Semiconductor detector technology for medical and scientific imaging:
Quantum processing and Medipix developments in particular

ERIK H.M. HEIJNE

ICFA - EU INFIERI School

Oxford 13 July 2013

Particle physics generates new instrumentation

Silicon microstrip detectors since 1980 replaced
bubble chambers for tracking and vertexing

Heijne NIM 178 (1980) 331, Kemmer IEEE NS-29 (1982) 733

True 2-D pixels much more useful for general imaging

Damerell NIM 185 (1981) 33

In 1987 my 'dream' was the Si 'Micropattern' detector:

not only data acquisition,

but also on-chip information processing

Heijne NIM A273 (1988) 615 (London Conf 1987)

Continuous Issue:

what must be on-chip, what can be off-line?

strong point

in particle physics detectors:

we deal with single quanta

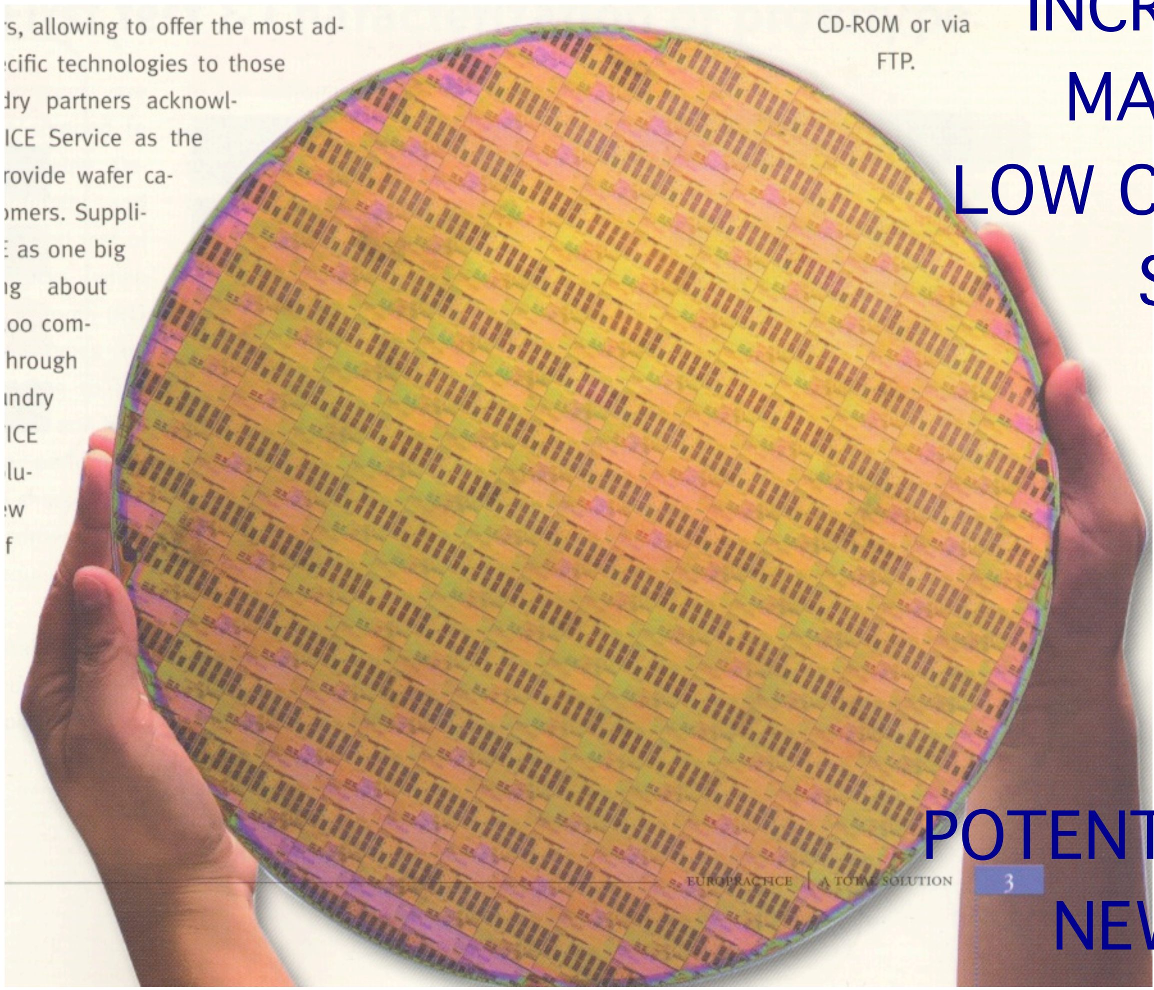
single quantum imaging is hardly known today

move beyond cell structure

towards molecular & atomic level

Si Technology

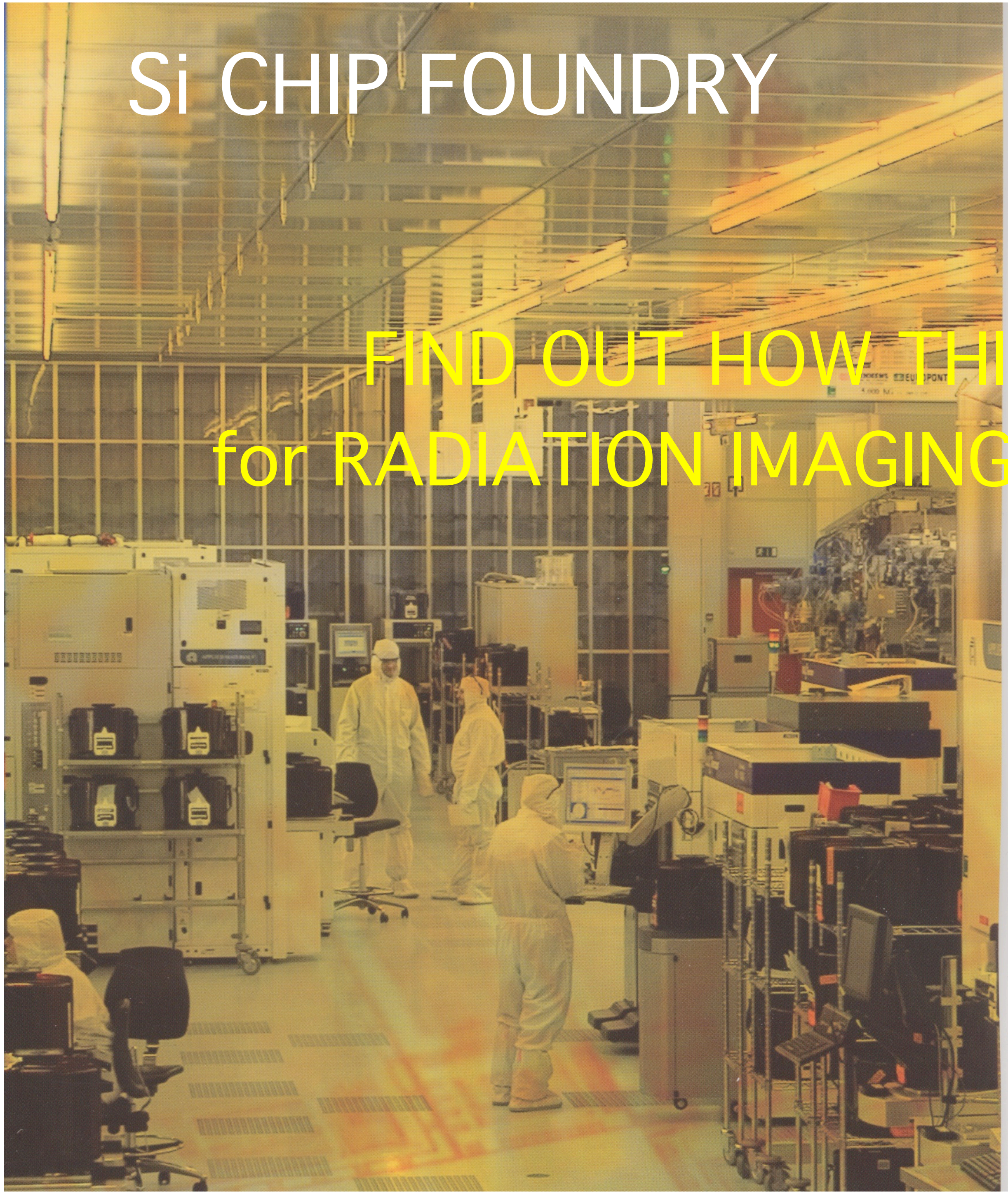
SILICON WAFER MANUFACTURING



INCREASE OF WAFER SIZE
MANY CHIPS PER WAFER
LOW COST IN HIGH VOLUME
SYSTEM INTEGRATION

BUT ALSO:
POTENTIAL FOR COMPLEXITY
NEW MODES OF IMAGING

Si CHIP FOUNDRY

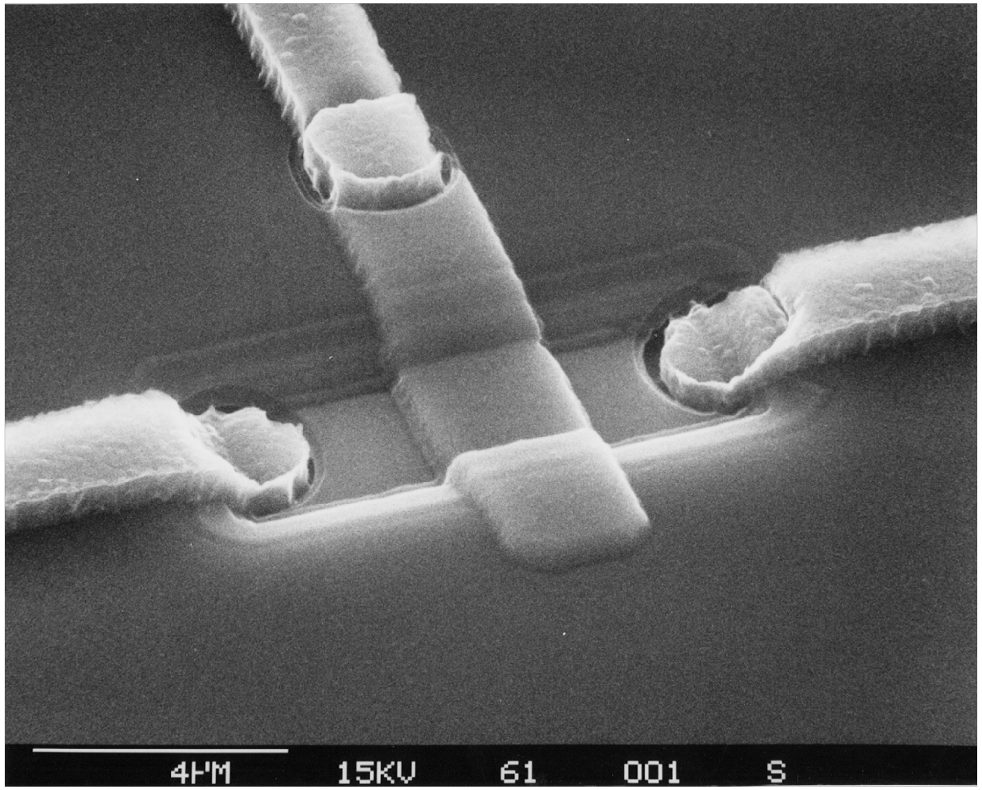


FIND OUT HOW THIS CAN BE USED for RADIATION IMAGING APPLICATIONS

TYPICAL INVESTMENT 3B$

DAILY PRODUCTION
1000-3000 WAFERS
TURNOVER 10M$ / DAY

SILICON MOS TRANSISTOR



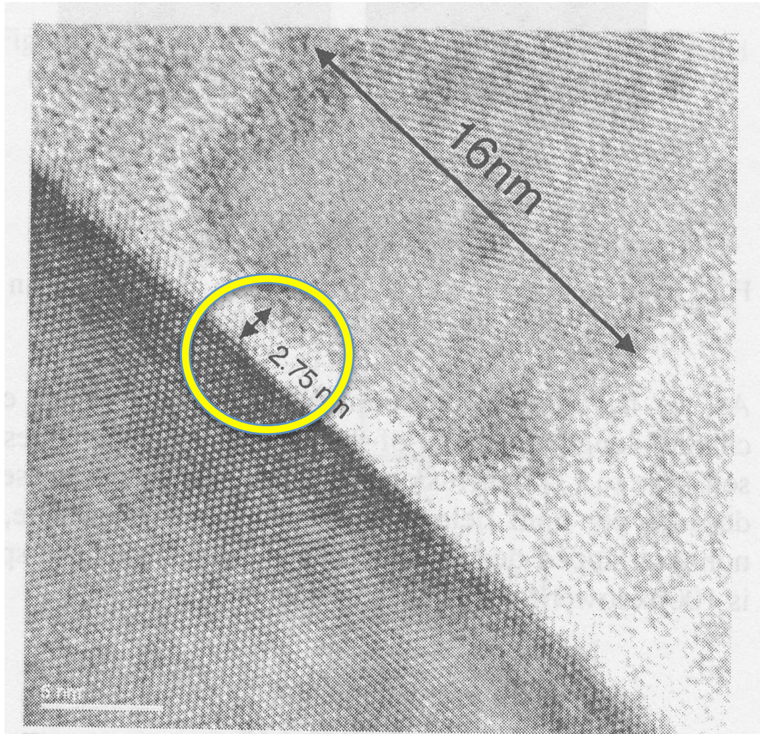


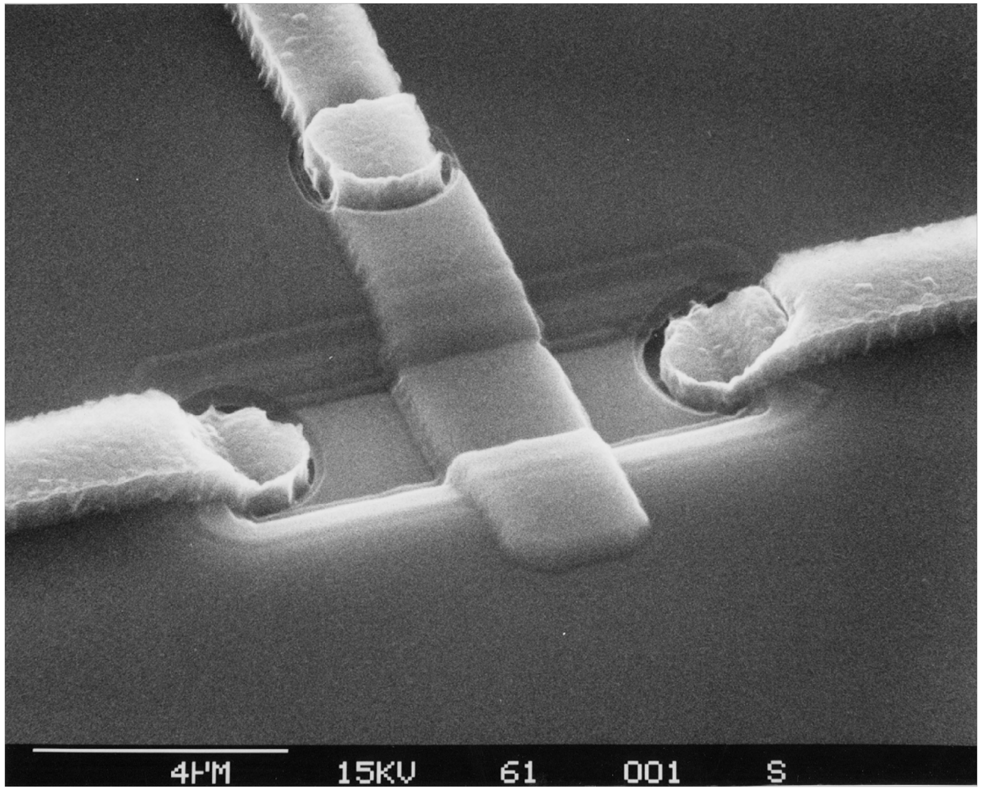
Fig. 1 : Hi-Res Cross section of the 16nm NMOS

SiO_2 gate 2.75 nm

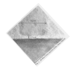
2 μm TECHNOLOGY

0.016 μm

SILICON MOS TRANSISTOR



CORRECT SCALE



SiO_2 gate 2.75 nm

2 µm TECHNOLOGY

0.016 µm

SOI TRANSISTOR LETI

LETI-SOITEC 3.4

SOI TRANSISTOR 18 nm
+ EPITAXIAL Si GROWTH

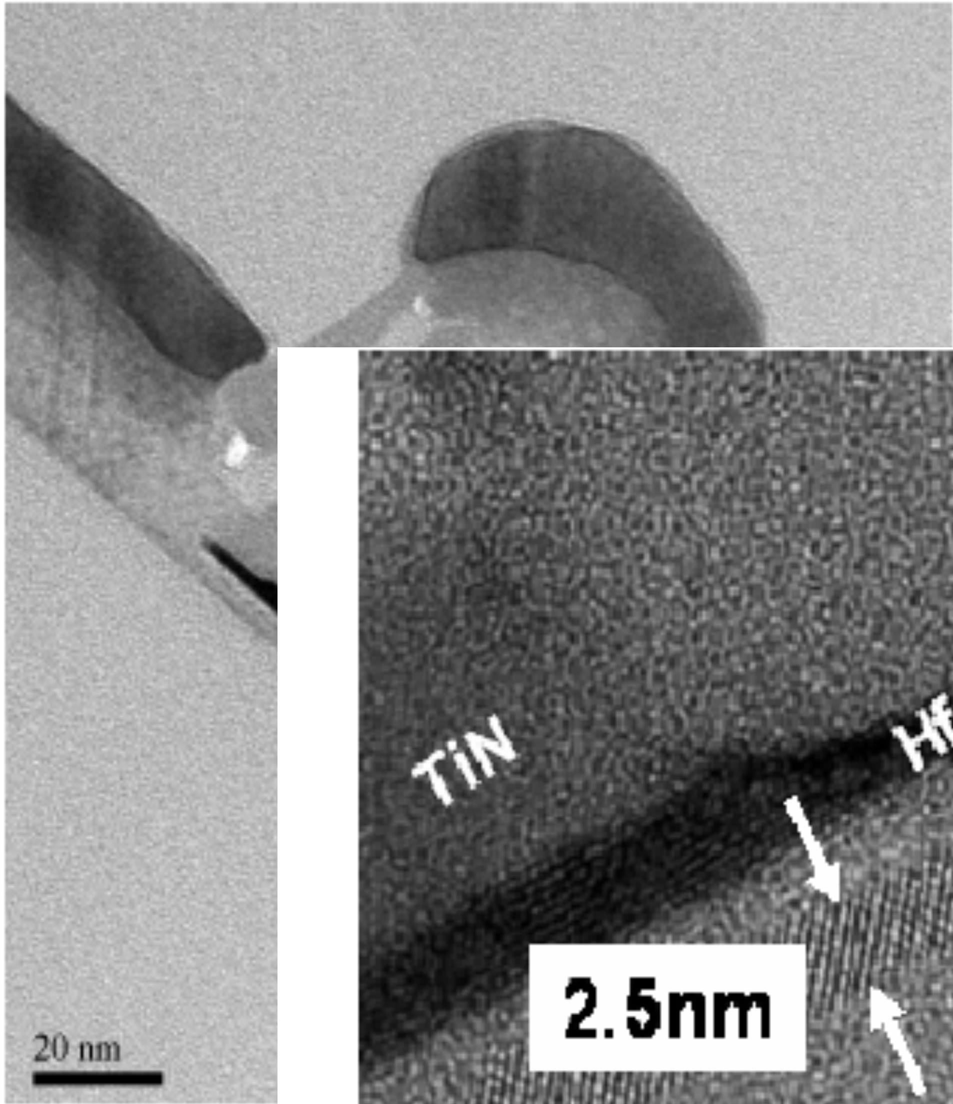


Fig. 1- TEM cross section (

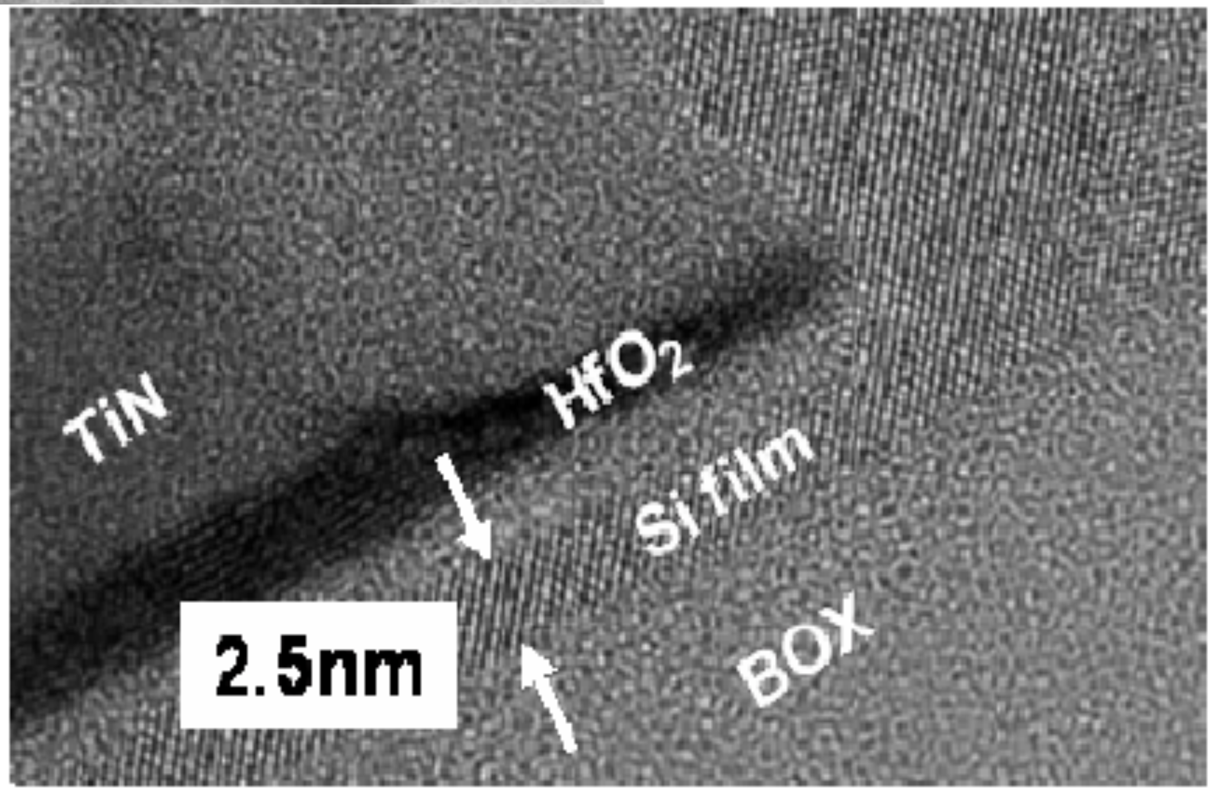


Fig. 2- HRTEM cross-section showing the detail of the channel edge. The Si film thickness is 2.5nm.

FinFET TRANSISTOR

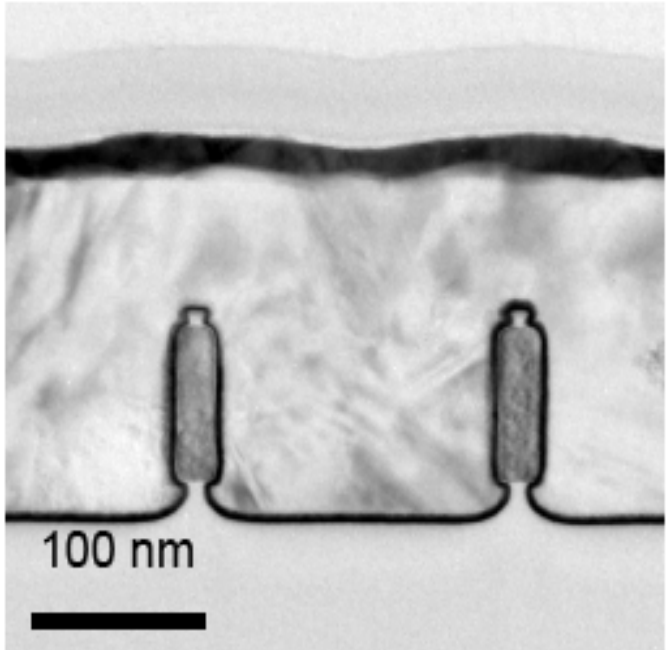


Fig 9. 20 nm FinFETs processed with similar gate dielectric and having Tinv=1.4 nm with Si(110) orientation.

HIGH k and METAL-GATE

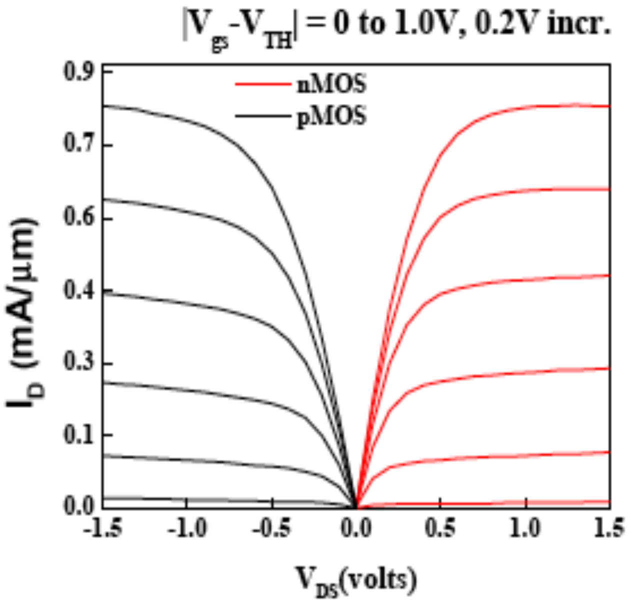


Fig 10. The Si(110) FinFETs (WFin=20nm and LDrawn=80nm) with high k / metal gate show the same symmetric performance as the planar devices. Short Channel effects are improved due to the intrinsic doping of the channel.

SEMATECH
paper 3.3

MOORE's TREND for SAMSUNG DRAM

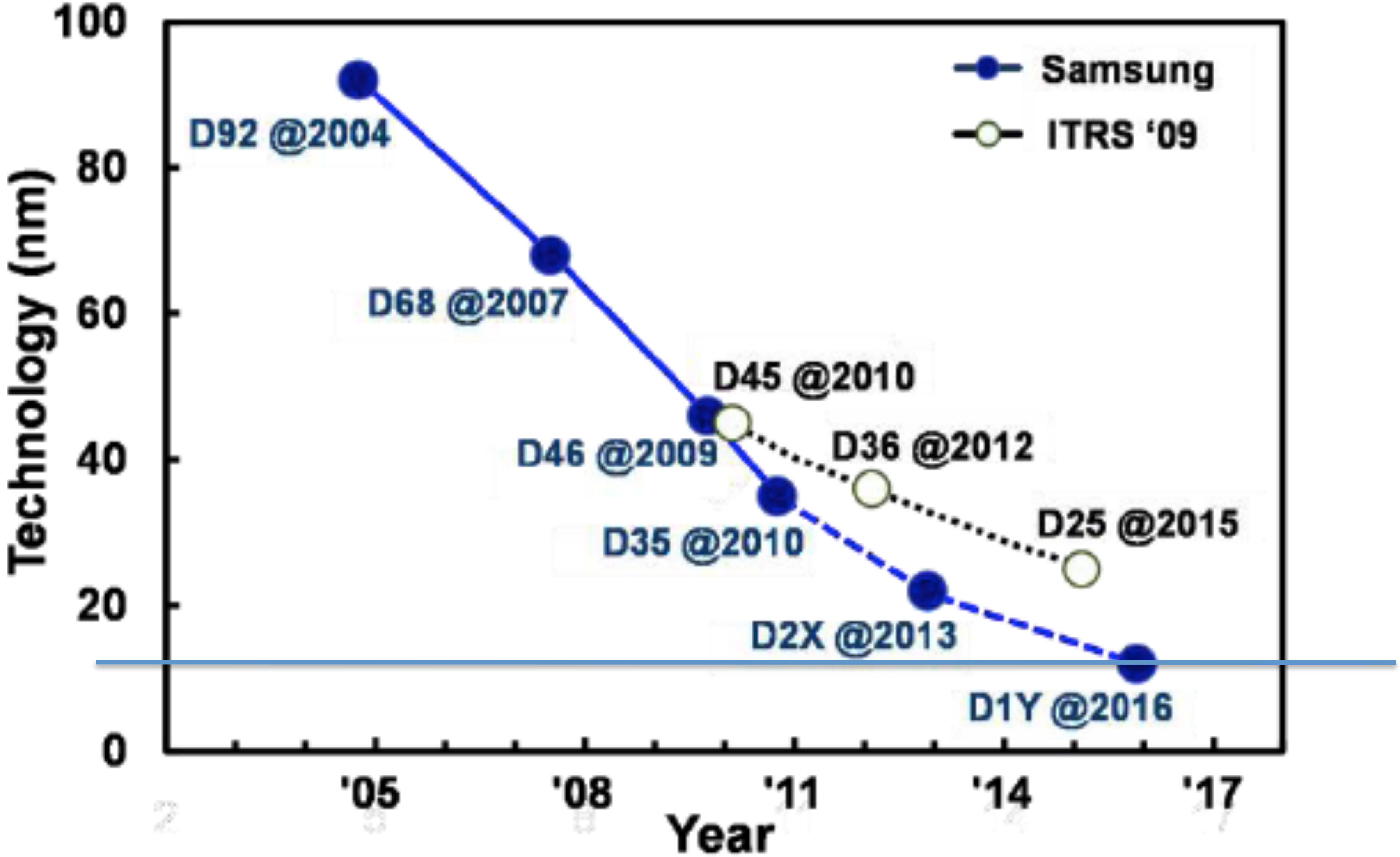
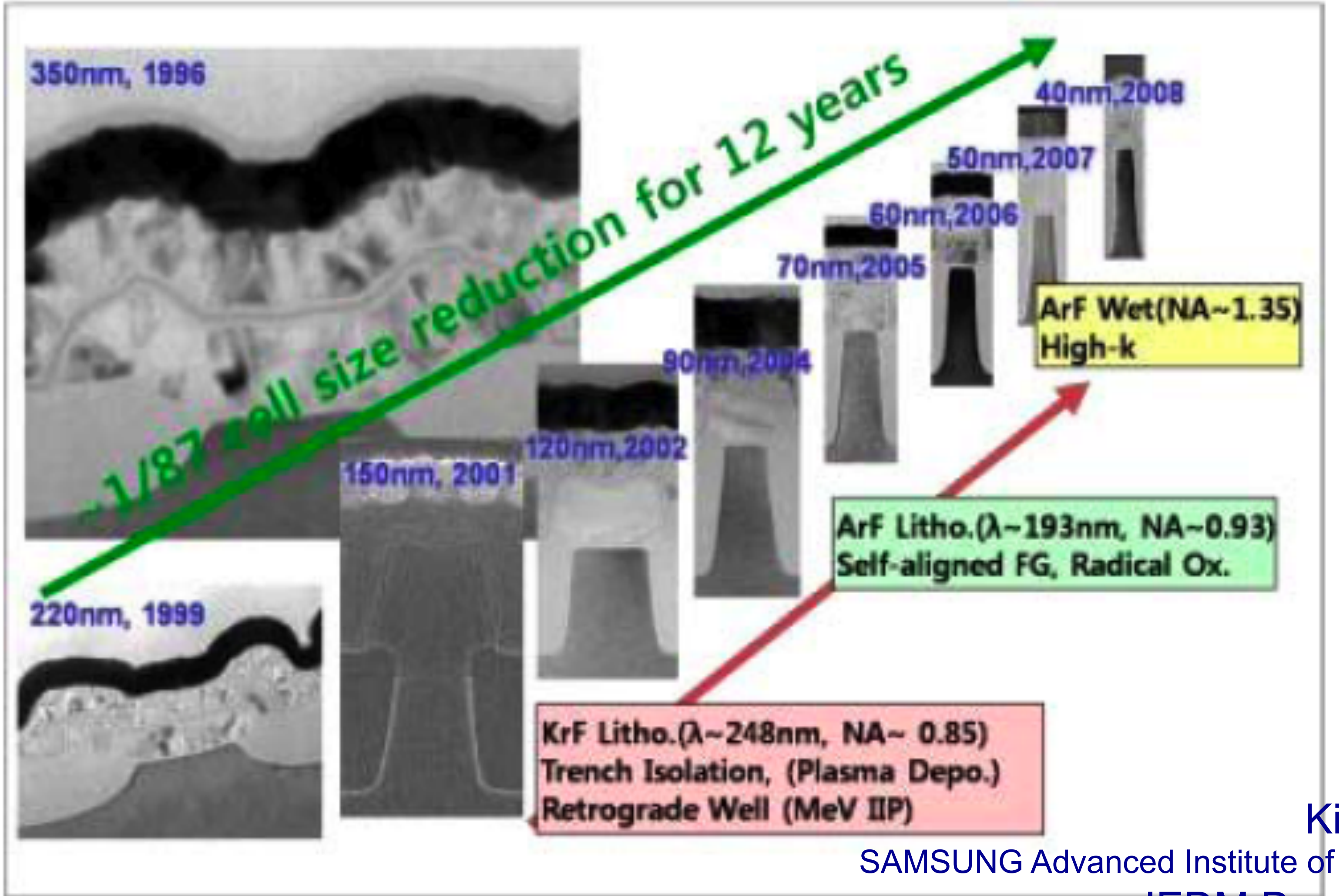


Fig. 1 ITRS & Samsung DRAM technology roadmap

Kinam KIM
SAMSUNG Advanced Institute of Technology
IEDM Dec 2010 1.1

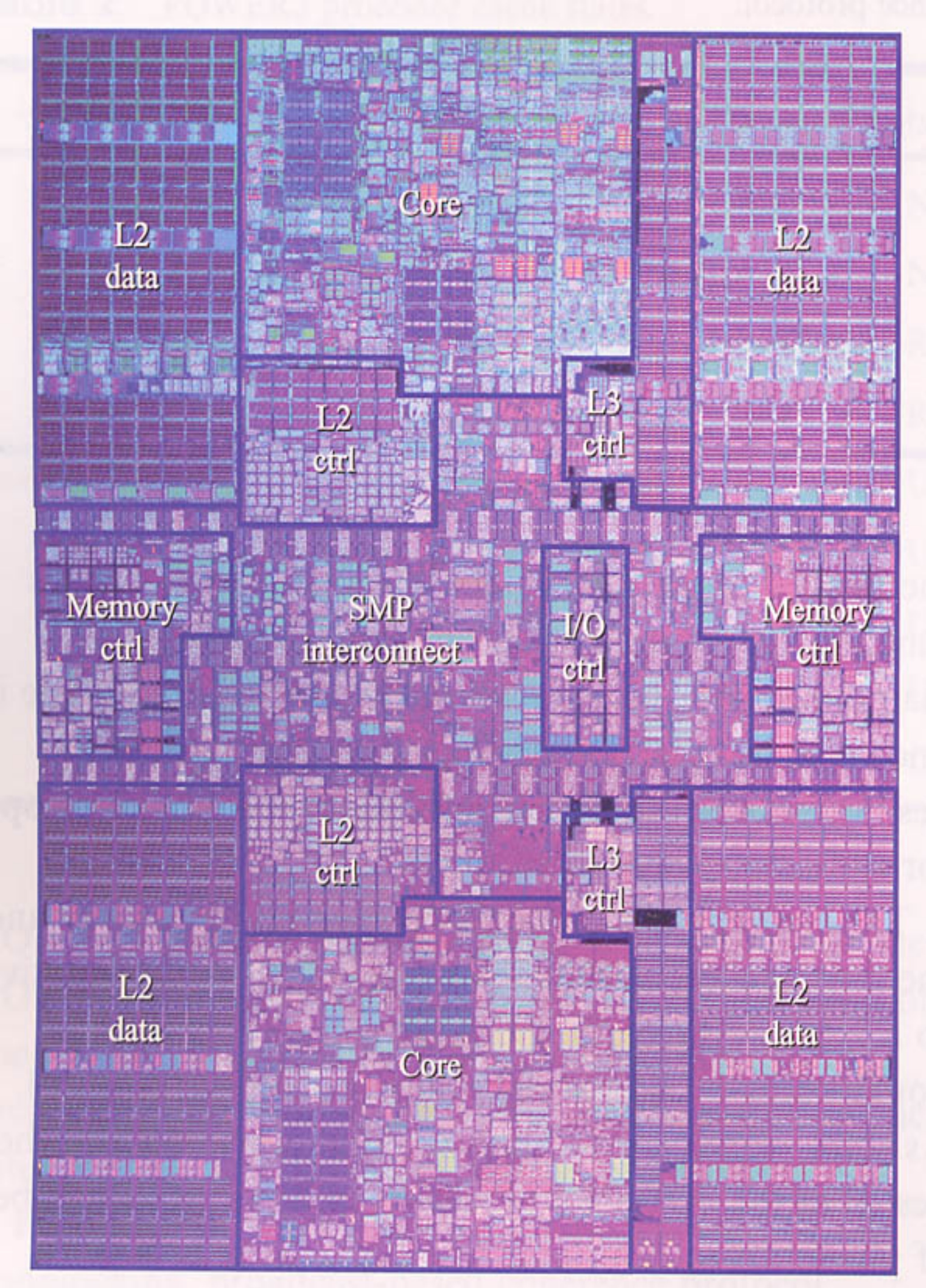
TREND in NAND cell 1999-2008



Kinam KIM
SAMSUNG Advanced Institute of Technology
IEDM Dec 2010 1.1

Fig. 3 NAND cell dimensional scaling and related technology evolution

SYSTEM CHIPS

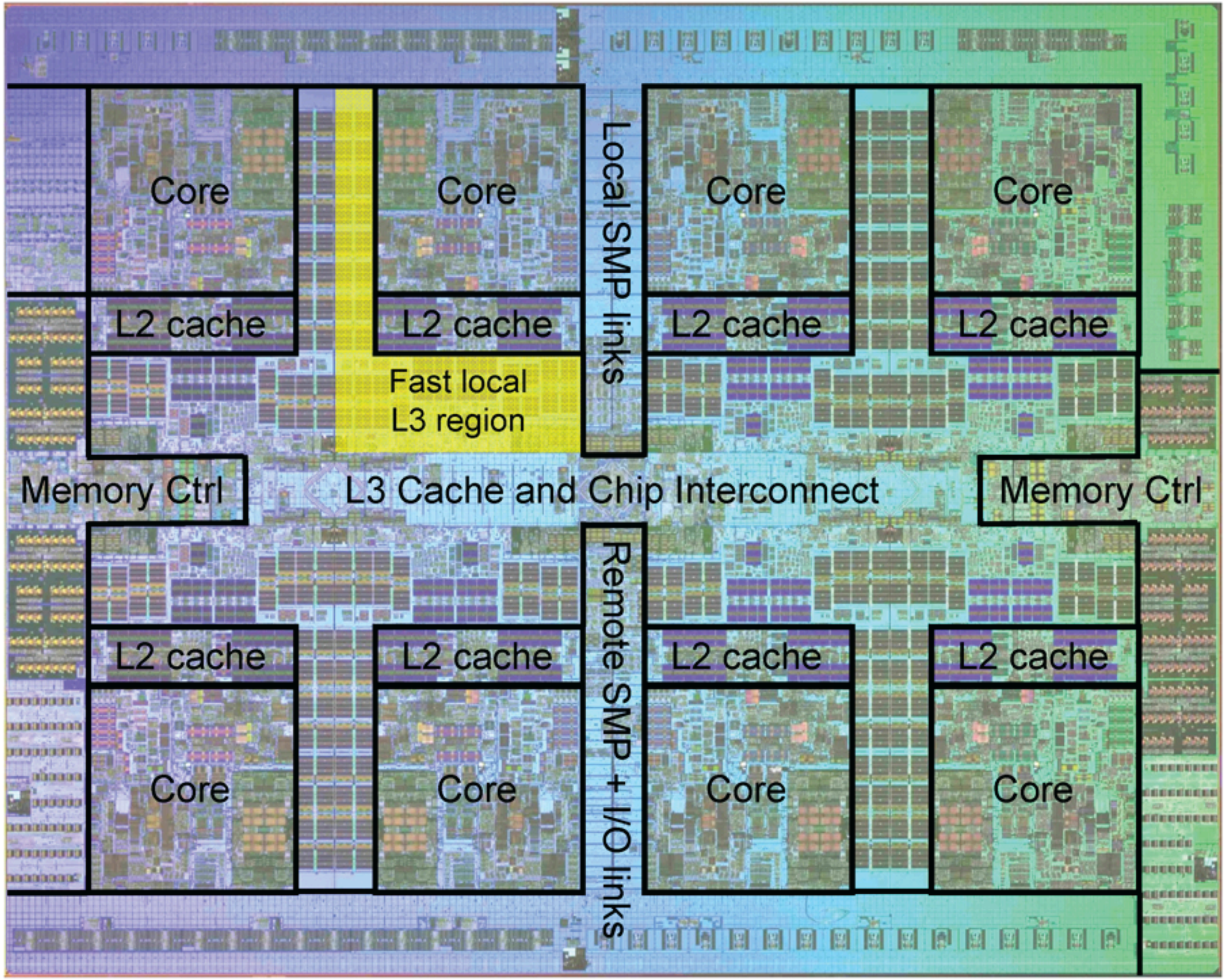


IBM POWER6

DUAL CORE > 4 GHz
0.065 um SOI n 40nm, p 35 nm
dual gate oxide 1.12 , 2.35 nm
4 V_T levels
10 levels Cu low-k dielectric
pitch 200 nm, 175 nm thick
e-fuse
341 mm2, ~16 mm x 21.3 mm
790 M transistors most at 1.15 V
I/O 1953 signal+test, 5399 power
D 64kb + I 96kb L1 in cores
2x2 4Mb L2 (+ 32Mb L3 off-chip)
64 bit, 800 MHz memory access

ERROR RECOVERY
CHECK POINT RETRY

PHOTO of REAL DIE



IBM POWER7

5.67 cm^2
1200 M transistors
8 Core Processor
45 nm SOI-CMOS

internal L3 cache
5nm SOI-CMOS

DIE PHOTO

ERROR RECOVERY
CHECK POINT RETRY

PIXEL DETECTORS at CERN INVENTED 1986

HIGH INTENSITY EXPERIMENTS
e.g. HEAVY IONS (Omega ion experiments) and FUTURE LHC

THE MEDIPIX2/3 SYSTEM for X-RAYS

MICROELECTRONICS, Si SENSORS & ASSEMBLY

CHIP DESIGN CERN:Michael Campbell, Xavier Llopart, Rafael Ballabriga
READOUT CARDS & SOFTWARE several Institutes: Pisa, Napoli, NIKHEF, IEAP-CTU (Pixelman), ESRF, Diamond-UK, ...

MEASUREMENTS with OTHER RADIATION QUANTA

DIFFERENT SENSORS (Si, CdTe, GaAs, diamond, gas,..)
DIFFERENT RADIATION ELECTRONS, NEUTRONS, PROTONS,IONS, VISIBLE LIGHT (gas, +MCP)
MANY DIFFERENT APPLICATIONS in Science and Industry

BASICS of a DETECTOR

SIGNAL if there is PARTICLE

→ DETECTION EFFICIENCY

NO SIGNAL if NO PARTICLE

MUCH MORE DIFFICULT

TAKE ONLY 'GOOD' PARTICLE

EVEN MORE WORK ON TRIGGER CONDITIONS

MICROELECTRONICS and COMPUTERS
ENABLE NEW PARTICLE PHYSICS EXPERIMENTS

BASICS of a DETECTOR

SIGNAL if there is PARTICLE

→ DETECTION EFFICIENCY

usually close to 100%, BUT....

→LOSSES CAN BE DUE TO

INSENSITIVE AREAS (FRAME, EDGE, DEAD WIRE, ..)
CRYSTAL BOUNDARY or DEFECT
WINDOW ABSORPTION (e.g. for low keV X-rays)
LOSS OF SIGNAL : TRAPS, BALLISTIC DEFICIT
INCLINED TRACKS
SIGNAL SHARING BETWEEN CELLS
PILE-UP/DEAD-TIME at HIGH RATE
OUT-OF-TIMING (for SYNCHRONOUS READOUT)
BOTTLE-NECKS in READOUT SYSTEM
(MEMORY OVERFLOW)
SOME REDUNDANCY is NEEDED
a few % CAN USUALLY BE TOLERATED

NOISE and RISETIME (τ_s 'speed') in PREAMPLIFIER

Series Noise: $$ENC_d^{\,2} \propto \frac{C_t^{\,2}}{g_m \tau_s}$$ Capacitance, Speed

Parallel noise: $$ENC_o^{\,2} \propto I_o \tau_s$$ Dark current I_0

Preamp rise time: $$t_r \propto \frac{C_t}{g_m} \frac{(C_L + C_f)}{C_f}$$

In general C_t should be as low as possible and g_m high, but more g_m implies more power

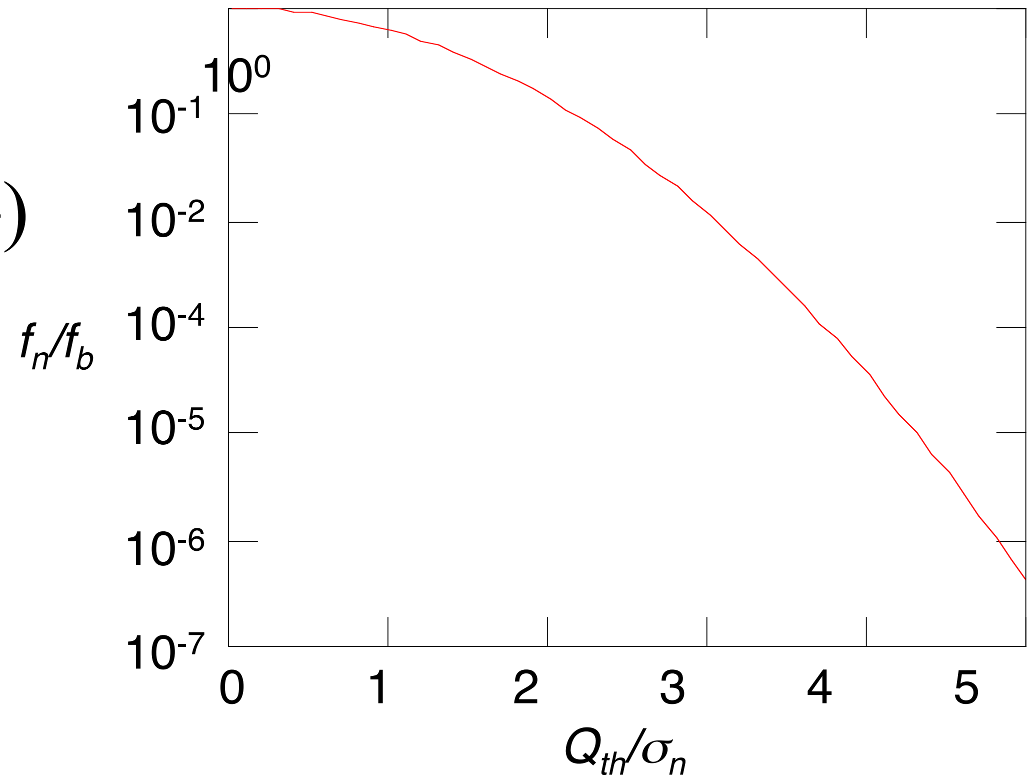
from Michael CAMPBELL
see also Seminar Ratti

RANDOM NOISE RATE

discriminator
bandwidth, f_b

$$f_n = \frac{1}{\sqrt{3}} f_b \exp\left(\frac{-Q_{th}^2}{2\sigma_n^2}\right)$$

Q_{th} = threshold
σ_n = noise rms



In a large bandwidth system (such as an HEP experiment) noise and threshold variation must be kept very far from the threshold and the signal to produce clean event information

from Michael CAMPBELL

'NOISE' in a DETECTOR

SPURIOUS SIGNALS if there is NO PARTICLE :

MANY CAUSES in DETECTOR and READOUT

e.g. AFTERPULSES from ION-FEEDBACK
in GASEOUS WIRECHAMBERS

SCINTILLATOR + PM USUALLY LOTS of NOISE
NEED for COINCIDENCES

Si APD MHz RANDOM PULSES

ELECTRICAL NOISE from DARK CURRENT, CAPACITANCE,

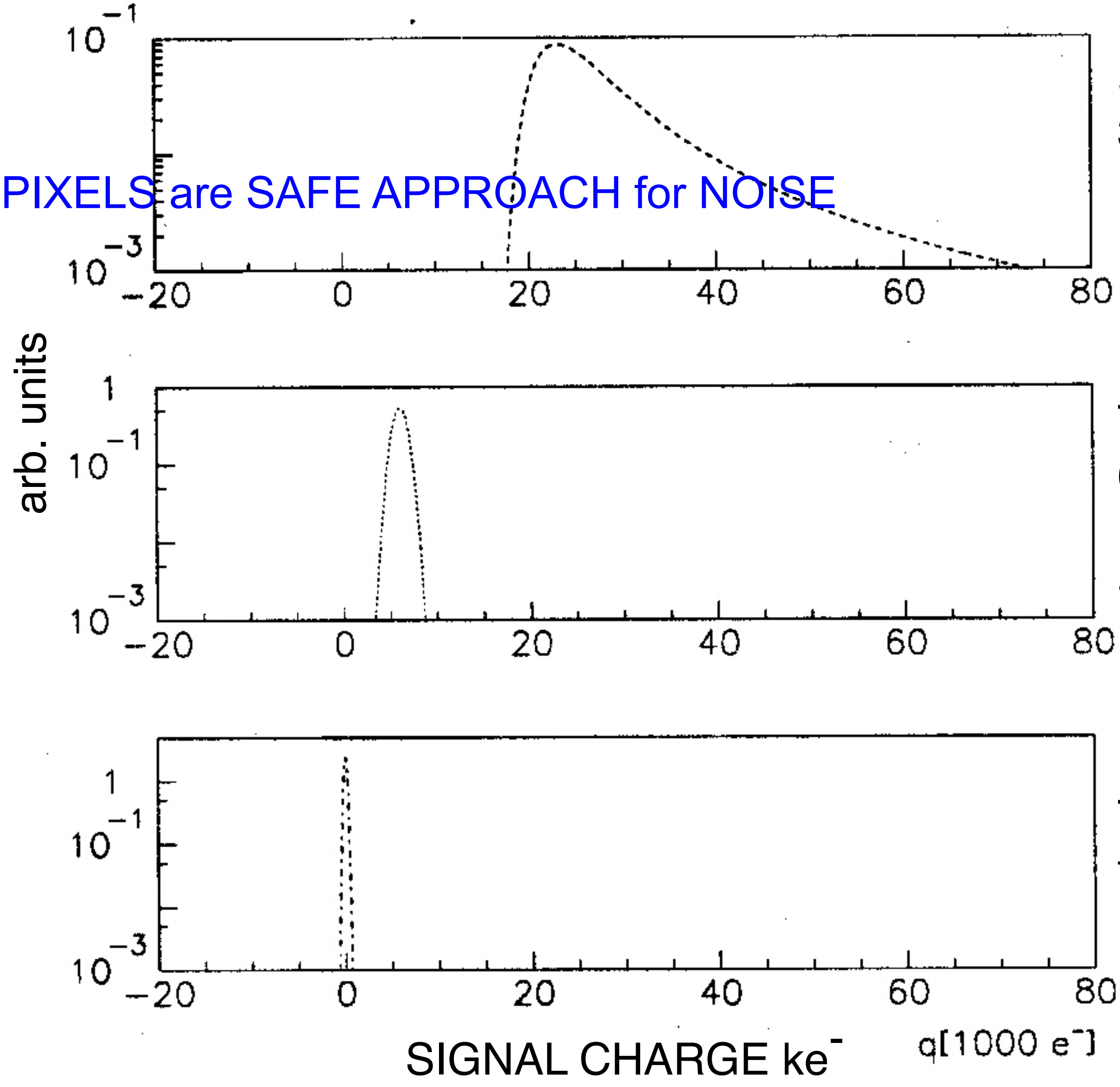
WIDTH of NOISE DISTRIBUTION IF GAUSSIAN

99.7% CONTAINED in $\pm 3\sigma$

with 6σ THRESHOLD one can haveas low as 10^{-7} PROBABILITY
BUT watch out: in LHC $4\ 10^{7}$ measurements/ s

CHARACTERISTICS for BINARY PIXEL SYSTEM

PIXELS are SAFE APPROACH for NOISE



SIGNAL DISTRIBUTION
300 μm Si

PEAK at ~22 ke$^-$

THRESHOLD
6 ke$^-$ with σ ~ 800 e$^-$rms

+6σ is ~11 ke$^-$

NOISE
TYPICALLY ~100 e$^-$rms
for Si PIXEL DETECTOR

PhD Thesis 1996
Peter Middelkamp
fig.36

RELATIONS BETWEEN CAPACITANCE, SPEED, NOISE and POWER

In the first approximation all characteristics are dominated by the input transistor of the front-end amplifier.

Transistor transconductance g_m

$$g_m = \frac{q}{kT} I$$

in weak inversion CMOS and in bipolar

I is transistor current, $\frac{kT}{q} \sim 0.025$ eV

Noise (series noise) is dominated by detector capacitance C_d

$$ENC^2 = \boxed{\frac{2\,kT\,C_d^2}{g_m\,\tau}} = \frac{2k^2T^2\,C_d^2}{I\,\tau} = \frac{2k^2T^2\,C_d^2\,V}{P\,\tau}$$

approximation

RELATIONS BETWEEN CAPACITANCE, SPEED, NOISE and POWER (2)

Express the power P_d for detector readout
as a function of noise and capacitance

$$P_d = \frac{2k^2 T^2 C_d^2 V}{ENC_d^2 \tau}$$

Power increases with square of capacitance,
therefore it would be useful
to work with as small C_d as possible: SEGMENTATION

$$P_s = \frac{2k^2 T^2 C_s^2 V}{ENC_s^2 \tau}$$

for segmentation in n sensors $C_d = n \times C_s$

RELATIONS BETWEEN CAPACITANCE, SPEED, NOISE and POWER : SEGMENTATION (3)

for segmentation in n sensors $C_d = n \times C_s$

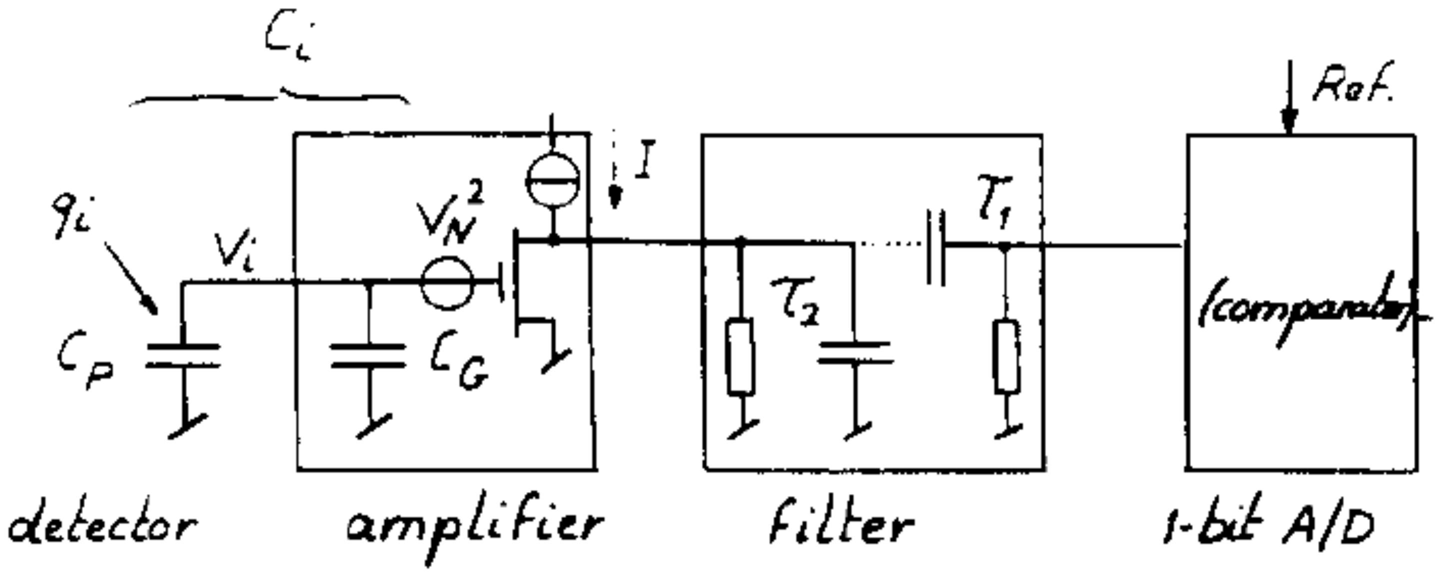
$$P_s = \frac{2k^2 T^2 \; C_s^{\,2} \; V}{ENC_s^{\,2} \; \tau}$$

Power for all segments together P'_d is original/n
(in first approximation)

$$P'_d = n \times P_s = \frac{2k^2 T^2 \; C_d^{\,2} \; V}{ENC_d^{\,2} \; n\tau} = \frac{P_d}{n}$$

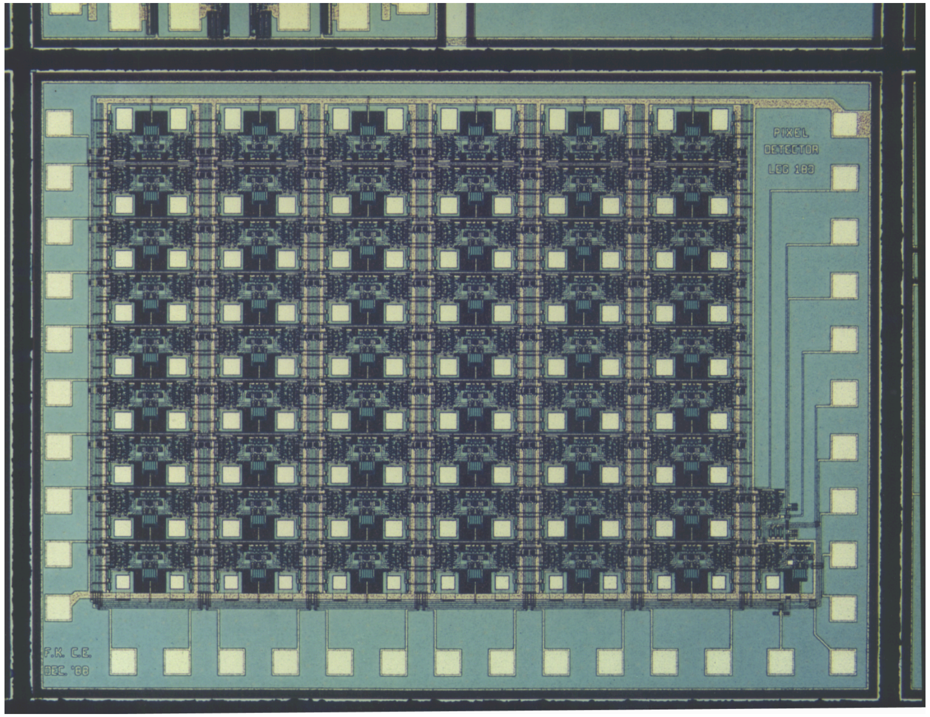
The invention of the pixel micropattern detector

Electronics Circuit in each Pixel 1988



Schematic Diagram
worked out by prof Eric Vittoz, for 1988 Leuven Pixel Workshop
NIM A275 (1989) 472

First Pixel Detector Prototype 1989



Krummenacher et al. NIM A288 (1990) 176
(presented at Munich Symp Feb 1989)
circuit description

Campbell et al. NIM A290 (1990) 149
(presented at IEEE Nucl Sc. Symp. 1989)
results including spectra
taken with radioactive sources

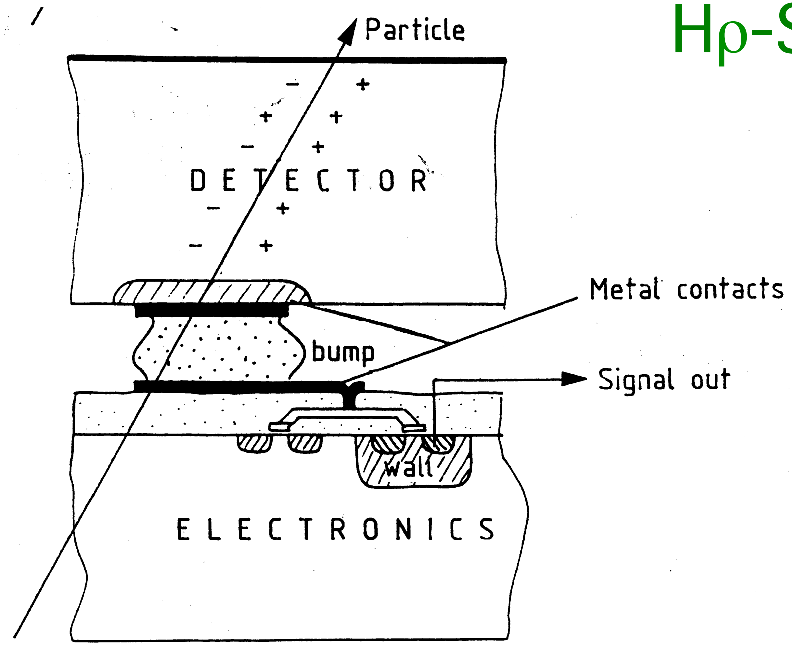
Pixel readout test chip 12x9 pixels, synchronous operation
designed Dec 1988 by Christian Enz and François Krummenacher,
in collaboration with CERN (Heijne, Jarron) and ETHZ (Viertel)

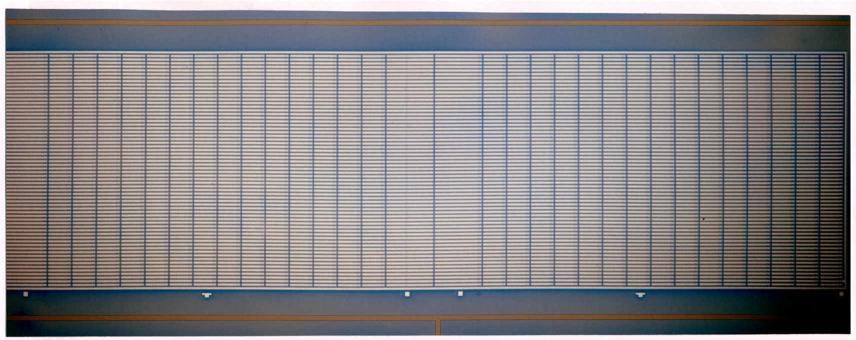
HYBRID Si PIXEL SENSOR 1991

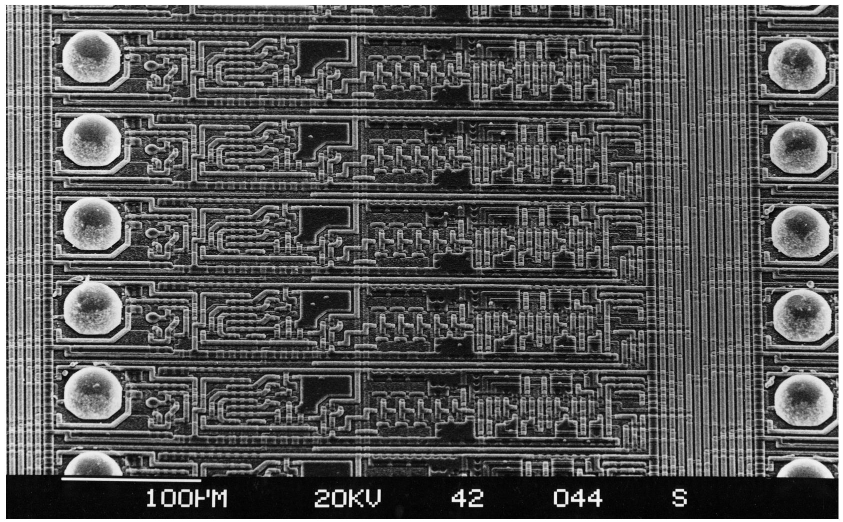
CERN : CAMPBELL, HEIJNE

SENSOR MATRIX TRUE 2 - D

Hρ-Si





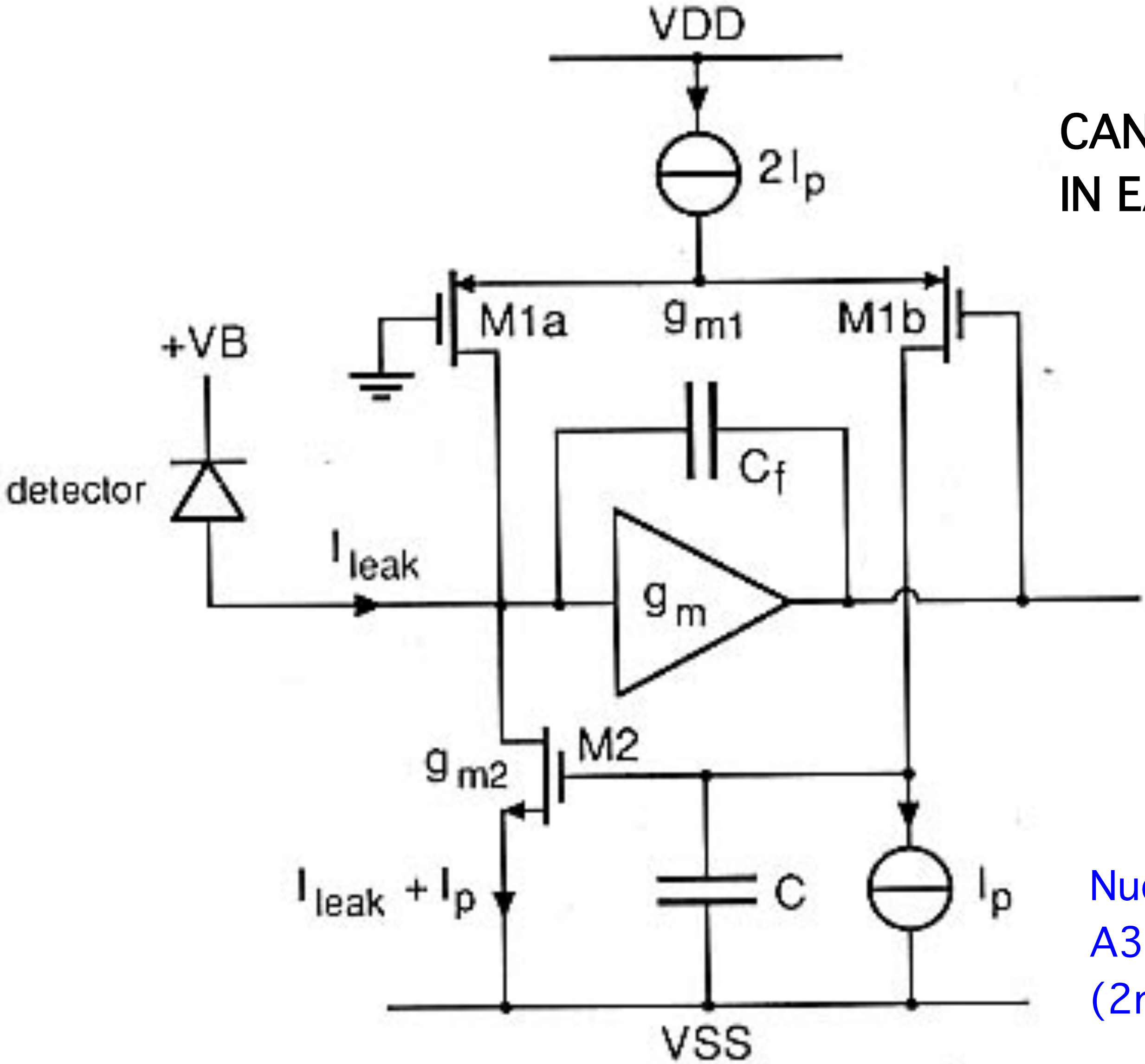


BUMPS

+

CMOS READOUT ELECTRONICS

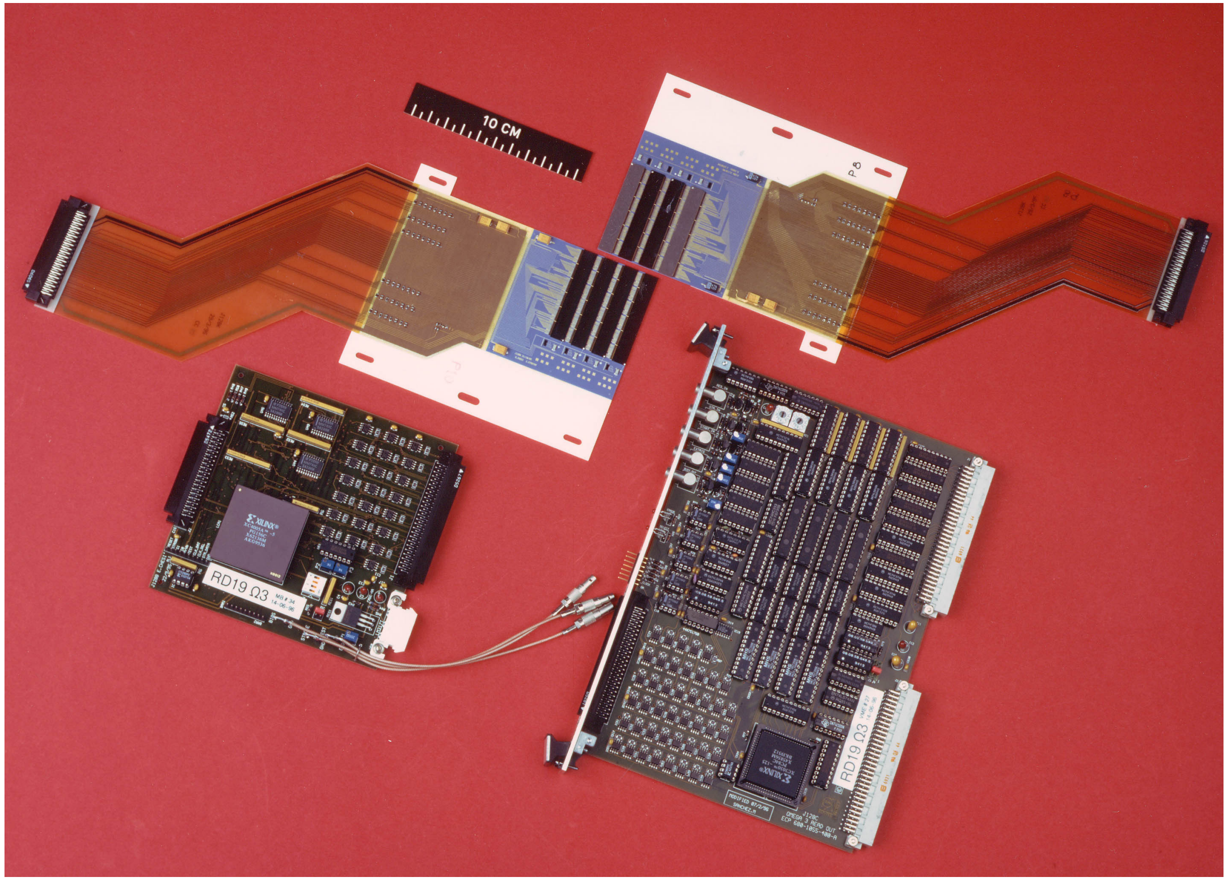
LEAKAGE CURRENT COMPENSATION KRUMMENACHER 1989



CAN BE IMPLEMENTED
IN EACH PIXEL CELL

Nucl. Instr. Meth.
A305 (1991) 527
(2nd Leuven Pixel Workshop)

LHC1 PIXEL ARRAYS 1995



2 x 4 LADDERS
with OVERLAP
COVER 5 x 5 cm^2

14 PLANES
BUILT 1992 - 97

PIXEL TELESCOPE USED in Omega Spectrometer at CERN
RD19 collaboration at CERN for LHC detector R&D

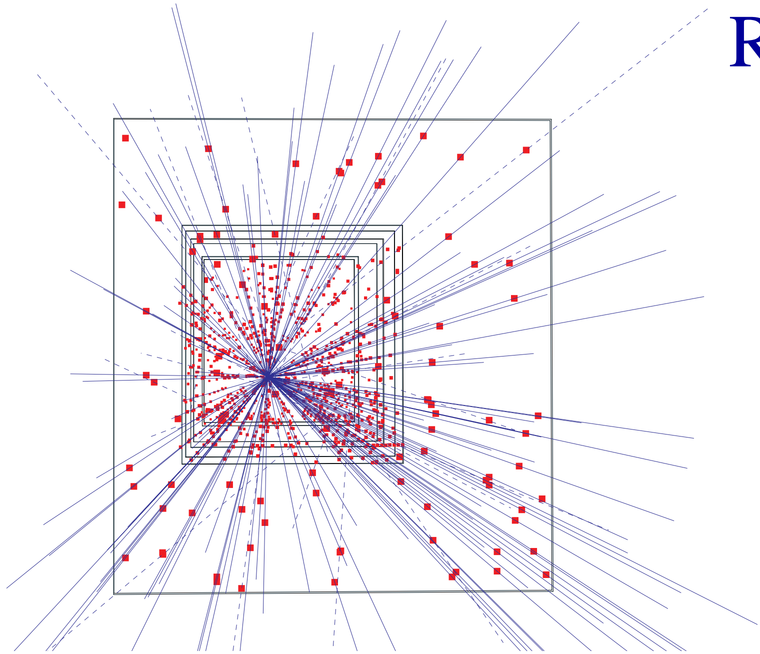
→ this pixel chip first presented in Hiroshima Symposium 1995
NIM A383 (1996) 55

TRACKING with PIXELS at CERN

1995

WA97

RD19



7 PLANES
1.1 M pixels

153 tracks

B-field OFF

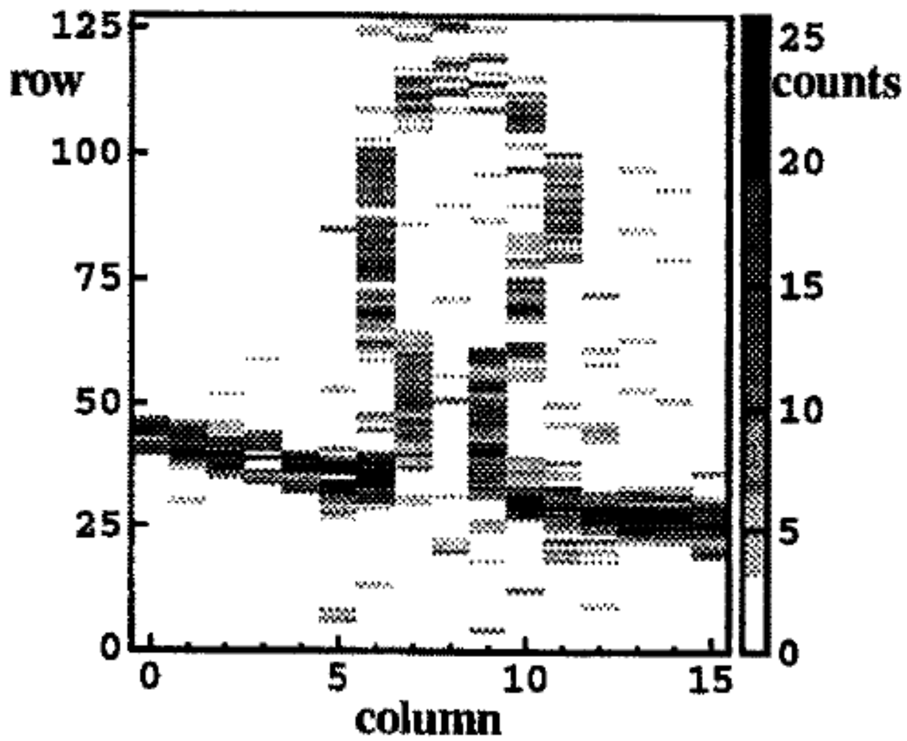
^{208}Pb ion at 158 A GeV/c on Pb target

Millions of EVENTS ANALYZED

SPACE POINTS
NOISE-FREE

Ideas for imaging were around since the beginning

Image made with GaAs assembly by Cinzia da Via and by Peter Middelkamp in 1996



Medipix effort really started at CERN in 1998 after the Trieste meeting by INFN

NIM A395 (1997) 148
PhD Thesis P. Middelkamp WUB-DIS 96-23
PhD Thesis C. Da Via Glasgow 1997

Medipix Pixel Detectors for X-ray imaging

Chips Designed in Framework of Medipix

Medipix1 (1998)	*1μm SACMOS, 64x64 pixels, 170x170μm^2* *PC / Frame based readout*
Medipix2 (2001)	*0.25μm CMOS, 256x256 pixels, 55x55μm^2* *PC / Frame based readout*
Timepix (2006)	*0.25μm CMOS, 256x256 pixels, 55x55μm^2* *PC, ToT, ToA / Frame based readout*
Medipix3 (2009)	*0.13μm CMOS, 256x256 pixels, 55x55μm^2* *PC / Frame based readout* *Event by event charge reconstruction and allocation*
Dosepix (2011)	*0.13μm CMOS, 16x16 pixels, 220x220μm^2* *ToT, PC / Rolling shutter (programmable column readout)* *Event by event binning of energy spectra (16 digital thrs)*
Timepix3 (2013)	*0.13μm CMOS, 256x256 pixels, 55x55μm^2* *PC; ToT, ToA (simultaneous)/ Data driven readout*
Smallpix	*0.13μm CMOS, 512x512 pixels, 40x40μm^2 (TBD)* *PC, iToT; ToA, ToT1 (simultaneous)/ Frame based (ZC)* *TSV compatible design*
Clicpix prototype	*65nm CMOS, 64x64 pixels, 25x25μm^2* *ToA, ToT1 (simultaneous)/ Frame based (ZC)*

Acknowledgement

Presented work is done by

many other people in the Medipix Collaboration

Several slides have been taken from their presentations

Information on Medipix:

http://medipix.web.cern.ch/medipix/

MEDIPIX2 PARTNERS

- U INFN Cagliari
- CEA-LIST Saclay
- CERN Genève
- U d'Auvergne Clermont
- U Erlangen
- ESRF Grenoble
- U Freiburg
- U Glasgow
- IFAE Barcelona
- Mid-Sweden University
- MRC-LMB Cambridge
- U INFN Napoli
- NIKHEF Amsterdam
- U INFN Pisa
- FZU CAS Prague
- IEAP CTU in Prague
- SSL Berkeley
--University Houston

SPOKESMAN Michael CAMPBELL

The Medipix3 Consortium

AMOLF, Amsterdan, The Netherlands (alphabetic by city)
NIKHEF, Amsterdam, The Netherlands
Space Sciences Lab, University of California, Berkeley, USA
Universidad de los Andes, Bogota, Colombia
University of Bonn, Germany
Brazilian Light Source, Campinas, Brazil
University of Canterbury, Christchurch, New Zealand
Universität Erlangen-Nurnberg, Erlangen, Germany
VTT, Information Technology, Espoo, Finland
Albert-Ludwigs-Universität, Freiburg, Germany
CERN, Geneva, Switzerland,
University of Glasgow, Scotland, UK
ESRF, Grenoble, France
DESY, Hamburg, Germany
University of Houston, USA
ISS, Forschungszentrum Karlsruhe, Germany
Leiden University, The Netherlands
Technical University of Munich, Germany
Diamond Light Source, Oxfordshire, England, UK
CEA-LIST, Paris, France
IEAP, Czech Technical University, Prague, Czech Republic
Mid Sweden University, Sundsvall, Sweden

Medipix2 PIXEL CELL LAYOUT

CMOS technology 0.25µm

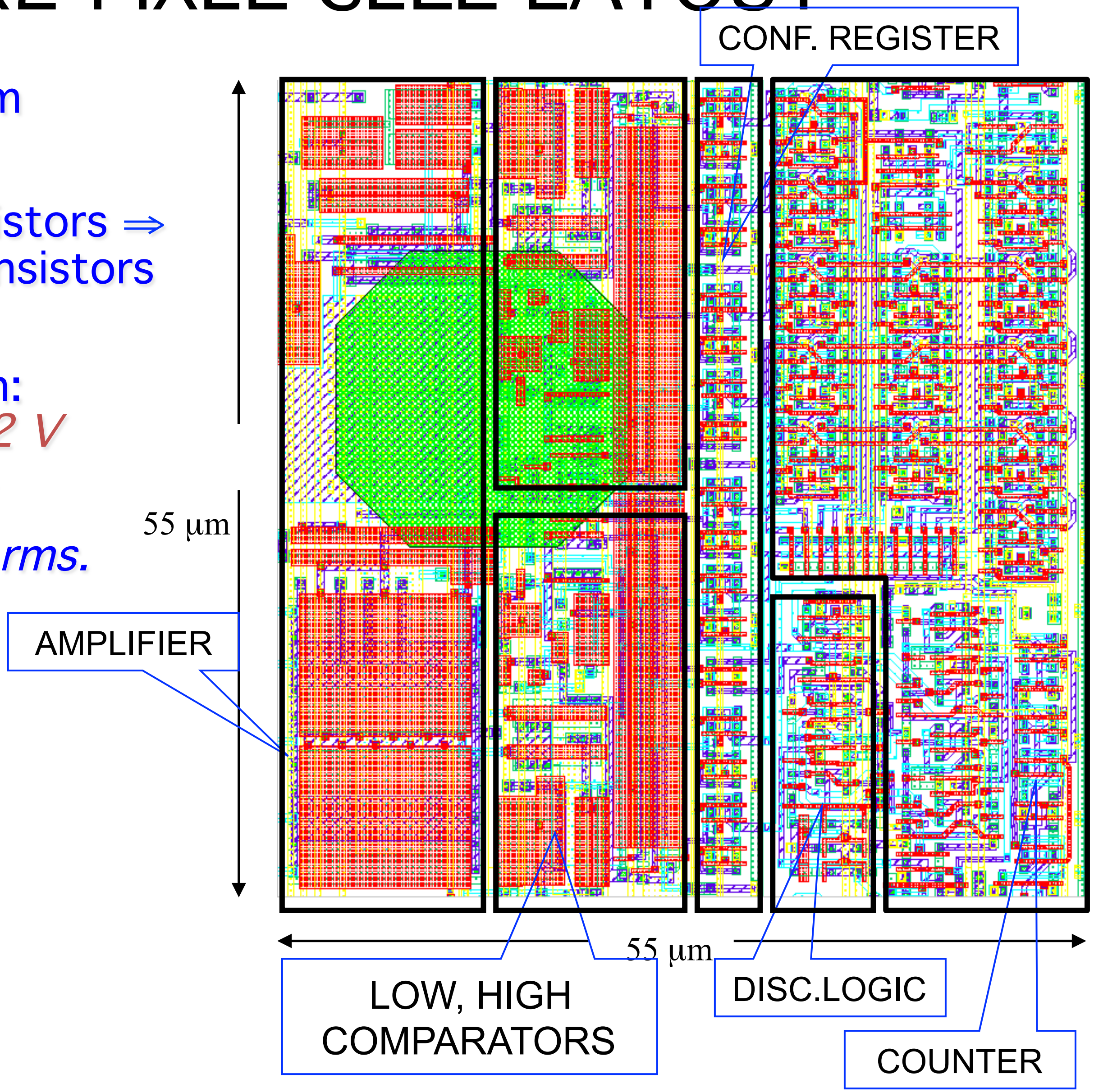
6 metal layers

pixel cell has ~500 transistors ⇒
chip ~33 million transistors

Static power consumption:
~8µW/channel @ 2.2 V

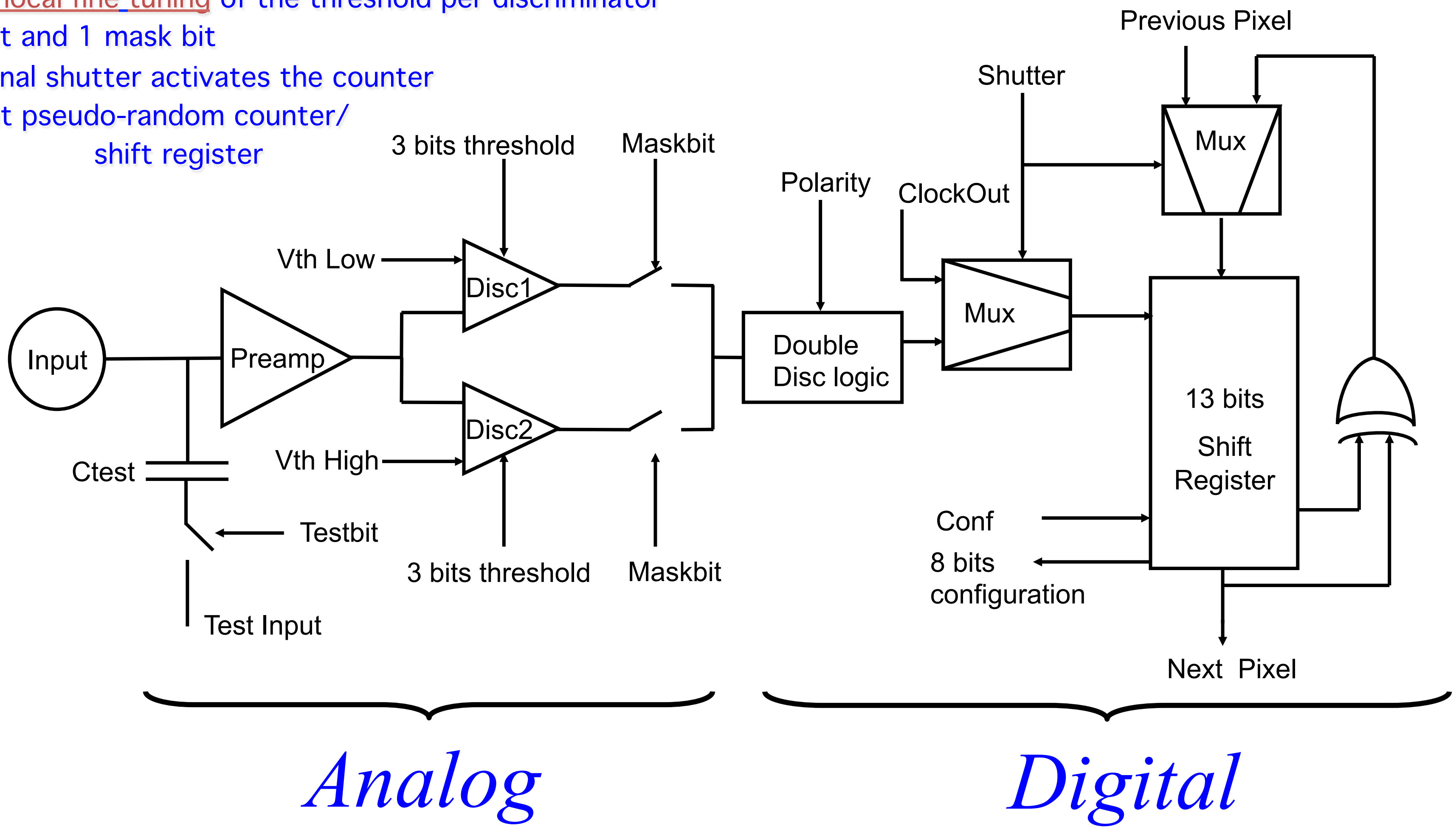
Amplifier Gain: ~11 µV/e⁻

Electronic Noise: ~100 e⁻ rms.



MEDIPIX2 pixel schematic block diagram

accepts positive and negative input → different detector materials
charge sensitive preamplifier with individual leakage current compensation
2 discriminators with globally adjustable threshold
3-bit local fine tuning of the threshold per discriminator
1 test and 1 mask bit
external shutter activates the counter
13-bit pseudo-random counter/ shift register



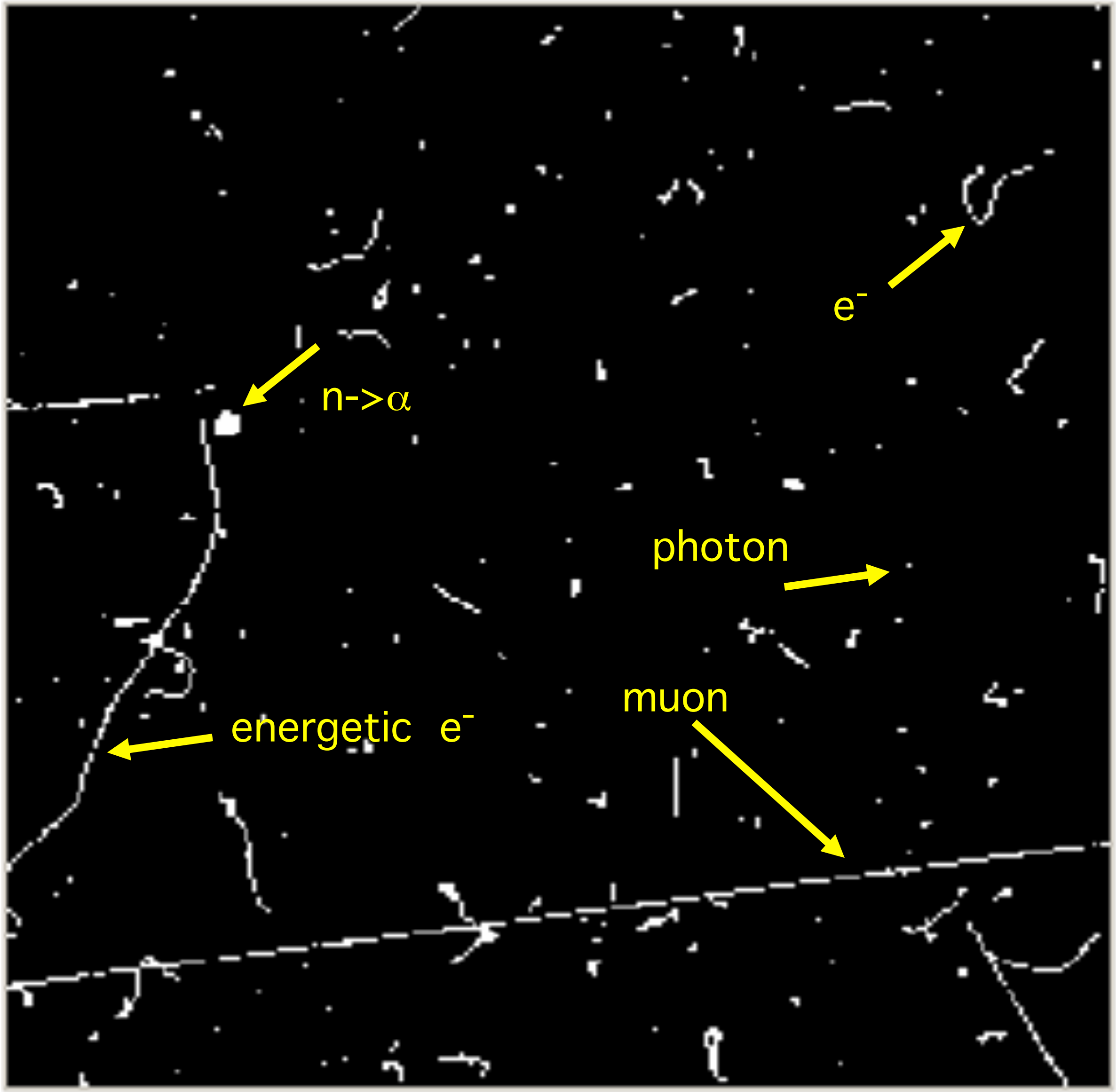
MEDIPIX as RADIATION MONITOR

256 x 256 PIXELS
300 μm THICK Si

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

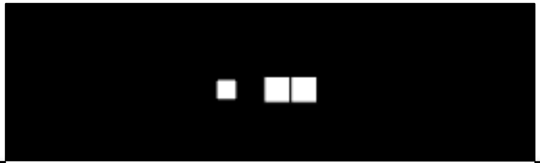
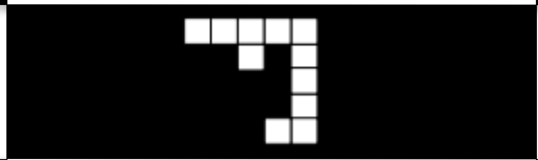
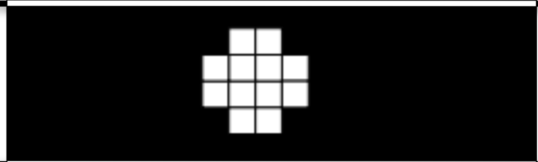
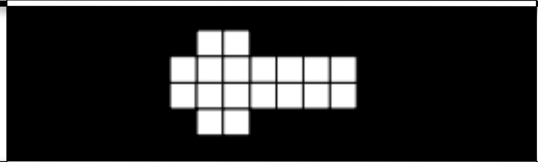
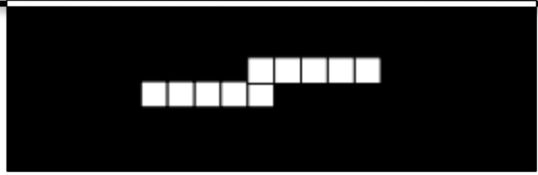
ADJUSTABLE EXPOSURE
ms – hours
LARGE DYNAMIC RANGE
few ns precision

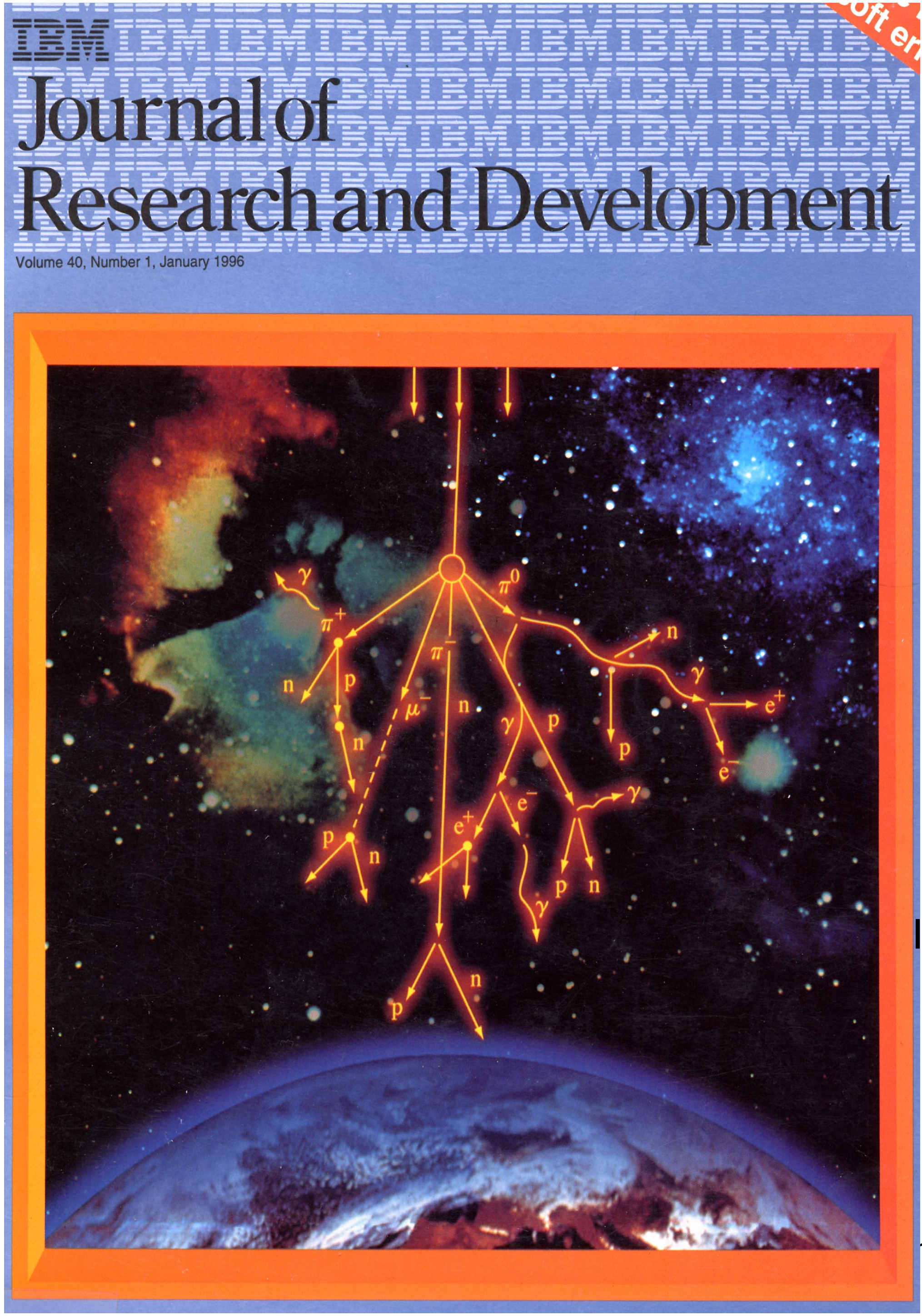
Miniature
electronic version of
tracking in
nuclear emulsion or
bubble chamber



typical frame
IEAP 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,…)



COSMIC RAYS

EFFECTS on ELECTRONICS
Ziegler, IBM J Res & Dev 1998

INCOMING FLUX $\sim 10^{3}$ $m^{-2}\ s^{-1}$

13 km HEIGHT $\sim 10^{6}$ $m^{-2}\ s^{-1}$

SEA LEVEL $\sim 10^{4}$ $m^{-2}\ s^{-1}$

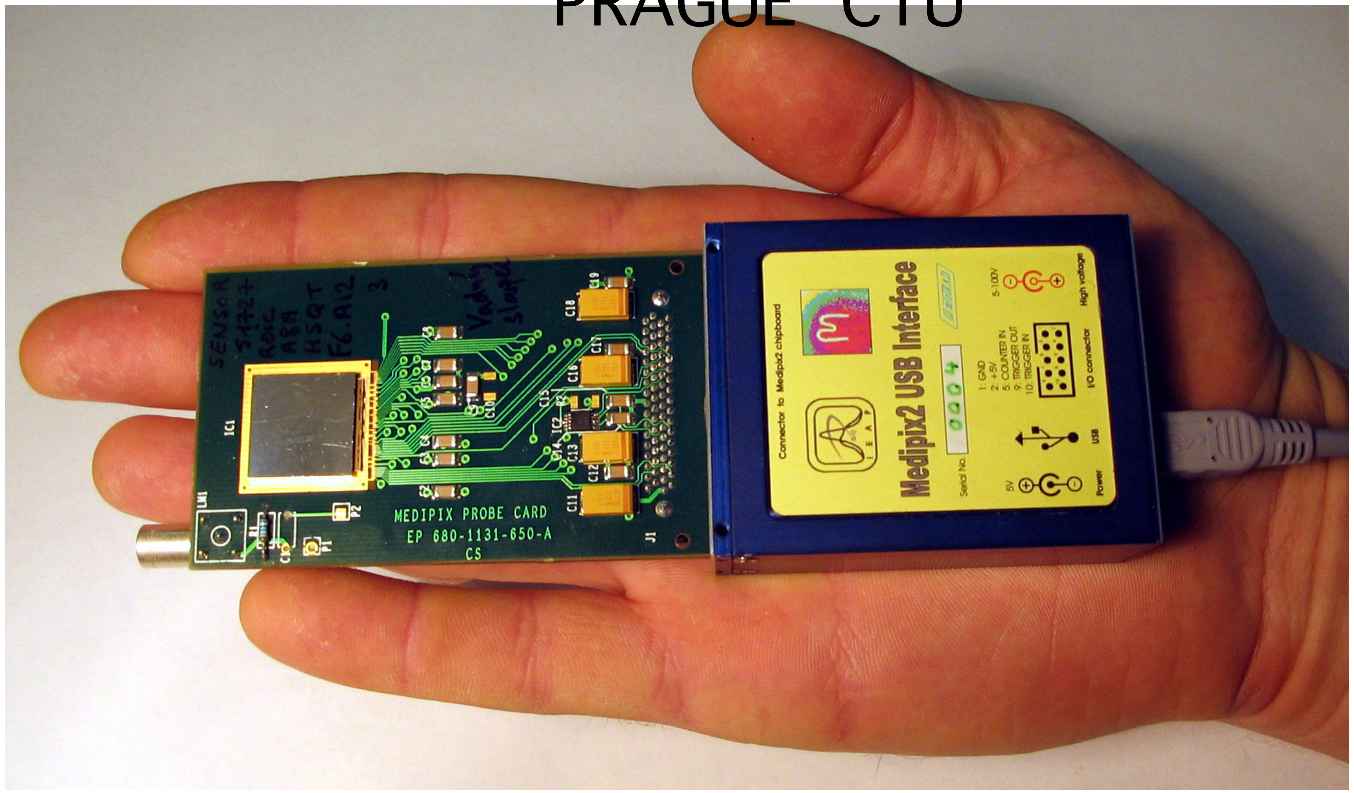
Ziegler,
IBM J Res & Dev 1998
mostly neutrons

RULE of THUMB ~ 1 $cm^{-2}\ s^{-1}$

MEDIPIX USB

USED and POWERED from PORTABLE

PIXELMAN SOFTWARE
PRAGUE CTU



Integrating cosmic rays at sea level

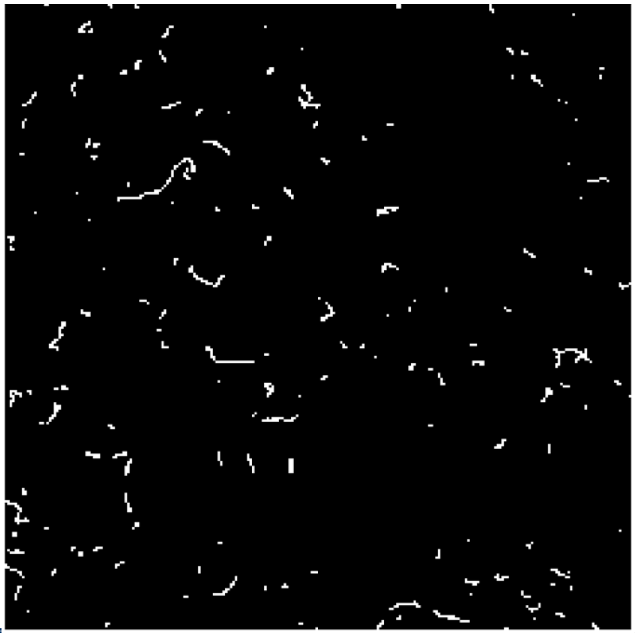
Dosimetry with Medipix

Two approaches: - classification + counting of quantum-induced clusters

- sum of deposited energy in all hit pixels

comparison with standard sources ^{60}Co and ^{137}Cs

photon energies 1173 & 1333keV   resp. 662keV

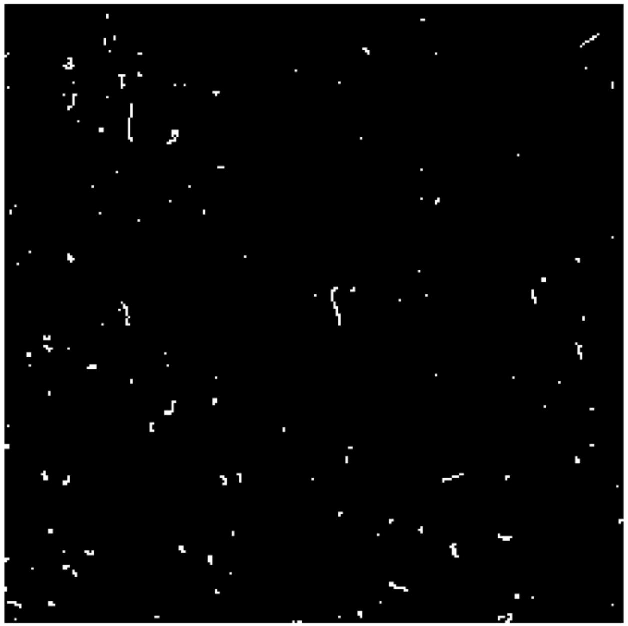


^{60}Co

many long trails

$2.26\ 10^{-10}$ Sv per cluster

±0.19



^{137}Cs

shorter trails

$1.71\ 10^{-10}$ Sv per cluster

±0.07

Dosimetry with Medipix

- clustercounting: assign $2\ 10^{-10}$ Sv per cluster

normalize exposure time to 1 h or 1y (8760h)

- energy deposit: 1Sv = 1Gy x quality Q = 1 J/kg x Q (Q=1)

sensor chip is 0.137 g : normalize per kg of Si

mean deposit 30keV/pixel 1 keV = $1.6\ 10^{-16}$ J

use 'typical' calibration curve for Medipix-T assembly with TOT (time-over-threshold ADC)

normalize exposure time to 1 h or 1y (8760h)

both methods fairly coherent:

cluster with 10 pixels -> ~300keV -> $3.5\ 10^{-10}$ Sv

clusters from alpha or long muon trails have to be treated separately with different algorithm. Also then Q≠1

Dosimetry with Medipix

some examples:

dosimetry in airplane above Groenland

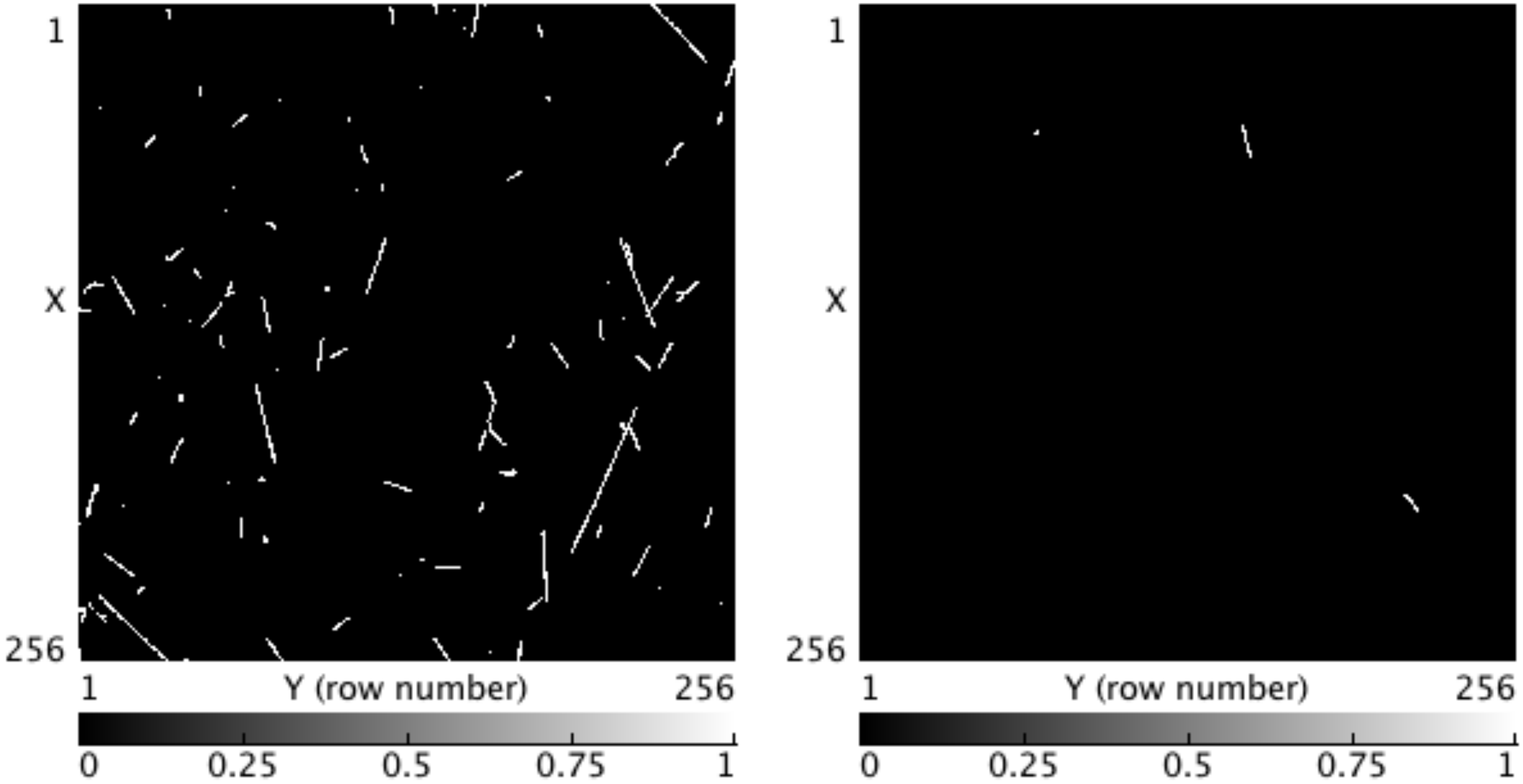
dosimetry in Atlas

dosimetry at home

educational tool: make radiation visible in school
amateur physics
easy measurements when something happens

MEDIPIX measurements in-flight

Compare radiation at 10km and sea level

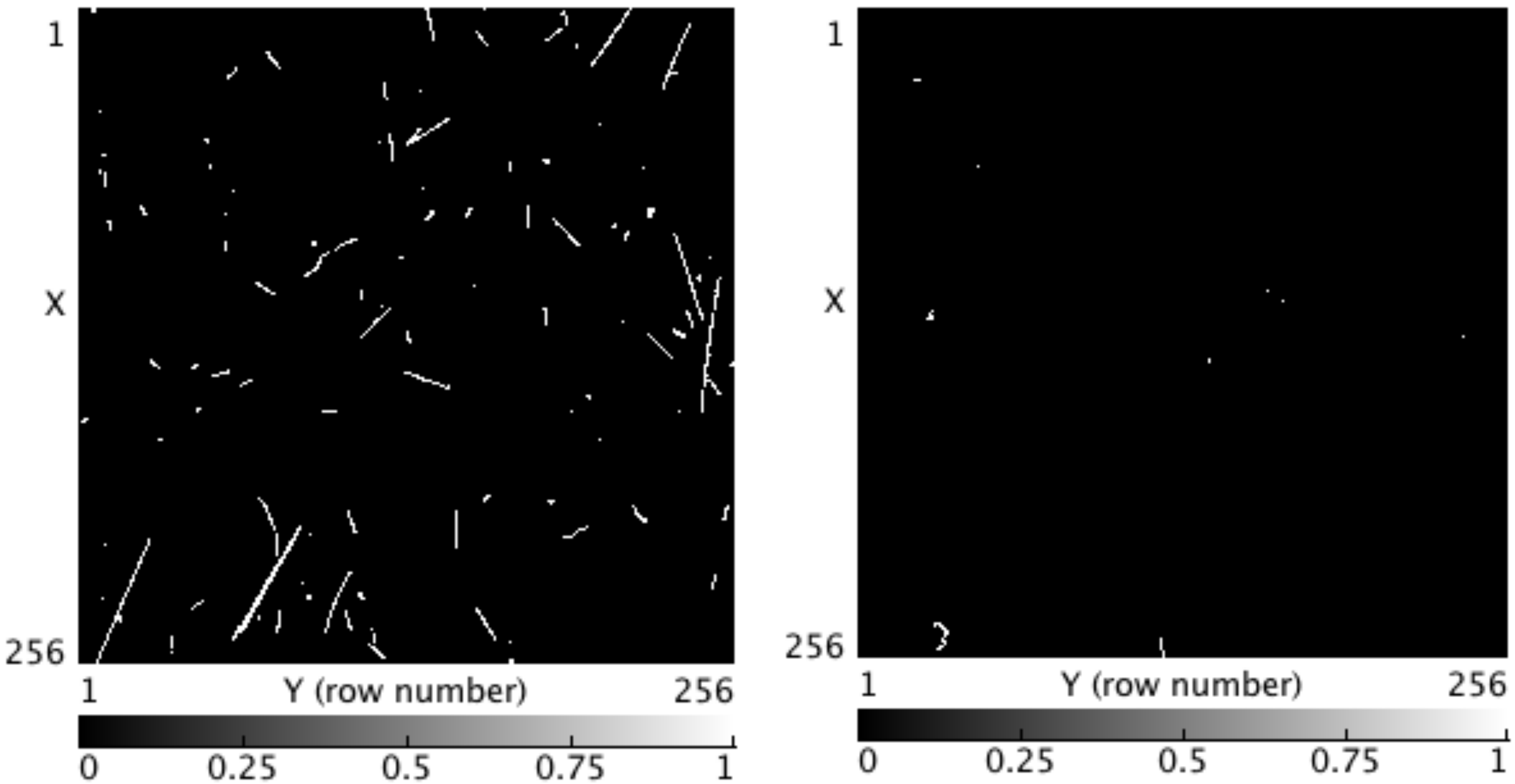


frame 20 at 10km 99 clusters (35 muons) frame 35 at SLAC 3 clusters

both longitudinal exposure of 60s (0.8+0.7)uSv/h vs 0.03uSv/h 50x

MEDIPIX measurements in-flight

Compare radiation at 10km and sea level

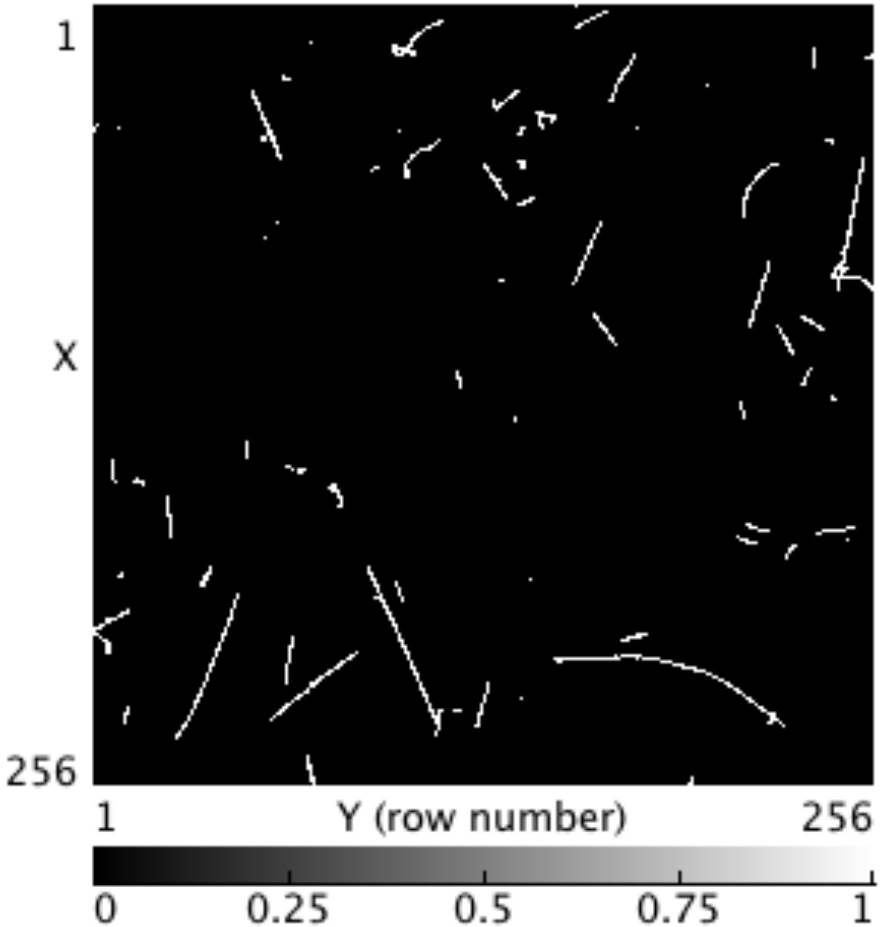


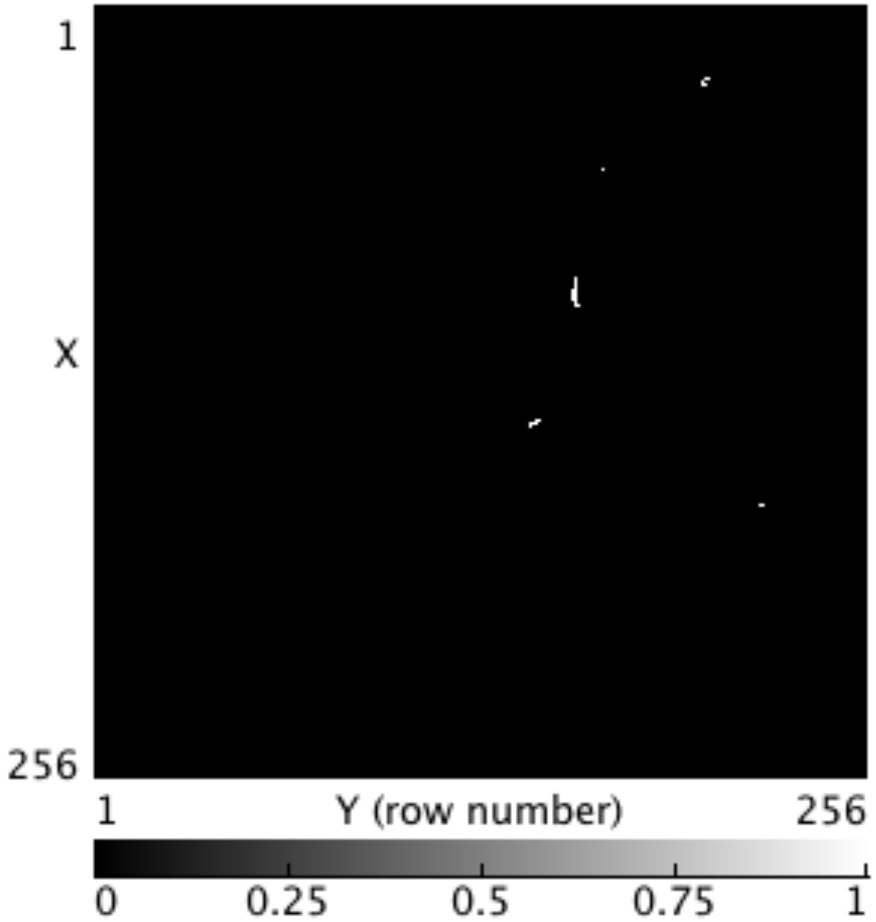
frame 21 at 10km 105 clusters (36 muons) frame 36 at SLAC 9 clusters

both longitudinal exposure of 60s (0.9+0.8)uSv/h vs 0.1uSv/h 17x

MEDIPIX measurements in-flight

Compare radiation at 10km and sea level



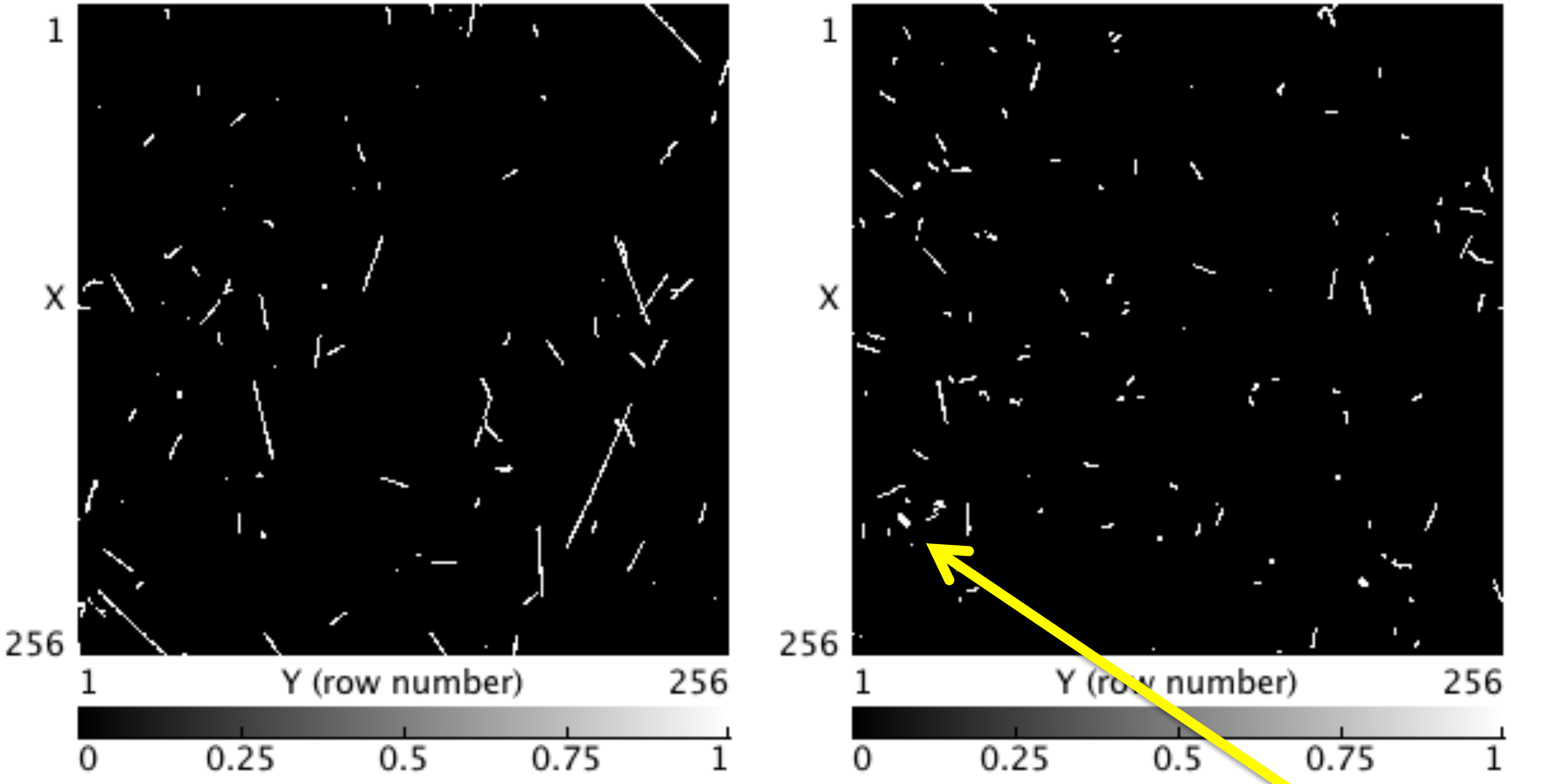


frame 24 at 10km   72 clusters (28 muons)   frame 38 at SLAC   5 clusters

both longitudinal exposure of 60s (0.6+0.5)uSv/h vs 0.06uSv/h 20x

MEDIPIX measurements in-flight

radiation parallel and perpendicular to sensor



frame 20 at 10km 99 clusters, 35 muons

both 60s exposures 1.5uSv/h

frame 13 at10km 119 clusters (31 muons)

1.8uSv/h much shorter muons, 1 heavy trail

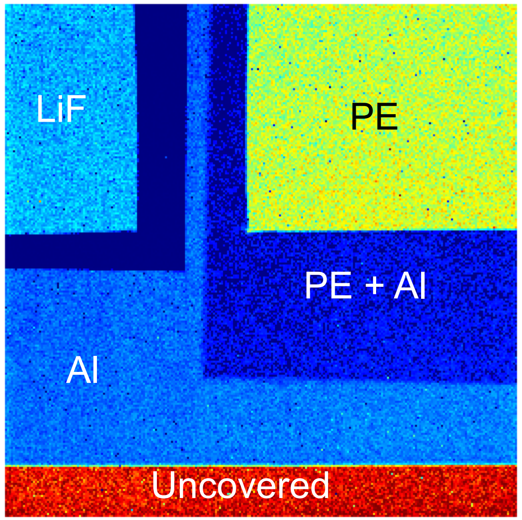
ATLAS – MPX

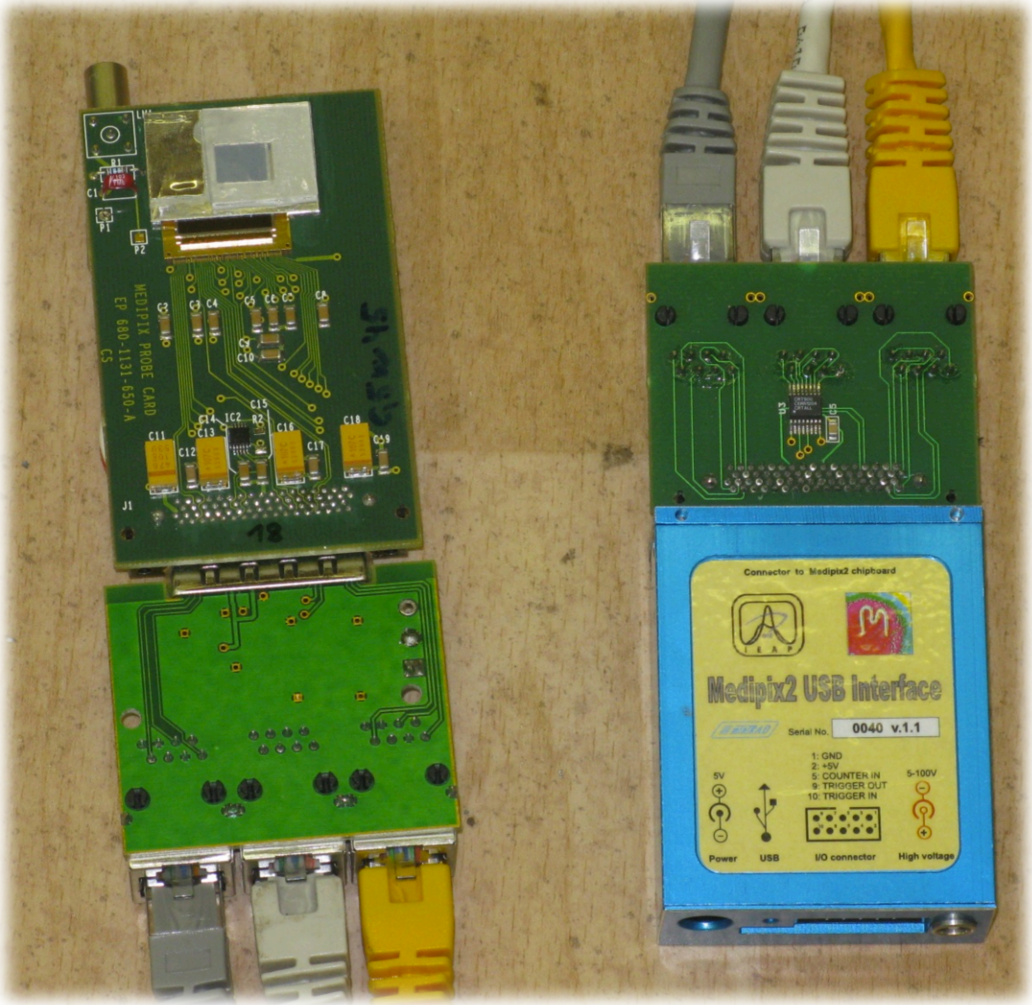
16 devices installed   emphasis on neutron environment

Medipix2 ASIC + 300μm Si sensor
connected to radhard drivers
3 ethernet cables
receiver and USB interface readout
Pixelman software in PC

Neutron conversion structures:
1) LiF+50μm Al foil area
2) 100μm Al foil area
3) PolyEthylene PE area
4) PE+50μm Al foil area
5) Uncovered area

geometry of conversion layers





Neutron efficiency calibration

work in IEAP-CTU Prague

Calibrated efficiency:

Thermal: 1.41E-2 ± 7.11E-4 $cm^{-2}s^{-1}$

^{252}Cf: 1.19E-3 ± 1.89E-5 $cm^{-2}s^{-1}$

^{241}AmBe: 2.86E-3 ± 5.46E-5 $cm^{-2}s^{-1}$

VanDGraaff : 7.23E-3 ± 5.81E-4 $cm^{-2}s^{-1}$

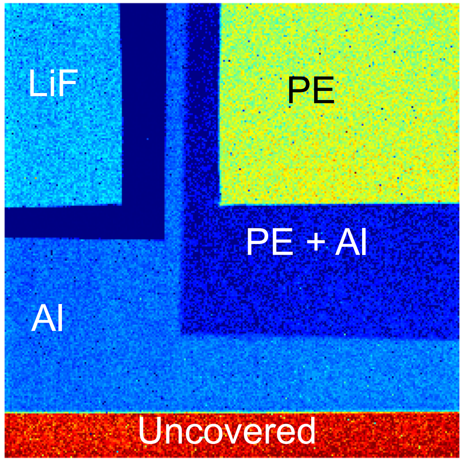
PE / PE+Al cluster count ratio:

^{252}Cf: 10.70 ± 0.04

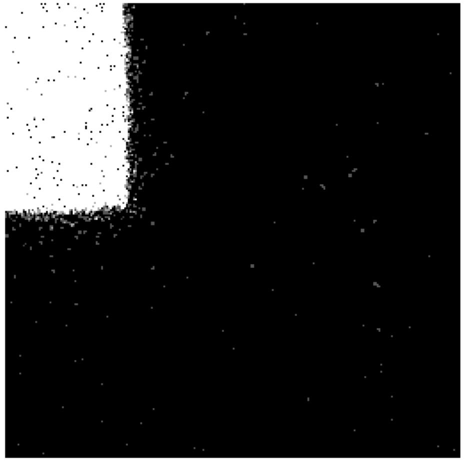
^{241}AmBe: 5.18 ± 0.03

VDG: 2.51 ± 0.03

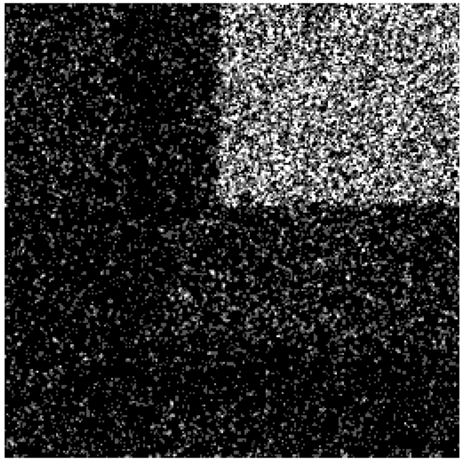
X-ray image of conversion layers



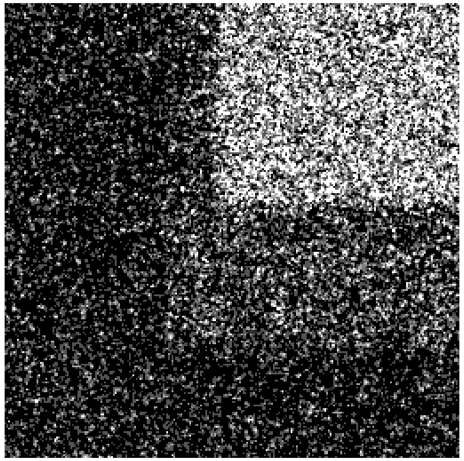
Thermal – 500s (2.5E6 neutrons)



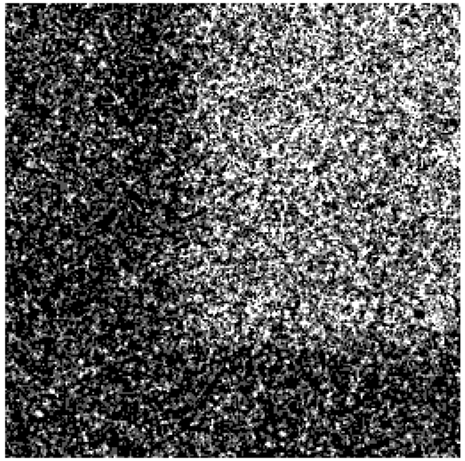
252Cf – 2000s (1E8 neutrons)



AmBe – 2000s (4E7 neutrons)

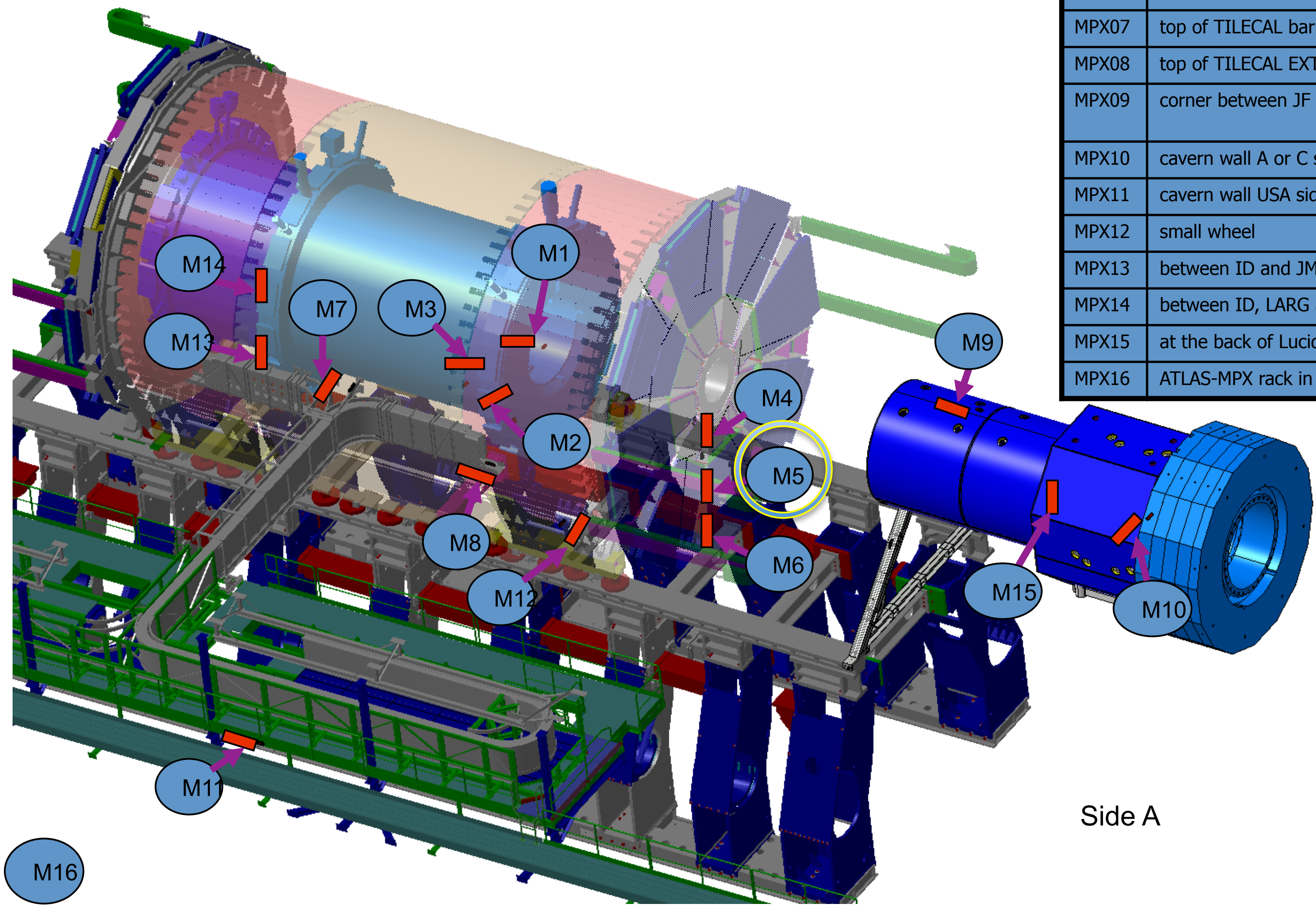


VDG – 1000s (1E7 neutrons)

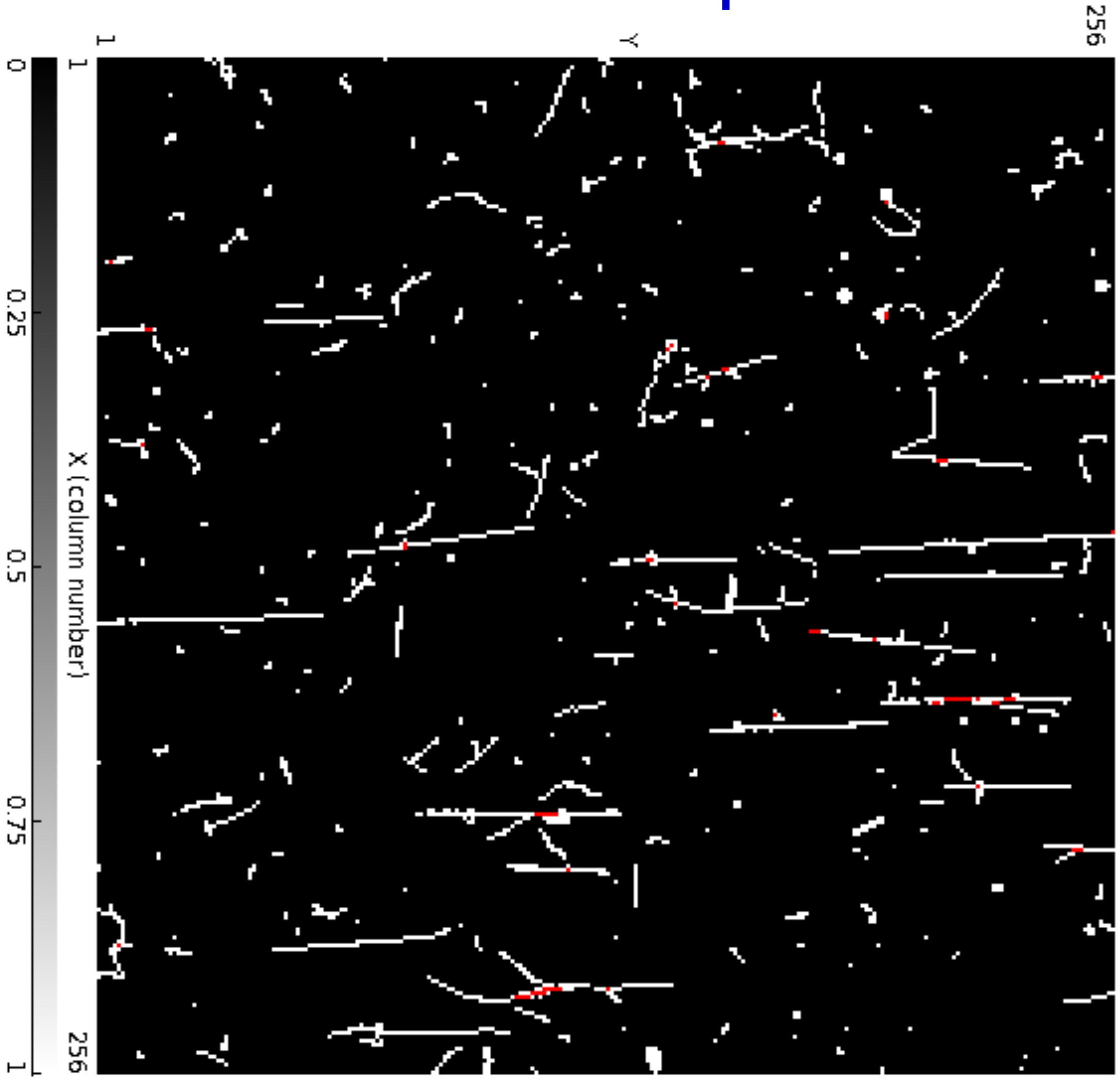


ATLAS-MPX LOCATIONS

MPX01	between ID and JM plug
MPX02	between ID, LARG and JM
MPX03	between LARG and LARG EC
MPX04	between FCAL and JT
MPX05	between LARG and JT wheel
MPX06	between LARG and JT wheel
MPX07	top of TILECAL barrel
MPX08	top of TILECAL EXT. barrel
MPX09	corner between JF cyl. and hexagon
MPX10	cavern wall A or C side
MPX11	cavern wall USA side
MPX12	small wheel
MPX13	between ID and JM plug
MPX14	between ID, LARG and JM
MPX15	at the back of Lucid detector
MPX16	ATLAS-MPX rack in USA15



Medipix in ATLAS

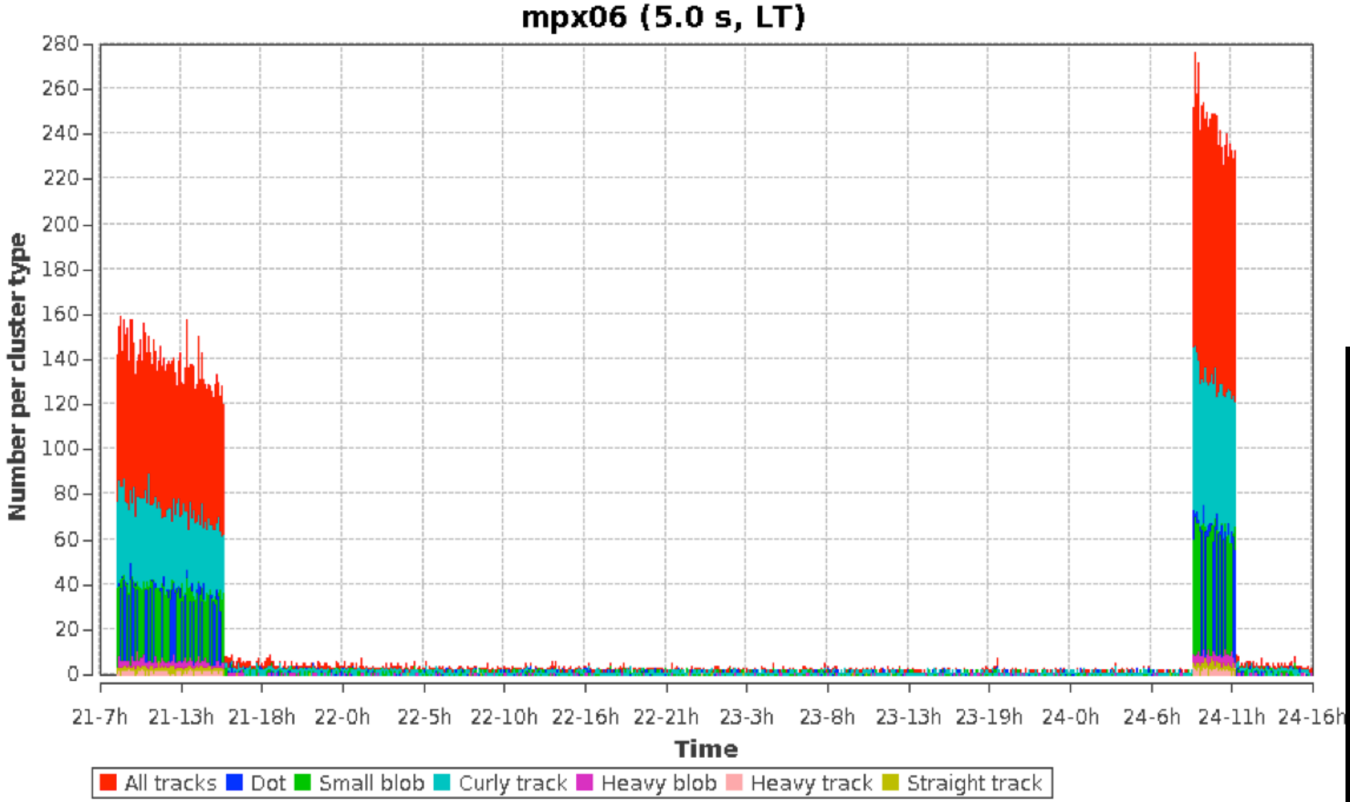


29 Sept 2011

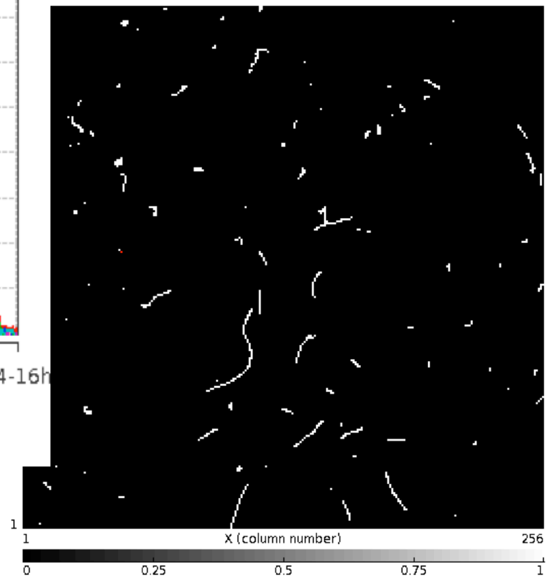
10s exposure

behind forward
muon wheel

Radiation in Atlas (preliminary)



example of recording
one station
21-24 June 2011



note decay of background after collison period

heavy tracks only during collisons

5s 91 clusters
13 uSv/h

'TIMEPIX' CHIP

MODIFICATION of MEDIPIX2 (2007)

CLOCK adjustable up to 100 MHz in EACH PIXEL

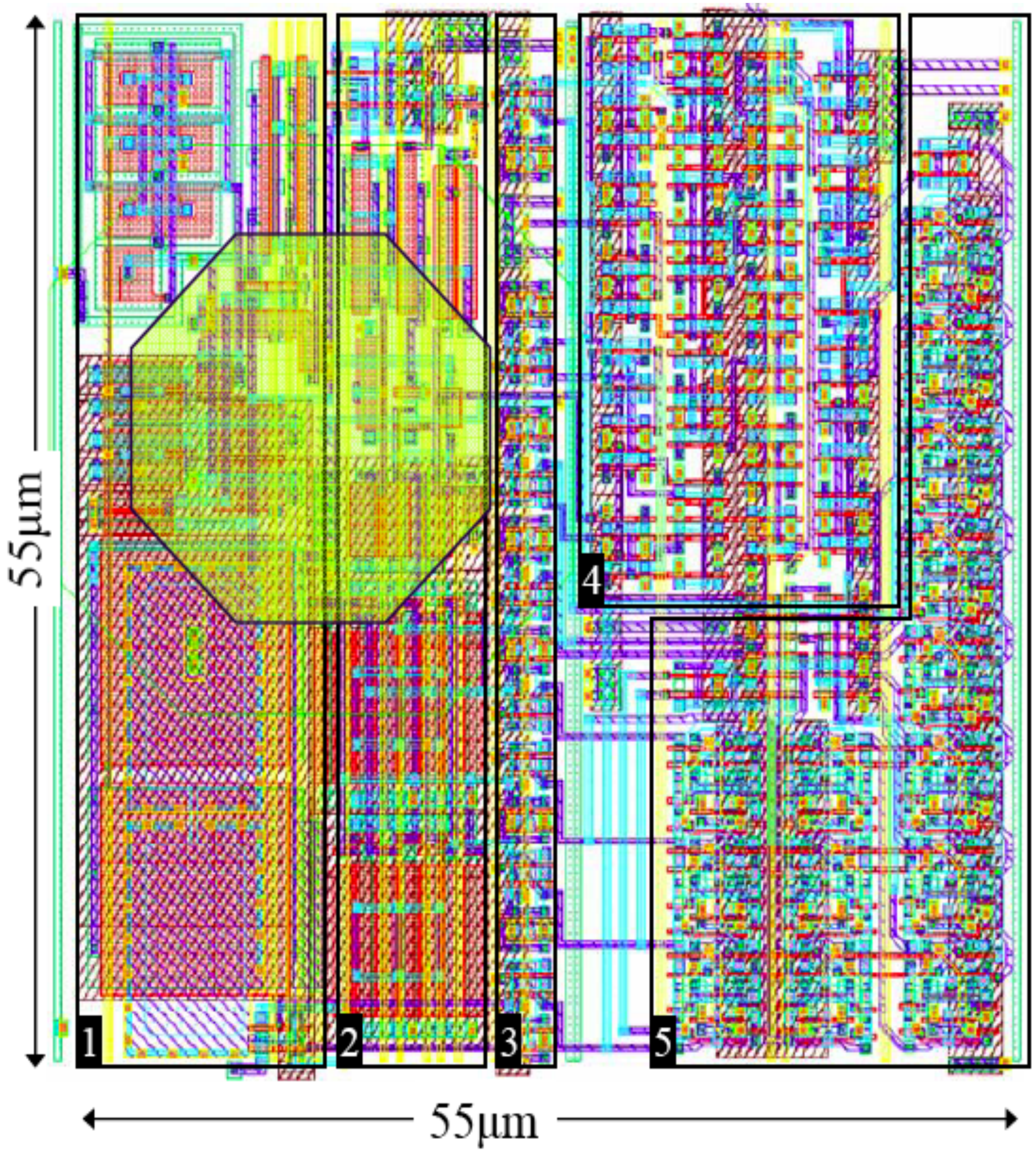
newly added operational modes:

- ENCODING of ARRIVAL TIME of PULSE
- ENCODING TOTAL 'TIME OVER THRESHOLD'

well adapted to dosimetry via
measurement of energy deposit in Si sensor

this readout chip was designed for GASEOUS TPC READOUT
as part of R&D for ILC by EUDET COLLABORATION
original ideas by Jan Visschers/NIKHEF and Xavier Llopart/CERN

TIMEPIX CELL LAYOUT



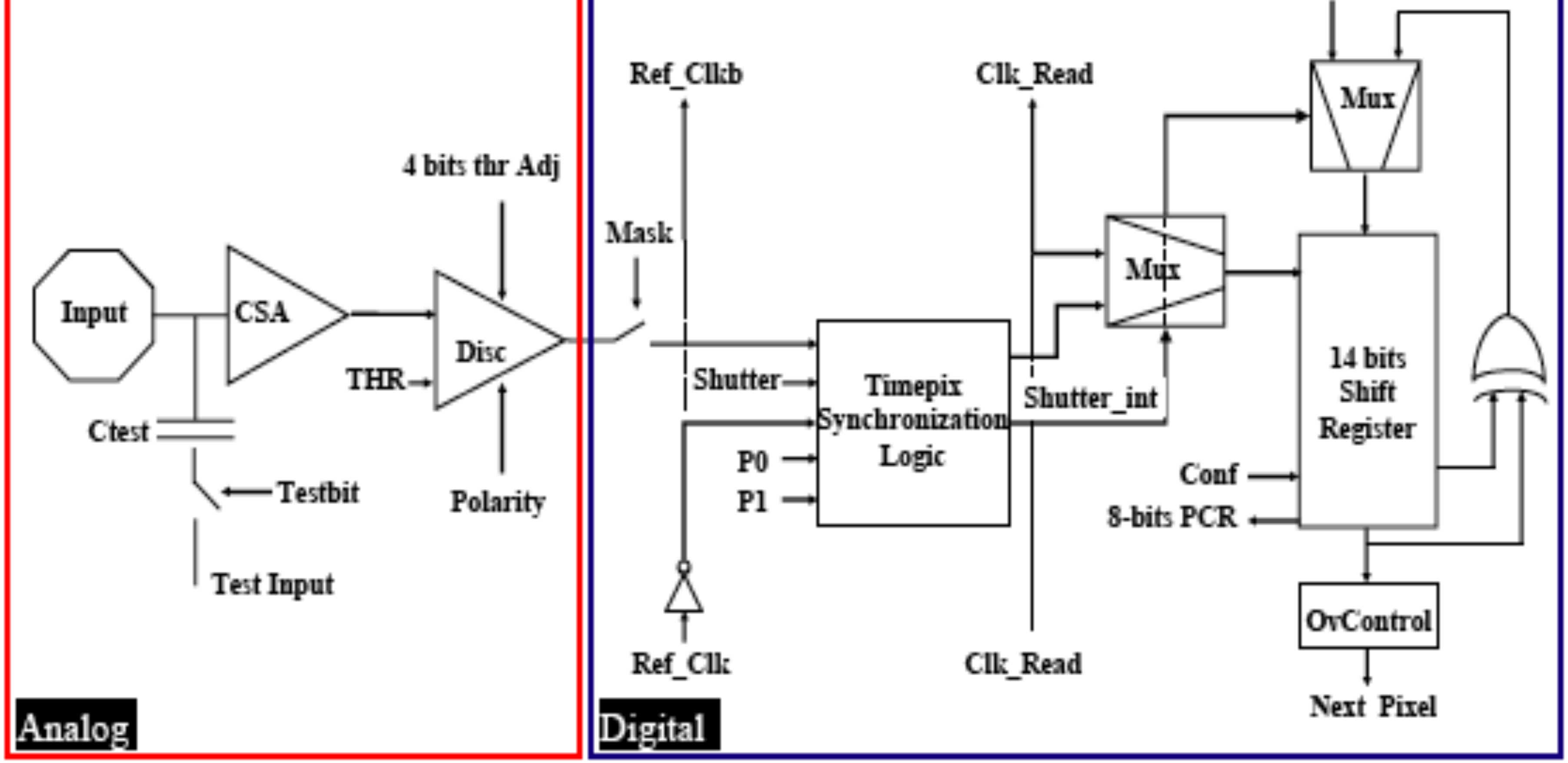
DESIGNER
Xavier LLOPART
CERN 2007
PhD Thesis p. 107

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

includes Time-Over-Threshold amplitude digitizer in each pixel

TIMEPIX schematic diagram

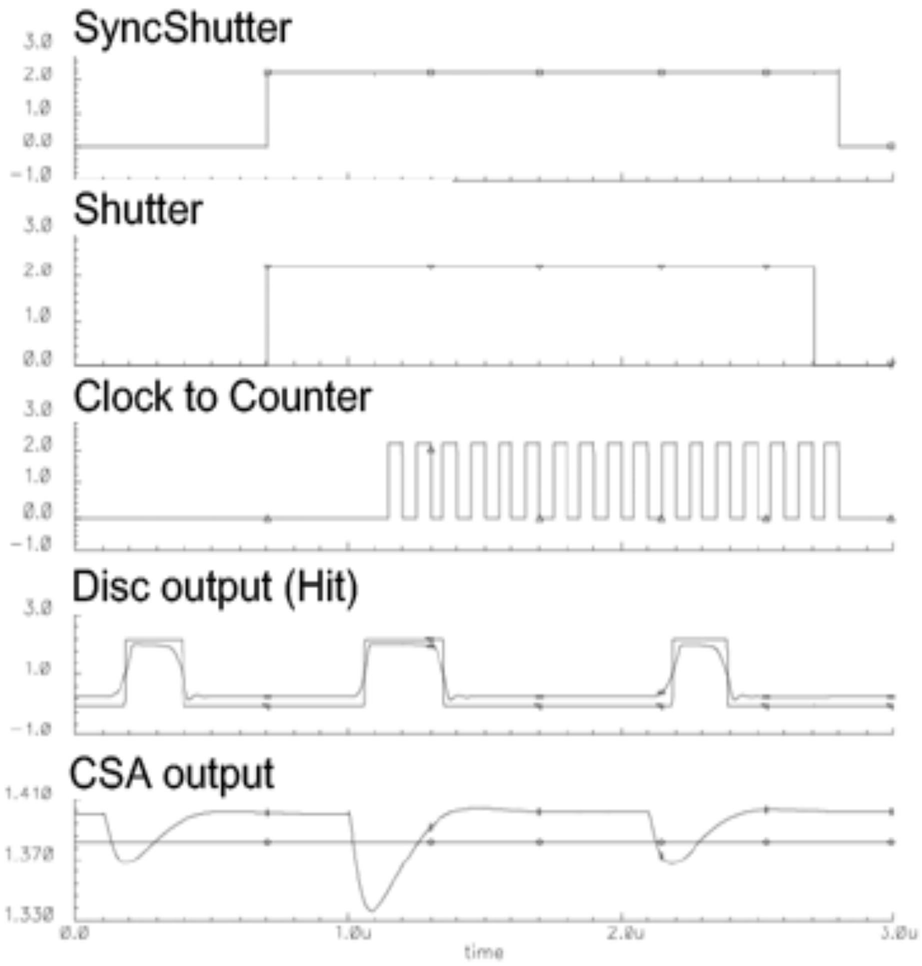
BASED on MPX2-MXR REF_CLK adjustable up to 100 MHz



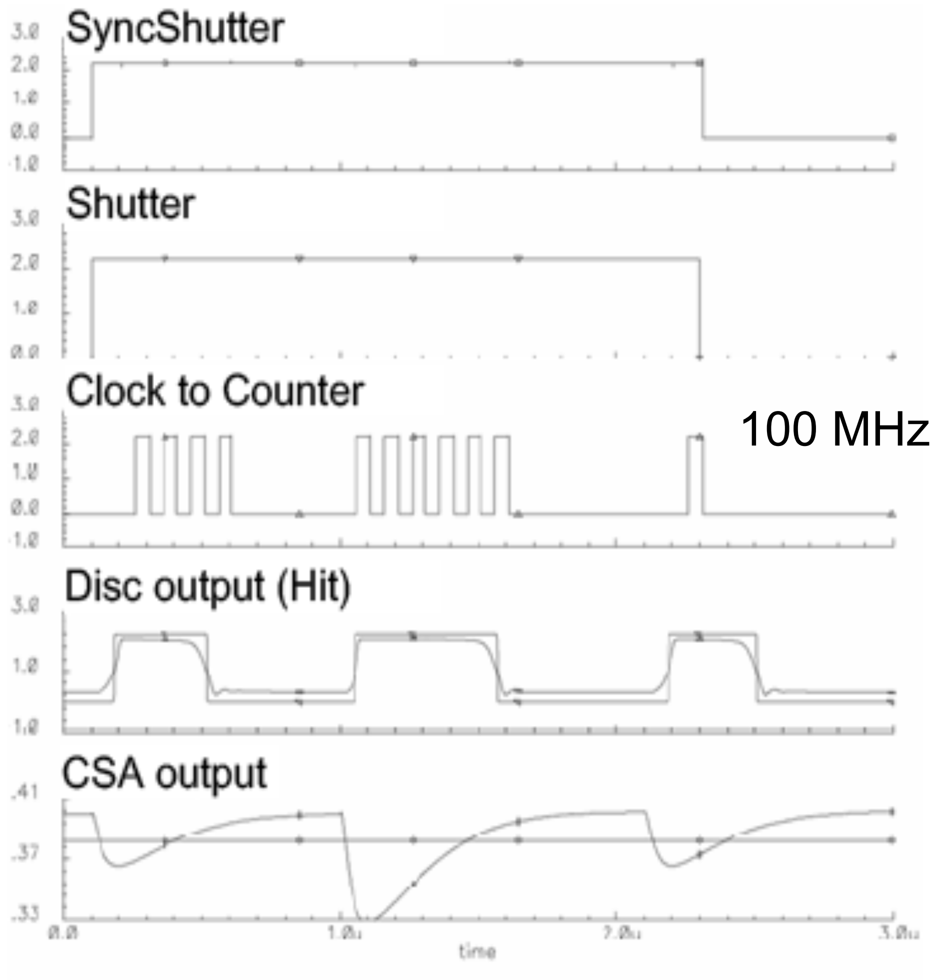
TIME-OVER-THRESHOLD, analog signal encoding in each pixel

NEEDS CLOCK DISTRIBUTION ALL-OVER MATRIX

TIMEPIX OPERATION



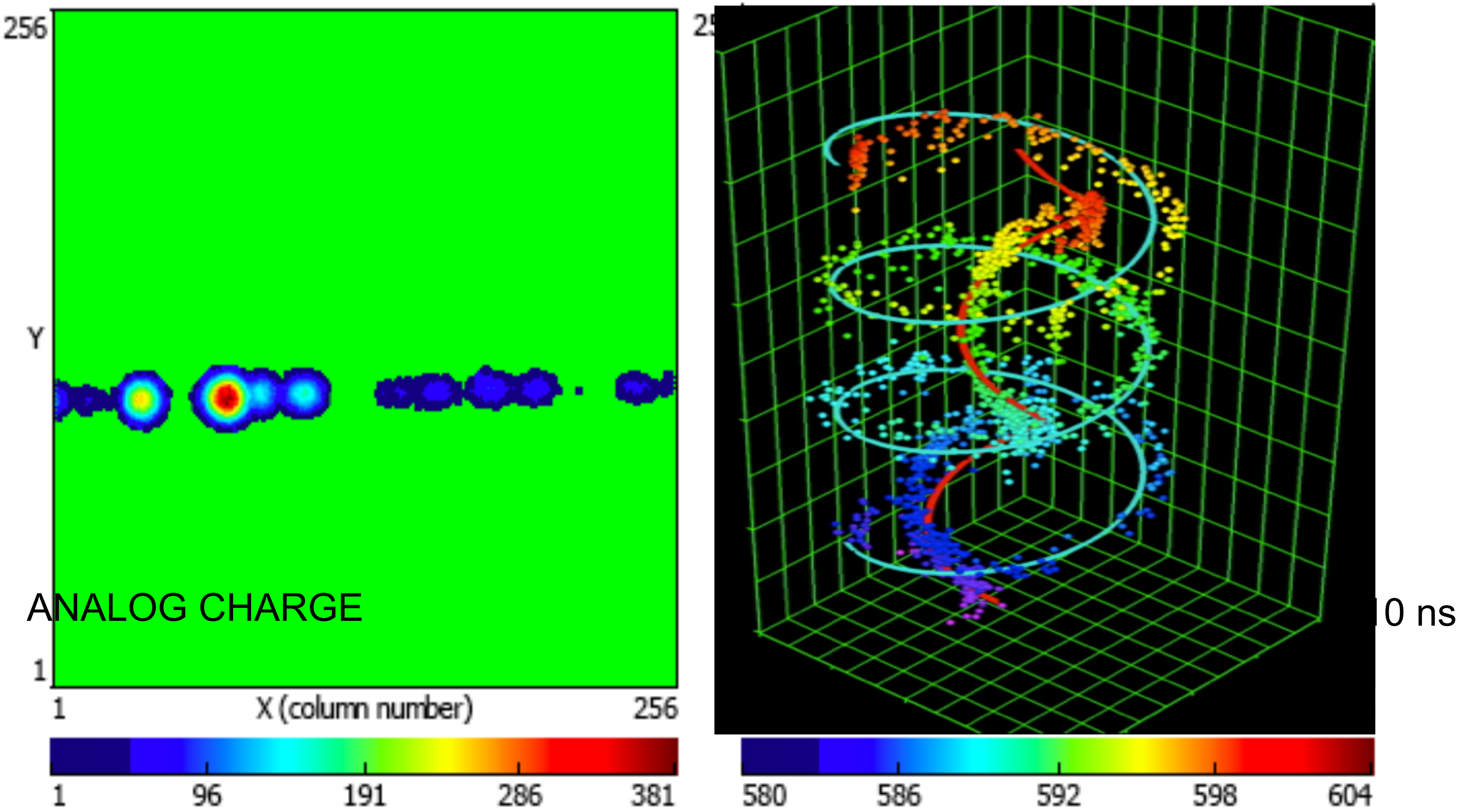
MODE : ARRIVAL
TIME



100 MHz

MODE : TOT 'TIME over THRESHOLD'

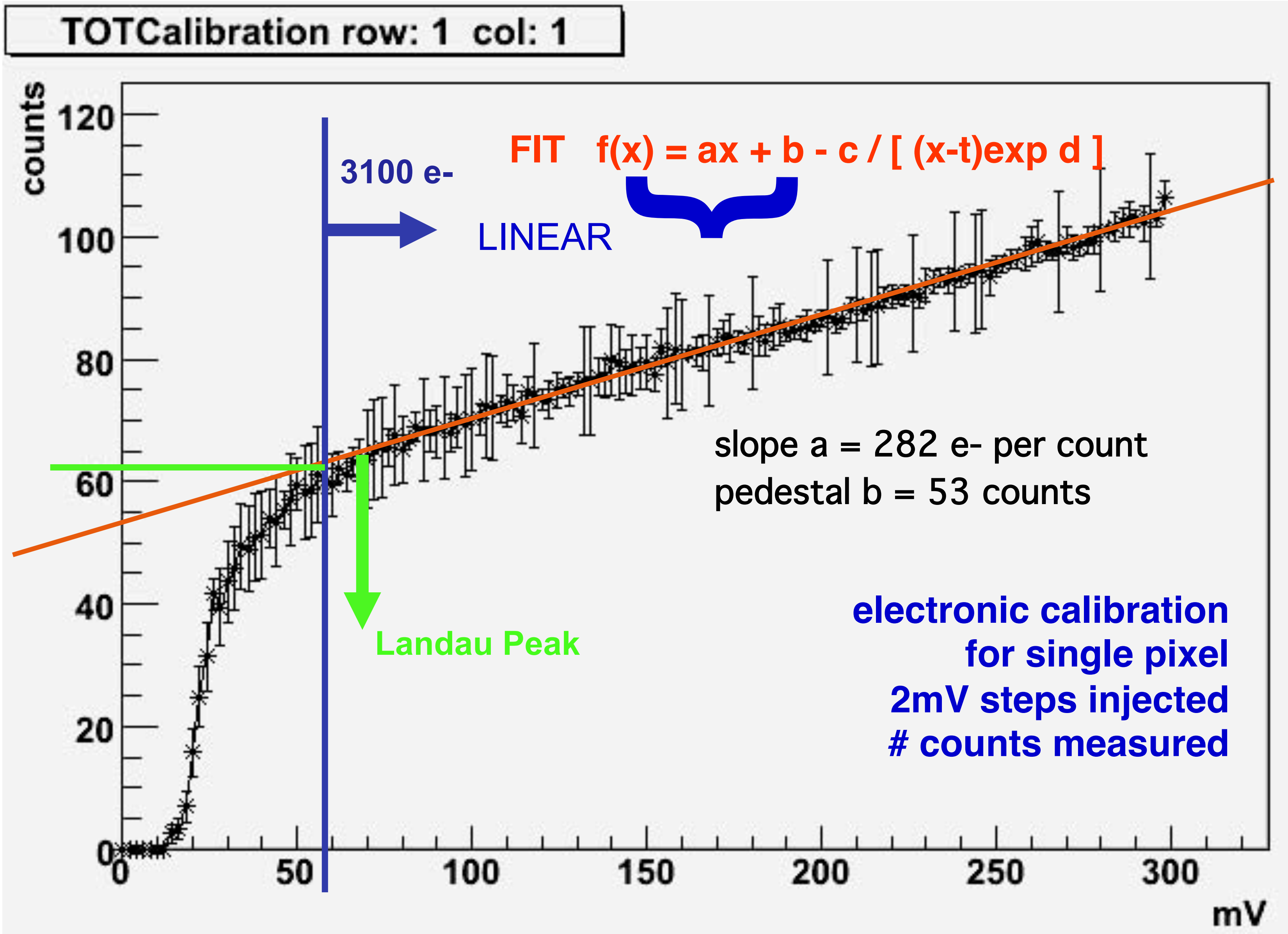
TIMEPIX + GEM in DESY e^- BEAM



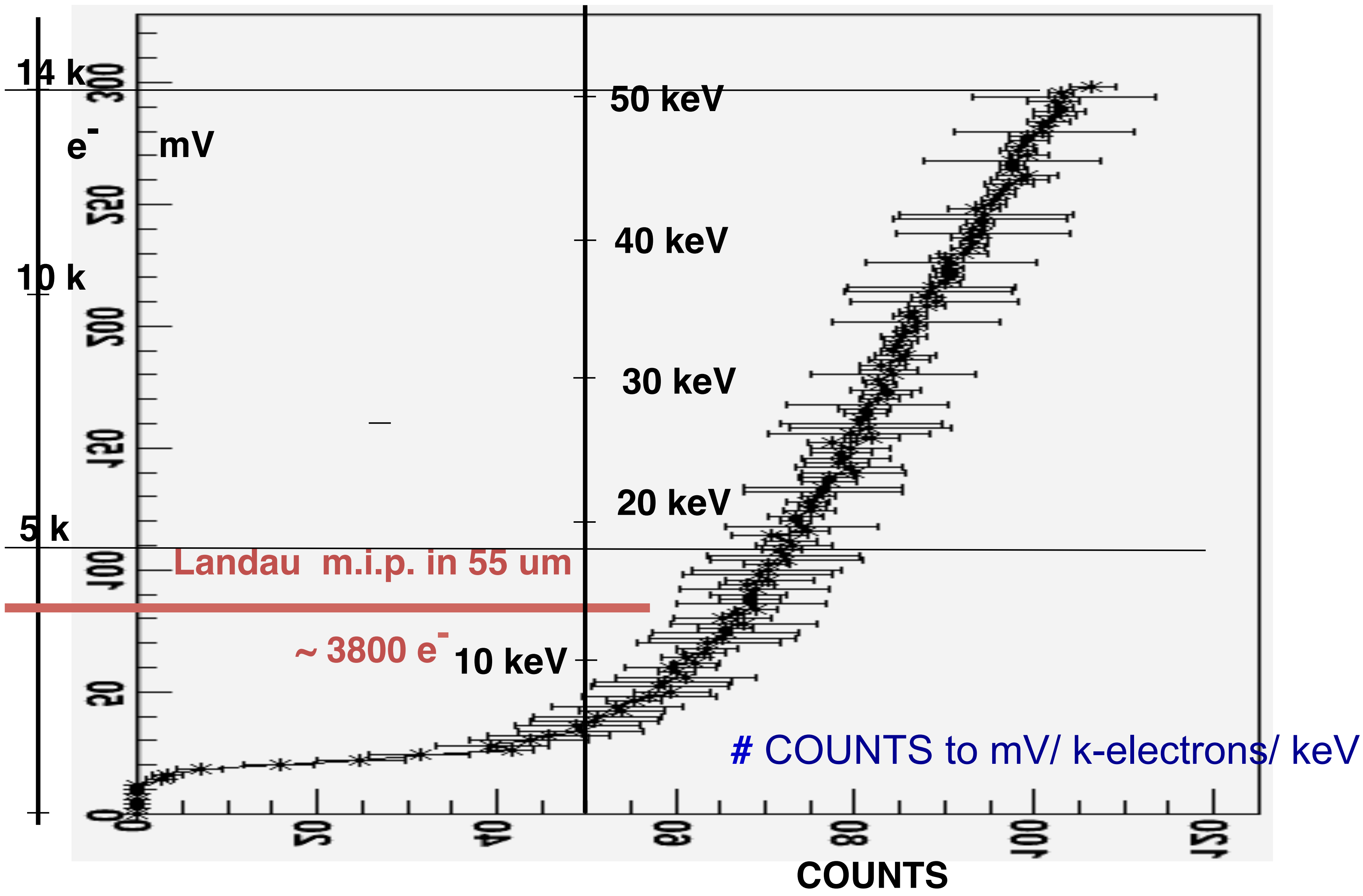
SIMULTANEOUS MIXED : TOT-MODE & ARRIVAL-TIME MODE

vdGraaf et al. NIM A628(2011)27-30

Typical pixel calibration TOT

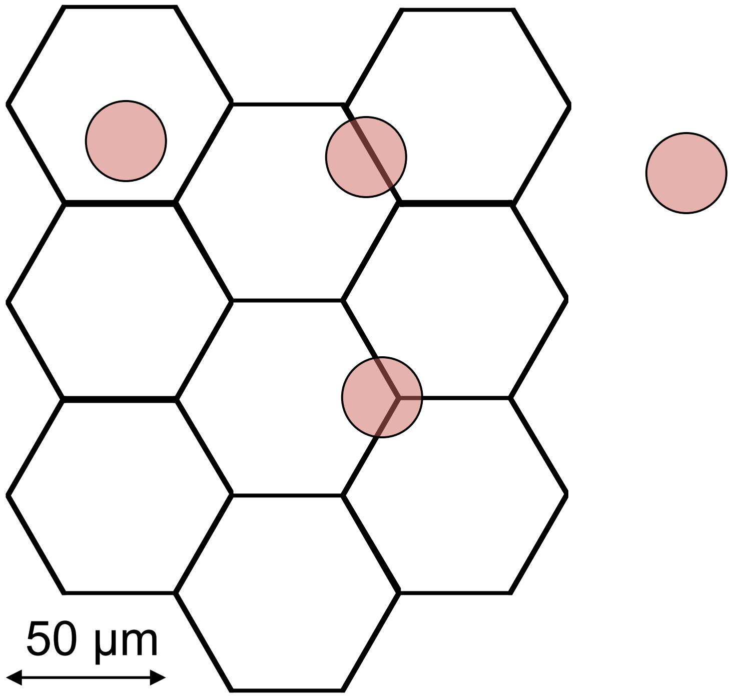


TIMEPIX TOT to mV CONVERSION



HEXAGONAL PIXEL GEOMETRY

ENERGY DEPOSIT is most often DISTRIBUTED
SUMMING of ENERGY needed for Spectrometry
in this case 6 equivalent neighbours, instead of 4
but ‘never’ quadruple hits



SINGLE/DOUBLE/TRIPLE HITS
MANY FACTORS ENLARGE 'HIT'

readout chip layout
and bump-bonding
more complicated
ADDTIONAL STUDY NEEDED

MEDIPIX3

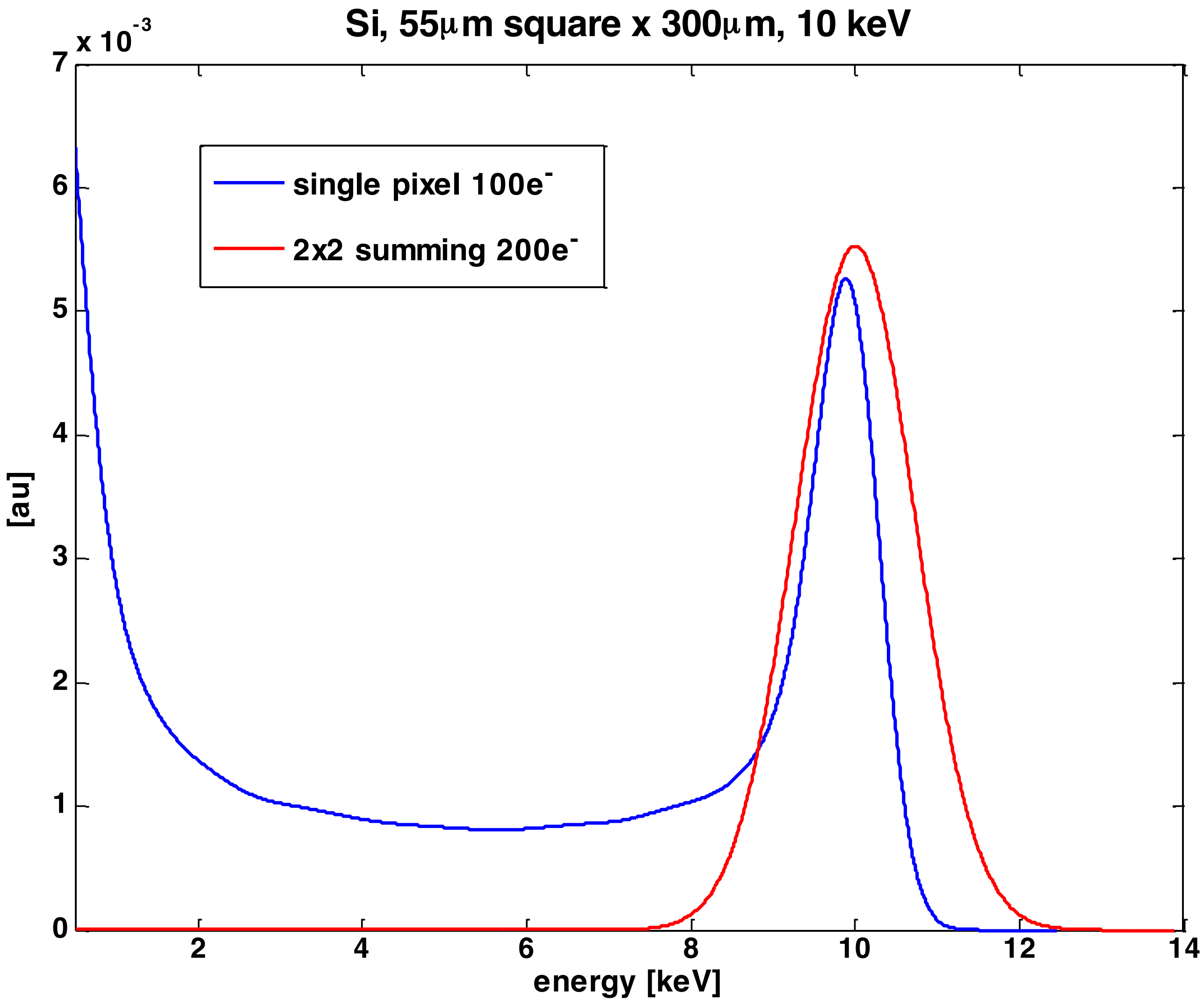
ATTACKS CHARGE SHARING

NEED for MORE TRANSISTORS

List of designed 'Medipix' chips

Medipix1 (1998)	*1μm SACMOS, 64x64 pixels, 170x170μm²* *PC / Frame based readout*
Medipix2 (2001)	*0.25μm CMOS, 256x256 pixels, 55x55μm²* *PC / Frame based readout*
Timepix (2006)	*0.25μm CMOS, 256x256 pixels, 55x55μm²* *PC, ToT, ToA / Frame based readout*
Medipix3 (2009)	*0.13μm CMOS, 256x256 pixels, 55x55μm²* *PC / Frame based readout* *Event by event charge reconstruction and allocation*
Dosepix (2011)	*0.13μm CMOS, 16x16 pixels, 220x220μm²* *ToT, PC / Rolling shutter (programmable column readout)* *Event by event binning of energy spectra (16 digital thrs)*
Timepix3 (2013)	*0.13μm CMOS, 256x256 pixels, 55x55μm²* *PC; ToT, ToA (simultaneous)/ Data driven readout*
Smallpix	*0.13μm CMOS, 512x512 pixels, 40x40μm² (TBD)* *PC, iToT; ToA, ToT1 (simultaneous)/ Frame based (ZC)* *TSV compatible design*
Clicpix prototype	*65nm CMOS, 64x64 pixels, 25x25μm²* *ToA, ToT1 (simultaneous)/ Frame based (ZC)*

Motivation for the Medipix3 chip

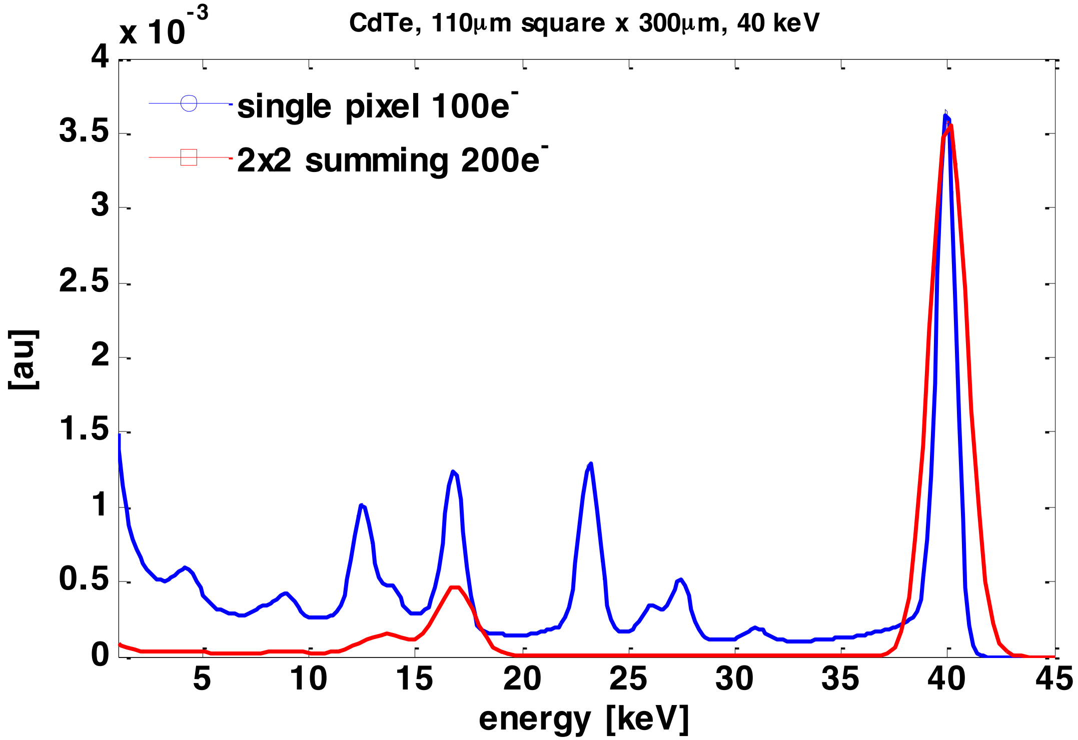


- *Simulated Data*
- *Si 300µm, 55µm pixel*
- *10keV monochromatic photon beam*

- *In the new architecture charge sharing tail is eliminated*

Simulation: L. Tlustos

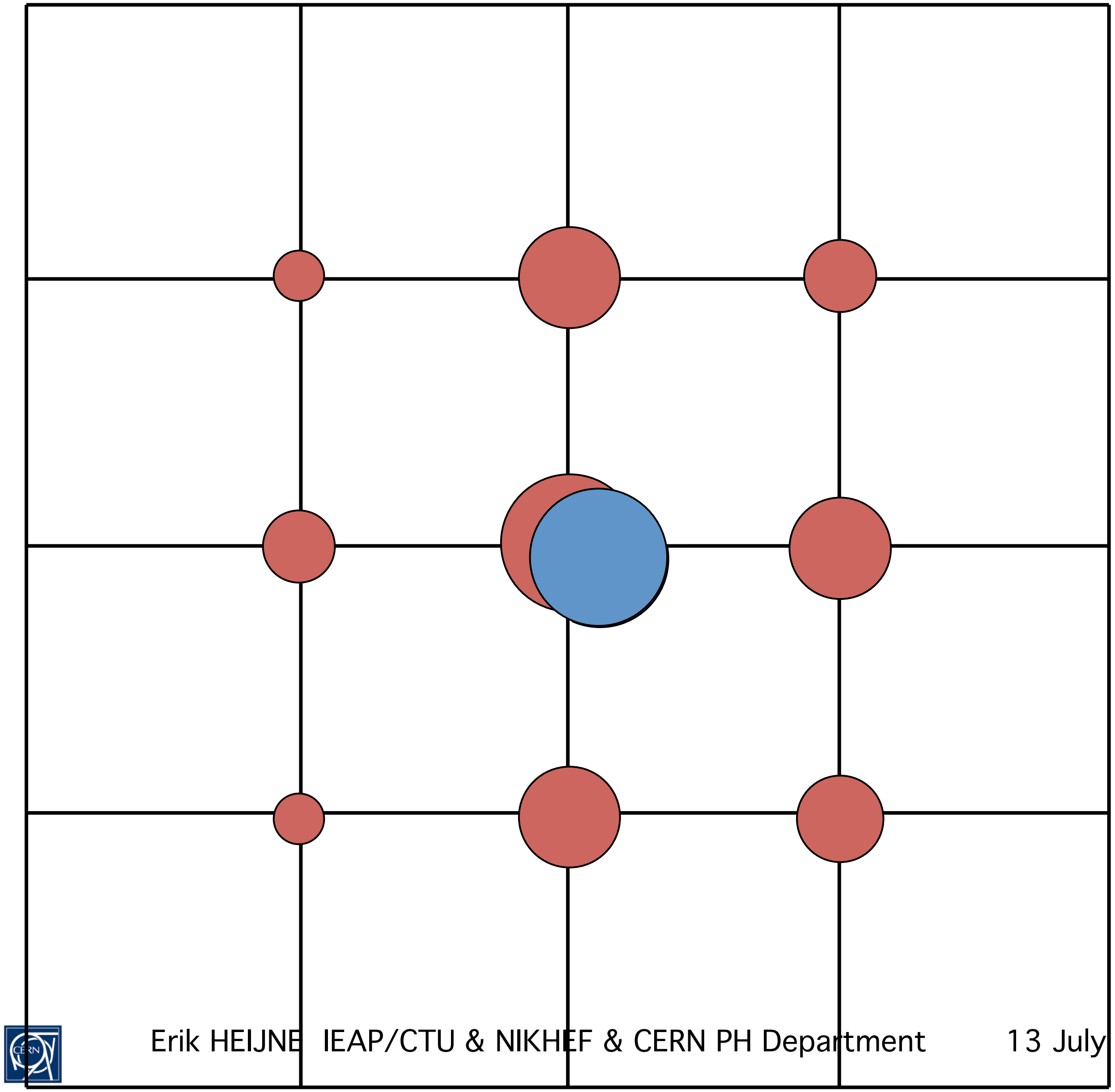
Motivation for the Medipix3 chip



- ***Simulated data***
- ***CdTe 300µm***
- ***110µm pixel pitch***
- ***40keV monochromatic beam***
- ***Fluorescence photons are included in charge sum if their deposition takes place within the volume of the pixels neighbouring the initial deposition***

Simulation: L. Tlustos

The algorithm for charge reconstruction and hit allocation: Charge Summing Mode



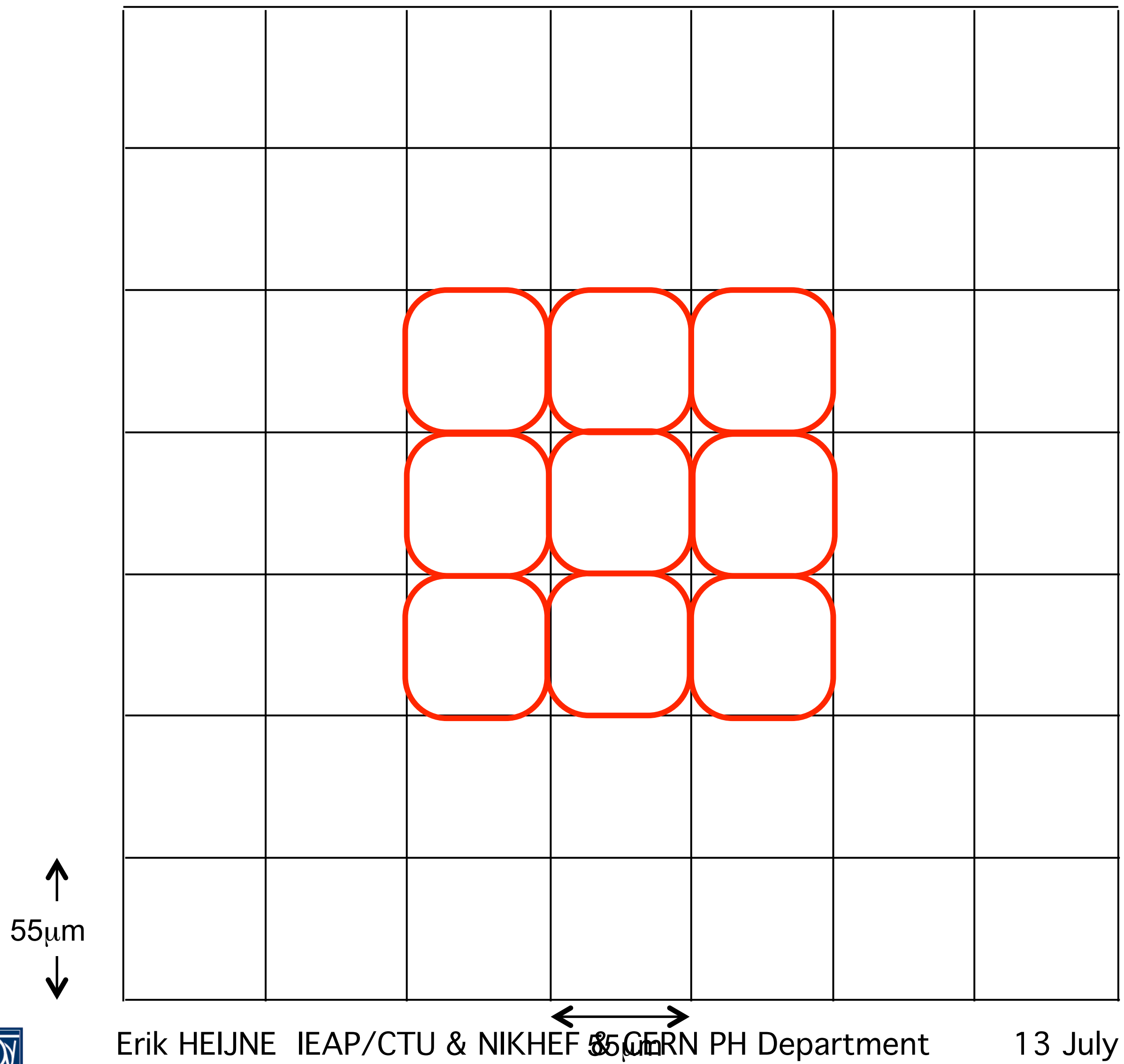
1. TH_0 is applied to the local signal

2. Arbitration circuitry identifies the pixel with largest charge and supresses the pixels with lower signal

3. In parallel, the charge has been reconstructed in the analog summing circuits

4. The pixel with highest charge checks the adjacent summing circuits to see if at least one of them exceeds TH_1

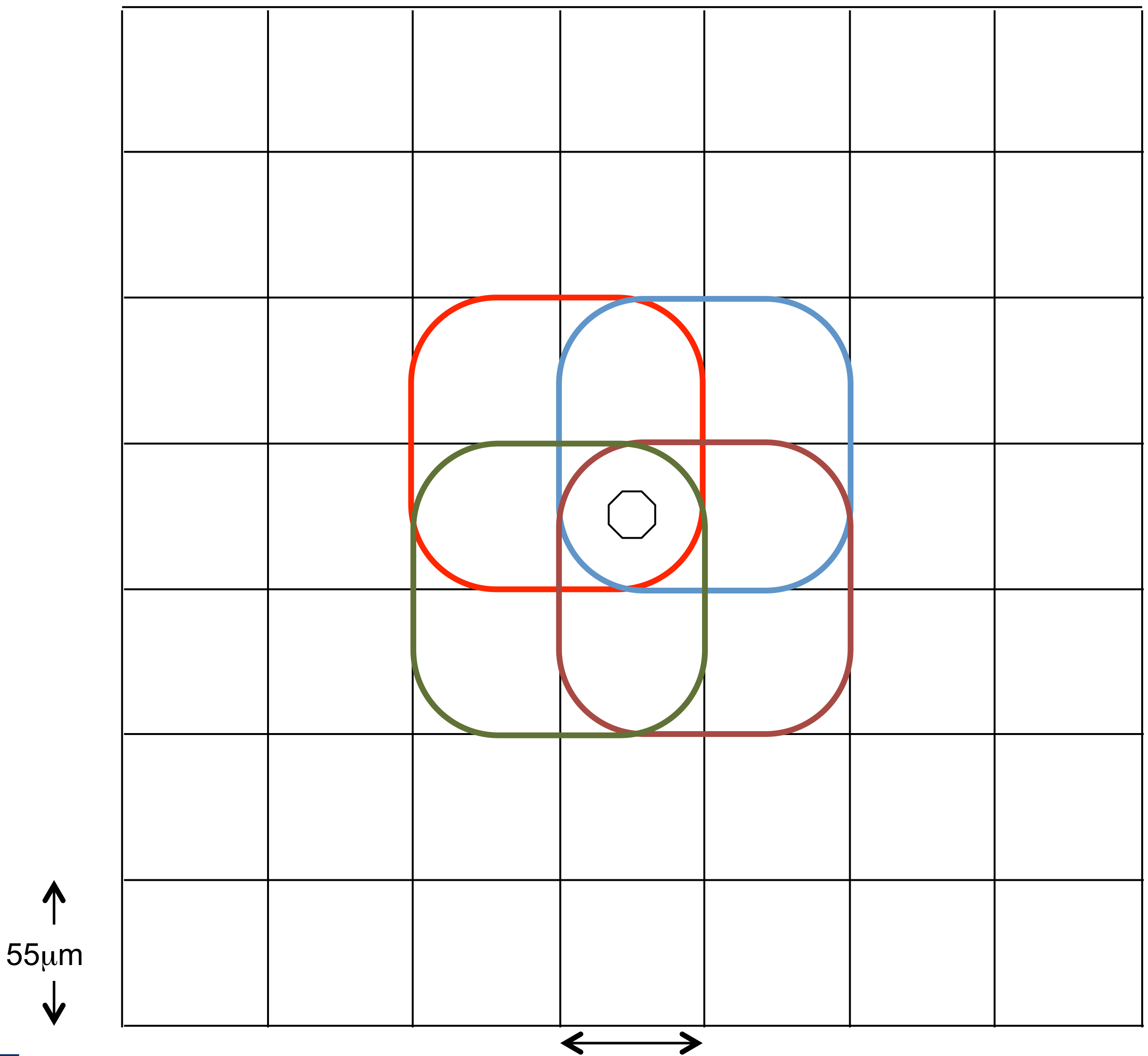
Fine pitch mode, Single Pixel Mode



- *55μm pixel pitch*
- *2 thresholds/pixel*
- *2 counters*

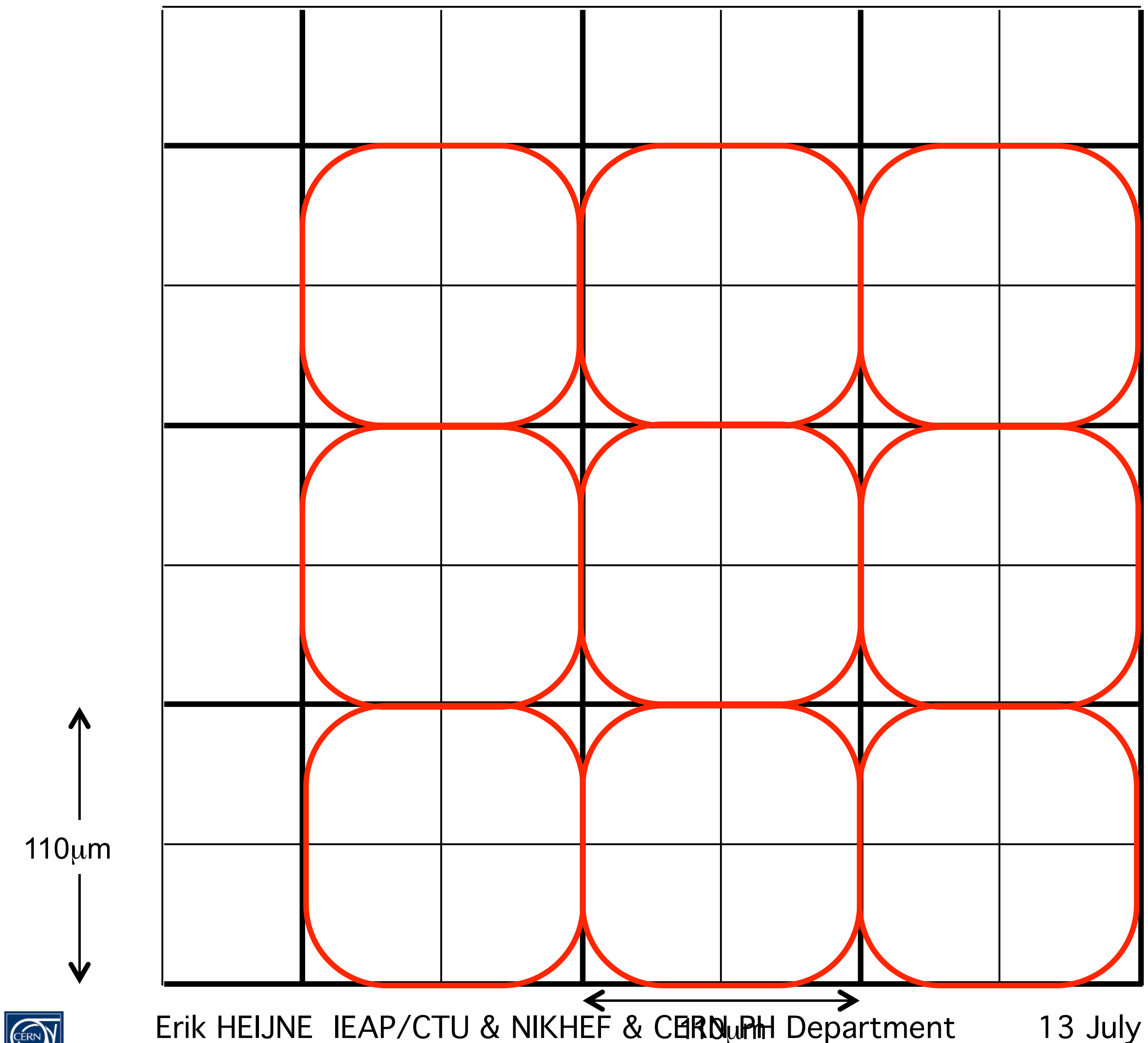
- *Pixels work independently from one another*

Fine pitch mode, Charge Summing Mode



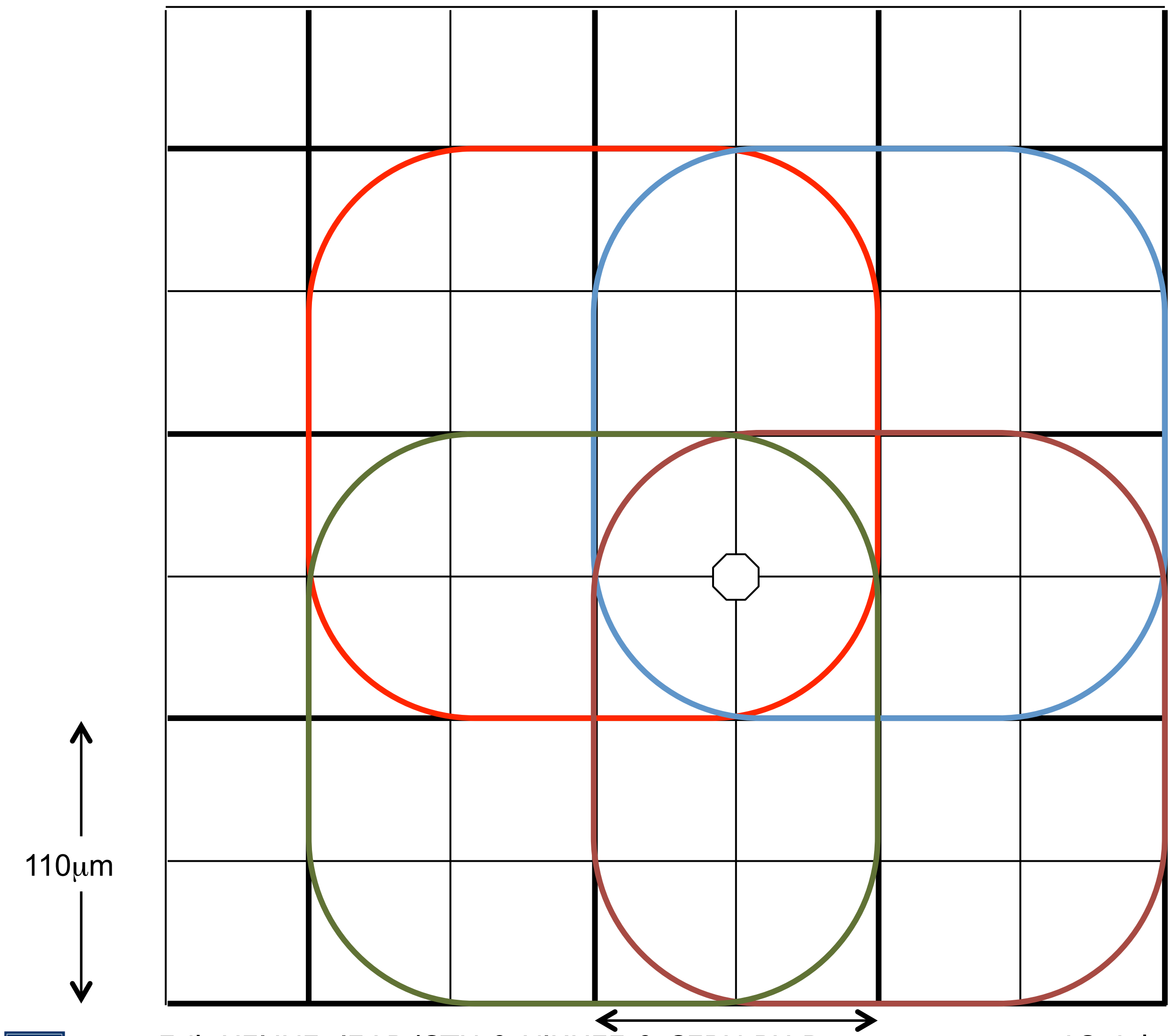
- ***55µm pixel pitch***
- ***Reconstruction over overlapping 110µm x 110µm areas***
- ***2 thresholds/pixel (1 for local charge/1 reconstructed charge)***
- ***2 counters***
- ***Advantage of small pixels without disadvantage of charge sharing***

Spectroscopic mode, Single Pixel Mode



- ***110µm pixel pitch***
- ***8 thresholds/pixel***
- ***8 counters***

Spectroscopic mode, Charge Summing Mode

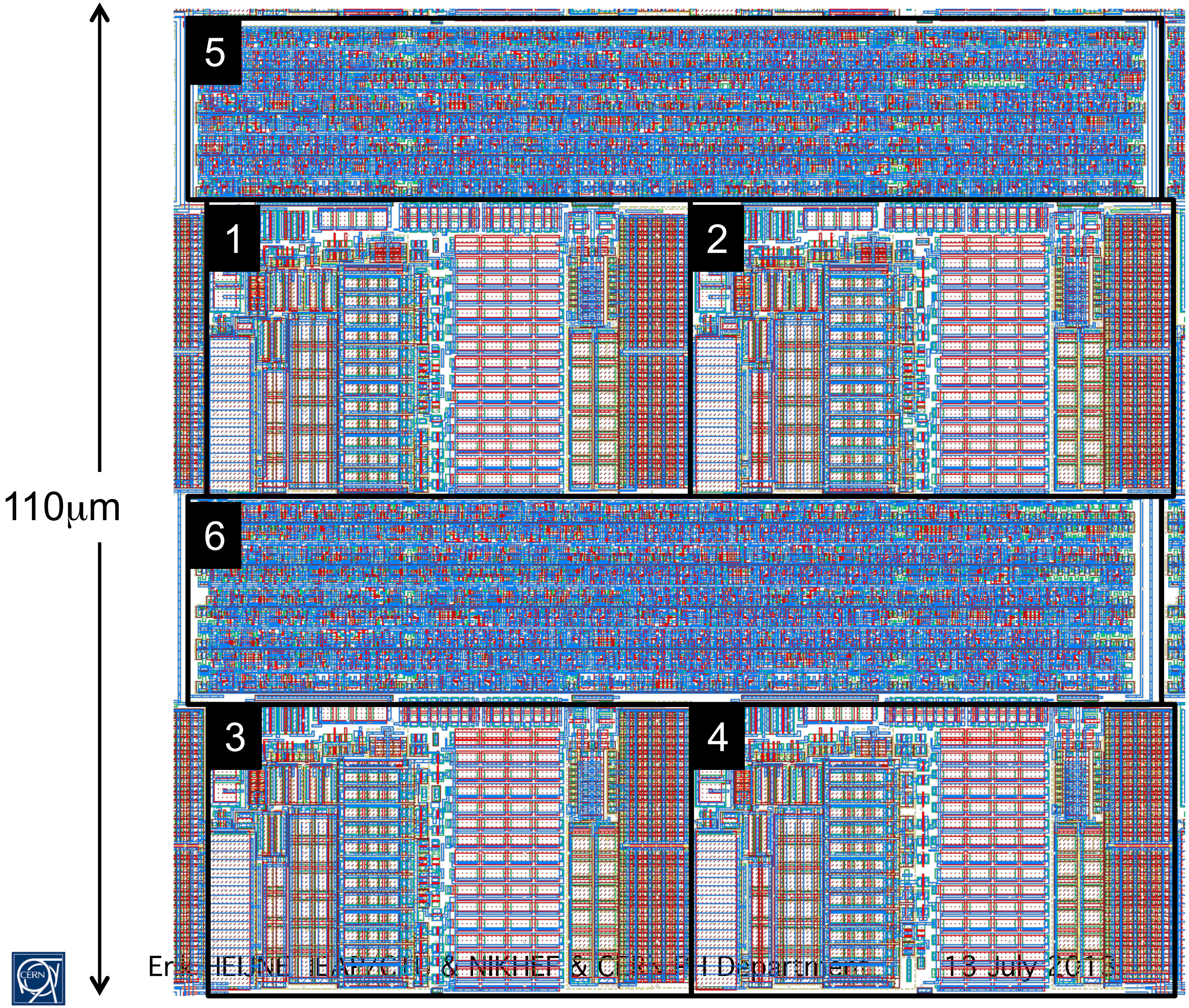


- *110μm pixel pitch*
- *Reconstruction over 220μm x 220μm area*
- *8 thresholds/pixel (4 for local charge/4 reconstructed charge)*
- *8 counters*

Common to all configurations:

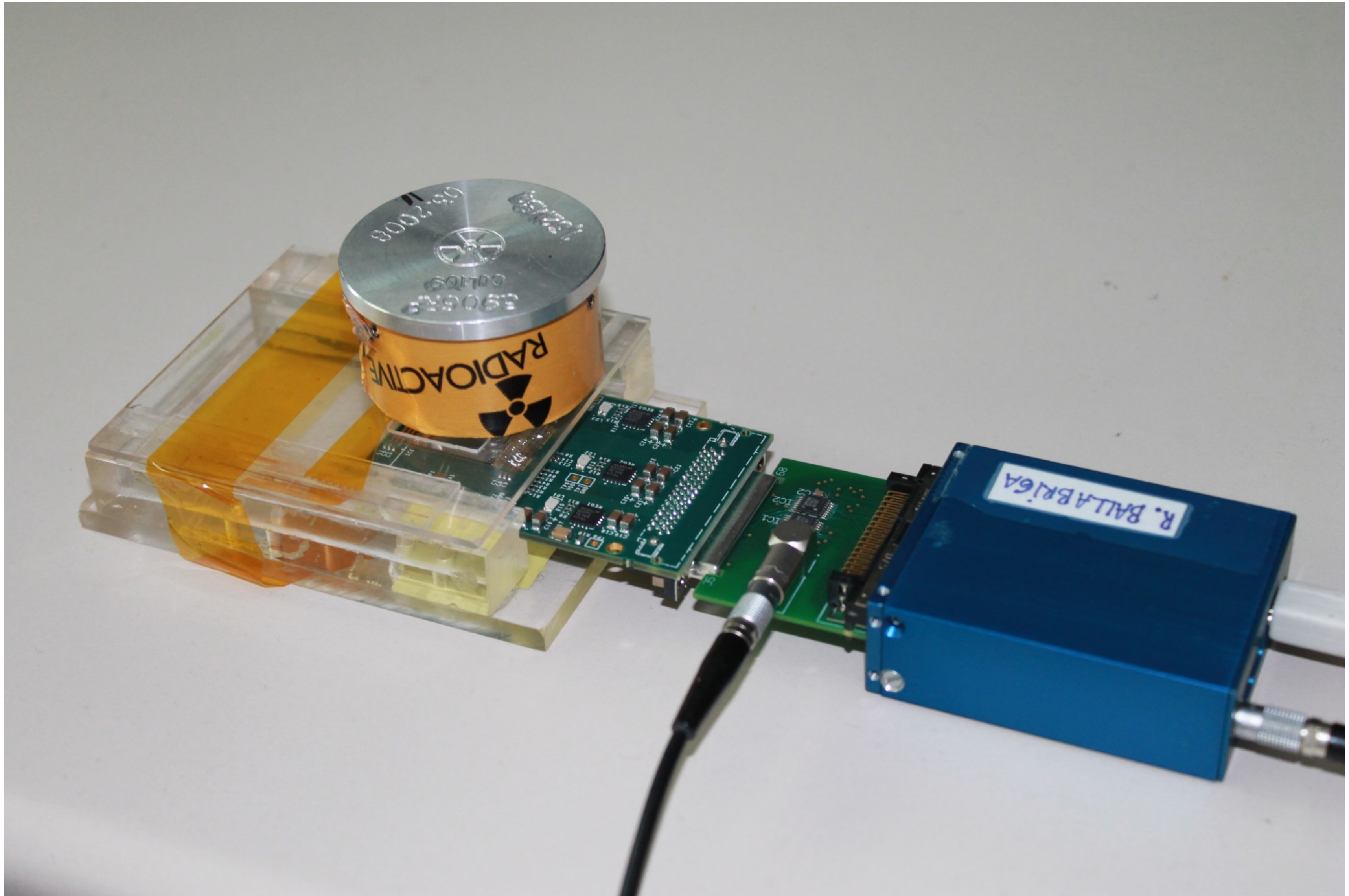
- *4 selectable gain mode*
- *Possibility of Continuous Acquisition/ Readout*

Medipix3RX Pixel layout

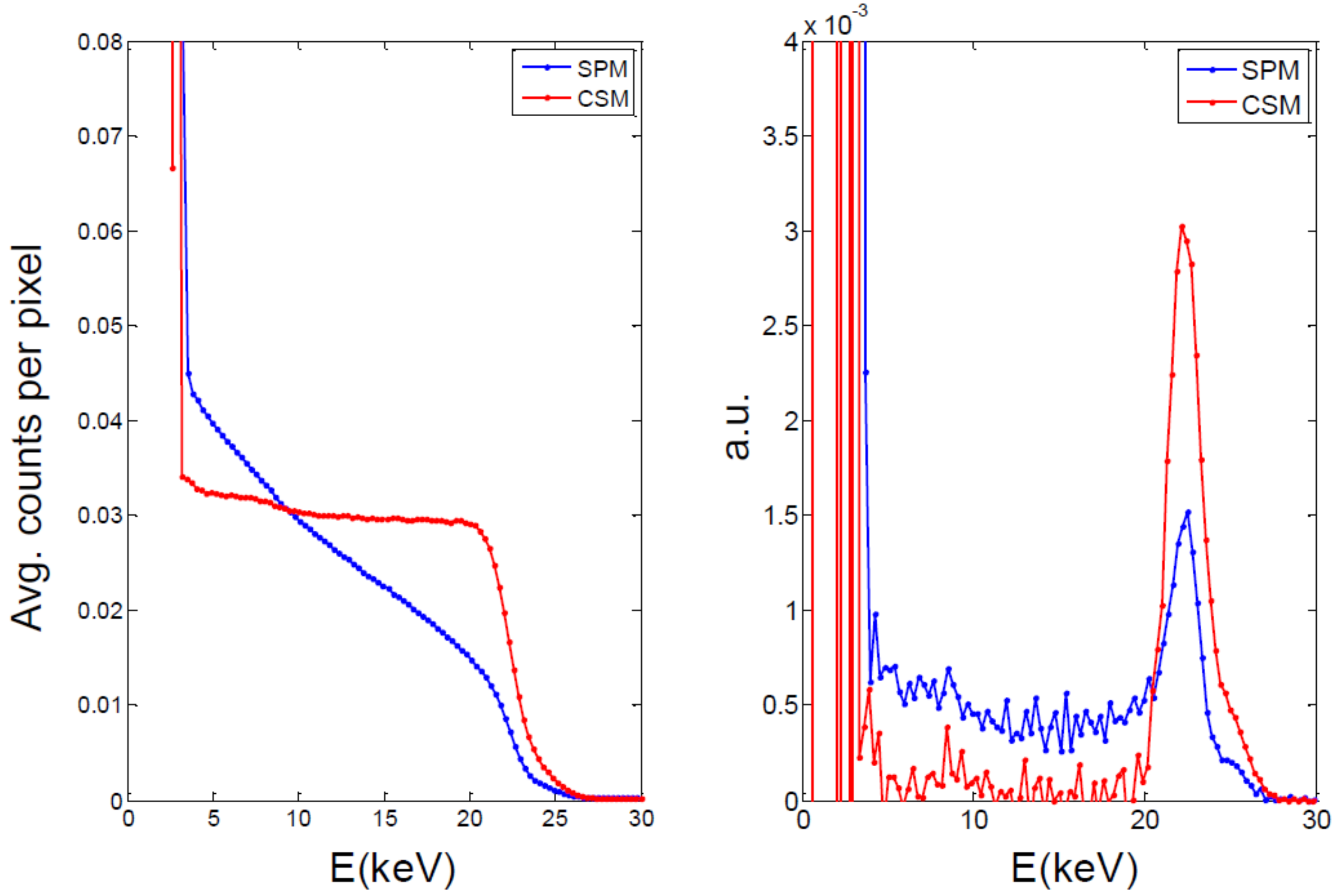


0.13μm
CMOS
8 metal layers

Measurements using Radioactive Sources

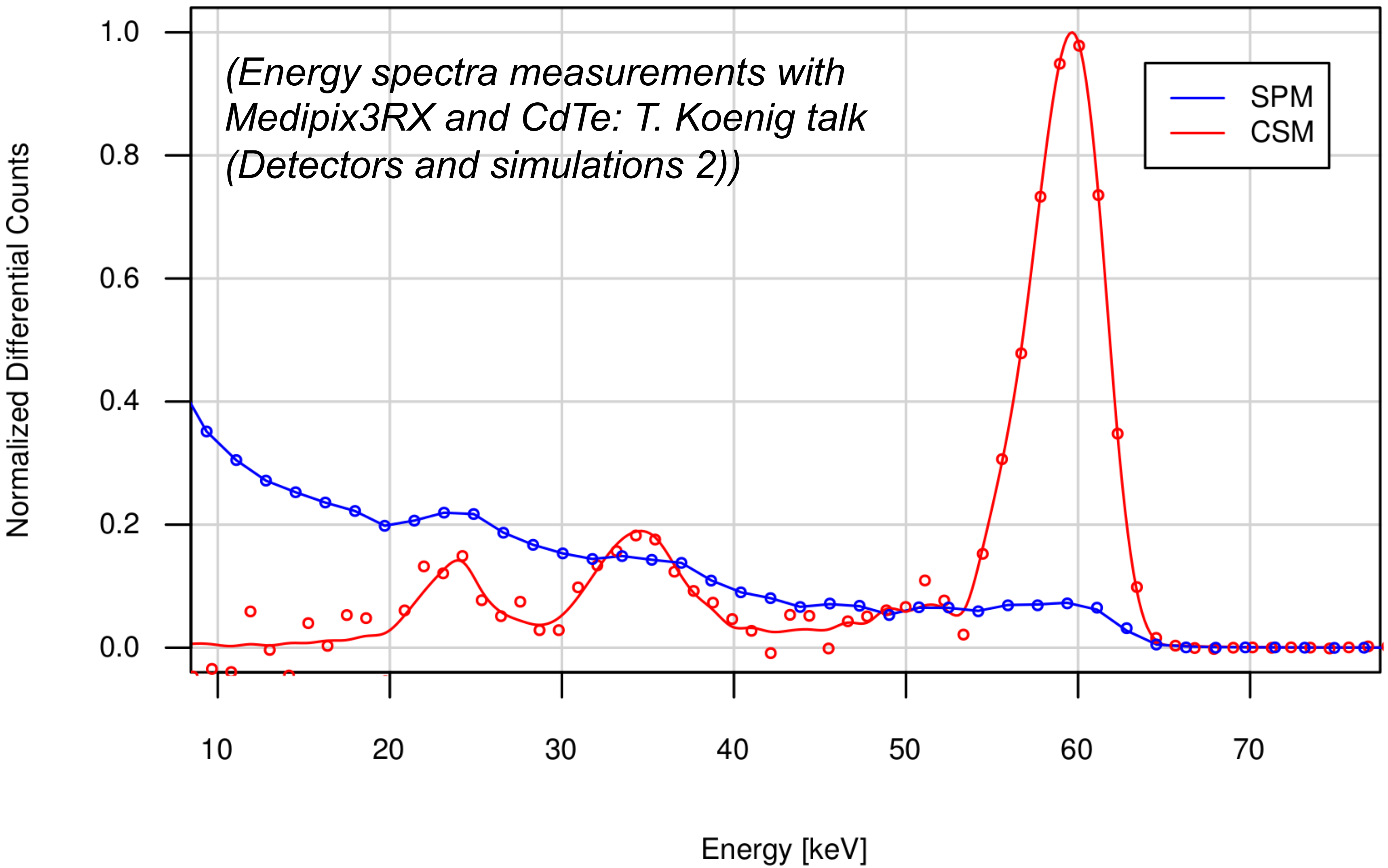


Measurement of ^{109}Cd energy spectrum

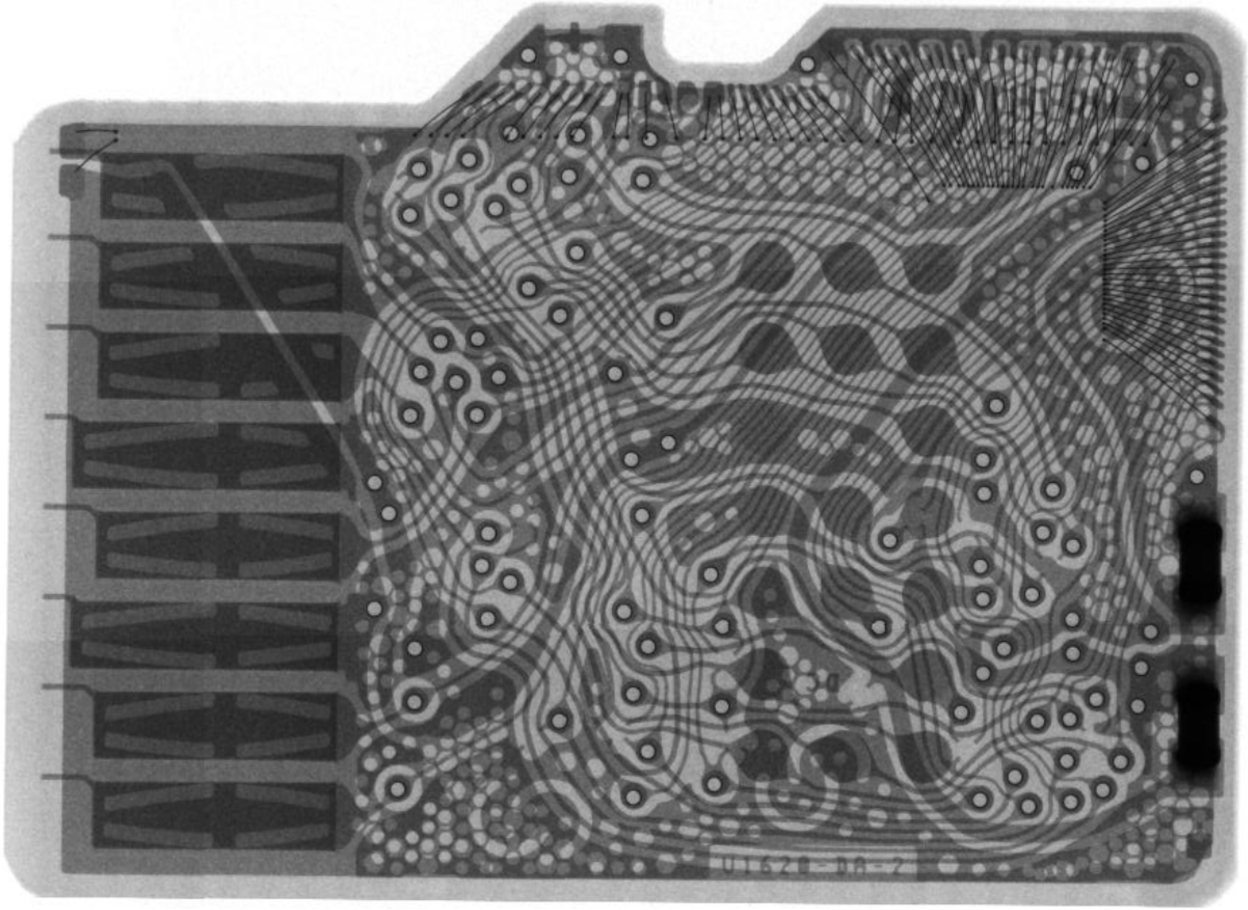


Measurement in HGM @ very low flux conditions
Only 4 pixels masked in the matrix
Raw data. No realignment in data
In Charge Summing Mode each photon is counted once

Measurements (60keV, 110μm pitch, 2mm CdTe)



Imaging a μSD card in CSM



μSd card

4x3 tiles, magnification 3.2x

X-ray tube voltage: 30 kVp, Tube current: 100μA, 1mm Al filtering, 5s acquisition

Courtesy of S. Procz (Freiburger Materialforschugszentrum FMF, Germany)

Medipix3RX electrical characterization: measurements obtained (chip with sensor)

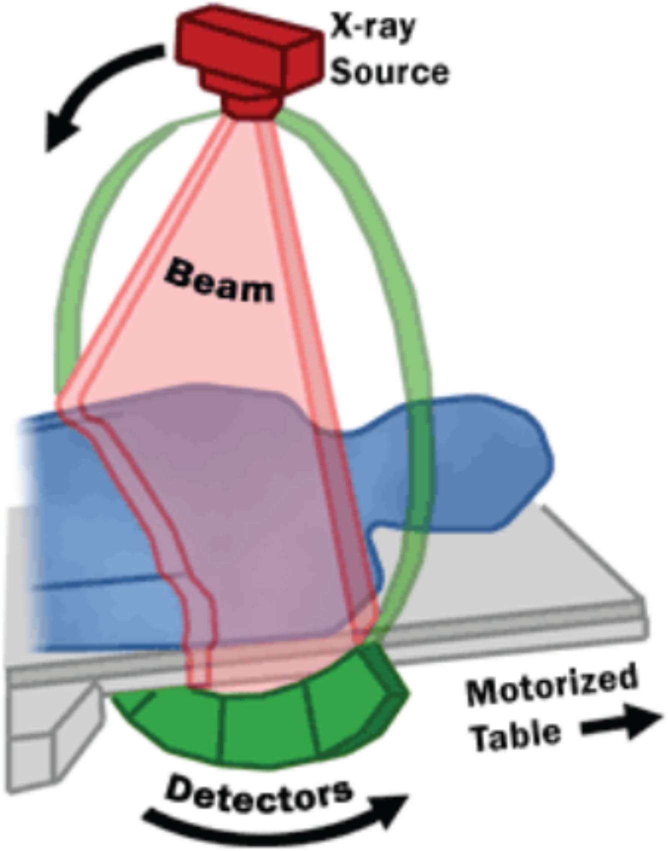
	SPM	CSM	Units
Gain (SHGM)	25	55	e^-/DAC step
ENC (SHGM)	75	150	e^- r.m.s.
Threshold dispersion (SHGM)	37.5	85.5	e^- r.m.s.
Peaking time	120	120	ns
Power consumption	0.78	1	W/chip
Dead time/channel*	0.22/4.5	2.94/0.34	μs/MHz
Count rate*	375	28	Mc/mm^2s

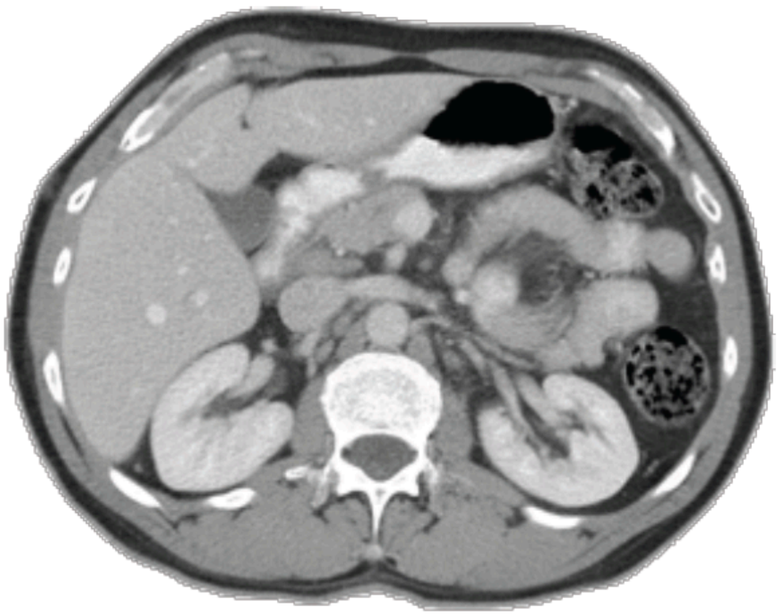
*Measurements with CdTe, 2mm thick at 110μm pitch (paralizable model fit)

MEDIPIX / TIMEPIX APPLICATIONS

CT Imaging

CT is now one of the most used imaging techniques





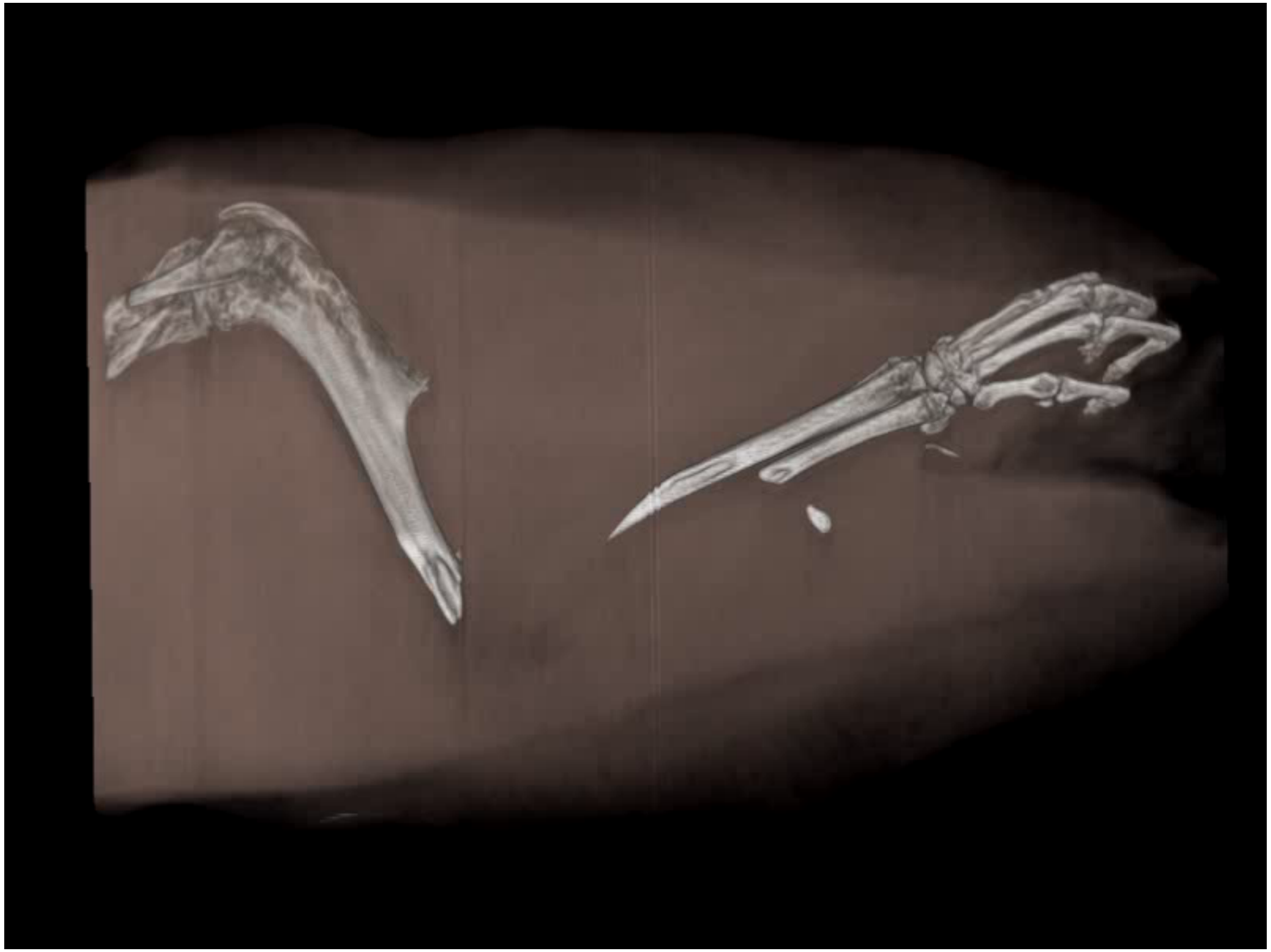
Cross-sectional image of abdomen
many slices combined into 3D image

Images from : http://www.fda.gov/radiation-emittingproducts

CT Imaging

example:

CT allows 3D reconstruction of part of a mouse



Medipix3 for small-animal CT scanning

Anthony Butler

mars

Medipix All Resolution System

UC UNIVERSITY OF CANTERBURY

UNIVERSITY OF OTAGO

Medipix3 for small-animal CT scanning

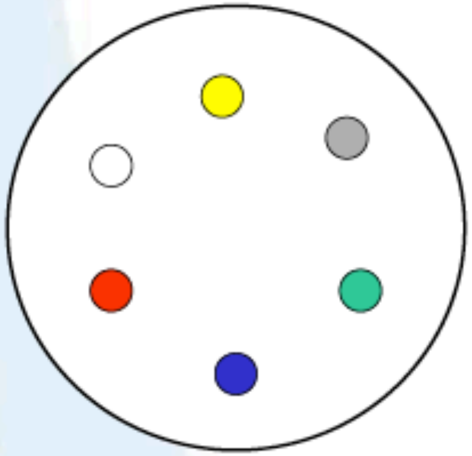
Test Objects: internal presentation

Mouse set in Perspex

- Gold in chest cavity

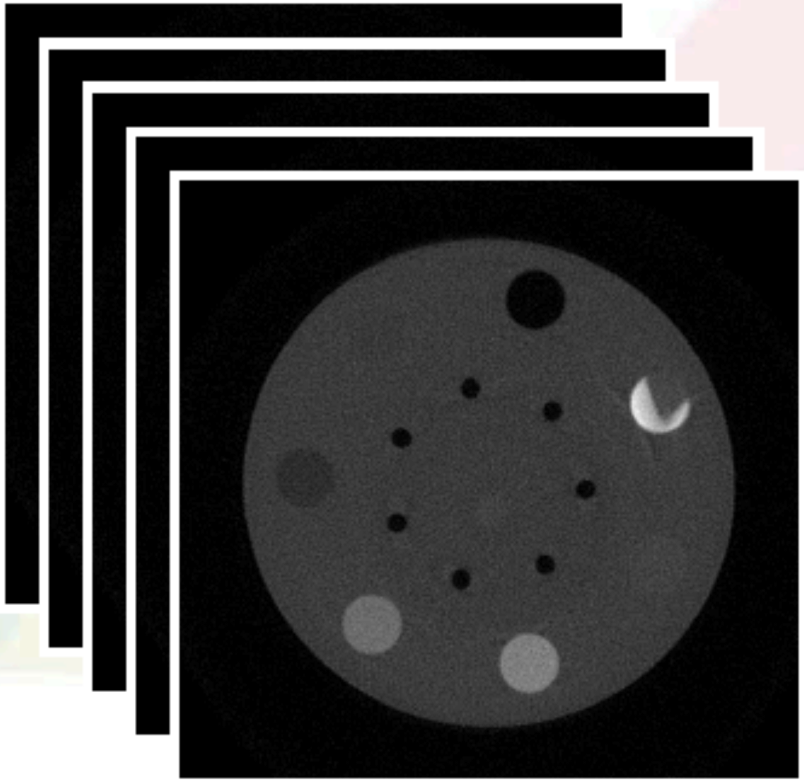
Perspex phantom

- 2cm diameter rod
- Contains air, fat, water, Ca, Au, I

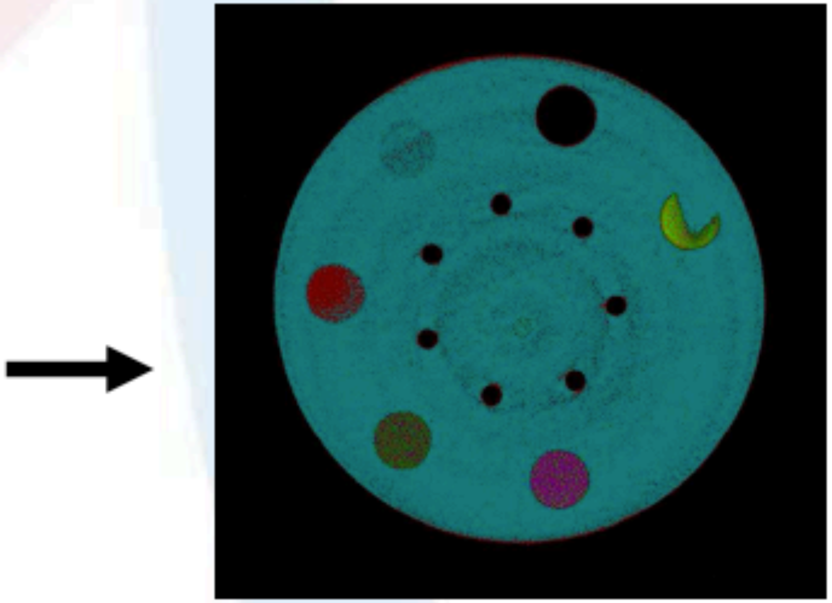


Medipix3.1 for small-animal CT scanning

GaAs sensor: Multi-material Decomposition now possible
for human X-ray energy one needs heavier sensor material



10-100 keV



Red - Fat
Cyan - Water
Purple - Iodine
Green - Calcium
Yellow - Gold

CT Imaging

Following slide is a comparison of Computed Tomography images of a mouse head taken under identical circumstances between
a conventional X-ray detector
the Medipix3 chip combined with a Si sensor.

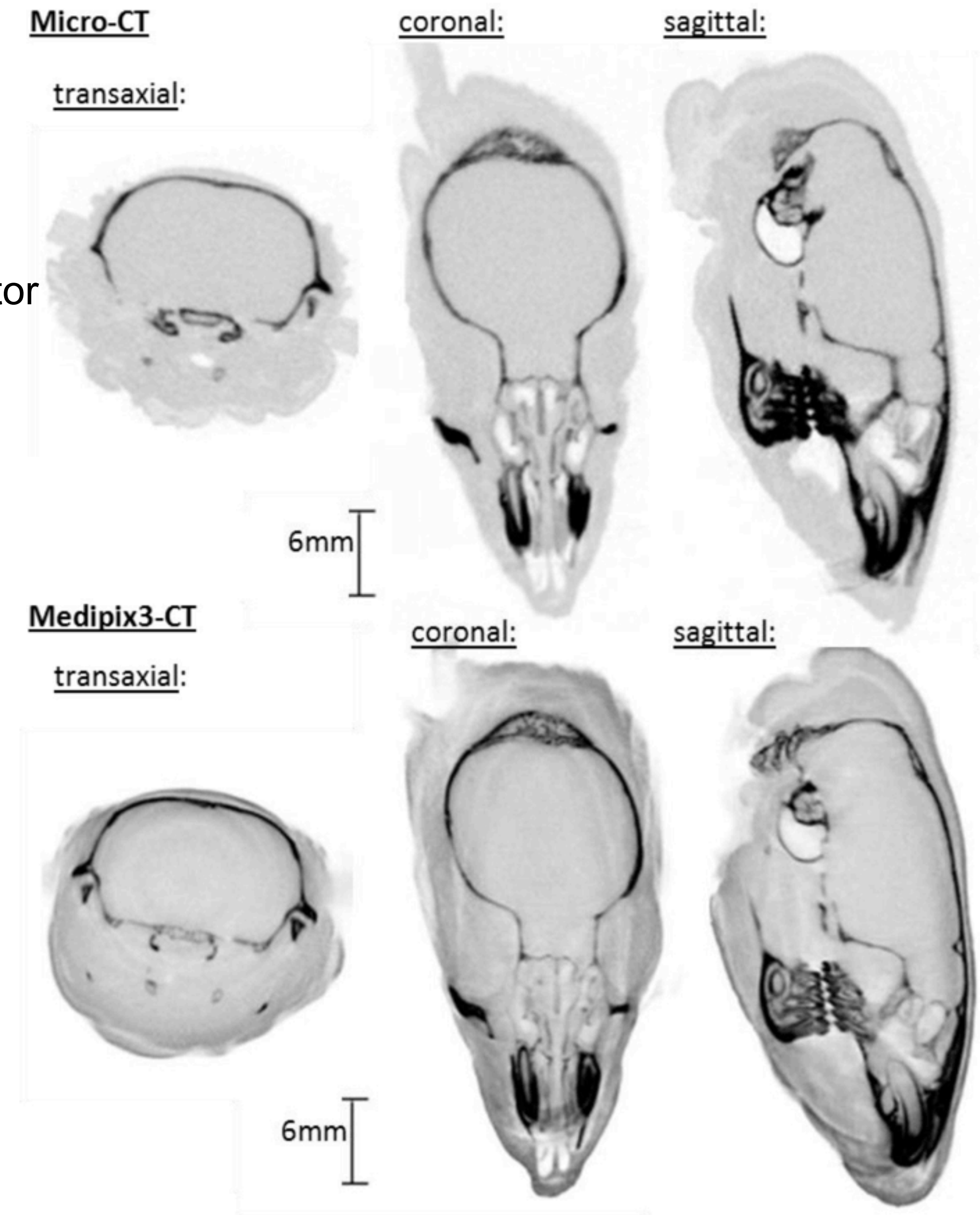
The improvement of clarity in the Medixpix3 image
is obvious even to the untrained observer.
The dose used for both measurements was about 170 mGy/cm.

from PhD Thesis: Jördis Lübke,
"Entwicklung eines iterativen Rekonstruktionsverfahrens
für einen Medipix3-Computertomographen",
Dissertation University of Freiburg 2011

Comparison of usual detector and Medipix3+Si

Usual detector

Medipix3



Human Medical Imaging

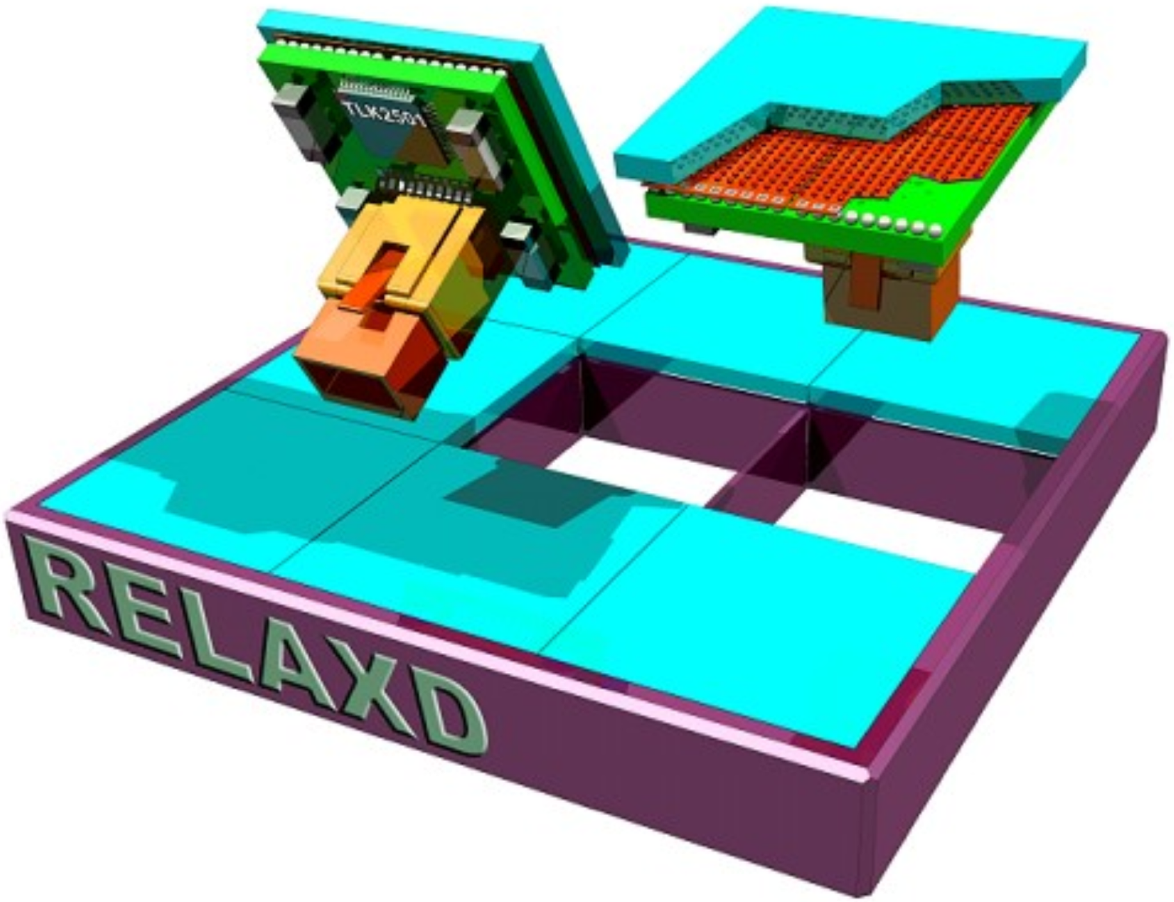
CT needs detectors
with good stopping power for hard X-rays 50-150 keV

radiation tolerance of sensors and electronics

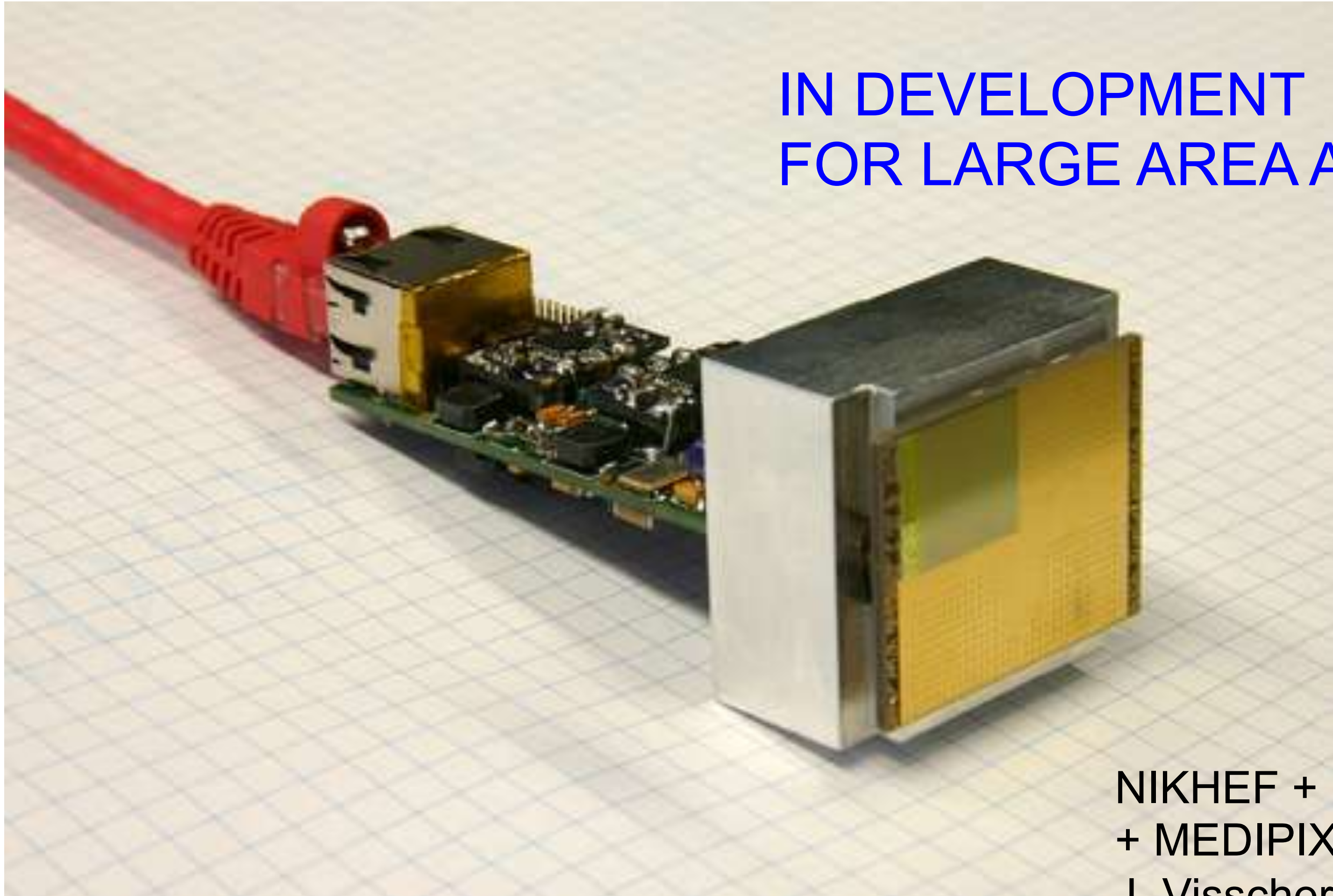
need for large area coverage, without gaps

cost is a major issue in commercial applications

Large Area X-Ray Detector RELAXD NIKHEF



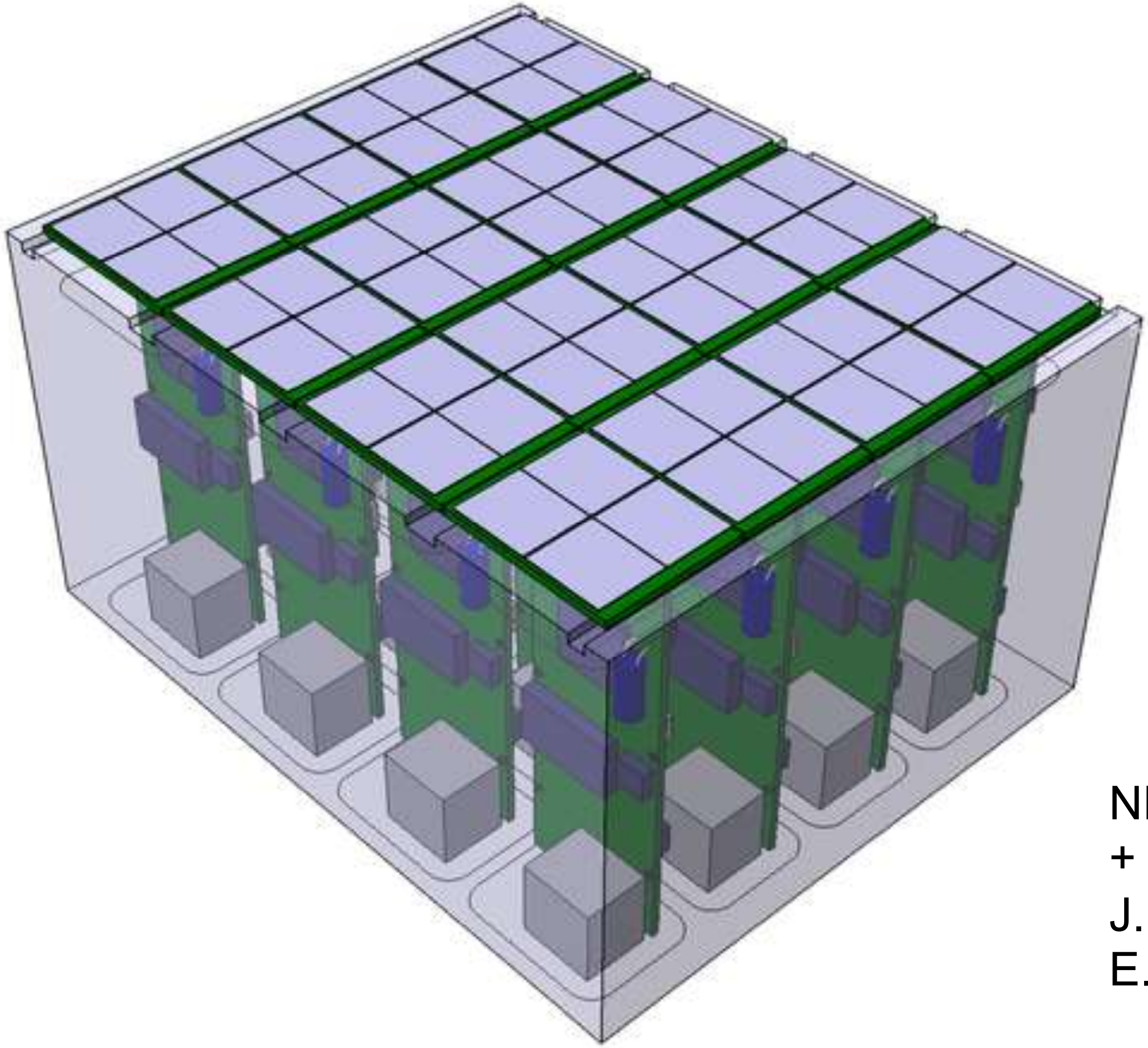
MEDIPIX UNIT "RELAXD"



IN DEVELOPMENT
FOR LARGE AREA ARRAY

NIKHEF + PANALYTICAL
+ MEDIPIX / CERN
J. Visschers, K.Bethke,
E. Heijne cs.

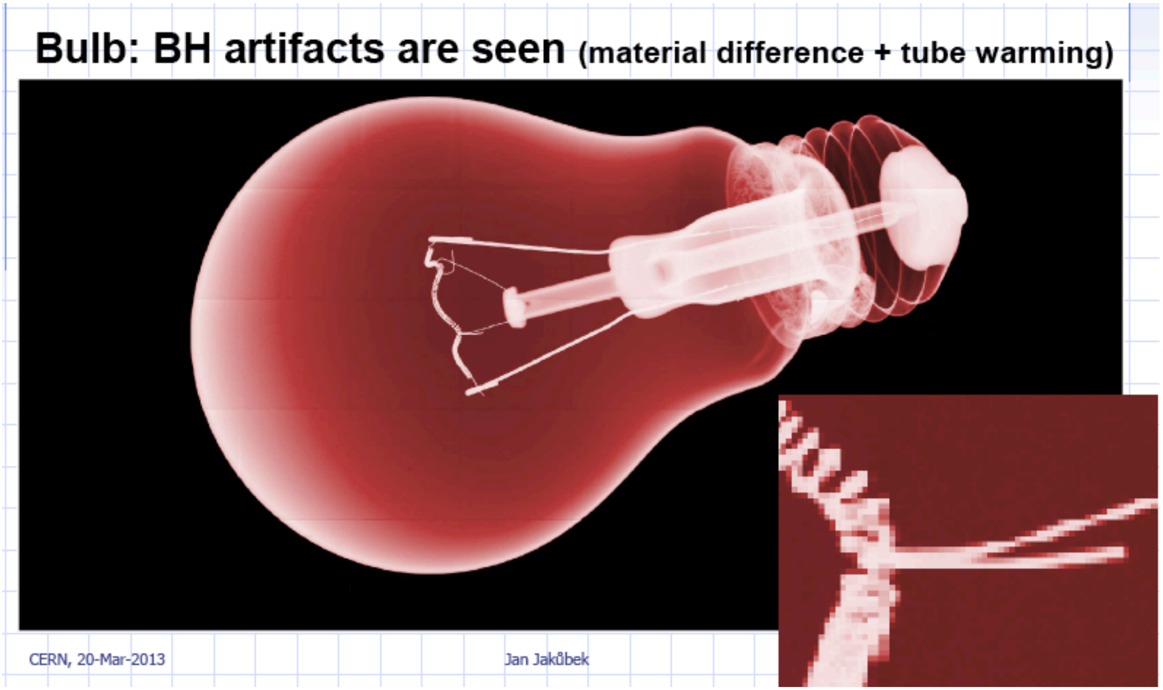
MEDIPIX ARRAY DESIGN

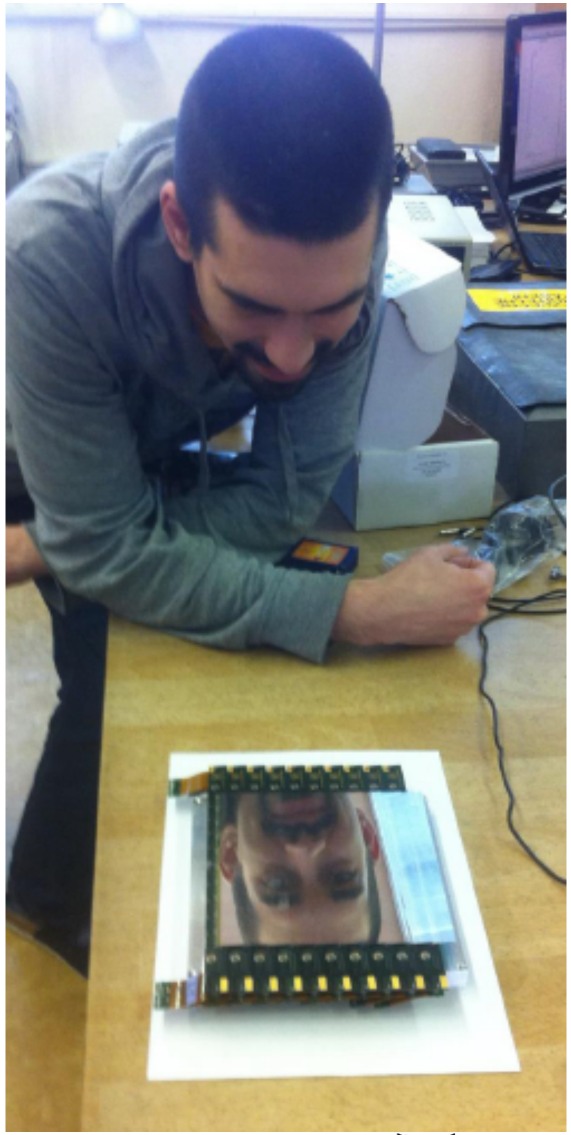


NIKHEF + PANALYTICAL
+ MEDIPIX / CERN
J. Visschers, K.Bethke,
E. Heijne cs.

A Large Area Timepix Detector

10 x 10 chip   ~ 14 cm x 14 cm
using edgeless sensors
wirebonds underneath, small angles
made at Inst Exp Appl Phys IEAP Prague
Jan Jakubek & colleagues





Some Applications of Medipix/Timepix

X-ray imaging other than medical

X-ray diffraction patterns XRD
X-ray fluorescence XRF
phase contrast enhancement
environmental applications

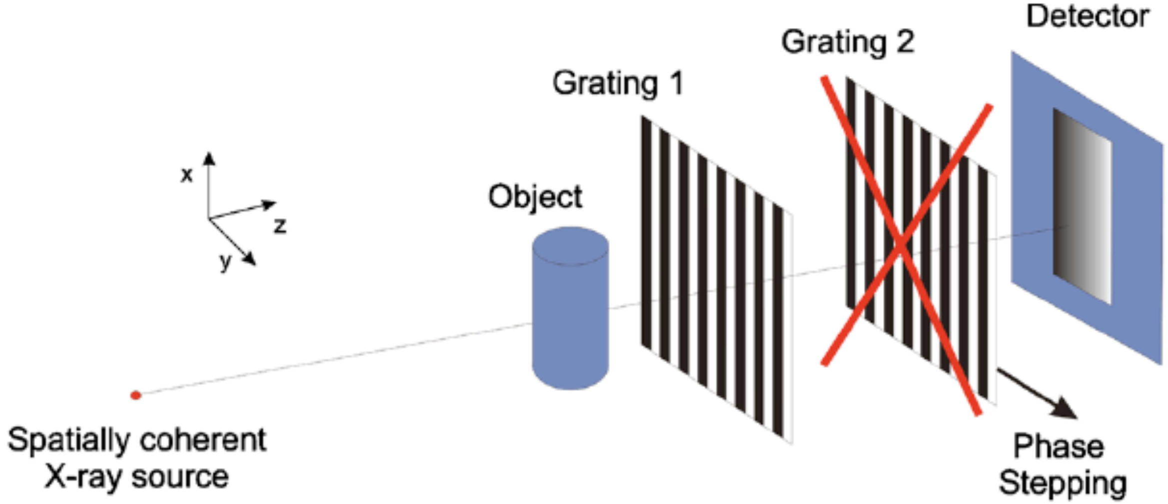
imaging of electrons, neutrons, molecules

electron microscopy (cryogenic, ..)
LEEM
visible light via micro-channel plate (MCP)
neutron imaging (enhanced by converter materials)
dosimetry
mass spectrometry imaging

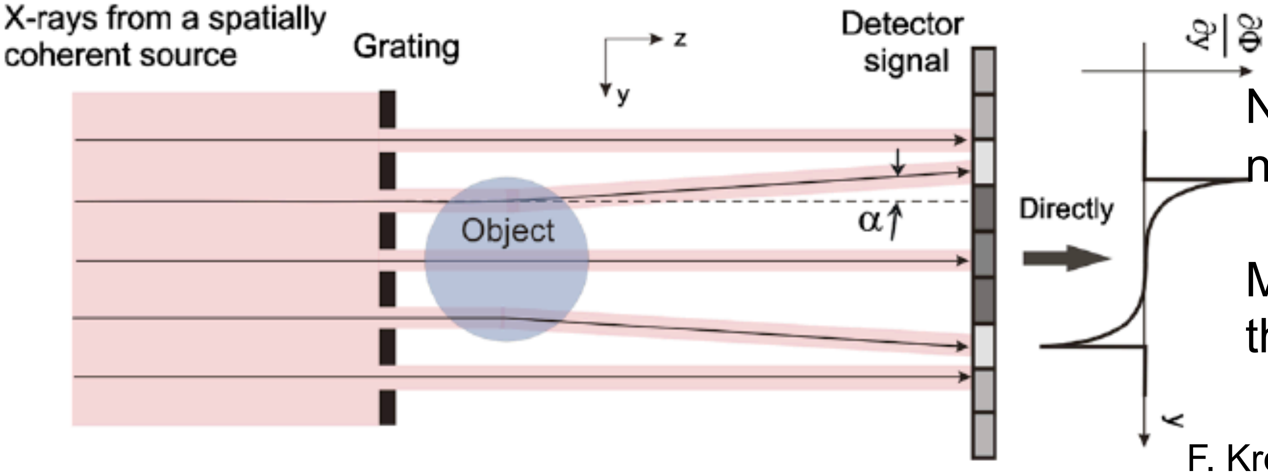
dosimetry

Timepix at International Space Station
Timepix anywhere (in school, also in LHC: ATLAS and CMS)
dedicated dosimeter chip Dosepix

Phase Contrast Imaging



Usually needs 2 gratings



New method with Medipix needs only a single one

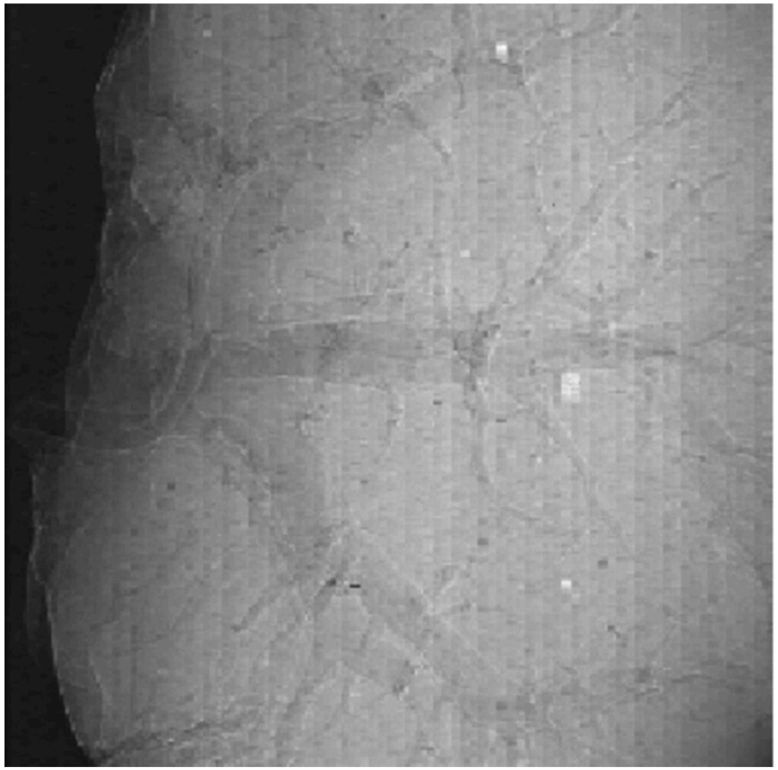
Measure intnsities without then WITH object

F. Krejčí et al.,
Rev. Sci. Instrum.81 (2010) 113702

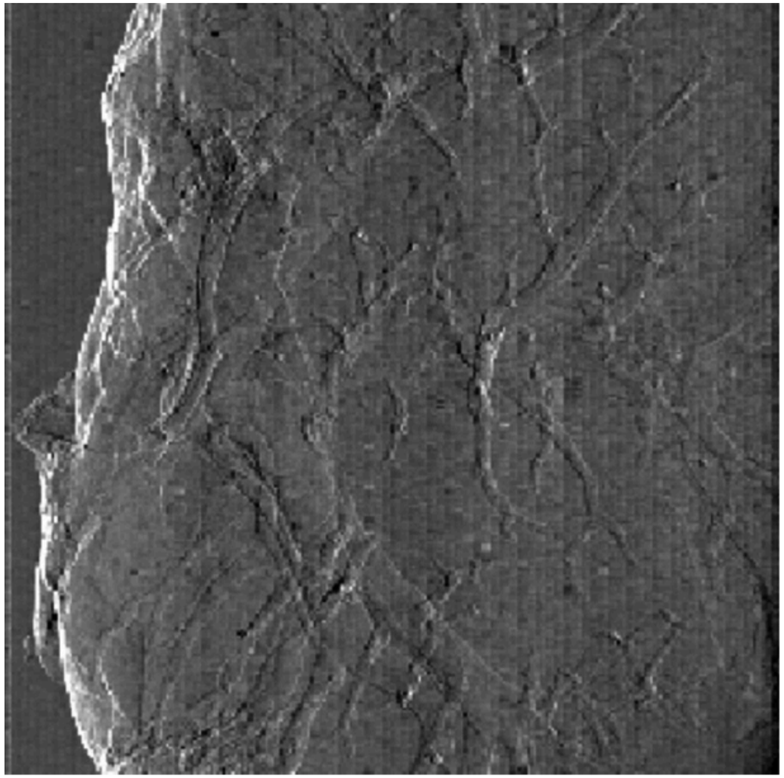
Phase Contrast Imaging

Can use only one single grating, if Medipix is used as detector

Mouse kidney:
50keV X-ray absorption

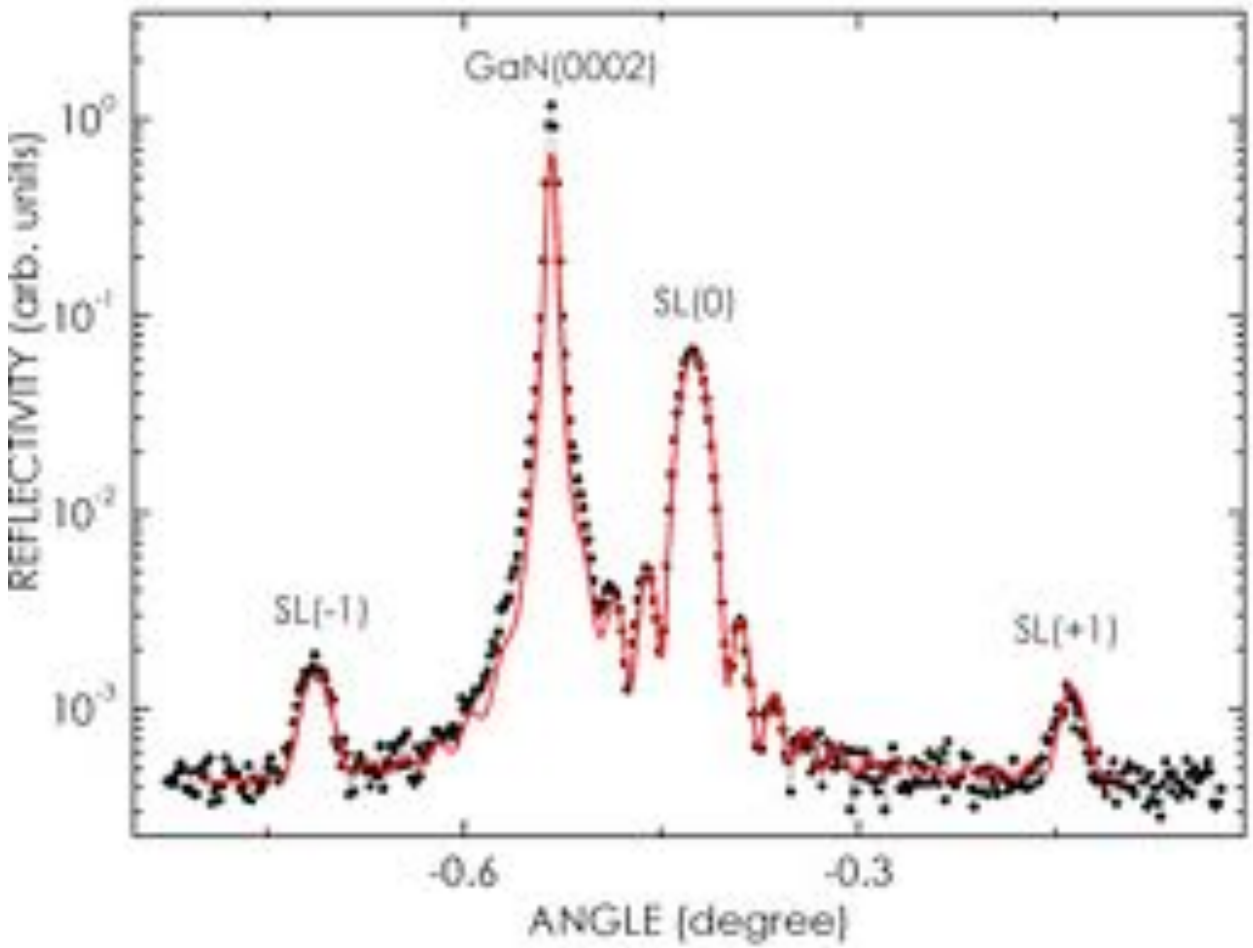


Mouse kidney:
50keV X-ray Phase Contrast



F. Krejčí, J. Jakůbek, M. Kroupa, " Hard x-ray phase contrast imaging using single absorption grating and hybrid semiconductor pixel detector", Rev. Sci. Instrum. 81 (2010) 113702

X-ray Diffraction for Materials Analysis



PIXCEL detector for X-RAY DIFFRACTION

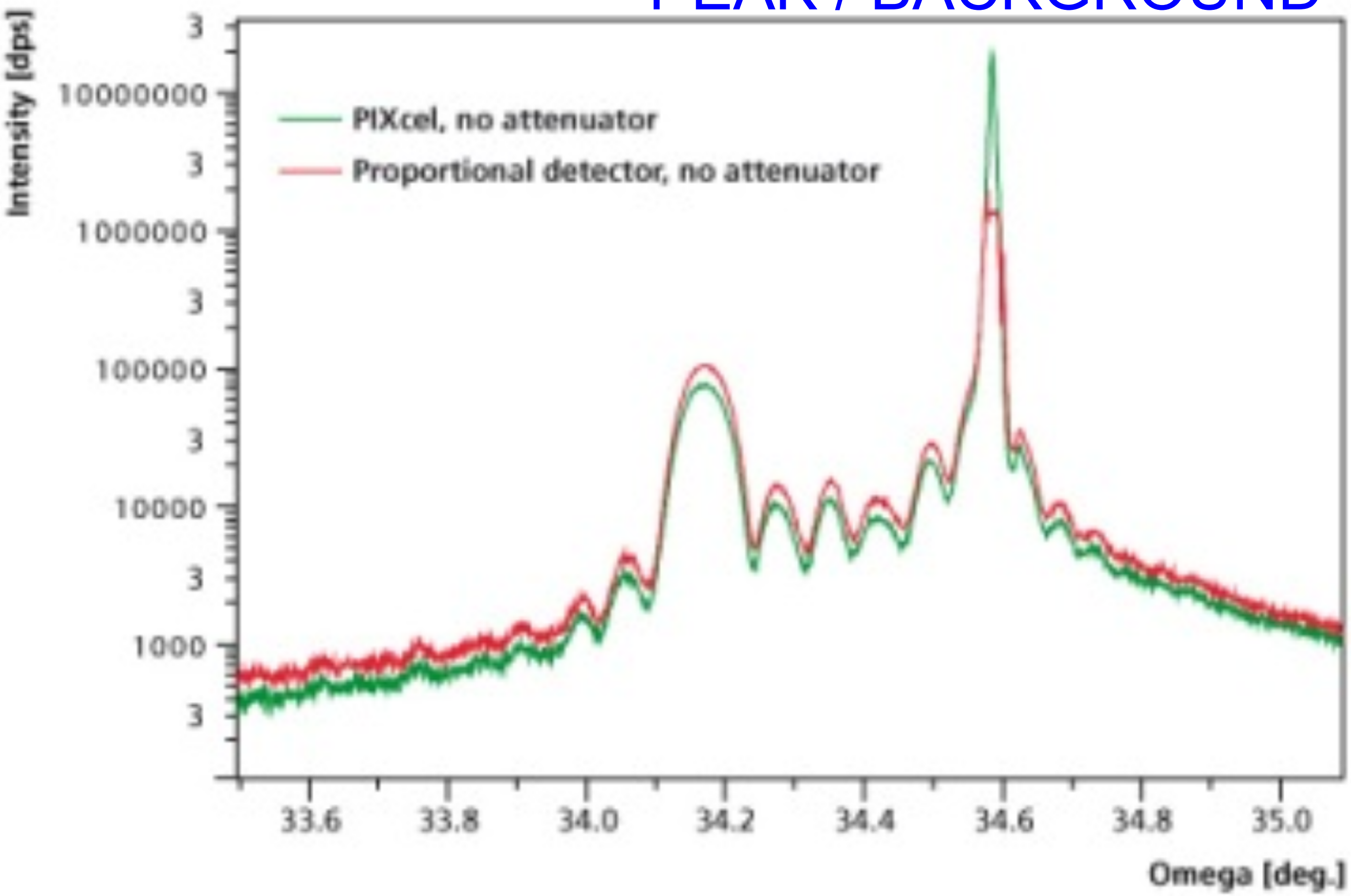
Replaces Si microstrip detector in theit analyzer

SPIN-OFF to
PANALYTICAL
Almelo, NL

http://www.panalytical.com/XPert-Powder/

PANALYTICAL X-RAY DIFFRACTION

Improvement in ratio
PEAK / BACKGROUND



ALMELO, NL PANalytical

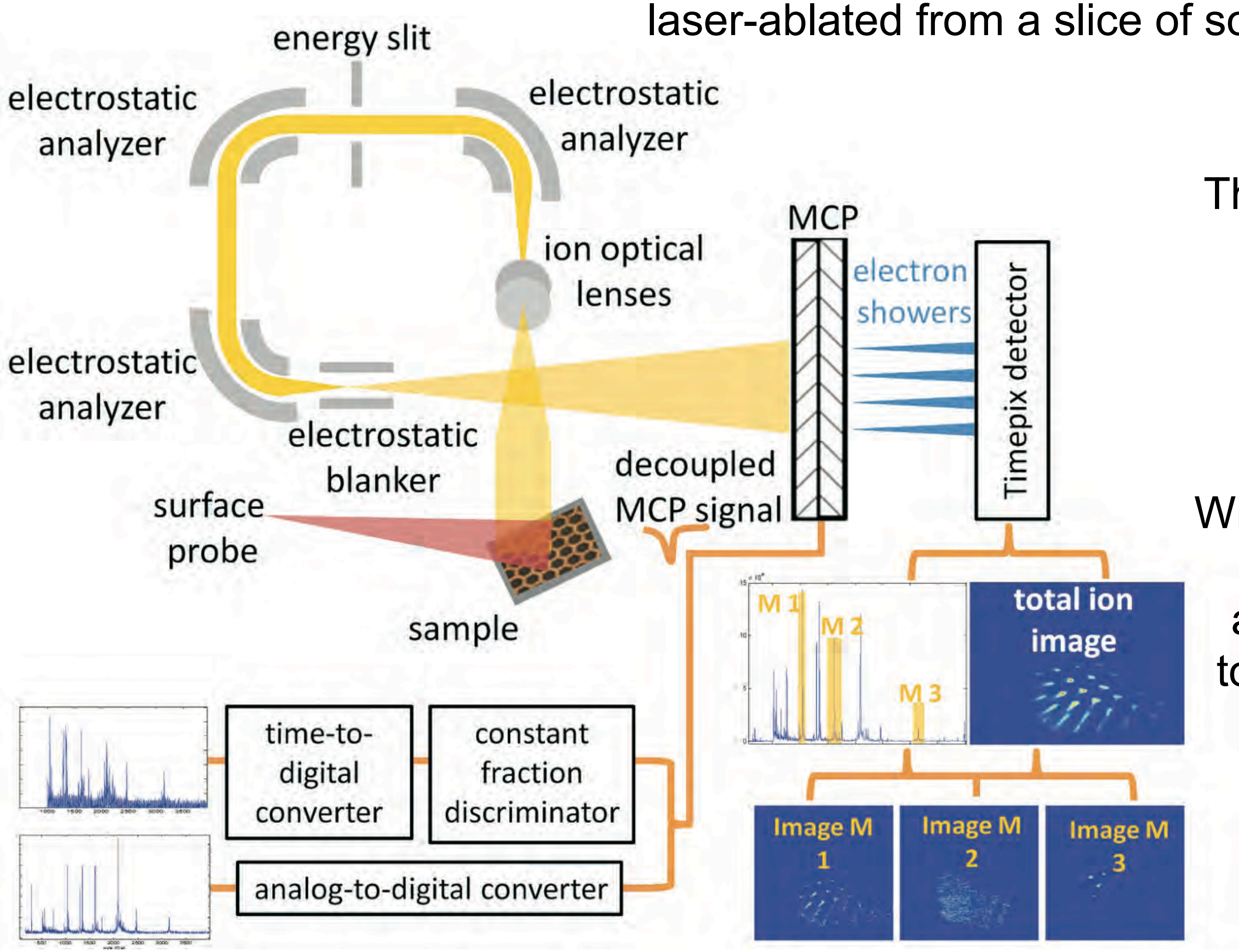
Environmental Imaging

Medipix Image superposed on photograph of container with radio-waste

CEA-LIST
Paris

Mass Spectrometry Imaging

Analysis of spatial distribution and types of molecules laser-ablated from a slice of some object



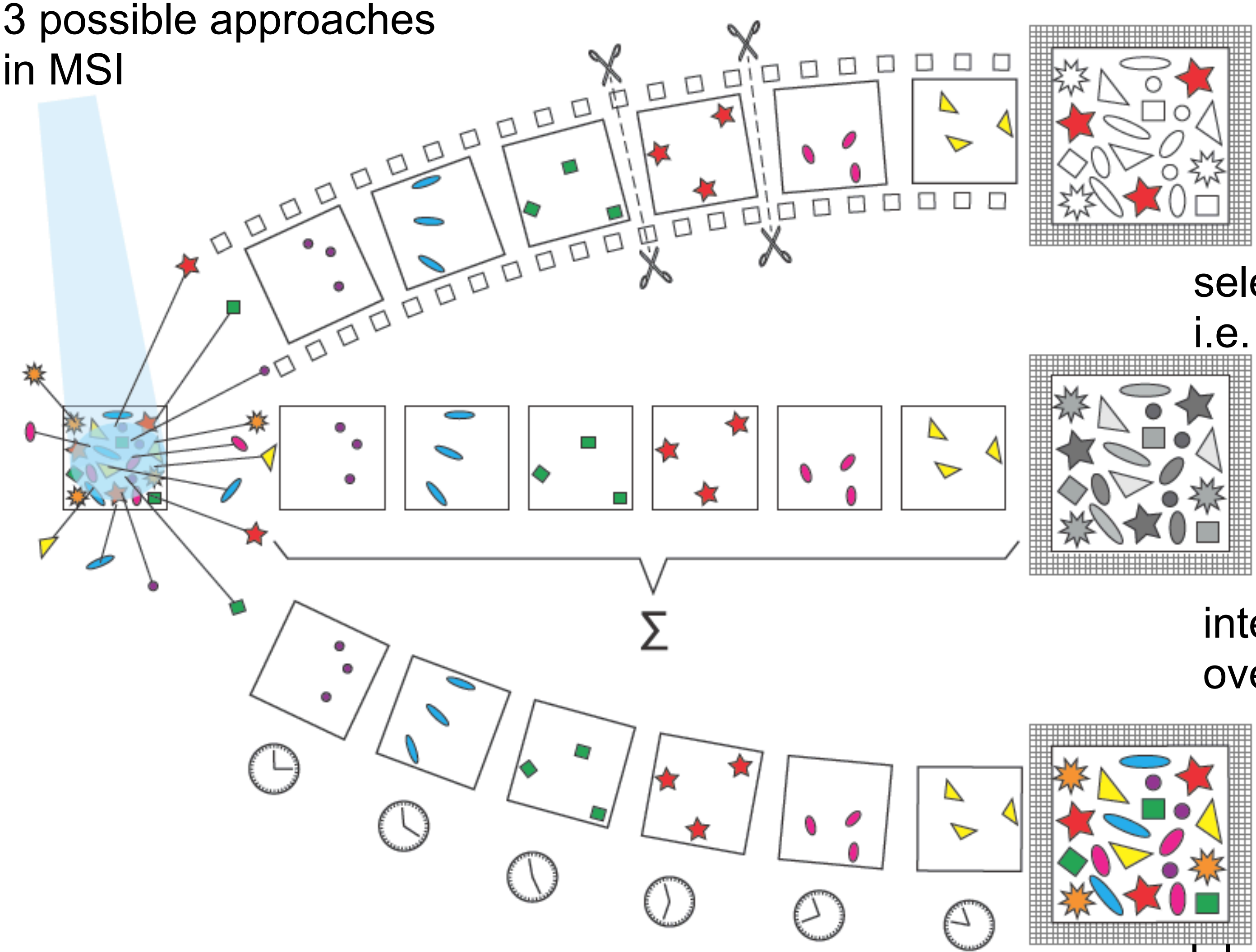
The masses are analyzed by their speed: time of arrival identifies the molecules

With very low speed/energy there is no penetration and chevron MCP is used to generate electron signal

J. Jungmann, PhD Thesis AMOLF Amsterdam
ISBN 978-90-77209-64-6.67 cm^2

Mass Spectrometry Imaging

3 possible approaches
in MSI



select one time-slice
i.e. one type of molecule

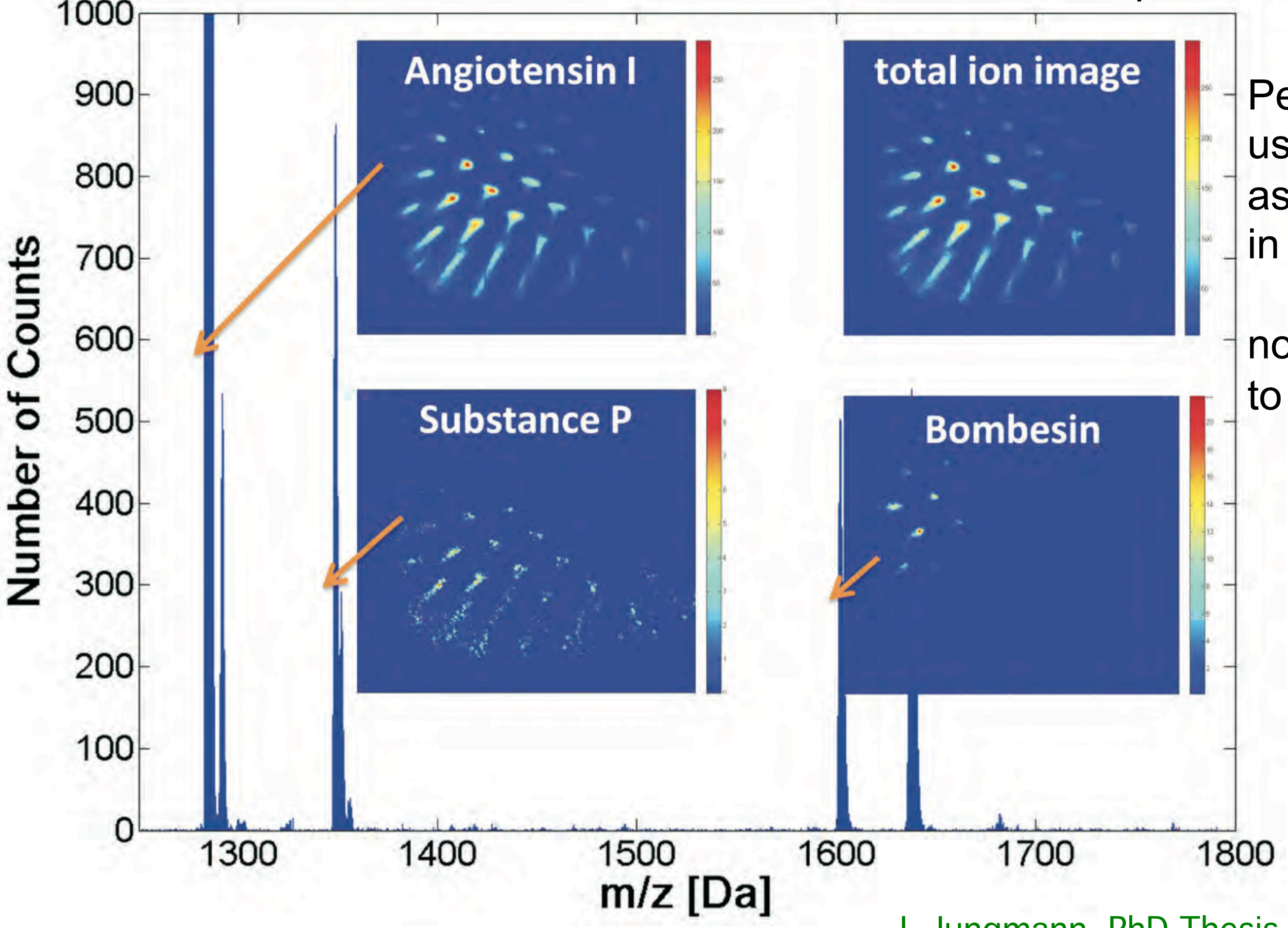
integrate everything
over time: no types

label arrival time
mapping of molecules

J. Jungmann, PhD Thesis AMOLF Amsterdam
ISBN 978-90-77209-64-6.67 cm²

Mass Spectrometry Imaging

MALDI Matrix-Assisted Laser Desorption/Ionization



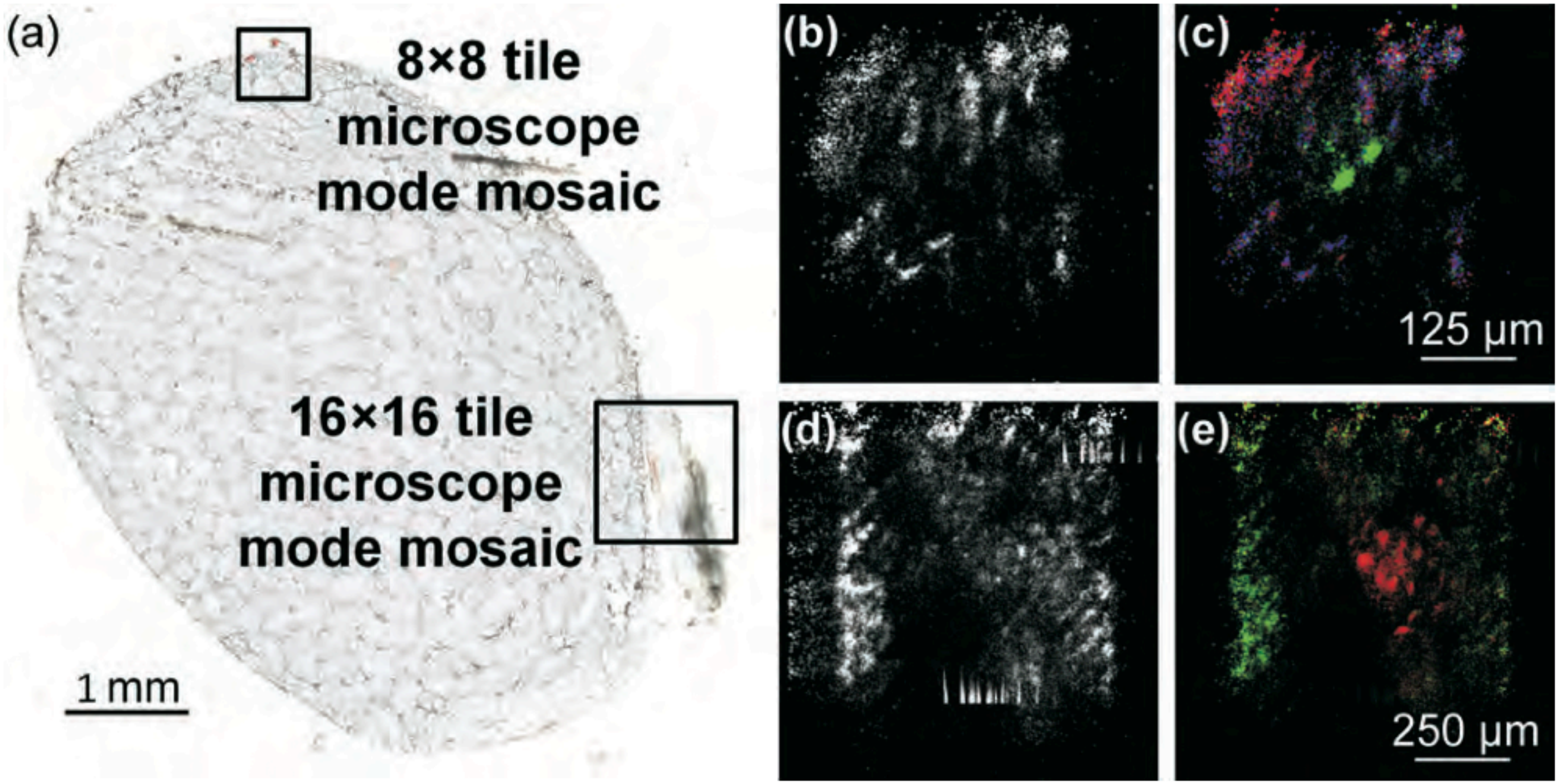
Peptide measured using Timepix as imaging device in a single pass

no blanker needed to select a molecule

J. Jungmann, PhD Thesis AMOLF Amsterdam

ISBN 978-90-77209-64-6.67 cm^2

Mass Spectrometry Imaging

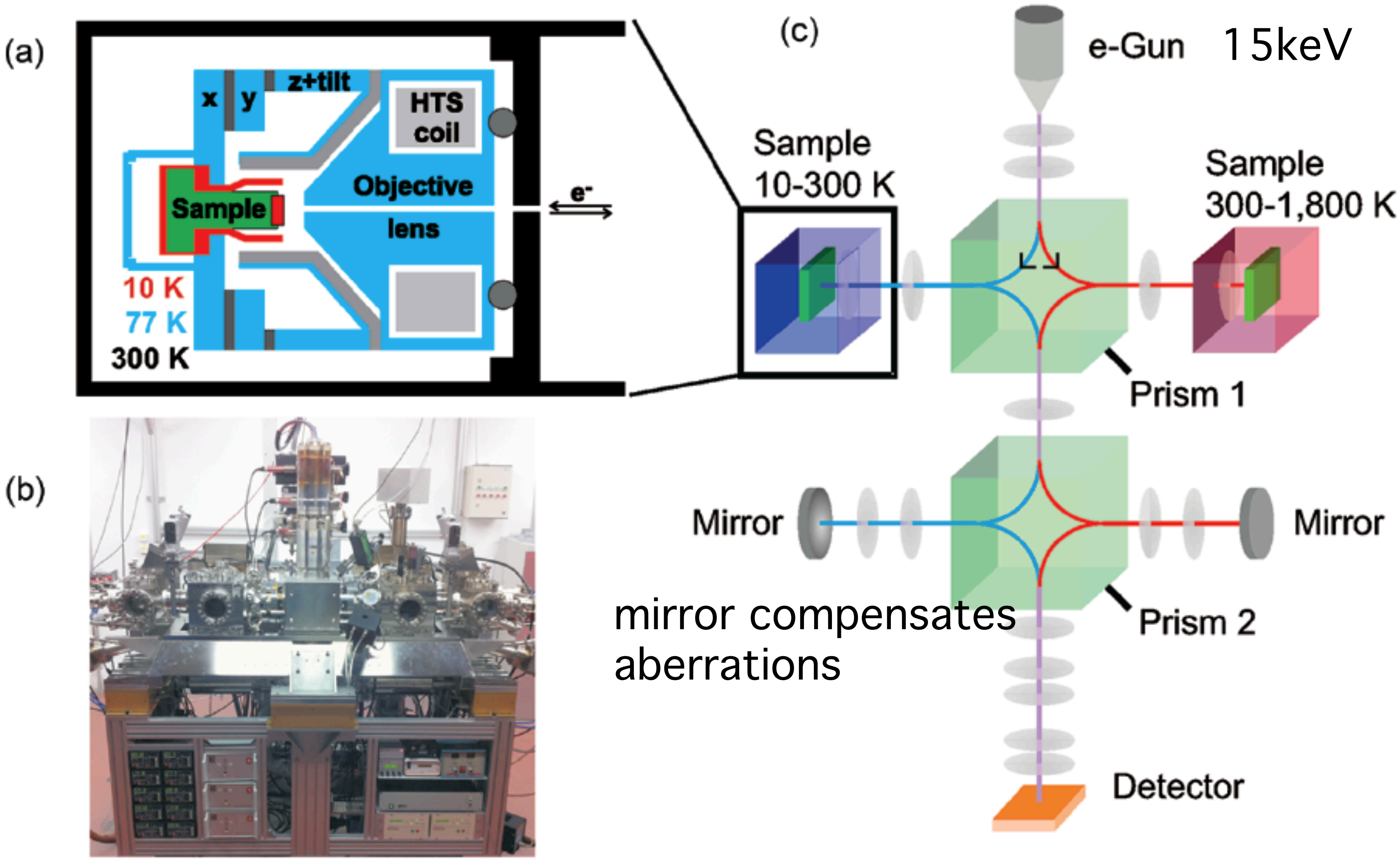


J. Jungmann, PhD Thesis AMOLF Amsterdam
ISBN 978-90-77209-64-6.67 cm^2

Low Energy Electron Microscopy LEEM

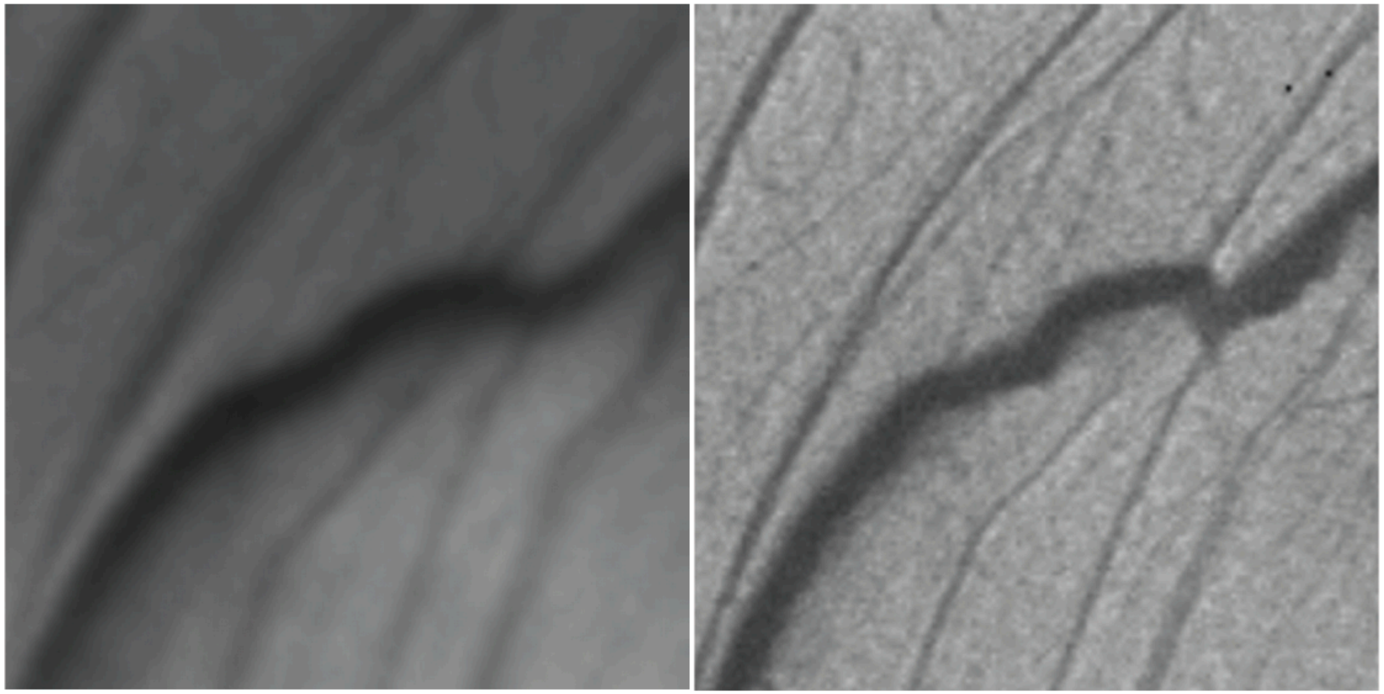
also Photo Emission Electron Microscopy PEEM

'Escher' set-up Leiden   from IBM J Res&DEv 55-5(2011) paper 1



Low Energy Electron Microscopy LEEM

15keV electrons are decelerated to a 0-100 eV before they reach the sample.
They reflect from the sample, and are re-accelerated to 15keV, and directed to the imaging detector.
Using magnification and sophisticated compensation by a segmented mirror, one can achieve a resolution of a few nm i.e. 1μm = 1000 pixels


(a) (b)

graphene flakes on Ir <111>surface 1.5μmx1.5μm

a) standard MCP+ CCD-based imager

b) with Medipix 256x256 imager

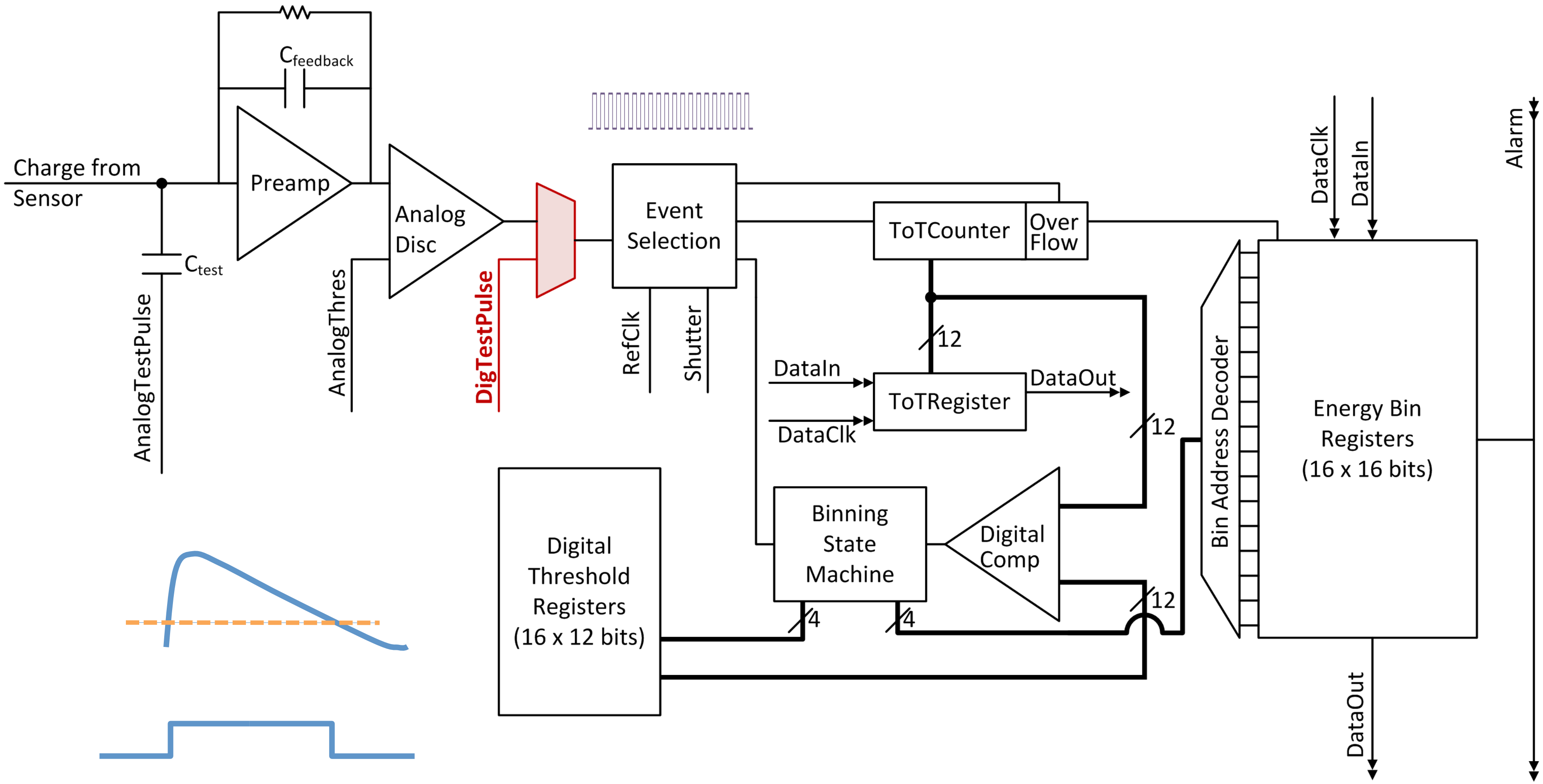
2x improvement

Designed chips

Chip	Description
Medipix1 (1998)	*1μm SACMOS, 64x64 pixels, 170x170μm²* *PC / Frame based readout*
Medipix2 (2001)	*0.25μm CMOS, 256x256 pixels, 55x55μm²* *PC / Frame based readout*
Timepix (2006)	*0.25μm CMOS, 256x256 pixels, 55x55μm²* *PC, ToT, ToA / Frame based readout*
Medipix3 (2009)	*0.13μm CMOS, 256x256 pixels, 55x55μm²* *PC / Frame based readout* *Event by event charge reconstruction and allocation*
Dosepix (2011)	*0.13μm CMOS, 16x16 pixels, 220x220μm²* *ToT, PC / Rolling shutter (programmable column readout)* *Event by event binning of energy spectra (16 digital thrs)*
Timepix3 (2013)	*0.13μm CMOS, 256x256 pixels, 55x55μm²* *PC; ToT, ToA (simultaneous)/ Data driven readout*
Smallpix	*0.13μm CMOS, 512x512 pixels, 40x40μm² (TBD)* *PC, iToT; ToA, ToT1 (simultaneous)/ Frame based (ZC)* *TSV compatible design*
Clicpix prototype	*65nm CMOS, 64x64 pixels, 25x25μm²* *ToA, ToT1 (simultaneous)/ Frame based (ZC)*

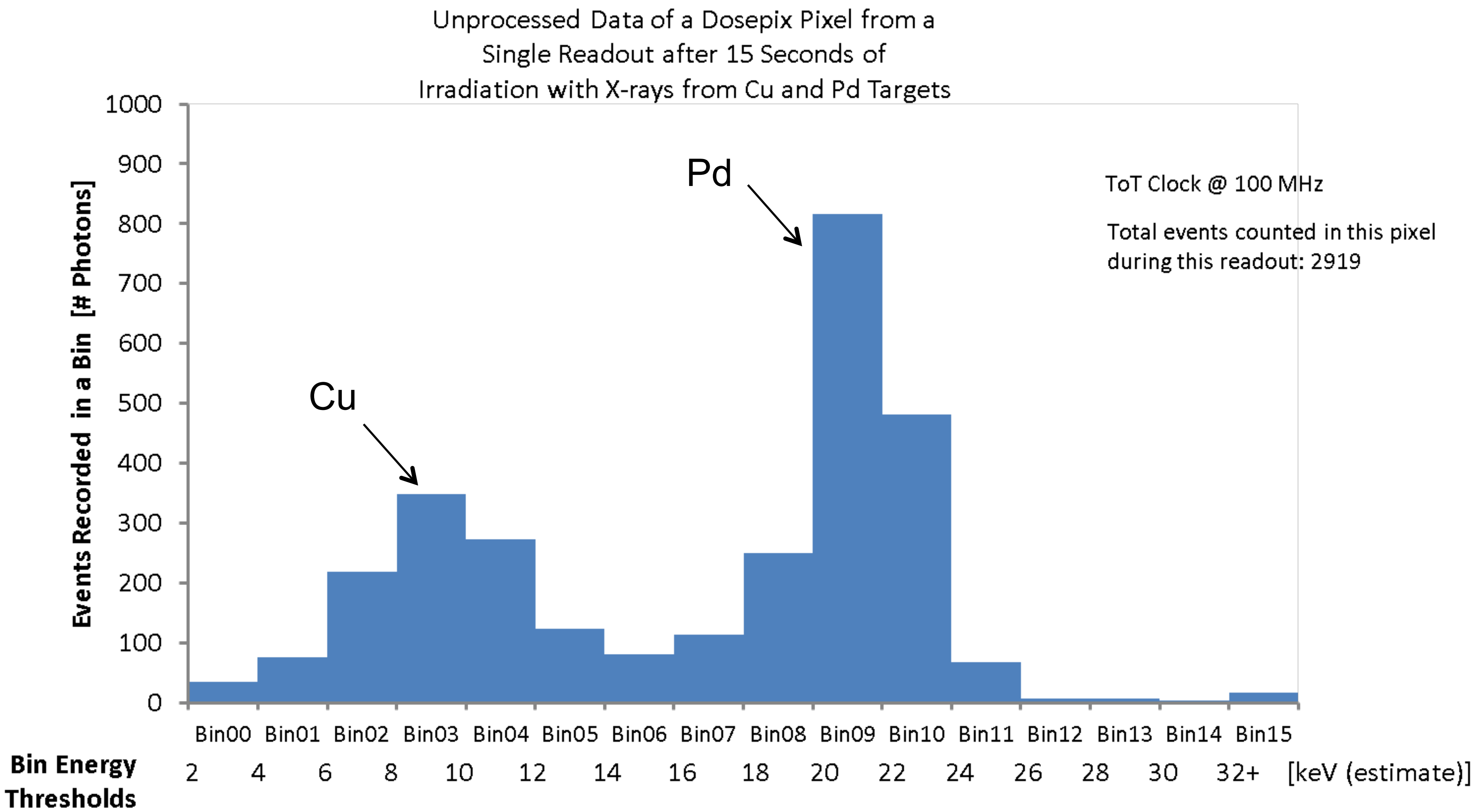
'Dosepix' schematic circuit diagram

Dosepix slide from W. Wong

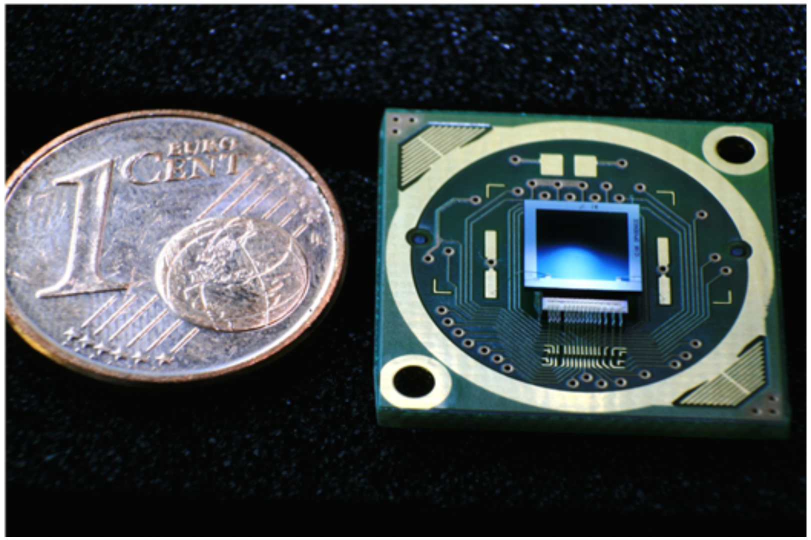


W. Wong, PhD Thesis Sundsvall, 2012

Dosepix single acquisition unprocessed data



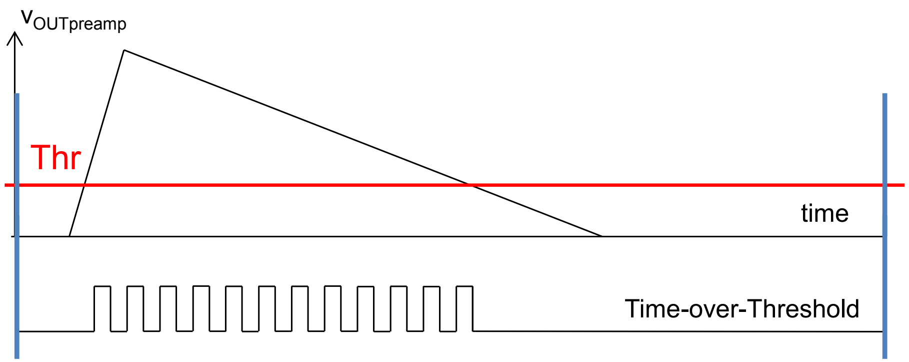
Dosepix



- Developed in the framework of the Medipix2 collaboration
- Main application: dosimetry

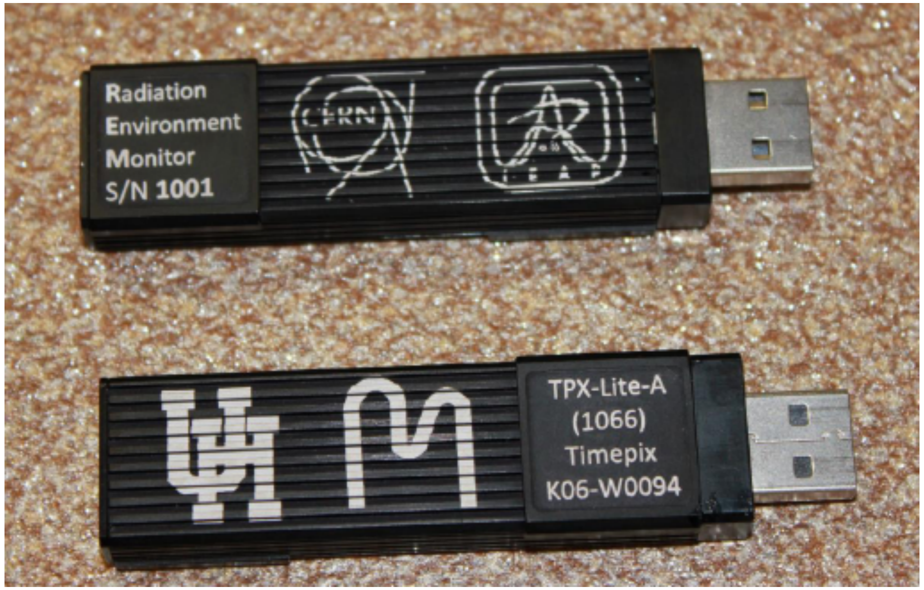
- 16x16 pixel matrix, 220x220μm^2 pixels
- CMOS 0.13μm technology
- 15mW full chip consumption
- 1 global analog threshold

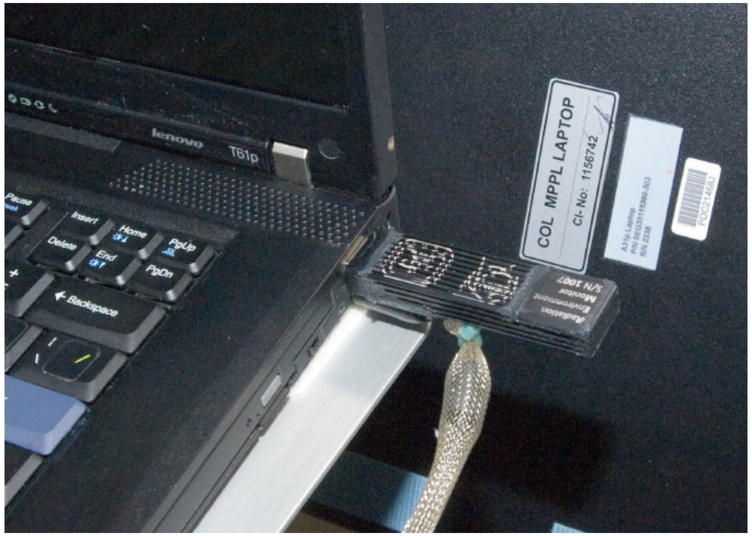
- Operation Modes:
  - Energy binning mode
    - 12 bit ToT measurement @100MHz
    - 16 digital thresholds for event-by-event energy binning
    - 16x16bit counters
  - Photon counting mode (8 bits)
  - Integral ToT (24 bits)



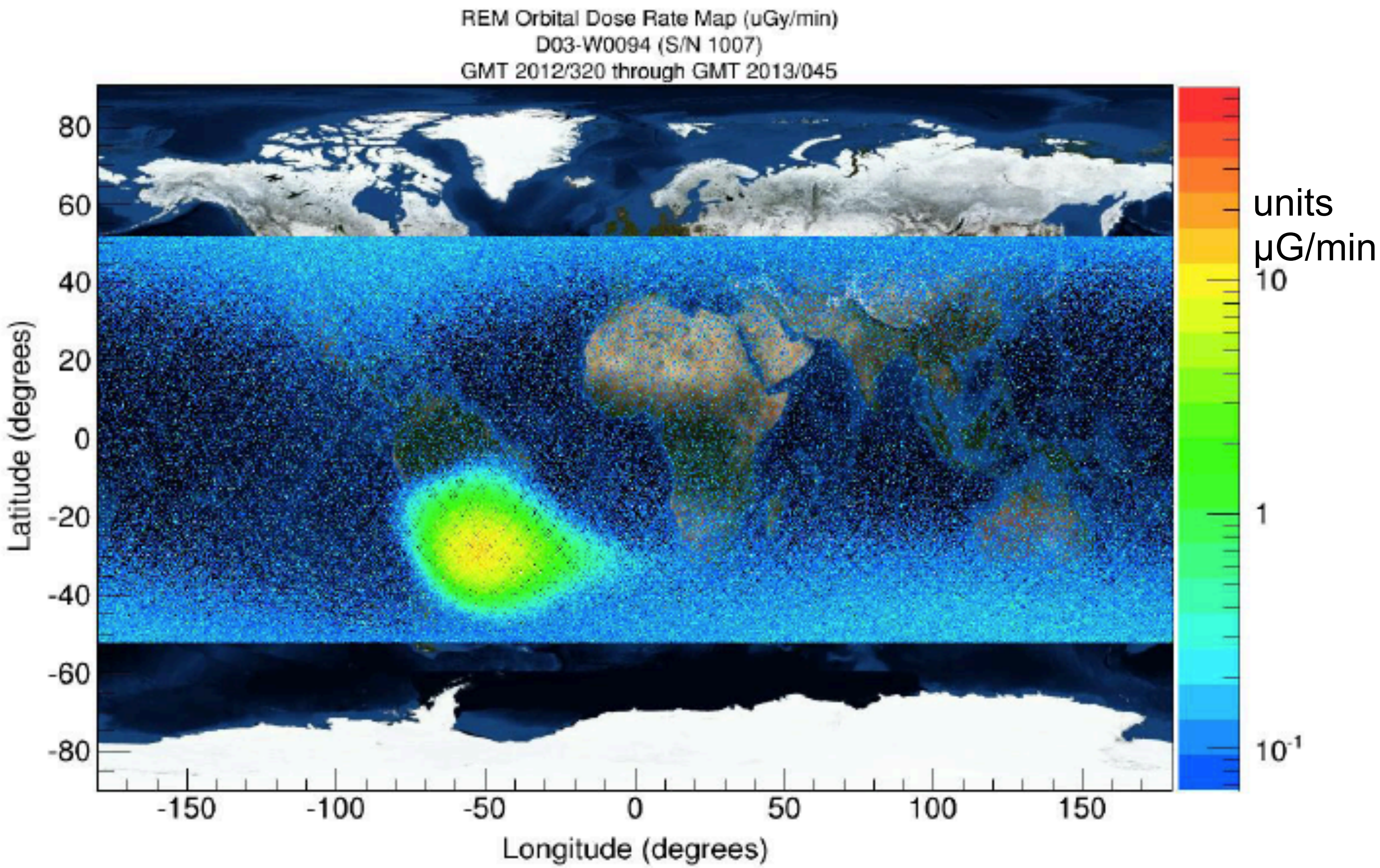
W.S.Wong et al., Electrical measurements of a multi-mode hybrid pixel detector ASIC for radiation detection, JINST 7 C01056 2012. doi:10.1088/1748-0221/7/01/C01056

Dosimetry at the Int Space Station ISS

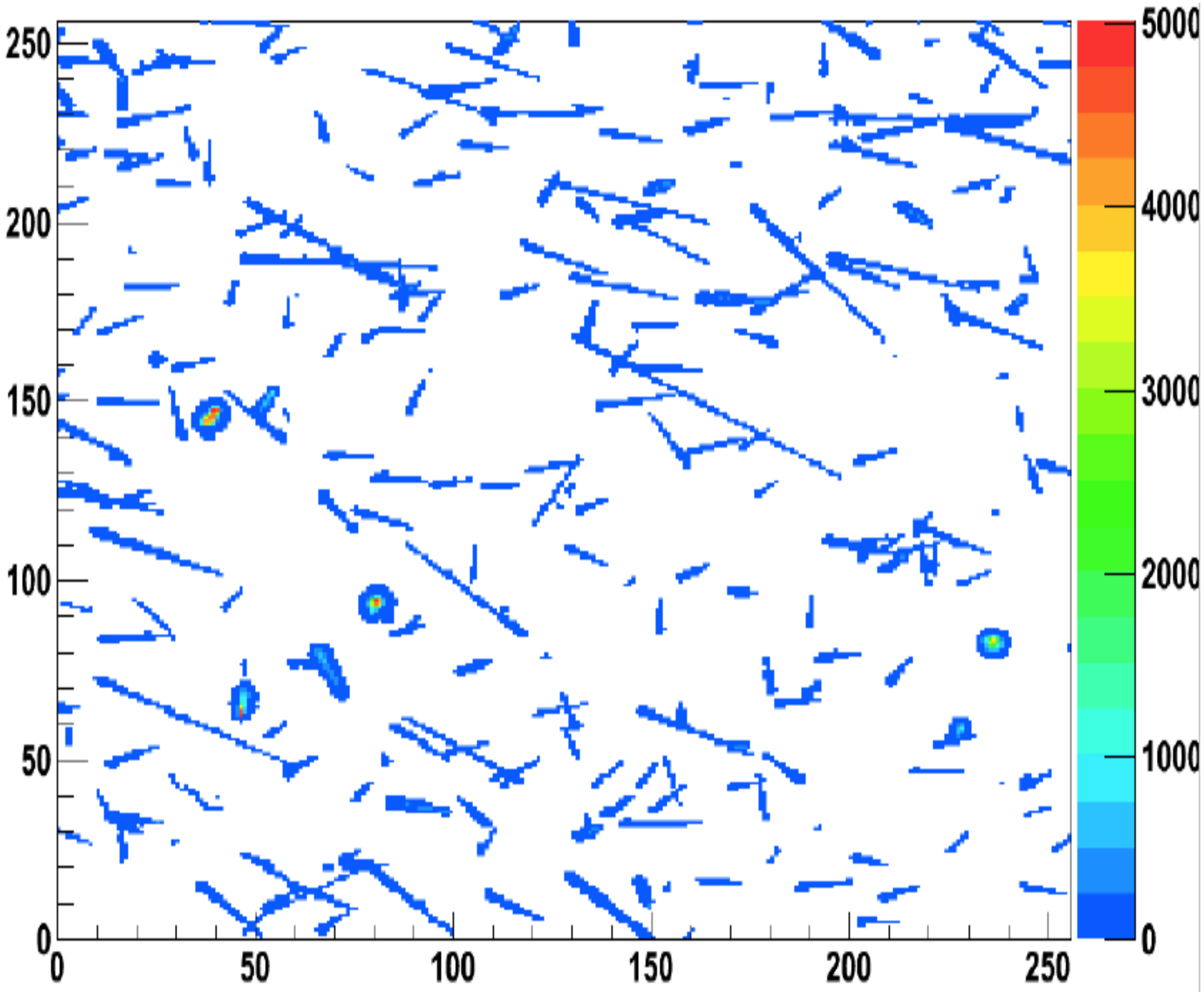




Dosimetry at the Int Space Station ISS

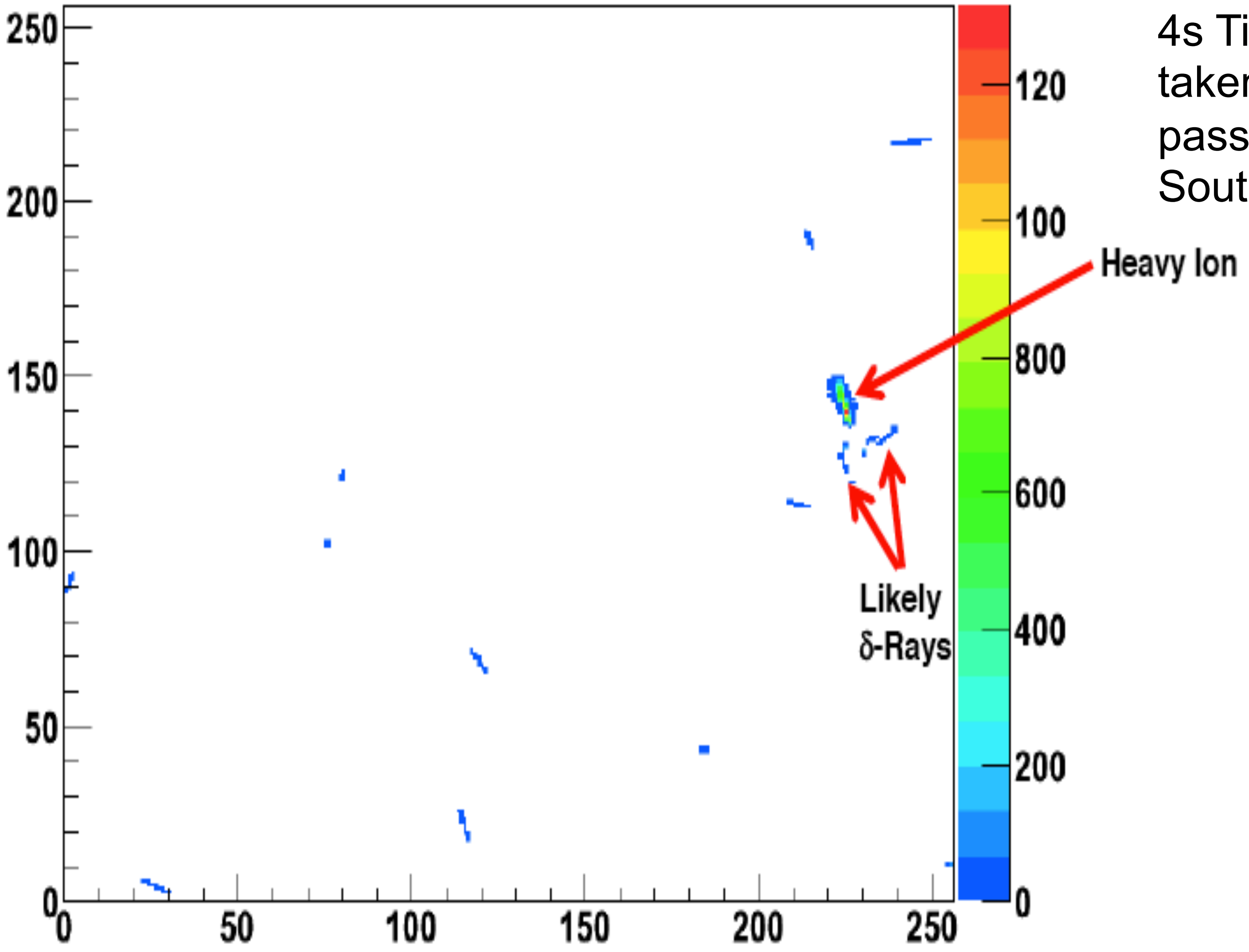


Dosimetry at the Int Space Station ISS



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

Dosimetry at the Int Space Station ISS



4s Timepix exposure taken in ISS passingover South China Sea

SOME CONCLUSIONS

DETECTION → IMAGING TECHNOLOGY

NEED FAST, CONTINUOUS FRAMES

already ~kHz

POTENTIAL for SPECTROSCOPY in IMAGE: MPX3

INTRODUCTION ASICS → NEW DEVICES

MULTIPLE PARTNERS in MEDIPIX2/3

MANY IDEAS PURSUED → MANY RESULTS

JUSTIFIES INVESTMENT in CHIP DESIGN

END