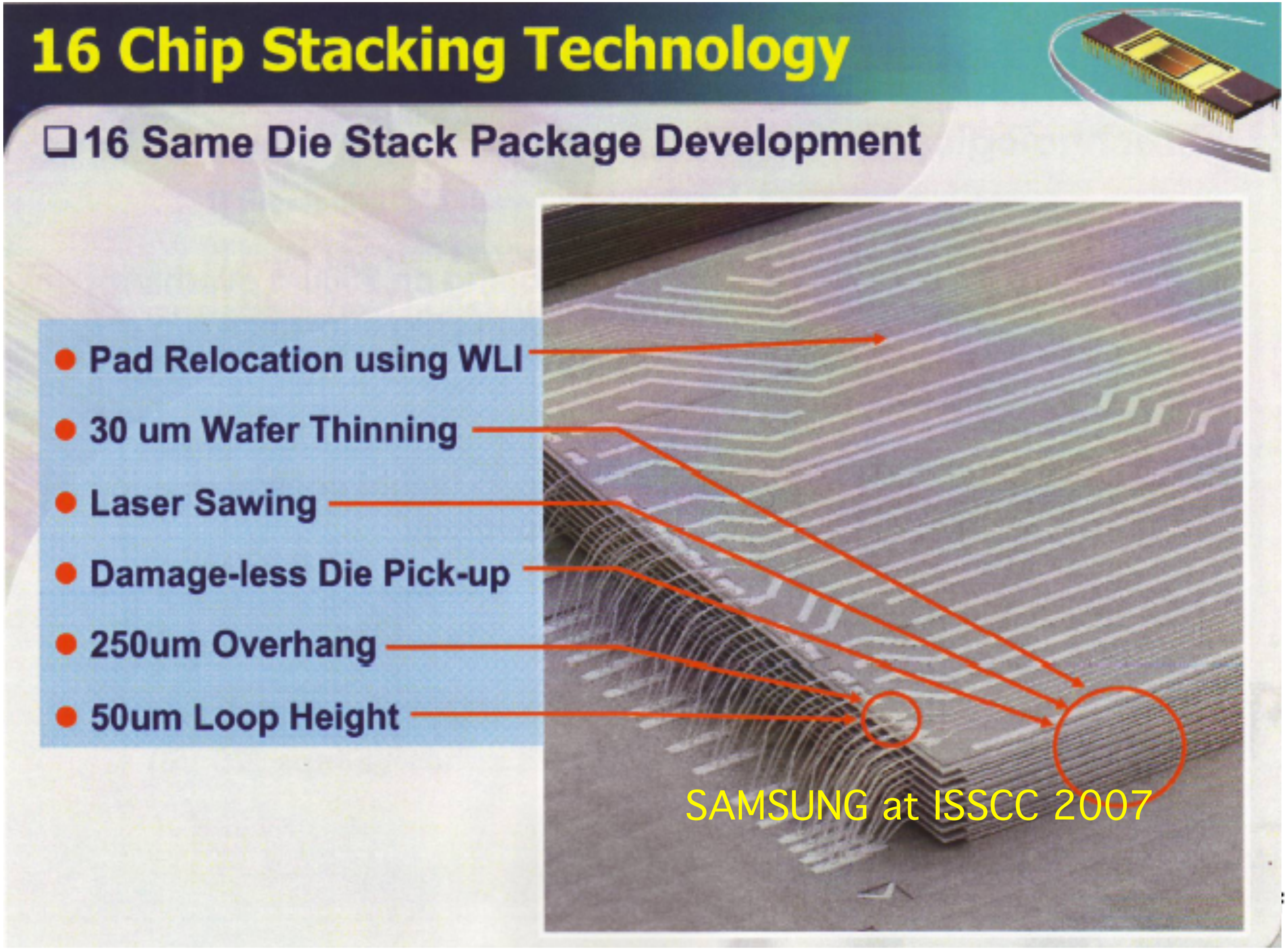
~6Tbyte
per inch^3

newest:
128 Gb



from Invited plenary talk A. Harari, 2012 ISSCC

another photo of 3D memory stacking; 48 layers 2016



Some Conclusions

Technical innovation essential for physics progress

silicon replaced emulsion, liquid and gas; rates Hz -> kHz -> MHz

Electronics determines sensors and systems

ultrapixels [3μmx3μmx3μm] in advanced nanotechnologies?

Low noise/high speed by sensor segmentation

pixel detectors for multiplicity, noise, precise positions

Si drift detectors for precise energy spectra, extreme signal/ noise

Timing at ps precision next frontier

silicon not adapted? light is faster than electrons

Can imaging technology deliver key information?

stacking of active layers integrated cooling real μm imaging

END