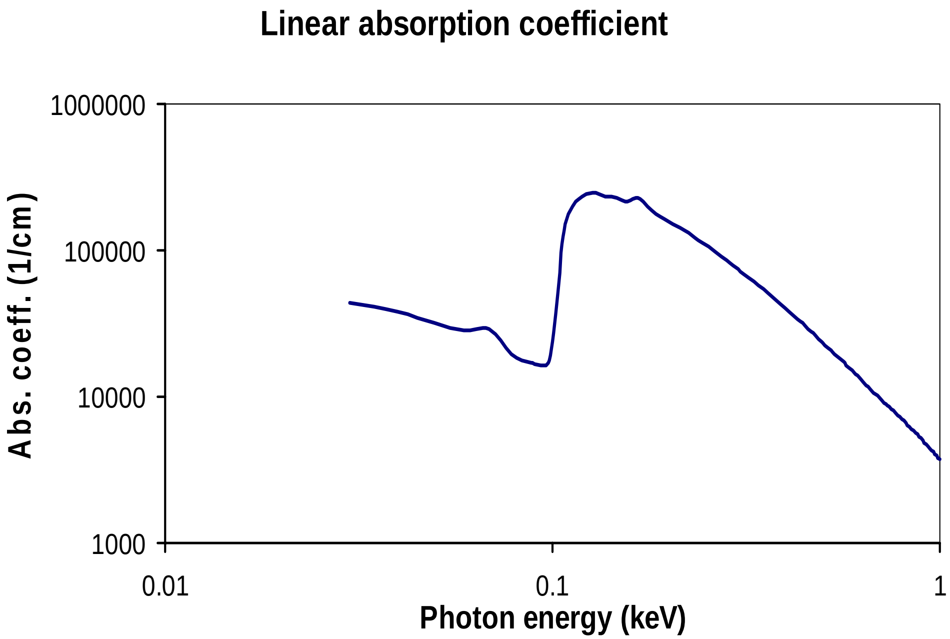
Instrumentation Seminar
March 17, 2004 at BNL

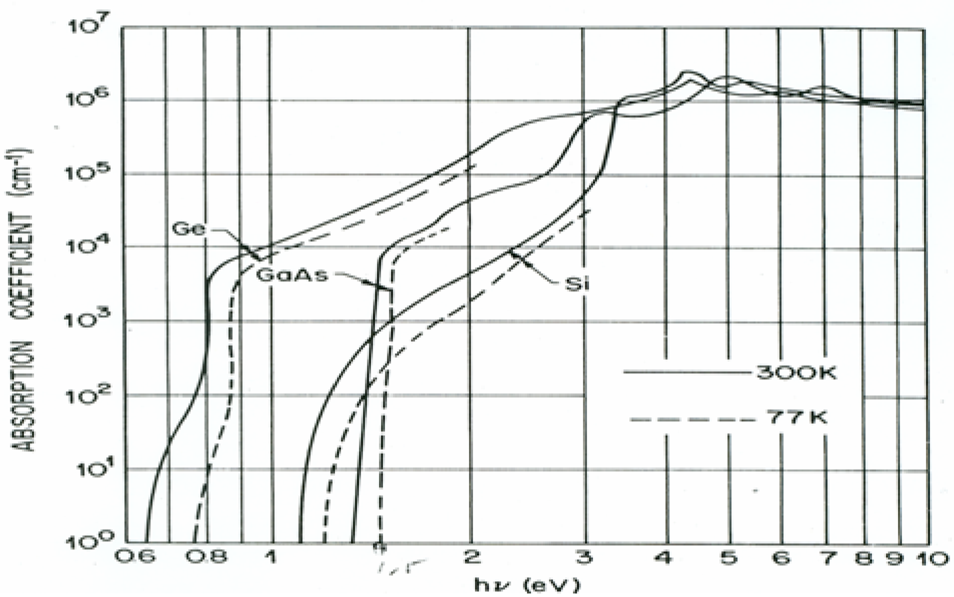
Silicon Radiation Detectors

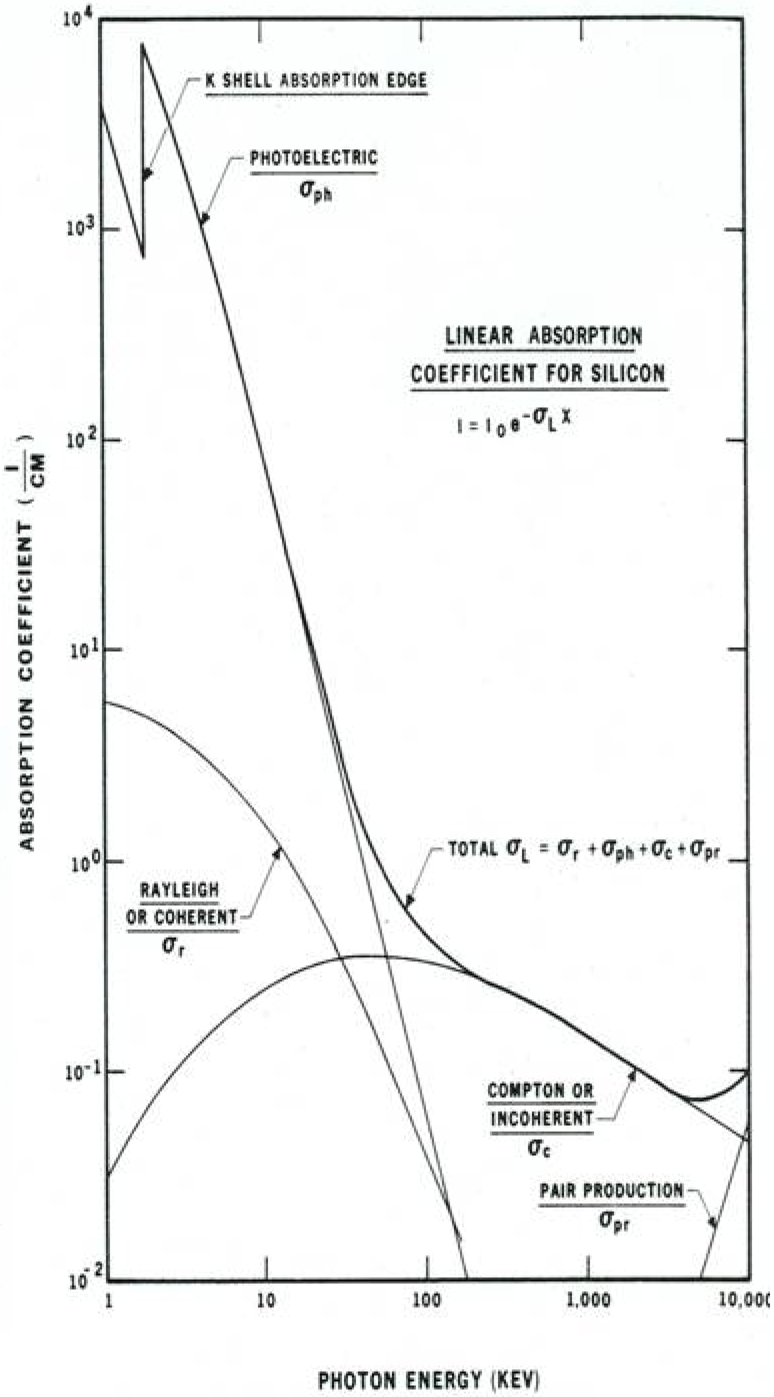
Pavel Rehak
Brookhaven National Laboratory

Outline of the Talk

- Silicon age (after the stone and iron ages)
- Silicon as the detection medium
- Detector grade silicon
- Simple diode silicon detectors
- Introduction of planar process for Si detectors
- Modern detector structures
- Perspectives

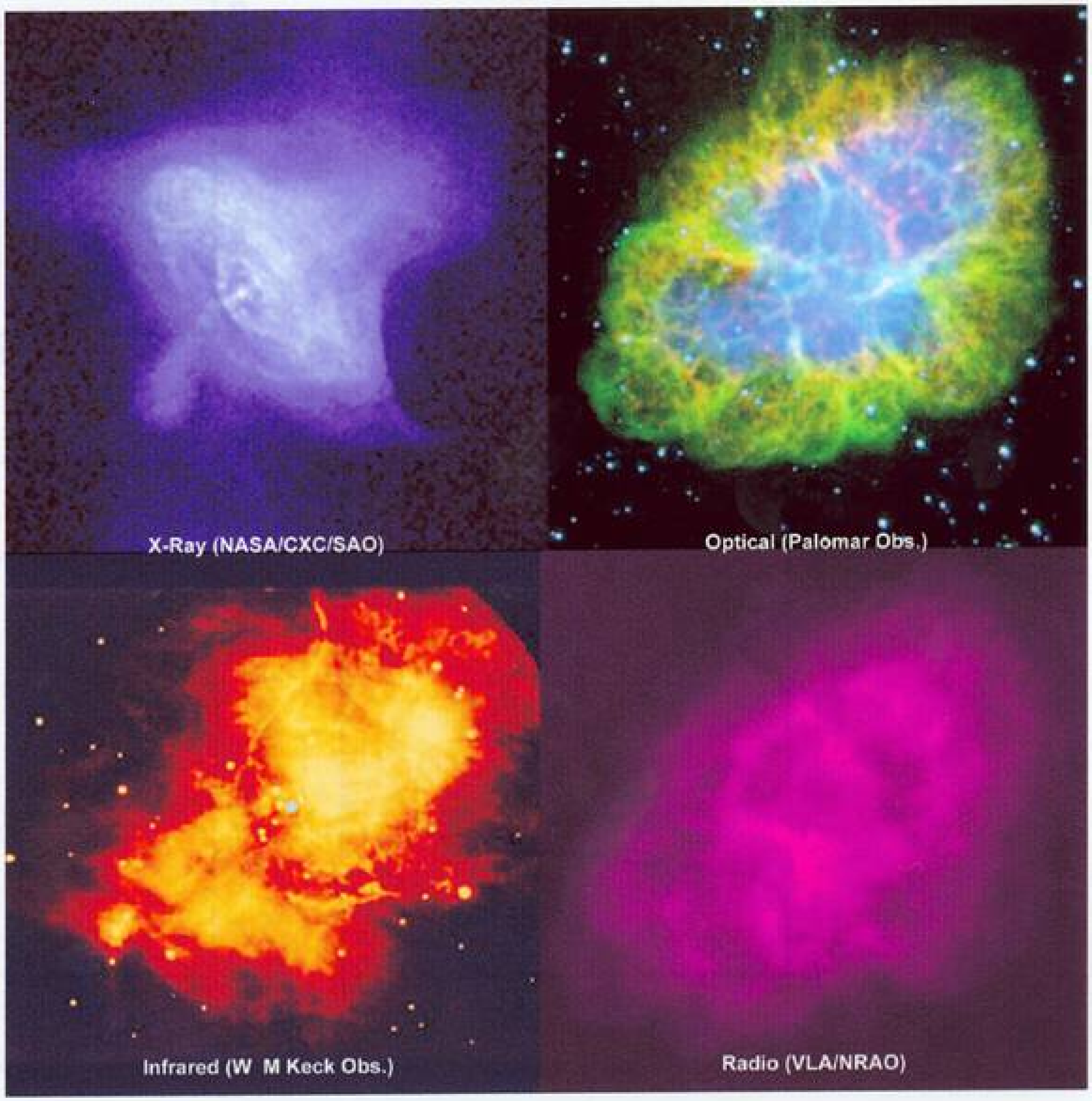

Linear absorption coefficient
1000000
100000
10000
1000
Abs. coeff. (1/cm)
0.01
0.1
1
Photon energy (keV)


10⁷
10⁶
10⁵
10⁴
10³
10²
10¹
10⁰
ABSORPTION COEFFICIENT (cm⁻¹)
Ge
GaAs
Si
300K
77K
0.6
0.8
1
2
3
4
5
6
7
8
9
10
hν (eV)


10⁴
10³
10²
10¹
10⁰
10⁻¹
10⁻²
ABSORPTION COEFFICIENT (1/CM)
K SHELL ABSORPTION EDGE
PHOTOELECTRIC
σph
LINEAR ABSORPTION
COEFFICIENT FOR SILICON
I = I0 e^(-σL X)
TOTAL σL = σr + σph + σc + σpr
RAYLEIGH
OR COHERENT
σr
COMPTON OR
INCOHERENT
σc
PAIR PRODUCTION
σpr
1
10
100
1,000
10,000
PHOTON ENERGY (KEV)

Chandra X-Ray Observatory

Crab Nebula



$$\sigma_{Si}{}^{2} = F \cdot E_{photon} w$$

$$ENC_{par}{}^{2} = qI_{leak} \int_{-\infty}^{\infty} h(t)^2 dt \approx qI_{leak} t_{peak}$$

$$ENC_{series}^{2} = \tfrac{1}{2} e_n^2 C_t^2 \int_{-\infty}^{\infty} \left[h'(t)\right]^2 dt \approx e_n^2 C_t^2 / t_{peak}$$

$$t_{peak}^{(optimal)} = e_n C_t / \sqrt{q \cdot I_{leak}}$$

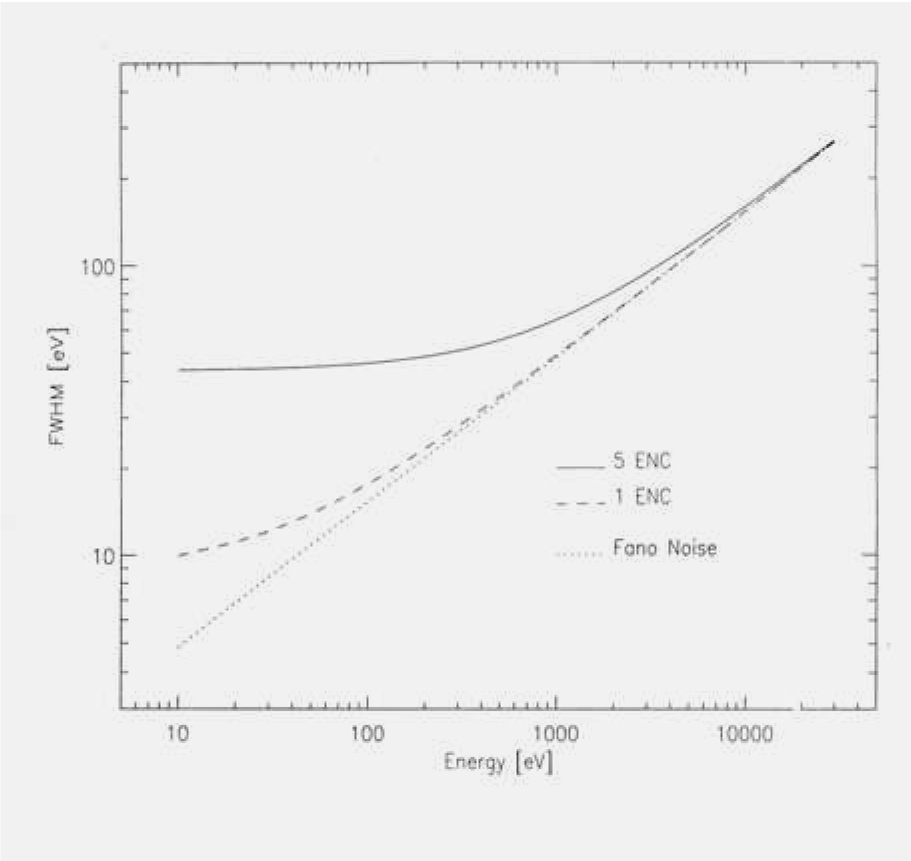
$$w = 3.62eV$$

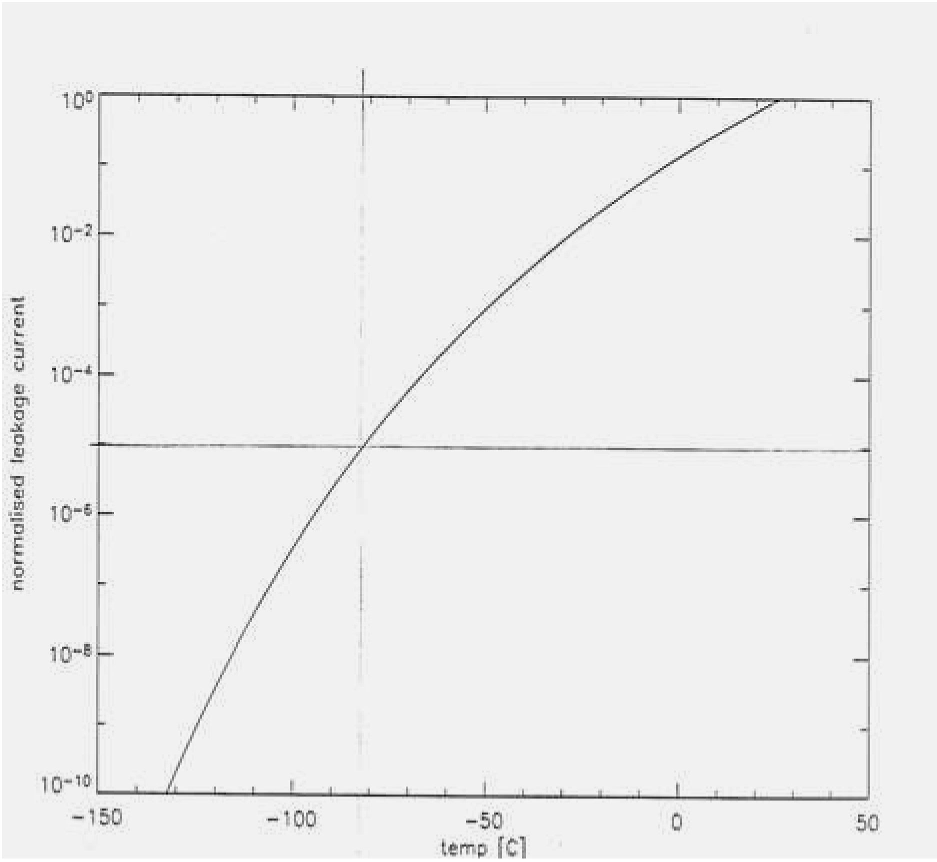
Leakage Current: $i_{leak} = q \cdot n_i / (2 \cdot \tau)$

Where n_i is the density of carrier in intrinsic silicon, tau is the life time and N_t the density of traps in silicon bulk.

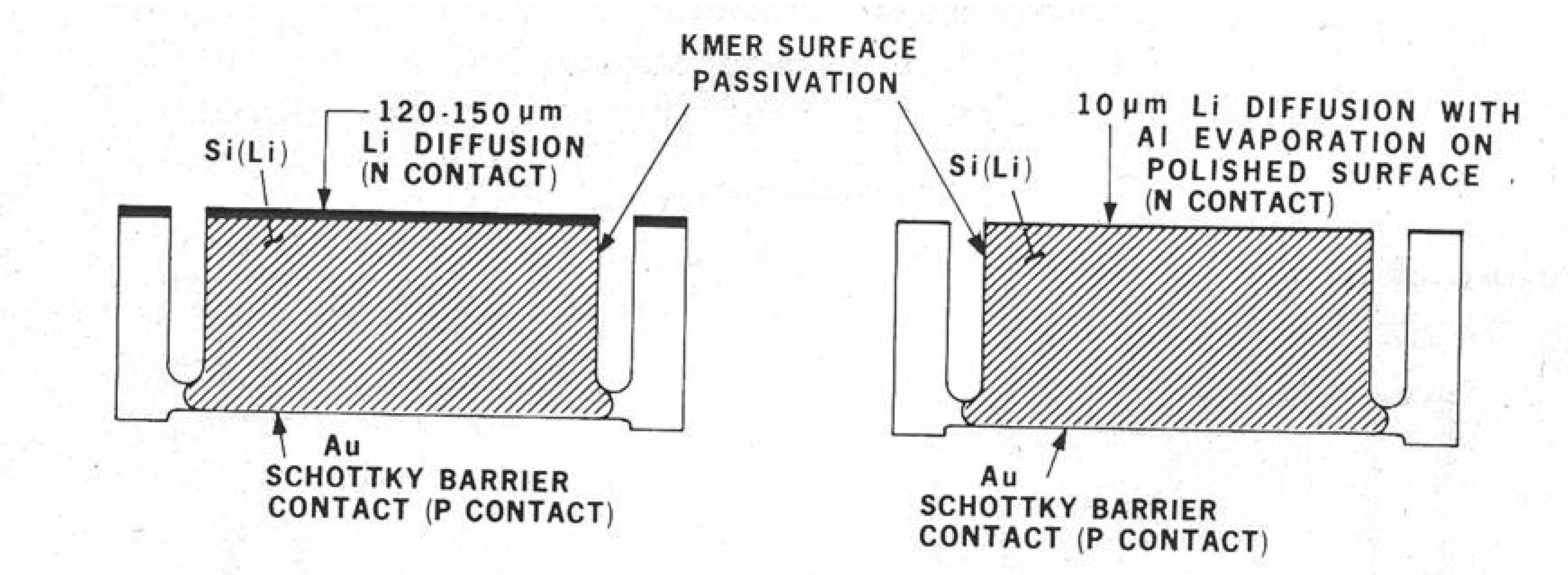
$$n_i \propto \exp(-E_{gap}/(2kT))$$

$$\tau \cong 1/(\sigma \cdot v_{th} \cdot N_t)$$





Si(Li) detectors before 1982



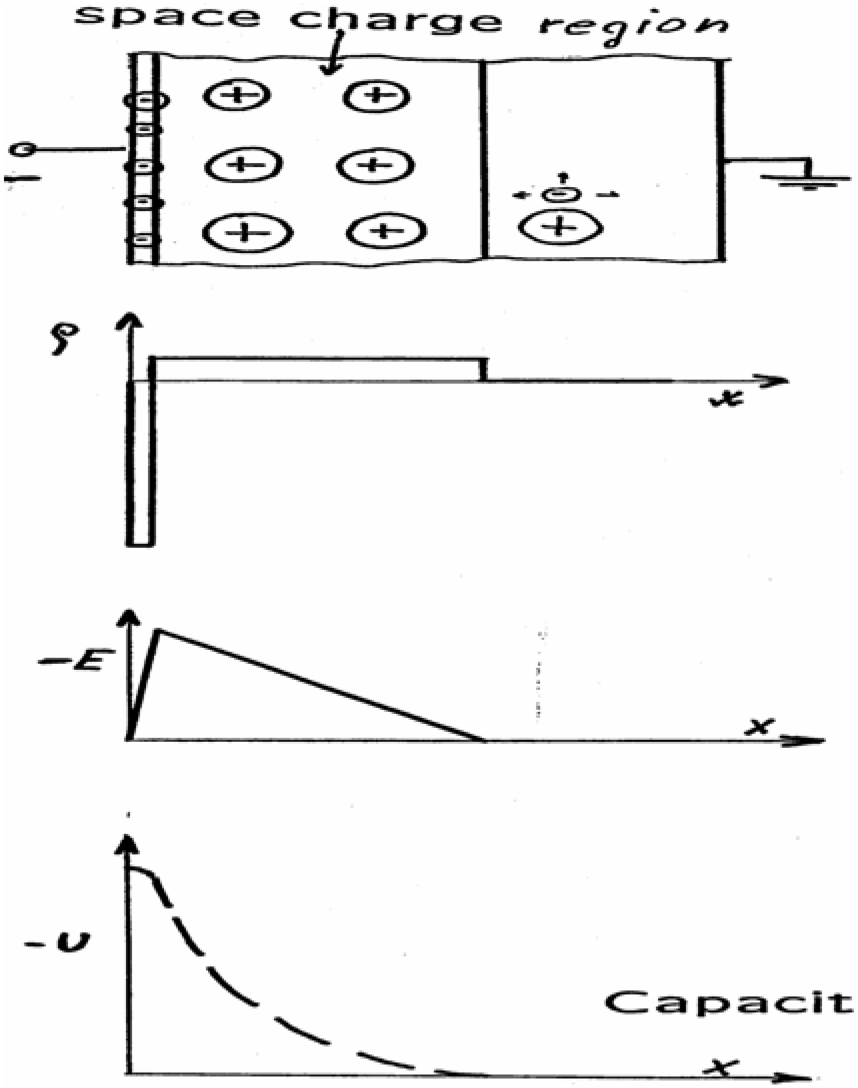
$$C_{\det} = \varepsilon_0 \cdot \varepsilon_r \cdot S / d$$

$$(\partial^2 / \partial x^2 + ... + \partial^2 / \partial z^2)U = -q \cdot N_{dop} / (\varepsilon_0 \cdot \varepsilon_r) = \rho$$

$$-U = 1/2 \cdot \rho \cdot z^2$$

Junction detector

- Abrupt one sided junction (rectifying bias)



space charge density

$\rho = qN_D$

N_D donor density

Eq. of electrostatics

$div E = \frac{\rho}{\epsilon}$

$\frac{dE}{dx} = \frac{\rho}{\epsilon}$

E linear

$E = -\frac{dV}{dx}$

V parabolic

Depletion lenght d

$d = \sqrt{\frac{2\epsilon V}{qN_d}}$

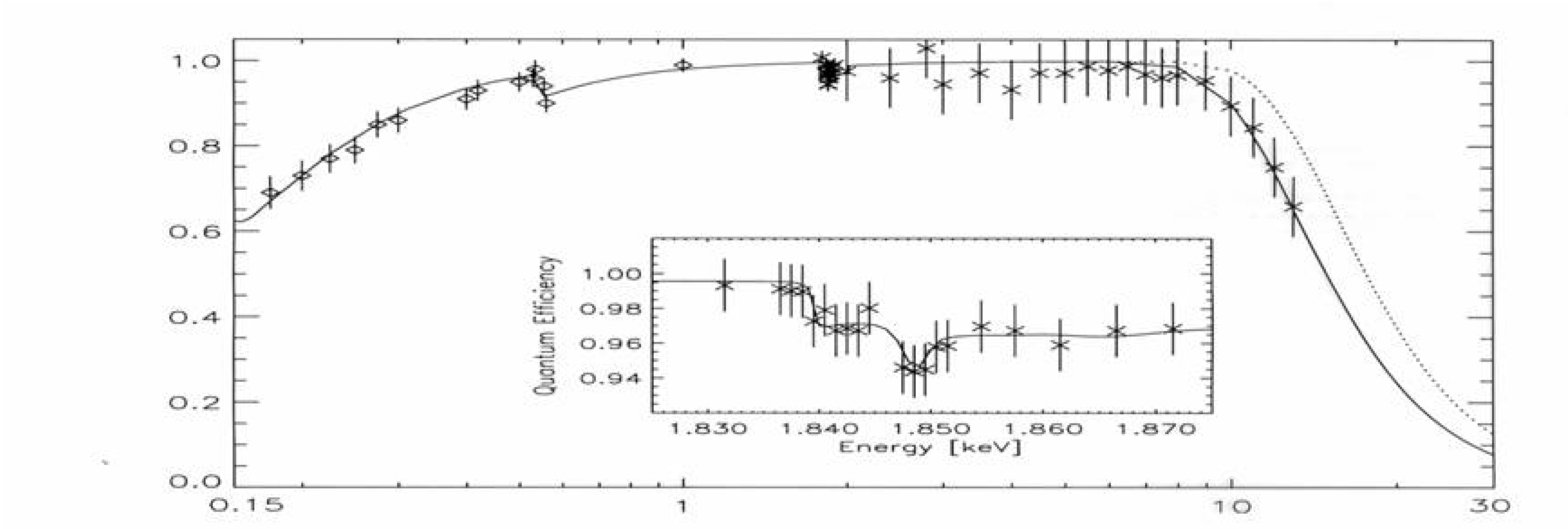
Capacitance $= \frac{\epsilon}{d} = \sqrt{\frac{q\epsilon N_D}{2V}}$ prop. $\frac{1}{\sqrt{V}}$

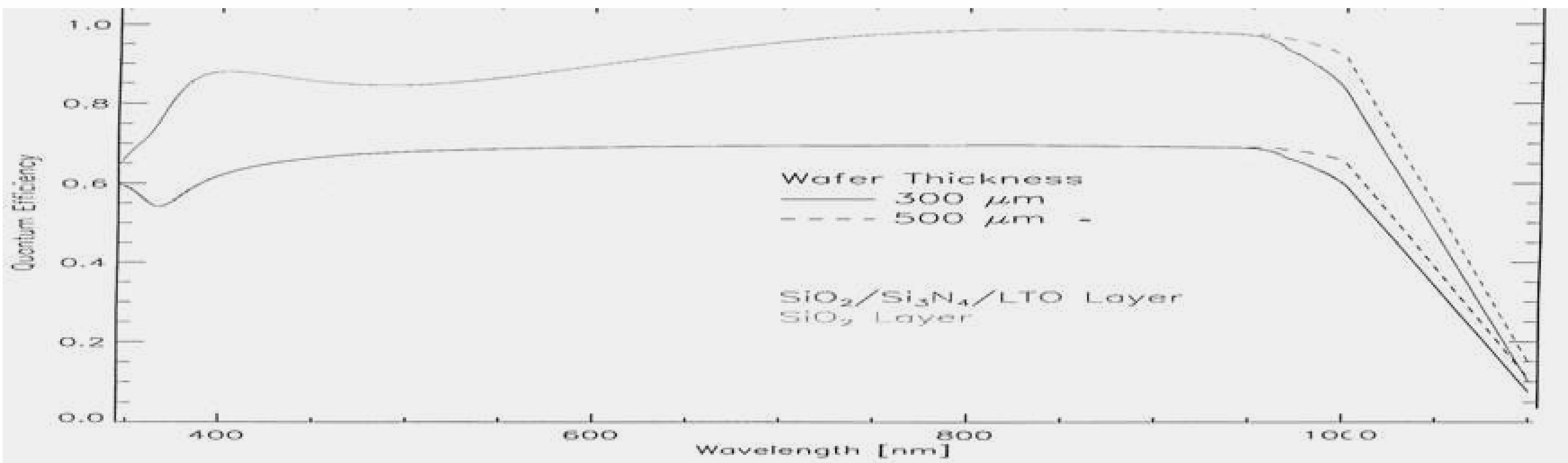
Developments in silicon detectors after 1982

1) Planar technology (from IC production) introduced to production of silicon detectors
2) Segmentation of the surface to form multi-detector
3) Application of the field parallel to the detector surface
4) Taking advantage of the field produced by ionized impurities (donors and acceptors).
5) Implementation of transistors within detector

Planar tech. limited thickness of the detector up to .5mm

Efficiencies of planar detectors





Silicon strip detector

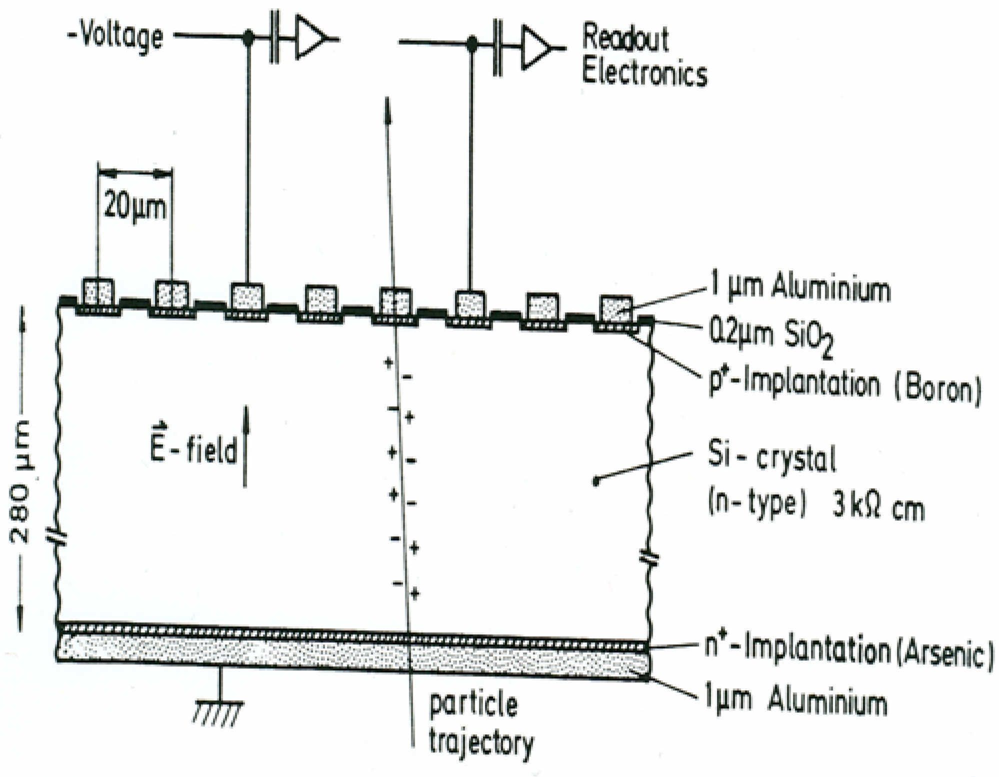


Table 1

Characteristics of the *TUM–MPI–CERN* silicon detectors

Material	3 k Ω cm n-doped Si single crystals
Size	2 inch Ø, 280 µm thickness
Radiation length	3×10^{-3}
Depletion voltage	120 V
Number of e—h-pairs for a min. i. particle	24 000
Number of strip diodes	1 200
Strip pitch	20 µm
Length of strips	36 mm
Sensitive area	24×36 mm^2
Number of read out strips	240
Pitch of read out strips	60 µm [a] 120 µm [b]
Spatial accuracy	4.5 µm [a] 7.9 µm [b]
Two particle resolution	60 µm [a] 120 µm [b]

[a] Central part of the detector;
[b] Outer parts of the detector.

New Types of Silicon Detectors

•Linear silicon drift detectors mainly for position sensing

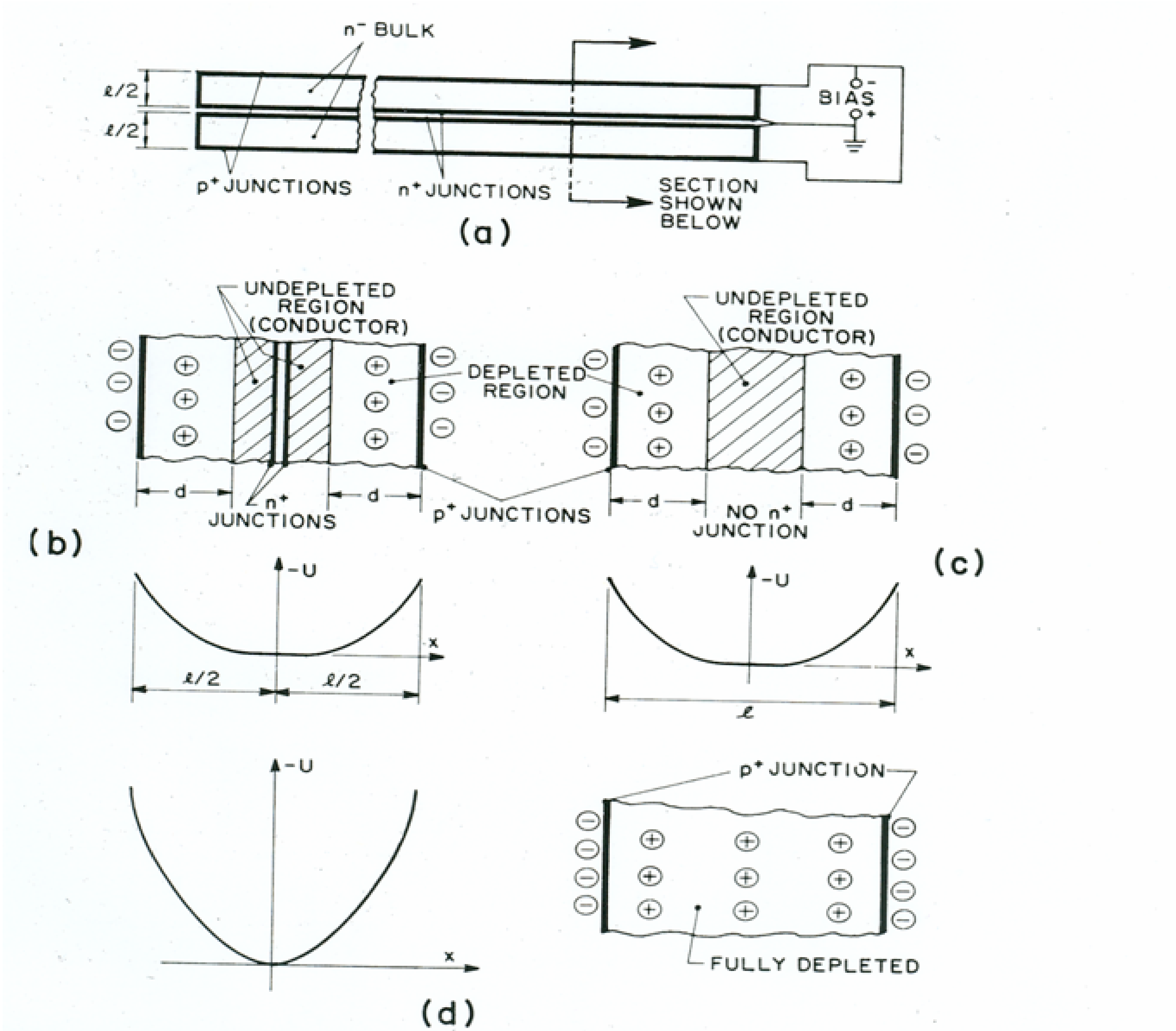
•Cylindrical drift detectors with extremely small capacitance as X-ray or optical photon detectors

•Fully depleted Charge Coupled Devices (CCD)

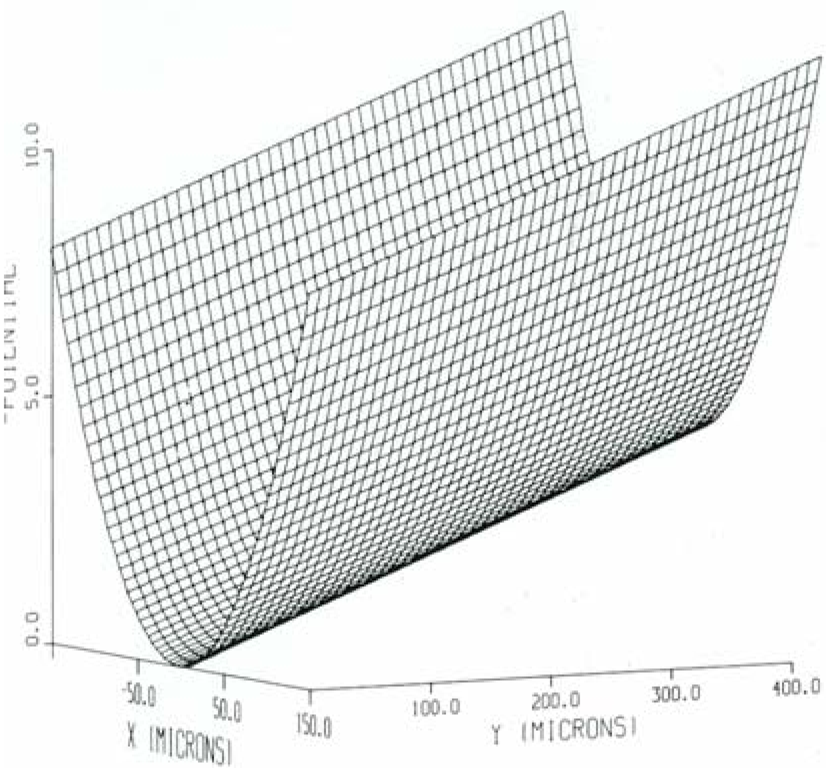
•Controlled Drift Detectors

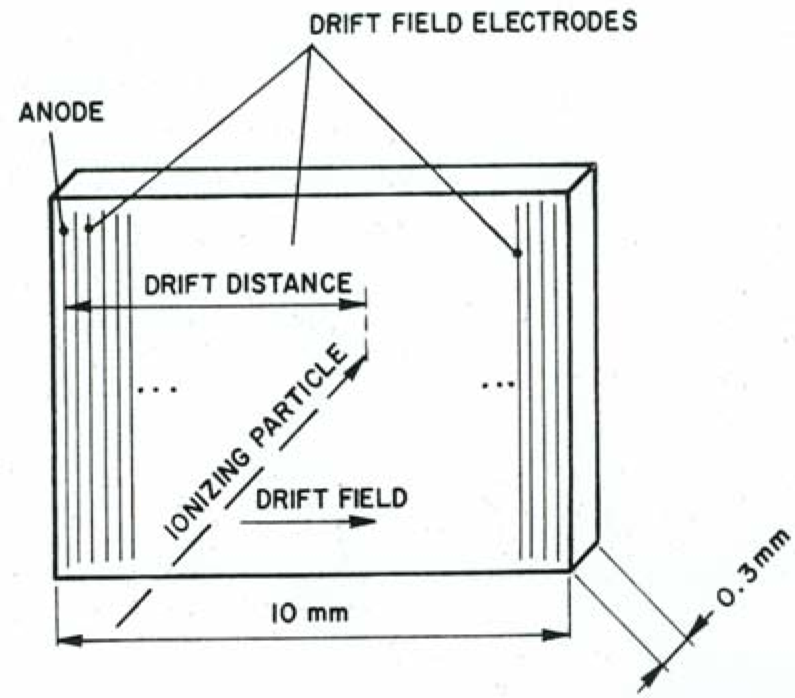
•Etc.

Storage of charge in bulk of silicon

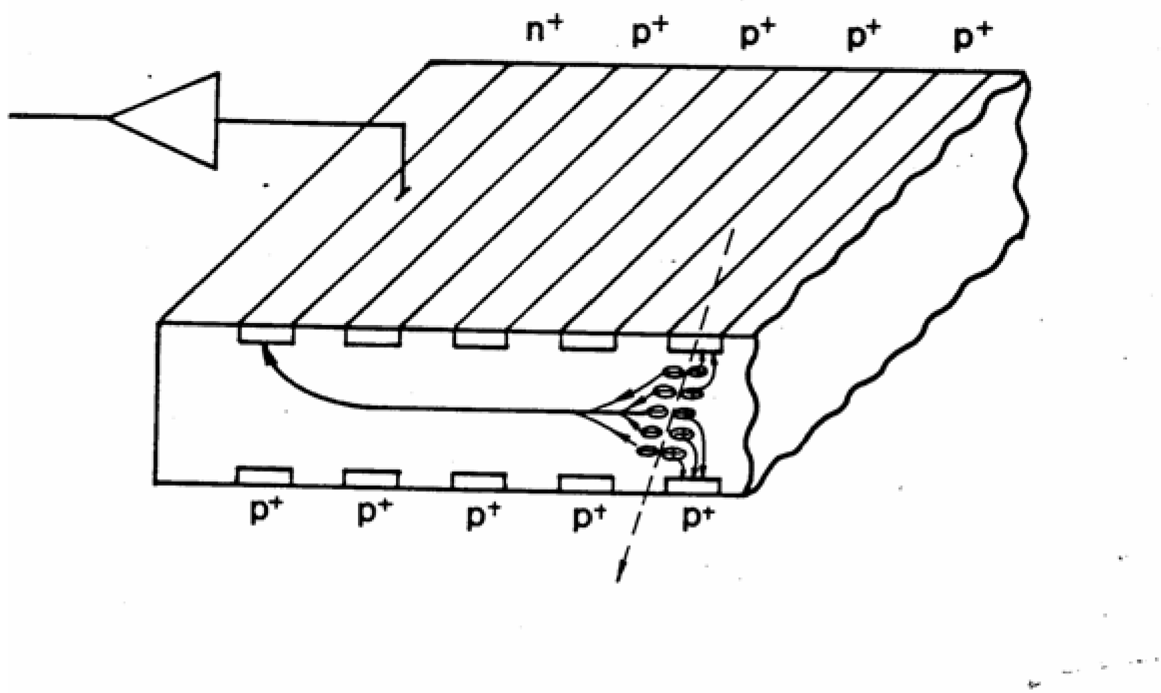


Principle of linear drift silicon detector (mainly for position determination)

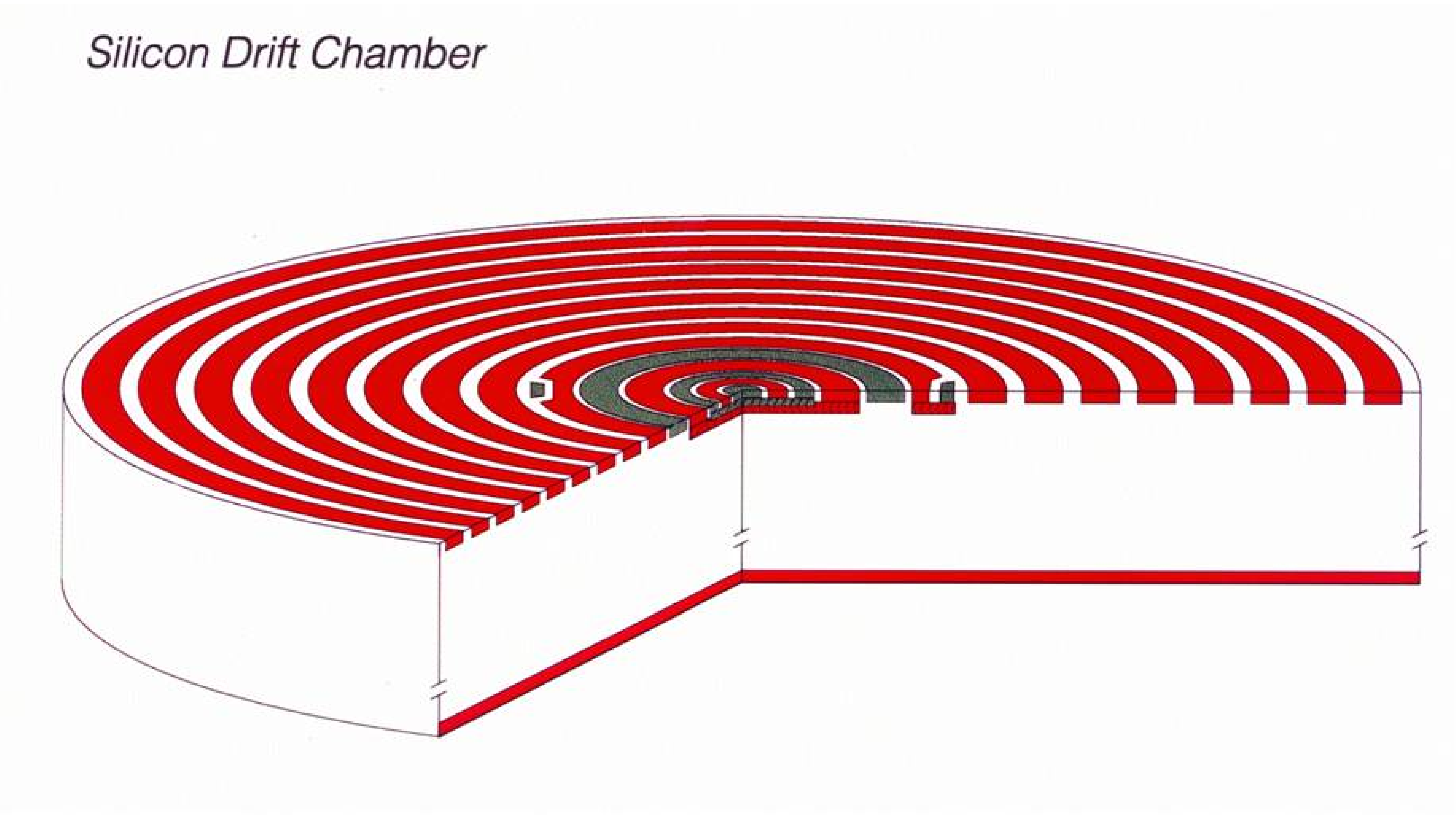




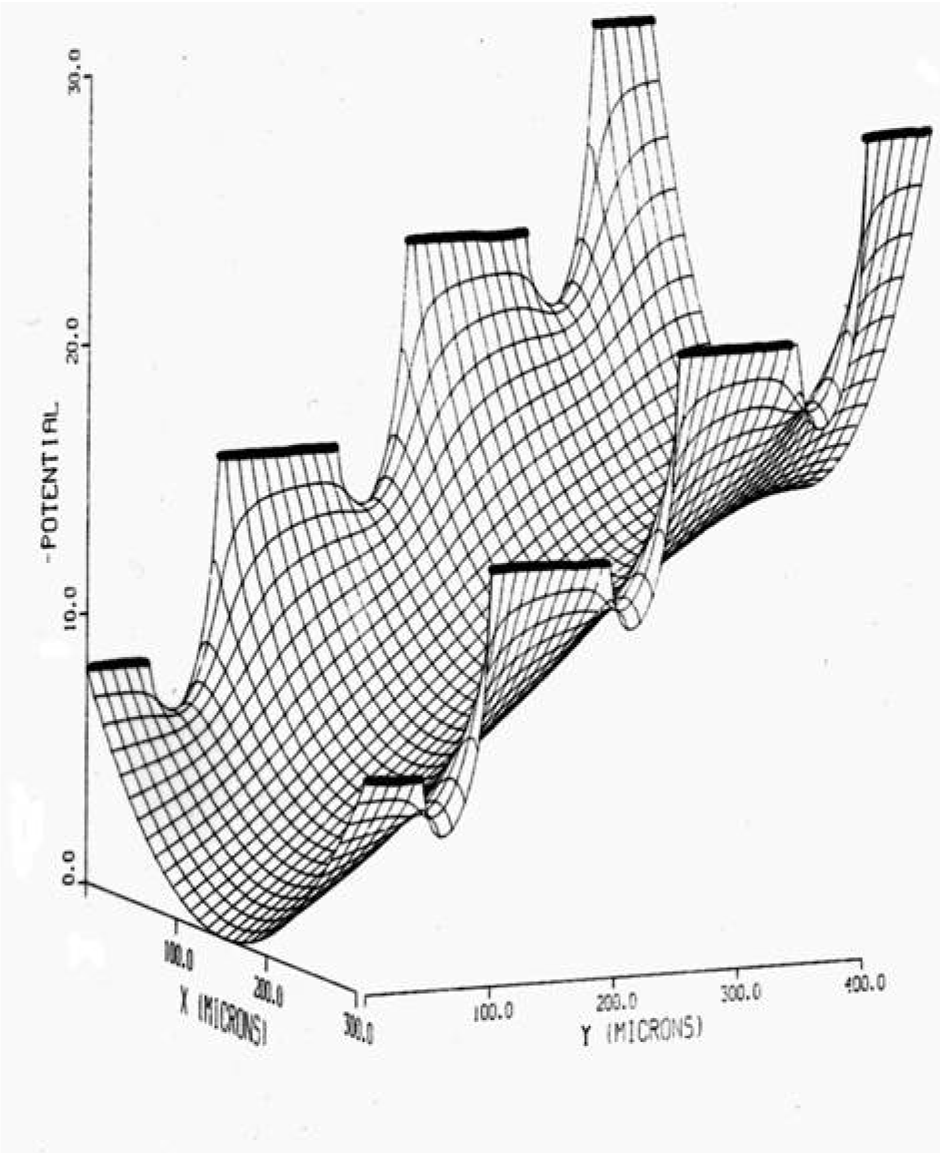
Linear drift detector with segmented rectifying electrodes

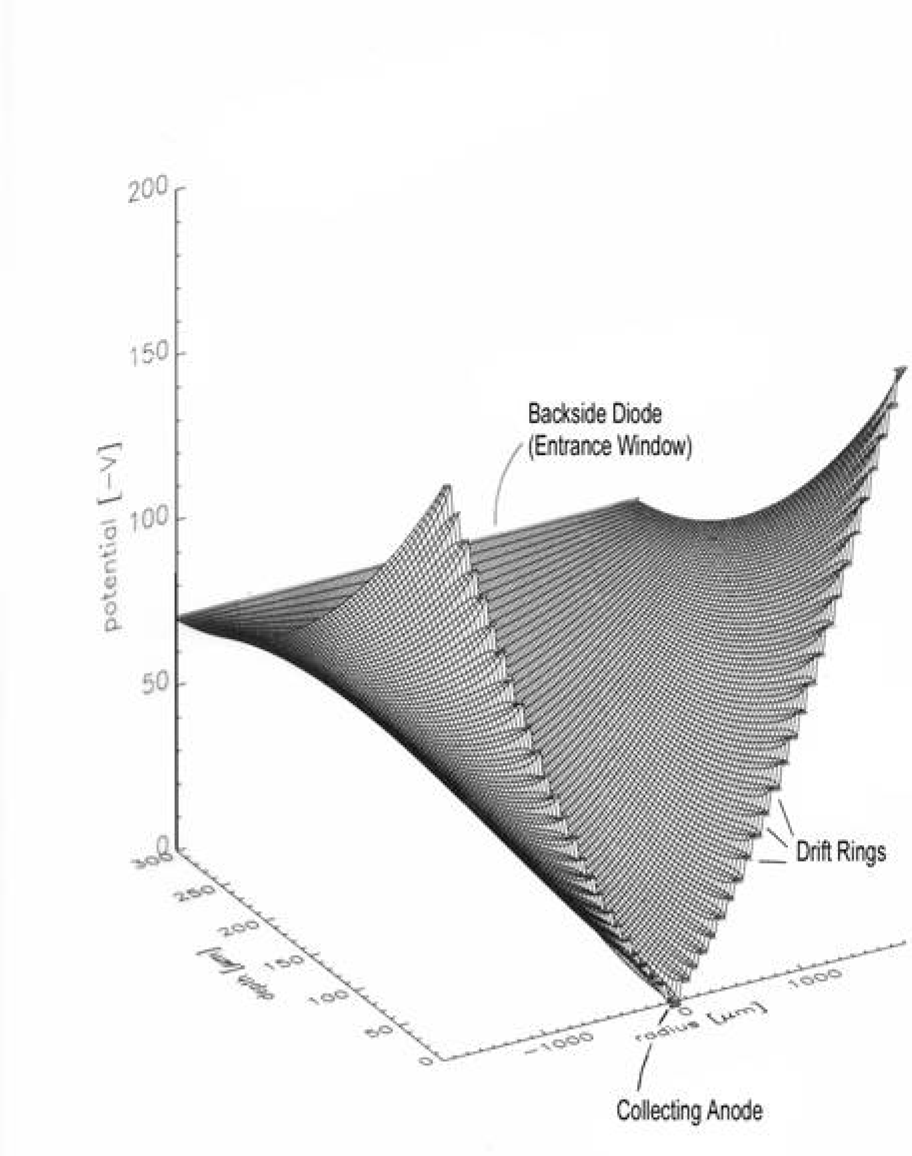


X-ray drift detector



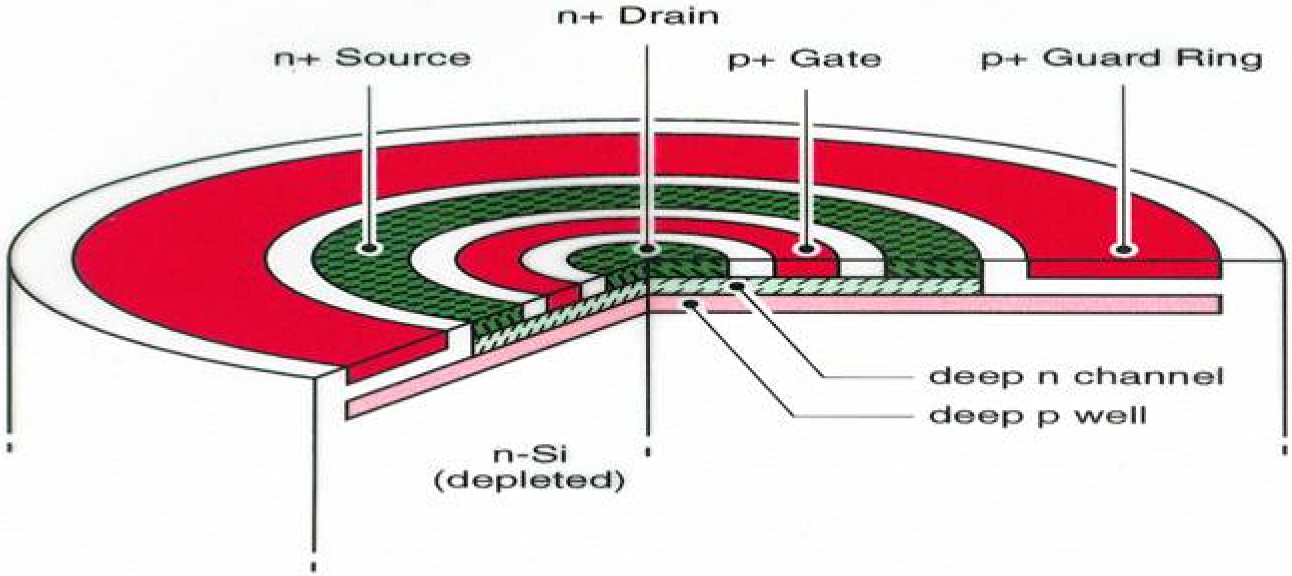
Potential within Drift Detectors





Single sided junction FET

N-Channel JFET on Depleted N-type Silicon



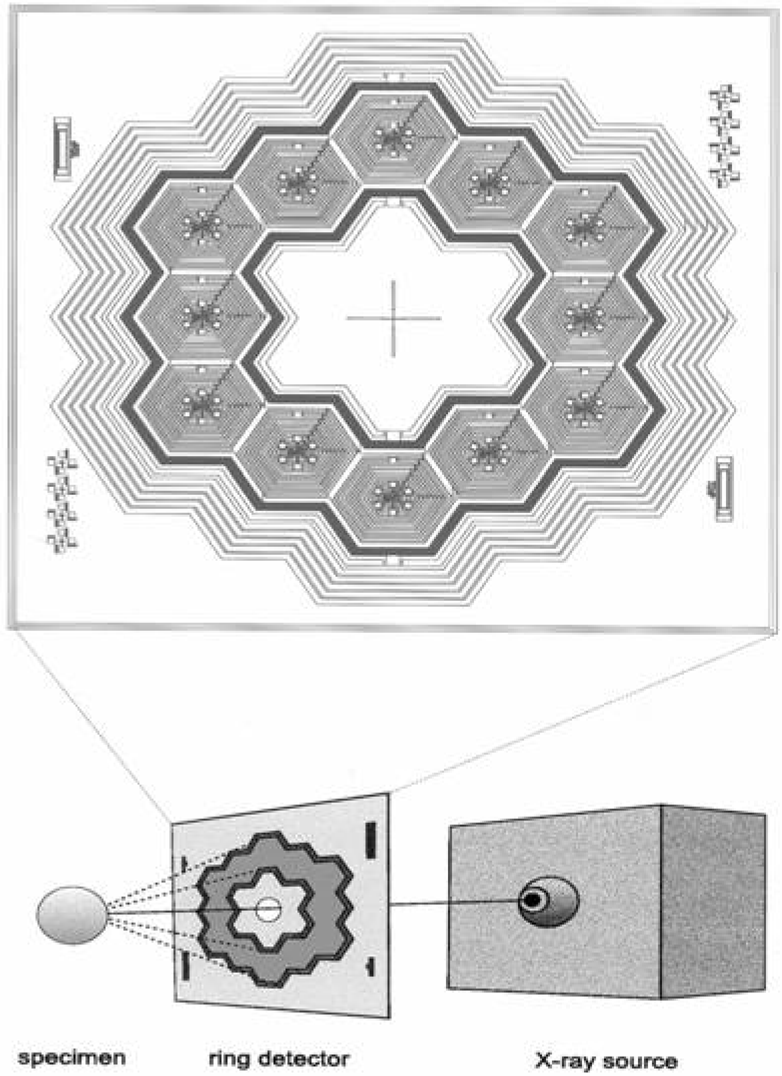
size & characteristics (typical):

gate length	5	μm
gate width	50	μm
saturation current	400	μA
transconductance	400	μA/V

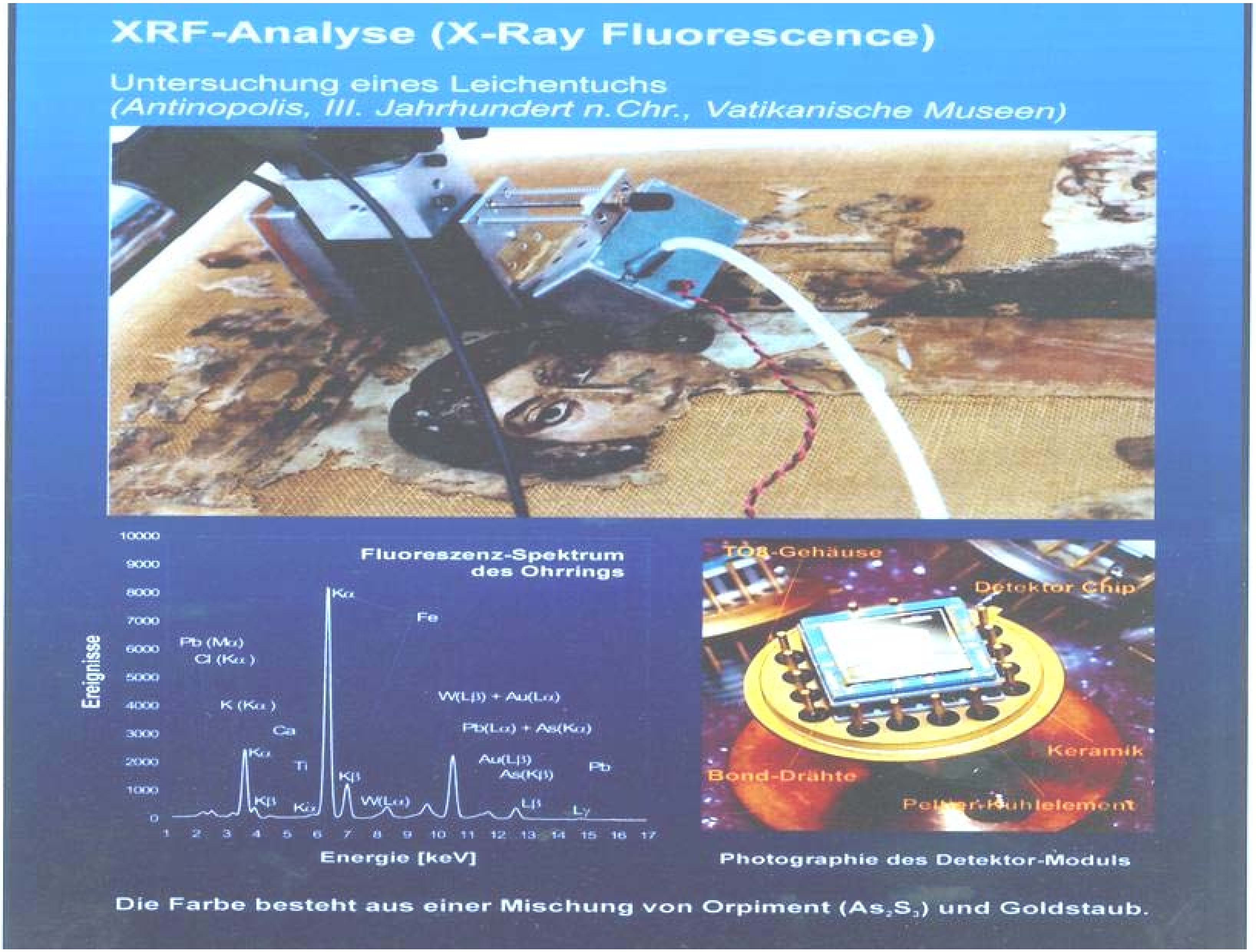
X-ray fluorescence system

Multi Channel SDD

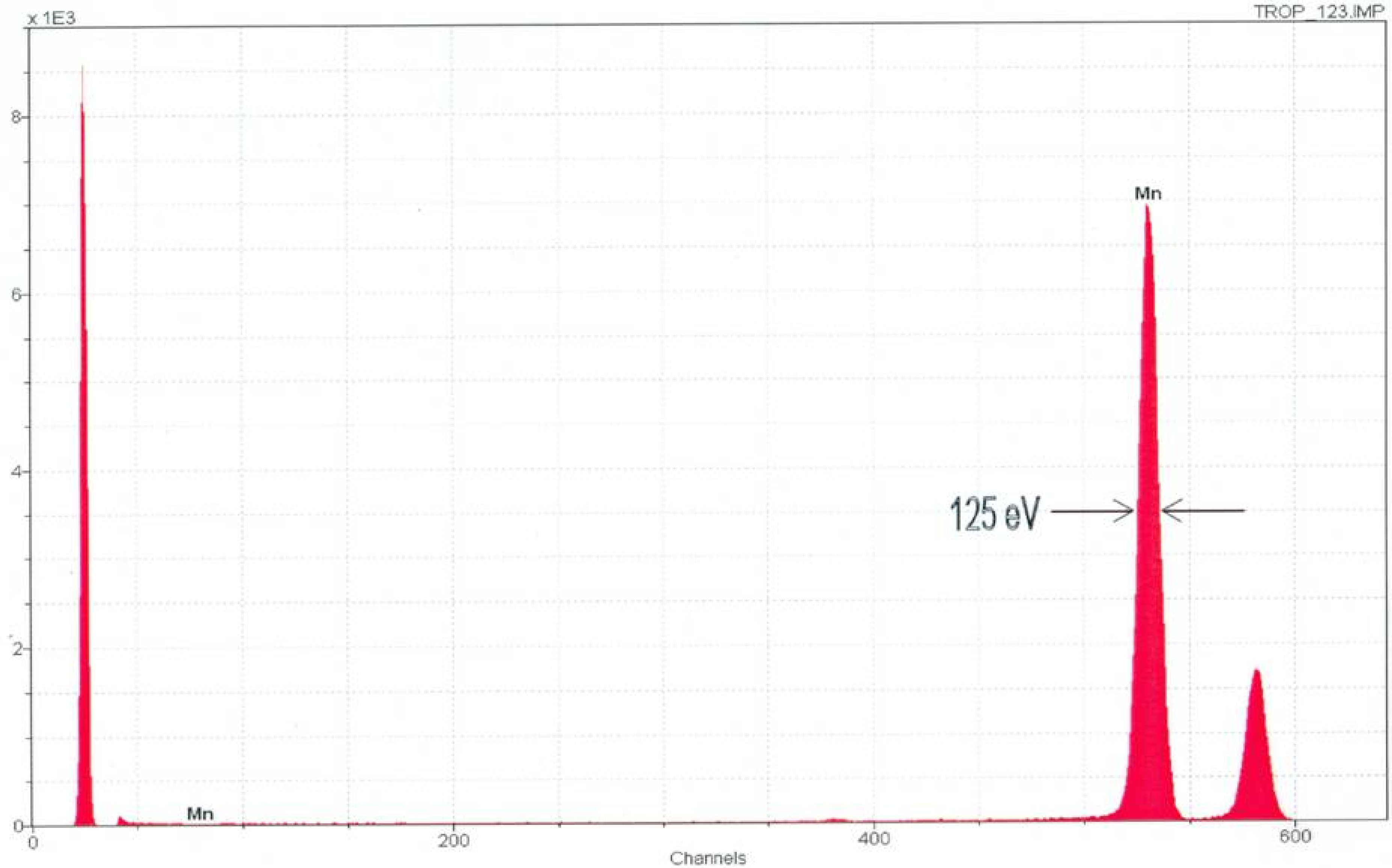
ring detector for compact XRF systens



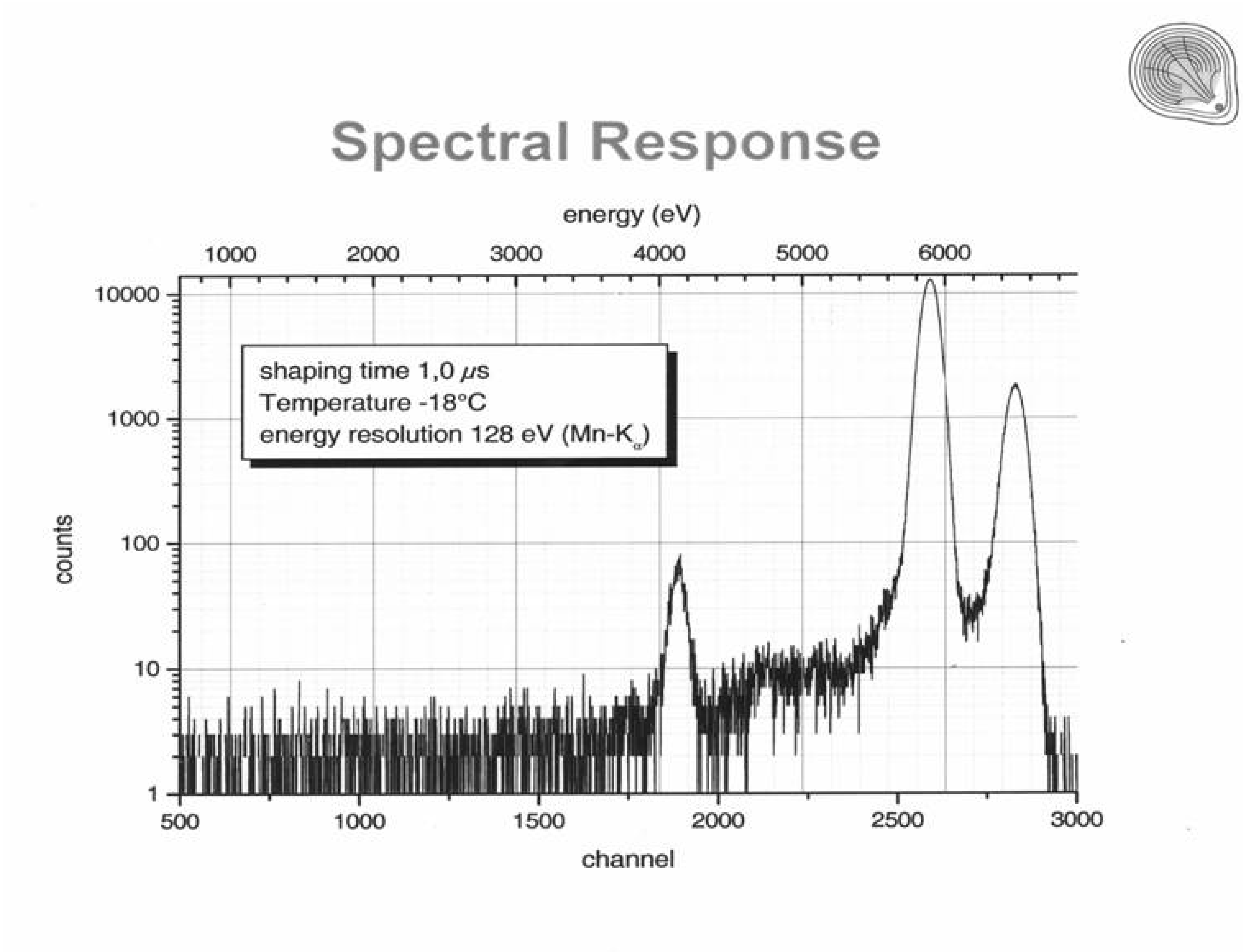
Applications in Art studies



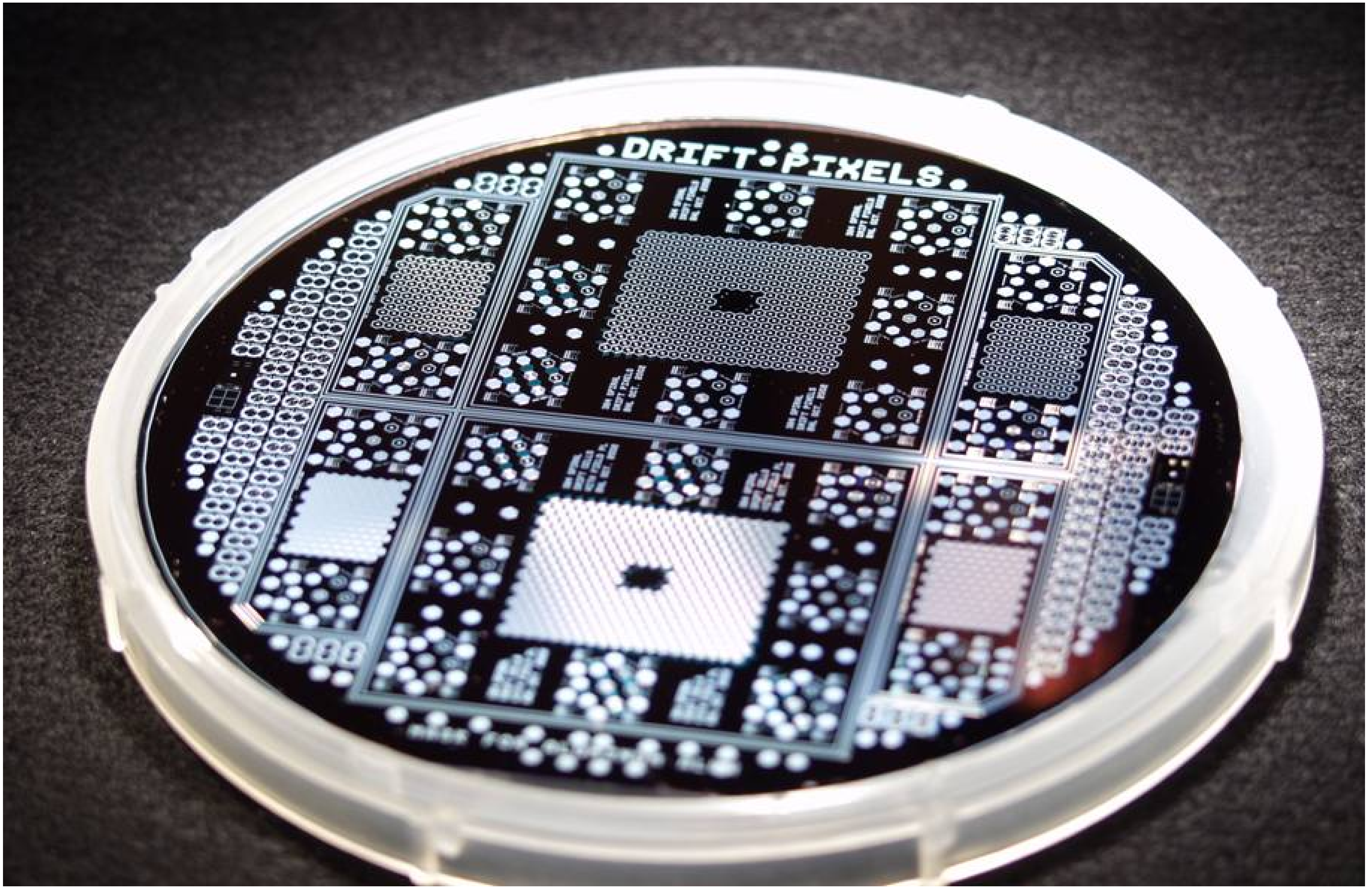
The best room temp. spectrum



Low energy tails

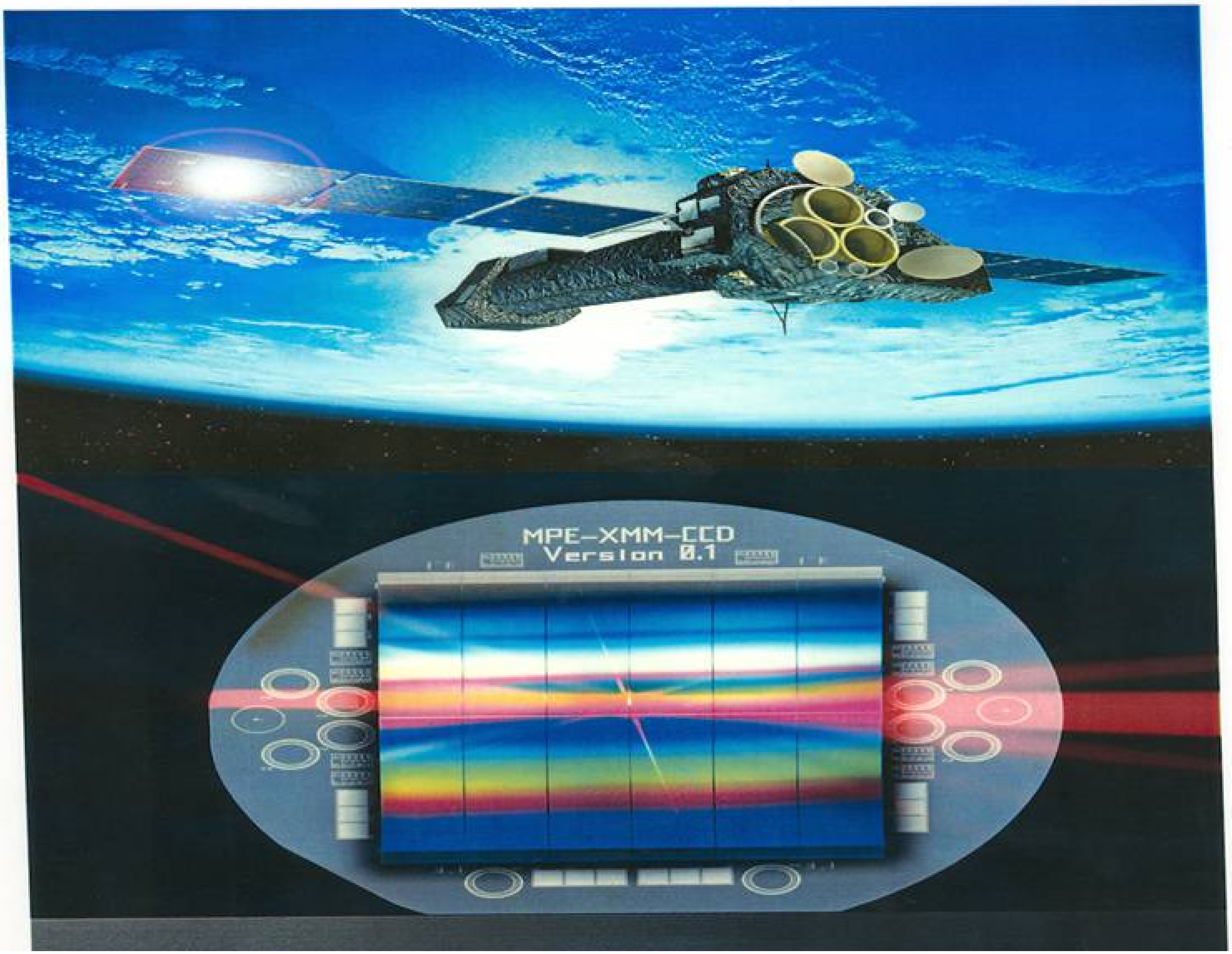


Very high rate applications

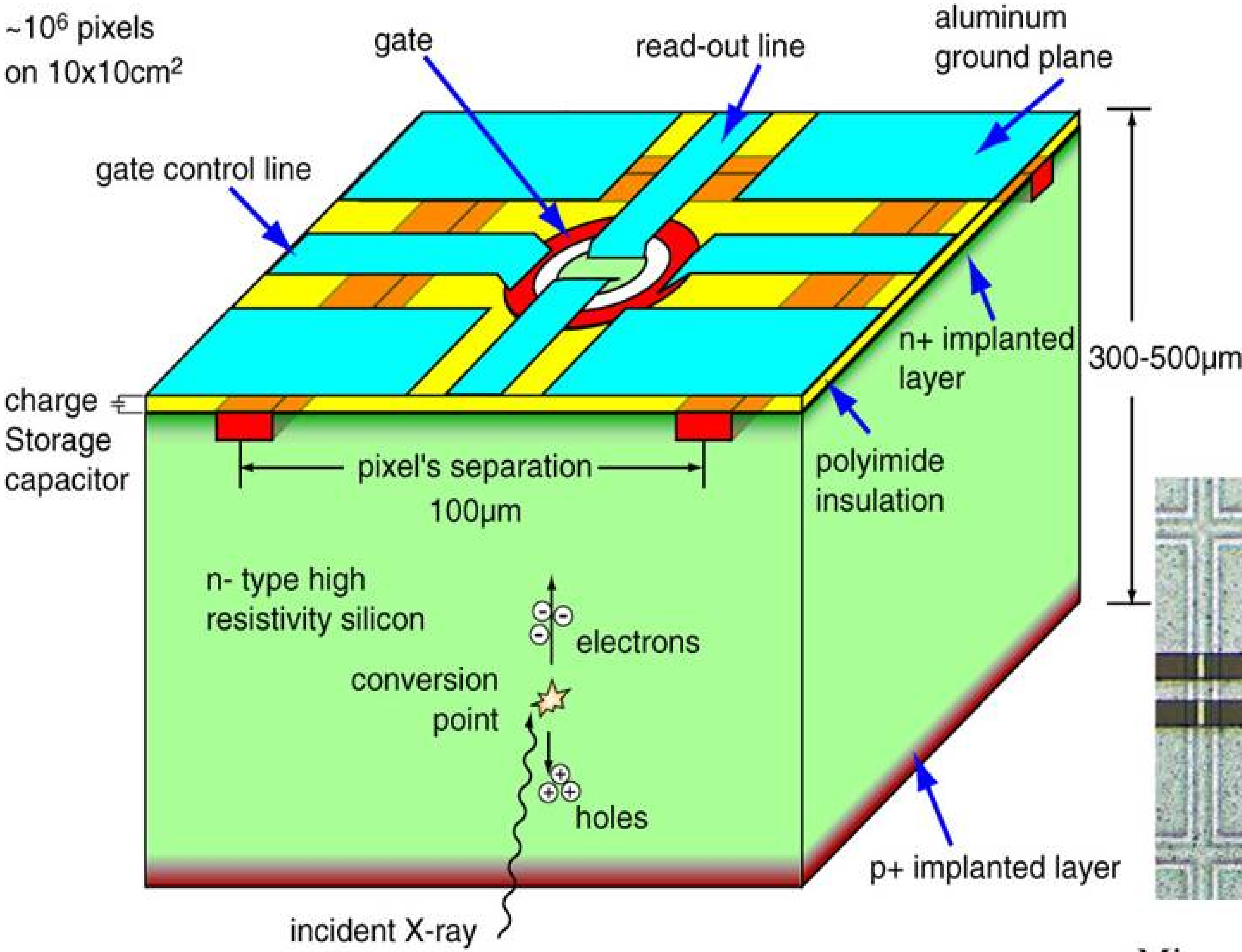


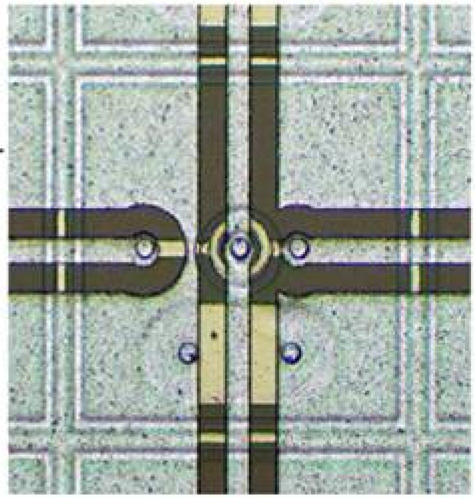
Fully depleted CCD

The pn-CCD on the XMM Observatory



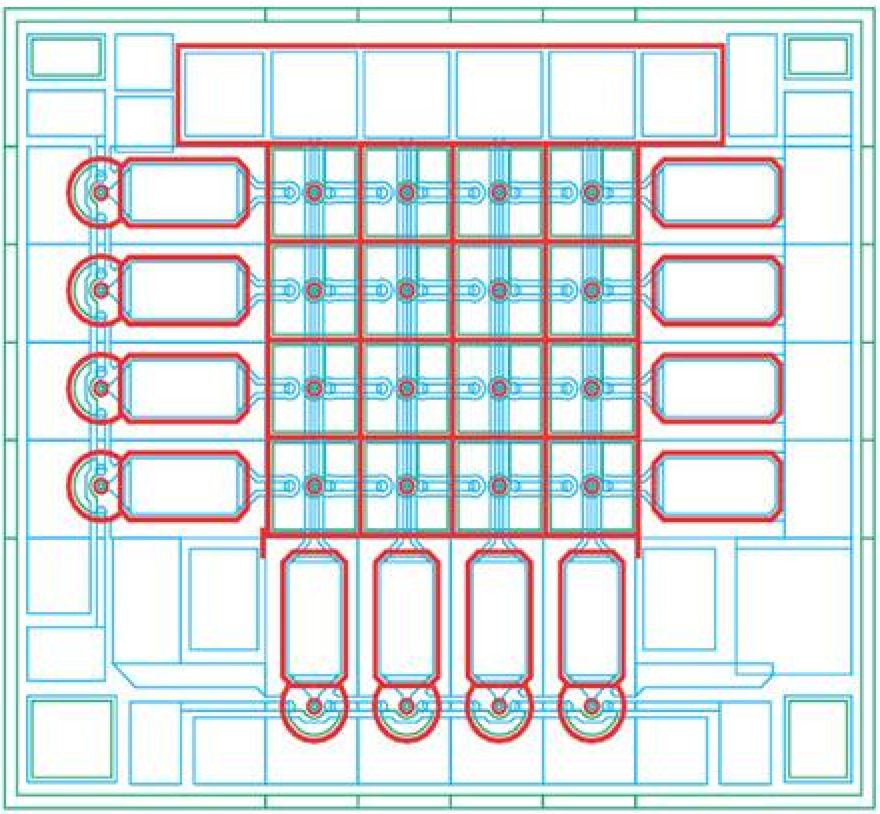
3D View of an X-ray Active Matrix Pixel

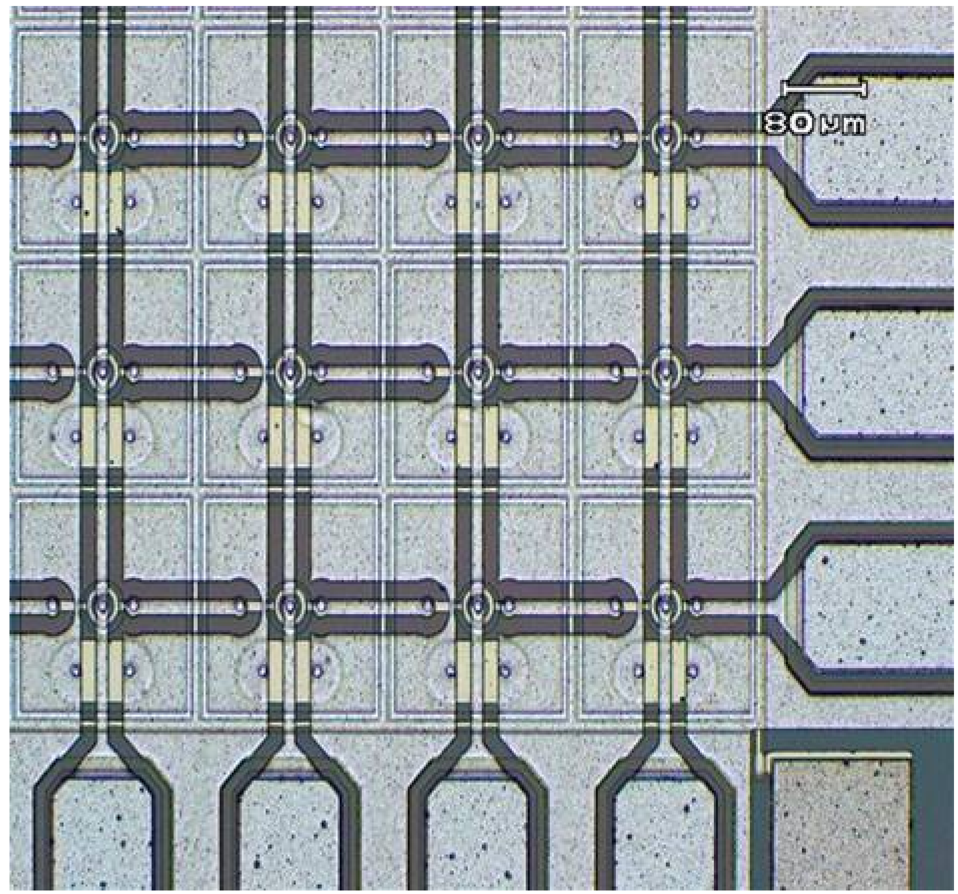




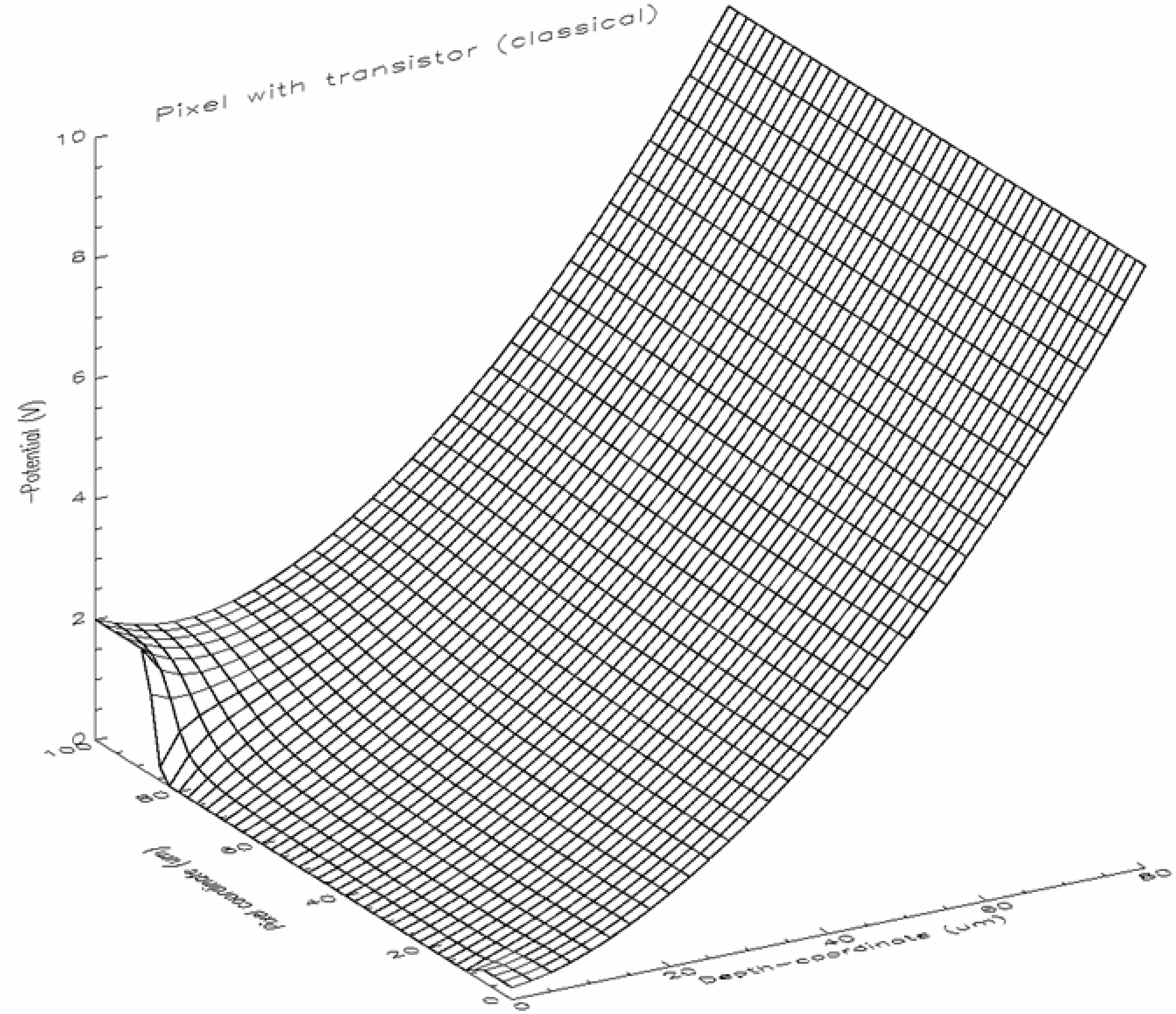
Microphotograph of a pixel

Planar view of XAPMS

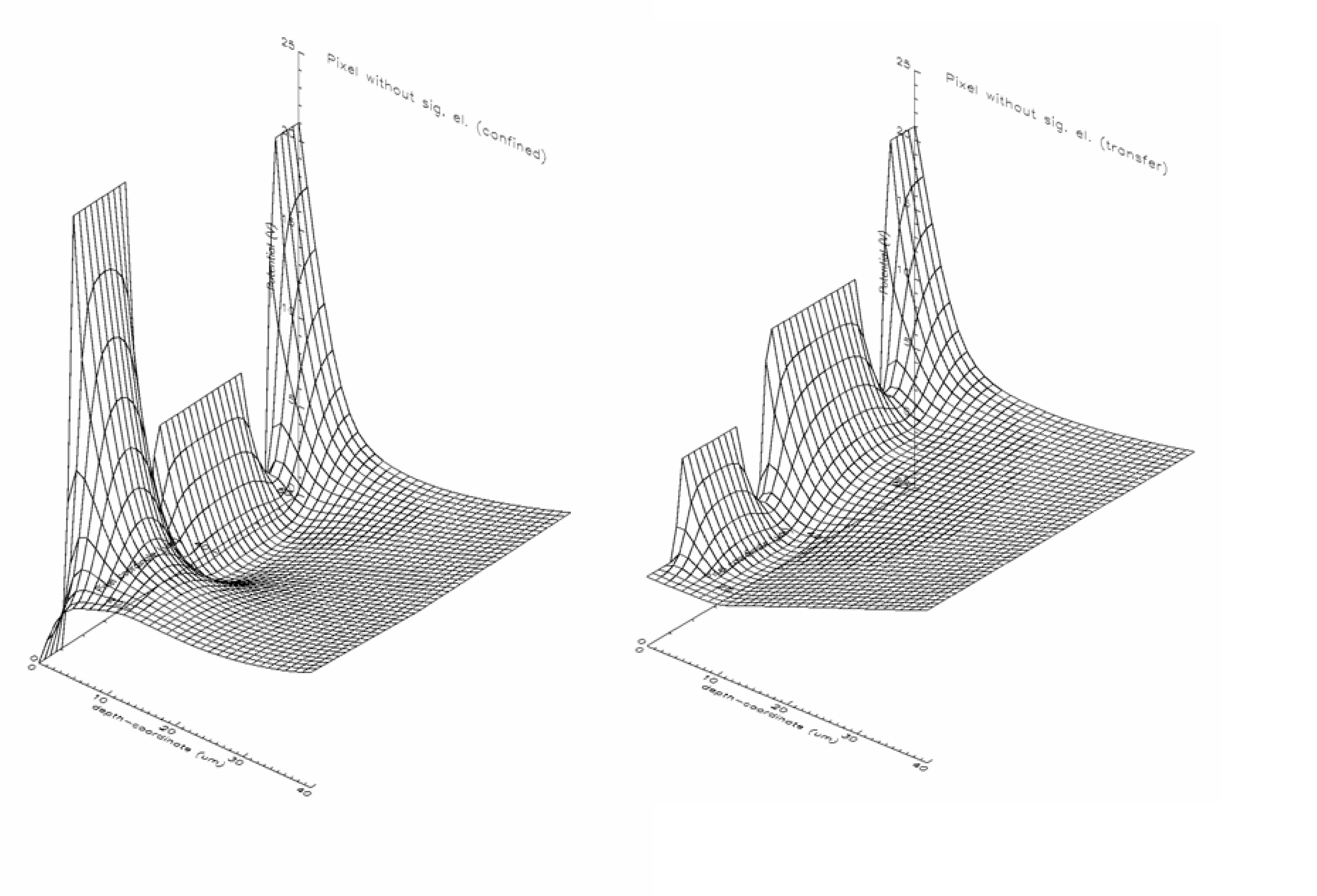


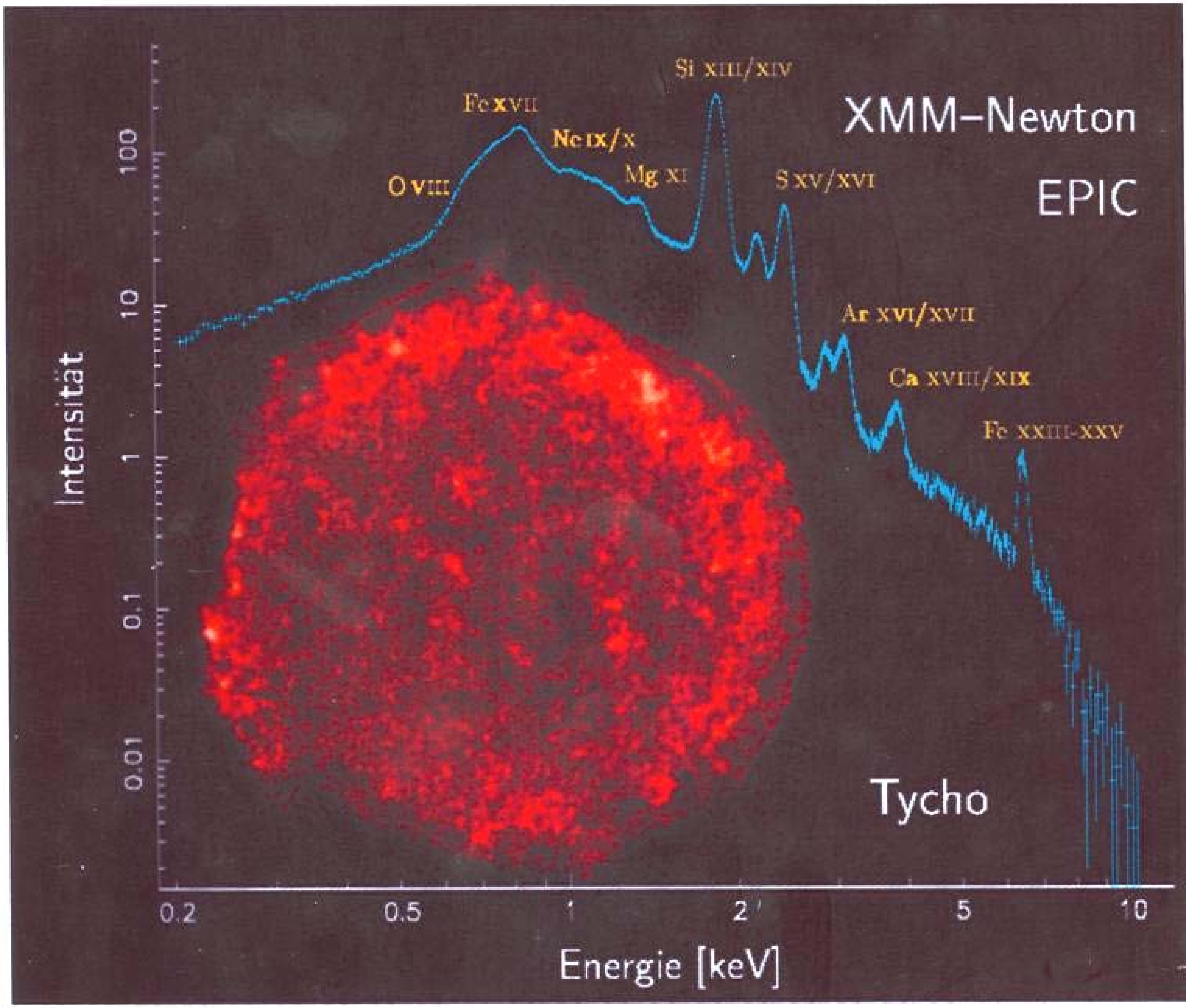


Electric field in classical XAPMS



Electric field in new XAMPS &FDCCD





XMM–Newton
EPIC
Tycho
Si XIII/XIV
Fe XVII
Ne IX/X
Mg XI
O VIII
S XV/XVI
Ar XVI/XVII
Ca XVIII/XIX
Fe XXIII-XXV
Intensität
100
10
1
0.1
0.01
0.2
0.5
1
2
5
10
Energie [keV]

XMM-NEWTON

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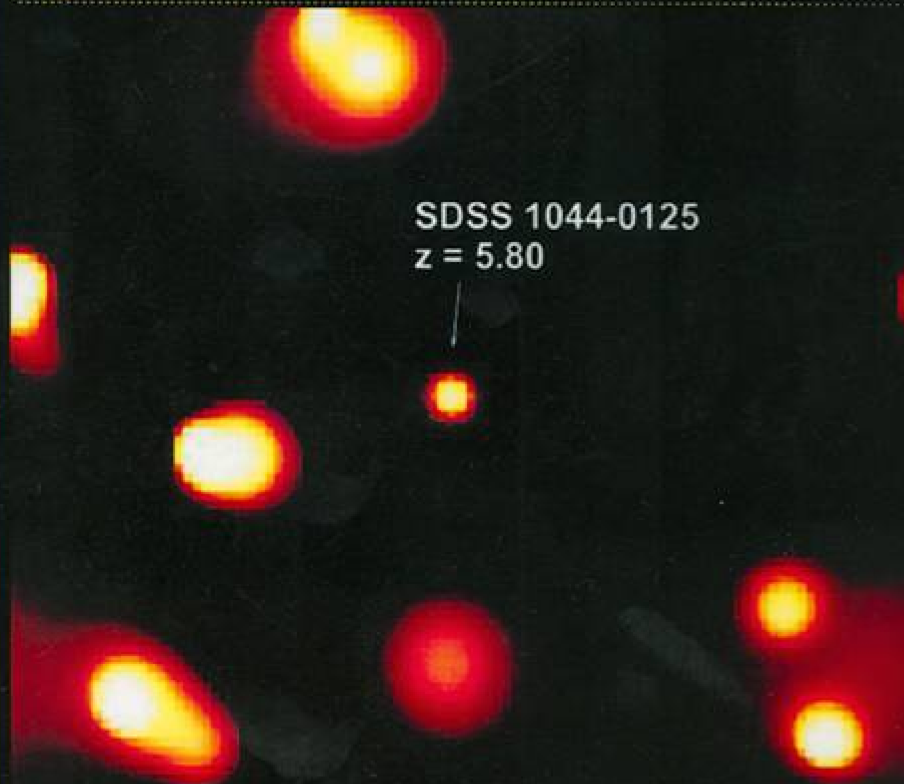
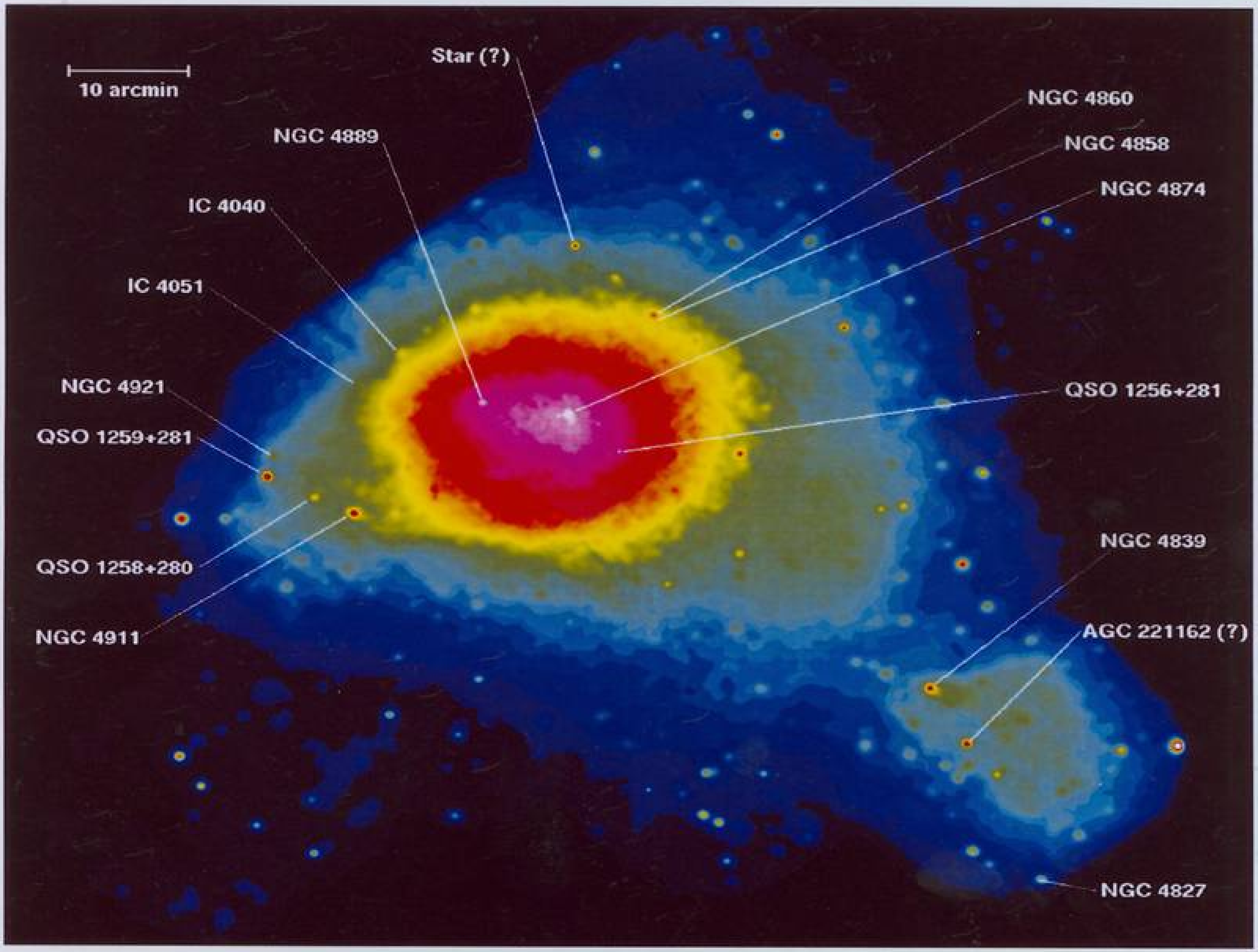


EPIC-pn image (0.5-2.0keV) of SDSS 1044-0125

European Space Agency

in the energy band from 0.3 to 2.0 keV (U. G. Briel et al.)
surface brightness distribution after smoothing with 2-dim Gaussians



Planar technology vs lithium

Performance of SD^3

	SDD	Si(Li)	SD^3
FWHM @ 1-10 kcps	142 – 147 eV @ - 10°C 138 – 142 eV @ - 20°C	130 eV @ LN	127 – 135 eV @ - 10°C 124 – 132 eV @ - 20°C
FWHM @ 100 kcps	180 eV	-----	170 eV
P/B-Ratio	3.000 – 5.000	10.000 – 20.000	6.000 – 7.000 homogenously
Active Area	5 and 10 mm^2	10 (30, 80) mm^2	5 mm^2 → 10 - 30 mm^2
Sensitive Thickness	0.3 mm	4 mm	0.3 mm → 0.5 mm
Stability	good radiation hard	sometimes critical	op.stab. improved rad.hard. improved

Summary & Conclusions

- Silicon is the ideal detection medium from 1 eV to 10keV of photon energy
- The progress in production technology make silicon detectors almost room temperature detectors
- The silicon prepared by standard CMOS processing technology may in a near future replace several traditional detector structures