593. WE-Heraeus-Seminar

X-ray detectors with high temporal resolution suitable for pulsar navigation

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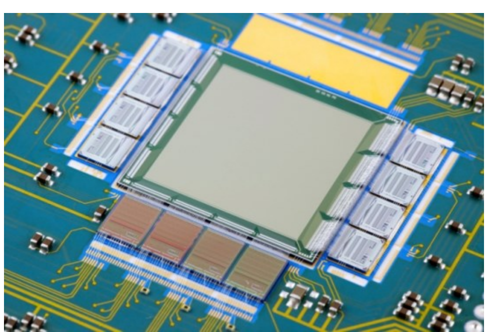
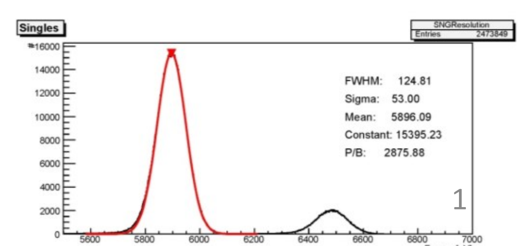




Overview

1. Introduction
2. PNCCD Detectors
   - XMM-Newton
   - eROSITA (2nd generation)
3. Silicon Drift Detectors (SDDs)
   - Space projects
4. DEPFET Active Pixel Detectors
   - MIXS on BepiColombo
   - WFI on Athena (2nd generation)
5. Summary + Outlook

1.Introduction

Requirements for X-ray detectors suitable for pulsar navigation (W. Becker):

I. **Time resolution << 1ms (ideally 10µs)**

II. **Energy range: 0.3keV – 10keV**

III. **State-of-the-art energy resolution** (e.g. FWHM(6keV)≈140eV)

IV. **Position resolution preferred**

(e.g. tracking of pulsar)

1.Introduction

Novel and promising silicon detector concepts

→ **developed** for **next generation of X-ray observatories**

→ potentially applicable for X-ray pulsar navigation in future:

A. **PNCCD** detectors (2nd generation)

B. **Silicon Drift Detectors** (SDDs)

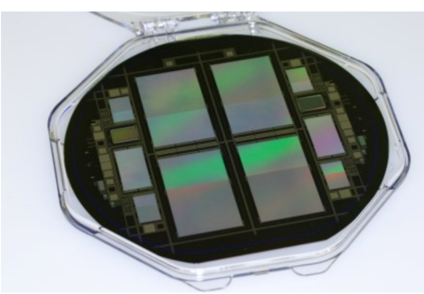
C. **DEPFET Active Pixel Sensors** (APS)

1.Introduction

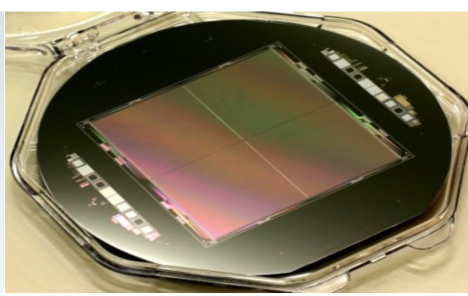
Our concept for spectroscopic detectors produced at MPG HLL

- **Ultrapure** silicon wafers (∅ = 150 mm)
- **Double-sided** processing permits full depletion of 450 µm thick sensor
  → high QE at high X-ray energies
- First stage of signal amplification (**transistor**) integrated **on-chip**
  → low readout noise
- **Back-illuminated** detectors → uniform QE over detector area
- **Shallow** p-implant of photon entrance window → high QE at low energies
- Deposition of **on-chip light filter** (Al) → no signal interference by visual light

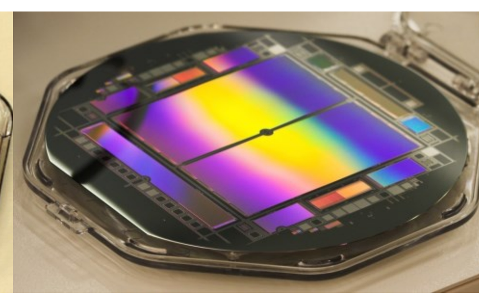
eROSITA



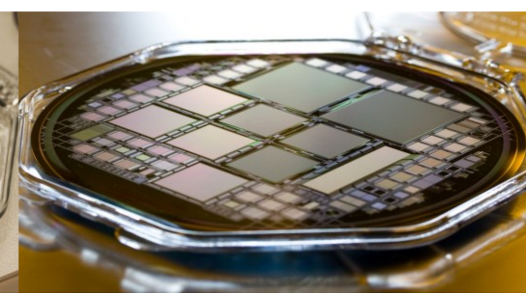
SIMBOL-X



CFEL



IXO

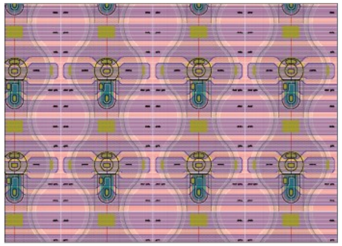


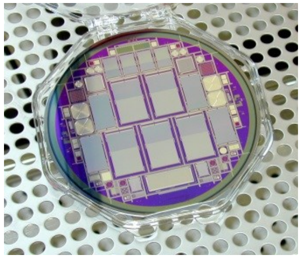
1.Introduction

Our concepts for spectroscopic detectors

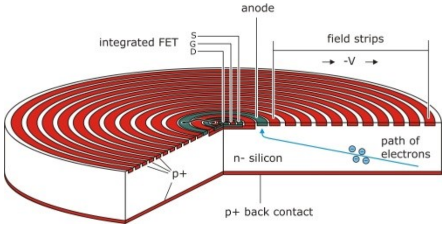
- Concept requires adequate process technology
  →developed at MPG semiconductor lab (HLL)

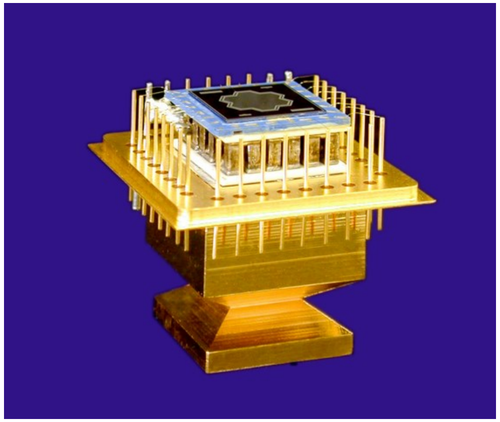
- **Basic spectroscopic detector concepts:**





- Silicon drift detectors
  readout node / cell
  time resolution: **µs**
  → **fastest** spectroscopic detector
  spatial resolution by array of SDD cells



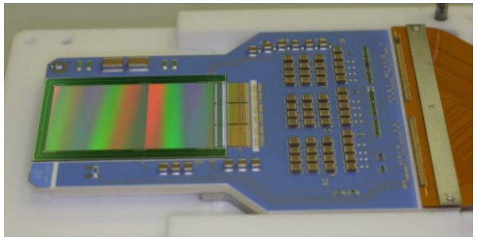


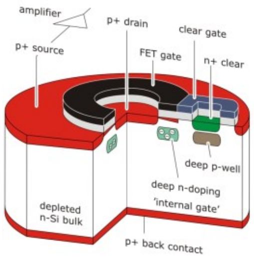
1.Introduction

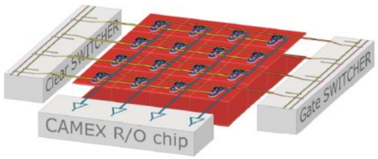
Our concepts for spectroscopic detectors

- **PNCCD**

  full-column-parallel CCD: **readout node / ch.**
  (no serial transfer)
  time resolution $\propto$ #rows
  spectroscopic + imaging detector

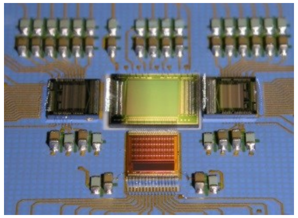






- **DEPFET active pixel sensor**

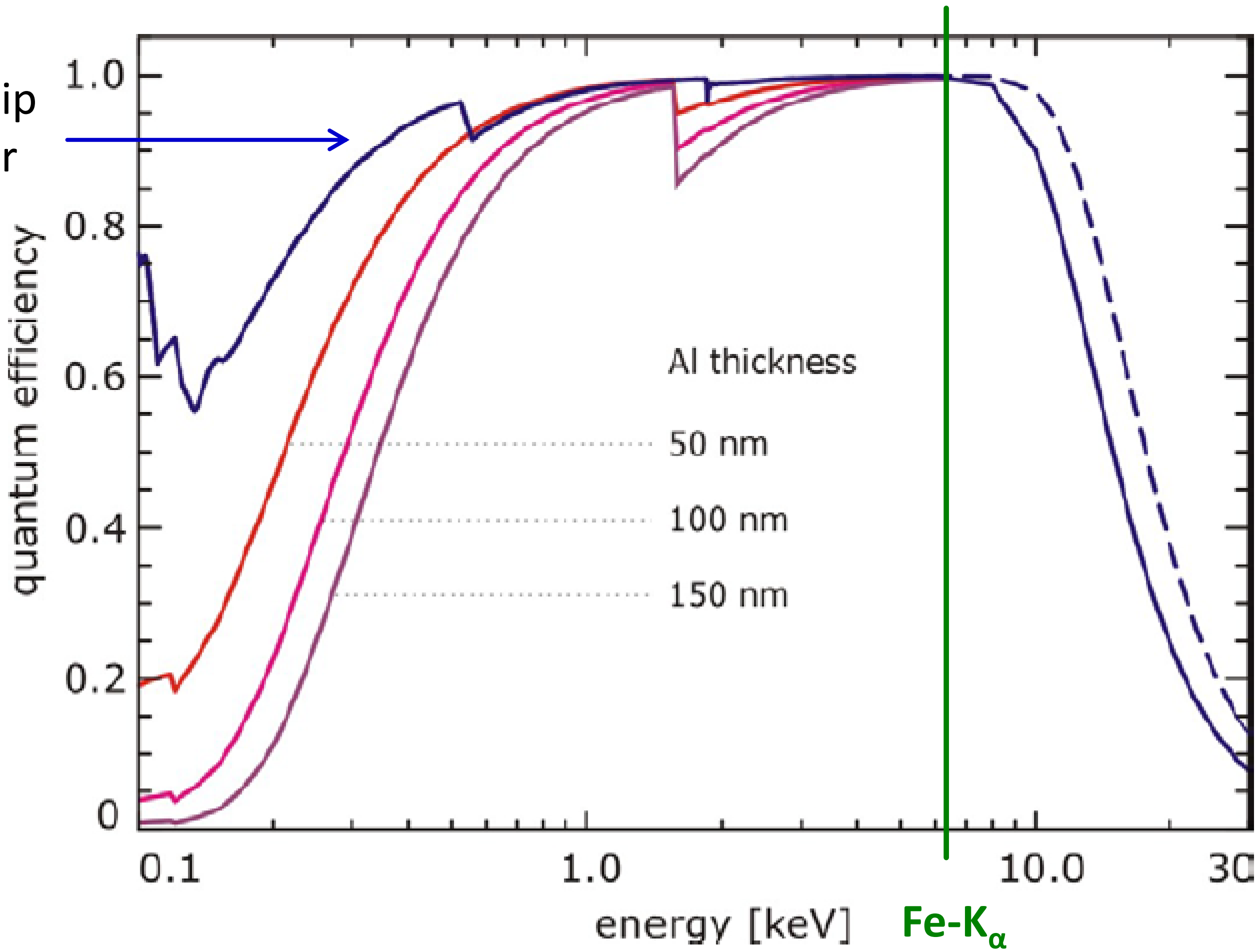
  readout node / pixel
  CCD-like but even faster + more radiation hard
  → **window mode** (readout of sensor sub-area)



1.Introduction

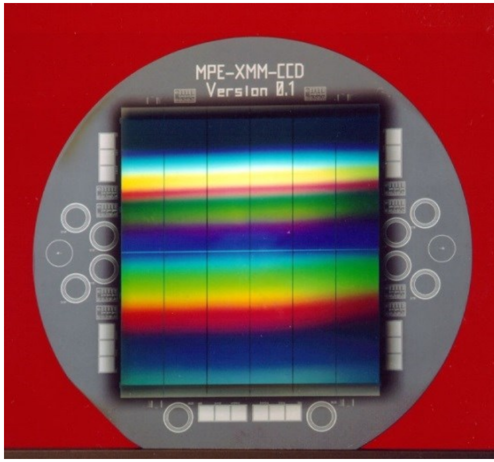
Quantum efficiency (PNCCD, SDD, DEPFET)

no on-chip light filter

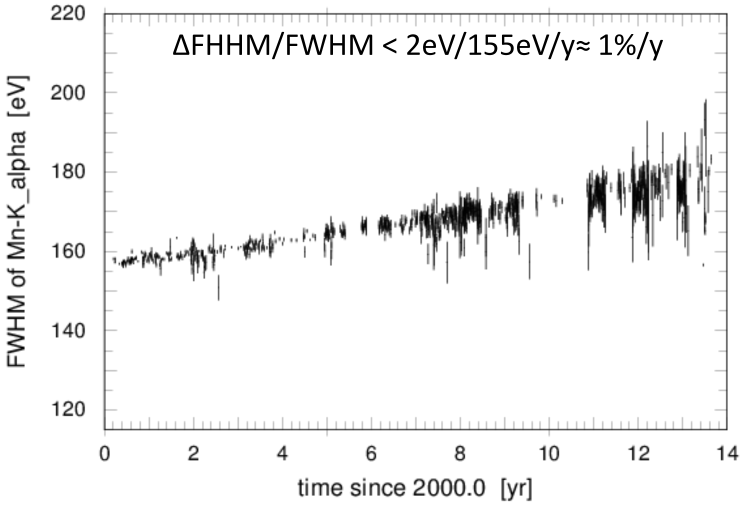


2.PNCCD Detectors: XMM-Newton

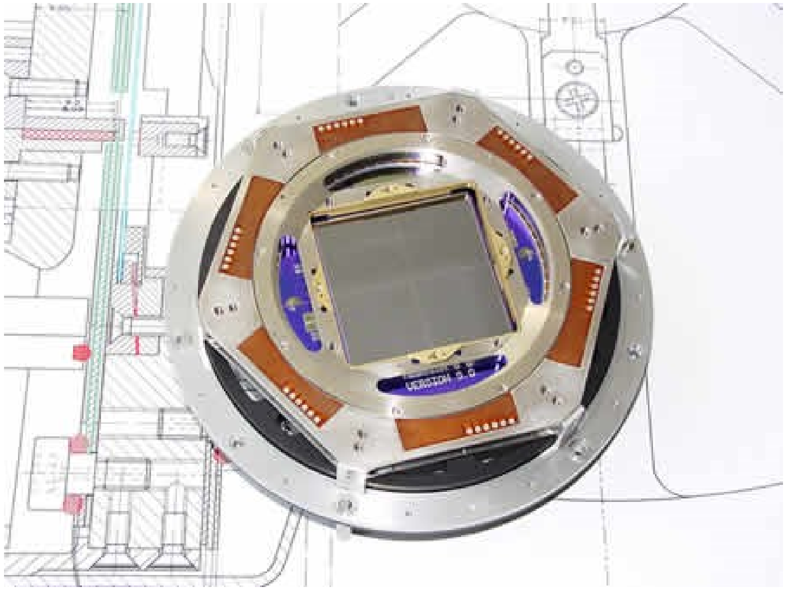
- **First generation of PNCCDs:**
- **developed for X-ray astronomy: XMM-Newton**
- **Satellite launch: 1999**
- **Pixel size: 150µm x 150µm (4.1 arcsec)**
- **12 CCDs: 64 x 200 pixels**

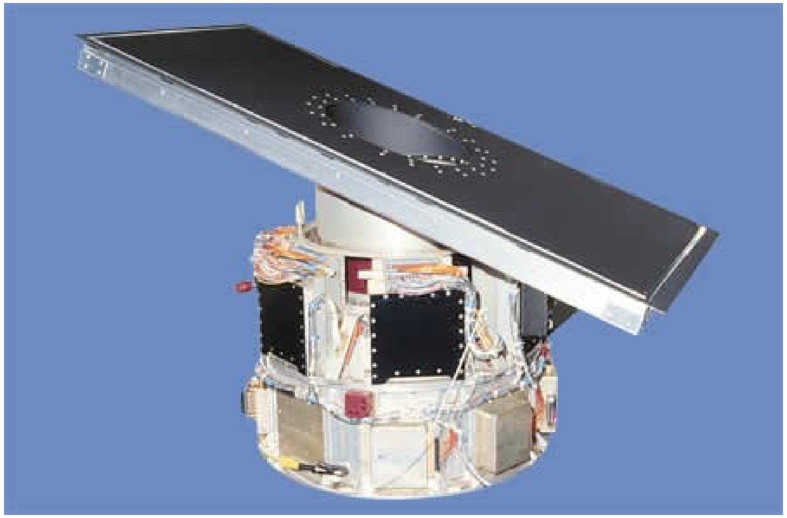


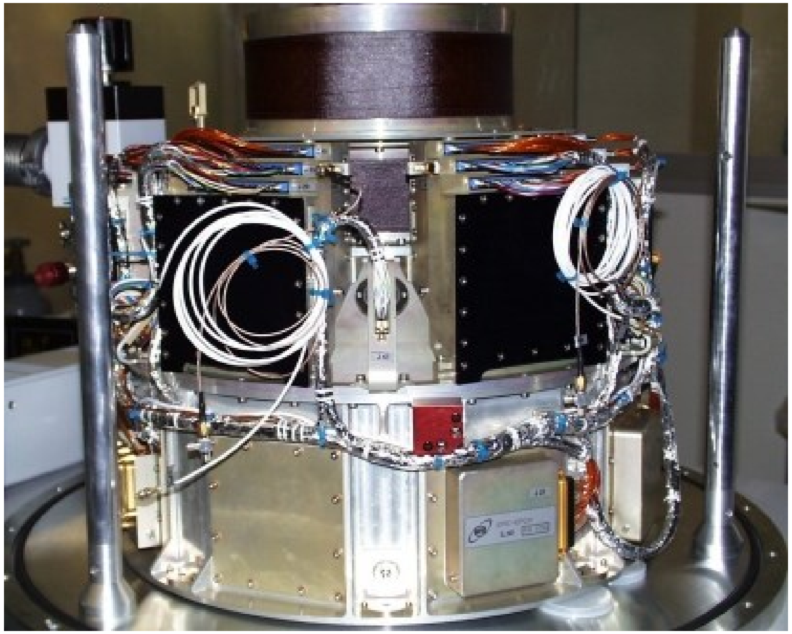
- **Long term stability of pnCCD detector (EPIC-PN camera) aboard XMM-Newton:**
  - all 12 CCDs are still operating
  - same operating parameters (T = -90°C)
  - quantum efficiency unchanged
  - slight radiation damage as expected: CTI



2.PNCCD Detectors: XMM-Newton







2.PNCCD Detectors

mode	field of view (FoV) in pixel format in arcmin	time resolution resolution in ms	out of time (OOT) events in %	life time with OOT events in %
full frame (1)	398 × 384 27.2 × 26.2	73.3	6.2	99.9
extended full frame (2)	398 × 384 27.2 × 26.2	199.2	2.3	100
large window (3)	198 × 384 13.5 × 26.2	47.7	0.15	94.9
small window (4)	63 × 64 4.3 × 4.4	5.7	1.1	71.0
timing (5)	199 × 64 13.6 × 4.4	0.03	100	99.5
burst (6)	20 × 64 1.4 × 4.4	0.007	depends on PSF	3.0

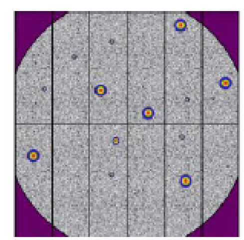
XMM-Newton EPIC-PN:

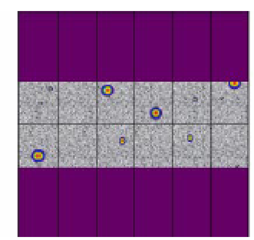
Full frame: 73.3ms

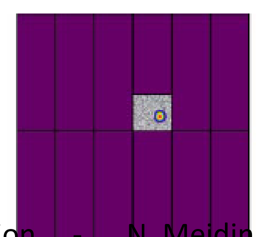
Small window mode: 5.7ms

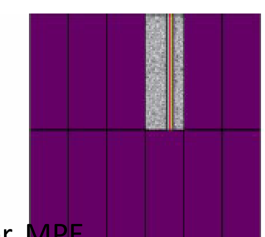
Timing mode: 0.03ms

Burst mode: 0.007ms

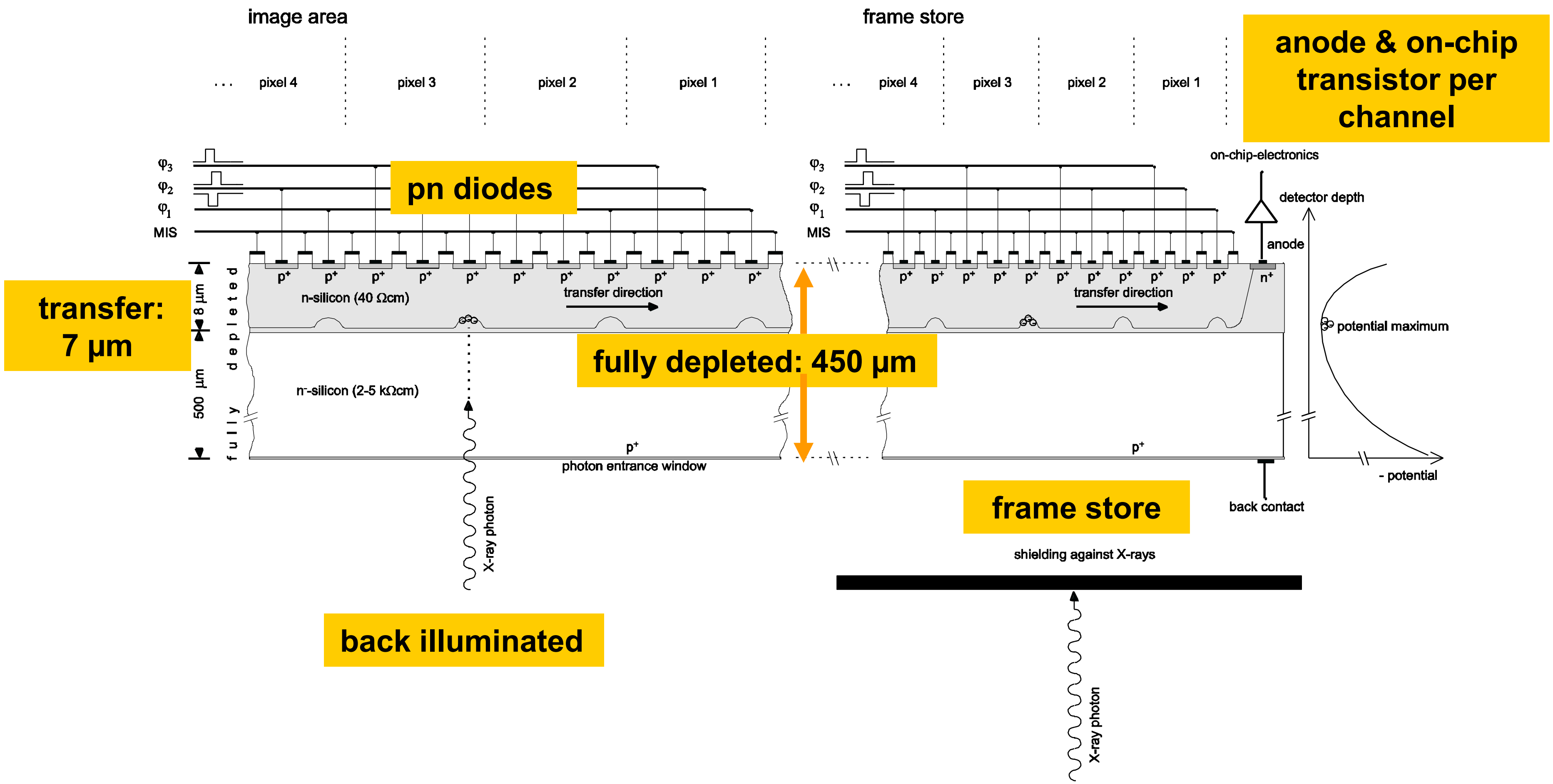

Full Frame & Extended Full Frame


Large Window


Small Window in Quadrant 1


Timing Mode in Quadrant 1

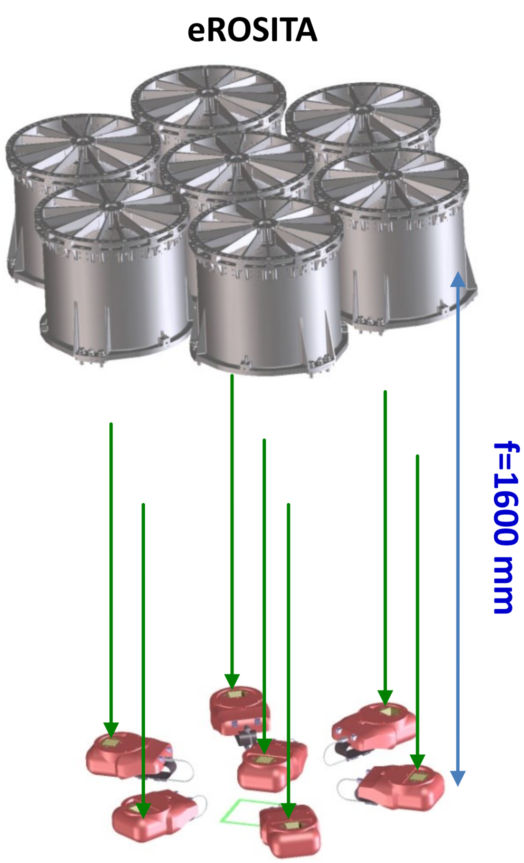
2.PNCCD Detectors: PNCCD concept



2.PNCCD Detectors

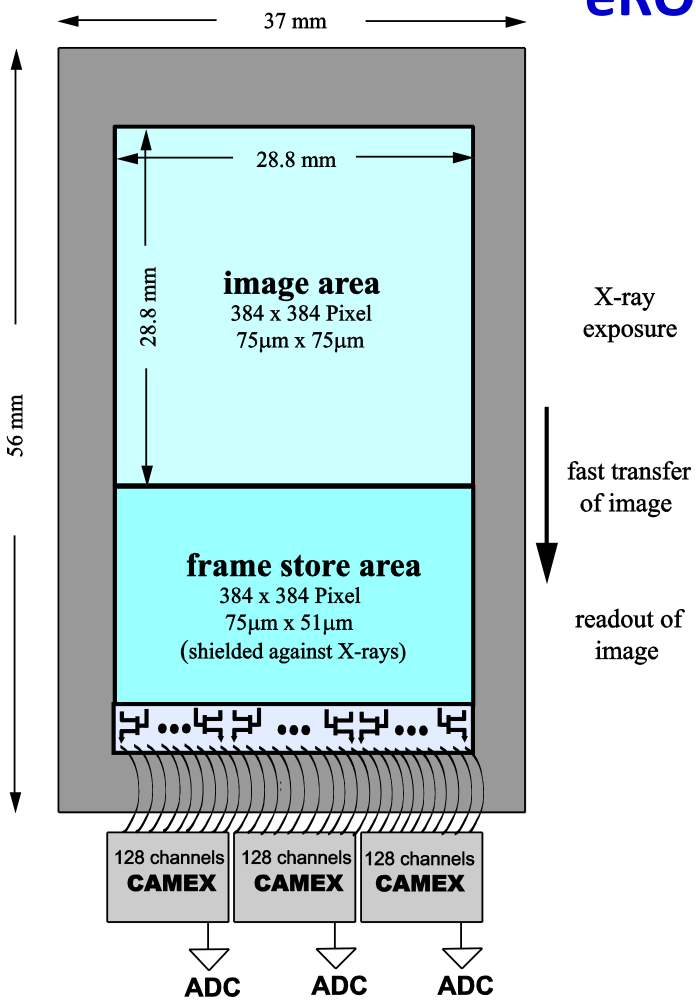
→ eROSITA (extended Roentgen survey with an imaging telescope array)

- all-sky survey: 4 y (/7.5y)
  - soft band: 30 x sensitivity of ROSAT
  - hard band (>2keV): first all-sky survey
- test of cosmological model (Dark Energy)
- eROSITA telescope developed unter responsibility of MPE
- Wolter-I mirror system: 54 shells
- PSF:15‘‘ resolution (HEW) on-axis
- FoV 1.0° diam.
- Russian SRG satellite → L2 orbit



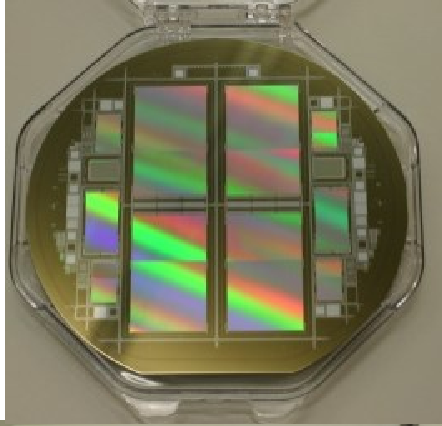
2.PNCCD Detectors

eROSITA PNCCD Detector



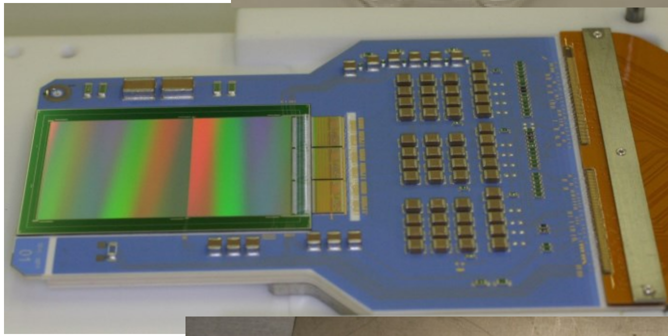
- based on XMM-Newton PNCCD
- back-illuminated frame-transfer CCD
- chip thickness (= 450 µm) fully sensitive
- image: **384 x 384** pixels of 75 x 75 µm^2 size
- column-parallel: 384 independent channels
- frame transfer: **0.12 ms**
- CAMEX: analog signal processor
- readout time: **9 ms**
- time resolution: 50 ms
  - on-board event processing
  - minimiz. heat dissipation (≈ 80% standby) → 0.7 W
- OOT events ≈ 0.2%
- excellent low energy response

2.PNCCD Detectors



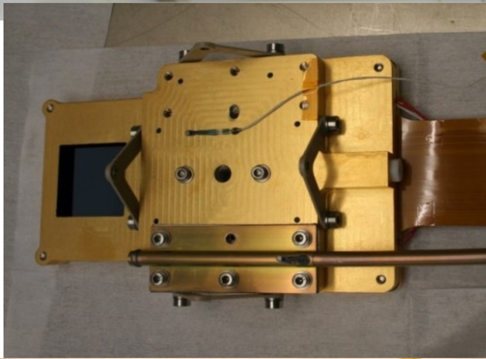
eROSITA detector:

- **PNCCD**
- eROSITA CAMEX
- Multi-layer detector board
- Flexible lead as I/F to CE (outside FP)



Detector housing:

- Mech. + thermal I/F
- Graded Z-shield: Be/B_4C - Al - Cu

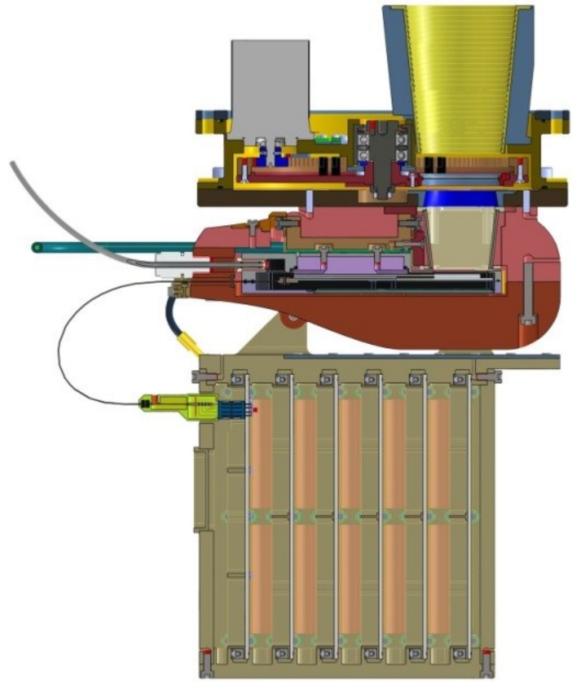


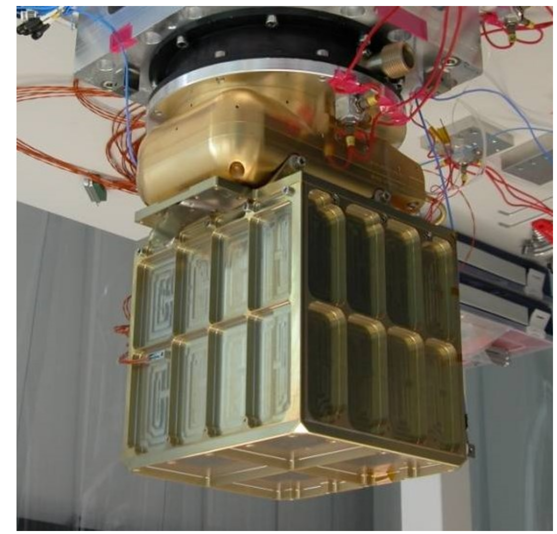
2.PNCCD Detectors

Filter wheel

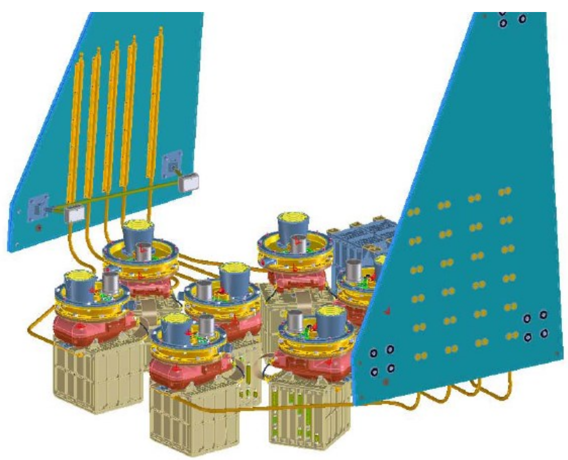
Camera Head

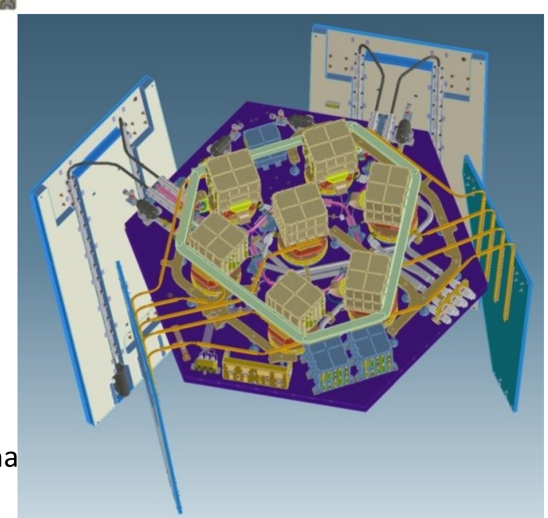
Camera Electronics





Array of 7 PNCCD focal plane cameras:

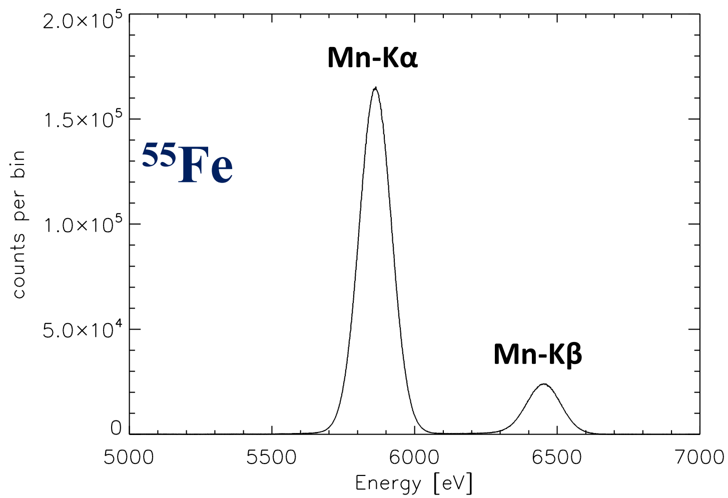


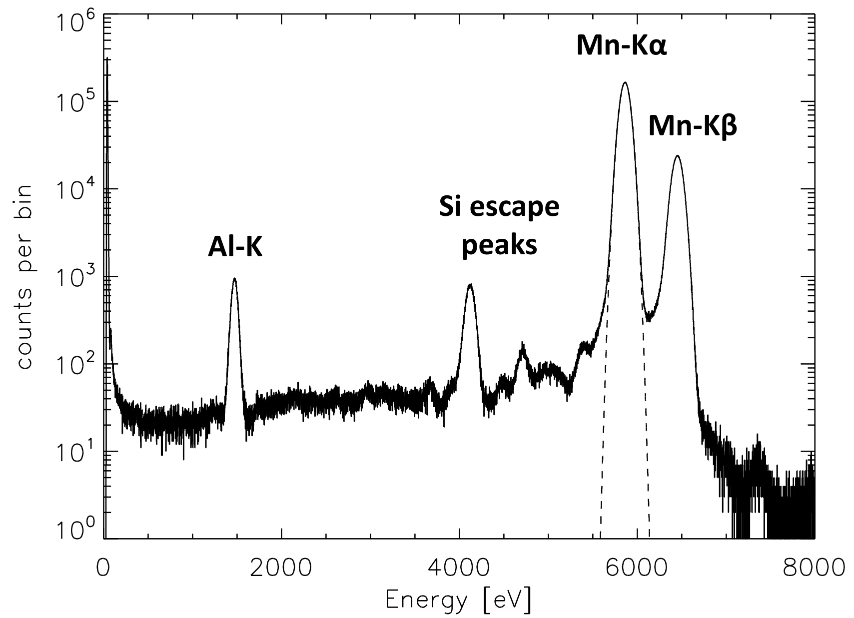


2.PNCCD Detectors

Energy resolution

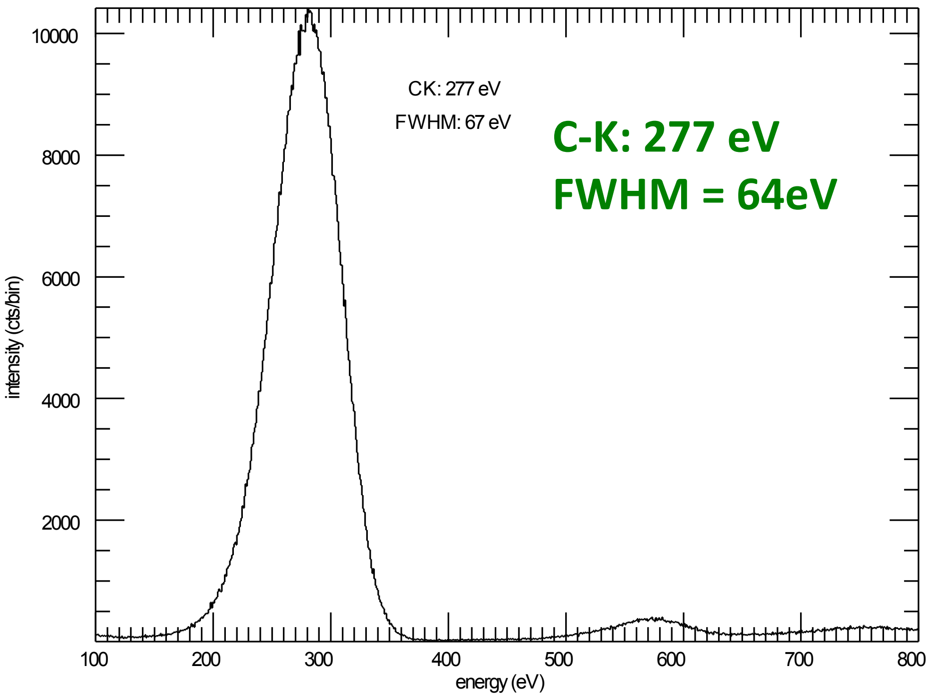
^{55}Fe spectrum: FWHM(5.9keV) = 131 eV





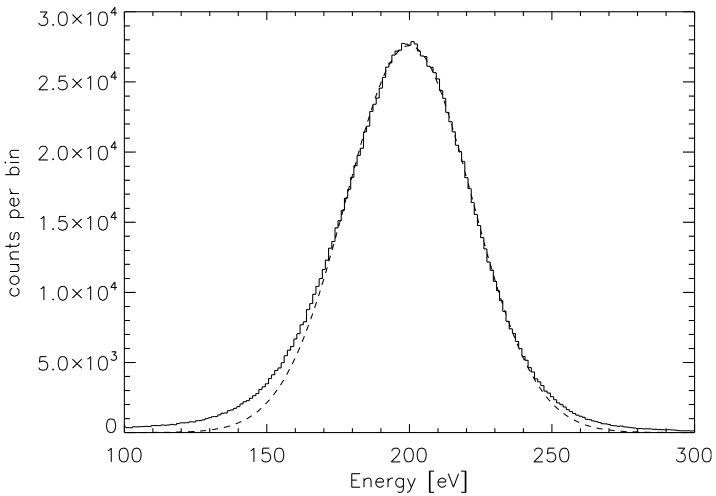
Signal spread over up to 4 pixels

2.PNCCD Detectors



C-K: 277 eV
FWHM = 64eV

BESSY synchrotron:
FWHM(200eV) = 52 eV

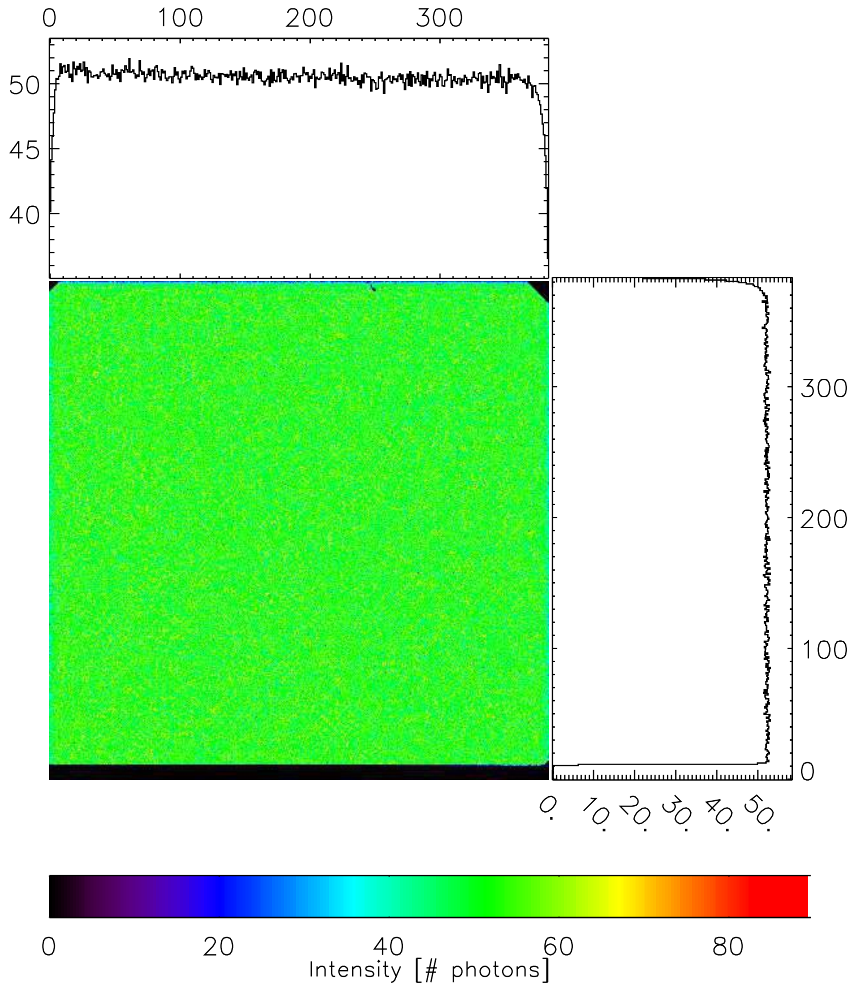


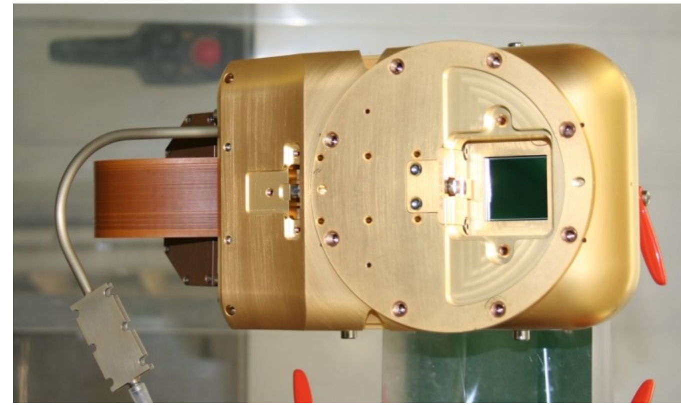
Gaussian shape !

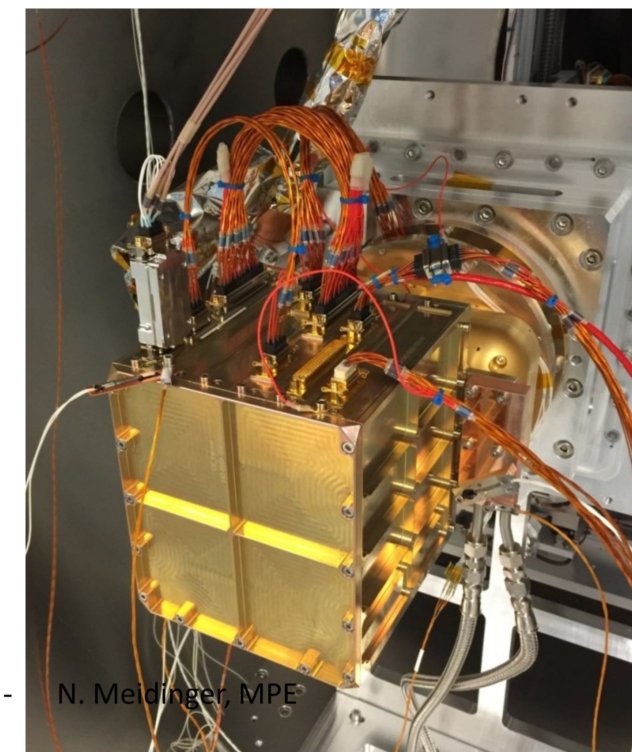
2.PNCCD Detectors

Intensity distribution over image area

Al-K of X-ray tube (QM_140123_06)







2.PNCCD Detectors

eROSITA PNCCD detector characteristics

Sensor	PNCCD
Illumination type	back-illumination
Image area	384 x 384 pixels
Pixel size	75 µm x 75 µm (< 10 arcsec)
Readout ASIC	128-channel eROSITA CAMEX (3 ASICs per PNCCD)
Read noise	2.4 electrons ENC rms
Energy resolution	FWHM(0.53 keV) ≈ 62 eV FWHM(5.9 keV) ≈ 140 eV
Operating temperature	-95°C (best wrt radiation damage)
Quantum efficiency	E = 1 keV: 89% (on-chip-filter) E = 5 keV: 99% (on-chip filter)
Readout time	9.2 ms
Time resolution	50 ms

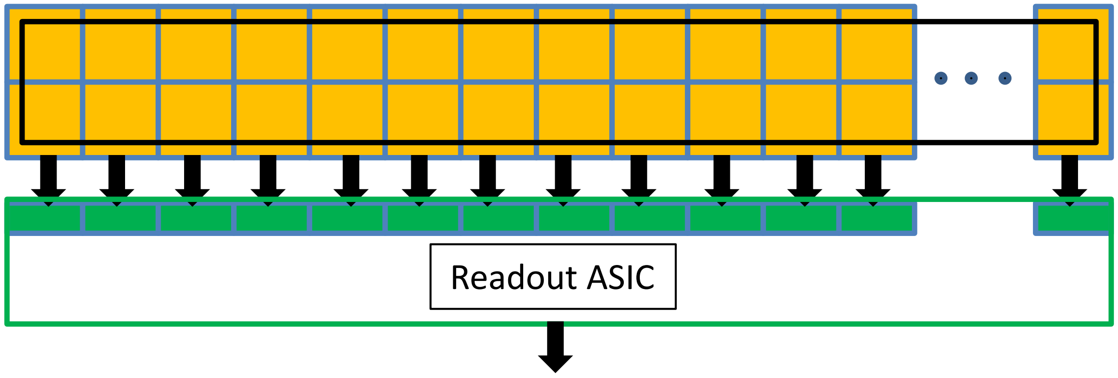
2.PNCCD Detectors

PNCCD detector for pulsar navigation:

Readout time per row for excellent spectroscopy:

- **CAMEX (eROSITA) ≈ 24 µs**
- **VERITAS2 (new dev.) ≈ 4 µs (tbc)**

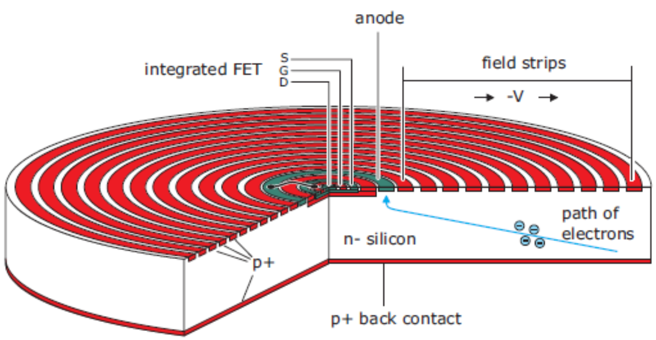
→ **few rows of large pixels (e.g. 150 µm) but many channels**

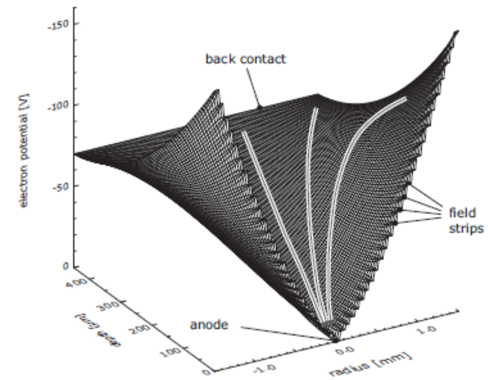


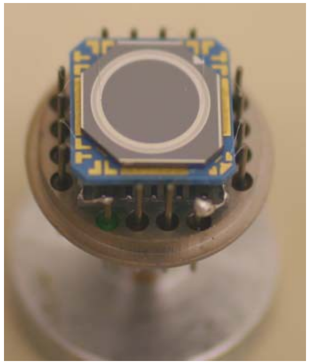
< 10 µs time resolution

1 ADC / 64 channels

3.SDD Detectors

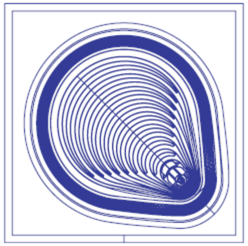






SDD features:

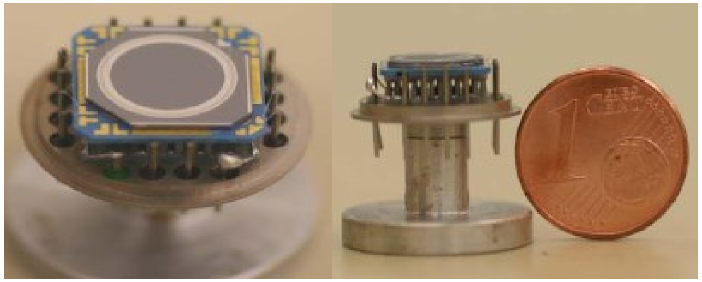
- **Drift rings** with **nJFET** in center (same as PNCCD)
- Integration of first transistor on-chip
  → robustness wrt **microphonic noise** + **electrical pickup**
- Small capacitance 35fF → **low noise** level + **high count rate** capability
- Depletion voltage ≈ -100 V
- Cell area: **5 mm² … cm²**
- good peak-to-background
  ≈ **15.000:1** (SD3 with int. collimator)



3.SDD Detectors **SDD features**

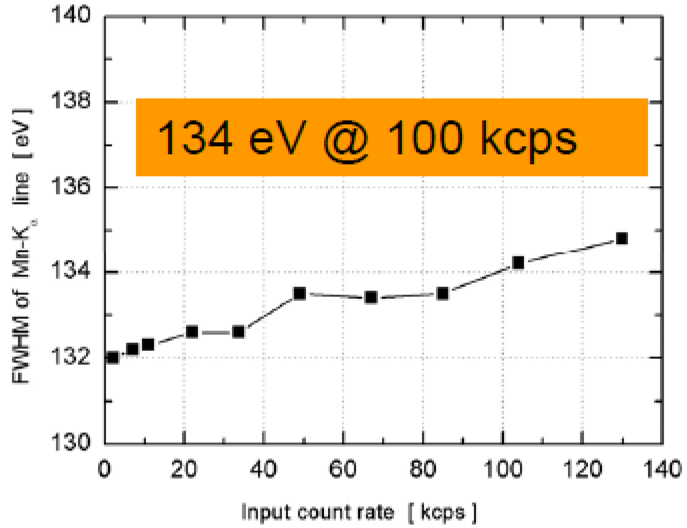
- Immediate readout of signal: **µs** (no signal storage like CCD)
- **No large arrays** of cells because each pixel has to be connected separately
- Count rate: **10^5 / s** per cell
- **Space applications** of single cell SDD:

  NASA Mars Exploration Rovers **SPIRIT, OPPORTUNITY** and **CURIOSITY**

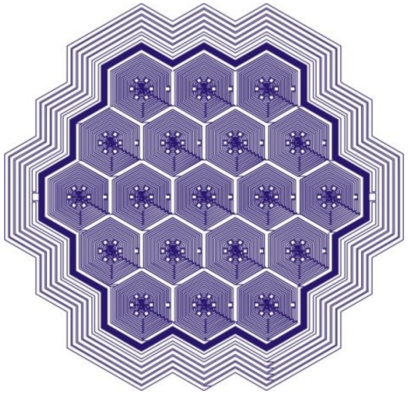


3.SDD Detectors

- Example: 10 mm² SDD, T=-17°C, 1 µs shaping, pulsed reset 1kHz: **FWHM(5.9keV) ≈ 134 eV @ 10^5 photons / s**



- **Array of SDD cells**, e.g. 7, 19 or 31 cells

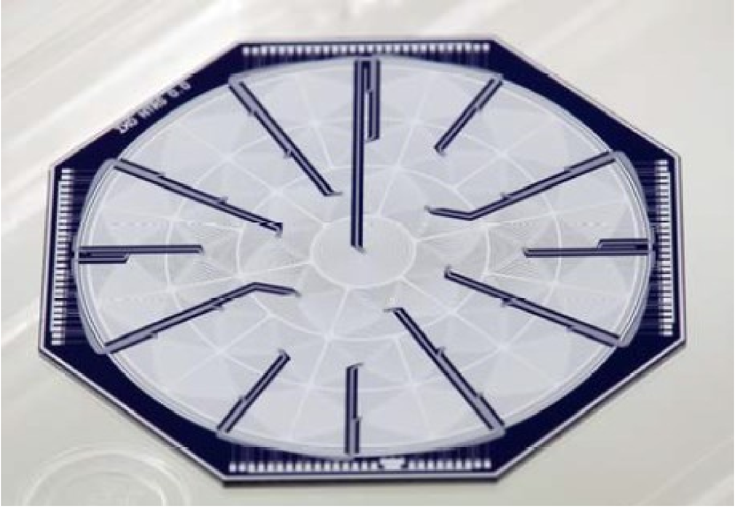


SDD 19 x 5 mm²
XTRA on XEUS

3.SDD Detectors

Concept for HTRS on IXO

- International X-ray Observatory (IXO) proposal/studies:
  High Time Resolution Spectrometer (HTRS)
- **31 SDD cells**
- Time resolution: **10 µs**
- Energy resolution: FWHM(5.9 keV) = 150 eV (T=-40°C, beginning of mission)
- Detector size: 24 mm diameter, **4.5 cm^2 area**
- Cell size: 14.6 mm^2



Spider web baffle:
- for suppression of split events
- area coverage: 10%

3.SDD Detectors

Silicon Drift Detectors in Space produced at MPG HLL

→ analysis of chemical composition of surface

- **APXS** (Alpha-Particle X-ray Spectrometer)

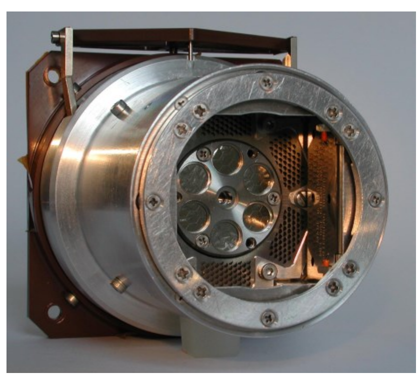
  on NASA's Mars Exploration Rovers **Spirit** and **Opportunity**

  anded Jan 04, Opportunity still active (in 2014)

  APXS "sniffer" by MPCh, Mainz

  SDD 10 mm² & Cu244 α-sources

Mars Exploration Rover



APXS system (MPCh)

- **APXS**

  on NASA Mars Science Laboratory Rover **Curiosity**

  landed August 2012

  with Peltier cooler

- **APXS** on ROSETTA Lander

  rendezvous with comet 67P/C-G

  (Churyumov-Gerasimenko)

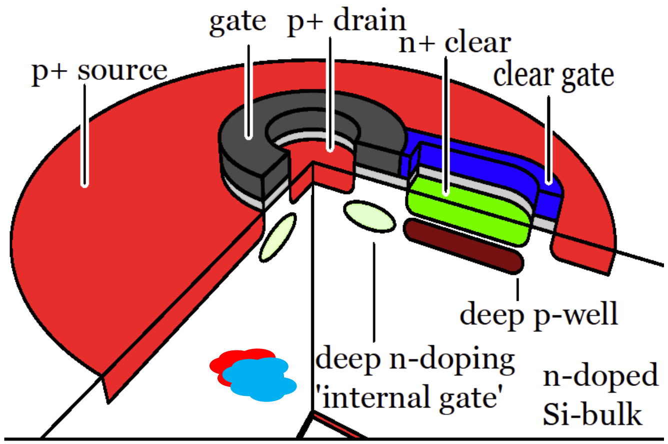
  Mar04, orbit Sept14,

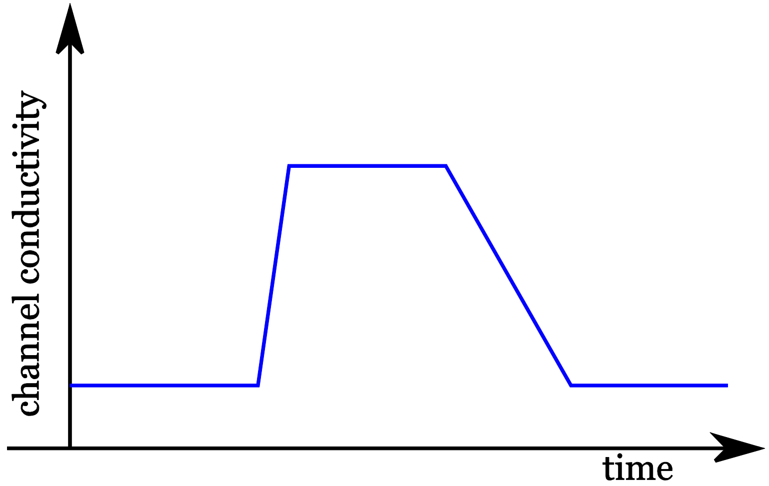
  Lander philae 12Nov14

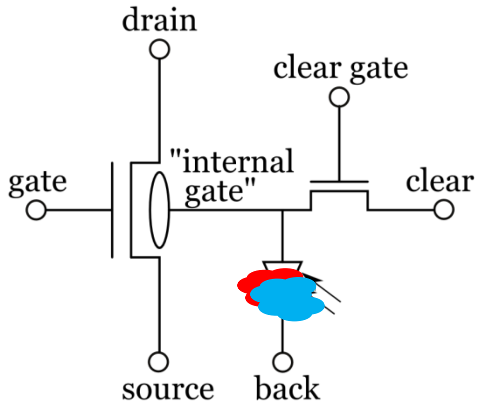
4. DEPFET APS Detectors: Concept

The DEPFET Principle

- p-FET on depleted n-bulk
  - ↳ signal charge is collected in **"internal gate"**
  - ↳ linear $\Delta I/Q_{sig}$ characteristics 300 pA/el.
- reset via ClearFET
- low capacitance & noise
- backside illuminated

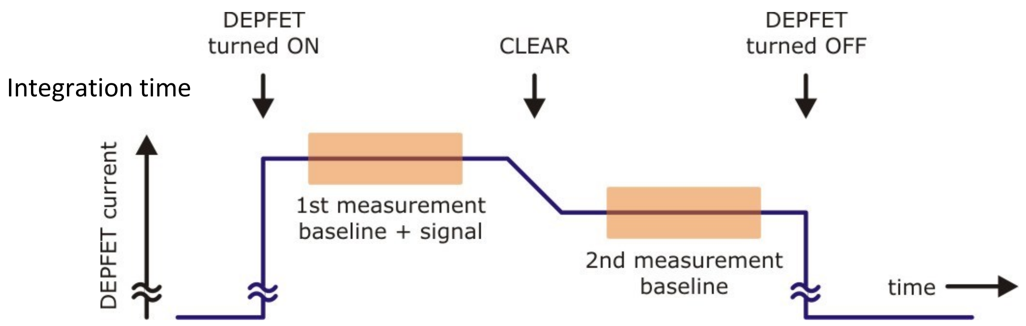




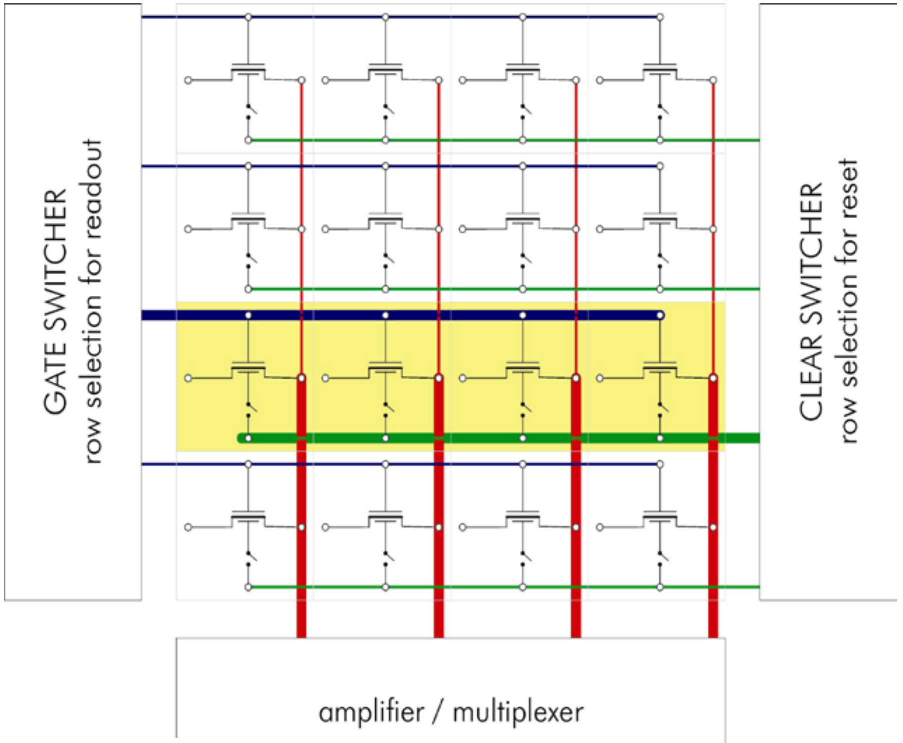


4. DEPFET APS Detectors

- readout sequence



- matrix organisation
  - ▷ one active row
    - ↳ all operations in parallel
    - ↳ fast processing
  - ▷ all other rows turned off
    - ↳ minimum power consumption
    - ↳ signal charge integration



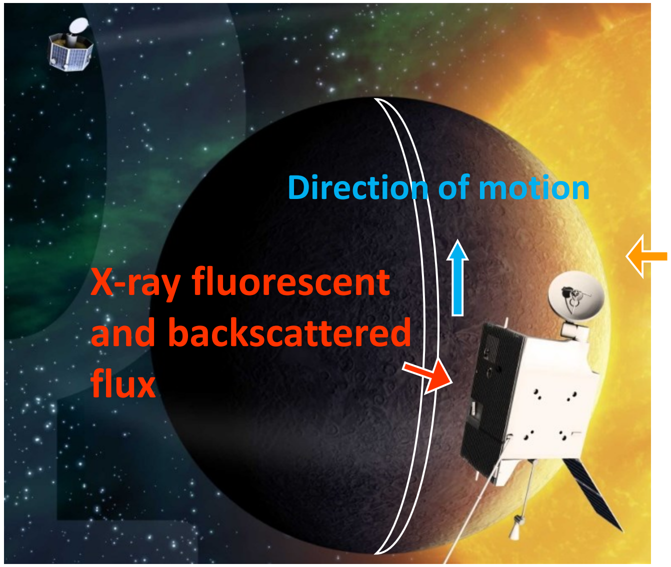
4. DEPFET APS Detectors

Example: MIXS on BepiColombo

BepiColombo

5th ESA cornerstone mission in collaboration with JAXA

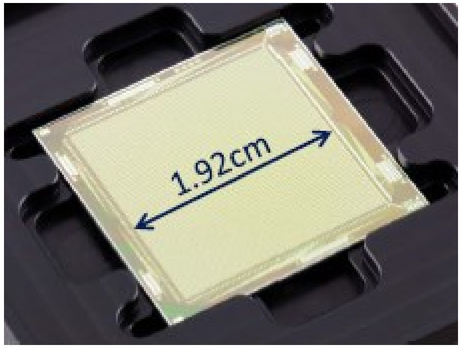
Launch: 2017
Arrival: 2024
Mission lifetime: 1 year (+1 year optional)



Solar coronal primary X-ray flux

MIXS (Mercury Imaging X-ray Spectrometer)

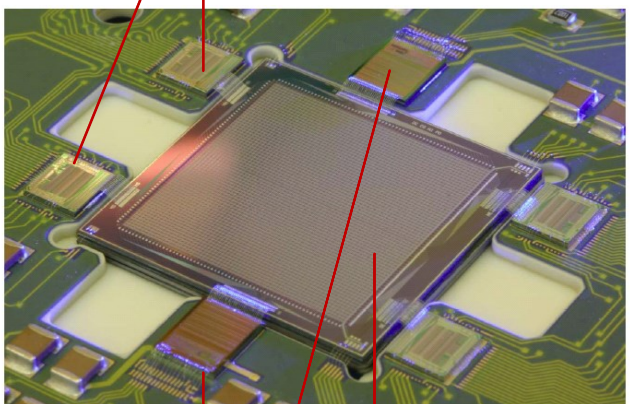
- PI institute: Univ. Leicester (GB)
- Planetary XRF to determine the surface element abundance
- **2** instruments with **identical DEPFET detector**
- Macropixels: **300 x 300 µm²**
- **64 x 64** pixel array = 1.92 x 1.92 cm² (**split-frame** readout)
- Time resolution: **165 µs / frame**
- Energy range: [0.5 keV; 10 keV] → Fe-L (700eV)
- Energy resolution: FWHM (1keV) < 200eV @ mission end
- Radiation environment: $1.4 \cdot 10^{10}$ 10-MeV protons/cm²
- T = -42°C (-45°C)

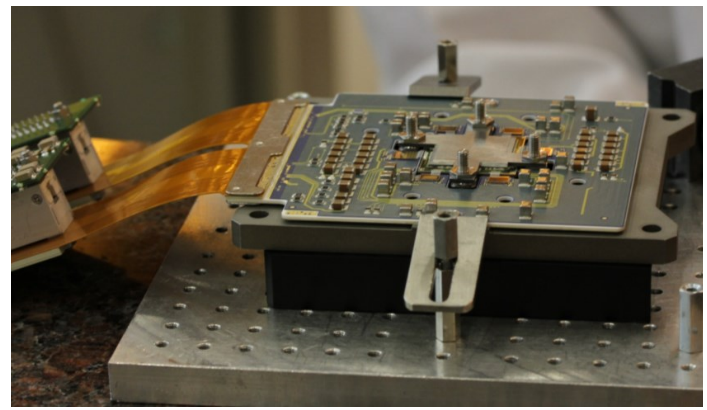


4. DEPFET APS Detectors

Example: MIXS on BepiColombo

SWITCHER control ASICs





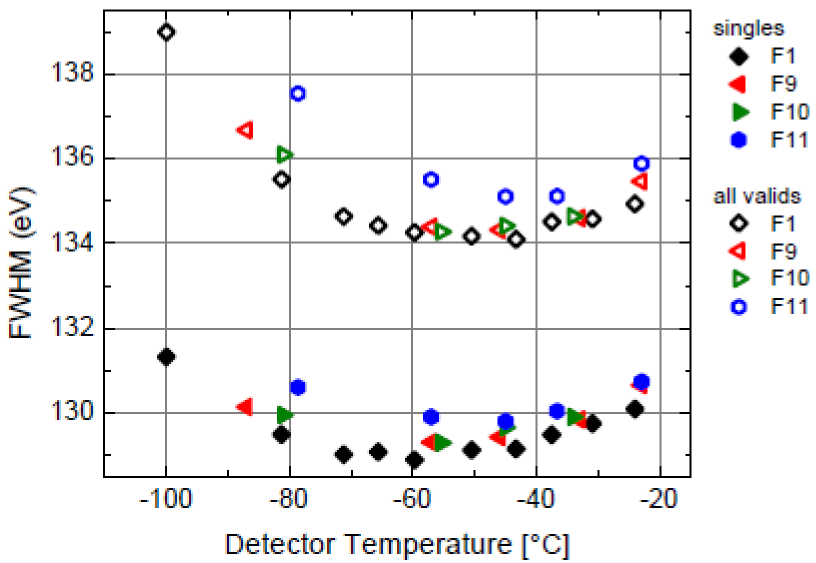
DEPFET sensor (2 x 2 cm^2)

ASTEROID readout ASICs

4. DEPFET APS Detectors

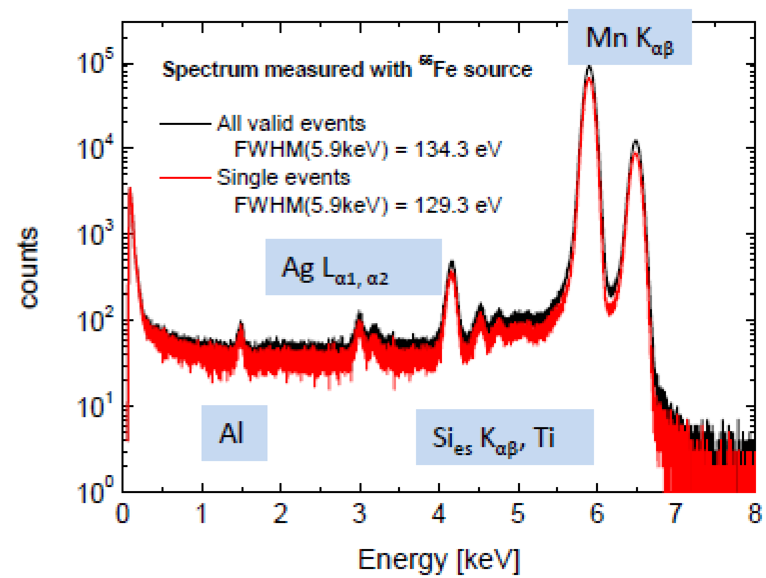
Example: MIXS on BepiColombo

Temperature dependence:



Excellent spectroscopic performance
over wide temperature range
(if no rad. damage)

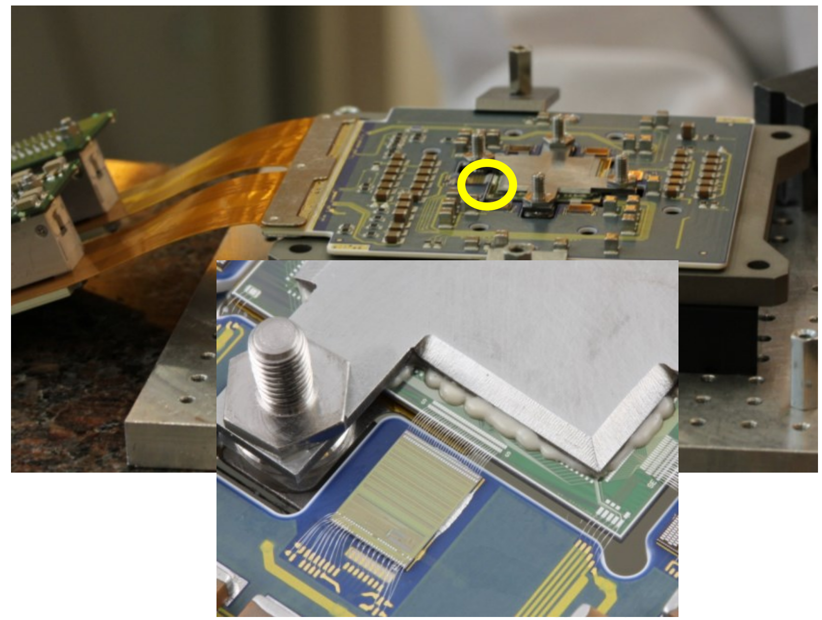
^{55}Fe spectrum:



FWHM(5.9keV)=134 eV

4. DEPFET APS Detectors

Example: MIXS on BepiColombo



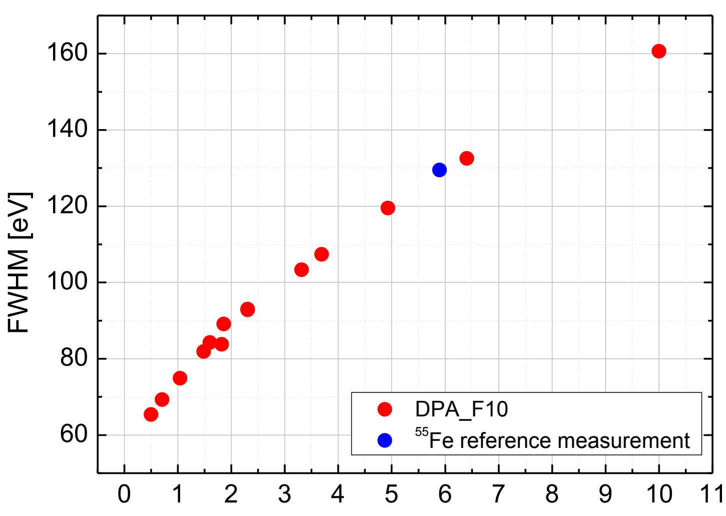
Calibration:

PTB Beamlines @ BESSY synchrotron (Oct/Nov 2011)

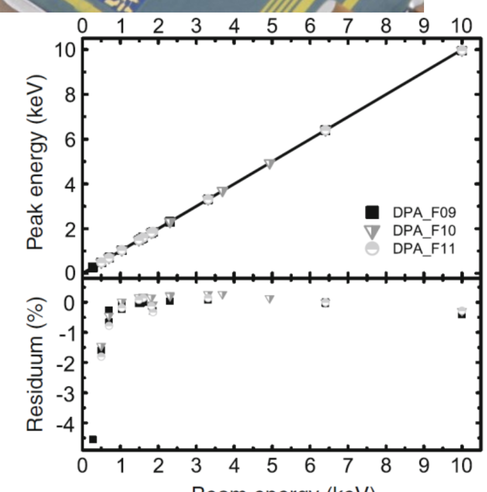
→ Calibration of flight and the flight spare detector at discrete energies from 0.5 to 10 keV

→ excellent performance

→ **ready for integration into the MIXS instrument**



good linearity:



4. DEPFET APS Detectors: WFI on Athena

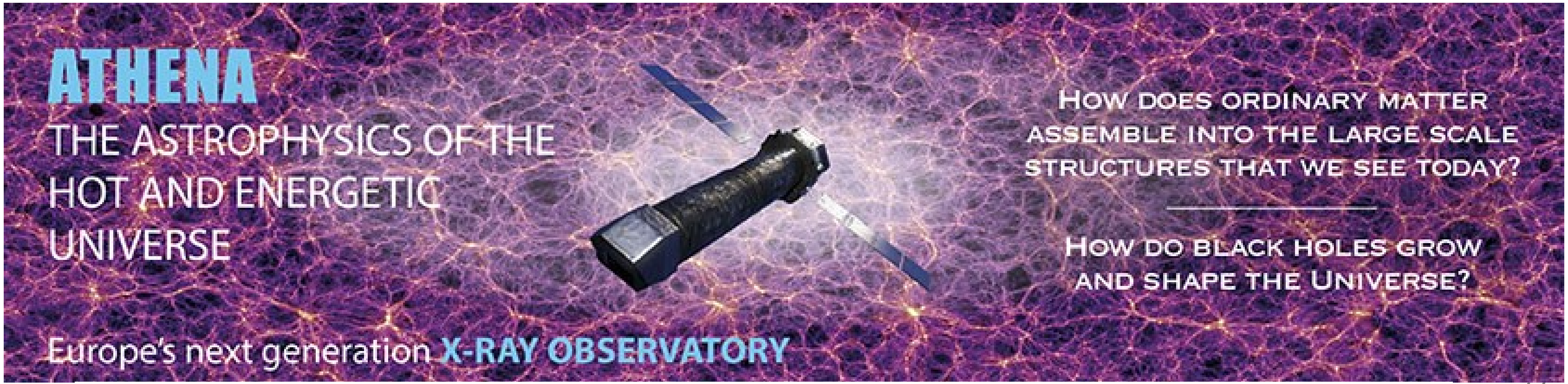
History: XEUS → IXO → ATHENA L1 proposals

ESA

Missions in the Cosmic Vision 2015-2025 Programme

L1 mission	JUICE
L2 mission	ATHENA
M1 mission	Solar Orbiter
M2 mission	Euclid
M3 mission	PLATO
S1 mission	CHEOPS

selected on 27 June 2014



4. DEPFET APS Detectors: Athena

ATHENA (Advanced Telescope for High-ENergy Astrophysics)

Science theme: **The Hot and Energetic Universe**

Primary goals: Mapping hot gas structures and determining their physical properties
Searching for supermassive black holes

How does ordinary matter assemble into the large-scale structures we see today?

→ *it will be necessary to map hot gas structures in the Universe – specifically the gas in clusters and groups of galaxies, and the intergalactic medium – determine their physical properties and track their evolution through cosmic time.*

How do black holes grow and shape the Universe?

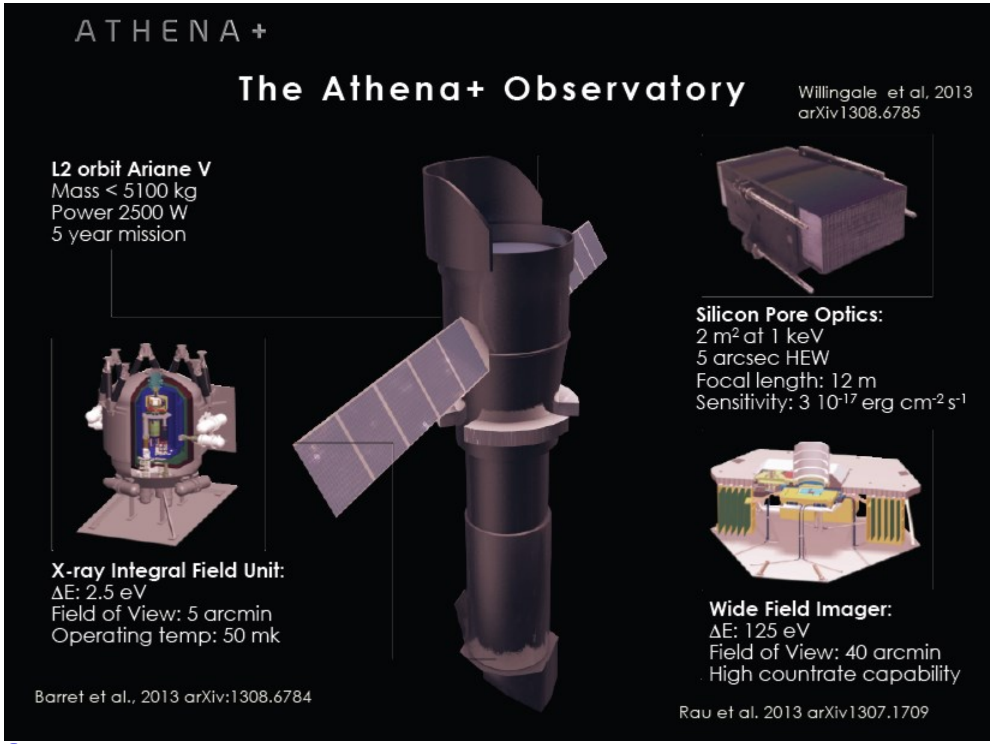
→ *supermassive black holes (SMBH) must be revealed, even in obscured environments, out into the early Universe, and both the inflows and outflows of matter and energy as the black holes grow must be understood*

Orbit: Halo orbit around **L2**, the 2nd Lagrange point of the Sun-Earth system

Lauch: **2028**

Lifetime: **5 years**, with possible **5-year extension**

4. DEPFET APS Detectors: WFI on Athena



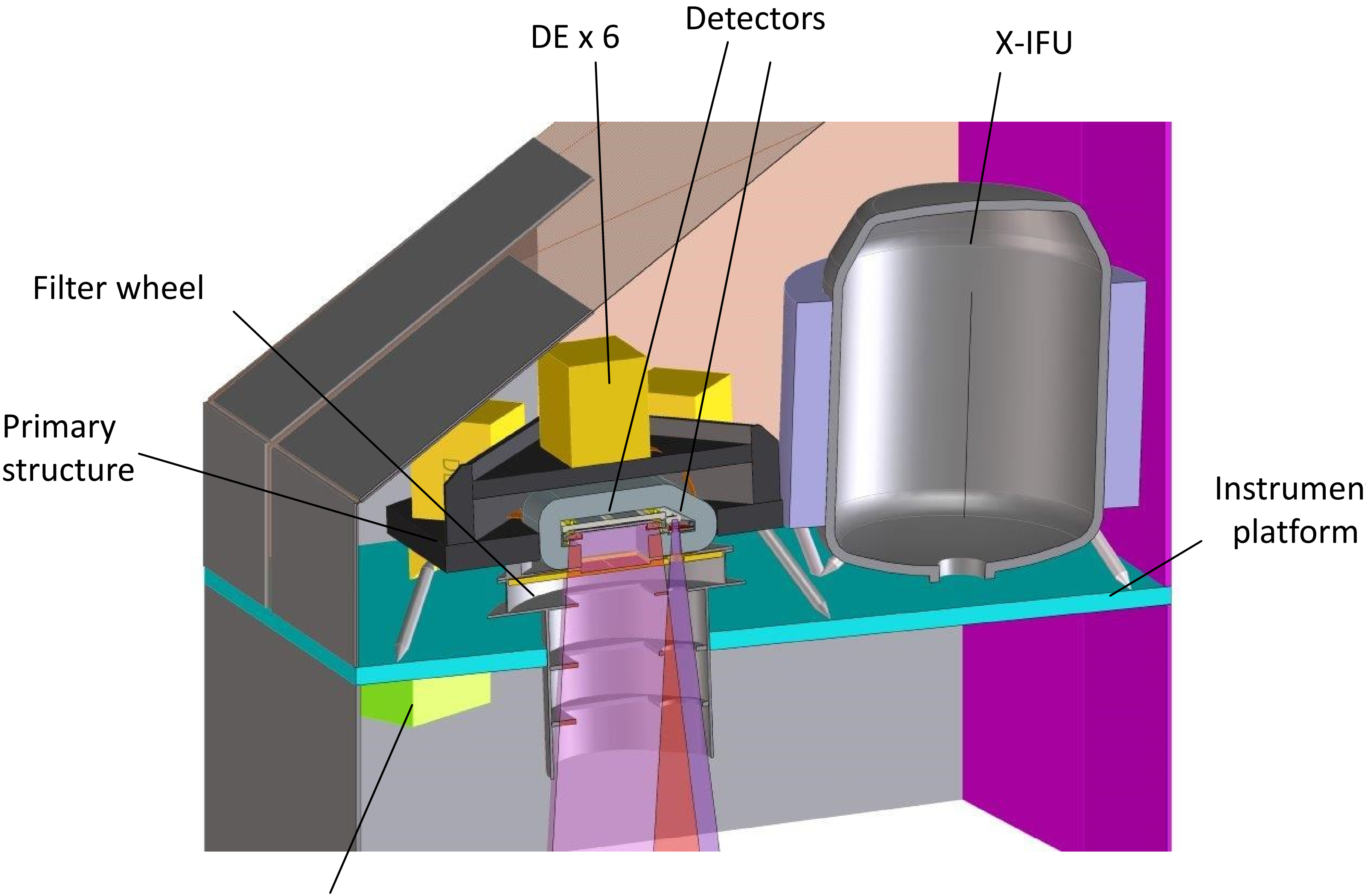
X-IFU:
X-ray micro-Calorimeter
ΔE=2.5eV
T=50mK

Mirror system:
f = 12 m
Aeff ≈2 m² at 1 keV

Wide Field Imager:

- **unprecedented survey power** (FoV = 40`x40`)
- **high count-rate capability** (1 Crab)
- E=[0.1 keV – 15 keV] state-of-the-art energy resolution
- focal plane detectors: **DEPFET APS**
  (enhanced type of DEPFET MIXS detector for BepiColombo)
- MPE lead institute

4. DEPFET APS Detectors: WFI camera on Athena



4. DEPFET APS Detectors: WFI on Athena

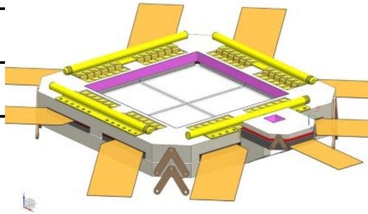
Concept for Signal Chain

(Detector + Electronics System) x 5

- **X-ray photon** focused on DEPFET APS
- **Signal electrons** collected in Pixel
- **First amplification** on-chip
- Signal amplification + shaping in **VERITAS2**
- Analog voltage signal fed into **ADC** cluster
- Frame **pre-processing (FPGA) in realtime** : Offset subtract., common mode correction, event filtering (lower + upper threshold), event pattern recognition
- **ICPU**: data compression
- Events buffered in mass memory + transmitted to **ground station**

4. DEPFET APS Detectors: WFI on Athena

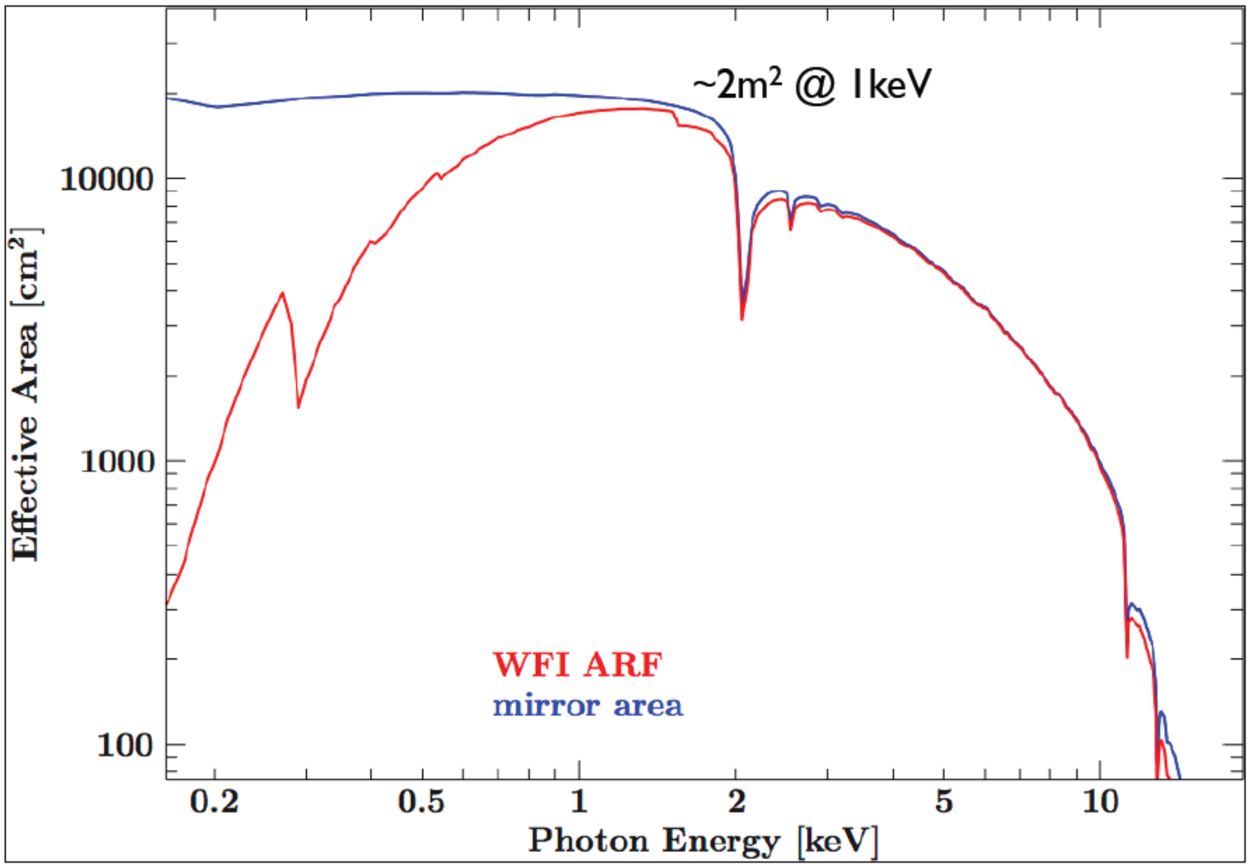
Main WFI Requirements / Characteristics



Parameter	Value
Energy Range	0.1-15 keV
Field of View	40' x 40'
Angular Resolution **Pixel Size**	PSF=5`` (on-axis) 130 x 130 $\mu m^2$ (2.2``)
Large DEPFET detector	4 quadrants: 512 x 512 Pixel
Fast DEPFET detector	64 x 64 pixel (2 halves) (gateable DEPFET with storage)
Quantum efficiency On-chip: 70 nm Al on-chip; Ext. filter: 40 nm Al + 320nm PP/200nm PI	24% @ 277 eV 87% @ 1 keV 96% @ 10 keV
Energy Resolution	FWHM(6 keV) ≤ 150 eV
Time Resolution full frame Fast detector Large detector	 80 µs (40 µs) 1.3 ms
Count Rate Capability	Fast DEPFET full frame + defocussed (PSF=80" HEW) 1 Crab: >90% throughput, <1% pile-up
Particle Background (L2 orbit)	$< 5 \times 10^{-3}$ cts cm^{-2} s^{-1} keV^{-1}

4. DEPFET APS Detectors: WFI on Athena

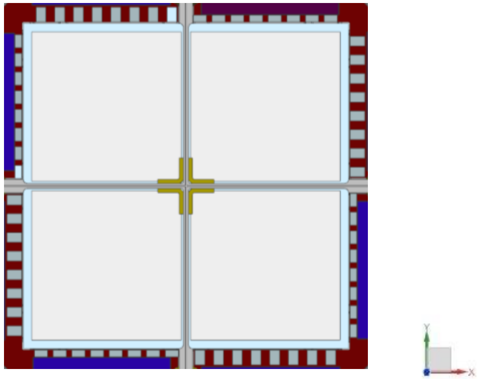
WFI effective Area (on-axis)

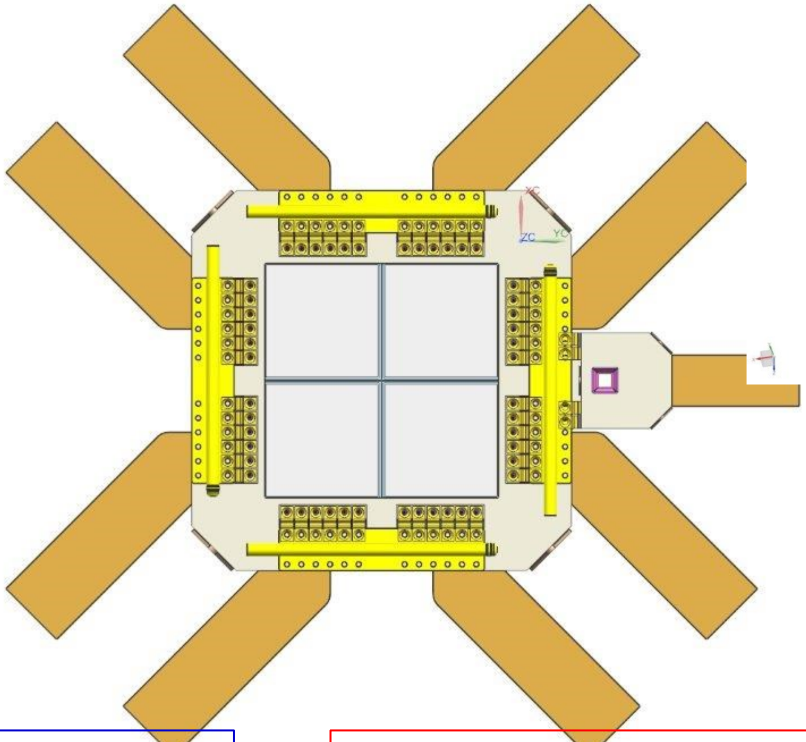


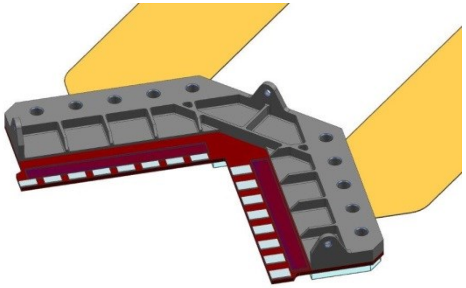
4. DEPFET APS Detectors: WFI on Athena

WFI Focal Plane

(2 on-axis positions)







Large detector: FoV = 40`x 40`

↔ Size ≈ 140 mm

4 x DEPFET (large standard):

- **512 x 512** pixels
- 130 µm x 130 µm (↔ 2.23'')
- 66.6 x 66.6 mm^2
- FF Time resolution: **1.3 ms**

Fast detector: High count rate capability

FoV = 143``

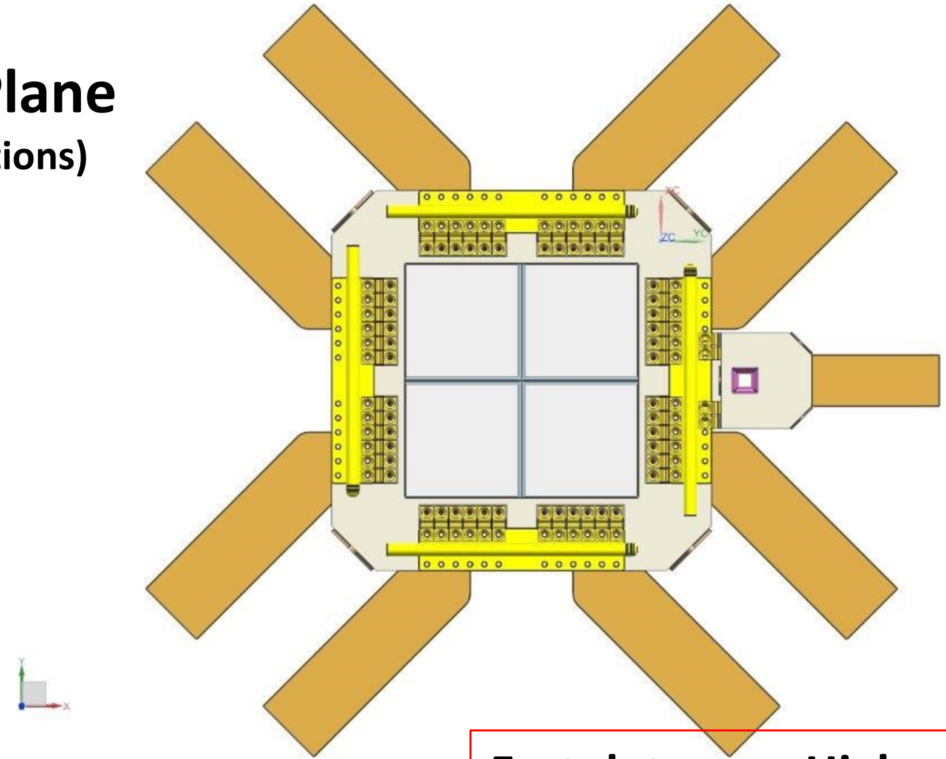
1 DEPFET (gateable + analog storage):

- **64 x 64** pixels subdivided in 2 halves
- 130 µm x 130 µm (↔ 2.23``)
- 8.3 x 8.3 mm^2
- FF Time resolution: **80 µs** (or **40 µs)**

4. DEPFET APS Detectors: WFI on Athena

WFI Focal Plane

(2 on-axis positions)



Fast enough for pulsar naviagation? If not, operate in Window mode!

Fast detector: High count rate capability

FoV = 143``

1 DEPFET (gateable + analog storage):

- **64 x 64** pixels subdivided in 2 halves
- 130 µm x 130 µm (↔ 2.23``)
- 8.3 x 8.3 mm^2
- FF Time resolution: **80 µs** (or **40 µs)**

4. DEPFET APS Detectors: WFI on Athena

Fast DEPFET detector:

- **Further development of DEPFET for high time resolution (= small #rows):**

Problem: photon hits during signal sampling → E_{meas} (<E_X) "energy misfits"

Step 1: **gateable DEPFET**

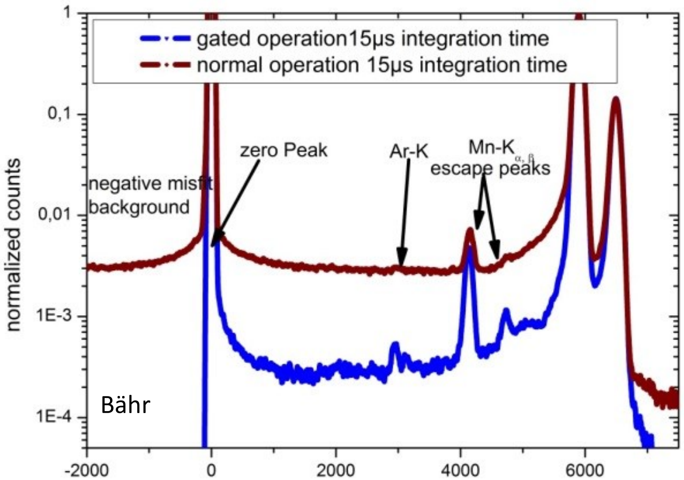
Electronic shutter built-in in each pixel

→ suppresses signals during sampling period

Status: **shielding 10^4** (sim.: 10^6)

→ **10 x less "background"**

(better spectral response)



4. DEPFET APS Detectors: WFI on Athena

Problem: e-shutter → **high dead time** for readout of small areas

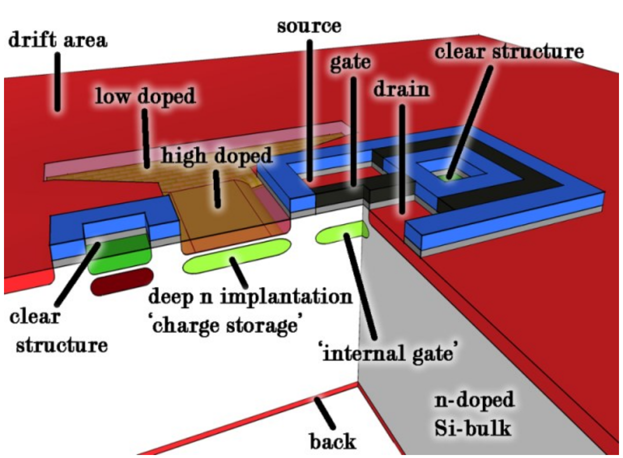
Step 2: **gateable DEPFET with storage region**

- when DEPFET performs signal processing
- generated e⁻ are stored outside of DEPFET to be processed in next frame

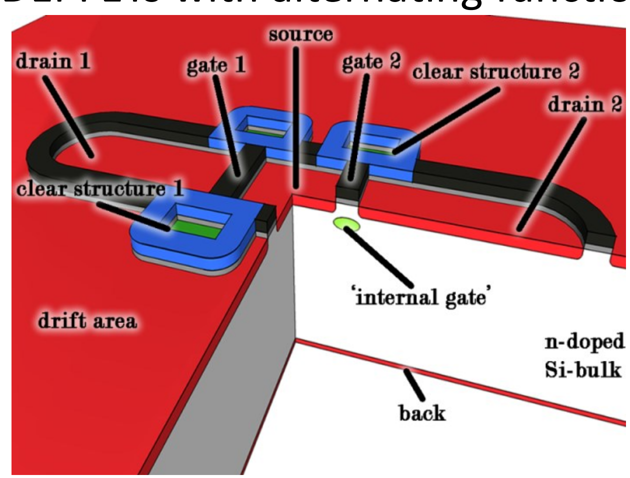
Advantage: **low background + min. dead time**

Status: prototype devices produced + under test

Transfer gate to DEPFET



2 DEPFETs with alternating functions



4. DEPFET APS Detectors

Adaption for pulsar navigation

DEPFET APS type **gateable + storage region**
Drain current readout (faster than SF readout)

Option 1:

DEPFET APS pixel array with 64 channels and 64 rows; split frame readout
pixel size: matched to optics
Time resolution: **64 rows** = **80 µs** full frame to find the pulsar
8 rows = **10 µs window mode** for navigation

Option 2:

- DEPFET APS array with e.g. 4 x 4 pixels and **all pixels** are **read out simultaneously**, i.e. **2.5 µs** time resolution
  (option 2.1: 4-line readout or
  2.2: bump bonding for larger array but more power – heat dissipation)

5. Summary and Outlook

- Detector time resolution **$\Delta t < 100\ \mu s$** **for pulsar navigation**
  → feasible for all 3 detector types
  (if large pixel array only in 1 dimension)
- **Large pixels**: minimizes split events
- PNCCD: few rows but many channels; new Veritas2 ASIC
- SDD: single cell or array of SDD cells (contiguous or not)
- DEPFET APS: of type "gateable + storage region "
  Option 1: split-frame + window mode
  Option 2: fully parallel readout of pixels (power!)
- Detector concept + technology mature for pulsar navig. app.

Acknowledgments

- Max-Planck-Institute for extraterrestrial physics, Garching
- MPG semiconductor laboratory, Munich
- PNSensor, Munich