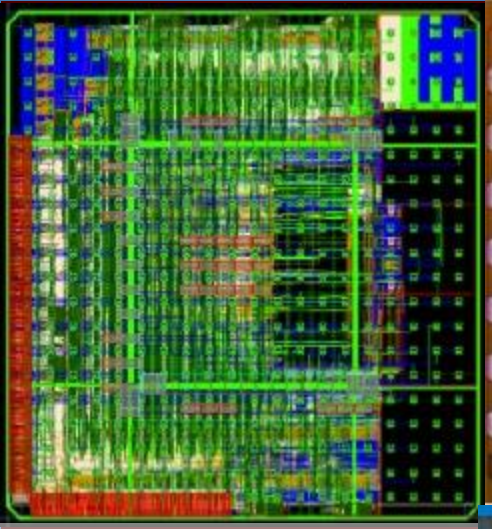

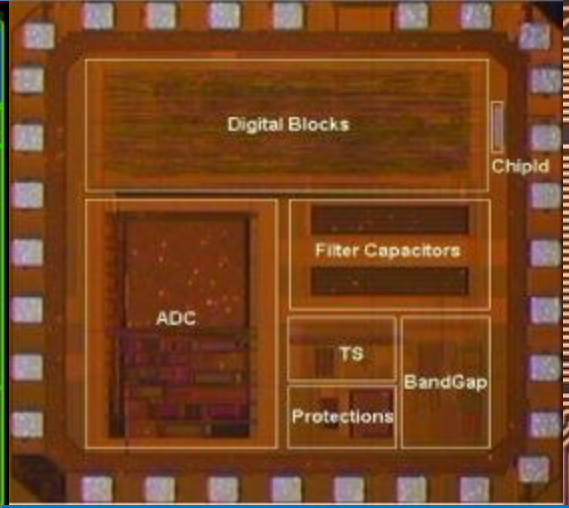

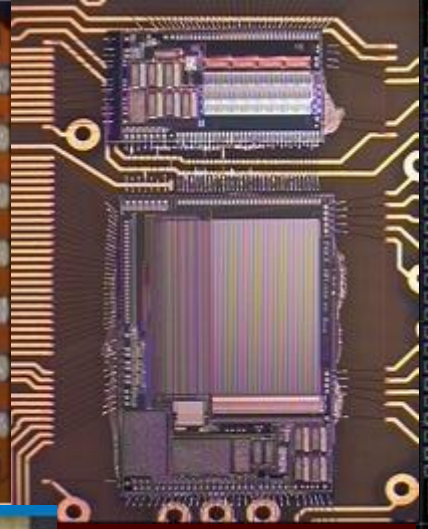

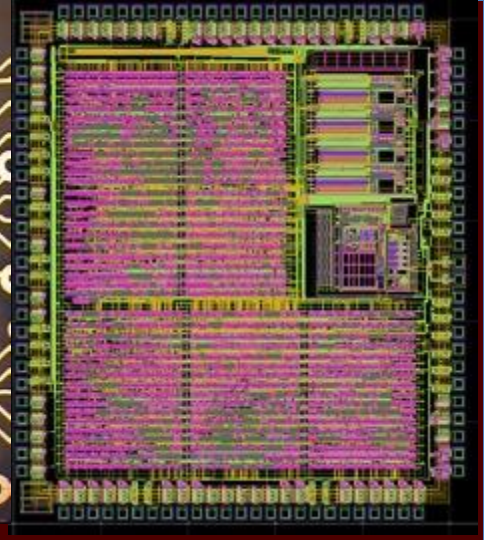

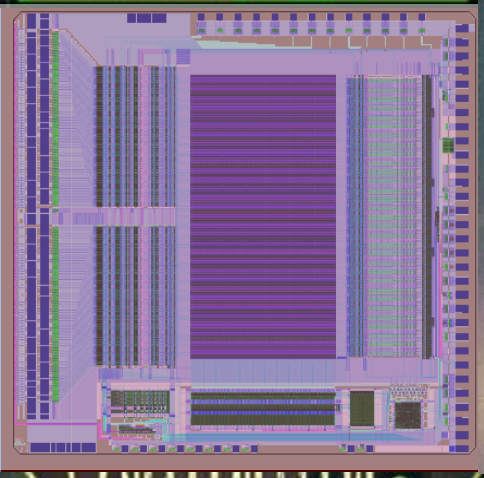

Silicium nano technologie

Pixel Detectors

Timepix en Medipix

Erik H.M. Heijne

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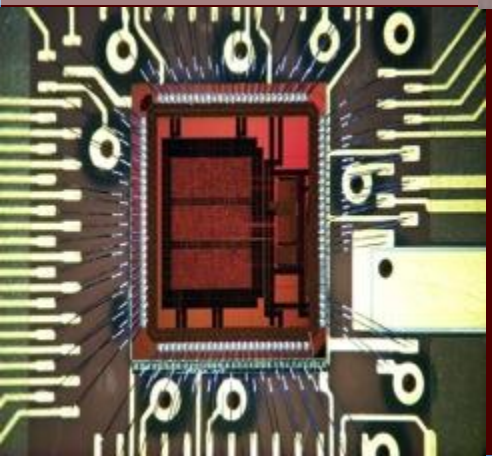
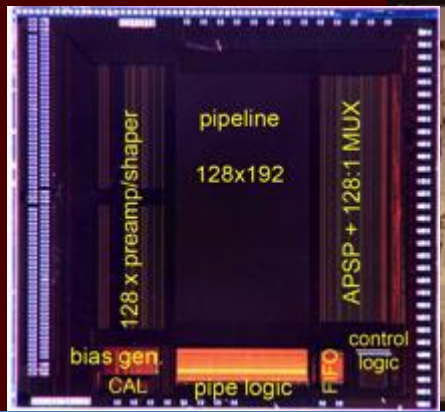
CH 1211 Geneva 23

Institute for Experimental and Applied Physics of the Czech Technical University in Prague

Nikhef Amsterdam

Erik.Heijne@cern.ch





mijn verhaal nu - de metingen morgenochtend
'Elementaire deeltjes vinden met silicium chips, in experimenten en overal'

1. elementaire ioniserende deeltjes: "straling" overal,
   onzichtbaar, maar heel gewoon
   meestal niet gevaarlijk, behalve wanneer TE VEEL

   maar 100g zout eten, of een emmer (heet) water is ook dodelijk !

2. met slimme elektronica kan je deeltjes toch direkt zien

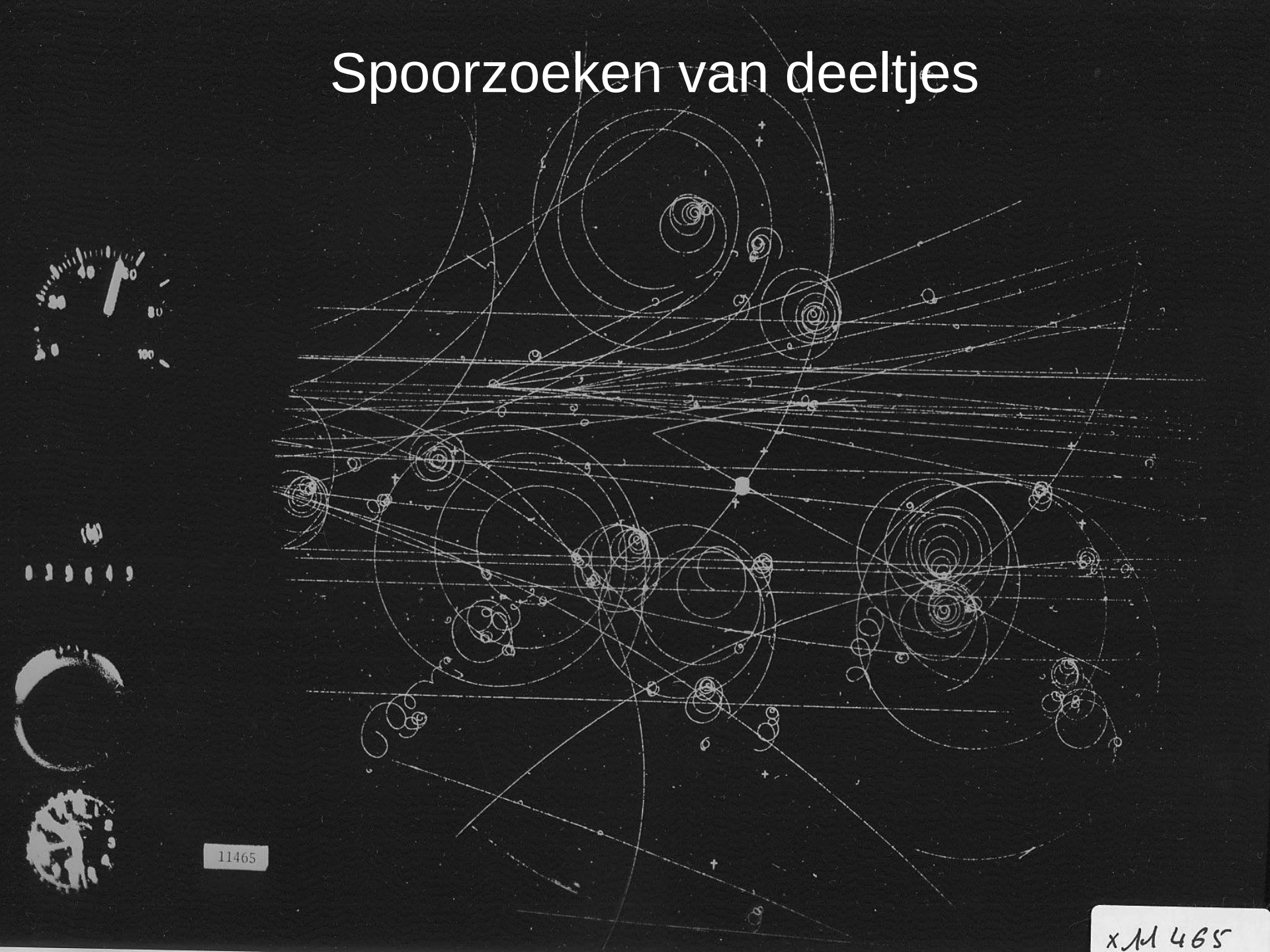
   kijk maar, en morgen ook zelf doen met een Timepix Si chip

3. deze elektronica werd door ons ontwikkeld om de sporen van onbekende elementaire deeltjes te vinden

   alle LHC experimente gebruiken nu deze Si 'spoorzoekers'

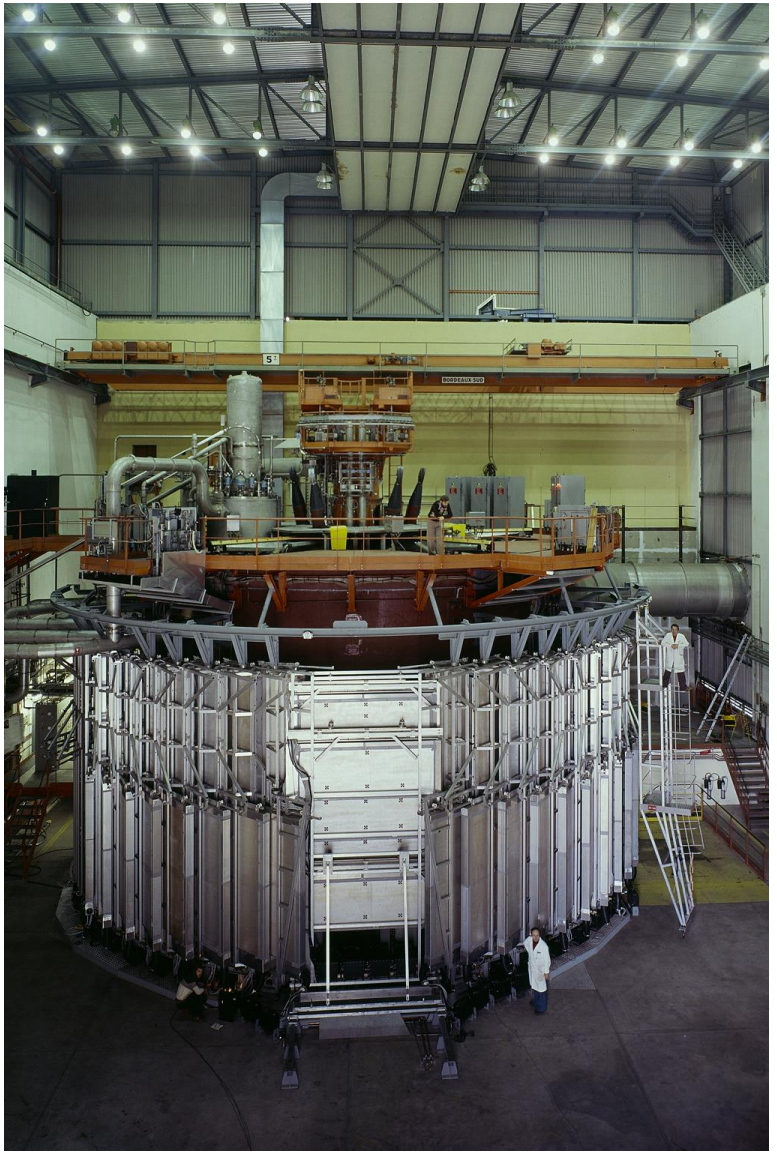
   vroeger veel moeilijker met film, nevelkamer of bellenvat

Spoorzoeken van deeltjes



Spoorzoeken van deeltjes
in 'antieke' bellenvaten 1955 - 1985

Spoorzoeken
grote CERN bellenvaten 1955 - 1985



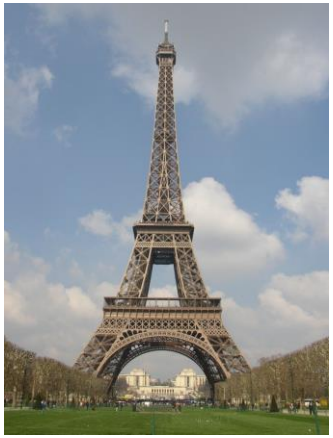
Gargamelle 1970 – 1982
vloeibaar propaan, zwaar

BEBC 1973 – 1984
de grootste in CERN 6.3 M foto’s

STEEN-TIJD

BRONS-TIJD

IJZER-TIJD



SILICIUM-TIJD

silicium (Si) is 2de meest voorkomend element (28%) in de aardkorst:

kristallijn kwarts (SiO_2)

zand - voornamelijk SiO_2

ontwikkeling van de mensheid

gebaseerd op kennis en gebruik van materialen

het is wel ongelooflijk
hoeveel vormen en dingen er zijn,
met maar 92 natuurlijke elementen

en deze opgebouwd met alleen
protonen
neutronen
elektronen

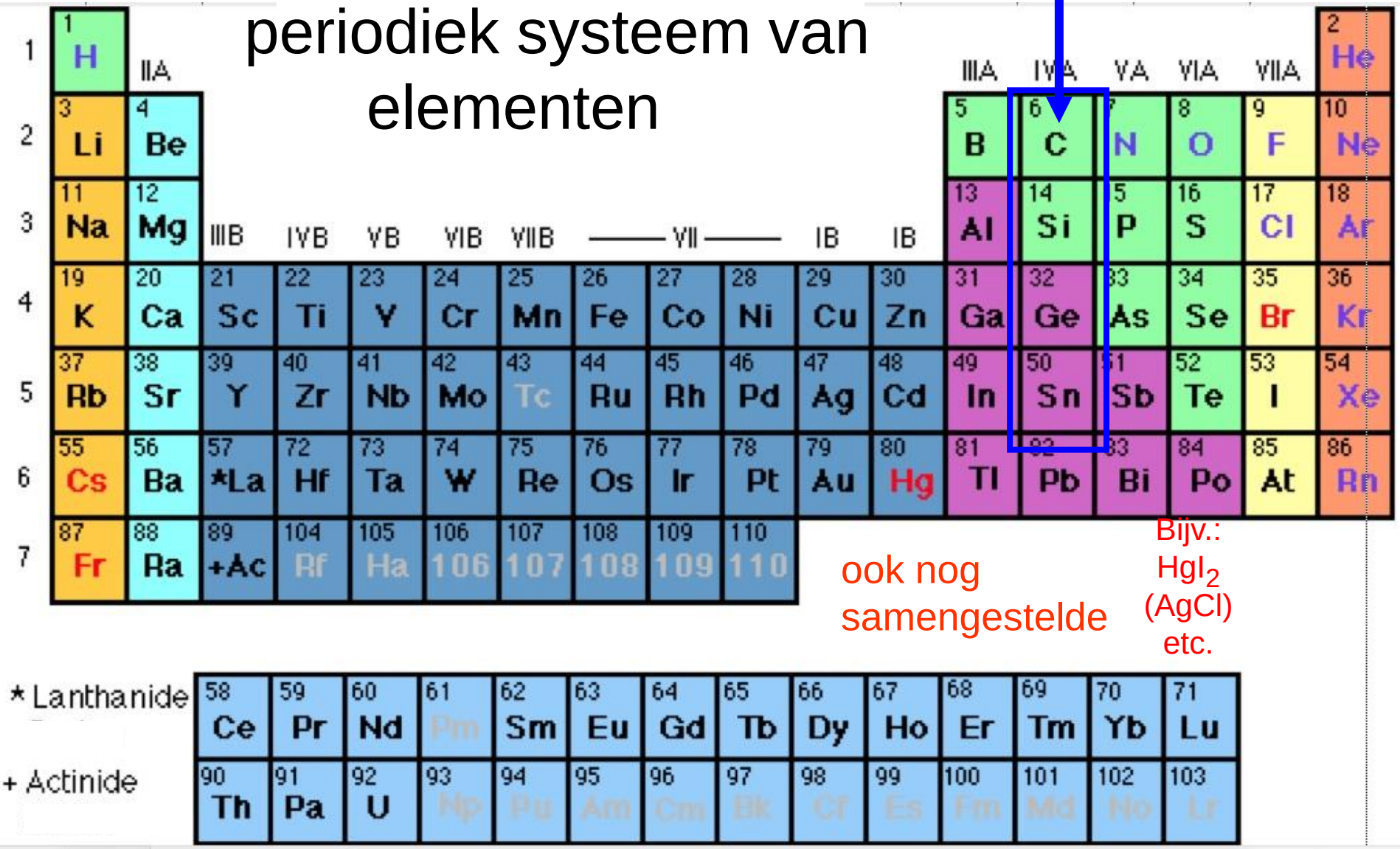
pas ondekt
< 100-150 jaar geleden

en wat komt er verder ?

Mendeleev <1900

periodiek systeem van elementen

Halfgeleiders
Elementen 4-waardig



ook nog samengestelde

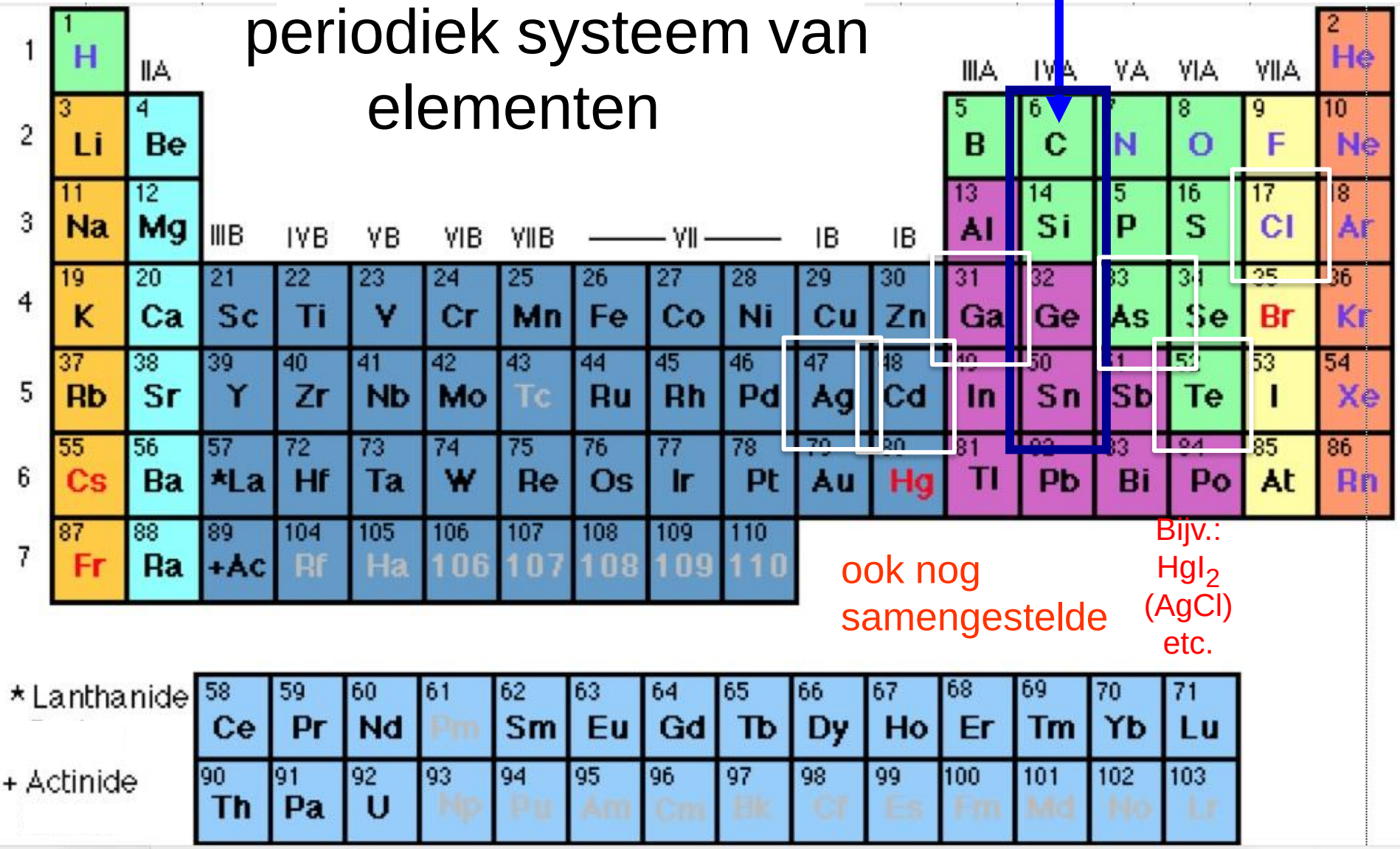
Bijv.:
HgI_2
(AgCl)
etc.

* Lanthanide	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	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

Mendeleev <1900

periodiek systeem van elementen

Halfgeleiders
Elementen 4-waardig



ook nog samengestelde

Bijv.:
HgI_2
(AgCl)
etc.

Isolatoren: alle electronen gebonden

keramische materialen, glas, ...

Geleiders: vol vrije electronen

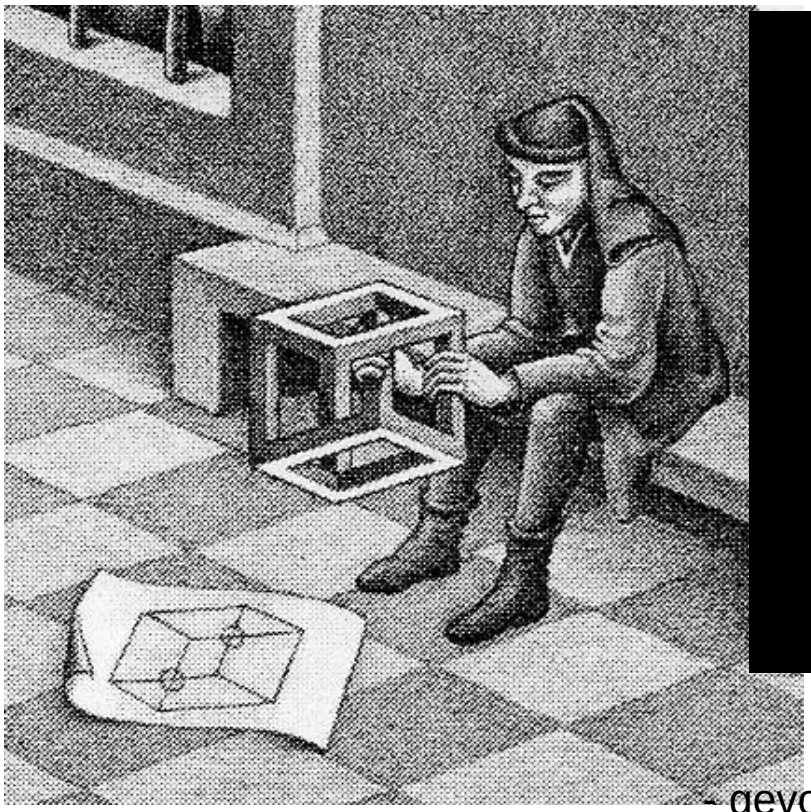
metalen: koper, aluminium, ijzer, ...
elektrische stroom wordt minder bij hogere temp

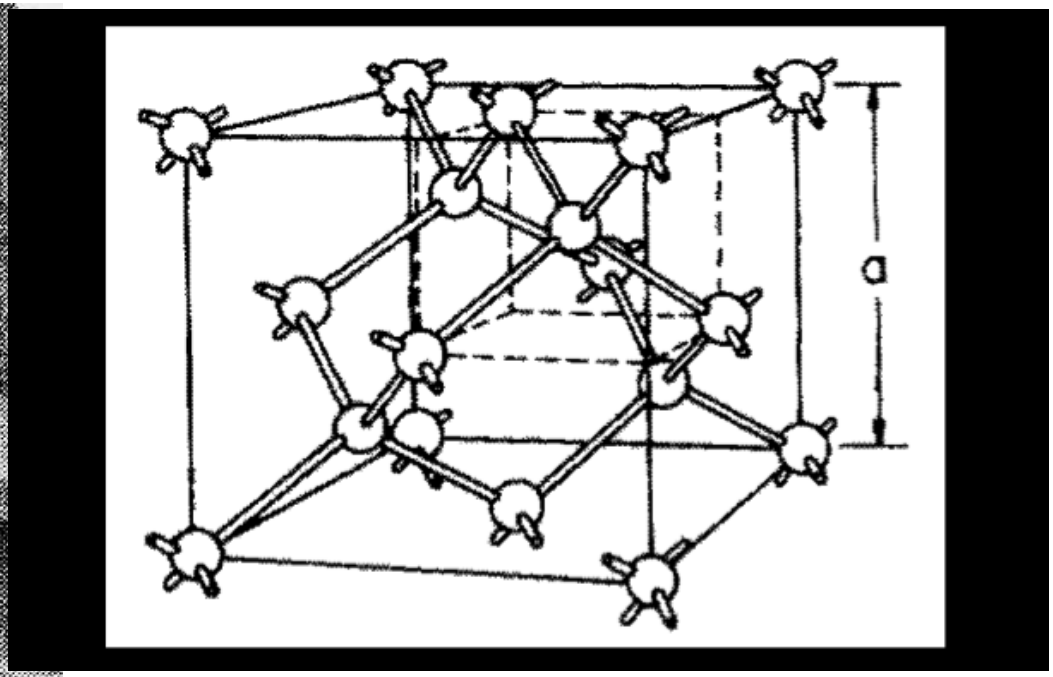
Halfgeleiders:

minder of meer electronen n en ‘gaten’ p

silicium, germanium, gallium-arsenide, ..
elektrische stroom wordt **grote**r bij hogere temp

Silicium als éénkristal is 'halfgeleider'





- gevoelig voor zichtbaar licht (CCD, CMOS kamera)
- ook voor allerlei andere straling (>1.12 eV bandgap)
  lage Z, niet erg efficient voor γ >10keV
- regelbare geleiding over 10 ordes (x10^{10})
- oppervlakte-oxide goede isolator

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

Silicium

'Imagination and Innovation'

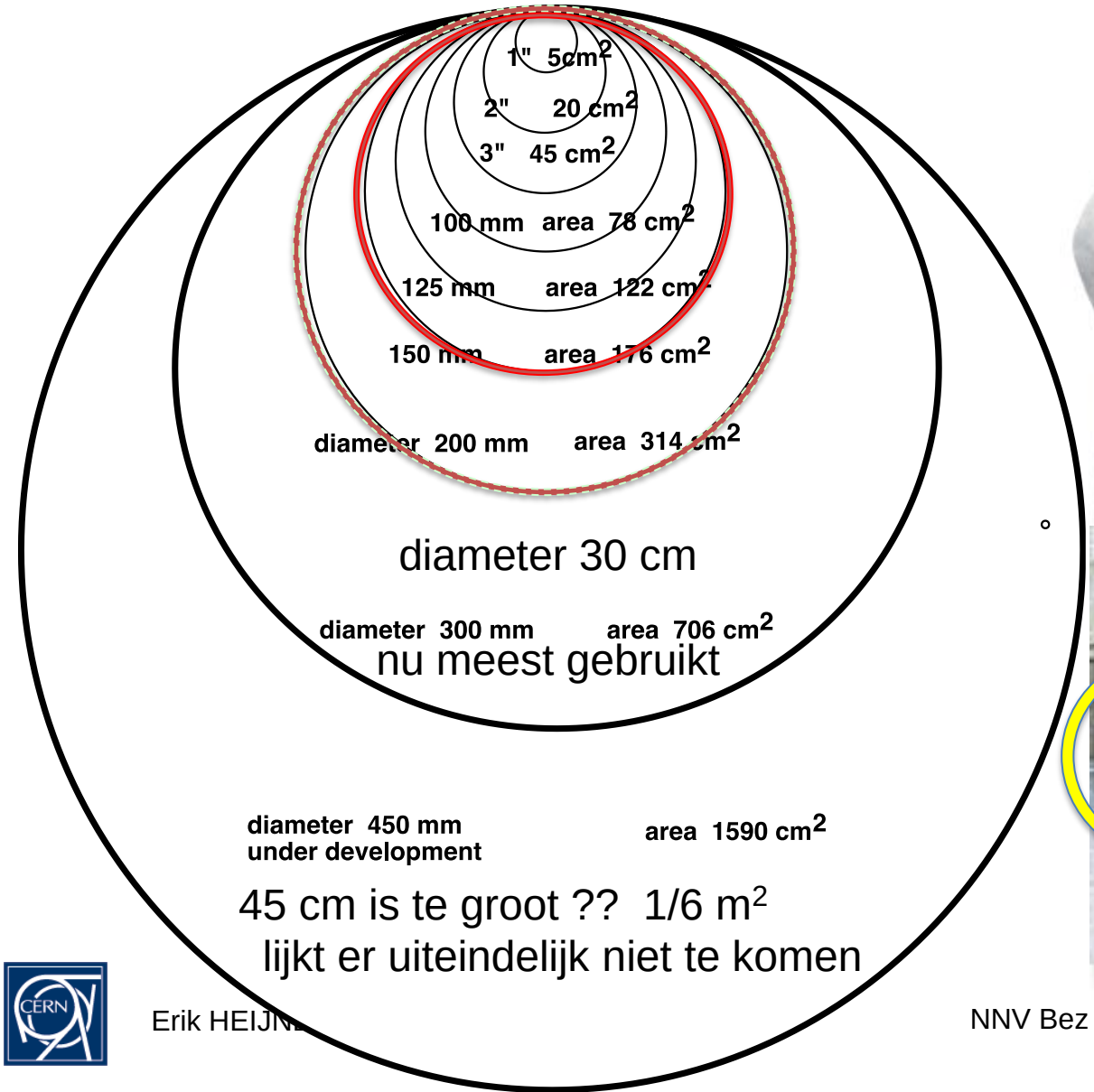
metalen geleiden minder bij hogere T

halfgeleiders juist méér bij hogere T

groeien van silicium éénkristal → Si plakken

1955-2015 **Wafer sizes**

Increase of wafer diameter 3/4” - 450mm



Single Crystal Silicon Ingot

CZ Crystal Pullers
(Mitsubishi Materials Silicon)

ontwikkeling van de mensheid

gebaseerd op kennis en gebruik van materialen

het is wel ongelooflijk
hoeveel vormen en dingen er zijn,
met maar 92 natuurlijke elementen

en deze opgebouwd met alleen
protonen
neutronen
elektronen

pas ondekt
< 100-150 jaar geleden

en wat komt er verder ?

elektronen zijn het meest belangrijk

- chemische eigenschappen van atomen
- de afmeting van de atomen
- ordening in kristalstrukturen

- je kan elektronen sturen met e-m velden

  eerst met 'roosters' in vakuum buizen

  ontdekking: kan ook in halfgeleiderkristallen

  interne elektrische spanningen sturen e of h

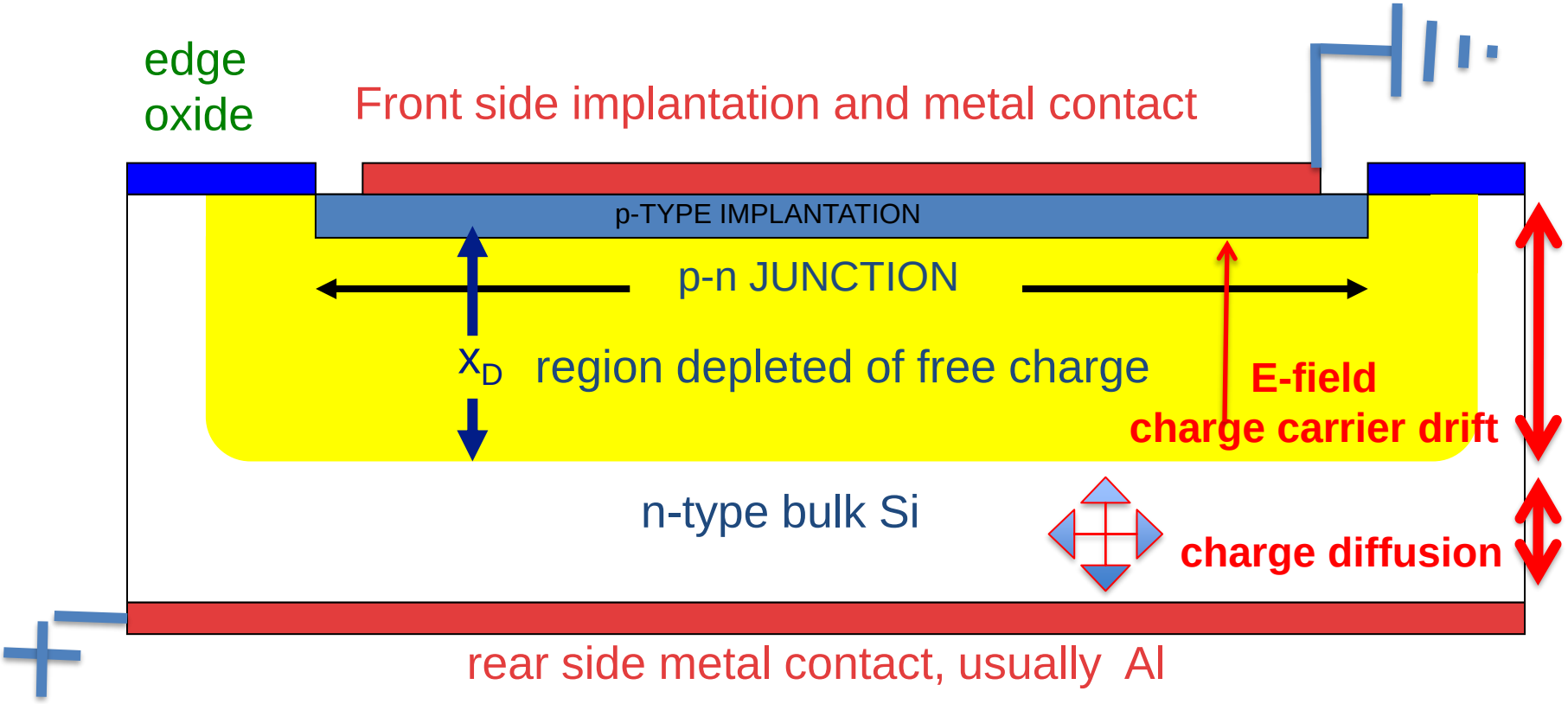
  'explosie' van elektronische instrumenten

- elektronika in kernfysika analyseert van alles

komponenten in elektronische circuits 'IC'

- stroombron of spanningsbron
- weerstand: energie van stroom → warmte
- capaciteit bewaart een hoeveelheid e-lading
- diode 'gelijkrichter' blokkeert/geleidt stroom
- transistor regelt hoeveel stroom er loopt
- geheugen cel: samenstel van transistors
  kan ja/nee of een hoeveelheid onthouden
- allerlei logische funkties mogelijk
- converter analoog signaal → binair ADC
- converter tijd → binair TDC

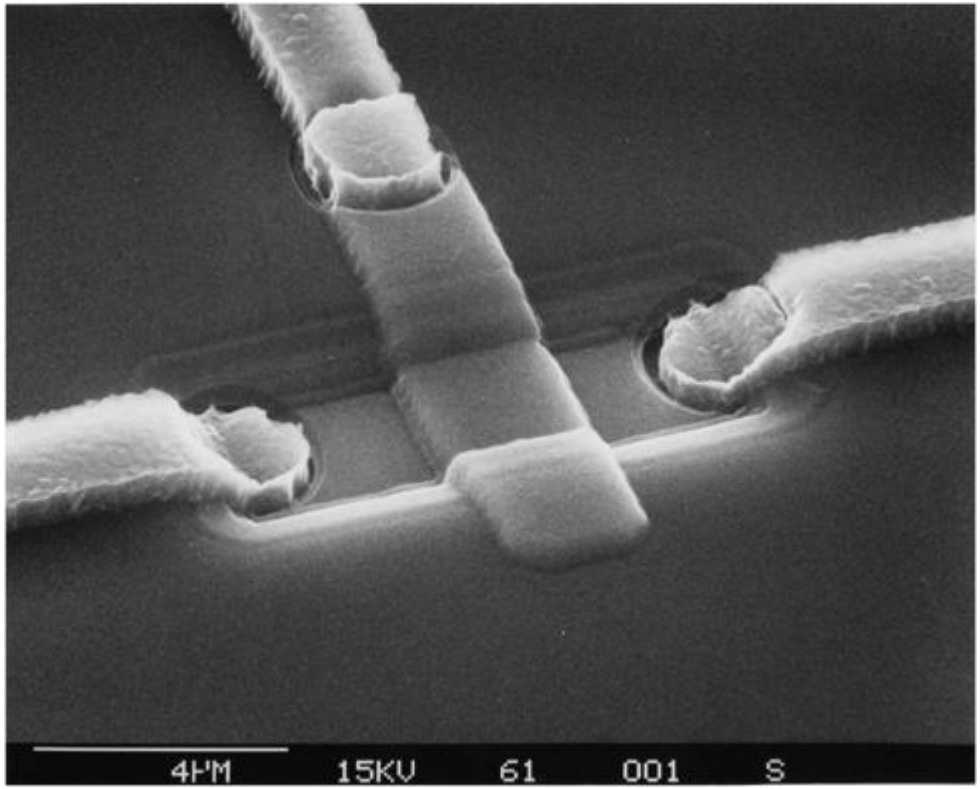
Schematic of thick Si diode for detection



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

x_D LARGE, up to 1000µm, because of HIGH RESISTIVITY ρ of BULK Si

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

Monteren van de CMS Si tracking detektor

source: CERN- CMS

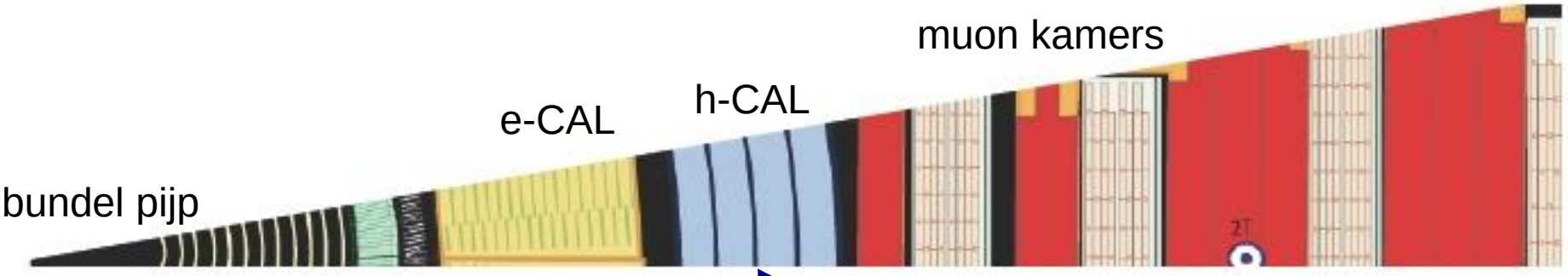
ATLAS of CMS zijn eigenlijk
één heel grote elektronische camera

Ze zitten vol met ICs: silicium chips

IC Integrated Circuits

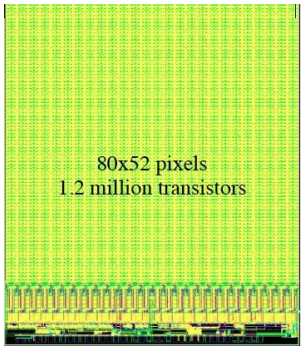
ieder >> een miljoen, zelf bedachte chips

Een paar van de ASICs in CMS

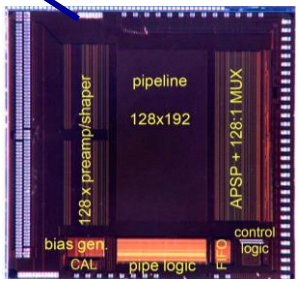


Si microstrip tracker

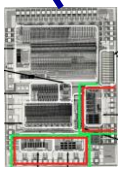
pixel detektor



PSI46 pix det
16 800 chips
66 M segments
1 m^2 Si sensor



APV25 Si det
110 000 chips
9.3 M segmenten
198 m^2 Si sensor



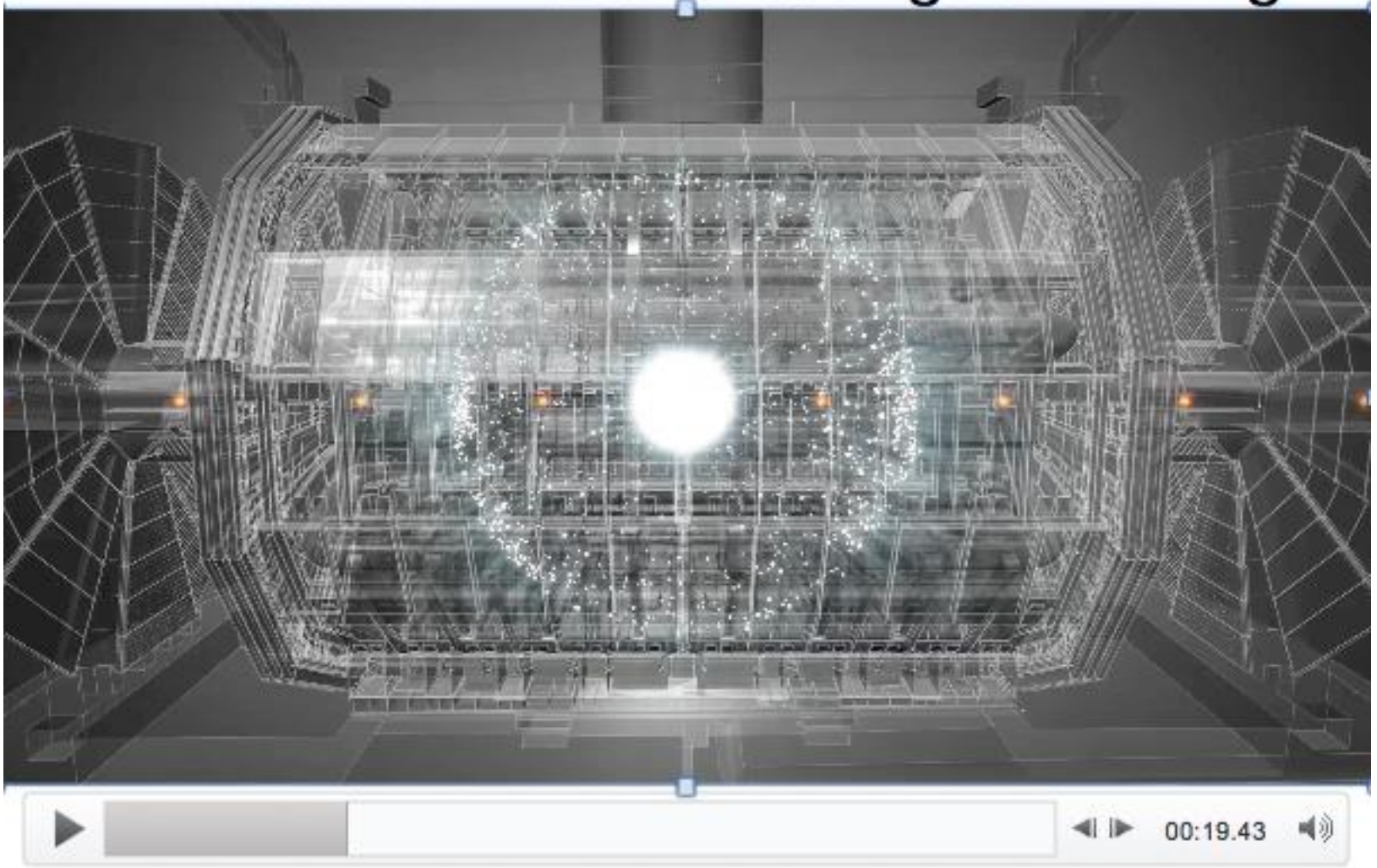
QIE8 calorimeter
220 400 chips

MAD muon det
181 000 chips
25 000 m^2 gasgevuld

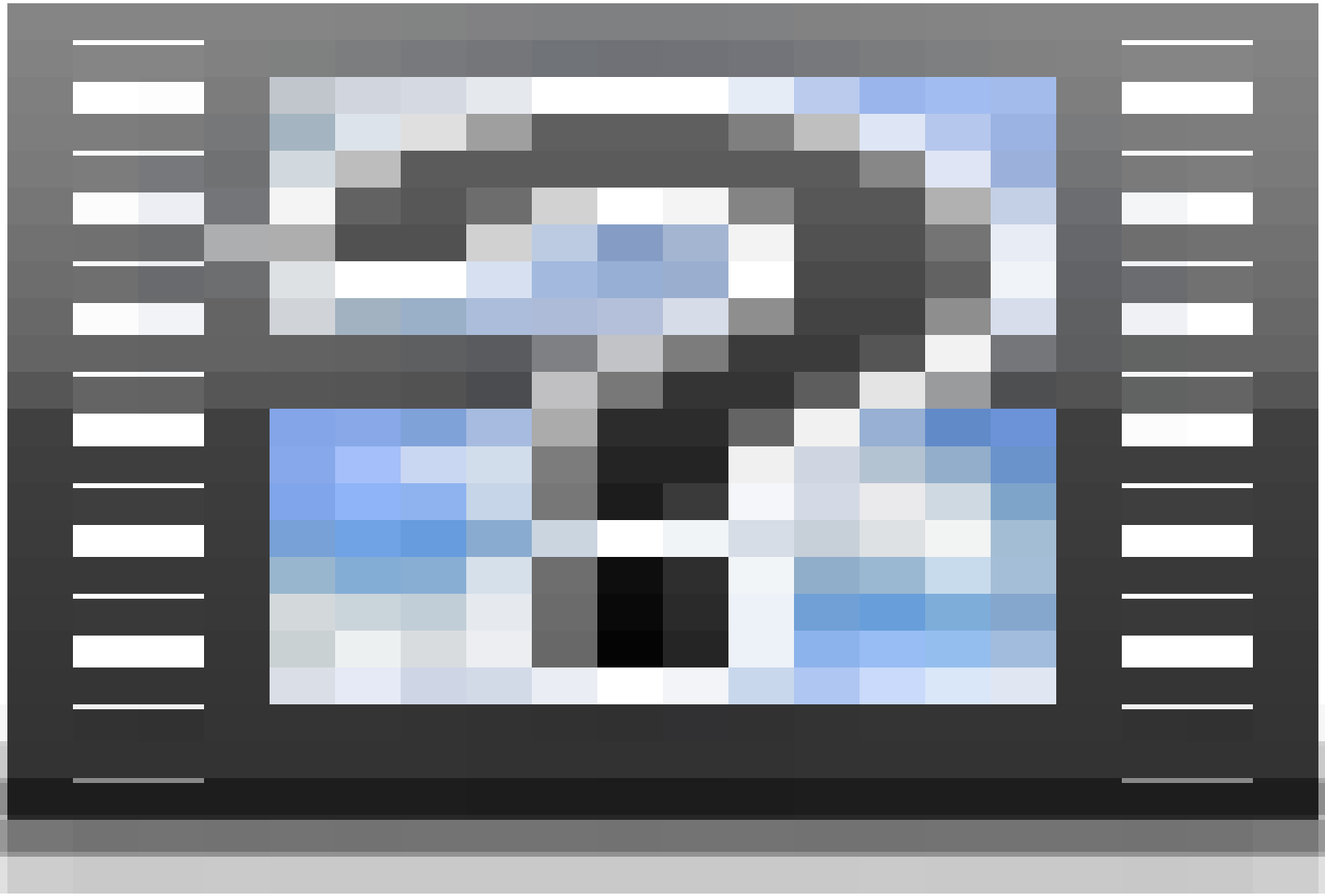
Chips to scale 1 cm

Totaal CMS
ong. 1 milljoen chips
waarvan 700 000 ASICs

Animatie van Bunch Crossings en Timing



Animatie van Bunch Crossings en Timing



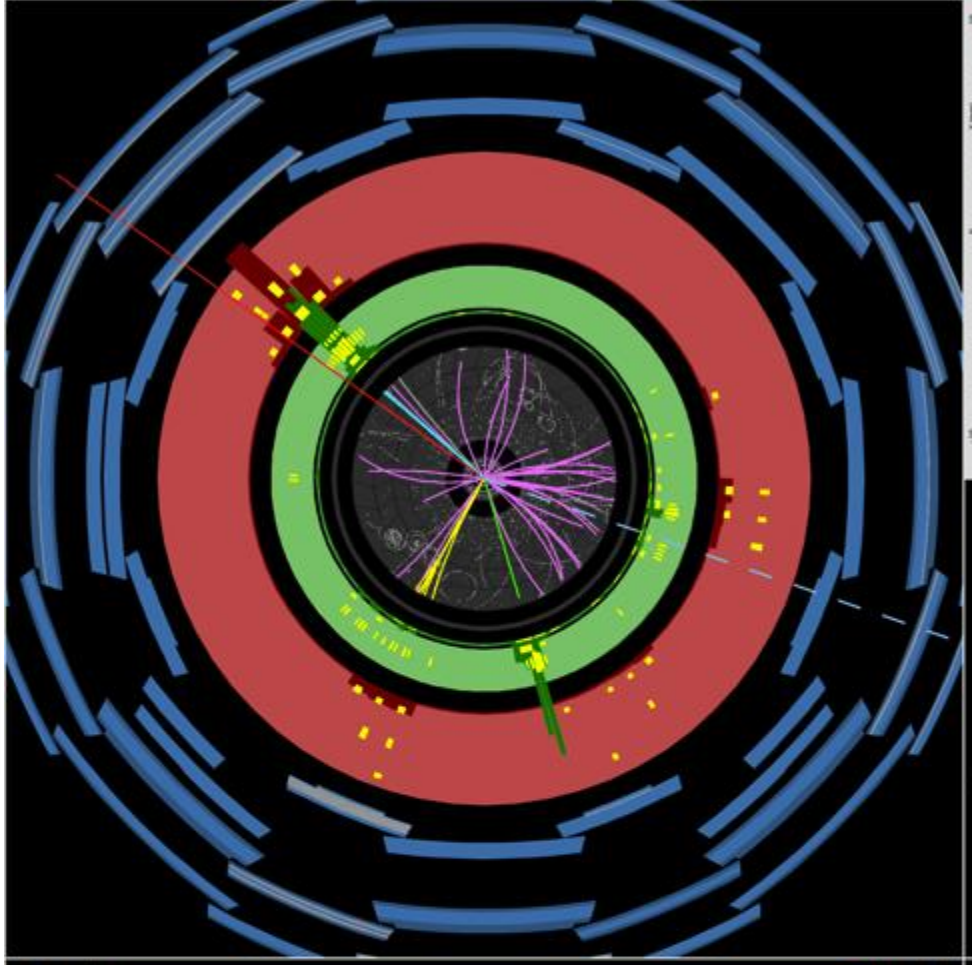
Imaging Now
All Electronic
with 3-D
Reconstruction

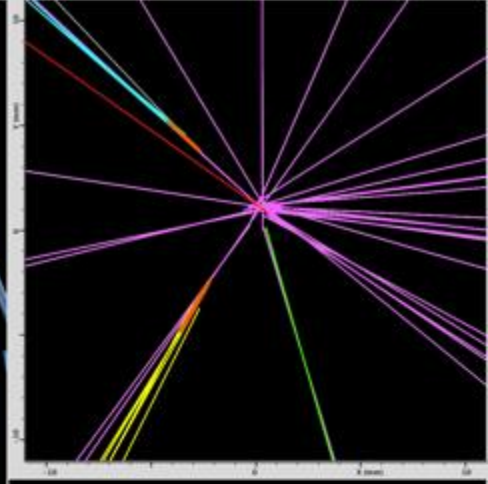
Many Tracks
and 2 “Jets”

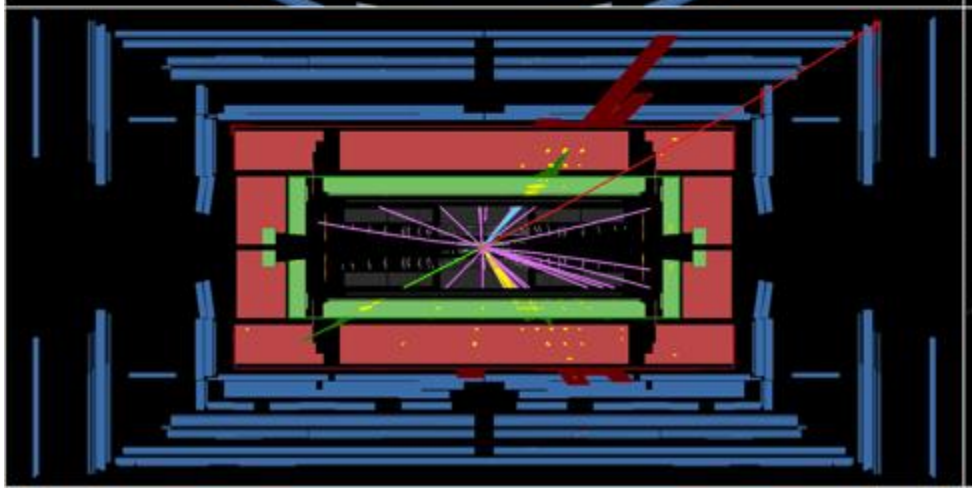
40 million / sec

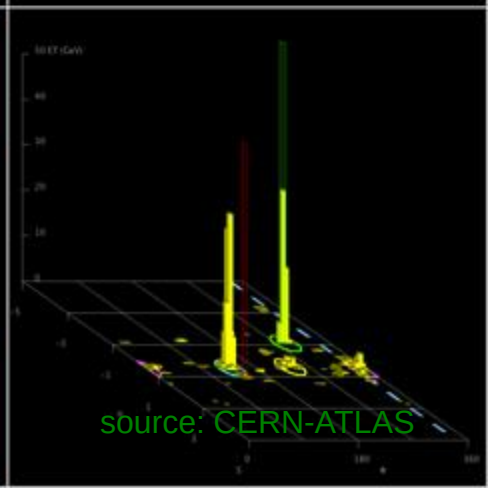
Secondary
Vertex:
a short-lifetime
particle is a
messenger for
something new

see blow-up







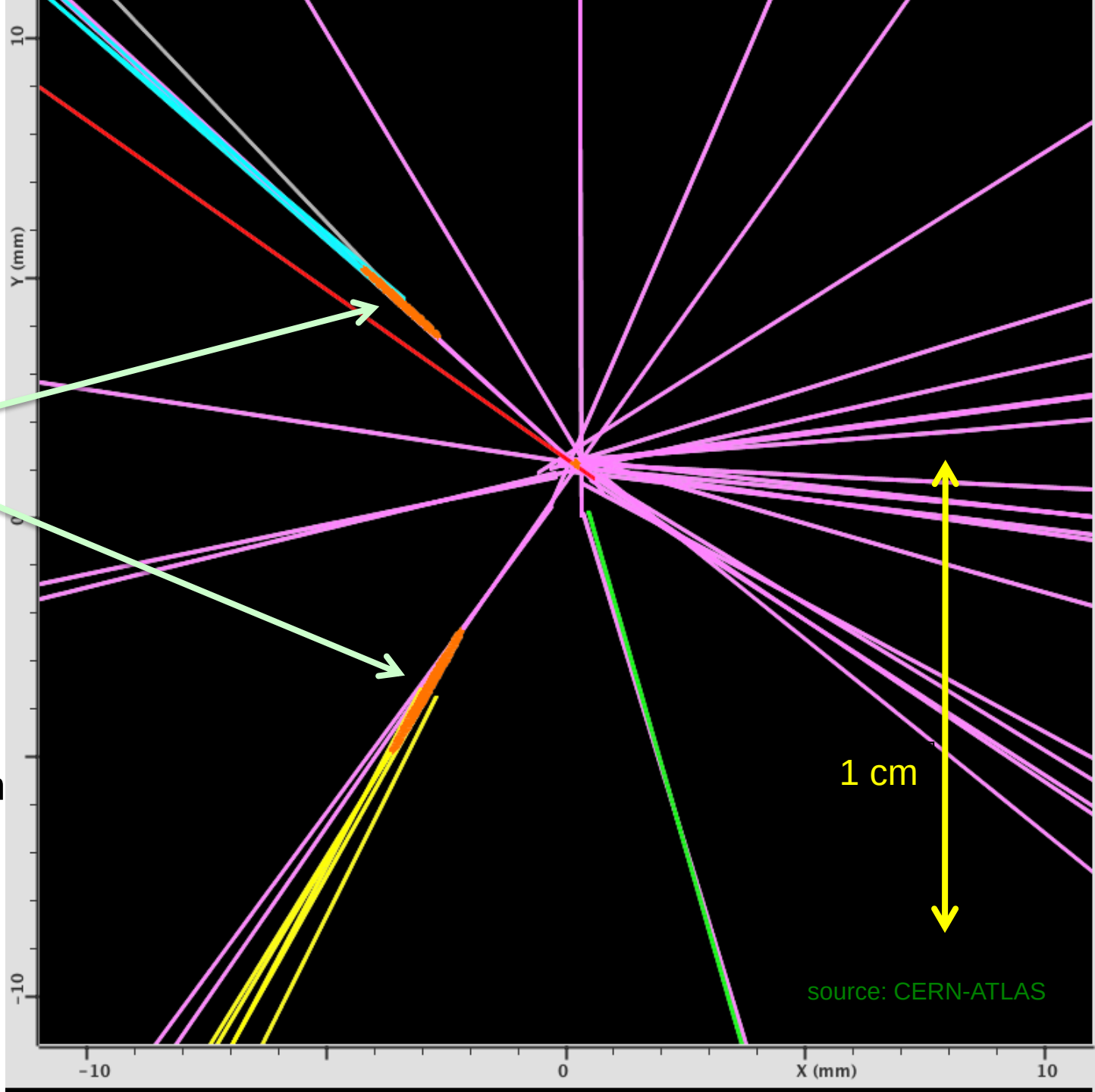


ATLAS

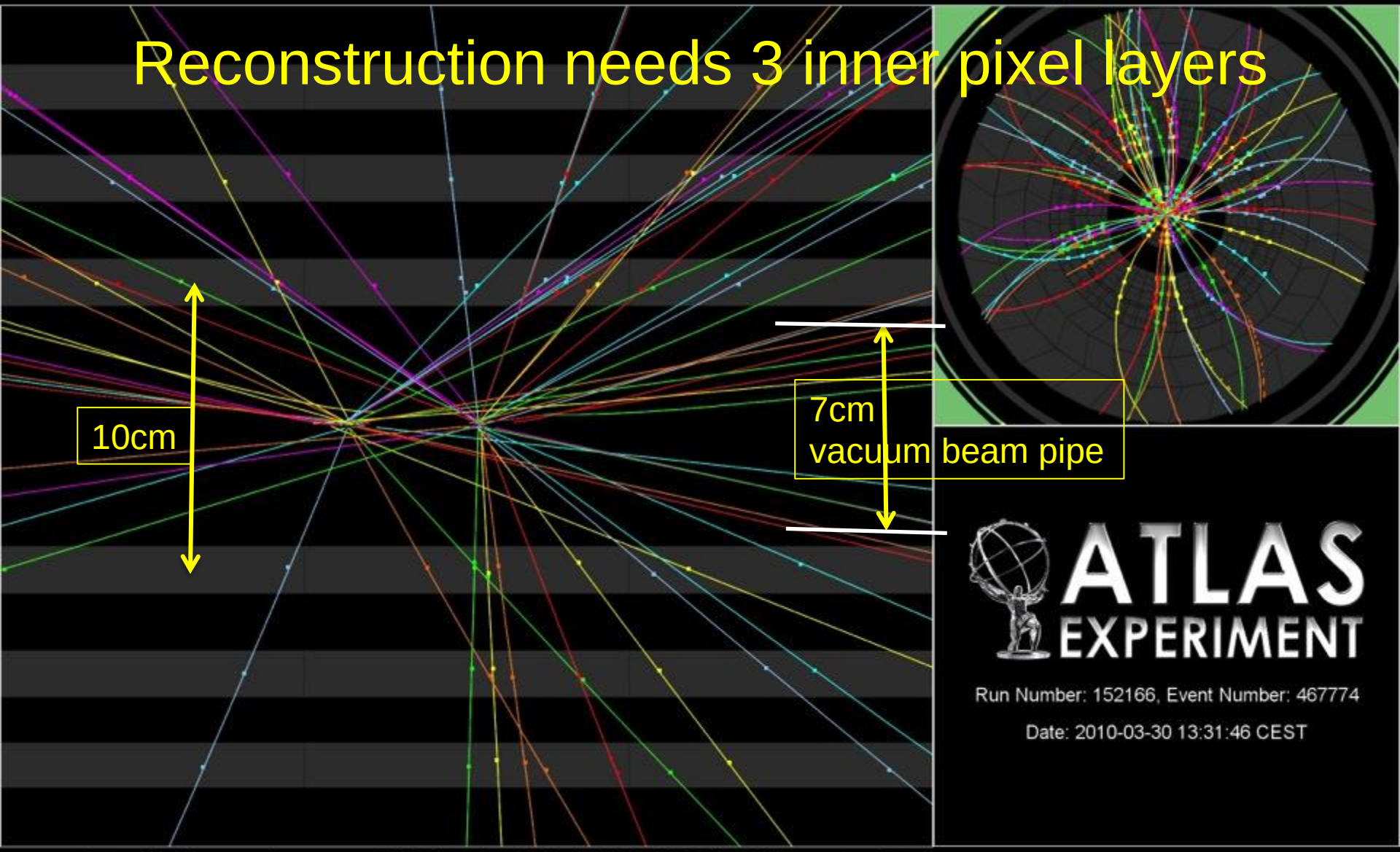
Details around
Primary Vertex

Two Secondary
Vertices

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



Collision Event at 7 TeV with 2 Pile Up Vertices



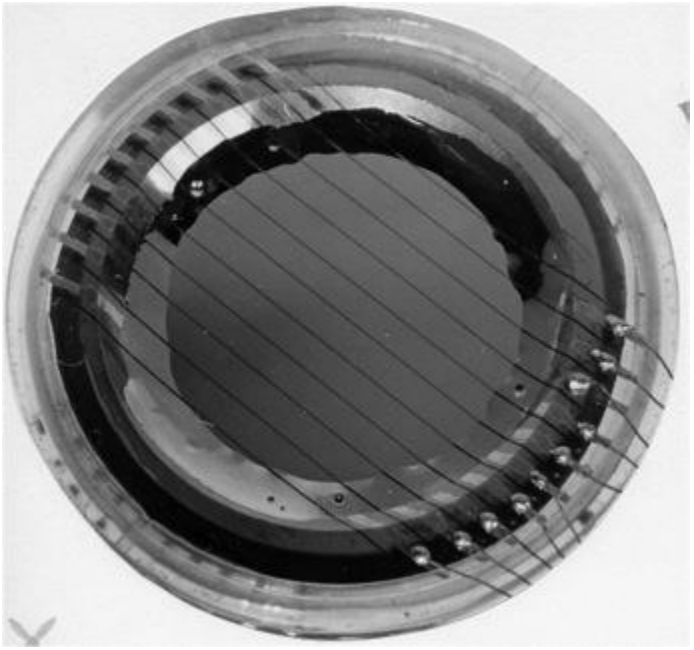
http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

source: CERN- ATLAS

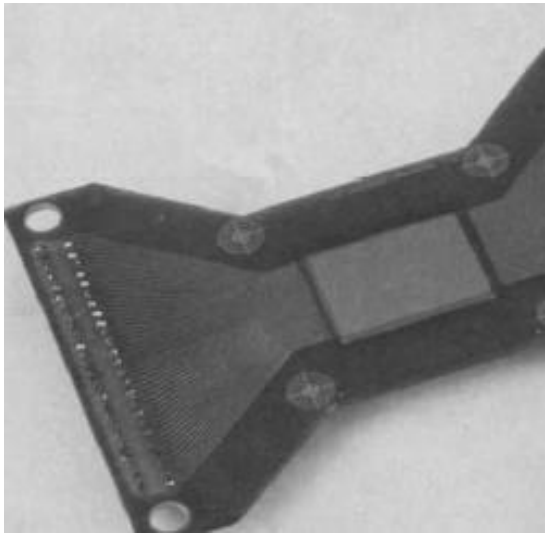
ATLAS binnenste Si pixel lagen

source: CERN- ATLAS

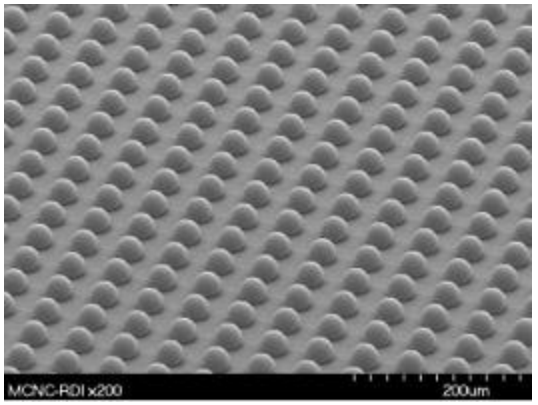
DIODE SEGMENTATION



~1965
PHILIPS – Amsterdam -IKO
100 x 1370umx1370um

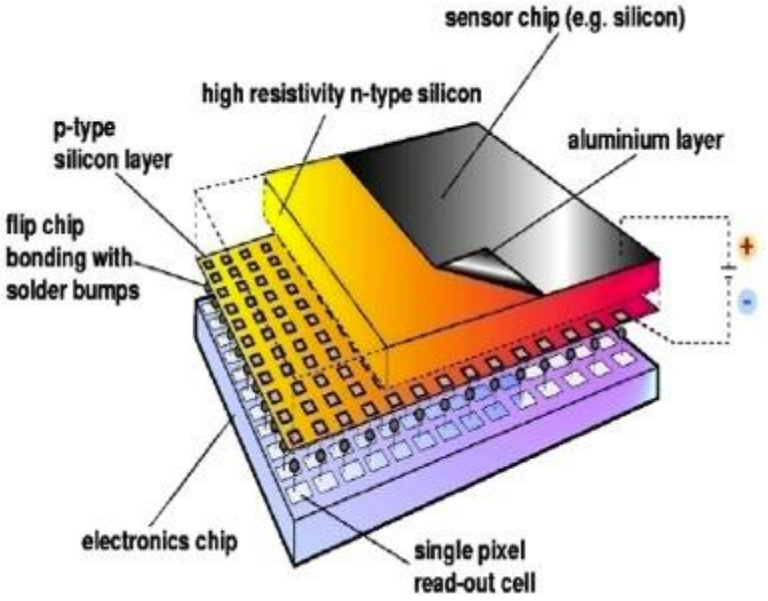


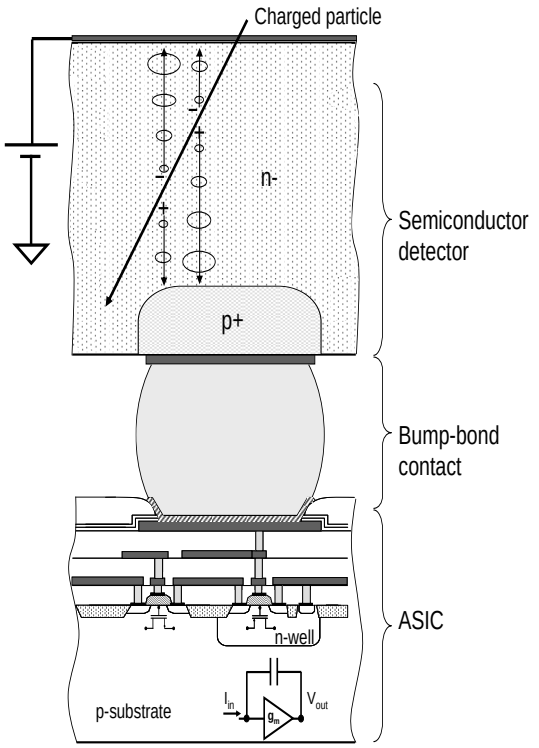
1980
CERN / ENERTEC
100 x 4000umx200um



~2000
CERN / MEDIPIX
65000 x 55umx55um

Hybrid Silicon Pixel Detectors

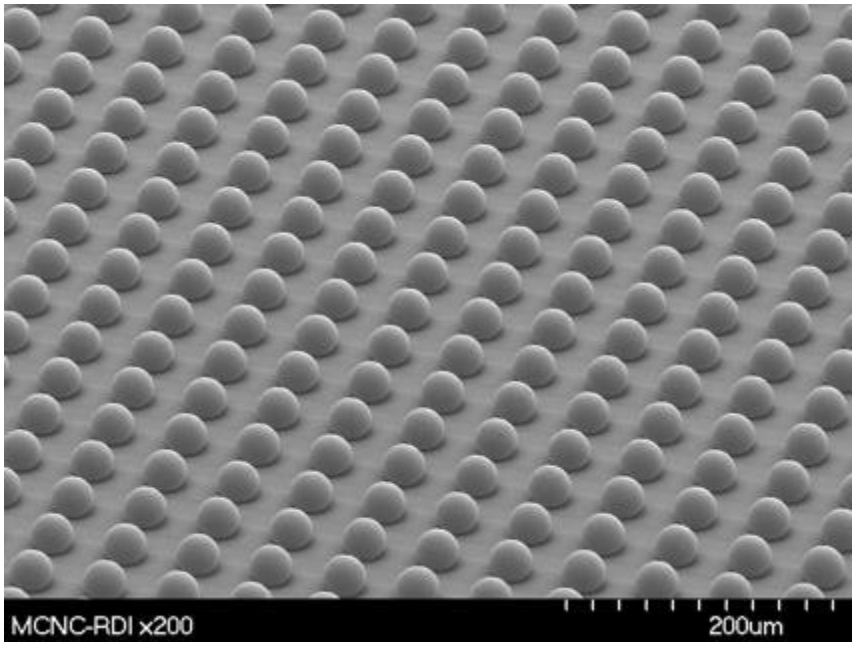




Standard CMOS can be used allowing on-pixel signal processing

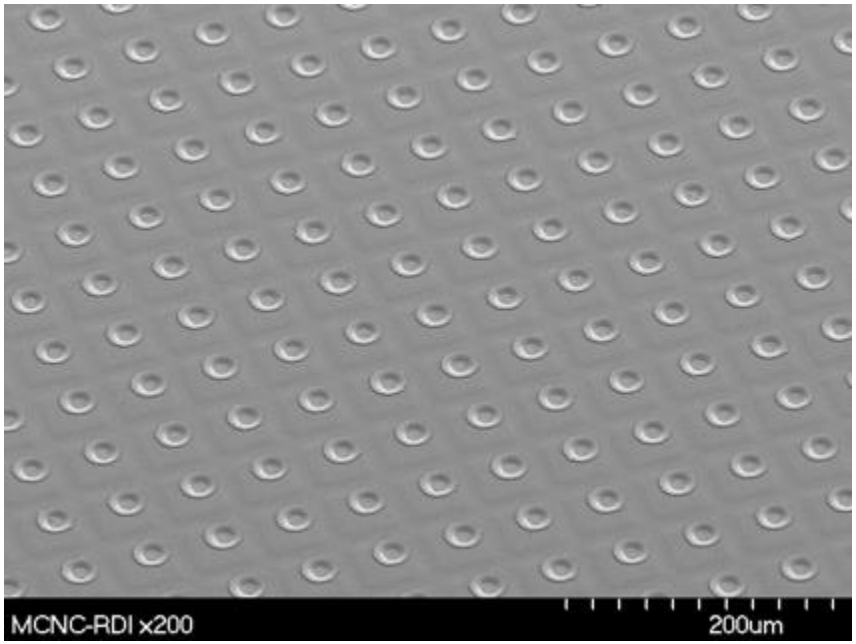
Sensor material can be changed (Si, GaAs, CdTe..)

Hybride pixel detektor Medipix



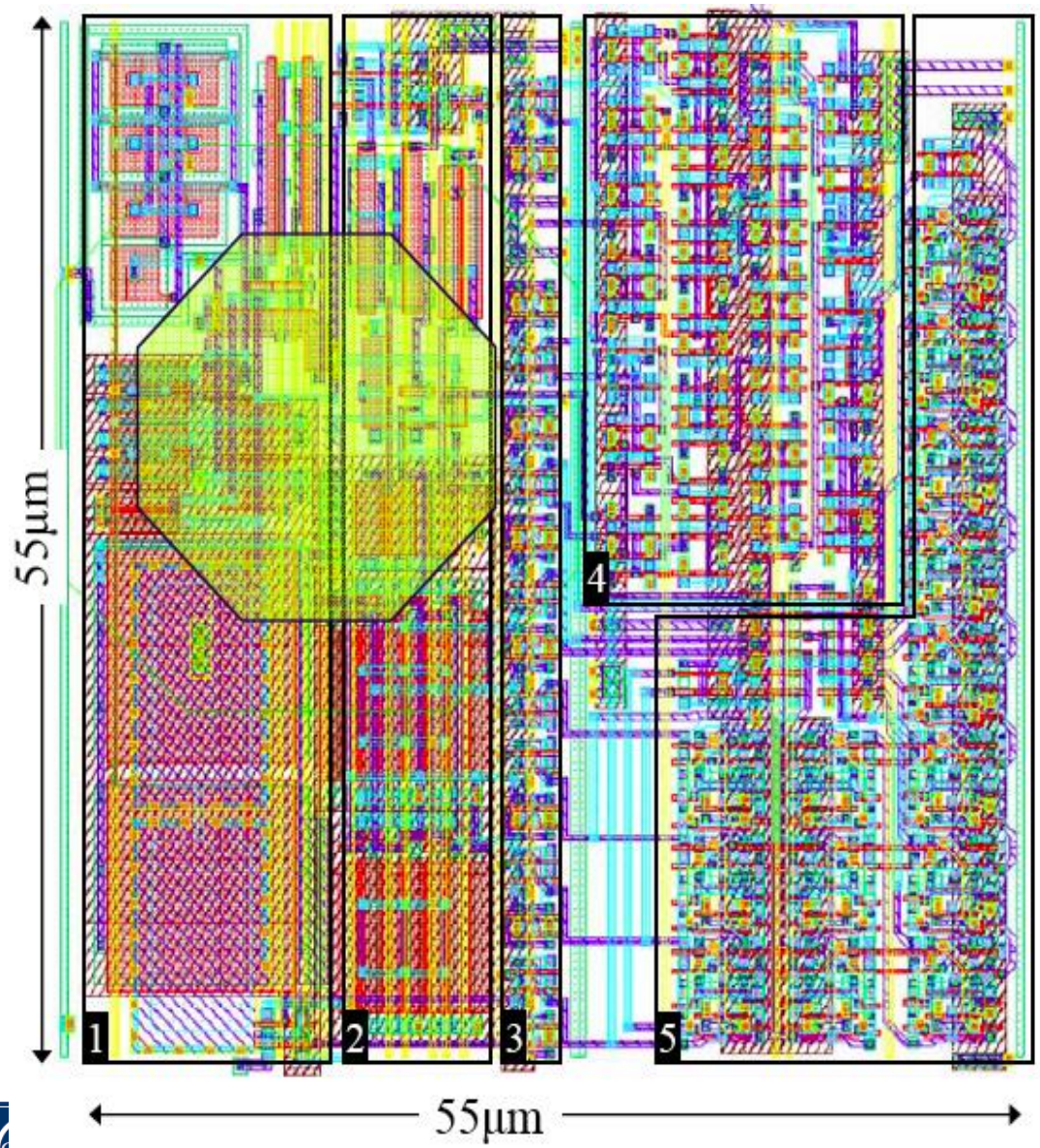
SEM fotos gemaakt door
MCNC-RDI, DURHAM NC - USA

PITCH 55 µm



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

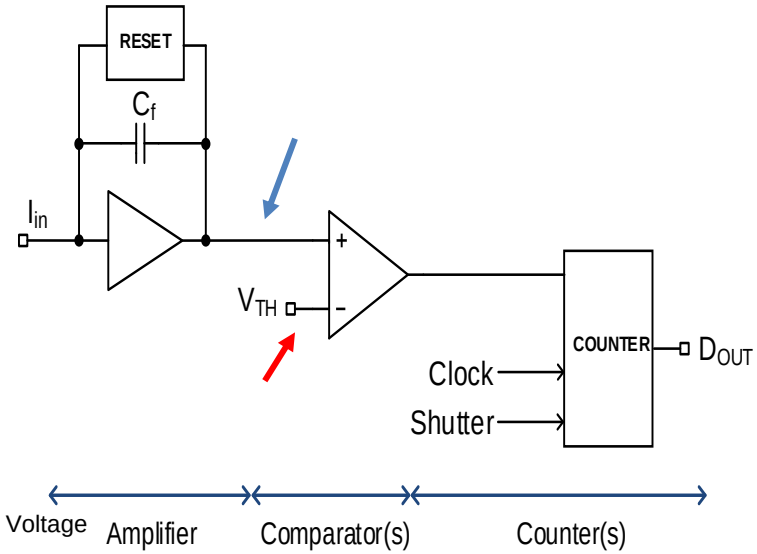
TIMEPIX CELL LAYOUT

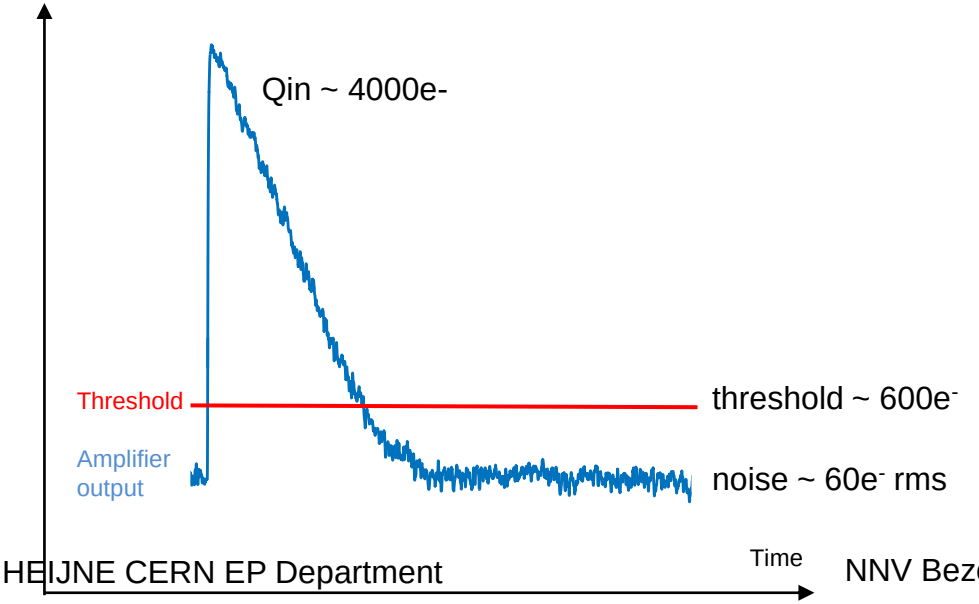


DESIGNER
Xavier LLOPART
CERN
PhD Thesis p. 107

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

Hybrid Pixel Detector - Basic Detection Pinciple



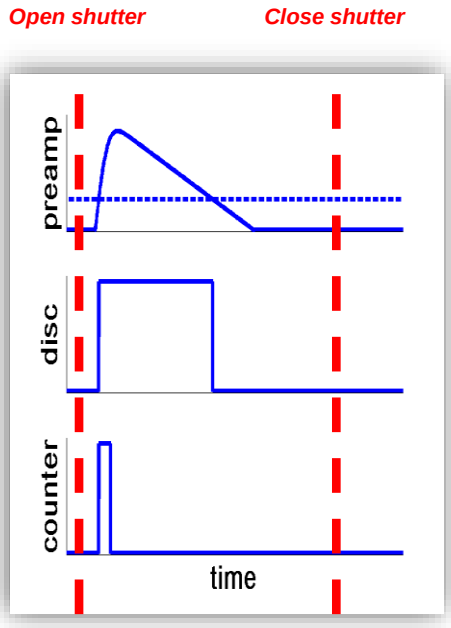


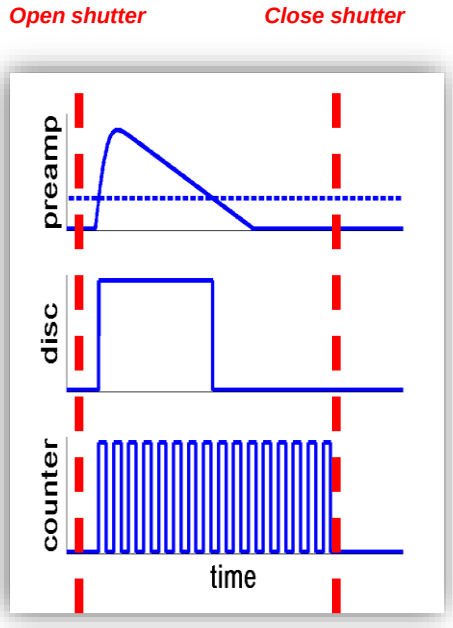
→ Noise hit free imaging

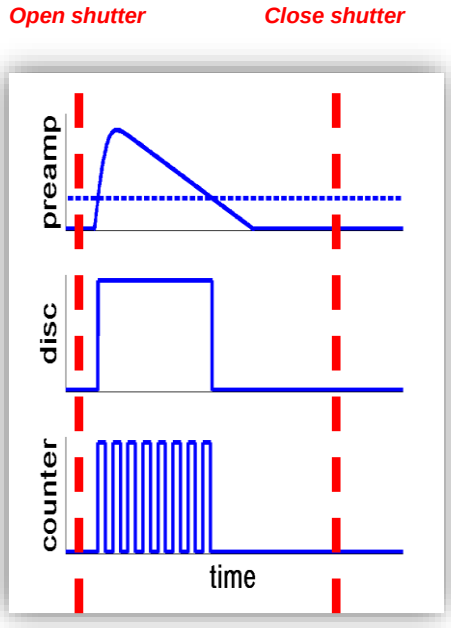
Timepix Pixel Operation Modes

Particle counting

- Arrival Time*
- Time over threshold







* Implemented at the request of the EUDet Collaboration

Timepix in een ‘USB’ stick

IEAP/CTU, Prague
Advacam : miniPix

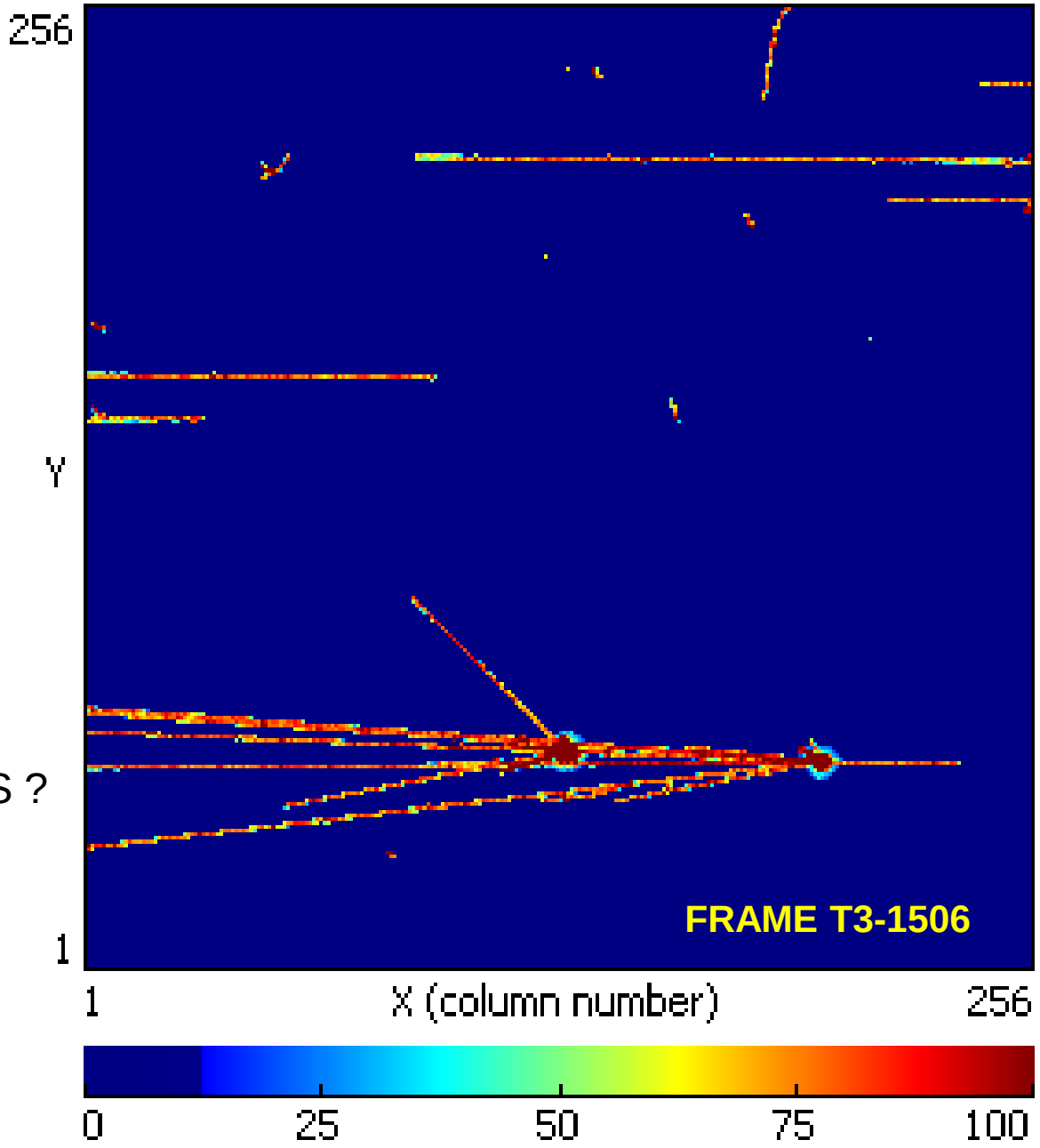
TIMEPIX CHIP as SILICON 'EMULSION' or 'BUBBLE CHAMBER'

H6 PION BEAM 2007

INCIDENT from RIGHT

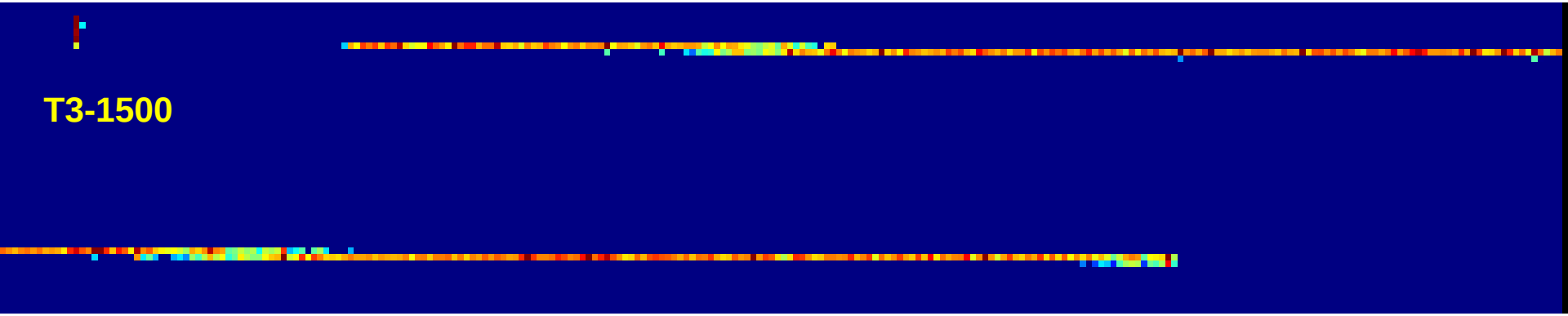
BEAM

WHICH DIRECTION of TRAILS ?

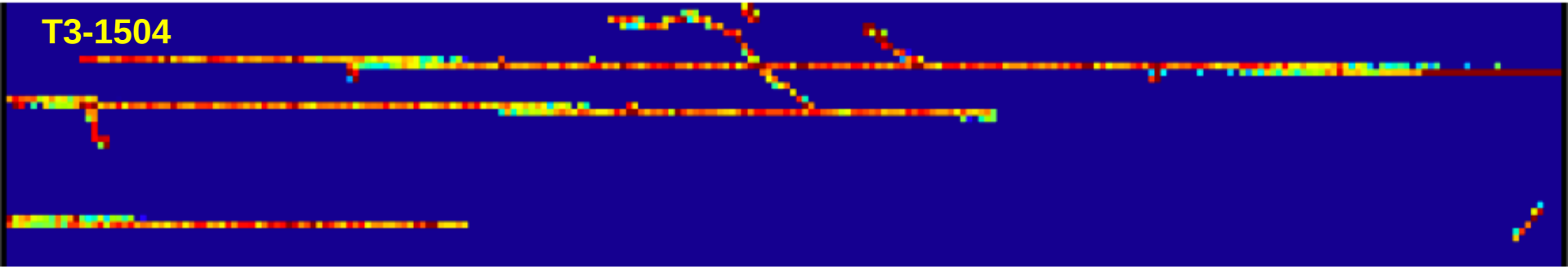


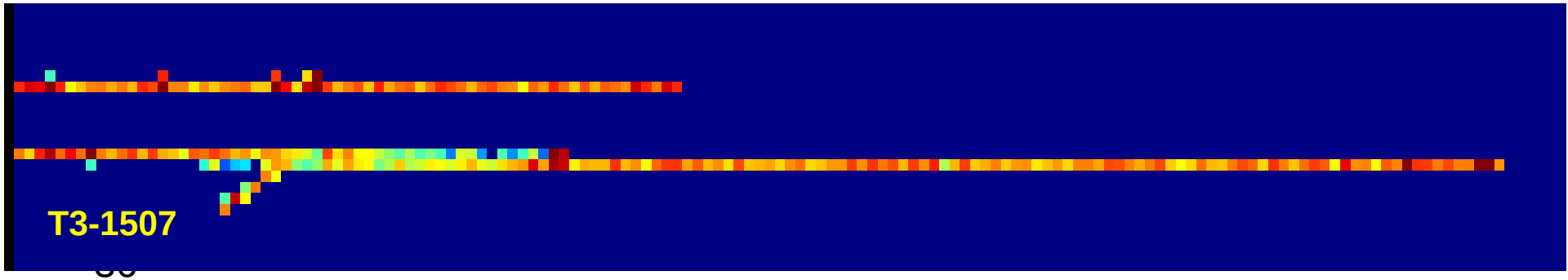
with John Idarraga / Montréal now

Erik HEIJNE CERN EP Departmer

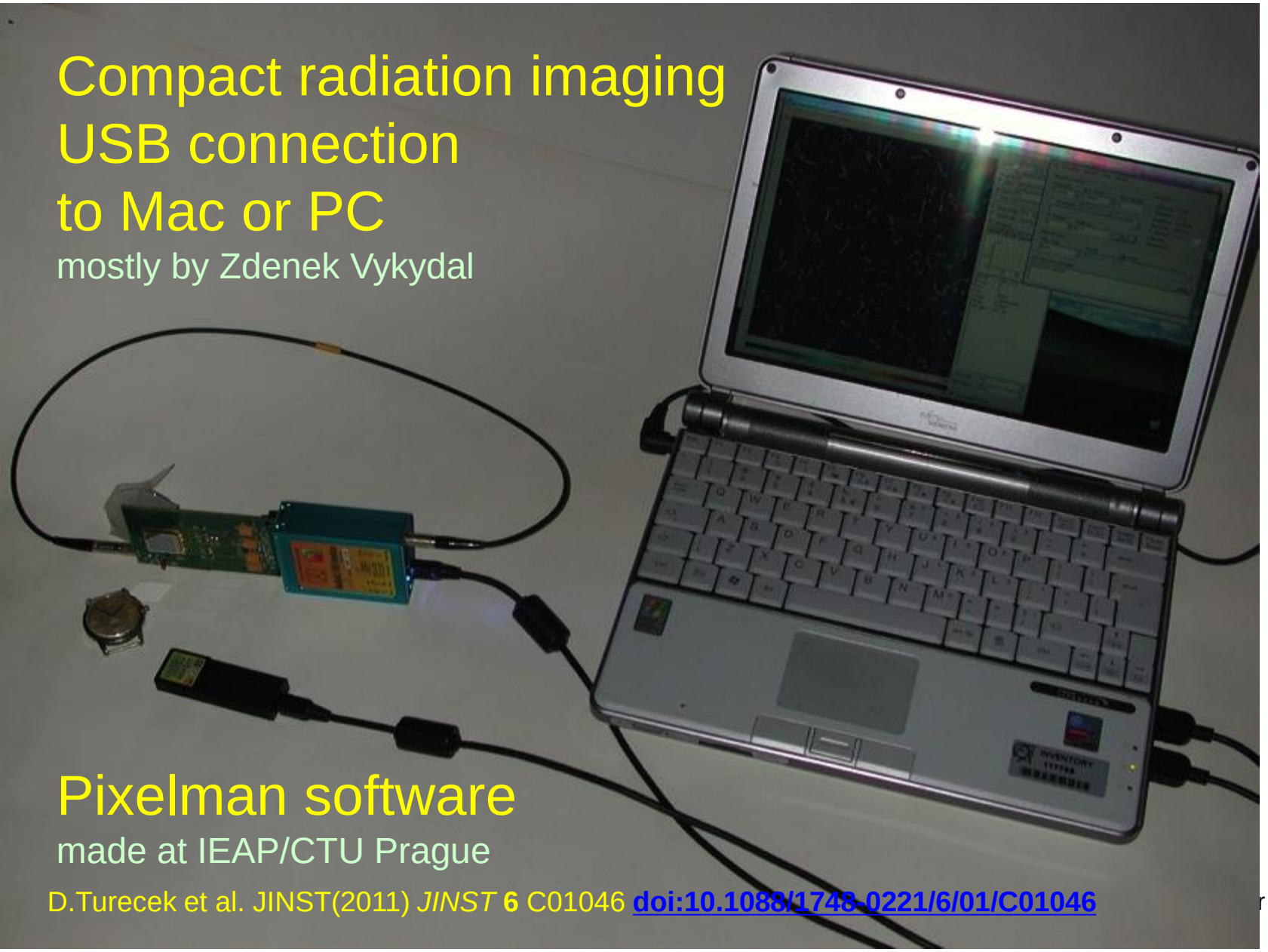


TYPICAL TRAILS ...





TIMEPIX radiation imaging at home



D.Turecek et al. JINST(2011) *JINST* **6** C01046 **doi:10.1088/1748-0221/6/01/C01046**

r 2023

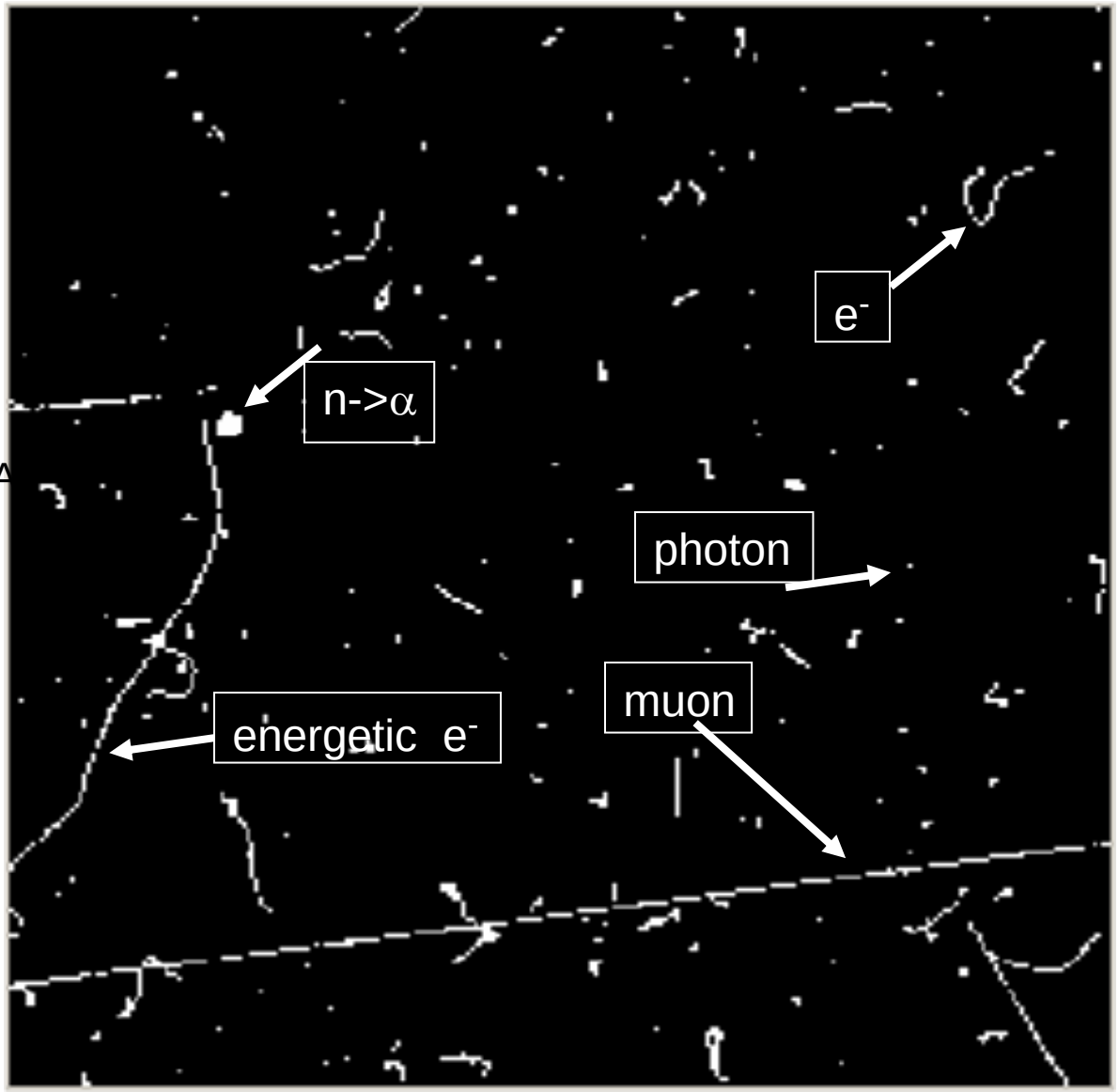
COSMIC PARTICLES in MXR Si PIXEL

256 x 256 PIXELS
300 µm THICK

CAN BE
RADIATION
DOSE METER

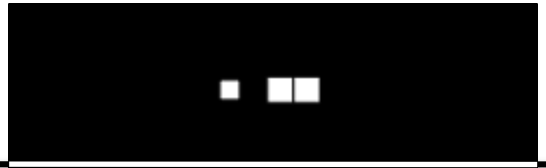
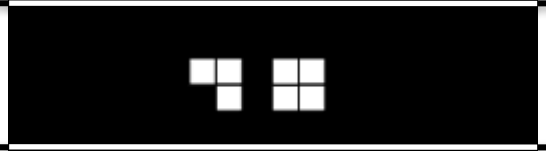
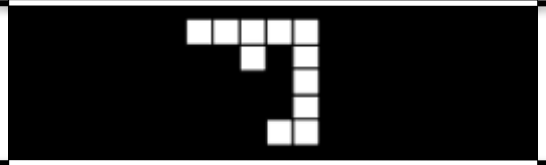
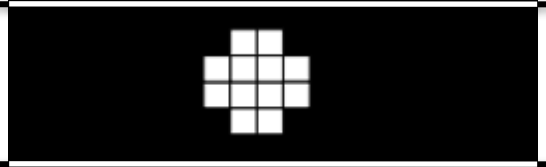
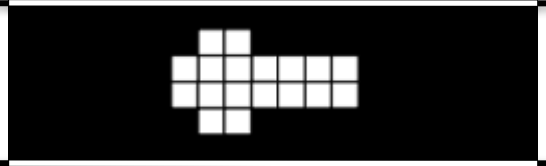
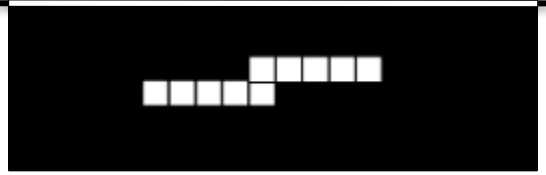
IDENTIFY SPECIFIC QUANTA
- ELECTRONS
- PHOTONS
- MIPs
- NEUTRONS -> ALPHAs

ADJUSTABLE EXPOSURE
ms - minutes GIVES
LARGE DYNAMIC RANGE



Frame CTU Prague

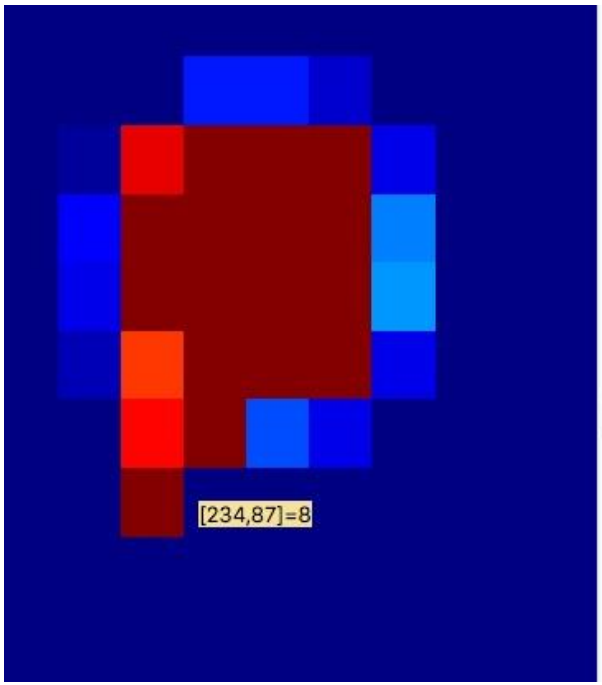
Characteristic cluster patterns in Medipix

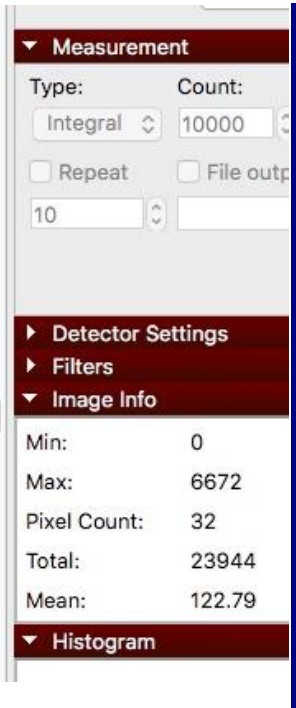
1) Dot		Photons and electrons (10keV)
2) Small blob		Photons and electrons (~100keV
3) Curly track		Electrons (MeV range)
4) Heavy blob		Heavy ionizing particles with short range (alpha particles,…)
5) Heavy track		Heavy ionizing particles (protons,nuclei, Fe, …)
6) Straight track		Energetic light charged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

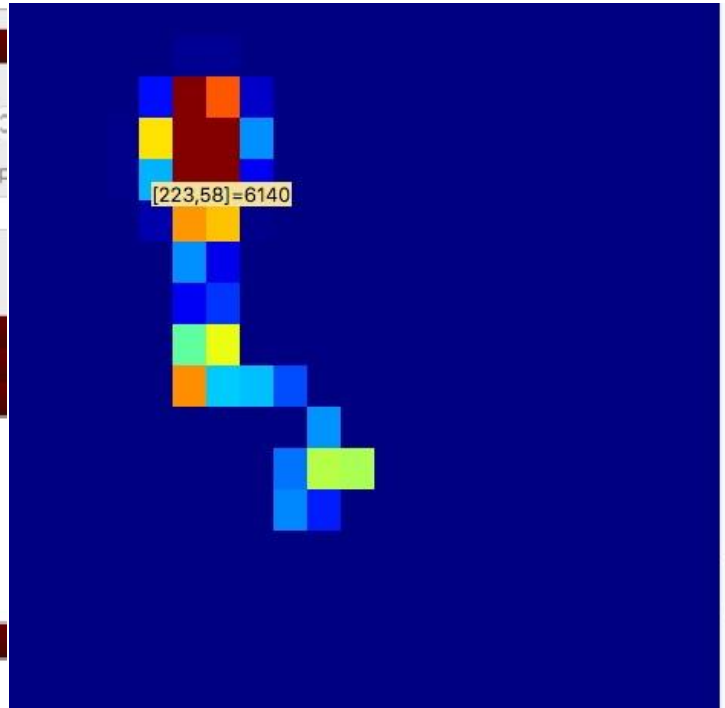
Herkennen van alfa deeltjes en hun oorsprong

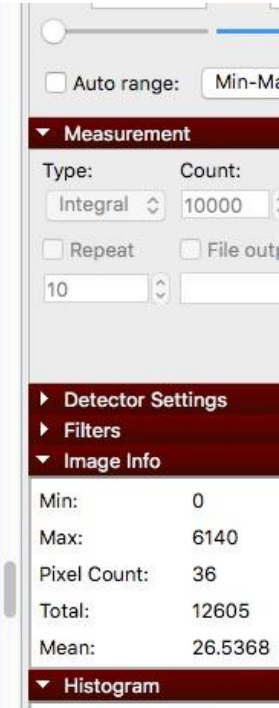
de energie van het alfa deeltje kan worden benaderd
met de som van de energieen in alle pixels

voor grote signalen is de conversie niet helemaal lineair

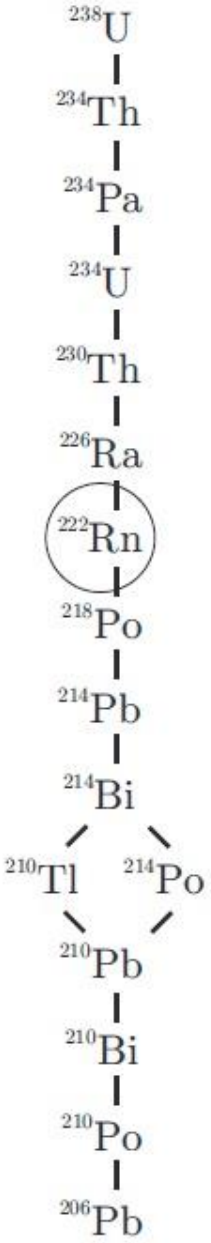


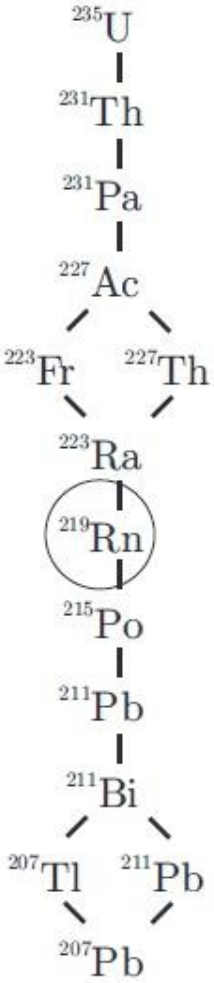


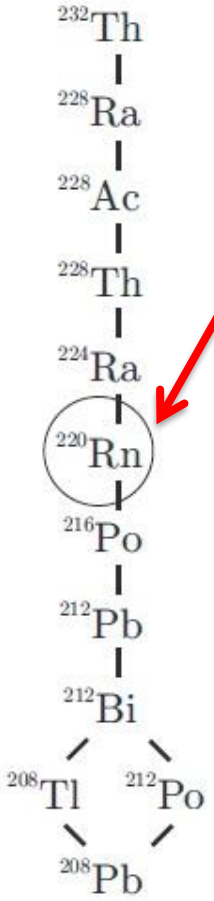




verval reeksen van uranium en thorium





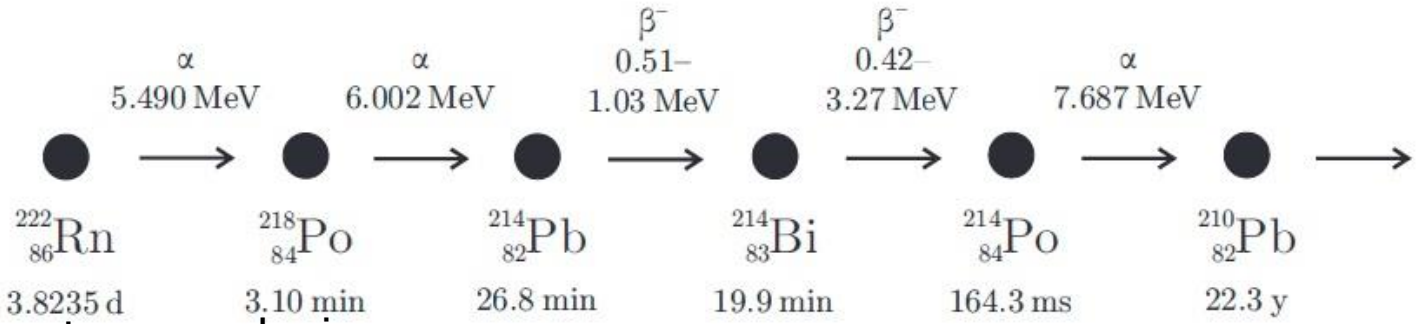


na een lange tijd
komt er radon,
een edelgas dat
kan ontsnappen.
We vinden het
in alle gebouwen,
vooral in kelders.

détails op
volgende pagina

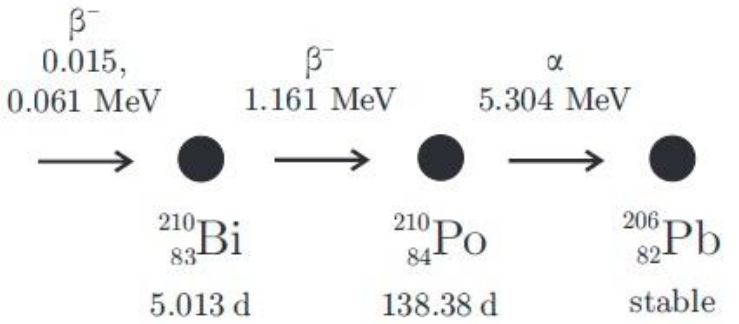
eindprodukt
na miljoenen jaren
is altijd lood

verval reeksen van radon / 'thoron'



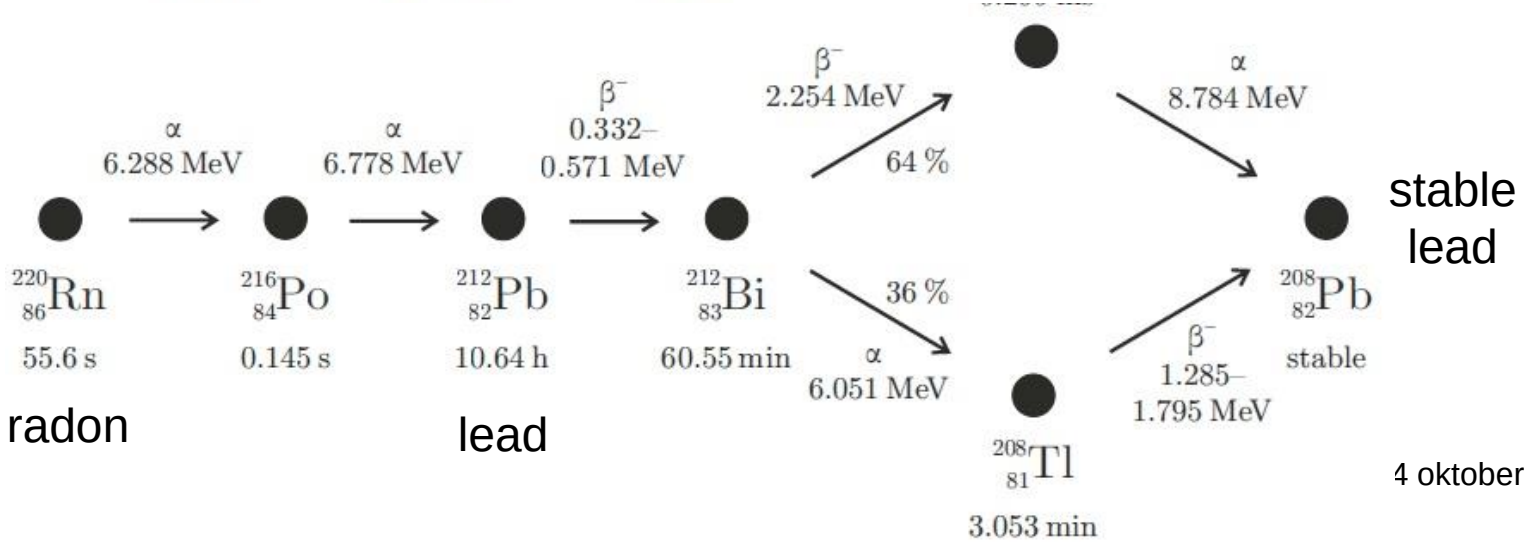
radon

polonium



stable lead

protactinium



radon

lead

stable lead

ook toepassigen buiten deeltjes fysika

andere toepassingen van pixel detektors

röntgen foto's' in kleur'

analyse van ieder apart foton in de pixel

neutronen foto's

converters op de sensor

beelden met materiaal-herkenning

analyse van ieder apart foton in de pixel

ruimtevaart dosis meting

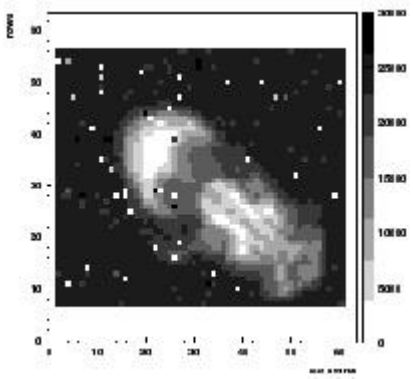
lichte instrumenten met deeltjesidentifikatie

moleculaire massa-spectroscopie

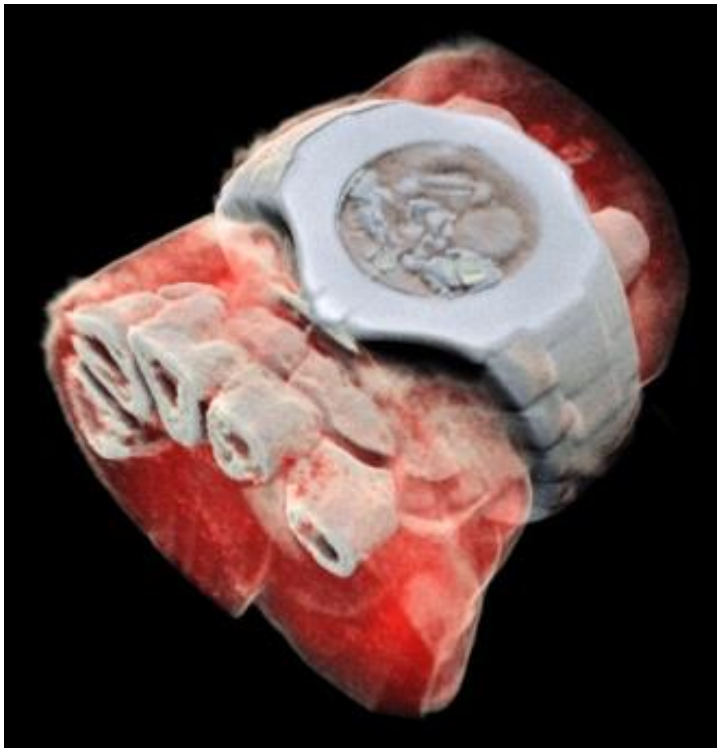
meting van vlucht-tijden in veld als functie van massa

etc.

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

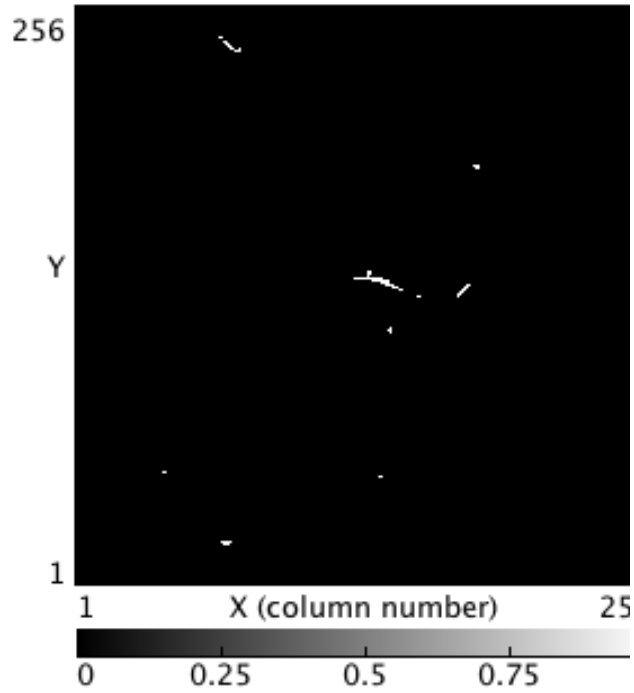
advances in processing of single photons
full potential now <u>begins</u> to be exploited

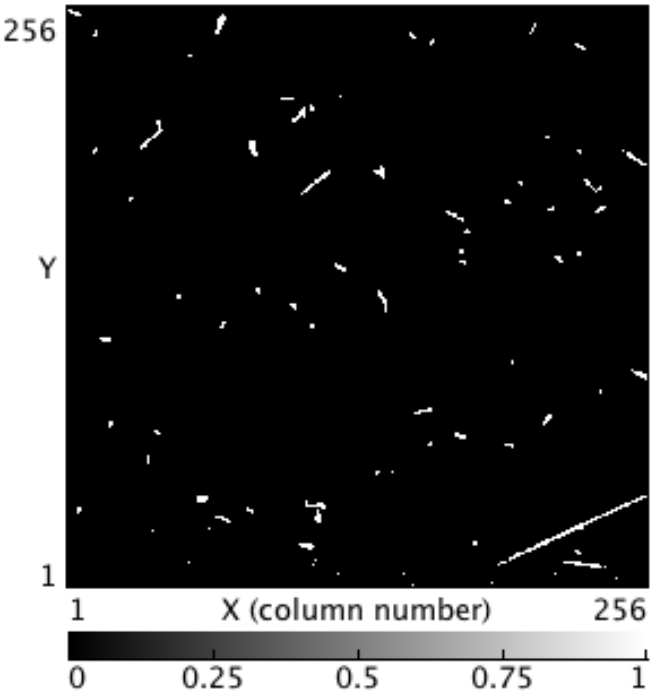
Single Quanta zijn overal om ons heen

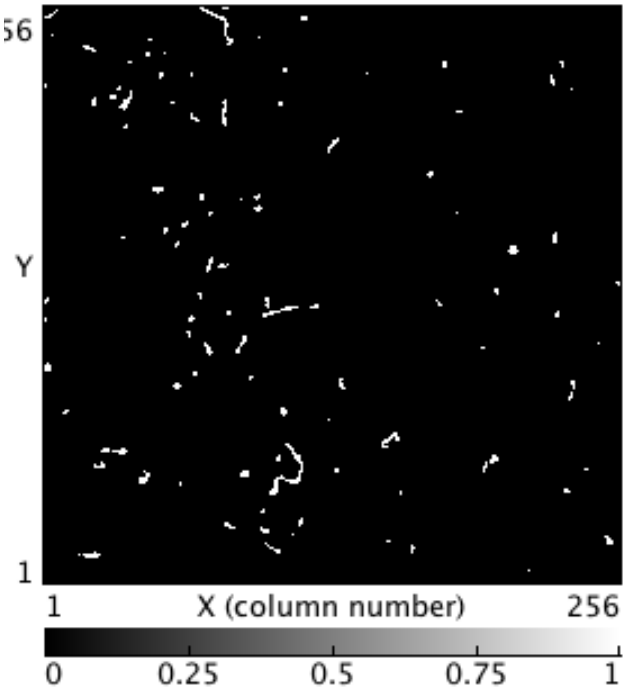
60s Exposure at ground level

60s Exposure in plane at 24 000 feet

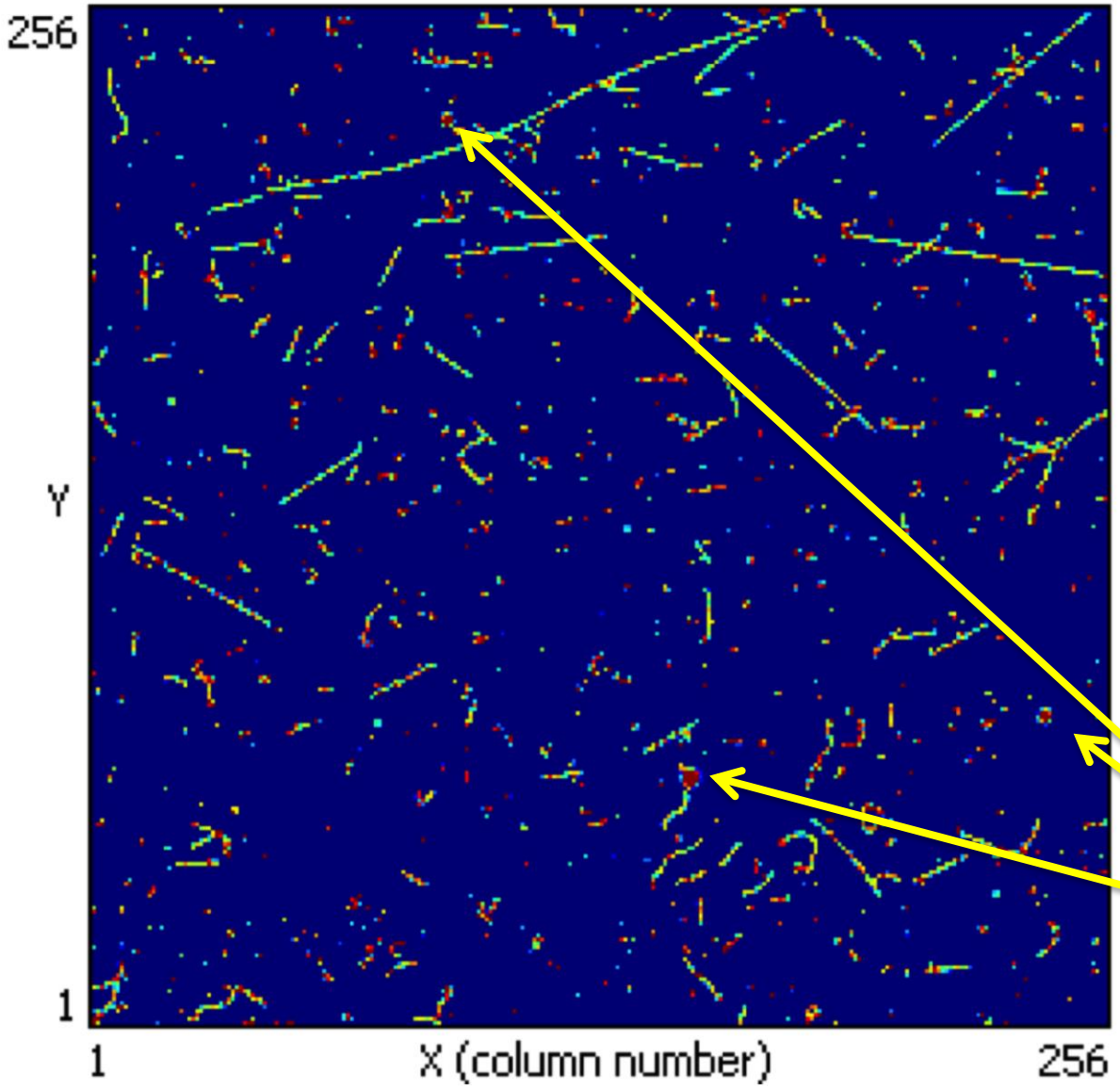
6s Exposure with old wristwatch (radium)







Dose levels steeds nog op veilig niveau



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 uSv/h
alpha 0.07 uSv/h

The 3 alpha impacts contribute >half of the dose

kwt-011May12-j-D9W15-tot-3n-4764s

E.H.M. Heijne et al. NIMA699(2013) 198

Silicon Timepix for mass spectroscopy

Separation of heavy molecules by Time-of-Flight

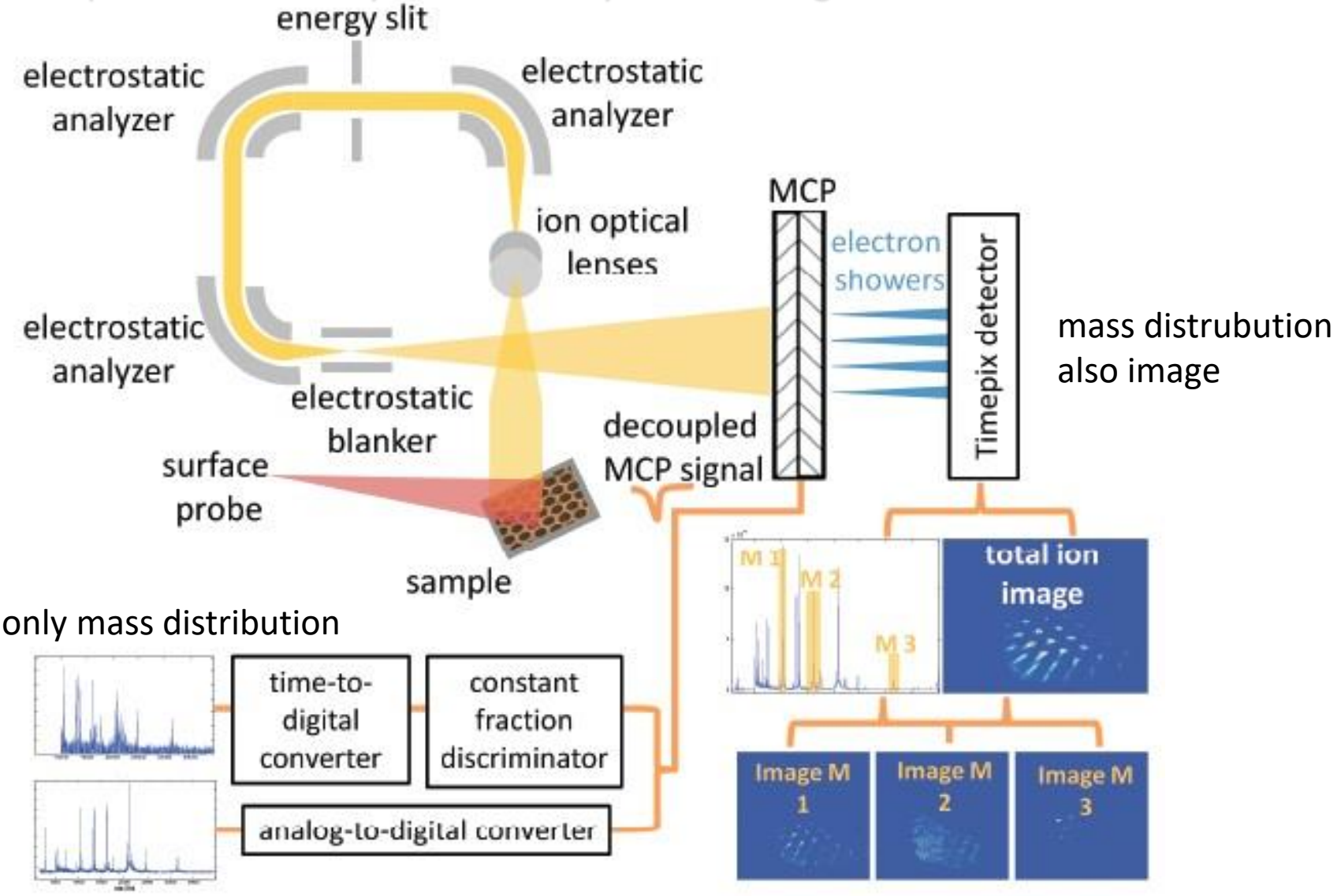
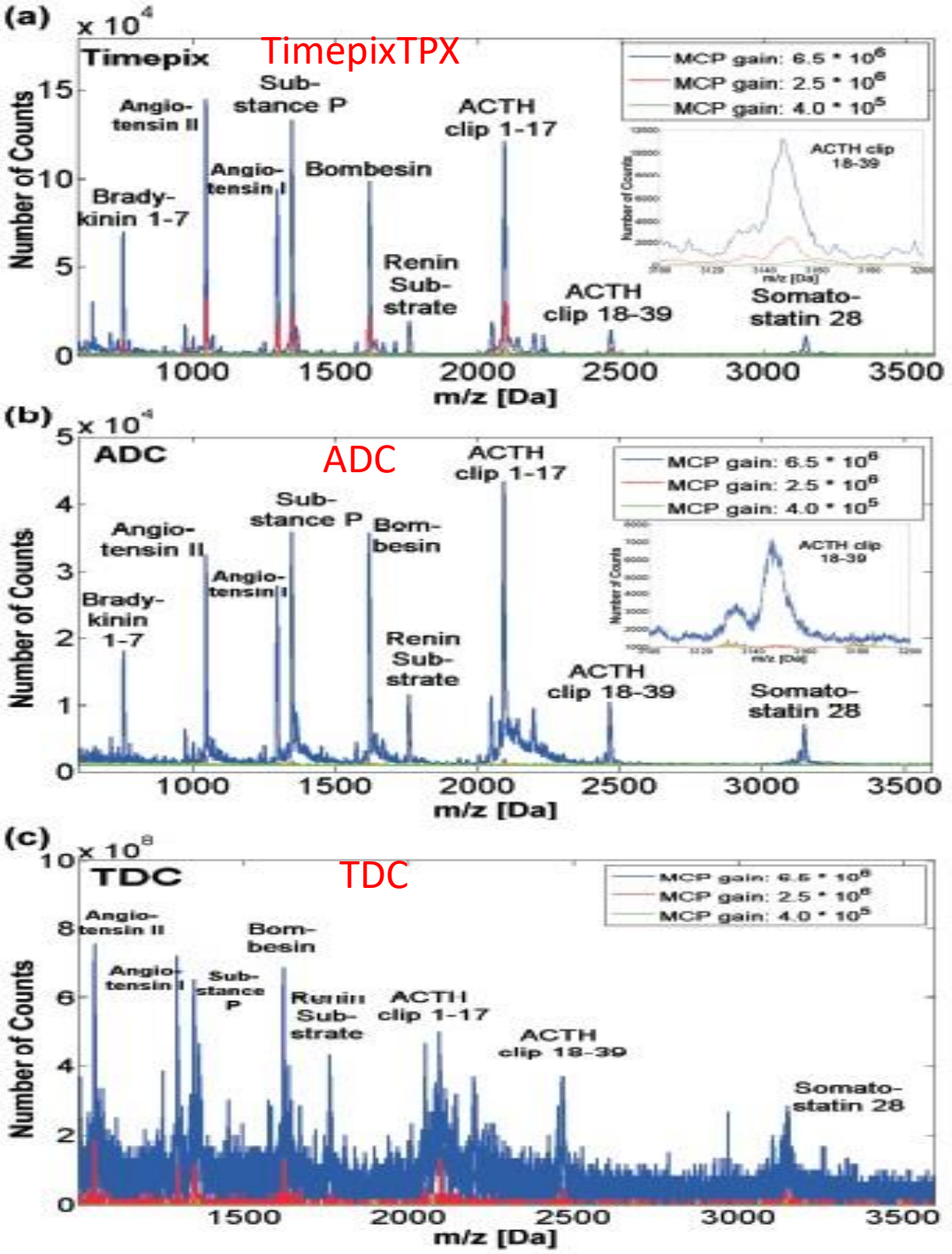


figure from J. Jungmann – PhD Thesis Univ Utrecht (2011) p. 96

Timepix for mass spectroscopy

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

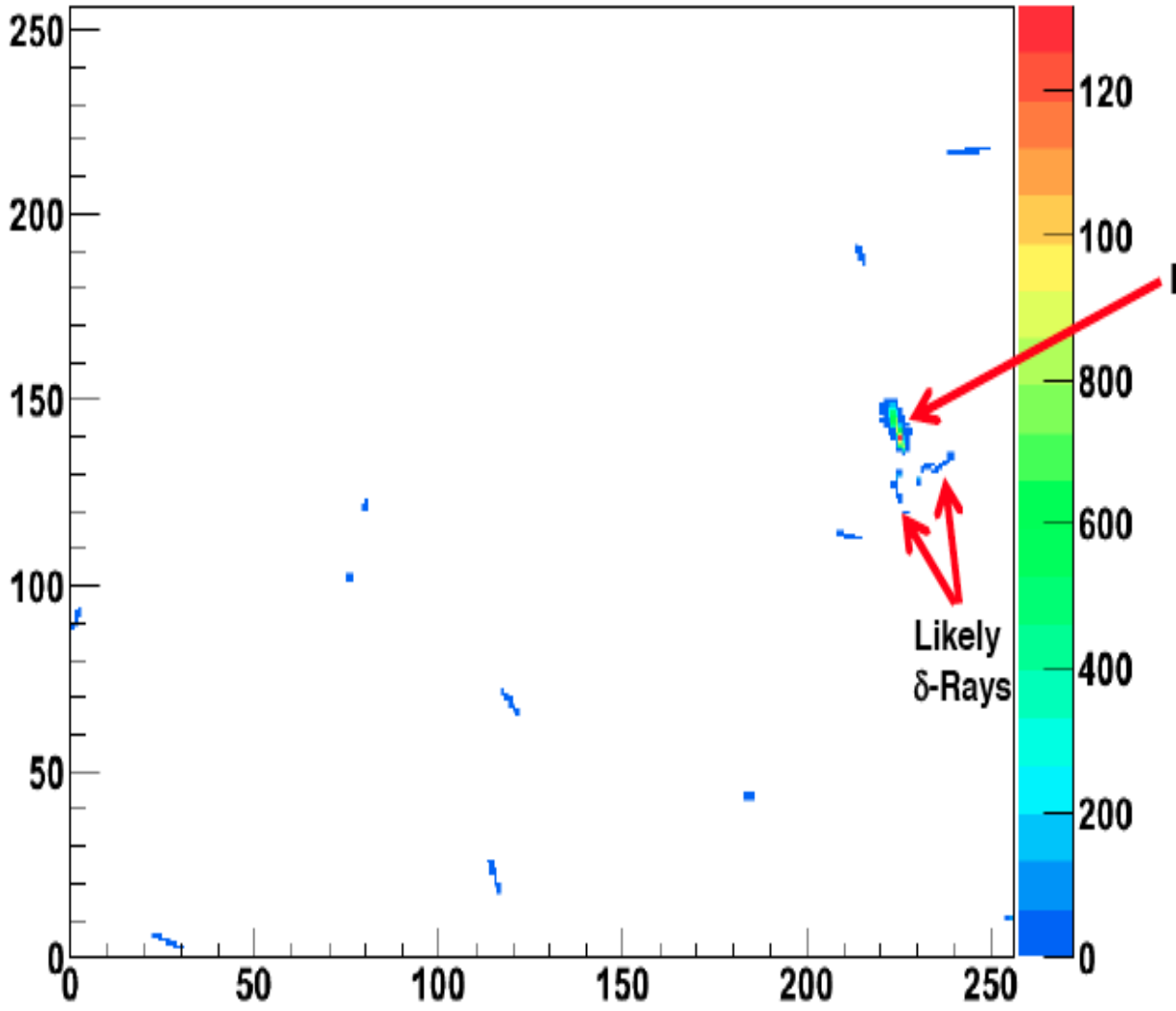


figures from J. Jungmann –
PhD Thesis
Univ Utrecht (2011) p. 97-103

Pixel chips for dosimetry in Int Space Station ISS

AMS largest experiment....
Pixel chip maybe smallest

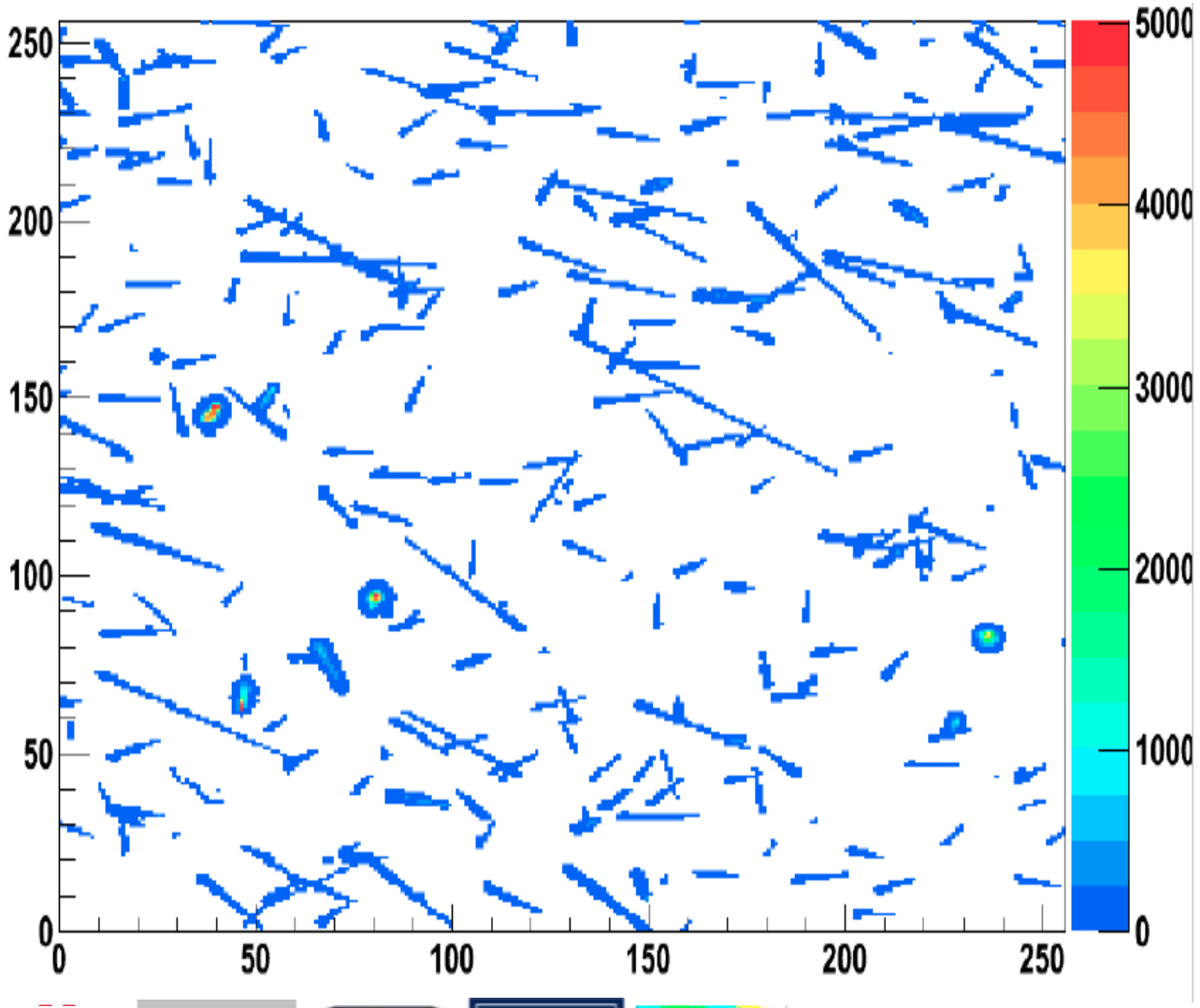
Dosimetry at the Int Space Station ISS



4s Timepix exposure taken in ISS passingover South China Sea

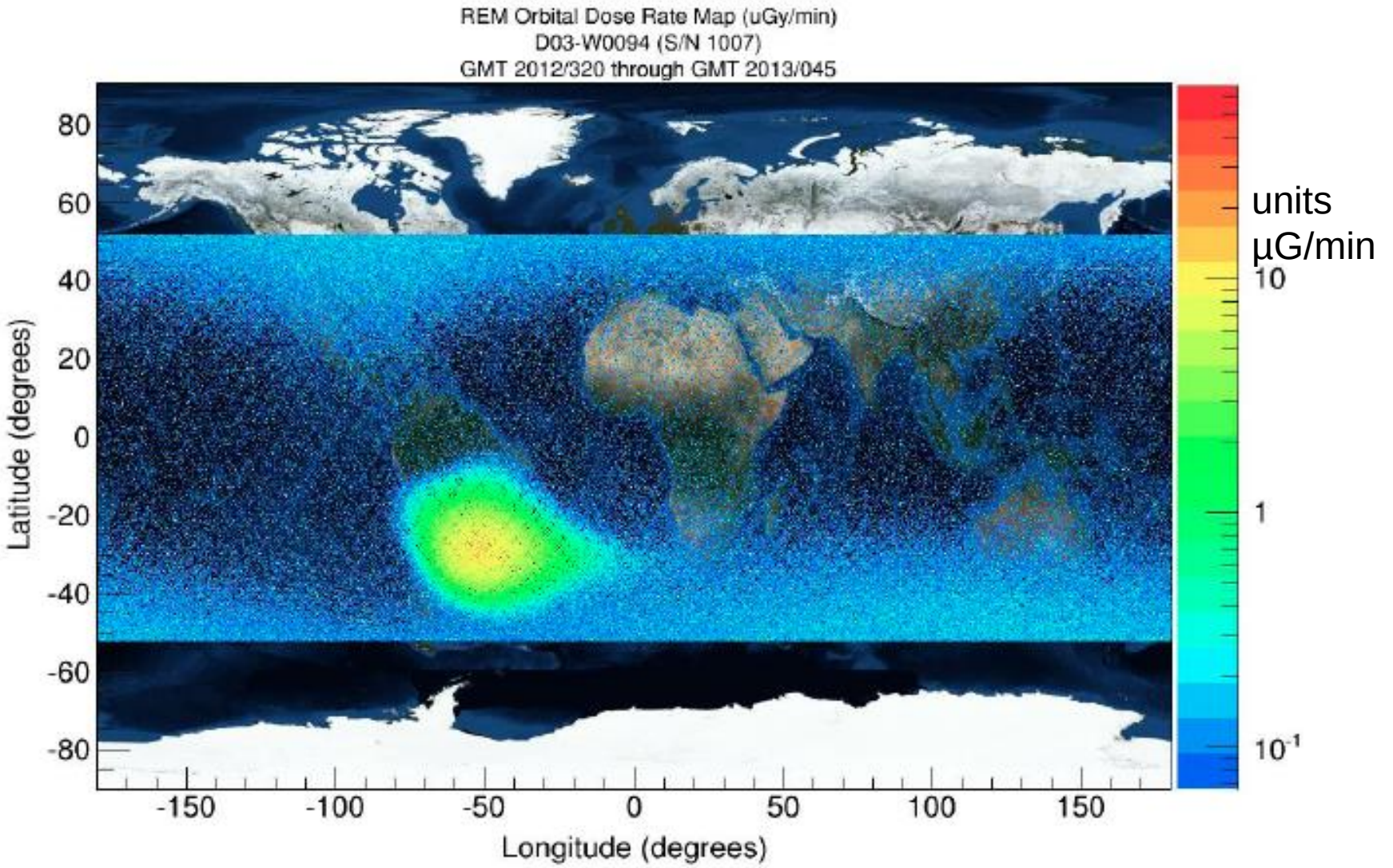
UNIVERSITY OF HOUSTON
Learning. Leading.
NASA
I E A P
CERN

Dosimetry at the Int Space Station ISS



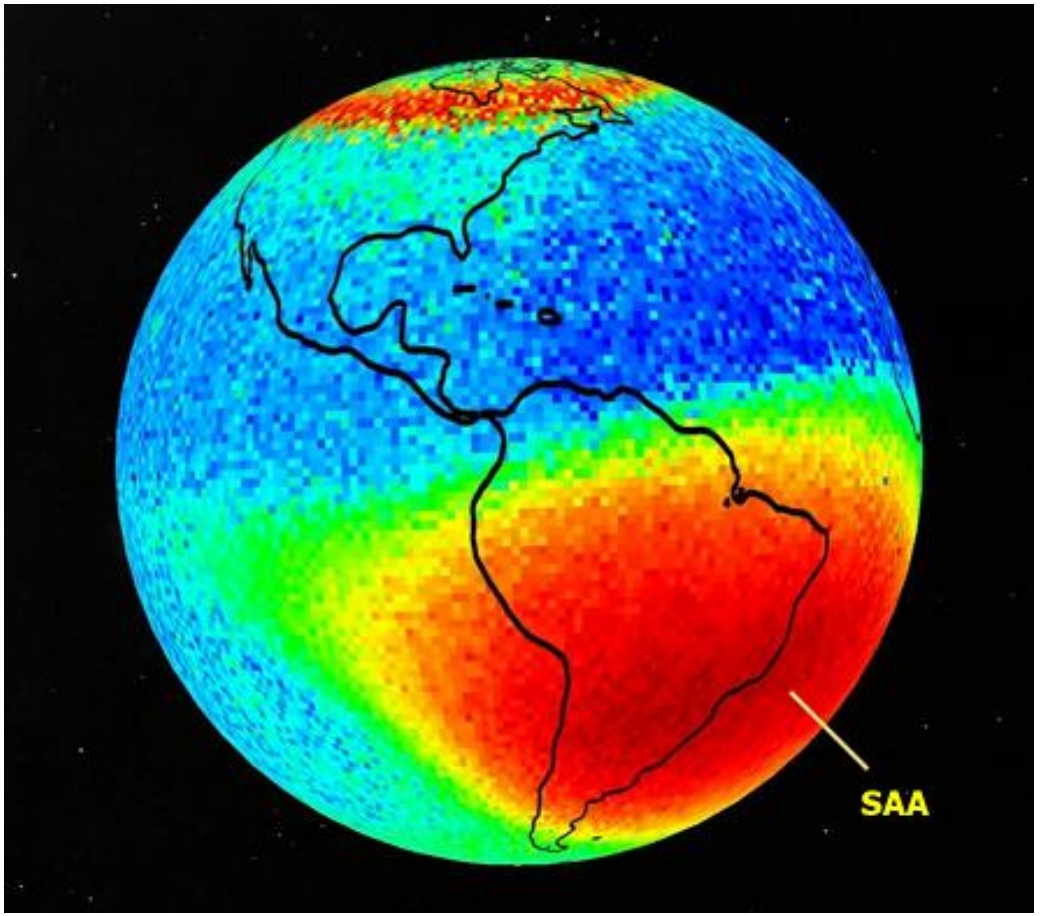
4s Timepix exposure
taken in ISS
passing through SAA
South America Anomaly

Dosimetry at the Int Space Station ISS

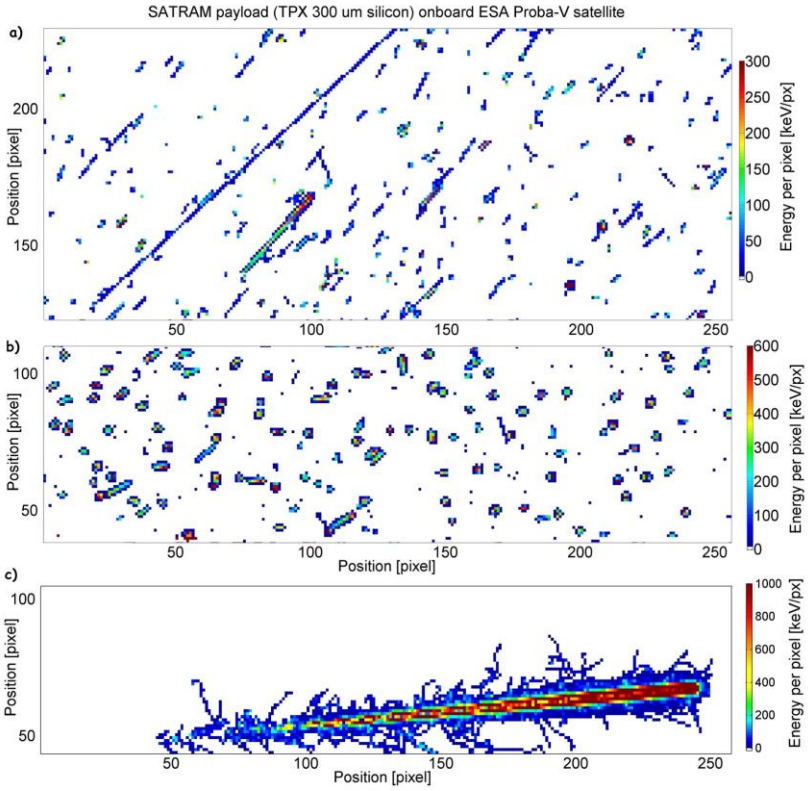


UNIVERSITY OF HOUSTON
Learning. Leading.

dosimetry with TPX on ESA satellite Proba-V



frames in LEO orbit ~800km, different positions



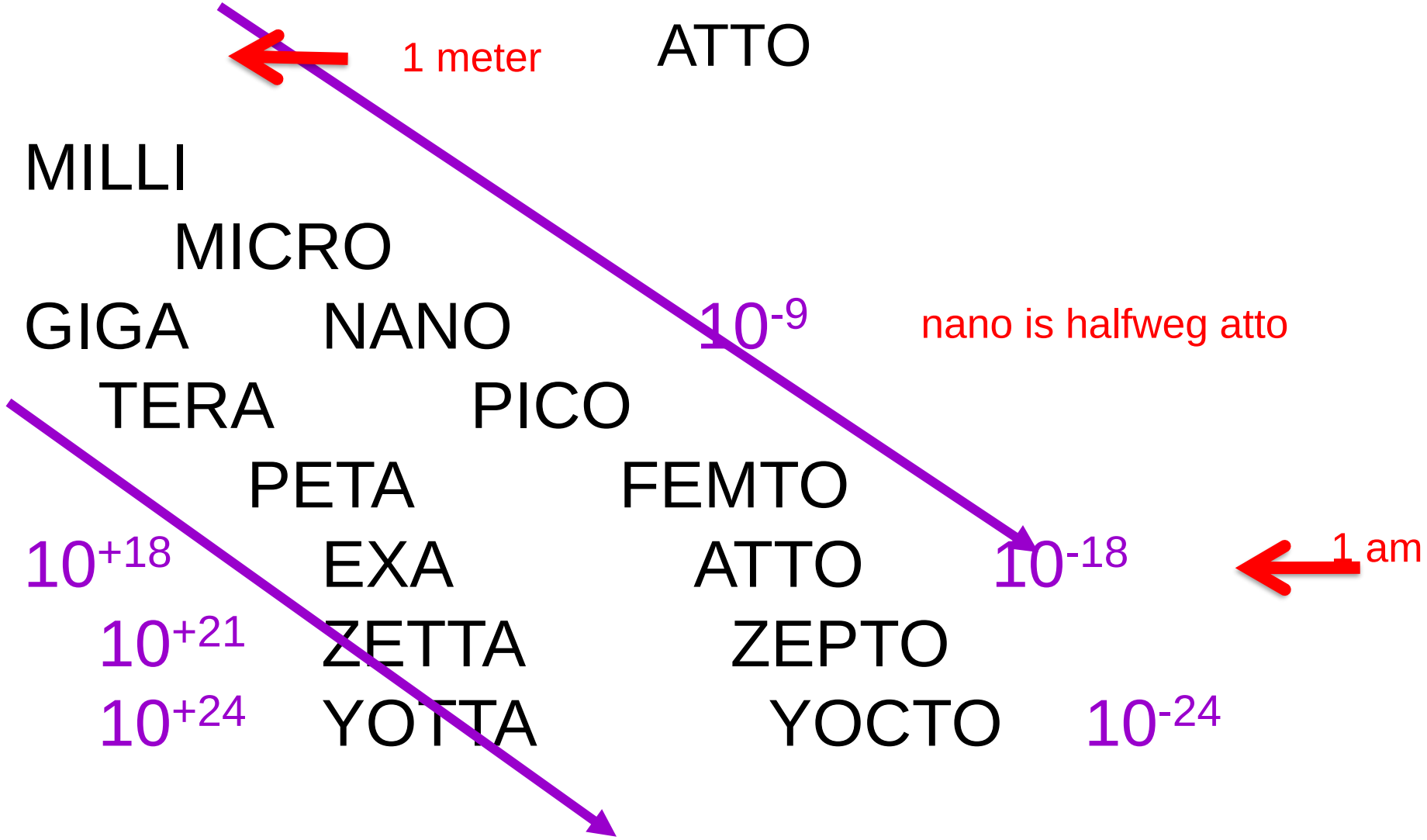
courtesy Carlos Granja IRAP-CTU (2015)

ion track with ∂ electrons

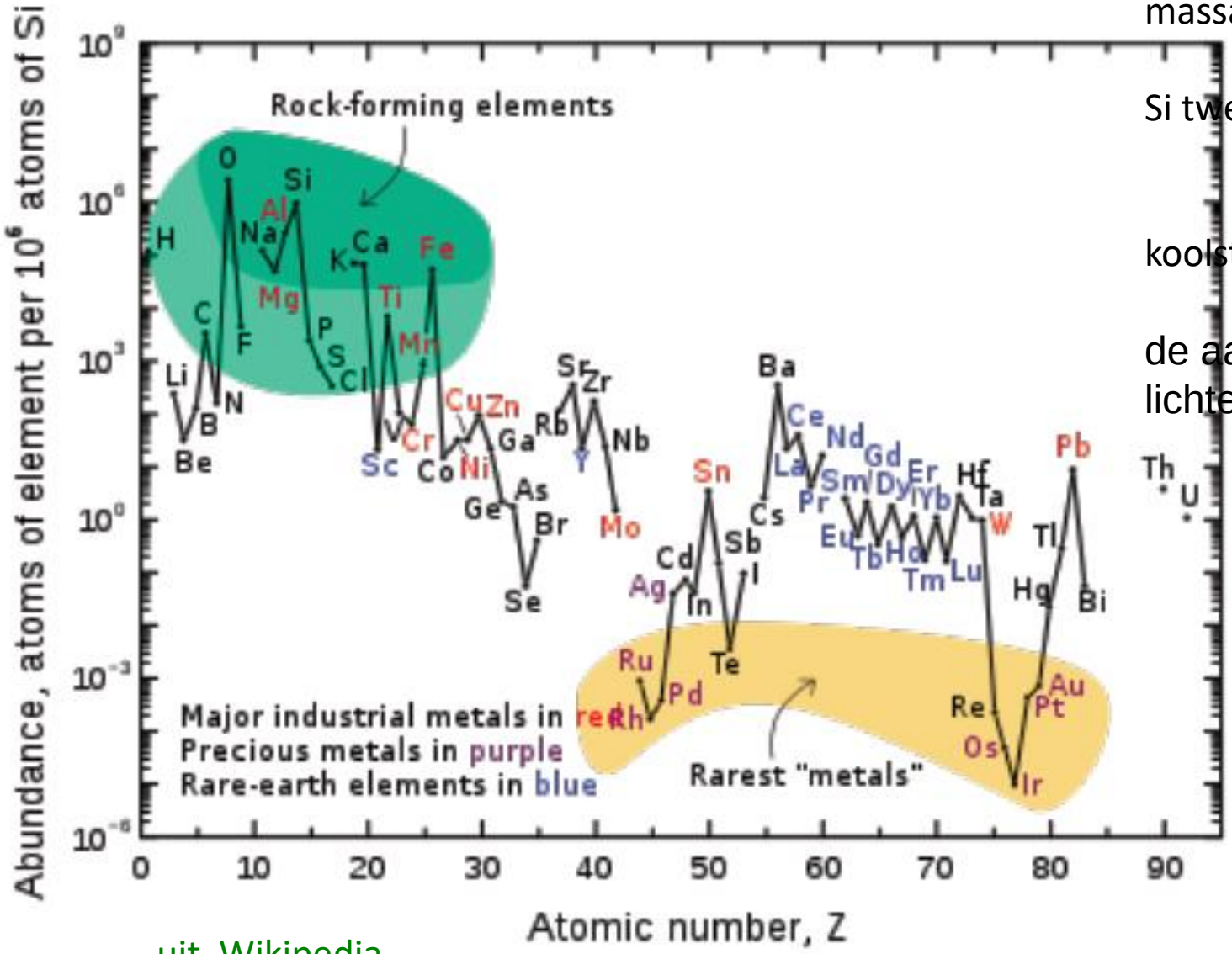
Besluit

extra pagina's

Groter en Kleiner
wat is atto?


1 meter
ATTO
MILLI
MICRO
GIGA
NANO
10^{-9}
nano is halfweg atto
TERA
PICO
PETA
FEMTO
10^{+18}
EXA
ATTO
10^{-18}
1 am
10^{+21}
ZETTA
ZEPTO
10^{+24}
YOTTA
YOCTO
10^{-24}

welke elementen in de aardkorst



massa voorkomen:

Si tweede 28%
na zuurstof 46%

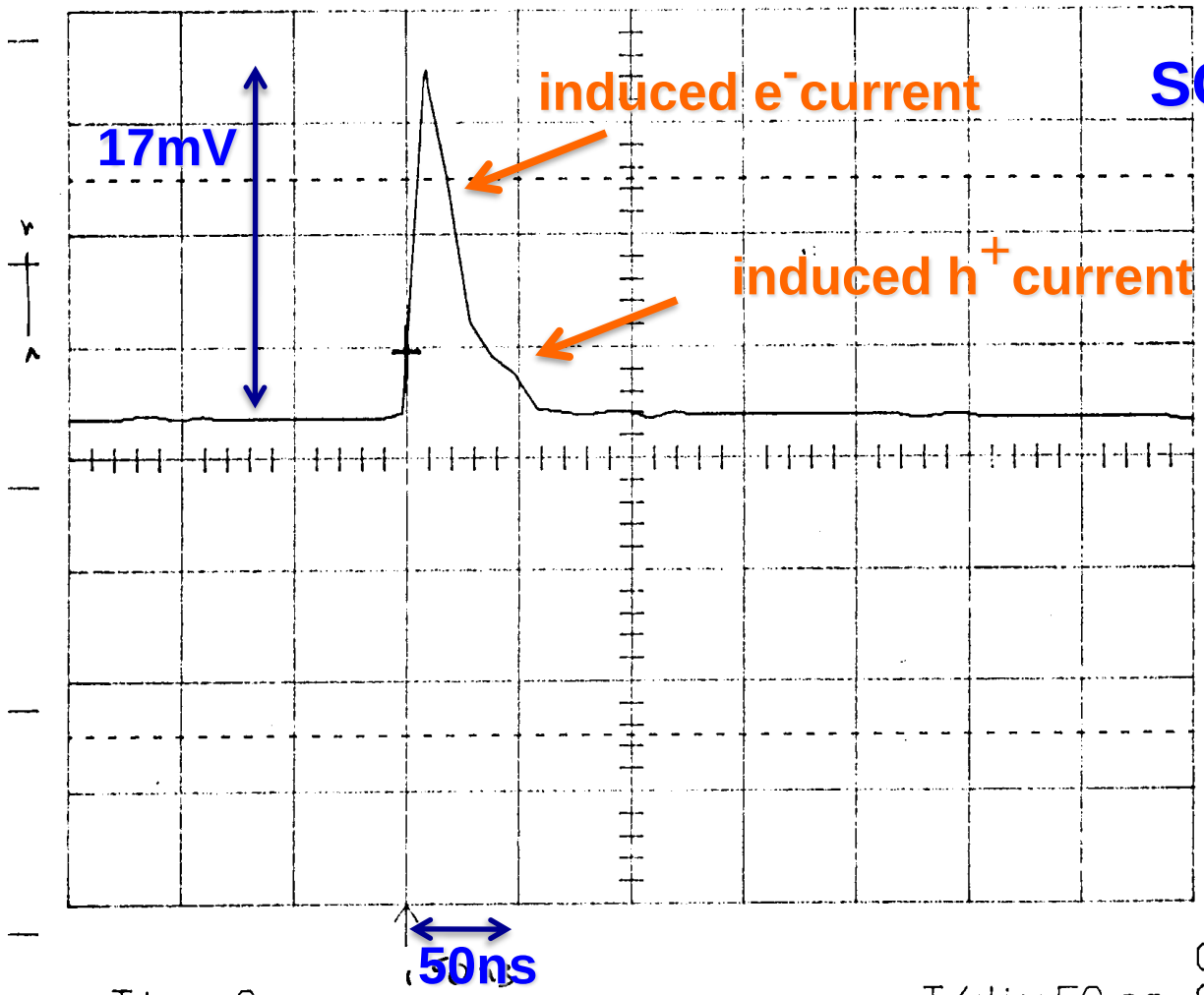
koolstof slechts ~ 0.08%

de aarde verliest steeds lichte elementen
vooral waterstofgas en helium

uit Wikipedia

Si SIGNAL SPEED

SIGNAL CURRENT from Pb ION in 200μm Si DETECTOR



SCOPE on 50 Λ ONLY

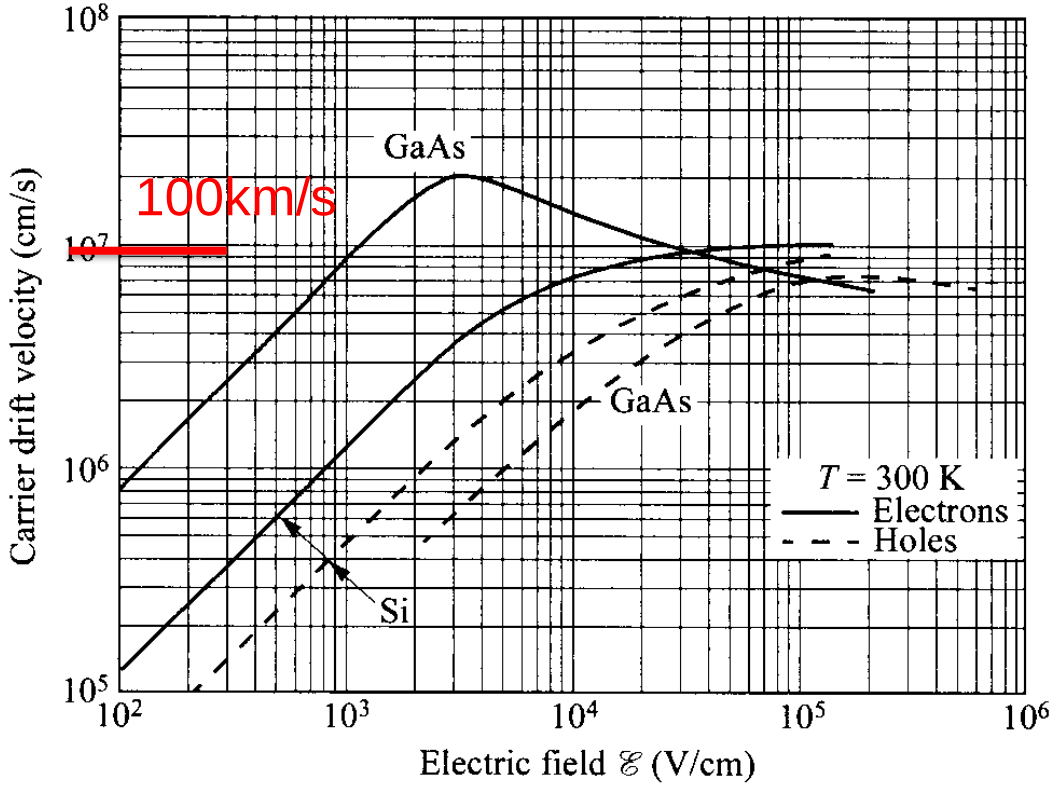
FAST RISE TIME

limited by RC time

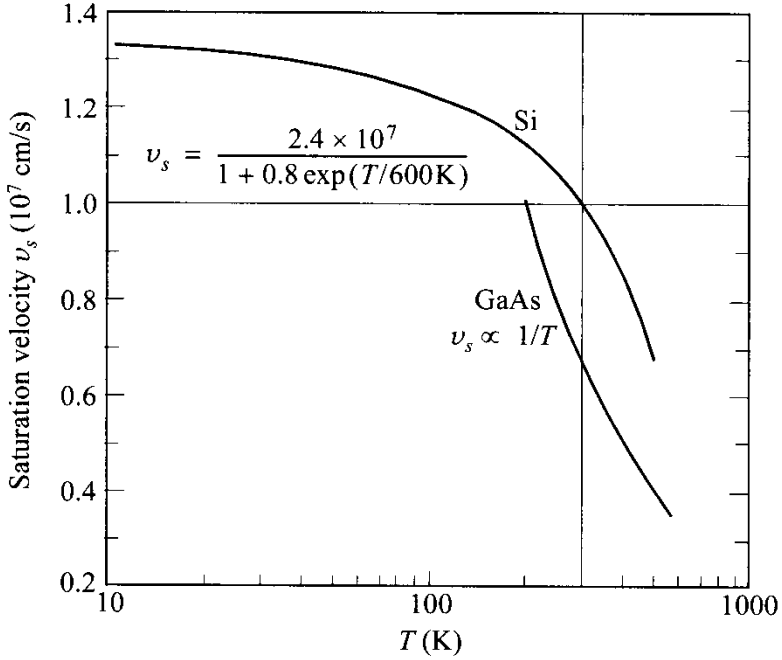
50 Λ x100pF=5x10^{-9}s

CARRIER TRANSPORT in Si and GaAs

CARRIER DRIFT VELOCITY vs FIELD



SATURATION vs TEMP



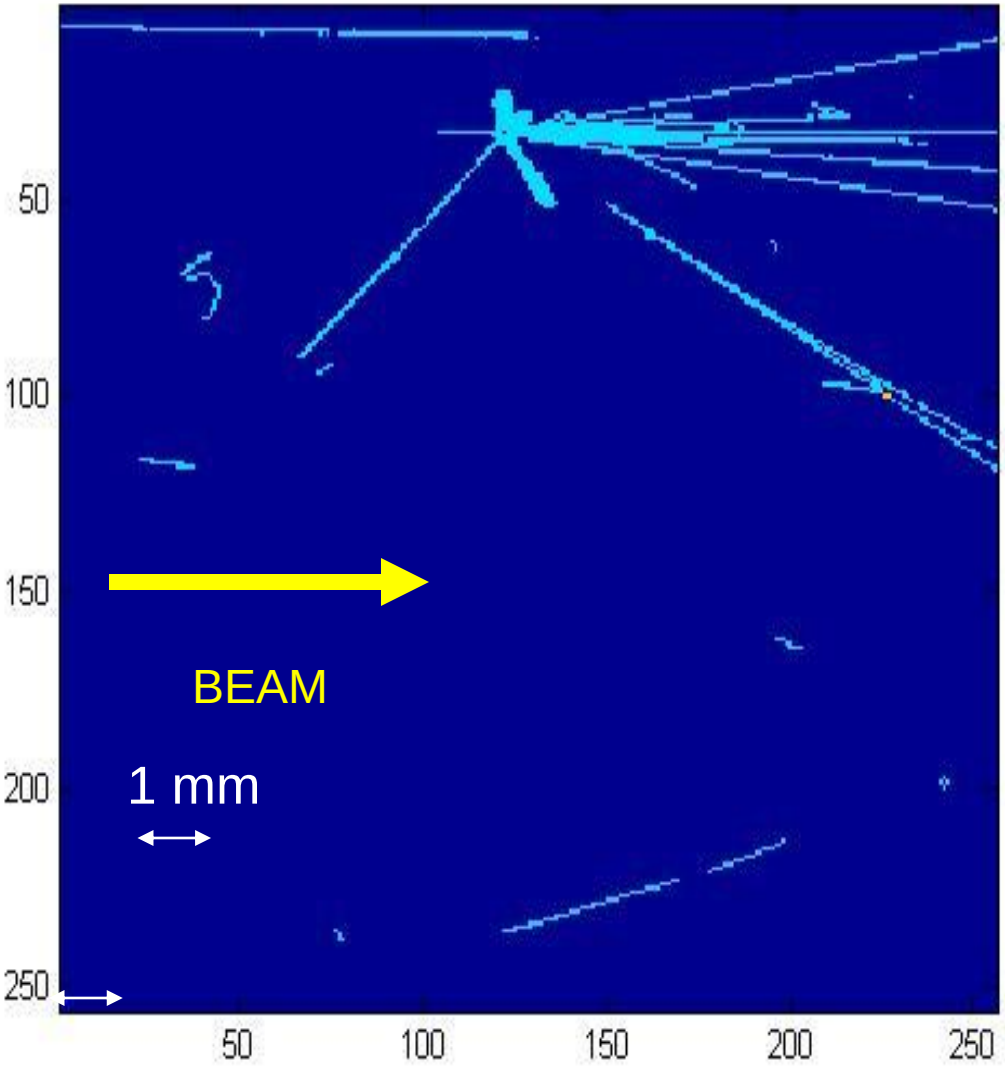
MOBILITY is a function of doping, temp, field..

SEMICONDUCTOR DETECTORS ARE INHERENTLY FAST : 5 - 20 ns

360 000 km/h

einde

120 GeV PIONS in Si IMAGER : MEDIPIX



INTERACTION in
Medipix DETECTOR
Si 'BUBBLE CHAMBER'

DECAY of K_0 ?

↔ 500 μm

July 2006 Parallel Medipix P-05-0583