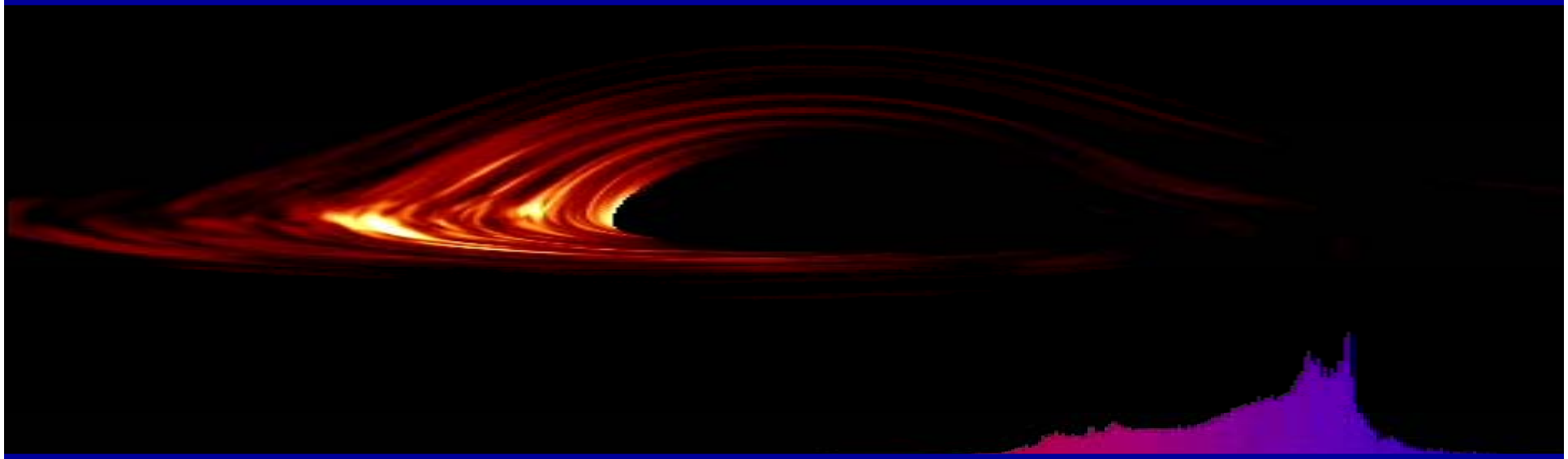
The MPI Semiconductor Laboratory

within Max-Planck Society

Semiconductor Detectors for Experiments In Basic and Applied Science



Detectors Systems for Astrophysics, High Energy Physics and Structure and Dynamics of Matter

Outline:

device basics of SDDs, pnCCDs and DePFETs

- functional principle
- technical realizations
- formats and geometries
- performance figures

SDDs present and future

- Planetary Science
- Material science
- Basic science

pnCCD present and future

- Astrophysics
- Wave Front Sensing
- X-ray FELs
- Electron Imaging

DePFET- APS present and future

- Functional principle
- QE, energy resolution, position resolution, radiation hardness
- Applications: BepiColombo, Athena, DSSC @ XFEL, Belle II,

Semiconductors as detector and electronics material

1. Semiconductors: $E_{Gap} \approx 1 - 2$ eV
   → small leakage currents
   → low noise, operation @ r.t.

2. Pair creation energy: $w = 2 – 5$ eV
   → large number of signal charges per energy deposit in detector

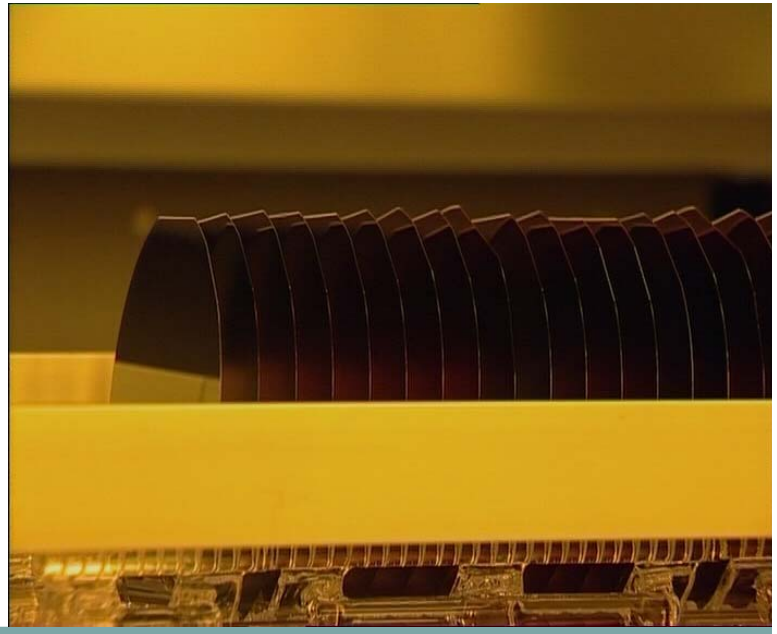
3. Density: $\rho = 2 - 5$ g cm^{-3}
   → high energy loss per unit length
   → low range of δ - electrons

This leads to:

good energy resolution
high spatial resolution
high quantum and detection efficiency
good mechanical regidity and thermal conductivity

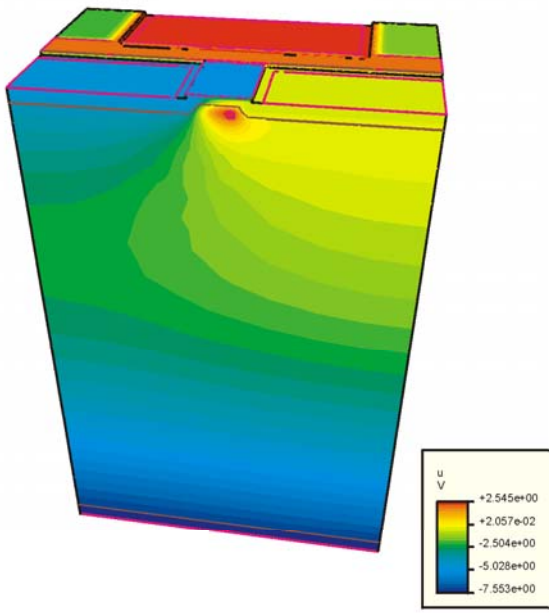
Semiconductors equally offer:

fixed space charges
high mobility of charge carriers

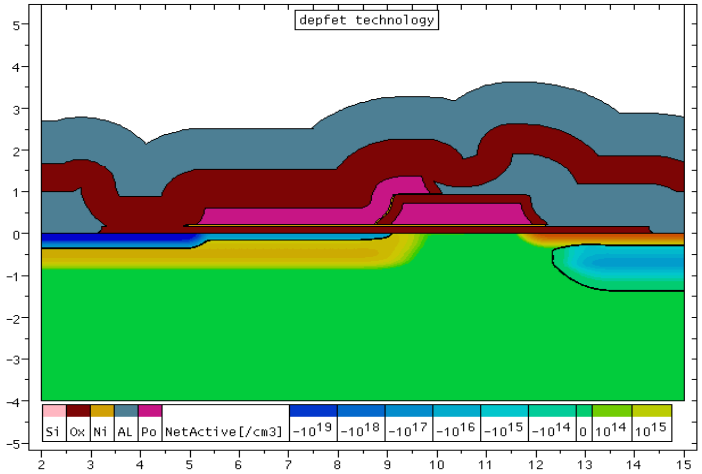


Detector and electronics simulation and layout

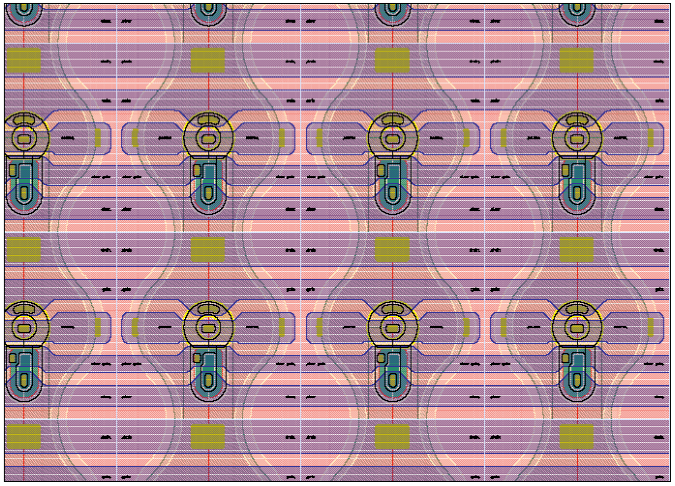
1. The detector idea: simulation of electrical properties



2. Simulation of the production process



3. Design and layout of the entire detetor system, including signal processing and DAQ



The location

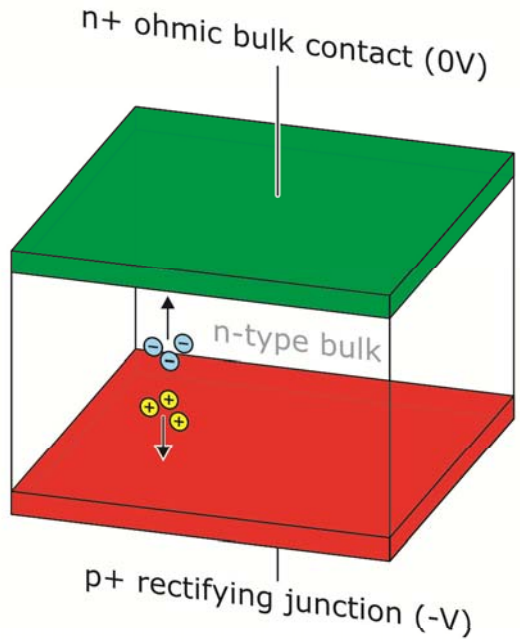
G

Dicing, r

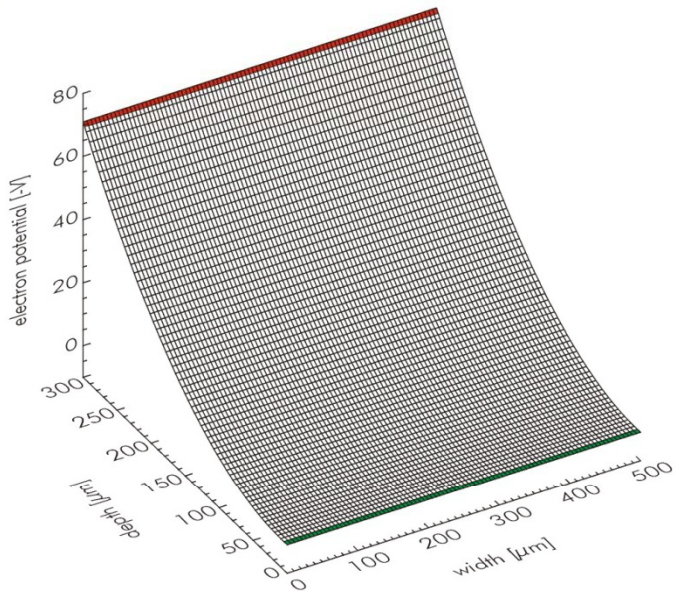
Device tests and operation

or, Munich, germany

Detector Structures

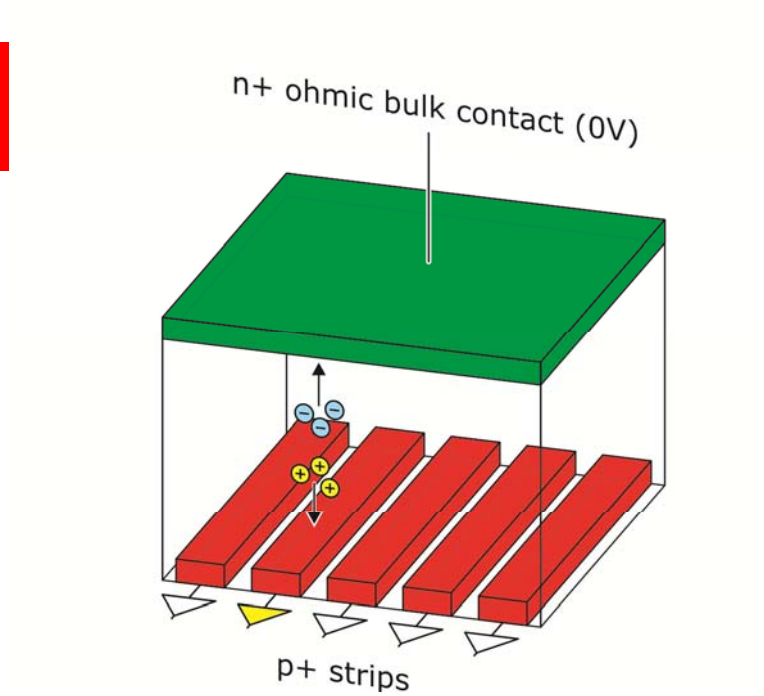


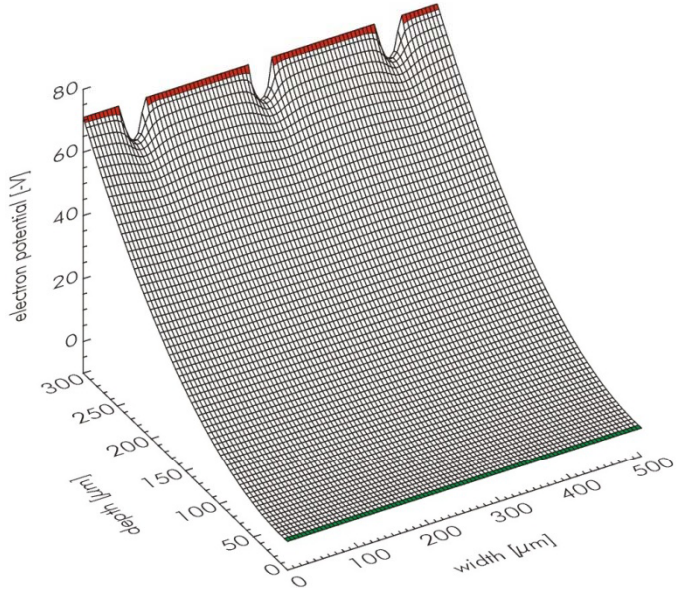
- diode
  - material silicon
    germanium
    compound semiconductors
    (CdTe, CZT, …)
  - geometry
    size 5 mm² … several cm²
    thickness 300, 500 μm, 1 mm
  - applications
    X-ray spectroscopy
    particle detection
    γ-ray spectroscopy



Detector Structures

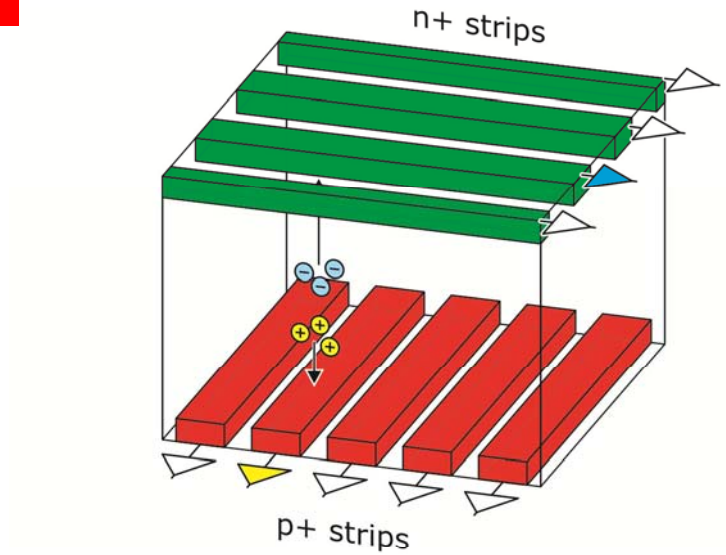
- **structured diode: single-sided strip detector**
  - **material** **silicon**
    germanium
    compound semiconductors
    (GaAs, CdTe, CZT, ...)
    diamond
  - **geometry**
    - **size** **wafer size**
      typ. **6 x 6 cm²**
      10 x 10 cm²
    - **thickness** **300, 500 µm**
    - **strip width/pitch** **it depends ...**
      10 µm ... 1 mm
    - **position accuracy** **down to few µm**
  - **applications**
    - **particle tracking**

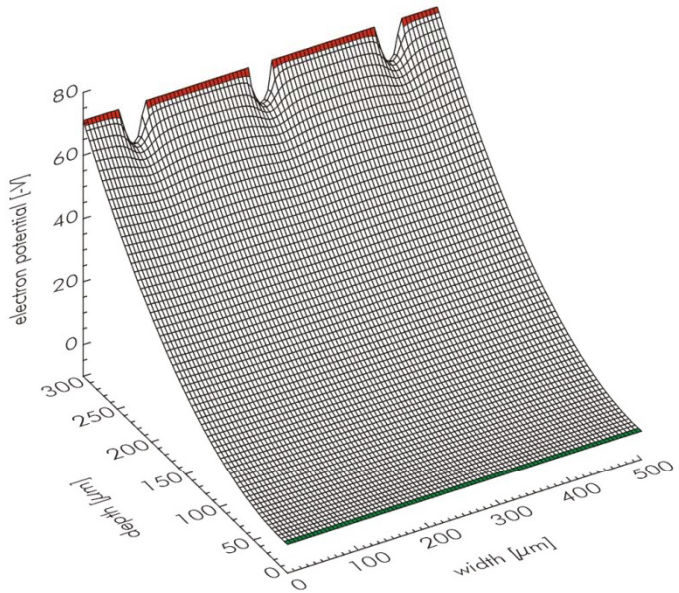




Detector Structures

- **structured diode: double-sided strip detector**
  - **material** **silicon**
    germanium
    compound semiconductors
    (GaAs, CdTe, CZT, ...)
    diamond
  - **geometry**
    - **size** **wafer size**
      typ. **6 x 6 cm²**
      10 x 10 cm²
    - **thickness** **300, 500 µm**
    - **strip width/pitch** **it depends ...**
      10 µm ... 1 mm
    - **position accuracy** **down to few µm**
  - **applications**
    - **particle tracking**



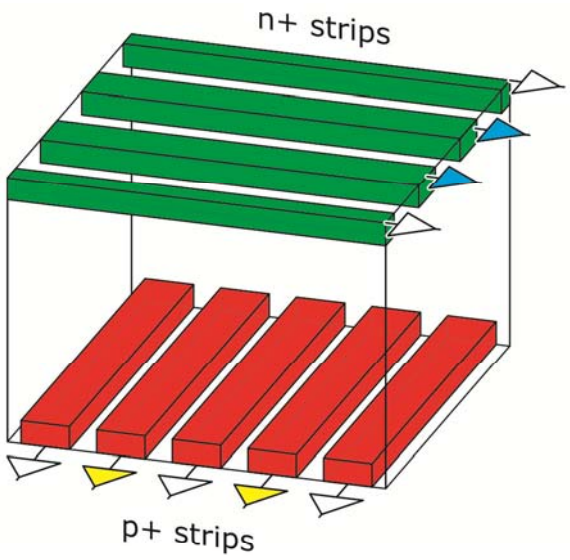


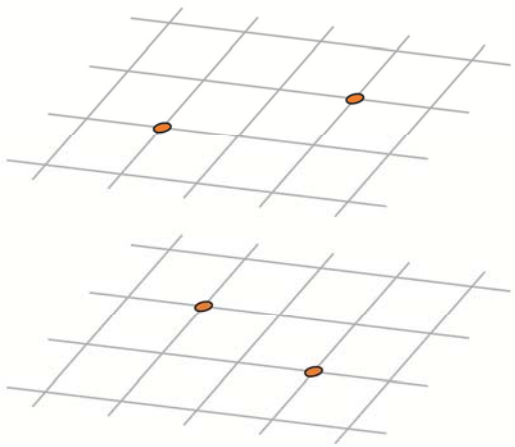
Detector Structures

- **double-sided strip detector**
  - **advantage**
    n^2 resolution elements with
    2n readout channels
  - **disadvantage**
    ambiguity at high occupancy

??

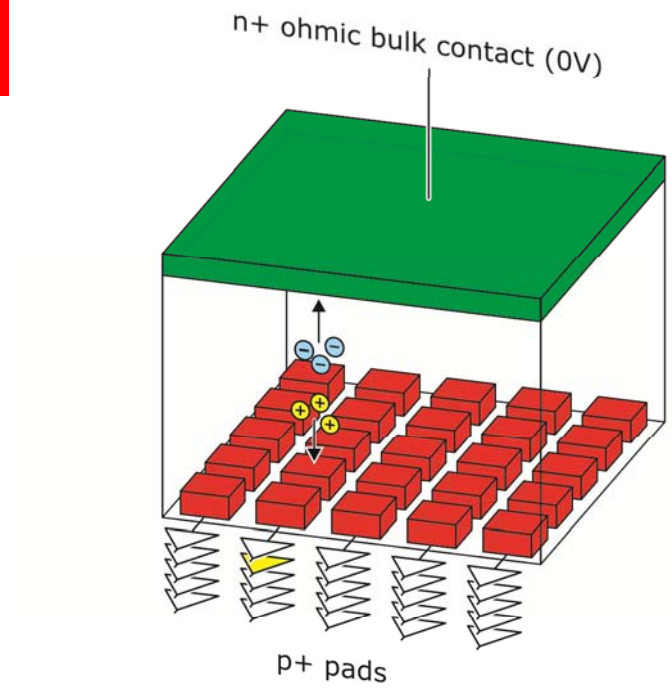
↳ **2dim pixel sensor**

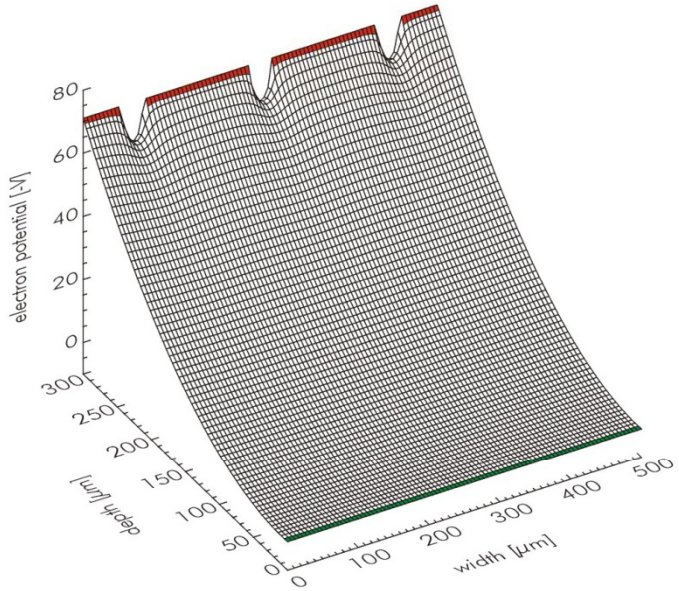




Detector Structures

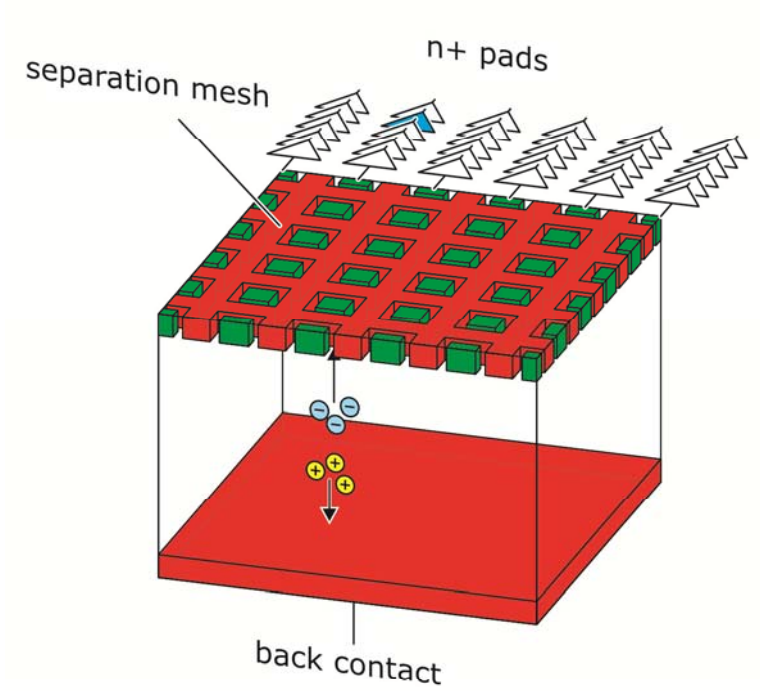
- **pad detector 'p on n'**
  - **material** **silicon**
    germanium
    compound semiconductors
    (GaAs, CdTe, CZT, ...)
    diamond
  - **geometry**
    - **size** **wafer size**
      typ. **6 x 6 cm²**
      10 x 10 cm²
    - **thickness** **300, 500 µm**
    - **pixel size** **≥ 50 µm**
  - **applications**
    - **particle tracking**
      ↳ **detection of individual charged particles**
    - **imaging**
      ↳ **count / integrate particles or photons**

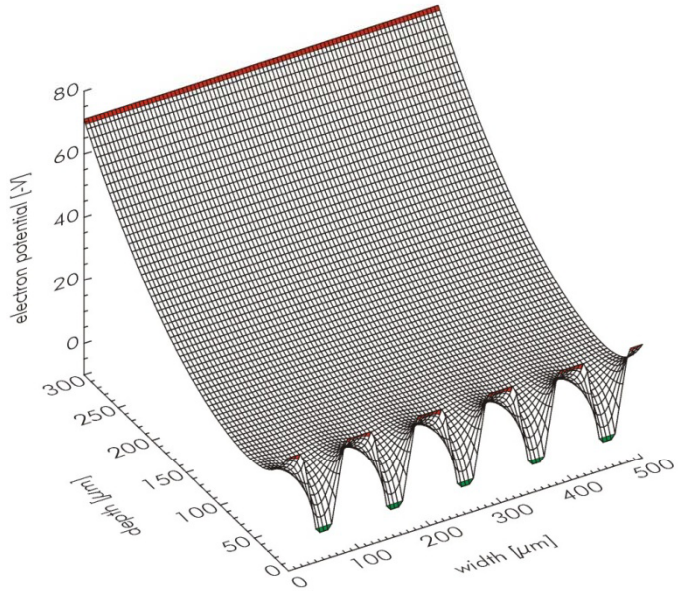




Detector Structures

- **pad detector 'n on n'**
  - **material** **silicon**
    germanium
    compound semiconductors
    (GaAs, CdTe, CZT, ...)
    diamond
  - **geometry**
    - **size** **wafer size**
      typ. **6 x 6 cm²**
      10 x 10 cm²
    - **thickness** **300, 500 µm**
    - **pixel size** **≥ 50 µm**
  - **applications**
    - **particle tracking**
      ↳ **detection of individual charged particles**
    - **imaging**
      ↳ **count / integrate particles or photons**





Detector Structures

diode

- electronic noise

$$ENC = \sqrt{\alpha \frac{2kT}{g_m} C_{tot}^2 A_1 \frac{1}{\tau} + 2\pi a_f C_{tot}^2 A_2 + q I_L A_3 \tau}$$

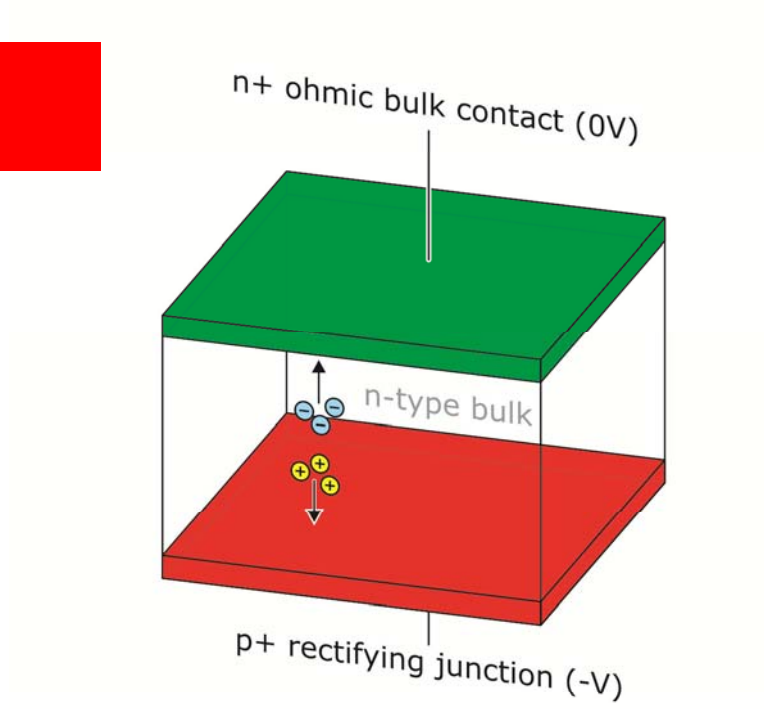
- optimum shaping time

$$\tau_{opt} = \sqrt{\frac{2A_3}{A_1} \frac{kT}{q} \frac{C_{tot}^2}{I_L} \frac{2}{3g_m}}$$

↳ for

- good resolution
- high count rate capability

the total capacitance must be minimised!!

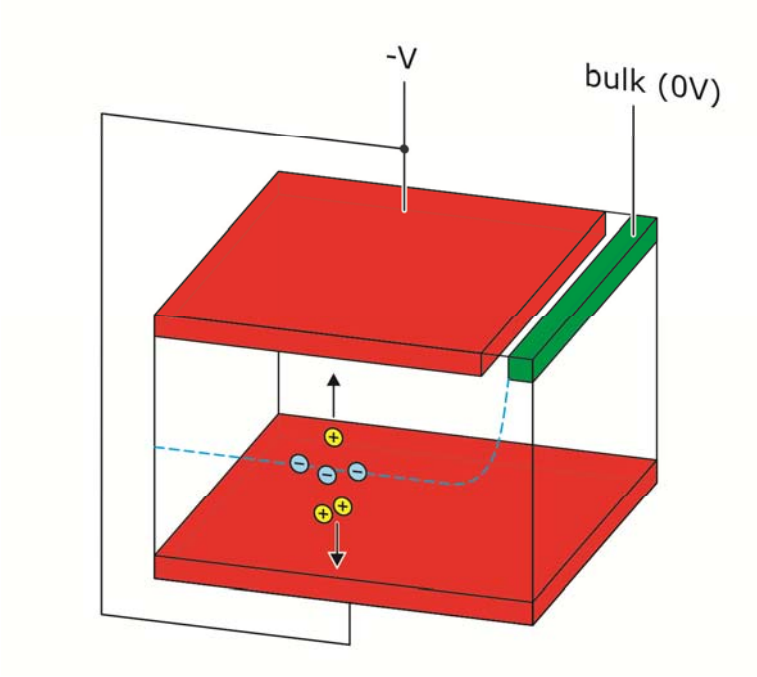


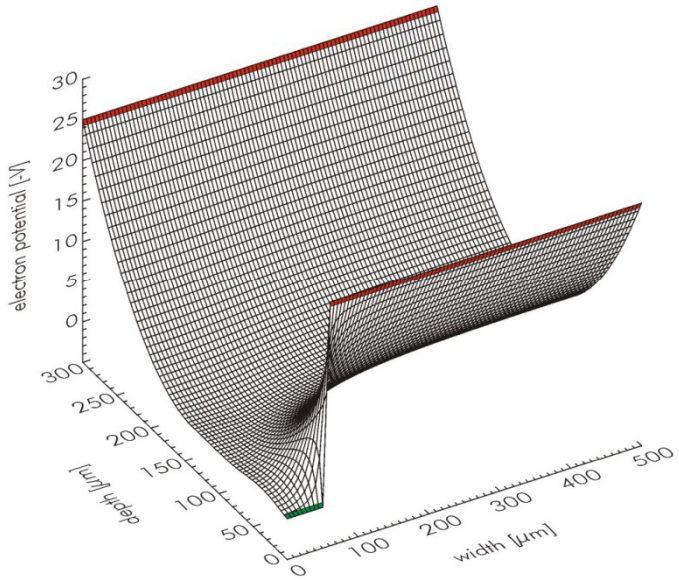
Detector Structures

- sideward depletion structure

Emilio Gatti & Pavel Rehak, 1983

  - symmetric bias
  - volume is fully depleted by reverse biased diodes on both surfaces
  - minimum capacitance of bulk contact, independent of overall area
  - potential minimum for majority carriers (electrons @ n-Si) in the centre plane





Detector Structures

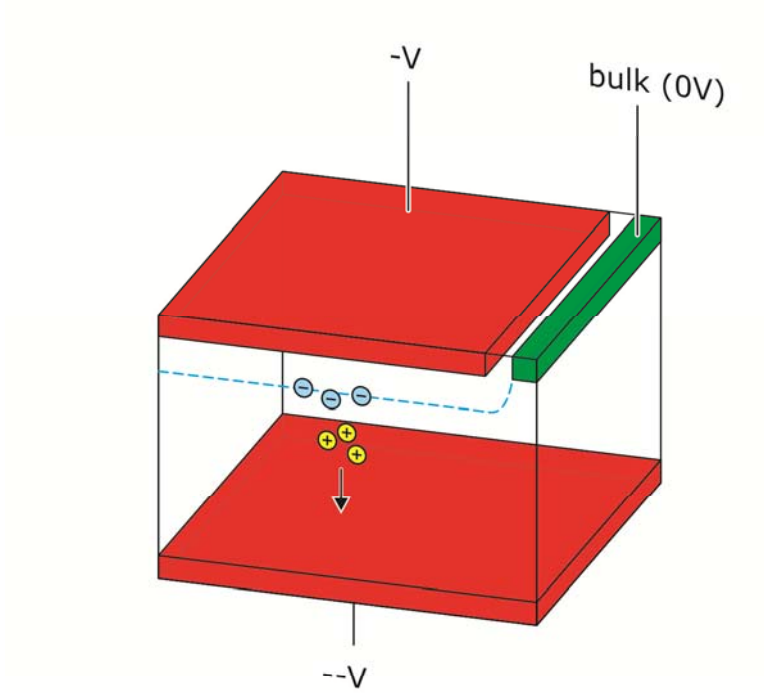
- sideward depletion structure

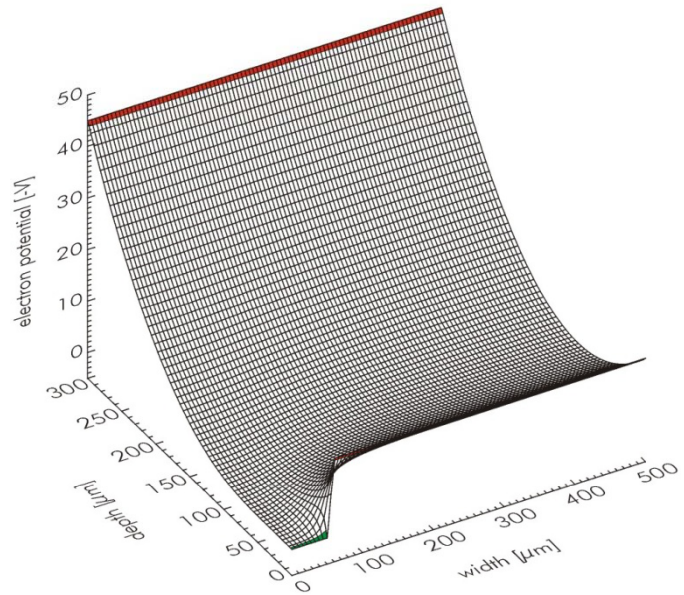
  asymmetric bias

  - volume is fully depleted by reverse biased diodes on both surfaces
  - minimum capacitance of bulk contact, independent of overall area
  - vertical shift of the potential minimum

  ?? signal extraction ??

  ↳ advanced detector concepts

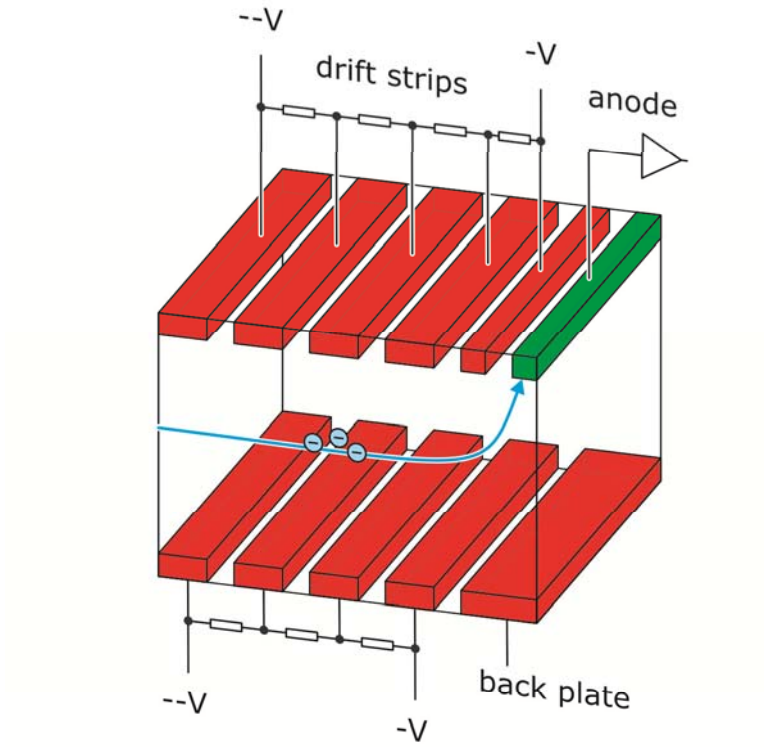


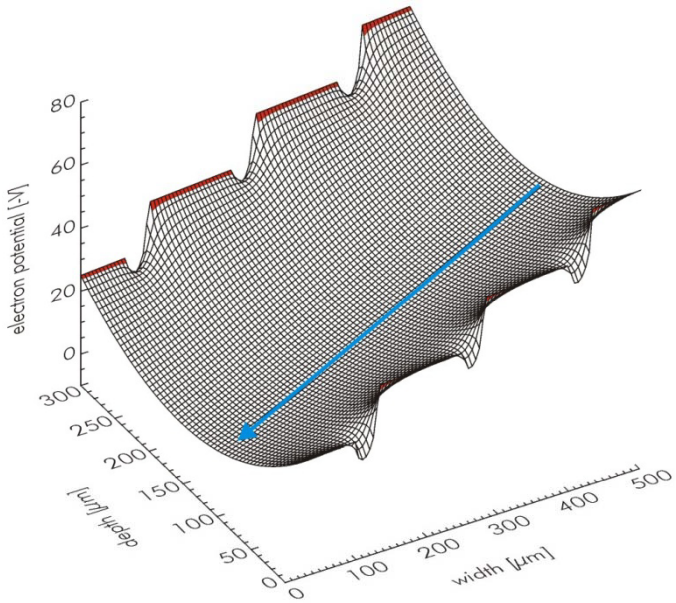


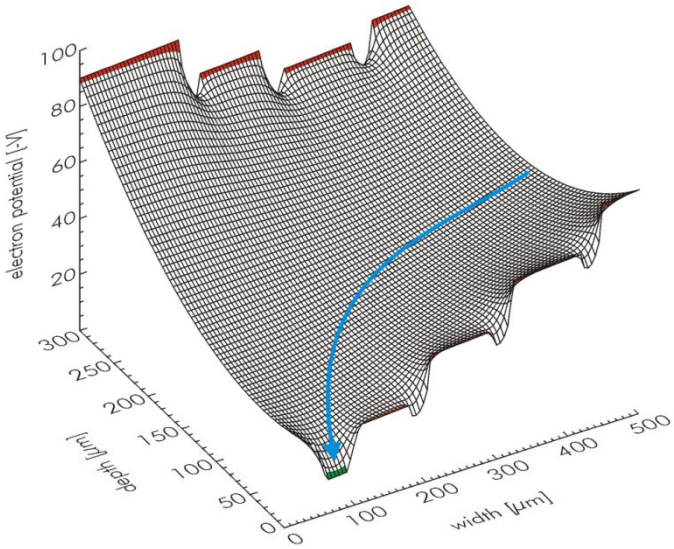
Detector Structures

- linear silicon drift detector (SDD)

  - segmentation and bias of diodes
    ↳ drift field || surface
  - 1dim position resolution by drift time measurement
    start trigger required!

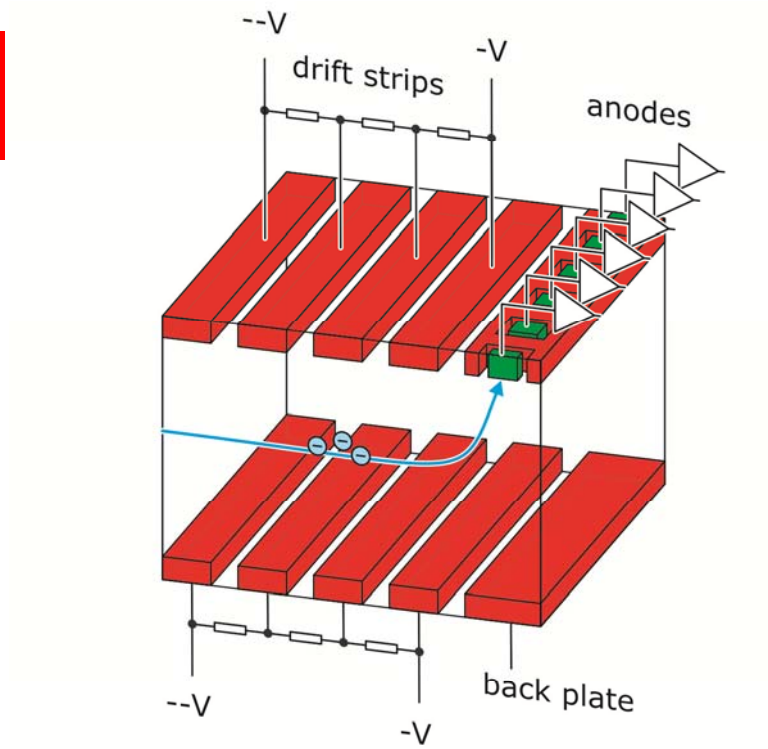


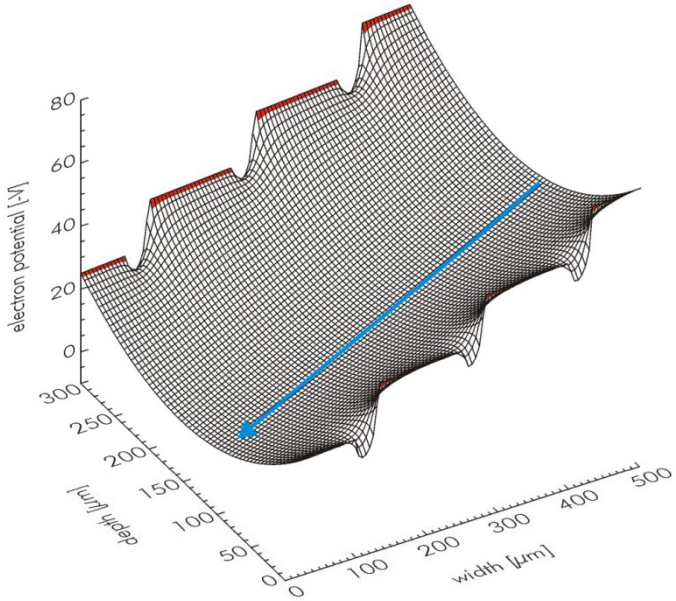


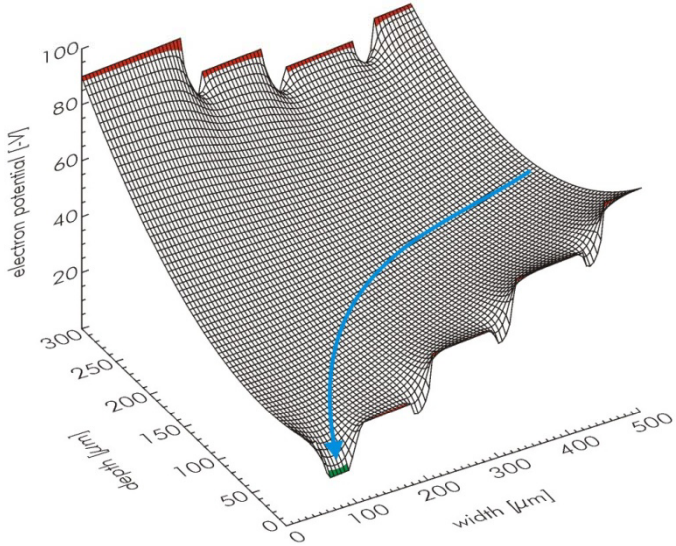


Detector Structures

- linear silicon drift detector (SDD)
  - segmentation and bias of diodes
    ↳ drift field || surface
  - 2dim position resolution by
    - drift time measurement (trigger!)
    - segmentation of the anode
  - application: particle tracking



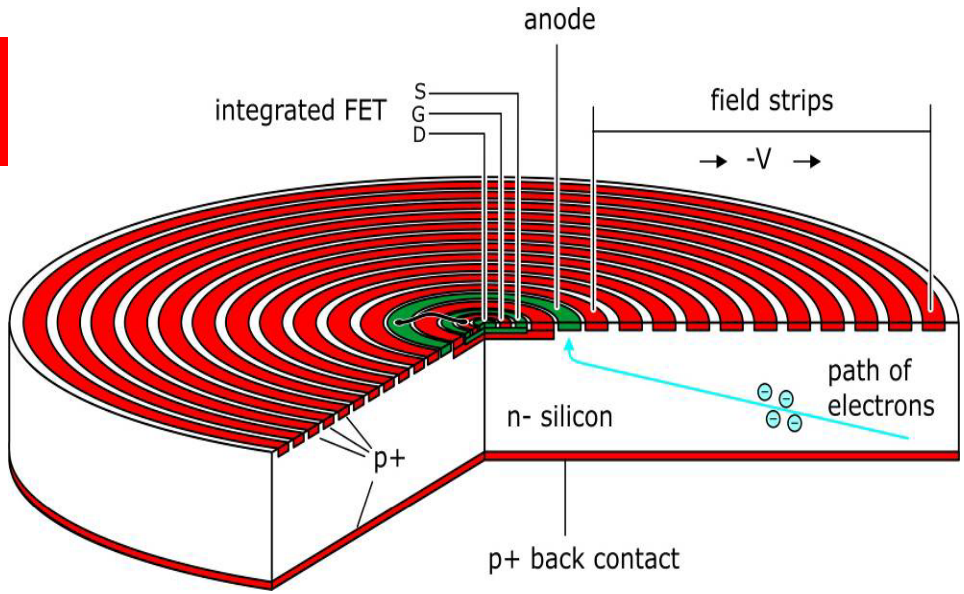


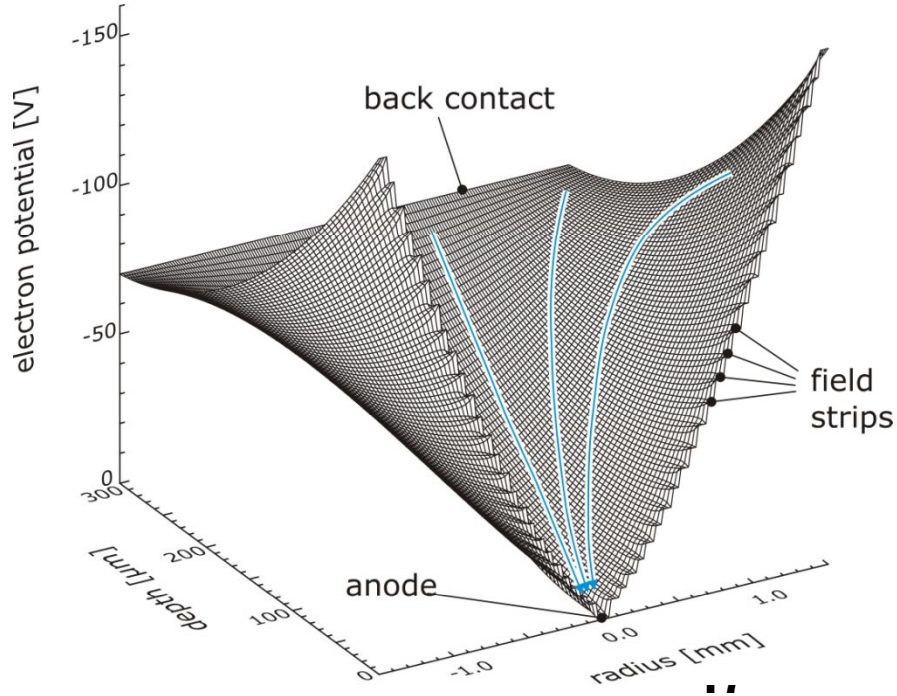


Detector Structures

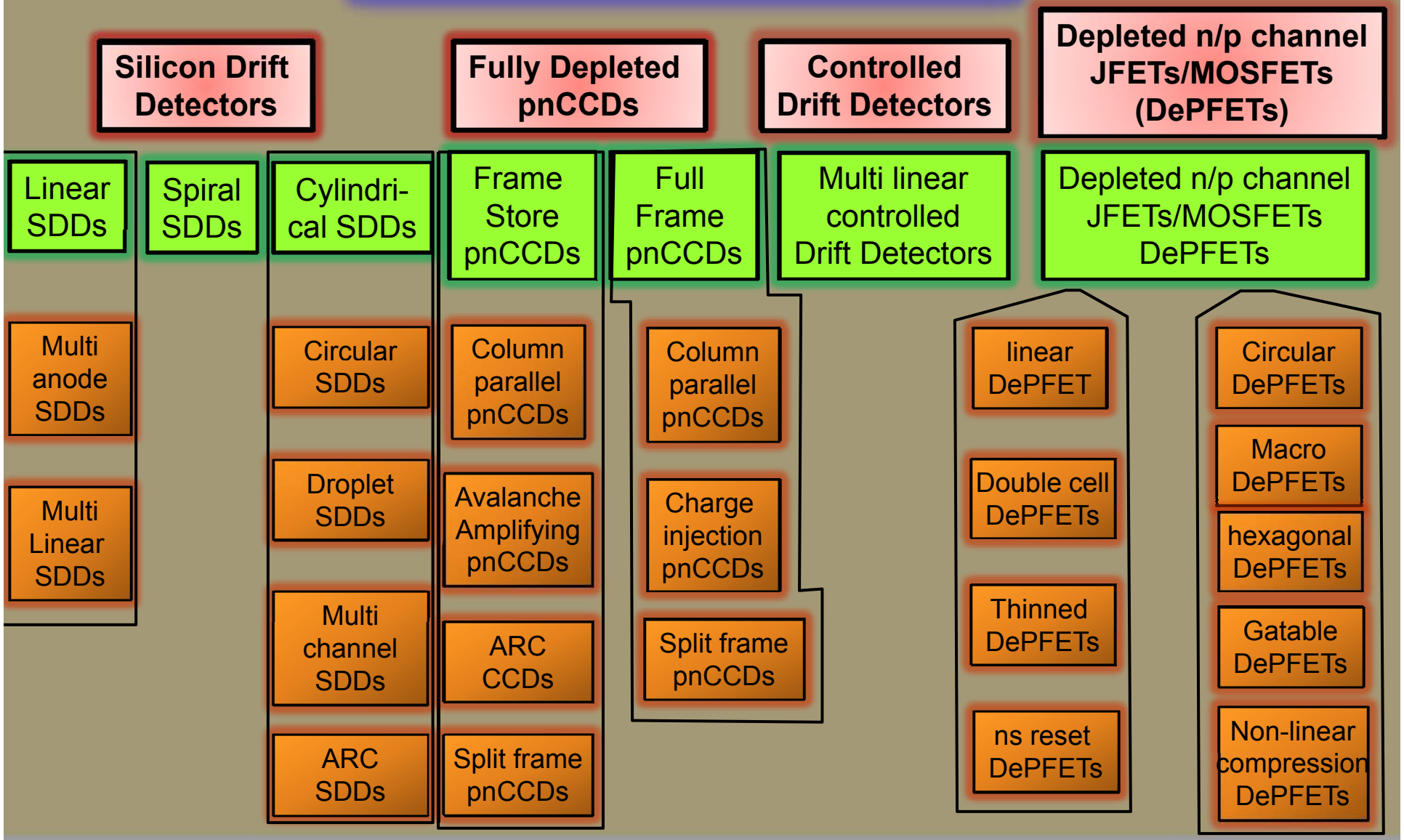
- SDD with on-chip FET

  - one-sided field strip system
  - backside illuminated
  - integration of 1st amplifying FET dedicated n-JFET
    - ↳ minimization of total capacitance
    - ↳ good energy resolution
    - ↳ high count rate capability
    - ↳ robust against pickup, microphony
  - comparison
    - pin diode 10 mm² x 300 μm
      C_{tot} = 3.5 pF
    - SDD with FET 10 - 100 mm²
      C_{tot} = 30 - 50 fF





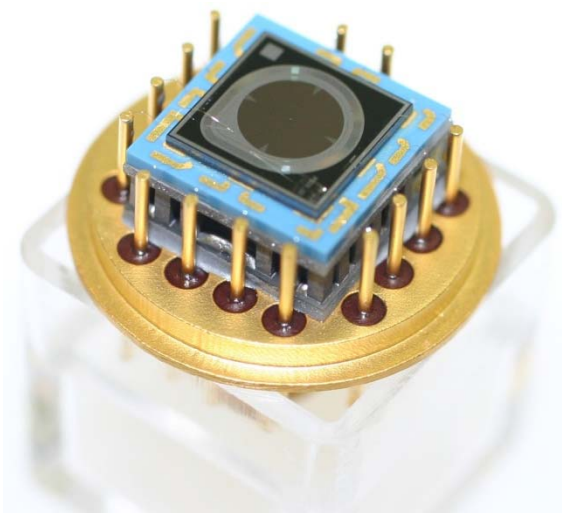
Principle of Sideward Depletion

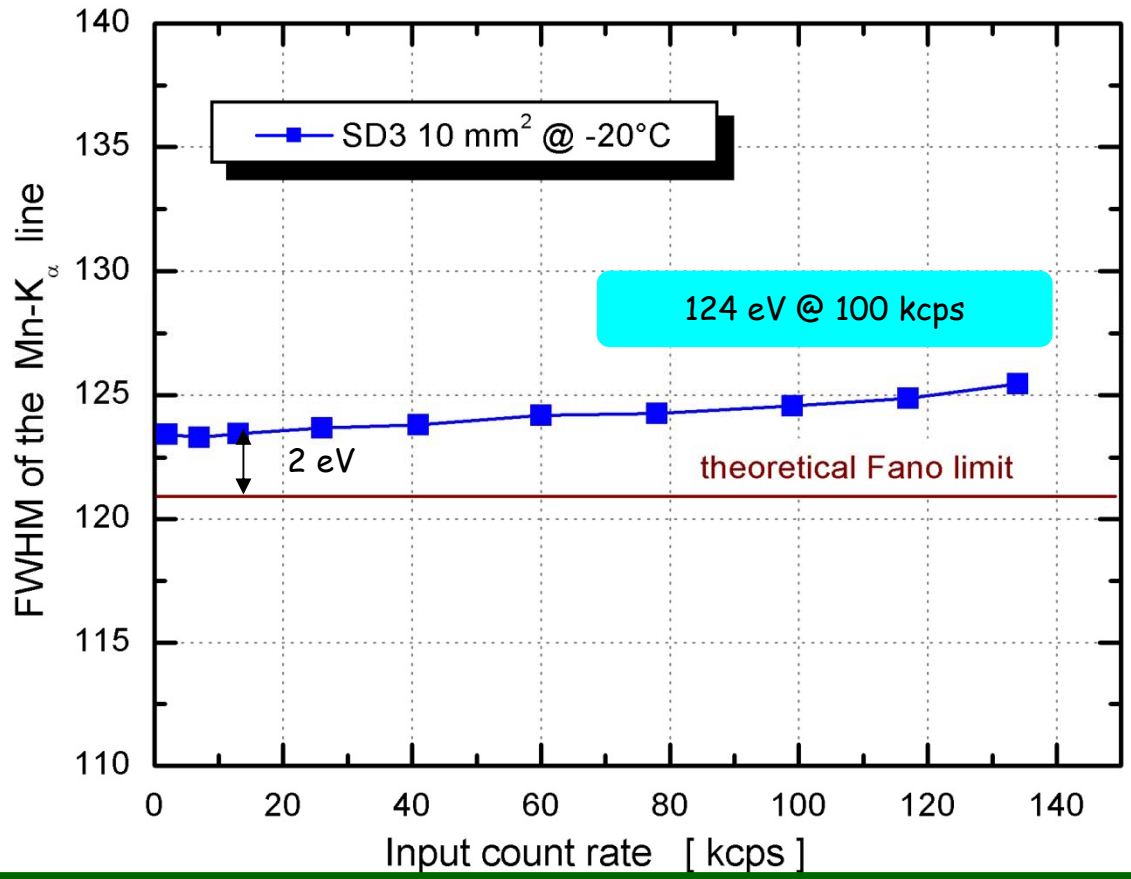


Spectroscopic performance of 5 and 10 mm² SD3 detectors

- operation temperature -20°C
- 1-stage Peltier cooler
- optimum shaping time 0.5 µs
- pulsed reset operation

Optimized detector entrance window for light element detection - pnWindow





A single SDD can process up to 1 M counts per sec below 170 eV

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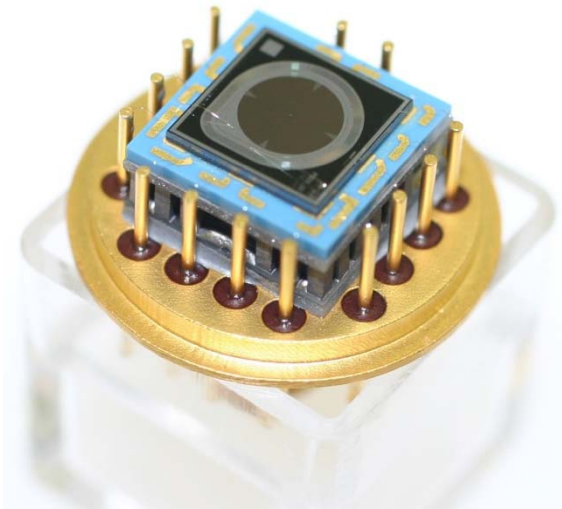

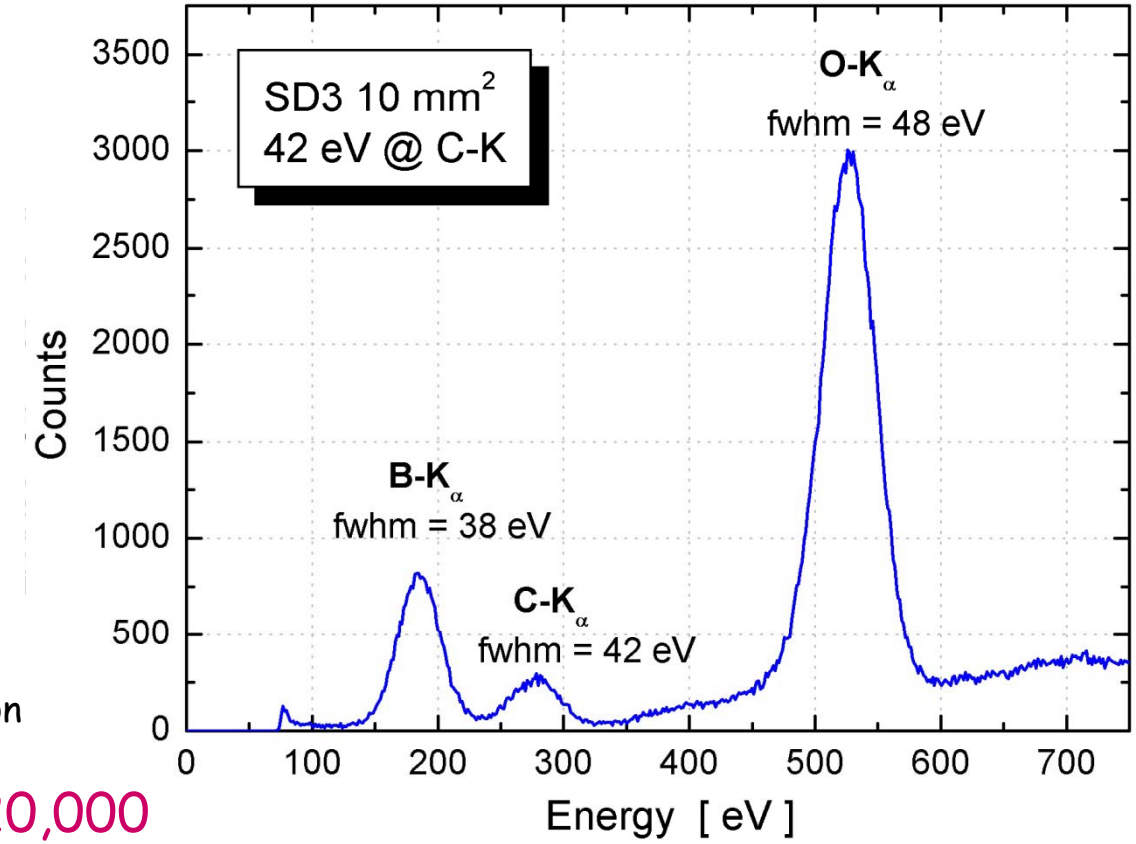

- Light element detection
  FWHM @ B-K = 38 eV
- P/B = 13,000 ÷ 20,000

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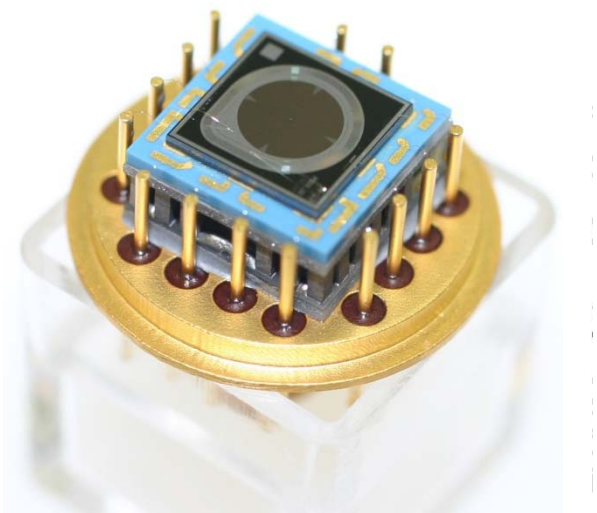
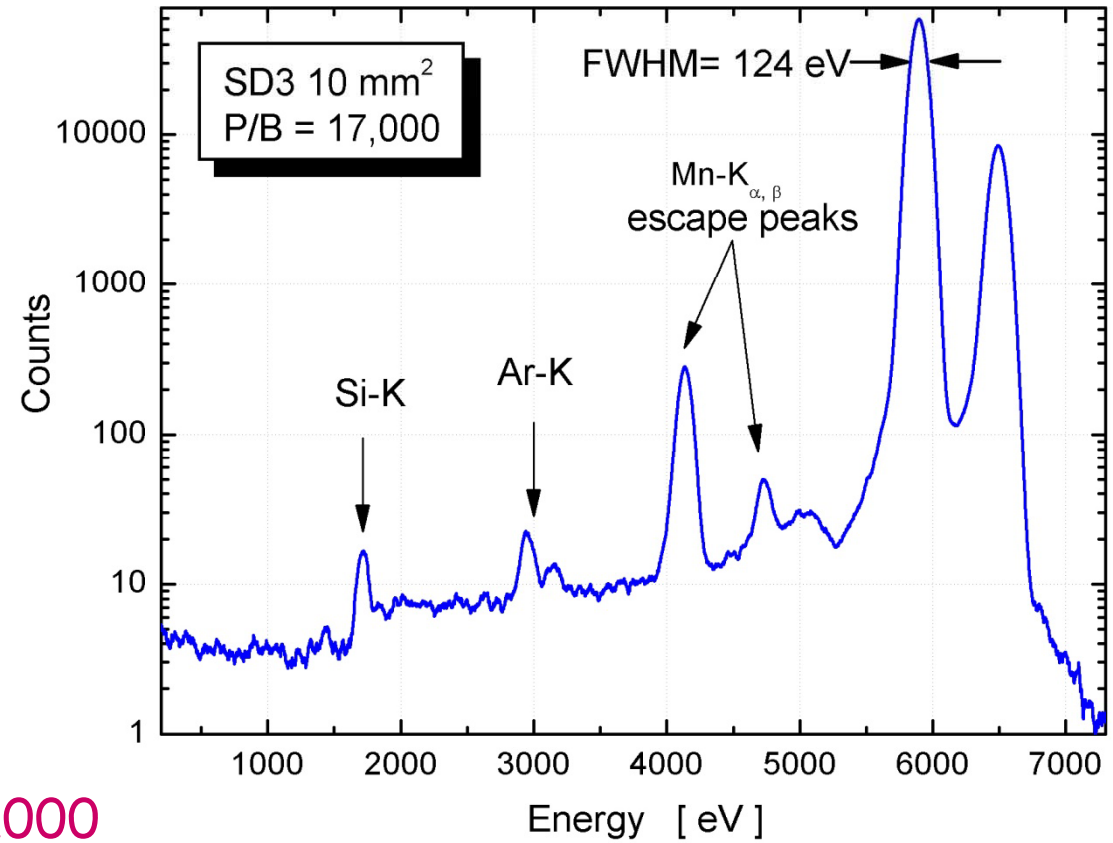
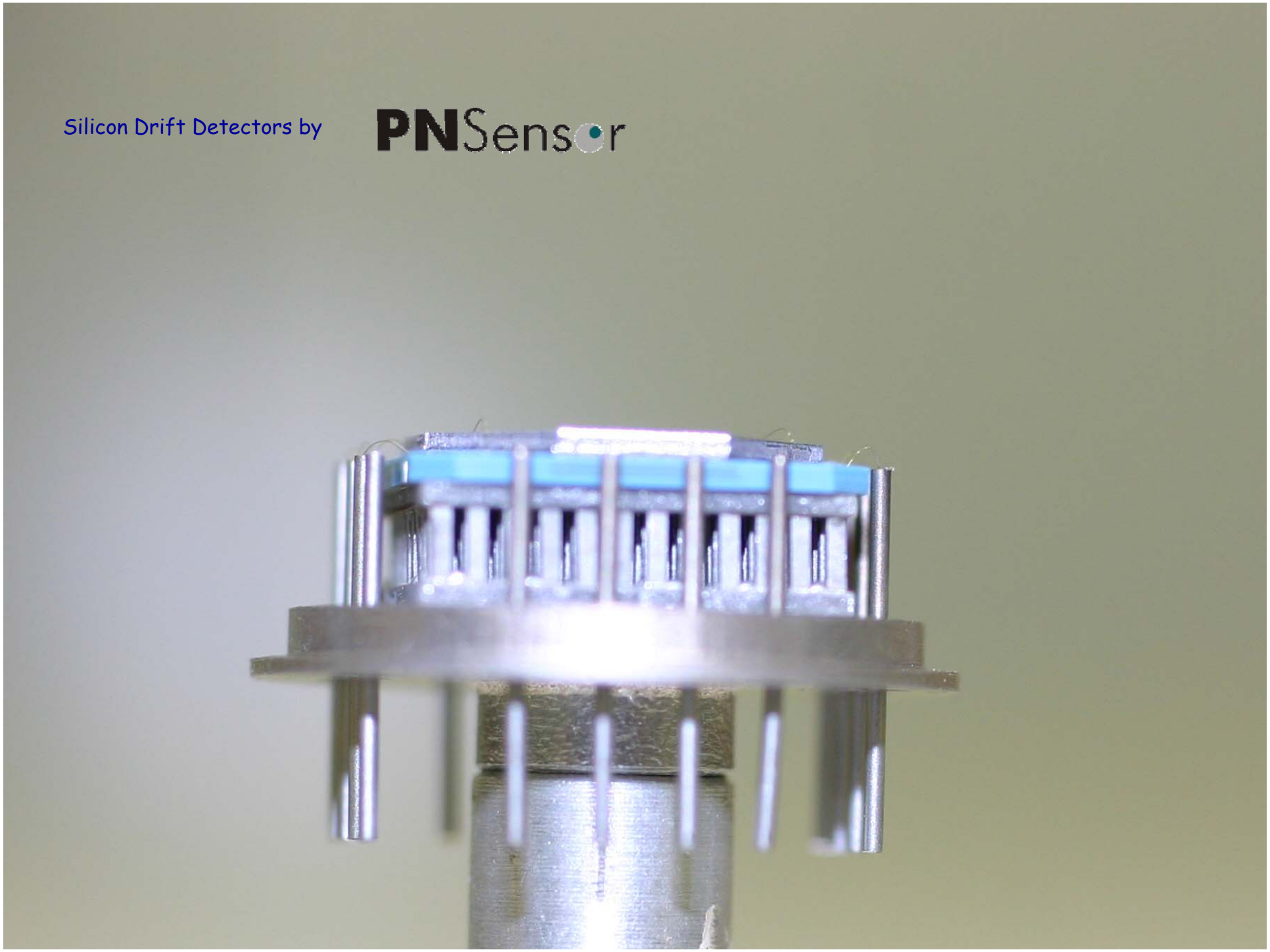




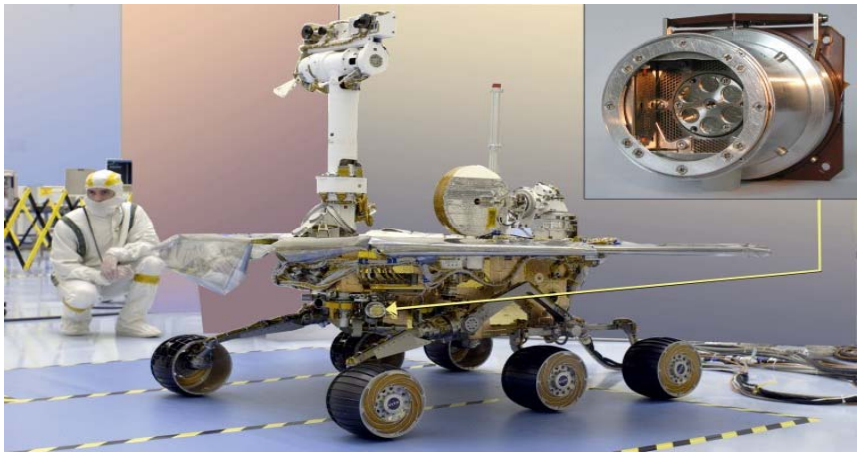
- Light element detection
  FWHM @ B-K = 38 eV
- P/B = 13,000 ÷ 20,000

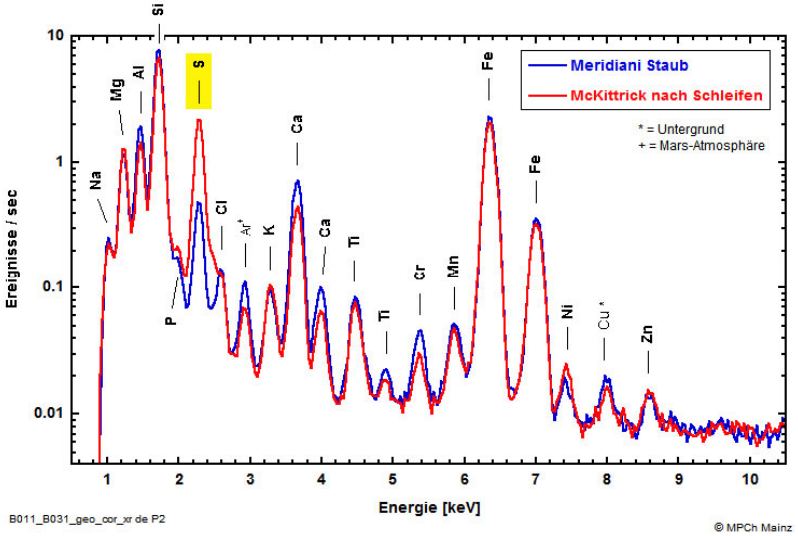
A single SDD can process up to 1 M counts per sec below 170 eV

Silicon Drift Detectors by PNSensor



SDDs on Mars Explorers Spirit and Opportunity

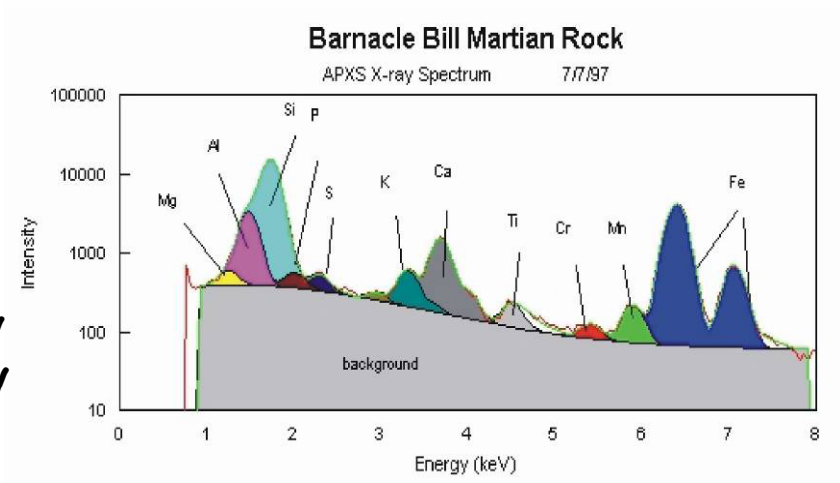


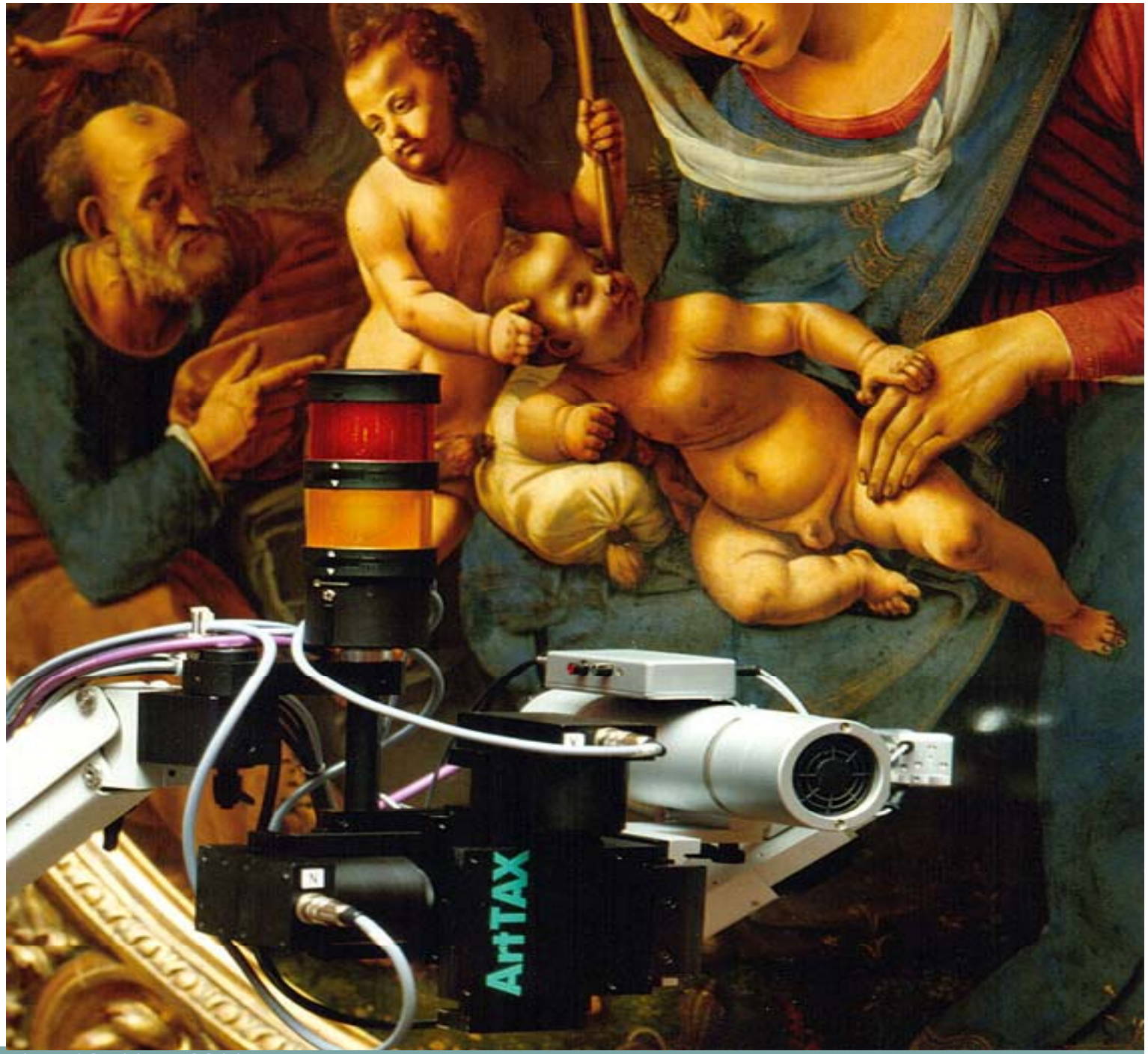


The APXS system of the MPICH in Mainz:

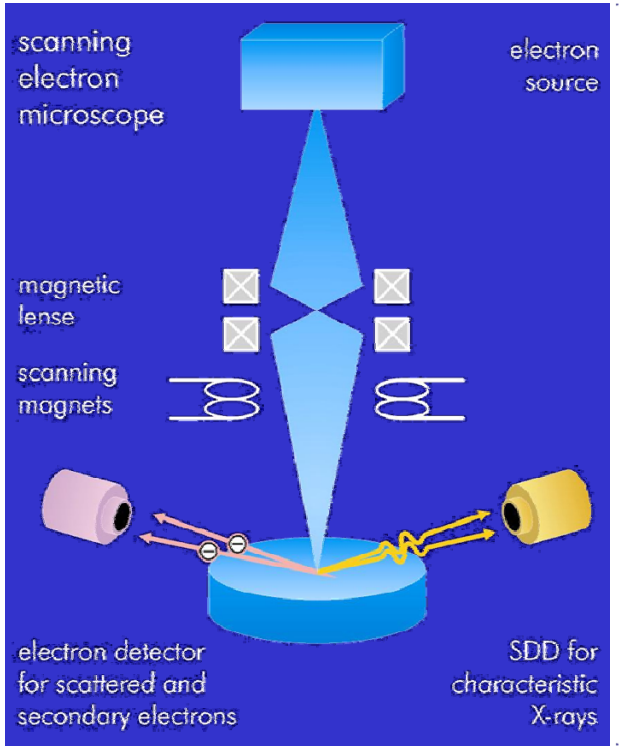
Excitation with Curium-244:
α – particles
X – rays

ΔE @ Spirit&Opportunity @ 1.5 keV: 80 eV
ΔE @ Pathfinder @ 1.5 keV: 280 eV

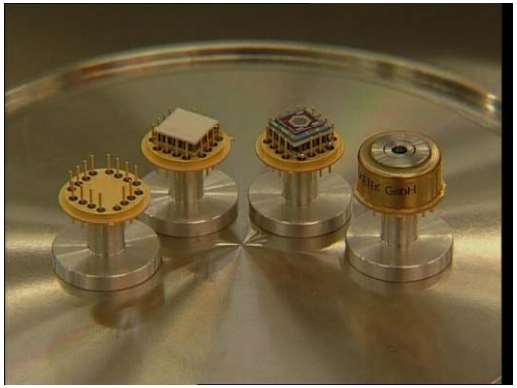



ArtTAX

Applications of SDDs



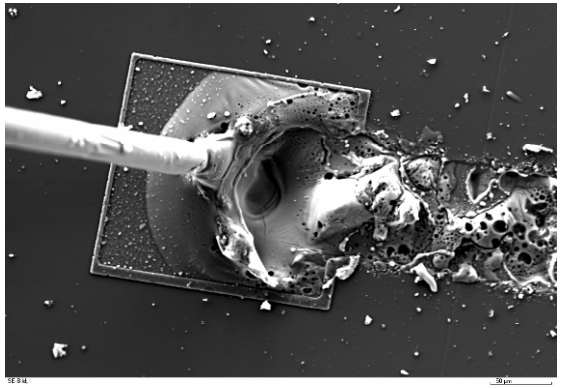
Scanning electron microscope with separated electron and X-ray detector



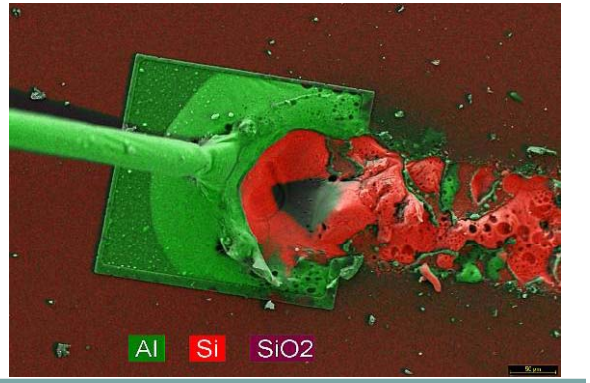
SDD – Modules from 5 mm² bis 100 mm², 1 – 77 Module/Chip

Measurements made by RÖNTEC, Berlin

SEM – image

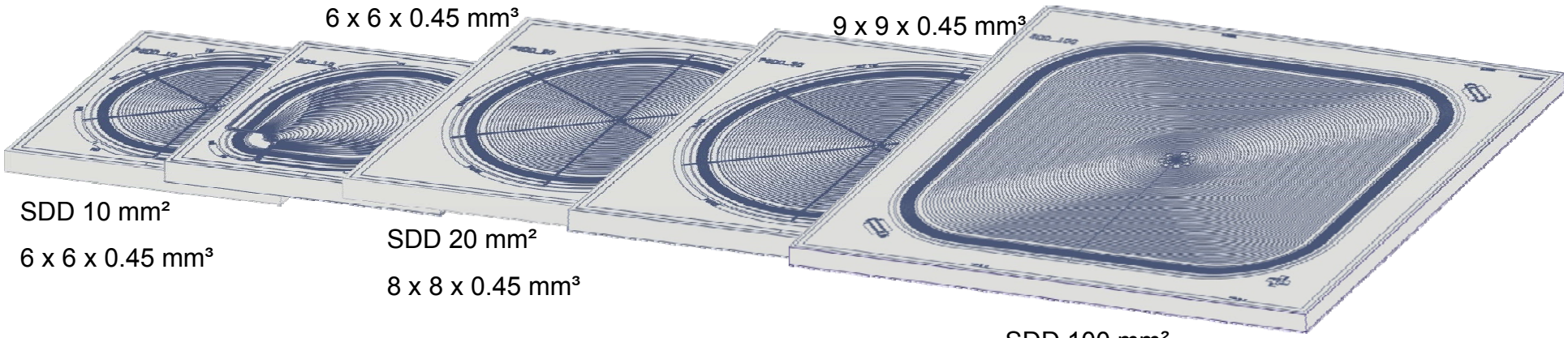


``colour – image´´

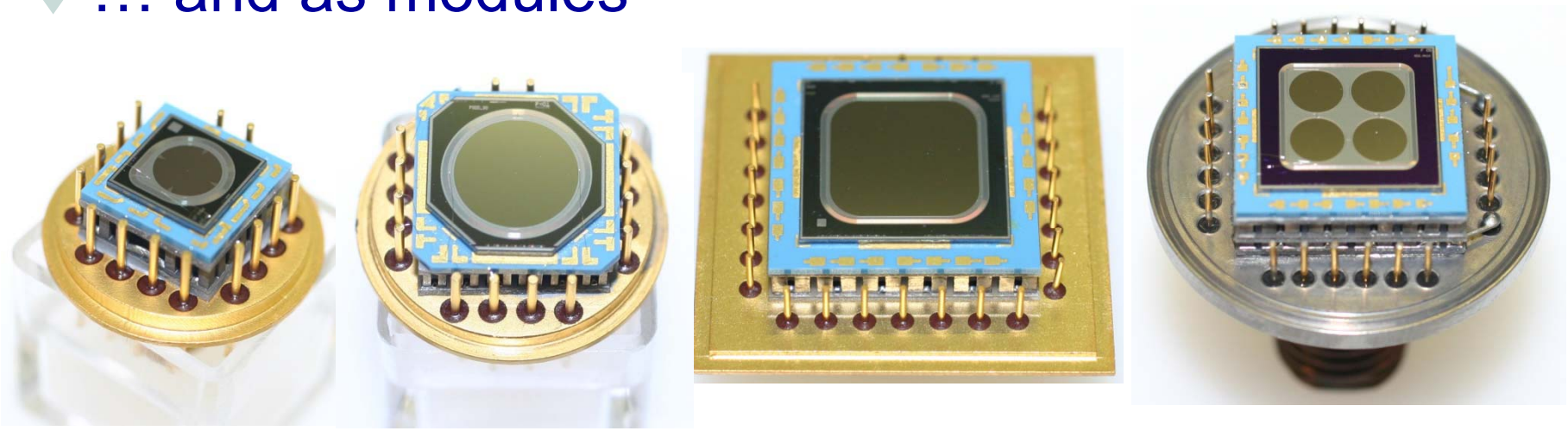


SDD with integrated FET

- SDDs as chips



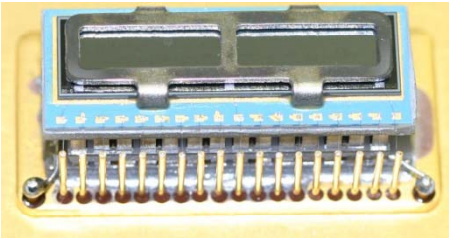
- … and as modules

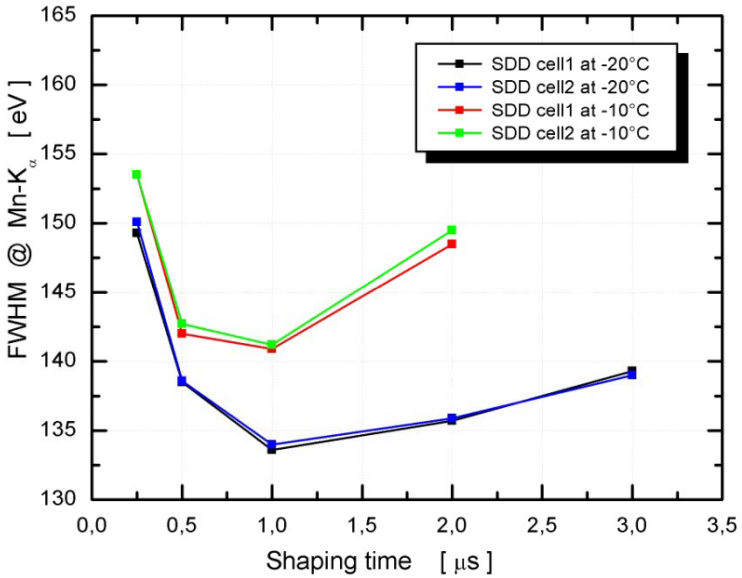


Extra Large Detector Area

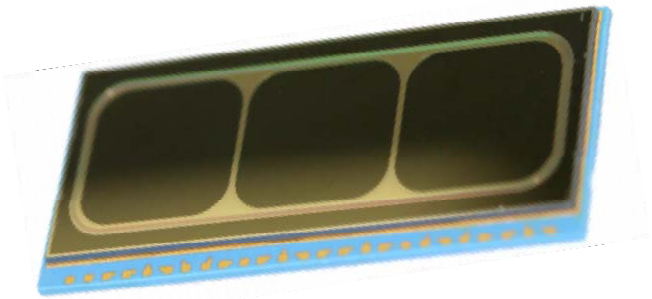
" Application adapted "

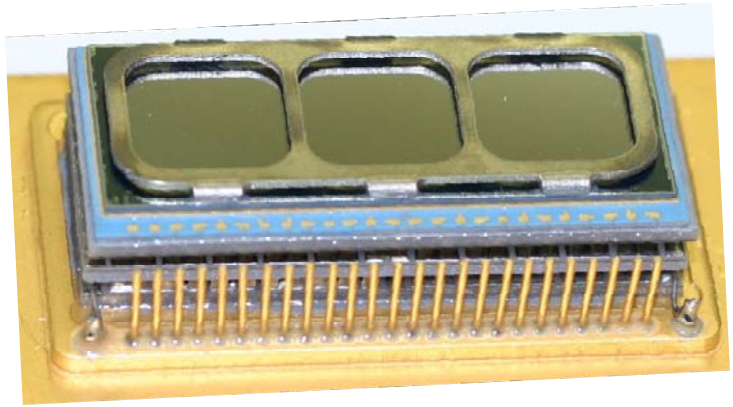
3 x 20 mm² SDD
(e.g.for fixed channel WDX instr.)





3 x 1 cm² SDD
(e.g. for sequential WDX instr.)

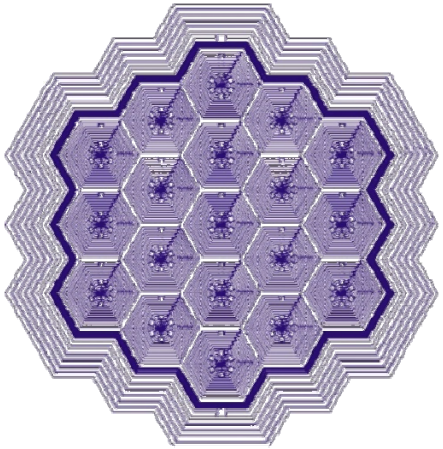




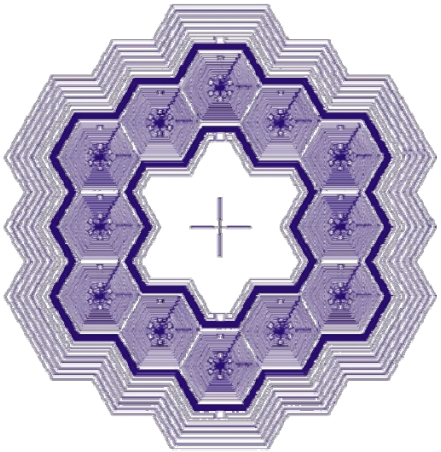
monolithically integrated, no dead area

Multi-Element SDDs

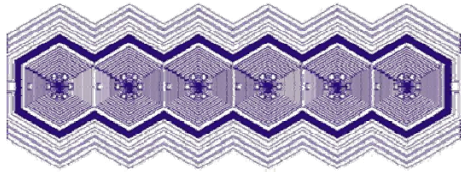
19x5 mm^2 = 95 mm^2



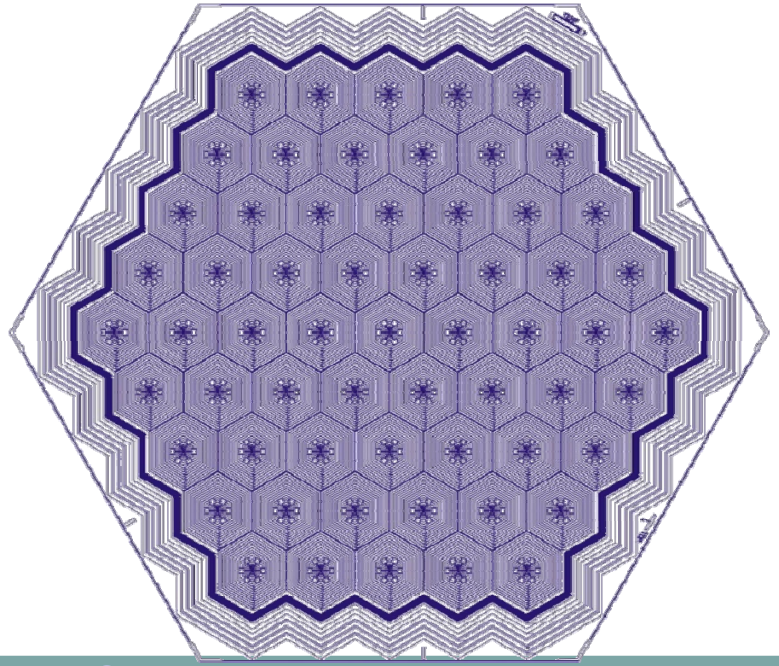
12x5 mm^2 = 60 mm^2



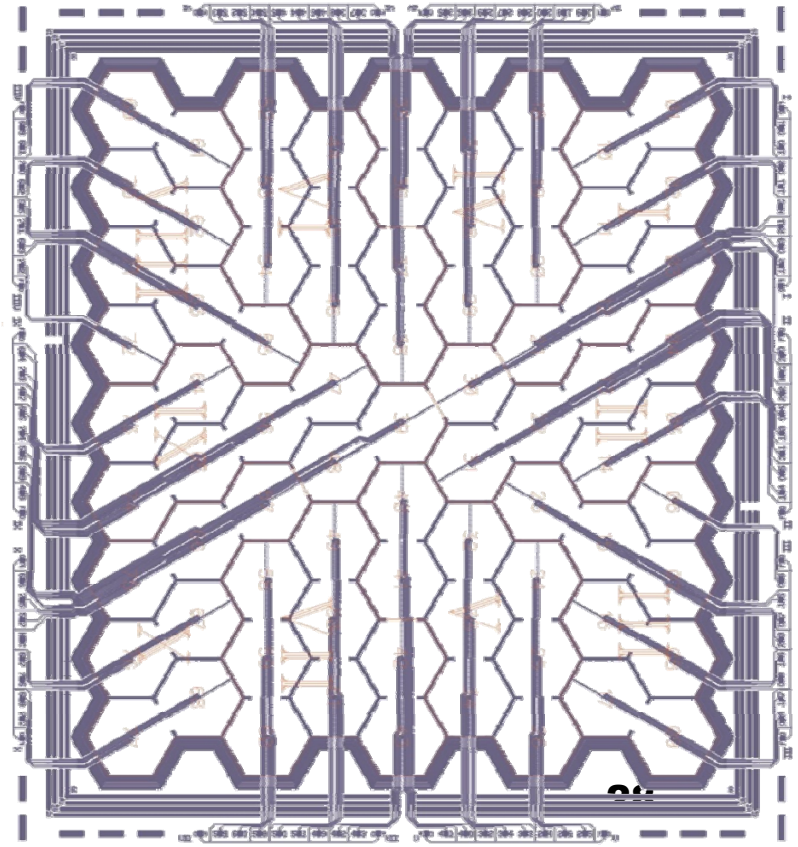
6x5 mm^2 = 30 mm^2



61x5 mm^2 = 305 mm^2

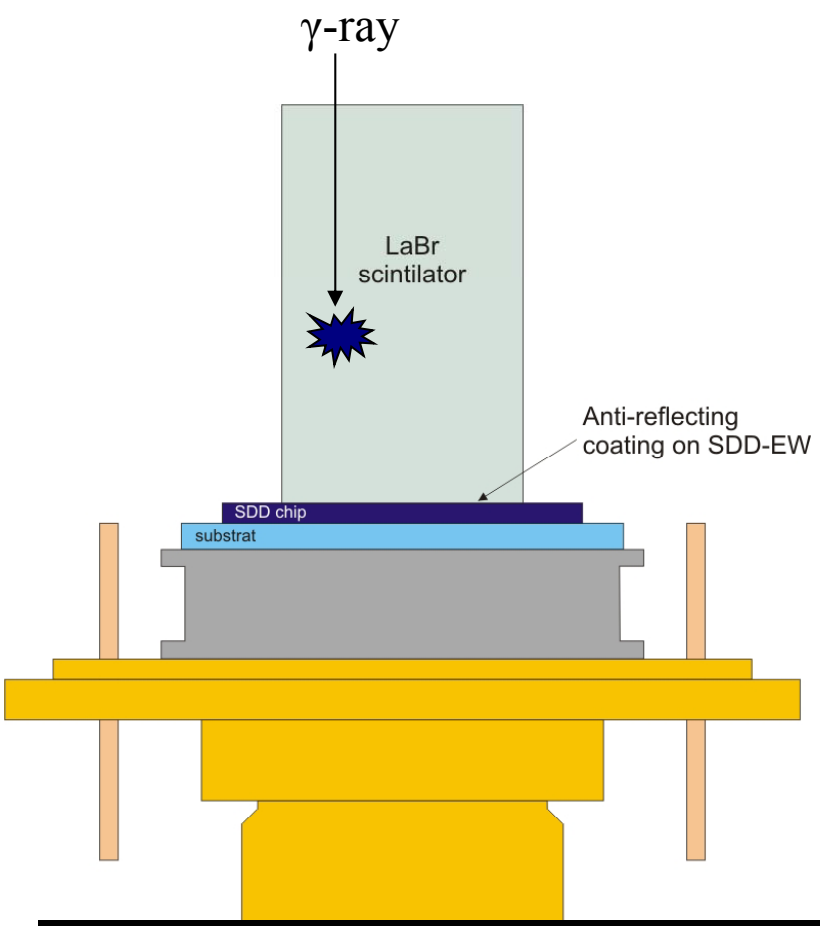


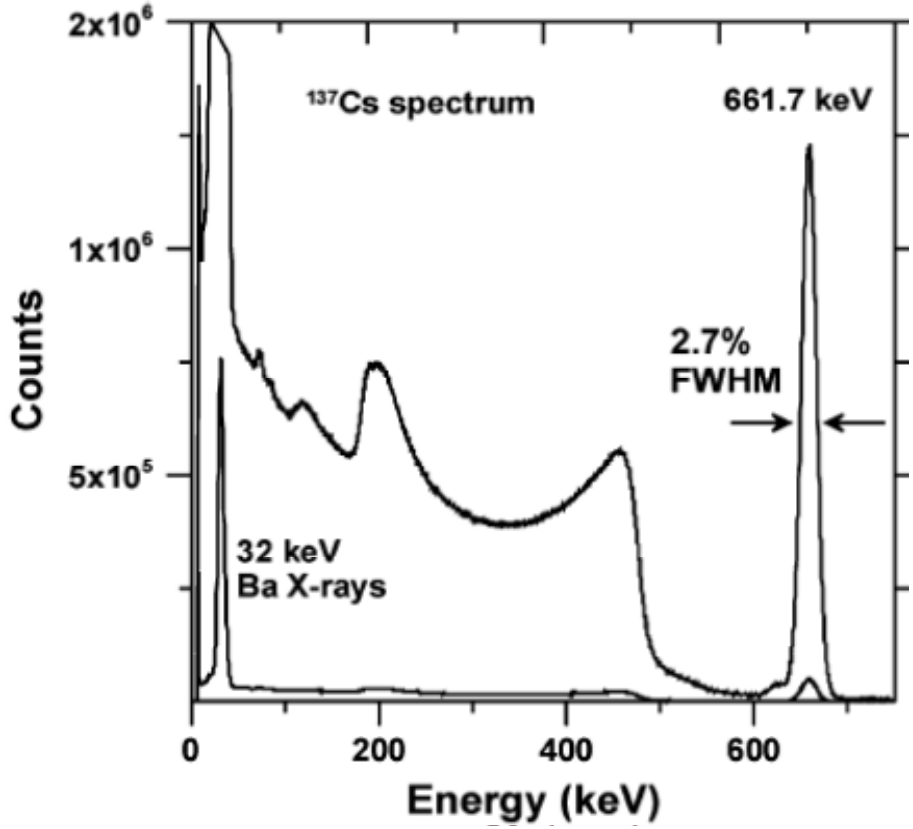
77x7 mm^2 = 539 mm^2



Detection range and quantum efficiency – hard x-rays

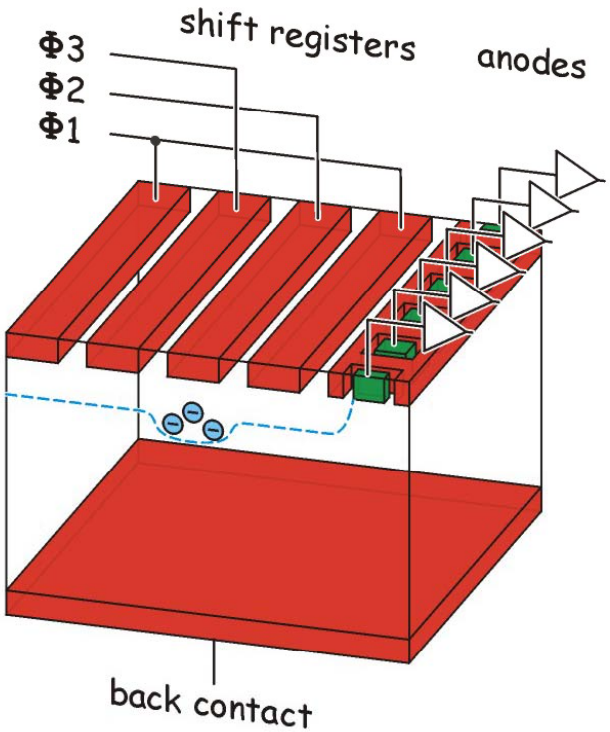
- combining SDD with modern scintillators

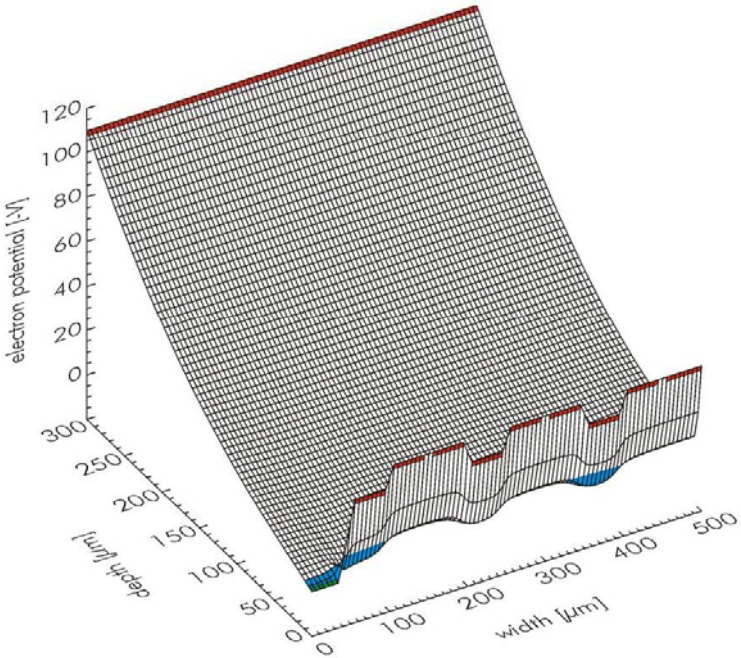


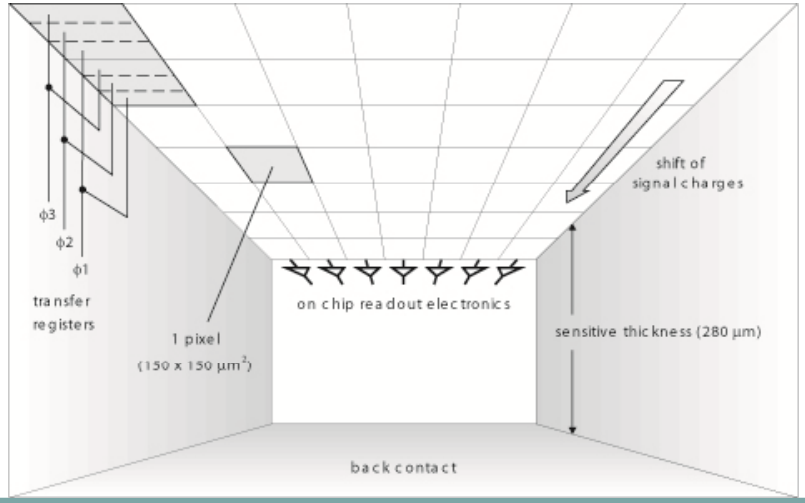


UV Light Visible Light	Soft X-Rays less than 1 keV	X-Rays 1 to 30 keV	Mid X-Rays to 50 keV	Hard X-Rays > 100 keV

CCD basics

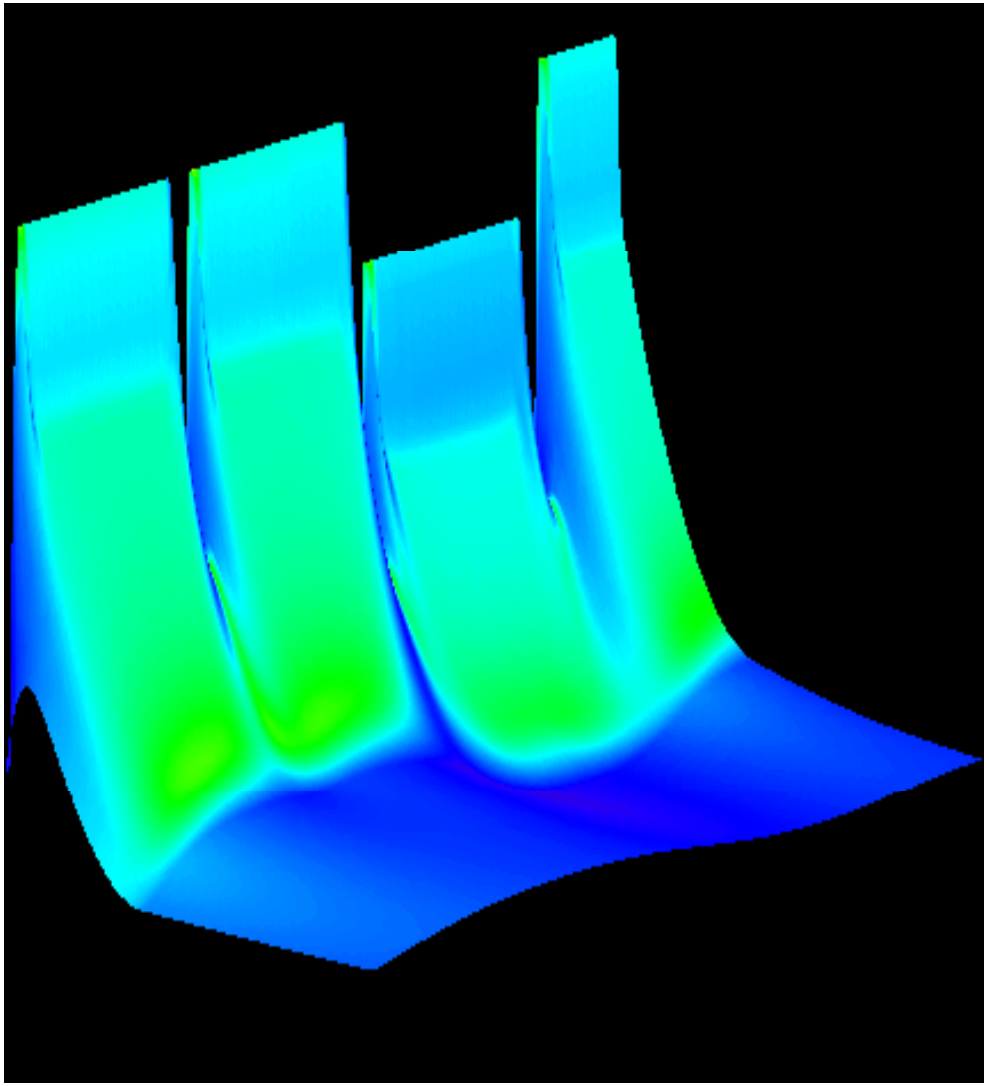


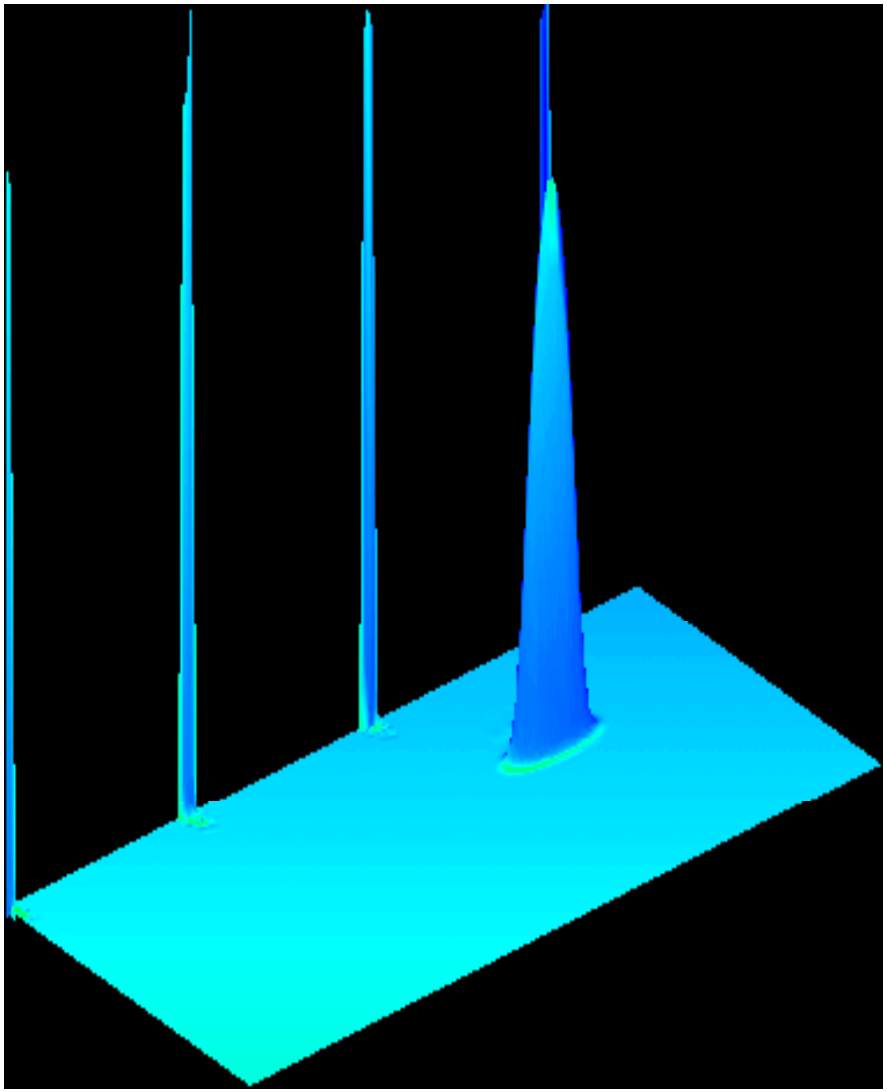




- full depletion (50 µm to 500 µm)
- back side illumination
- radiation hardness
- high readout speed
- pixel sizes from 30 µm to 650 µm
- charge handling: more than 10^6 e^-/pixel
- high quantum efficiency

pnCCD operation





Limitations: quantum efficiency

energy range

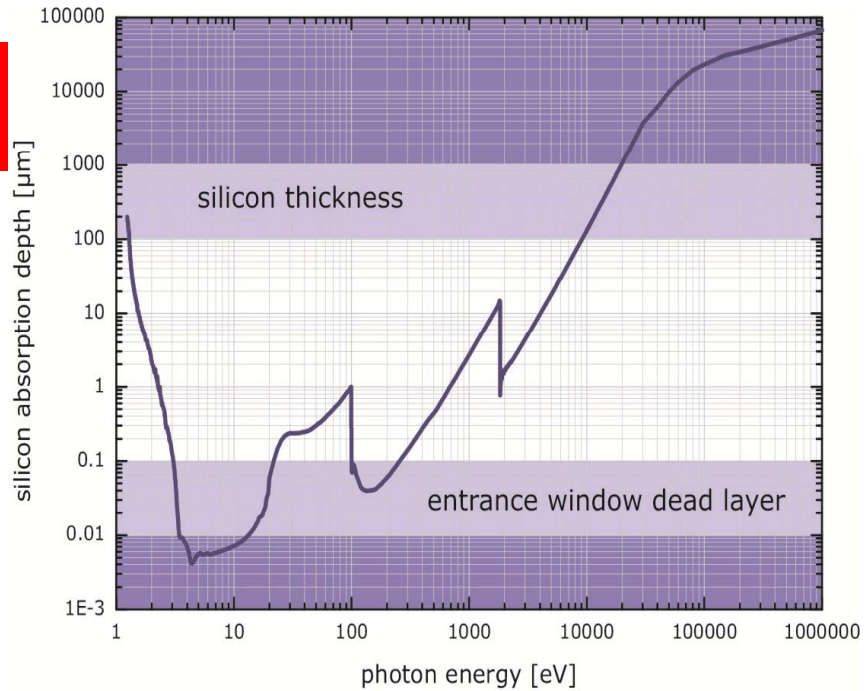
- **m.i. particles no problem**
- **photons**

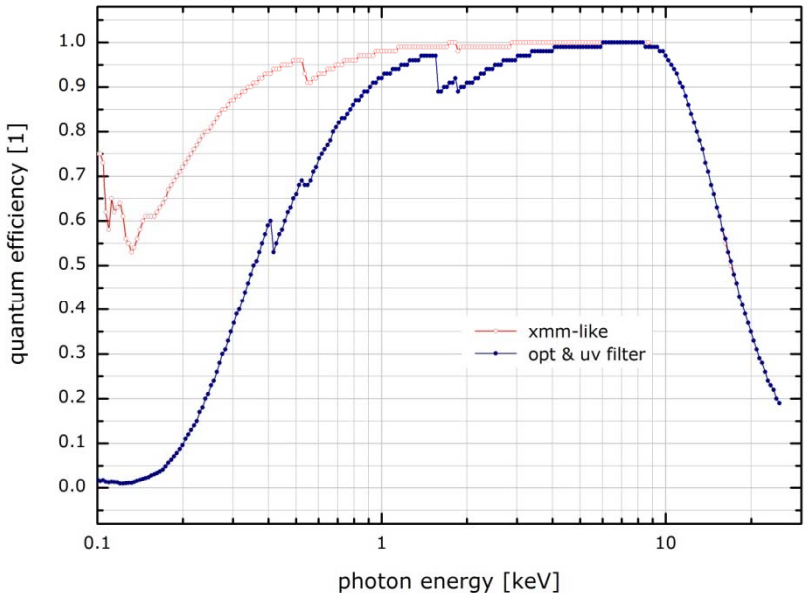
  Si is 'transparent'
  - at high energies » 10 keV
    absorption ~ Z^5/E^3
  - in the IR
    photon energy < E_{gap}

  ↳ transmission without interaction

  Si is a good absorber
  - in the optical
  - in the UV
  - at X-rays from 100 eV to 15 keV

  ↳ loss of signal charges in the entrance window dead layer

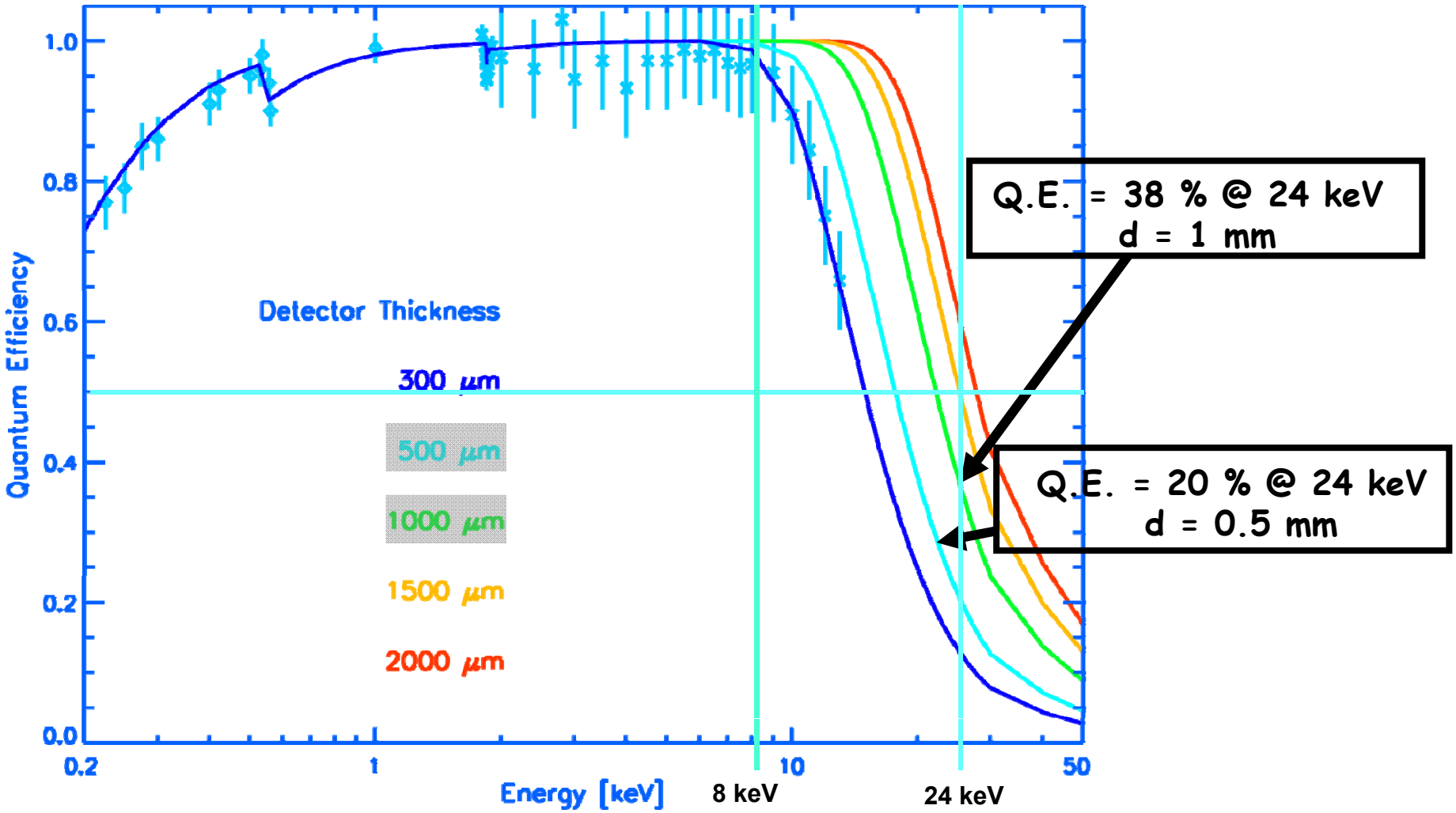




What is limiting the quantum efficiency ?

The thickness of Silicon !!

And the radiation entrance window !!



Limitations: Energy

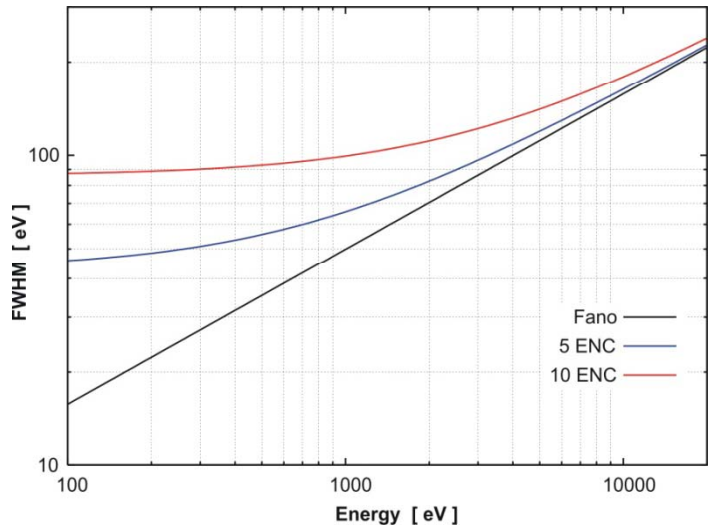
- energy resolution limited by

$$ENC_{el} = \sqrt{\alpha \frac{2kT}{g_m} C_{tot}^2 A_1 \frac{1}{\tau} + 2\pi a_f C_{tot}^2 A_2 + q I_L A_3 \tau}$$

  - electronic noise can be influenced by
    - detector design, integrated electronics
    - cooling
    - fast operation
    - repetitive readout
  - Fano noise, ultimate statistical limit

$$ENC_{fano} = \sqrt{\frac{F \cdot E_X}{w}}$$

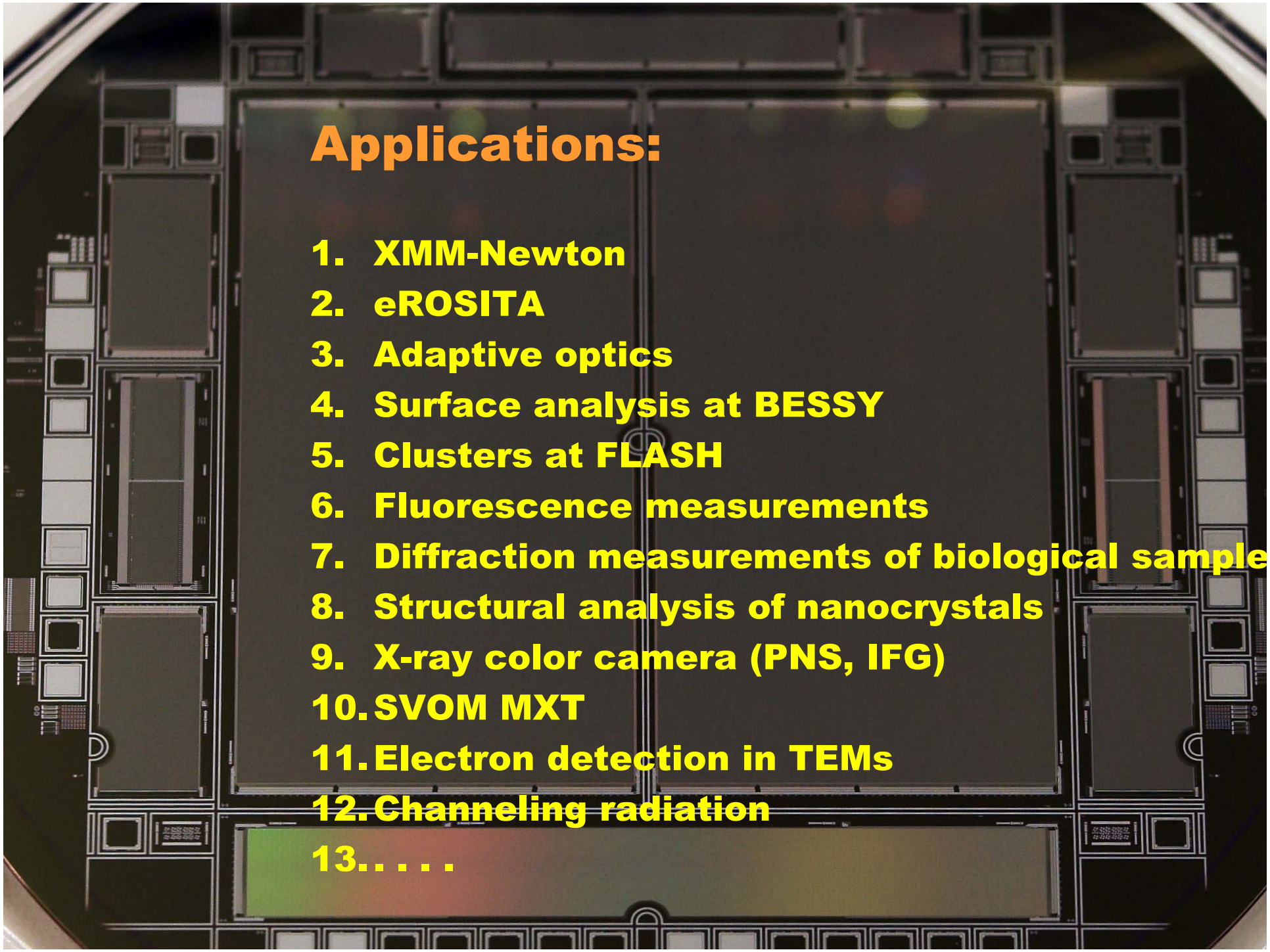
  - total noise $ENC_{tot}^2 = ENC_{el}^2 + ENC_{fano}^2$



- different electronic noise levels
- Fano limit

pnCCD - Measured Performance

Parameter	pnCCD performance
Energy range	1 eV … 25 keV (optimized for 0.1 … 15 keV)
Number of pixels per chip	up to 1024 x 1024
Sensor Pixel Shape	square or rectangular
Pixel size	30 x 30 μm^2 . . . . 600 x 600 μm^2
Dynamic range / pixel / pulse	3.000 photons @1 keV
Resolution (S/N >4:1)	Single photons @ 100 eV
Electronics noise	2 - 8 electrons r.m.s.
Frame rate	Up to 2.000 Hz
Sensitive detector thickness	50 µm . . . . 1.000 µm
Operating temperature	0˚C . . . . - 100˚C
Dynamic range	10.000 : 1

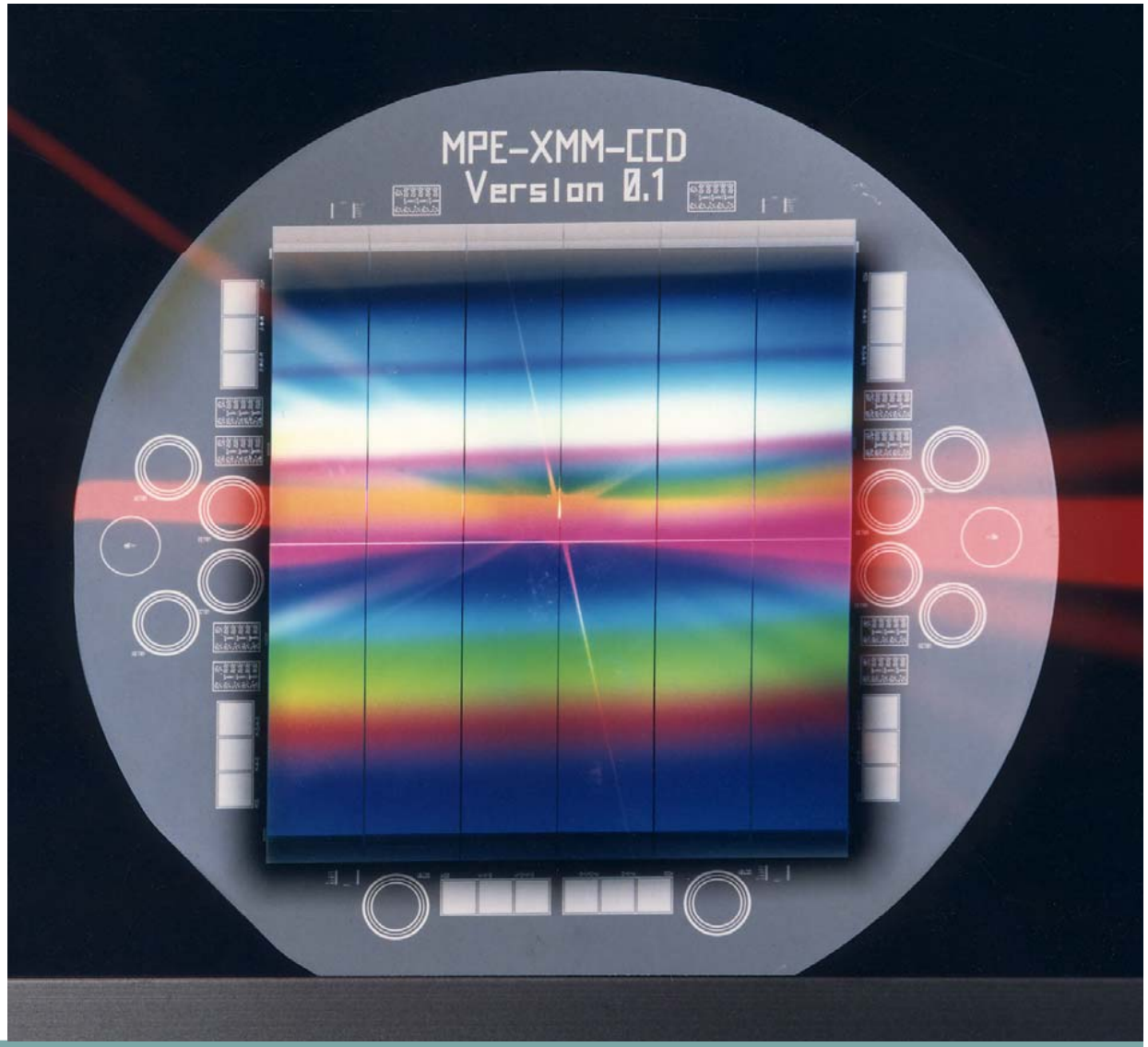


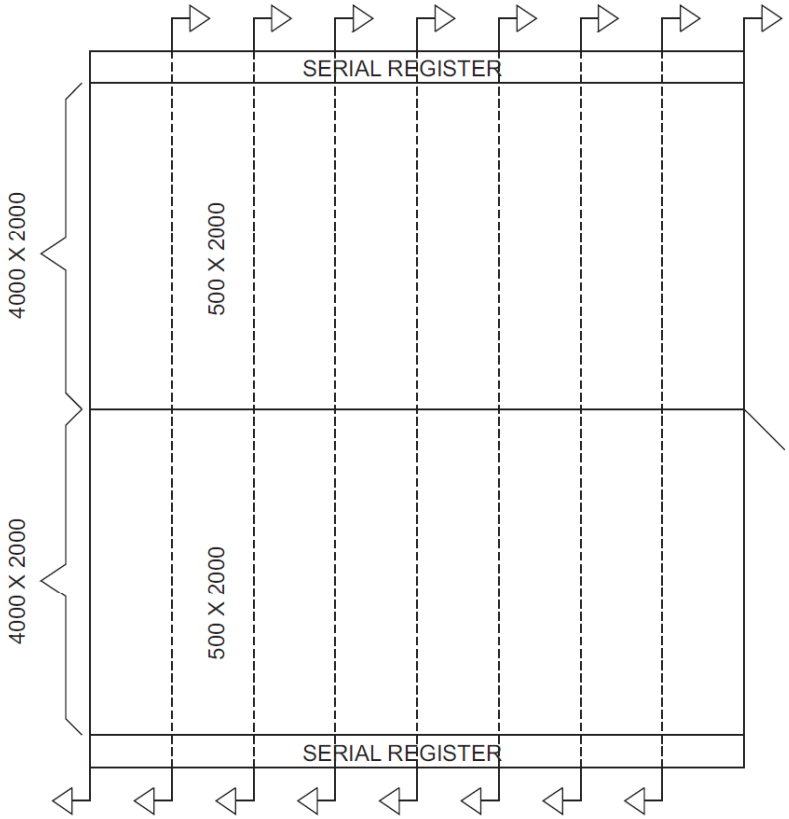
Applications:

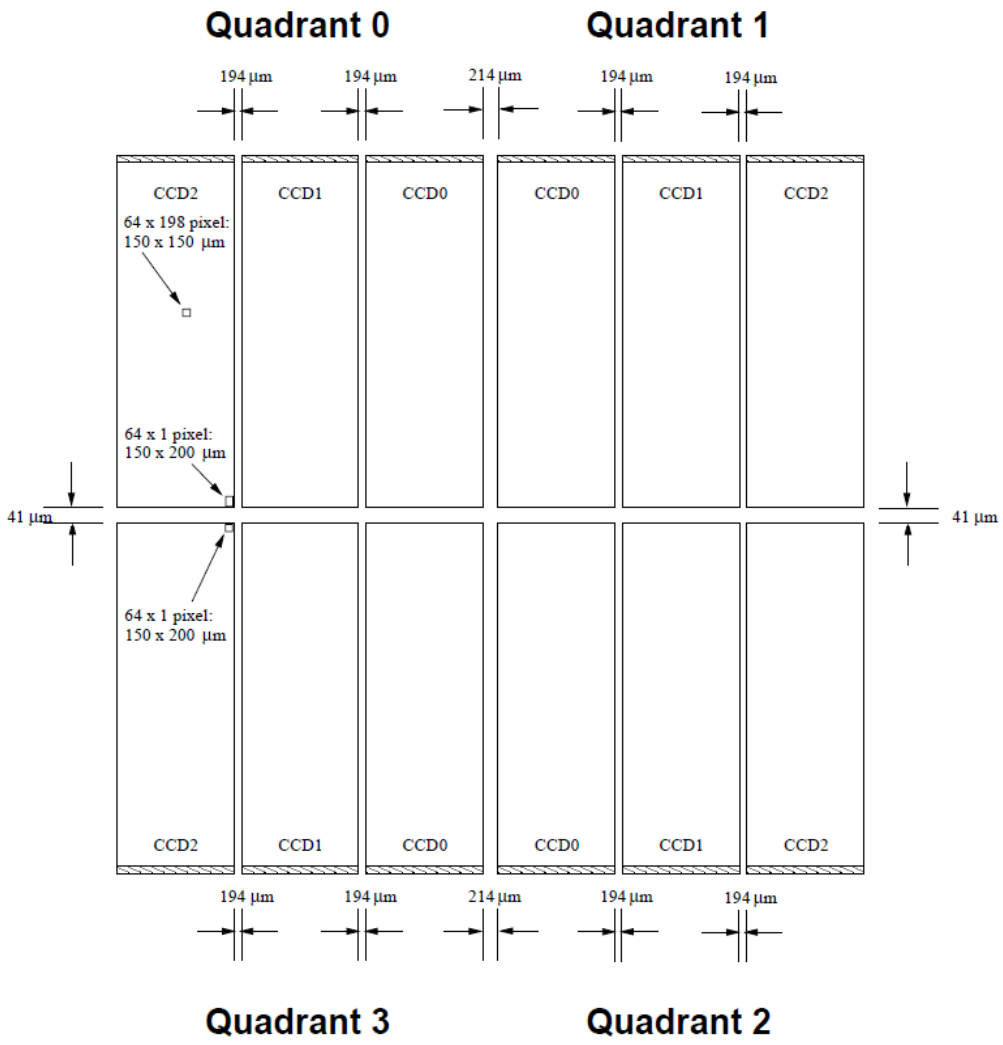
1. XMM-Newton
2. eROSITA
3. Adaptive optics
4. Surface analysis at BESSY
5. Clusters at FLASH
6. Fluorescence measurements
7. Diffraction measurements of biological sample
8. Structural analysis of nanocrystals
9. X-ray color camera (PNS, IFG)
10. SVOM MXT
11. Electron detection in TEMs
12. Channeling radiation
13. . . . .

XMM EPIC pnCCD

- Device
  - ▷ Monolithic array of 12 pnCCDs
  - ▷ 200 x 64 pixels each
  - ▷ pixel size 150 x 150 μm^2
  - ▷ 6 x 6 cm^2 area
  - ▷ 4“ wafer
  - ▷ 280 μm thick
  - ▷ Common entrance window
- Performance
  - ▷ 5 e- ENC
  - ▷ Readout time 4.5 ms
  - ▷ Integration time 100 ms
  - ▷ Energy resolution 150 eV FWHM @ 5.9 keV







P. O´Connor et al.,
Technology of the LSST Focal Plane
NIM A582, p 902 – 909, 2007

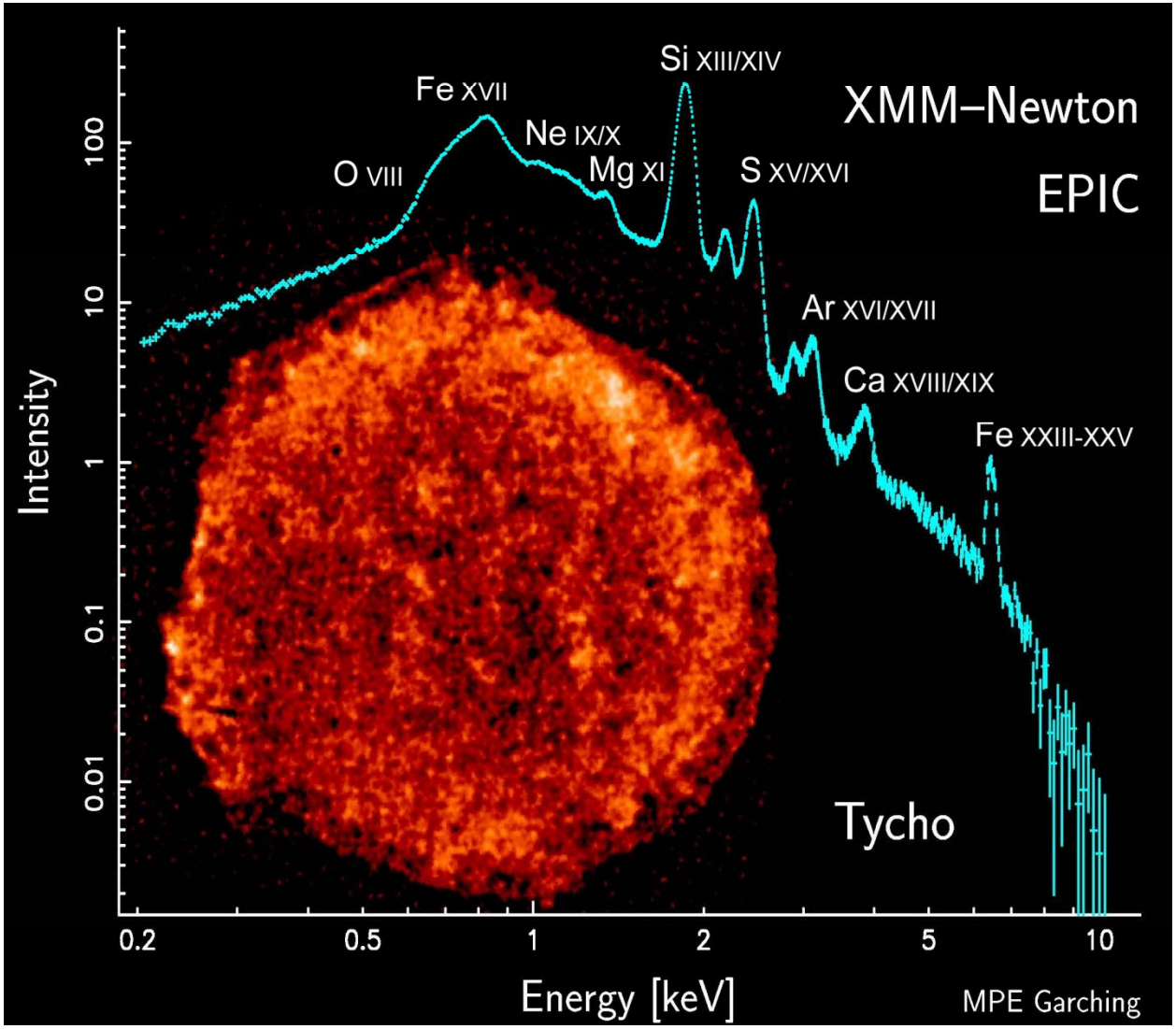
L. Strüder et al.,
The MPI / AIT X-Ray Imager (MAXI) – High Speed pn-CCDs for X-ray Detection
NIM A 288 p 227 - 235, 1990

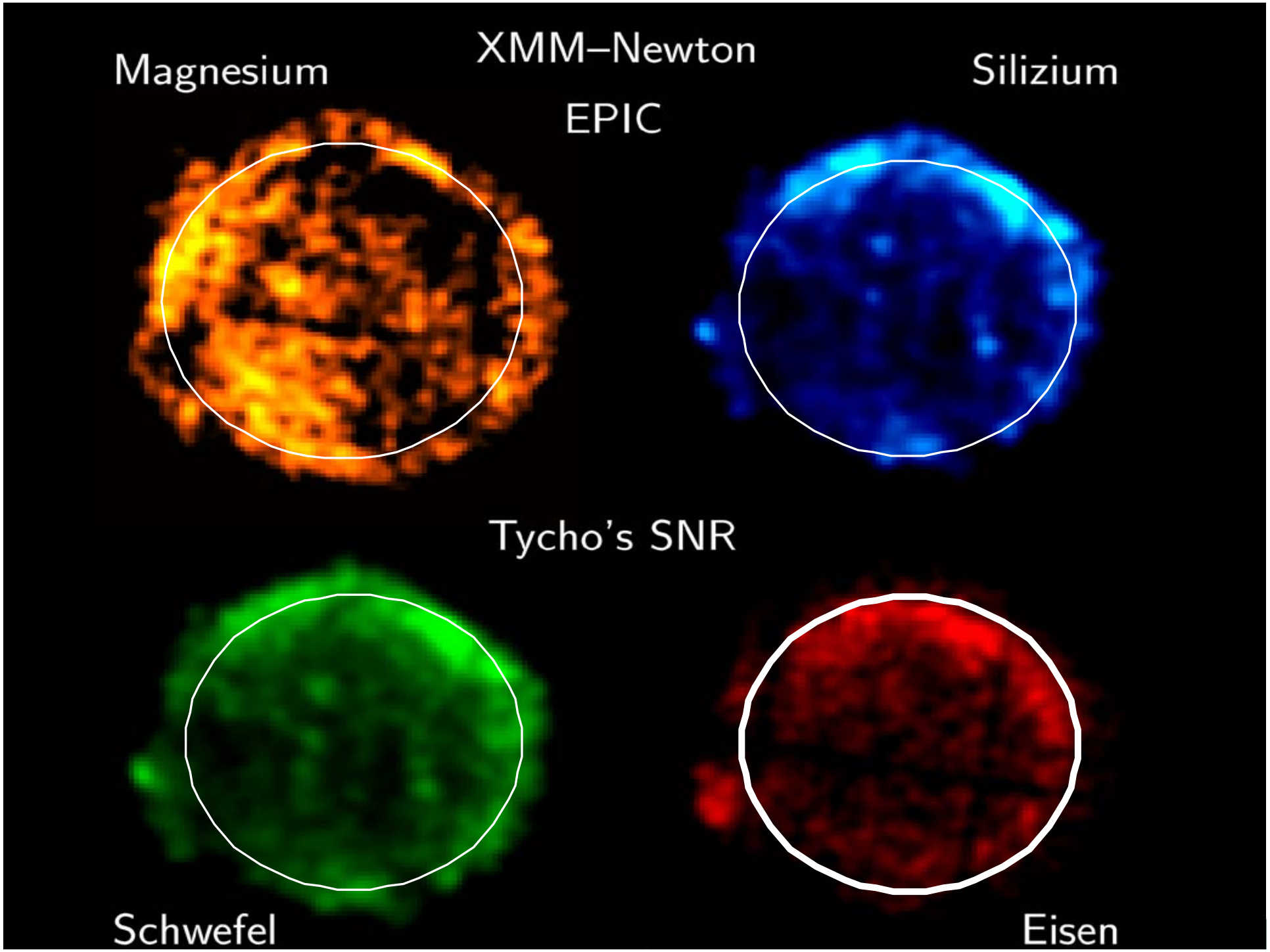
XMM-Newton observations

Tycho SNR

- Image and spectrum
- Supernova remnant
- Observed by Tycho Brahe in 1532

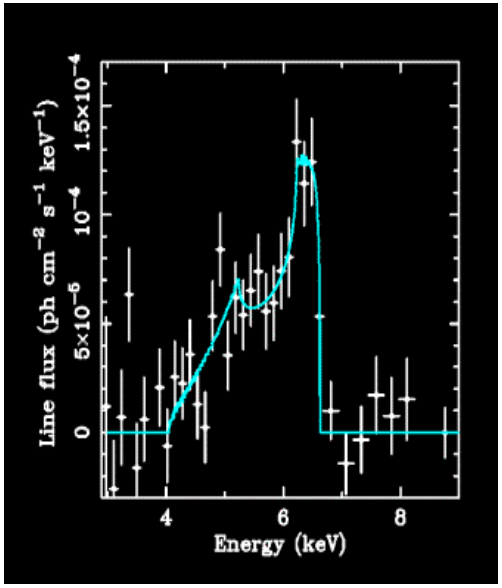
- Single photon counting in X-rays
- Timing with X-rays
- Todate: 4.000 ref. XMM papers

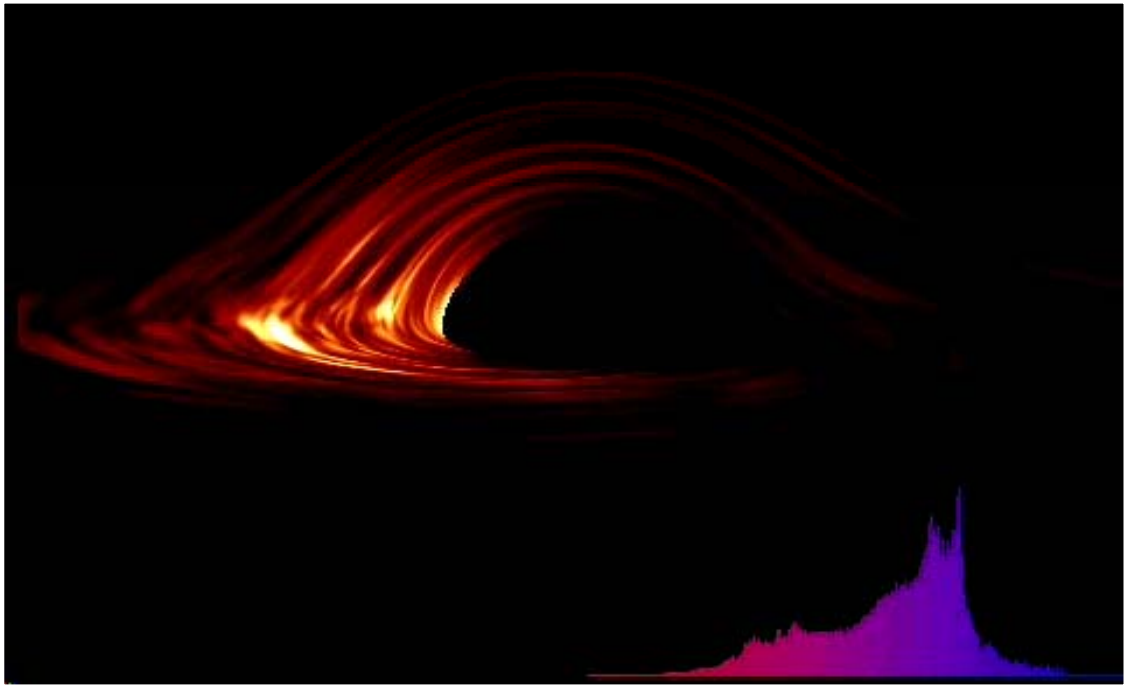



XMM–Newton
EPIC
Magnesium
Silizium
Tycho's SNR
Schwefel
Eisen

XMM measurement of the bradening of the iron line

Relativistic
Fe-line
was measured by
XMM - Newton





courtesy of Chris Reynolds

A&A 365, L18–L26 (2001)
DOI: 10.1051/0004-6361:20000066
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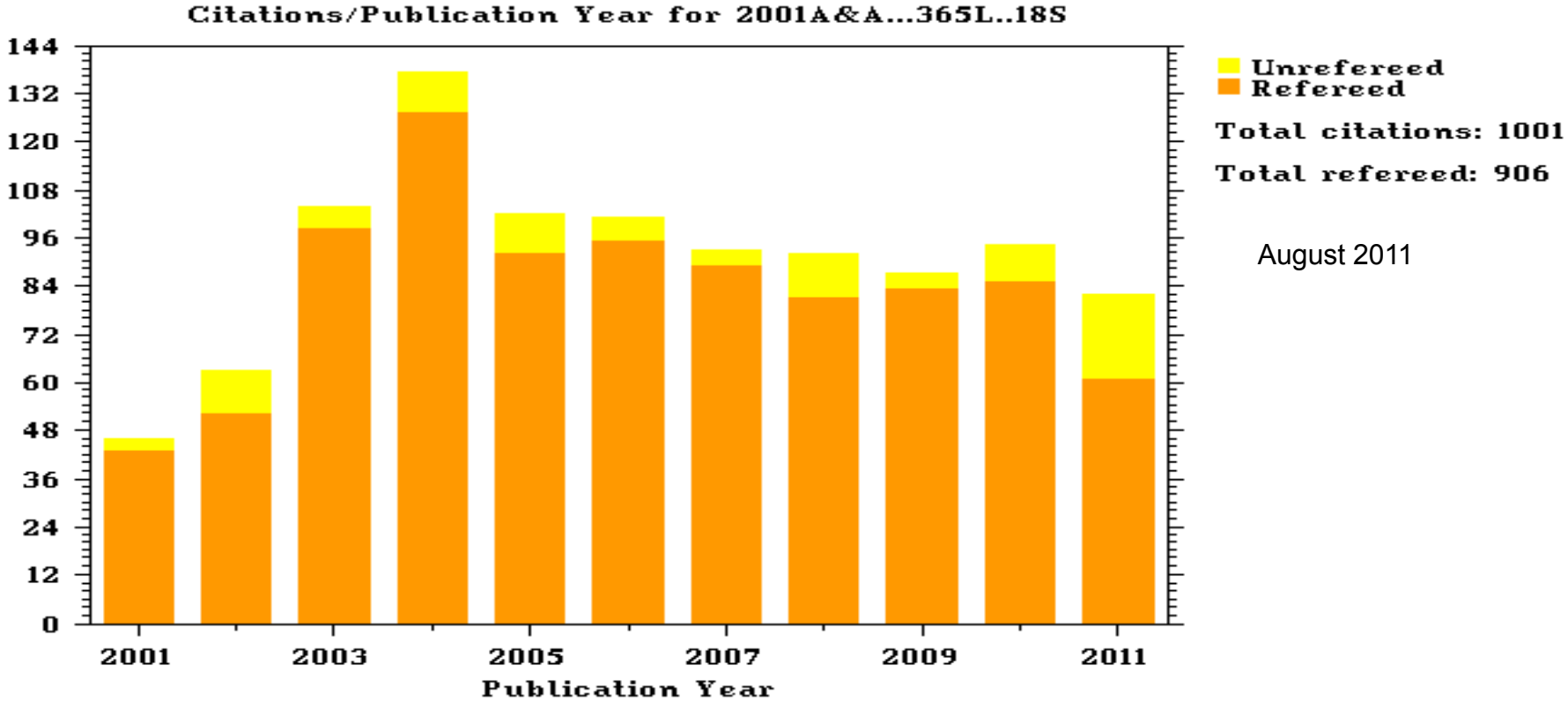
Astronomy & Astrophysics

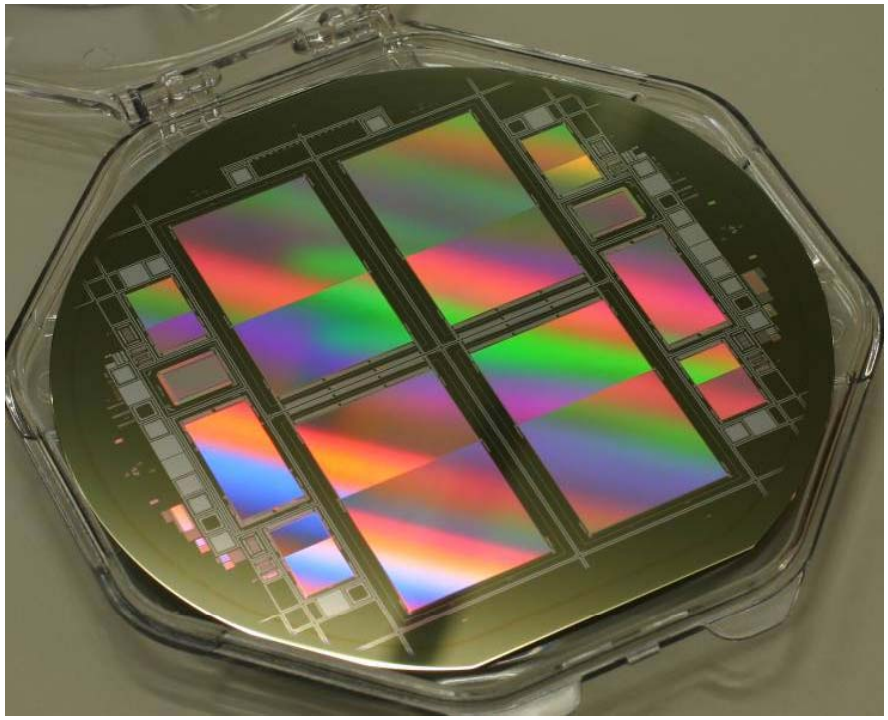
The European Photon Imaging Camera on XMM-Newton: The pn-CCD camera*

L. Strüder[1], U. Briel[1], K. Dennerl[1], R. Hartmann[2], E. Kendziorra[4], N. Meidinger[1], E. Pfeffermann[1], C. Reppin[1], B. Aschenbach[1], W. Bornemann[1], H. Bräuninger[1], W. Burkert[1], M. Elender[1], M. Freyberg[1], F. Haberl[1], G. Hartner[1], F. Heuschmann[1], H. Hippmann[1], E. Kastelic[1], S. Kemmer[1], G. Kettenring[1], W. Kink[1], N. Krause[1], S. Müller[1], A. Oppitz[1], W. Pietsch[1], M. Popp[1], P. Predehl[1], A. Read[1], K. H. Stephan[1], D. Stötter[1], J. Trümper[1], P. Holl[2], J. Kemmer[2], H. Soltau[2], R. Stötter[2], U. Weber[2], U. Weichert[2], C. von Zanthier[2], D. Carathanassis[3], G. Lutz[3], R. H. Richter[3], P. Solc[3], H. Böttcher[4], M. Kuster[4], R. Staubert[4], A. Abbey[5], A. Holland[5], M. Turner[5], M. Balasini[6], G. F. Bignami[6], N. La Palombara[6], G. Villa[6], W. Buttler[7], F. Gianini[8], R. Lainé[8], D. Lumb[8], and P. Dhez[9]



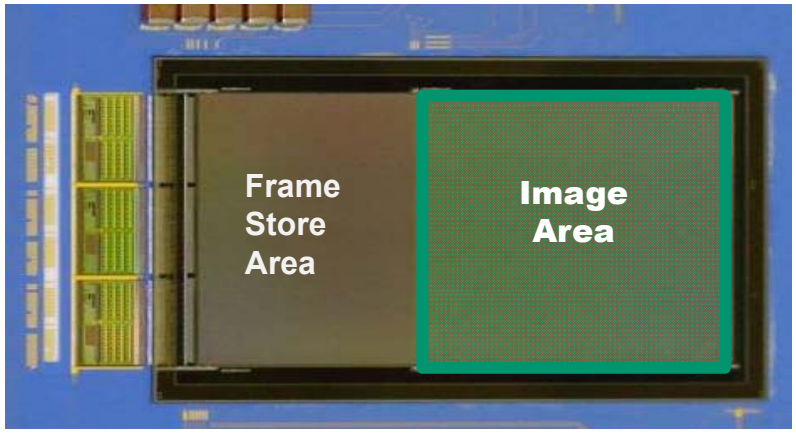
August 2011

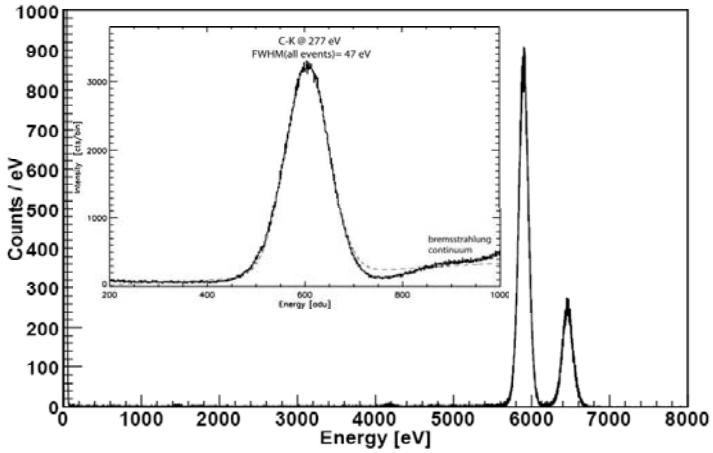
eROSITA pnCCD CCD-Module, launch in 2013



Four 3cm x 3cm CCDs still on Si-Wafer.
The CCDs have 384 × 384 pixels in both image and framestore area.

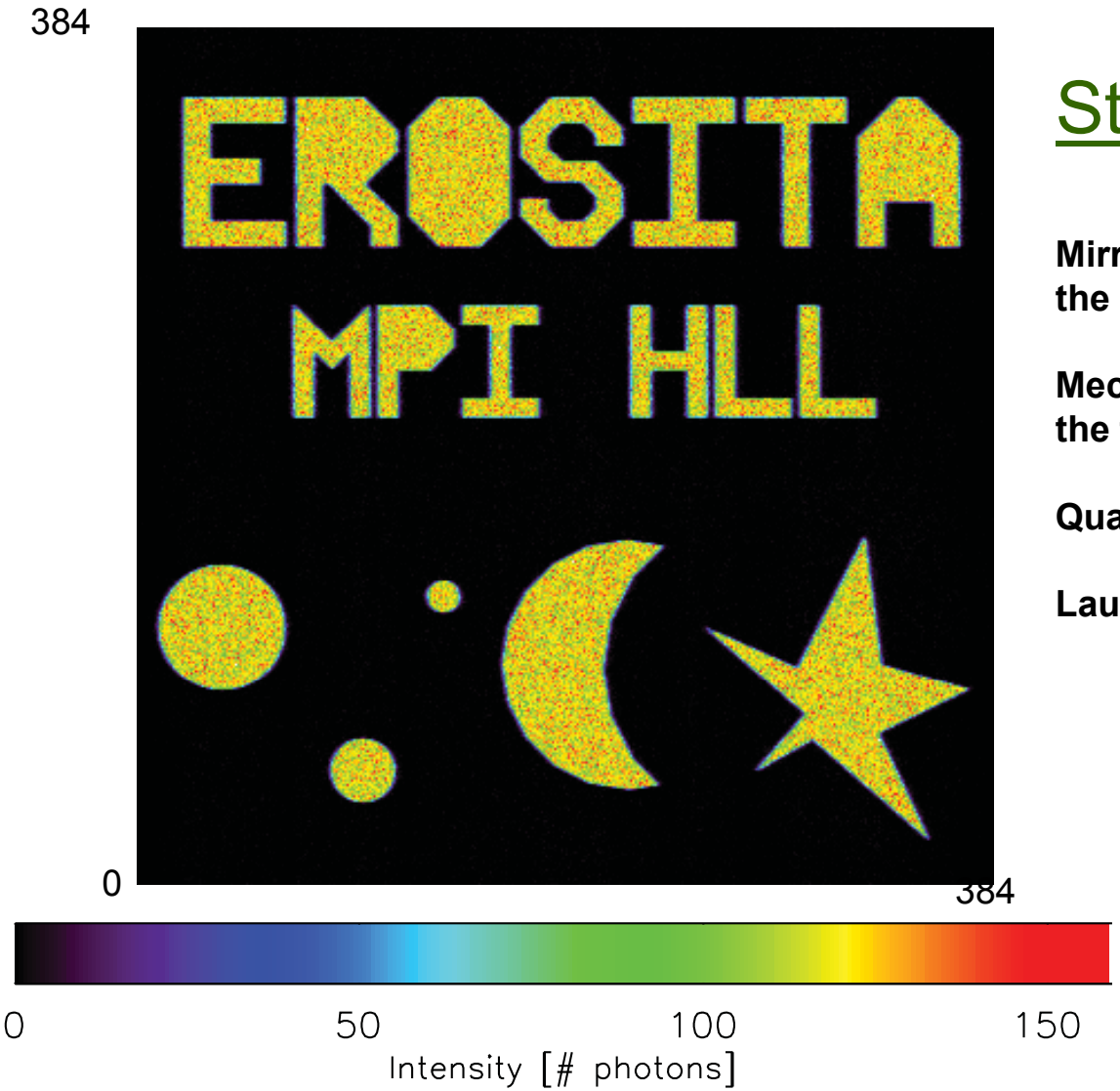
Pixelsize: 75 x 75 µm².





Measurements at C Ka (277eV) and Mn Ka (5,9 keV) on flight- CCDs show the expected energy resolution and low energy response.

Imaging



Status of eROSITA

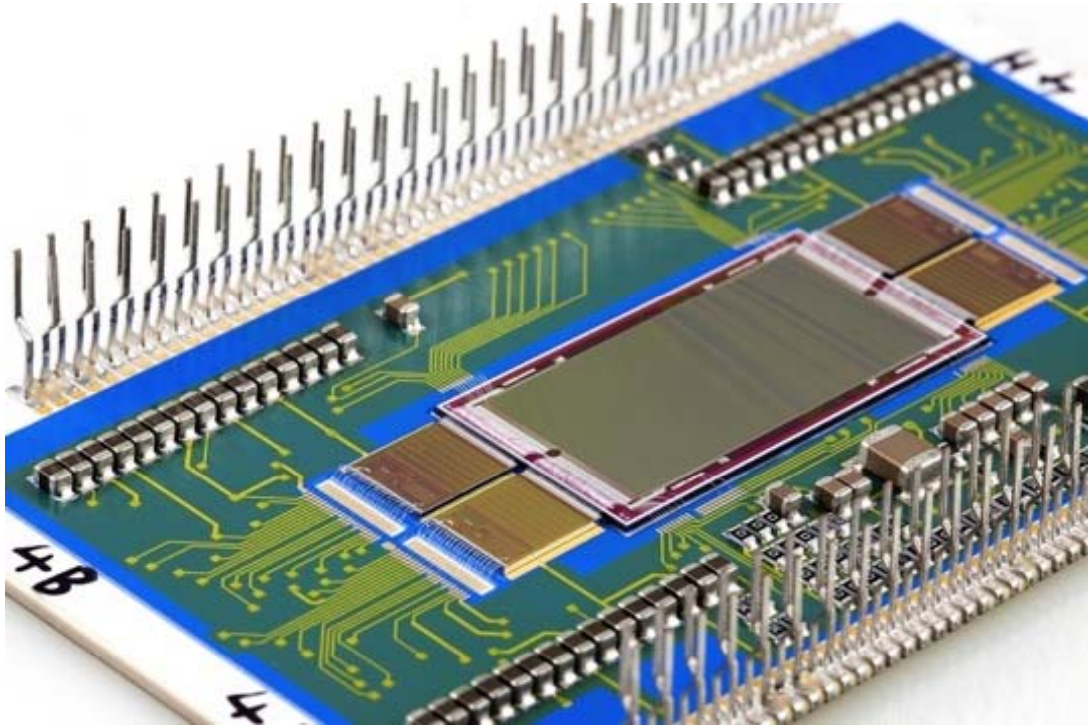
Mirror fabrication is contracted to the companies MediaLario and ZEISS

Mechanical and electrical models of the flight cameras have been built

Qualification models are tested

Launch is expected to be in 2014

48µm pnCCD with a double-sided readout, mounted onto a ceramic substrate



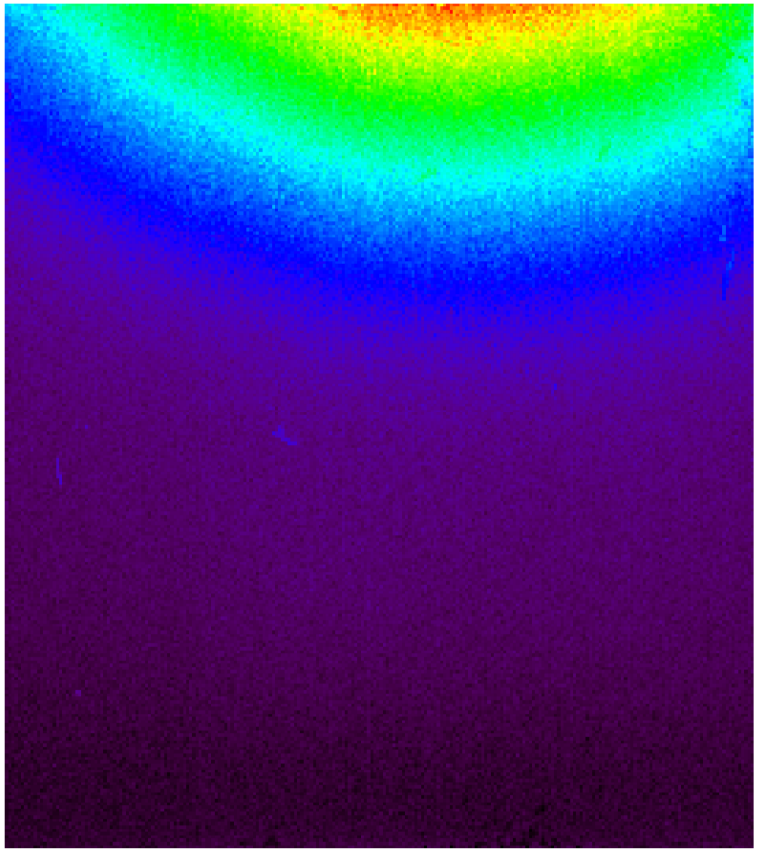
- detector size = 27×13.5 mm^2
- 48 µm □ pixel size
- 528×264 pixel in total
- readout transfer to both sides
- image transfer time = 30 µs
- OOT probability = 3% @ 1000 fps
- charge transfer loss CTI ≈ 10^{-5}
- charge handling capability > 10^5 e^-
- 100% fill factor
- readout noise vs. frame rate:

  2.3 e^- @ 10 .. 400 fps

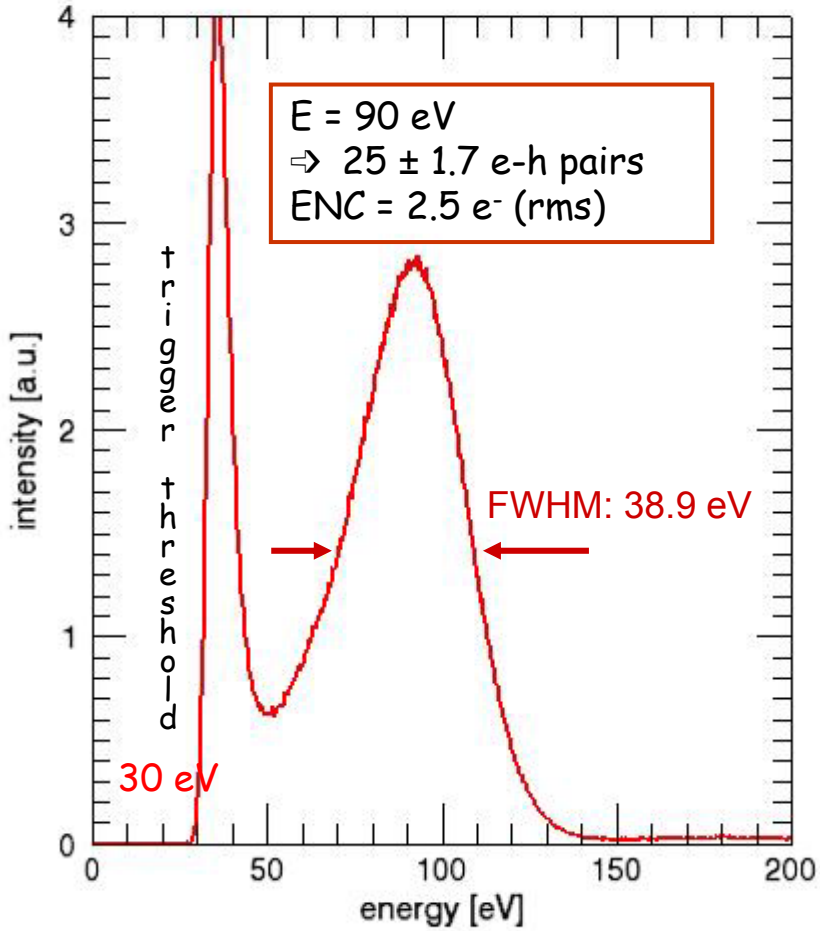
  2.8 e^- @ 400 .. 1000 fps
- With binning:

  2.8 e^- @ 2000 .. 4000 fps

90 eV X-rays in single photon counting mode !!!



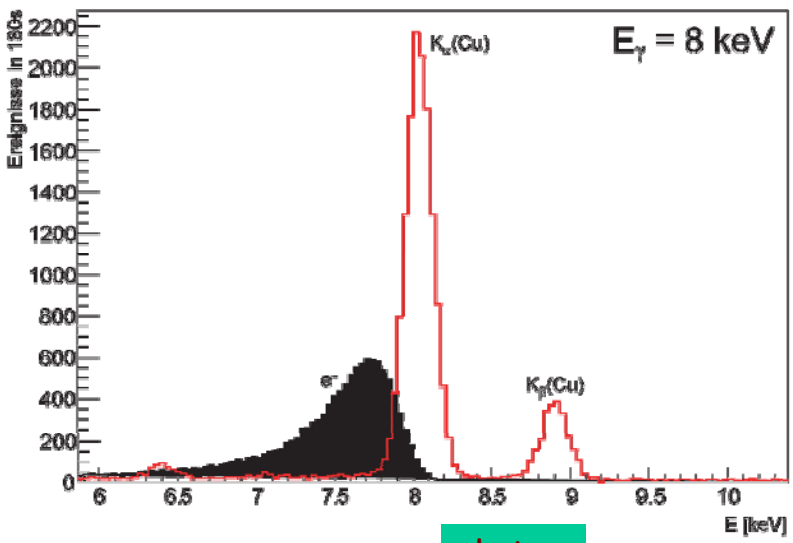
T = -50° C

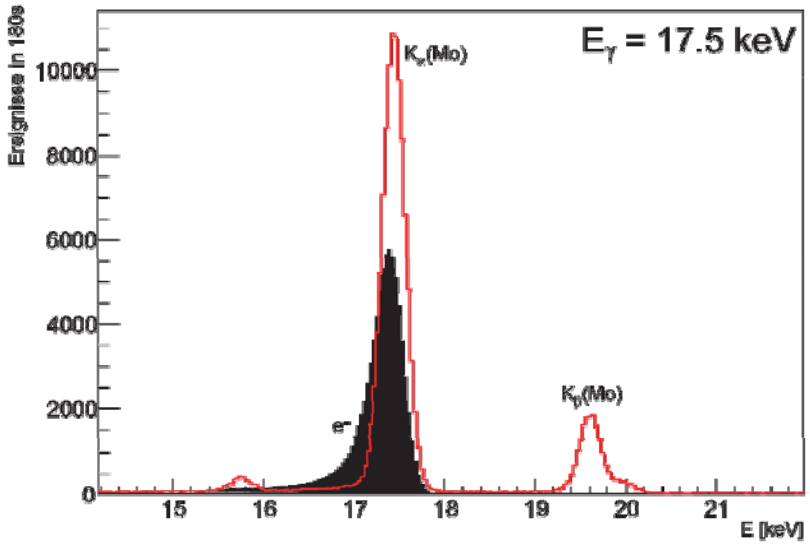


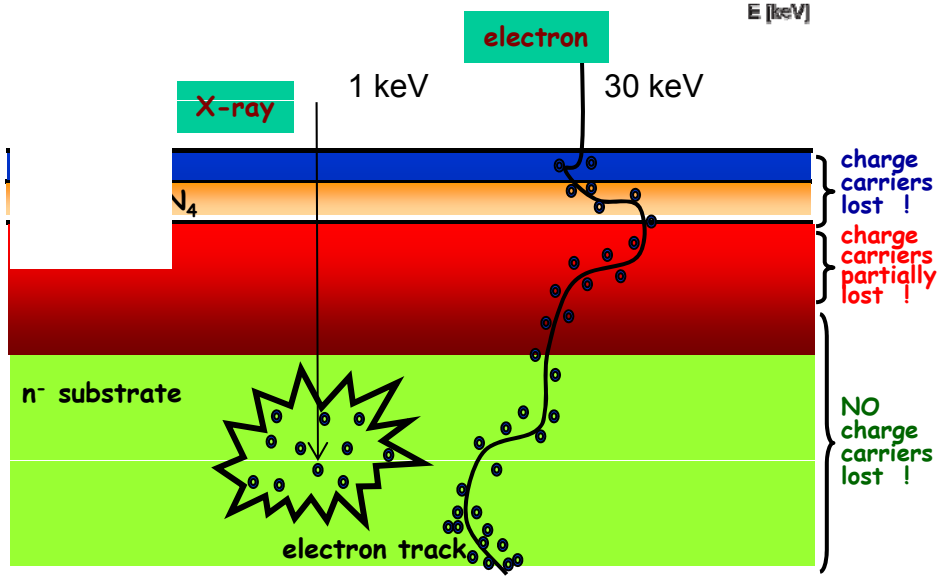
Spectrum from 4.000 frames
with 0.01 photons/pixel/frame

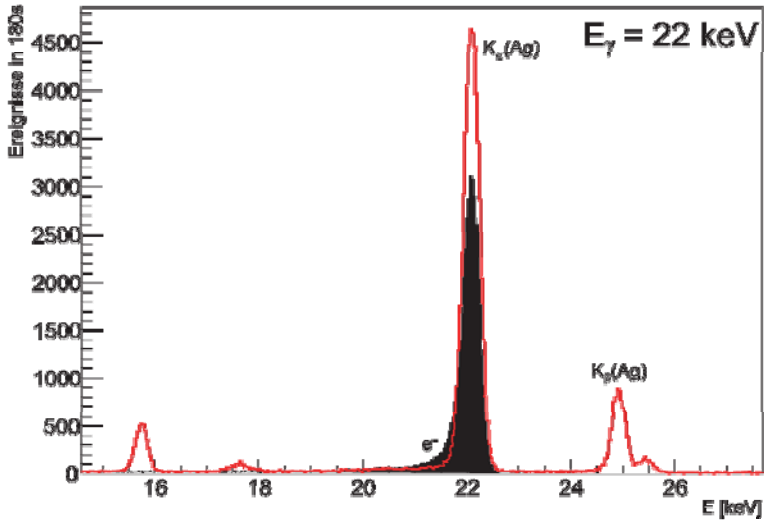
pnCCDs for electron imaging spectroscopy

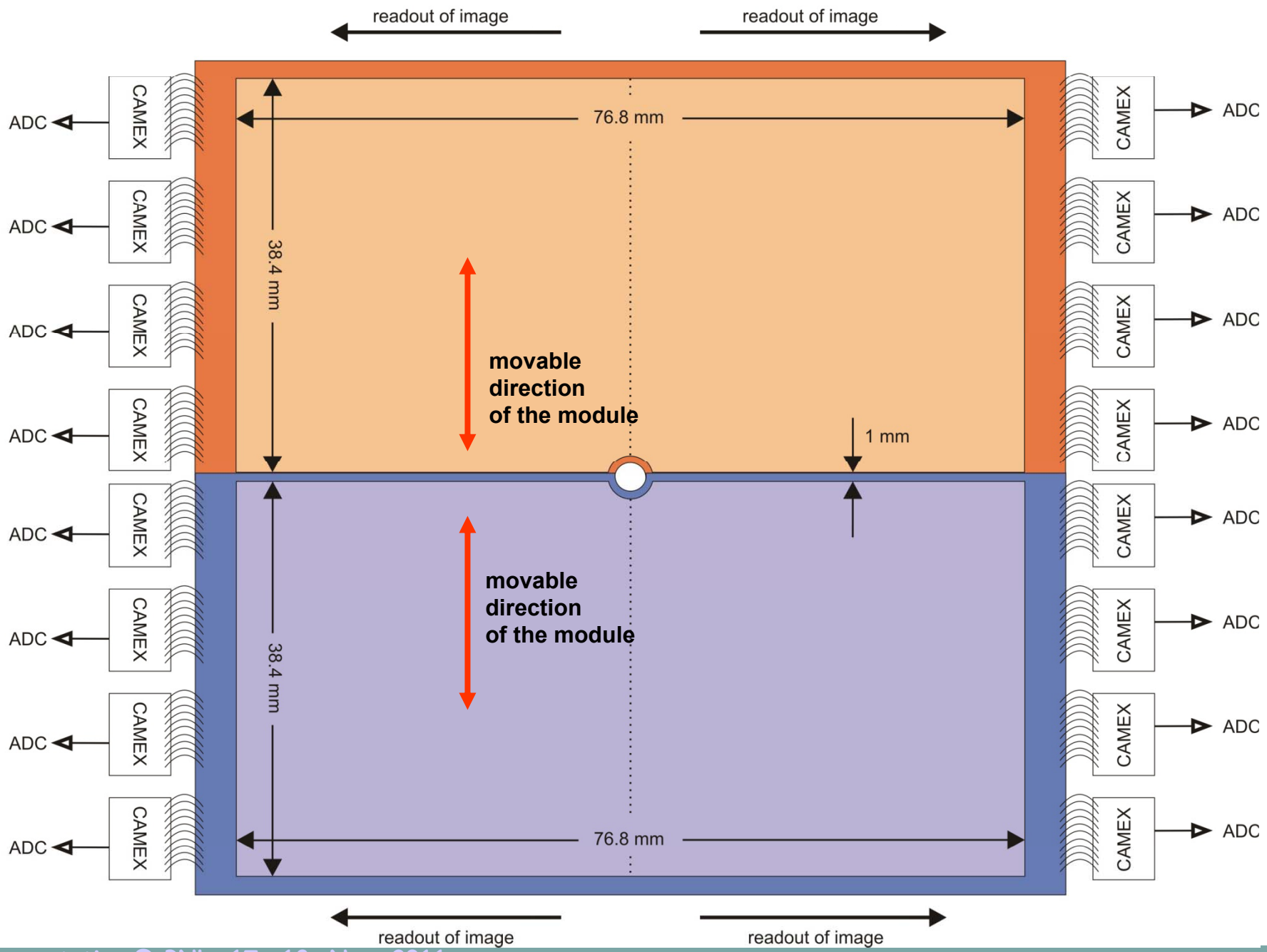
simultaneous measurement of electrons and X-rays



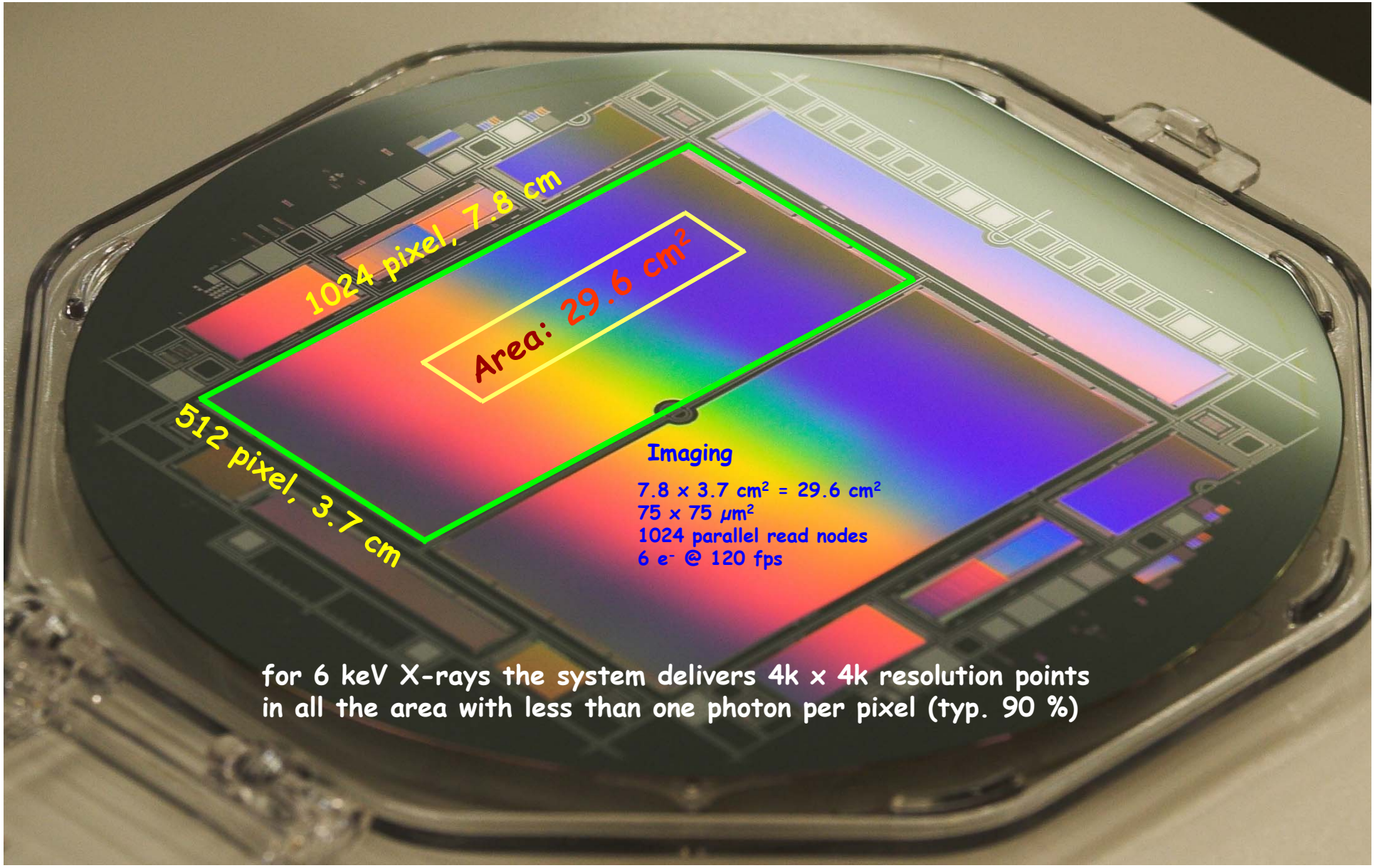







readout of image
readout of image
ADC
CAMEX
76.8 mm
38.4 mm
movable
direction
of the module
1 mm
movable
direction
of the module
38.4 mm
76.8 mm
readout of image
readout of image

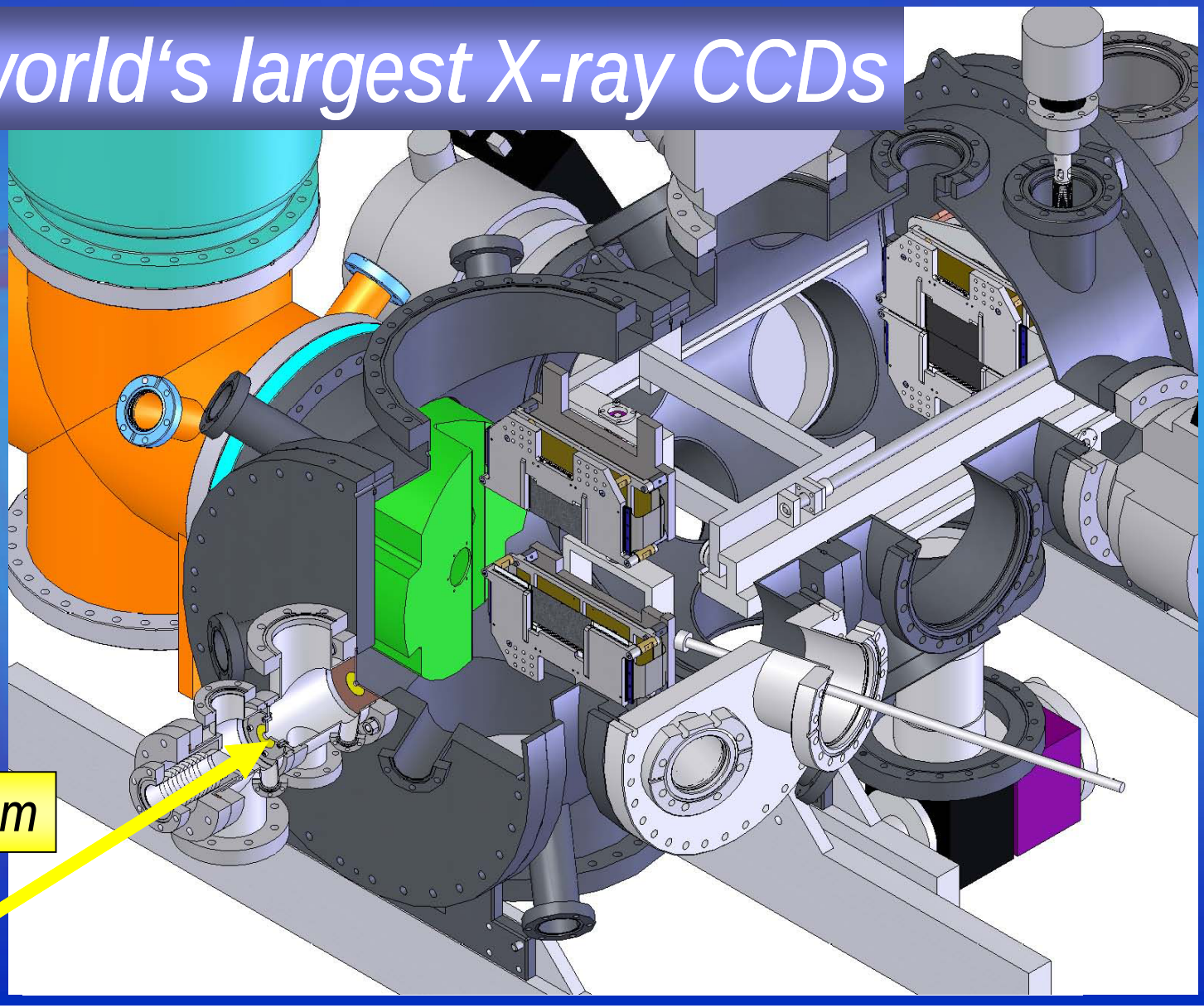
pnCCD: 2 x 1024 x 512, 60 cm^2



for 6 keV X-rays the system delivers 4k x 4k resolution points in all the area with less than one photon per pixel (typ. 90 %)

CFEL-ASG MultiPurpose Chamber

The world's largest X-ray CCDs



Mimi virus experiment: Janos Haidu

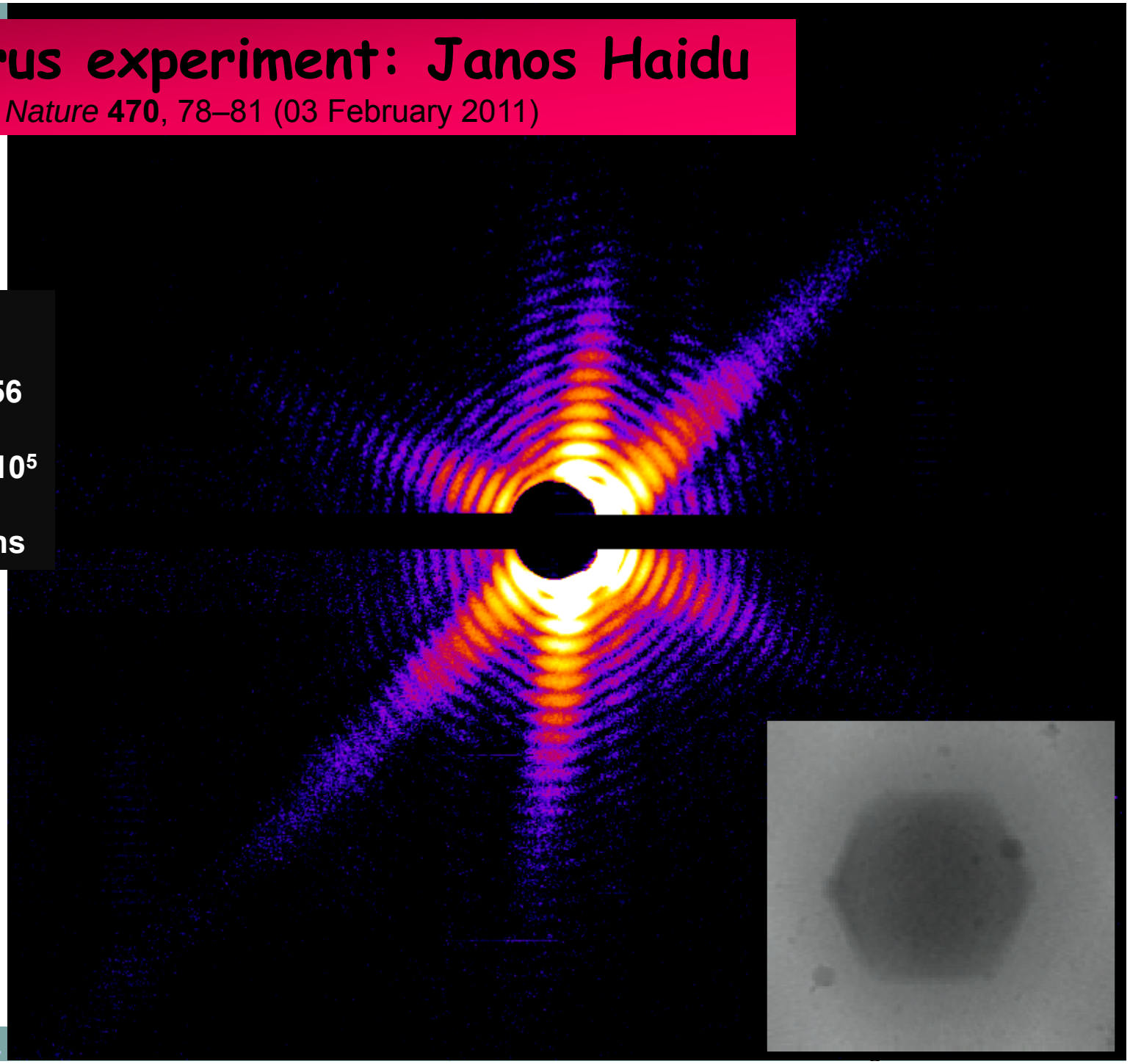
Nature **470**, 78–81 (03 February 2011)

Back detector:

Gain: High gain/256

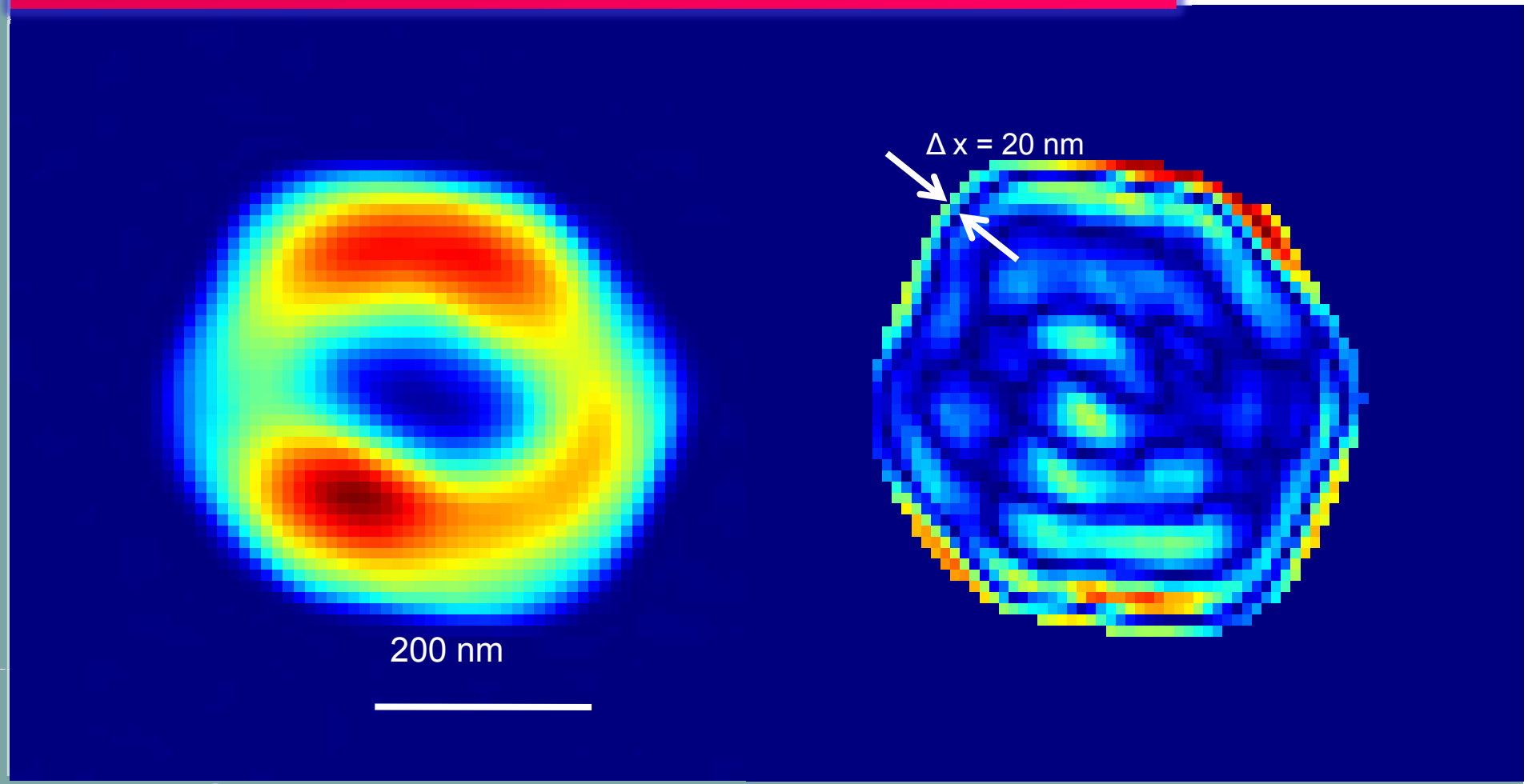
Max. charge: 2.5×10^5

Noise: 25 electrons



Mimi virus experiment: PI: Janos Haidu

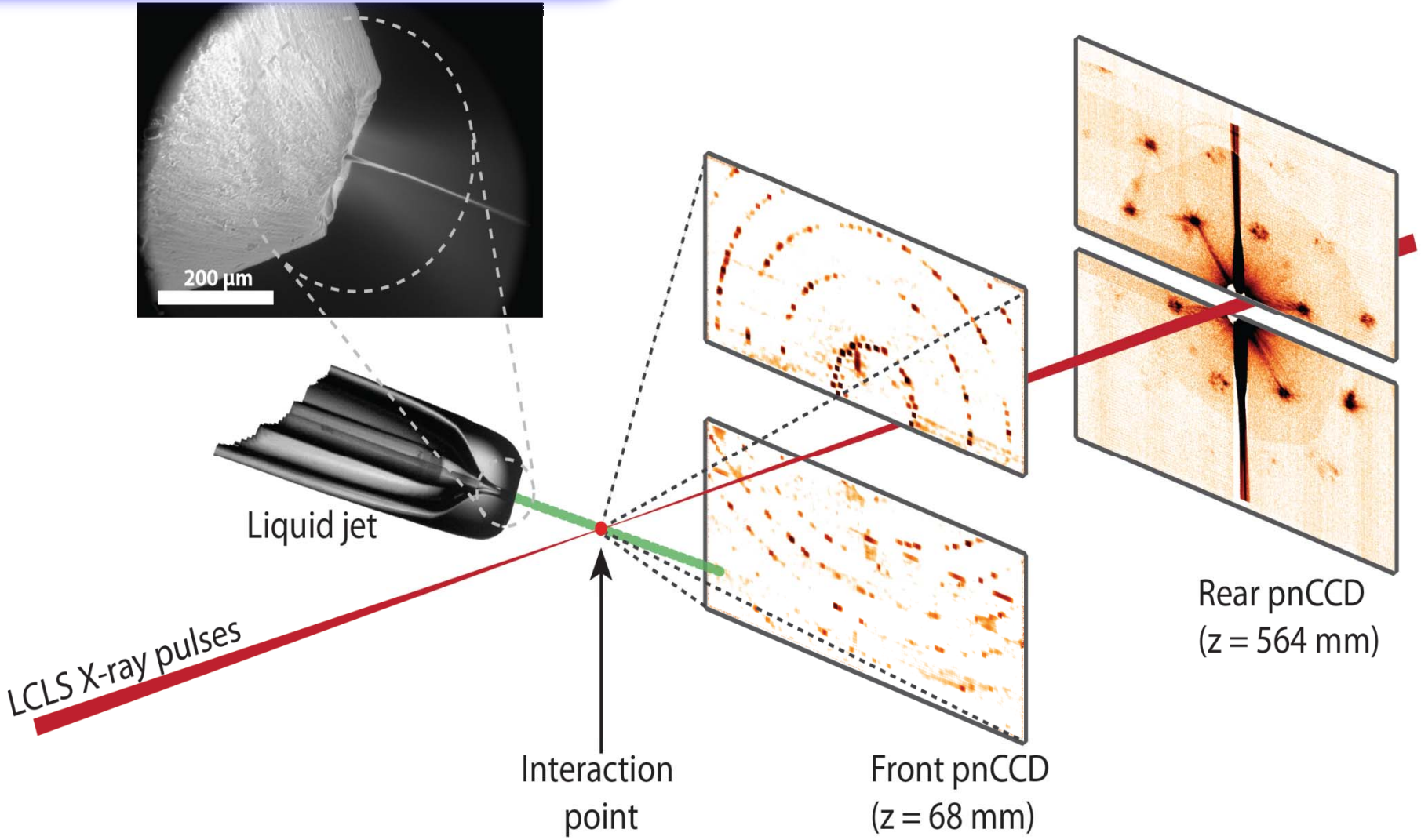
Nature **470**, 78–81 (03 February 2011)



PSI experiment: Henry Chapman

Nature **470**, 73–77 (03 February 2011)

PS1:Membrane protein photosystem I,
typical size: 100 nm to 1 µm

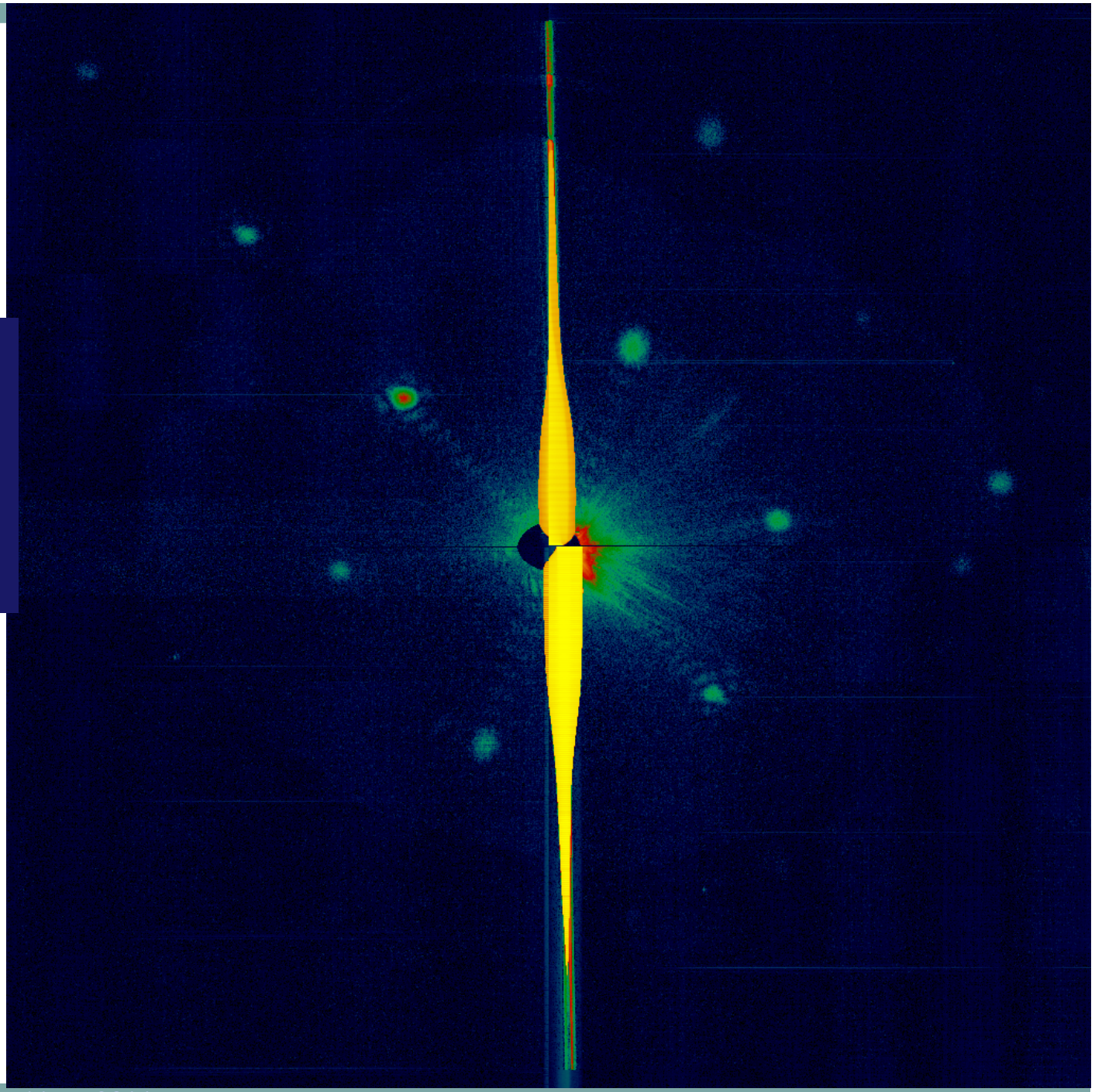


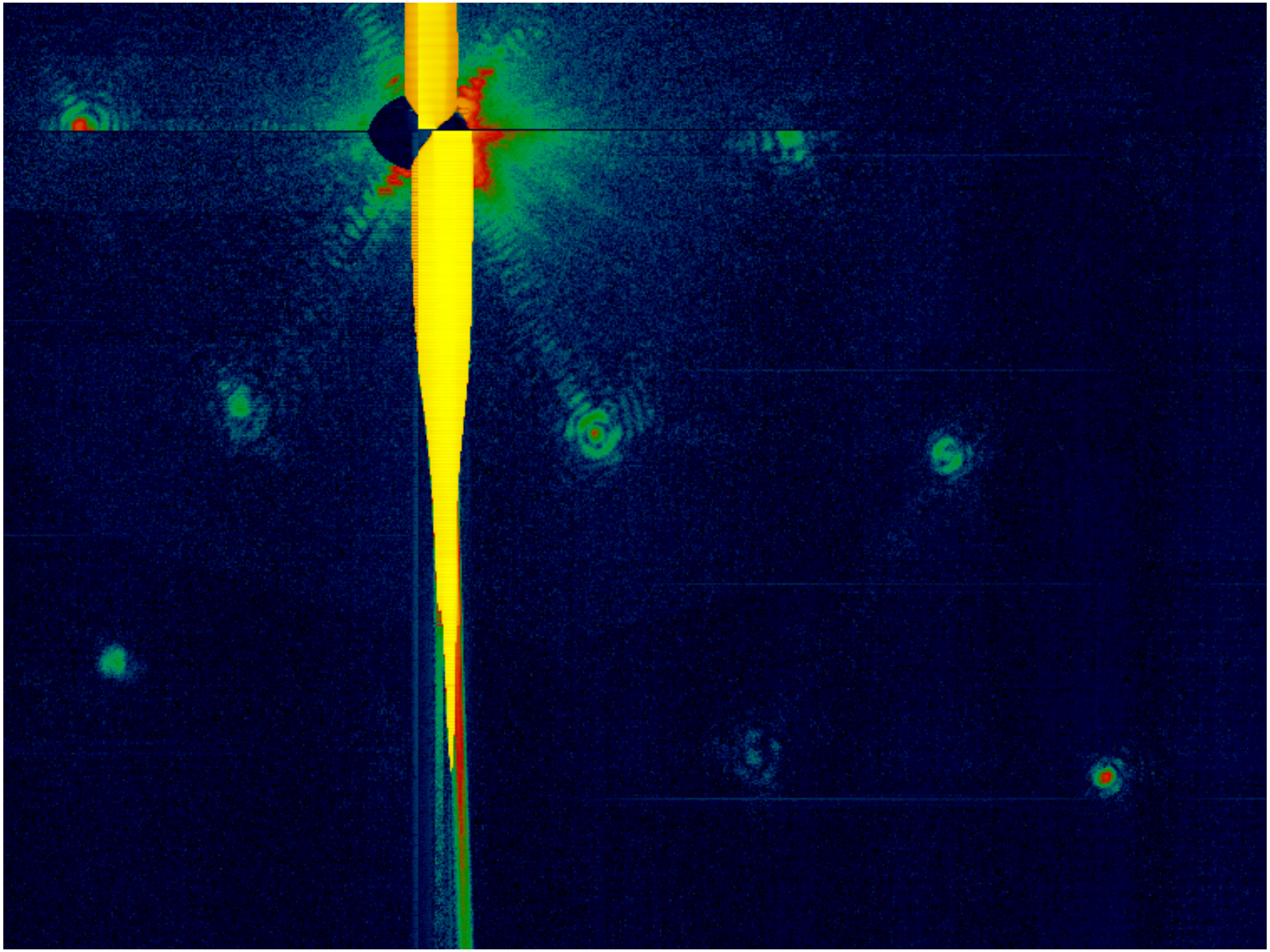
Back detector:

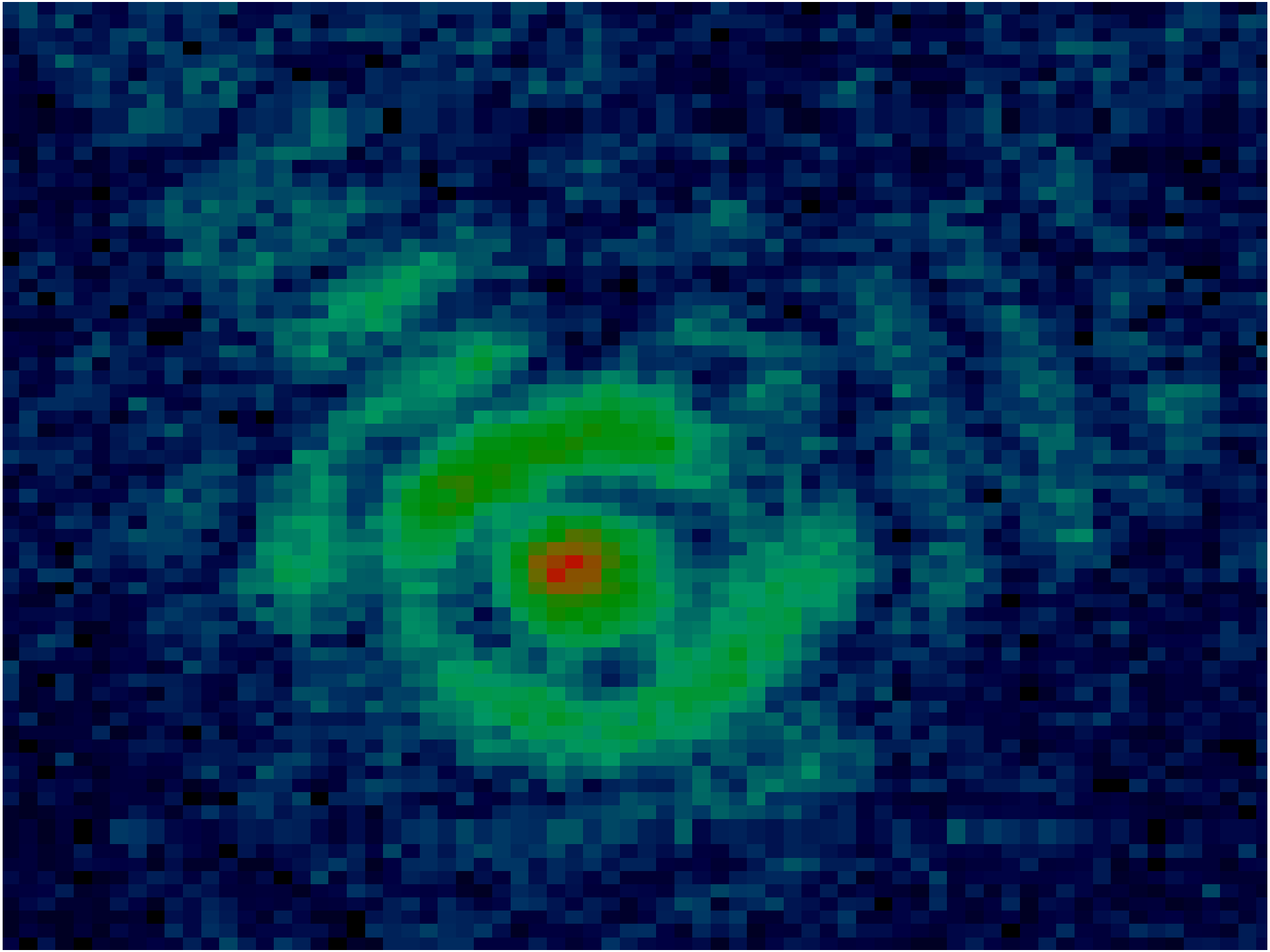
Gain: High gain/256

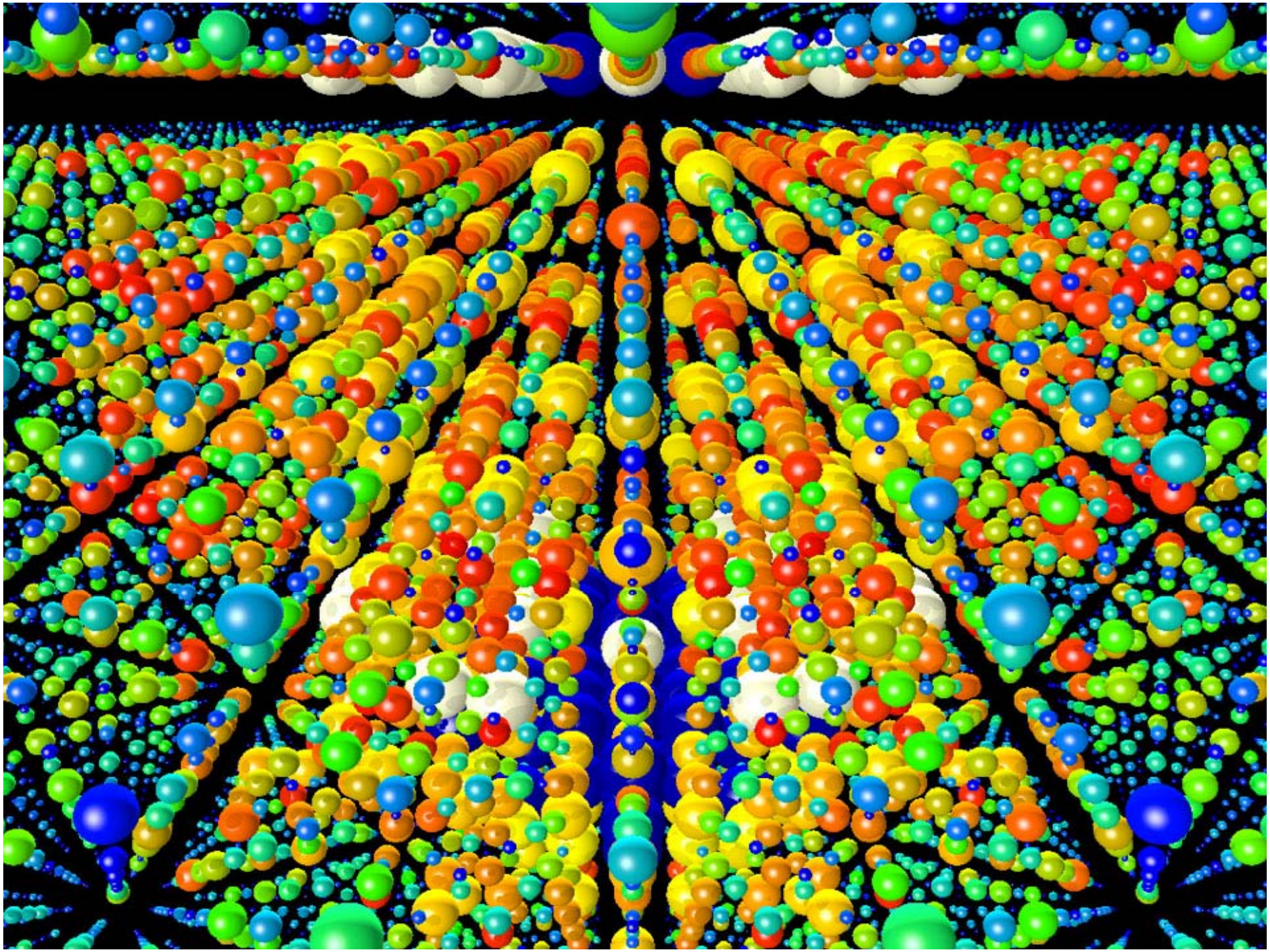
Max. charge: 2.5×10^5

Noise: 25 electrons

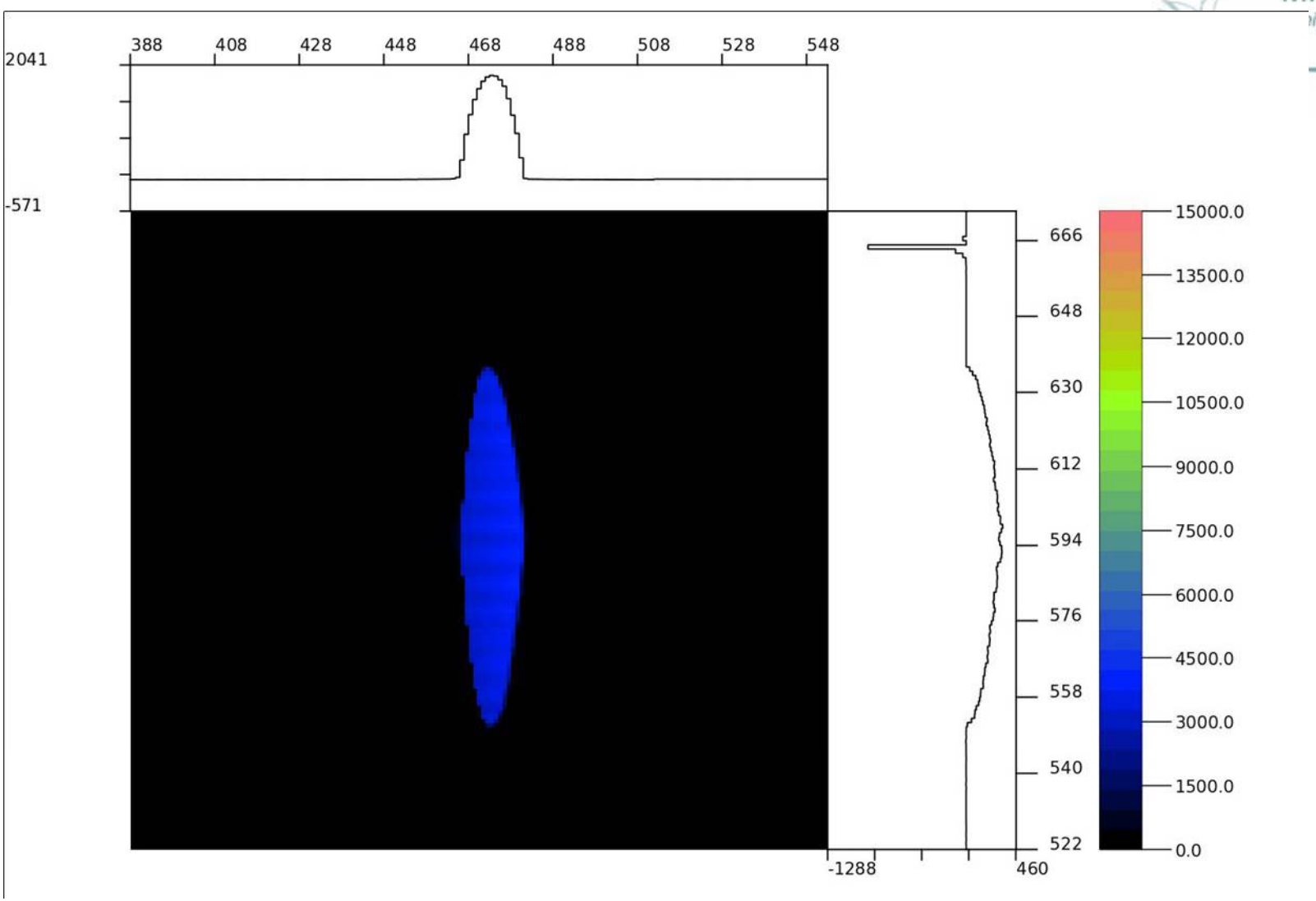




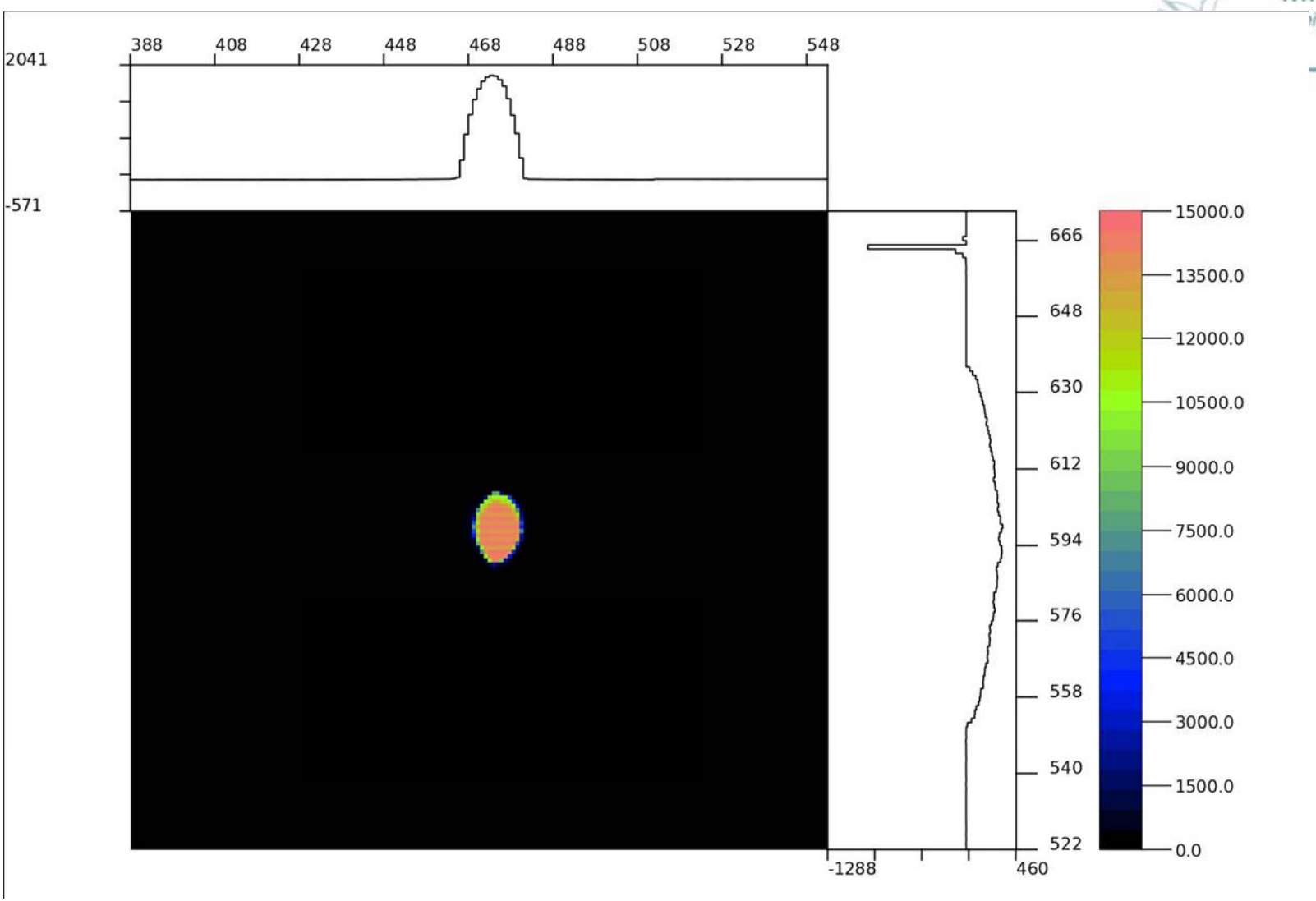




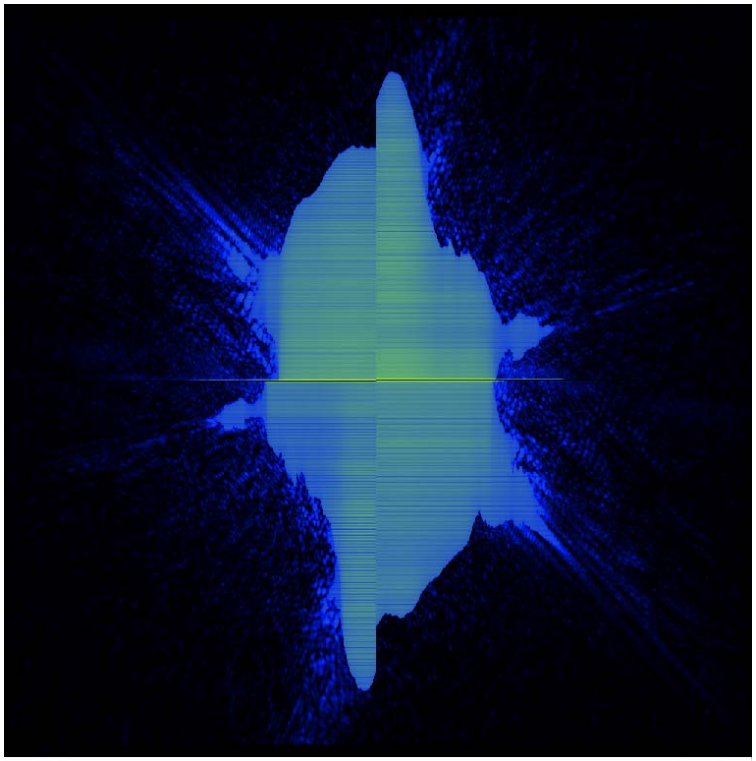
Charge Handling Capacitance

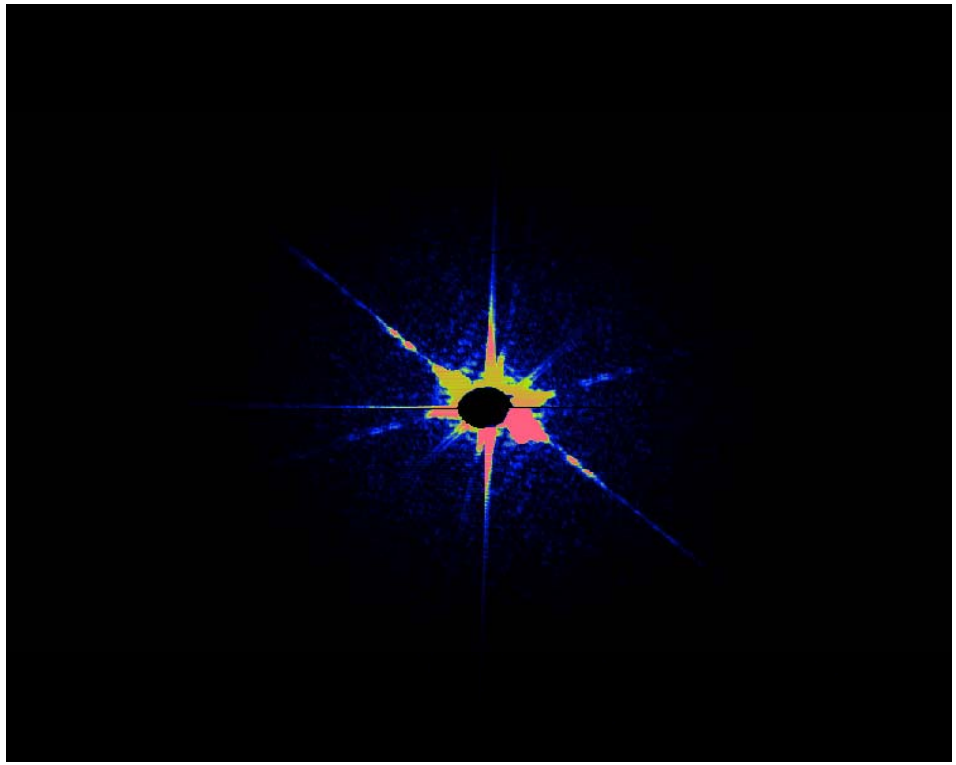


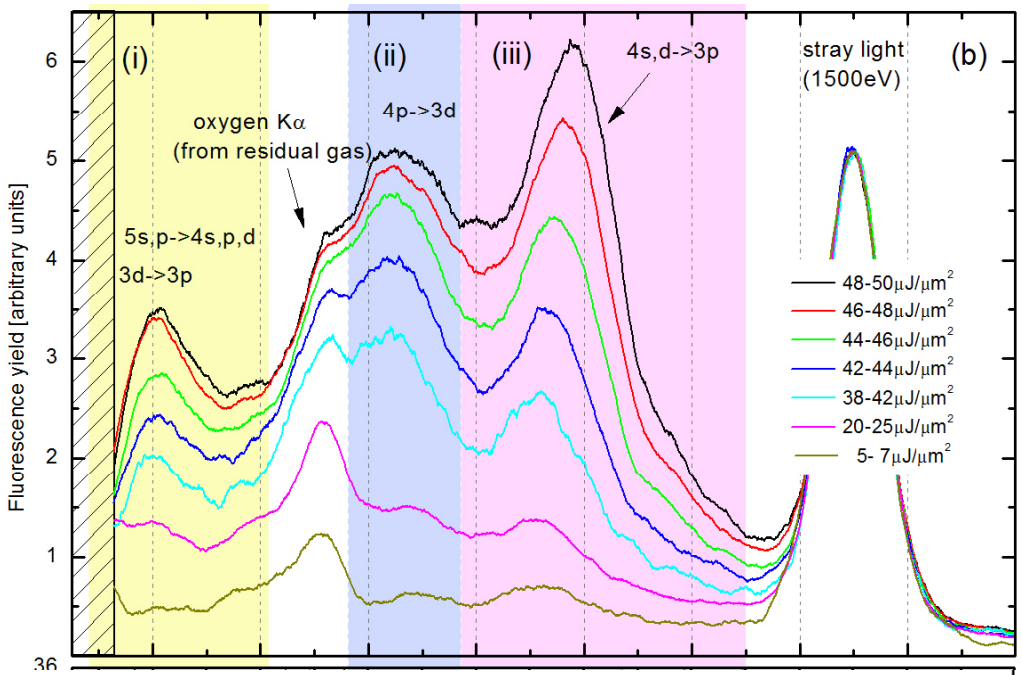
Charge Handling Capacitance

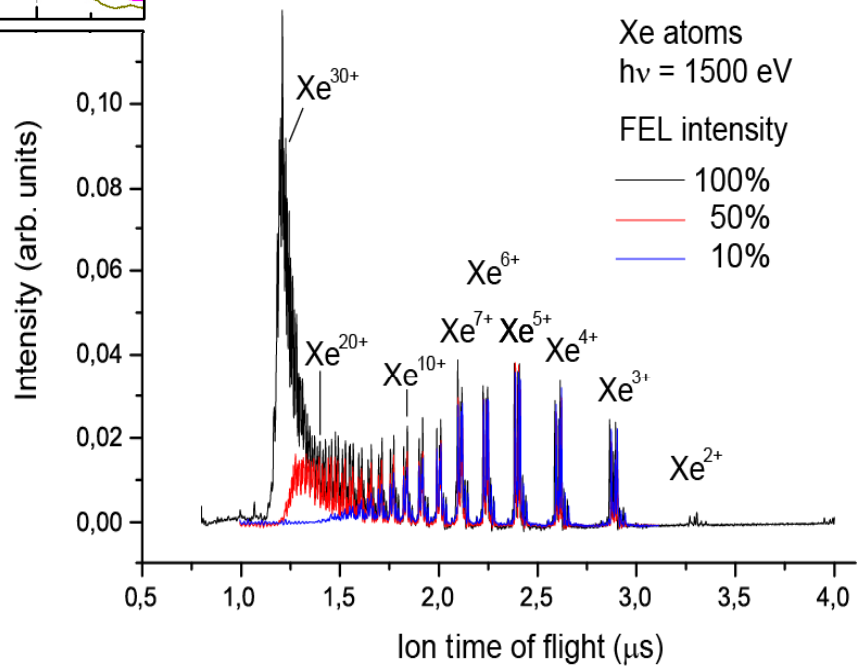


Imaging Performance

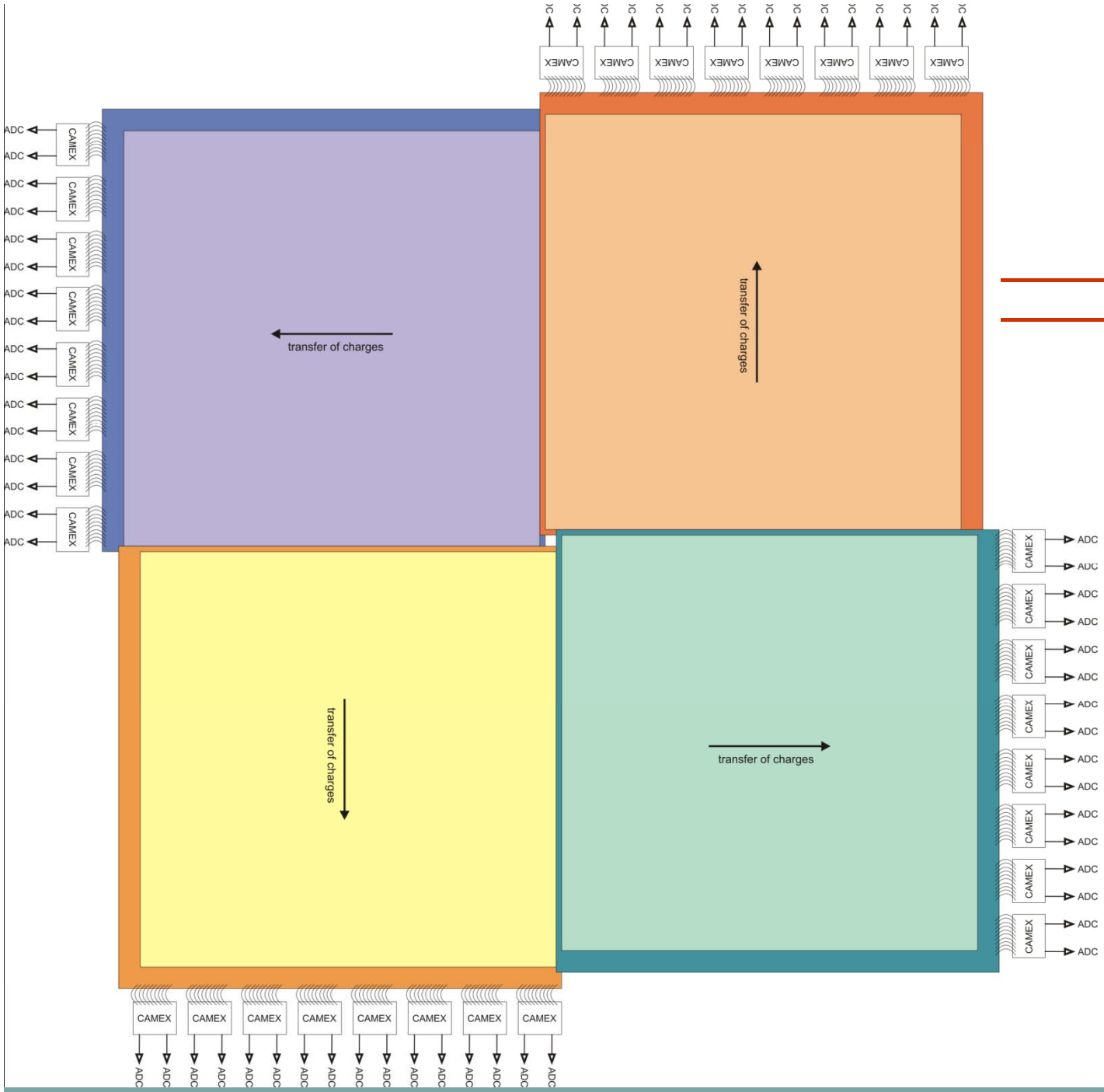








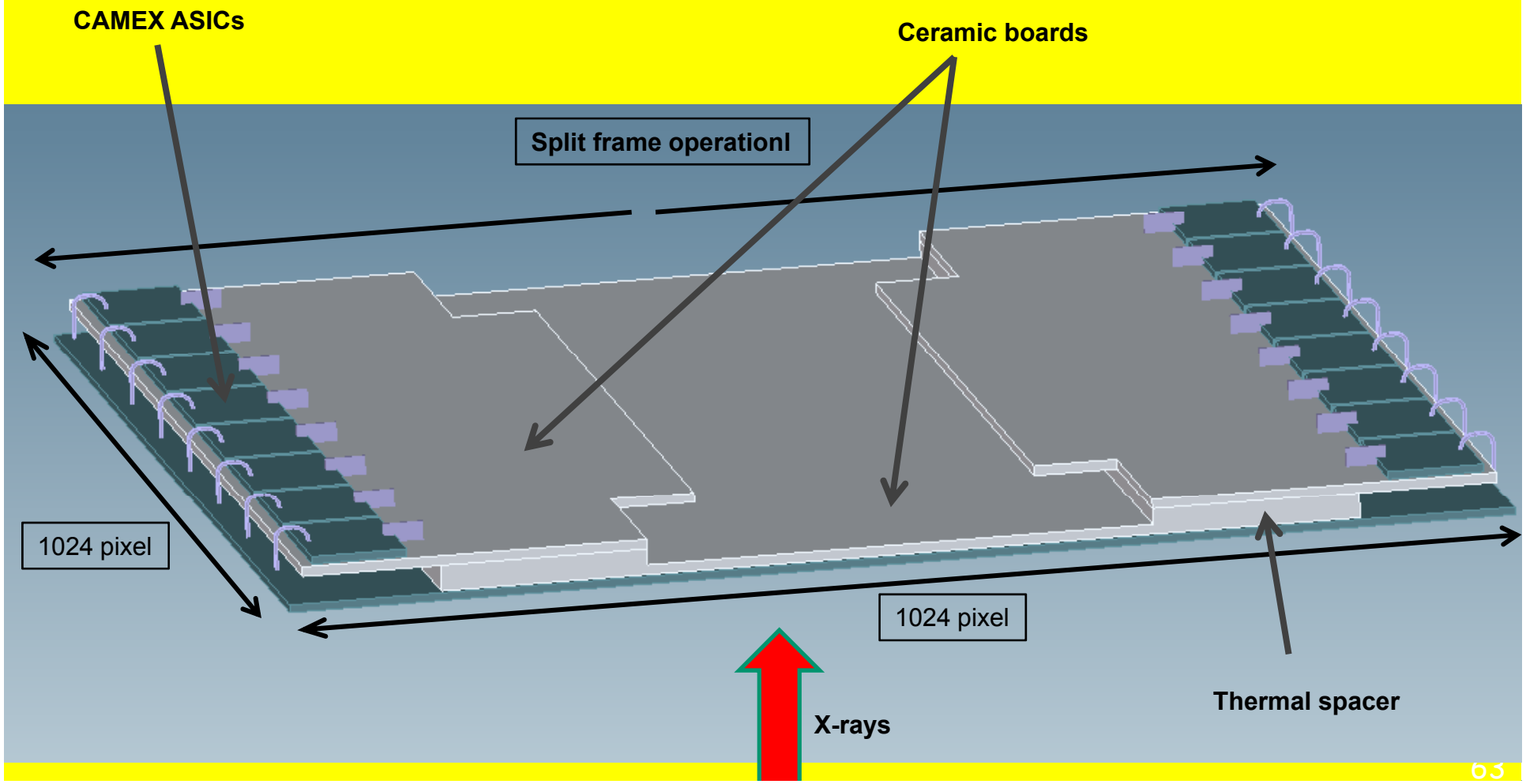
$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^{10}\ 4s^2\ 4p^6\ 4d^{10}\ 5s^2\ 5p^6$

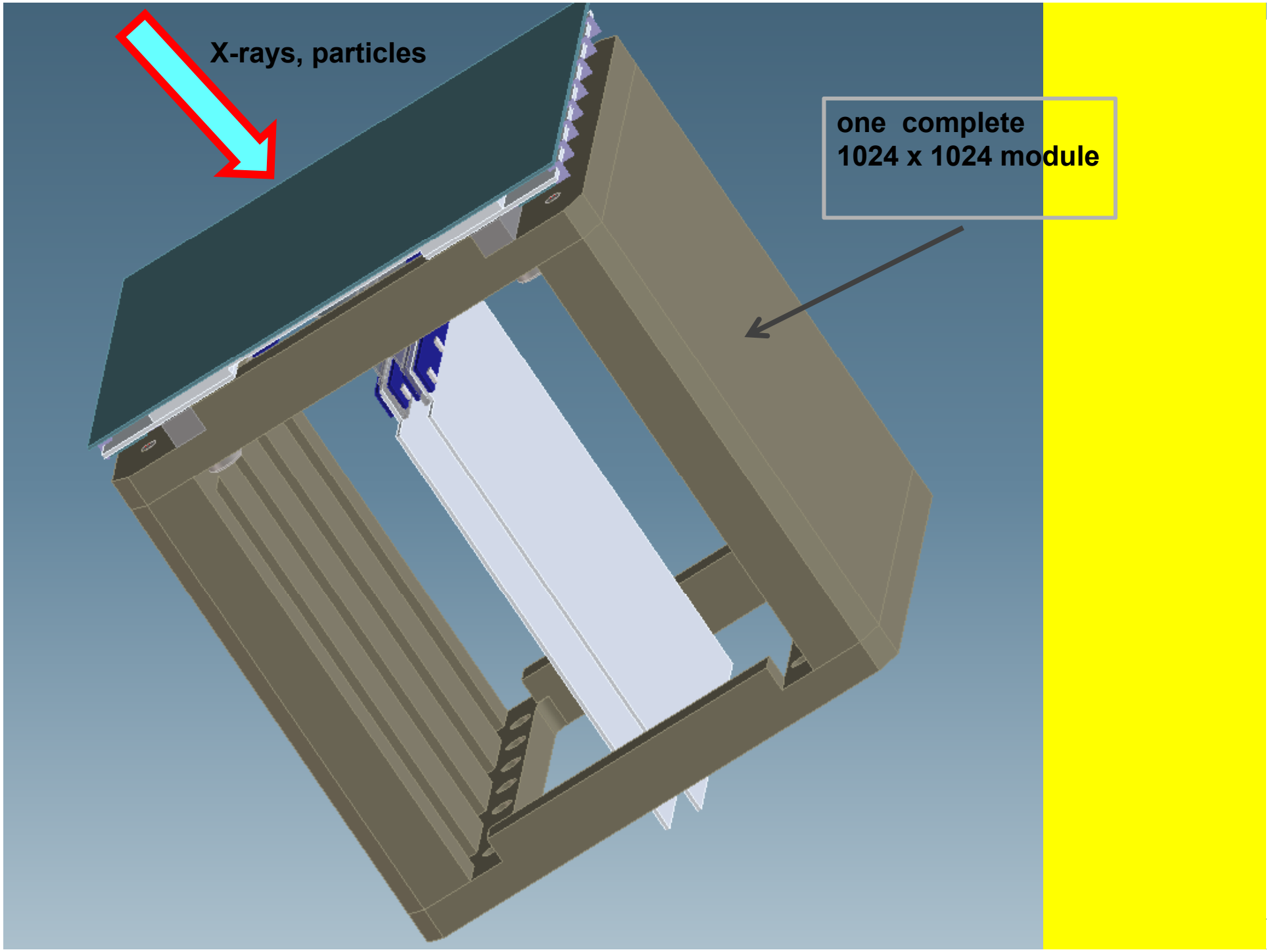


Expected system properties

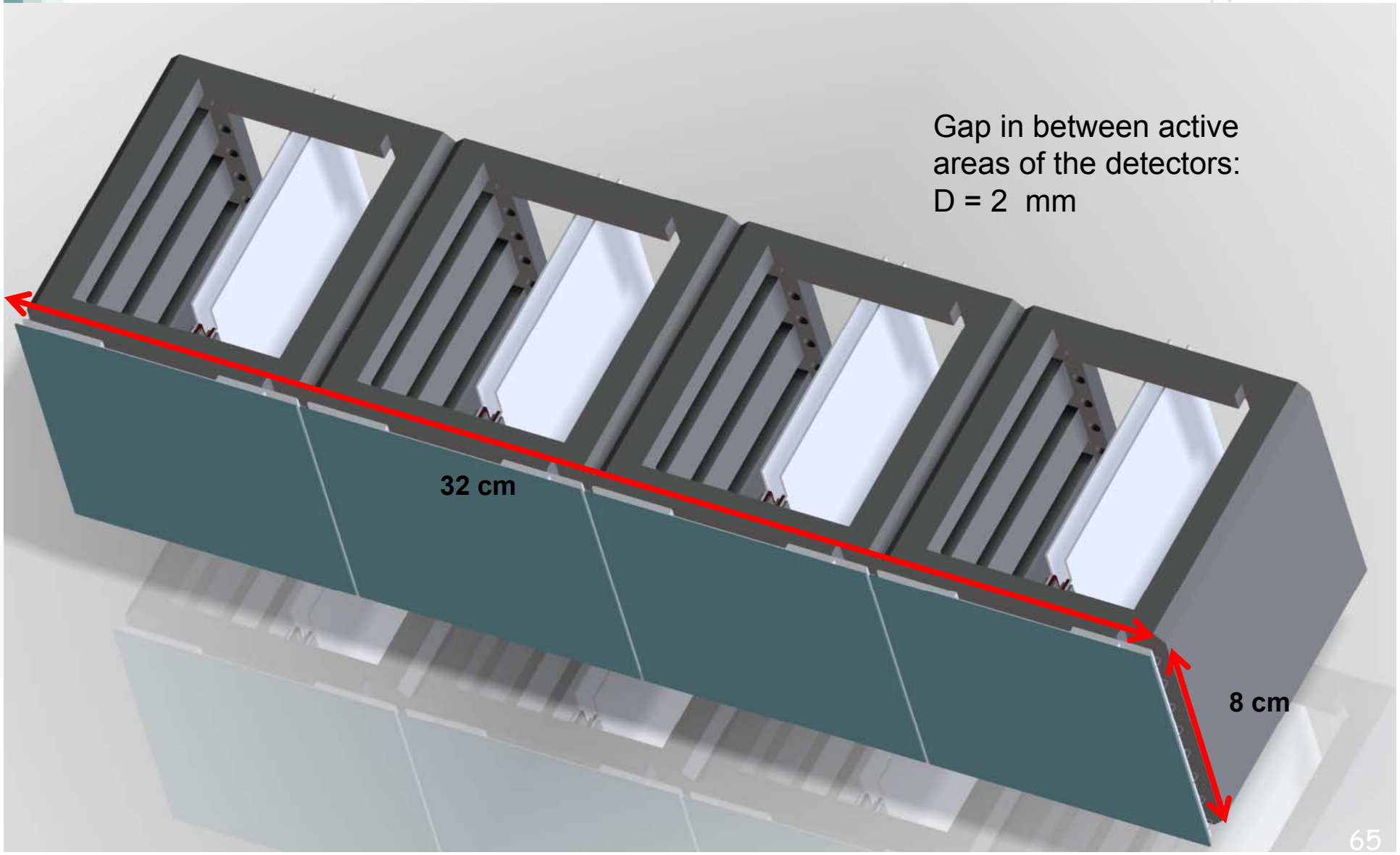
pixel size: 50 x 50 μm^2
or 75 x 75 μm^2
resolution: $\sigma_{x,y} \leq 10\ \mu m$
frame rate: 360 Hz
noise: 5 el. (rms)
CHC: 1.000.000 el.
PSF: typ. 3x3
EDpP: 3 MeV
thickness: 450 µm

Layout of a 1024 x 1024 pixel focal plane




X-rays, particles
one complete
1024 x 1024 module

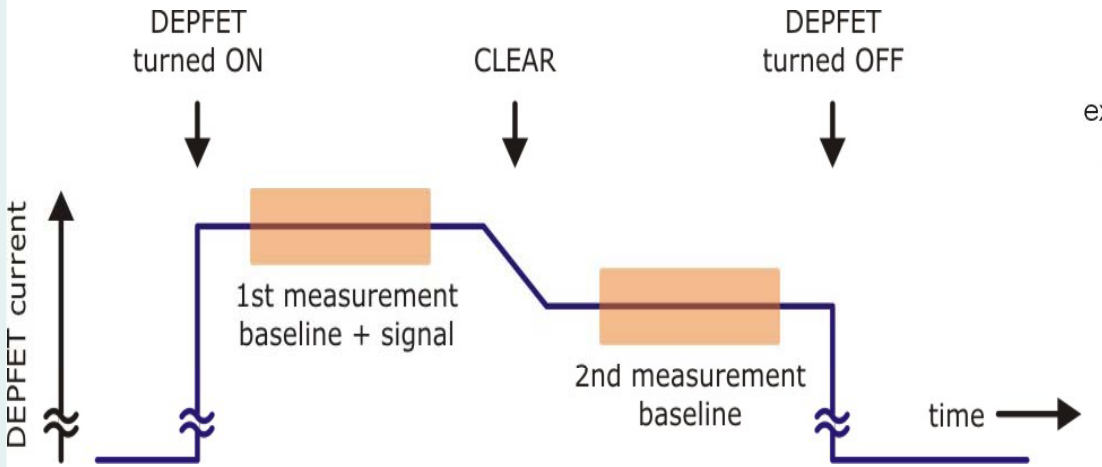
4096 x 1024 pixel array

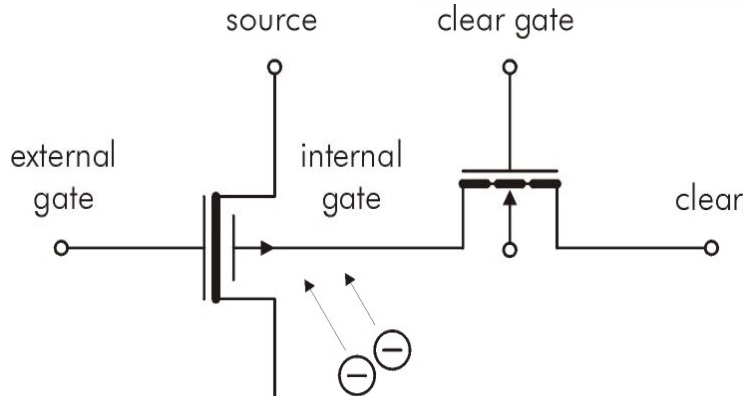


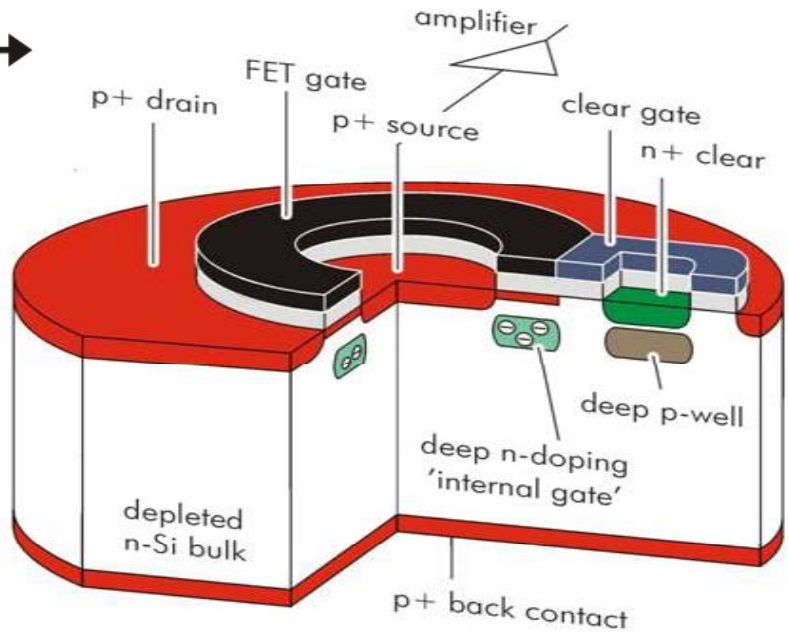
2048 x 2048 pixel array

Array of 2048 x 2048
Pixel of 75 x 75 µm^2

DEPFET readout



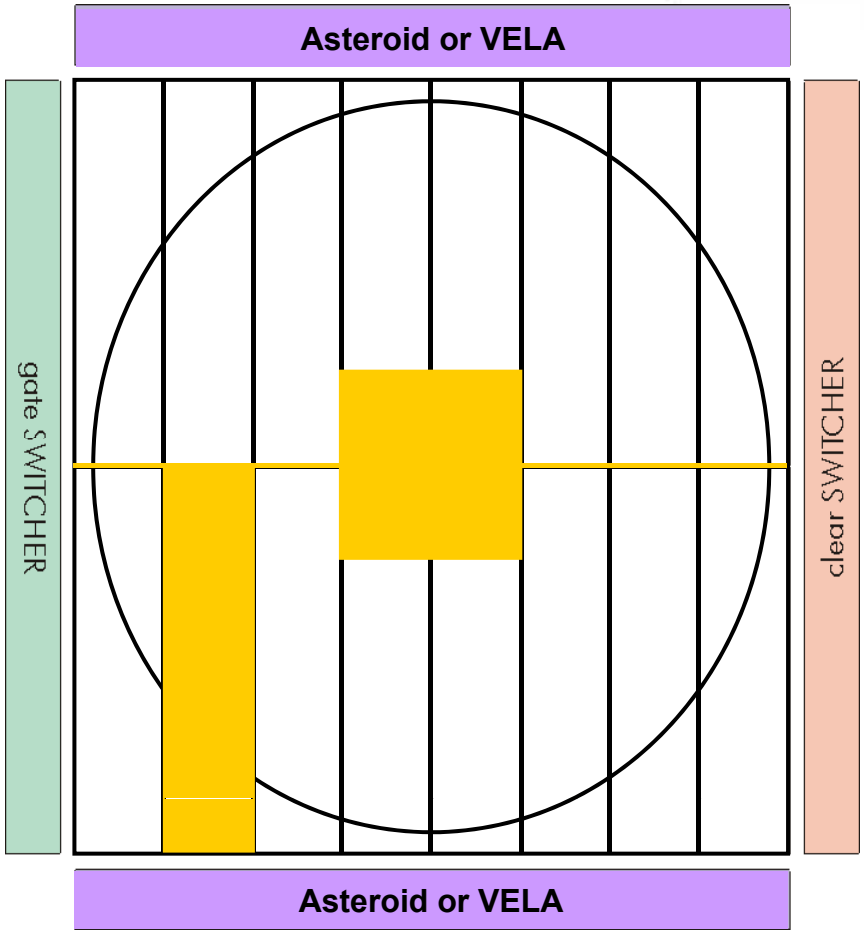


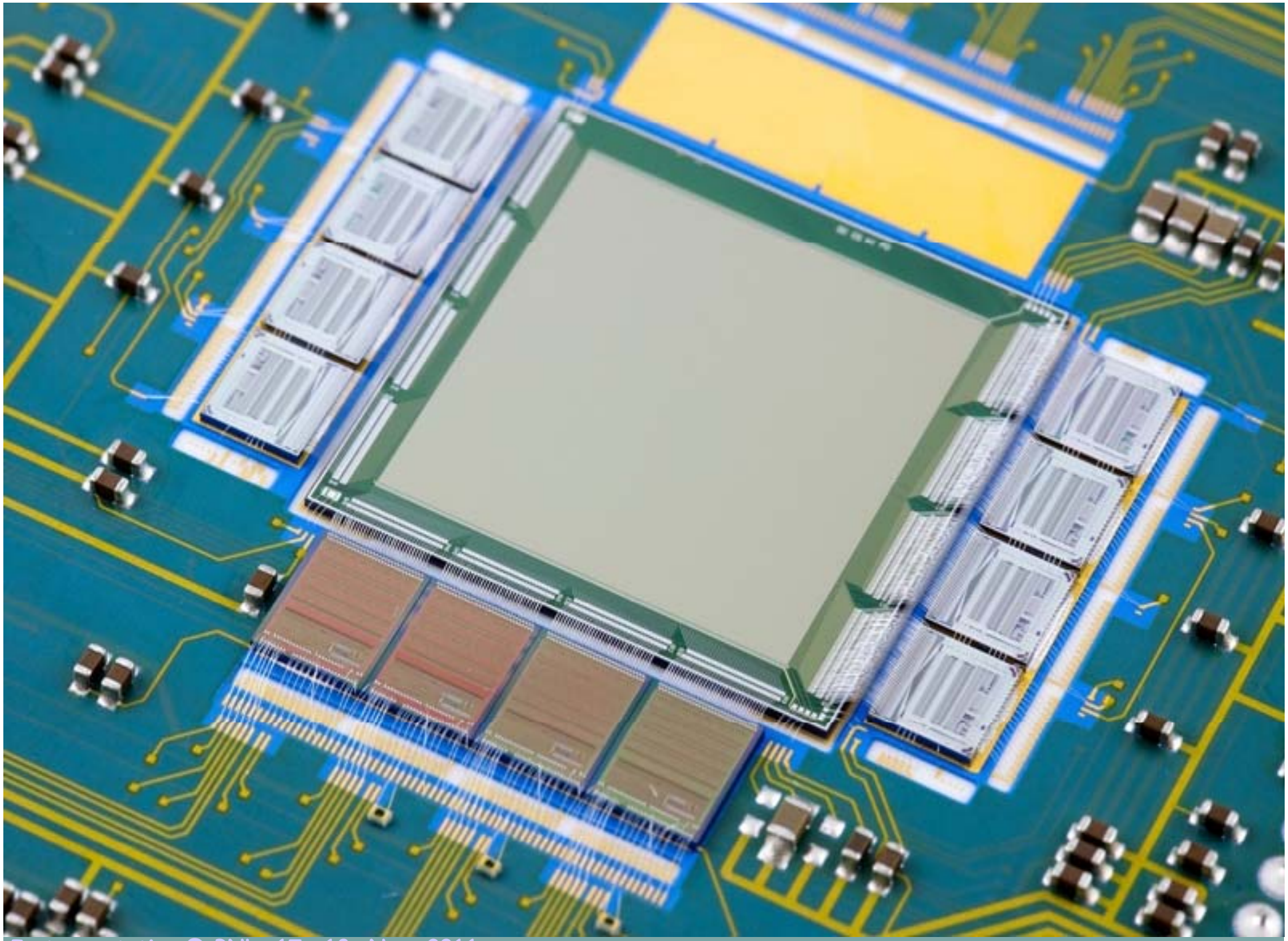


- *Measurement of signal*
  - ▷ Measure signal levels
    - source potential / drain current
  - ▷ Measure both before and after clear
  - ▷ Calculate the difference
    - correlated double sampling (CDS)

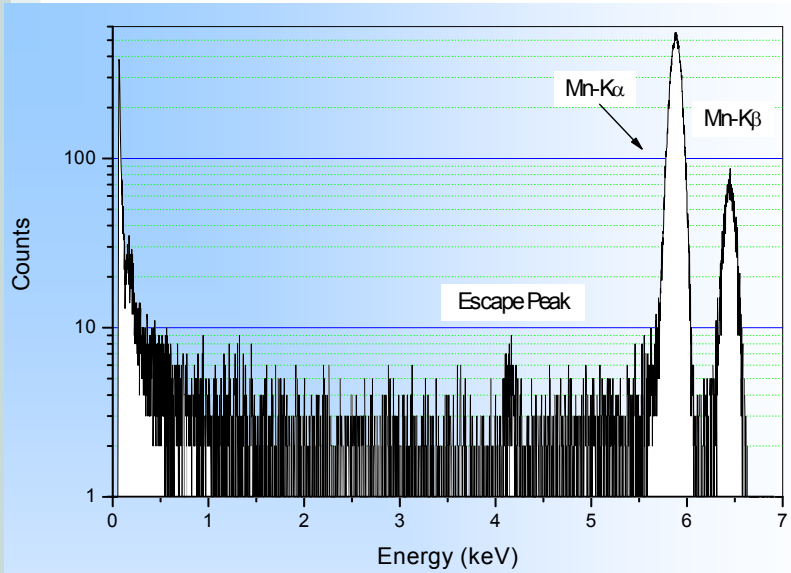
DEPFETs for the Athena WFI

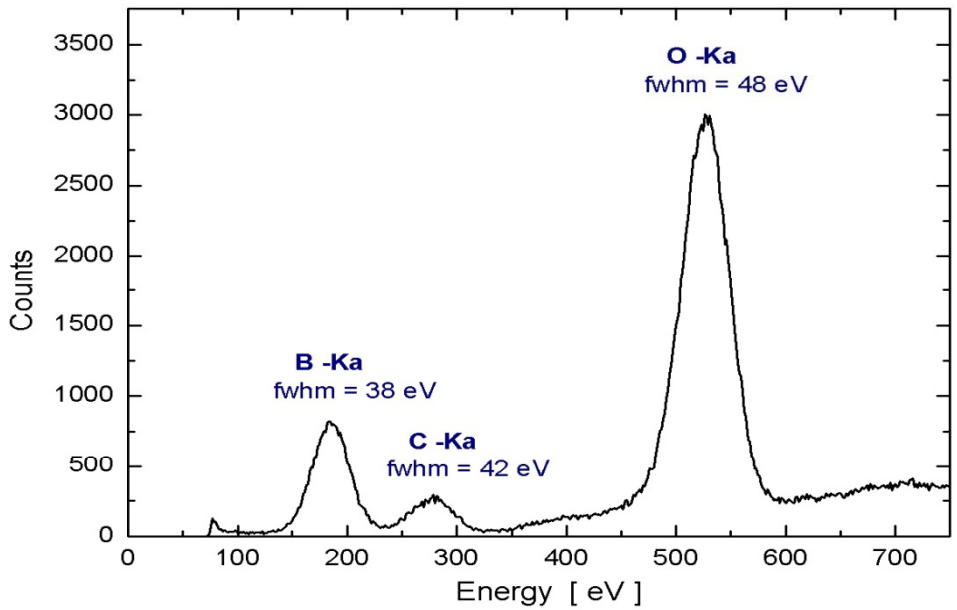
1. Flexible operating modes
2. low power dissipation (less than 2 W in 100 cm^2, DePFETs only)
3. Fano limited energy resolution from 0.5 keV to 30 keV
4. Spatial resolution better than 20 µm @ 100 µm pixel size
5. Homogeneous radiation entrance window
6. Intrinsic radiation hardness, no charge transfer needed
7. ENC was lowered to 0.2 e^- rms with RNDR
8. Thin optical ``Blocking Filter´´ can be directly integrated
9. Operation at ``warm temperatures´´, e.g. – 40 ° C





"Backside" illumination: Source on top of entrance window





- timing

  2 µsec/row <-> 32 µsec/32x512 sensor

- room temperature

  220 eV FWHM @ 5.9 keV **(singles)**

- moderate cooling -40 °C

  126 eV FWHM @ 5.9 keV **(singles)**

  131 eV FWHM @ 5.9 keV **(all events)**

- extrinsic speed & resolution limitations

- **yield & homogeneity**
  - defect pixels

    2 in 45 devices (> 10^6 pixels)

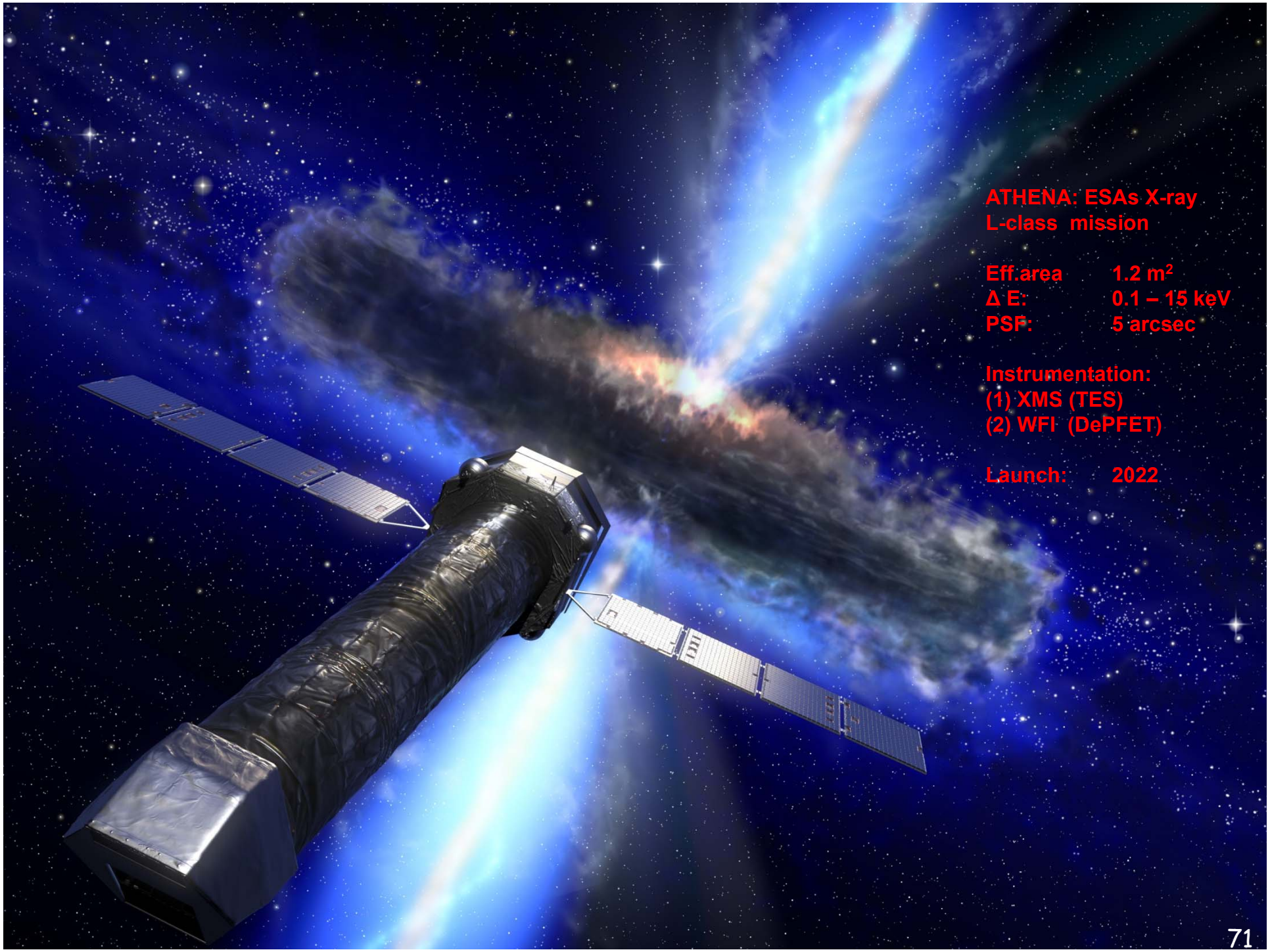
    pixel yield > 0.99999

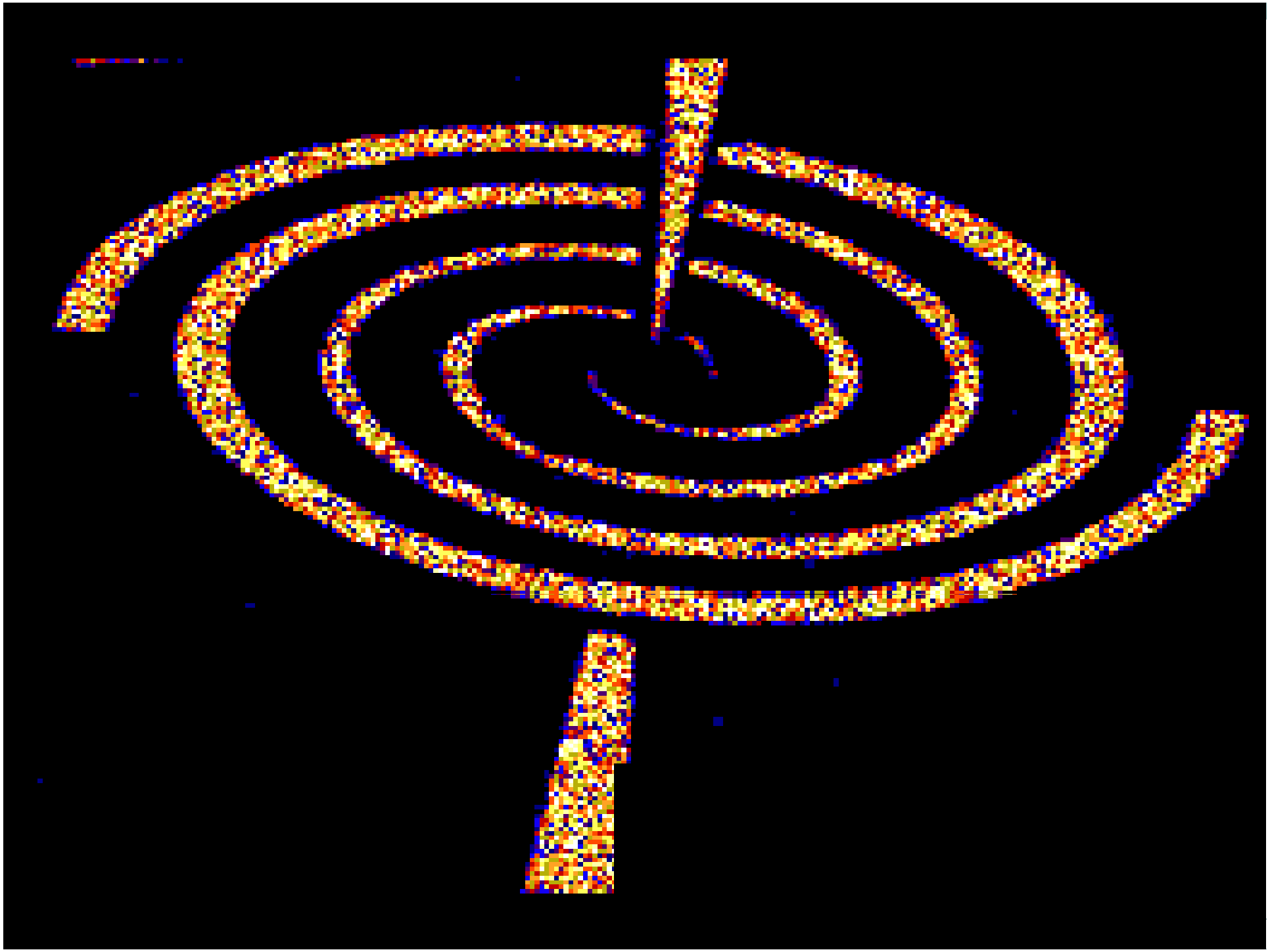
  - dispersions

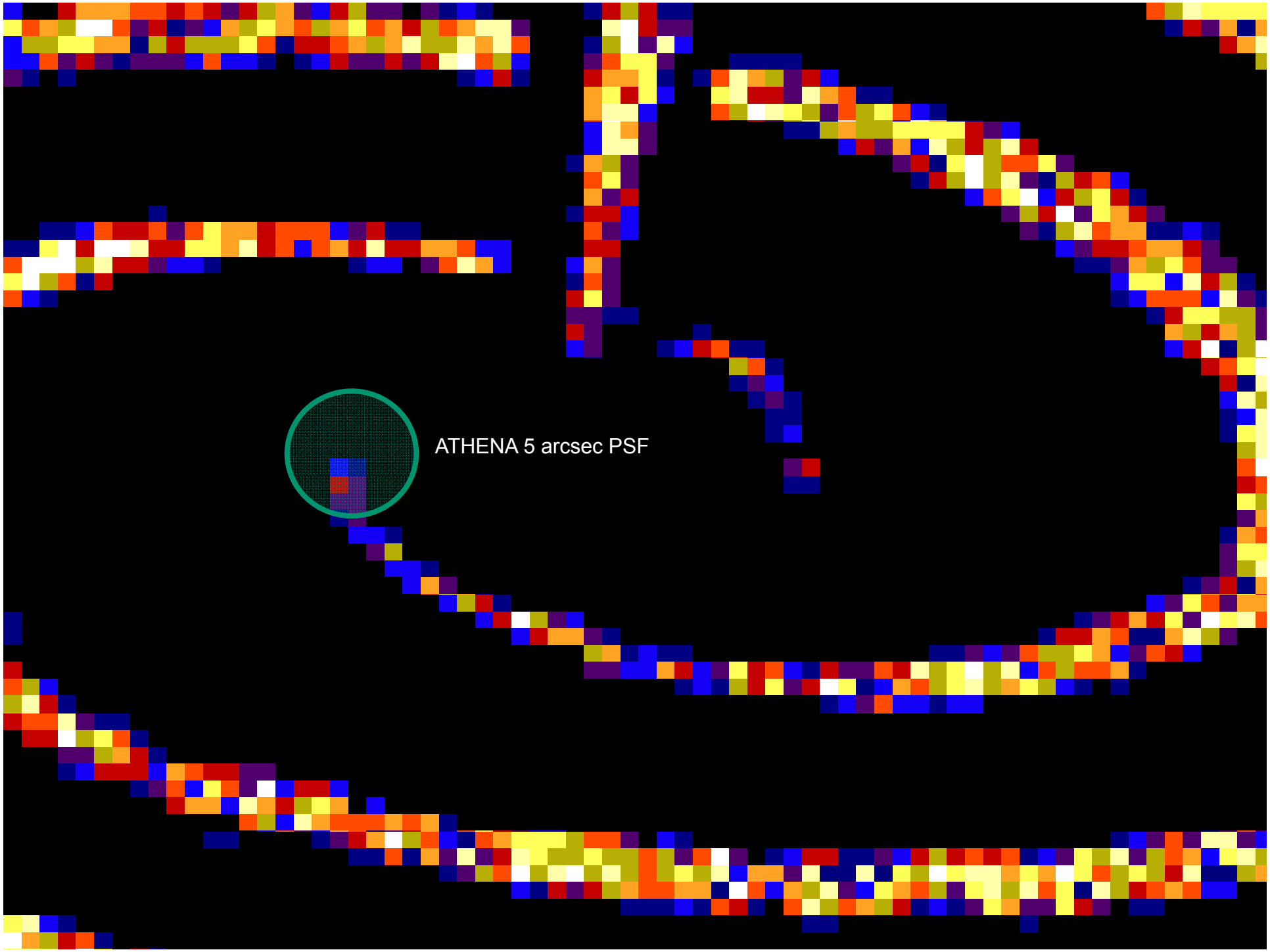
    offset **< 2 %** (of Mn-Kα)

    gain **< 5 %**

    noise **< 10 %**

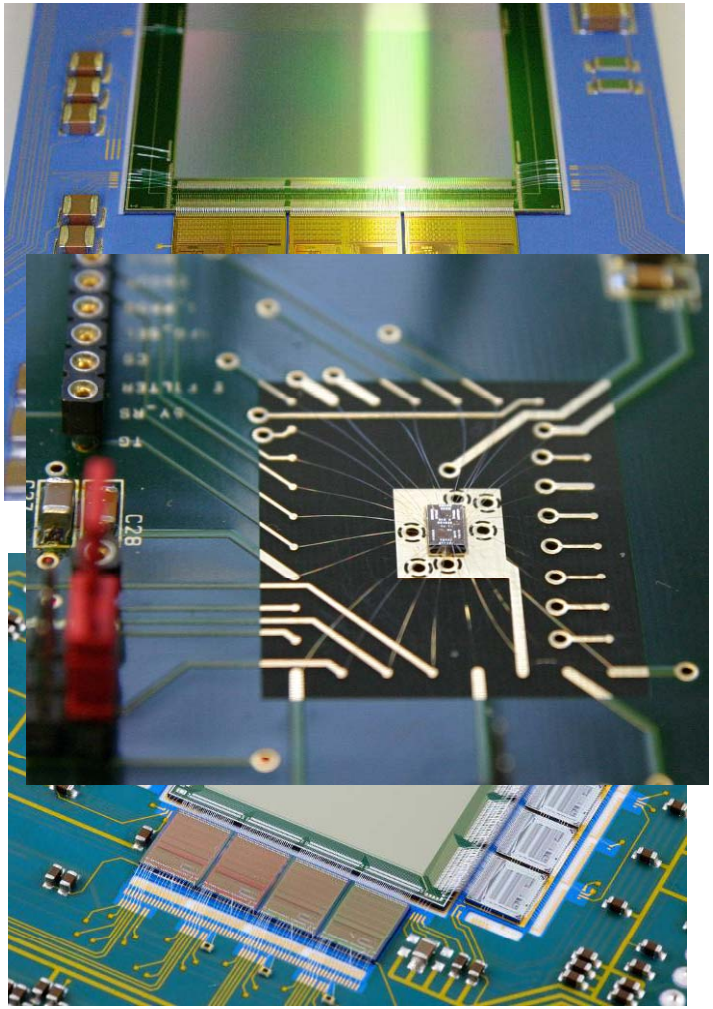

ATHENA: ESAs X-ray
L-class mission
Eff.area 1.2 m²
Δ E: 0.1 – 15 keV
PSF: 5 arcsec
Instrumentation:
(1) XMS (TES)
(2) WFI (DePFET)
Launch: 2022



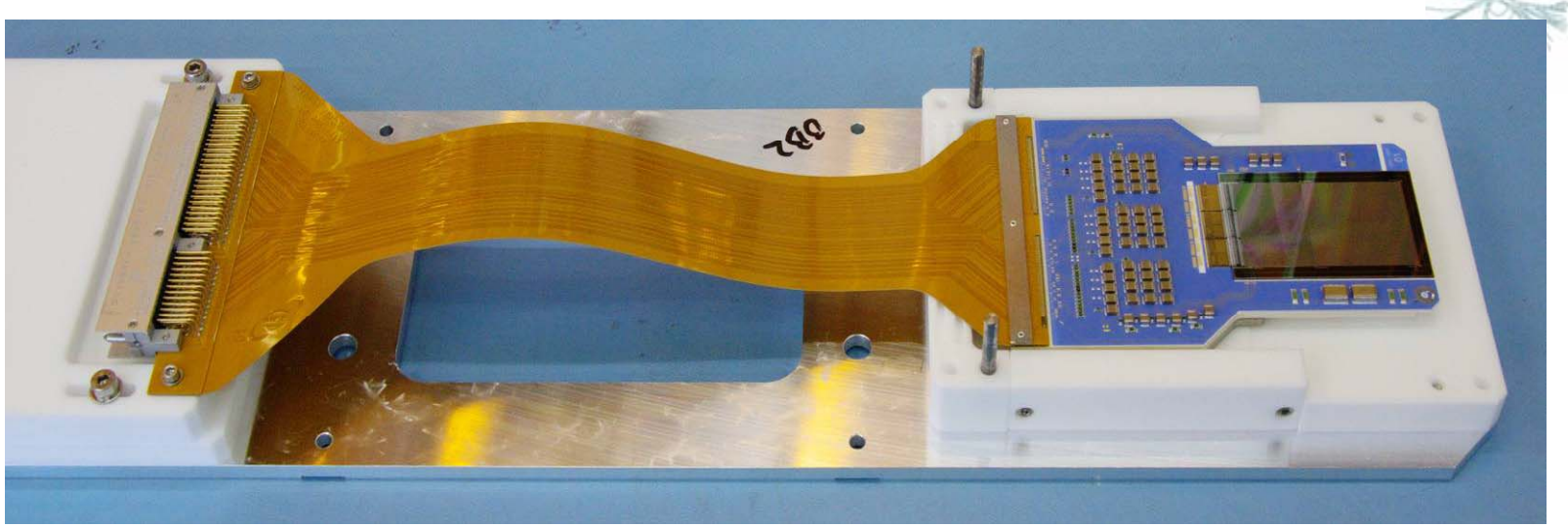

ATHENA 5 arcsec PSF

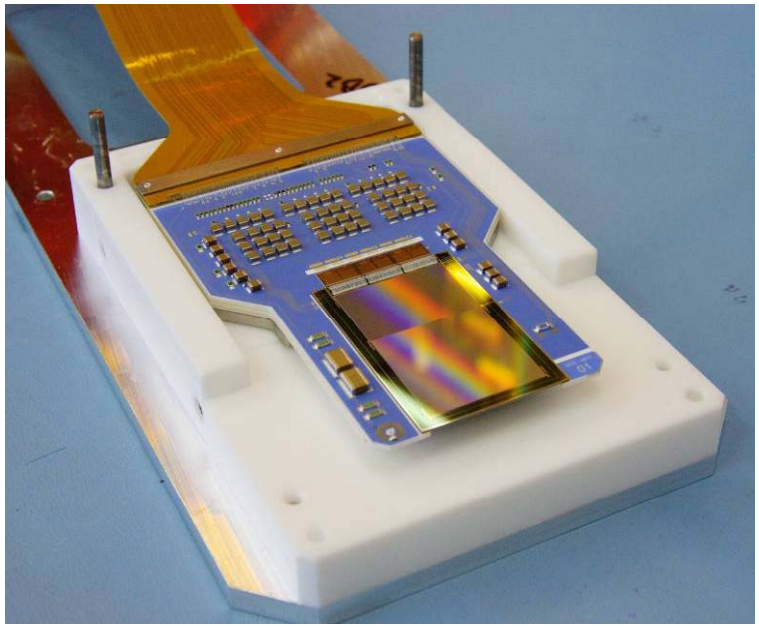
Frontend ASIC's

- **CAMEX** 0.8μm
  - readout ASIC for use with CCDs & DEPFET Pixel
- **ASTEROID & VELA** *& VERITAS* 0.35μm
  - readout ASICs for DEPFET Pixel *& CCD*
- **SWITCHER** 0.35μm HV
  - DEPFET matrix control -> selection of a pixel row for readout or clear
- **DSSC ASIC** 130nm
  - preamplifier with high speed and high dynamic range for XFEL DEPFETs
- **DHP cluster engine** 90nm
  - data clustering engine for data reduction for tracklets of Belle II

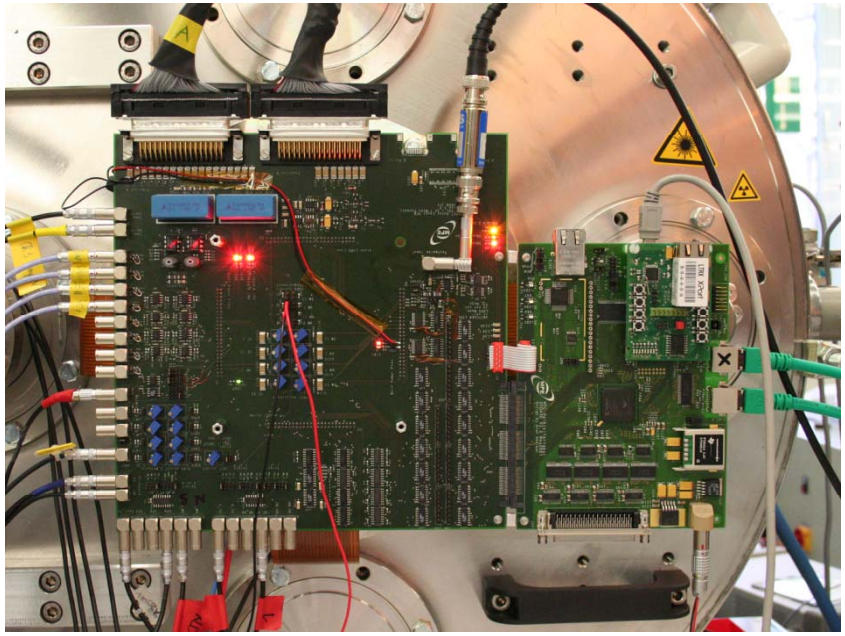


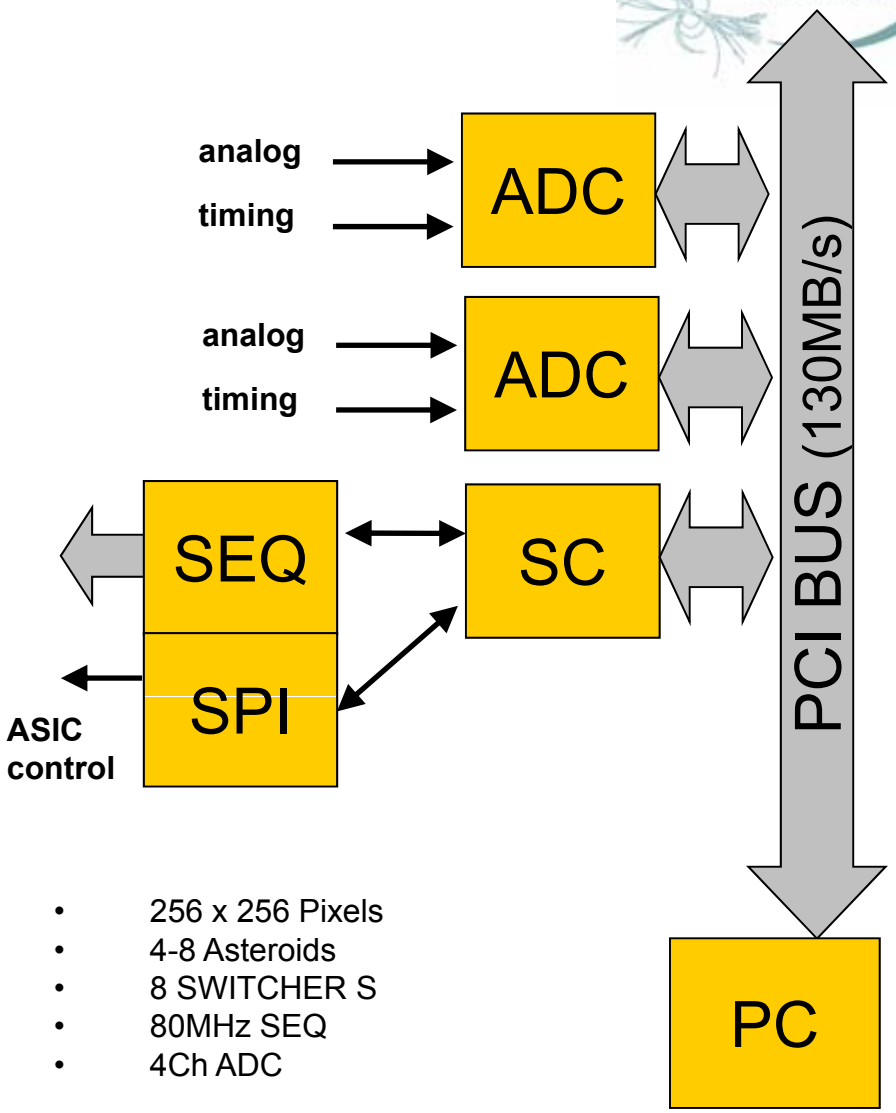
Where to find - Examples





PCI DAQ System (PXD5+,SX,XL)



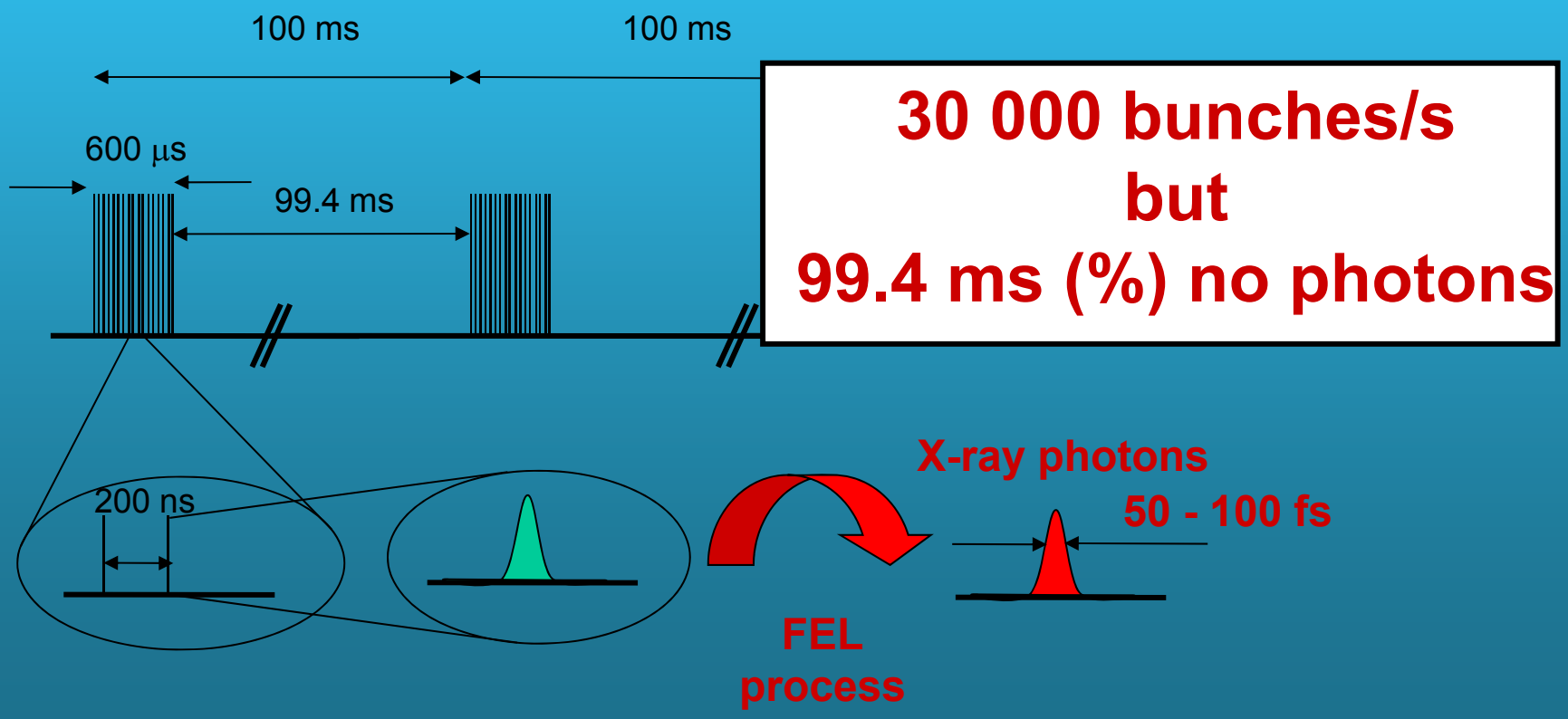


- 256 x 256 Pixels
- 4-8 Asteroids
- 8 SWITCHER S
- 80MHz SEQ
- 4Ch ADC

What is the challenge for Detectors @ XFEL ?

Time structure: difference with "others"

Electron bunch trains; up to 3000 bunches in 600 μsec, repeated 10 times per second.
Producing 100 fsec X-ray pulses (up to 30 000 bunches per second).



30 000 bunches/s
but
99.4 ms (%) no photons

The European XFEL project

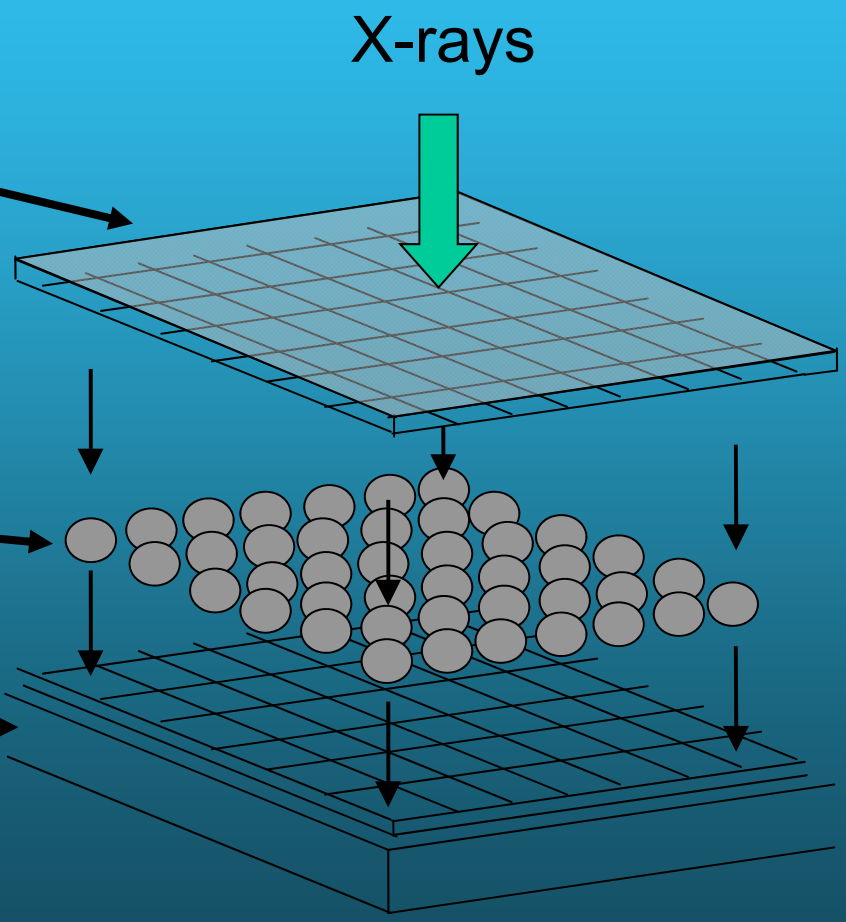
DePMOS Active Pixel Sensor

Connecting Bumps

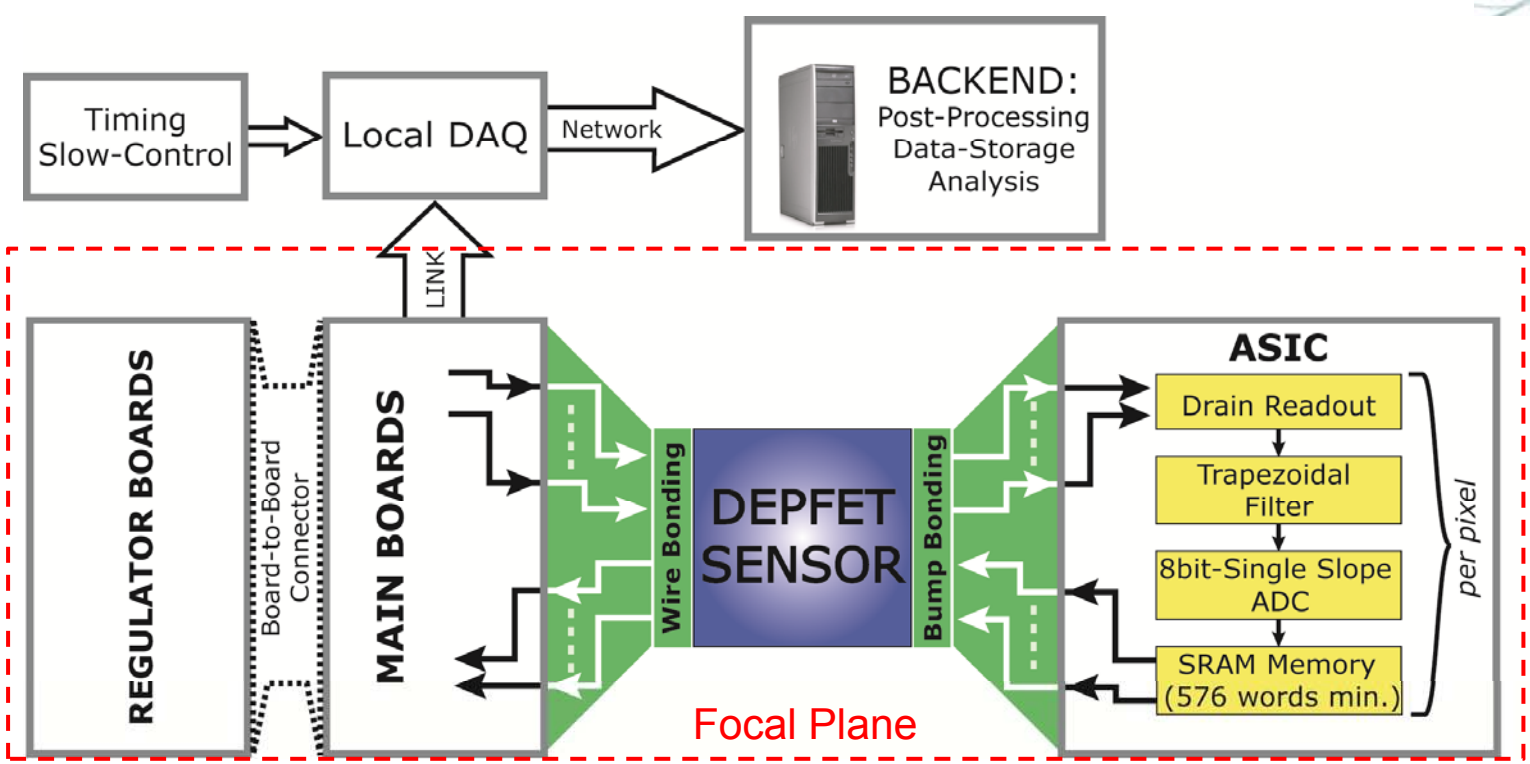
- **1 per pixel**

CMOS Layer

- **Signal processing**
- **Signal storage & output**



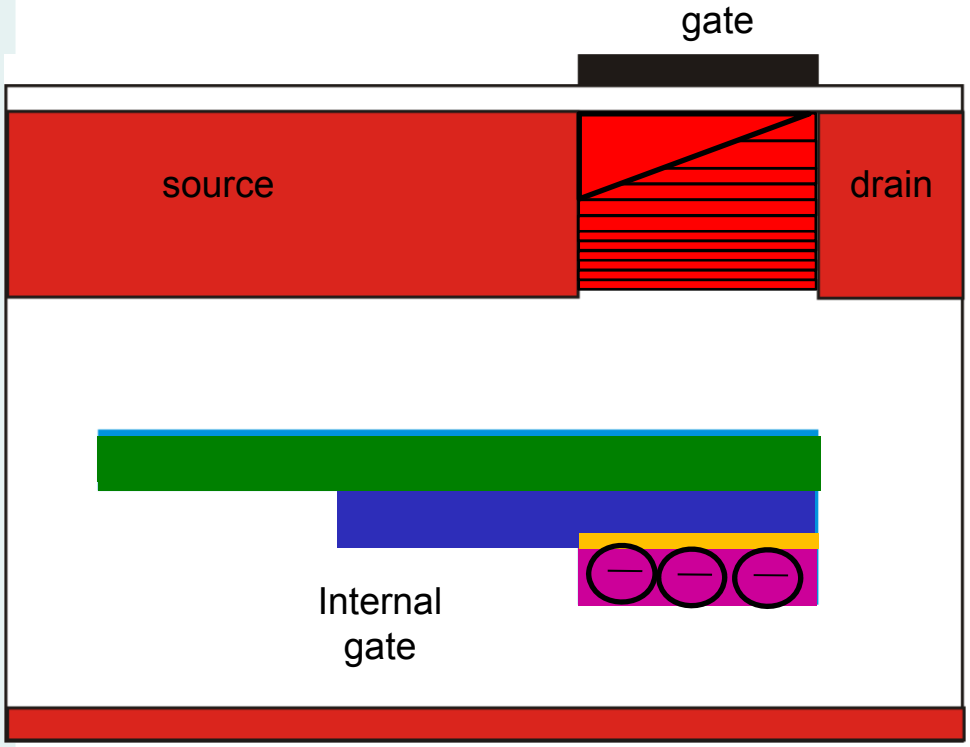
System Block Diagram

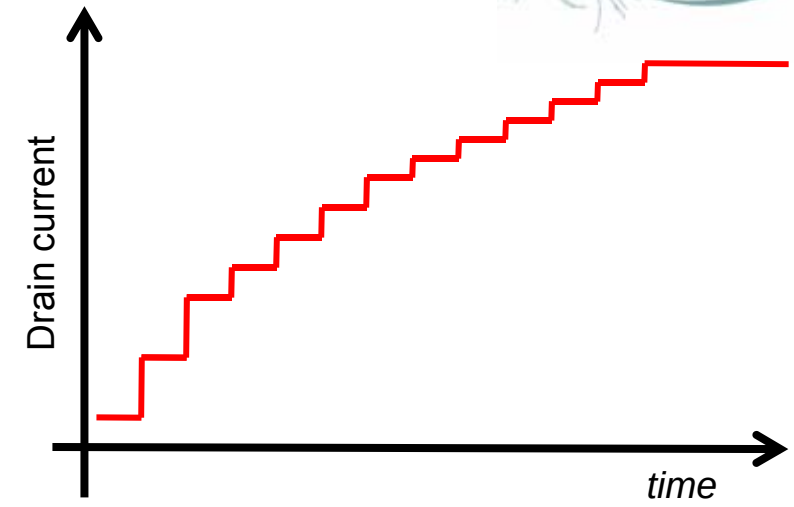


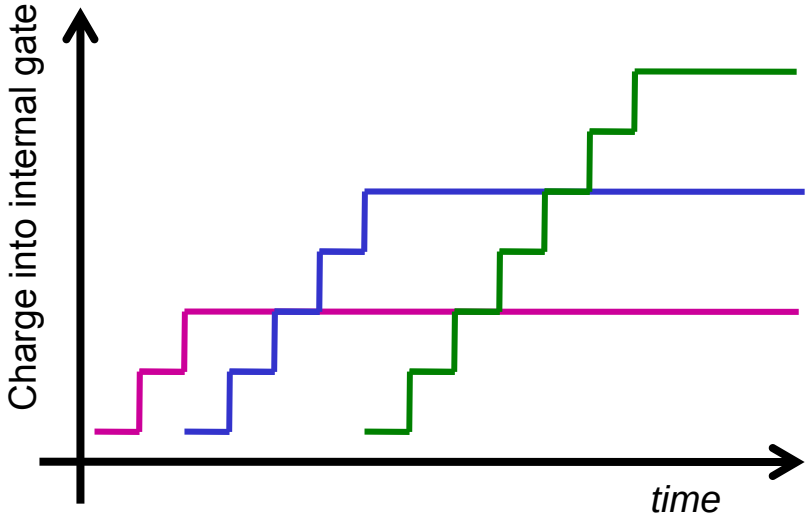
Readout Concept

- Optimum analog shaping
- Immediate 8 bit digitization (9 bit for f ≤ 2.2 MHz)
- In-Pixel SRAM
- Digitized data are sent off the focal plane during 99ms gap
- Sensor & Front-end electronics can be switched off during the gaps

Non-Linear DEPFET Working Principle



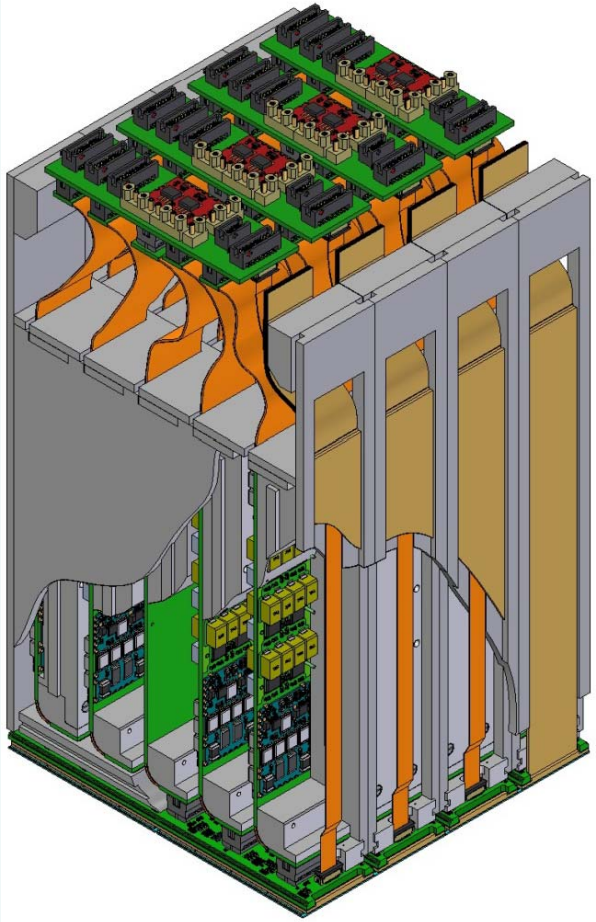


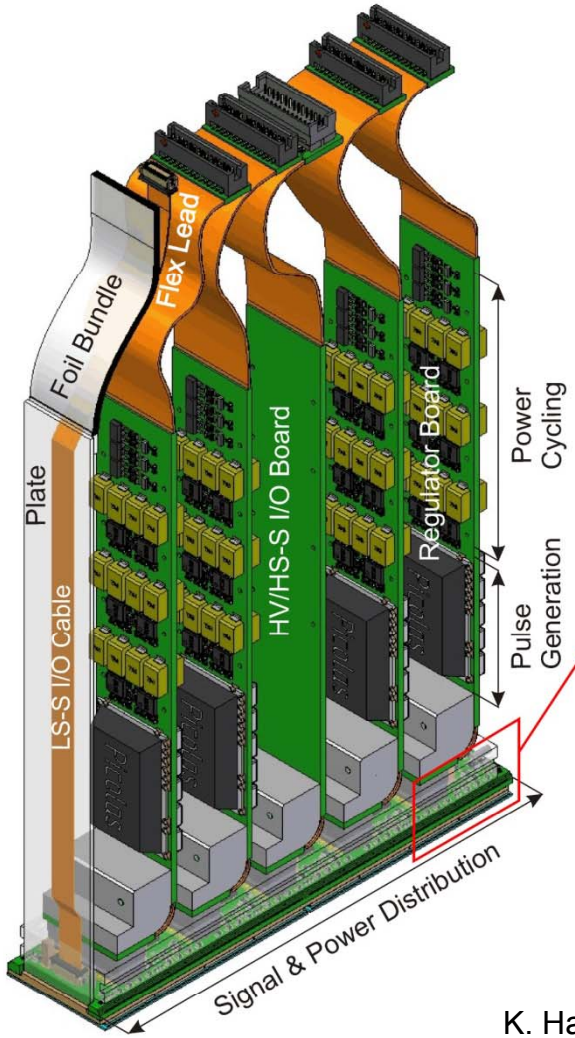


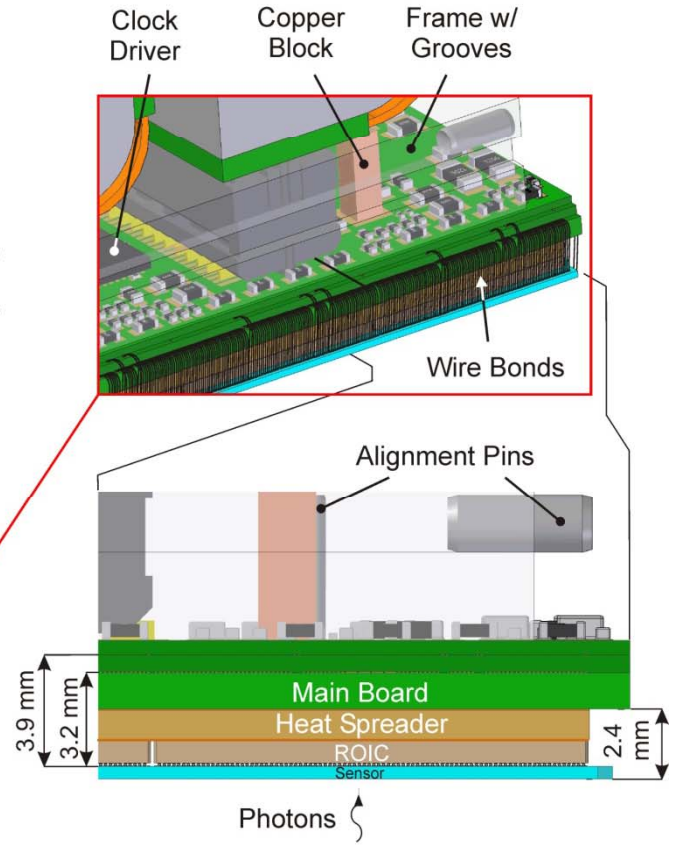
- The internal gate extends into the region below the source
- Small signals assemble below the channel, being fully effective in steering the transistor current
- Large signals spill over into the region below the source. They are less effective in steering the transistor current.

module, mechanics and power

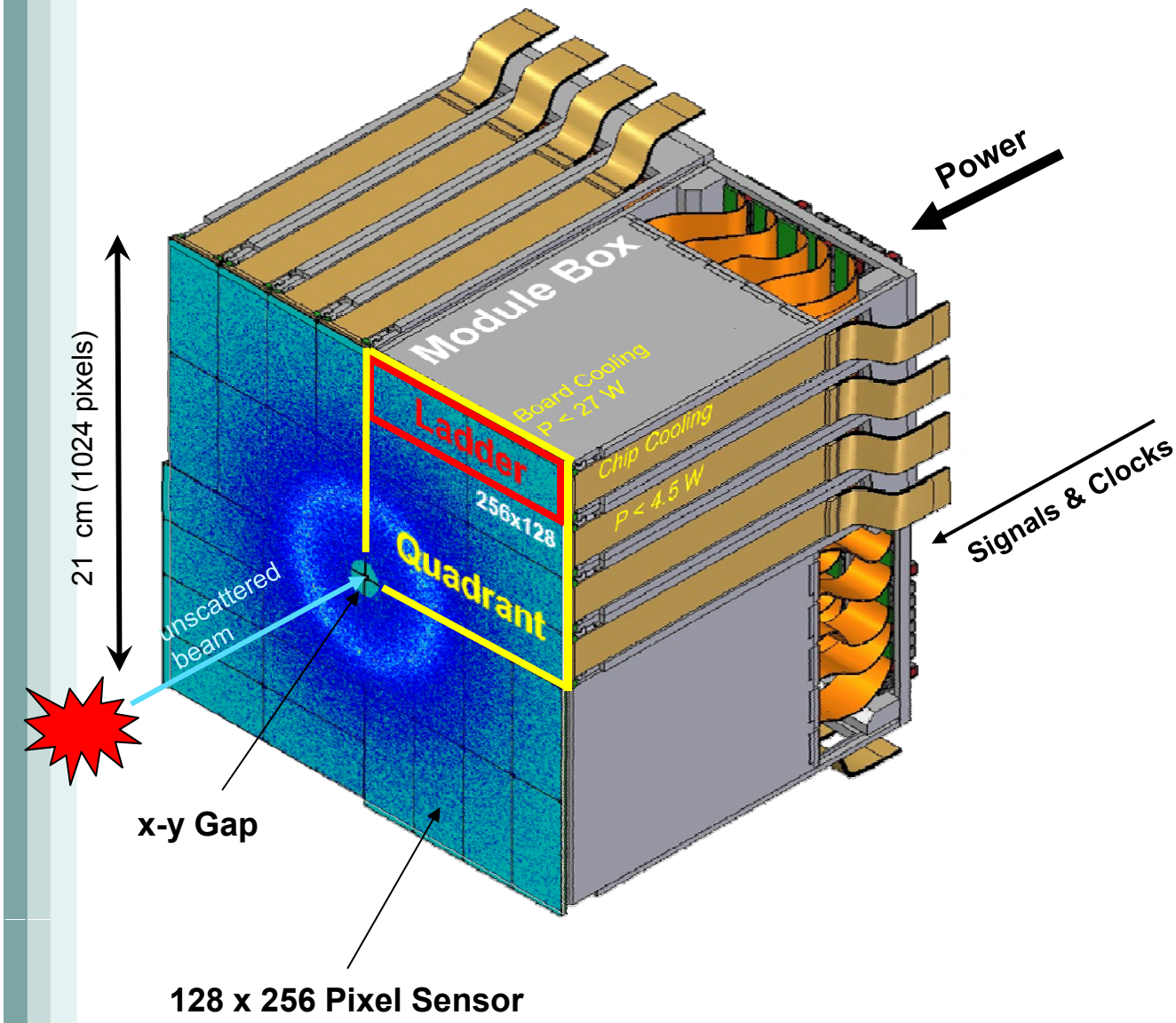
- 1-2 mW/pixel peak power → 1-2 kW peak power
- Power cycling about 1/100
- 10-20 W mean power
- A careful thermal design is needed
- Voltage regulators have to be deliver a lot of power in a short time







K. Hansen - DESY



- 1024x 1024 pixels
- 16 ladders/hybrid boards
- 32 monolithic sensors 128x256 6.3x3 cm^2
- DEPFET Sensor bump bonded to 8 Readout ASICs (64x64 pixels)
- 2 DEPFET sensors wire bonded to a hybrid board connected to regulator modules
- Heat spreader
- Dead area: ~15%

DSSC - Expected Performance

Parameter	Expected DSSC performance
Energy range	0.5 … 25 keV (optimized for 0.5 … 4 keV)
Number of pixels	1024 x 1024
Sensor Pixel Shape	Hexagonal
Sensor Pixel pitch	~ 204 x 236 μm^2
Dynamic range / pixel / pulse	> 10.000 photons @1 keV
Resolution (S/N >5:1)	Single photon @ 1 keV (5 MHz) Single photon @ 0.5 keV ($\leq$ 2.5 MHz)
Electronics noise	< 25 electrons r.m.s.
Frame rate	1-5 MHz
Stored frames per Macro bunch	≥ 512
Operating temperature	-10˚C optimum, RT possible

Belle II Vertex Detector Upgrade

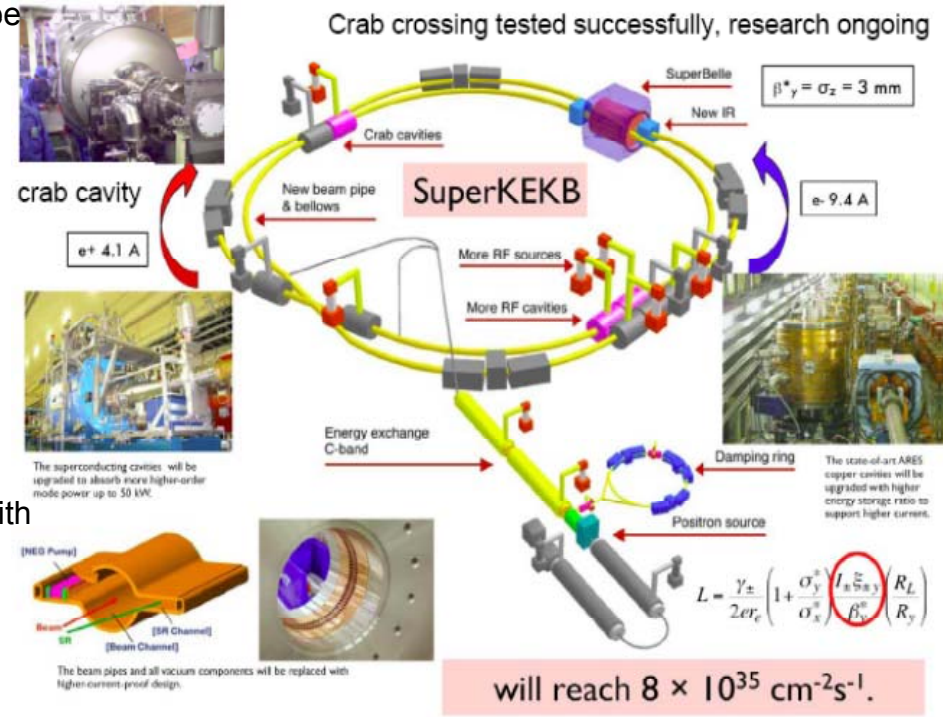
KEKB will be upgraded to reach a luminosity of $8 \times 10^{35} cm^{-2} s^{-1}$
The Belle detector, especially the vertex detector needs to be upgraded:

- Background occupancy 8x – 15x Belle
- Radiation damage (1-2 MRad/year)
- Better performance (resolution)

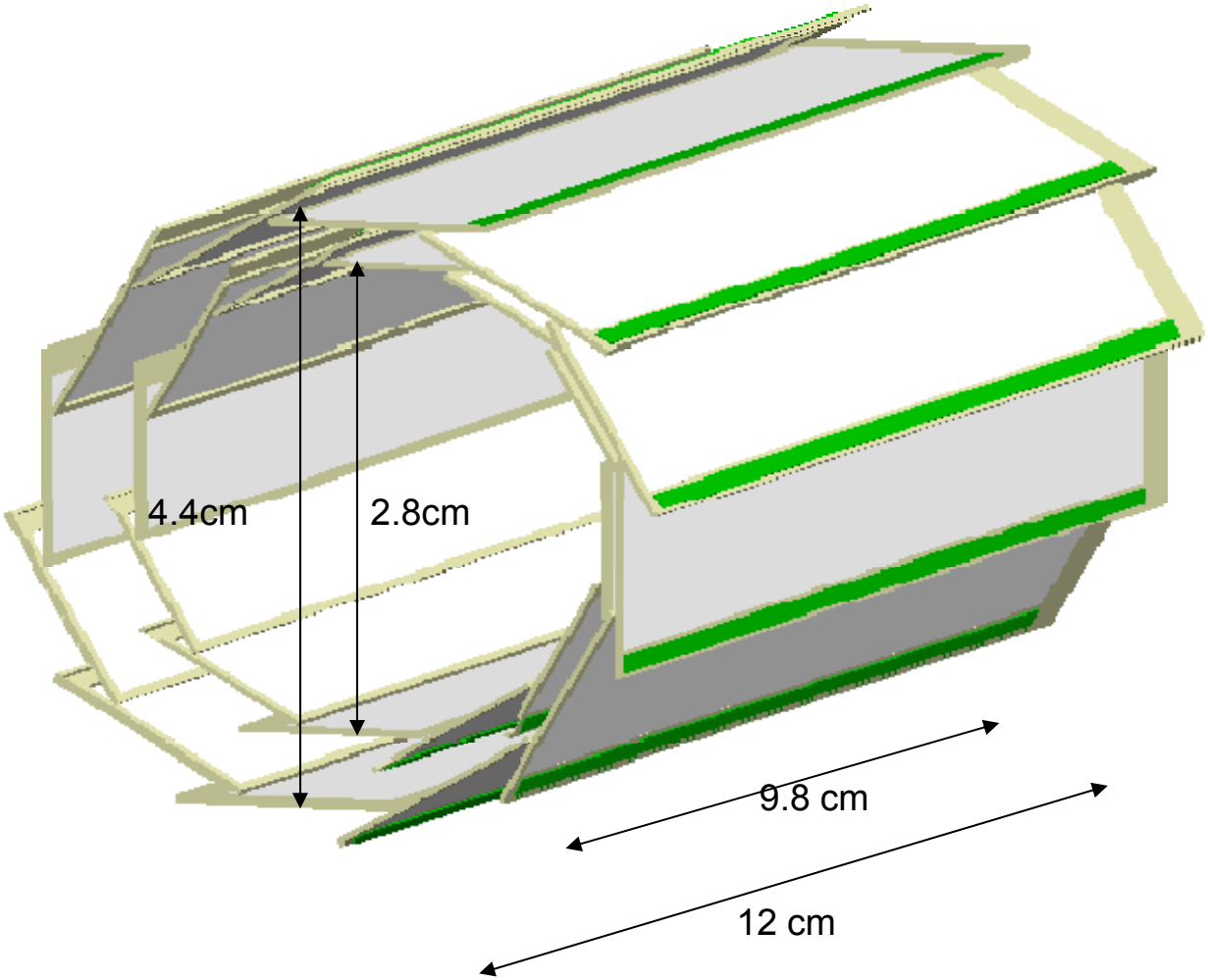
High occupancy excludes strip detectors
=> Pixel detector
=> Fast readout
Resolution dominated by multiple scattering:
=> Thin sensors needed

Due to its superior performance of the DEPFET can cope with this challenges

MPP (& collaborators) will construct a pixel vertex detector based on DEPFET technology for Belle II



Belle II Vertex Detector



20 modules

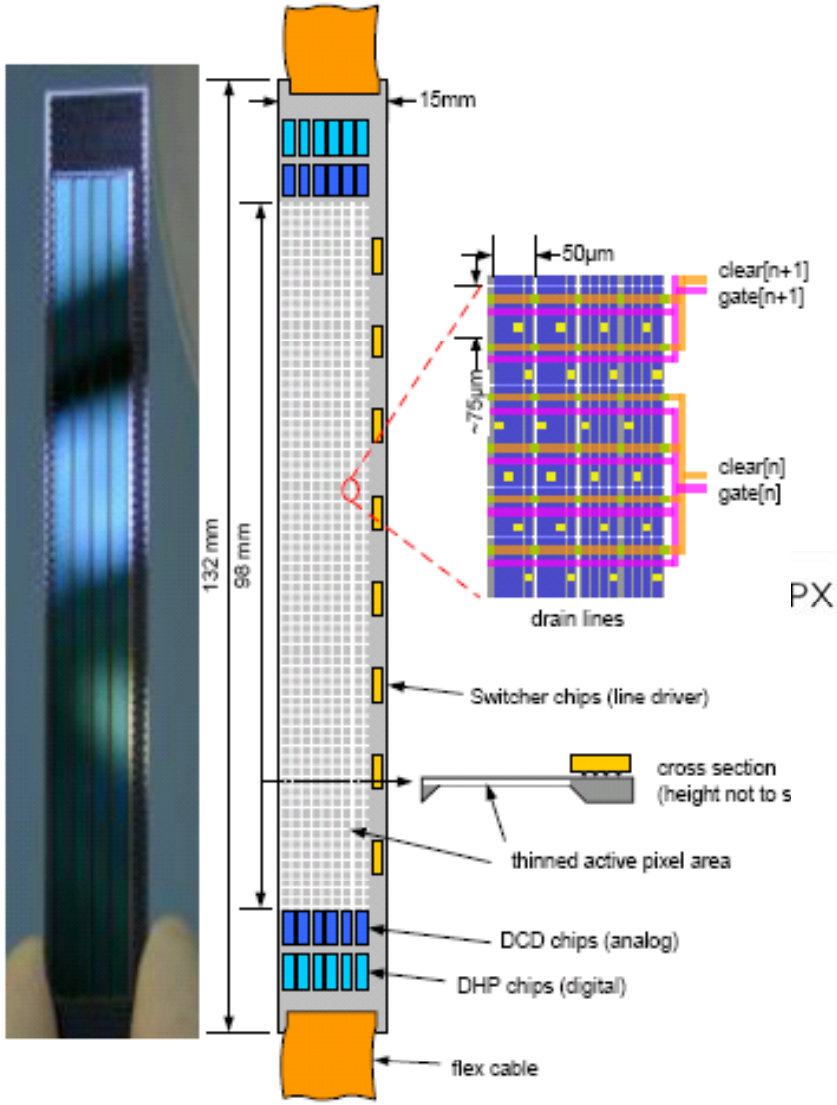
with 400.000 pixel each

thinned to 50 µm

read out with 50 kHz

DePFET noise level around 40 electrons

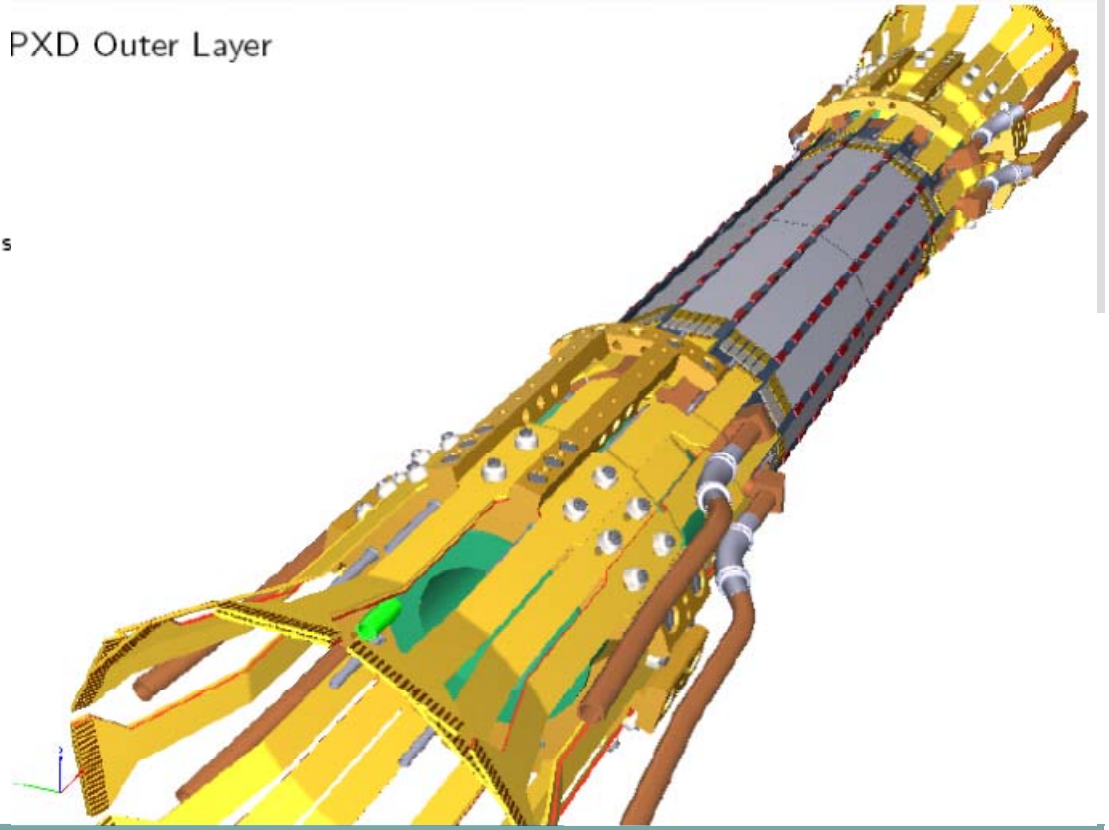
System noise level around 100 electrons



Monolithic all silicon module
No additional support structure

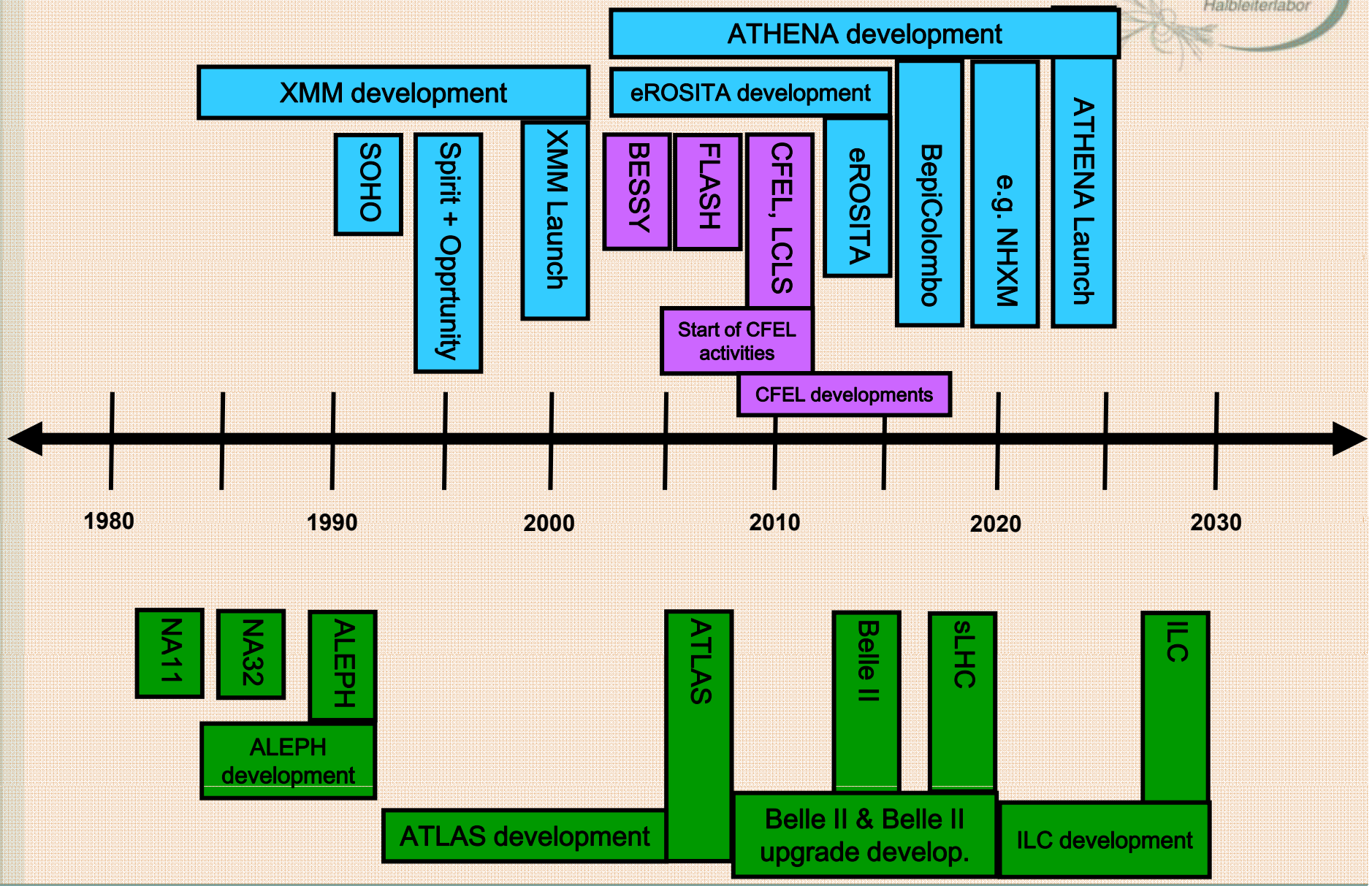
Thickness of active sensor: 50 µm
Pixel size: 50µm x 50µm
Number of Pixels: 400.000
Frame readout: 50 kHz

Low power: 0.1 W/cm² in active area



Prototype Module, thinned down to 50µm

Main projects at the MPI HLL



Summary and Outlook:

- SDDs are heavily used in science and industry
- pnCCDs are used in different fields of basic science
  Their performance figures are close to theoretical limits
- They can be monolithically built as large as 9 x 9 cm^2
  they can be read out up to 1.000 times per second
- DePFET active pixel sensors are being developed for a 5 MHz operation in a 3D technology for single photon counting from 300 eV up to 25 keV
- DePFET detectors are able to deliver a dynamic range up to 5×10^4 with non-linear signal compression

MPI Halbleiterlabor* on the SIEMENS Campus in Neuperlach

End