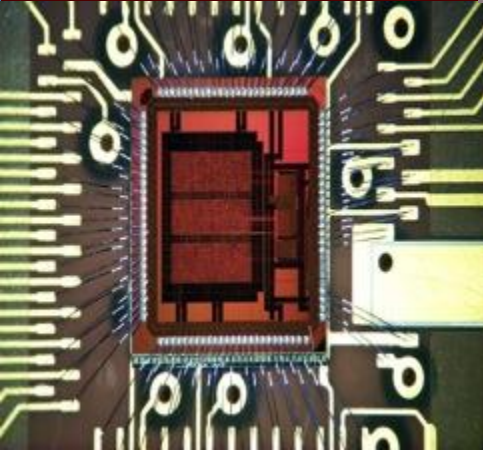


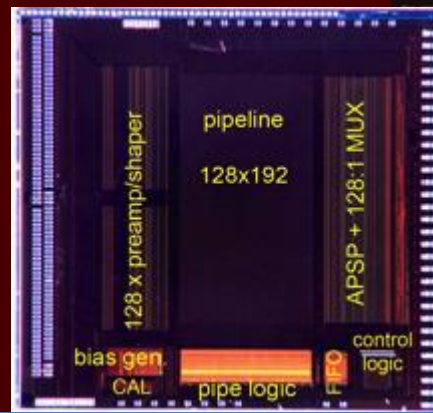
Silicium nano technologie

Pixel Detectors

CERN en Medipix



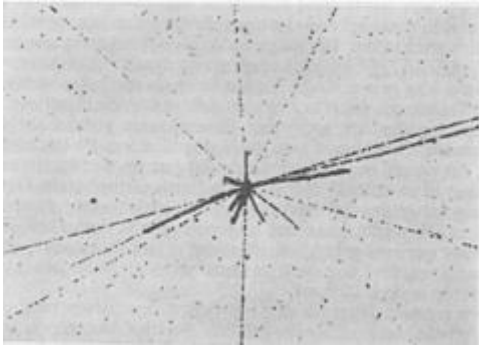
Erik H.M. Heijne
CERN – EP Dept.
CH 1211 Geneva 23
Institute for Experimental and
Applied Physics of the Czech
Technical University in Prague
Nikhef Amsterdam
Erik.Heijne@cern.ch



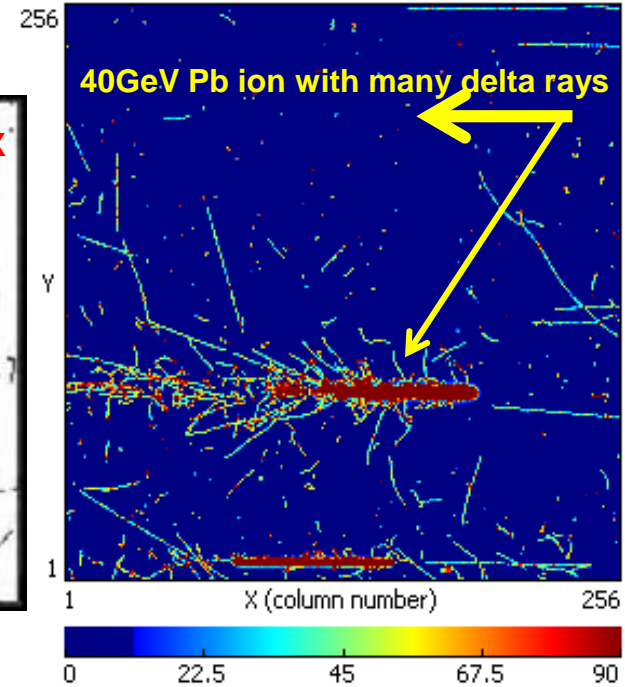
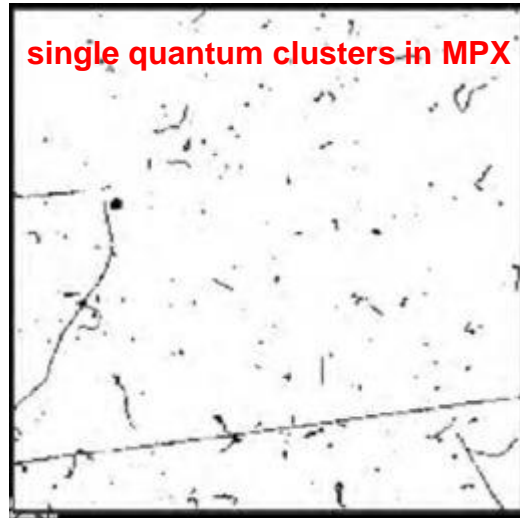
nog eens basics

imaging of radiation

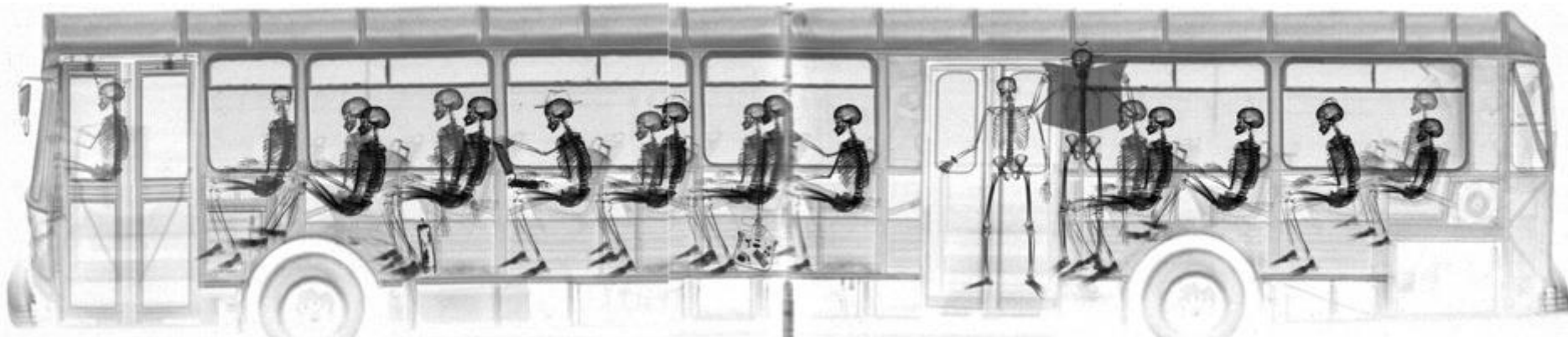
nuclear decay in emulsion



single quantum clusters in MPX



vs imaging with radiation



Nick Veasey

composed image, using large 200keV X-ray generator in WW-II bunker

ISBN 978 1 84796 076 4

Wat doen we eigenlijk op CERN?

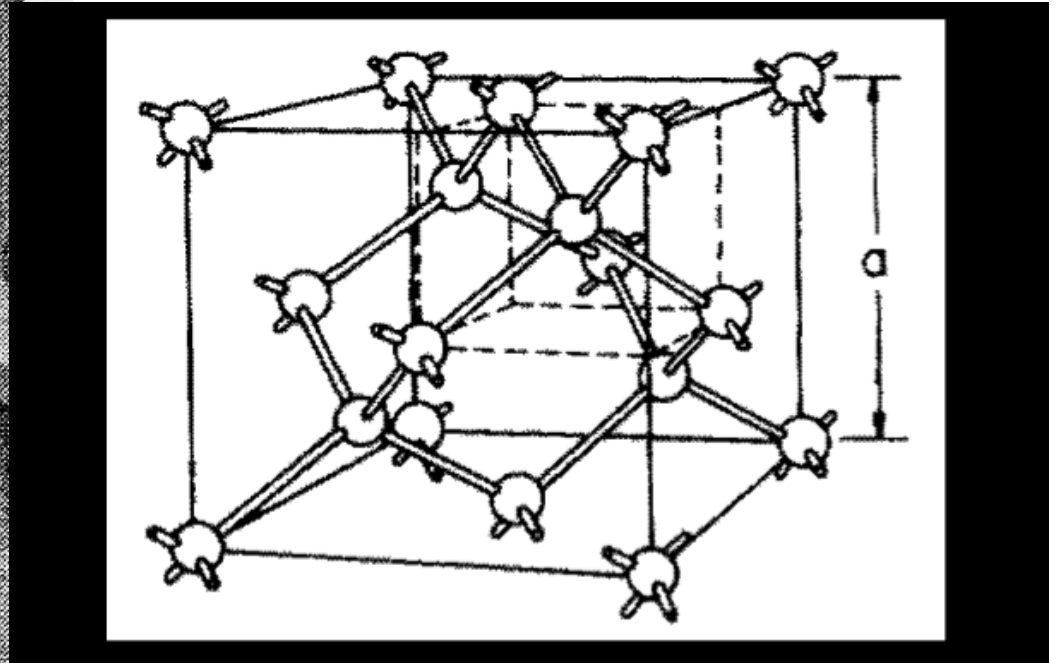
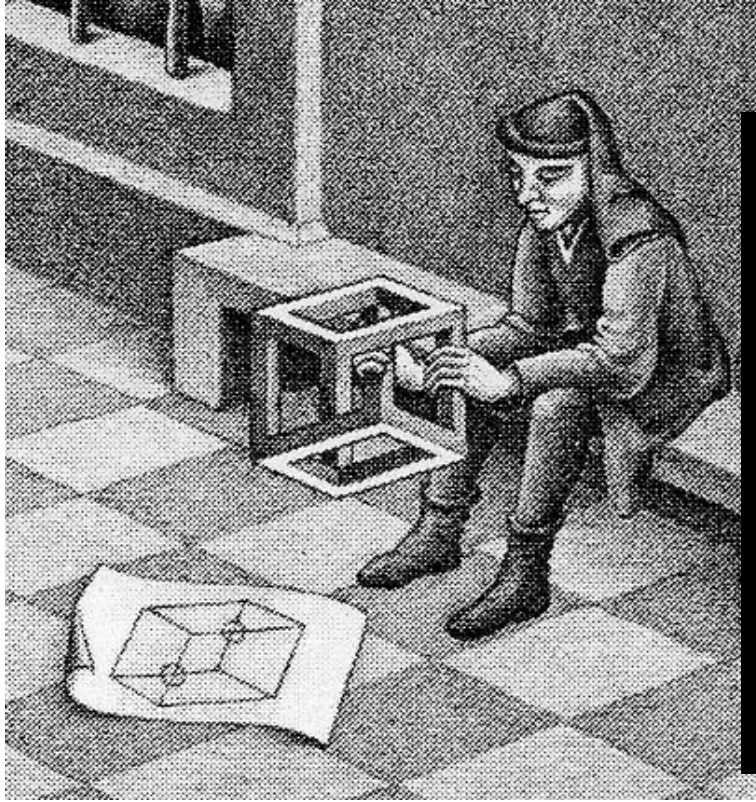
1. Versneller:
energie in zo klein mogelijk volume om
nieuwe deeltjes te scheppen

2. Metingen met detektoren om deze
deeltjes ook te kunnen bestuderen

direkt omheen het interactiepunt
wordt nu meestal silicium gebruikt



Silicium als éénkristal is halfgeleider



Silicium

'Imagination and Innovation'

- gevoelig voor zichtbaar licht (CCD, CMOS kamera)
- ook voor allerlei andere straling (>1.12 eV bandgap)
lage Z, niet erg efficiënt voor $\gamma > 10$ keV
- regelbare geleiding over 10 ordes ($\times 10^{10}$)
- oppervlakte-oxide heeft een hoge impedantie/isolatie

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

Mendeleev <1900

Periodic Table of Elements

ELEMENT 4-waardig

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

Samengesteld

Bijv.:
Hgl₂
(AgCl)
etc.

* Lanthanide Series

58	59	60	61	62	63	64	65	66	67	68	69	70	71
Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu

+ Actinide Series

90	91	92	93	94	95	96	97	98	99	100	101	102	103
Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

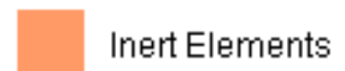
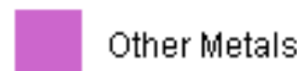
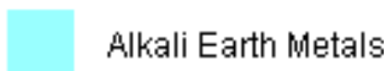
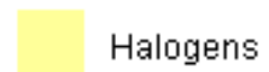
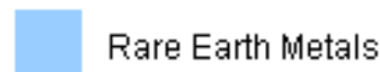
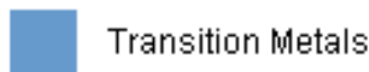
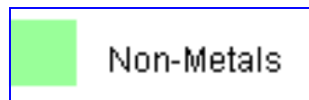
Legend - click to find out more...

H - gas

Li - solid

Br - liquid

Tc - synthetic



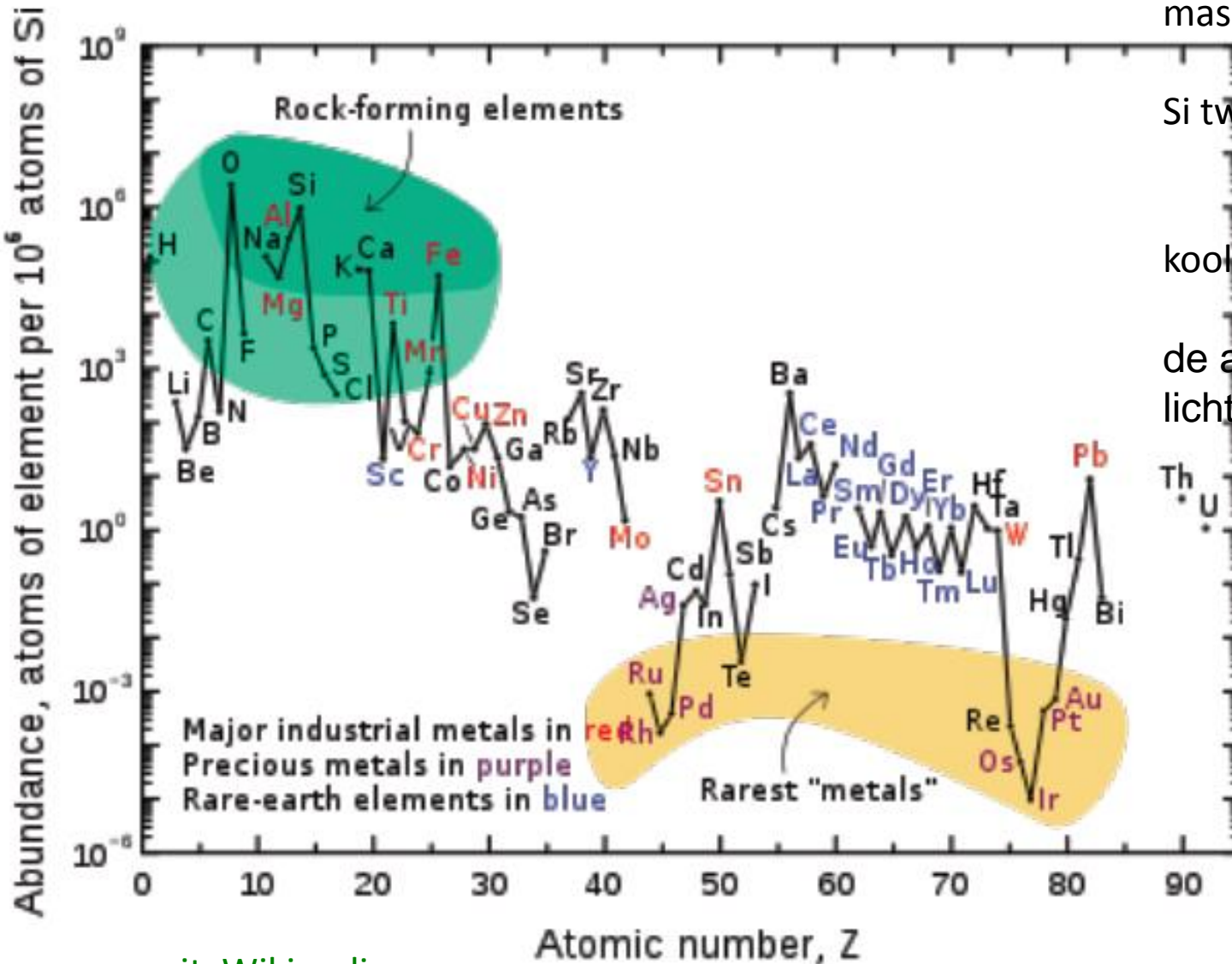
welke elementen in de aardkorst

massa voorkomen:

Si tweede 28%
na zuurstof 46%

koolstof slechts ~ 0.08%

de aarde verliest steeds
lichte elementen
vooral waterstofgas
en helium



uit Wikipedia





STONE AGE



BRONZE AGE



IRON AGE



SILICON AGE

Isolatoren: alle electronen gebonden

→ keramische materialen, glas, ...

Geleiders: vol vrije electronen

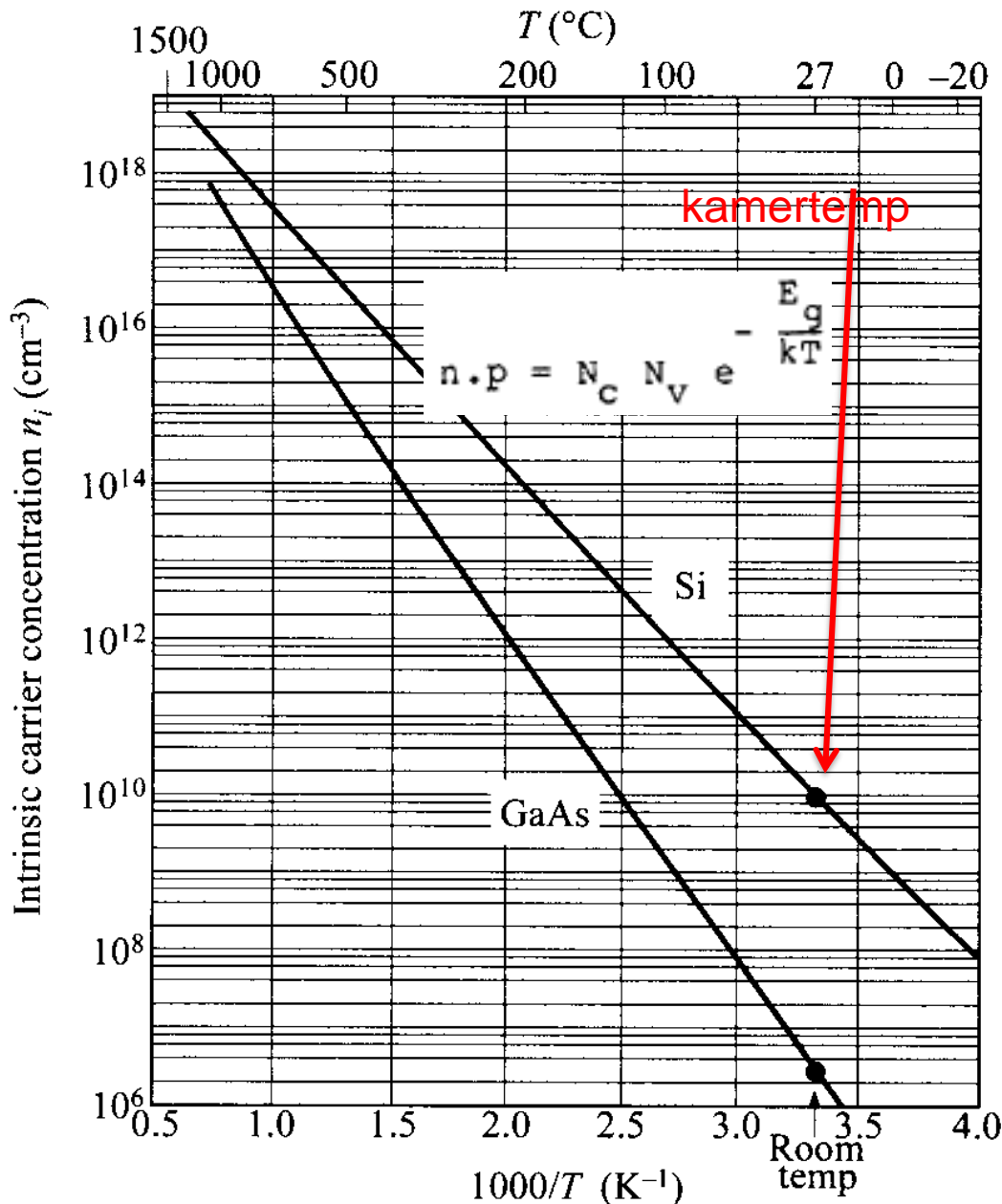
→ metalen: koper, aluminium, ijzer, ...

Halfgeleiders:

minder of meer electronen **n** en 'gaten' **p**

→ silicium, germanium, gallium-arsenide, ...

concentratie van ladingdragers n_i varieert



$$n_i^2 = n \cdot p = \text{konstant}$$

n elektronen

p gaten

hangt af van

bandgap en temperatuur

bij kamertemp

$$\text{Si } n_i^2 = 2.6 \times 10^{20} \text{ cm}^{-3}$$

6-8 ordes v grootte

bij $n = 10^{13} \text{ cm}^{-3}$

gaten slechts

$$p = 10^7 \text{ cm}^{-3}$$

$$\text{GaAs } n_i^2 = 1.2 \times 10^{14} \text{ cm}^{-3}$$

volgens Sze

Physics of semiconductor devices

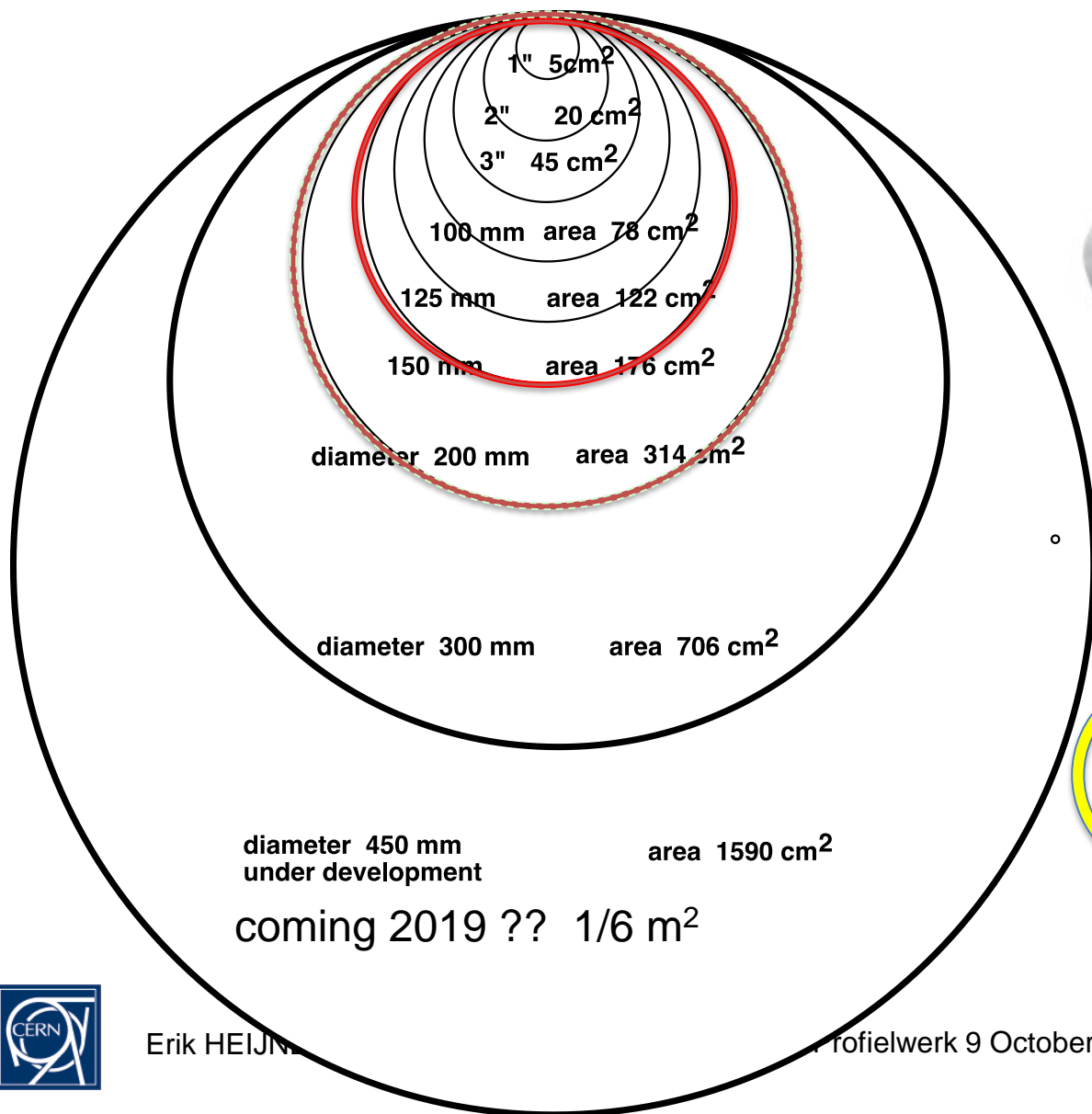
Wiley

groeien van silicium ééncrystal → Si plakken

Increase of wafer diameter 3/4" - 450mm

1955-2015

Wafer sizes



Single Crystal Silicon Ingot



CZ Crystal Pullers
(Mitsubishi Materials Silicon)



Elektronica: spelen met elektronen

vanaf ~1900 in vaküüm buizen

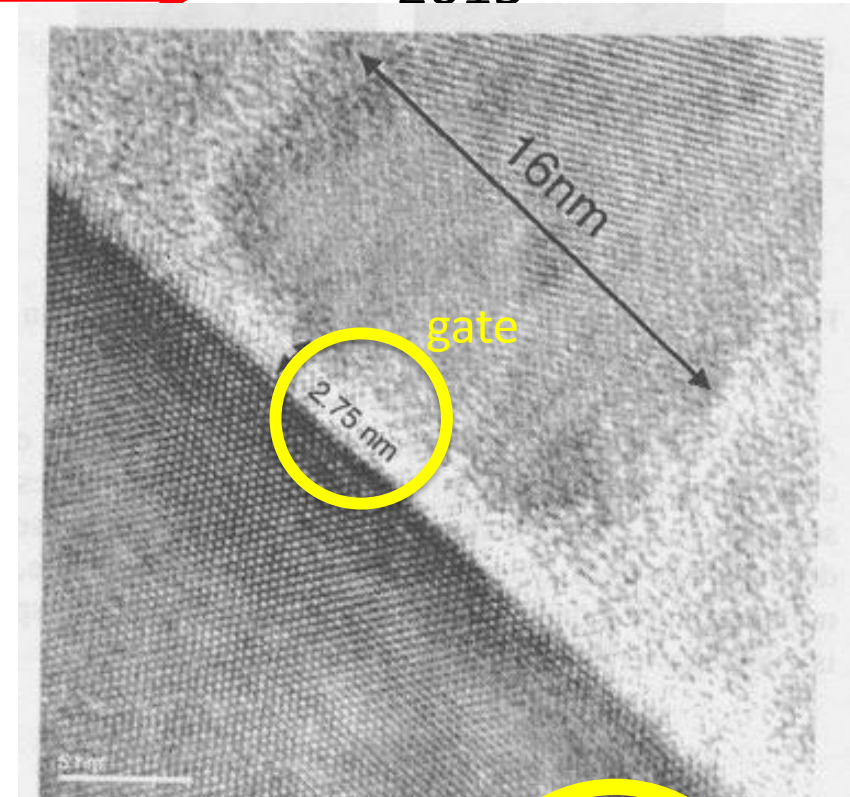
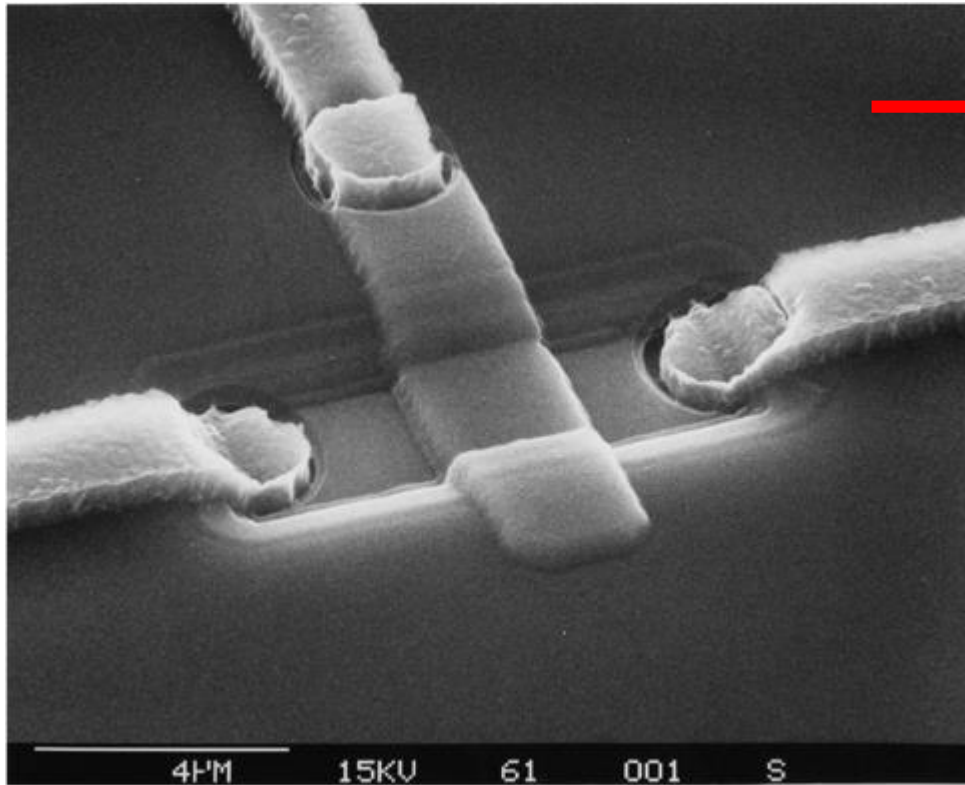
in 1948 halfgeleider transistor

eerst germanium, later silicium...

Integrated electronics is key: silicon MOS transistor

continuous scaling/miniaturization

2015



2 μm TECHNOLOGY

1985

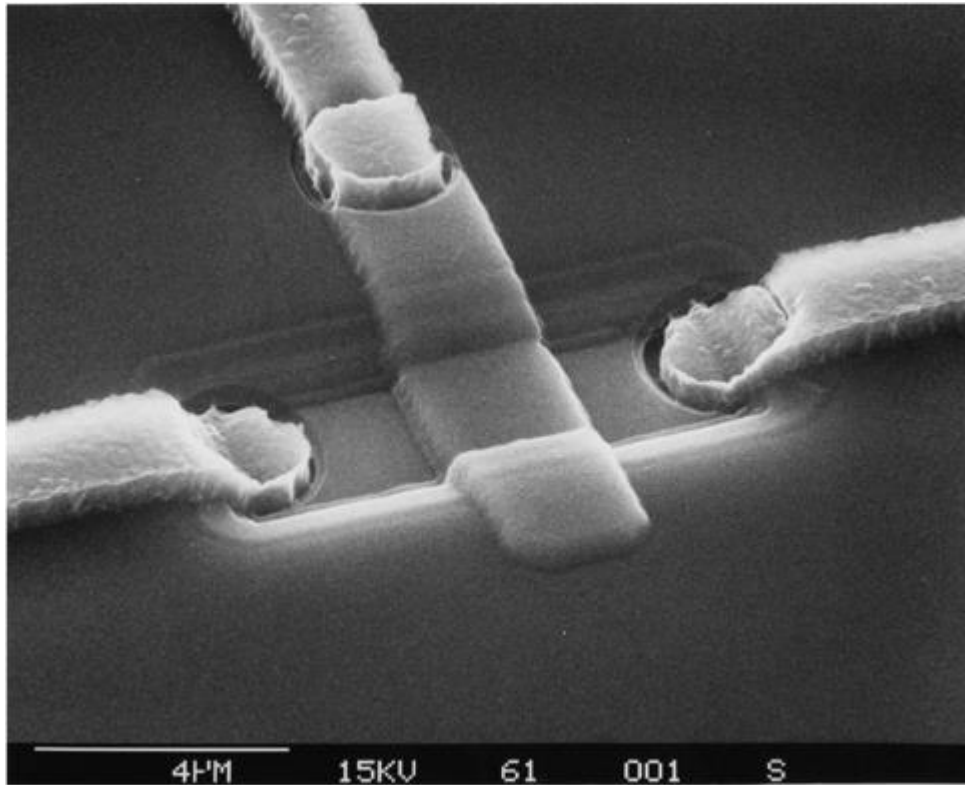
HEP was 2 generations behind industry

gate length .016 μm

SiO₂ gate thickness 2.75 nm



SILICON MOS TRANSISTOR



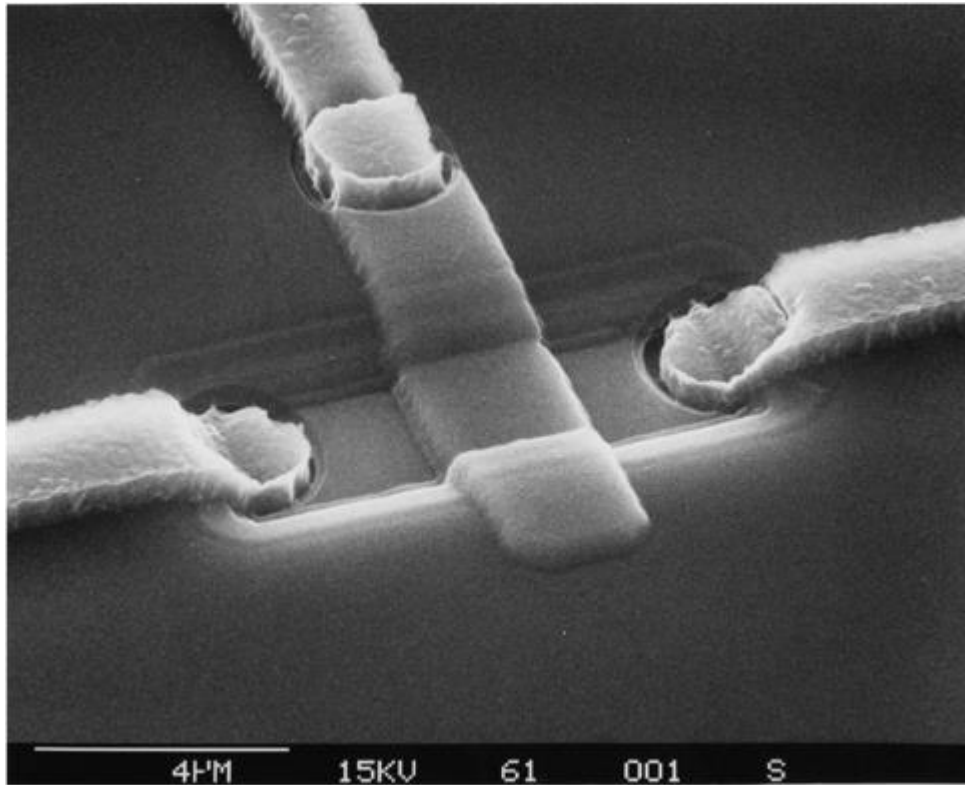
CORRECT SCALE



SiO₂ gate 2.75 nm

2 µm TECHNOLOGY 1982 0.016 µm 2007

Integrated electronics is key: silicon MOS transistor



2 μm TECHNOLOGY

1985

HEP was 2 generations behind industry

continuous scaling/miniaturization

2015



same scale

gate length .016 μm

SiO₂ gate thickness 2.75 nm

thin gate usually radhard



2017 development at IBM



gate-all-around
source IBM

not same scale

0.005 μm

2017

now HEP is 8 generations behind



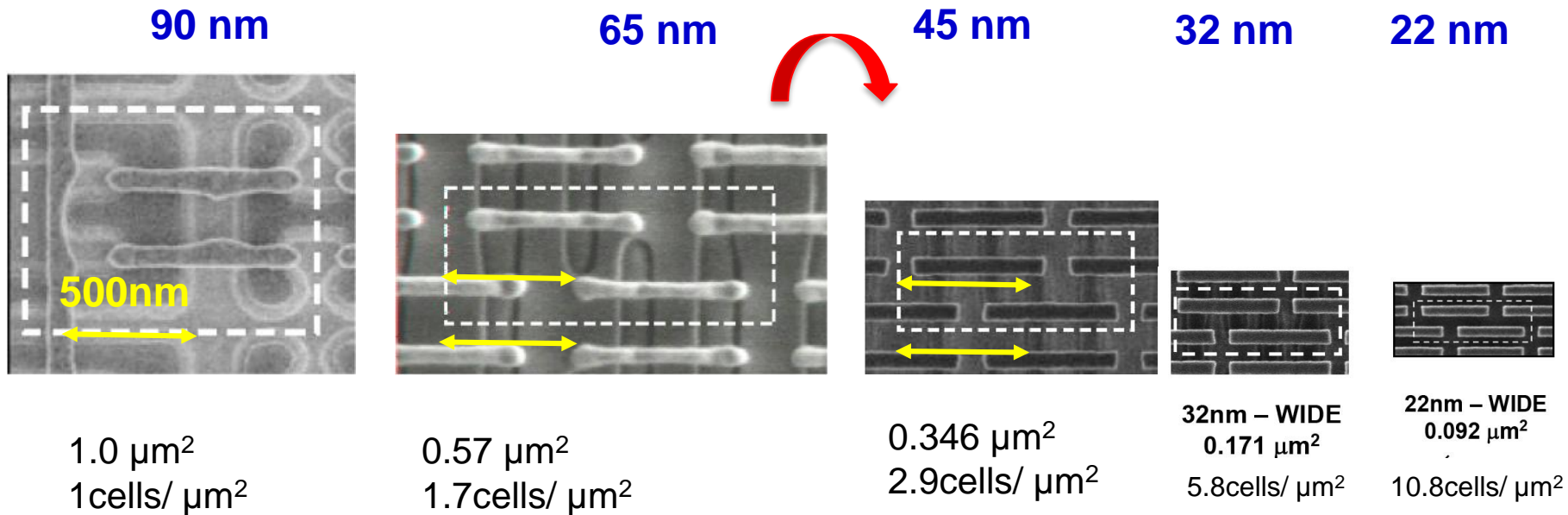
Ever more advanced (smaller) nm CMOS

INTEL : large improvement in lithography ≤ 45 nm

example: minimal SRAM cell

~ TO SCALE

Several characteristics also have been improved, well beyond expectations



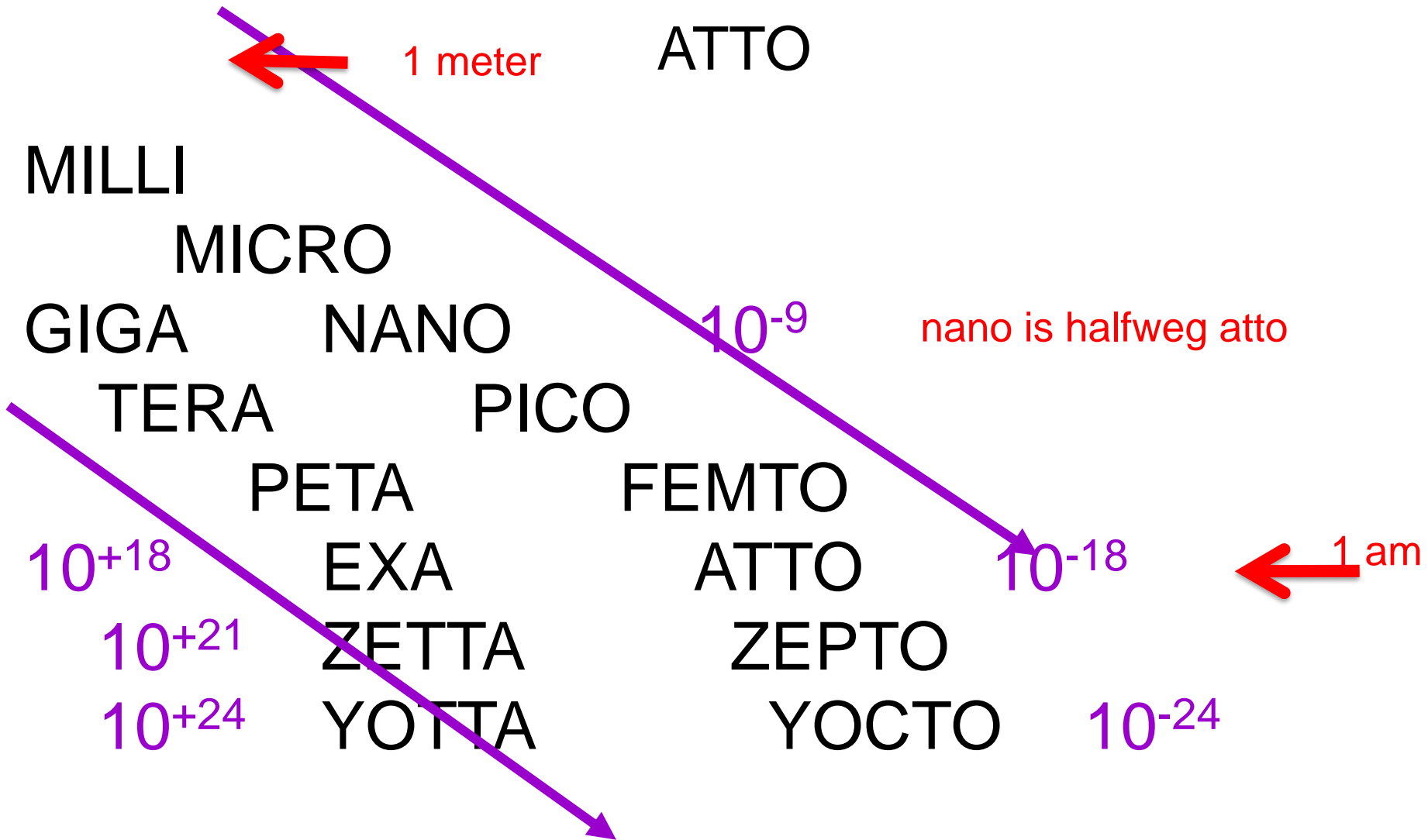
linear scale 4x smaller; area 10.8 x smaller

Mrs Kelin KUHN
IEEE IEDM 2007 & 2010



Groter en Kleiner wat is atto?





Kun je elementaire deeltjes zien?

het deeltje zelf niet, maar wel het spoor
omdat energie wordt afgegeven in materie

moet wel een handig materiaal kiezen als detector

gas: Geiger-Müller, nevelkamer, dradenkamer, ..

vloeistof: bellenvat, argon-ionisatiekamer, ..

vaste stof: film, scintillator, halfgeleider, ..

signaal: zwarting, belletjes, licht, elektrische puls



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signaal: zwarting, belletjes, licht, elektrische puls



gelijkrichtende diode is
eenvoudigste component in Si

kan licht en ioniserende deeltjes waarnemen

signaal van elektronen en gaten



gelijkrichtende diode is
eenvoudigste component in Si

kan licht en ioniserende deeltjes waarnemen

zonnecel is meestal een Si diode (lekstroom groter bij hitte !!!)

signaal van elektronen en gaten

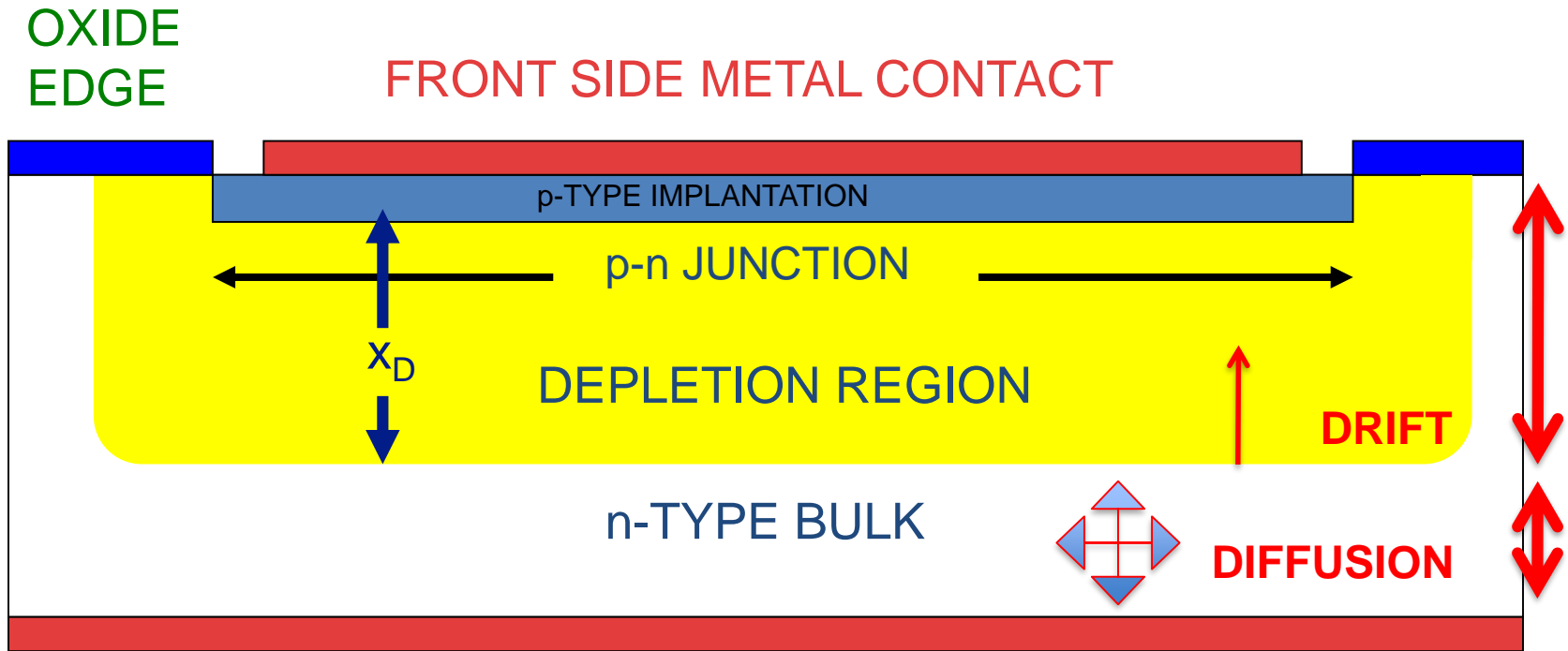


Een halfgeleider-volume/diode als detektor

Een ioniserend deeltje verliest energie, die maakt elektronen 'e' / gaten 'h' los
zodat er een signaal kan worden geïnduceerd op elektrodes aan de buitenkant van de diode



SCHEMATIC of DIODE



REAR SIDE METAL CONTACT

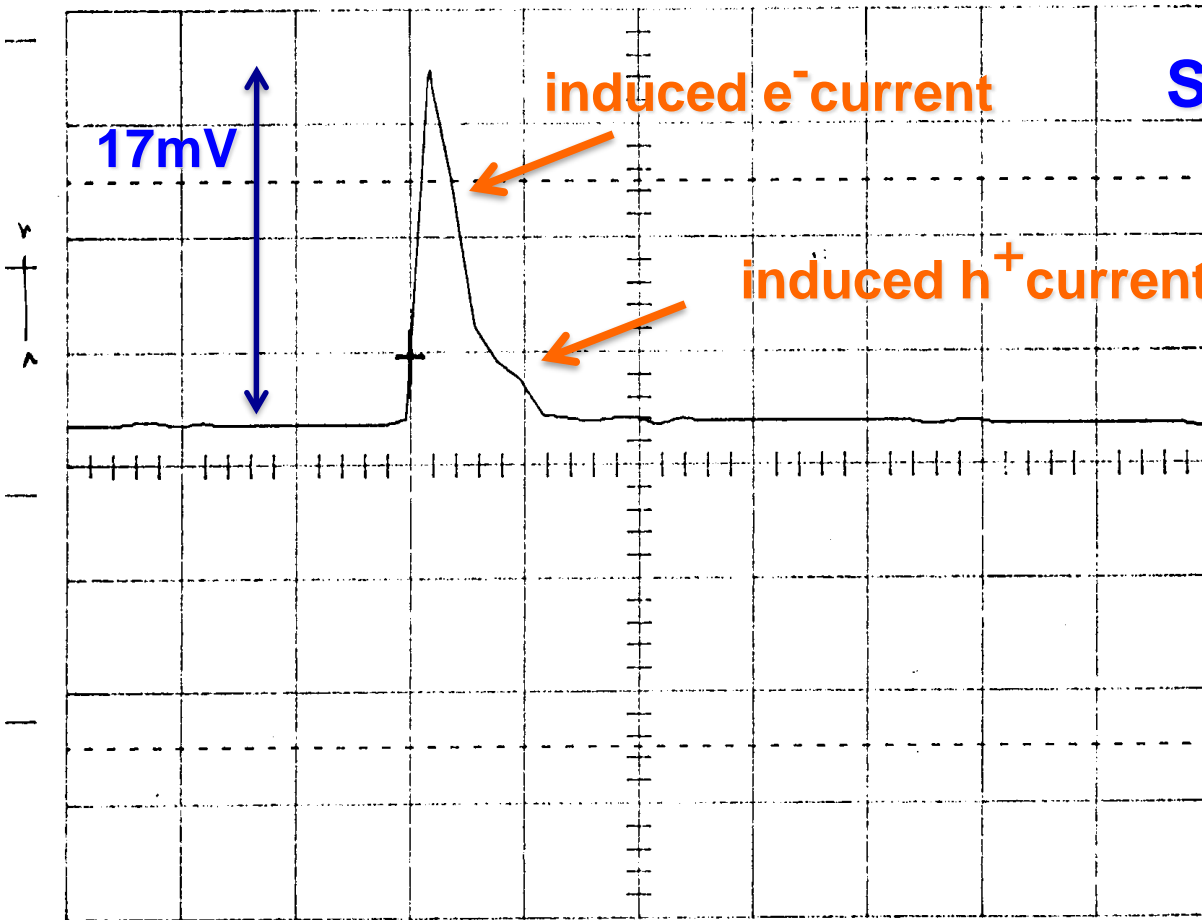
$$x_D = \sqrt{\frac{2 \epsilon}{q n} (V_0 + V_B)} = \sqrt{2 \epsilon \mu_e \rho (V_0 + V_B)}$$

x_D CAN BE LARGE, BECAUSE HIGH RESISTIVITY of BULK Si

Si SIGNAL SPEED

SIGNAL CURRENT from Pb ION in 200 μ m Si
DETECTOR

SCOPE on 50 Δ ONLY



FAST RISE TIME

limited by RC time

$$50 \Delta \times 100\text{pF} = 5 \times 10^{-9}\text{s}$$

Channel 1
3.22 mV

Ch 1 5 mV 50
Ch 2 .5 V 50

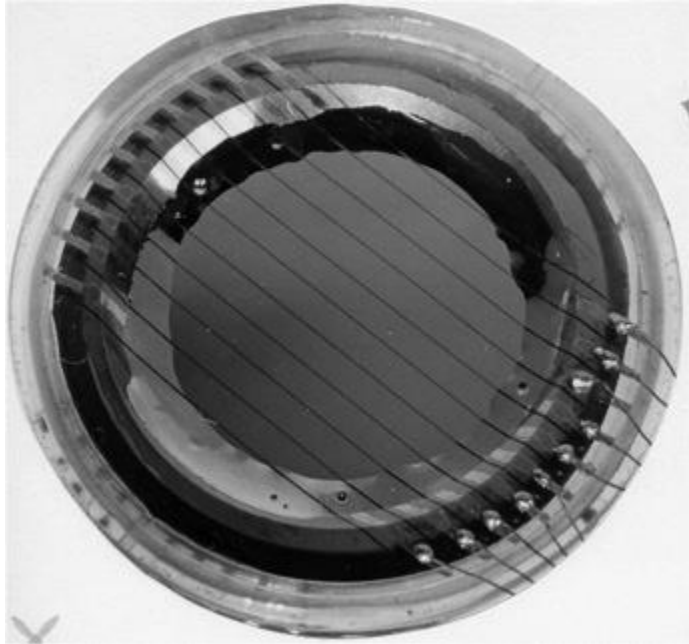
T/div 50 ns
Trig 1.28 div + CHAN. 1 =

diode-oppervlak kan worden gesegmenteerd

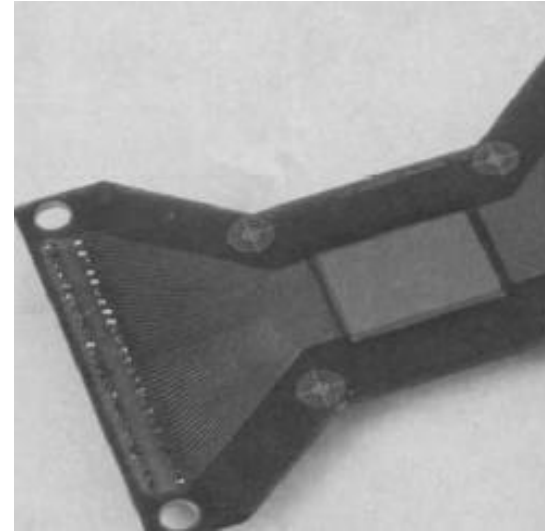
allerlei patronen mogelijk:
microstrips
pixels



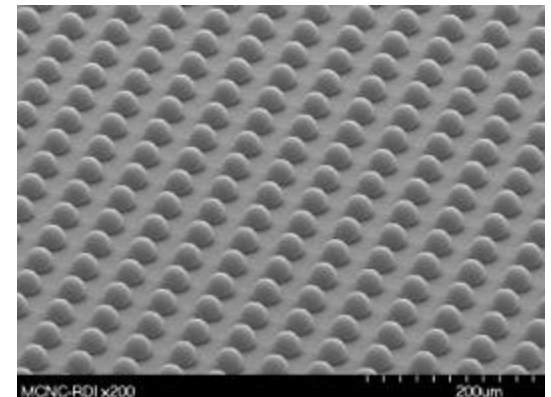
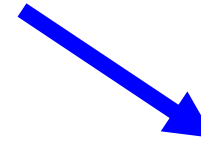
DIODE SEGMENTATION



~1965
PHILIPS – Amsterdam -IKO
100 x 1370umx1370um



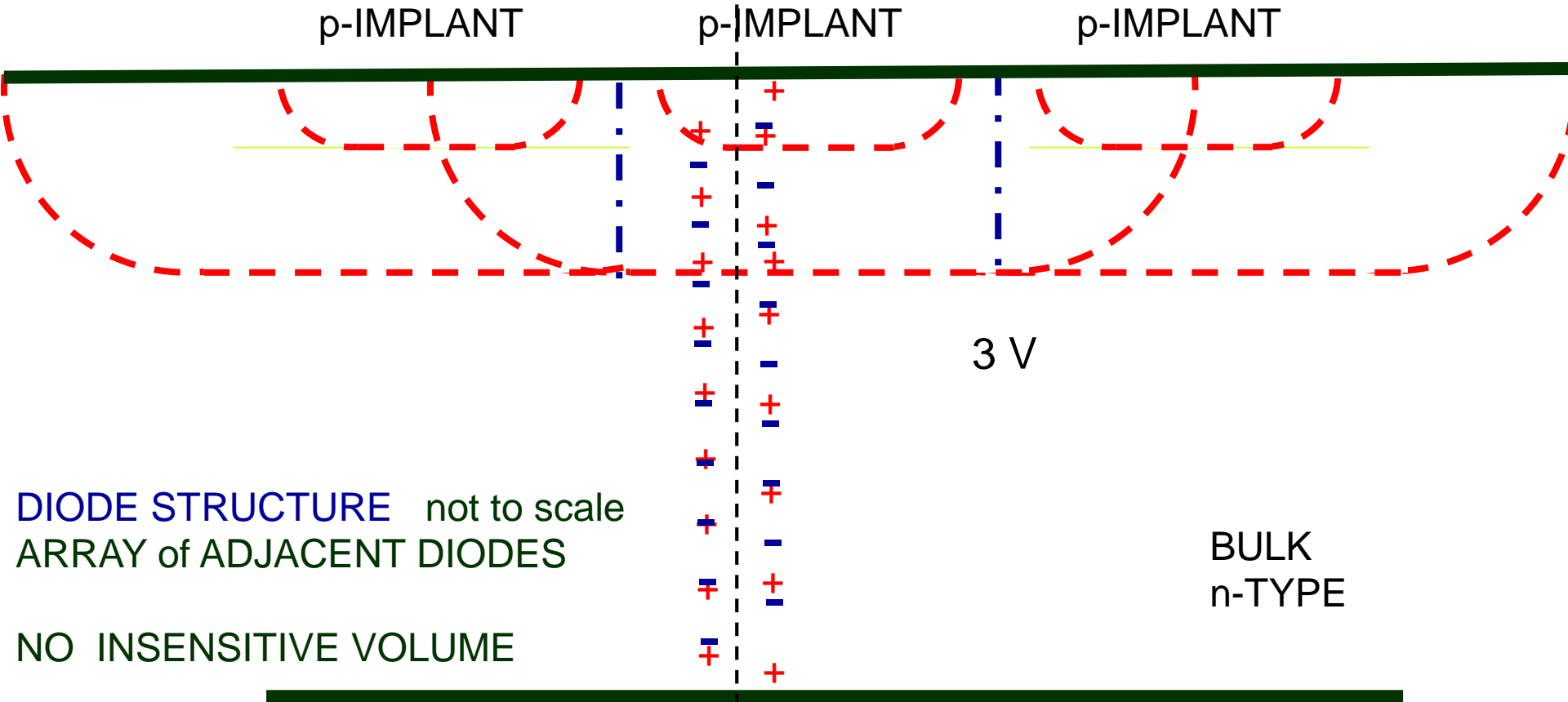
1980
CERN / ENERTEC
100 x 4000umx200um



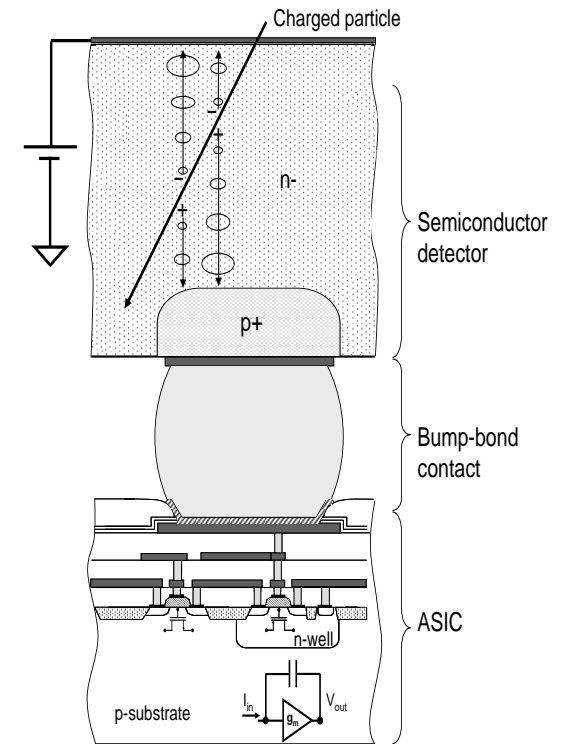
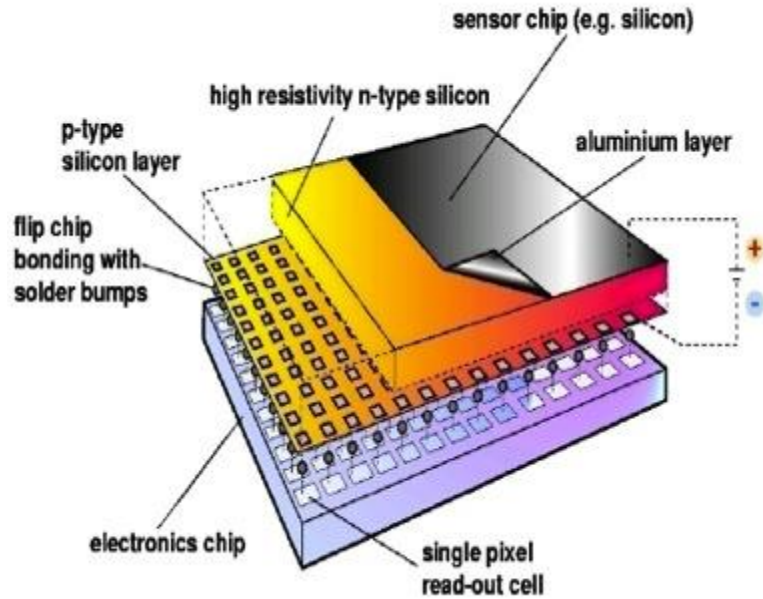
~2000
CERN / MEDIPIX
65000 x 55umx55um

SILICON DIODE DETECTORS

IONIZING PARTICLE
LOCALIZED SIGNAL



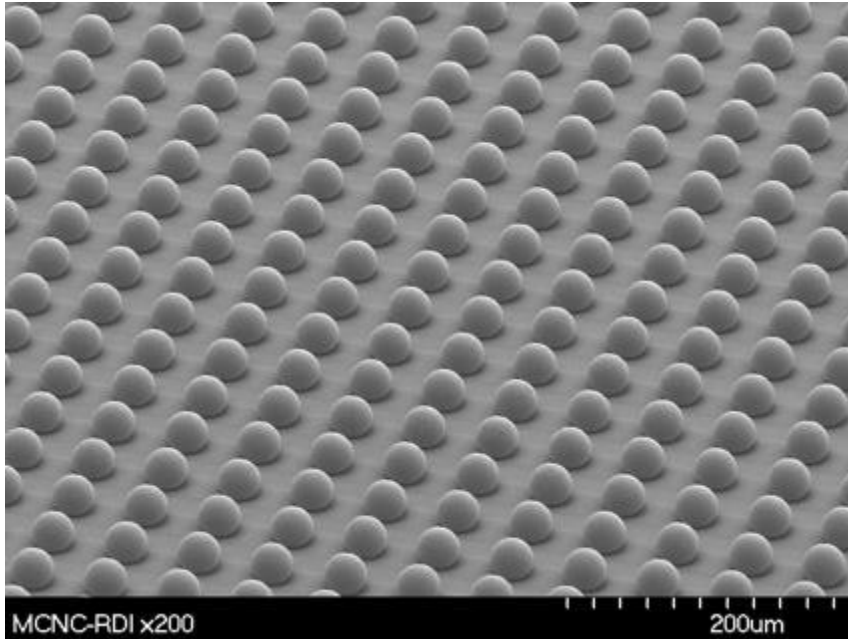
Hybrid Silicon Pixel Detectors



Standard CMOS can be used allowing on-pixel signal processing

Sensor material can be changed (Si, GaAs, CdTe..)

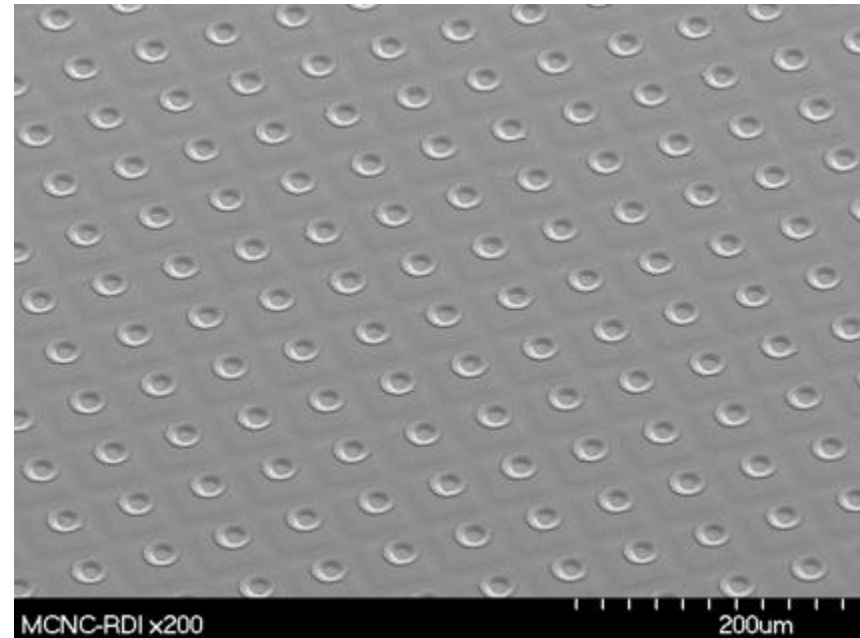
Hybride pixel detector Medipix2



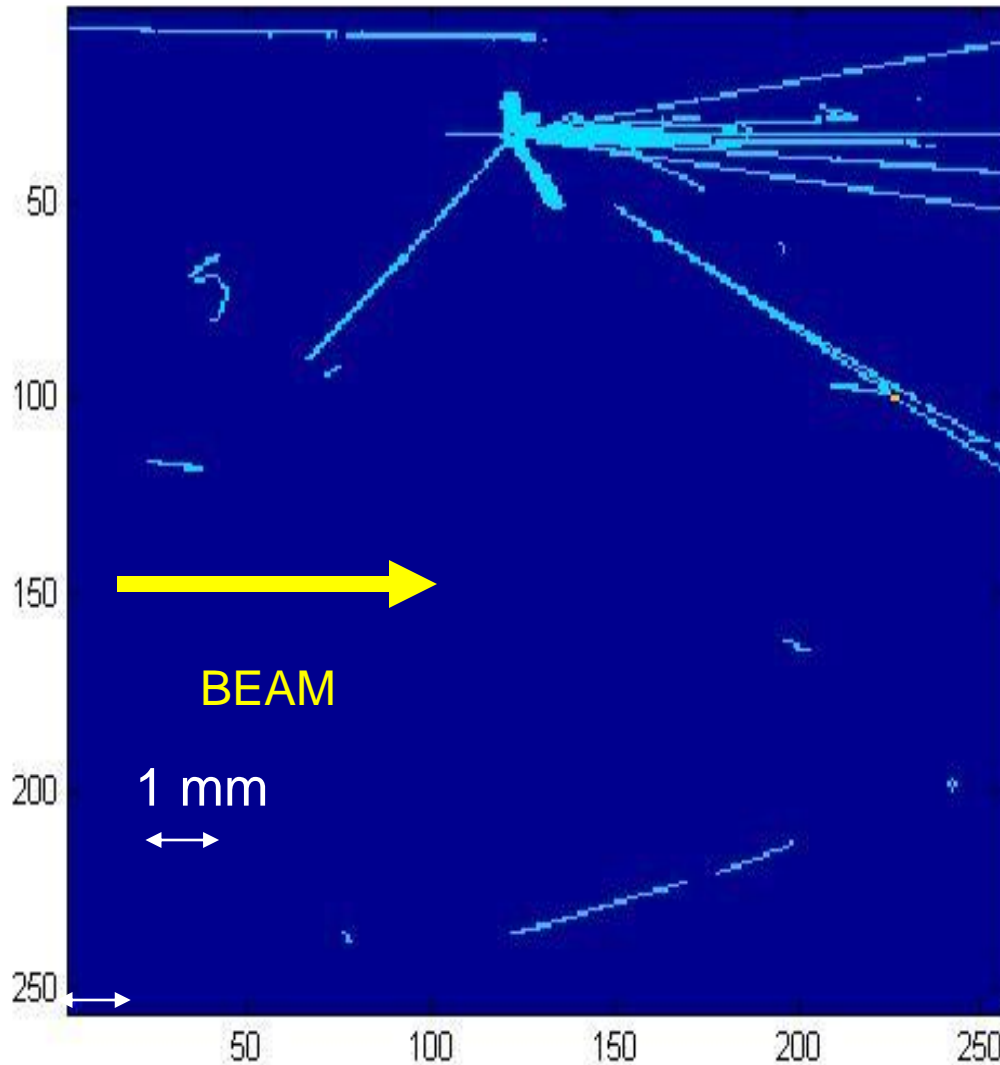
SEM fotos gemaakt door
MCNC-RDI, DURHAM NC - USA

PITCH 55 μm

MEDIPIX2 CERN 2001
CAMPBELL & LLOPART
256 kolommen x 256 rijen
pixel 55 μm x 55 μm



120 GeV PIONS in Si IMAGER : MEDIPIX



INTERACTION in
Medipix DETECTOR
Si 'BUBBLE CHAMBER'

DECAY of K_0 ?

July 2006 Parallel Medipix P-05-0583



T3-1500

TYPICAL TRAILS ...

T3-1504

T3-1507

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

H6 PION BEAM 2007

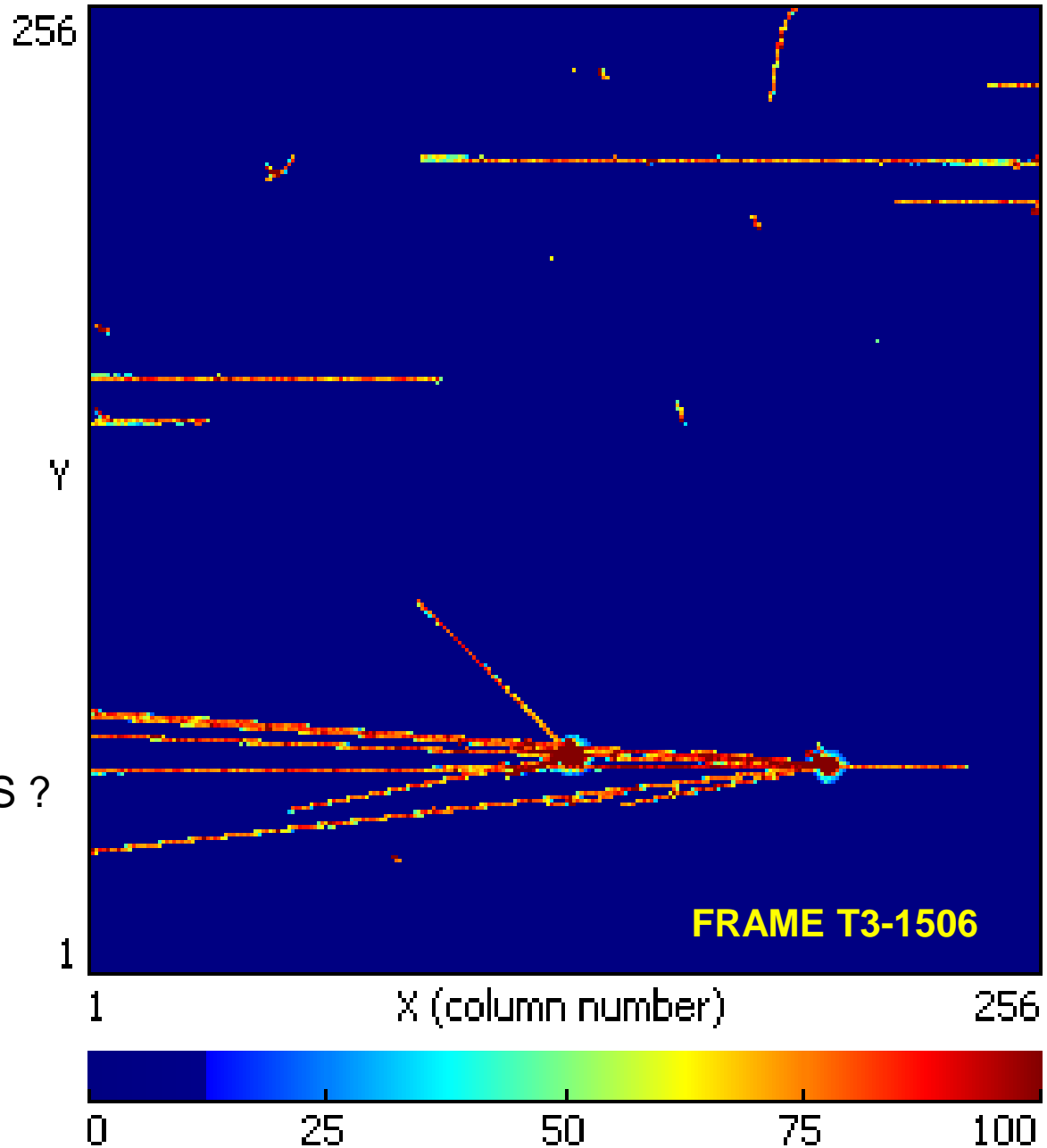
INCIDENT from RIGHT

BEAM



WHICH DIRECTION of TRAILS ?

with John Idarraga / Montréal
now



Een halfgeleider-volume/diode als detektor

Een ioniserend deeltje verliest energie, die maakt elektronen 'e' / gaten 'h' los
zodat er een signaal kan worden geïnduceerd op elektrodes aan de buitenkant van de diode

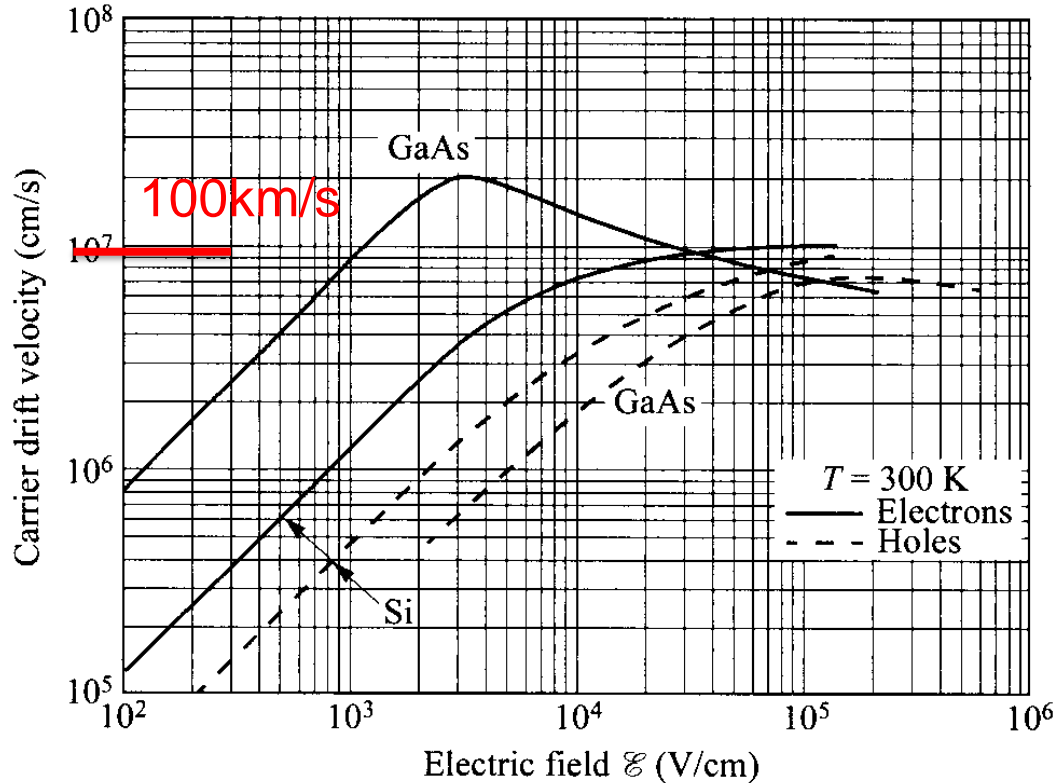
Dankzij een aangelegd elektrisch veld vliegen vrijgemaakte ladingen met hoge snelheid

zie volgende snelheids grafiek voor e en h

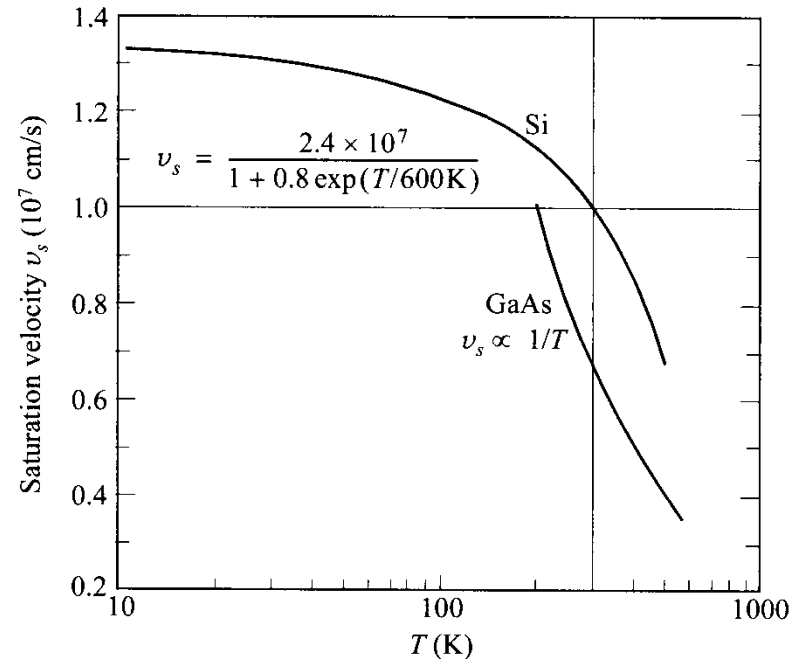


CARRIER TRANSPORT in Si and GaAs

CARRIER DRIFT VELOCITY vs FIELD



SATURATION vs TEMP

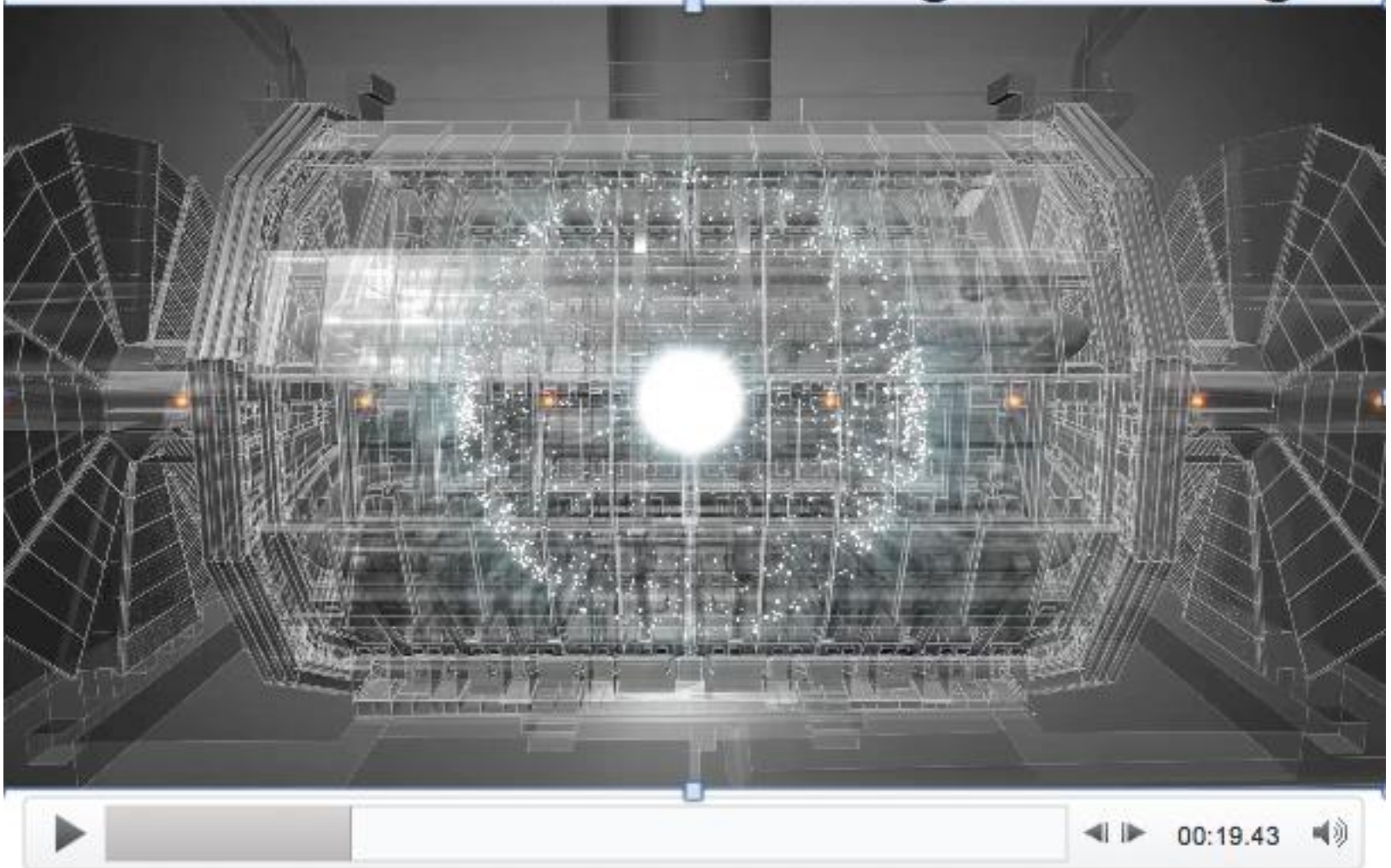


MOBILITY is a function of doping, temp, field..

SEMICONDUCTOR DETECTORS ARE **INHERENTLY FAST** : 5 - 20 ns

360 000 km/h

Animatie van Bunch Crossings en Timing



Animatie van Bunch Crossings en Timing



Hoe moet je je de 'Big Bang' voorstellen?

het is ondenkbaar, alle energie in het heelal was opgekropt in één punt

dan is opeens het transformeren begonnen
na 10^{-xx} seconde begon massa te ontstaan

sindsdien is alles aan het uitzetten en afkoelen
en wordt nog steeds energie omgezet in massa

Bedenk dat materie, zoals wij die voelen, praktisch leeg is
Alleen lichte elektronen geven grootte aan atomen ($\sim 0.1\text{nm}$)

de kernen ($\sim\text{fm}$) met massa zijn maar 0.0000000000000001 % van het volume

Silicium is nu overal in de LHC detektors

Speciale Chips (ASICs) voor alle sub-systemen

Si sensors in de binnenste schillen:

 Pixels (2D) en Microstrip (1D) in meerdere lagen

 Groot aantal sensor elementen: veel chips

Teams ontwerpen onze ASICs zelf, niet in industrie

Ondanks 'kleine' aantallen, toch essentieel:

 volume, compacte functies, lokaal geheugen

Simulaties moeten zorgen dat chip meteen goed is

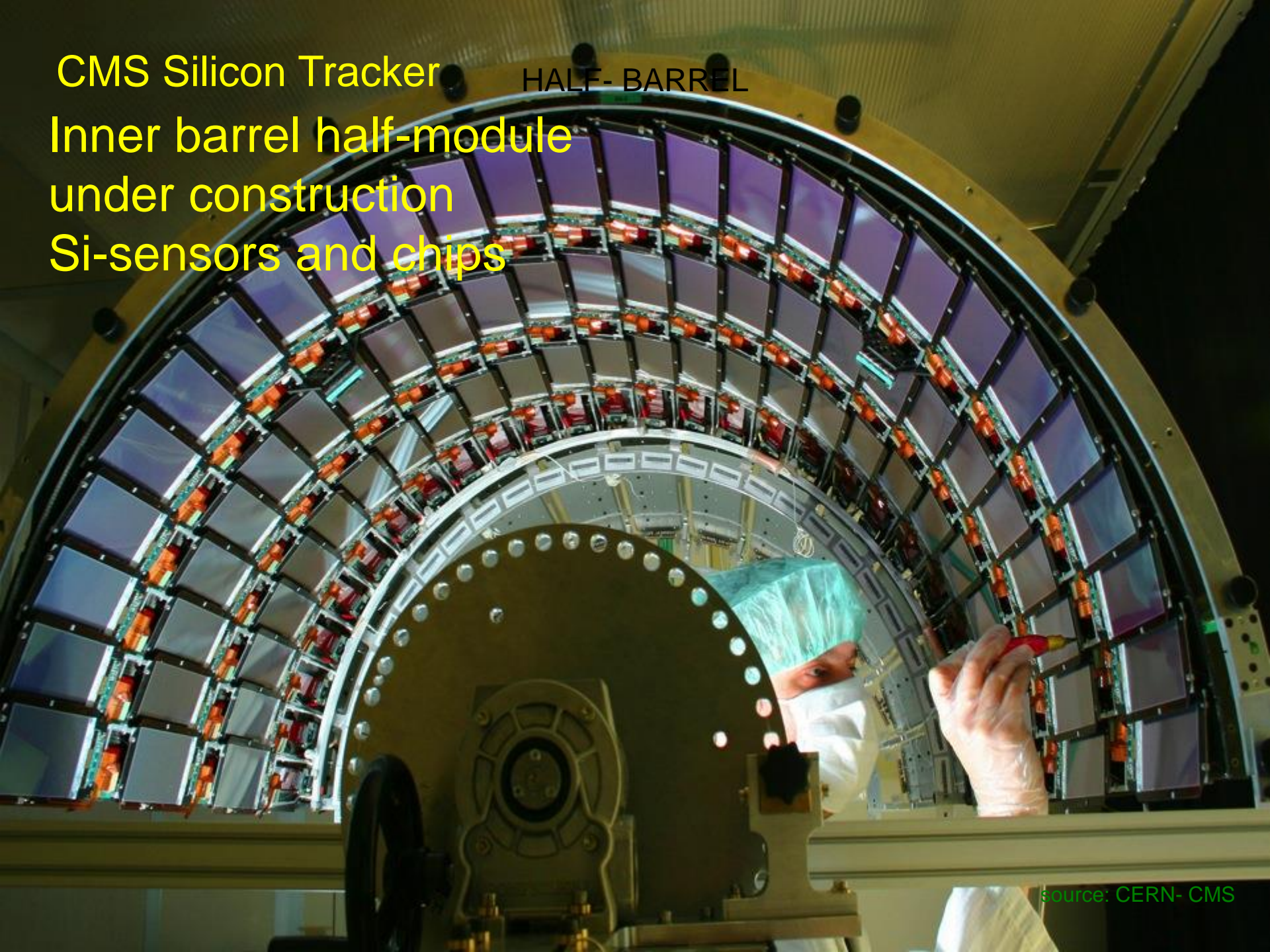
ATLAS binnenste Si pixel lagen



CMS Silicon Tracker

HALF-BARREL

Inner barrel half-module
under construction
Si-sensors and chips



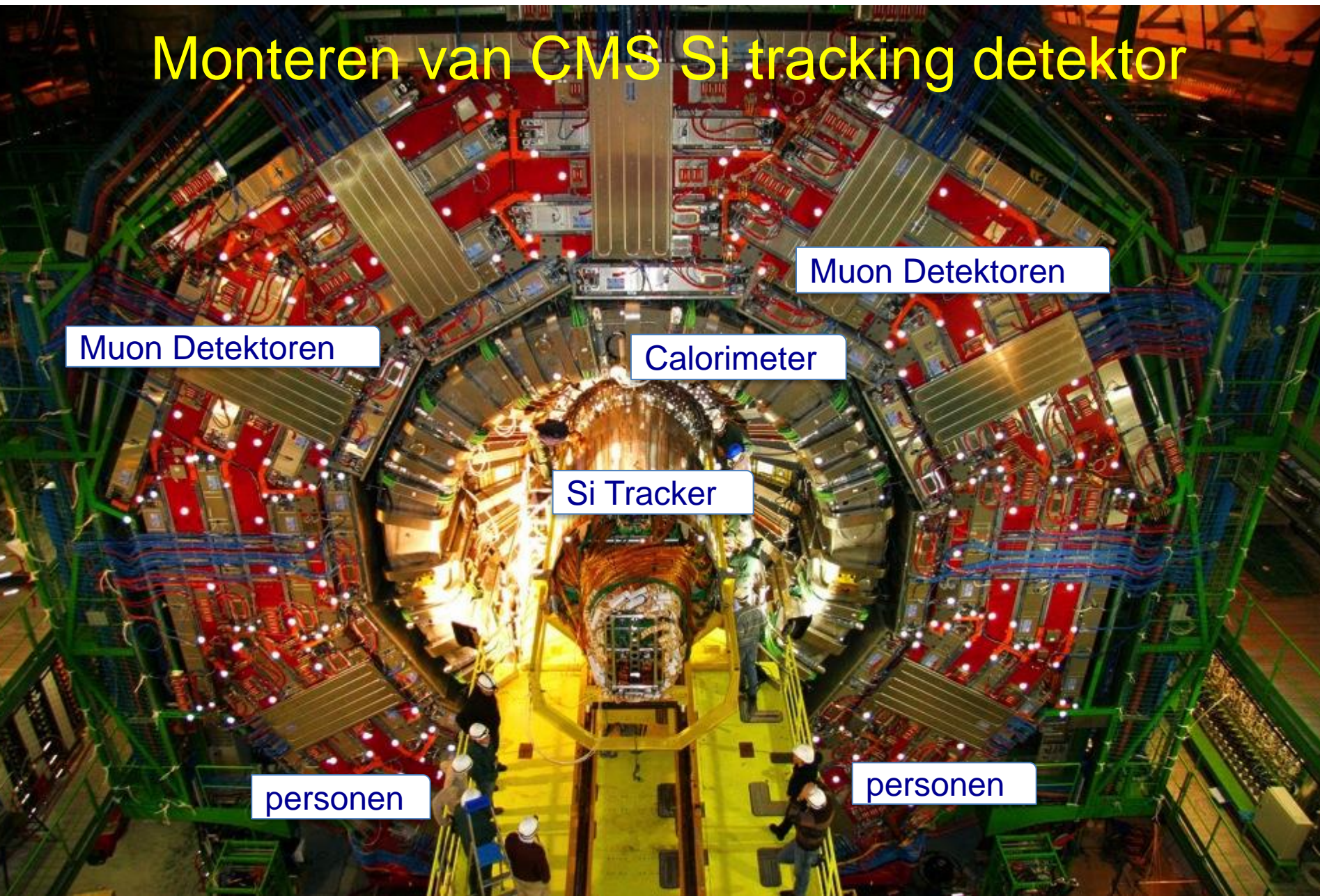
CMS Silicon Tracker
Forward wheel
Si-sensors and chips

Barrel

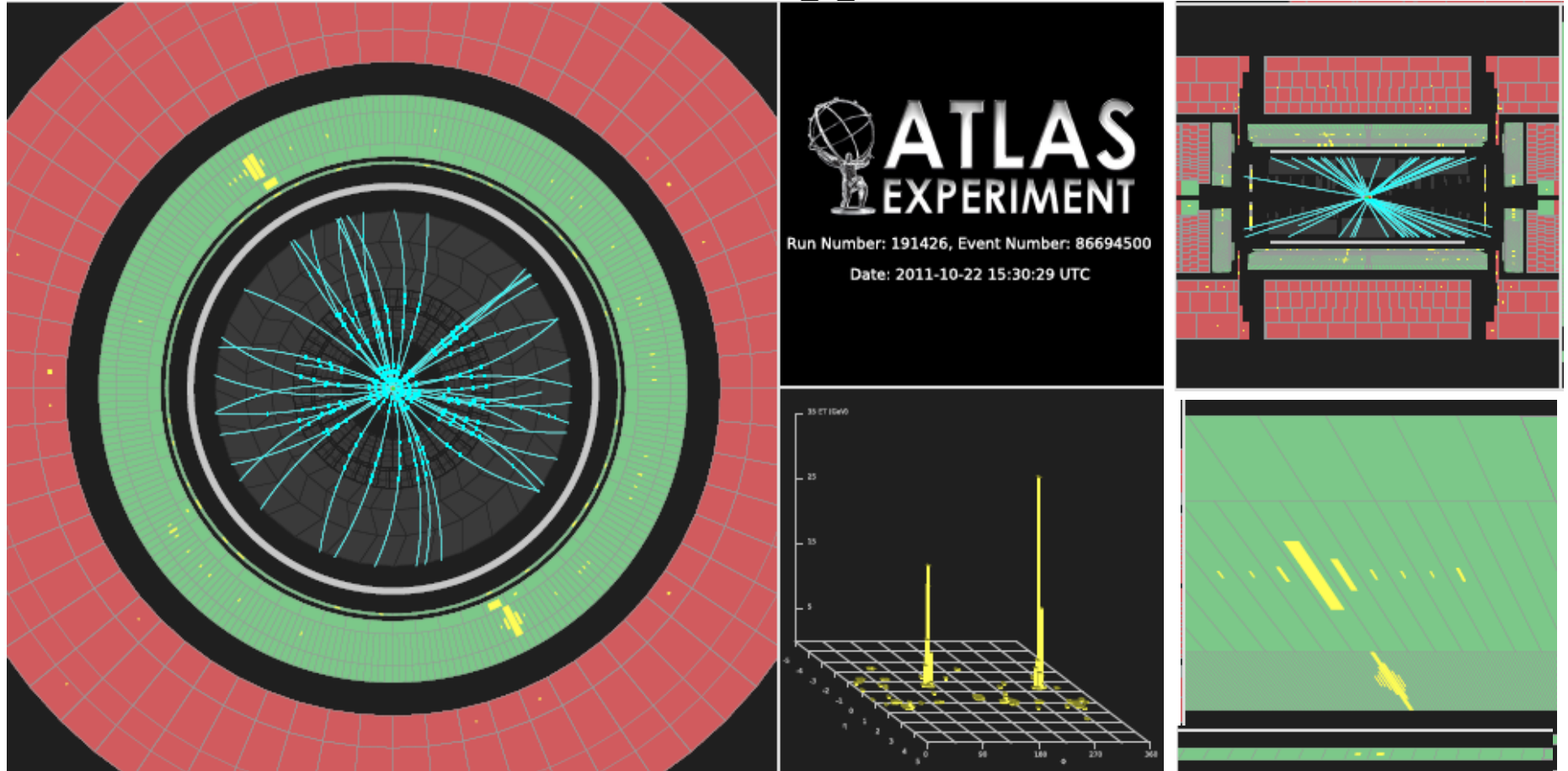
source: CERN- CMS



Monteren van CMS Si tracking detector

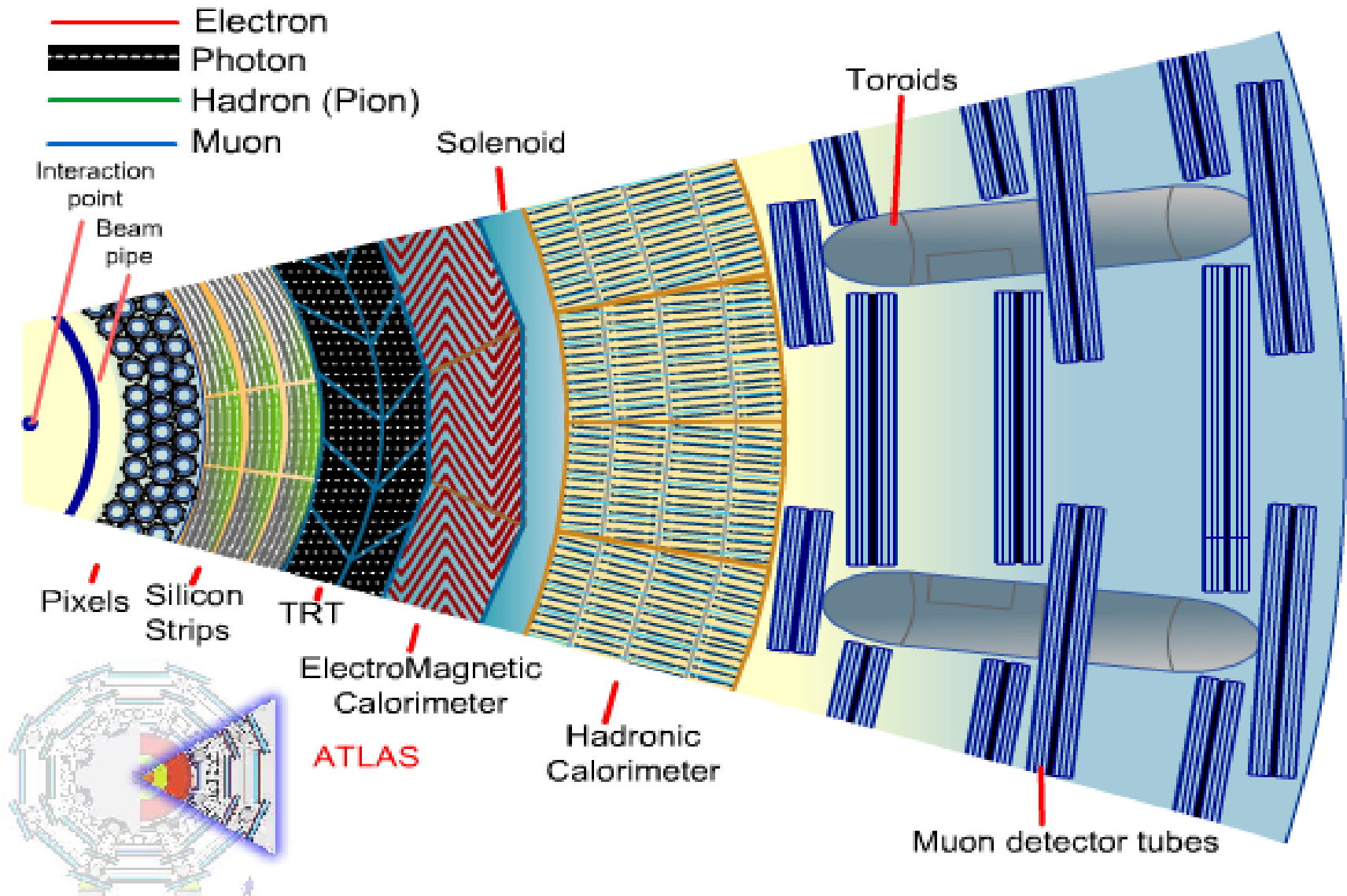


Atlas event Higgs --> twee-fotons

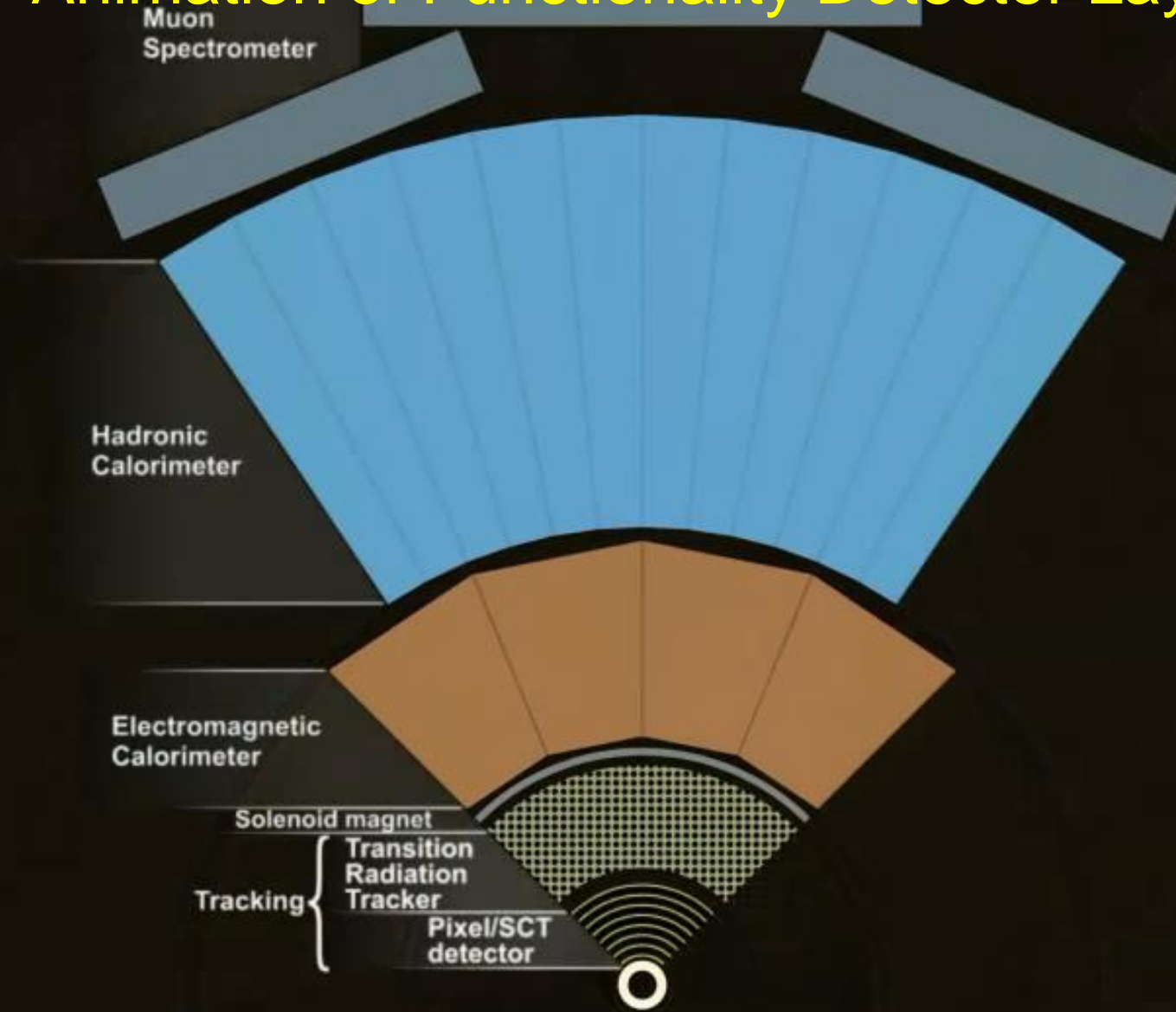


Event display of a candidate diphoton event where both photon candidates are unconverted. The event number is 86694500, recorded in run 191426. The leading photon has $ET=64.2$ GeV and $h=-0.34$. The subleading photon has $ET=61.4$ GeV and $h=-0.61$. Measured diphoton mass is 126.6 GeV. The p_T and p_{Tt} of the diphoton are 6.1 GeV and 5.4 GeV, respectively. Only reconstructed tracks with $p_T > 1$ GeV, hits in the pixel and SCT layers and TRT hits with a high threshold are shown.

Detector Bestaat uit Schillen : e.g. ATLAS

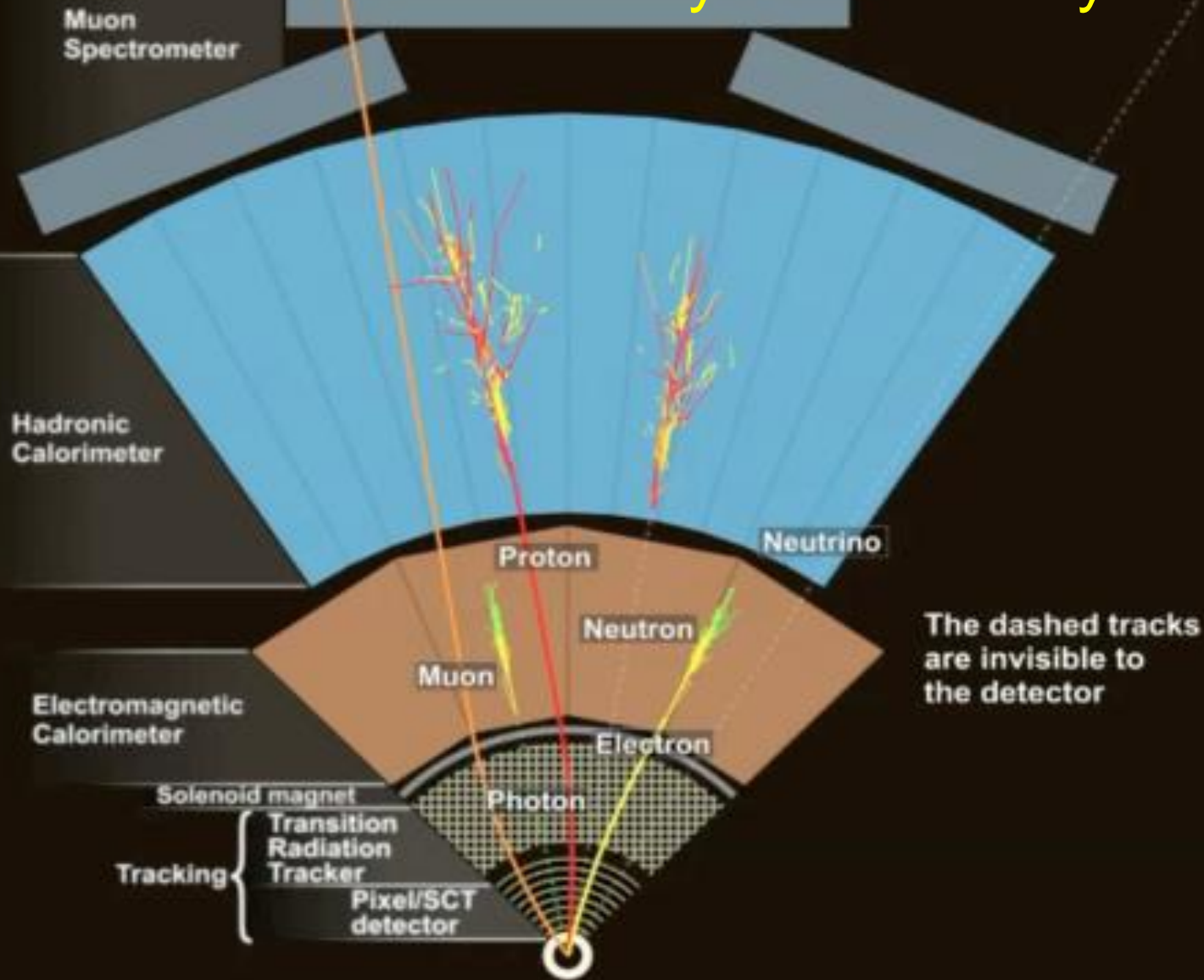


Animation of Functionality Detector Layers



source: CERN-ATLAS

Animation of Functionality Detector Layers



00:52.50



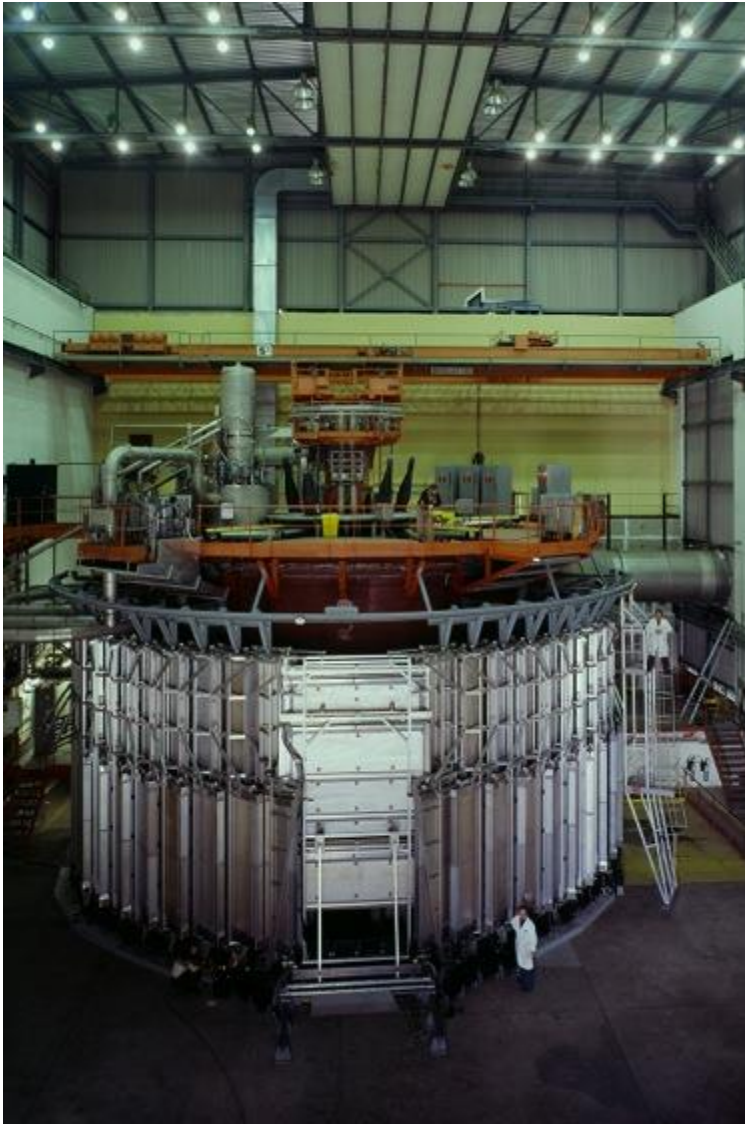
APRIL 2015

Hoe waren experimenten vroeger?

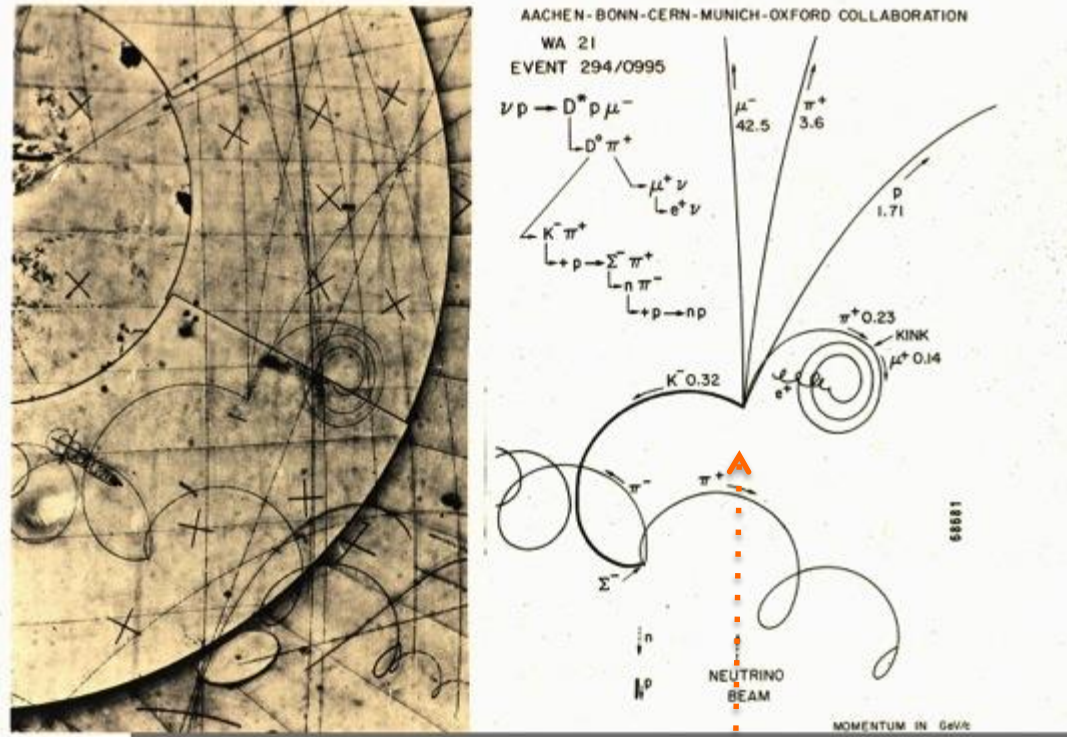
ik kwam in 1973 naar het CERN....



Big European Bubble Chamber BEBC



BEBC Bellenvat Neutrino Interactie



precisie van de banen ~ 1mm
hele volume is gevoelig --->

meten van impulsen

belangrijkste apparaat tot ~ 1985

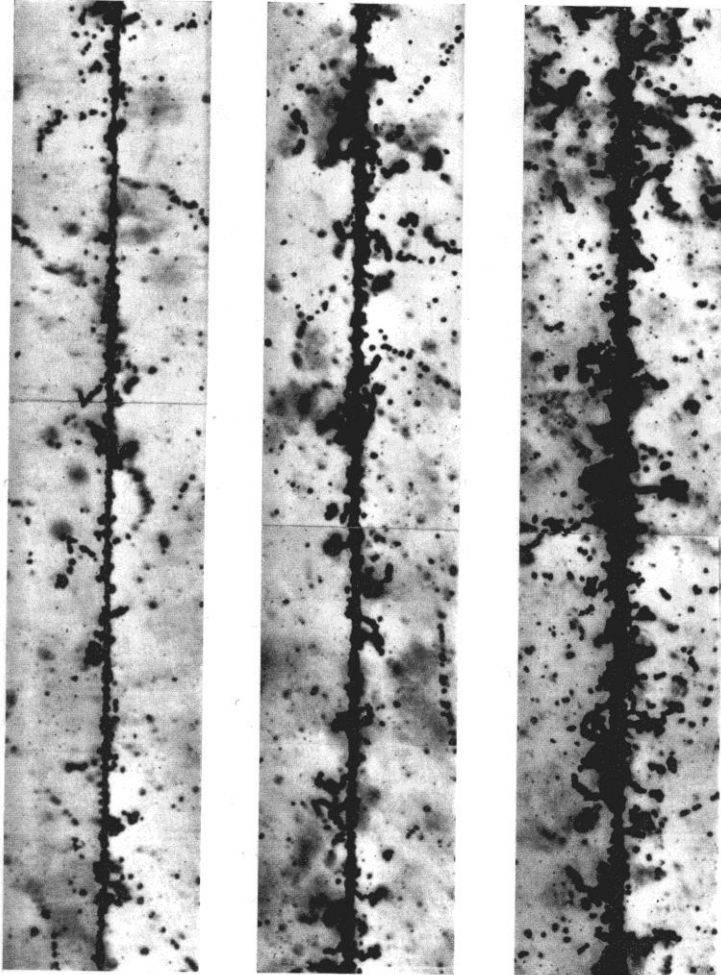
single quanta recorded in sensitive emulsion, since 1930's

ions in cosmic rays

dE/dx with δ -electrons

Powell, Fowler & Perkins- Pergamon 1959

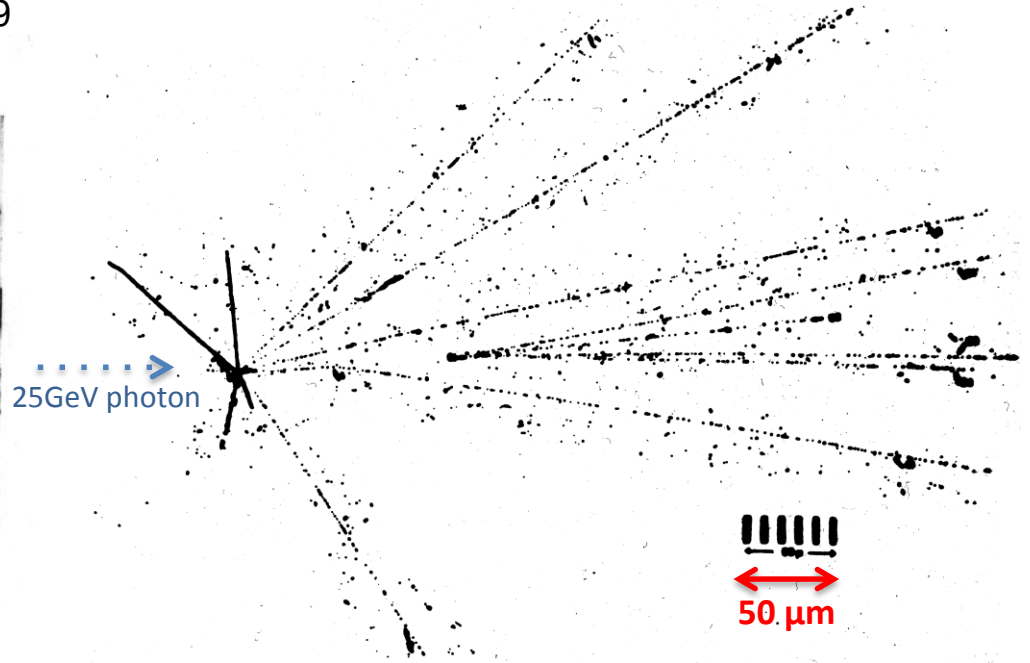
Tracks of heavy nuclei of the cosmic radiation moving at relativistic velocities
 $Z=12$ $Z=14$ $Z=20$



50 μm

PLATE 16-6

DAINTON, FOWLER and KENT (1952).



1980

charm decay in Omega experiment WA58

M.J. Adamovich et al., Observation of pairs of charmed particles produced by high-energy photons in nuclear emulsions coupled with a magnetic spectrometer, Phys.Lett. 99B (1981) 271-276

NNV Profielwerk 9 October 2019

single quanta recorded in sensitive emulsion, since 1930's

ions in cosmic rays

dE/dx with δ -electrons

Powell, Fowler & Perkins- Pergamon 1959

Tracks of heavy nuclei of the cosmic radiation moving at relativistic velocities
 $Z=12$ $Z=14$ $Z=20$

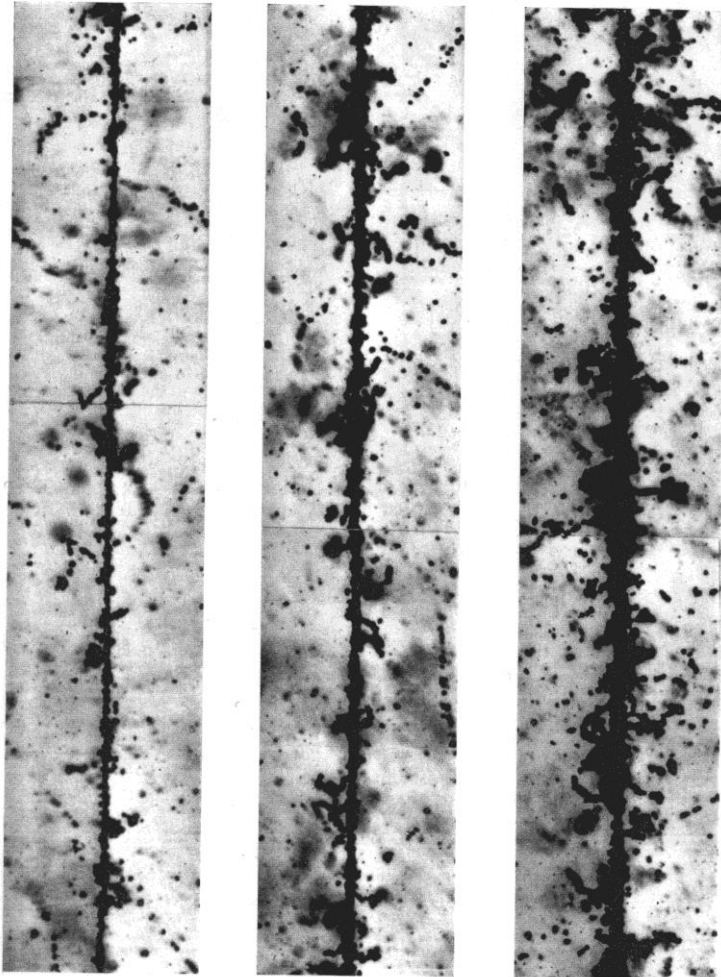
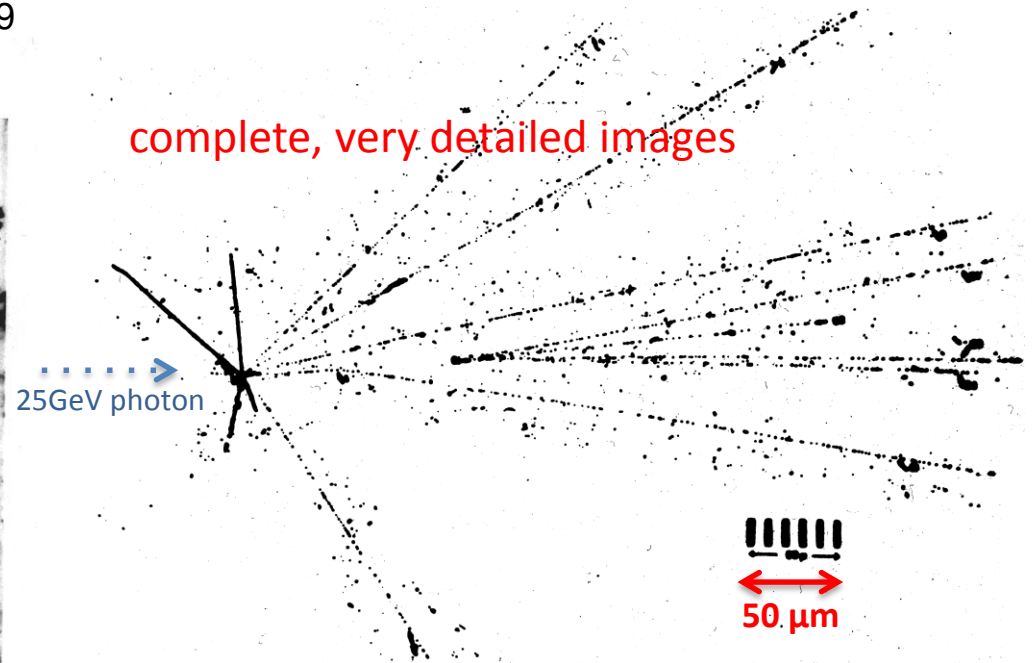


PLATE 16-6

DAINTON, FOWLER and KENT (1952).



complete, very detailed images

1980

charm decay in Omega experiment WA58

M.J. Adamovich et al., Observation of pairs of charmed particles produced by high-energy photons in nuclear emulsions coupled with a magnetic spectrometer, Phys.Lett. 99B (1981) 271-276

NNV Profielwerk 9 October 2019

Lichtgevoelige Emulsie als Detektor (>1945)

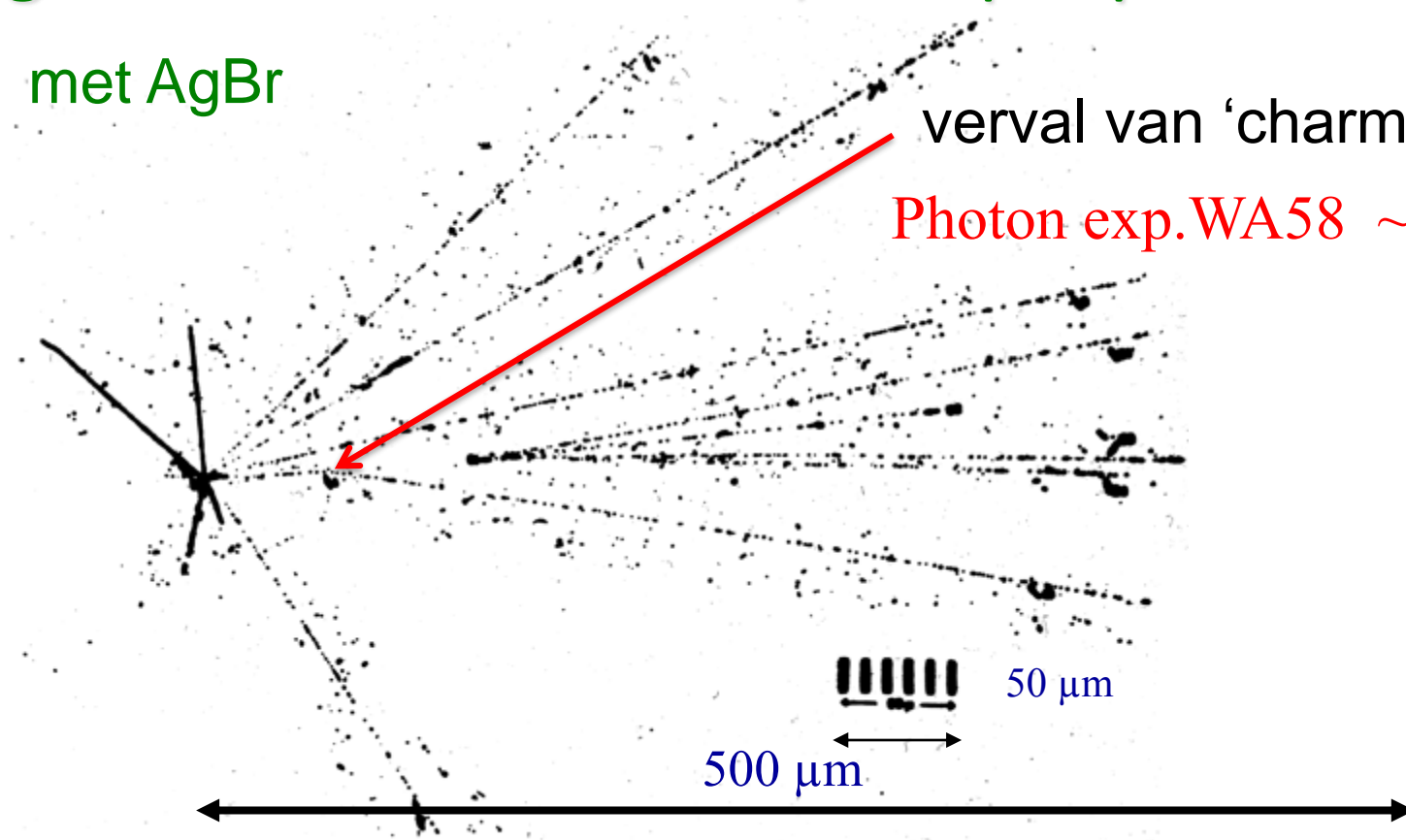
gelatine film

3D, sub- μm precisie

met AgBr

verval van 'charm' deeltje

Photon exp. WA58 ~ 1985



opeenvolgende ioniserende overdrachten van energie ($\sim 5\text{keV}$) creëren latent beeld van zilverkorrels, zichtbaar na ontwikkelbad
afstand $\sim 50\mu\text{m}$ met lichtsnelheid $3 \times 10^8\text{m/s} = 3 \times 10^{14}\mu\text{m/s}$ dus $t = 1.6 \times 10^{-13}\text{ s}$

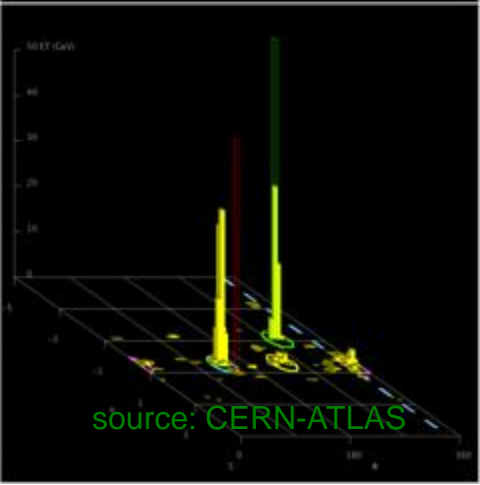
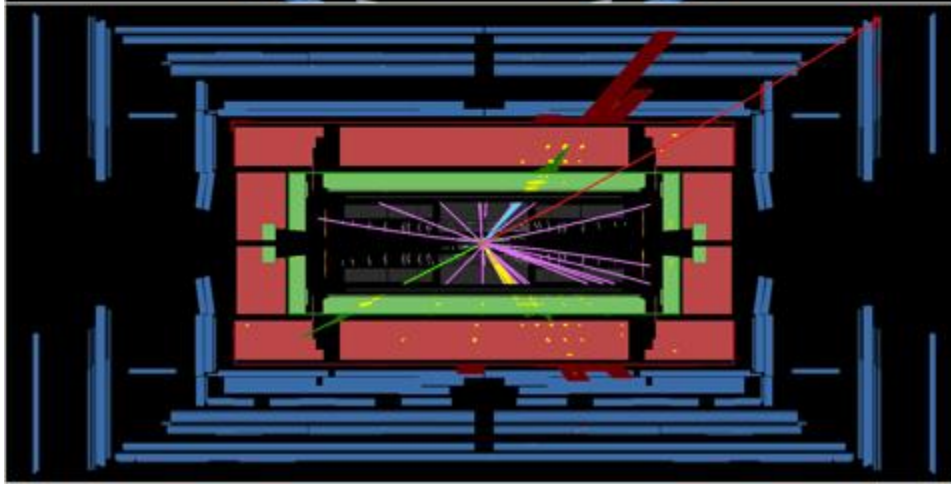
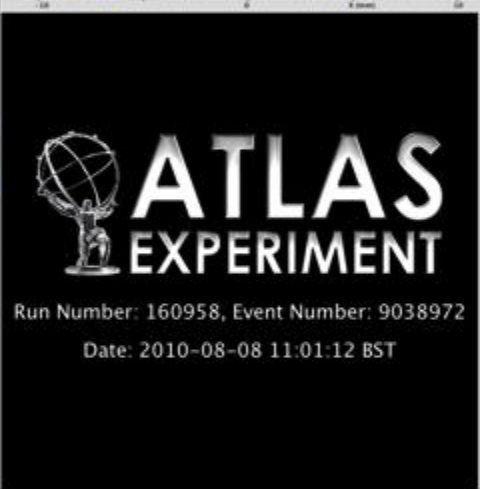
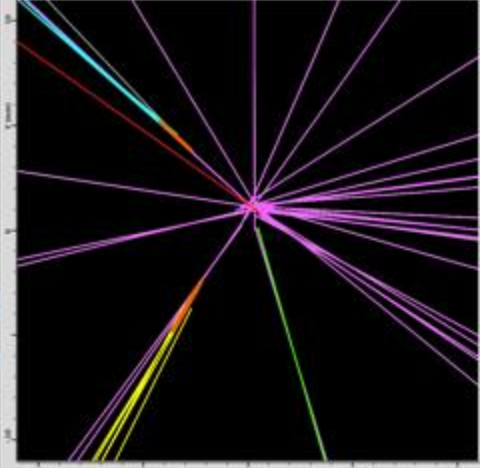
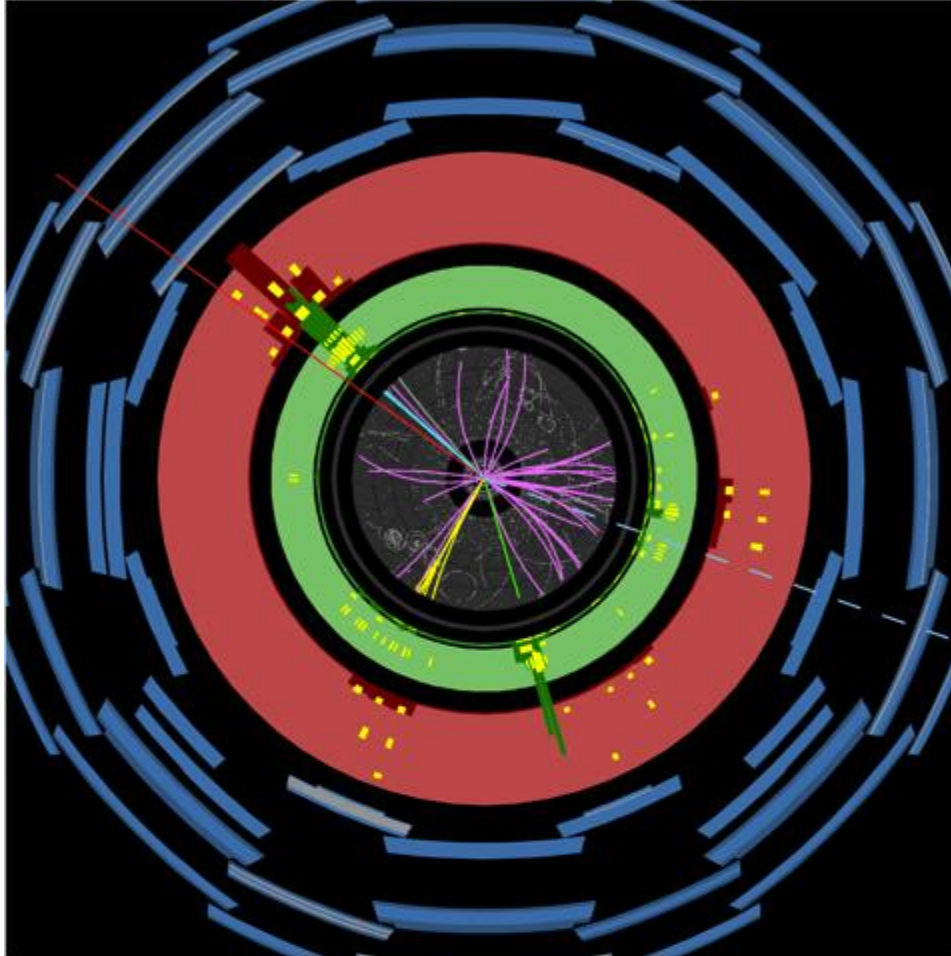
Imaging Now
All Electronic
with 3-D
Reconstruction

Many Tracks
and 2 “Jets”

40 million / sec

Secondary
Vertex:
a short-lifetime
particle is a
messenger for
something new

see blow-up

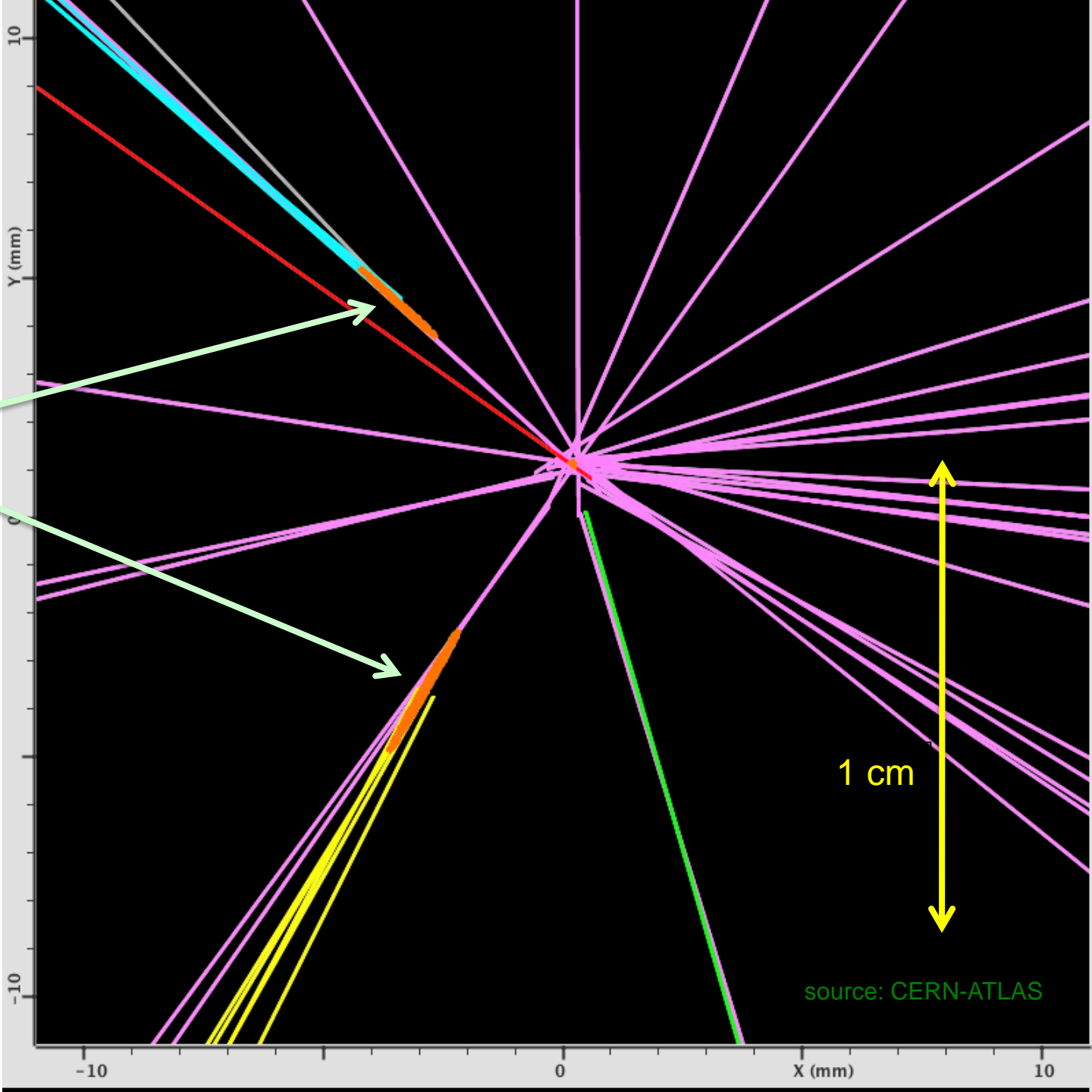


ATLAS

Details around
Primary Vertex

Two Secondary
Vertices

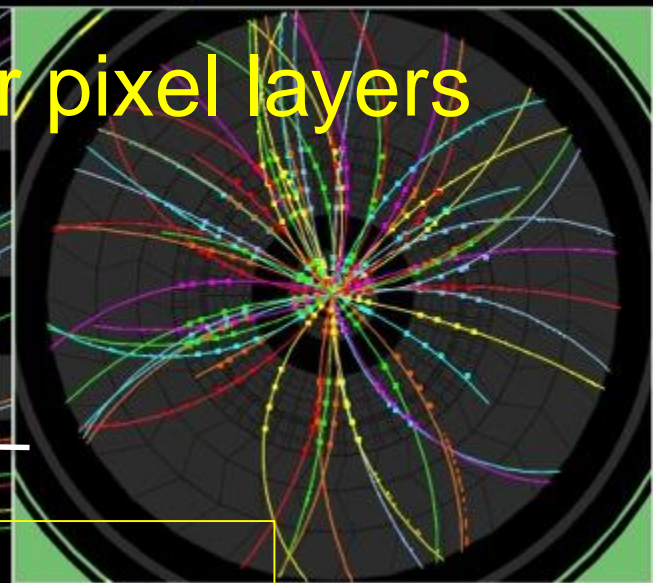
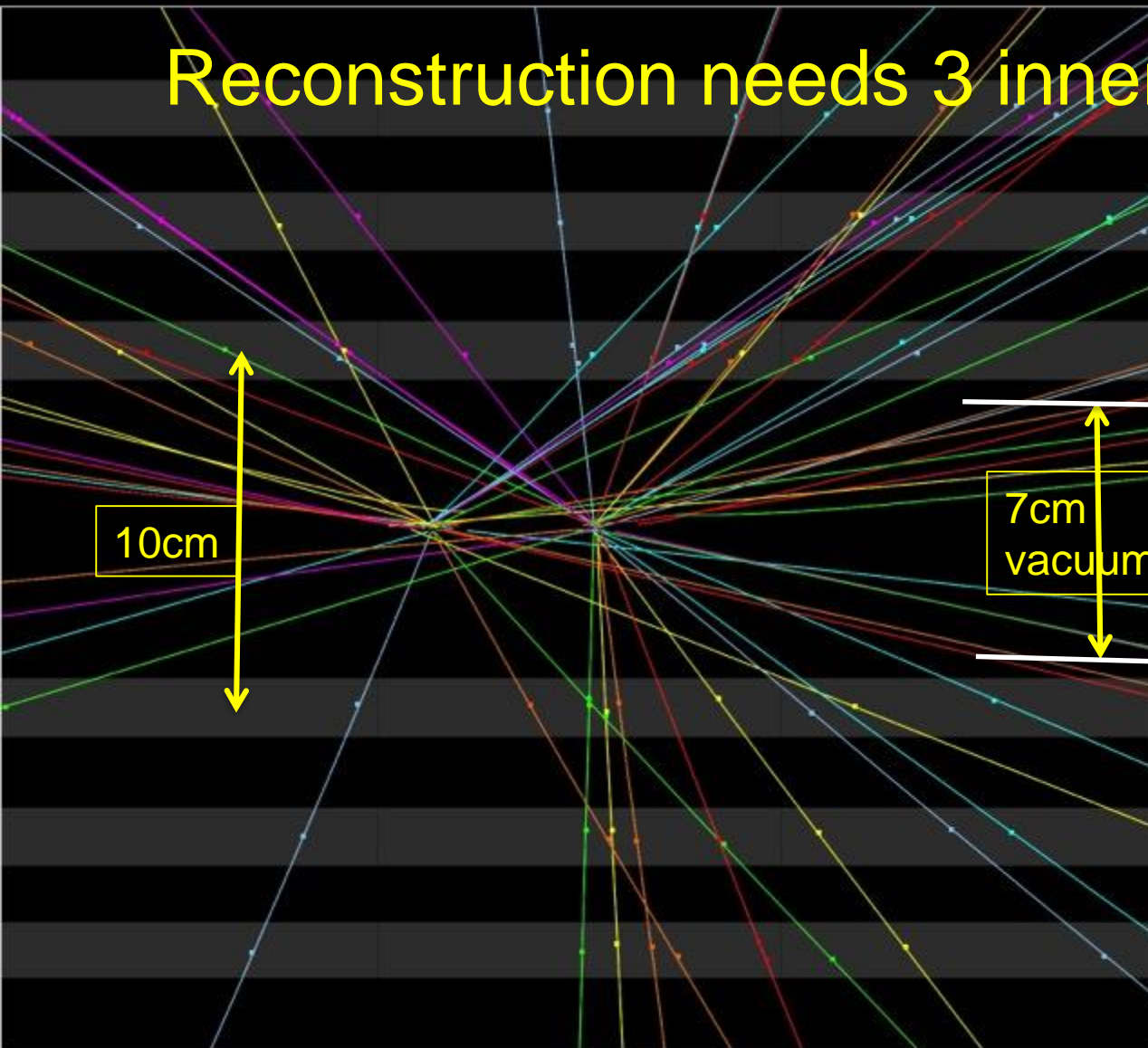
Note scale
1cm
all this is INSIDE
beam pipe \varnothing 7cm



source: CERN-ATLAS

Collision Event at 7 TeV with 2 Pile Up Vertices

Reconstruction needs 3 inner pixel layers

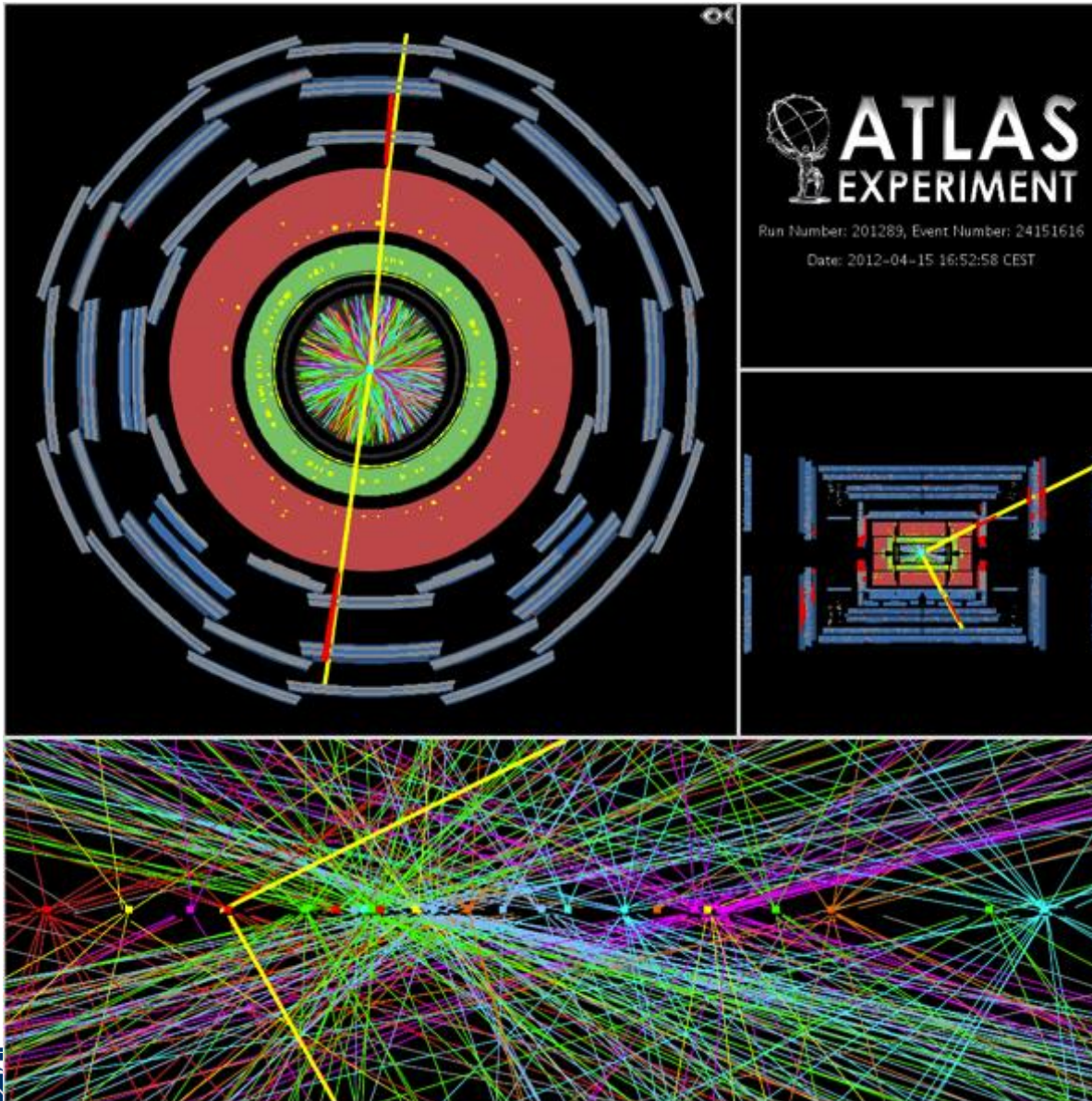


ATLAS EXPERIMENT

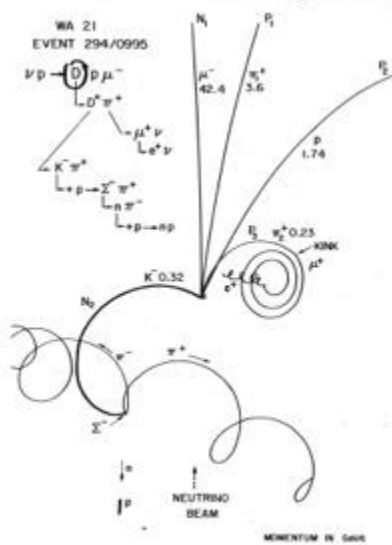
Run Number: 152166, Event Number: 467774

Date: 2010-03-30 13:31:46 CEST

Multiple interactions in one LHC crossing

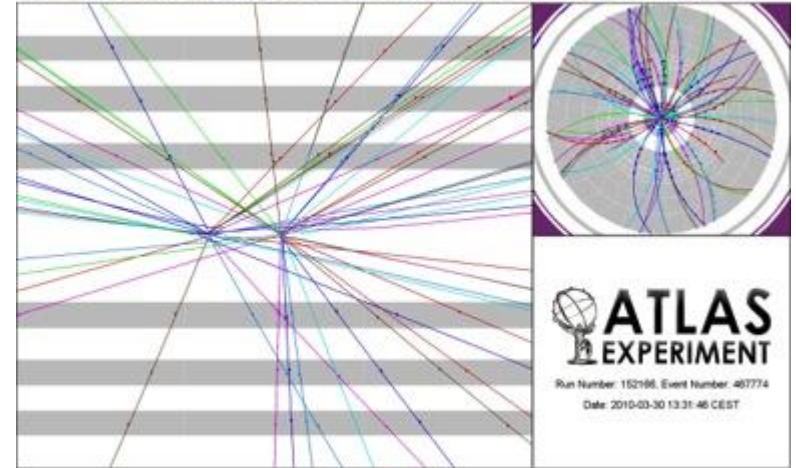


Study of elementary particles: from Bubble Chambers to fully Electronic Imagers



ATLAS experiment 2012

Collision Event at 7 TeV with 2 Pile Up Vertices



BEBC 1981
photo every ~1s

40 million
records per s

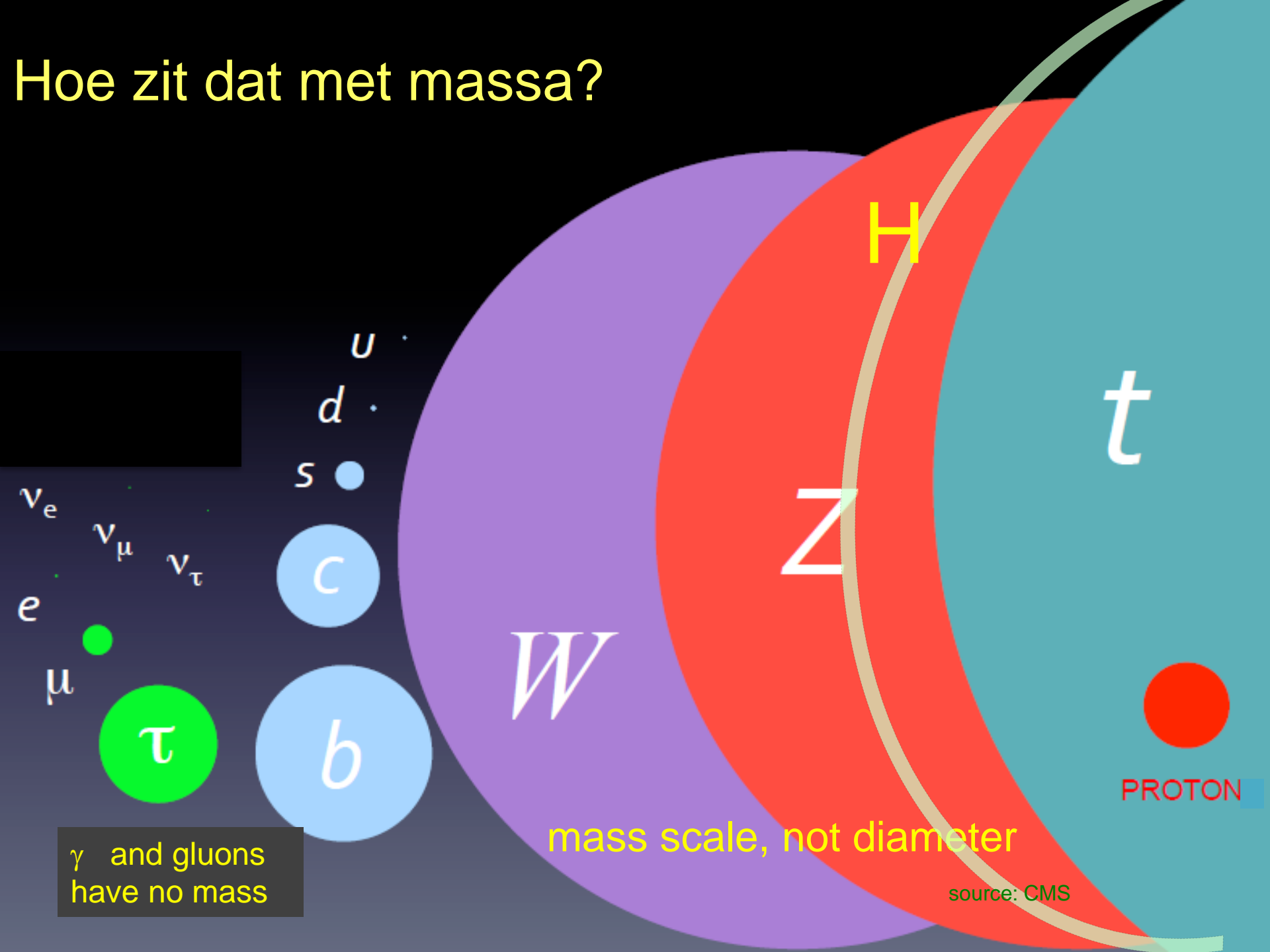


Liquid H  silicon for vertexing (but image information is lost)

apparaten steeds groter,
deeltjes steeds 'kleiner' en 'zwaarder'
afmeting en massa onafhankelijk



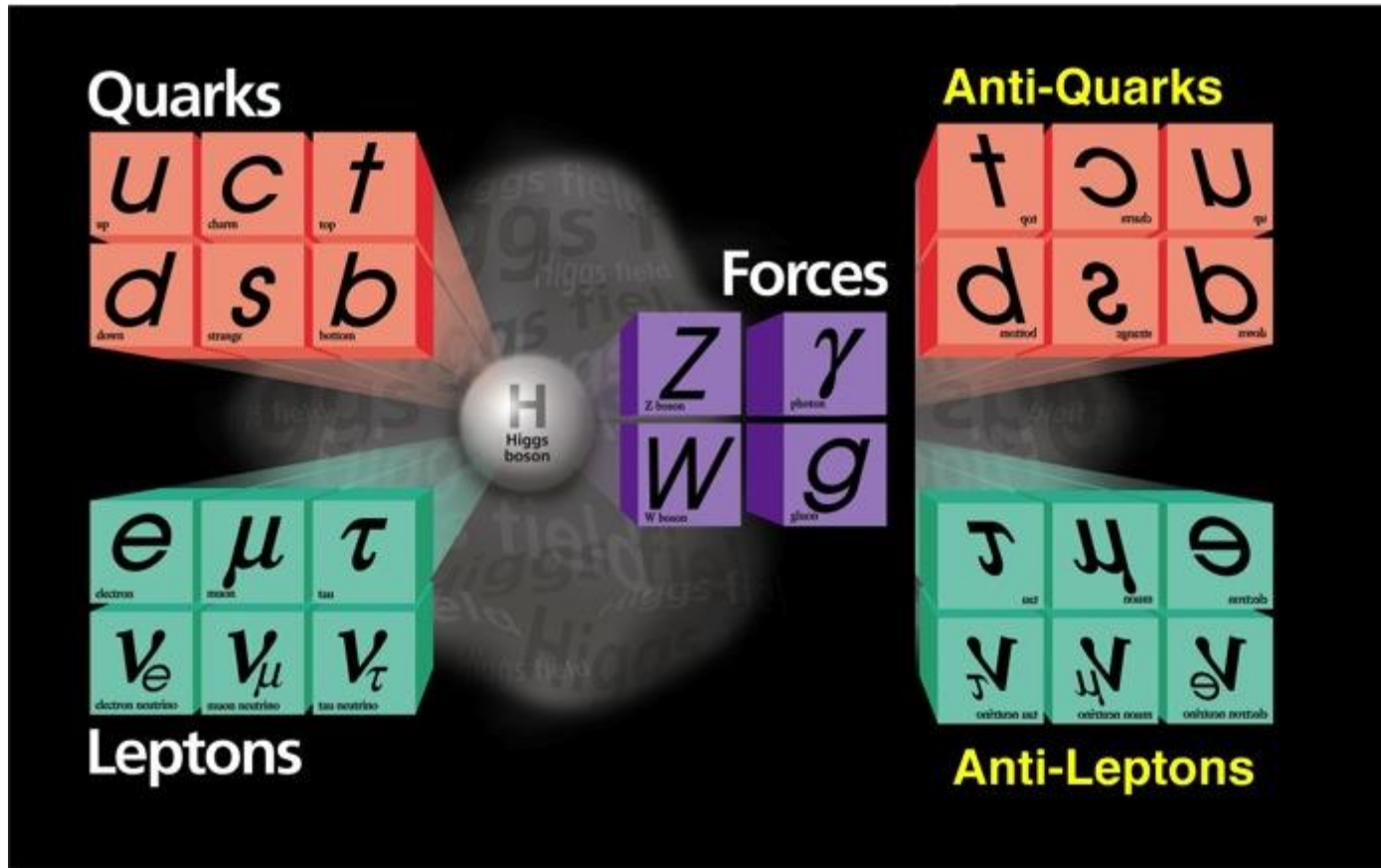
Hoe zit dat met massa?



γ and gluons
have no mass

PROTON

Periodiek Systeem volgens “Standard Model” Krachten en Fundamentele Deeltjes



source: Fermilab

Er blijven veel vragen:

waarom nu juist 3 generaties
waar zijn de originele anti-deeltjes gebleven
waar past hierin de zwaartekracht
.....en nog veel meer

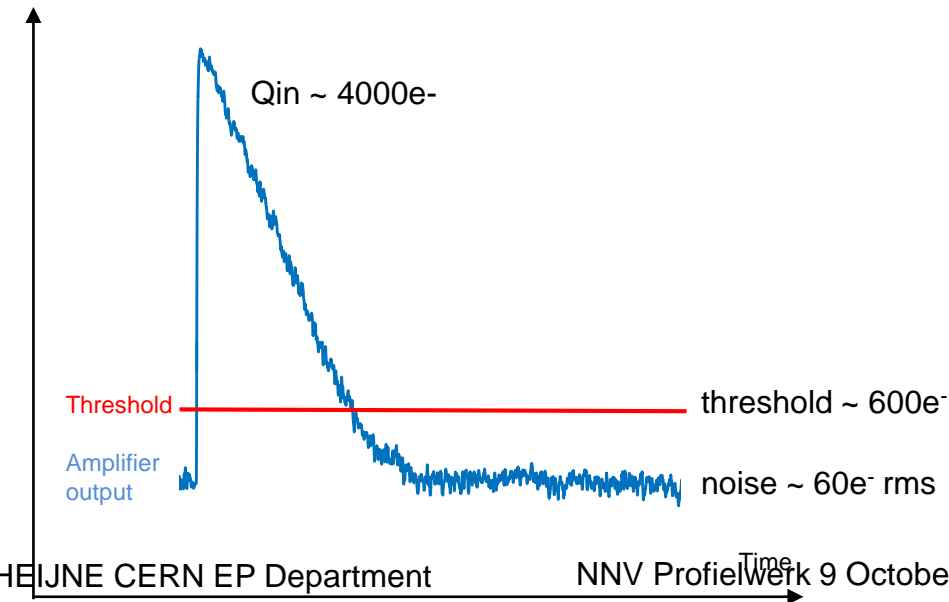
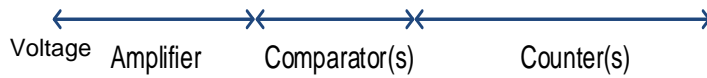
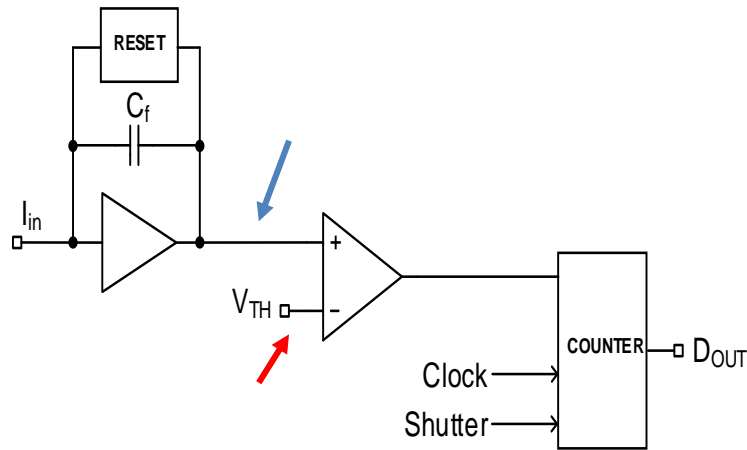
Timepix in een 'USB' stick



IEAP/CTU, Prague
Advacam : miniPix



Hybrid Pixel Detector - Basic Detection Principle



→ Noise hit free imaging



Timepix Pixel Operation Modes

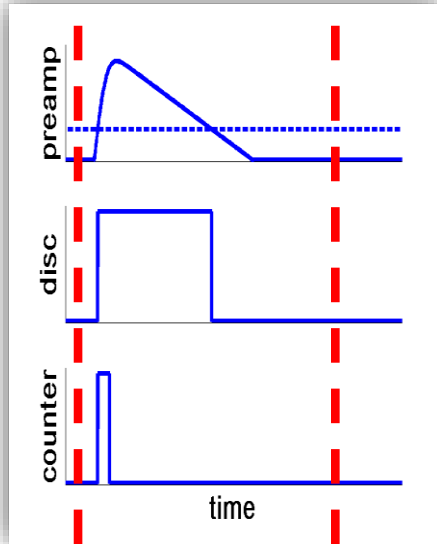
Particle counting

- Arrival Time*

- Time over threshold

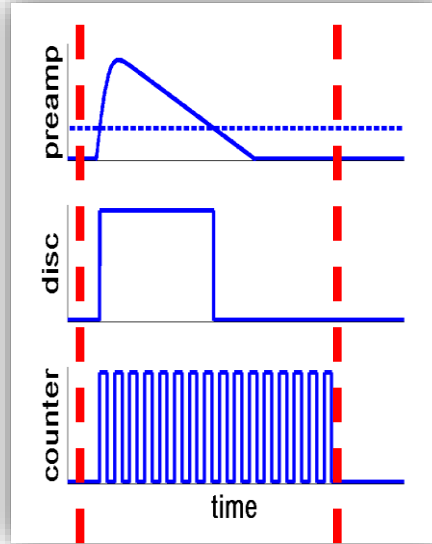
Open shutter

Close shutter



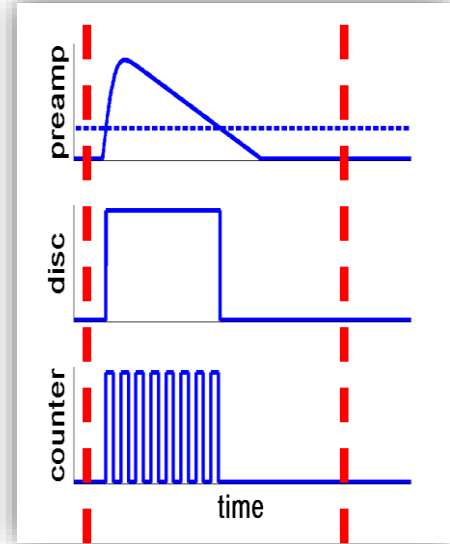
Open shutter

Close shutter



Open shutter

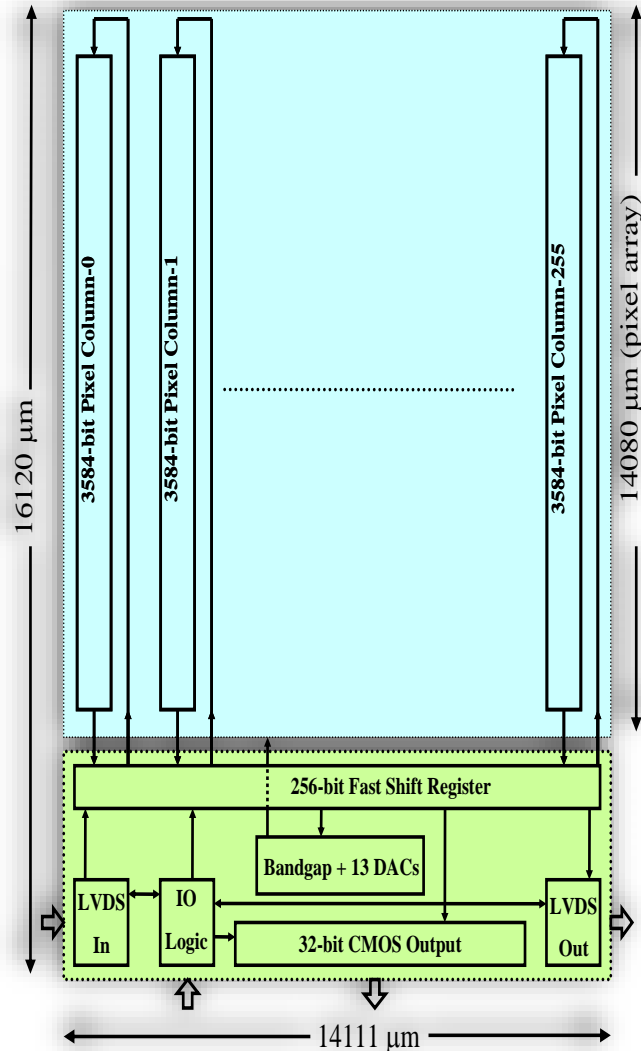
Close shutter



* Implemented at the request of the EUDet Collaboration



Timepix chip architecture



3-side Buttable floorplan

In acquisition mode chip an external clock is used as a time reference (up to 100 MHz)

256x256 55μm square pixels

Analog Power → 440mW

Digital Power (Ref_Clk=50MHz) → 220mW

> 36M Transistors

System on chip design:

On-chip digital global biasing:

14 DACs + Bandgap

Simple control logic

Serial readout (@100MHz) → 9.17 ms

Parallel readout (@100MHz) → 287 μs

Daisy-chain (serial only) for simple multiple chip readout



Timepix Specificaties

CMOS node	250nm
Pixel Array	256 x 256
Pixel pitch	55 μ m
Charge collection	e ⁻ , h ⁺
Pixel functionality	PC (Particle Counting), TOT (Energy) or TOA (Arrival time)
Preamp Gain	~16.5mV/ke ⁻
ENC	~100e ⁻
FE Linearity	Up to 50ke ⁻
TOT linearity (reolution)	Up to 200ke ⁻ (<5%)
TOA resolution	Up to 10ns (@ 100 MHz)
Time-walk	<50ns
Minimum detectable charge	~700e ⁻ → 2.5 KeV (Si Sensor)
Counter Depth/Overflow	14-bits(11810)/Yes
Max Analog power (2.2V)	6.5 μ W/pix 190mA/chip
Static Digital Power (2.2V)	~500mW@100MHz/chip
Readout (@ 100 MHz)	Serial readout → 9.17 ms 32-bit Parallel readout → 287 μ s

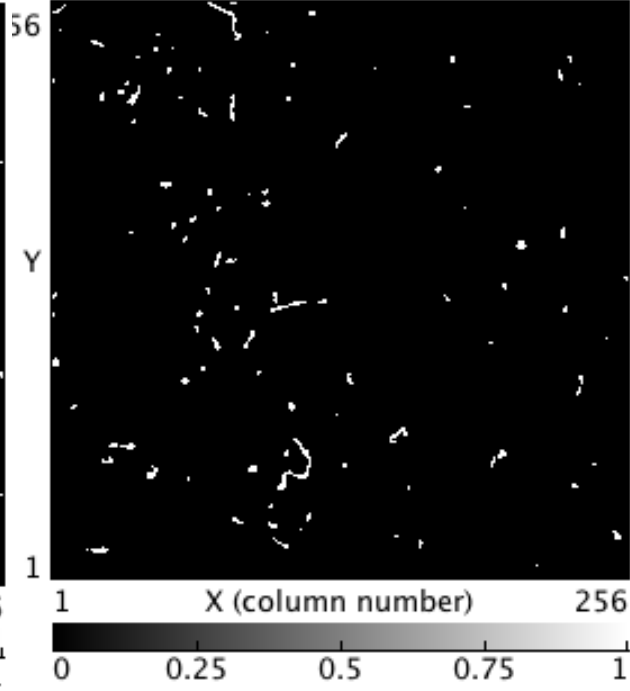
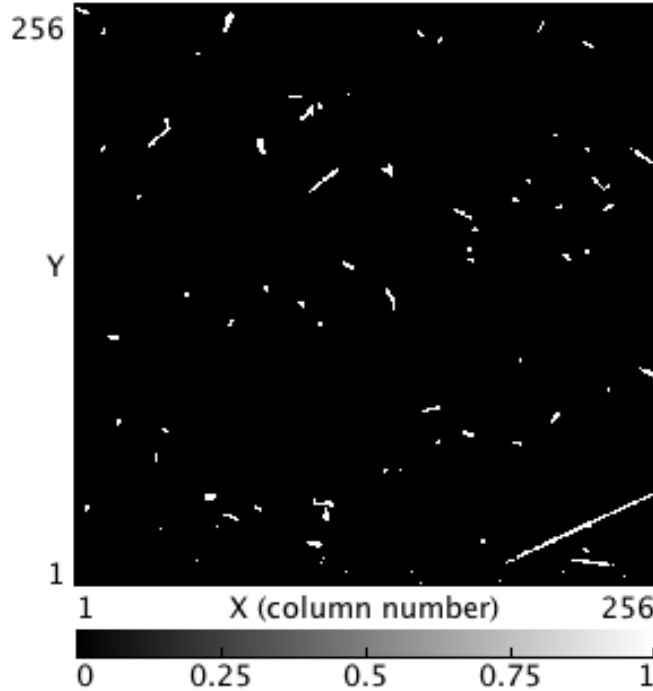
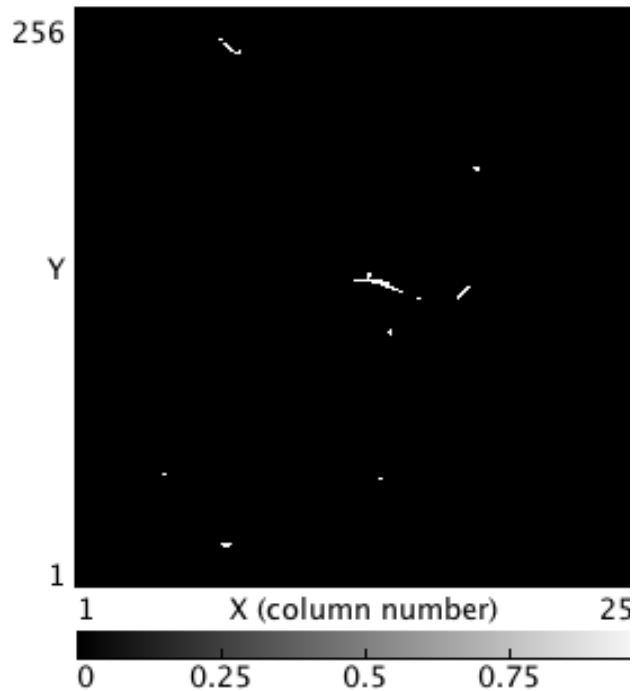


Single Quanta zijn overal om ons heen

60s Exposure at
ground level

60s Exposure in plane at
24 000 feet

6s Exposure with old
wristwatch (radium)



Dose levels steeds nog op veilig niveau

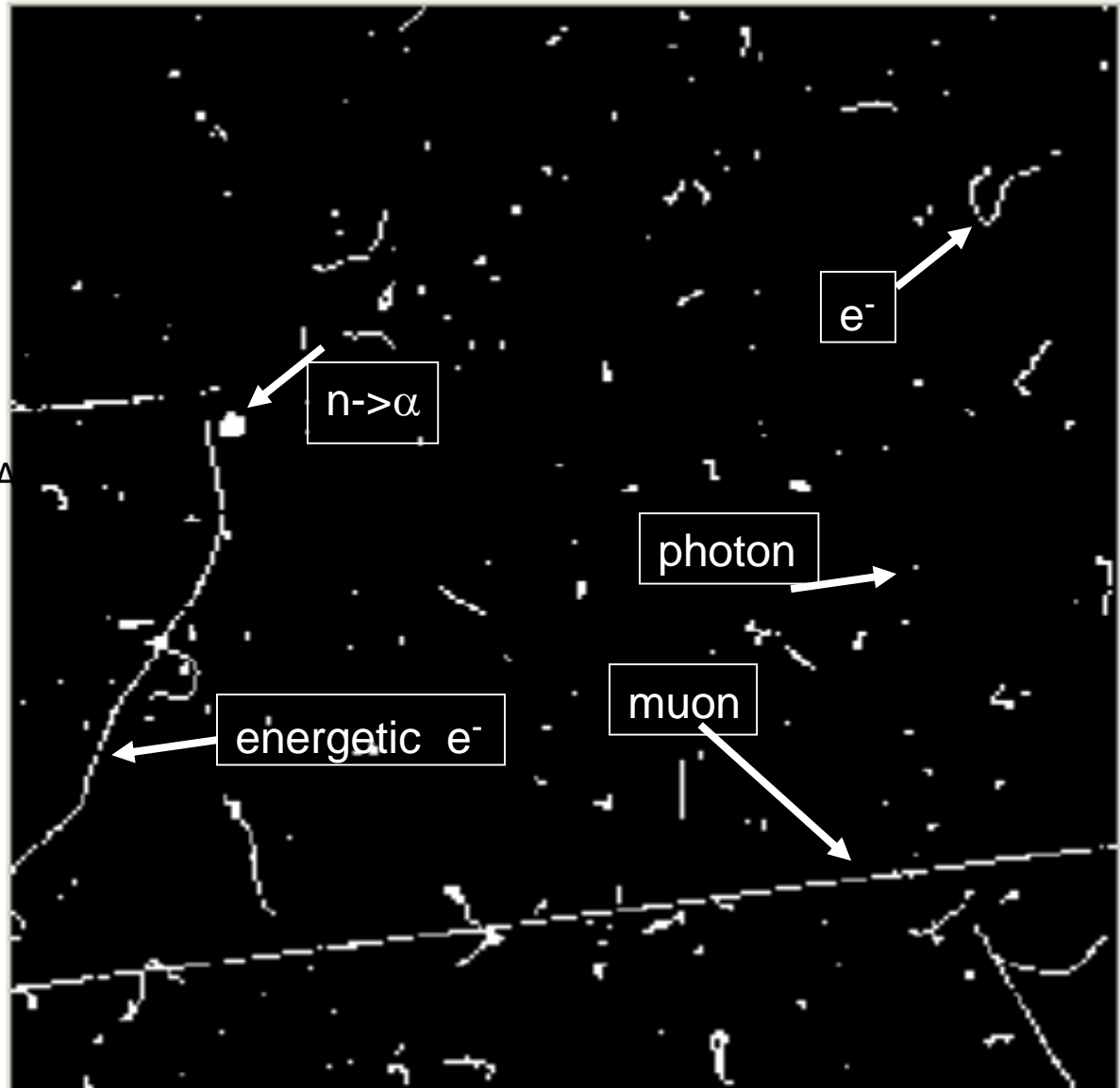
COSMIC PARTICLES in MXR Si PIXEL

256 x 256 PIXELS
300 μm THICK

CAN BE
RADIATION
DOSE METER

IDENTIFY SPECIFIC QUANTA
ELECTRONS
PHOTONS
MIPs
NEUTRONS \rightarrow ALPHAs


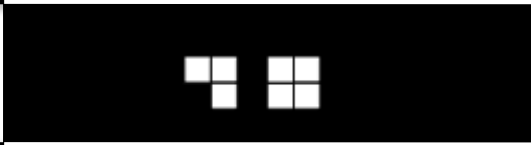
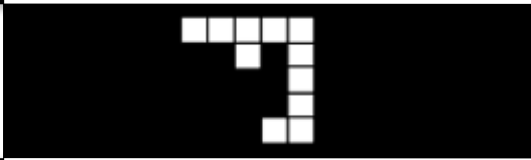
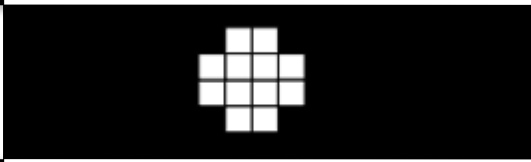
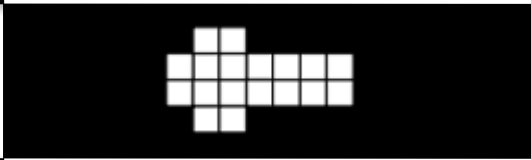

ADJUSTABLE EXPOSURE
ms - minutes GIVES
LARGE DYNAMIC RANGE

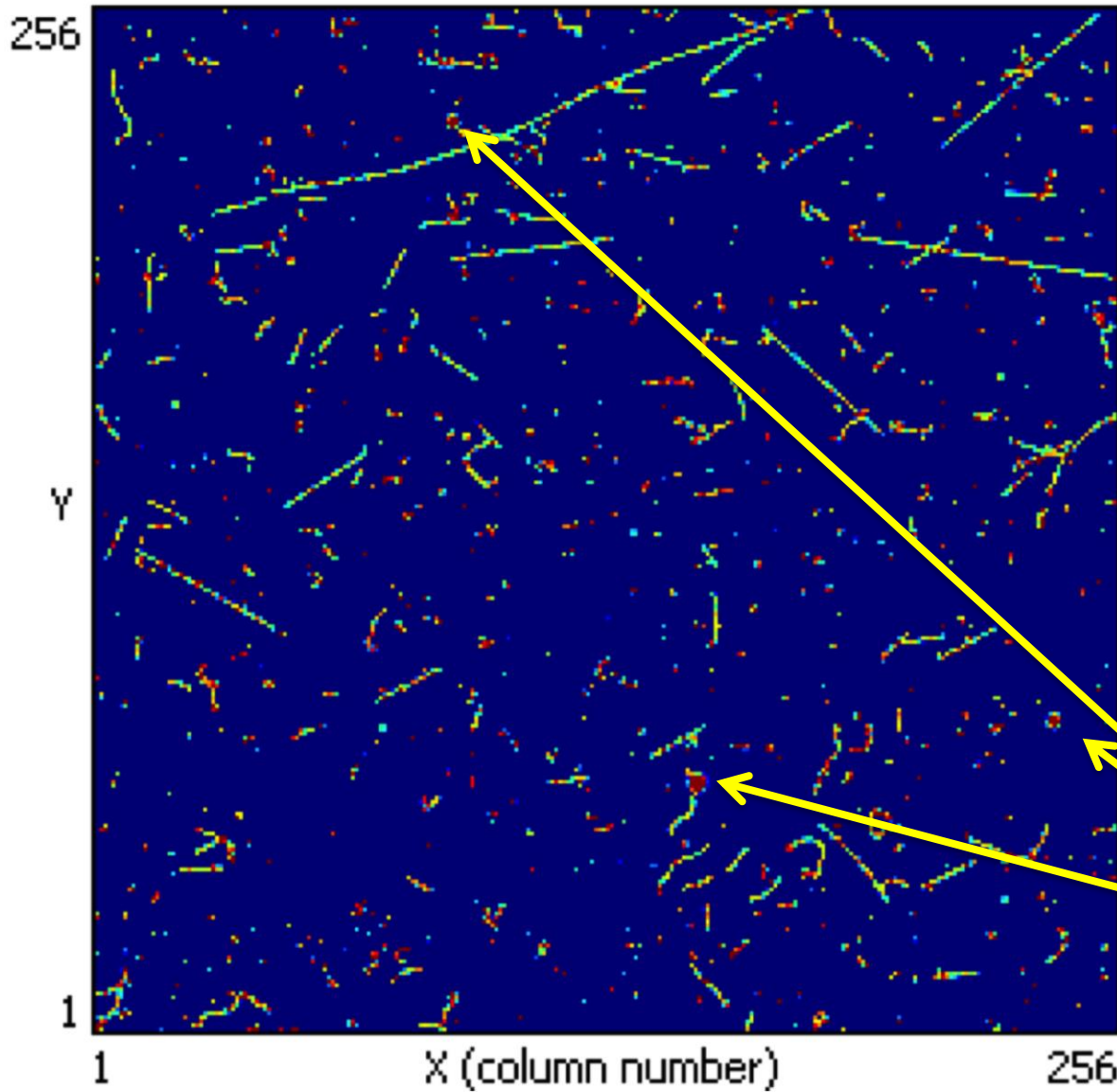


Frame CTU Prague



Characteristic cluster patterns in Medipix

1) Dot		Photons and electrons (10keV)
2) Small blob		Photons and electrons (~100keV)
3) Curly track		Electrons (MeV range)
4) Heavy blob		Heavy ionizing particles with short range (alpha particles,...)
5) Heavy track		Heavy ionizing particles (protons,nuclei, Fe, ...)
6) Straight track		Energetic light charged particles (MIP, Muons,...)



Natural background
at home
with Medipix-T

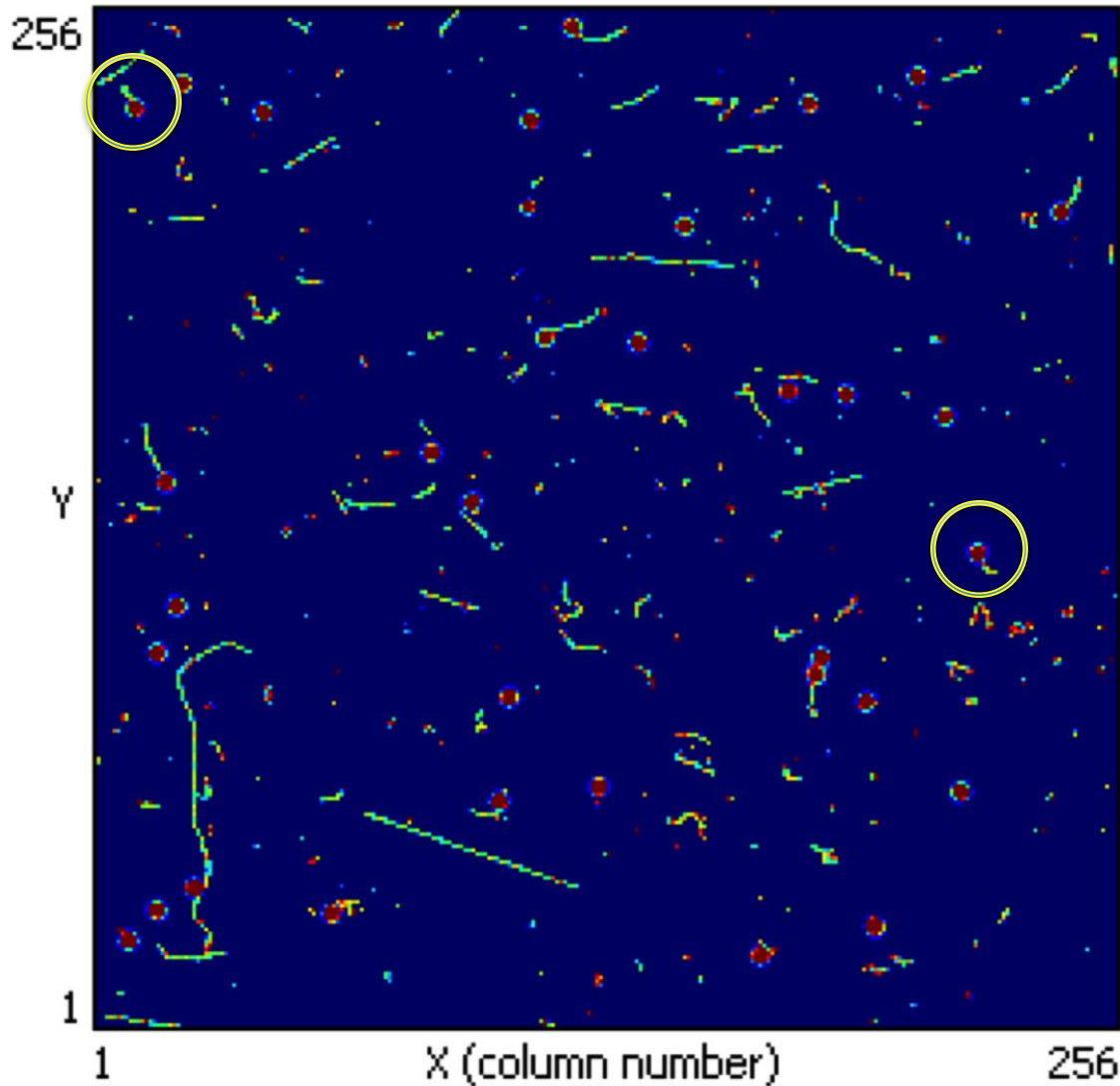
0.51 mSv el.mag.component
0.63 mSv alpha.component

4764s exposure
(extrapolated per year)

dose per hour
e.m. 0.06 μ Sv/h
alpha 0.07 μ Sv/h

The 3 alpha impacts
contribute >half of the dose

23 June 2010 20.45 TPX D9-W15 1400 s EXPOSURE

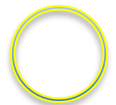


NEXT MEASUREMENT

23 MINS

34 ALPHA

13 with e-TAIL



a little FRIGHTENING !!

1.5 per minute
MYSTERY.....?



Nov 2010 in Zeeuwse krant

totale stralingsdosis waaraan Nederlanders blootstaan.

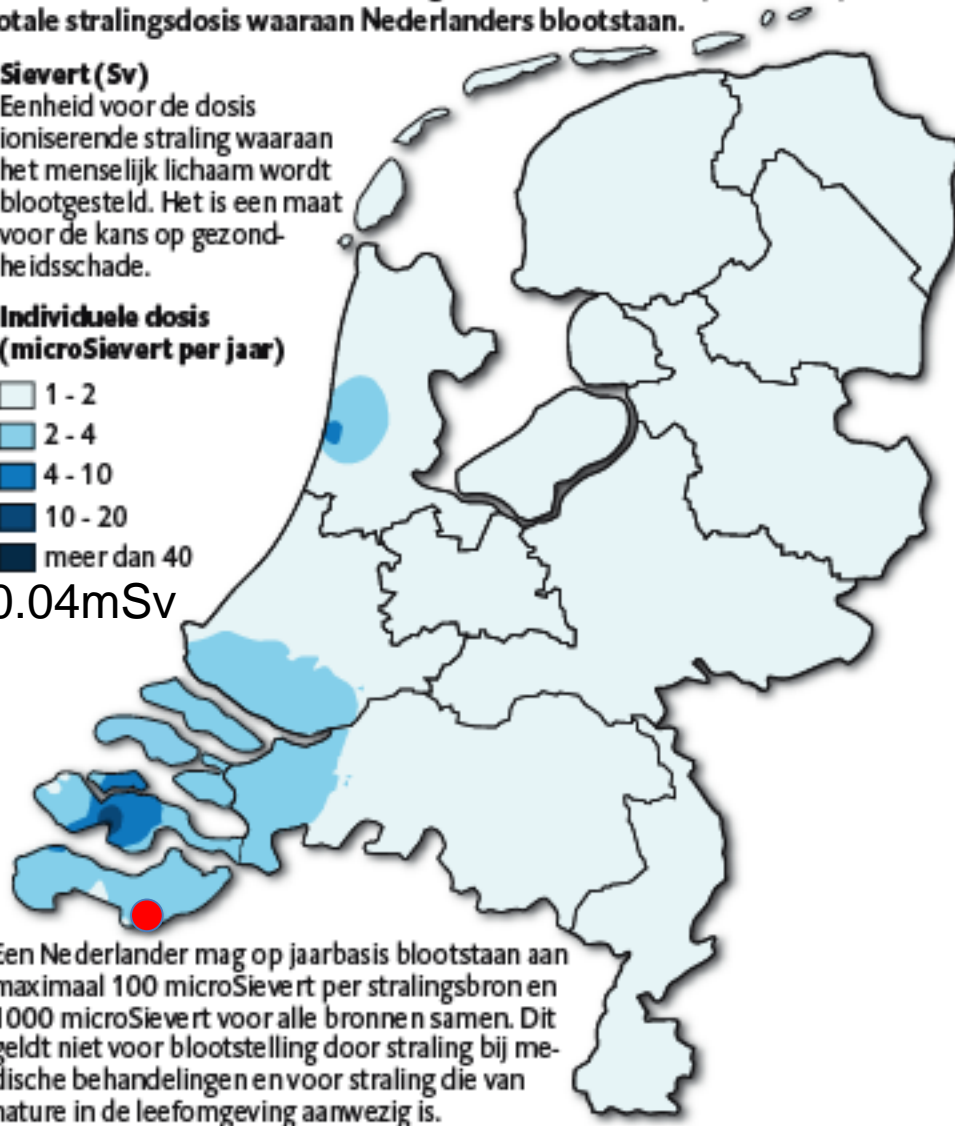
Sievert (Sv)

Eenheid voor de dosis ioniserende straling waaraan het menselijk lichaam wordt blootgesteld. Het is een maat voor de kans op gezondheidsschade.

Individuele dosis (microSievert per jaar)

- 1 - 2
- 2 - 4
- 4 - 10
- 10 - 20
- meer dan 40

>0.04mSv



Een Nederlander mag op jaarbasis blootstaan aan maximaal 100 microSievert per stralingsbron en 1000 microSievert voor alle bronnen samen. Dit geldt niet voor blootstelling door straling bij medische behandelingen en voor straling die van nature in de leefomgeving aanwezig is.

Donja Odijk | bron Compendium voor de Leefomgeving

ThermPhos (vroeger Hoechst)
bij Borssele
NU gesloten --> Kazakstan

fabriek haalt fosfor uit erts
hoofdzakelijk voor
fosfaat kunstmest

voornaamste vervuiling: DIOXINE

maar ook radioactiviteit die
als bij product in het erts zit
(uranium, thorium, polonium etc.)

was grootste bron
voor radioactiviteit in lucht NL

Readout systems

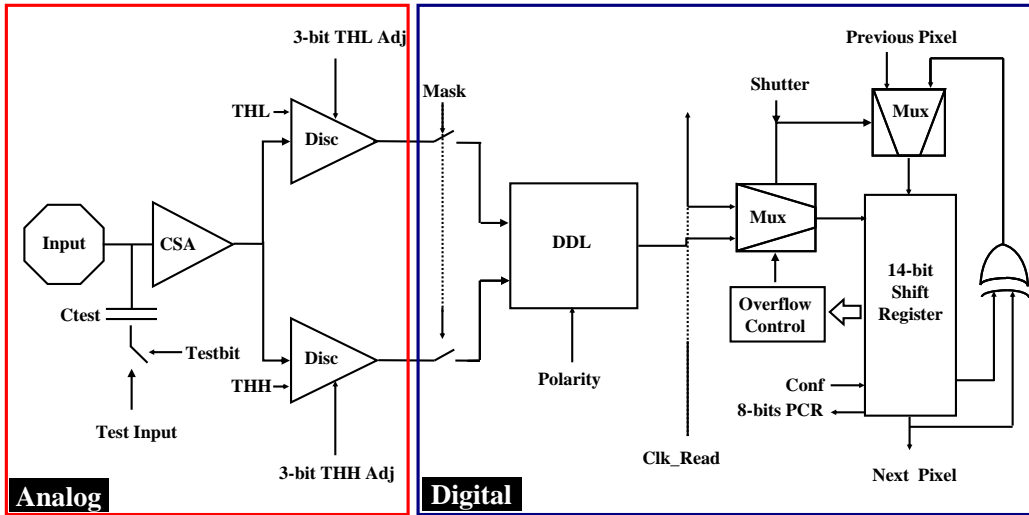
various readout systems have been developed
institutes or companies (really none at CERN)

in participating

name	software	who	for	available
VME system		Laben/Napoli/Pisa	PCC	1997 - 2005
MUROS, MUROS2	Medisoft	Nikhef	MPX2 TPX	2002 - 2010
FITPix USB	Pixelman	IEAP-CTU	MPX2 TPX	2006 - now
USB Lite	Pixelman	IEAP-CTU	MPX2 TPX	2009 - now
Maxipix	LIMA	ESRF	TPX	2007 - now
Smartpix	LIMA	ESRF	MPX3 + arrays	soon
SPIDR ethernet	system	ASI / Nikhef	MPX3 TPX3	2014 - now
Pixet	Advadaq	Advacam	all	2016 - now
Katrin	Burdaman	IEAP-CTU	all	now
DDIMAS	MedipixJ	Glasgow	TPX	2017 - now
Lambda Camera	system	X-Spectrum/DESY	MPX3	now
MARS CT scanner	system	MARS/Canterbury	MPX3	now
MERLIN	system	Quantum / DIAMOND	MPX3	2014 - now
π -M3GA		LNLS Brasil	MPX3	now
possibly others	???			



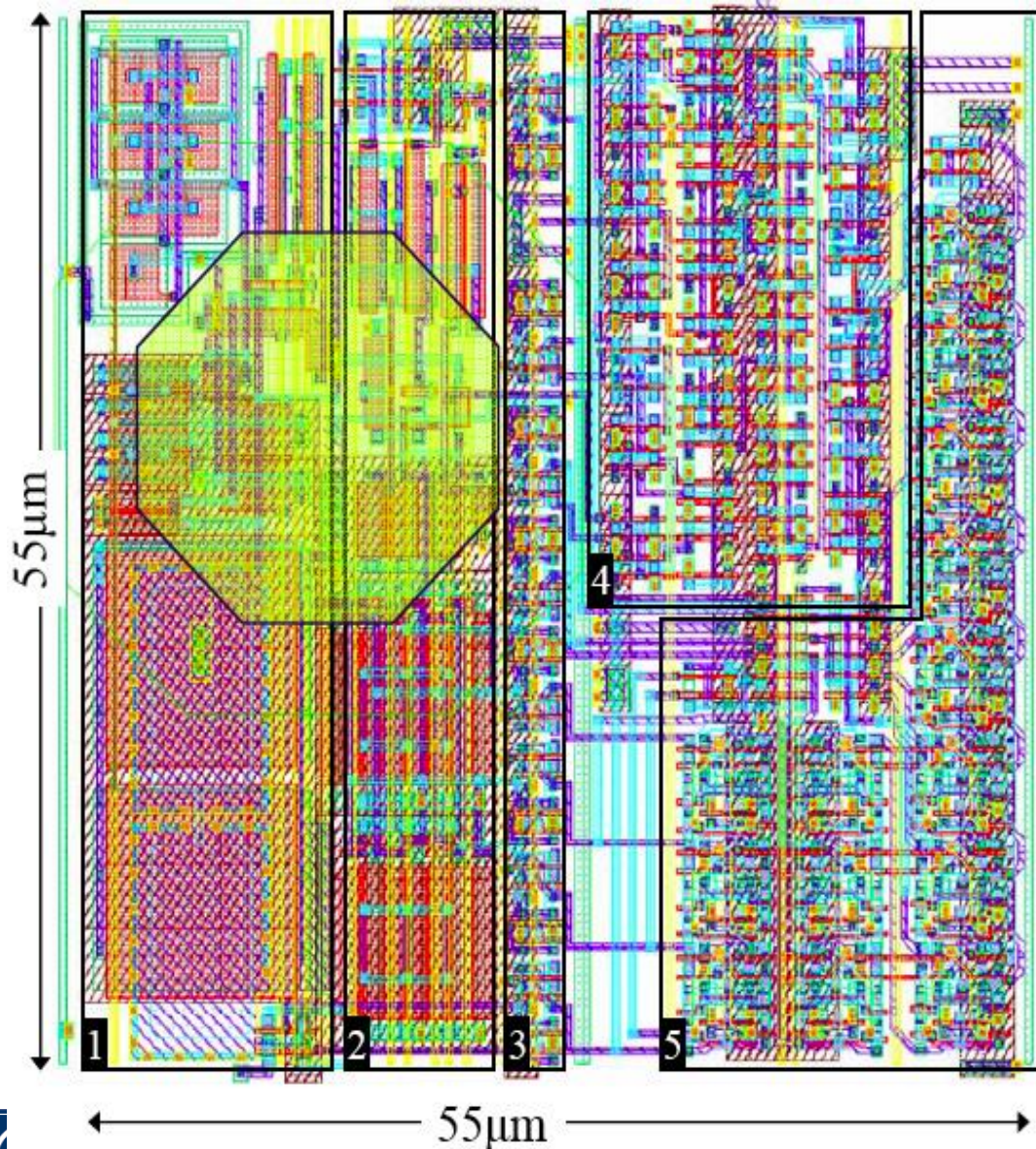
Medipix2: Mpix2MXR20 (2005)



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



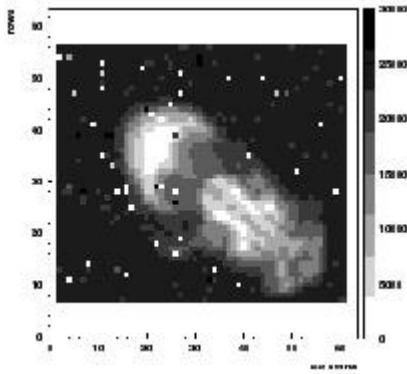
TIMEPIX CELL LAYOUT



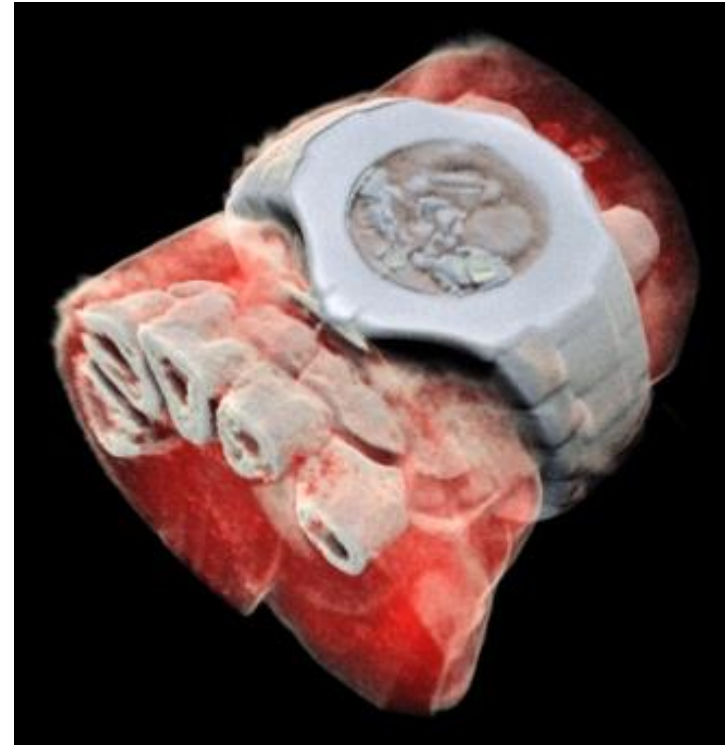
DESIGNER
Xavier LLOPART
CERN
PhD Thesis p. 107

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

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 now begins to be exploited



Materiaal-herkenning in scanner gebruikmakend van Medipix-3 detectoren



Silicon Timepix for mass spectroscopy

Separation of heavy molecules by Time-of-Flight

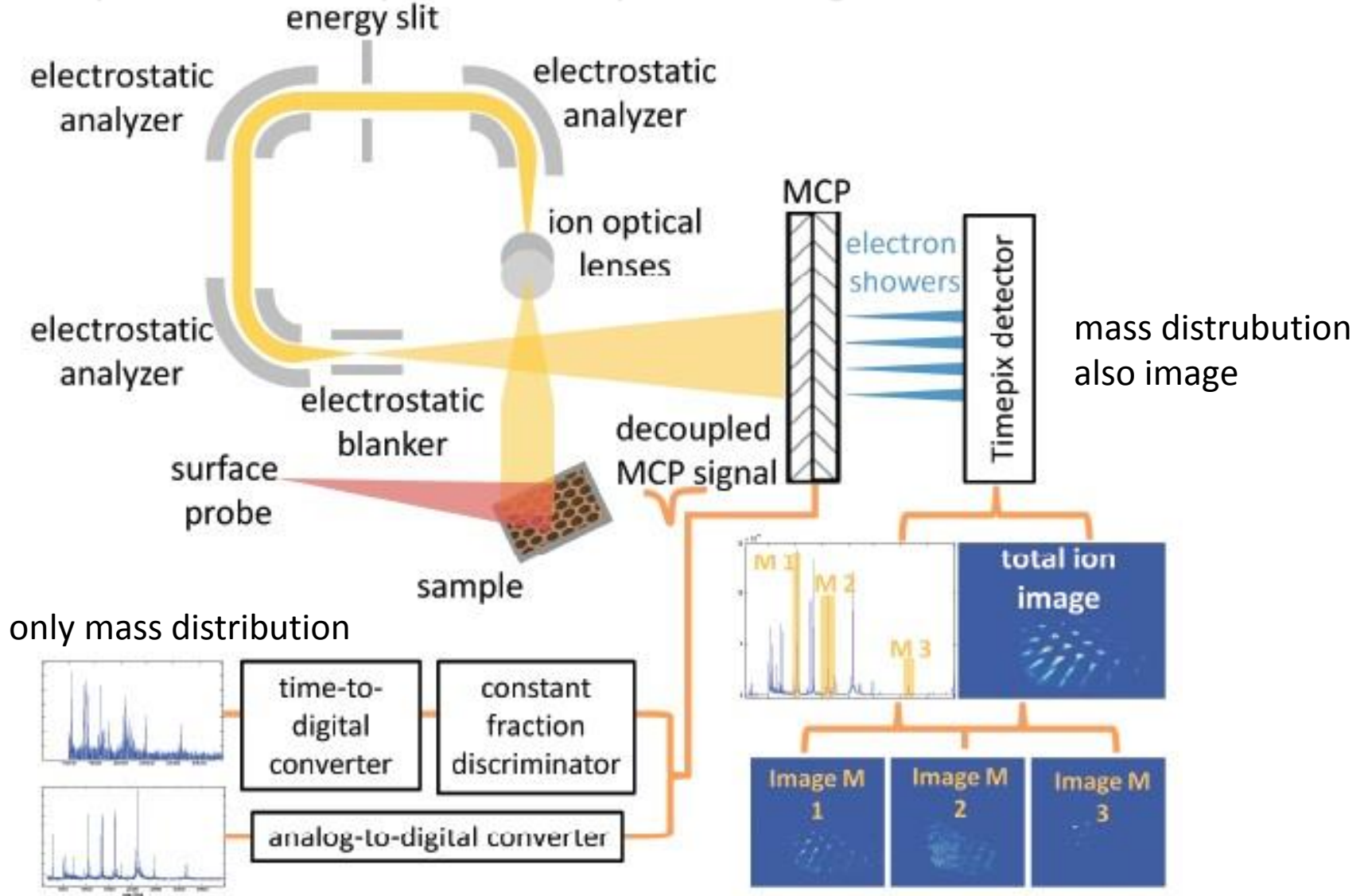
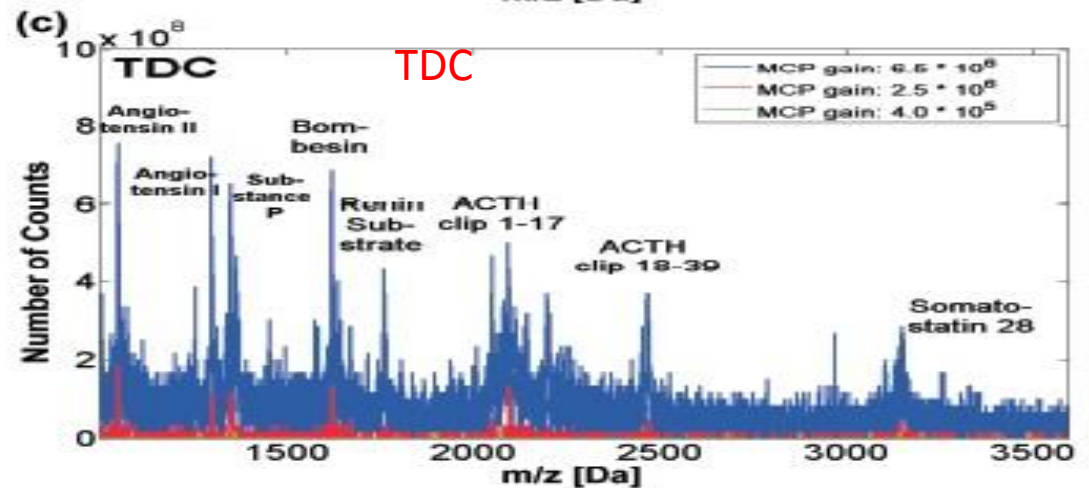
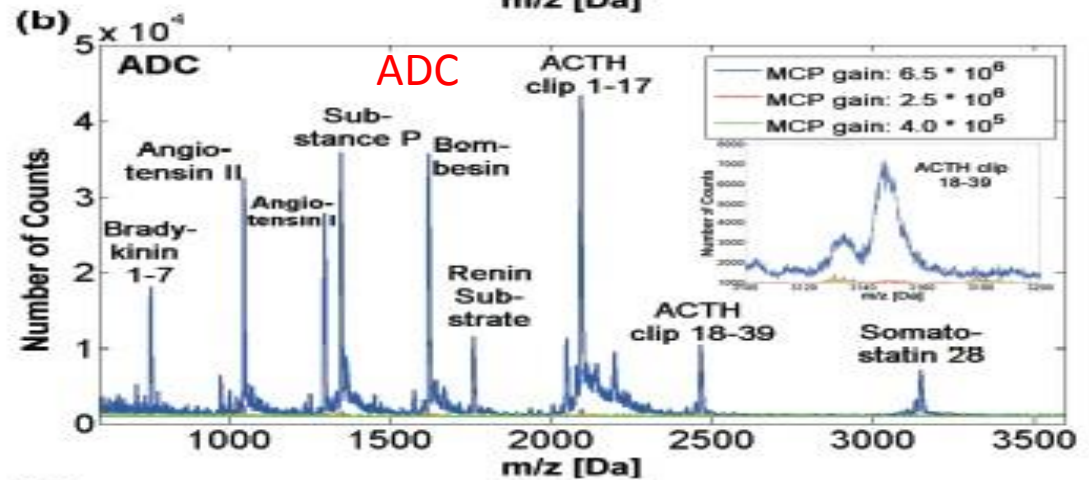
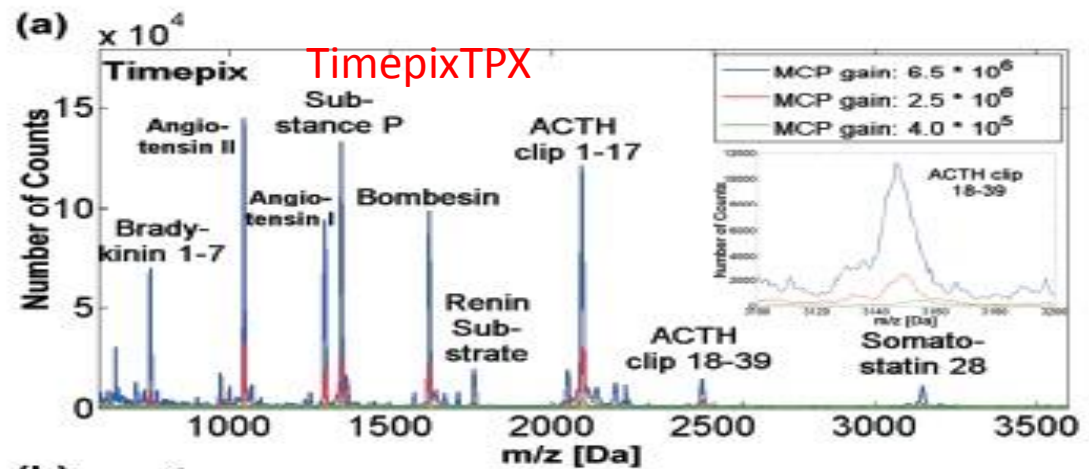


figure from J. Jungmann – PhD Thesis Univ Utrecht (2011) p. 96

Timepix for mass spectroscopy

Comparison of mass spectra for different methods and 3 gains in MicroChannelPlate



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

TIMEPIX radiation imaging at home

Compact radiation imaging
USB connection
to Mac or PC

mostly by Zdenek Vykydal



Pixelman software

made at IEAP/CTU Prague

Radiation imagers for schools and amateurs with educational kit

IEAP/CTU, Prague



Jablotron &
IEAP/CTU, Prague



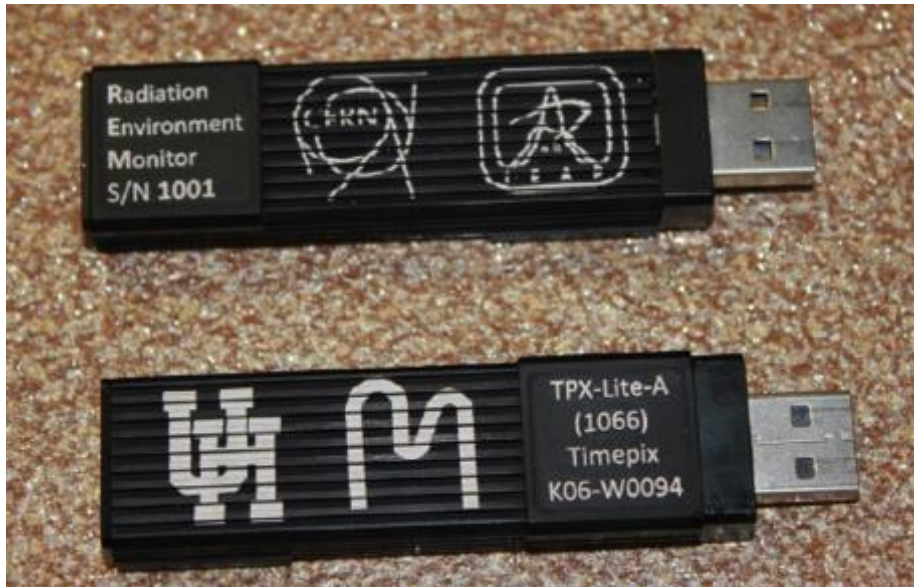
AdvaCam &
IEAP/CTU, Prague



CERN Timepix imager inside

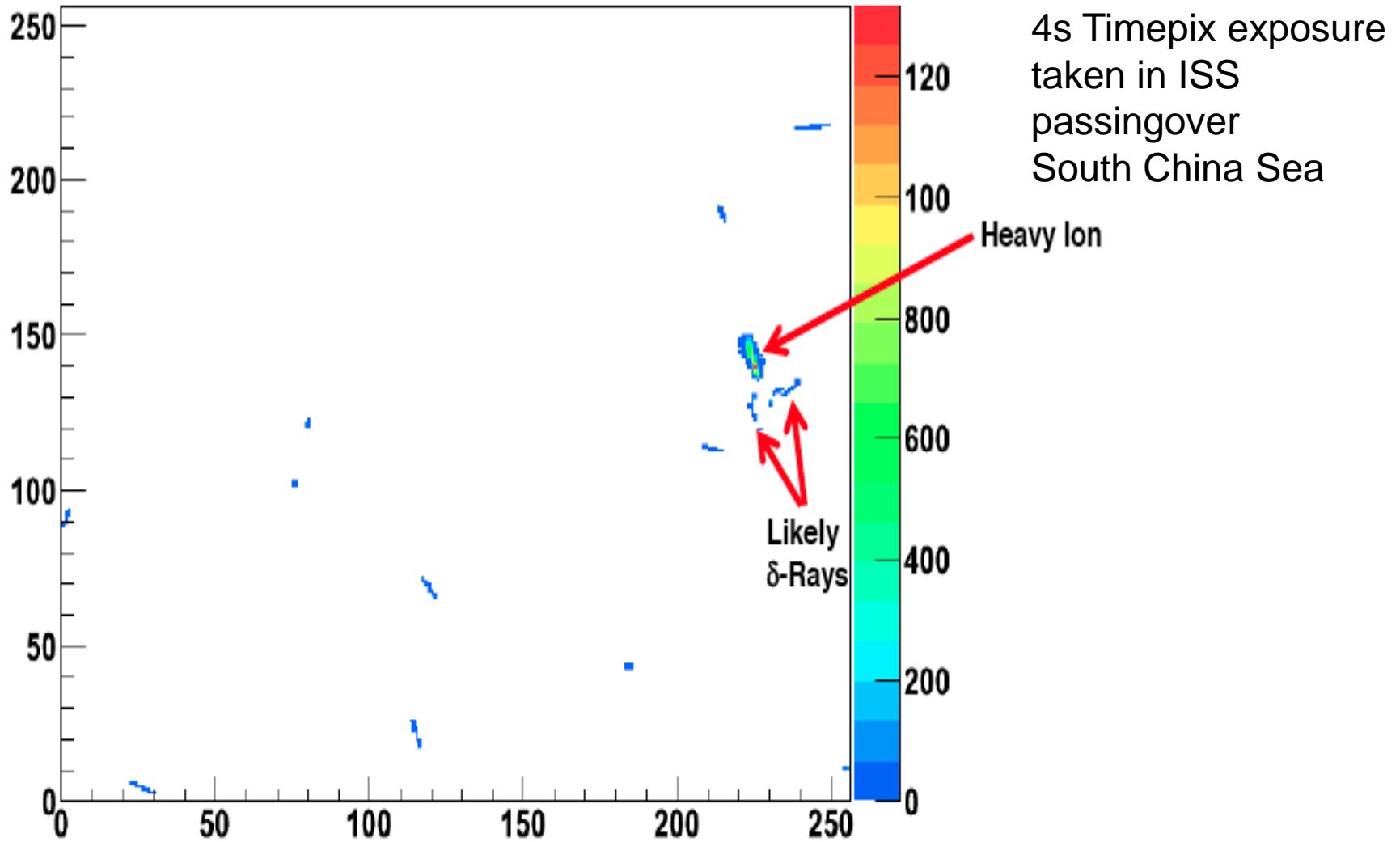
<http://ardent.web.cern.ch/ardent/ardent.php>

Pixel chips for dosimetry in Int Space Station ISS



AMS largest experiment....
Pixel chip maybe smallest

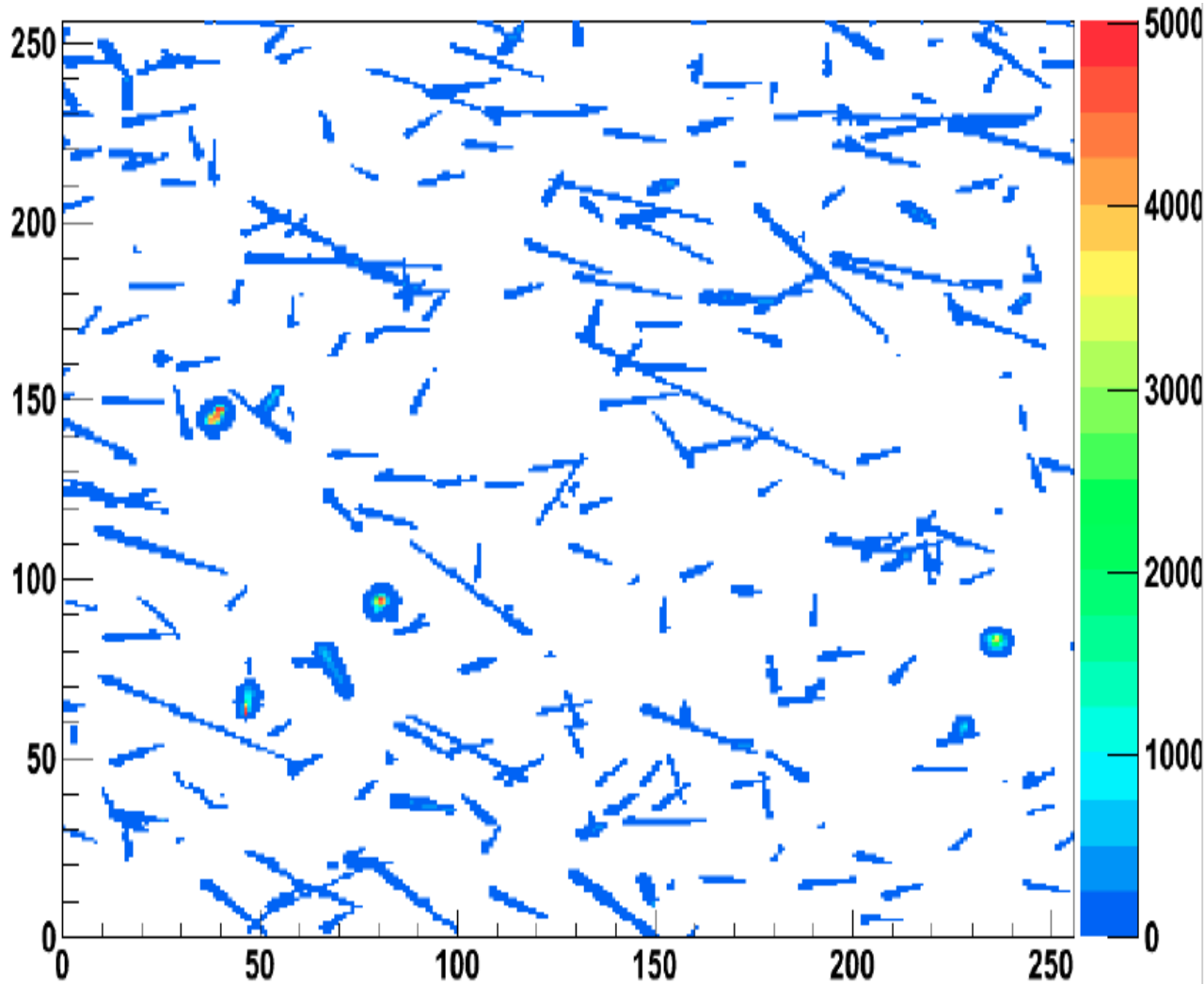
Dosimetry at the Int Space Station ISS



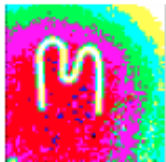
UNIVERSITY OF HOUSTON
Learning. Leading.



Dosimetry at the Int Space Station ISS

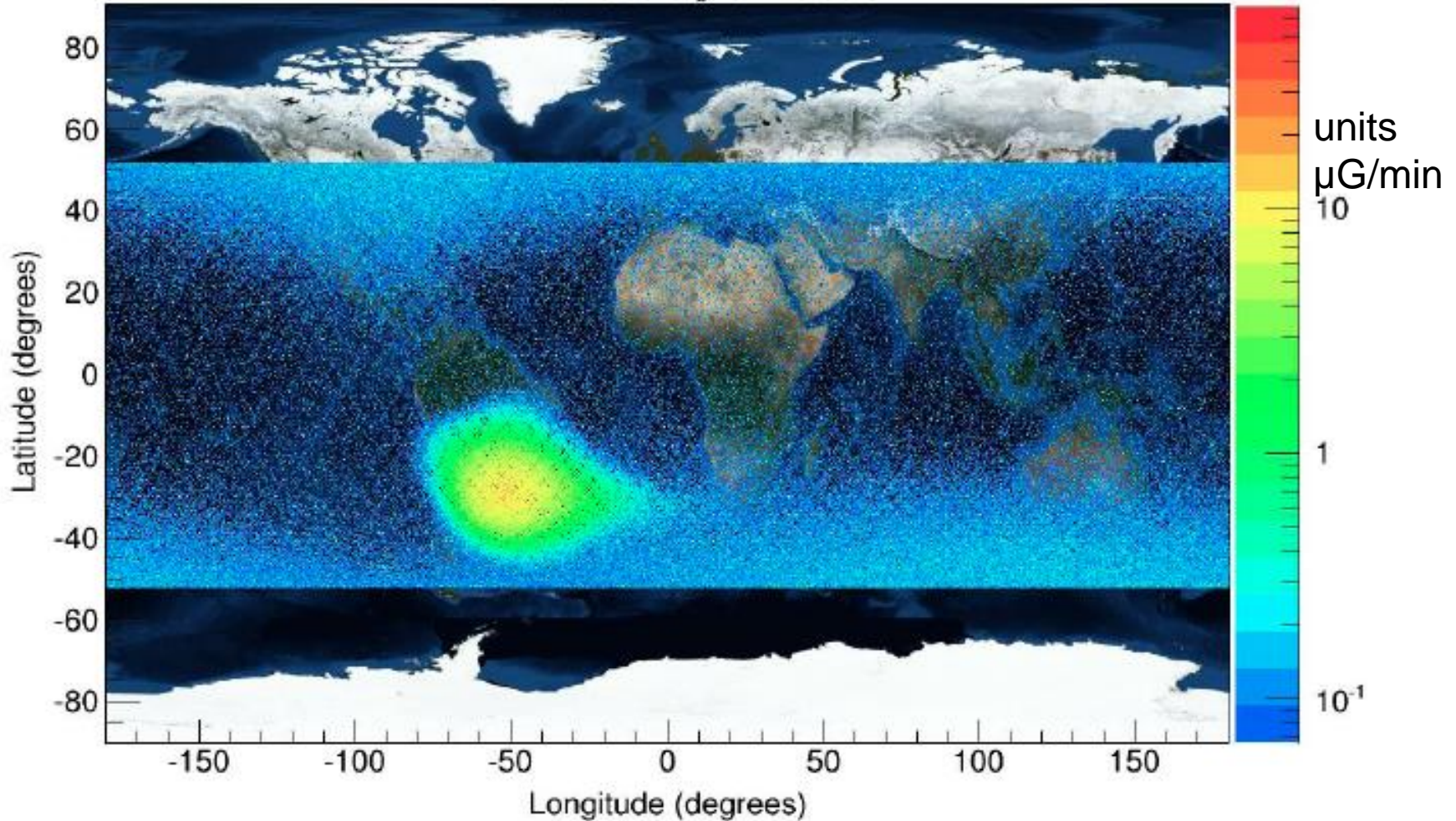


4s Timepix exposure
taken in ISS
passing through SAA
South America Anomaly

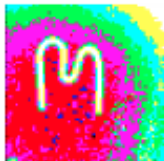


Dosimetry at the Int Space Station ISS

REM Orbital Dose Rate Map ($\mu\text{Gy}/\text{min}$)
D03-W0094 (S/N 1007)
GMT 2012/320 through GMT 2013/045

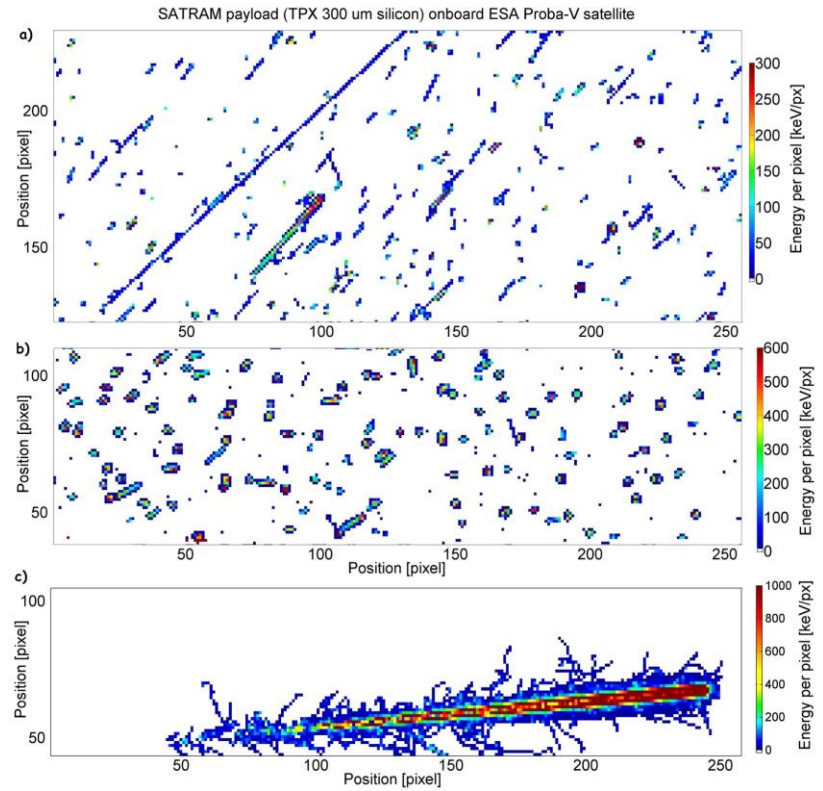
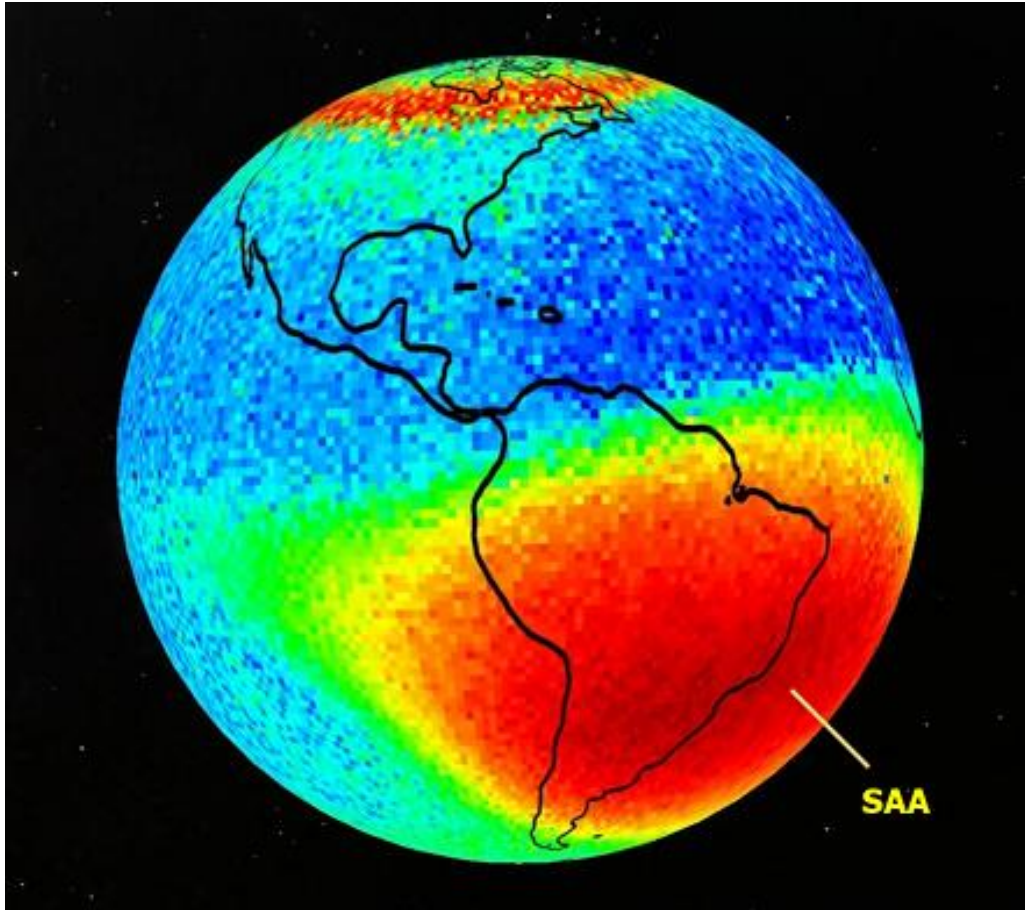


UNIVERSITY OF HOUSTON
Learning. Leading.



dosimetry with TPX on ESA satellite Proba-V

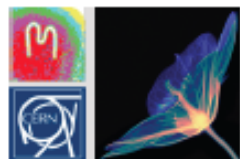
frames in LEO orbit ~800km,
different positions



courtesy Carlos Granja IRAP-CTU (2015)

ion track with ∂ electrons





Acknowledgements – Commercial Partners

COLLABORATION NAME	Medipix2			Medipix3		Medipix4	
	Medipix2	Timepix	Timepix2	Medipix3	Timepix3	Medipix4	Timepix4
ADVACAM s.r.o., Czech Republic	X	X	X	X	X		
Amsterdam Scientific Instruments, The Netherlands	X	X	X	X	X		
Kromek, UK	X	X	X				
Malvern-Panalytical, The Netherlands	X	X	X	X			
MARS Bio Imaging, New Zealand				X			
Quantum Detectors, UK				X			
X-ray Imaging Europe, Germany	X	X	X				
X-spectrum, Germany				X			

so far 8 companies have Medipix licenses

range of application areas still mostly in X-ray imaging & analysis

source: Michael Campbell CERN KT presentation 13 June 2019



Besluit



Future developments ?

much smaller pixels, nearer to matrices for visible
also thin, typically $3 \times 3 \times 3 \mu\text{m}^3$ attoFarad
capacitance: single electron \rightarrow some μV monolithic integrated
front-end in sensor layer multiple stacked layers TSV through-Si-
via copper-to-copper interconnect pitch $\sim 1 \mu\text{m}$

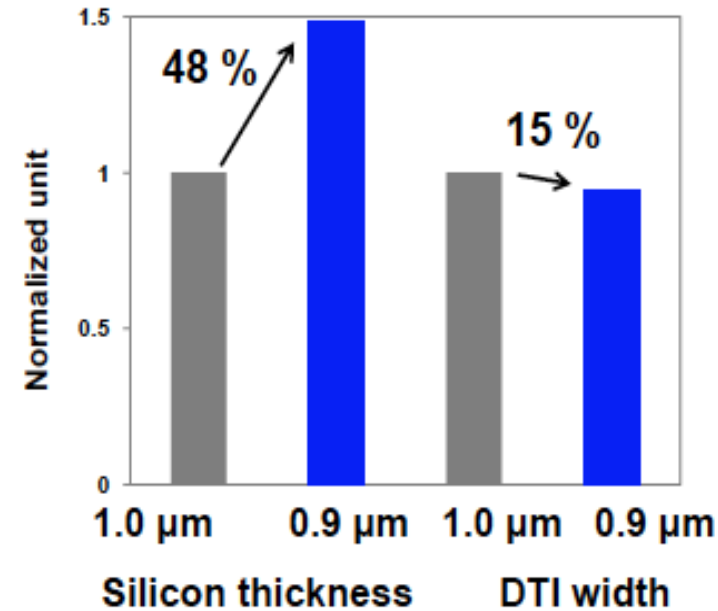
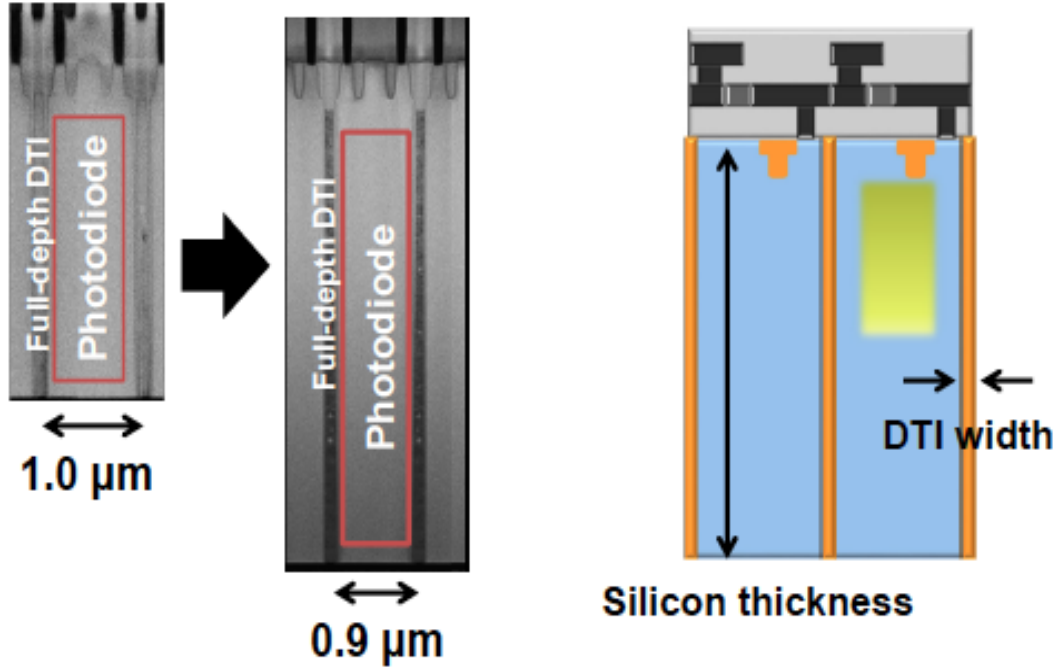
apply recent SONY/Samsung imager technology

well matched to some applications: good
for particle tracking speed, noise, precision
imaging with micro-channel plates visible, neutrons,...



Samsung 0.9 μm imager with deep-etched separation

*1st gen 1.0 μm pixel



ISSCC 2018 paper 5.3

use 4 μm i(earlier 2.7 μm) to improve signal for red light

physics does not really need trenches between pixels

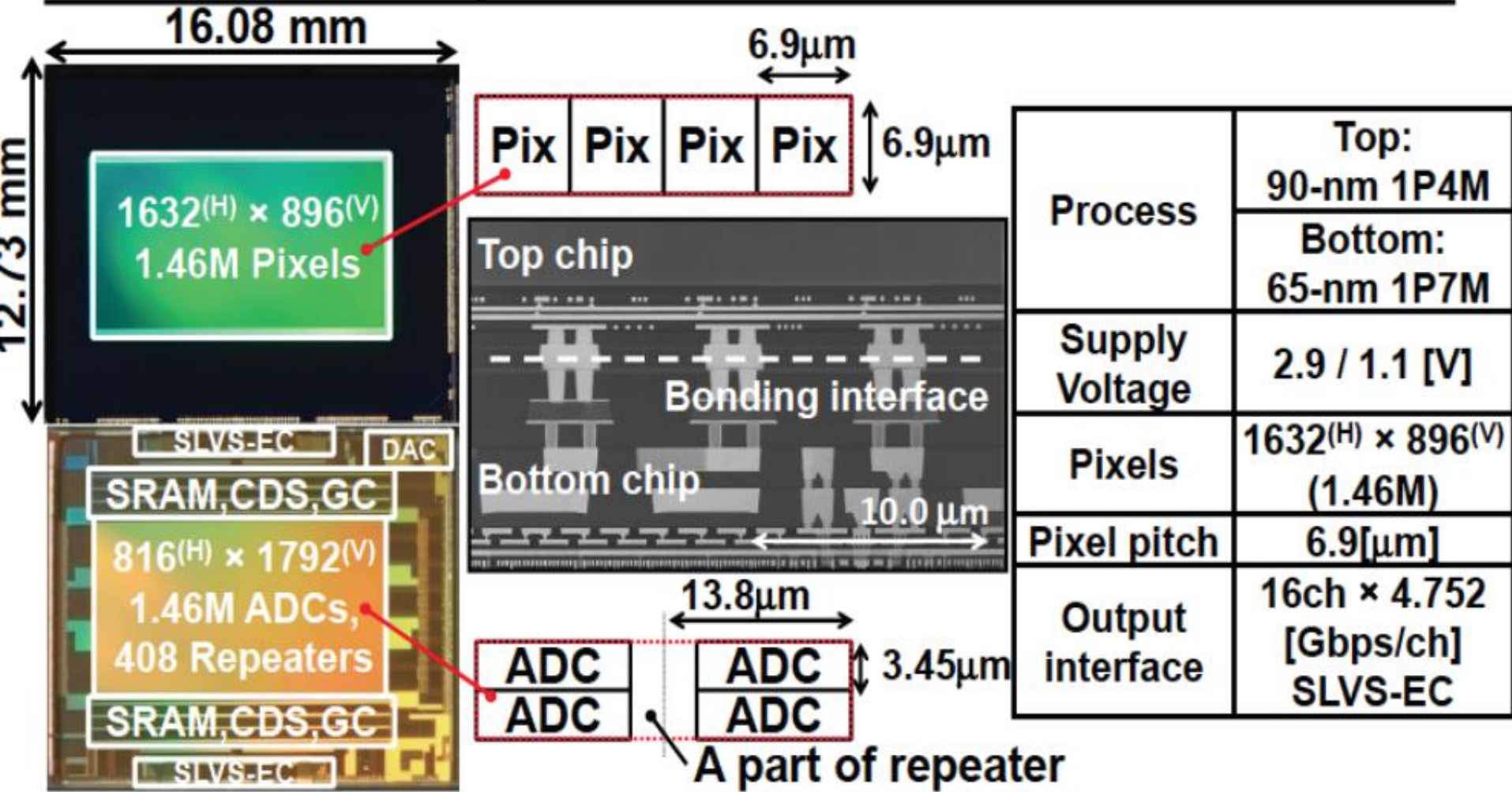
anyway, also delta rays

charge sharing

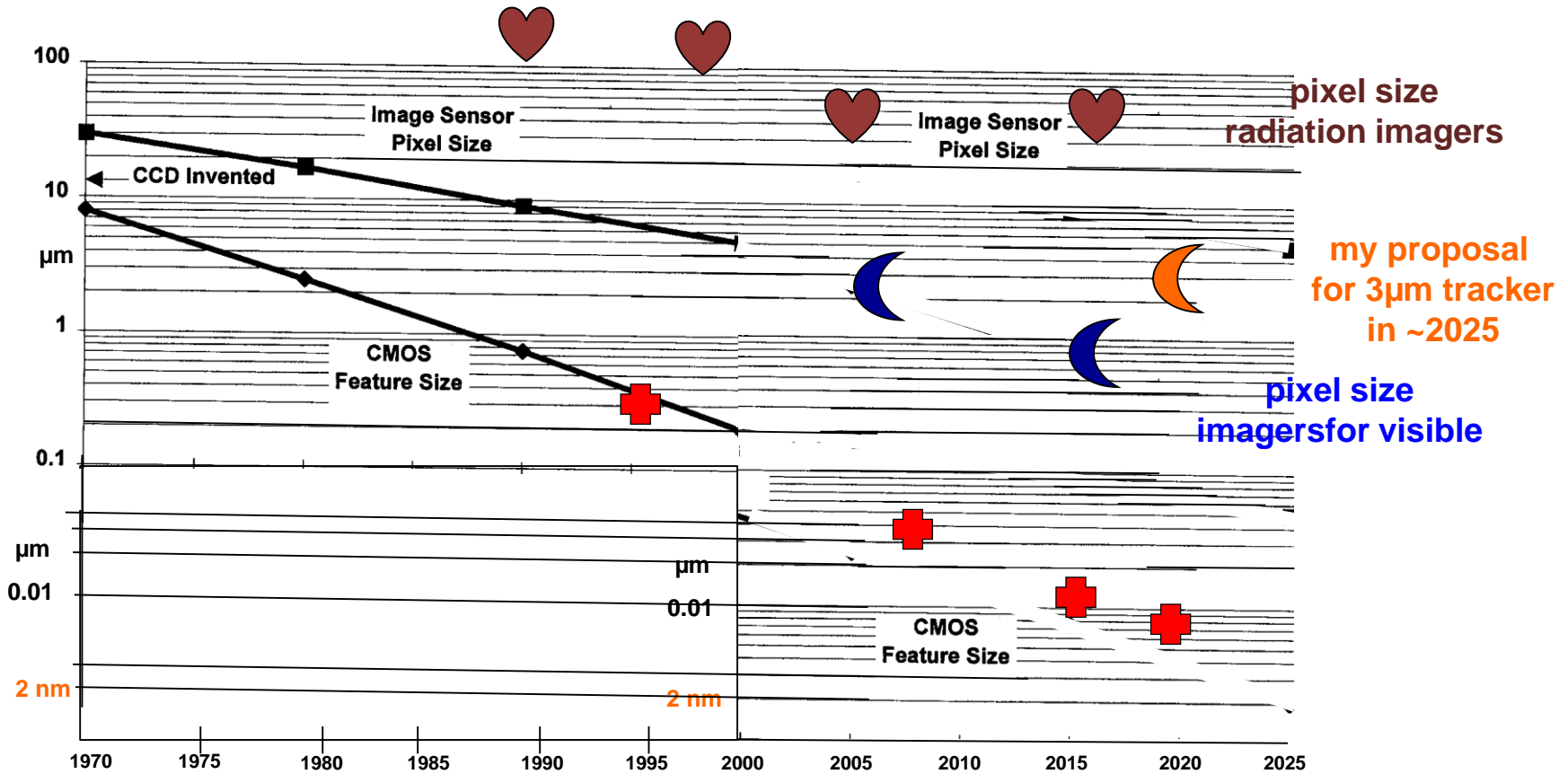


Stacked imager Sony : ADC connected to each pixel

Implementation result



Complexity for CMOS Si imagers



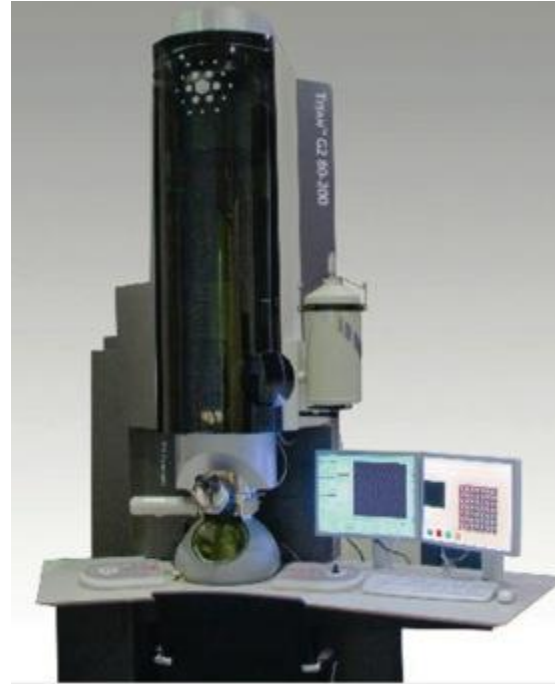
after Eric Fossum, Pixel Workshop Bari, 1996

➔ illustrates growing gap between CMOS features and pixel area in imagers

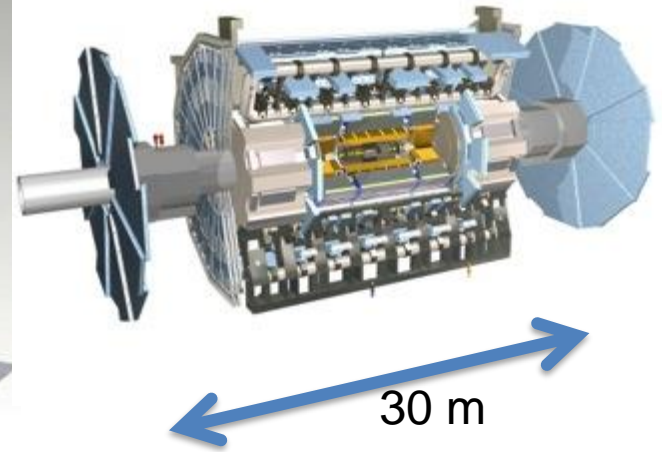
Hoe korter de golflengte, hoe groter de imager



microscoop
zichtbaar licht
fotons $\sim 1\text{eV}$
afmeting 30 cm
 μm objecten

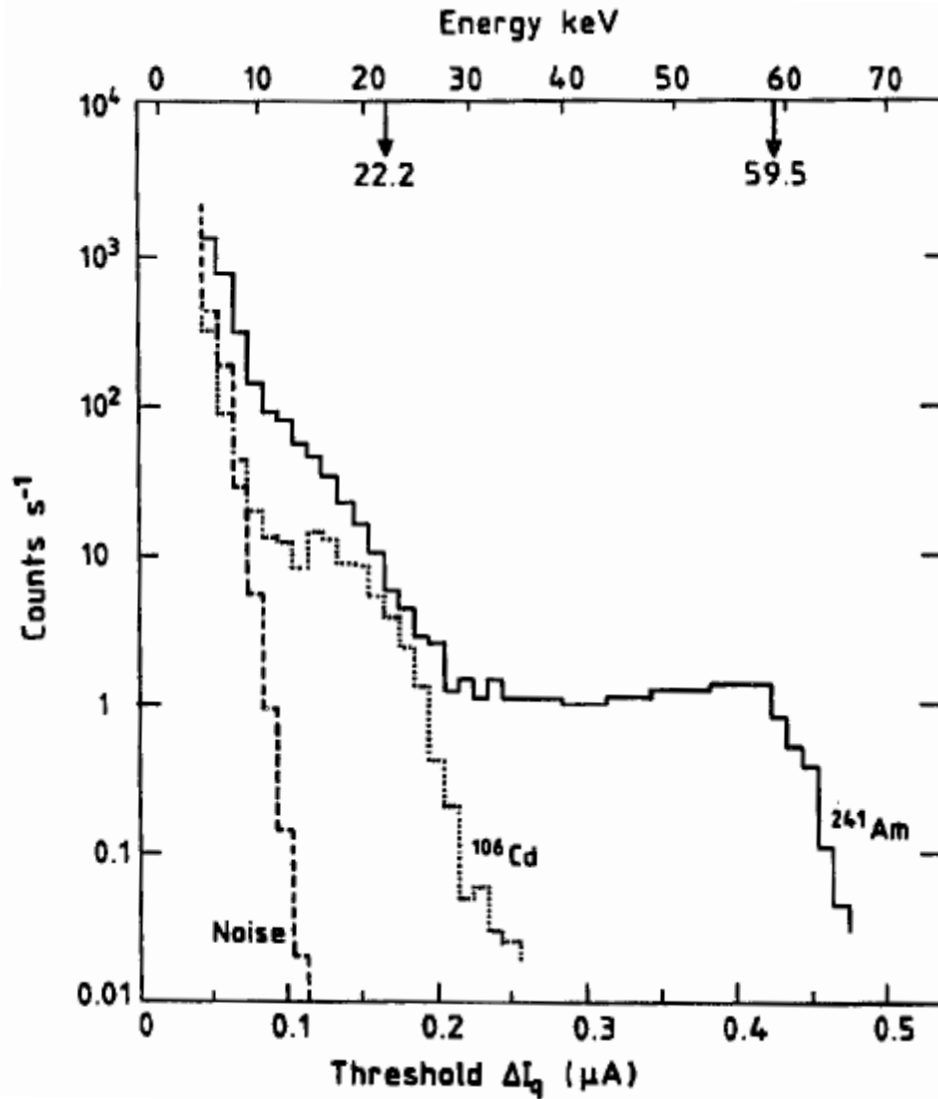


TEM transmissie
electron microscoop
electron bundel $\sim 100\text{ keV}$
afmeting 3 m
 \AA objecten



'attoscope' CERN
met protonen 7 TeV
30 m + 30 km ring
atto meter objecten

Besluit



Timepix Specificaties

CMOS node	250nm
Pixel Array	256 x 256
Pixel pitch	55 μ m
Charge collection	e ⁻ , h ⁺
Pixel functionality	PC (Particle Counting), TOT (Energy) or TOA (Arrival time)
Preamp Gain	~16.5mV/ke ⁻
ENC	~100e ⁻
FE Linearity	Up to 50ke ⁻
TOT linearity (resolution)	Up to 200ke ⁻ (<5%)
TOA resolution	Up to 10ns (@ 100 MHz)
Time-walk	<50ns
Minimum detectable charge	~700e ⁻ → 2.5 KeV (Si Sensor)
Counter Depth/ Overflow	14-bits(11810)/Yes
Max Analog power (2.2V)	6.5 μ W/pix 190mA/chip
Static Digital Power (2.2V)	~500mW@100MHz/chip
Readout (@ 100 MHz)	Serial readout → 9.17 ms 32-bit Parallel readout → 287 μ s

