Silicon Detectors and Readout Electronics

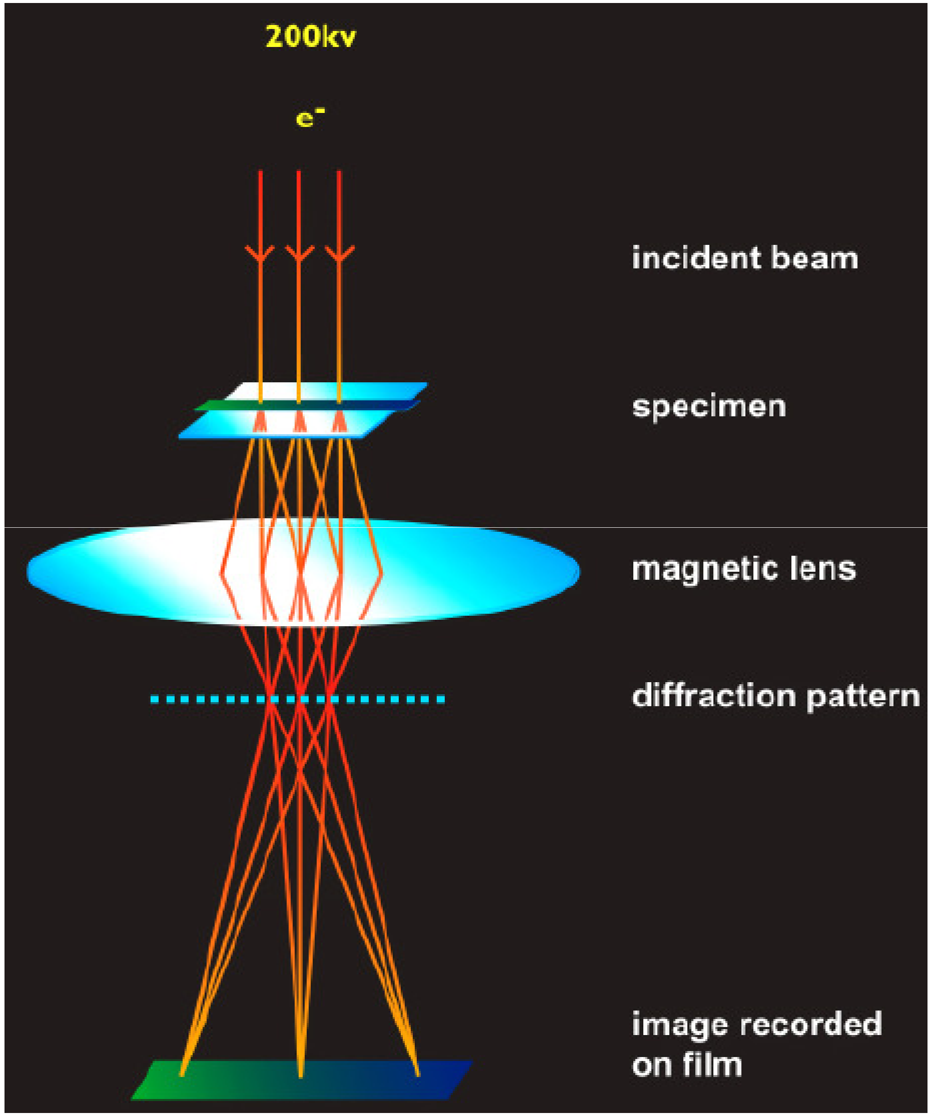
Part 2: Applications

Peter Fischer, ziti, Universität Heidelberg

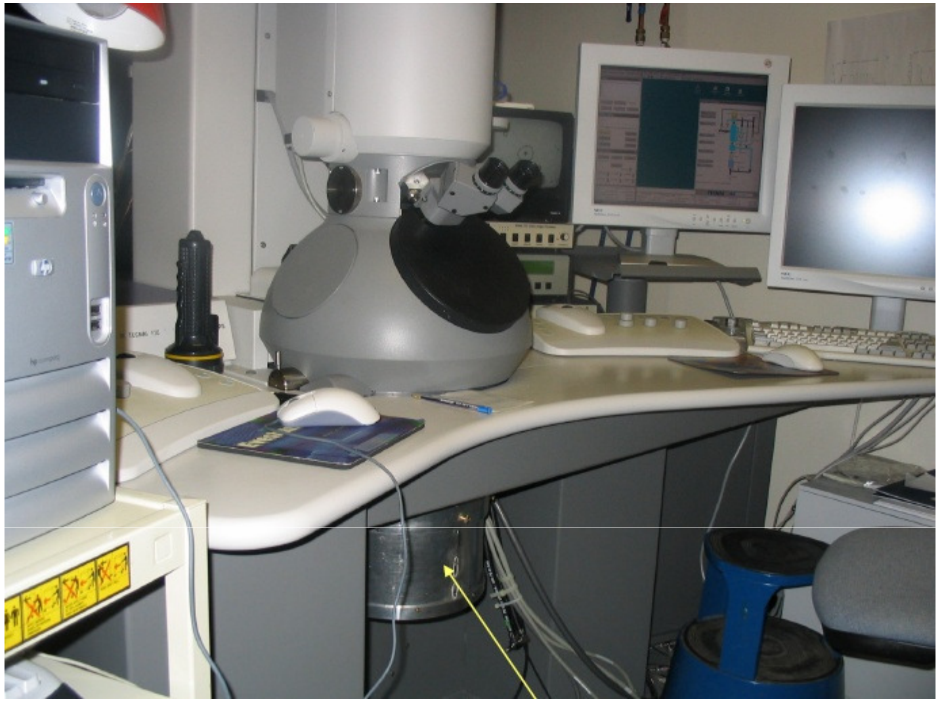
RUPRECHT-KARLS-
UNIVERSITÄT
HEIDELBERG

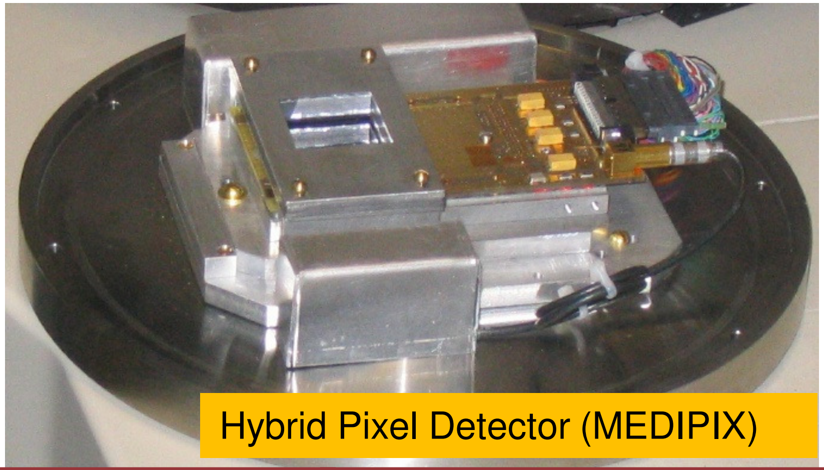
ELECTRON – MICROSCOPY WITHOUT FILM

Principle



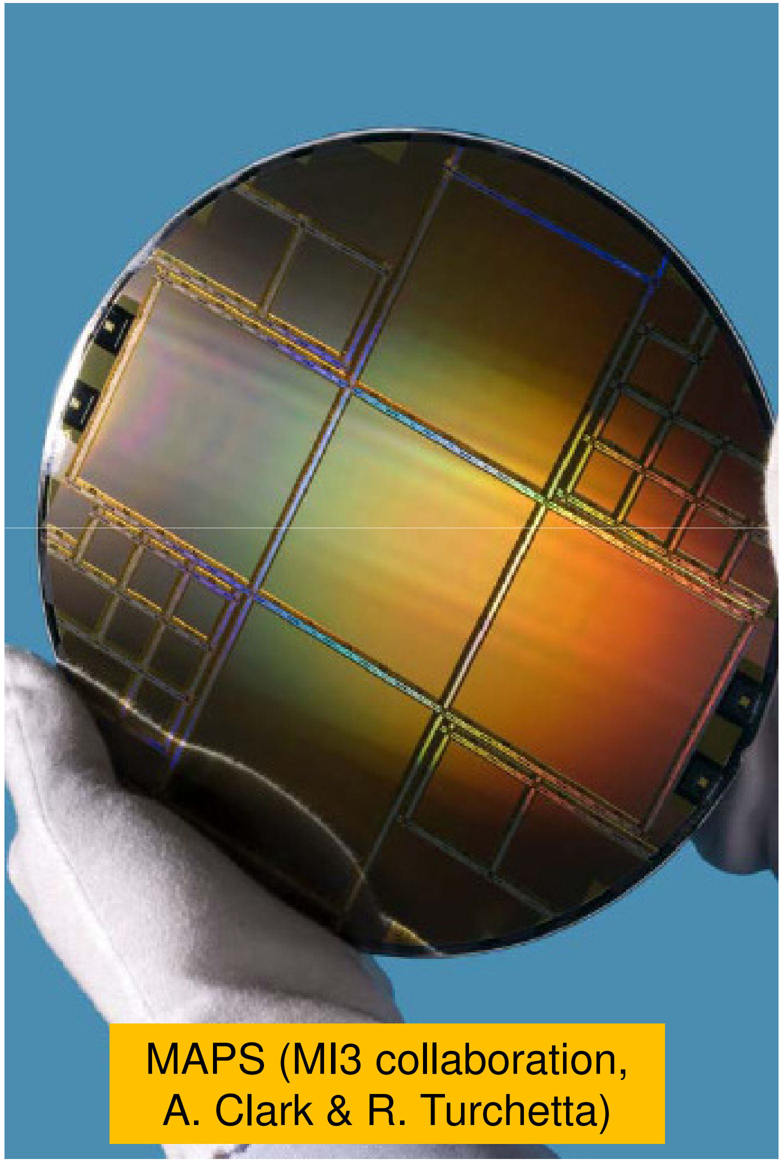
Bilder: Wasid Faruqui, Cambridge



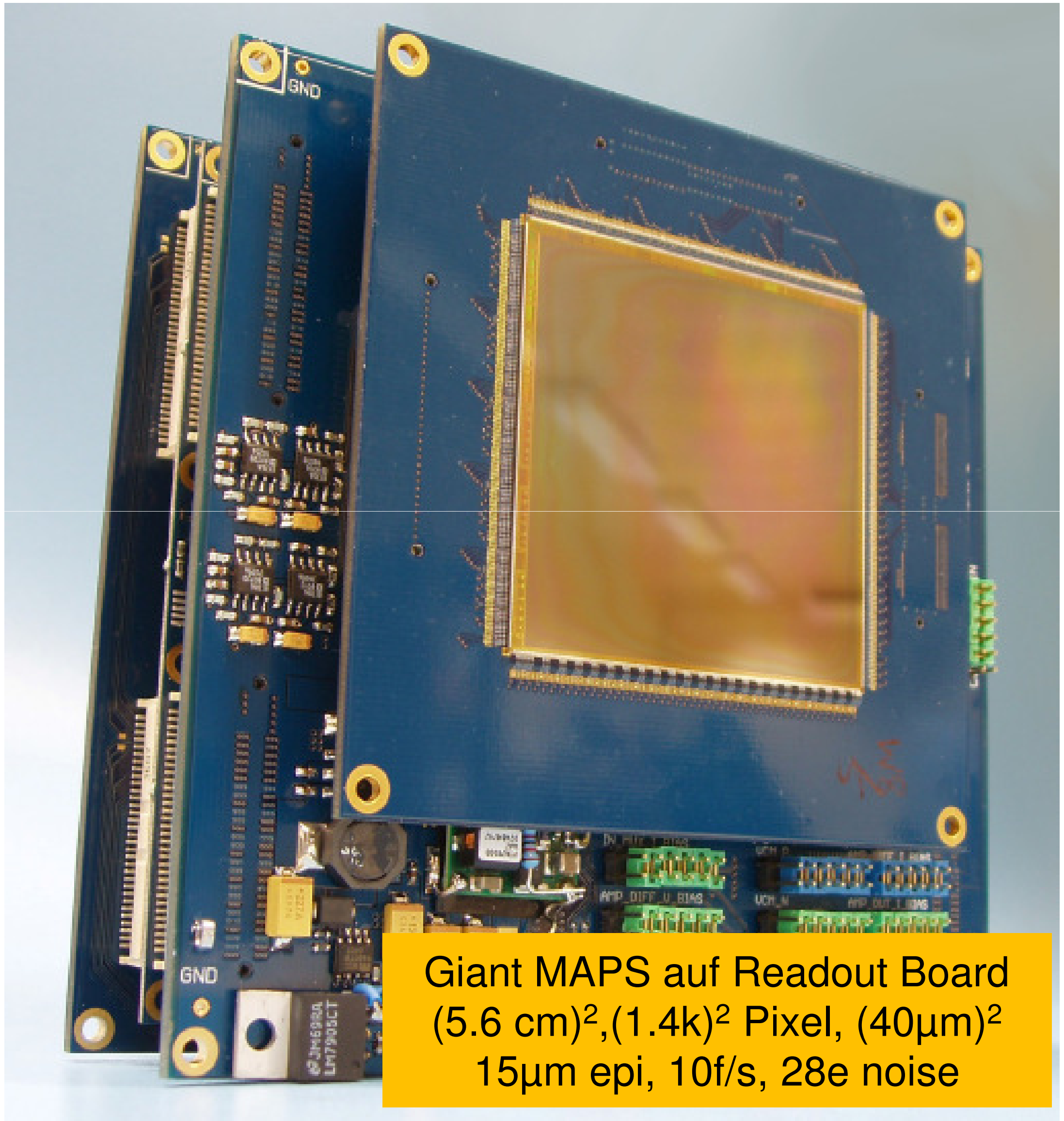


Hybrid Pixel Detector (MEDIPIX)

Detectors: For Instance MAPS or Hybrid Pixel

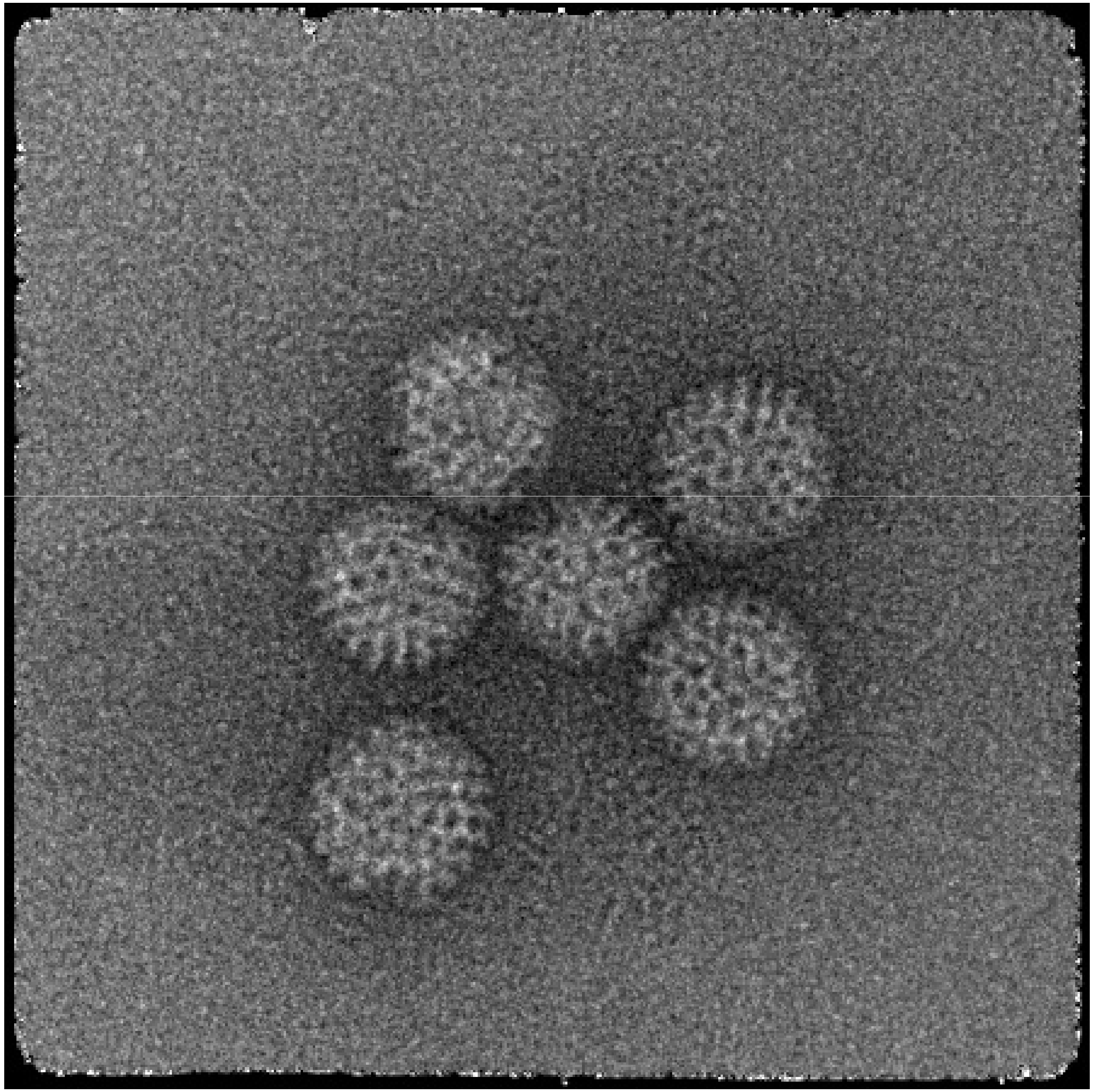


MAPS (MI3 collaboration,
A. Clark & R. Turchetta)



Giant MAPS auf Readout Board
(5.6 cm)^2,(1.4k)^2 Pixel, (40µm)^2
15µm epi, 10f/s, 28e noise

Example: Single Virus



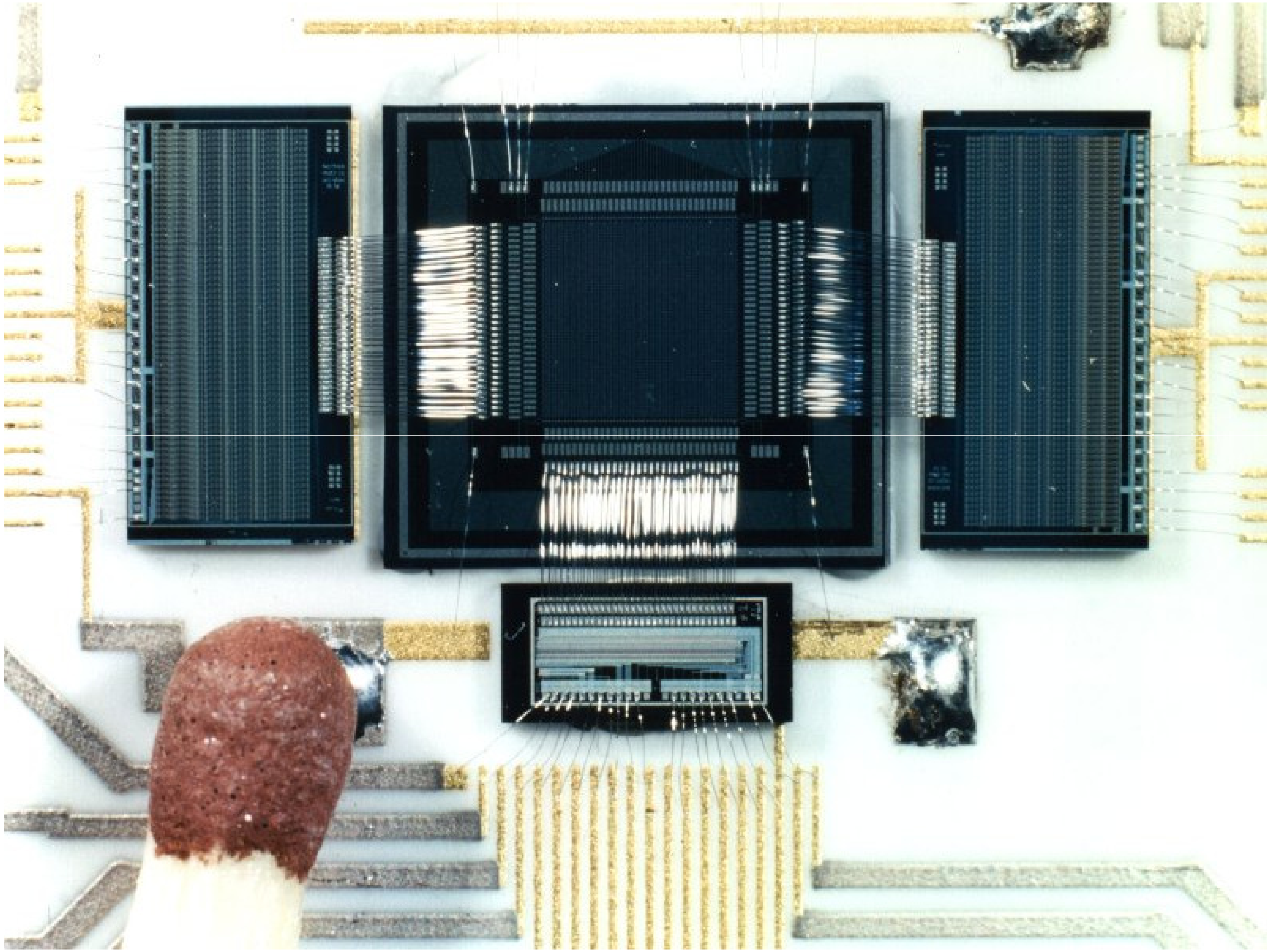
MEDIPIX Quad
(hybrid Pixel)

120keV
160 e / Pixel
4 e / Å^2

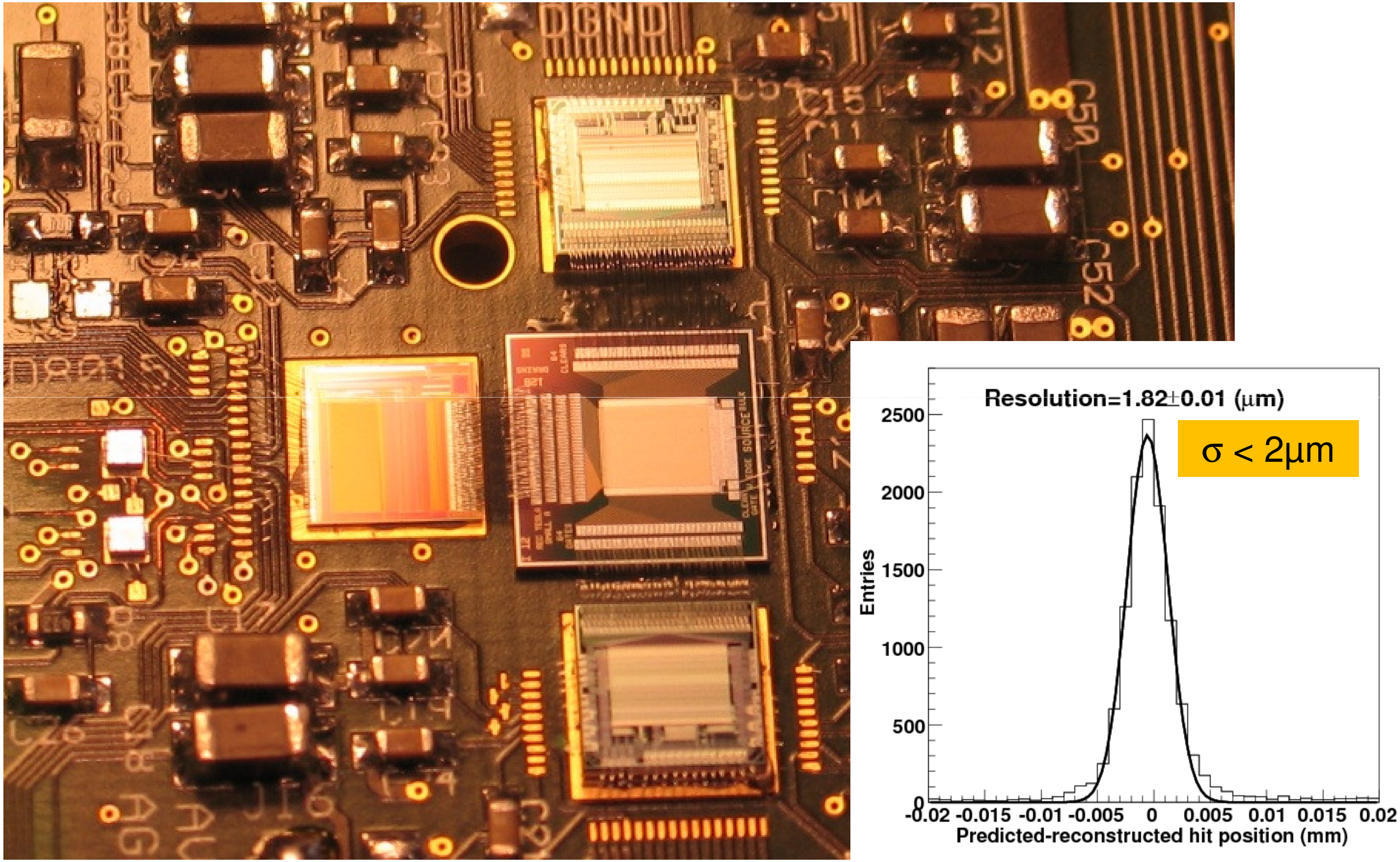
McMullan, Faruqi:
NIM A 591 (2008) 129-133
LMB, Cambridge

PRECISE POSITION MEASUREMENT / TRACKING

DEPFET Pixel Detektor

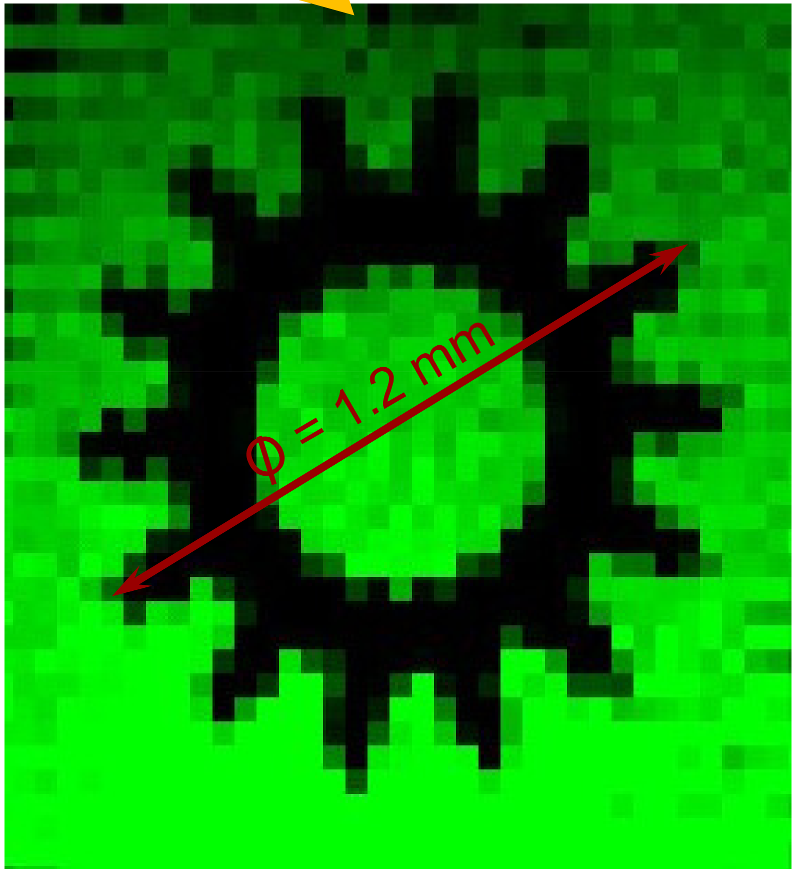


DEPFET Resolution



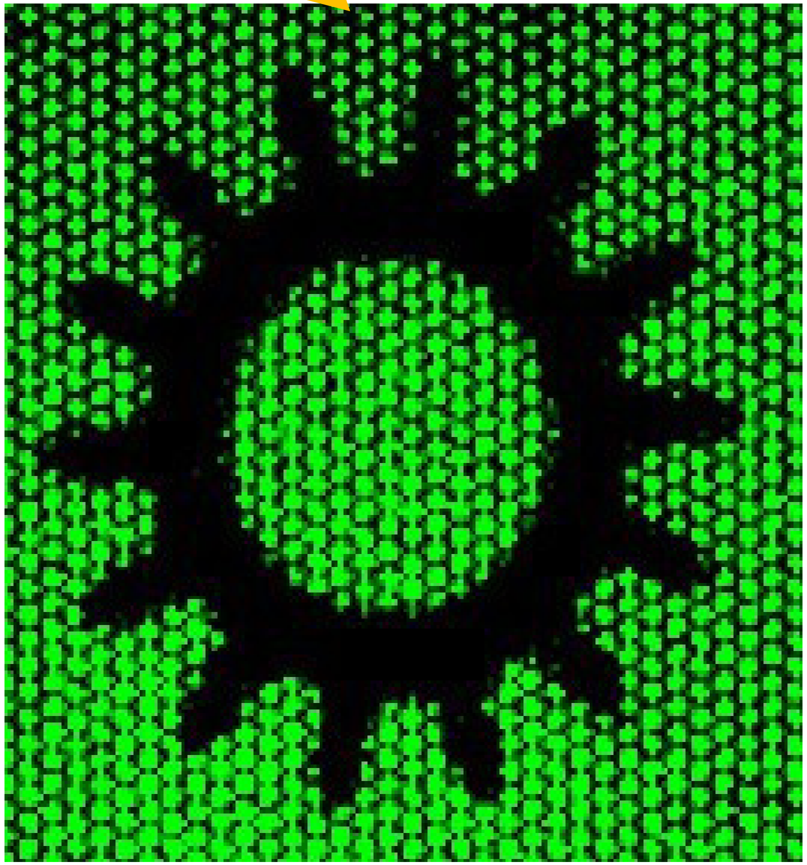
DEPFET Imaging with X-rays

Raw data (50x50µm^2 pixels)



(tooth wheel of a wrist watch)

Analog Interpolation

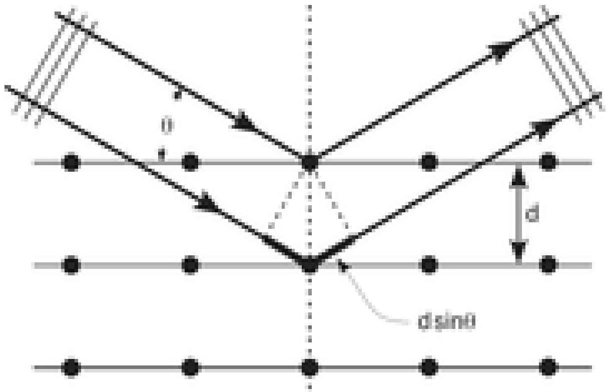


Much better image

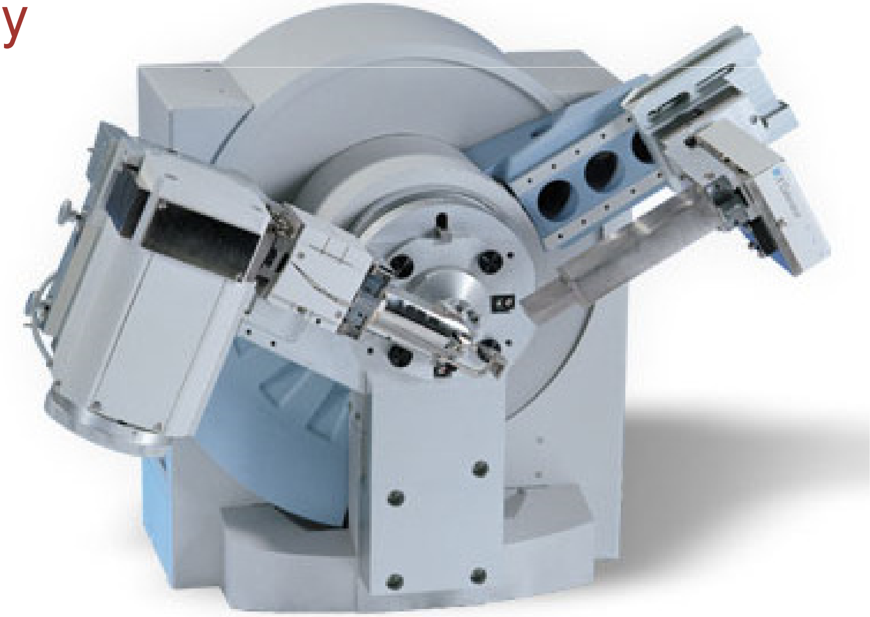
DETECTION OF SYNCHROTRON RADIATION

Principle

- In crystals, reflections for given λ occur at fixed angles. They depend on the lattice spacing according to Bragg's law $2d\sin\theta = n\lambda$



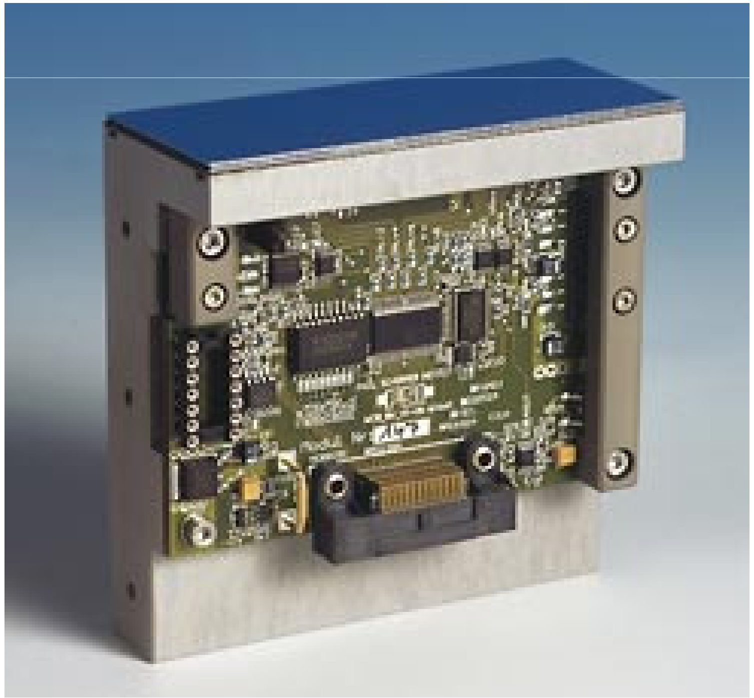
- Radiation sources are X-ray tubes or Synchrotrons
- Crystal is rotated



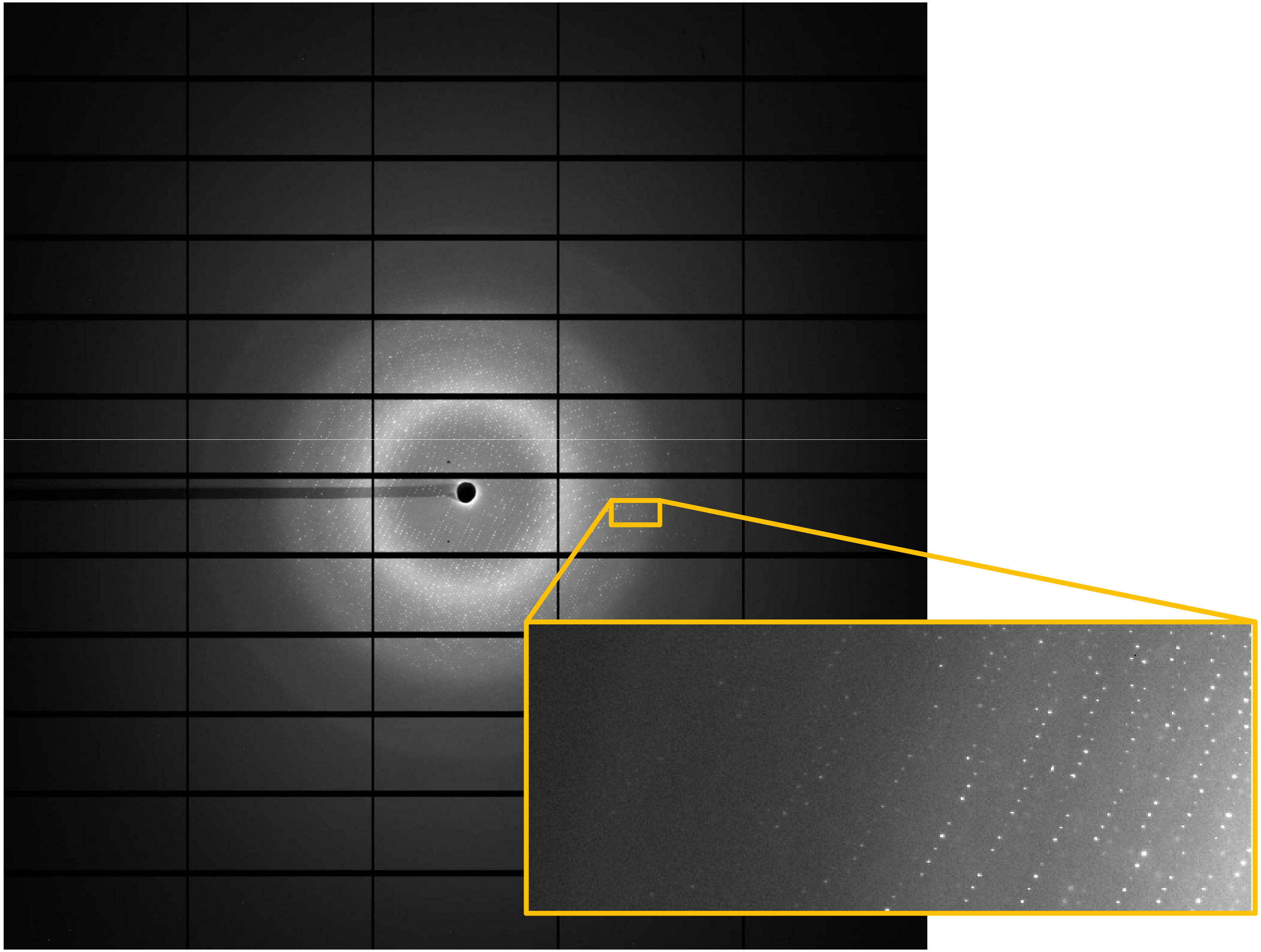
- Detectors are point, 1d, 2d
- Used in biology, chemistry, material sciences
- Increasing interest

Largest commercial pixel detector: Pilatus 6M

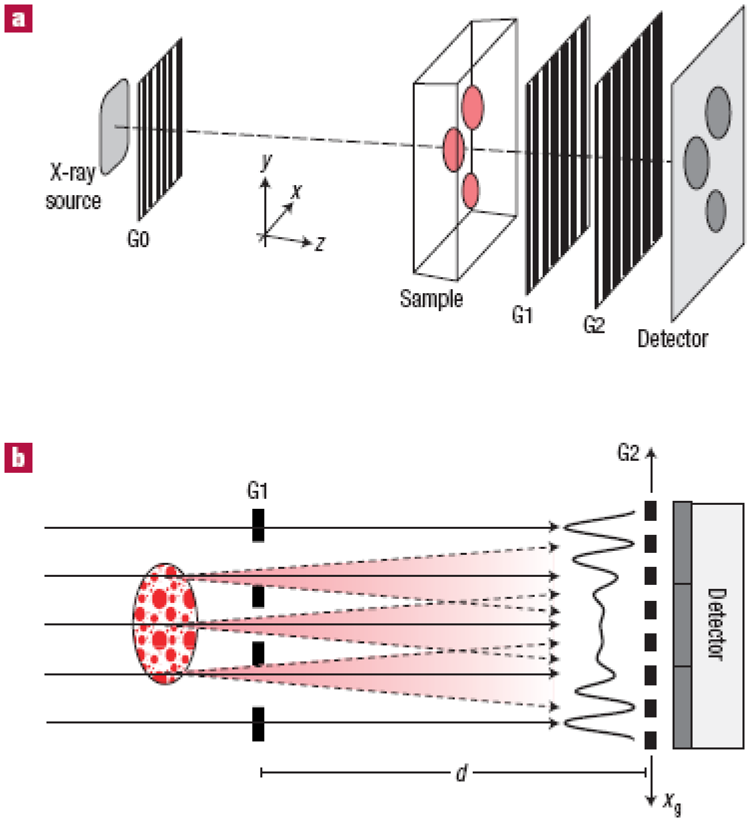
- DECTRIS: Spin – Off PSI, Villigen, Schweiz
- 43.1 x 44.8 cm^2 Fläche, (172µm)^2 Pixel, 6 MPixel, 10 Hz
- Chips count photons in every pixel

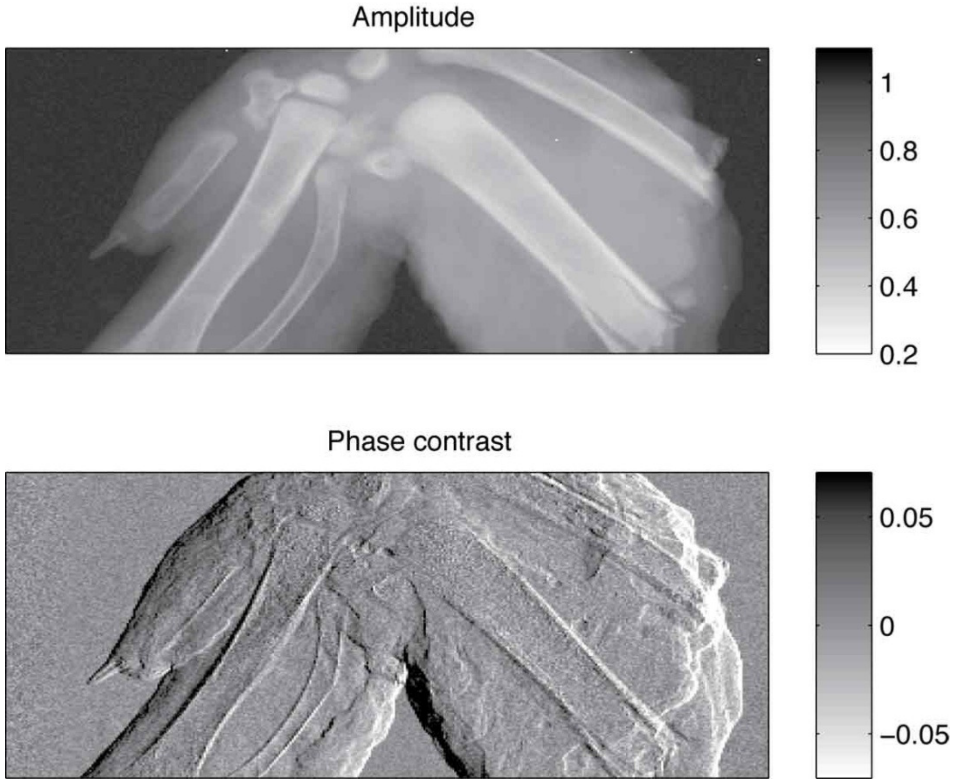


Diffraction Pattern of Crystallized Macro Molecules



A New Idea: Phase contrast X-ray Imaging



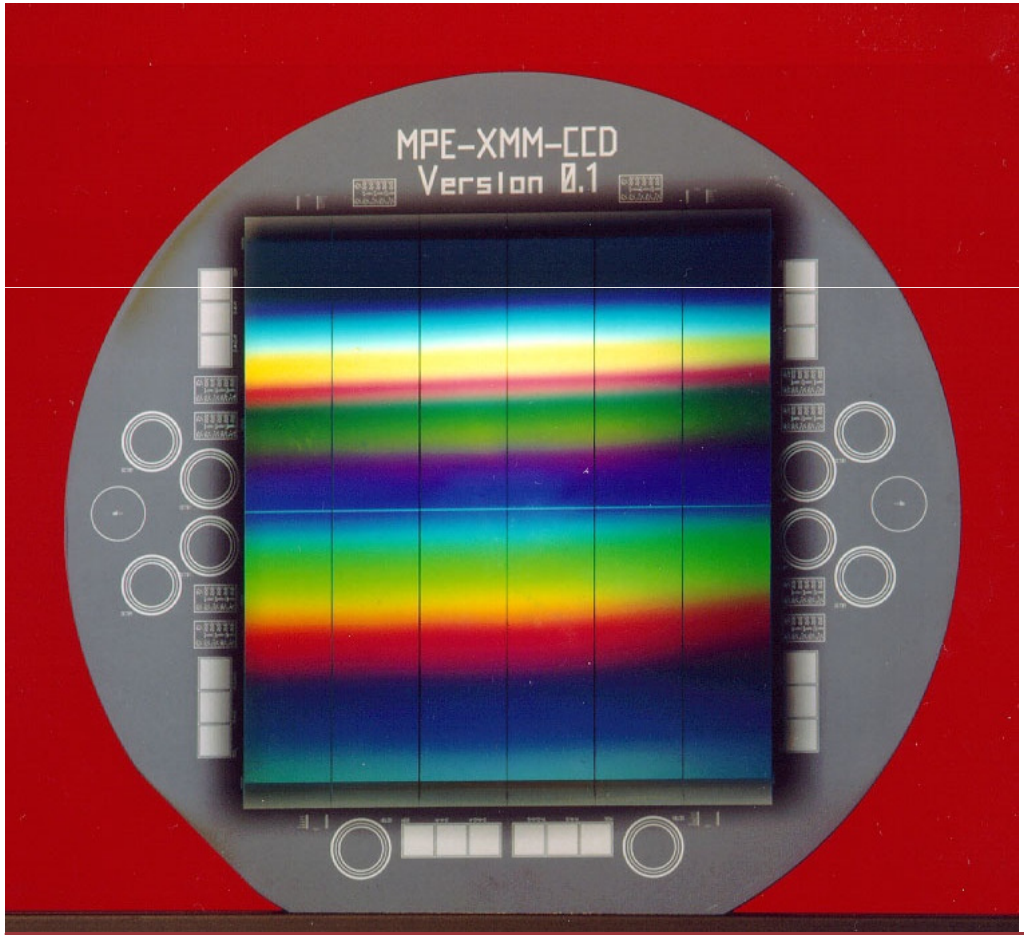


F. Pfeiffer, T. Weitkamp, O. Bunk, and C. David. Phase retrieval and differential phase-contrast imaging with low-brilliance X-ray source. Nature Physics 2, 258–261 (2006)

X-RAY ASTRONOMY

CCD for soft X-rays

- Energy: 0.2 – 5 keV
- Detector: pn – CCD (HLL of MPG Munich)
  (6 cm)^2, (150µm)^2 Pixels, 73 ms per image



XMM-Newton Mission

- XMM = X-Ray Multi Mirror. (http://xmm.esac.esa.int/)
- Satellite launched 1999 by ESA
- X-ray mirror by shallow incidence reflection
- Need a parabolic and a hyperbolic mirror (‘Wolter Type 1’)

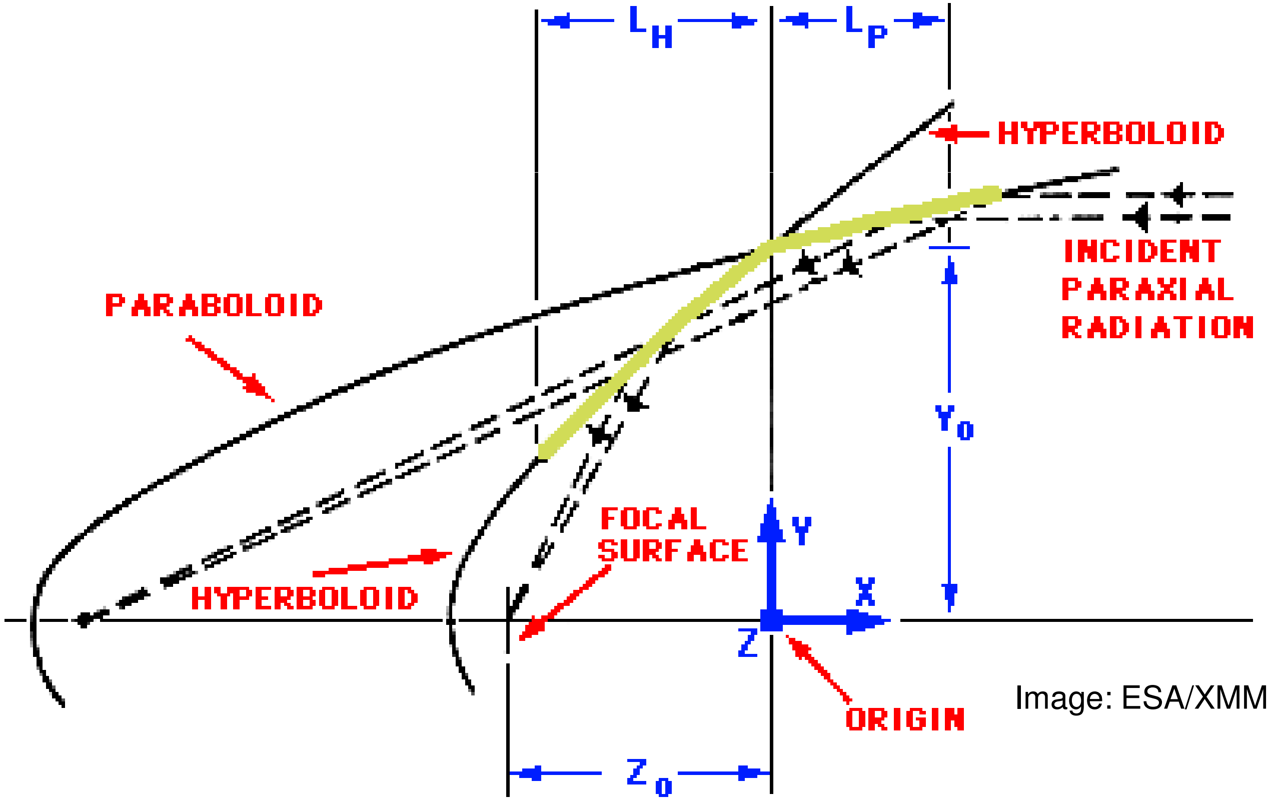
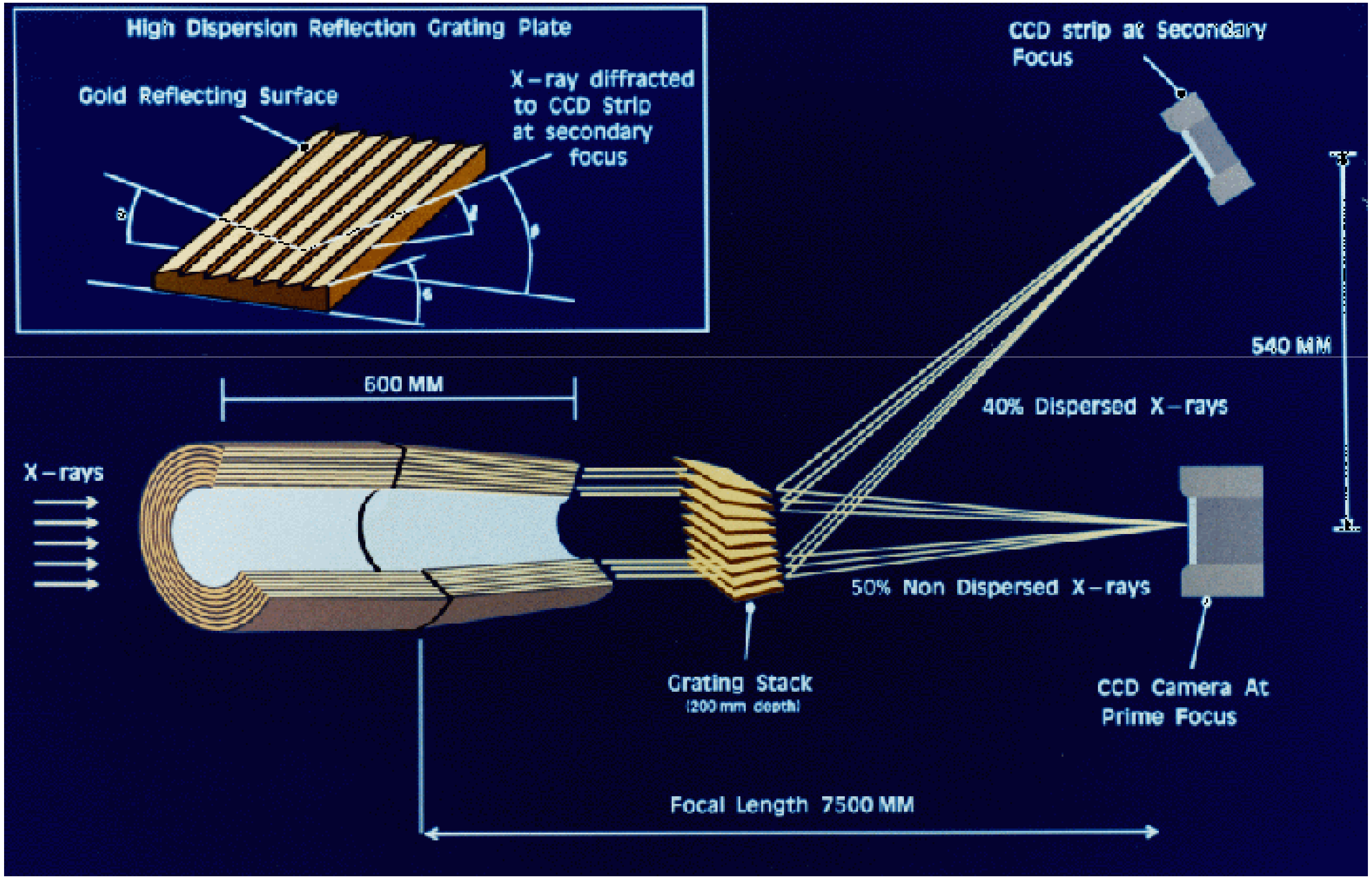


Image: ESA/XMM/MPE

XMM Mirror Stack

- Use many layers to increase light throughput (~42 %)



XMM Mirrors

- 58 Mirror shells total (0.47 mm thick in 3mm pitch)

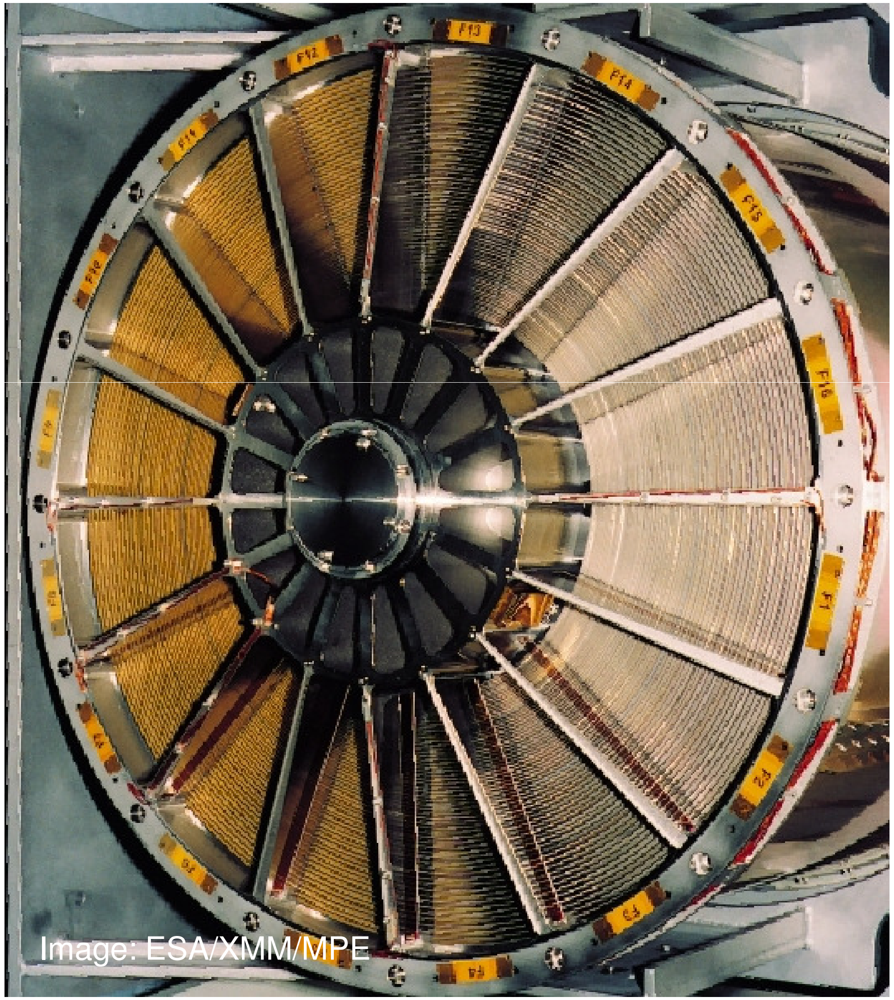


Image: ESA/XMM/MPE

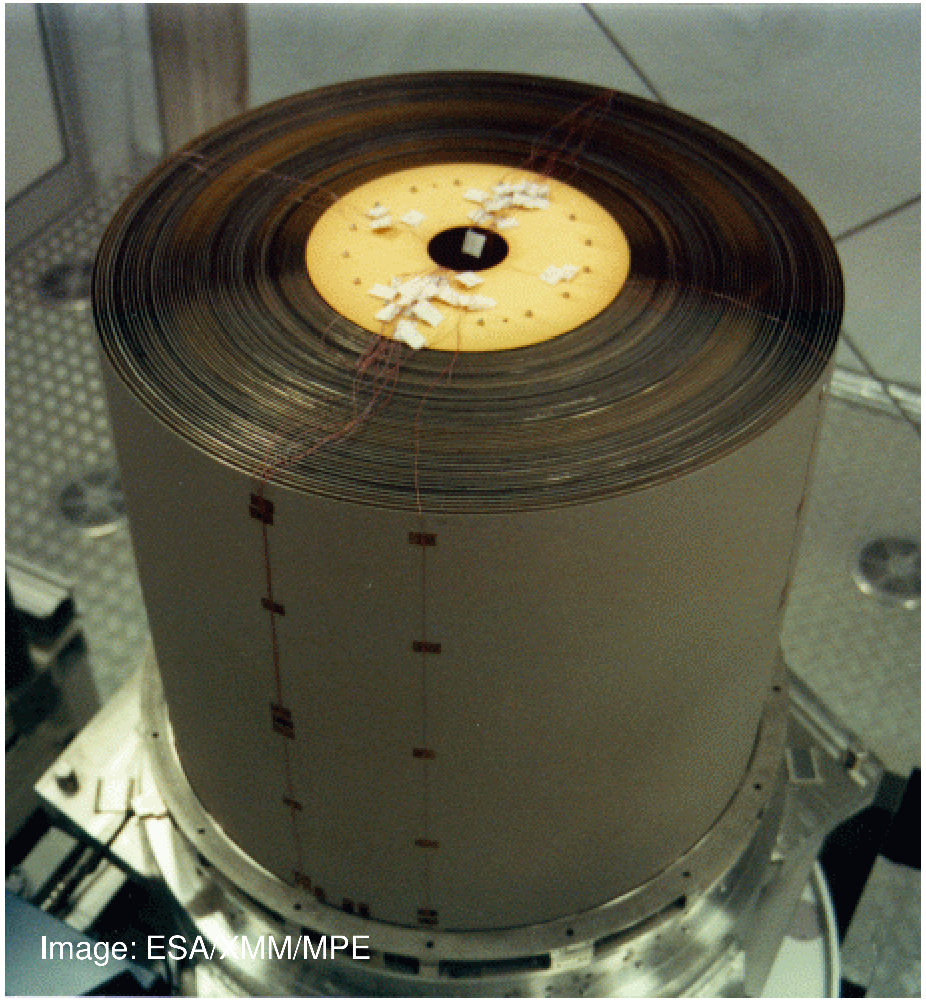


Image: ESA/XMM/MPE

XMM-Newton CCD Detector

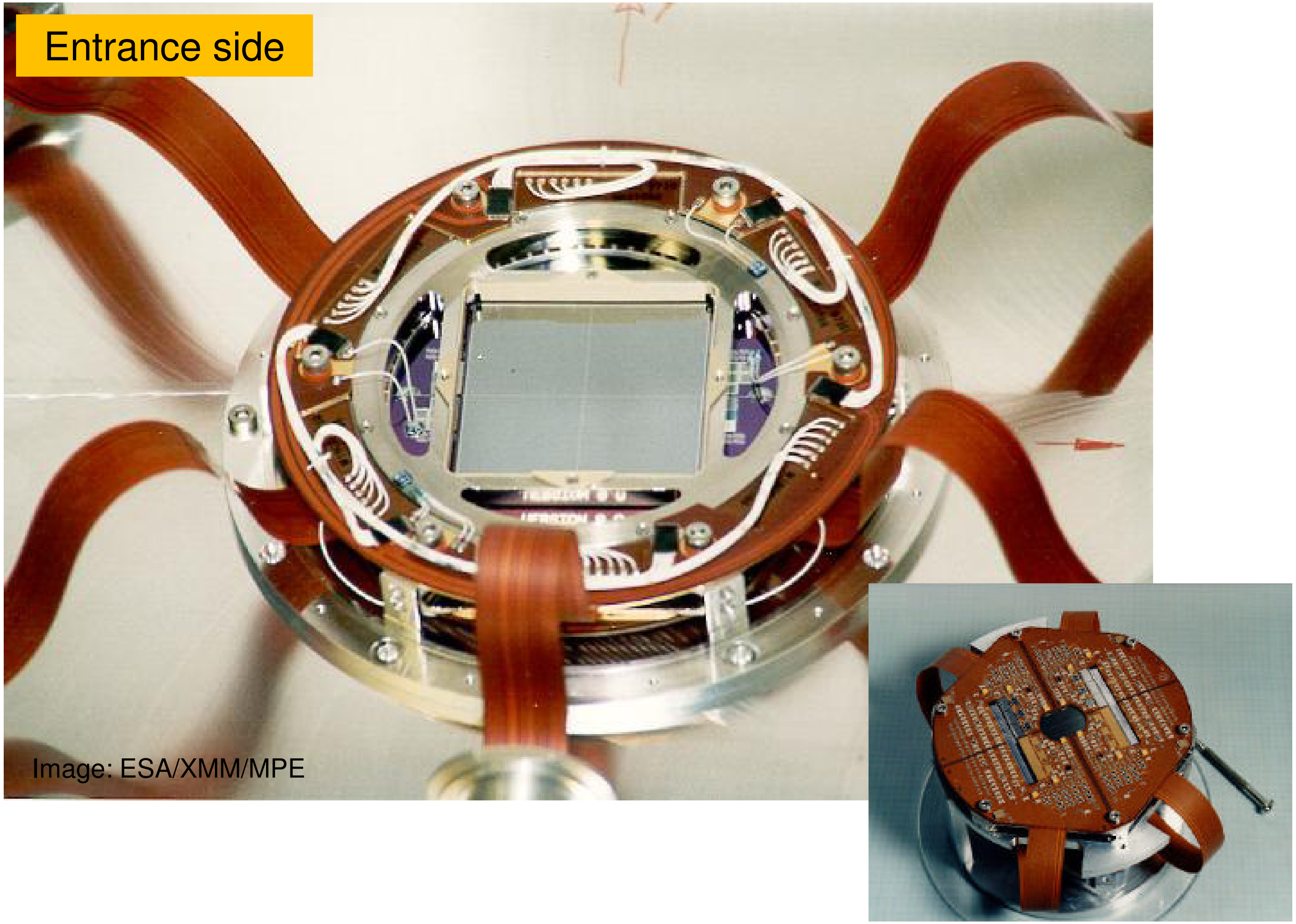
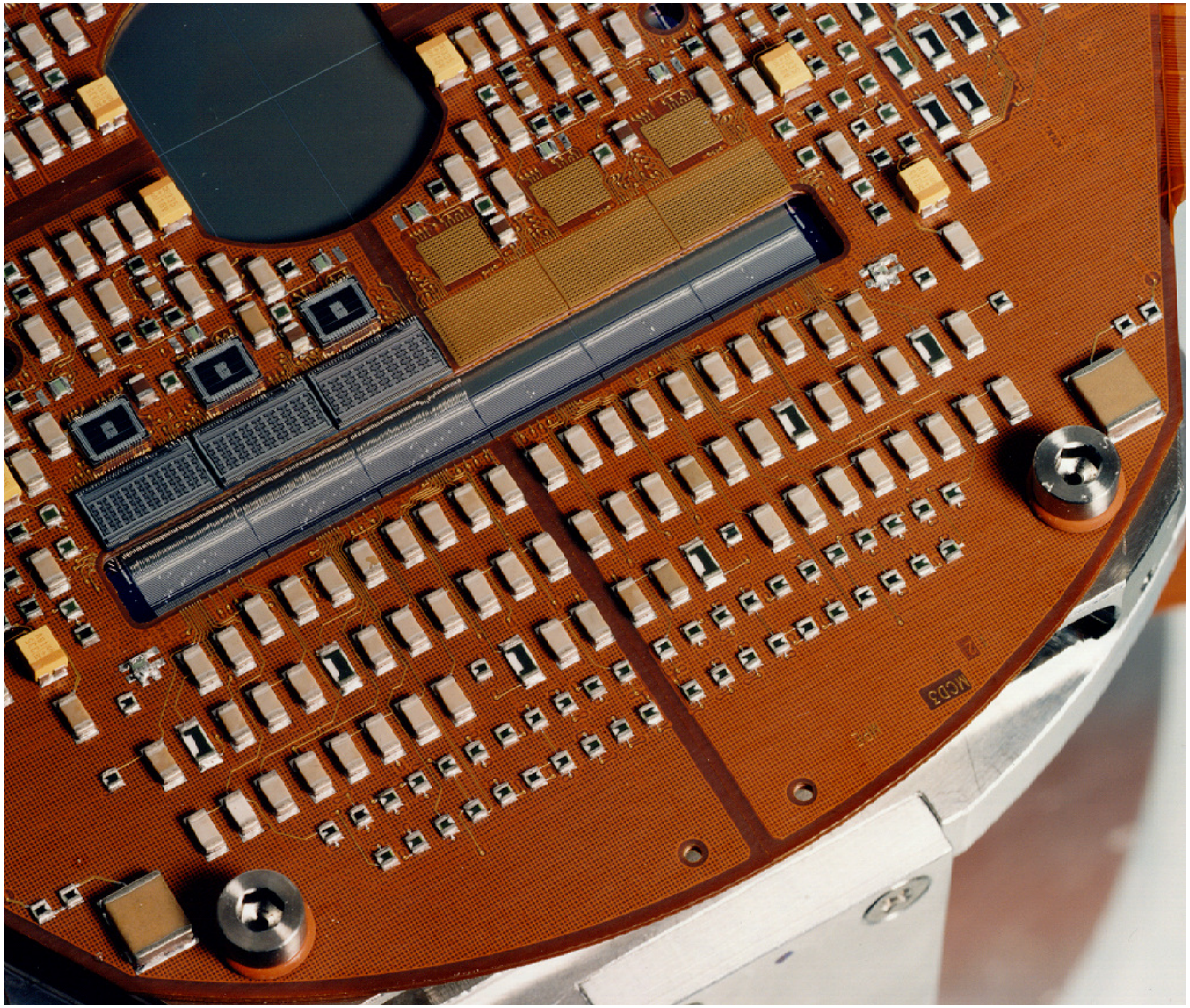


Image: ESA/XMM/MPE

Backside With Readout Chips



Cosmic X-ray Sources: Supernova

- Supernova discovered 1987
- Intensity increased by x 10 since year 2000

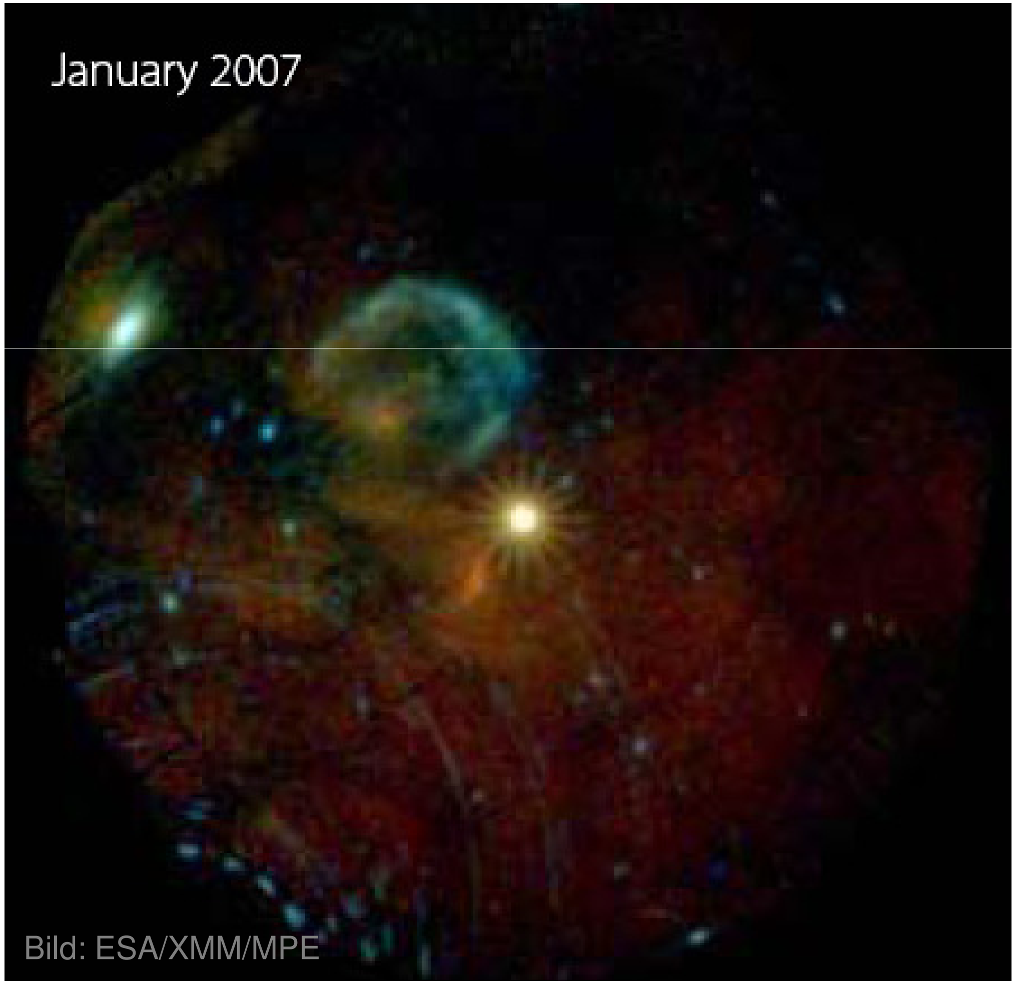


Bild: ESA/XMM/MPE

Cosmic X-ray Sources: Pulsar

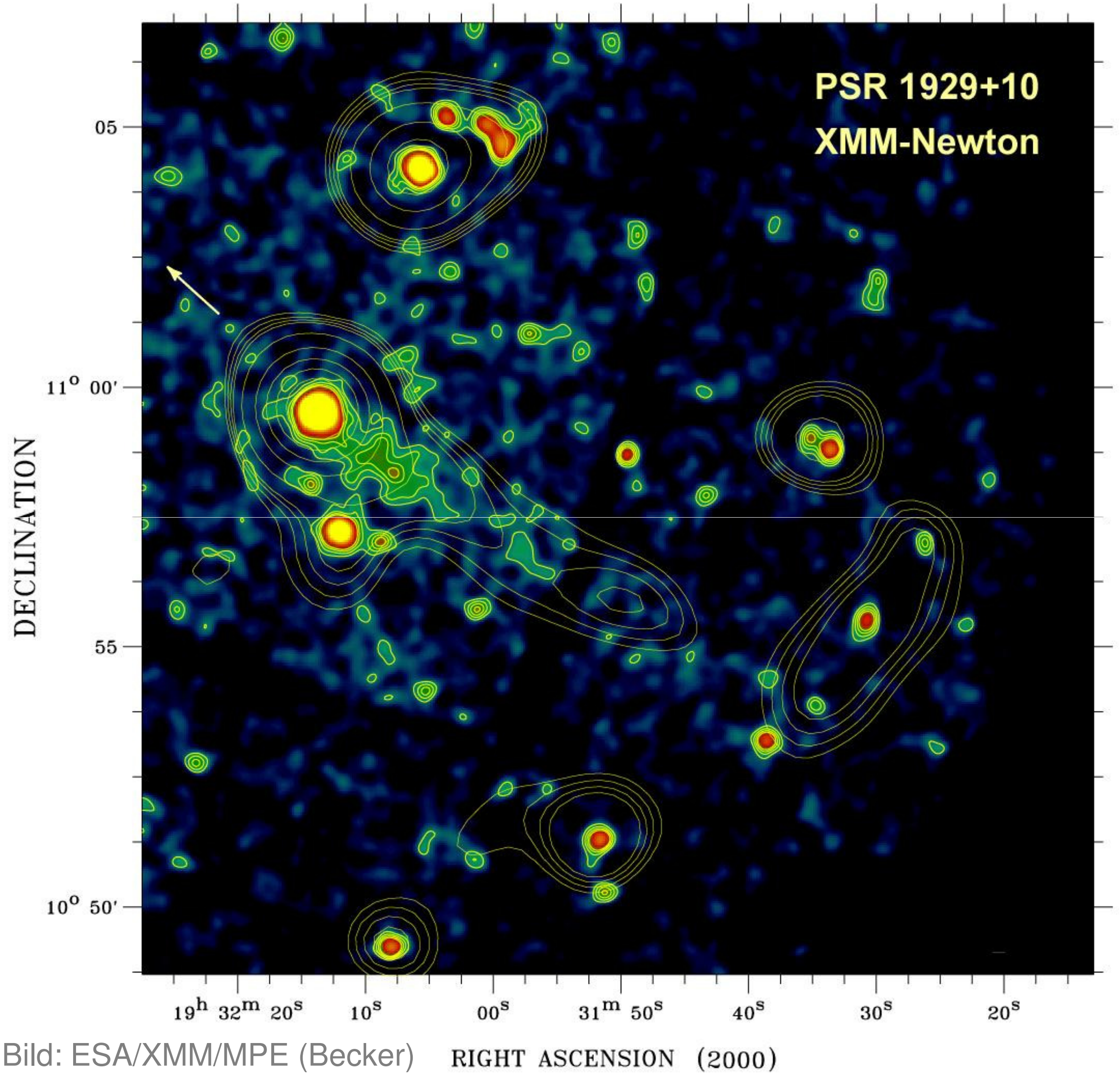


Bild: ESA/XMM/MPE (Becker)

XMM-Newton view on the old pulsar PSR B1929+10 and its X-ray trail

Image courtesy of Werner Becker / Max-Planck Institut fuer extraterrestrische Physik

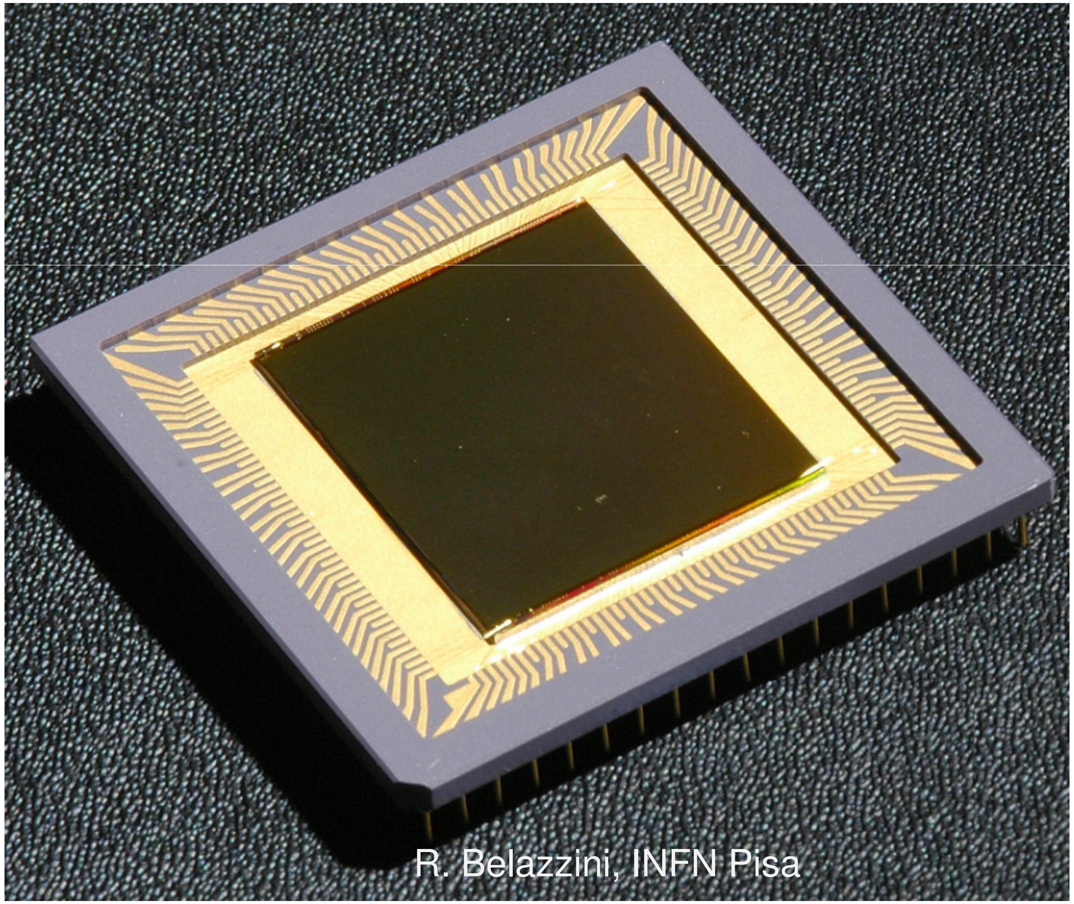
European Space Agency

RUPRECHT-KARLS-
UNIVERSITÄT
HEIDELBERG

DIGITAL X-RAY IMAGING

Digital X-ray– the LARGEST Pixel Chip

- 600x800 Pixel, ~(40µm)^2 (hexagonal)
- 24 x 28 mm^2, 480.000 Pixel,
- Presented early 2008 (IWORID conference)



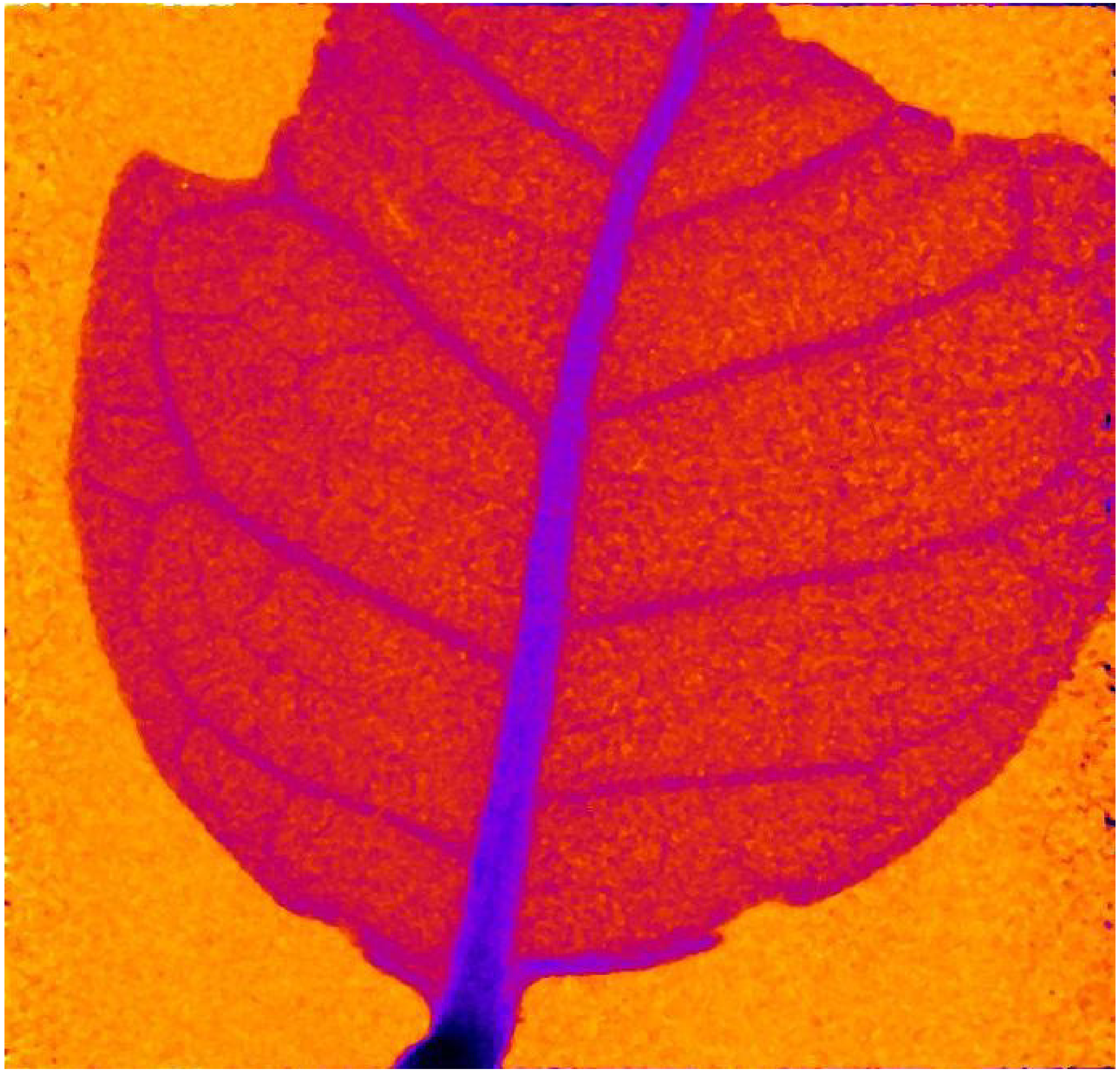
R. Belazzini, INFN Pisa

A Big Chip

Real Hardware at the Conference
Dinner of the IWORD 2008 in Helsinki...

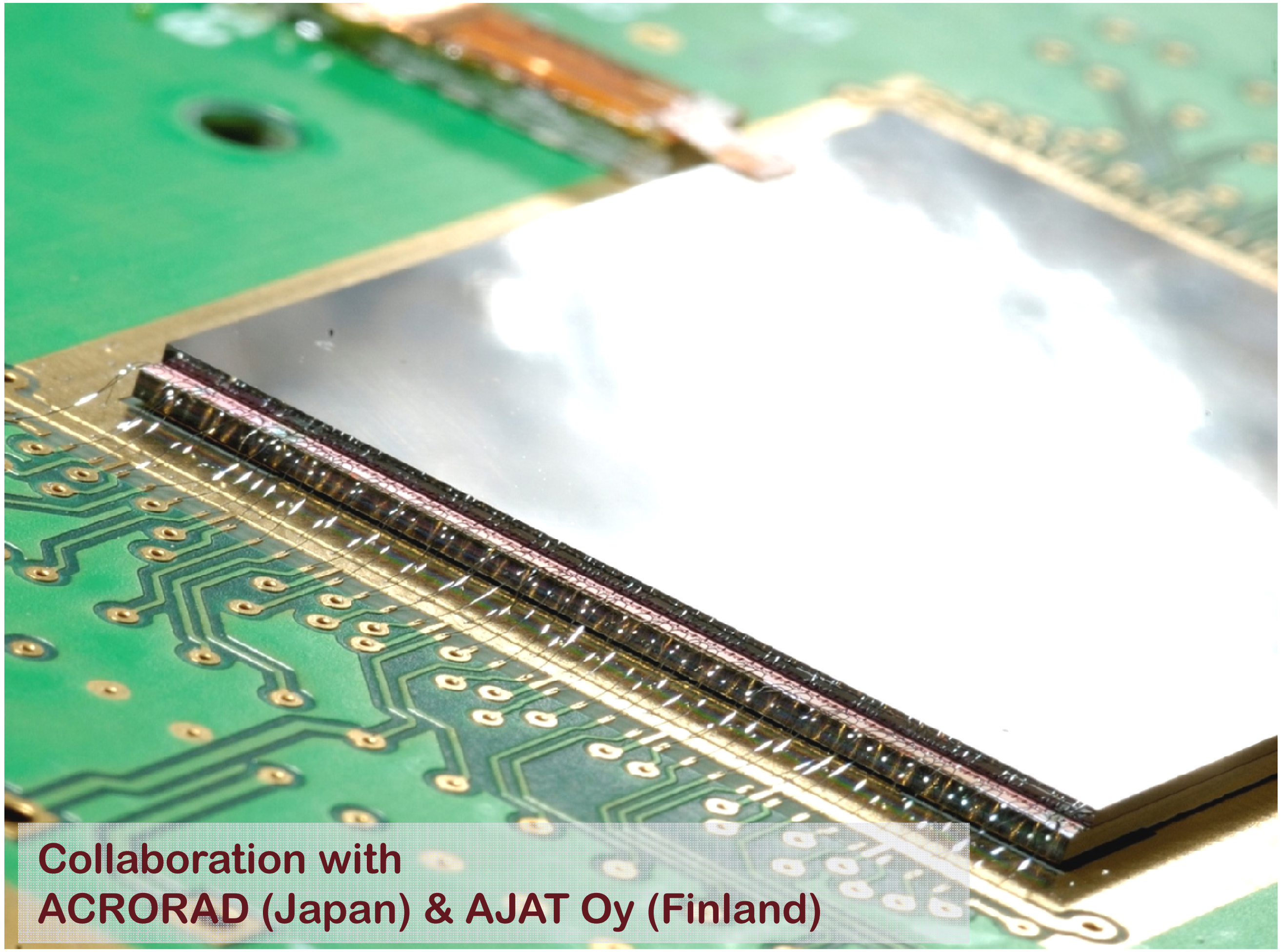
Xray Image of a leaf @ 8 keV

- Simple Detector: Xe @ 12 bar. ~600 e per X-ray photon



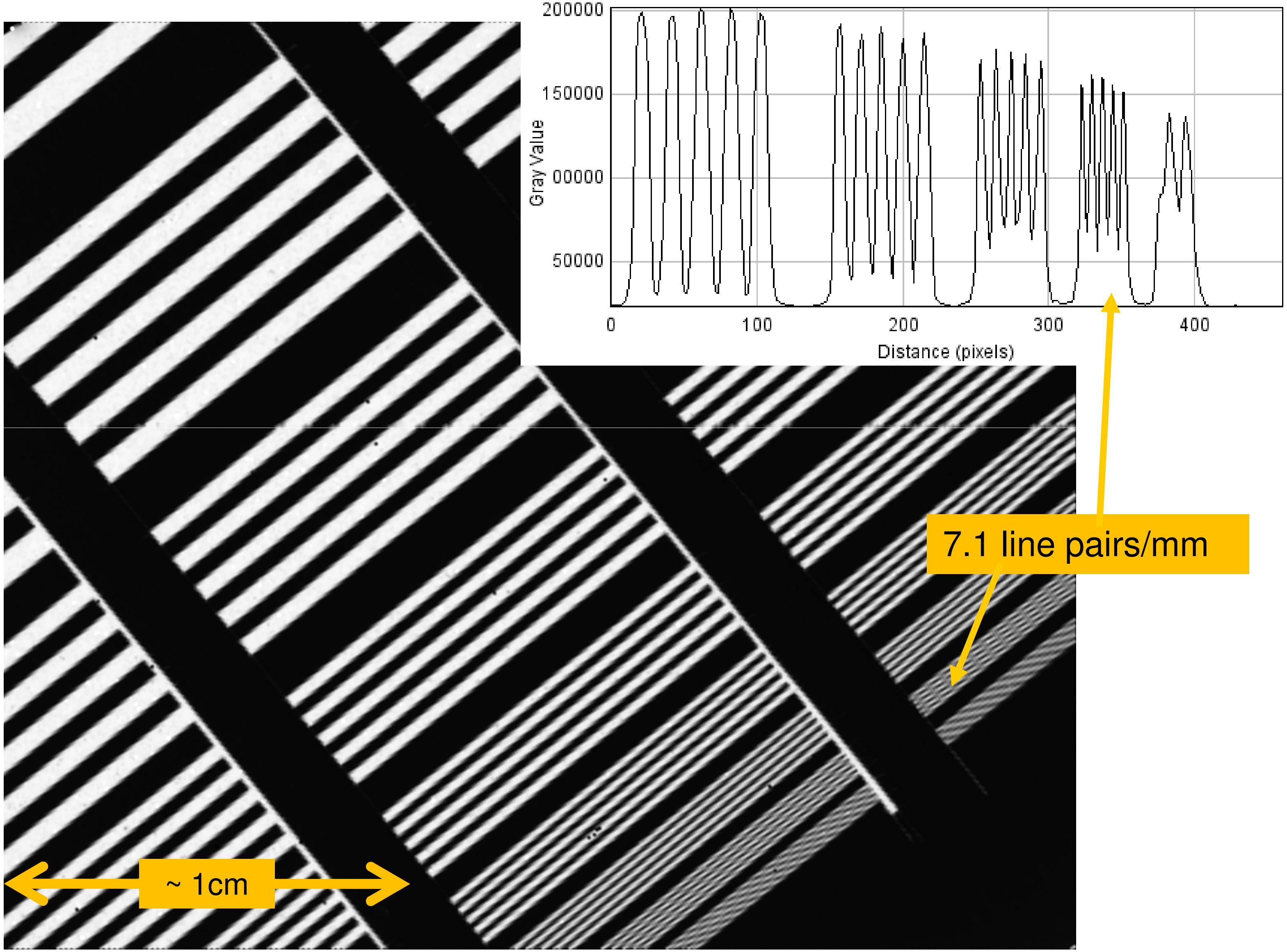
Chip with CdTe Detector

- CdTe has high absorption for X-rays with ‘high’ energy
- Bump Bonding of ~8 cm^2!



**Collaboration with
ACRORAD (Japan) & AJAT Oy (Finland)**

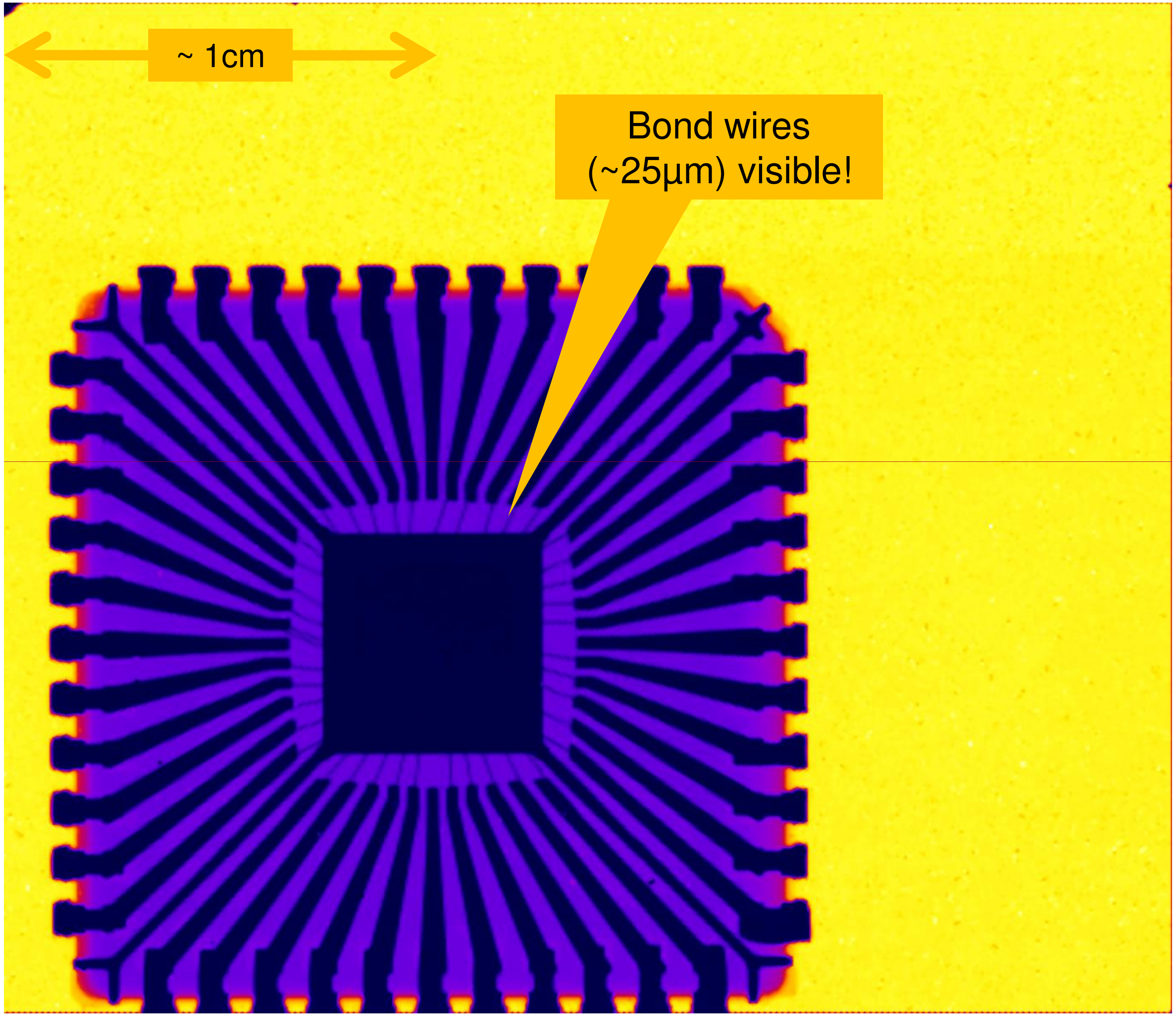
Spatial resolution with Line Chart



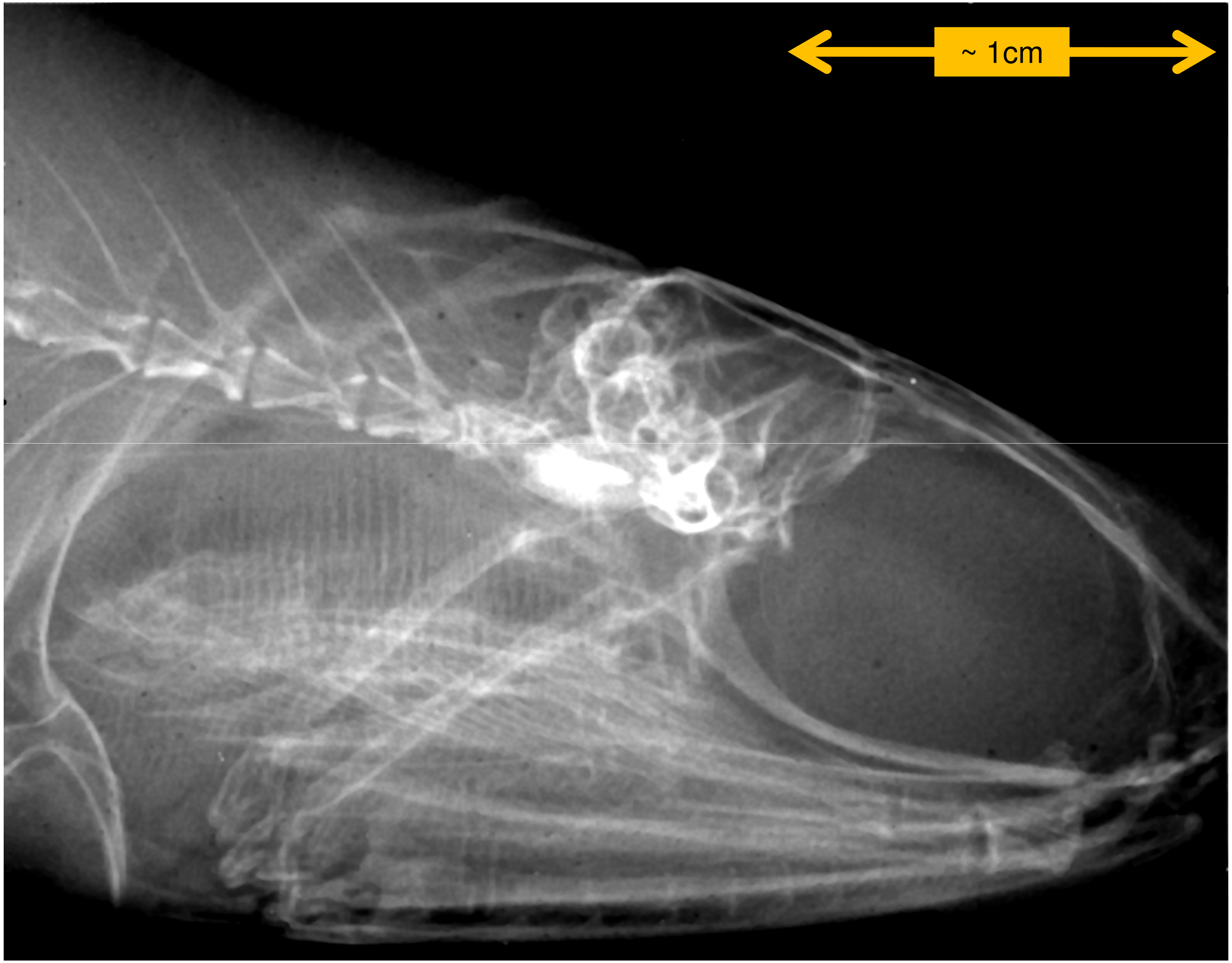
7.1 line pairs/mm

~ 1cm

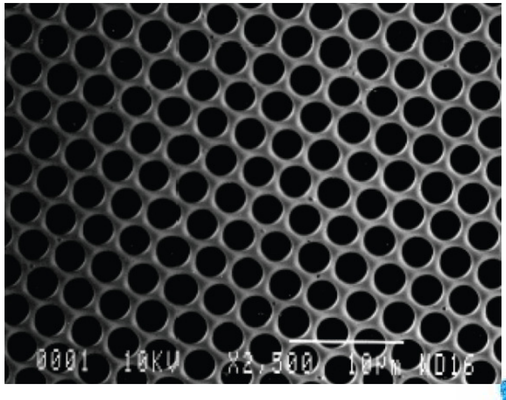
IC in package @ 35 keV

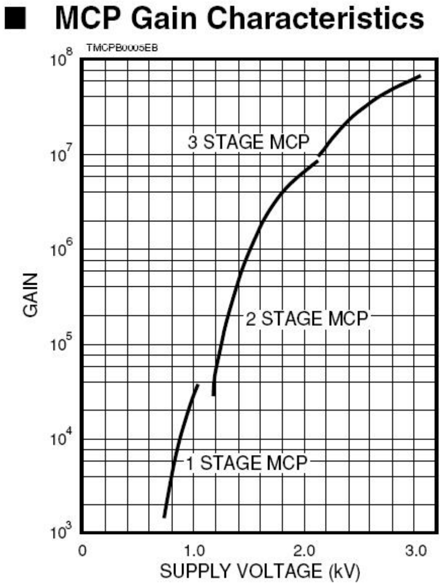


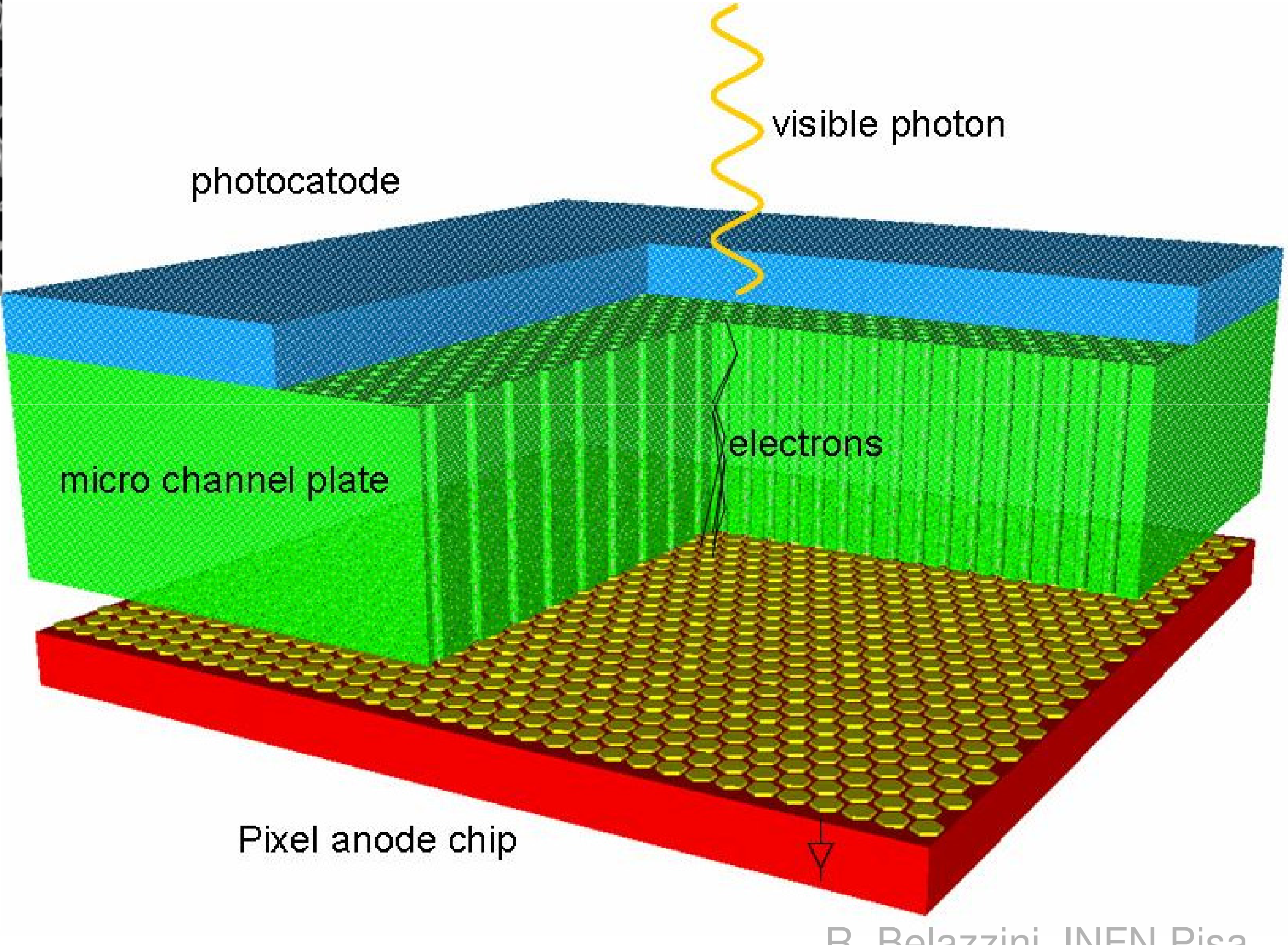
Biological sample (fish, 25keV, 800ms)



Variation: Multi Channel Plate (no silicon)



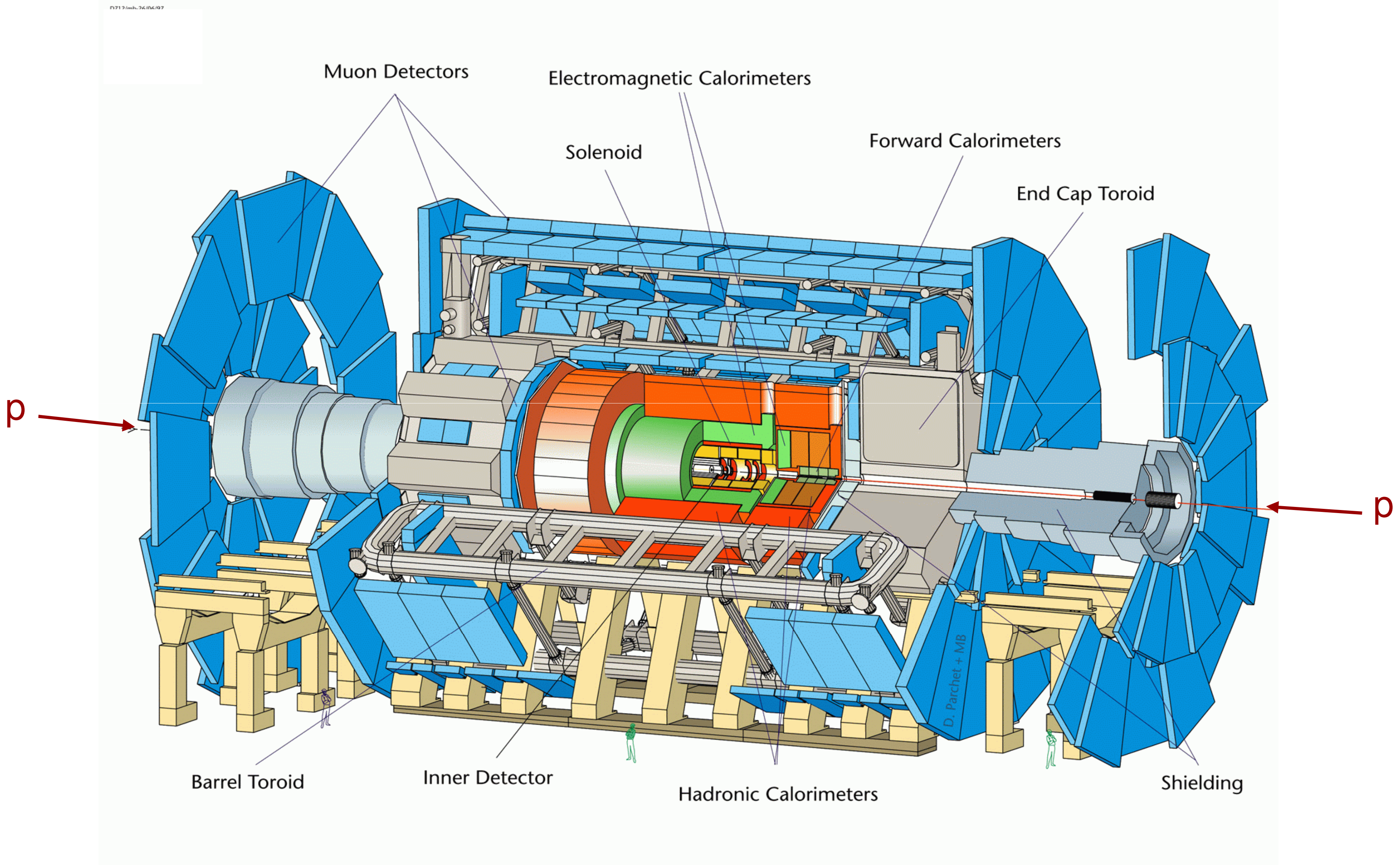




R. Belazzini, INFN Pisa

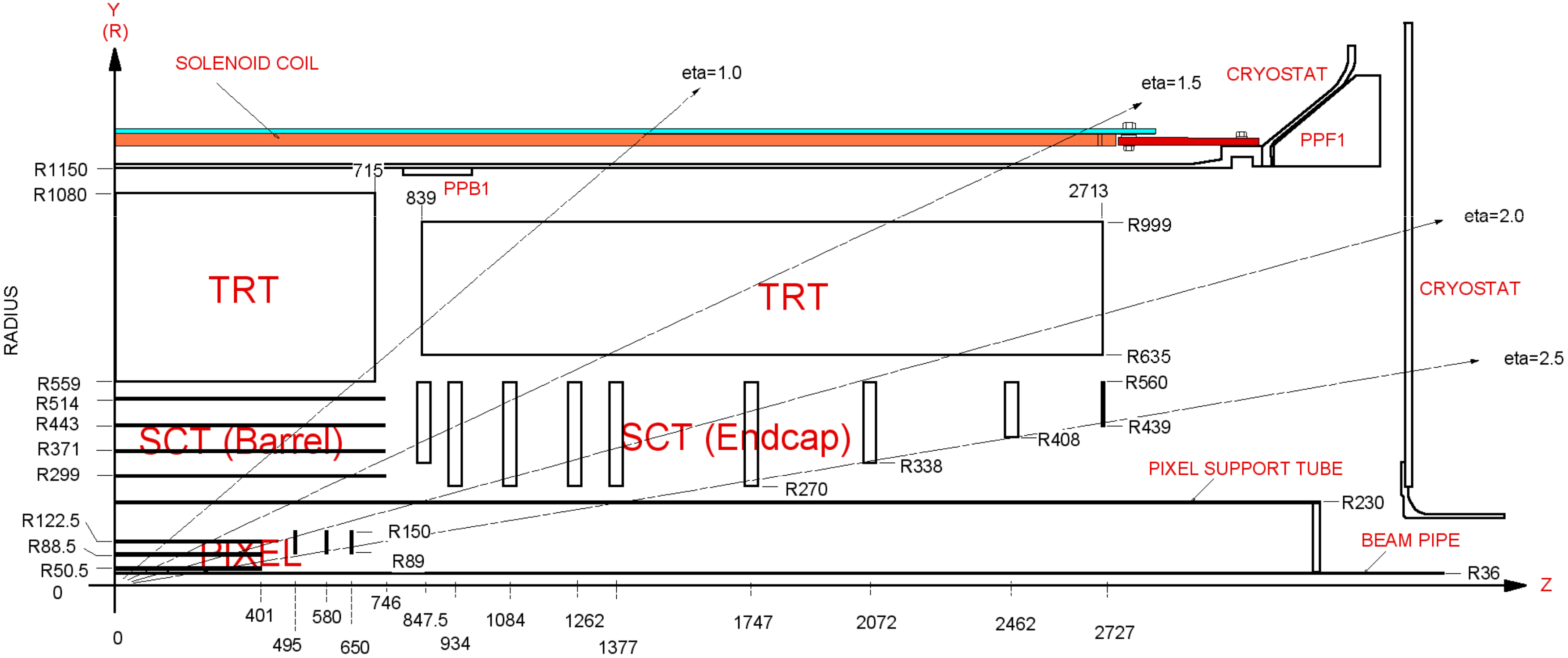
PARTICLE TRACKING AT LHC

The ATLAS Detector

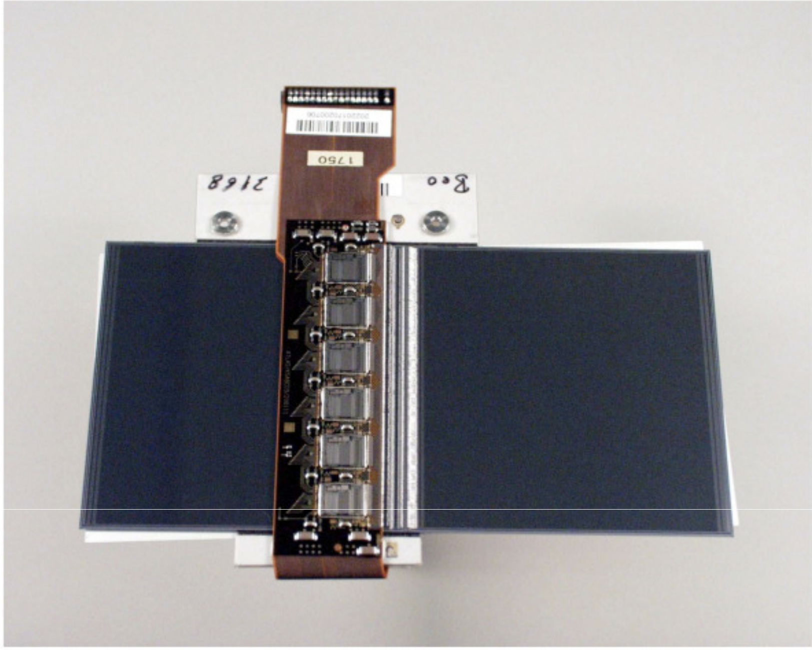


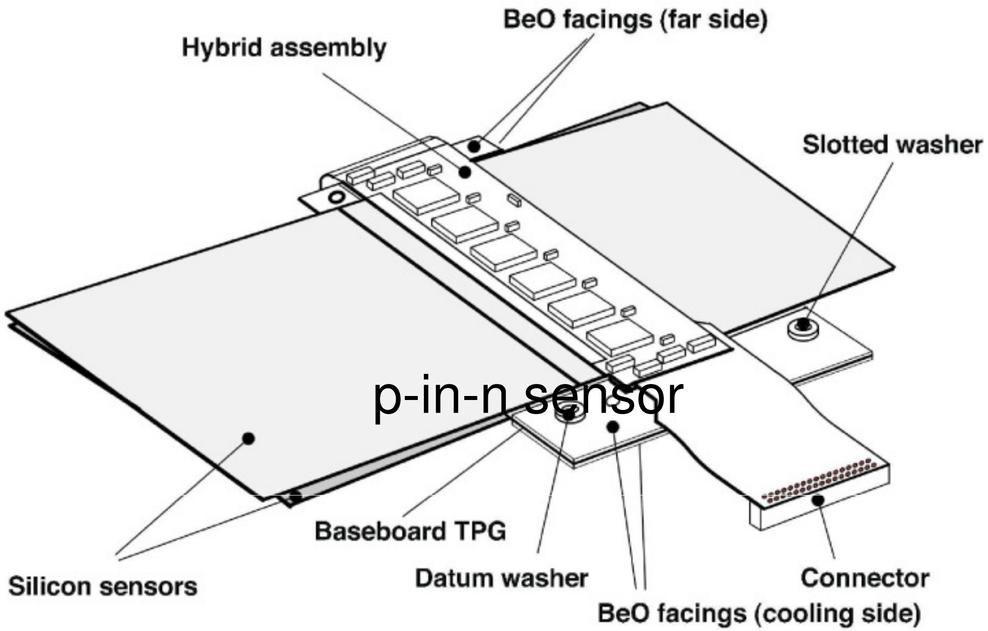
ATLAS Inner Tracker

- Luminosity 1×10^{34} cm^{-2}s^{-1}
- Integrated fluence 2×10^{14} 1-MeV n_{eq}/cm^2 at r~30 cm

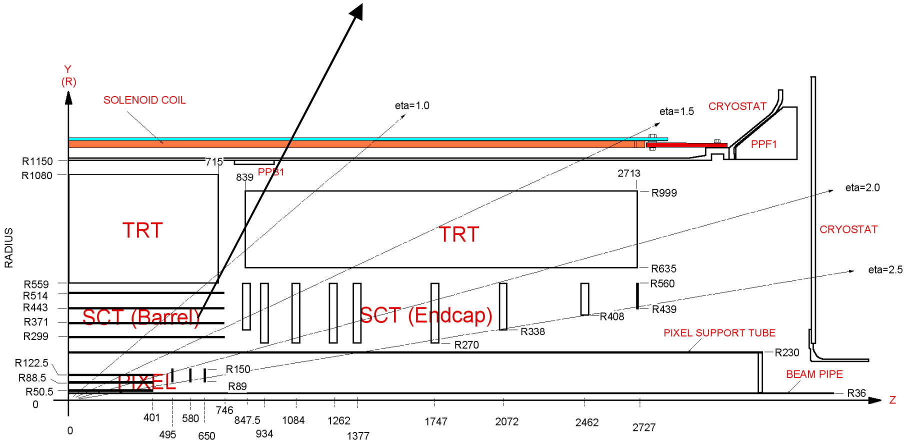


SCT Modules (silicon strips)

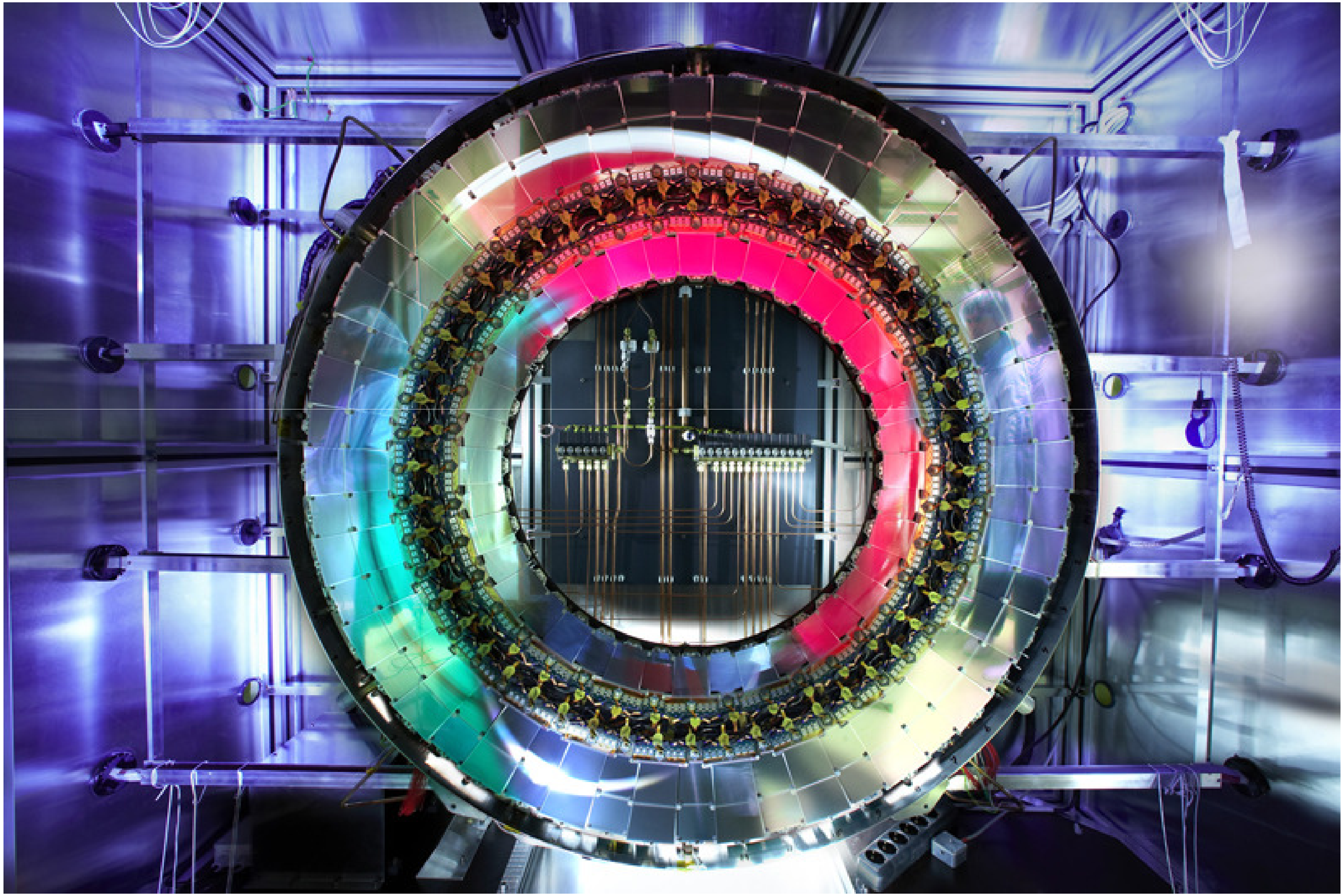




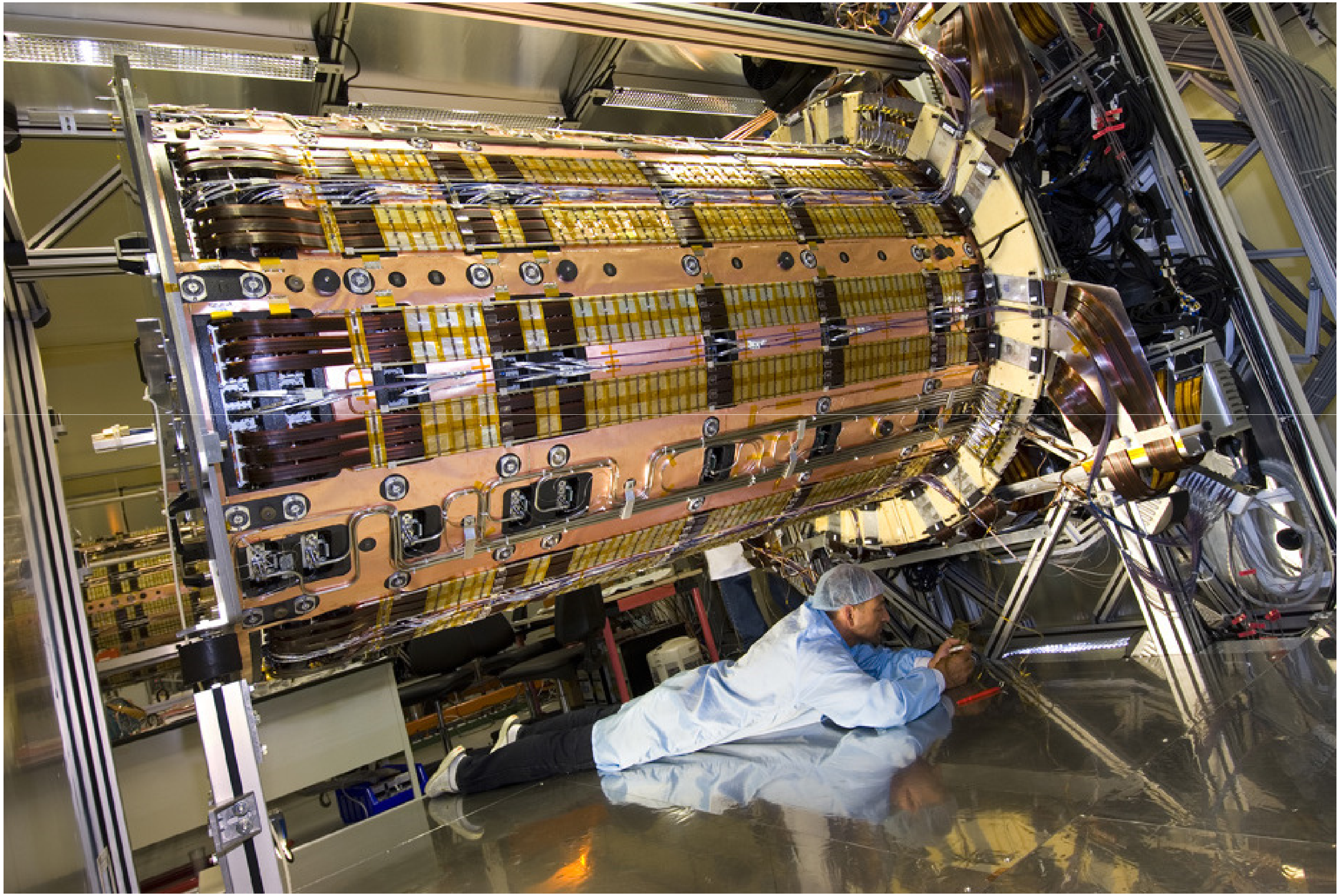
p-in-n sensor



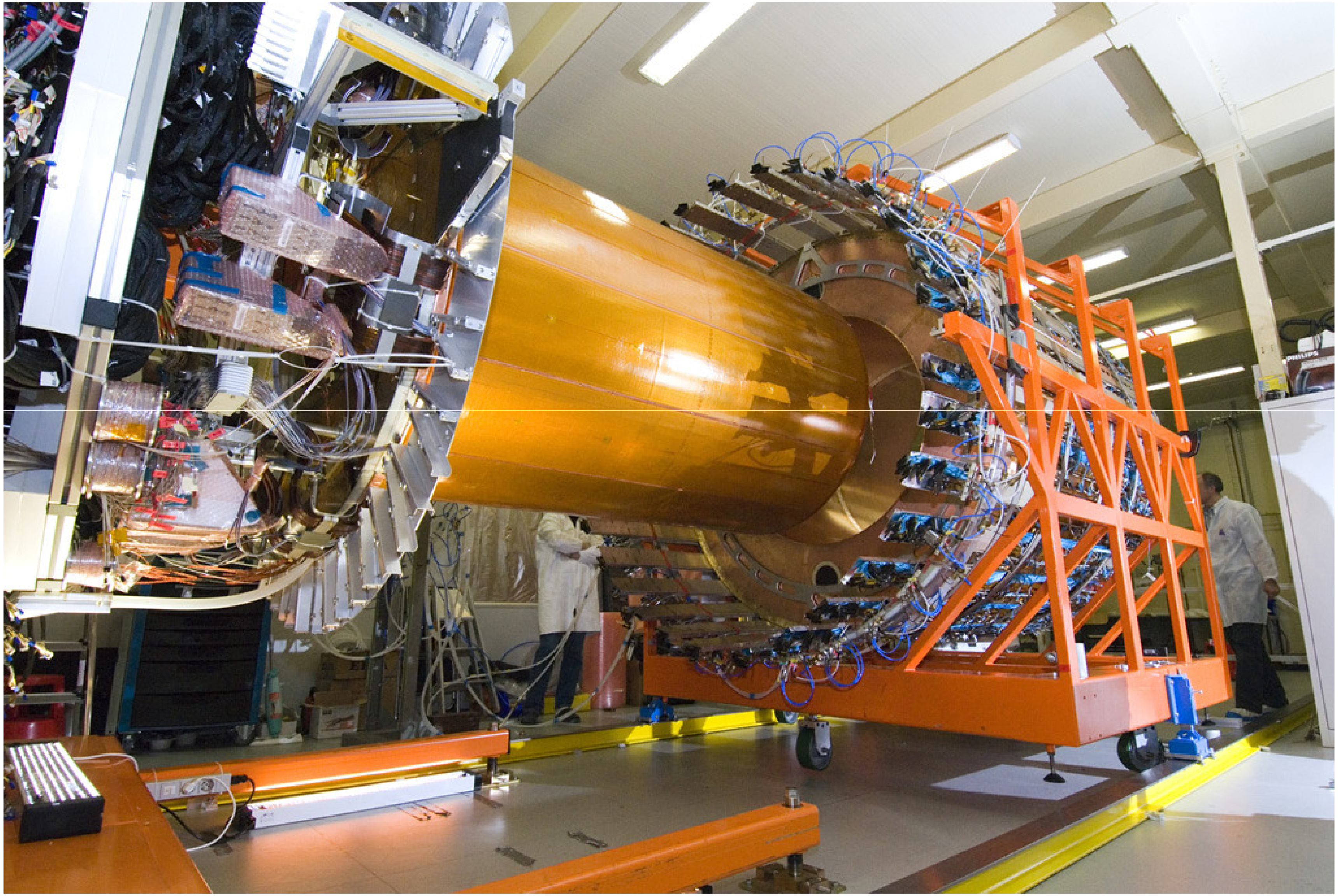
ATLAS SCT (Strip Tracker)



ATLAS SCT

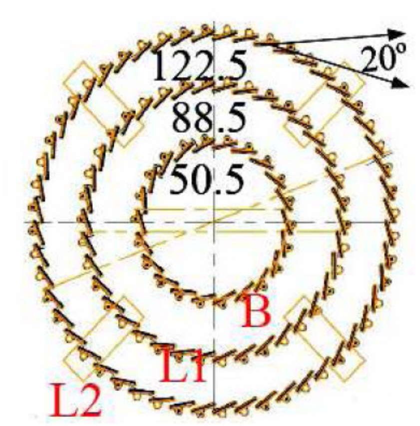


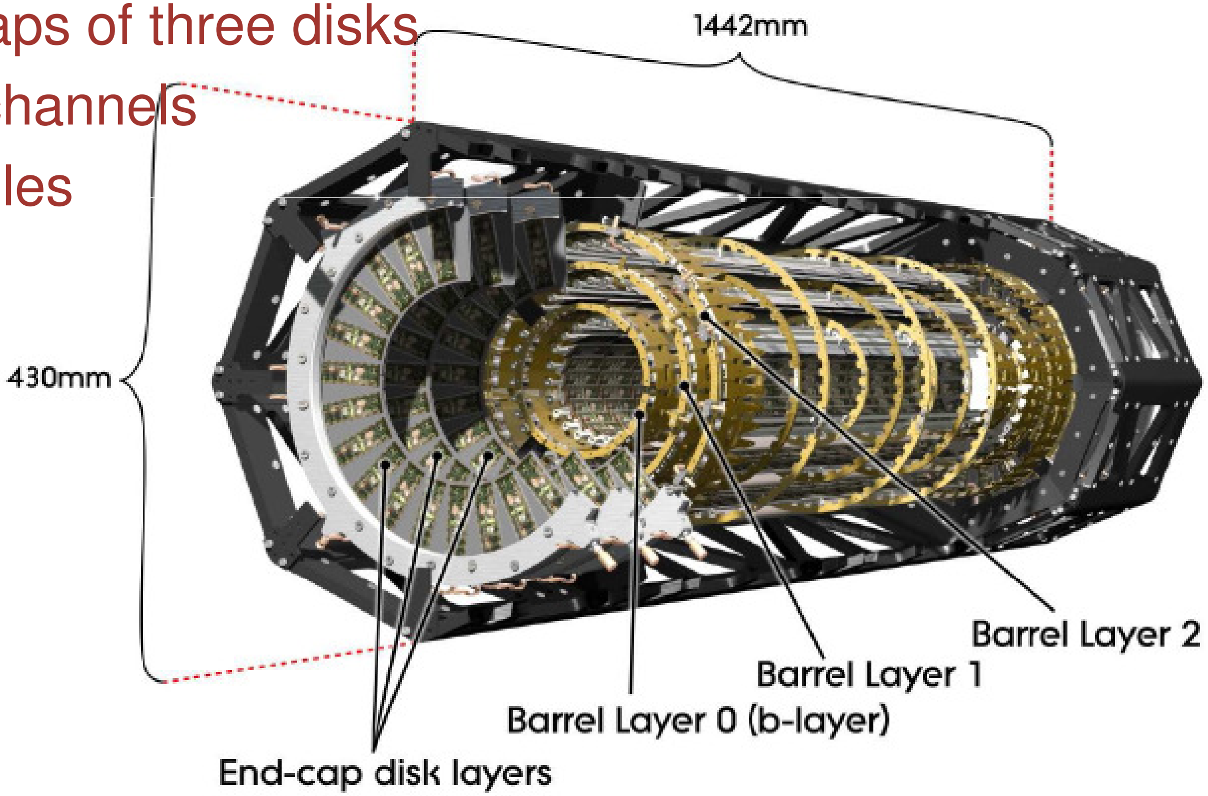
SCT in TRT



ATLAS Pixel Detector: Overview

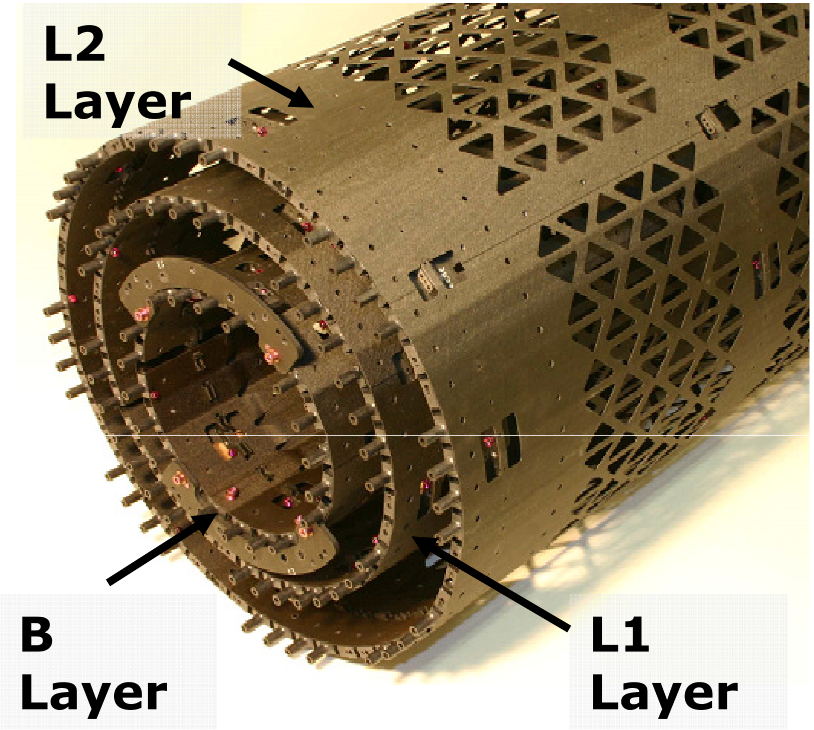
- Innermost detector of ATLAS
  - precision tracking and impact parameter measurements
  - Radiation-hard silicon sensors and front-end electronics
- Three ‘barrel’ layers in the central region
- Two end caps of three disks
- 80 million channels
- 1744 modules

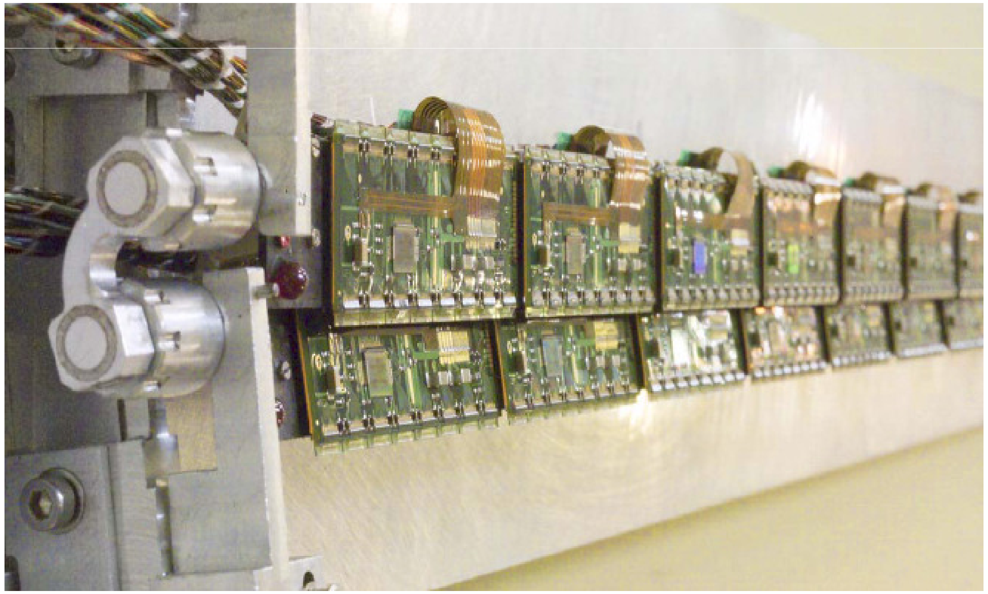




ATLAS Pixel 'Barrel' (cylindrical part)

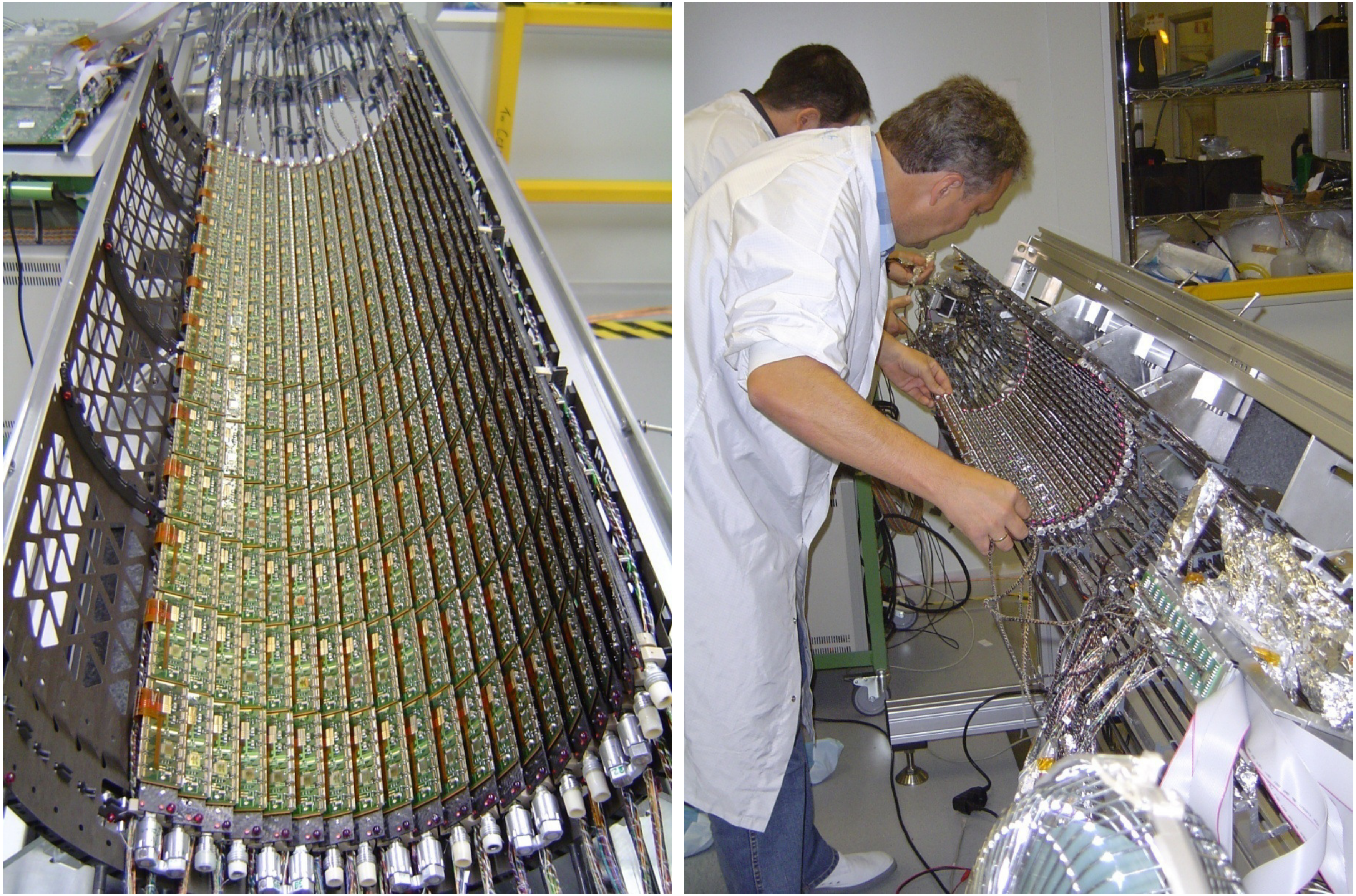
- barrel frame (carbon fiber laminate)
- 'staves'
  - 13 modules
  - carbon-carbon support



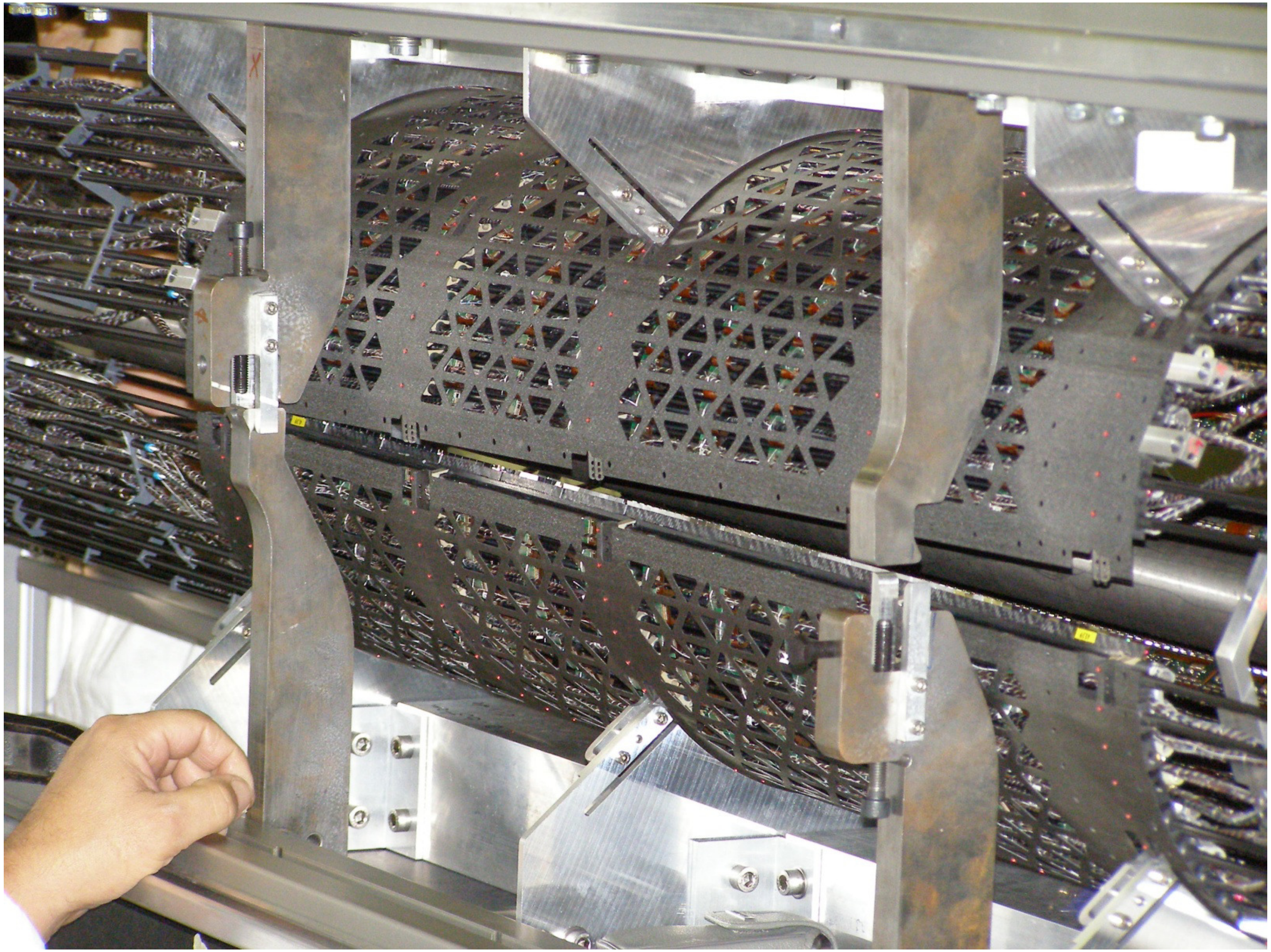


- two staves are linked by a unique cooling tube

Filling the Barrel

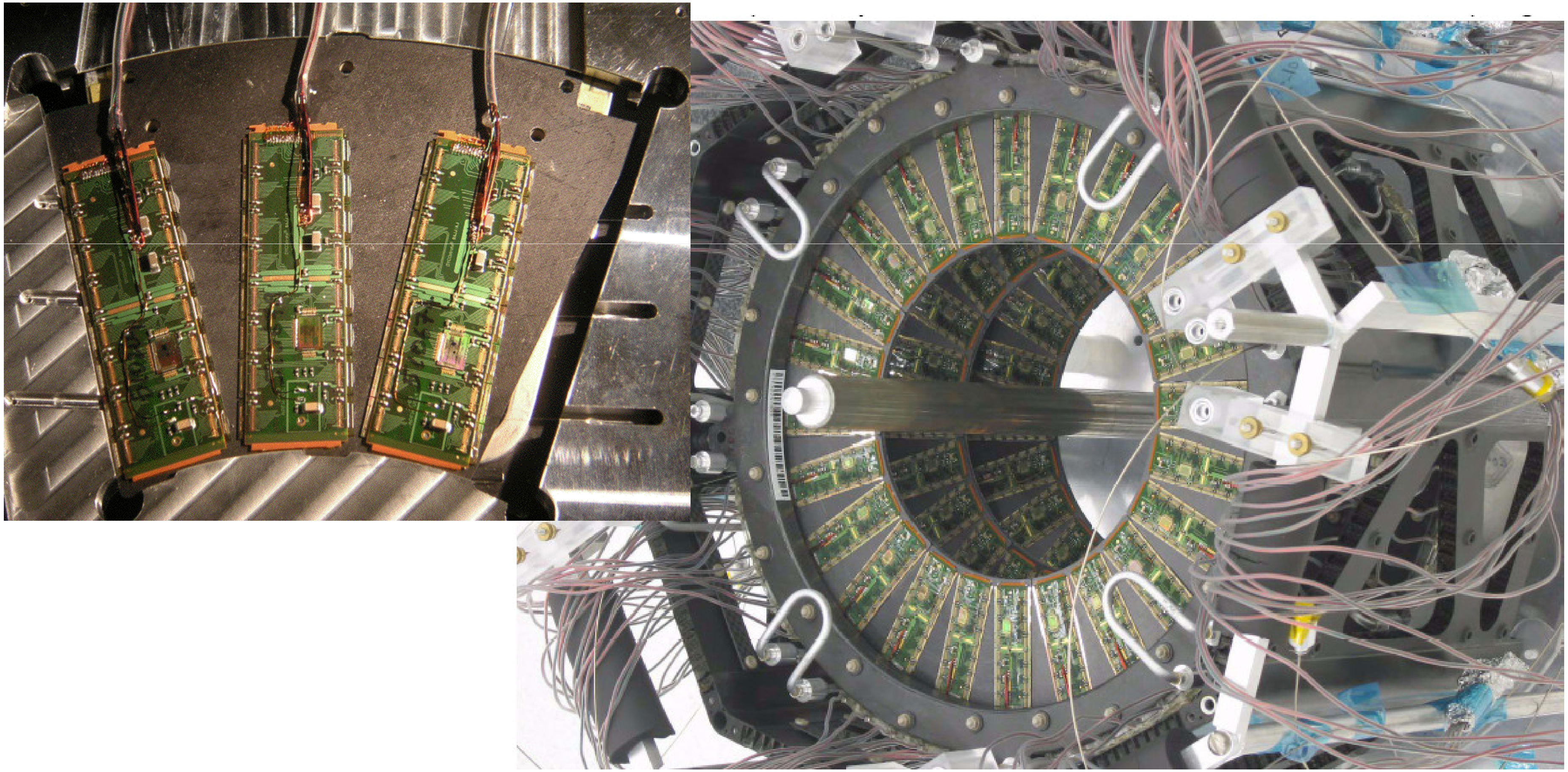


Joining the two Half-Shells



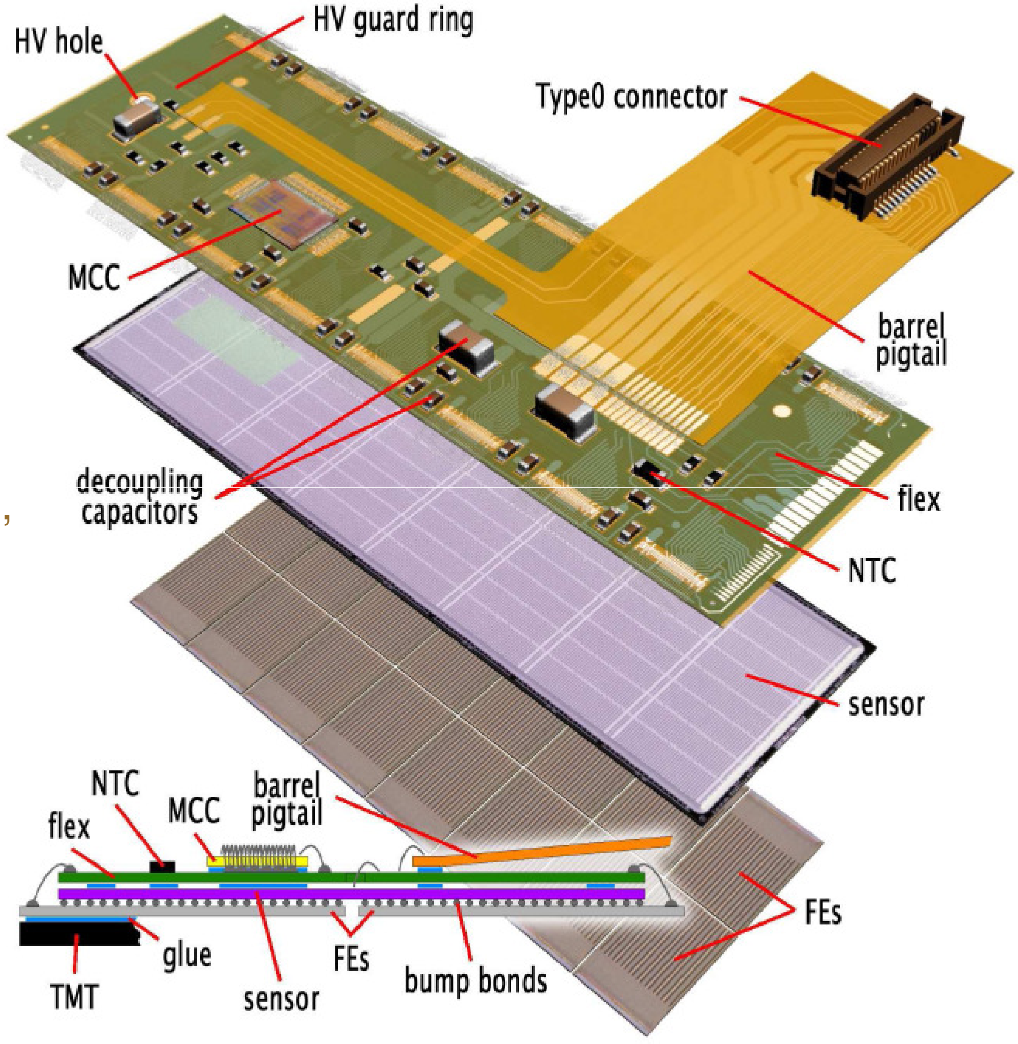
ATLAS Pixel ‘End Caps’

- Sector: 6 modules mounted on carbon-carbon plates, sandwiching the cooling pipe.
- A disk has 8 sectors



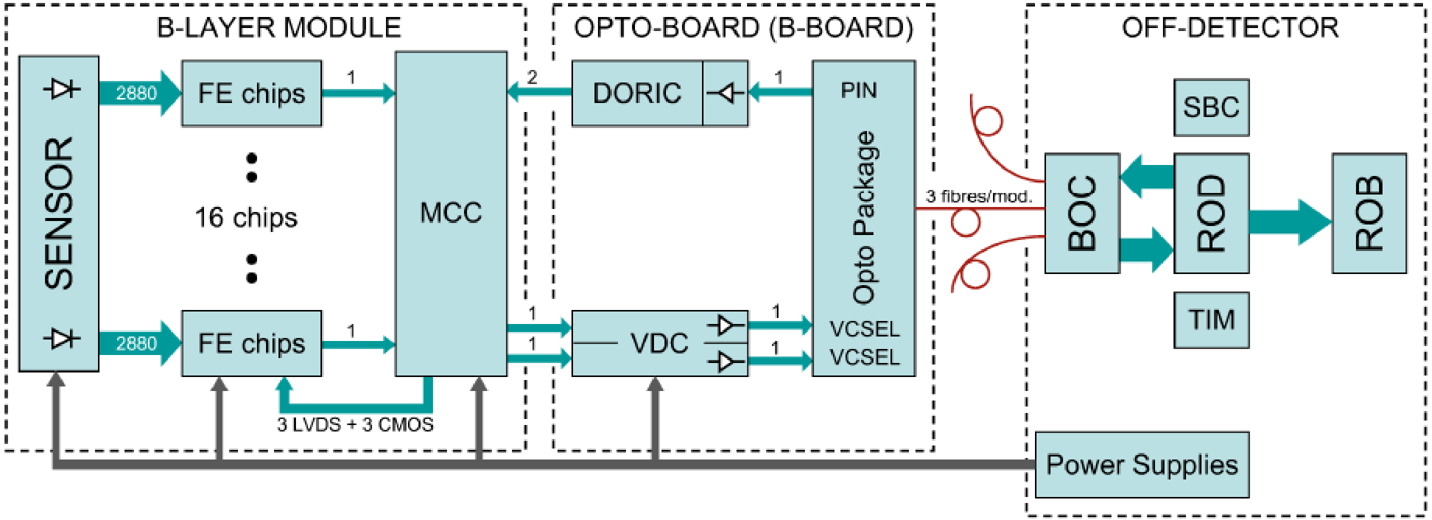
Pixel Modules

- Sensors
  - n-doped bulk with n^+ pixels
  - pixel dimensions: 50 μm × 400 μm
  - Bulk depth: 250 μm
  - Radiation-hard to 50 MRad
- 16 Front-end (FE) chips
  - Bump-bonded to the pixels
  - 0.25um CMOS technology
  - Analog pre-amplification, discrimination, (TOT) measurement, and digitization
- Flex Board
  - Connection to readout electronics
  - Distribution of power and HV
  - Temperature measurement (NTC)
  - Module control chip (MCC)
    - Communication with FE
    - Multiplexing FE data



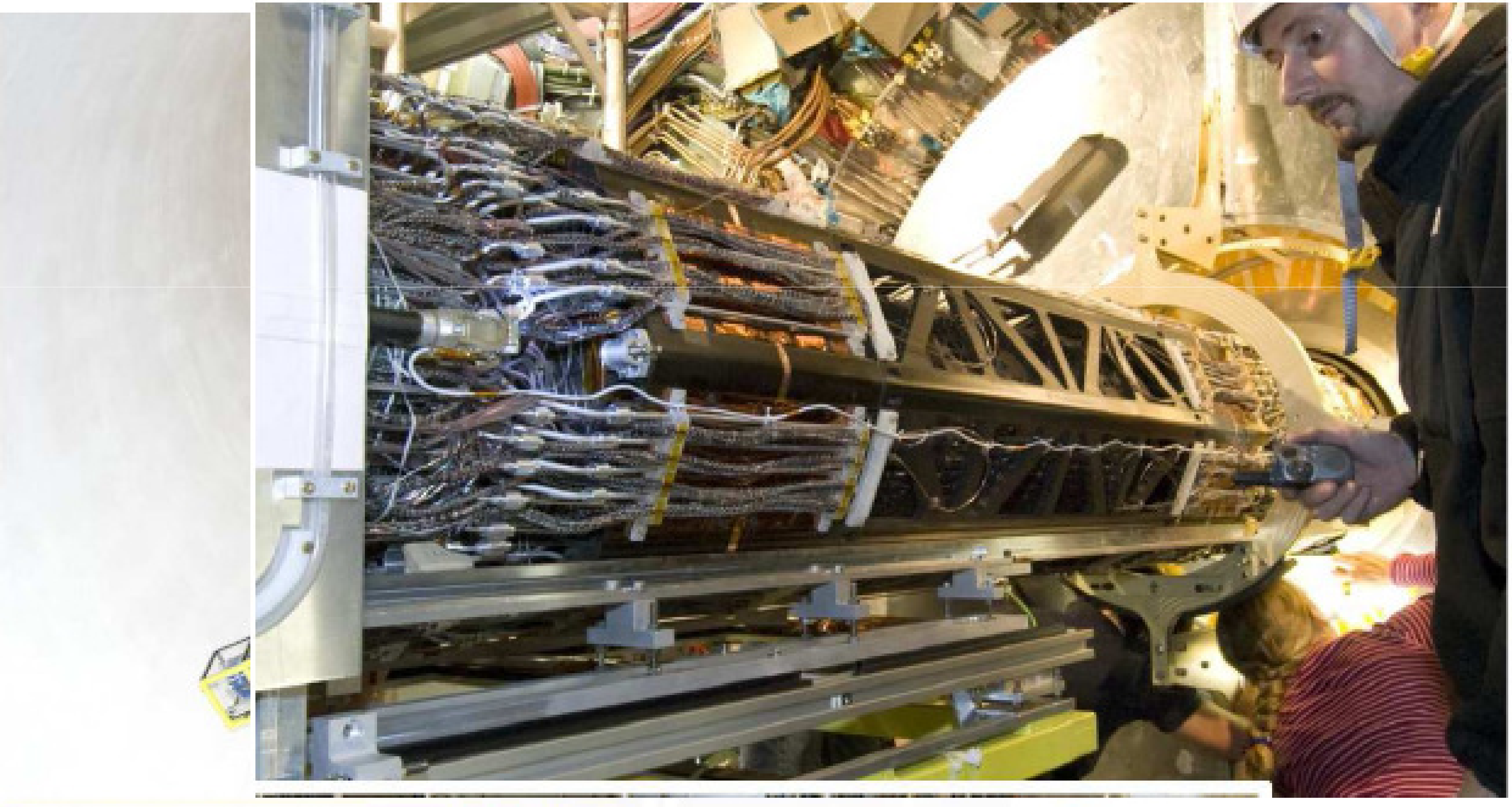
Readout

- Opto-boards
  - Close to modules
  - Convert signals from electrical to optical (VCSEL lasers)
- Off-detector DAQ crates
  - Back-Of-Crate (BOC) card converts back from optical to electrical and de-serializes the data into 40 MHz streams
  - Read-Out-Driver (ROD) units format and monitor the data
- Similar path from DAQ → Modules

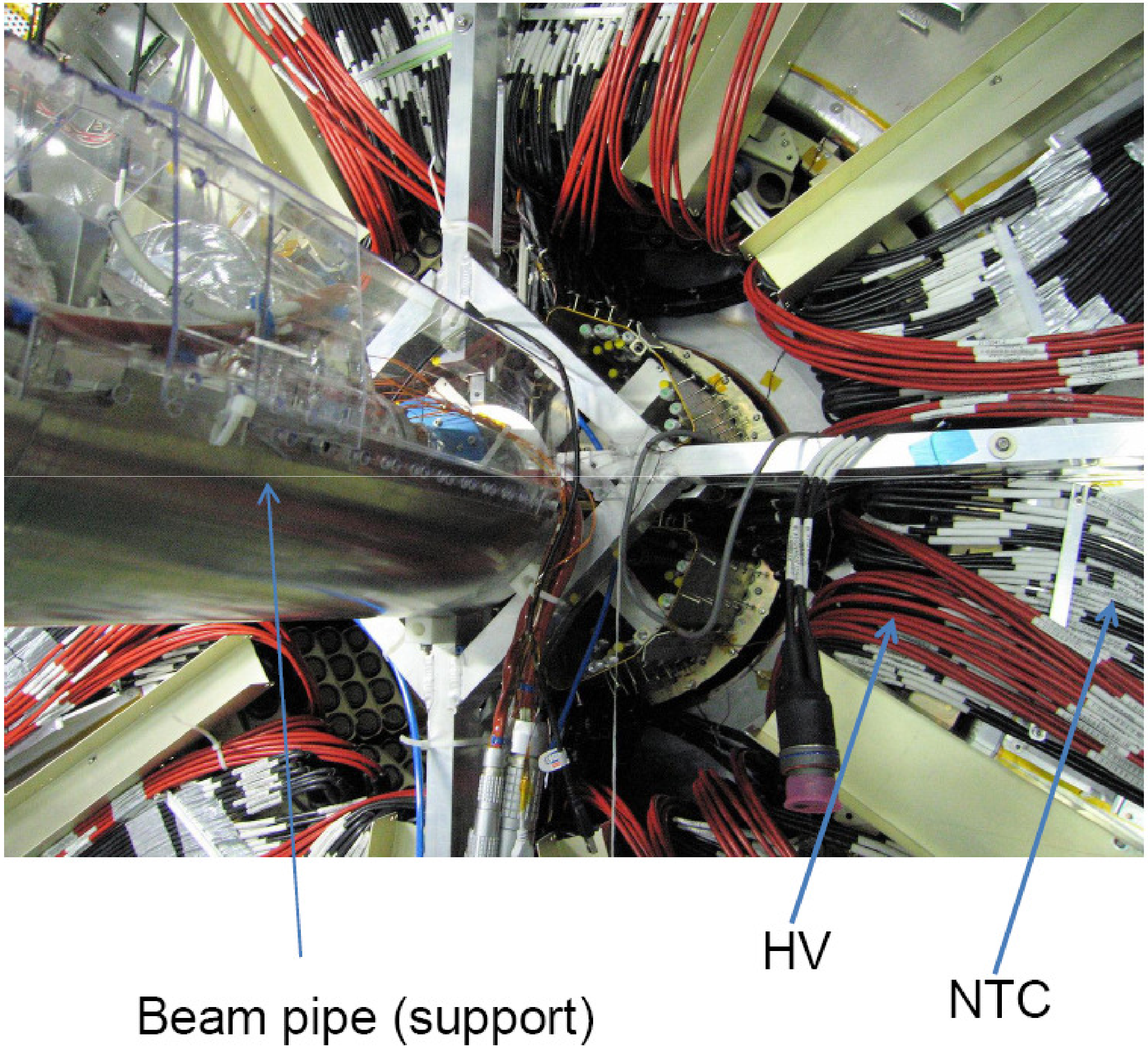


Installation Timeline

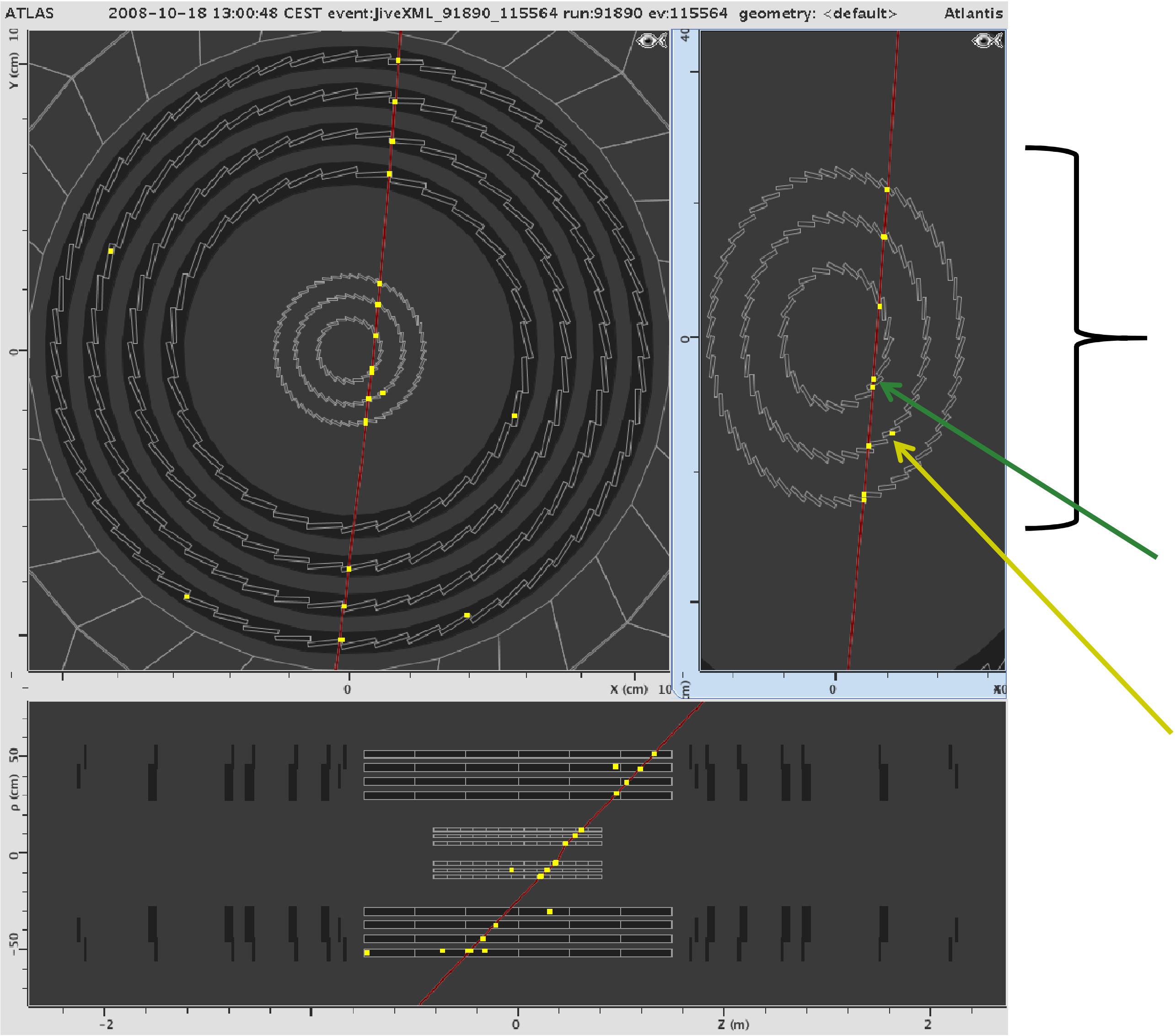
- Installed @ CERN 6/2007, connected 4/2008
- Cooling system was commissioned loop by loop (88 loops total)
  - Three loops with significant leaks and some with instabilities at low heat load



How a Detector System Really Looks…



An Example of a Golden Cosmic Track

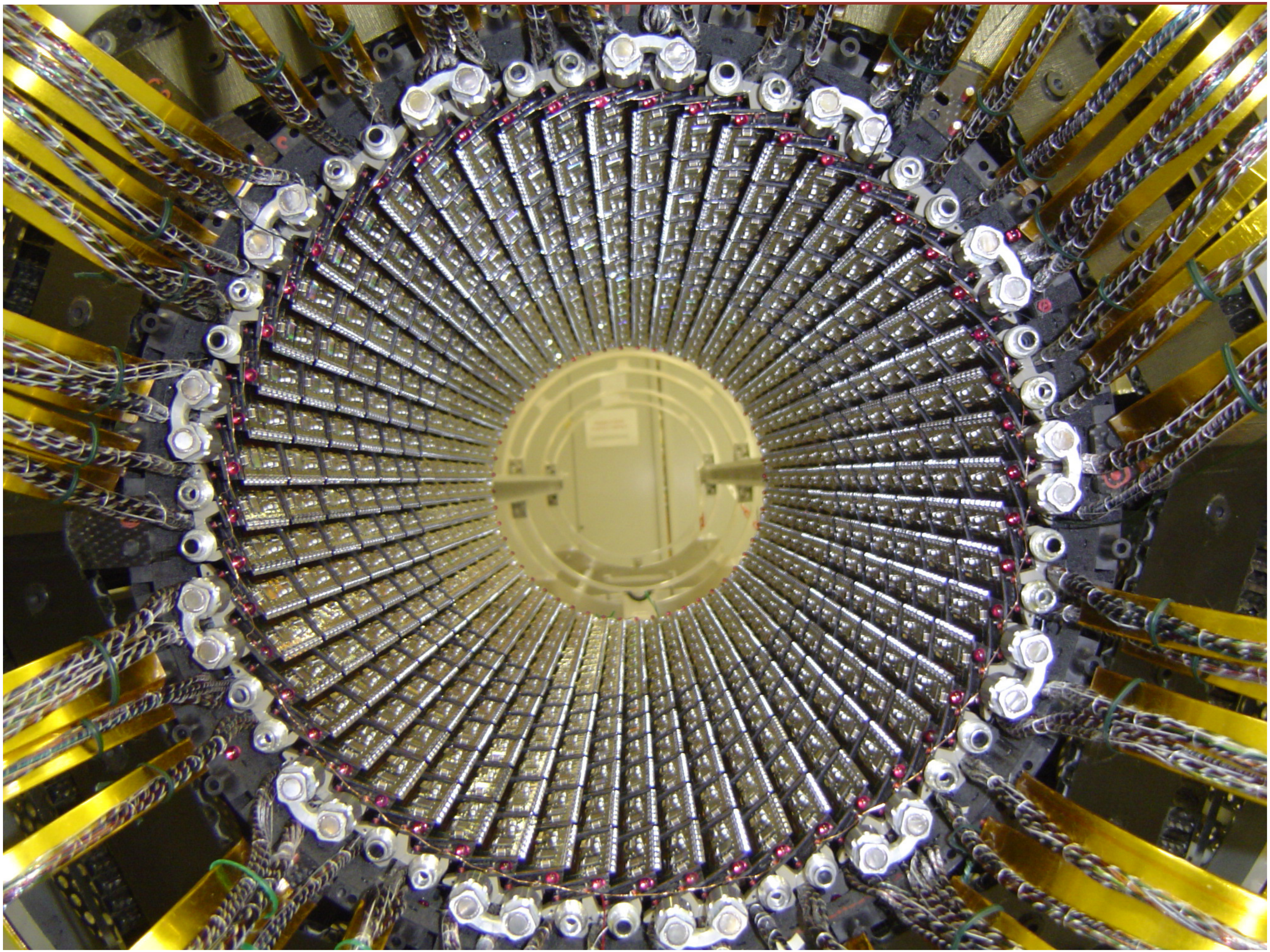


Hits in both hemi-cylinders

A double hit in module-overlap region

Only one noise hit

After masking noisy pixels (0.01%), noise occupancy at 2×10^{-10} per BC



For Comparison: CMS Tracker

RUPRECHT-KARLS-
UNIVERSITÄT
HEIDELBERG

SPECTROMETER IN SPACE

AMS: The Alpha Magnetic Spectrometer Experiment

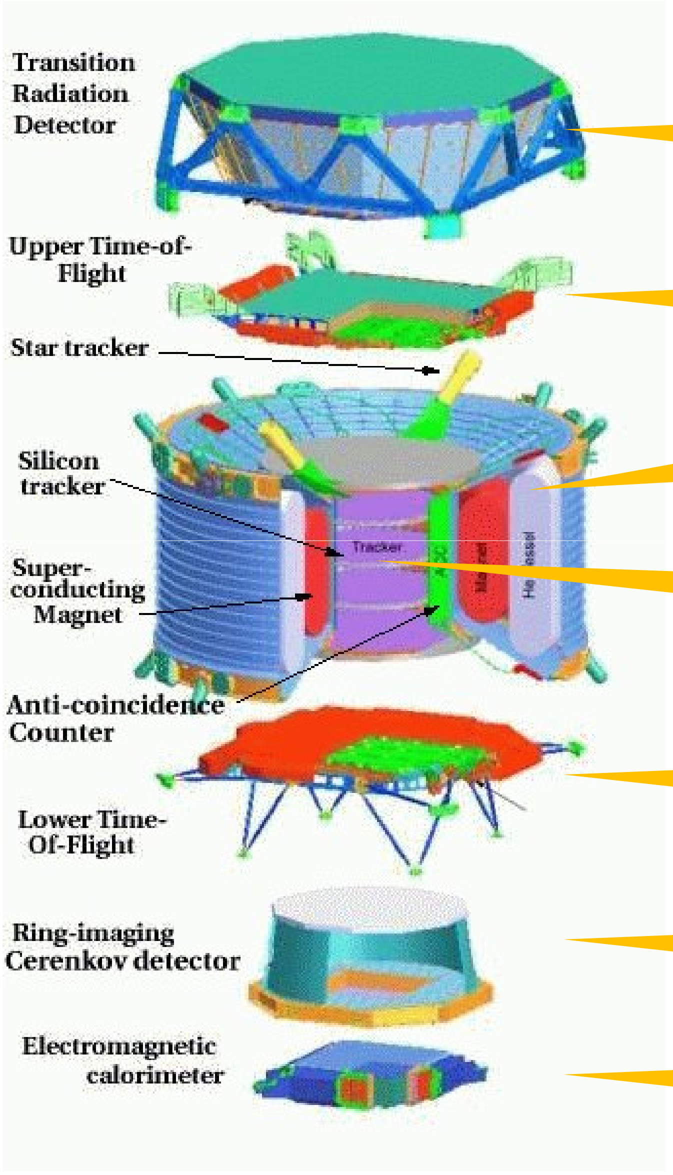
- Launched finally in 2011 (after many delays since 2005..)

- Detector has been installed at the ISS
  - 6.7 tons
  - 2000 W
  - 2 MB/sec data to ground
  - 750 MHz PC with Linux, 4 redundant copies

AMS Scientific Goals

- search for **heavy antimatter** in cosmic rays, by measuring the charges on ~1,000,000,000 helium and other nuclei
- collect precision cosmic ray data at **high energies**, including 10^{10} protons
- discover or rule out certain particles as explanations for **dark matter**
- study **cosmic ray propagation** in the galaxy
- search for **exotic particles** or spectral features among cosmic rays

AMS Detector



Velocities of high energy particles

Speed of slower particles

Superconducting (!) Magnet

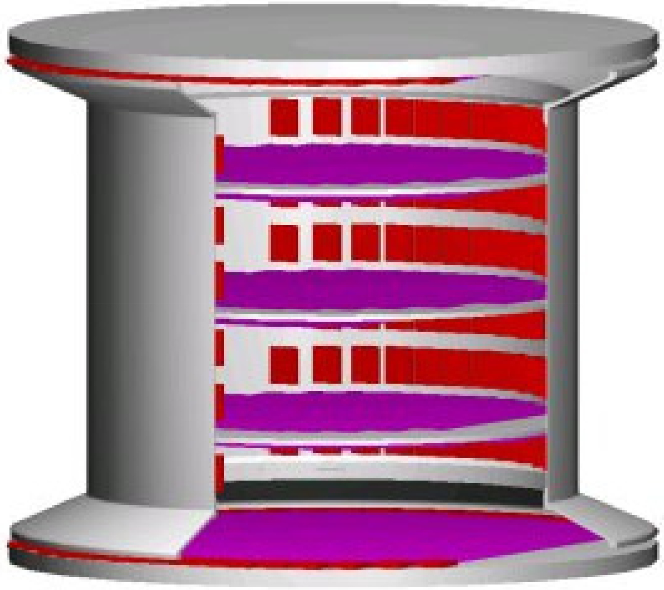
Silicon Tracker

Speed of slower particles

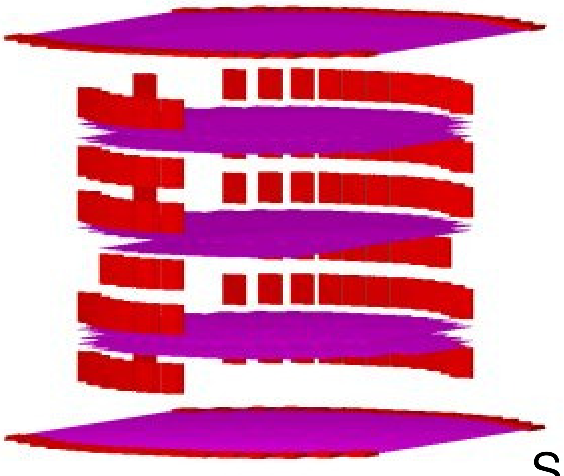
Precise velocity of fast particles

Energy & Type of particle

AMS Silicon Tracker



Support



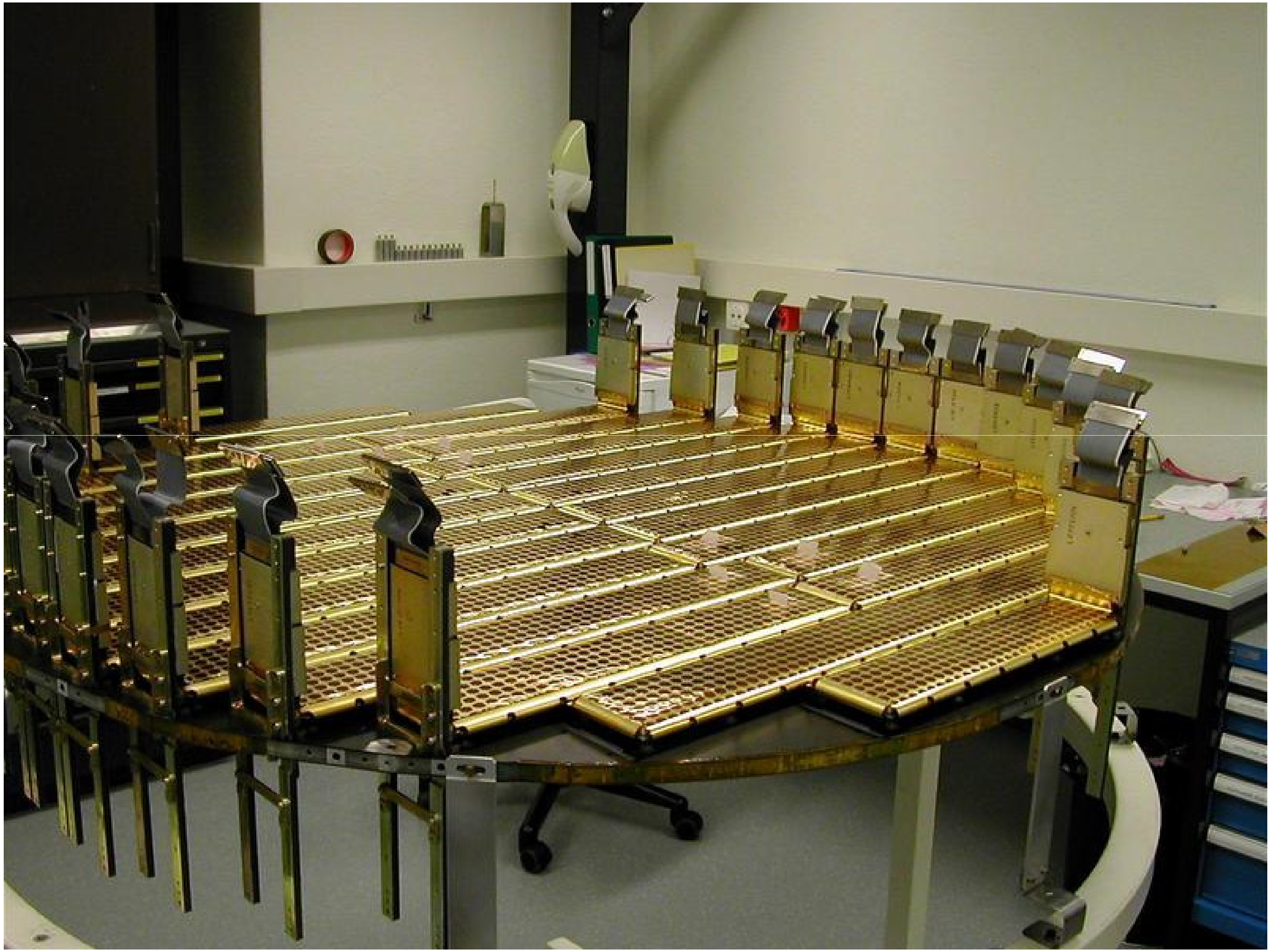
Silicon

Ladders

AMS Ladder in test stand

AMS Readout Hybrids

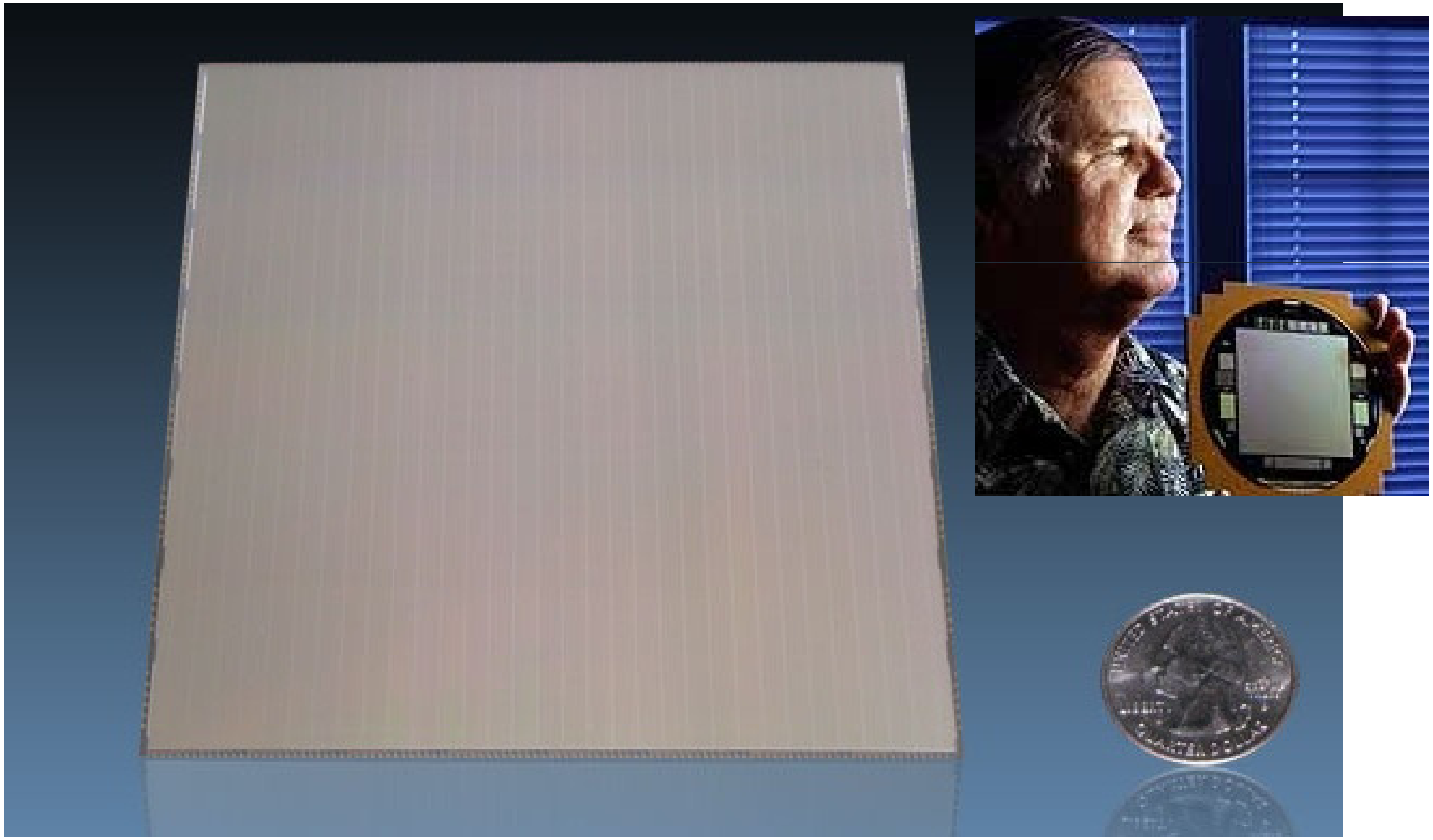
AMS Silicon Tracker + Support



Earth Observation with CCDs

Ultra High Resolution (optical) CCDs

- 10560 x 10560 pixels (9x9um^2) > 100 Mpixel !
  (Semiconductor Technology Associates)
- CCDs have (much) better QE than APS!



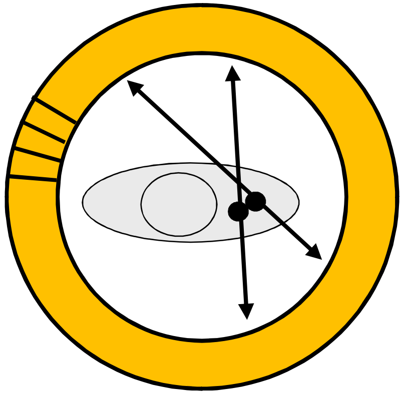
Making Test Pictures from Space

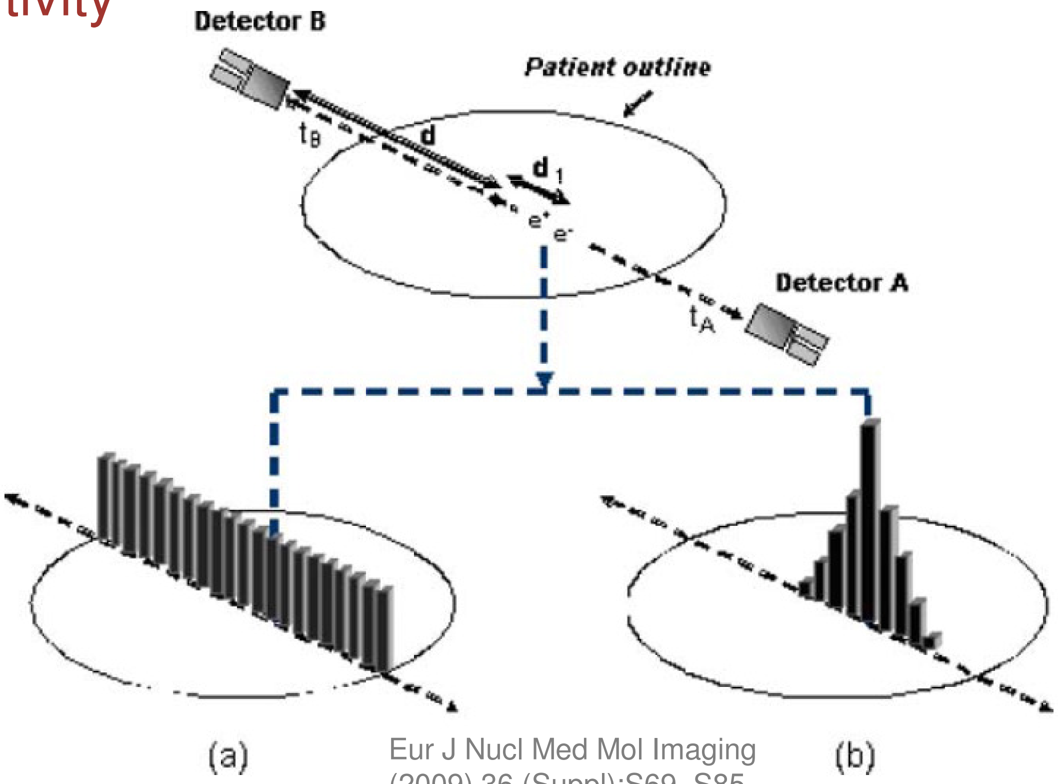
- ‘Siemensstern’ on a house roof

PET

PET Principle

- Positrons annihilate at marker positions
- Must detect coincident pairs of 511 keV γ
- With very good time resolution (some 100 ps), can determine decay position along line of flight (‘ToF’) → higher sensitivity

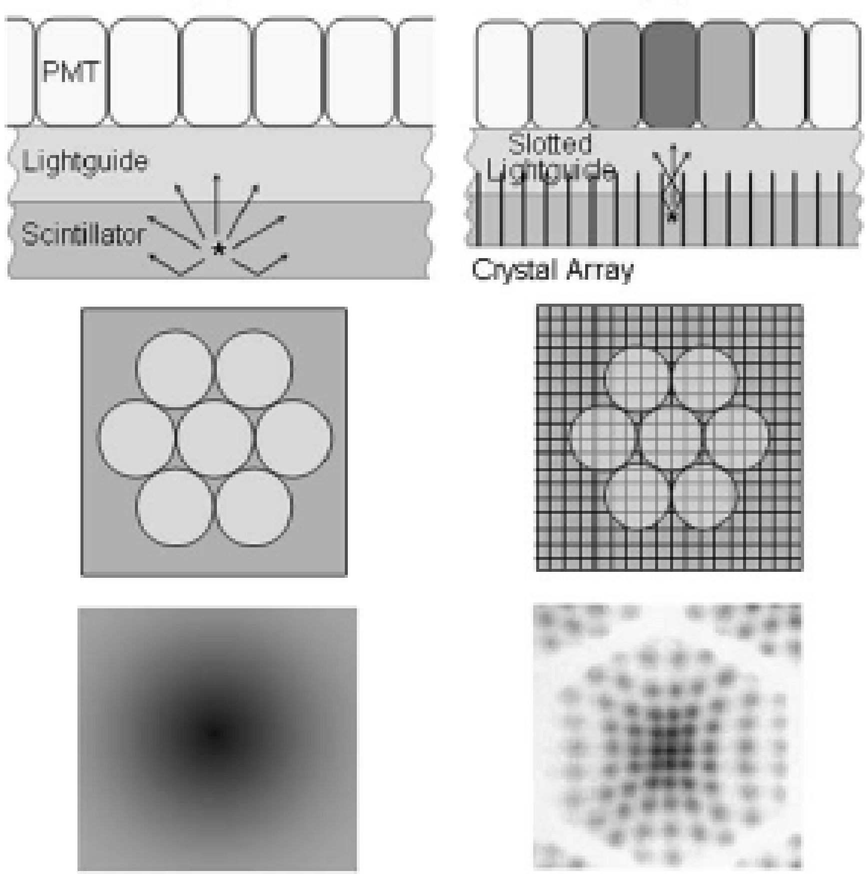




Eur J Nucl Med Mol Imaging (2009) 36 (Suppl):S69–S85

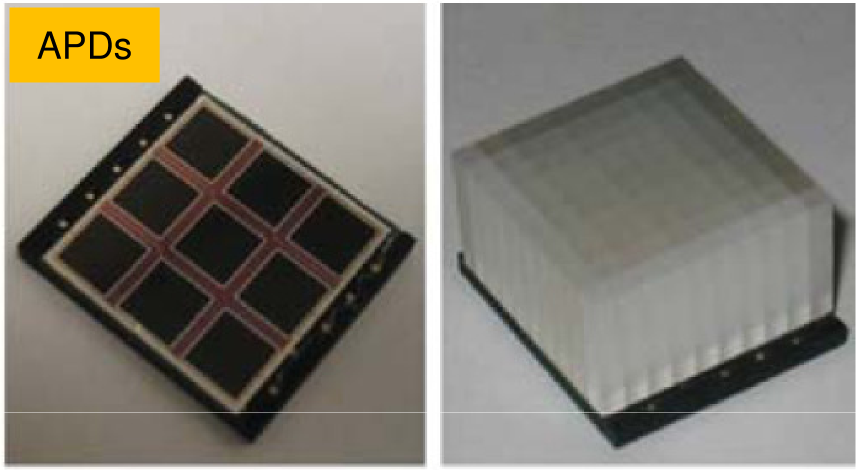
Classical Gamma Detector

- Crystals + PMTs for photo detection
  - Resolution via interpolation
  - Not possible in magnetic field

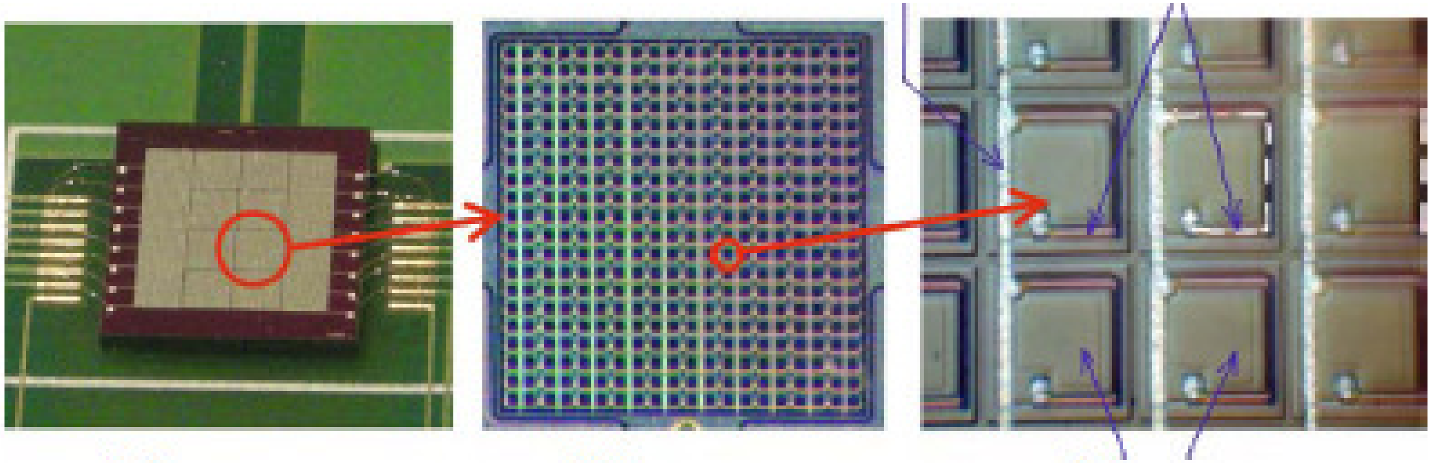


Next Generation: Solid State Detectors

- For use inside of MRI Scanners ‘PET-MR’, can use
  - APDs
  - SiPMs



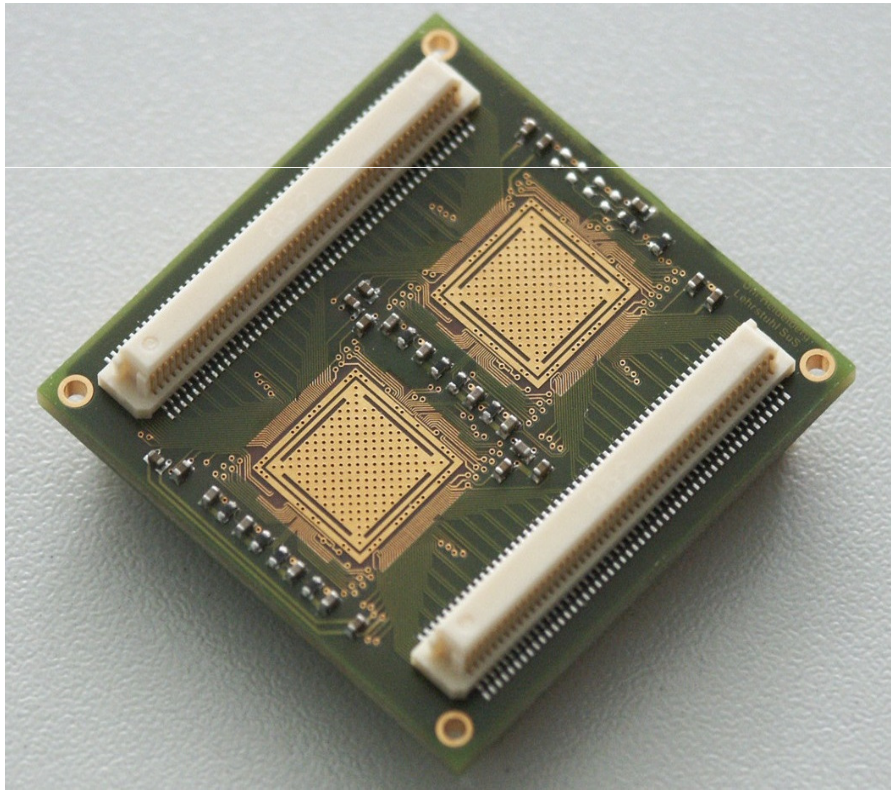
Eur J Nucl Med Mol Imaging
(2009) 36 (Suppl):S69–S85

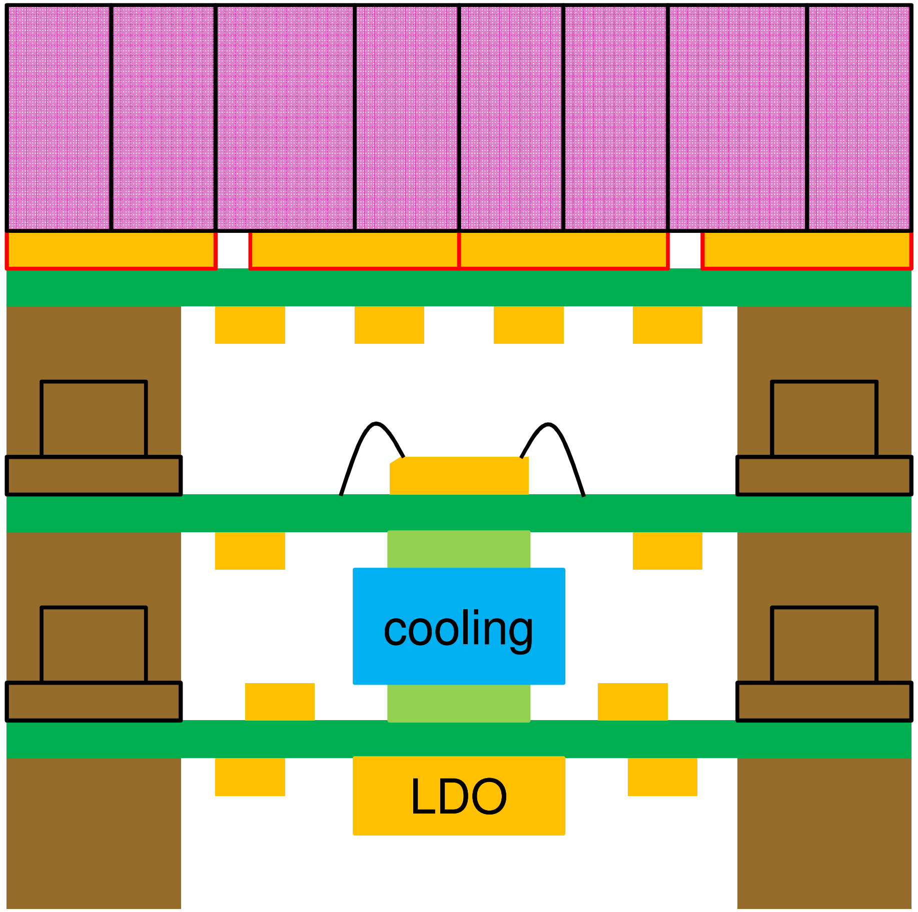


(a) SiPM array **(b)** SiPM pixel **(c)** SiPM cells

8 x 8 Channel PET Module

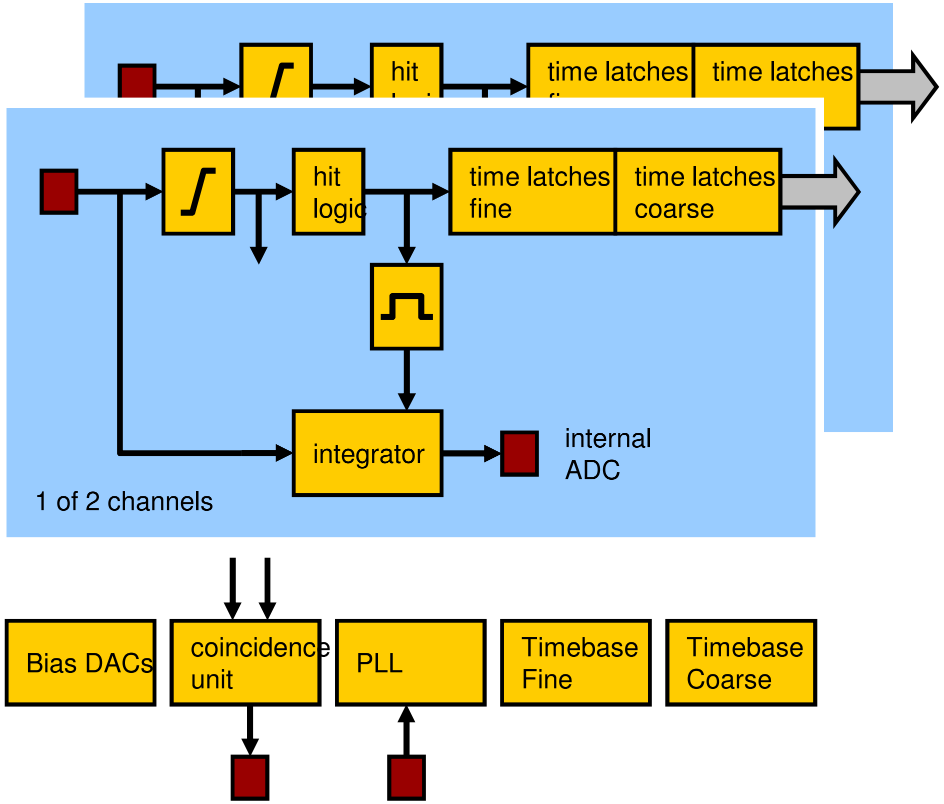
- Stack of 3 PCBs (~3x3 cm^2):
  1. SiPMs
  2. Amp. + Timing Chip
  3. Control & Power

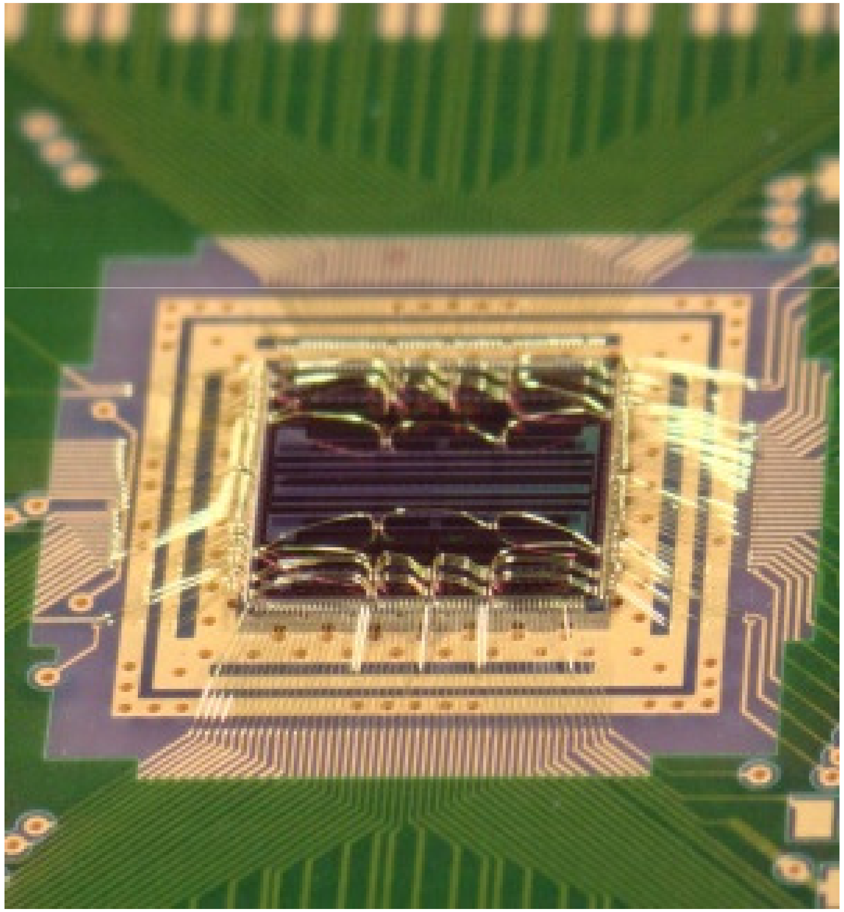




40 Channel PET Chip

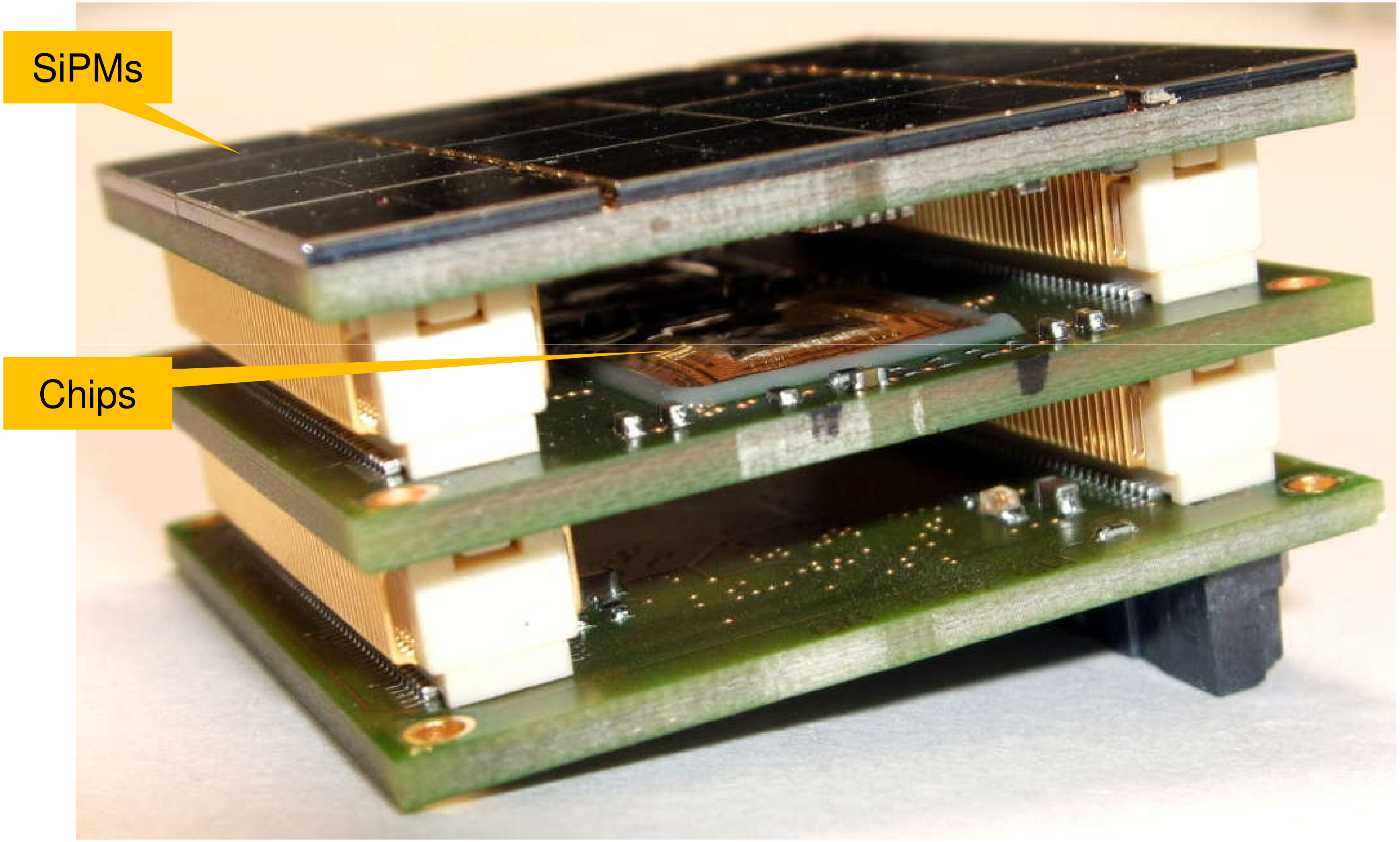
- Need integrated chip solution for many channels
  - ToF: better resolution
  - larger detector (capture more gammas → reduced patient dose)





The Finished Stack

- Constructed by my group in the ‘HyperImage’ Project



SUMMARY

Measured Quantities

- Directly detected:
  - Visible Light … soft X-rays
  - Charged Particles (electrons, protons, pions,… , ions)
- With additional tricks
  - Neutrons (convert with ^{157}Gd, track electrons (29-181keV))
  - Gammas (Scintillators + photo detector, converter foil)
  - High energy neutral particles (segmented calorimeters)
  - …
- Position
  - Imaging, momentum measurement,…
- Charge
  - X-ray energy, dE/dx, Z, light intensity
- Arrival Time
- Rates (particles/time)

Applications

- Astronomy
  - Optical Photons, also time resolved
  - X-rays (On satellites)
  - Polarimeter (Polarization of X-rays)
- Medicine
  - Radiography, Mammography
  - Auto radiography
  - Phase contrast X-ray imaging
- Biology
  - Microscopy
  - Single Molecule Detection
- Material Science, Industry, Safety
  - Crystal structure, Material composition,…
- ...

Requirements

- High Segmentation → Position
- Low Noise → precise charge, precise position
- Thick detectors → good X-ray / Photon absorption
- Thin detectors → low multiple scattering (HEP, TEM)
  → fast charge collection
- Radiation Hardness → no degradation
- Low Cost → Large Area
- Low Power → Low cooling, many channels
- Small Dead Time → little signal loss
- …