# The Medipix2 project: high-resolution 2-dimensional imaging using a hybrid pixel detector in counting mode

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**Geneva, Switzerland**

**Spokesman, Medipix2 Collaboration**

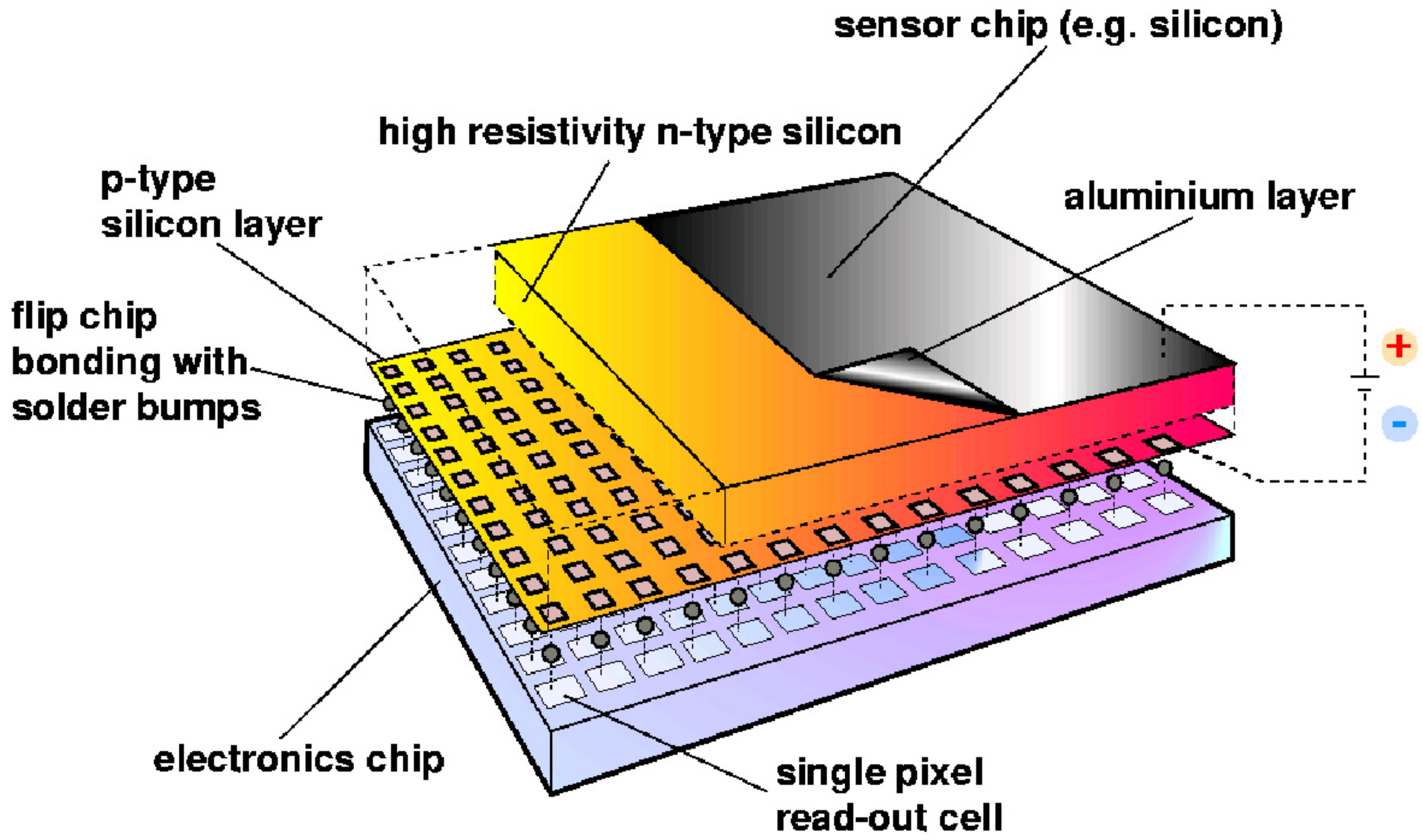
# The Medipix2 Consortium

- **Institut de Fisca d'Altes Energies, Barcelona, Spain**
- **University of Cagliari and INFN Section thereof, Italy**
- **CEA, Paris, France**
- **CERN, Geneva, Switzerland,**
- **Universitat Freiburg, Freiburg, Germany,**
- **University of Glasgow, Scotland**
- **Universita' di Napoli and INFN Section thereof, Italy**
- **NIKHEF, Amsterdam, The Netherlands**
- **University of Pisa and INFN Section thereof, Italy**
- **University of Auvergne, Clermont Ferrand, France,**
- **Laboratory of Molecular Biology, Cambridge England**
- **Mitthogskolan, Sundsvall, Sweden,**
- **Czech Technical University, Prague, Czech Republic**
- **ESRF, Grenoble, France**
- **Academy of Sciences of the Czech Republic, Prague**
- **Universität Erlangen-Nurnberg, Erlangen, Germany**
- **University of California, Berkeley, USA**

# Outline

- **Introduction**
  - Origins of the hybrid pixel detector
  - Requirements for High Energy Physics (HEP)
  - Front-end electronics design considerations
  - From High Energy Physics to imaging
- **Progress in CMOS**
  - Moore's law
  - Implications for present and future designs
- **The Medipix2 System**
  - Chip design and electrical behaviour
  - Characterization of hybrid devices using radioactive sources and monochromatic x-ray beams
- **Applications**
  - X-ray imaging
  - Synchrotron (Pilatus)
  - Particle tracking
  - Neutron imaging
  - Electron microscopy
  - Adaptive optics for ground-based astronomy
- **Conclusions and Future Developments**

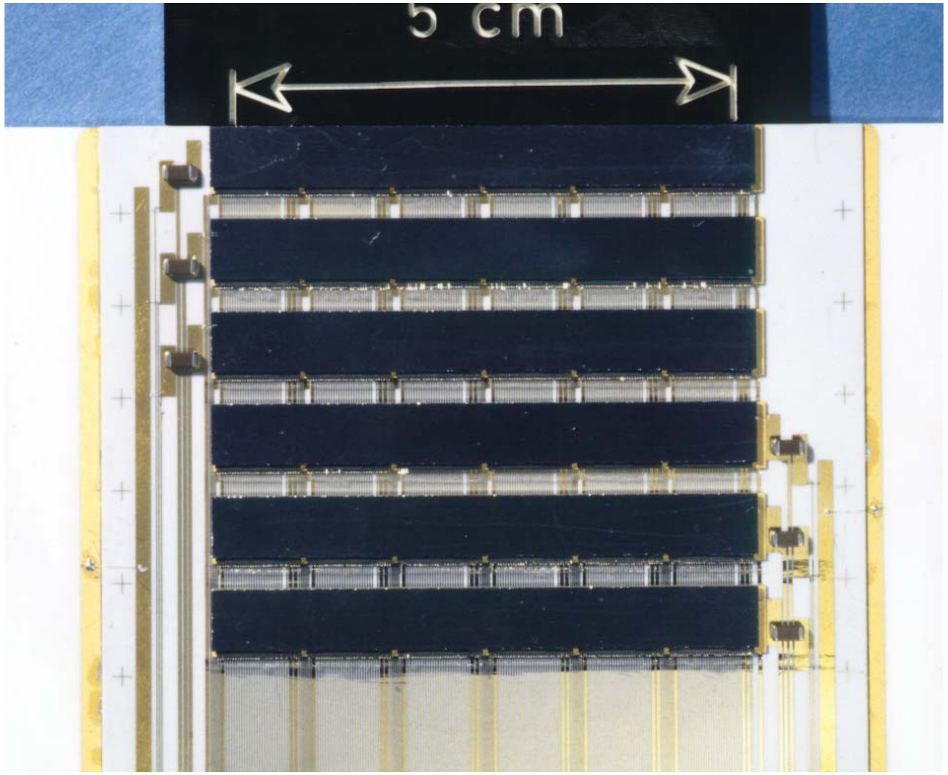
# Hybrid Pixel Detector




**Detector and electronics readout are optimized separately**

# Hybrid Pixel Detector - Cross Section

# The first large area pixel detector array




36 000 pixels

6 ladders of 6 chips

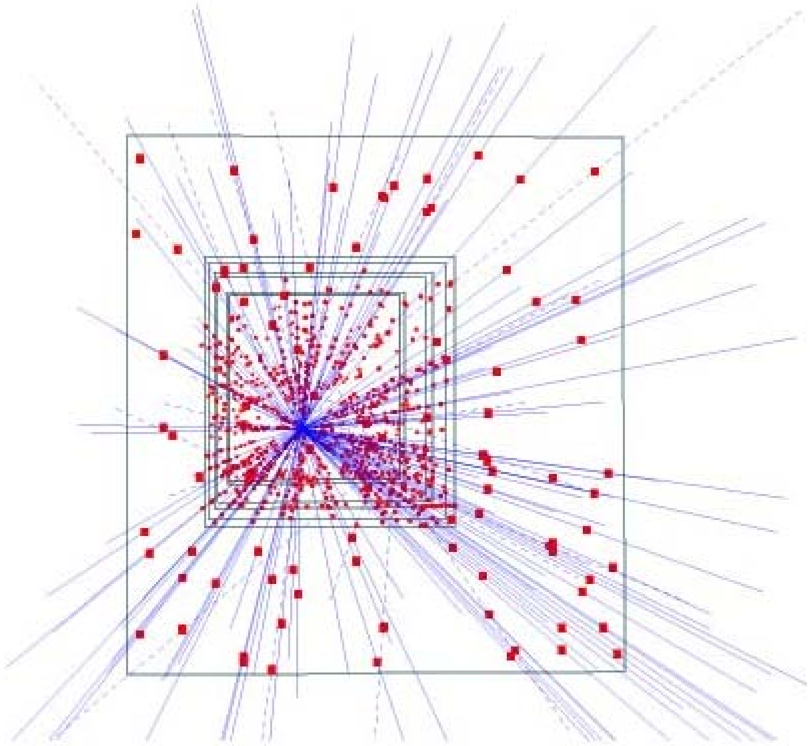
Each chip has 1000 pixels

2 arrays make up one logical plane

[E. Heijne, E. Chesi]

**Work carried out by RD19 for WA97.**
**Basic development funded by CERN-LAA programme.**

# One Heavy Ion Physics Event



**CERN Experiment WA97 (1995)**

**5 x 5 $cm^2$ area**
**7 detector planes**
**~ 0.5 M pixels**
**Pixel dimensions 75 x 500 $\mu m^2$**
**Trigger precision 1 $\mu$sec**
**1 kHz trigger rate**

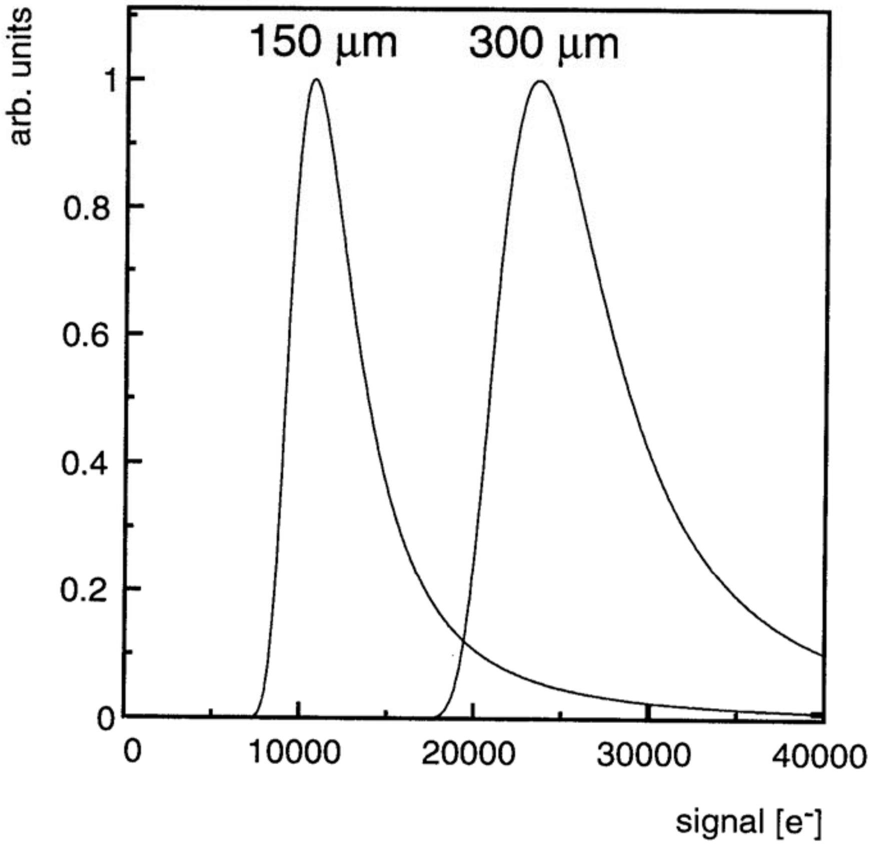
# Implications of HEP requirements on front-end electronics design

- At LHC there will be 40M bunch crossing per second each generating around 1 000 tracks
- Therefore only 'interesting' events are read out and data must be stored until those events are selected
- Clean hit information must be provided to make tracking possible – 'pattern recognition'

- Tracking detectors therefore must tag events to single bunch crossings (high speed), provide clean hit information (low noise), consume little power (because of the cooling which would be required in a confined space) and tolerate high levels of radiation

- Pulse processing electronics must be used and event selection must take place on chip

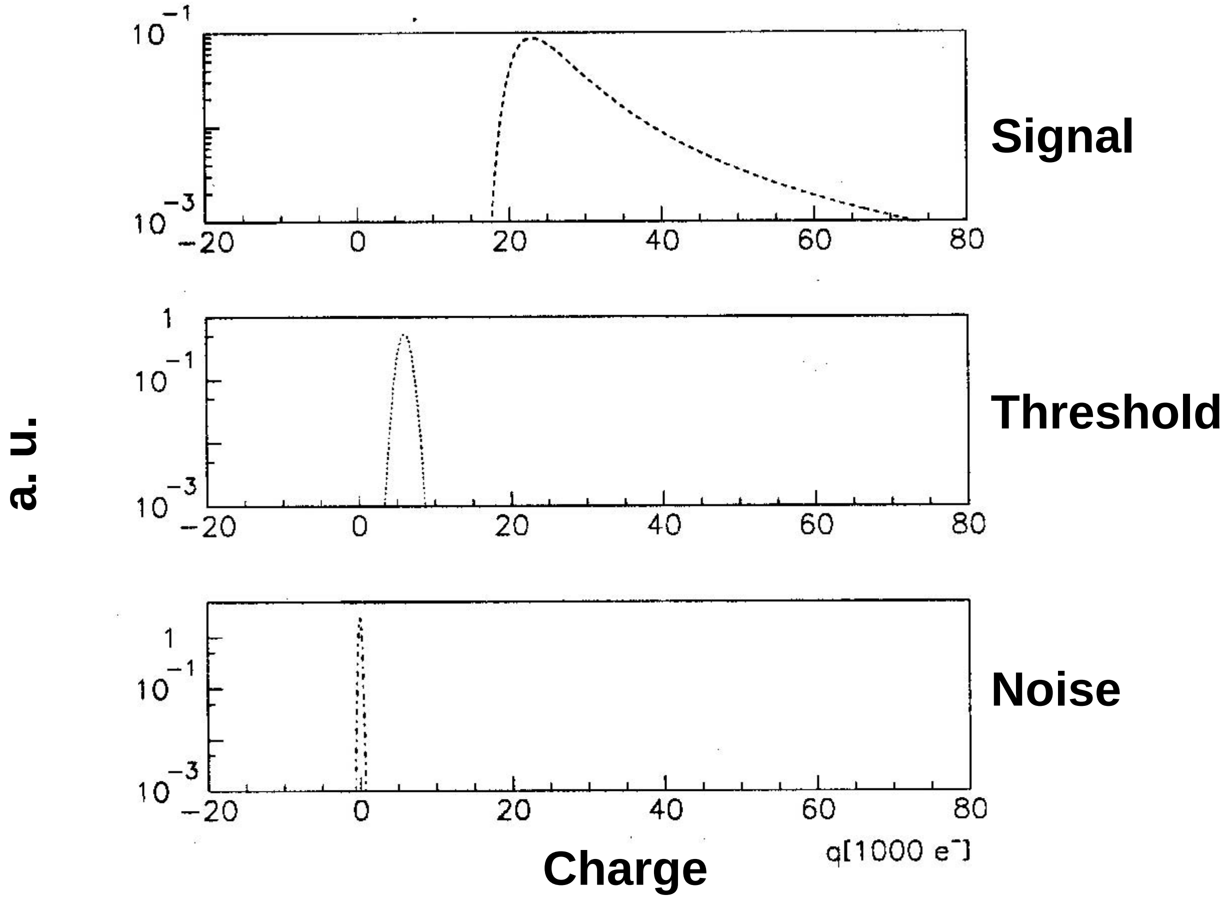
# Minimum Ionizing Charge Deposition in Si




**For 300µm thick detector most probable peak is 24 000 e-, roughly 60 keV**

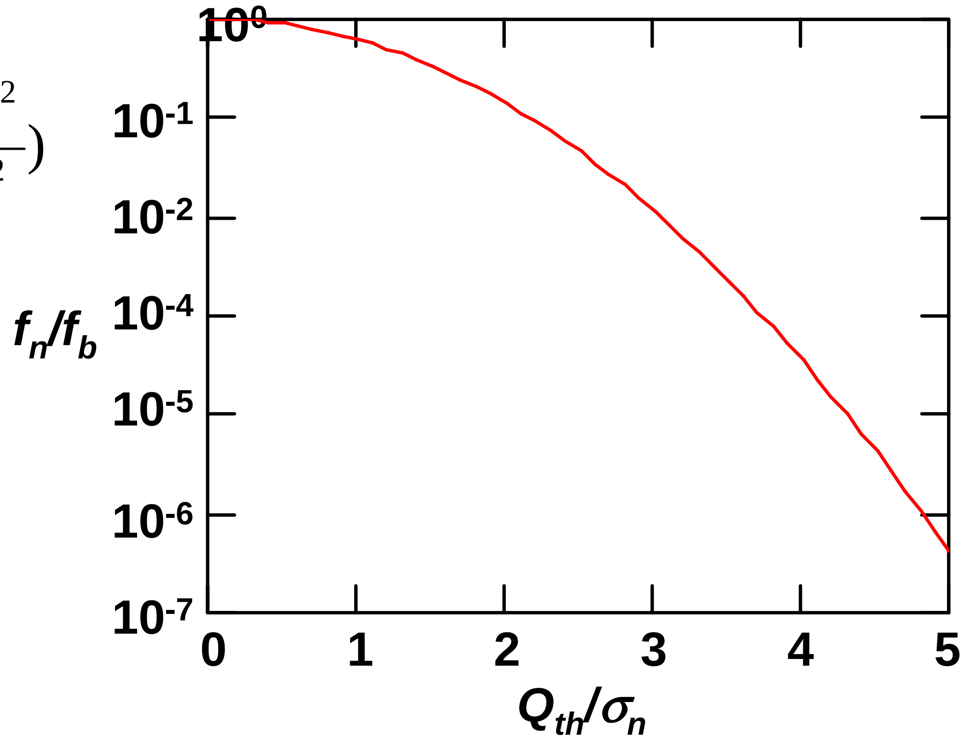
**Because of charge sharing threshold normally set around 1/3rd Landau peak ( 4 - 8ke-)**

# Signal, Threshold, Noise



# Noise hit rate for a discriminator with bandwidth, $f_b$

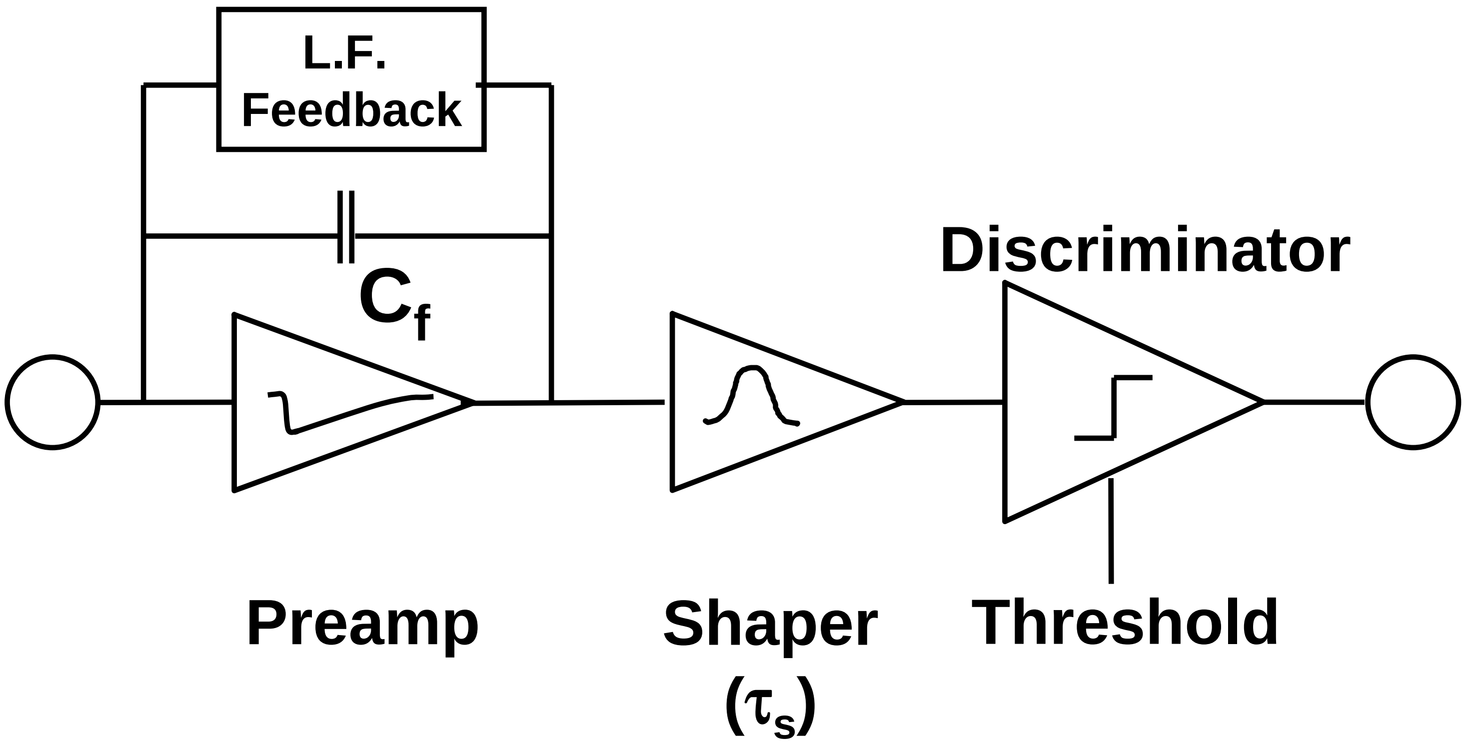
$$f_n = \frac{1}{\sqrt{3}} f_b \exp\left(\frac{-Q_{th}^2}{2\sigma_n^2}\right)$$




**$Q_{th}$ = threshold**
**$\sigma_n$ = noise**

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

# Typical front-end for HEP or single photon counting



# Preamplifier noise and rise time

**Series Noise:**

$$ENC_d^{\,2} \propto \frac{C_t^{\,2}}{g_m \tau_s}$$

**Parallel noise:**

$$ENC_o^{\,2} \propto I_o \tau_s$$

**Preamp rise time:**

$$t_r \propto \frac{C_t}{g_m} \frac{(C_L + C_f)}{C_f}$$

**In general $C_t$ should be minimized and $g_m$ maximized, but more $g_m$ means more power consumption.**

## Discrimination Threshold mismatch depends on transistor threshold mismatch..

$$\sigma^2(V_{th}) \propto \frac{A^2}{WL}$$

**Transistor matching**

**good matching requires large area transistors**
**but A is proportional to gate oxide thickness**

**Therefore matching improves with technology shrinkage**

# From HEP to x-ray imaging

- Pulse processing circuitry eliminates the effect of dark current noise from an image
- But readout should be changed from HEP (event stored until trigger arrival) to single photon counting (using a shutter)
- HEP pixels are small, but the wrong shape - usually rectangular for momentum measurements in magnetic fields
- All HEP applications use high $\rho$ silicon because of uniformity and price. For x-ray imaging front-end circuits should allow both electron and hole collection to permit the use of exotic detector materials with high hole trapping

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  - **Requirements for High Energy Physics (HEP)**
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  - **From High Energy Physics to imaging**
- **Progress in CMOS**
  - **Moore's law**
  - **Implications for present and future designs**
- **The Medipix2 System**
  - **Chip design and electrical behaviour**
  - **Characterization of hybrid devices using radioactive sources and monochromatic x-ray beams**
- **Applications**
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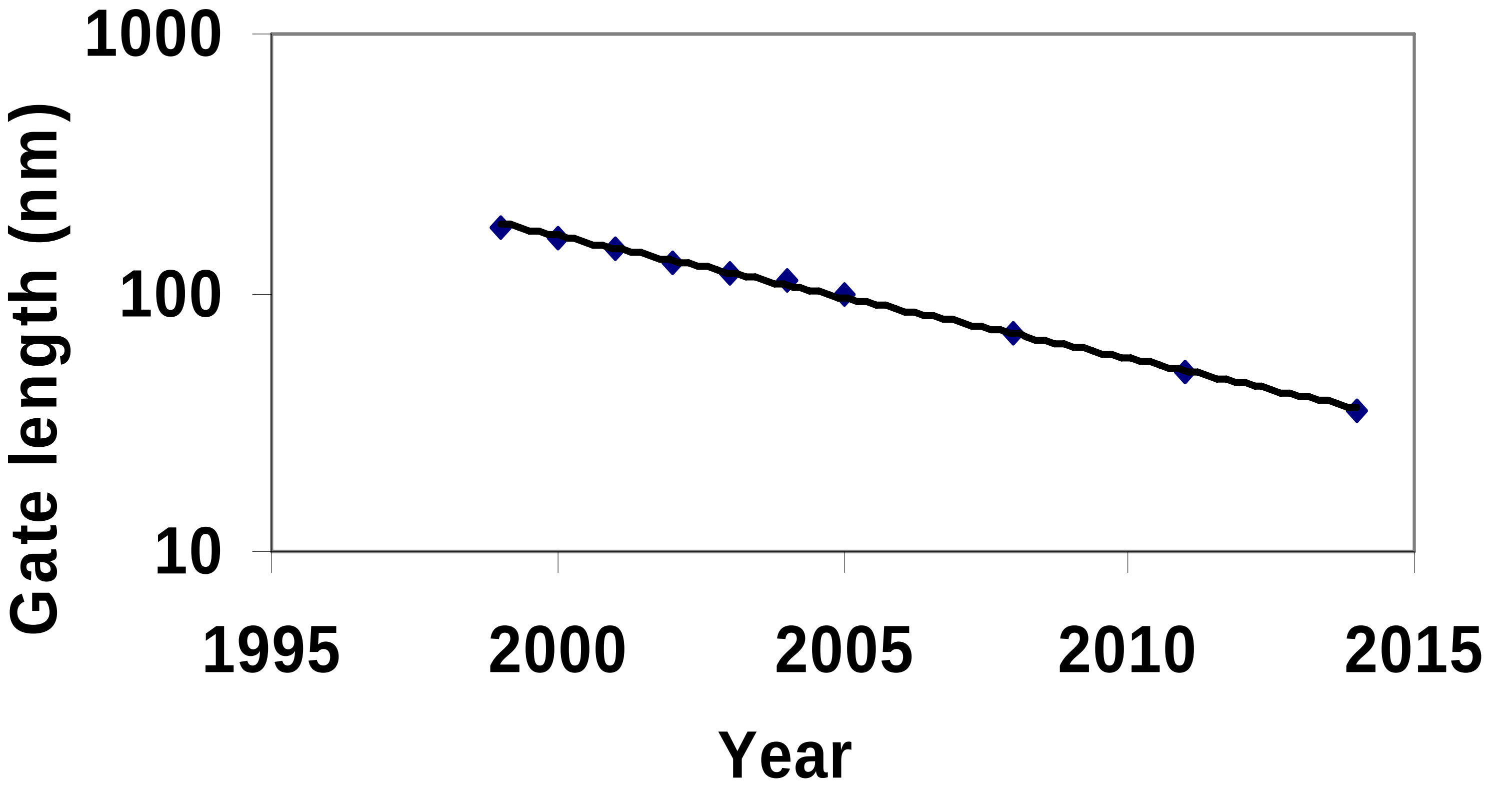
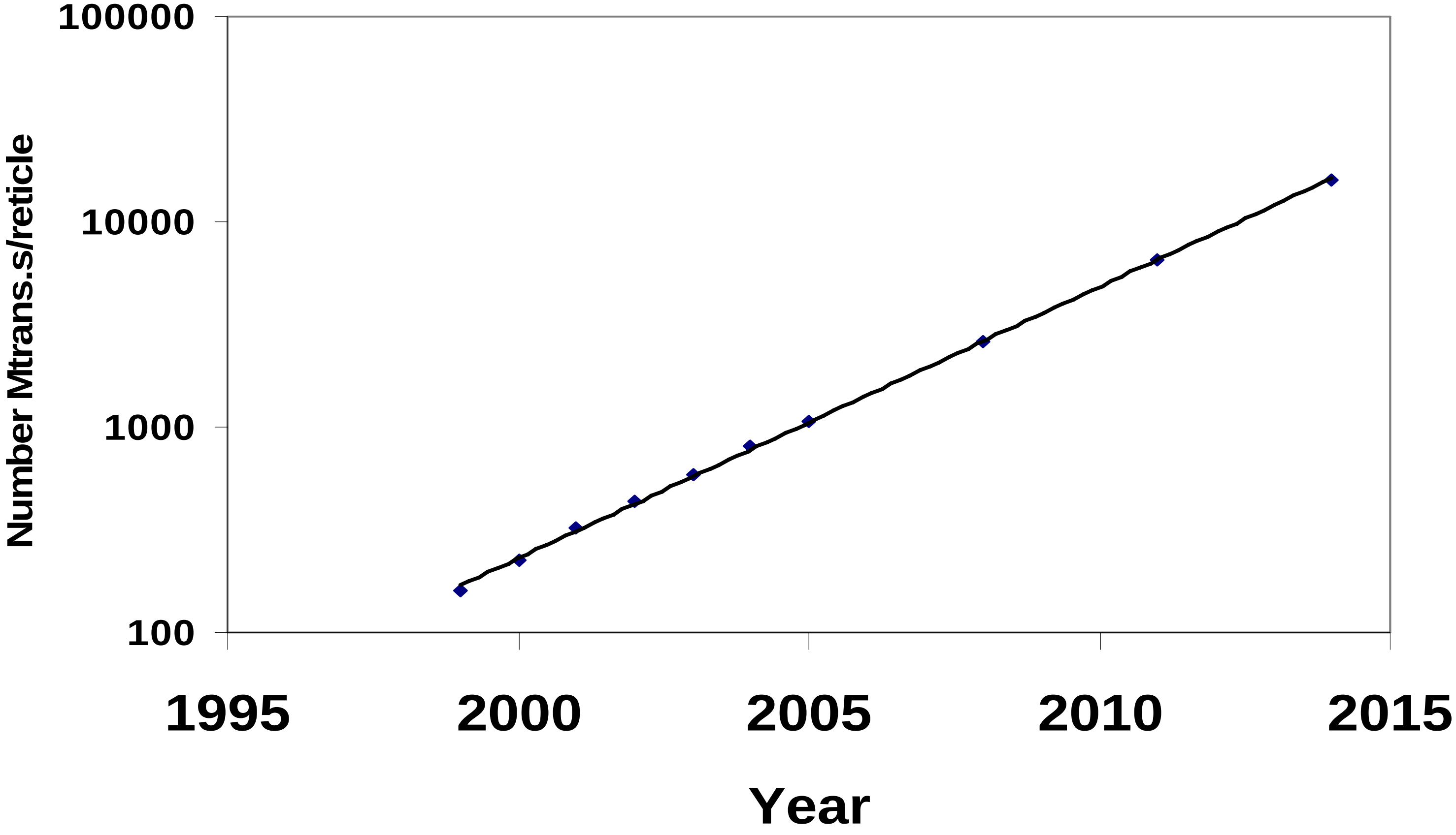
# Moore's law - transistor feature size




**SIA Roadmap 1999**

# Moore's Law - components per chip




**SIA Roadmap 1999**

## Implications of progress in CMOS processing for single photon counting

- More and more functionality can be packed into a pixel
- Transistor matching for a fixed area and therefore pixel-to-pixel matching improves
- The cost/unit area of Si is more-or-less constant
- However, prototyping costs are increasing
- Power management becomes an issue

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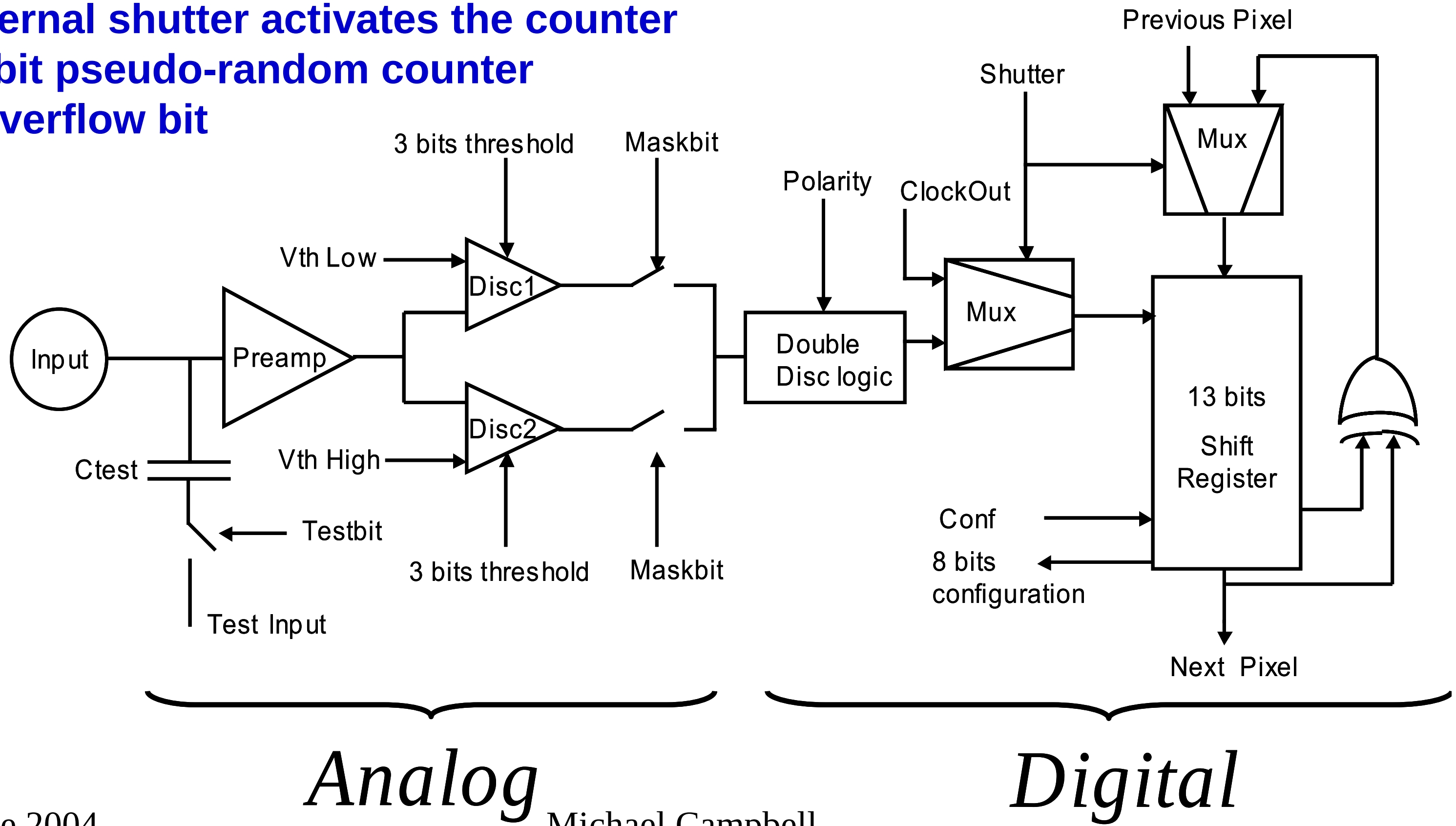
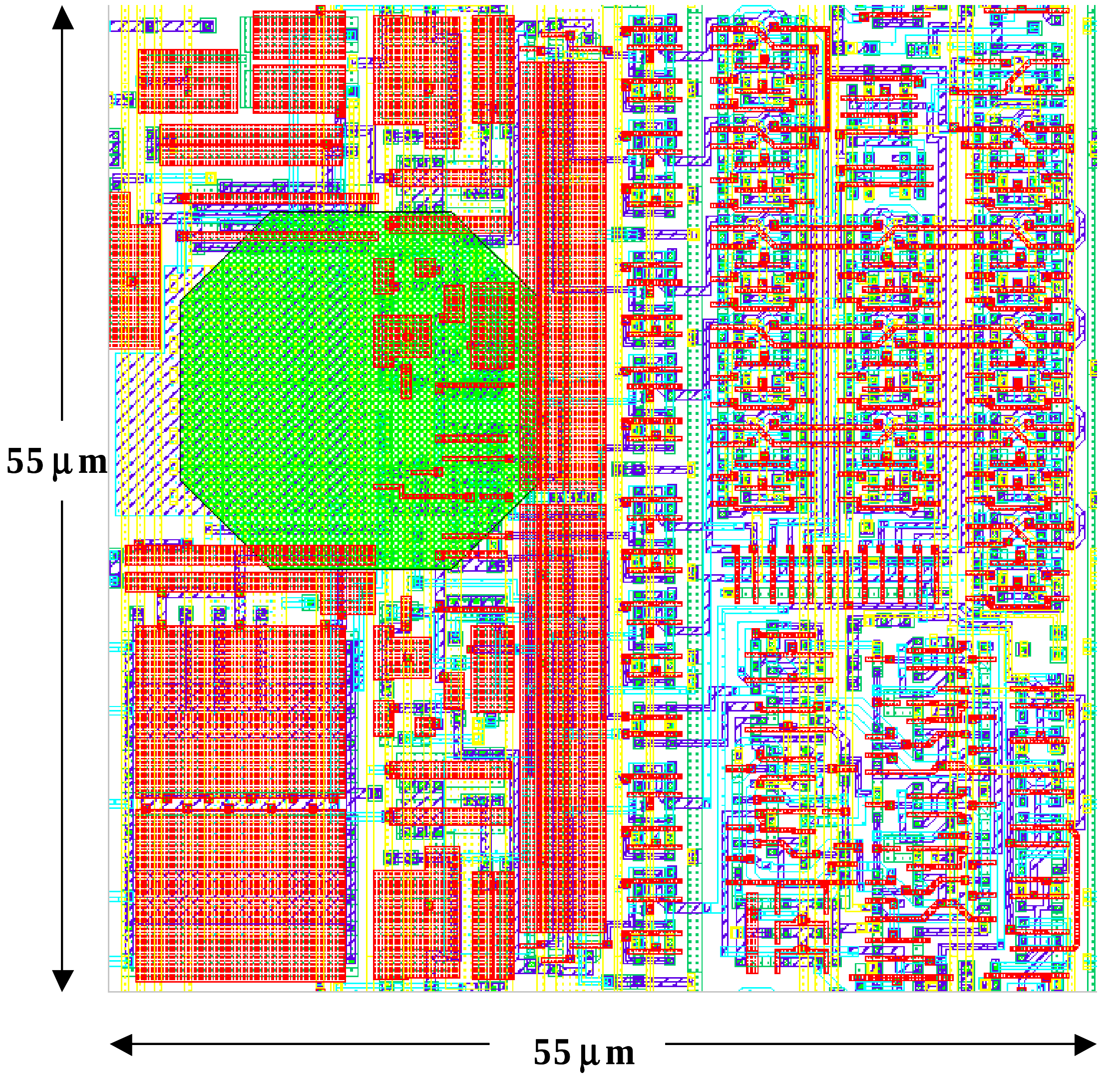
# Medipix2 Cell Schematic

- 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 and1 mask bit
- External shutter activates the counter
- 13-bit pseudo-random counter
- 1 Overflow bit

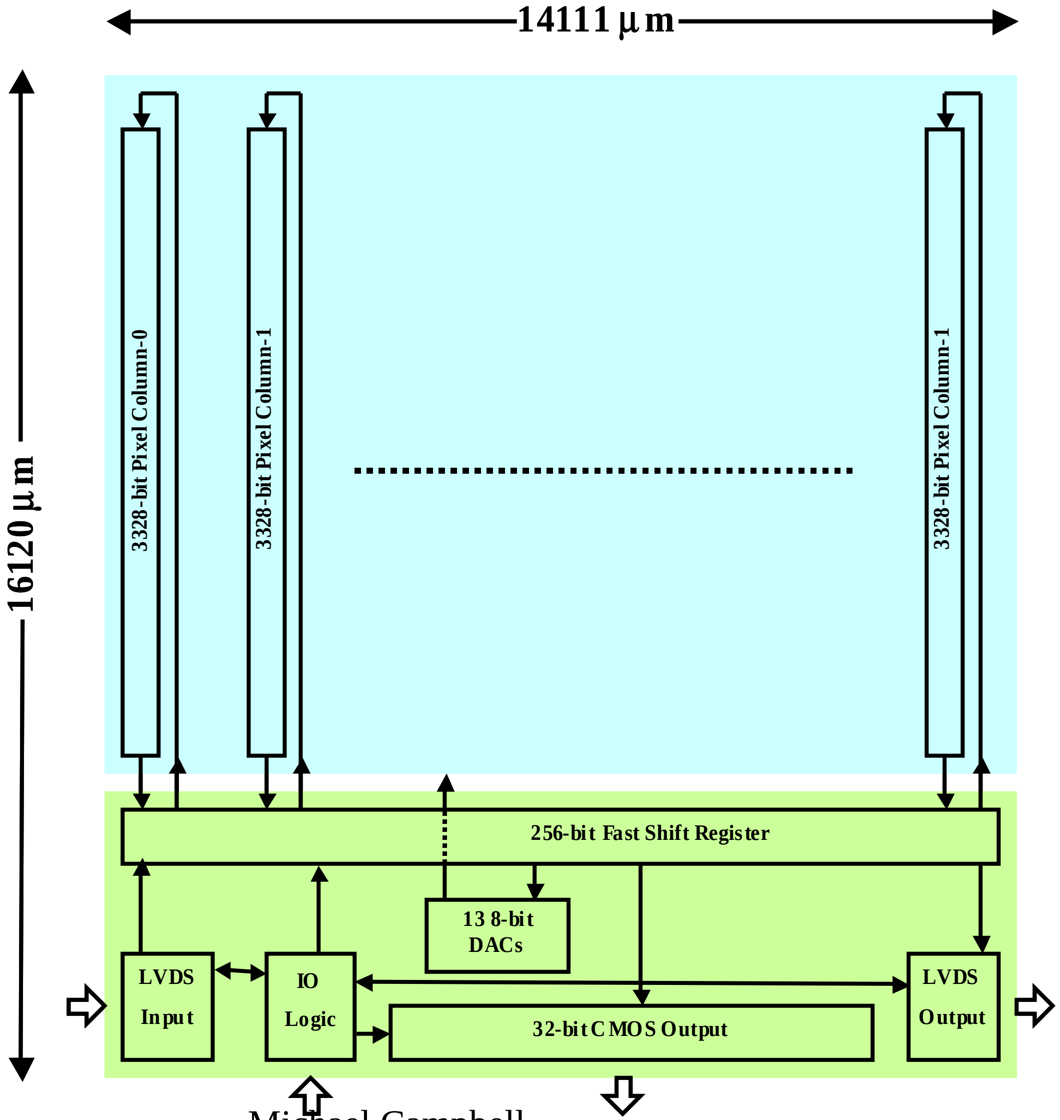


# Medipix2 Cell Layout

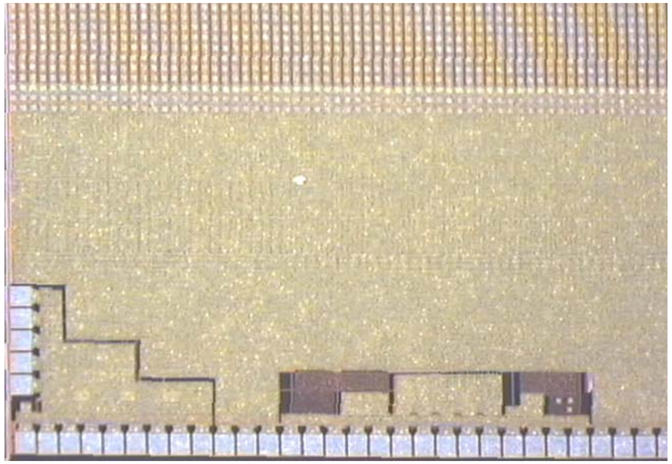


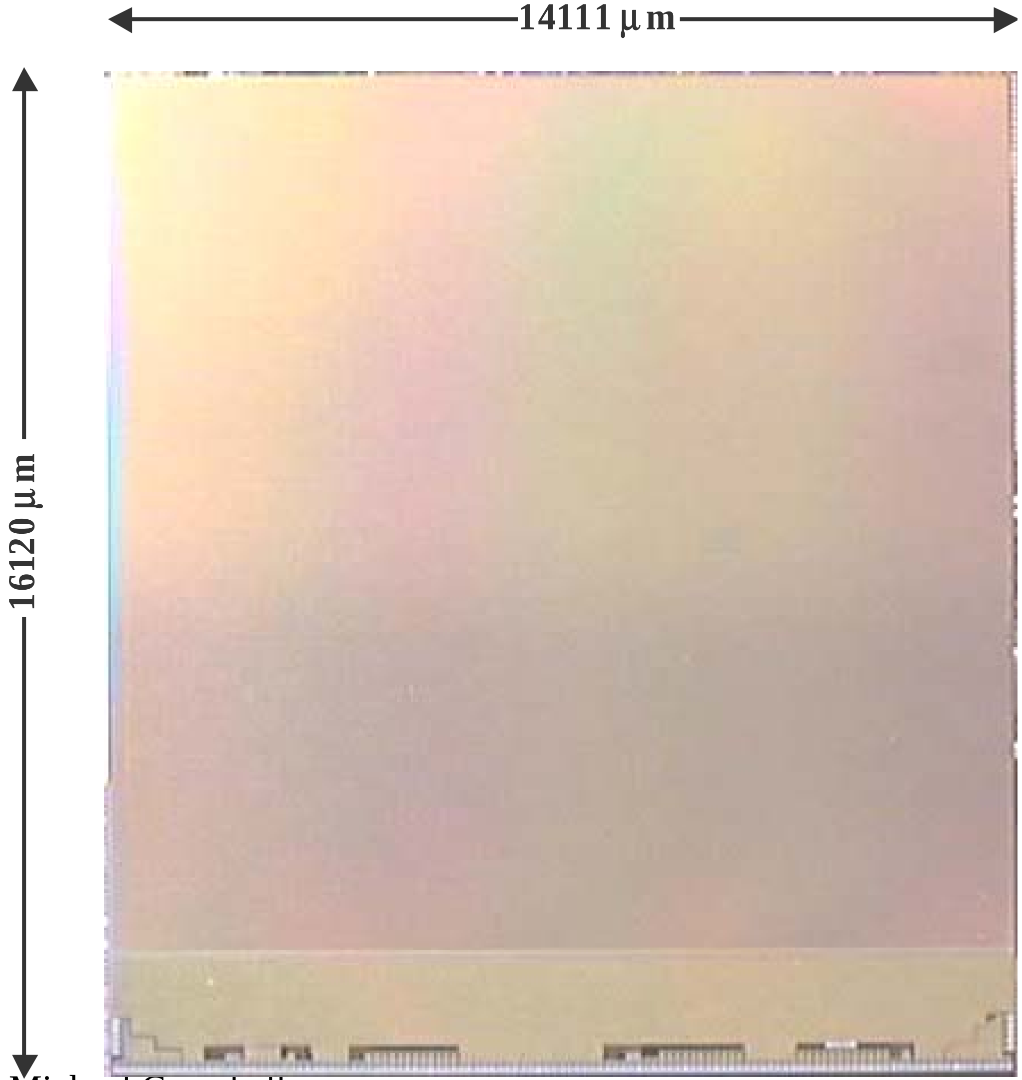
# Medipix2 Chip Architecture

**256 x 256 pixels**
**3ms readout time**



# Medipix2 Chip Architecture (II)



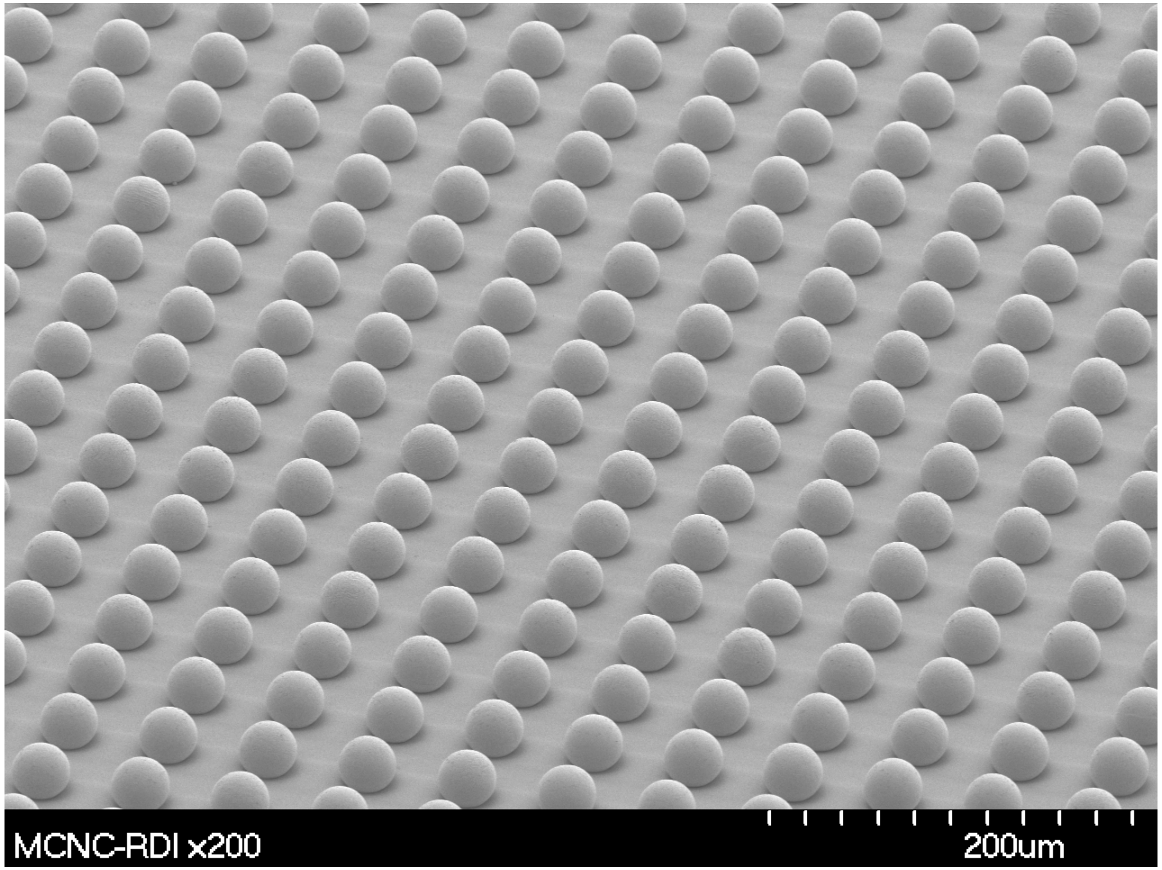


# Electrical measurements

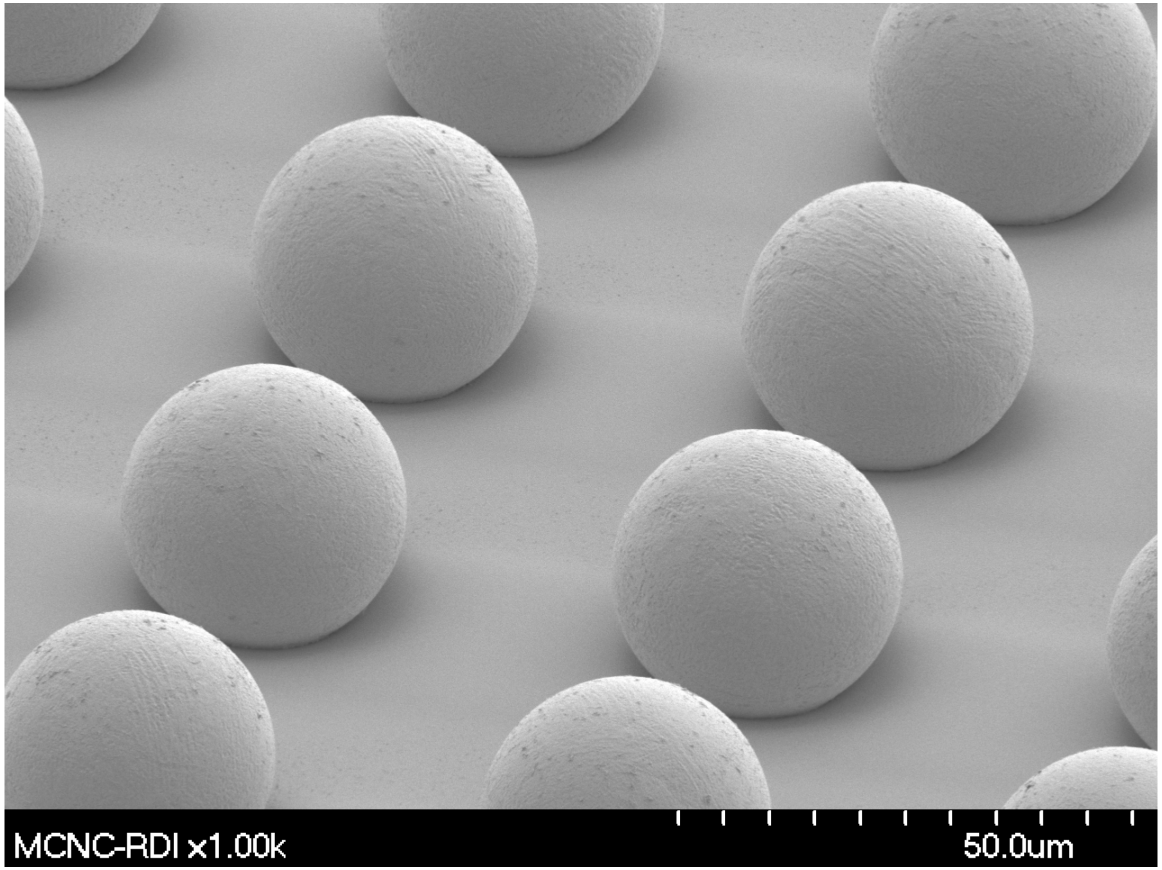
| | Electron Collection | Hole Collection |
|---|---|---|
| Gain | *12.5 mV/ke* | *13.25 mV/ke* |
| Non linearity | *<3% to 100ke$^-$* | *<3% to 80ke$^-$* |
| Peaking time | *<150ns* | |
| Return to baseline | *<1μs for Qin <50 ke$^-$* | |
| Electronic Noise | *σnL~ 110 e- σnH~ 110 e-* | |
| Threshold dispersion | *σnTHL~ 360 e- (~ 90 e- tuned)* | |
| Analog power dissipation | *~8 μW/channel for 2.2V supply* | |

# Medipix2 bump bonded to a 300 μm Si sensor

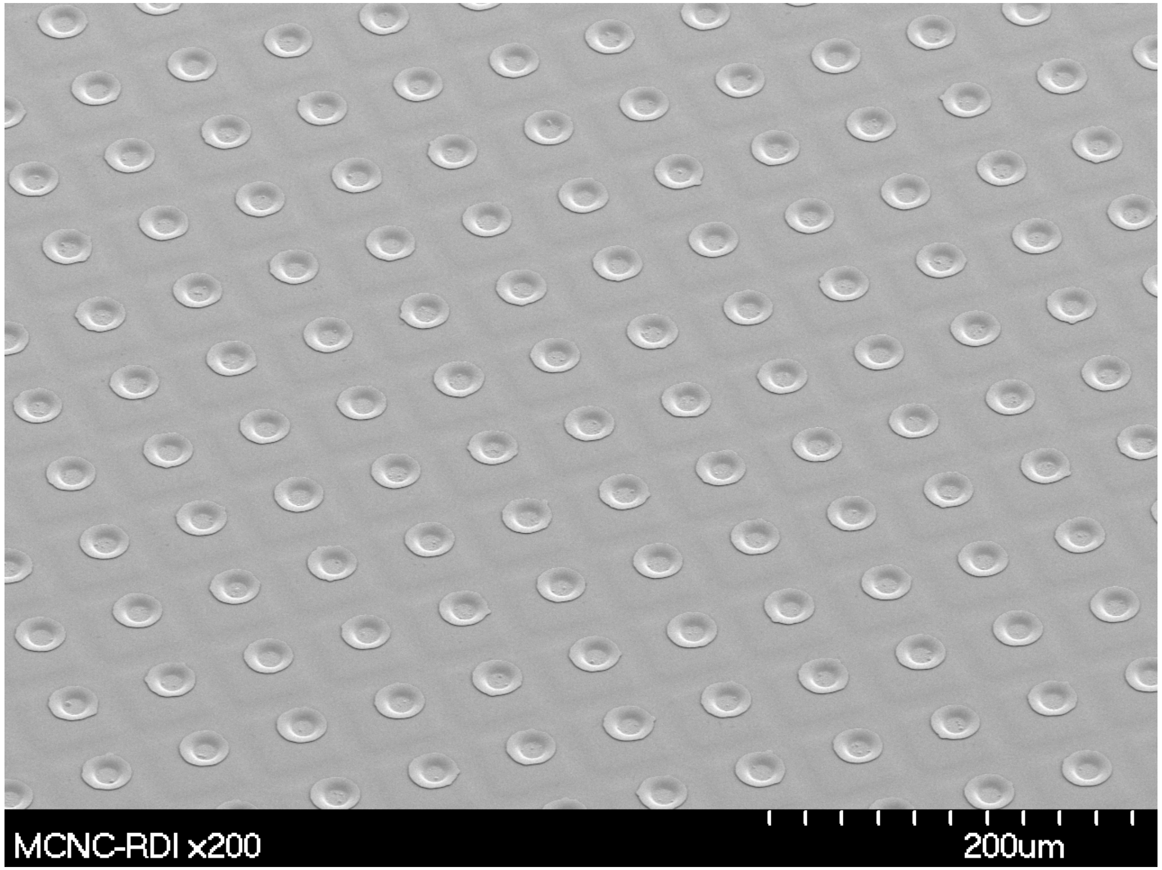
# Bumps of readout side



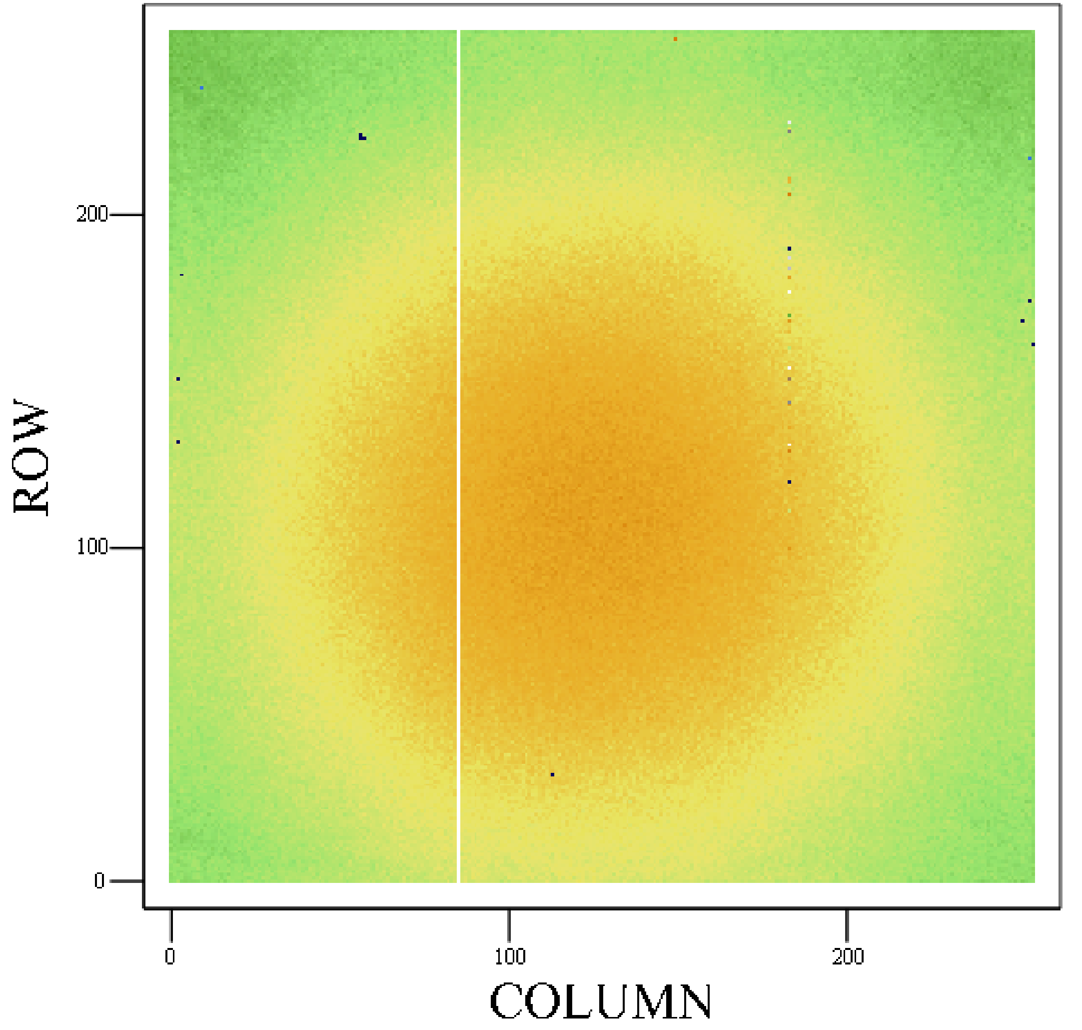
# Bumps of readout side – close up



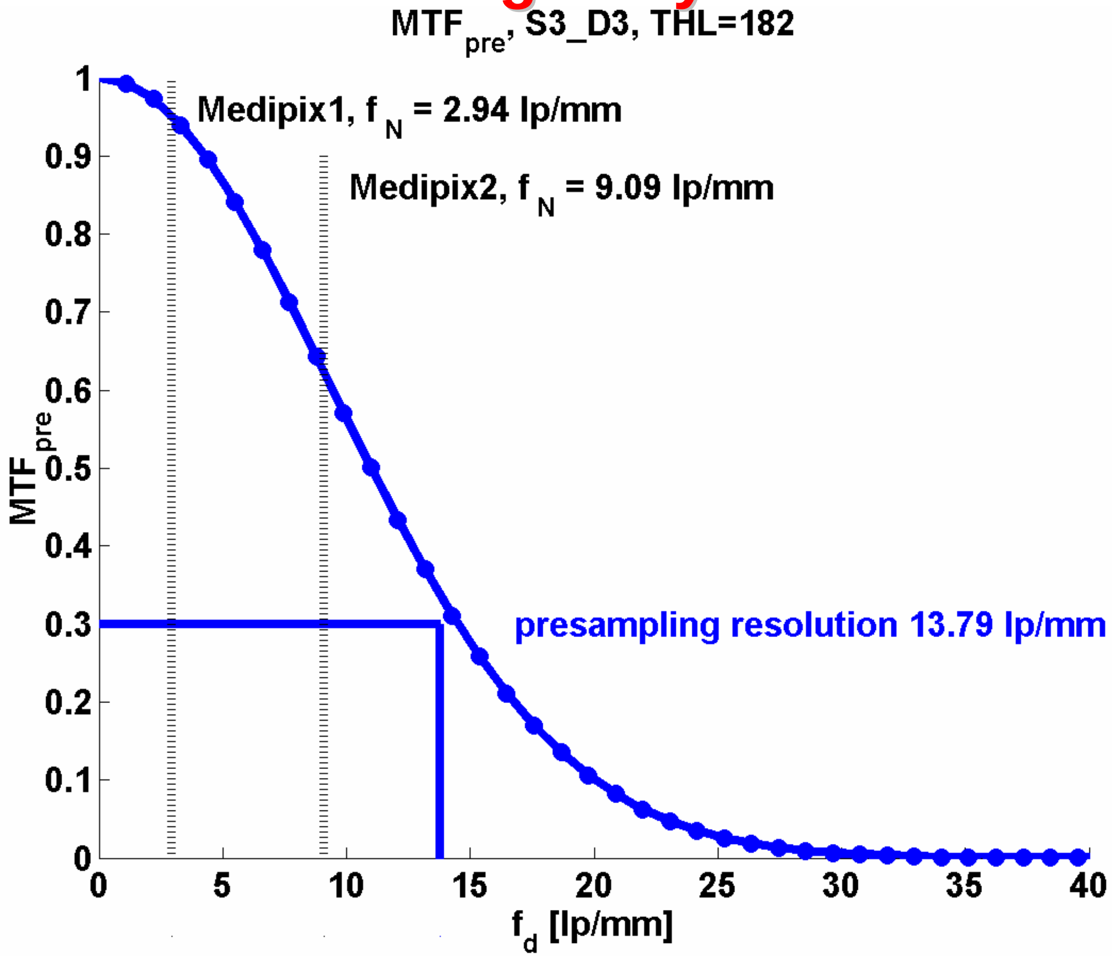
# Under bump metallization on sensor side



# Response to $^{109}$Cd source

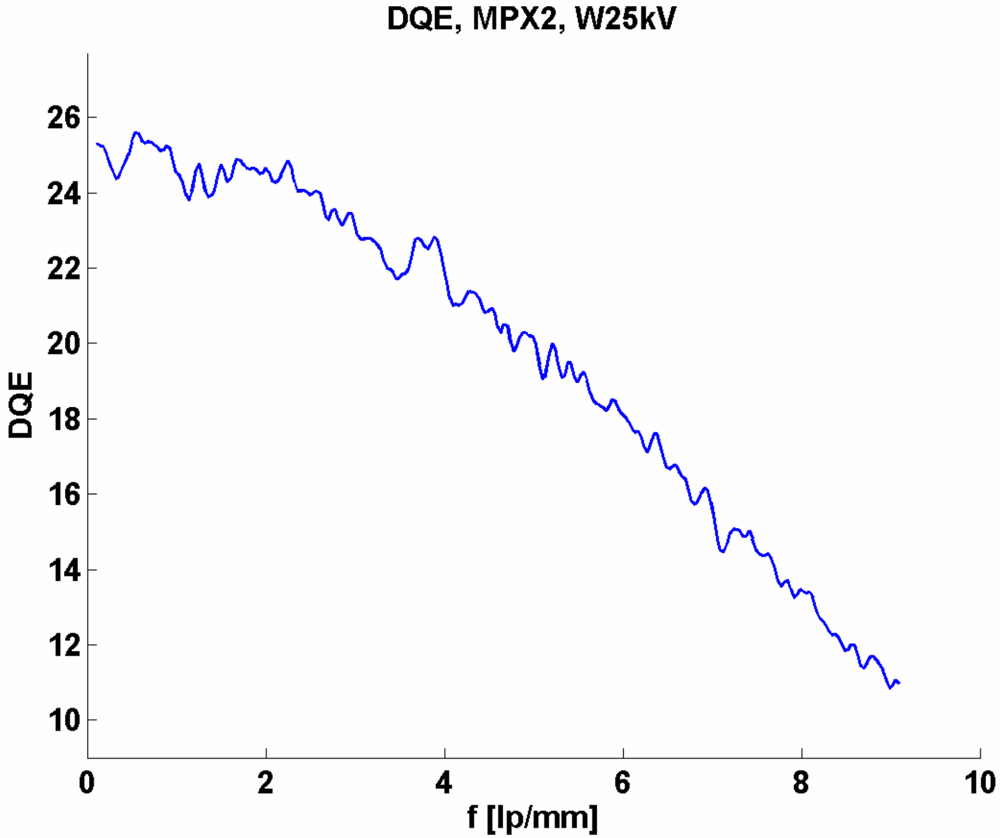


# MTF of Medipix2 and 300 μm thick Si detector using x-ray machine



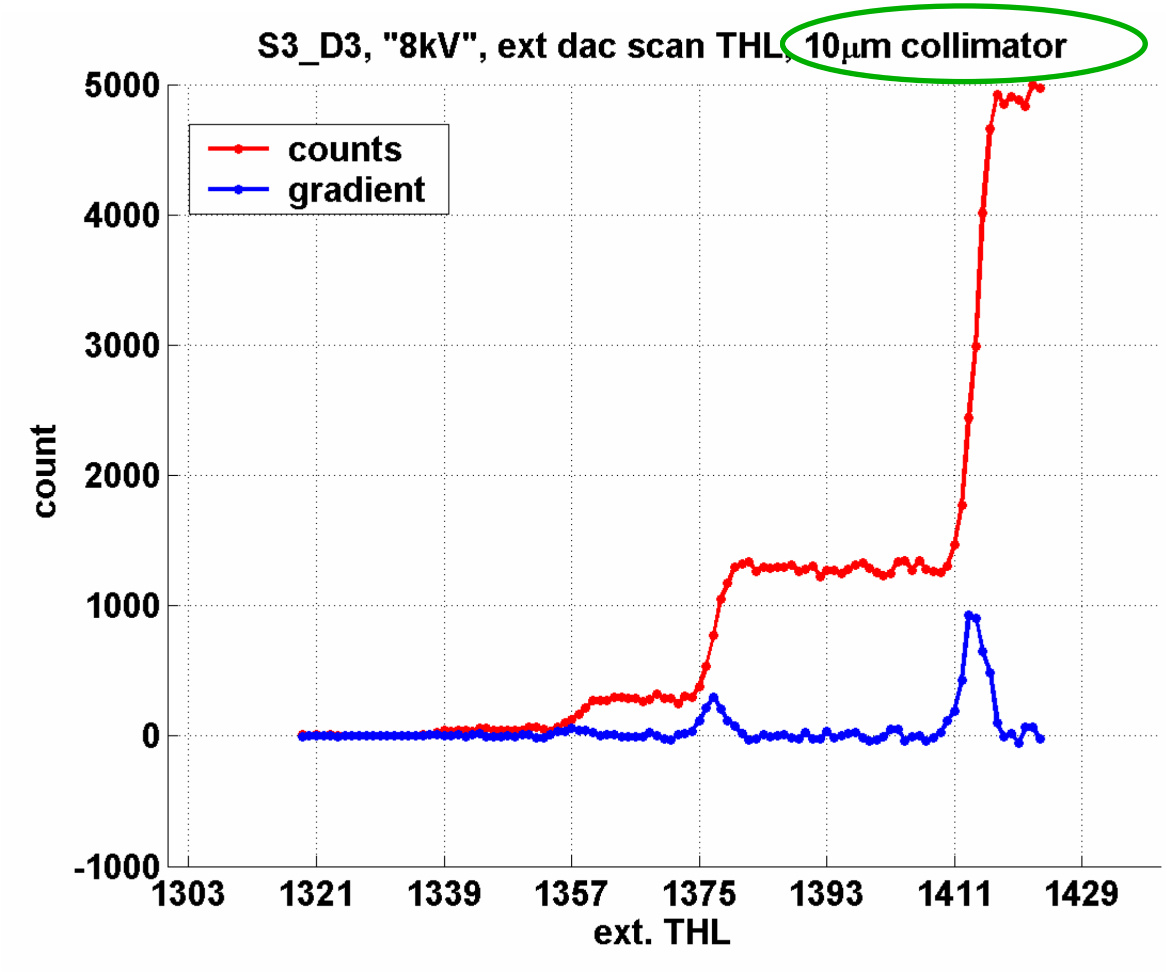

**Measurement taken using a Seifert FK61-04x12 X-ray source, W target, 25kV, and a filter equivalent to 2.5 mm of Al.**

# DQE of Medipix2 and 300 μm thick Si detector using x-ray machine




**Measurement taken using a Seifert FK61-04x12 X-ray source, W target, 25kV, and a filter equivalent to 2.5 mm of Al. Agrees with theoretical calculation.**

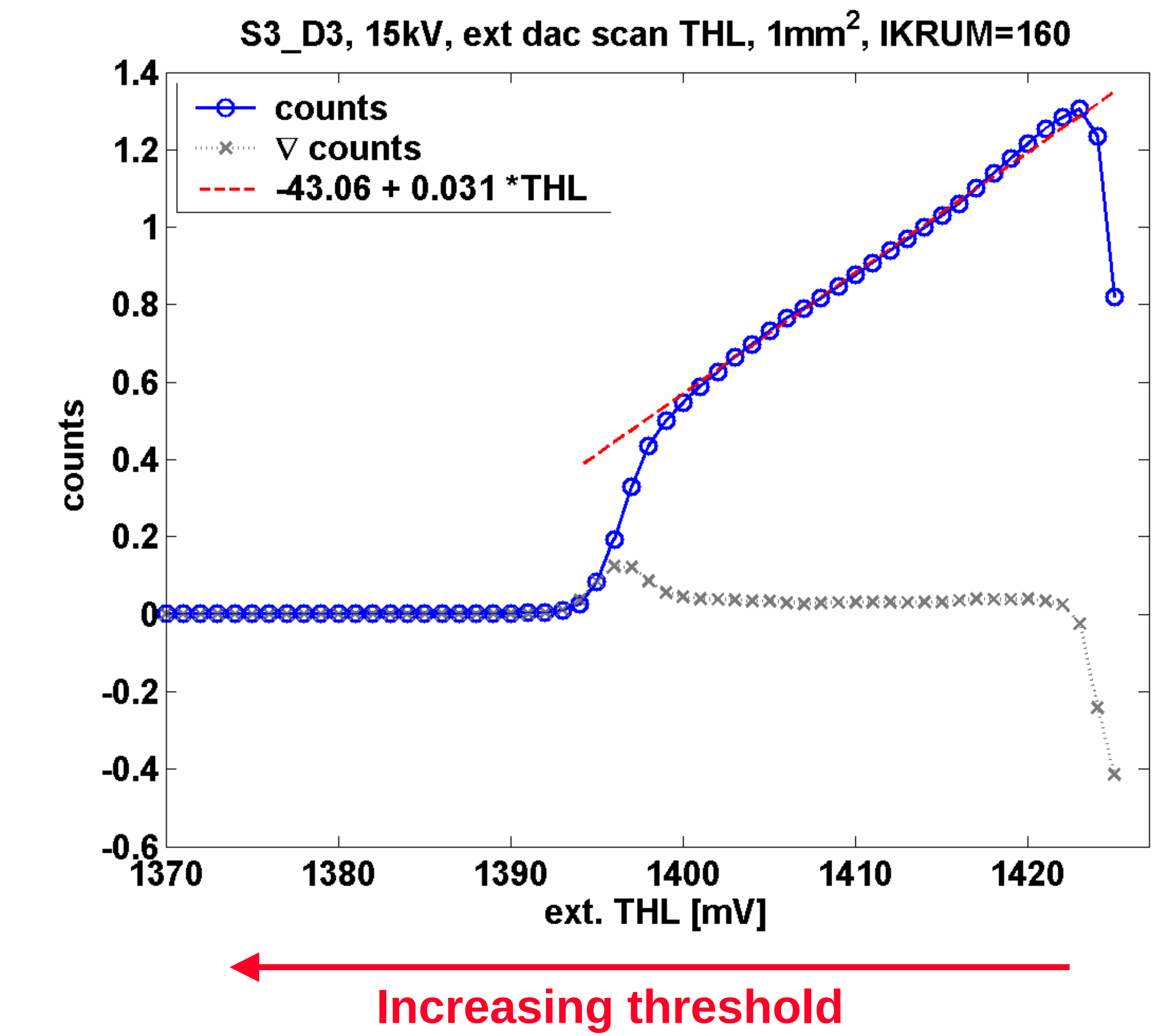
# Calibration at ESRF – monochromatic pencil beam at pixel centre




Increasing threshold

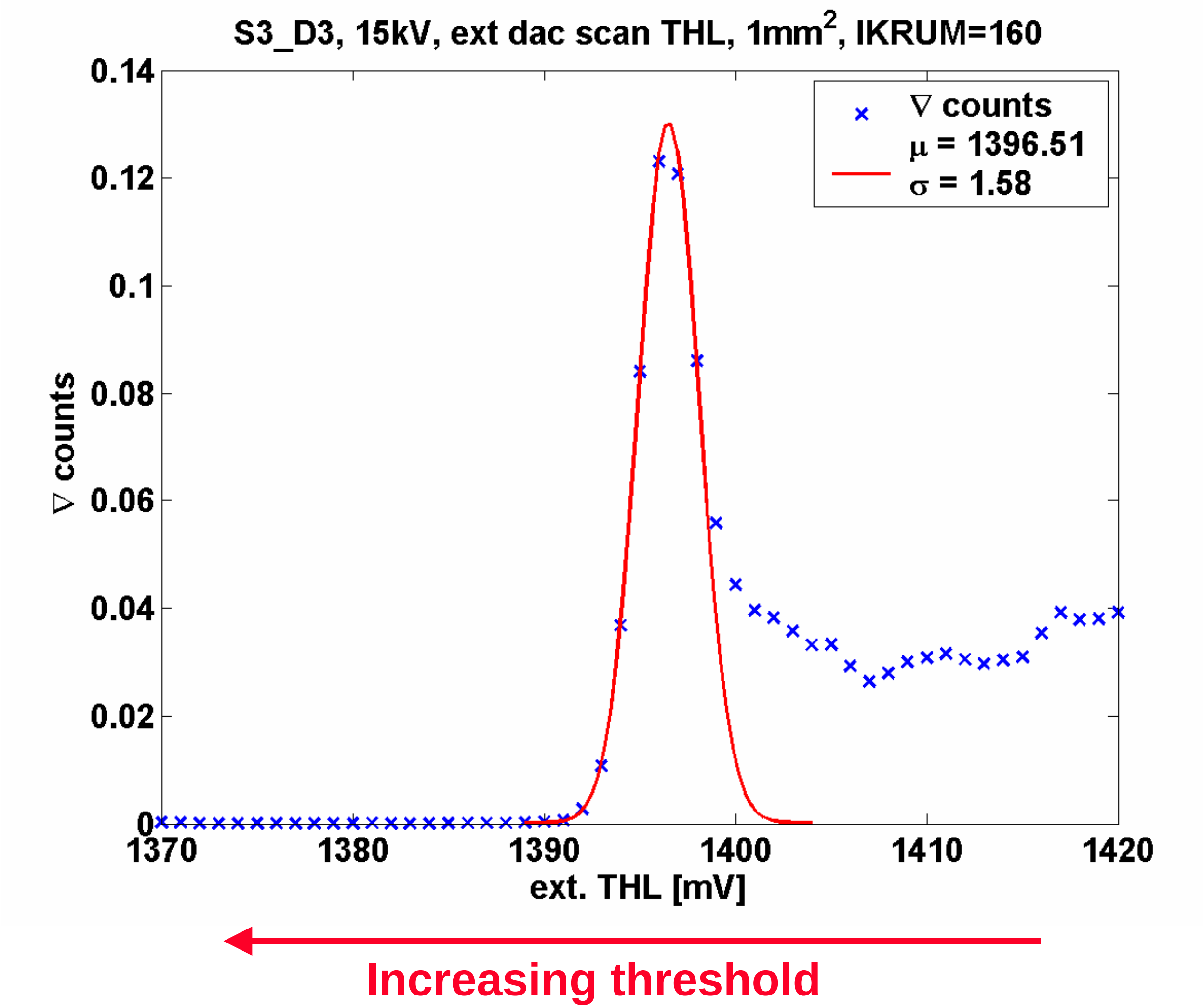
**8kev plus harmonics….**

# Effect of Charge Sharing on Energy Resolution – monochromatic 1mm² beam




22 June 2004 Michael Campbell

# Effect of Charge Sharing on Energy Resolution – monochromatic 1mm² beam



# The implications of charge sharing between pixels

- **Pixel-to-pixel threshold variation together with charge sharing implies that flat field correction is necessary when image statistics approach or exceed threshold variation induced count spread**
- **Flat field correction becomes sensitive to incoming spectrum**
- **But solutions are possible (see further work)**

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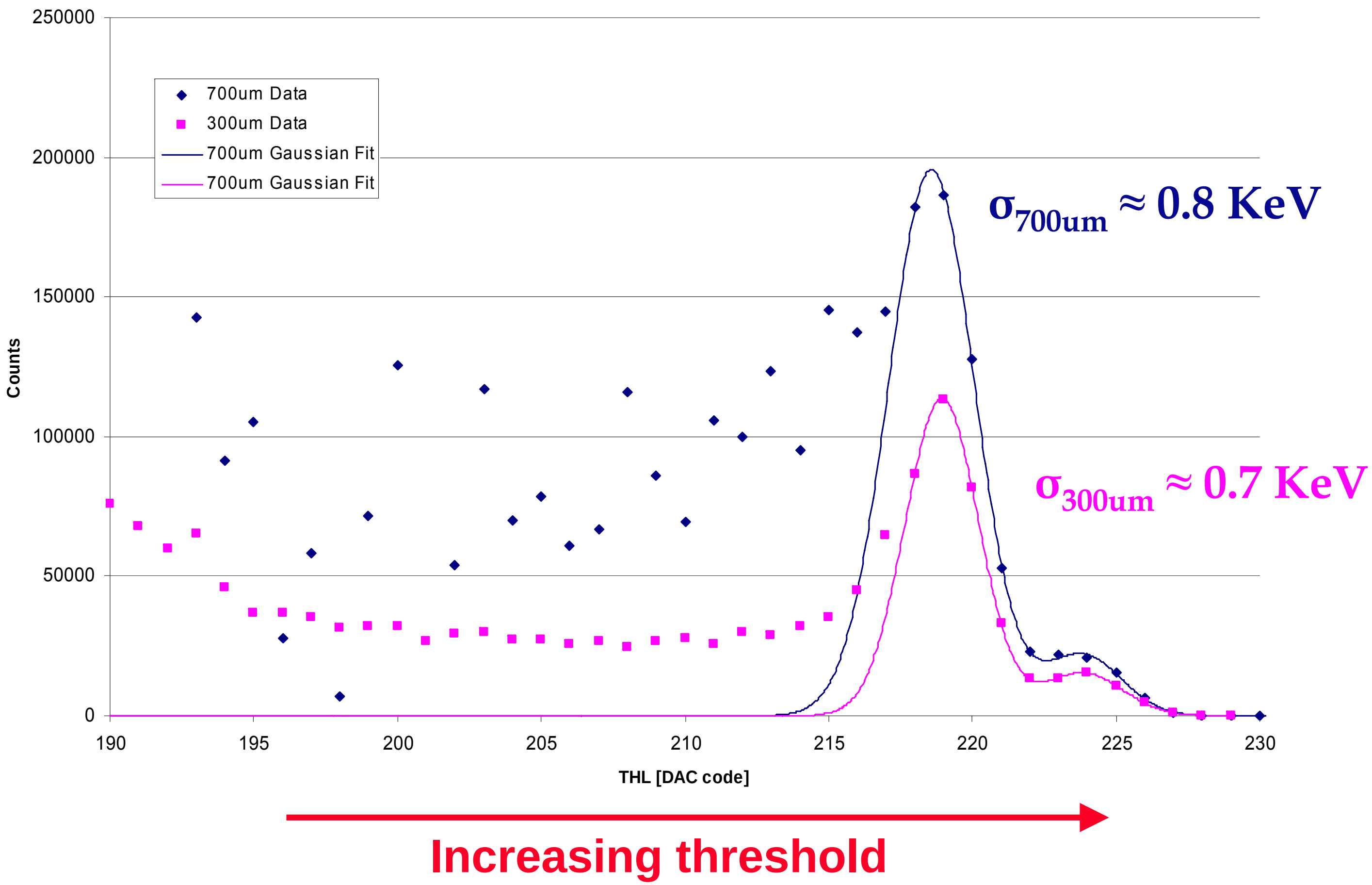
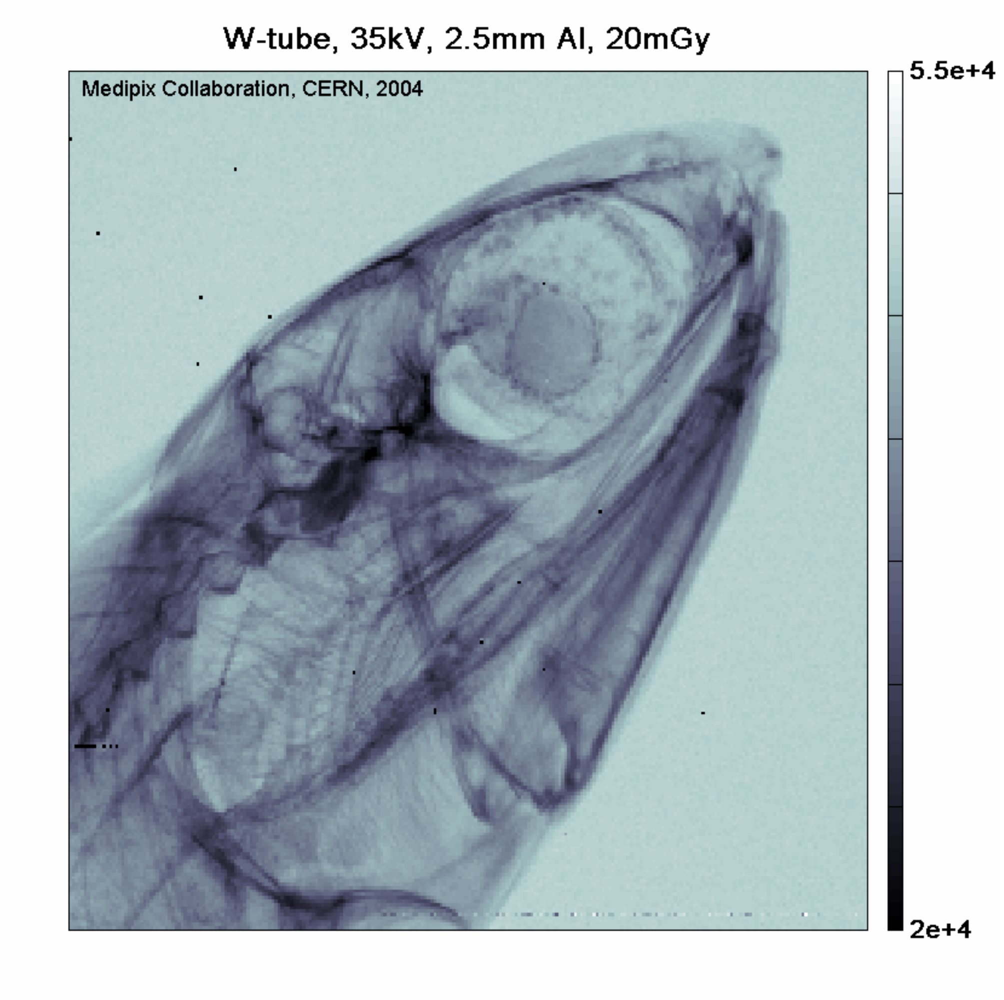
# Spectrum of $^{109}$Cd Source

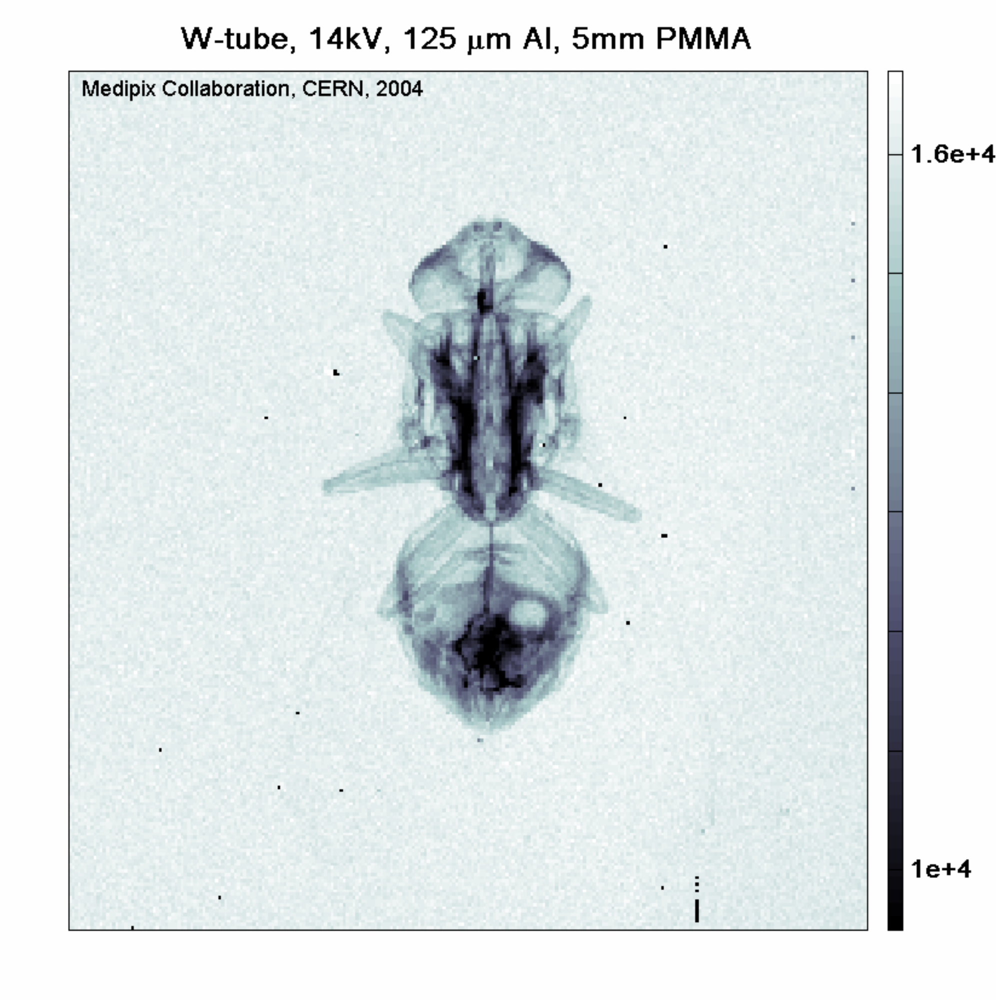



**Spectra obtained summing the response of all pixels using 300μm and 700μm thick Si sensors.**

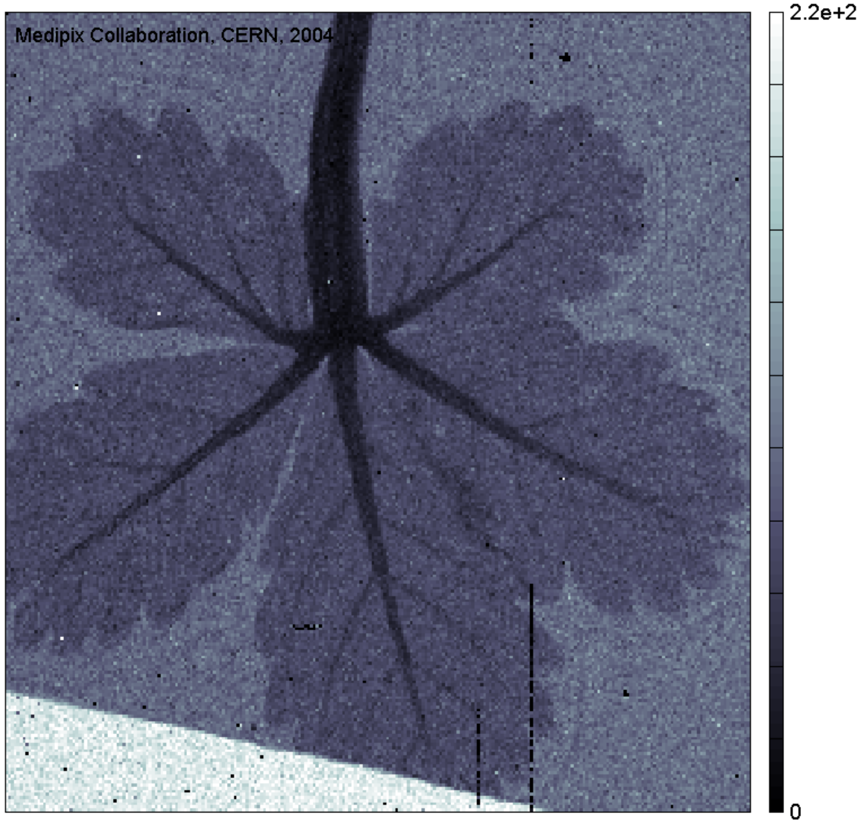
# Image of a dried anchovy



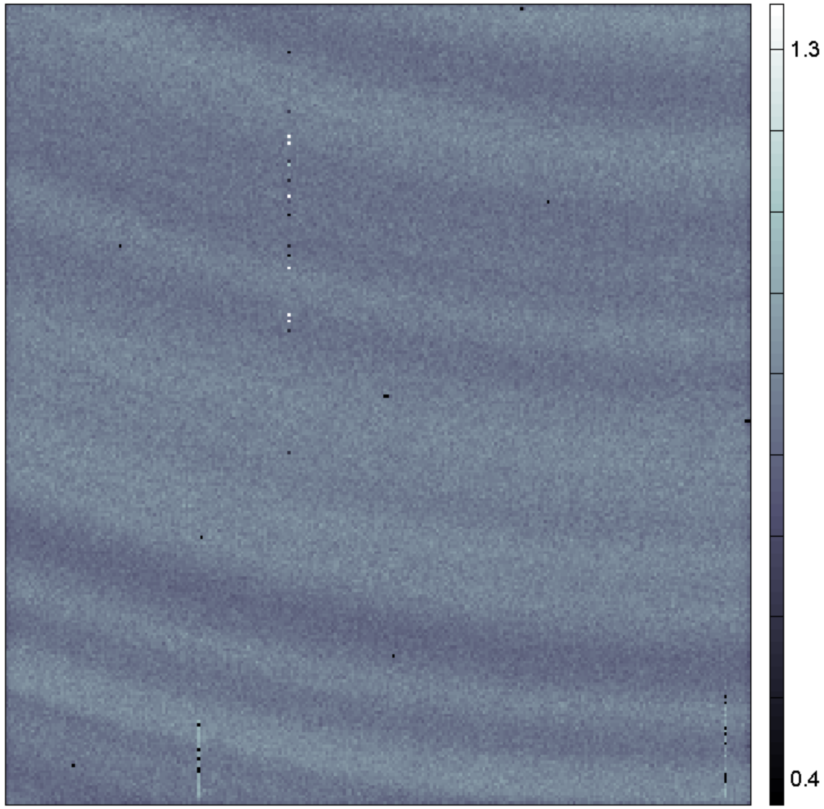
# Image of a fly



# Image of a leaf ($^{55}Fe$)

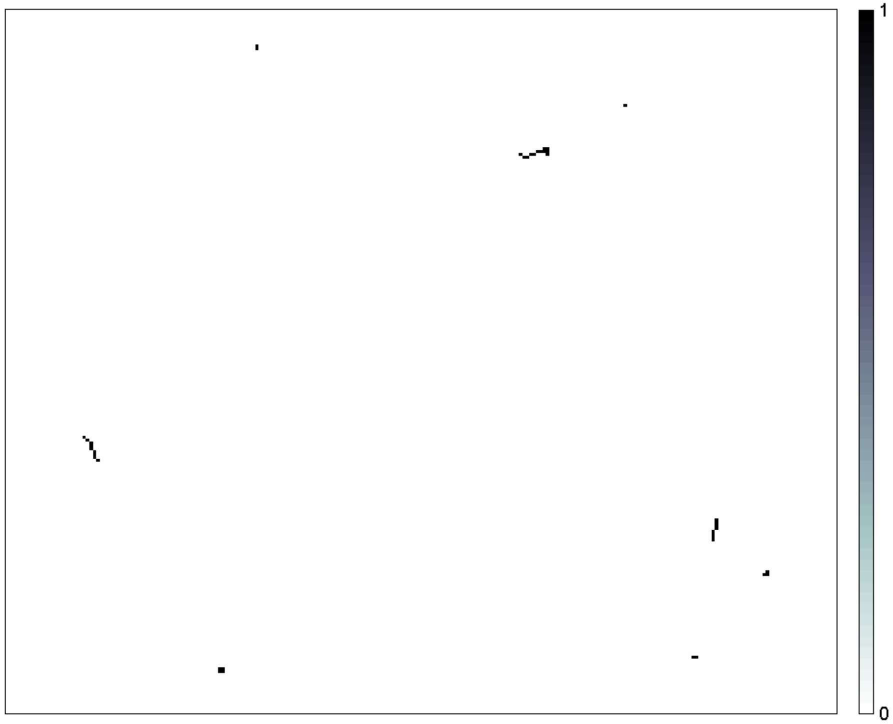


# Detector inhomogeneities using Medipxi2



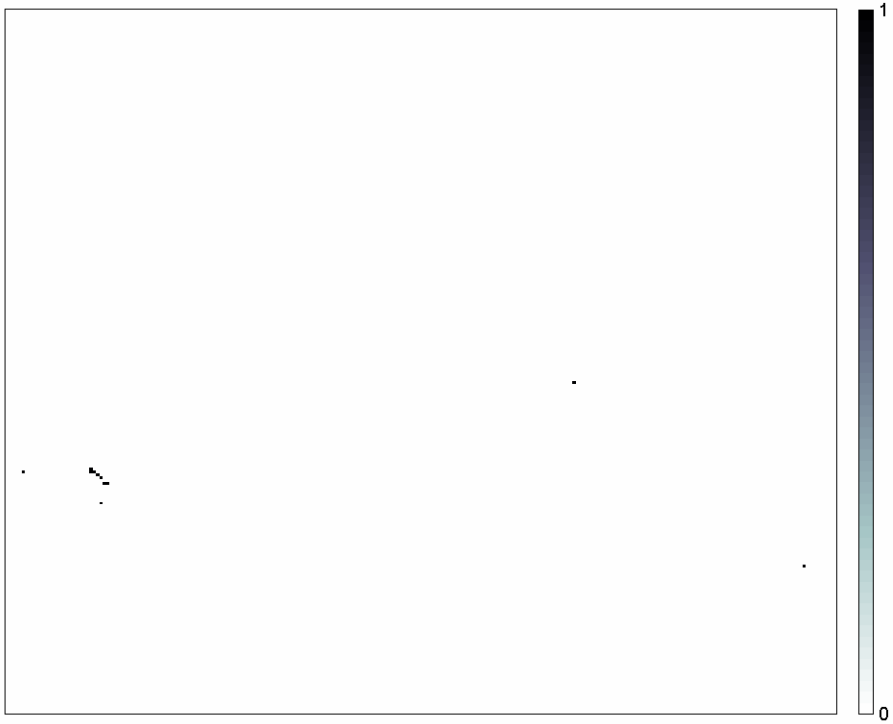

**Flood image taken using an x-ray source and an under-depleted sensor. The image has been corrected with a flat filed correction map taken using a the same setup in over-depletion.**

# Background radiation - 1



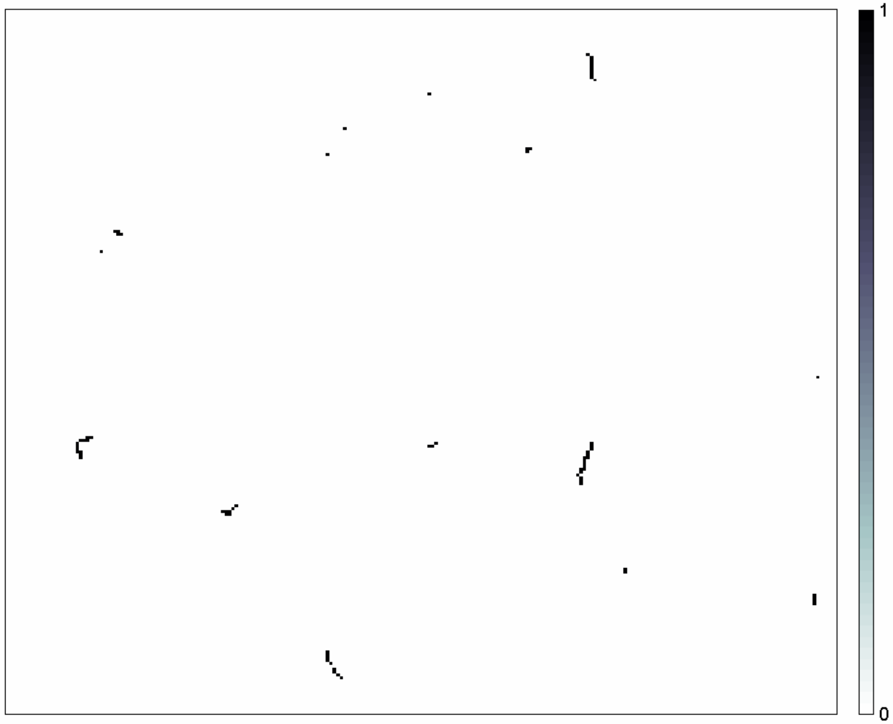

**Exposure of 1 min - no source in vicinity**

# Background radiation - 2



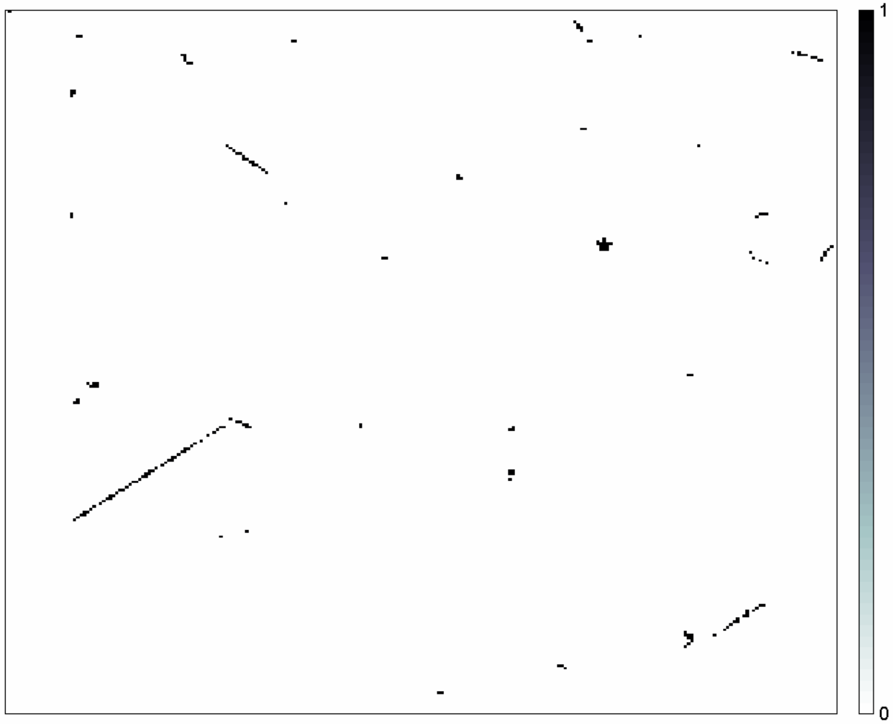

**Exposure of 1 min - no source in vicinity**

# Background radiation - 3




**Exposure of 1 min - no source in vicinity**

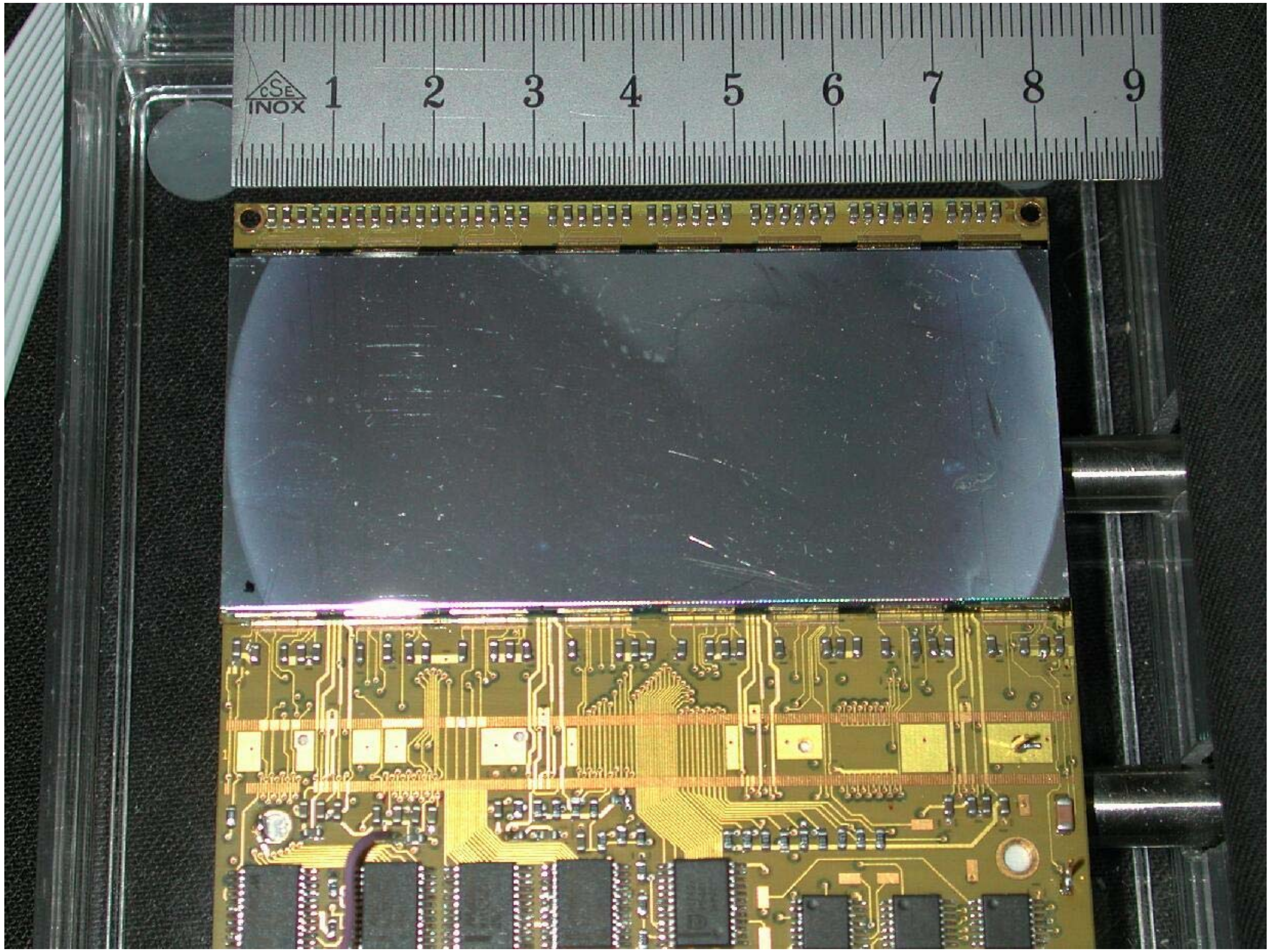
# Background radiation - 4




**Exposure of 1 min  - no source in vicinity**

Ch. Brönnimann,
SLS Detector Group

PILATUS Module Typ I (readout electronics flat)

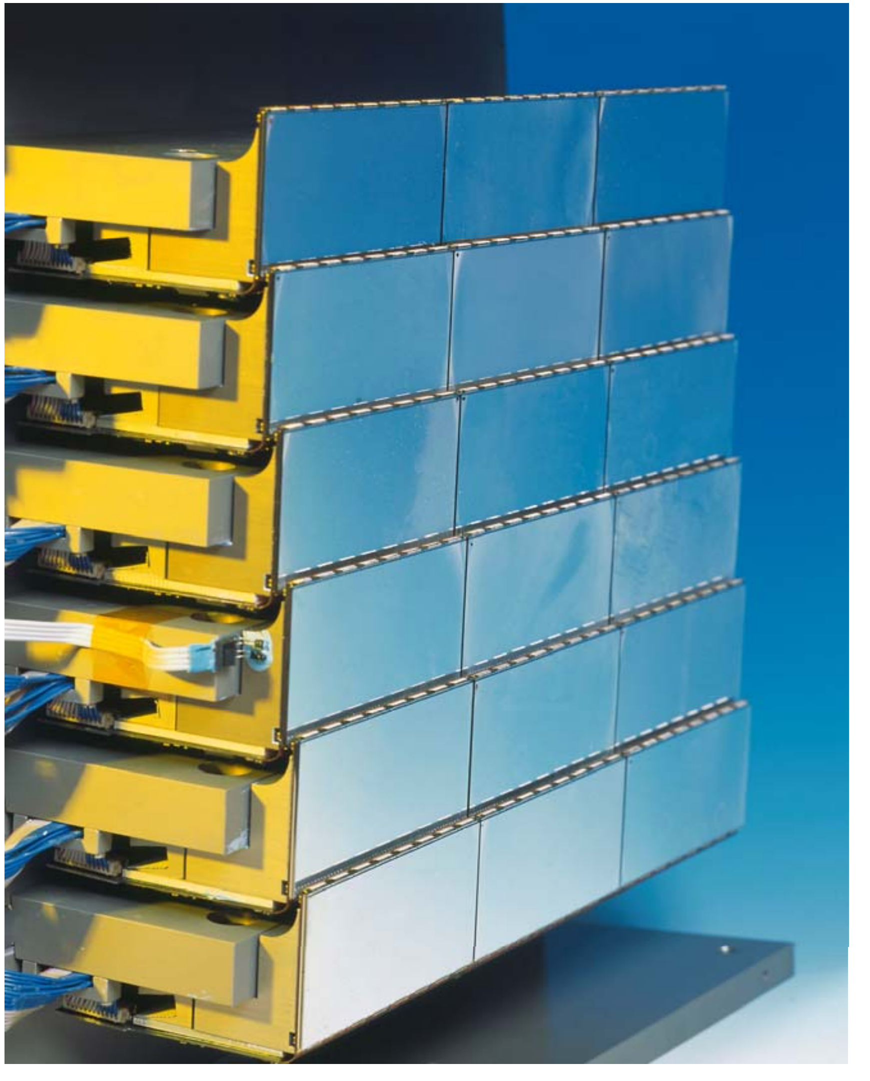



# Module Data

- Active Area: 79.6 x 35.3 $mm^2$ (continuously sensitive)
- 157 x 366 = 57462 pixels
- 16 chips (radiation hard)
- Pixel size 0.217x0.217 $mm^2$
- Readout-time: 6.7 ms
- Energy Range: $E\gamma$ >4.5 keV
- Minimum Threshold: 3 keV
- Threshold adjust per pixel
- Threshold RMS 6% of threshold
- Rate: ~10KHz/pixel
- 15-bit counter/pixel
- single photon counting, no readout noise

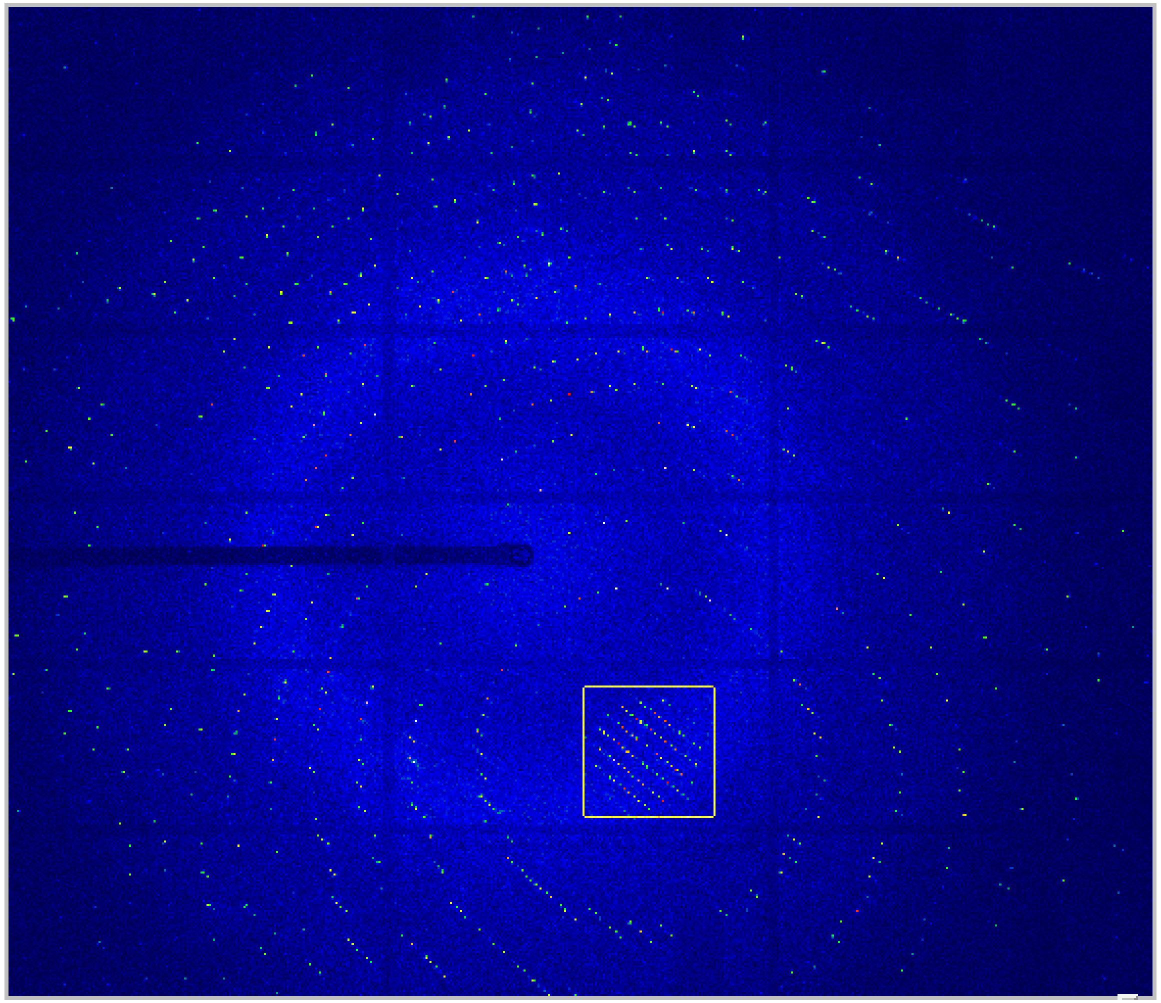
PILATUS 1M Detector for Protein Crystallography

- Largest pixel detector array for SR
- 6 banks a 3 modules, 1120 x 967 pixels
- Area: 21 x 24 $cm^2$
- 288 chips->~300x$10^6$ transistors
- Readout time: 6.7ms
- Currently 2 frames/s
- goal 10 frames/ s
- Active area: 85%
- Moderate count rates (<10kHz/pixel)



**Benefits for PX:**

- Single Photon Counting-> Excellent S/N ratio for weak reflections
- Short read-out time -> Fine-$\phi$-slicing

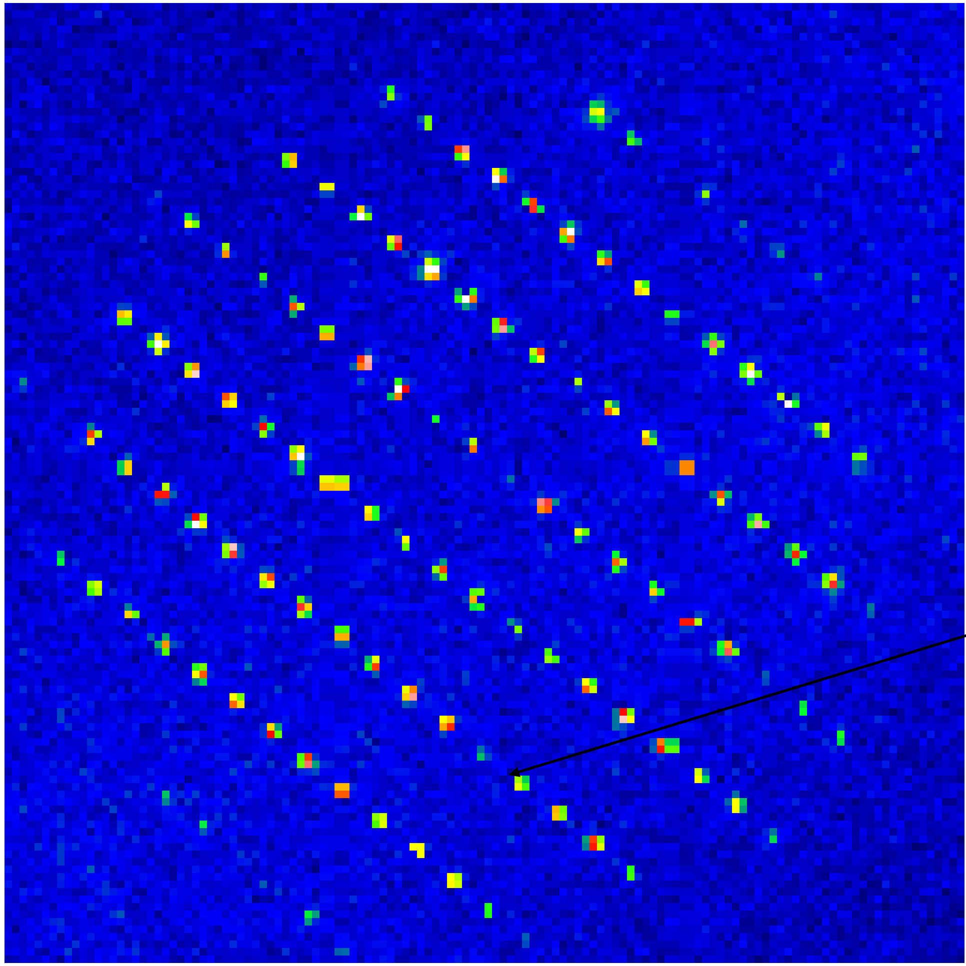


Thaumatin

90º data-set,
0.5s, 0.5º
11.9 keV

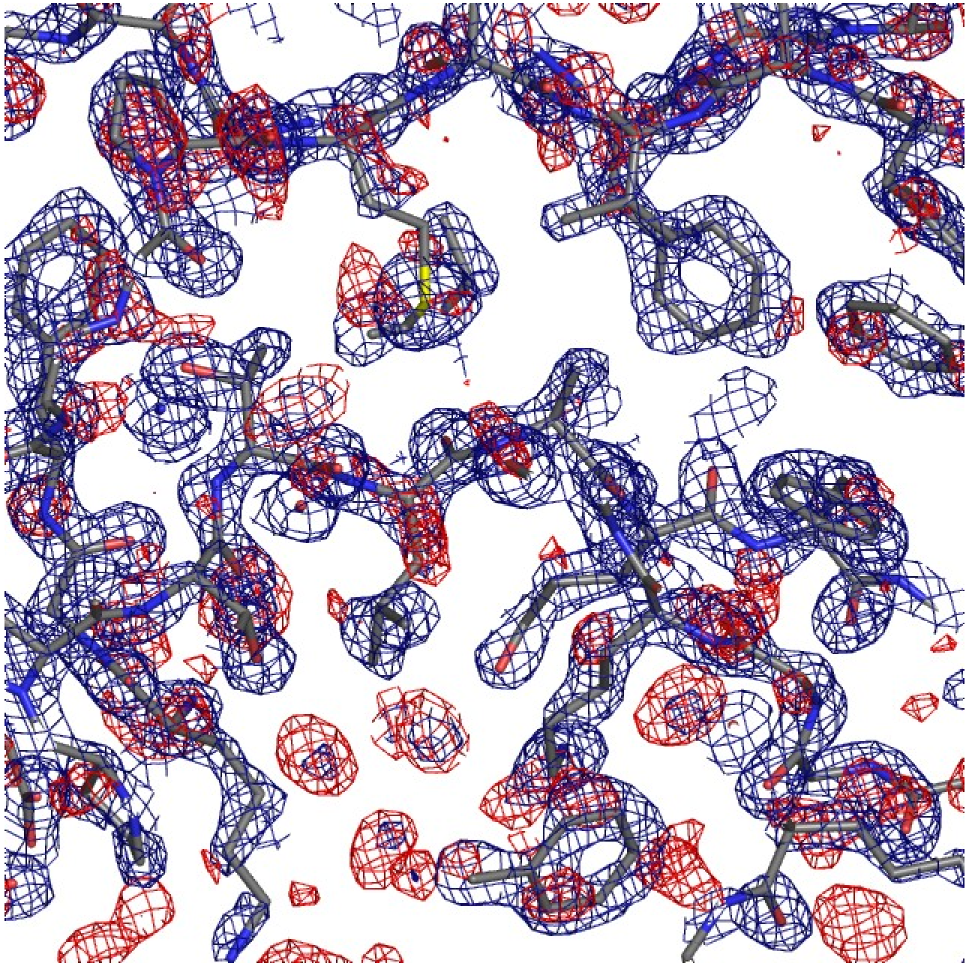
Beam intensity 0.68%

(fully corrected
image)



Thaumatin
(zoom in)
0.5s, 0.5º
11.9 keV

Very good point spread function
-> Very sharp reflections



Preliminary thaumatin electron density map

Processing with XDS

$R_{sym}$ ~ 10%

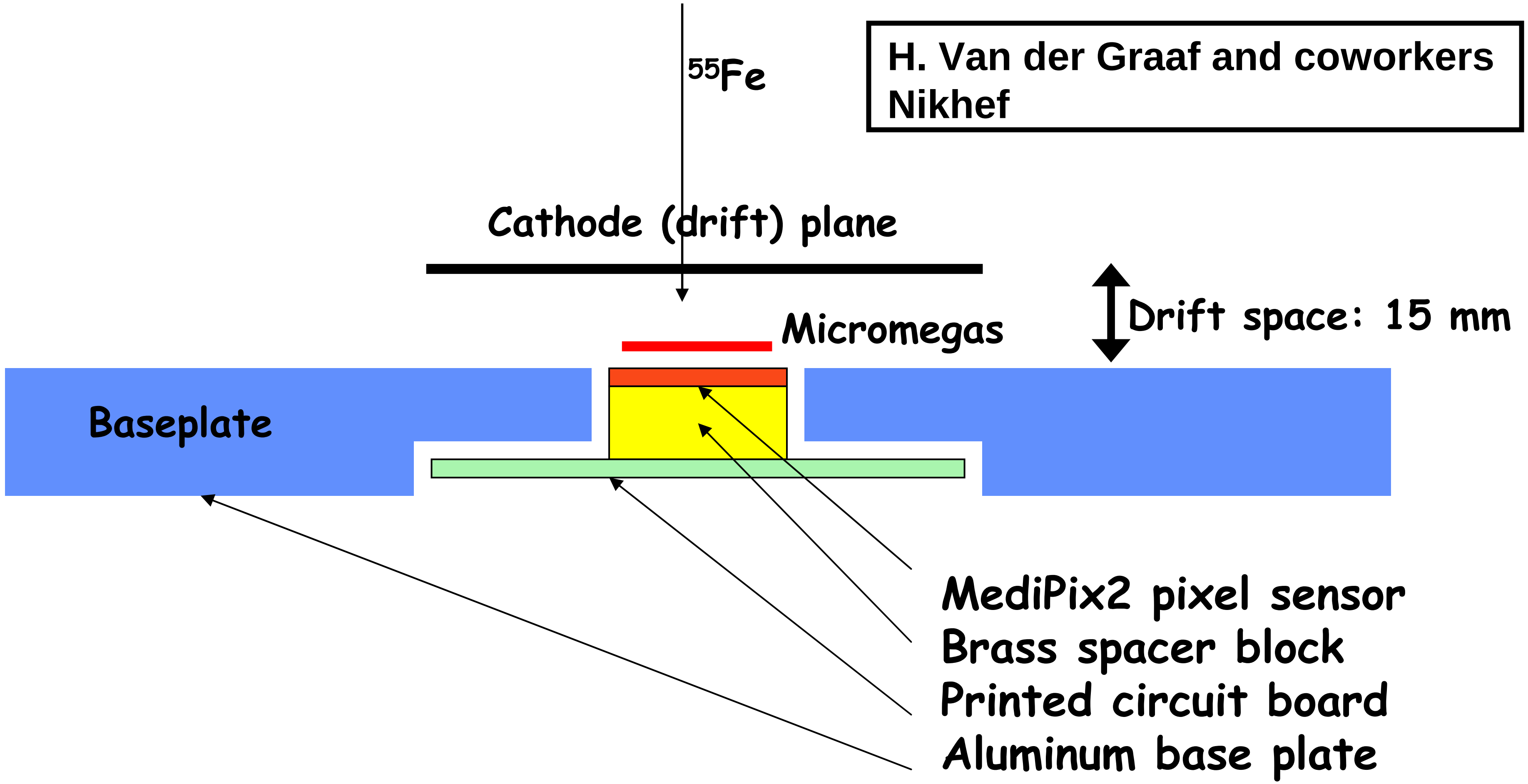
Resolution: 1.5 Å

Refinement:
R-Factor 28%

blue contours: 2*Fo-Fc (2sigma)
red contours: Fo-Fc (2sigma)

# Sinlge electron detection using Medipix2

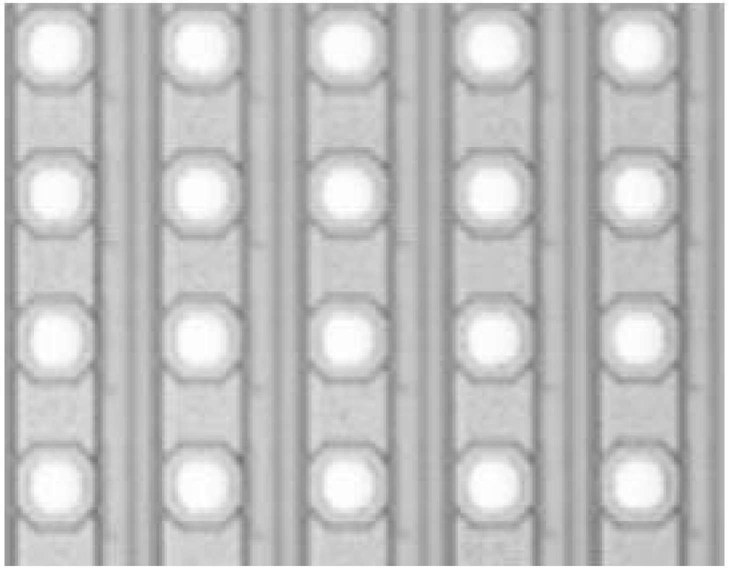
H. Van der Graaf and coworkers
Nikhef




Very strong E-field above (CMOS) MediPix!

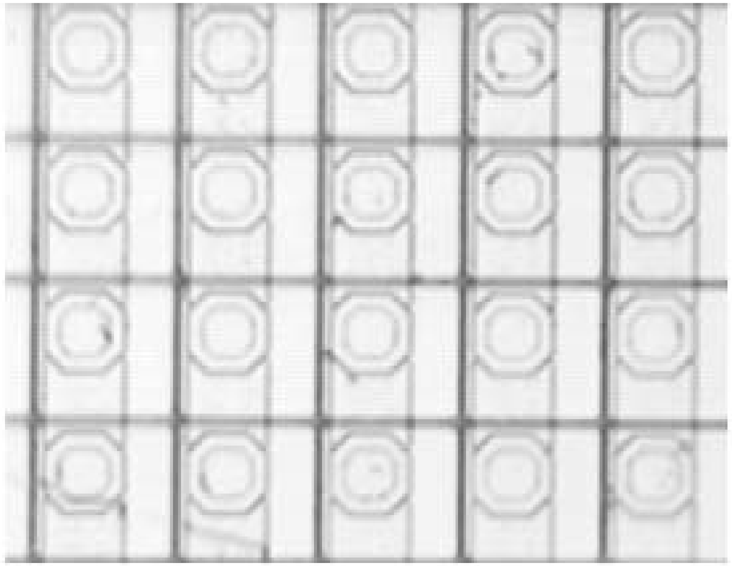
# Chip post processing

MediPix modified by MESA+, Univ. of Twente, The Netherlands



a)

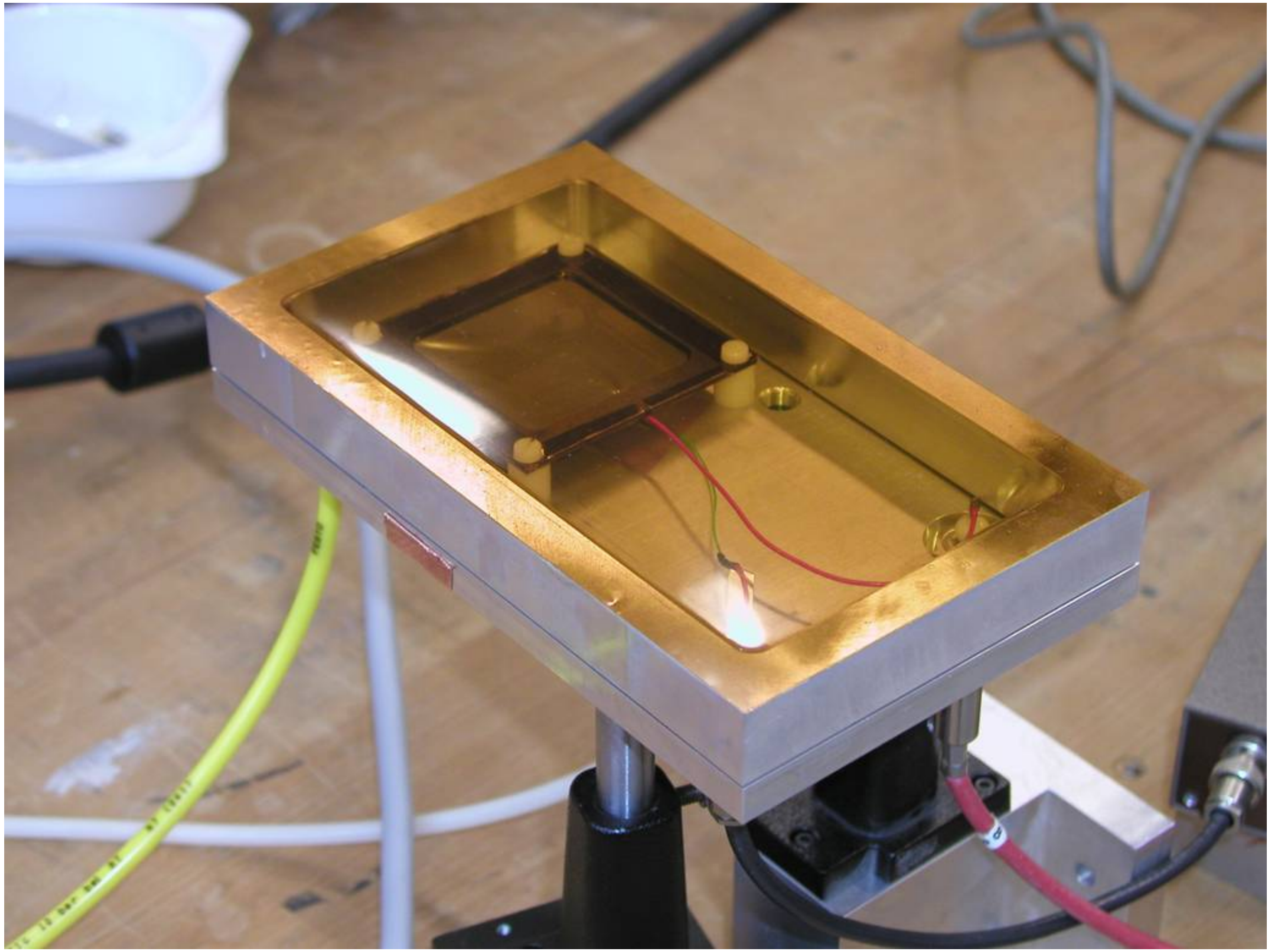
Pixel Pitch: 55 x 55 $\mu m^2$
Bump Bond pad: 25 μm octagonal
75 % surface: passivation SiN
New Pixel Pad: 45 x 45 $\mu m^2$



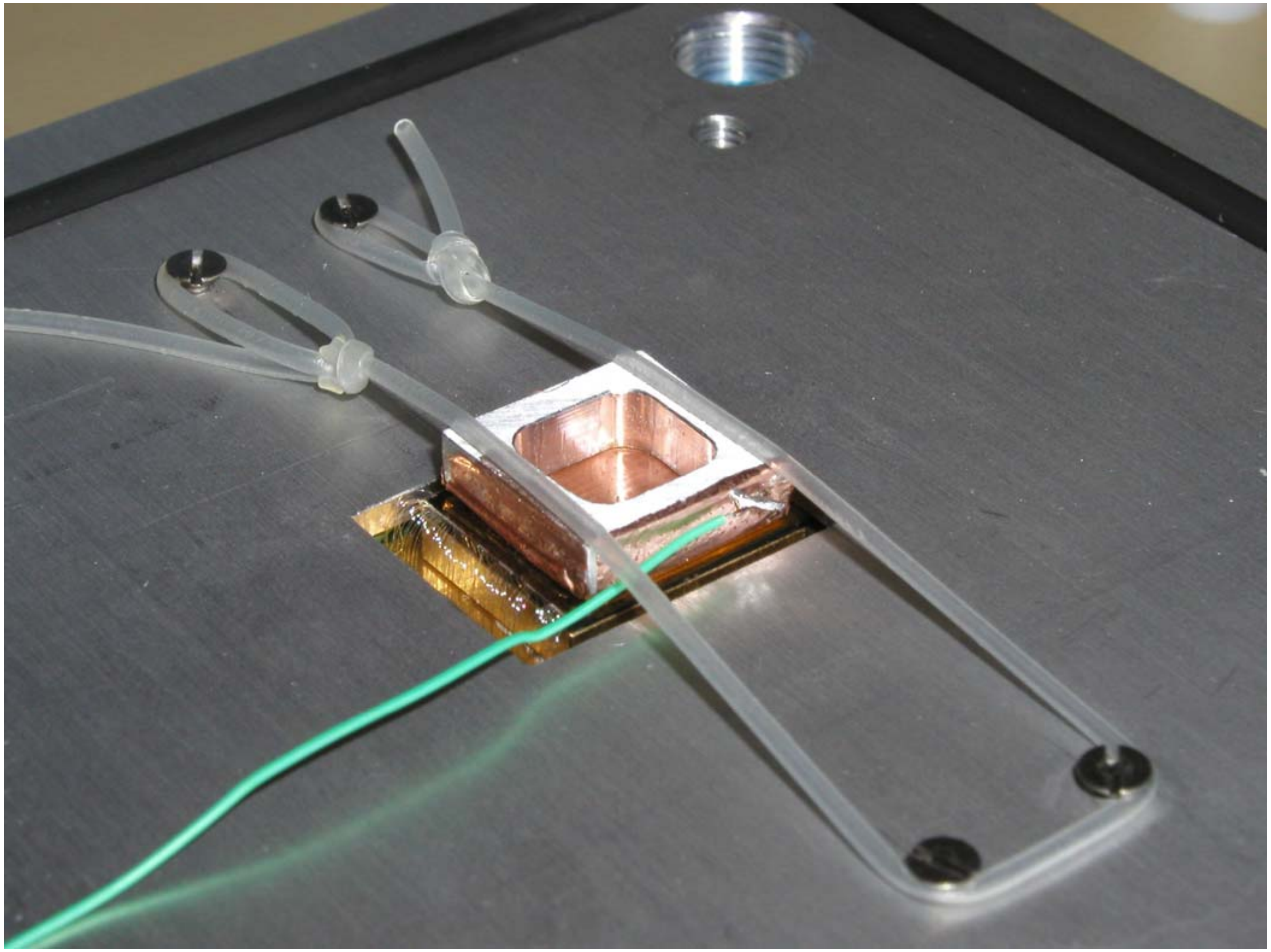
b)

Insulating surface was 75 %
Reduced to 20 %

# Micromegas-Medipix2 setup



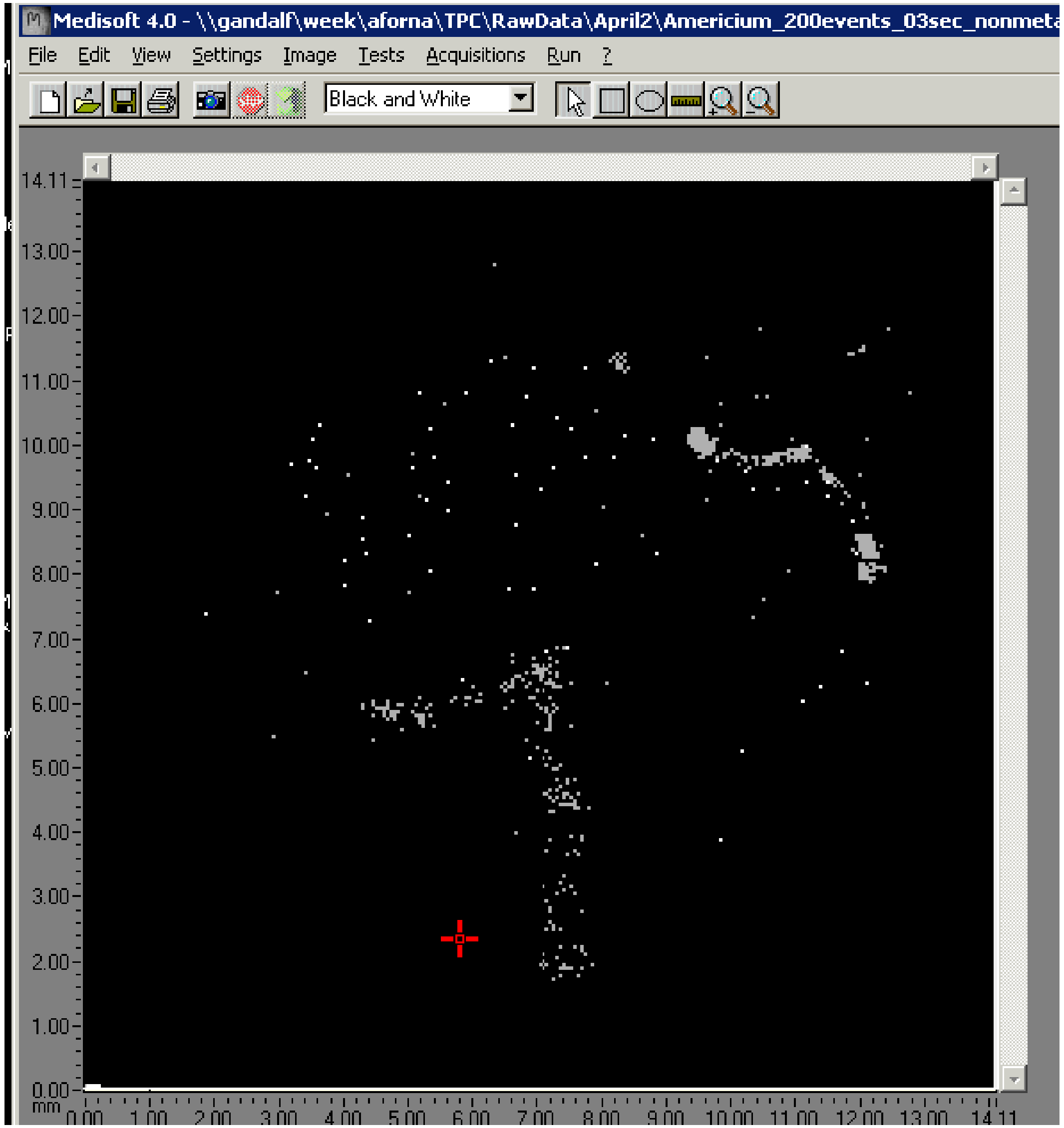
# Chamber Mechanics



# Radioactive source observation

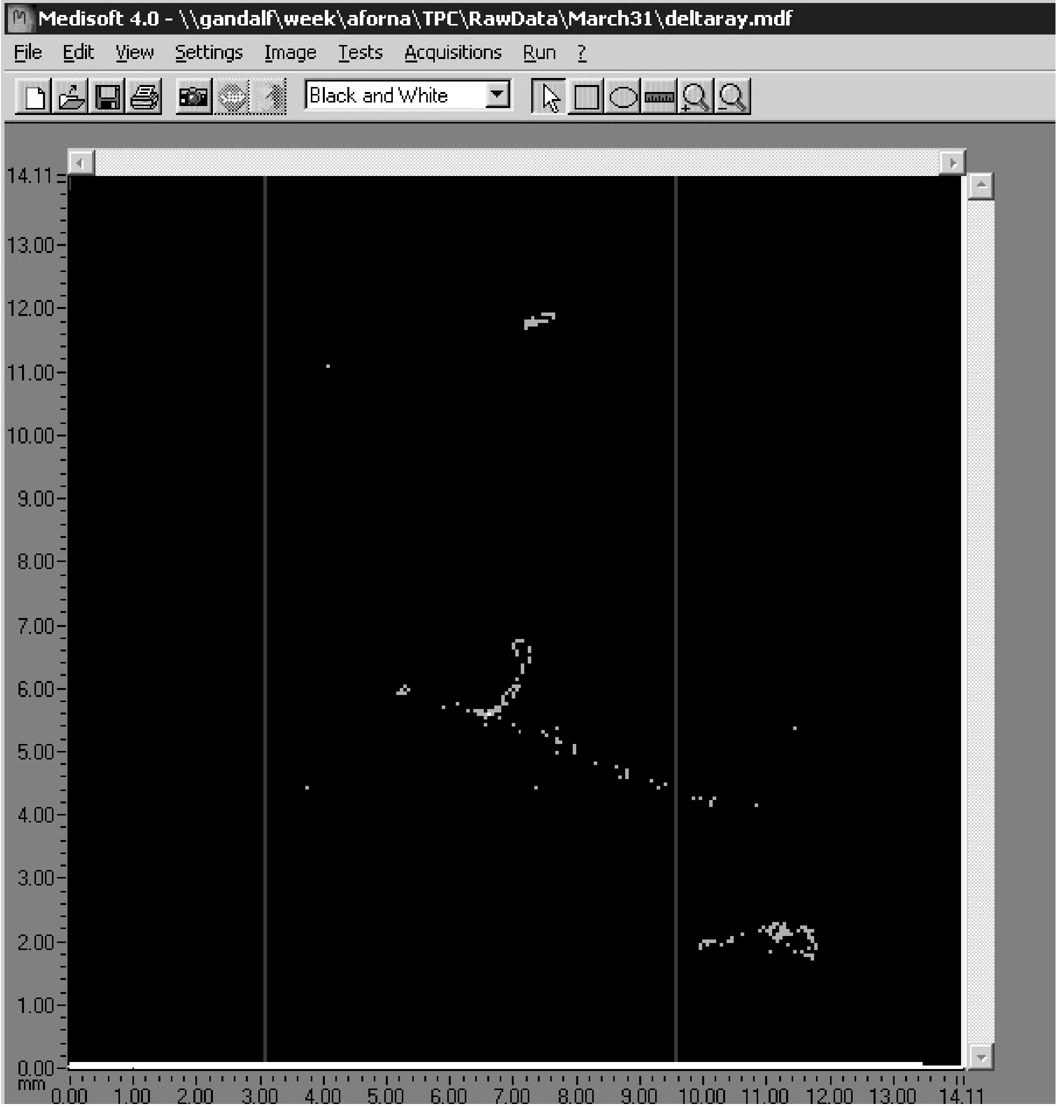
He/Isobutane
80/20
Non Modified
MediPix

Americium Source



# Cosmic with associated delta ray

He/Isobutane
80/20
Modified MediPix



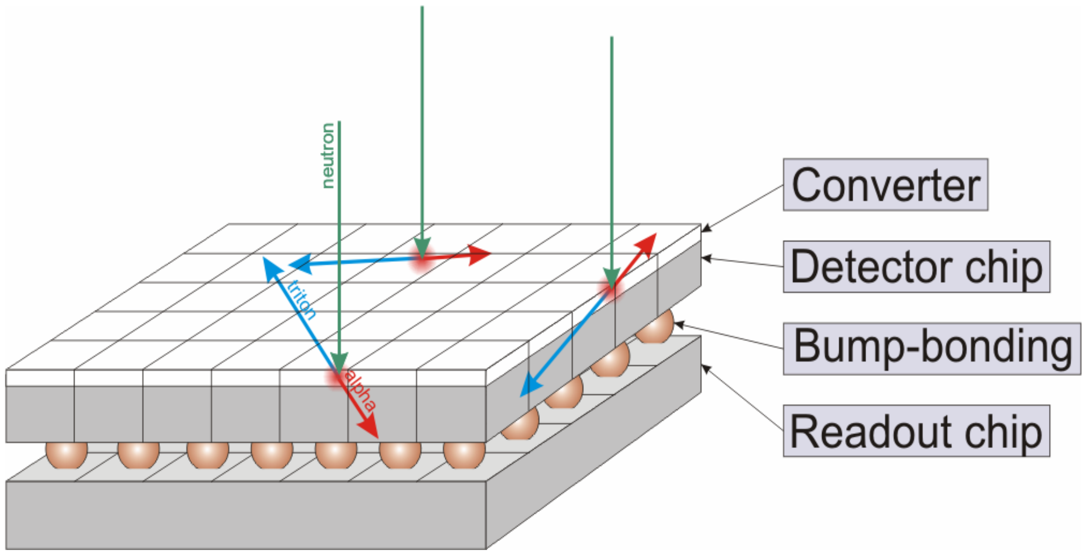
# Neutronography with Medipix2

**S. Pospisil and co-workers, Czech Technical University, Prague**

**Conversion of thermal neutrons to heavy charged particles in $^6$Li converter layer**

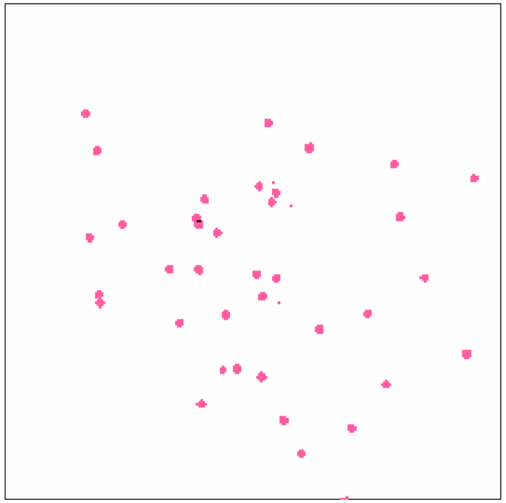
**Reaction:** $^6Li + n \rightarrow \alpha$ (2.05 MeV) + $^3H$ (2.72 MeV)

**Cross section:** 940 barns (0.0253 eV)

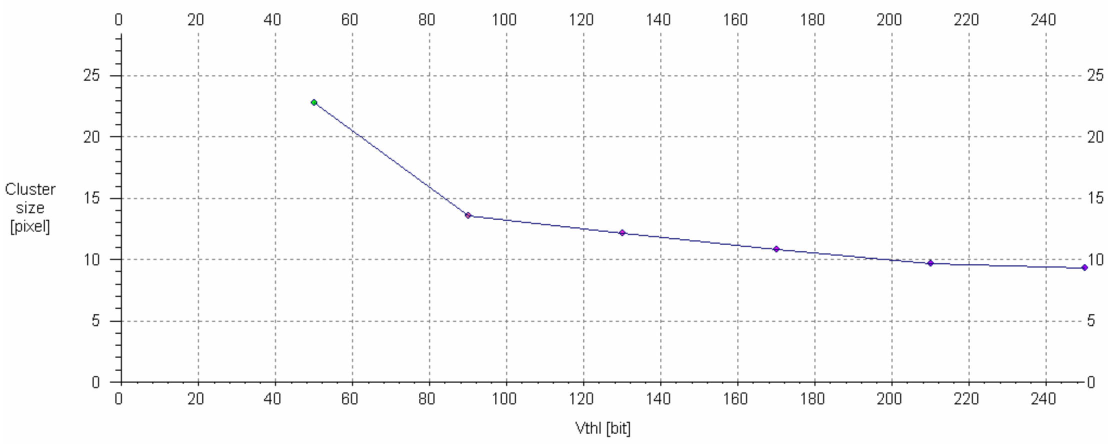


# Tests with $^{241}$Am alpha source

- Medipix-2 without converter layer
- Energy of alpha particles: 5.6 MeV
- Short exposition time
- Clusters observed

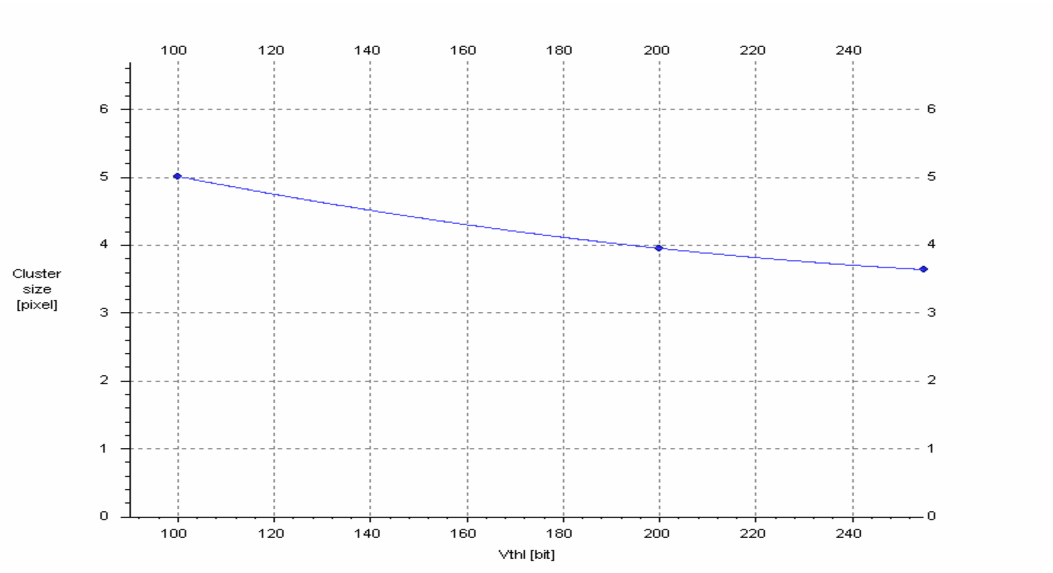


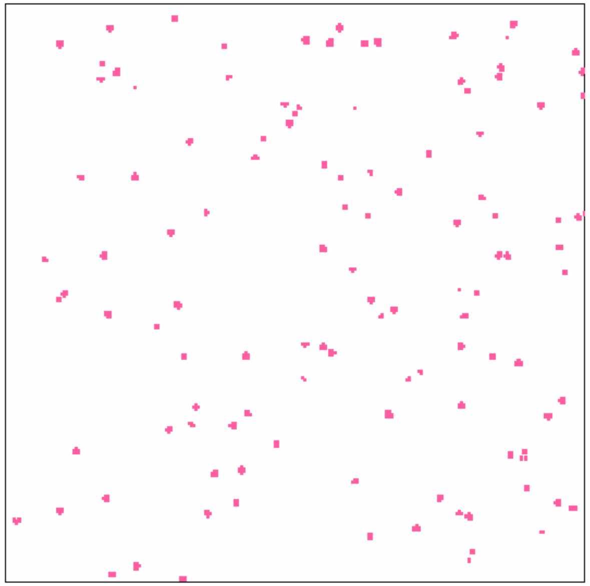
Dependence of average cluster size on threshold



# Clusters observed with neutron beam

Dependence of average cluster size on threshold

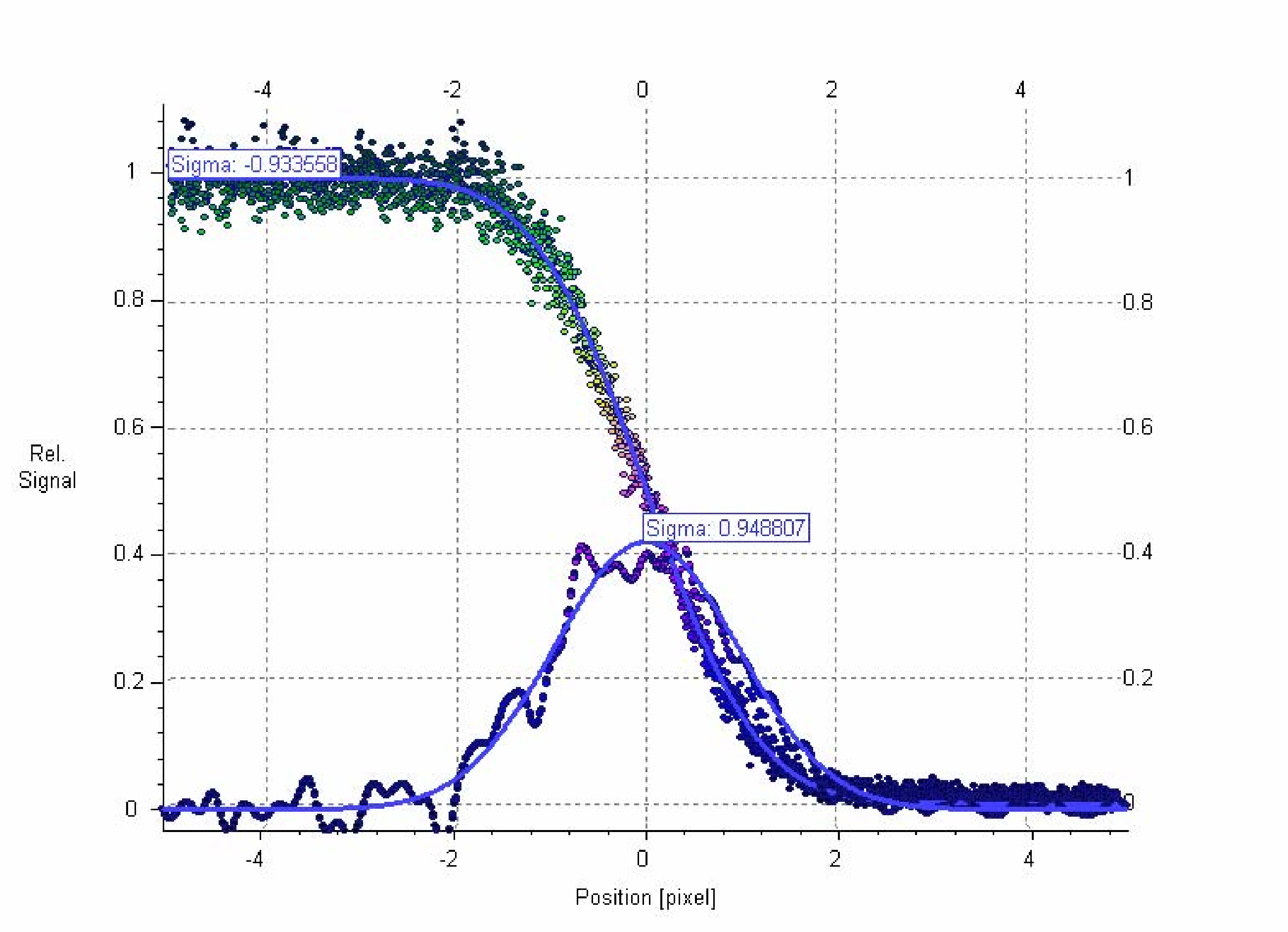


Exposition time = 1 ms

Vfbk=120

# Spatial resolution – edge response

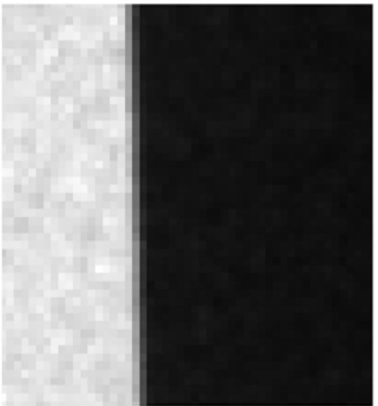
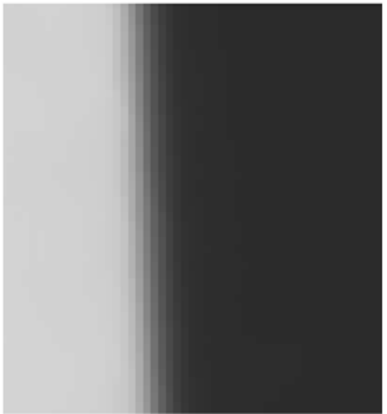
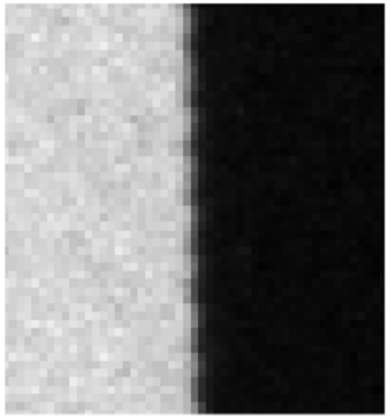


# Comparison of Medipix-2 and other neutron imaging detectors

**The following tests of Medipix-2 neutron device were done on NEUTRA facility (PSI, Switzerland) in co-operation with E. Lehmann et al. The device was compared to:**

**-CCD camera with scintillator mixed with $^{6}$Li (pixel size 0.139 mm)**

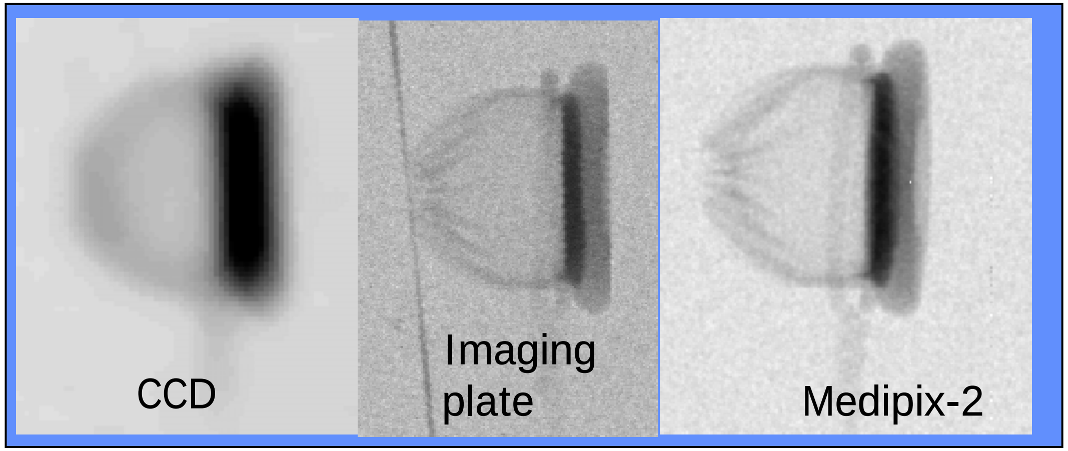
**-Imaging plate (excitation by neutrons, de-excitation by laser scanner followed by light emission, pixel size 50μm)**

| Medipix-2 | CCD camera | Imaging plate |
|---|---|---|
|  |  |  |
| $\sigma$=0.83 pixel =46 μm | $\sigma$=2.5 pixel =350 μm | $\sigma$=1.06 pixel =53 μm |

# Sample objects – blank cartridge


Roentgenography

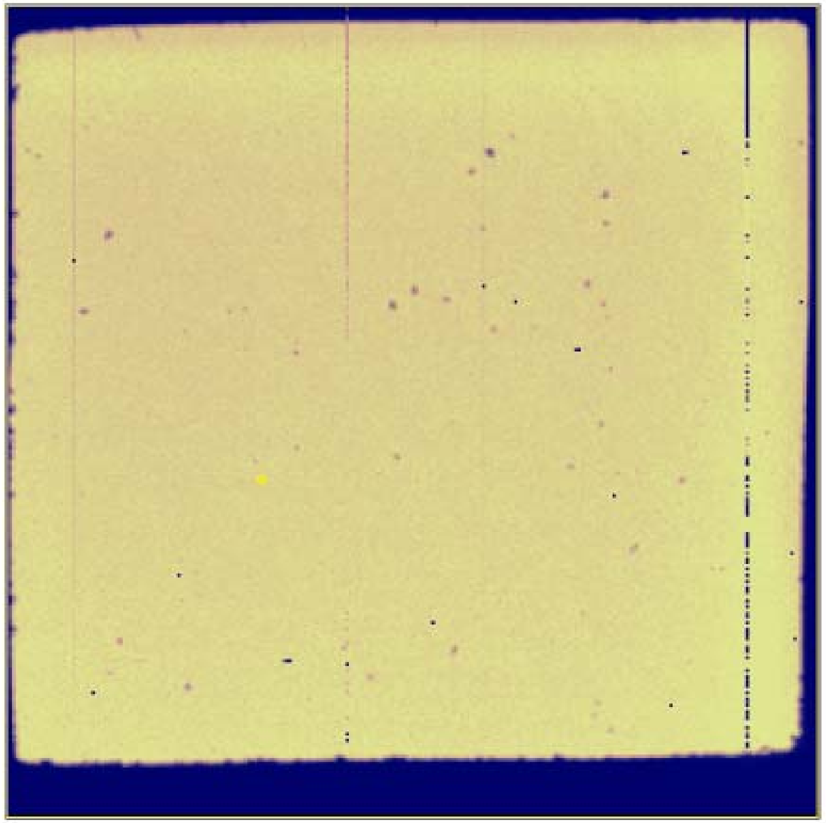

Neutronography



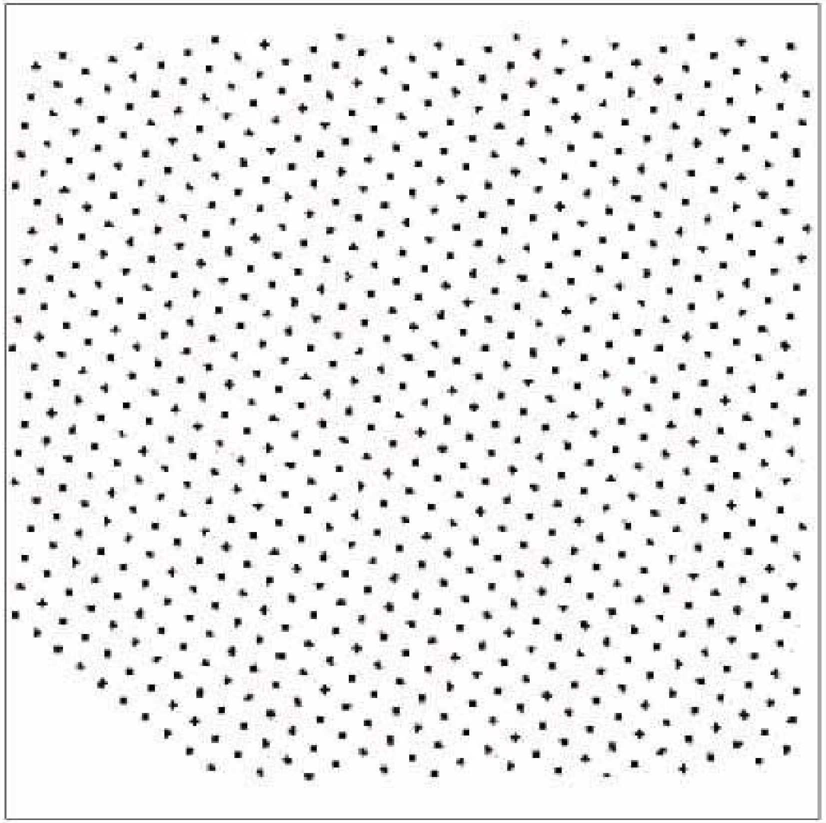
# Medipix2 as an electron detector in a TEM for molecular biology

**Flood field image with Si assembly and 150keV electrons**

**W. Faruqi and co-workers**
**Laboratory of Molecular Biology, Cambridge**

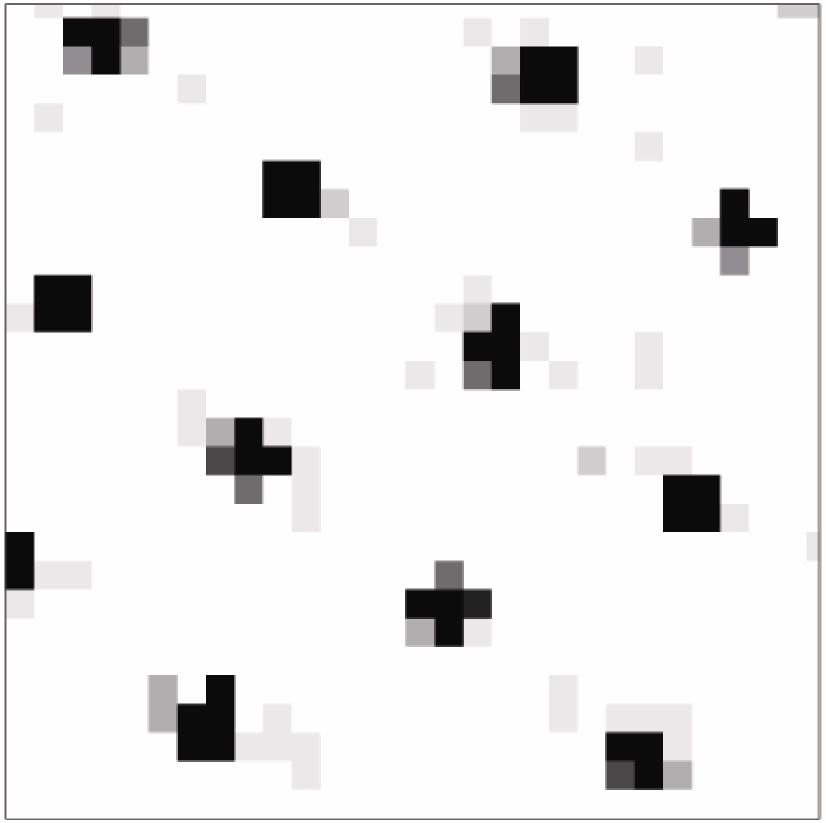


# Spot scan



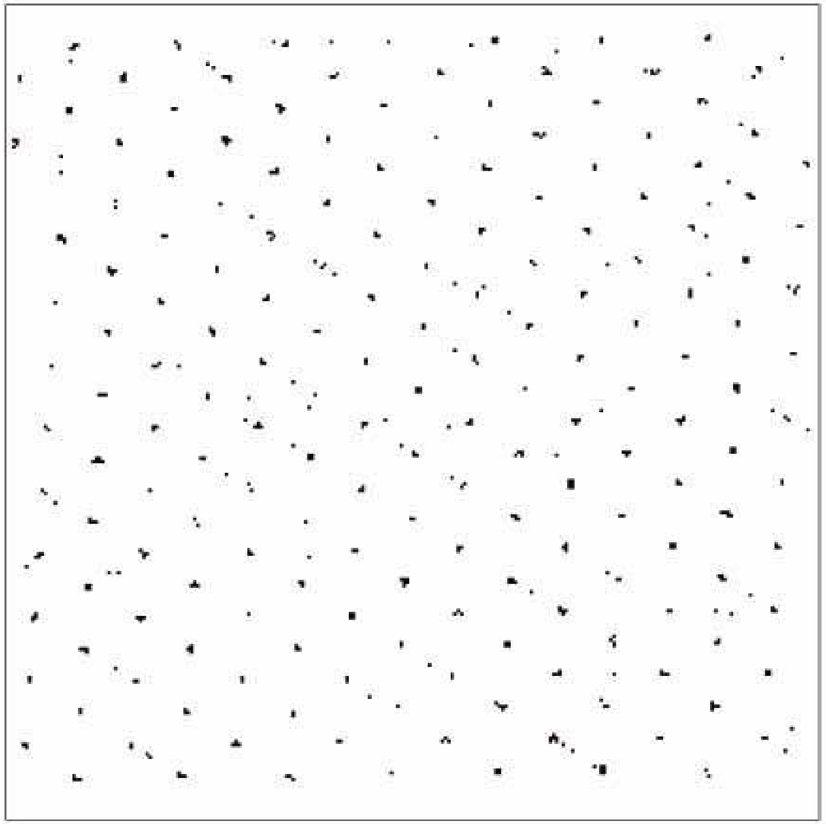
**Mean counts** **111**
**σ counts** **11**

# Spot scan – close up

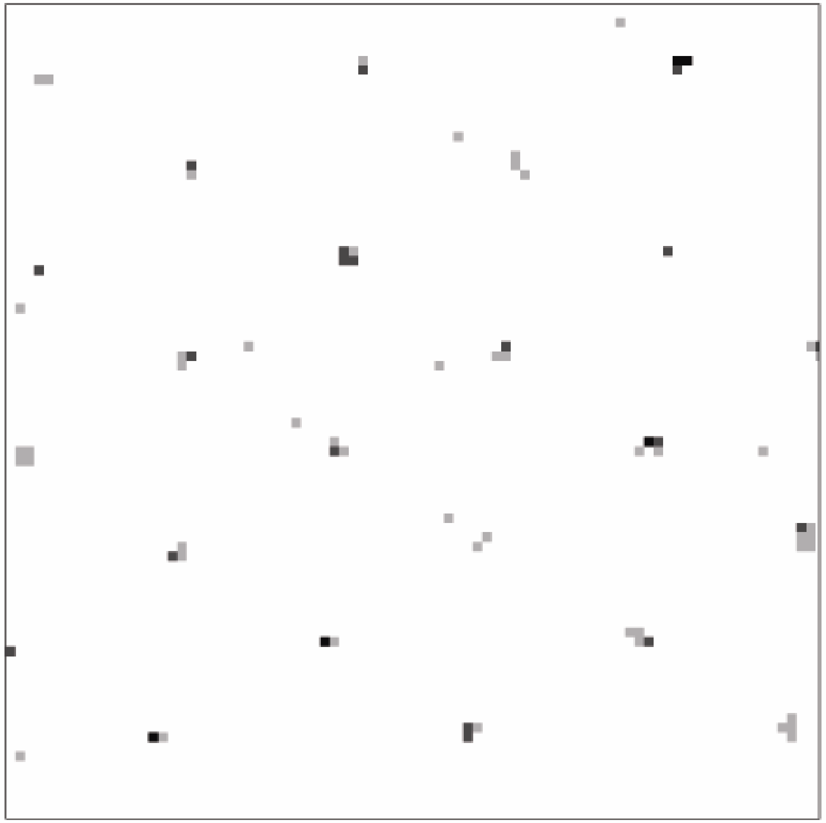


# Spot scan

**Mean counts** **4.7**
**σ counts** **1.8**



# Spot scan – close up



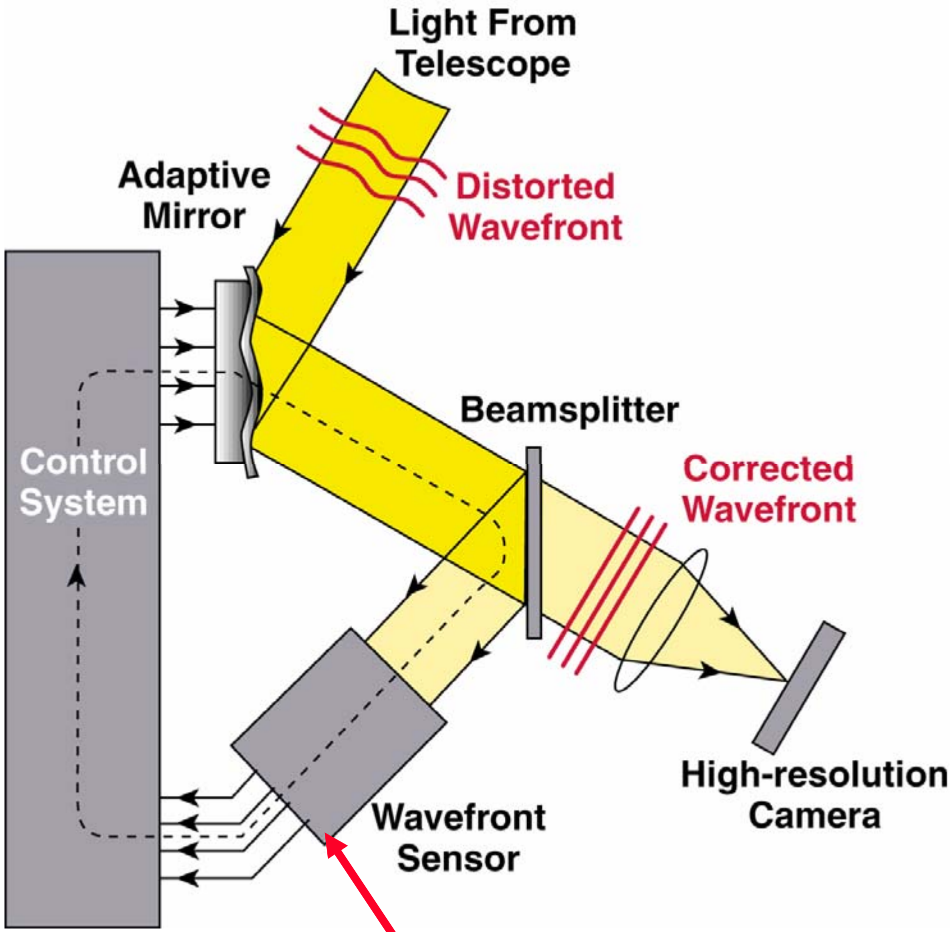
# Comparison with film

| | mean | σ |
|---|---|---|
| **Spotscan1** | | |
| Medipix2 | 111 | 11 |
| Film | 116 | 24 |
| **Spotscan7** | | |
| Medipix2 | 4.7 | 1.8 |
| Film | spots invisible | |

# Schematic of adaptive optics system

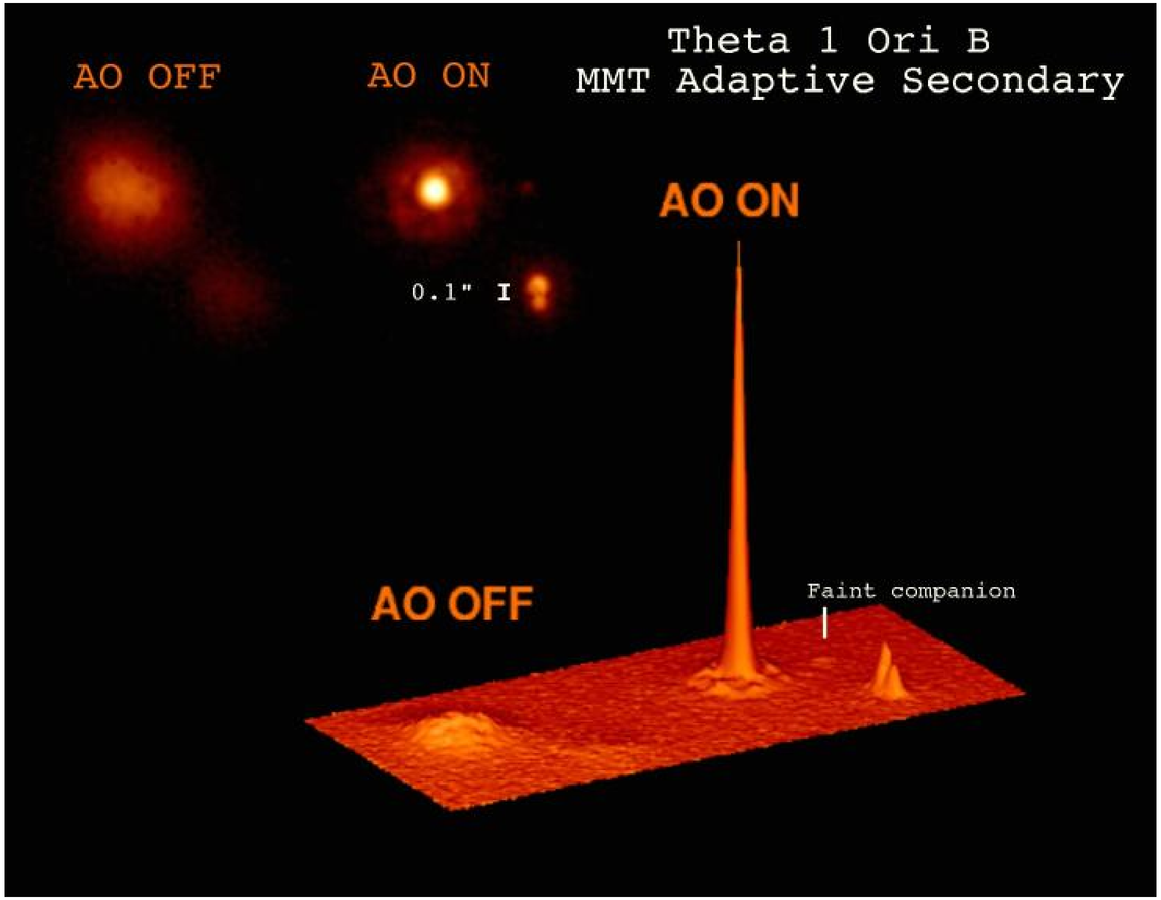
J. Vallerga and coworkers
UC Berkeley
B.Mikulec
Univ. Geneva

Feedback loop: next cycle corrects the (small) errors of the last cycle




Optical Medipix tube goes here

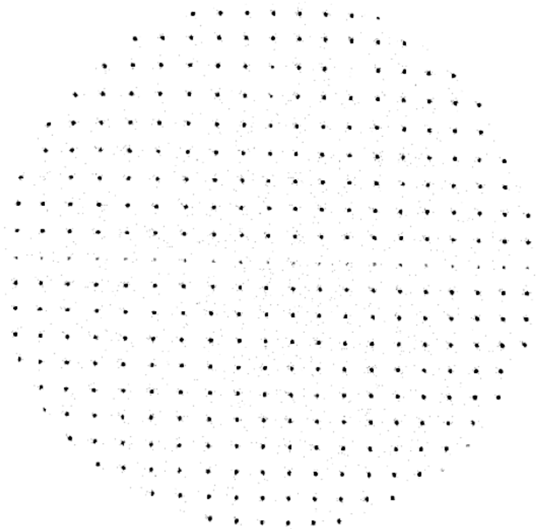
# Example for the improvements using AO



# Wavefront Sensors

- **Future large telescopes need > 5000 actuators**
  - **(70 x 70 spot centroids to measure wavefront)**
- **Kilohertz feedback rates (atmospheric timescale)**
- **1000 detected events per spot for sub-pixel centroiding**

**5000 x 1000 x 1000 =**

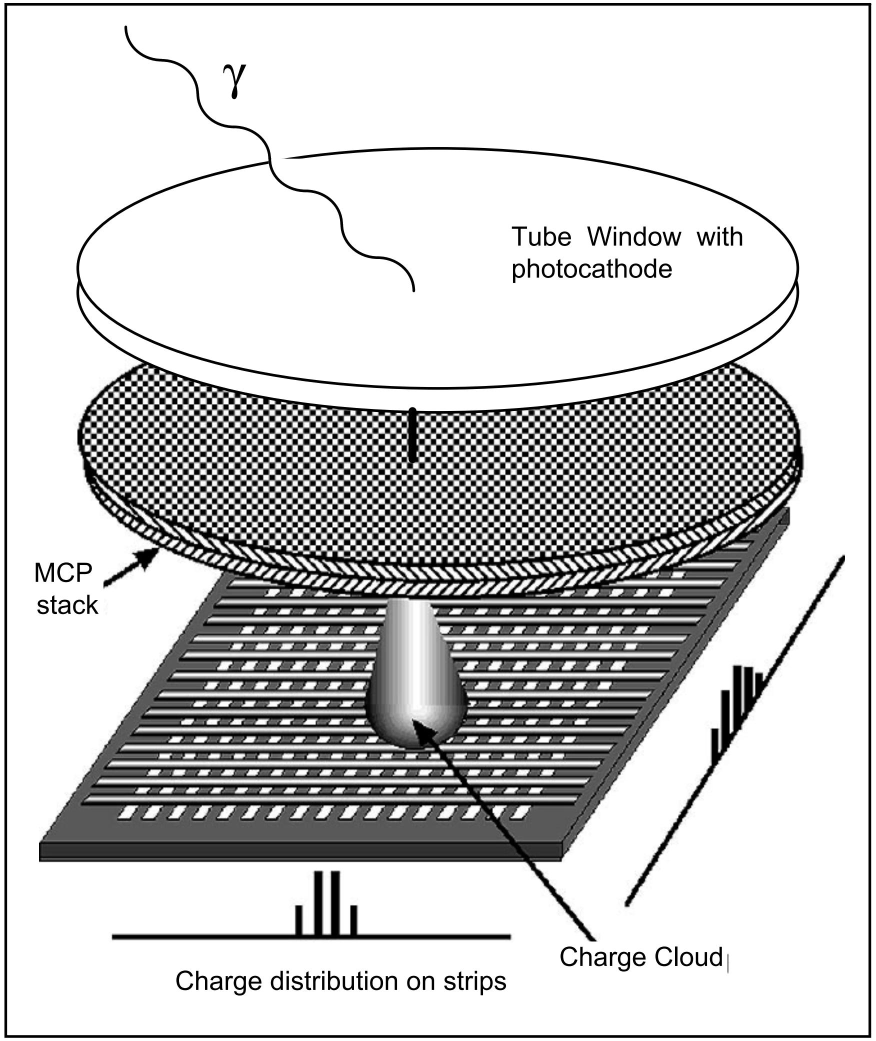


> 5 Gigahertz counting rate!

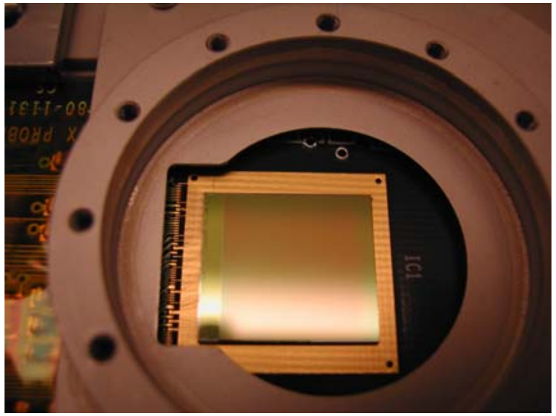
- **Requires detector integrating several events in time**

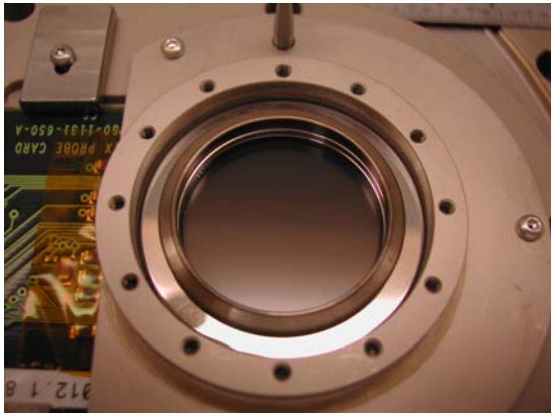
# Imaging, Photon Counting Detectors

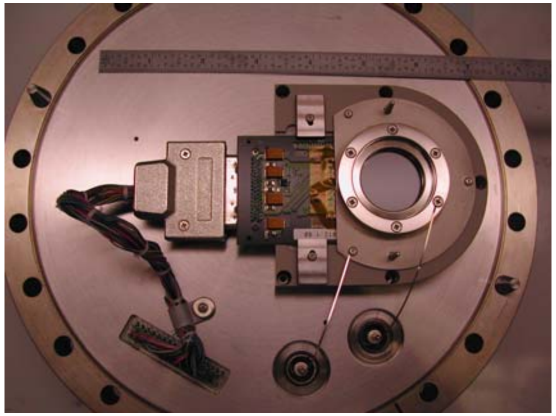
- Detects individual quanta of light via photoelectric effect
- Signal per photon >> noise
- Imaging gives X,Y of every event
- Time of every event also available
- Maximum ct. rate ~ 2 MHz

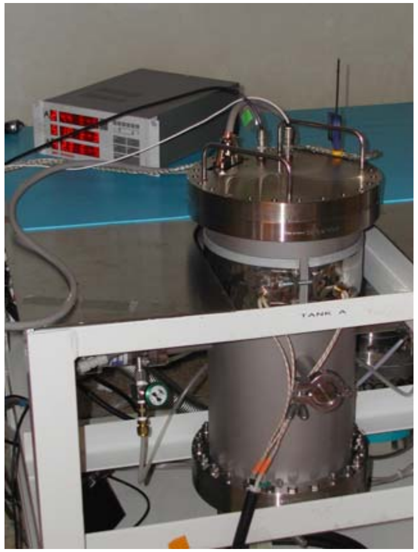


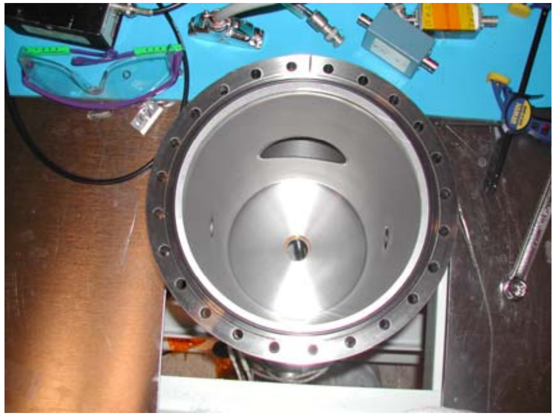
# The Setup at SSL - Photos

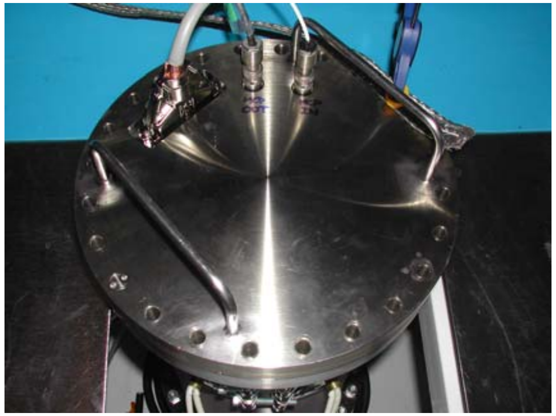






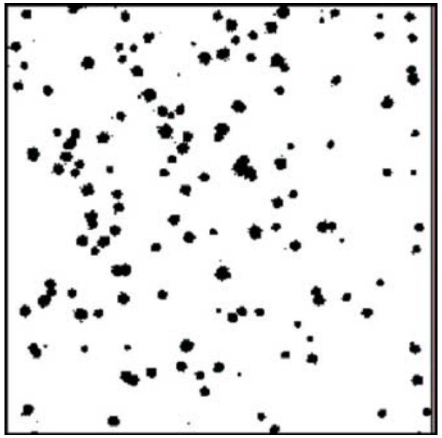




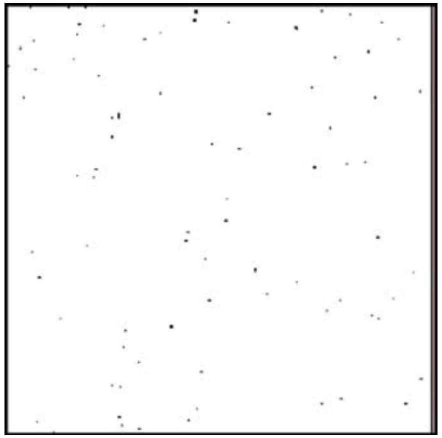


# Investigating the Parameters…

- **Spot area [no. of pixels] is a function of**
  - **MCP gain (voltage across MCPs):**
    **decreases with decreasing gain (threshold effect)**
  - **Rear field (voltage between MCP exit and Medipix chip):**
    **decreases with increasing rear field**



single photon events



gain $10^6$, rear field 427 V

gain 50k, rear field 980 V

- **Increasing $VTH_{low}$ over the available range (no ext. DAC used) at MCP gain of ~200k results in a decreasing spot area size, but the number of spots stays approximately constant.**

# Flat Field Image

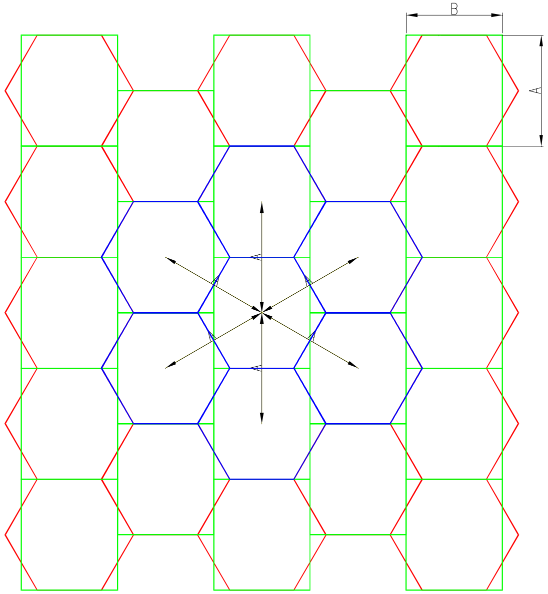
- **Take image at 50ke gain and 1600 V rear field (~5000 counts/pixel). Average single spot area: 2.4 pixels**

# Limitations of Medipix2 system

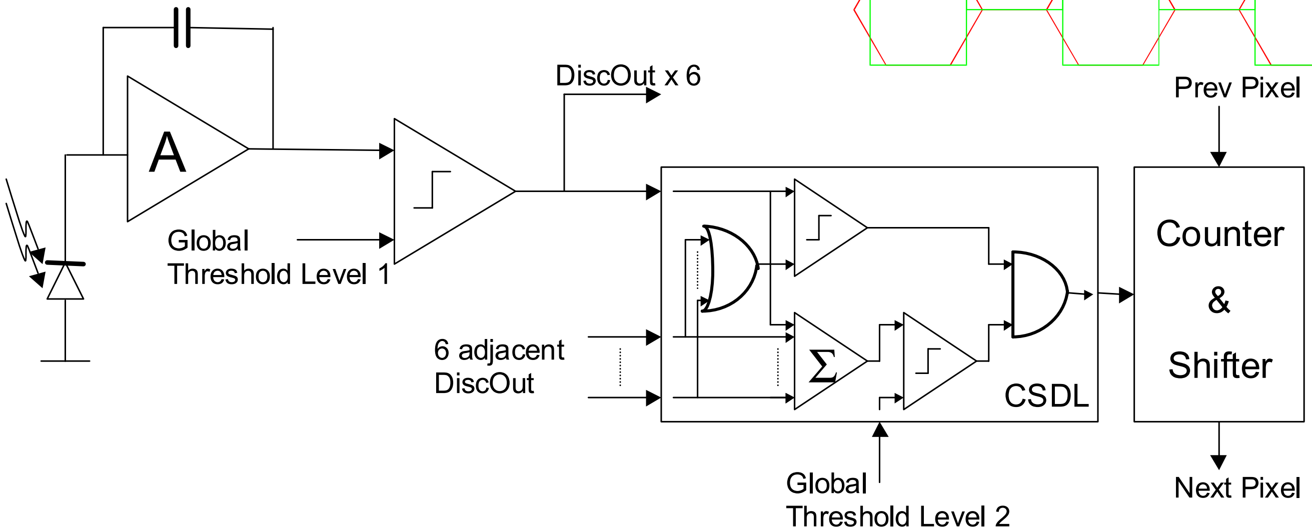
- Counting only hits in one energy window
- Charge sharing between pixels leads to low energy tail
- Tiling only possible on 3 sides

- Solutions exist for these but a new chip design would be required

# Charge sharing – possible solution

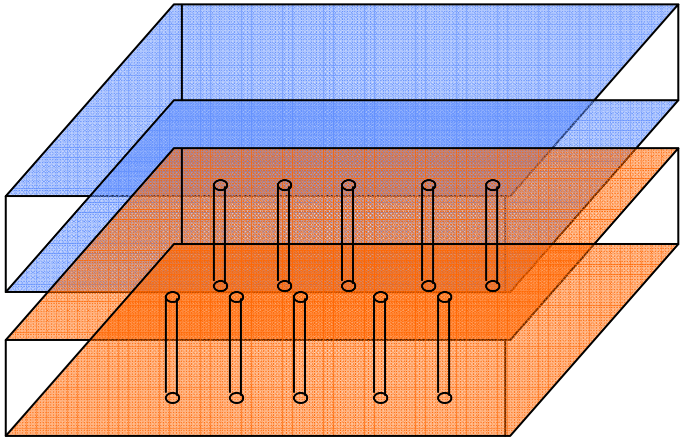



- sensor pixels: hexagons ⇨6 neighbours
- electronic pixels: rectangular
  - 2 different threshold levels
  - longest pulse ⇨ biggest share of charge
  - sum of 7 pixels is compared to second threshold



# Tiling- possible solution

High-Z detector tile



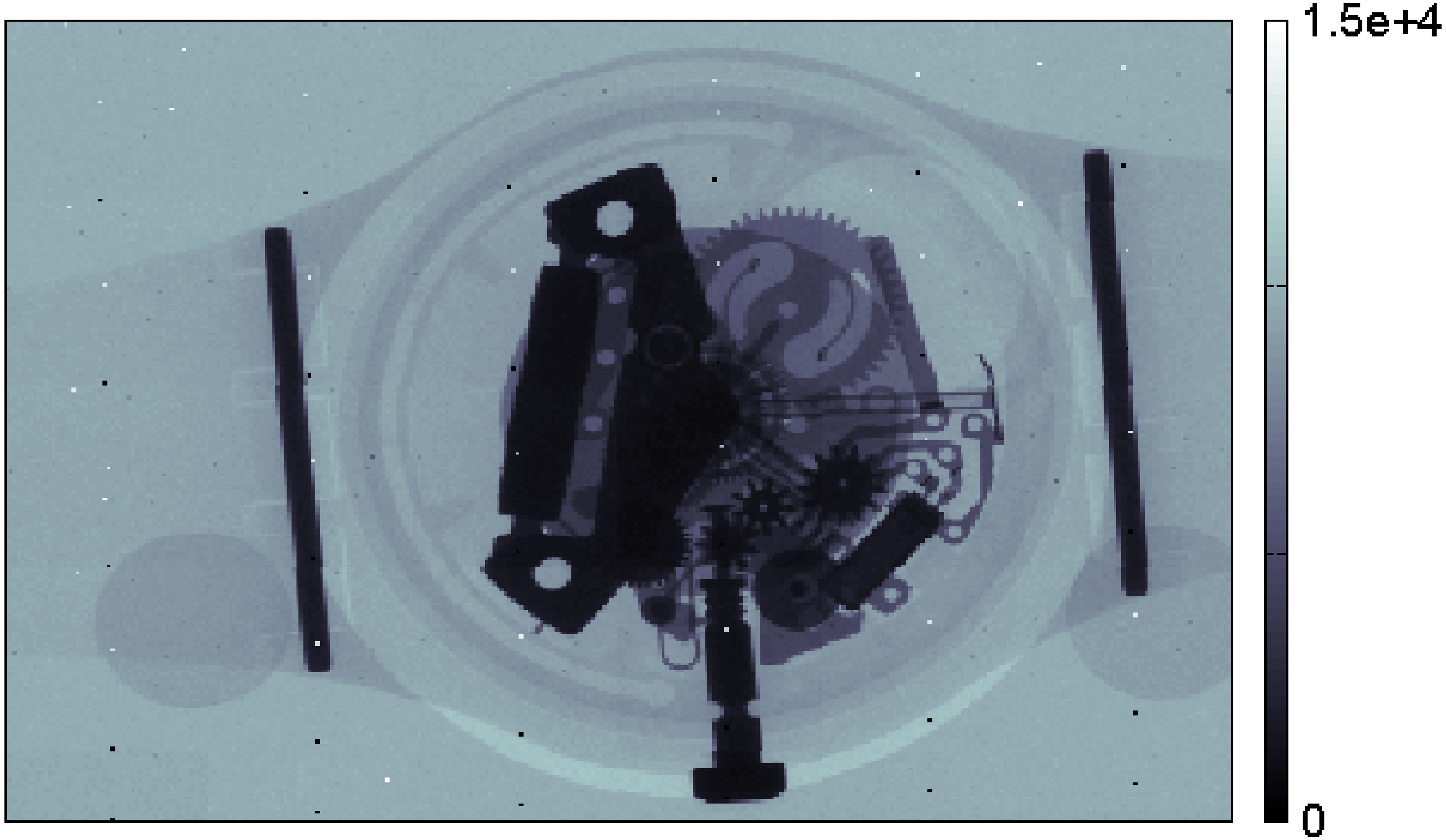
CMOS readout chip
with vias for IO

# Concluding remarks

- **Medipix2 is a successful spin off project based heavily on developments for HEP. Application fields (foreseen and otherwise) include:**
  - **Medical x-ray imaging and tomography**
  - **X-ray imaging for material science**
  - **Synchrotrons light imaging**
  - **Neutron imaging**
  - **TEM for biological structural analysis**
  - **Fast visible photon imaging (when combined with MCP)**
- **Access to modern CMOS technology and to sophisticated design tools is a key this kind of project**
- **High prototyping costs led to the formation of a large collaboration of scientific institutes**
- **As well as being a low cost beacon activity for HEP the enthusiasm and activity generated by such developments spins back into detector development for HEP (Gas detector readout and fast visible light detection)**

**…and lastly…**

# Its fun!




**Thanks to R. Ballabriga, E. Heijne, X. Llopart and L. Tlustos**