The pnCCD camera on XMM-Newton

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

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The pnCCD sensors on XMM-Newton

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

+ input for this talk from Michael Smith

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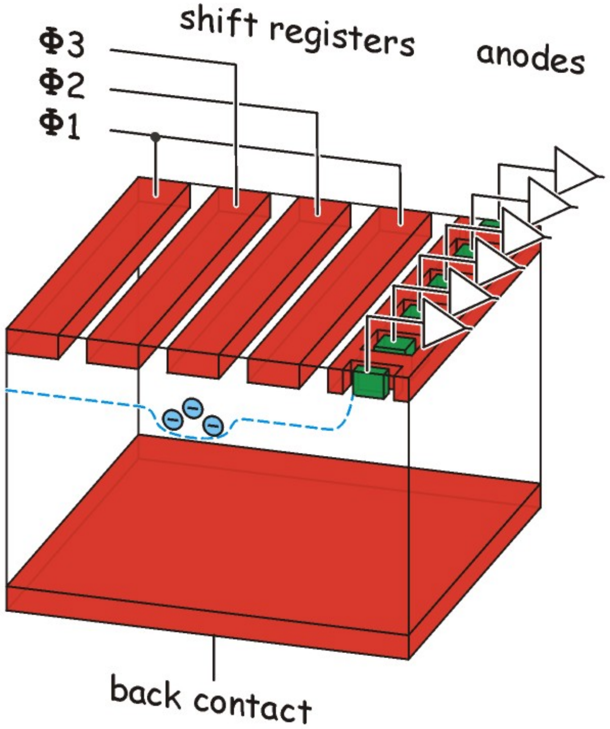
Outline

1. The first years of the pnCCD detector development
   - the very first steps, the concept and the idea behind
   - upgrading the fabrication technology
2. Performance in space
   - stability, radiation hardness
   - micrometeorite impact
   - X-ray background
3. Lessons learnt during the camera development
4. The use of pnCCDs today
   - in basic and applied science
   - in industry

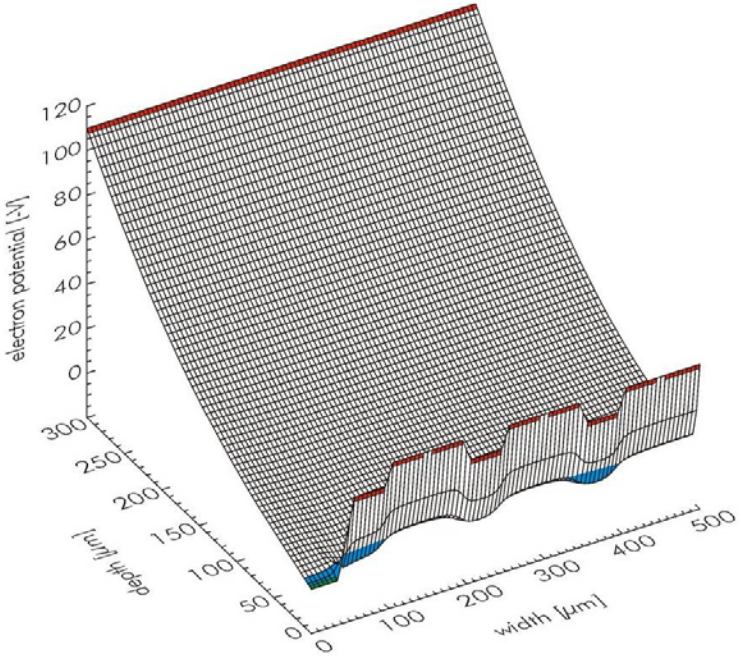
pnCCD basics

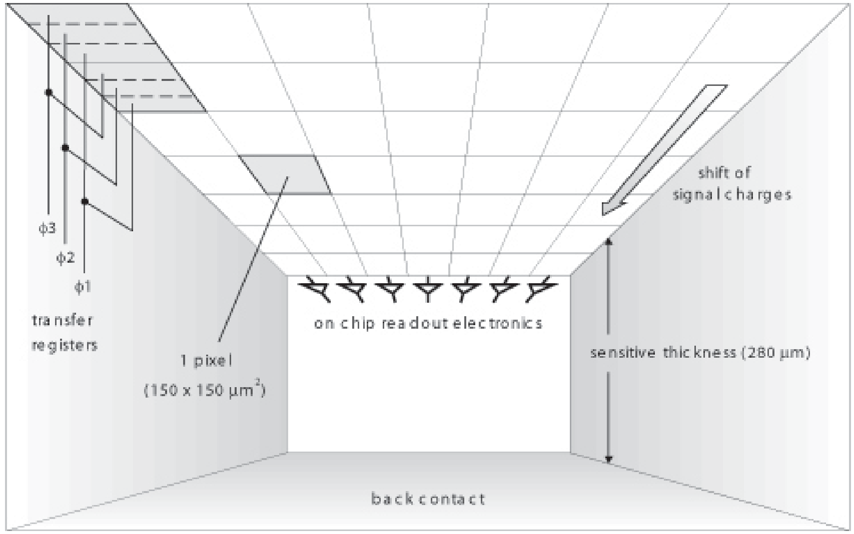
Emilio Gatti
(1922 – 2016)

Pavel Rehak
(1945 – 2009)

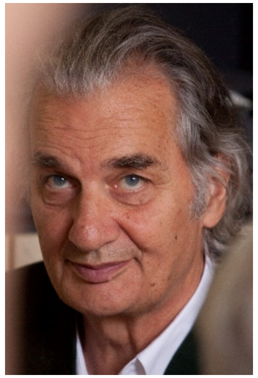


- full depletion (50 µm to 500 µm)
- back side illumination
- radiation hardness
- high readout speed
- pixel sizes from 30 µm to 500 µm
- charge handling: more than 10^6 e^-/pixel
- high quantum efficiency up to 20 keV





Josef Kemmer
1935 - 2007



Gerhard Lutz
1939 - 2017

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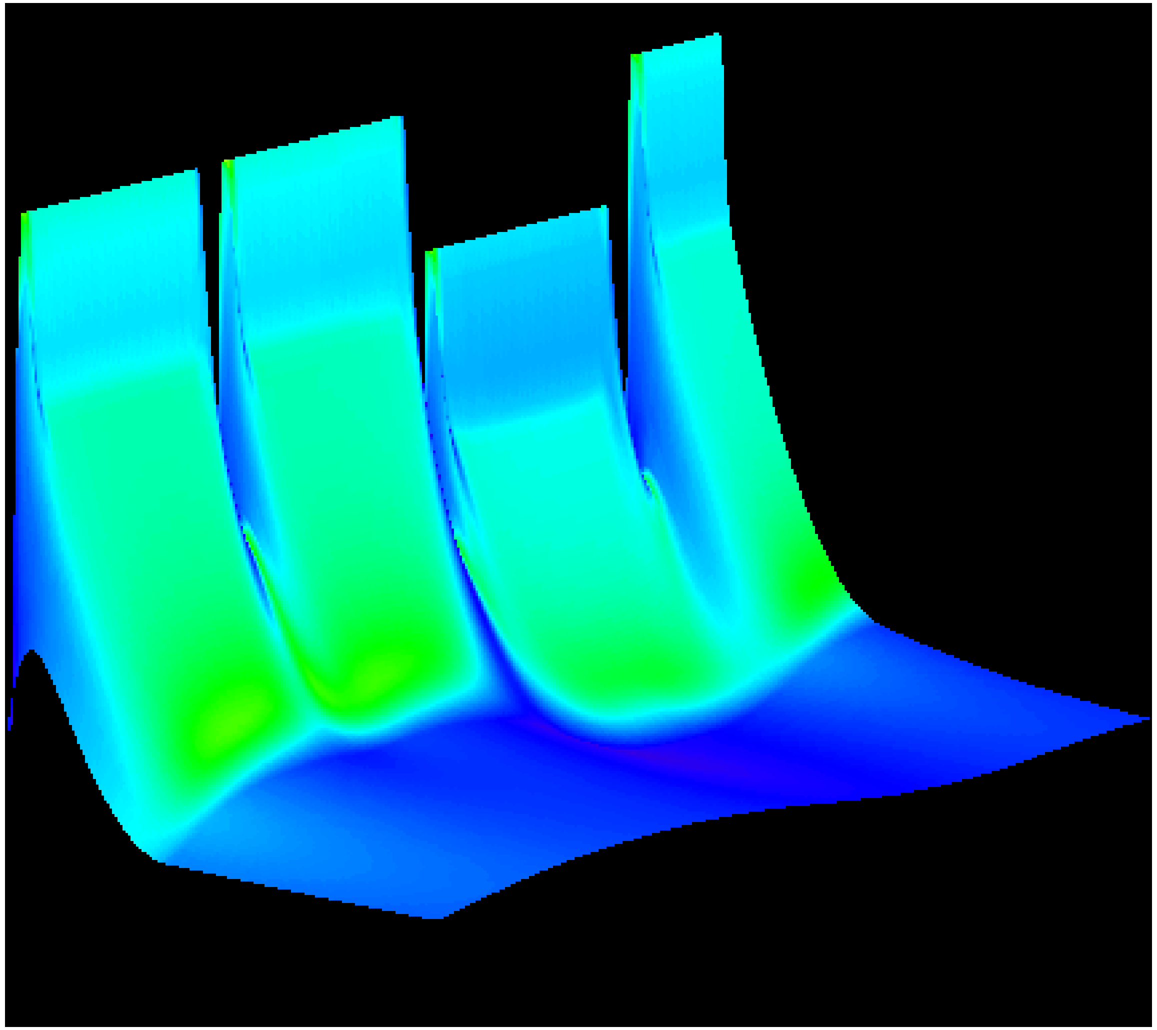
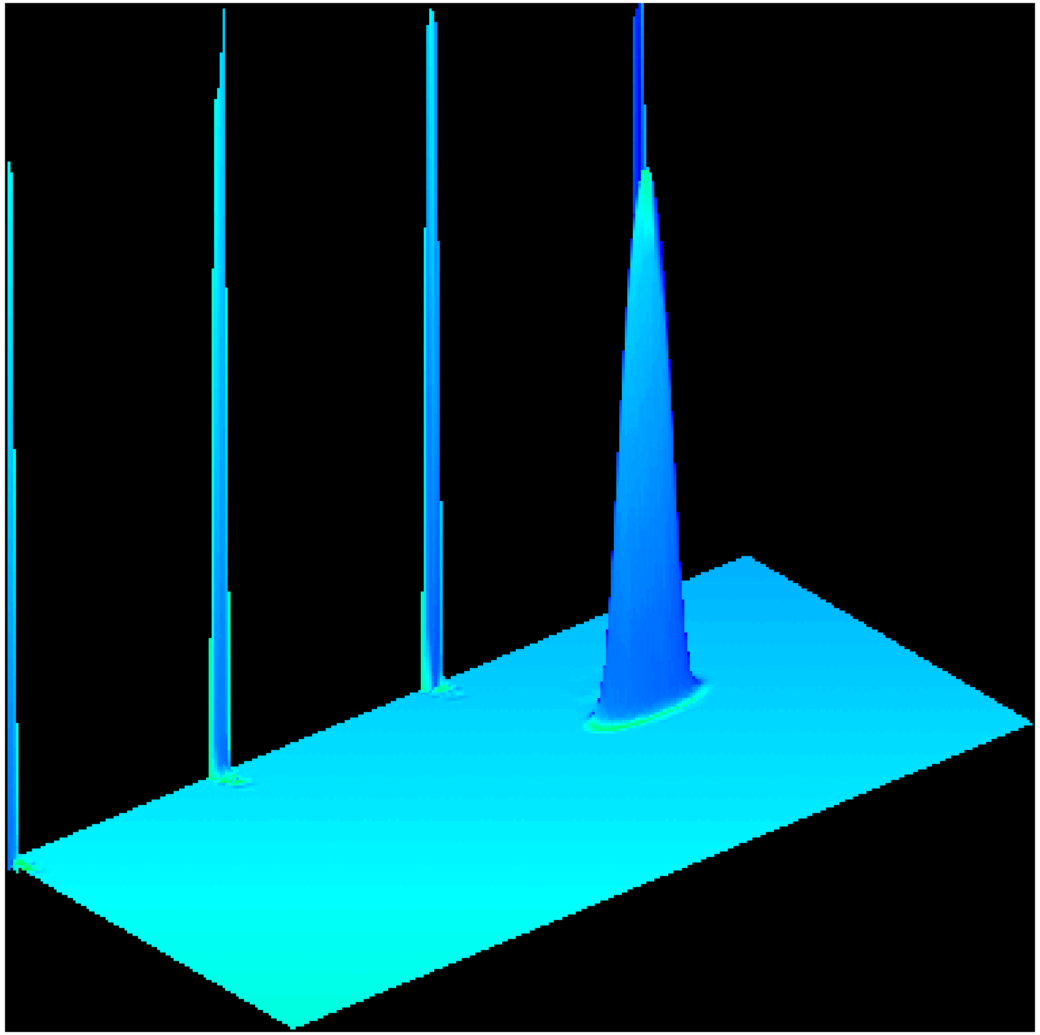
pnCCD operation





pnCCD development history

First publication about the possibility of making pnCCDs:	≈ 1983
Start of my PhD on the development of pnCCDs for HEP:	≈ 1984
Proposal of pnCCDs for X-ray astronomy	≈ 1987
First operating devices (1 x 52 pixel):	≈ 1987
Invention of the fully parallel readout and associated ASIC:	≈ 1990
Electro Optical Breadboard (EOBB) Phase (64 x 200 pixel):	≈ 1992
Move semiconductor laboratory from Garching to Munich-Pasing	≈ 1991 – 1992
Camera development	≈ 1993 – 1999
First flight type pnCCDs with moderate performance:	≈ 1995 – 1996
Production of the flight and flight spare devices:	≈ 1997 – 1998
Delivery to ESA/ESTEC:	≈ 1998/1999

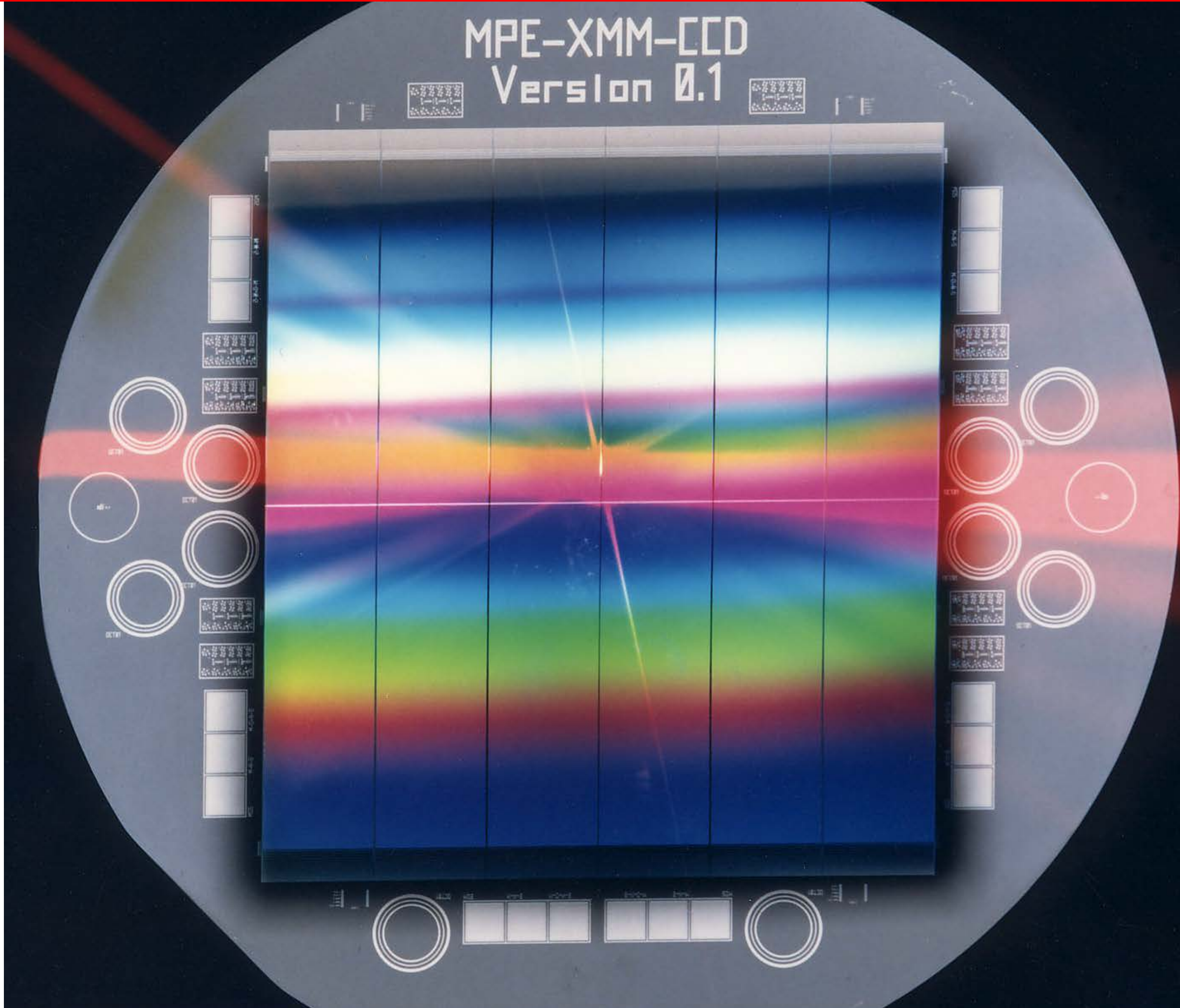
detector fabrication around 1980 @ the TUM

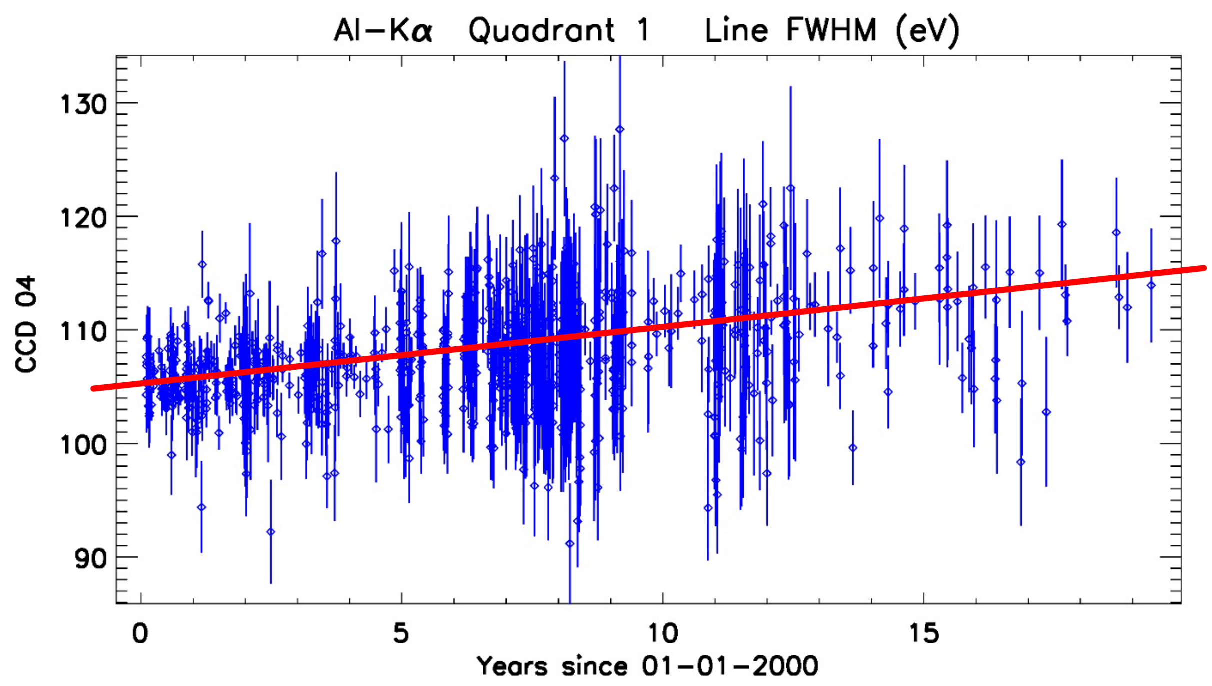
detector fabrication around 1995 @ the MPI HLL in Munich – Pasing where all XMM flight sensors were processed

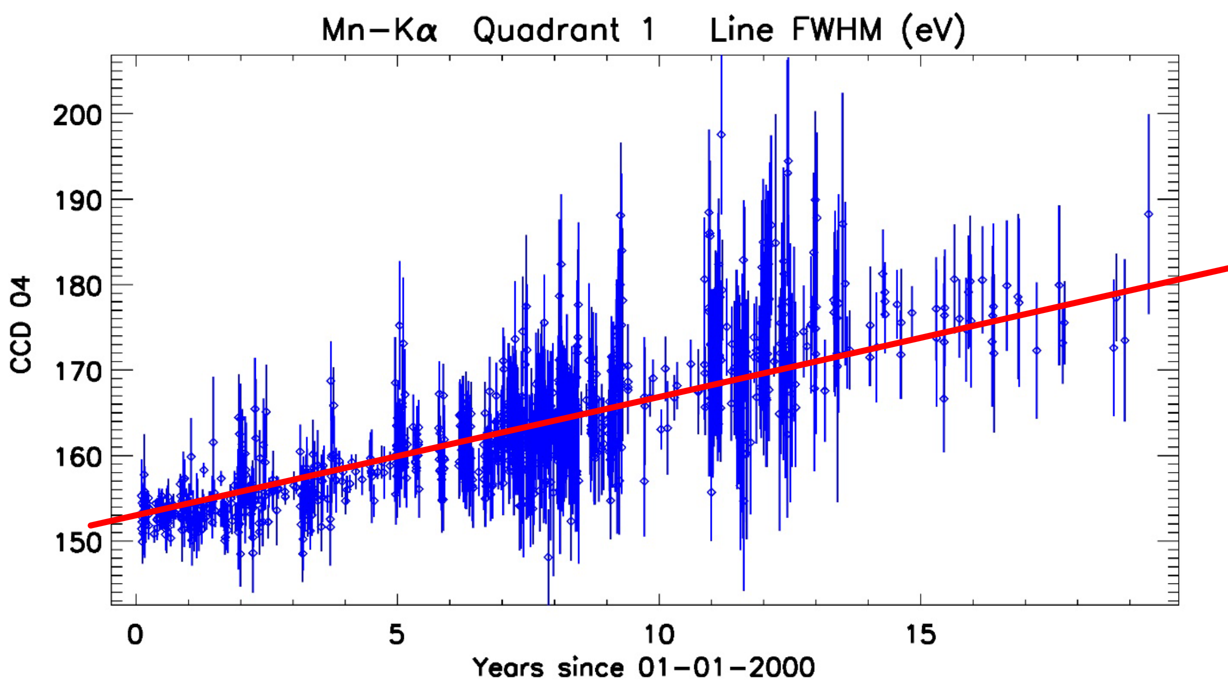
The XMM EPIC pnCCD

- Device parameter
  - ▷ Monolithic array of 12 pnCCDs
  - ▷ 200 x 64 pixels each
  - ▷ pixel size: 150 x 150 μm^2
  - ▷ 6 x 6 cm^2 sensitive area
  - ▷ 4“ wafer
  - ▷ 280 μm thick
  - ▷ Common entrance window

- Performance
  - ▷ 5 e- ENC
  - ▷ Readout time 4.5 ms
  - ▷ Integration time 100 ms
  - ▷ Energy resolution 153 eV FWHM @ 5.9 keV



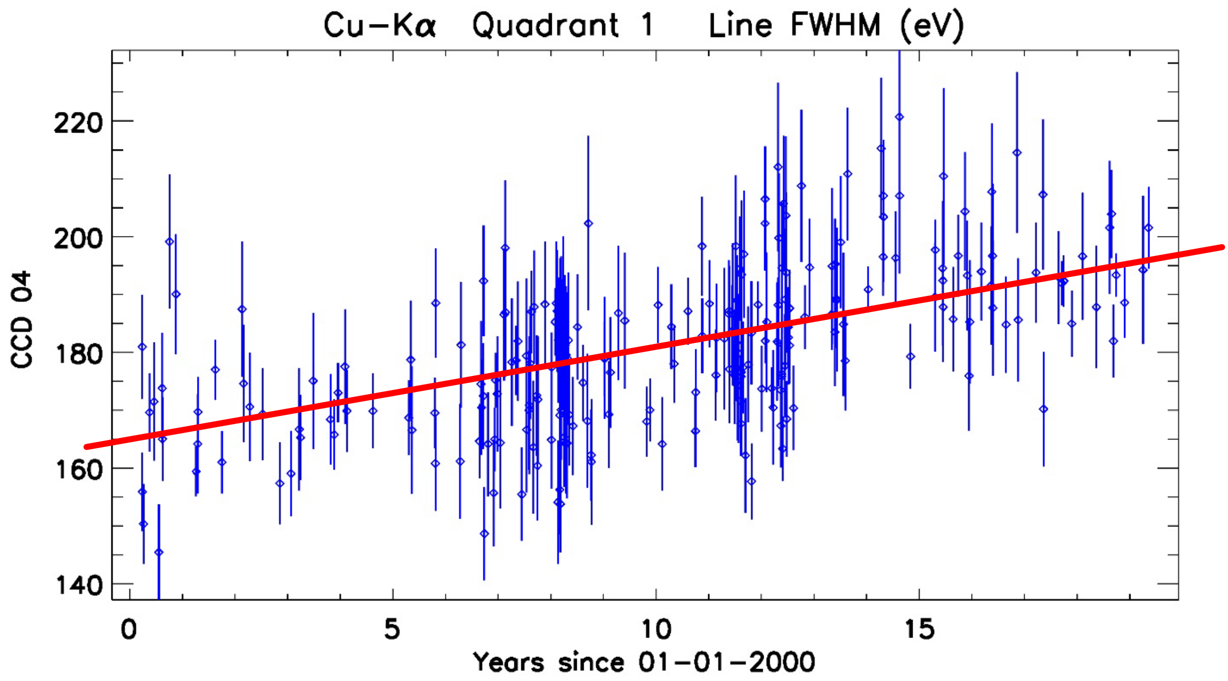




ΔE_{deg} = 115 eV -105 eV = 10 eV in 20 years @ 1.5 keV

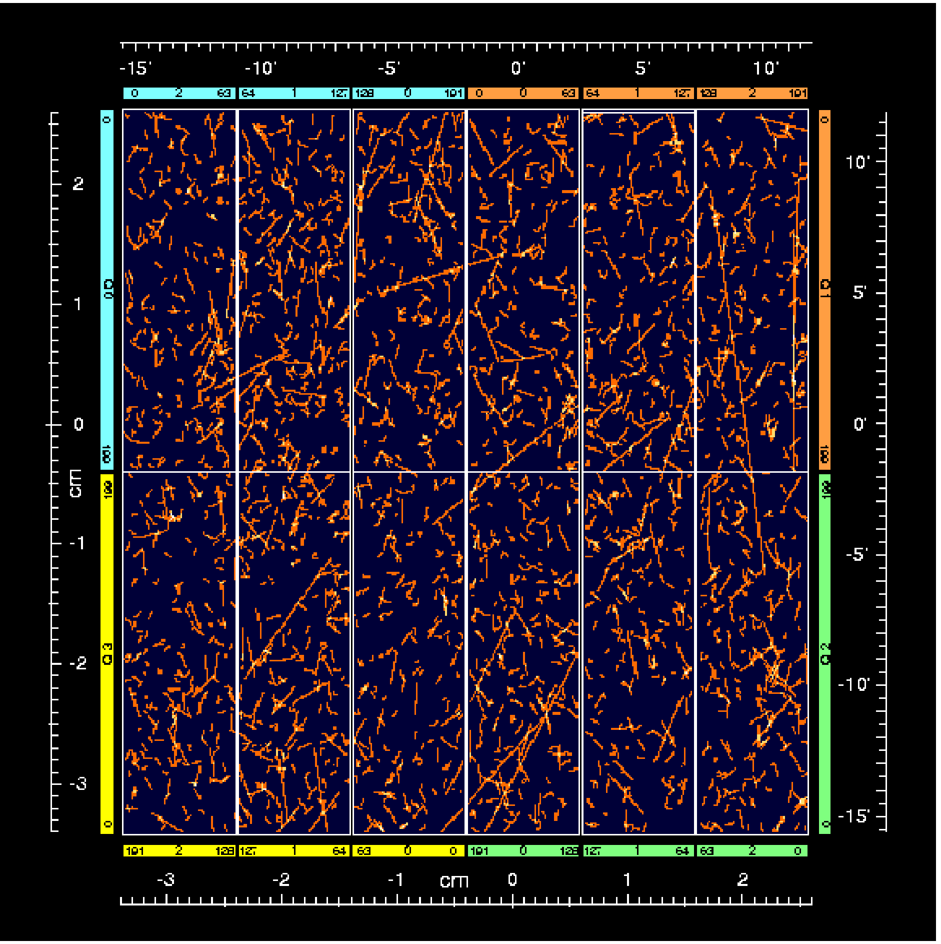
ΔE_{deg} = 180 eV -153 eV = 27 eV in 20 years @ 5.9 keV

ΔE_{deg} = 195 eV -165 eV = 30 eV in 20 years @ 8.05 keV

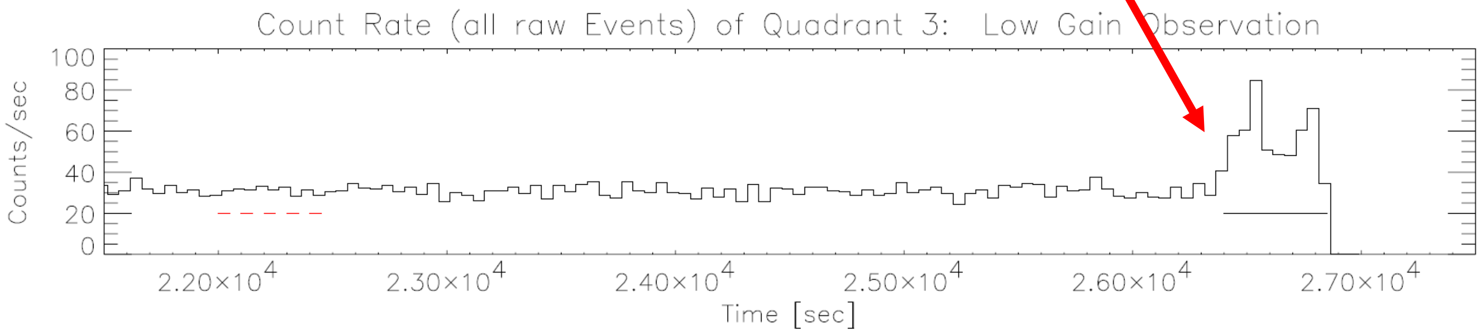


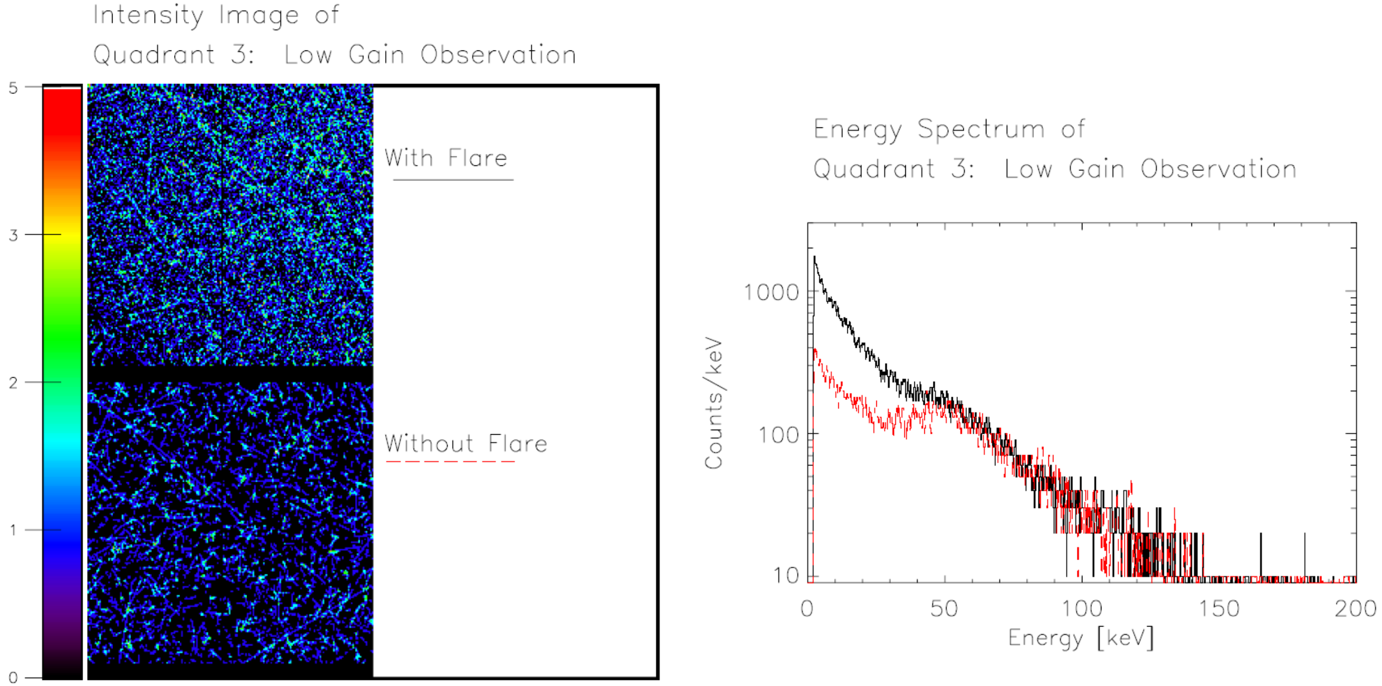
proton flare measured during flight

minimum ionizing particles



start of a proton flare during flight





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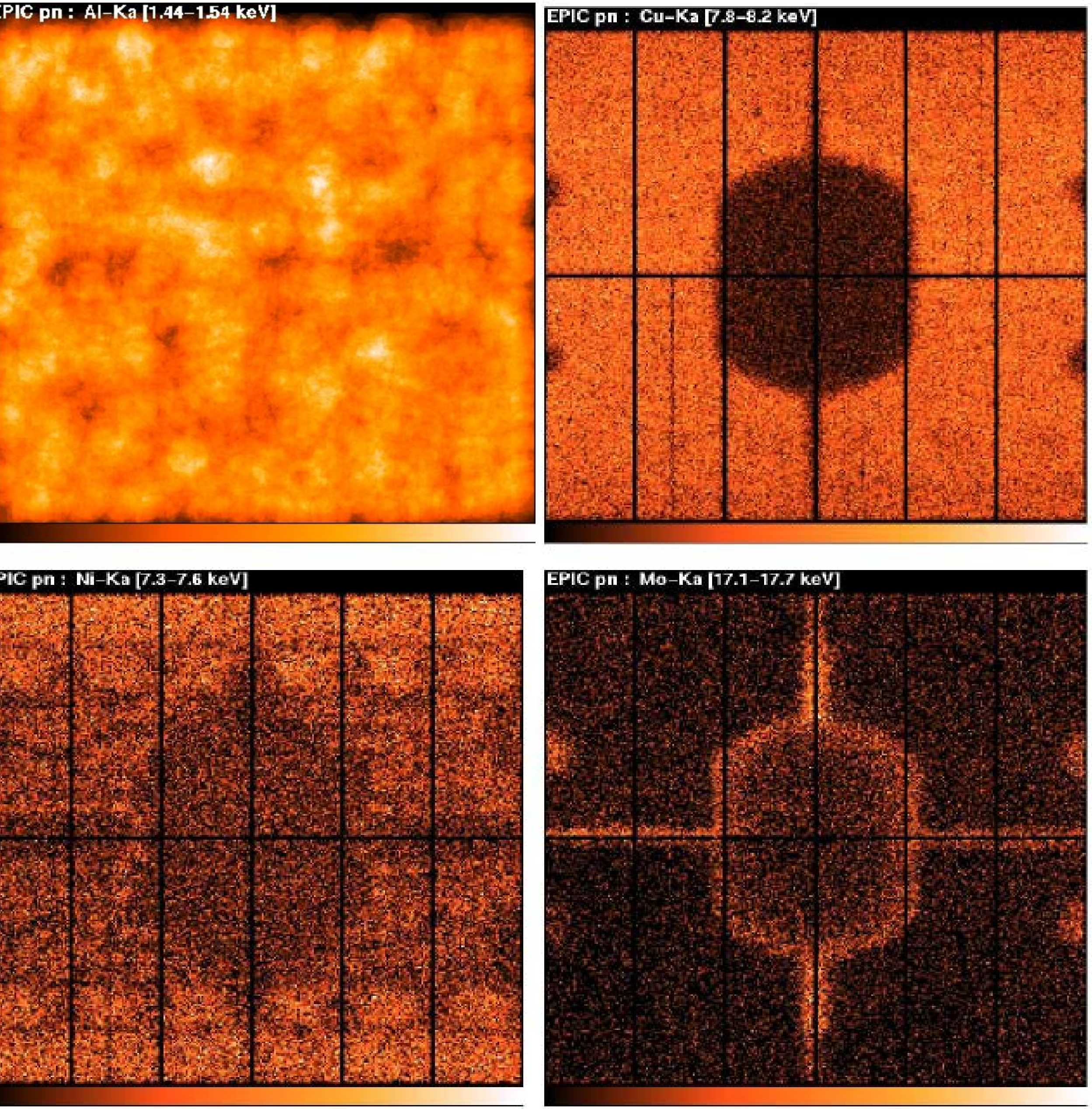
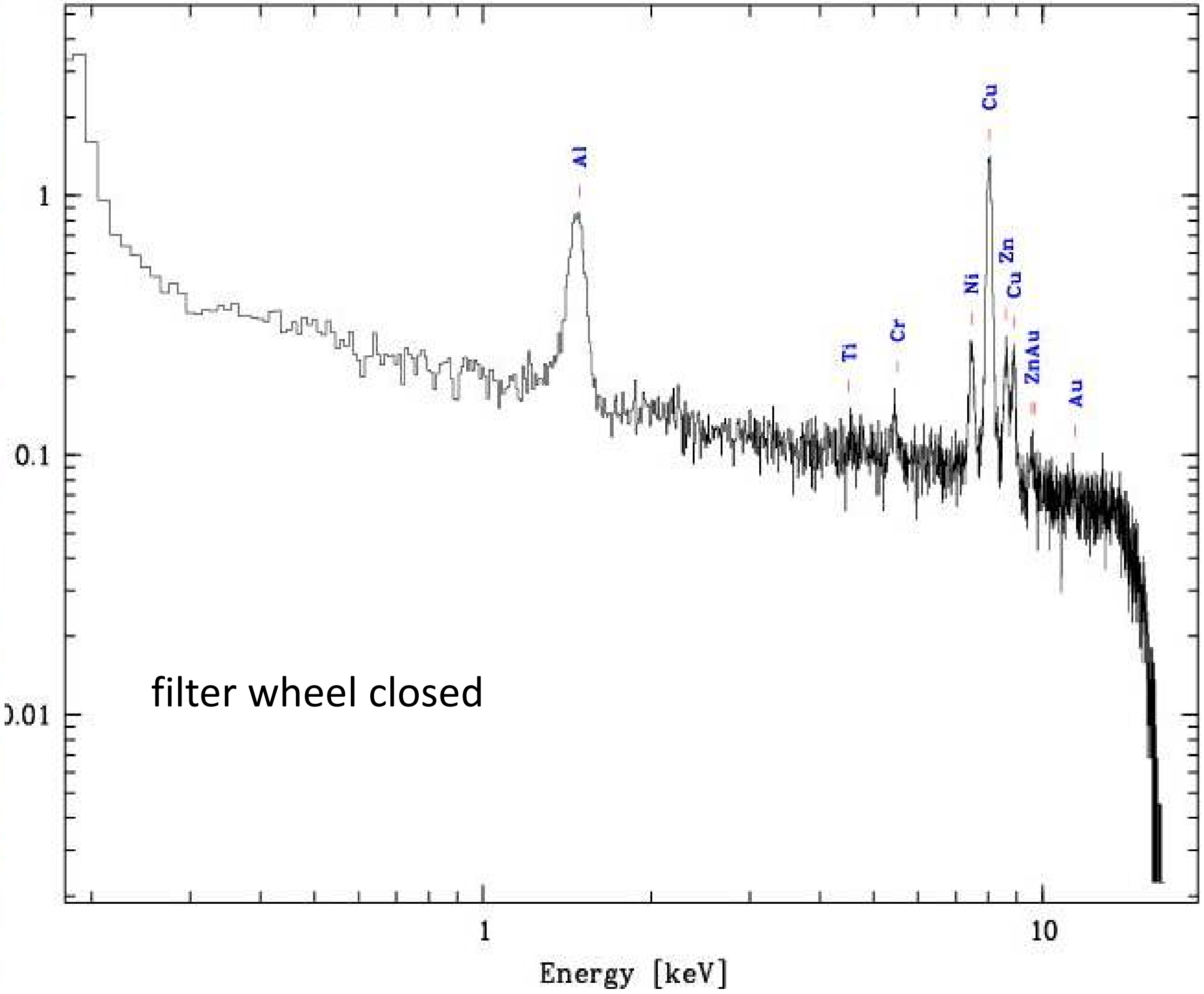
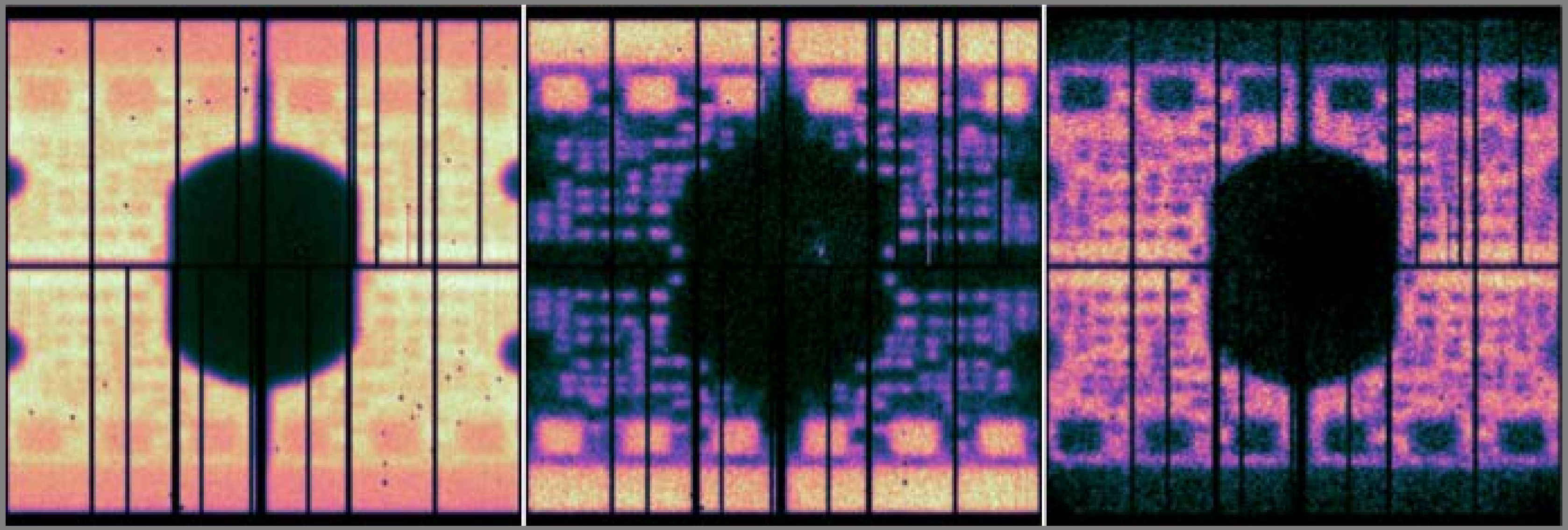
calibration source ^{55}Fe with Mn_Kα and Mn_Kβ X-rays
half life time: $\tau_{½}$ = 2.5 years

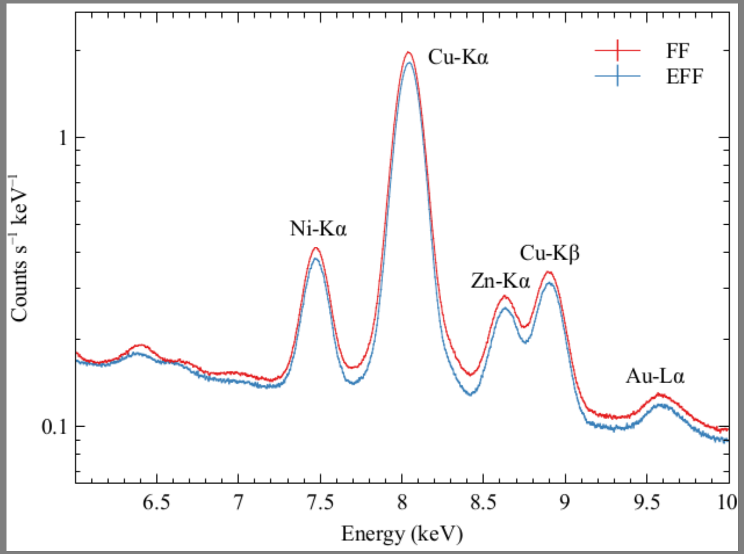




The instrumental Cu lines - energy calibration at 6-9 keV



Cu-Kα 7.805-8.285 keV Ni-Kα 7.280-7.680 keV Cu-Kβ/Zn-Kα 8.455-9.075 keV

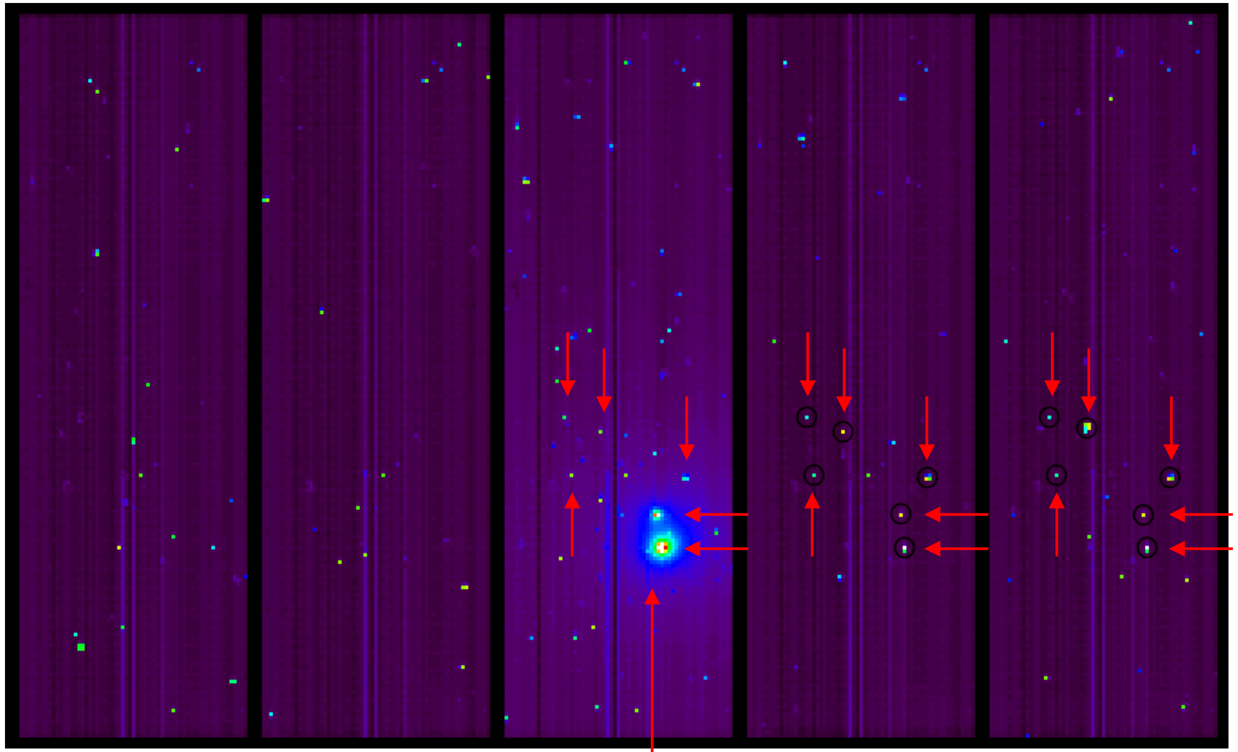


64 Ms of astrophysical data

Sanders et al. 2019, A&A in press

Analysis of scatter particles: CCD damage

impact of particles → 17 bright pixels at 6 locations



Frame # 11777 11778 11779 11780 11781

(44ms/frame)

light flash

A&A 375, L5–L8 (2001)
DOI: 10.1051/0004-6361:20010916

Astronomy & Astrophysics

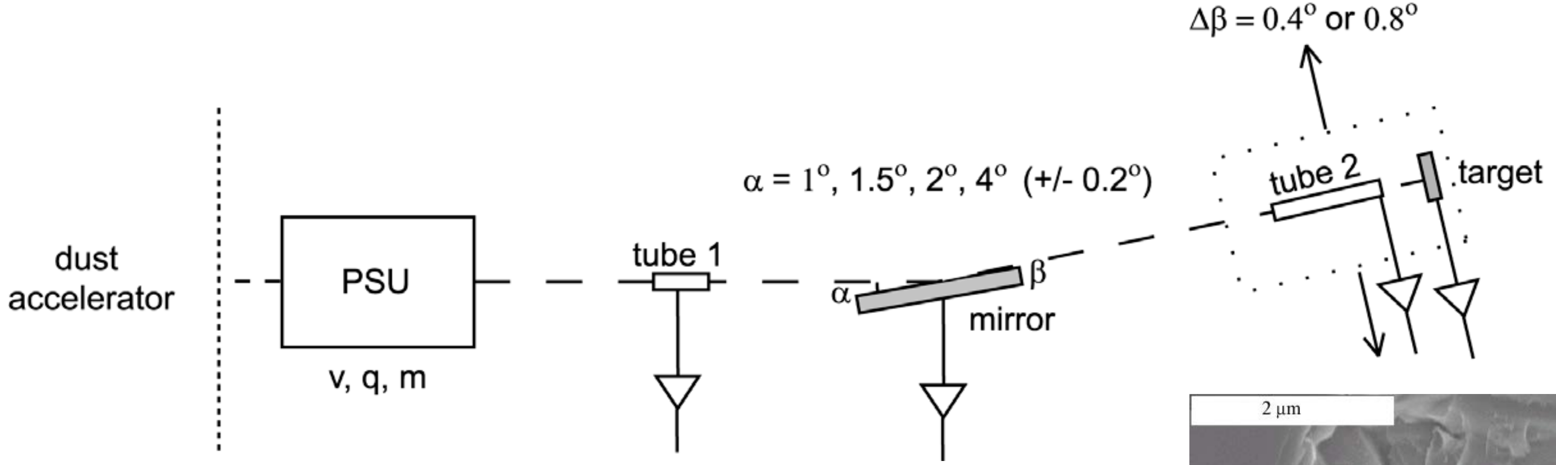
Evidence for micrometeoroid damage in the pn-CCD camera system aboard XMM-Newton

L. Strüder[1], B. Aschenbach[1], H. Bräuninger[1], G. Drolshagen[3], J. Englhauser[1], R. Hartmann[2], G. Hartner[1], P. Holl[2], J. Kemmer[2], N. Meidinger[1], M. Stübig[4], and J. Trümper[1]

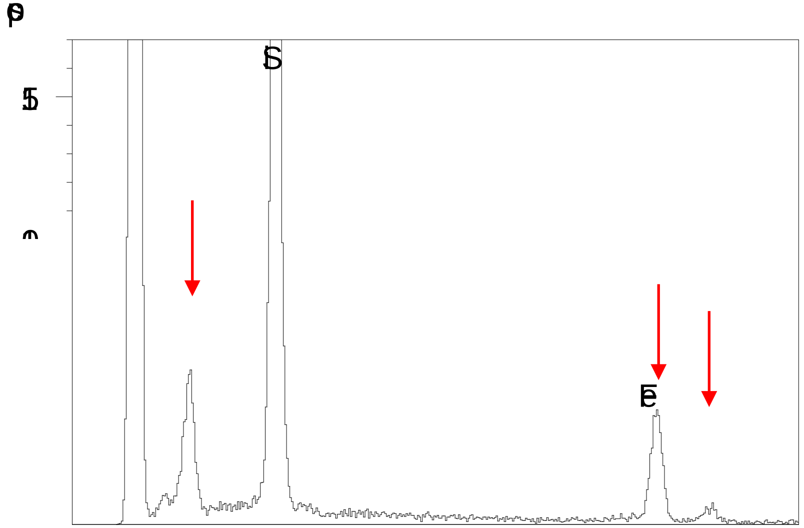
Experimental Verification of a Micrometeoroid Damage in the PN-CCD Camera System aboard XMM-Newton

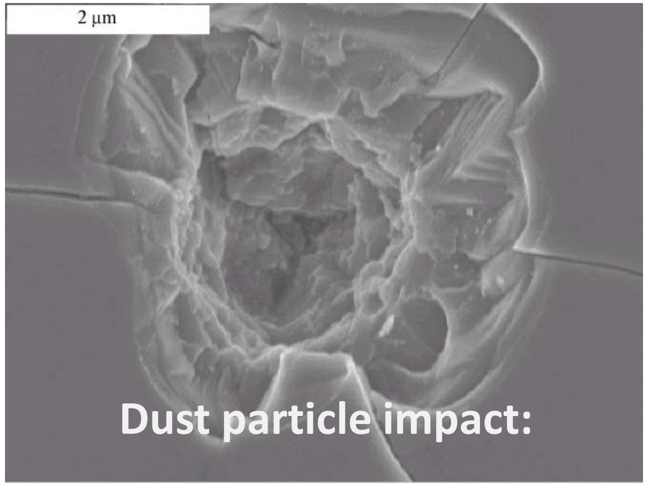
Norbert Meidinger[a,*], Bernd Aschenbach[a], Heinrich Bräuninger[a], Gerhard Drolshagen[b], Jakob Englhauser[a], Robert Hartmann[c], Gisela Hartner[a], Ralf Srama[d], Lothar Strüder[a], Martin Stübig[d], and Joachim Trümper[a]

Analysis of scatter particles: SEM, XRF

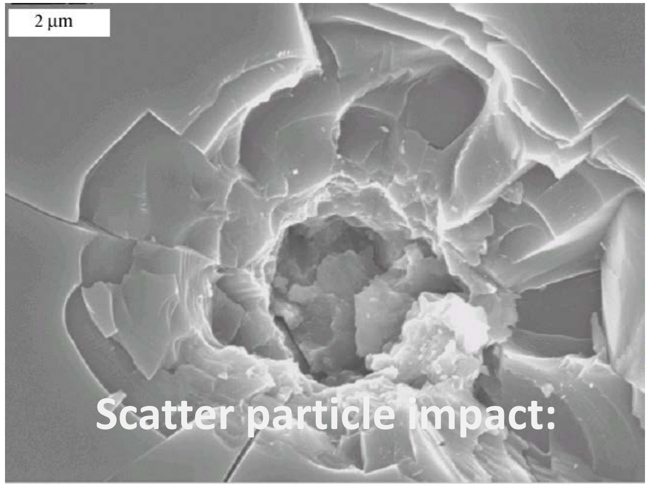


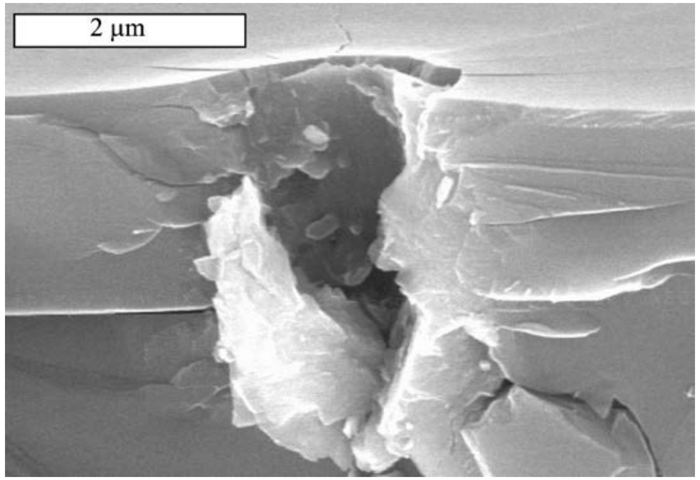
Dust particle impact:





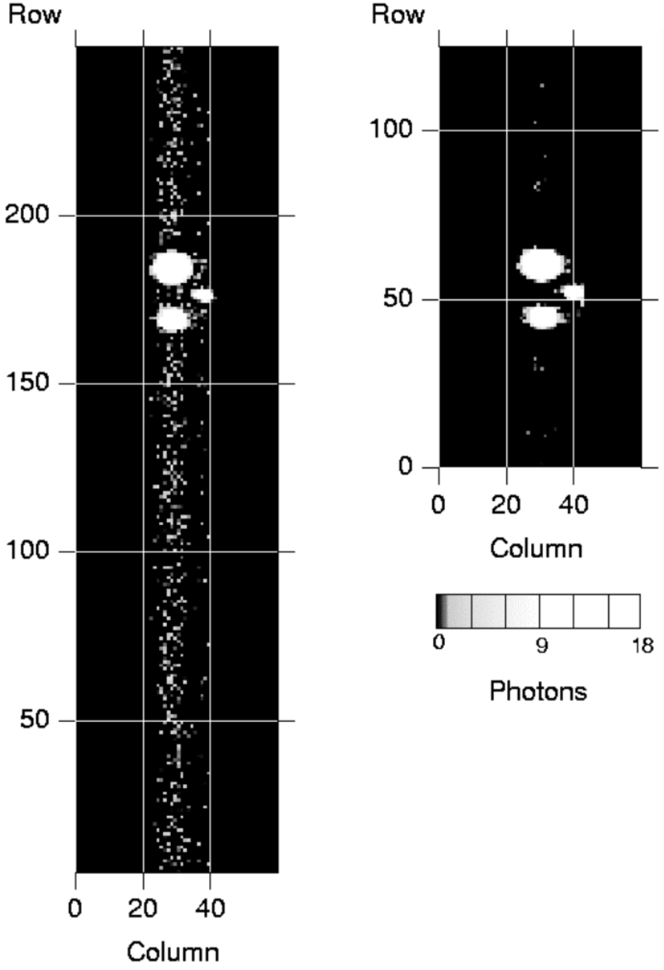
- craters in silicon: 0.1 µm and 10 µm
- similar for dust and scatter particles



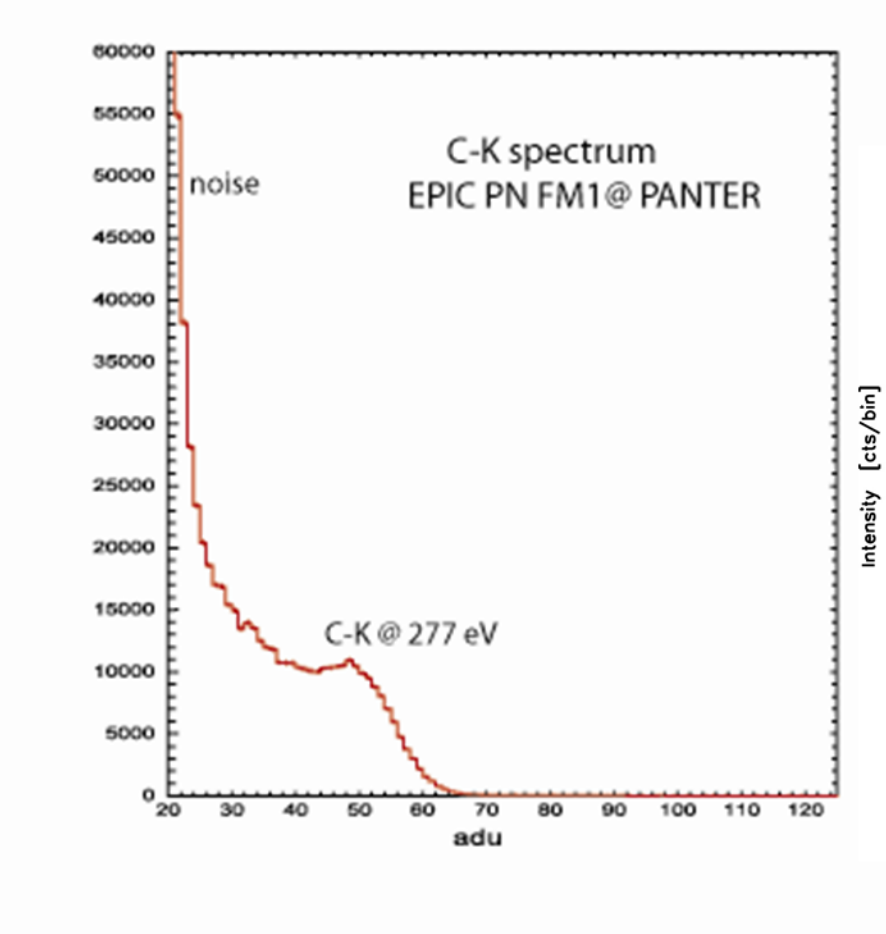


Examples of improvements of pnCCDs (e.g. for eROSITA and others, fabricated in 2008)

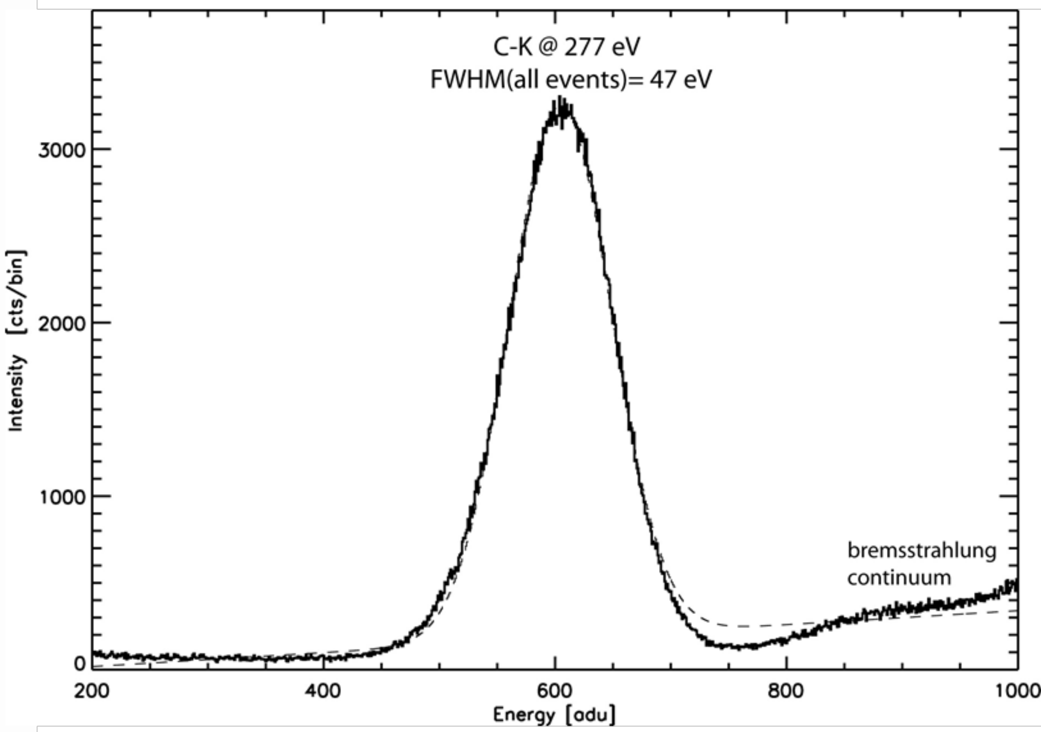
Transition to FS mode
out-of-time events

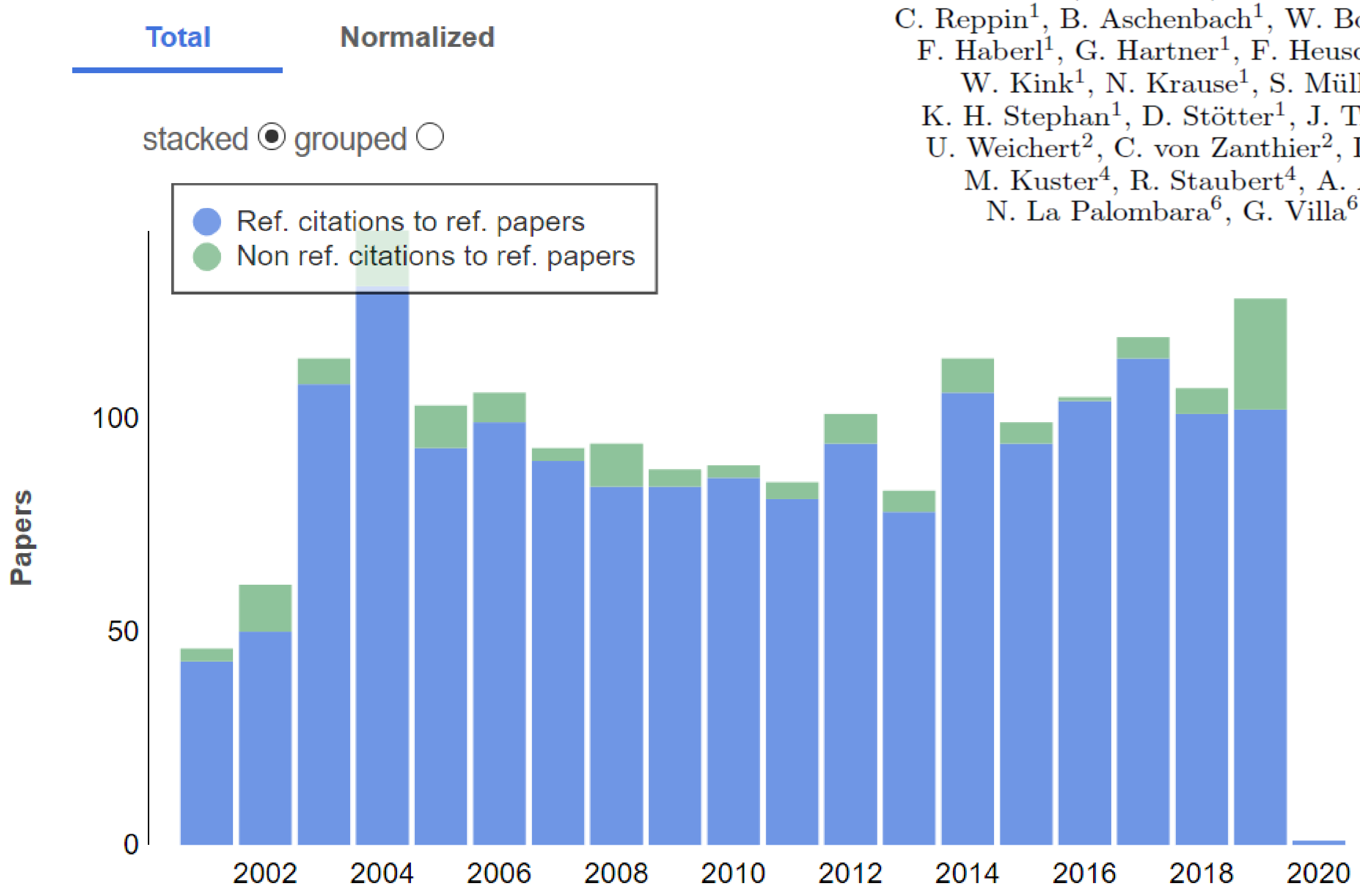


low energy performance: left: C-K @ 277 eV of XMM



right: for eROSITA

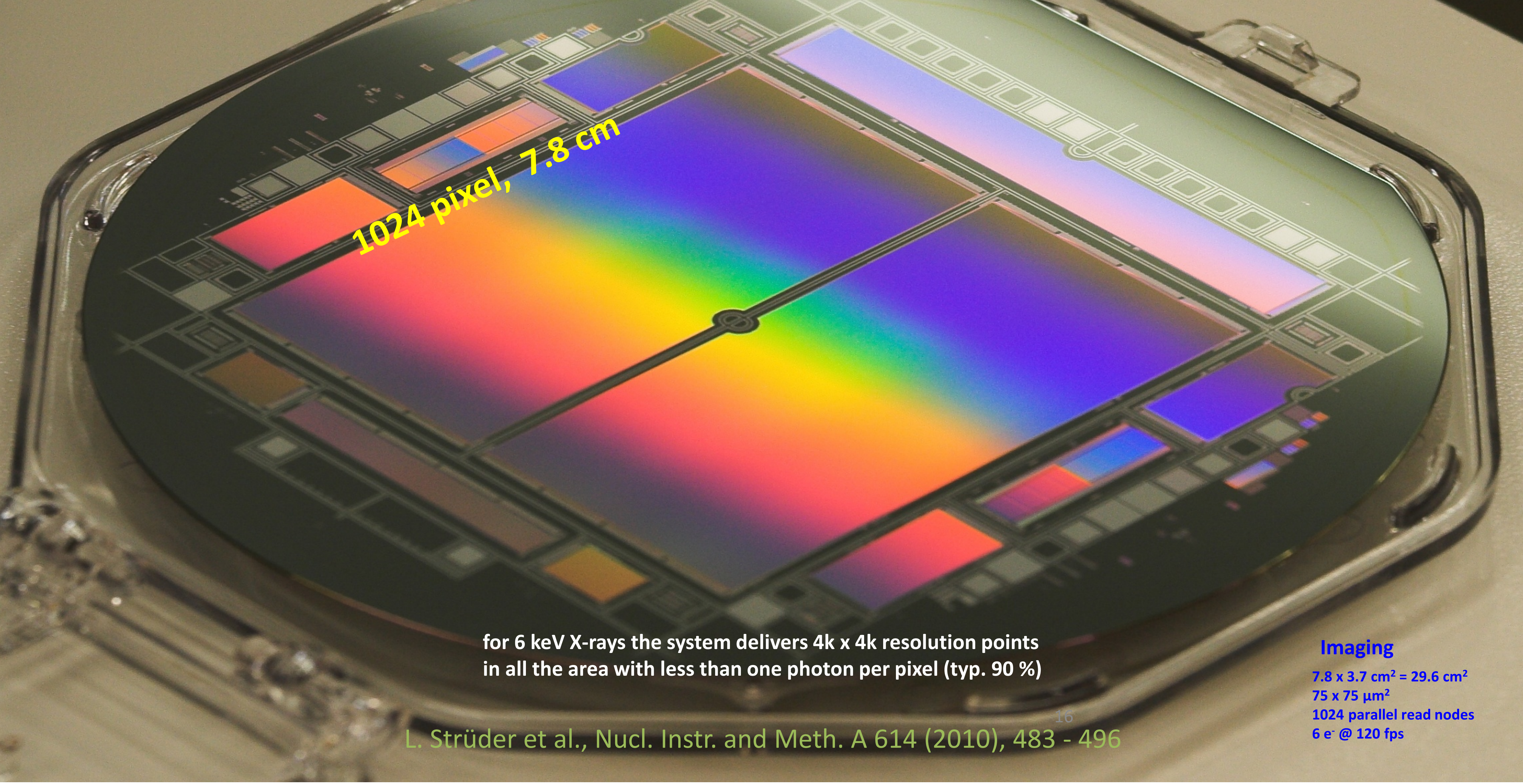




Astronomy & Astrophysics

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]



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 %)

L. Strüder et al., Nucl. Instr. and Meth. A 614 (2010), 483 - 496

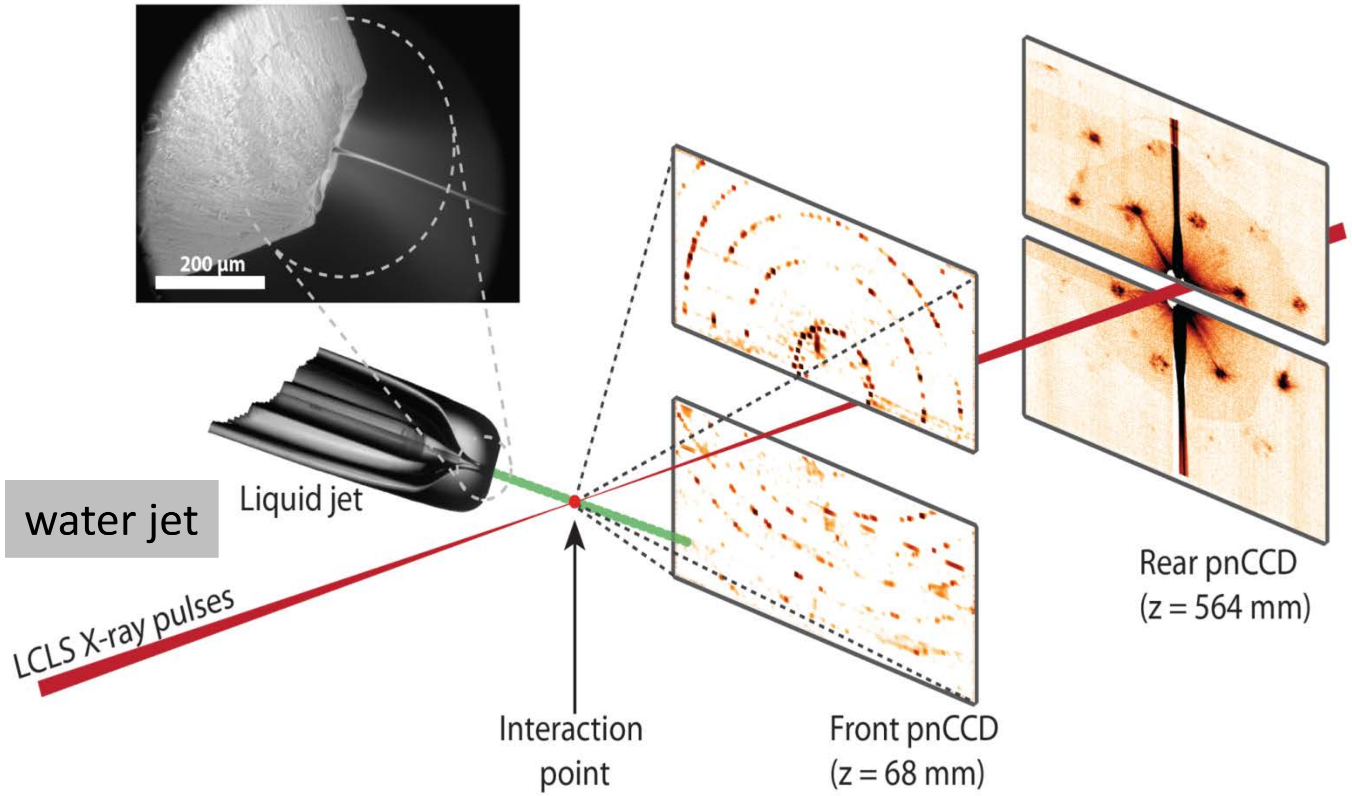
Imaging

7.8 x 3.7 cm^2 = 29.6 cm^2
75 x 75 μm^2
1024 parallel read nodes
6 e^- @ 120 fps

Imaging of X-rays at LCLS

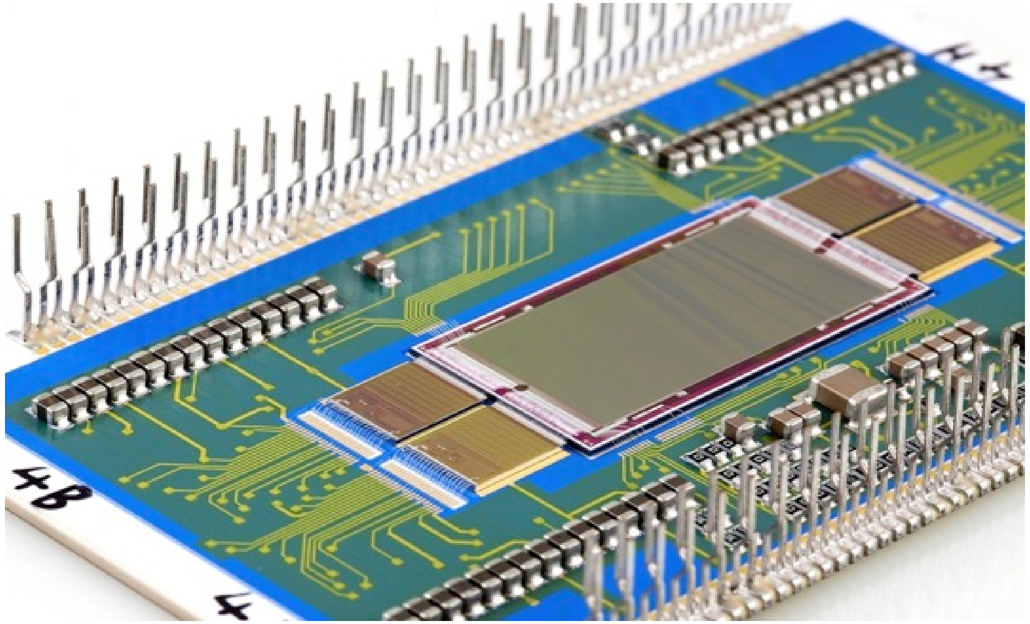
Henry Chapman et al., Nature **470**, 73–77 (03 February 2011)

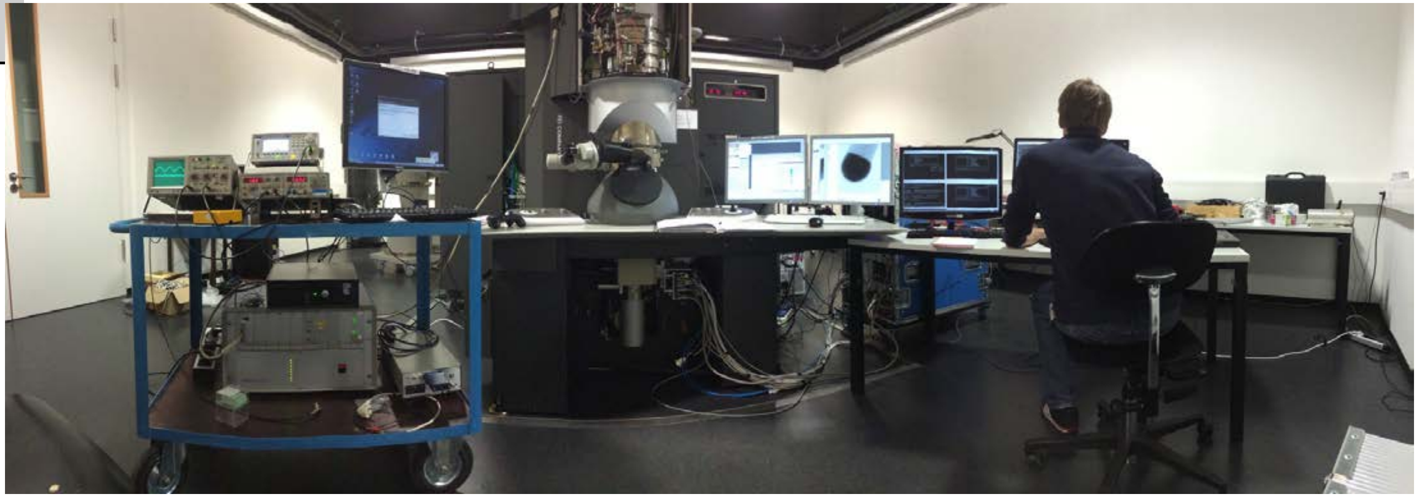
PS1: Membrane protein photosystem I,
typical size: 100 nm to 1 µm



Specifications of the pnCCD for transmission electron microscopy

Parameter	Value
Image Area	12.7 mm × 12.7 mm
Physical pixel size	48 µm × 48 µm
Detector Thickness	450 µm
Number of Pixel	264 × 264
Number of Subpixel	1,320 × 1,320
Full Frame Rate	2,000 fps
Windowing/Binning Modes	e.g. 7,500 fps (4-fold binning)
Pixel-Readout Rate	70 Mega Pixel / s
Radiation Hardness	$> 10^{18}$ e^-/cm^2 (300 keV)
Readout-Noise (RMS) (low gain)	ENC < 30 e^- / Pixel @ 1000 Hz, 120 keV
Working Energy Range	10 keV – 300 keV (and above)



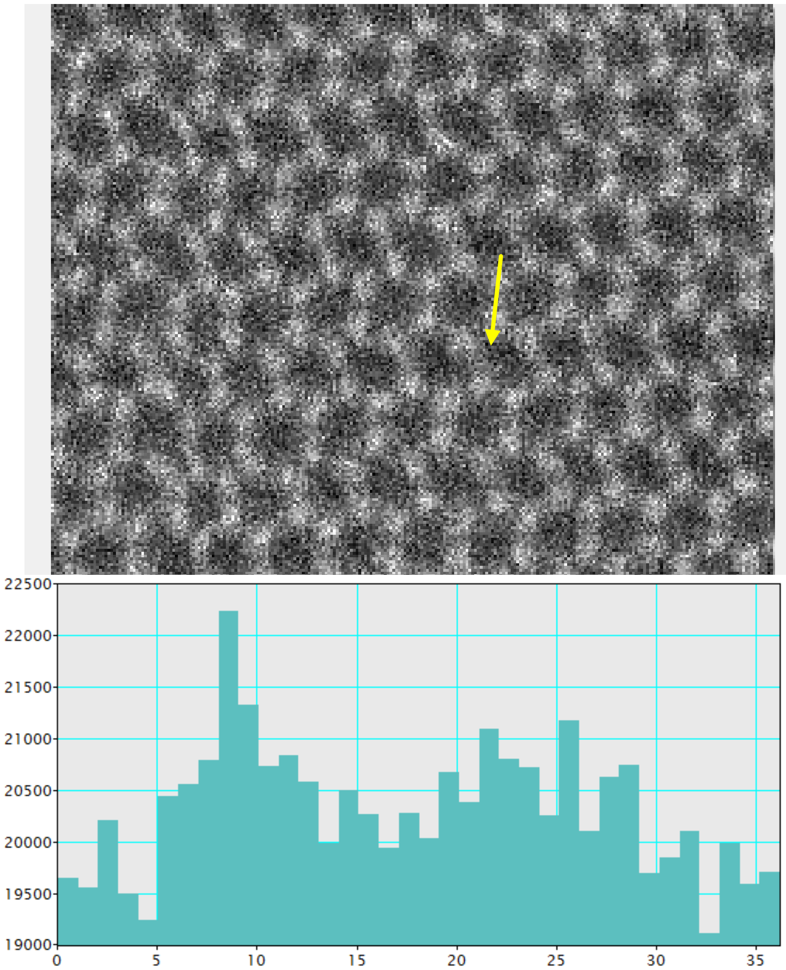


Application: Electron ptychography

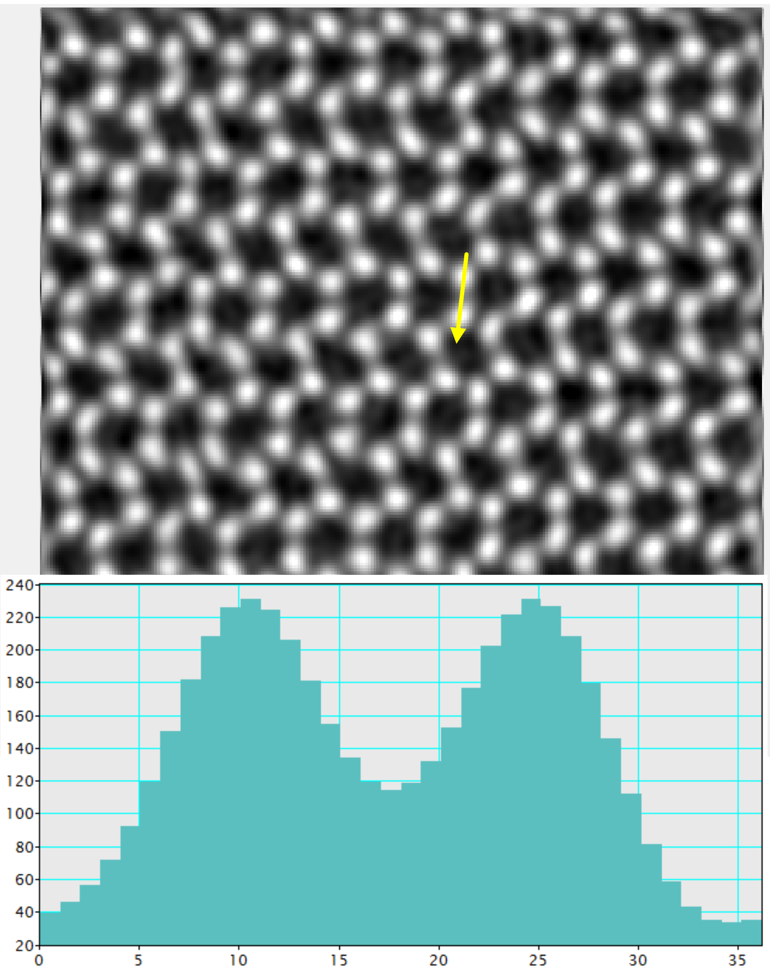
- **Sample:** Graphene
- JEOL ARM 200F @ 80keV
  Emission 10.3µA, Spot 10C, Mag x80M
- 256 × 256 probe positions in < 35 sec
- 2 000 fps read out

In cooperation with
Y. Kondo, R. Sagawa, JEOL Ltd.

simultaneously obtained ADF image



phase image (contrast inverted)



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Summary and conclusions

- the pnCCDs on XMM-Newton are operating according to expectations : fast, low noise, highly sensitive, stable
- pnCCDs are insensitive to soft proton flares
- pnCCDs are not destroyed by micrometeorites

- pnCCDs are used at brillant light sources:
  - X-ray Free Electron Lasers: LCLS, FLASH, SACLA, Eu-XFEL,
  - Synchrotrons: BESSY I+II, ESRF, Diamond, NSLS, . . .
- Wave front sensors in adaptive optics
- Full Field X-ray fluorescence with conventional X-ray sources
- X-ray diffraction
- . . .

Not yet

The End