Sviluppo di rivelatori a semiconduttore per spettrometria, imaging e polarimetria per raggi X duri/gamma molli

Ezio Caroli and Natalia Auricchio OAS-Bologna

on the behalf of the Solid State Detector Group

Requirements for future hard X and soft gamma ray space instruments (10-1000 keV).

- At least a **two–order of magnitude increase in sensitivity** and angular resolution, with respect to current instrumentation, in the energy band up to several hundreds of keV (600-700 keV) is required to be able to solve several still open hot scientific issues.
- **Polarimetry** shall become a “standard” observational mode of cosmic ray sources in the hard X and soft gamma ray regime

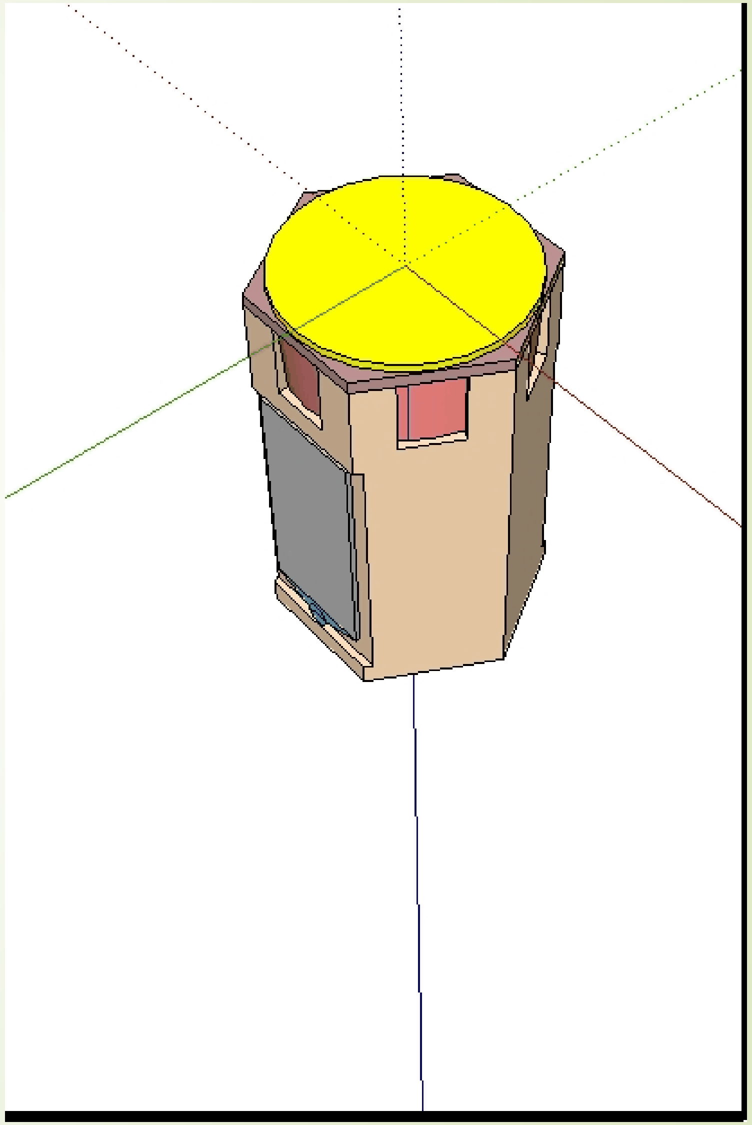
These requirements can be fulfilled only with space telescopes implementing new high energy focusing systems.

ASTENA
Advanced Surveyor of Transient Events and Nuclear Astrophysics
Mission concept proposed and studied in the AHEAD project framework (H2020)

- University of Ferrara: P. Rosati (Lead proposer), F. Frontera, C. Guidorzi, E. Virgilli.
- INAF-IASF Bologna/Palermo: L. Amati, N. Auricchio, L. Bassani, R. Campana,
- E. Caroli, F. Fuschino, C. Labanti, A. Malizia, M. Orlandini, J. B. Stephen, S. Del Sordo
- DTU Space, Copenhagen: C. Budtz-Jorgensen, I. Kuvvetly, S. Brandt
- INAF, Osservatorio Astronomico Brera, Merate: G. Ghirlanda
- INAF, Osservatorio Astronomico Bologna: R. Gilli
- University of Coimbra/LIP, Portugal: R. M. Curado da Silva
- CEA-Irfu/Saclay: P. Laurent

The ASTENA payload: two complementary high performance instruments covering the 1-20000 keV range.

- **A modular wide field monitor/spectrometer (WFM/S)**, with a passband from 1 keV to 20 MeV. The WFM/S relies on the THESEUS heritage: the instrument comprises18 detector modules based on the same technology and configuration for a total of 1.8 m^2 with a FOV of at least 1 sr.
- **A narrow field telescope (NFT)**, composed of a broad-band Laue lens (50 – 600/700 keV) of 15-20 m focal length, with a FOV= 2-3 arcmin, and an angular resolution of ≈20”. The NFT is coupled to a high efficiency (>80% above 600 keV) focal plane position sensitive detector, with 3D spatial resolution of 300 μm in the (X,Y) plane, fine spectroscopic response (1% @511 keV) and with high polarimetric capabilities.



ASTENA Hot scientific points

- **GRB science (WFM and NFT):**
  - Detection, characterization and localization within a few arcmin of all classes of GRBs: high-z (-> GRB cosmology), soft/weak (GRB-SN connection), short (-> GW and multi-messenger astrophysics), ultra-long (-> pop III stars)
  - Spectra, light curves and polarization over a very wide band (1 keV – 20 MeV (-> GRB physics, fundamental physics with GRBs)
  - Investigation of poorly explored X-ray afterglows (>10 keV) and of totally unexplored soft gamma-ray afterglows with NFT (-> GRB and shock-emission physics, GRB jet structure and energetics)
- **Nuclear Astrophysics and Hard X-/soft γ-ray sources deep observation (NFT)**
  - Measurements with unprecedented sensitivity and angular resolution of the 511 keV line from the GC: origin (diffuse vs. discrete sources), dark matter, physics of galactic sources.
  - NFT measurements of the intensity and time behavior of lines emitted by the heavy elements produced in supernova explosions: e.g. nuclear burning processes in Type-1a supernovae, hypernovae associated to GW after-glow
  - High sensitivity polarization measurements for a wide class of sources (MDP<1% for a mCrab Source)

Cutting-edge technologies able to meet the challenges of the next space missions for hard X and soft gamma ray astronomy.

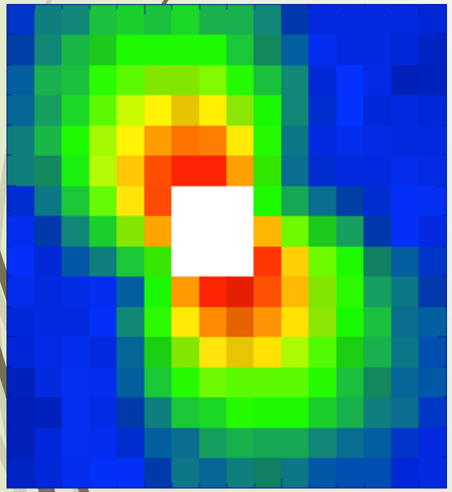
- **Broad band Laue lens.**
- New optics based on bent crystals (GaAs, Ge, Si) operating between 30-700 keV;
- Moderate focal length (15-20 m); Low mass (60 kg including the support) for a 2 m diameter lens.
- Italian leadership (University of Ferrara, INAF, IMEM/CNR) Development supported by ASI: (a) HAXTEL project (2007), (b) "Laue: a gamma ray lens" Project (2010-2013); (C) TRILL (INAF/ASI 2018)

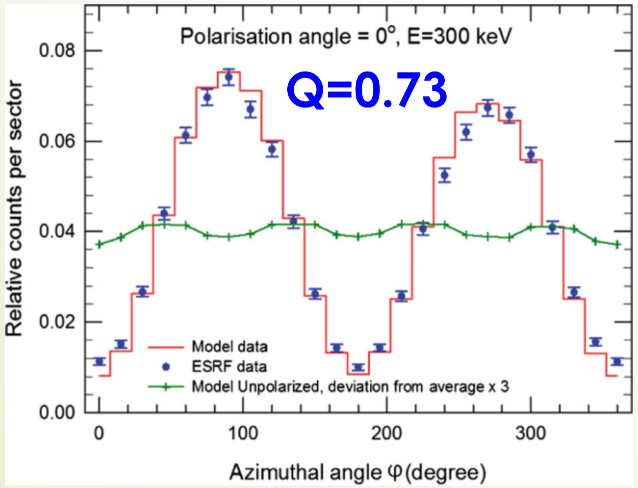
- **3D CZT spectro-imager.**
- High efficiency using Compton events in addition to photoelectric; rejection of environmental and instrumental background, e.g. using Compton kinematics;
- Uniform response achievable by means of signal compensation techniques;
- Very low degradation of the point spread function of the flux focused by a Laue lens or similar optics with energy by the identification of the photon interaction points for scattered events.
- High efficiency scattering polarimetry in high energy astrophysics above 100 keV;
- Fine spectroscopy also for multiple events because each hit signal comes from a small sensitive volume (voxel)

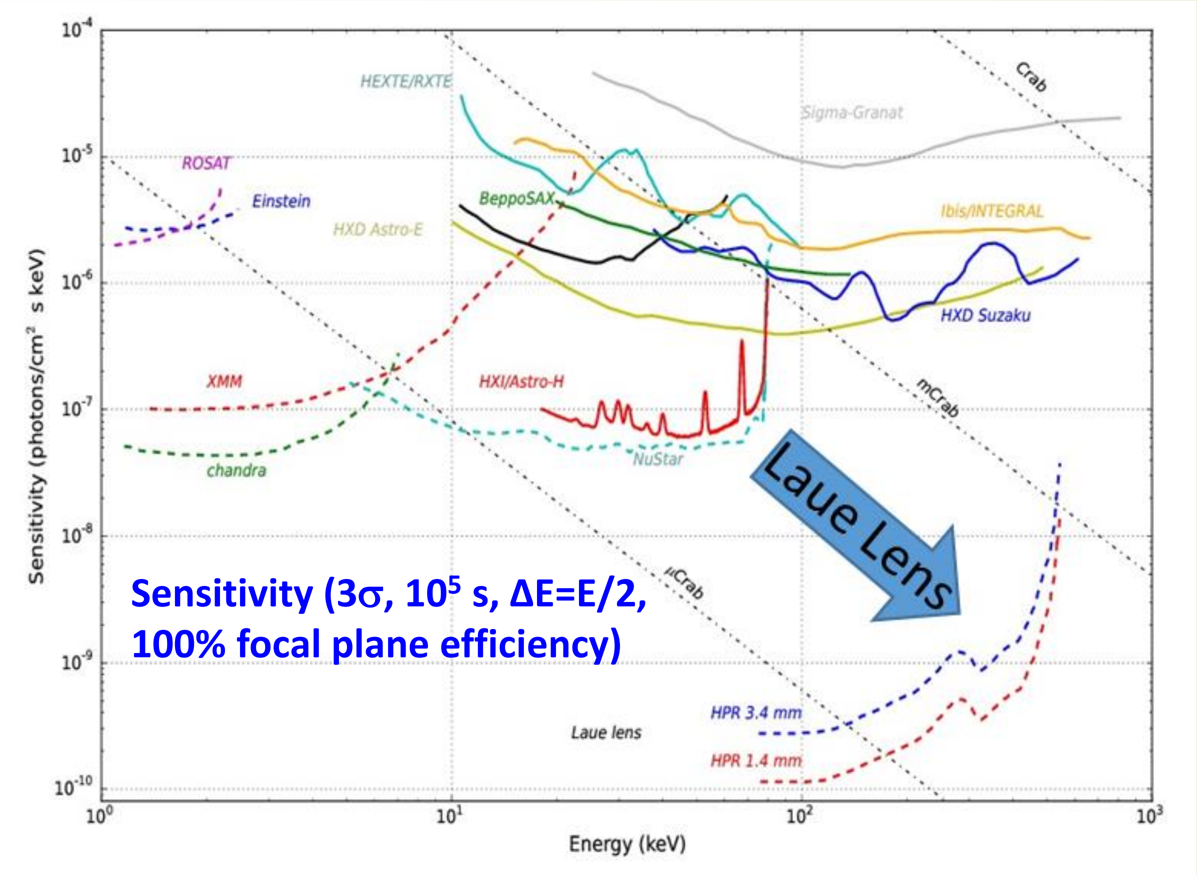
Key performances of a telescope based on Laue broad band optics and advanced CZT segmented focal plane detector

- Broad band laue lens telescope with 20 m focal length and 70-700 keV energy pass band (right)

- Polarimetric capability of a highly segmented (0.6 mm) CZT spectro-imager with fine energy resolution (1% @ 511 keV) (bottom)







Outline

- Solide State Group
- Collaboration
- 3D Spectro-Imager: Requirements and Advantages
- Detector implementing the drift strip method
- Approved and future projects
- 3D sensors and their characterisation

Solide State Group

- Ezio Caroli
- John B. Stephen
- Natalia Auricchio
- Milena Schiavone
- Angelo Basili
- Stefano Silvestri
- Giovanni De Cesare

Collaboration

Scientific Institutions:

- OAS Bologna, INAF, Bologna, Italy
- Dept. of Physics and Earth Science, University of Ferrara, Ferrara, Italy
- IMEM, CNR, Parma, Italy
- IASF-Palermo, INAF, Palermo, Italy
- INFN Sez. Pavia, Pavia, Italy
- DiFC/University of Palermo, Palermo, Italy
- CEA/Saclay, Paris, France
- DTU Space, Lingby, Denmark
- LIP, Coimbra, Portugal
- Physics & Astronomy Dpt., Sacramento, CA, USA

Industries :

- DTM-Modena, Italy
- TAS I-Milan and Turin, Italy
- Due2Lab S.r.l., Reggio Emilia, Italy
- 3D Plus, France

Detector Requirements and Advantages

- High detection efficiency (>80% at 500 keV), achievable with increased thickness;
- Fine spectroscopy (1% FWHM at 511 keV), achievable with small volume charge collection;
- Fine spatial resolution (<0.5 mm), achievable with high segmentation;
- Fine timing resolution (<1 μs) (in particular for transient as GRB's);
- Scattering polarimetry in parallel with spectroscopy, imaging and timing.

How we can fulfil these requirements?

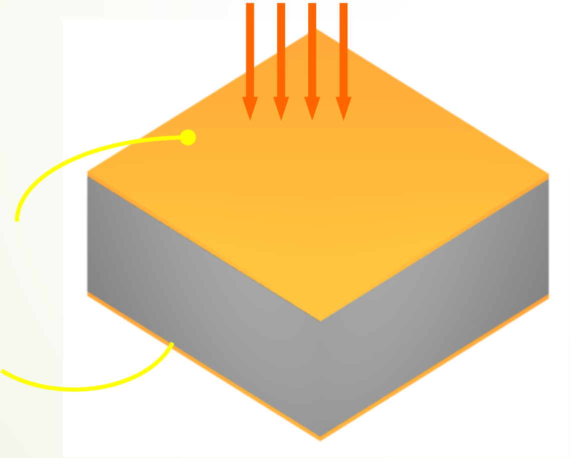
- Material: CZT (High Z ,RT)
- 3D Sensor Unit: drift strip anodes, segmented orthogonal cathode, depth sensing
- 3D Module: Package of 3D sensor units in a particular irradiation configuration

↓

3D High Z spectro-imager

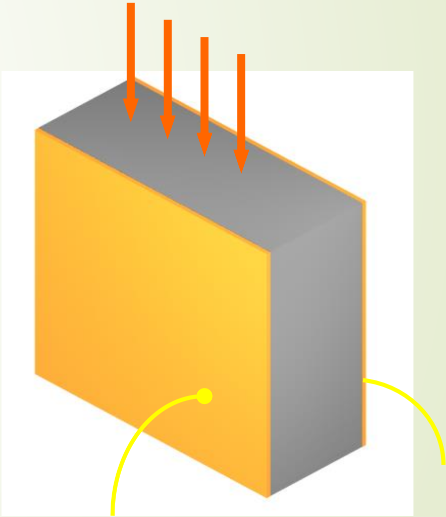
3D CZT Sensors - the starting point: Irradiation configuration

- ✓ Standard illumination geometry



PPF: Planar Parallel Field

- ✓ Side illumination configuration

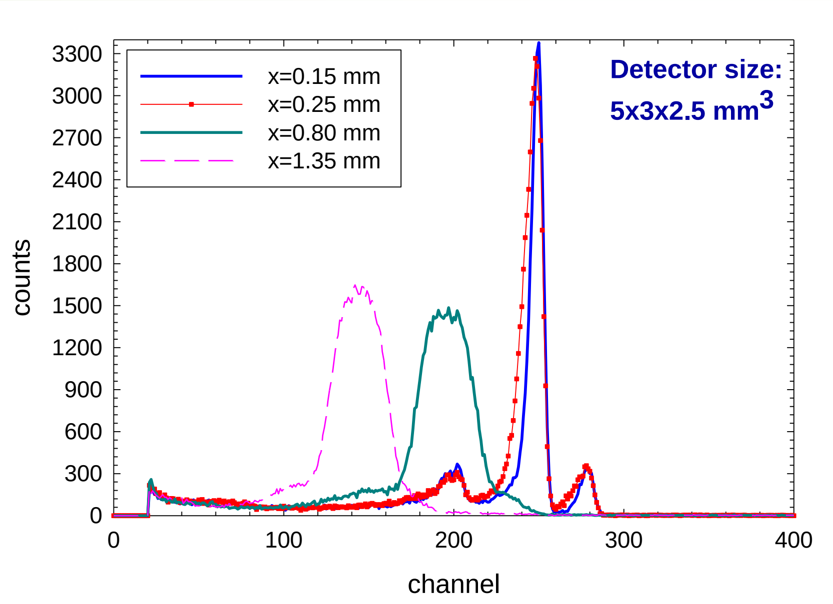


PTF: Planar Transverse Field

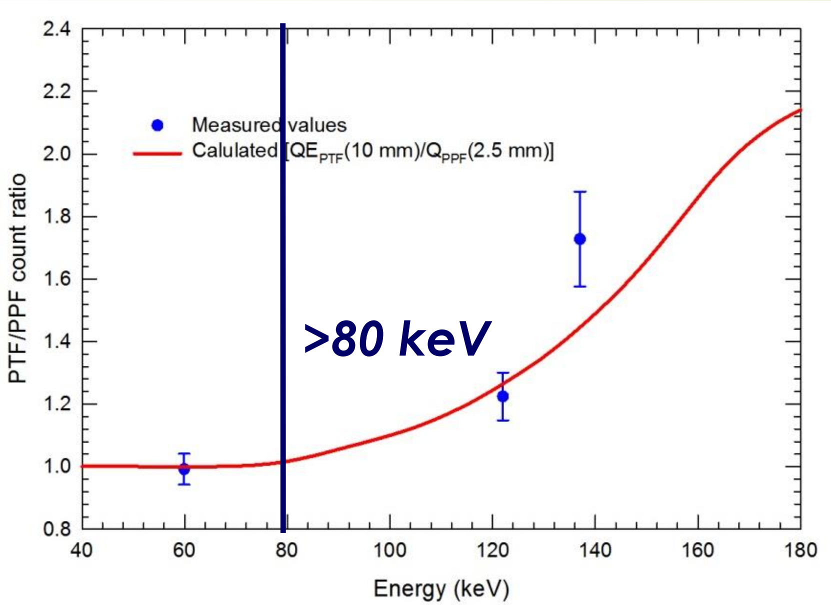
Decoupling between photon absorption thickness and charge collection distance

Irradiation configuration: PPF vs. PTF

- Drawback of PTF ⇨ all the positions between the collecting electrodes are uniformly hit by radiation ⇨ the effect of the difference in CCE at different positions plays an important role .



Spectra obtained with a fine collimated ^{57}Co source placed at various distances (x) from the cathode (x=0) in the PTF configuration.



Detection efficiency of the PTF configuration improves above ~80 keV.

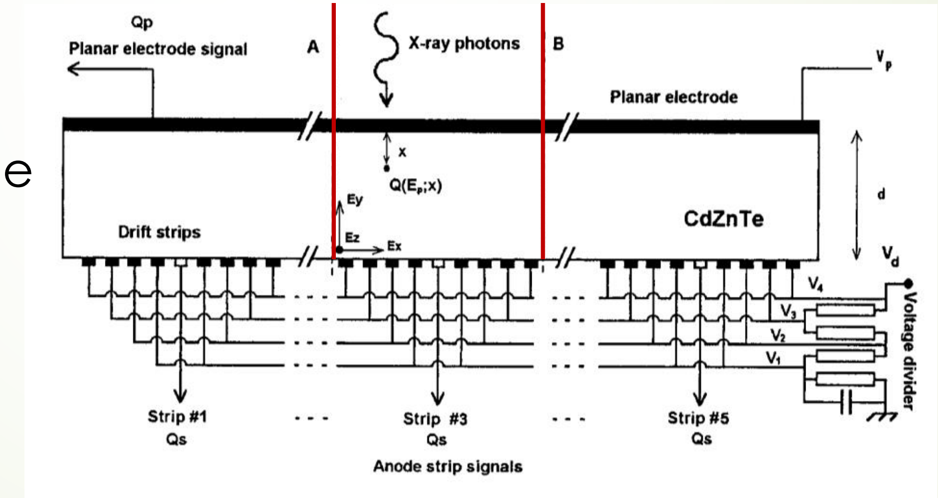
PPF: 81% @122keV PTF: 99.8%@122keV

CZT Drift Strip Detector configuration

- To overcome the PTF drawback we have used a configuration, realized at DTU (Copenhagen, DK), based on electrodes modified such that the detector is more sensitive to electron collection and less sensitive to hole collection.

Design:

- 8 drift strip electrodes and one collecting anode readout strip.
- The drift strip electrodes are biased by a voltage divider providing $-V_i = -V_d \cdot (i/4)$.



Detector: eV-Products *Spectrometer Grade*

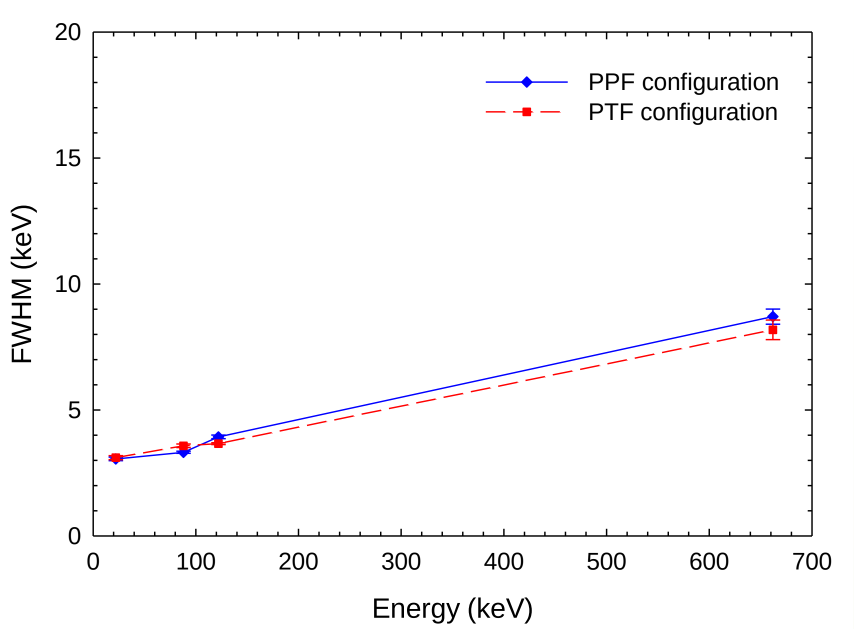
Size: 10 x 10 x 2.5 mm^3

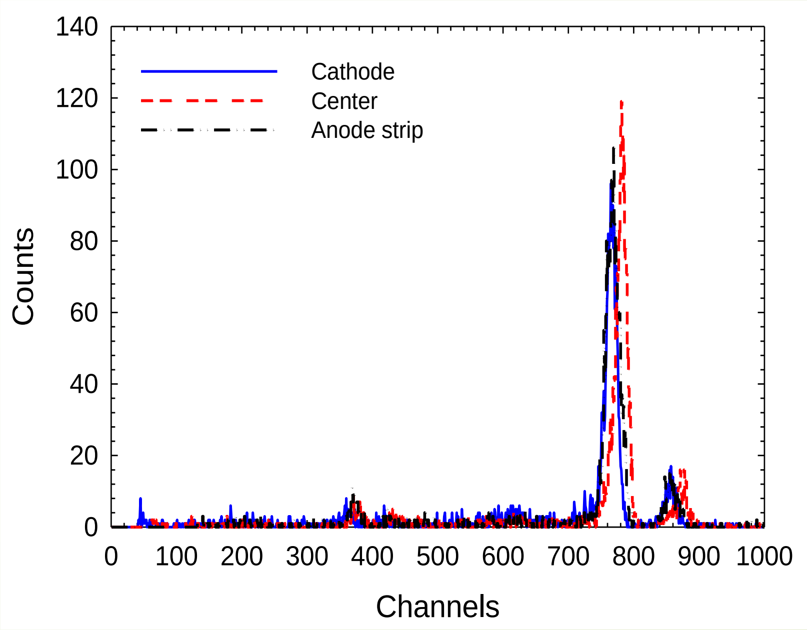
Pt/Au Strip size: 10 x 0.1 mm^2 (0.2 mm pitch)

Drift detector cell pitch: 1.8 mm.

CZT Drift Strip Detector performances

- **Full energy peak channel does not significantly change (~2%), and the energy resolution slightly increases moving toward the anode**



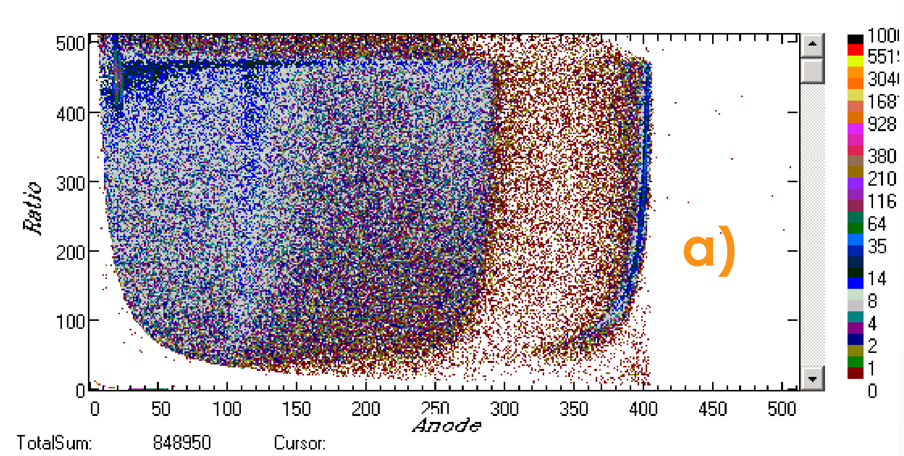


- **Energy resolution in PTF and PPF geometry**

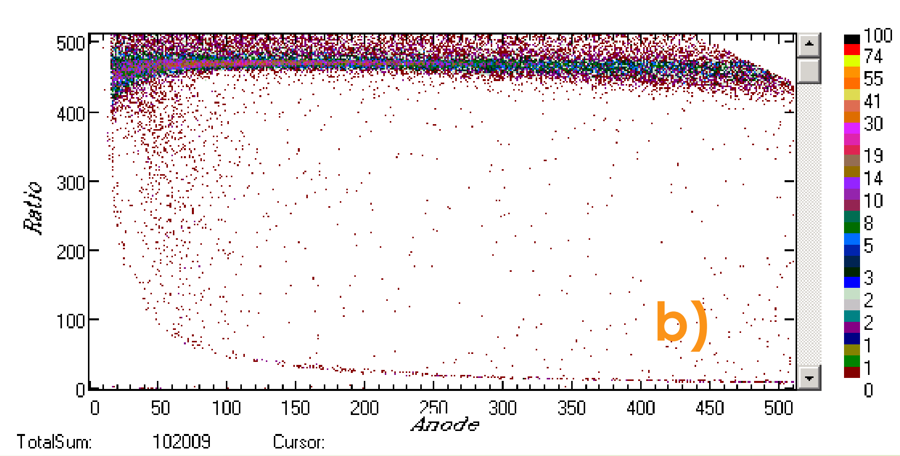
Depth information

- The depth information can be used to discriminate between gamma rays (a) and charged particles (b).

^{137}Cs gamma photons



^{90}Sr beta particles



- The different distributions demonstrate that the electrons are absorbed near to the planar electrode, whereas the gamma ray absorption is dependent on the depth of interaction within the detector.

How this sensor type provides a 3D interaction position

- Orthogonally segmented anode and cathode

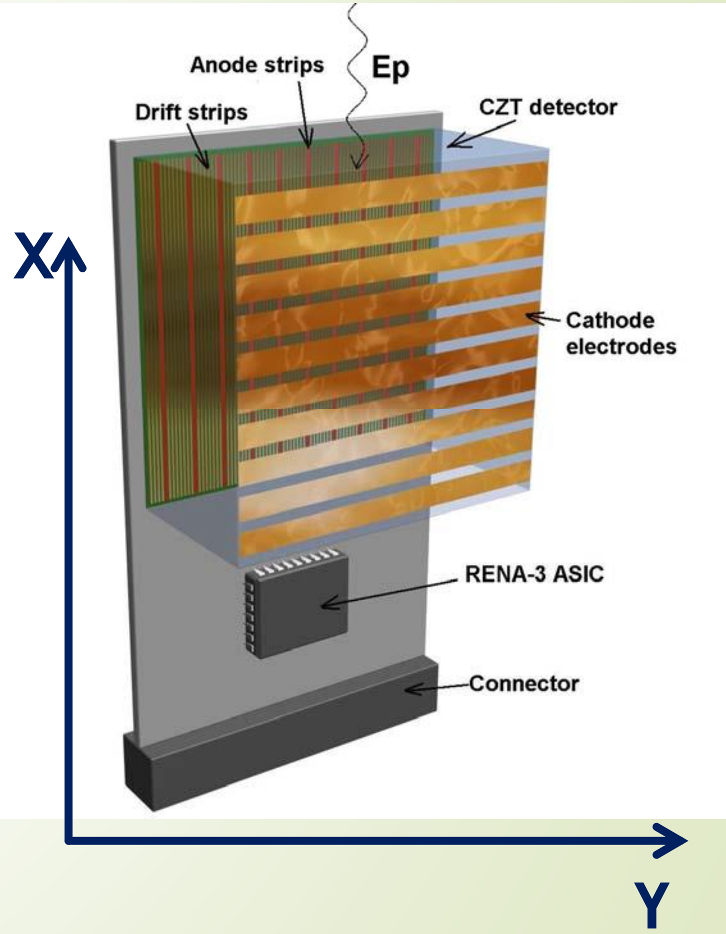
⇩

2D position (X;Y)

- Depth information (**Z**) can be derived from the ratio R =Qp/Qs, where Qp is the negative electrode signal and Qs the anode strip signal

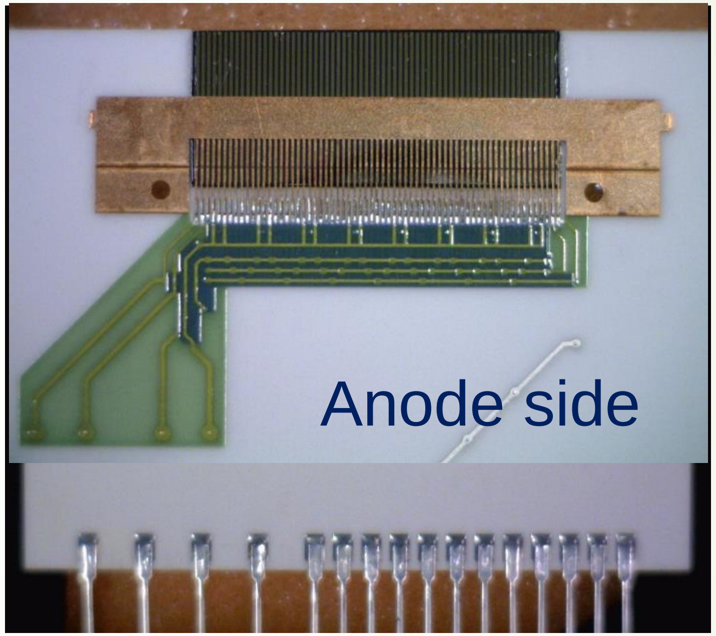
⇩

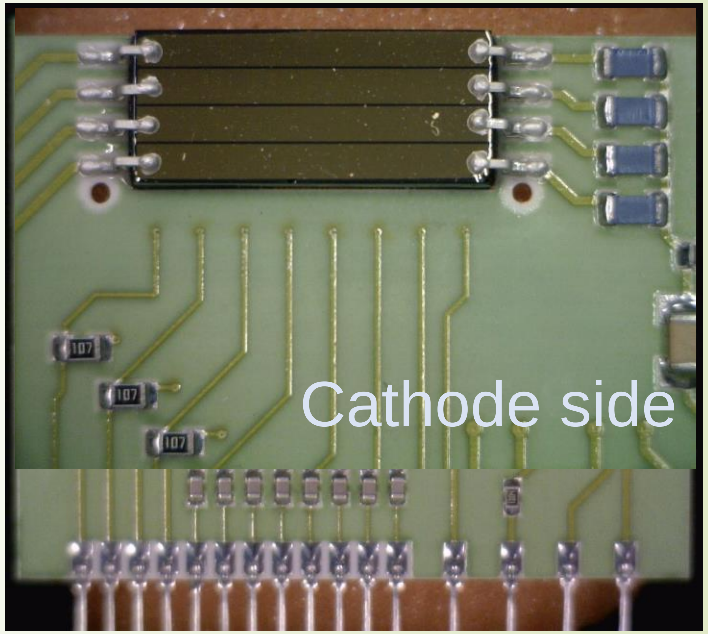
3D detector (Z)



A first 3D CZT sensor implementation

- **External Dimensions**: 20×8×2.4 mm^3
- **Anode side:**
  - 8 collecting microstrips (Ni/Au) 0.15 mm wide
    - strip pitch = 2.4 mm
  - drift strip width = 0.15 mm
  - gap between strips = 0.15 mm
- **Cathode side:**
  - 4 horizontal strips (Ni/Au) ~1.9 mm wide
  - gap between strips = 0.10 mm
- The cathode is segmented into 4 strips in the direction orthogonal to the anodes to obtain 3D sensitivity ⇨ equivalent to a stack of thinner CZT horizontal layers with the advantage of not having any passive material between each layer.



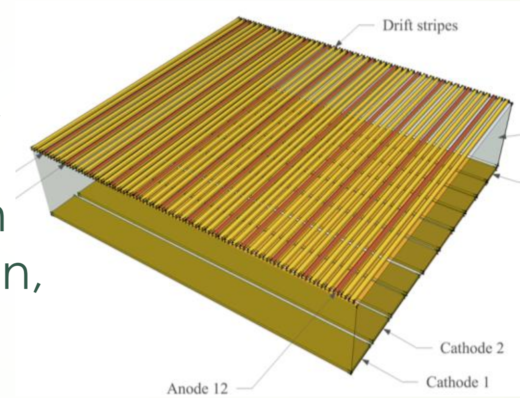


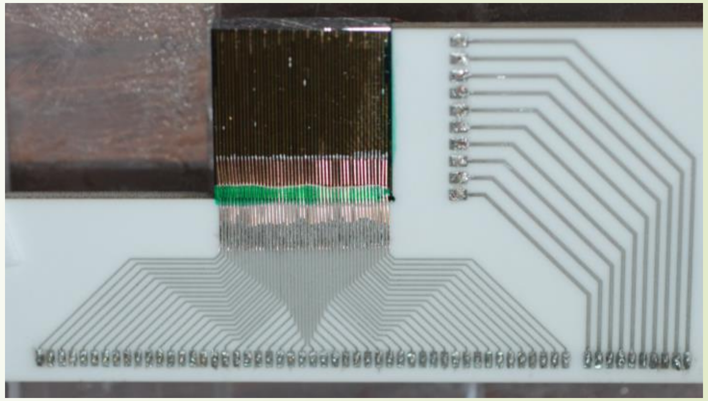
The bonding between the anode strips and the metallic pads on the alumina layer is realized by **a thin (50 μm) Cu comb** obtained by photo engraving technique. The Cu comb has the same fine μ-strip pattern with the metallic teeth 100 μm wide

3D CZT sensor: evolution and improvement

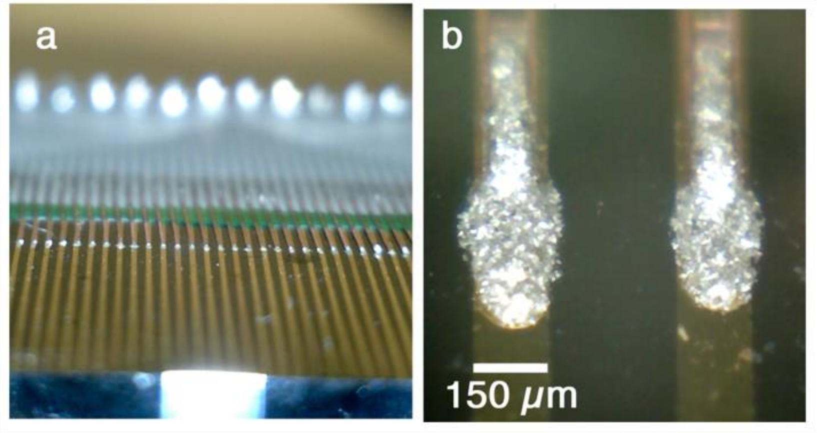
- ESA independent R&D development project P.I.: DTU-Space, Denmark
- "**3D CZT High Resolution Detectors**" Ref. 4000104191/11/NL/Cbi"

Redlen CZT Material
Sensor realisation: IMEM/CNR
Size: 20 mm x 20 mm x 5 mm
Cathode: 10 strip, 2 mm pitch
Anode: drift strip configuration, 1.6 mm pitch; strip width: 0.2 mm
Drift strips: three between each collecting anode couple

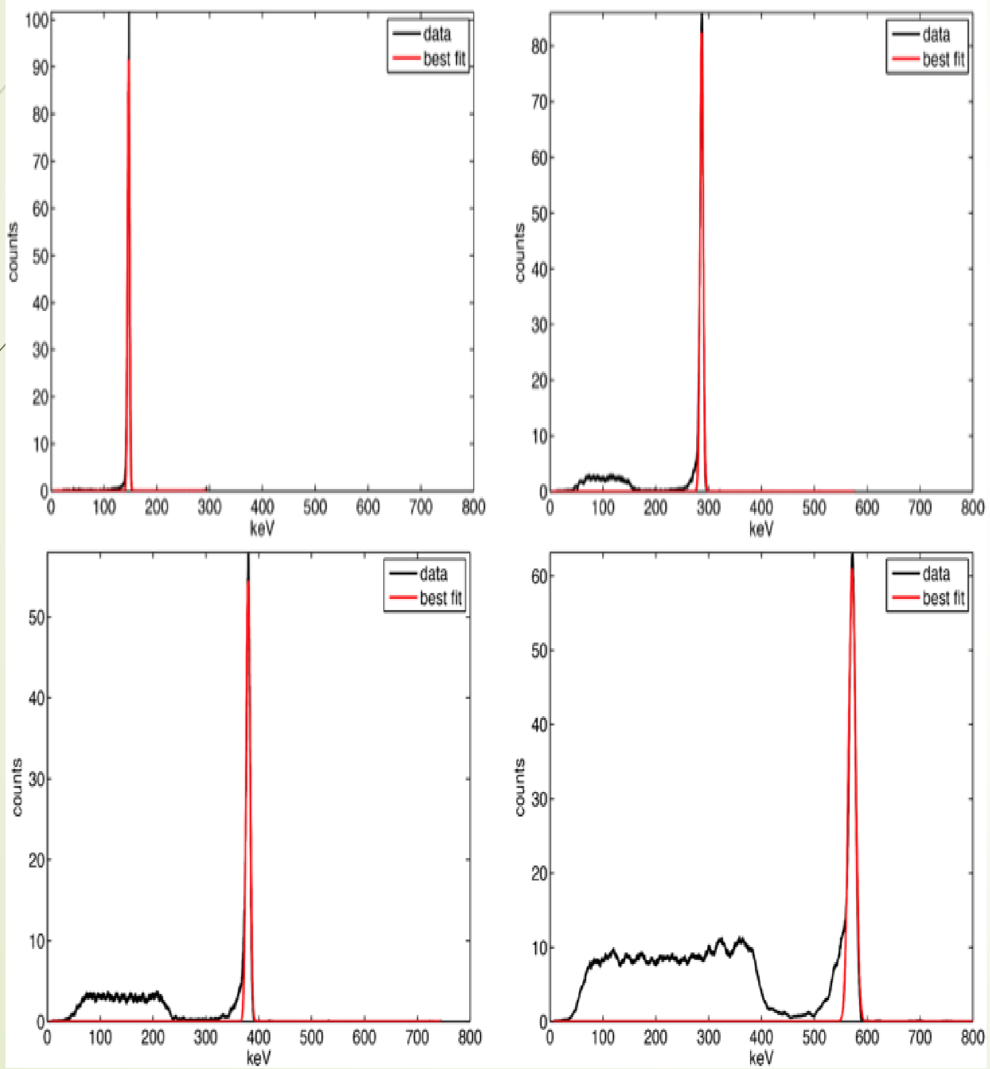




The bonding is made by using the thin copper comb techniques developed for the previous prototype



3D Spectro-imager sensor spectroscopic performance



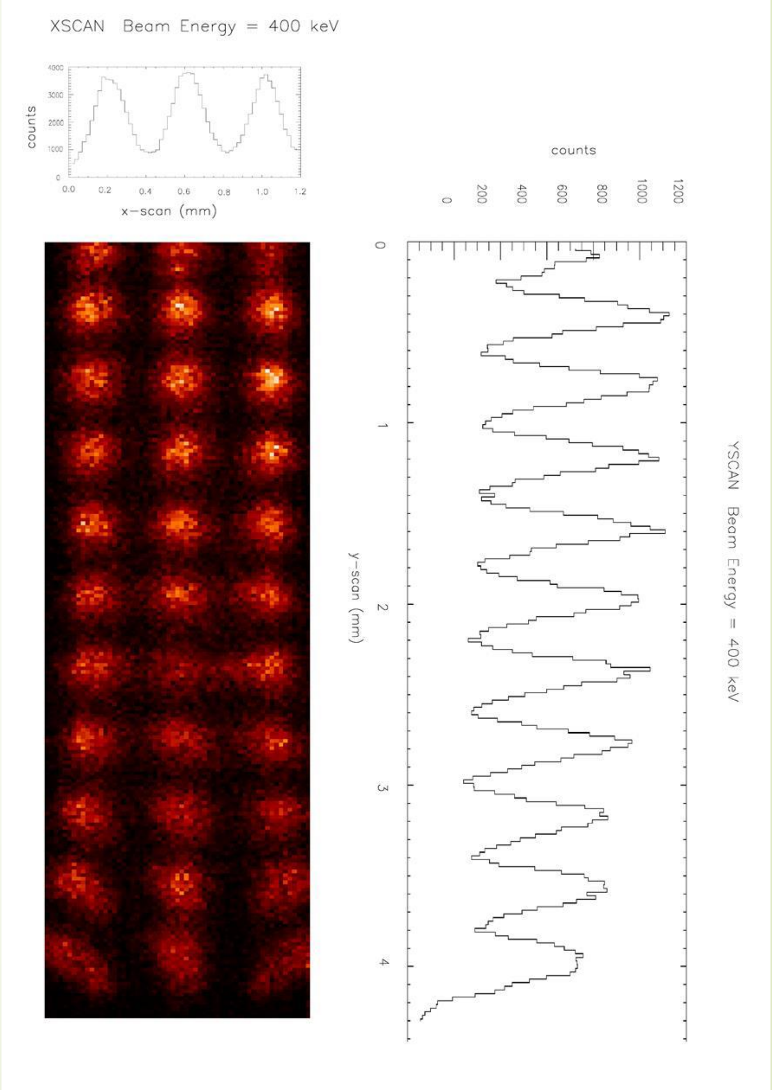
Energy resolution

$$\Delta E_{Tot} = \sqrt{\Delta E_{\det}^2 + \Delta E_{beam}^2 + \Delta E_{Elet}^2}$$

Beam Energy keV	ΔE_{Tot} Meas keV	ΔE_{Elet} Electr keV	ΔE_{beam} Beam keV	ΔE_{det} Achiev keV	ΔE_{det} (%)
150	4.2	3.67	0.73	1.91	**1.3**
300	6.1	3.67	1.88	4.5	**1.5**
400	7.4	3.67	3.18	5.58	**1.4**
580	10.8	3.67	6.7	7.63	**1.3**

3D Spectro-imager sensor spatial resolution performance

- The test demonstrated that the proposed sensor unit is a X and gamma ray detector with fine energy resolution and 3D imaging capability.
- Best performances at 400 keV:
- Δx = 0.25 mm
- Δy = 0.15 mm
- Δz = 0.65 mm
- ΔE (FWHM): 1.4%
- **Few readout channels (30/40) to obtain a sensor segmentation equivalent to: 80000 voxels.**
- "PERFORMANCES COMPLIANT WITH THE NEW HIGH ENERGY FOCUSING SYSTEM (LAUE and Multilayer)".

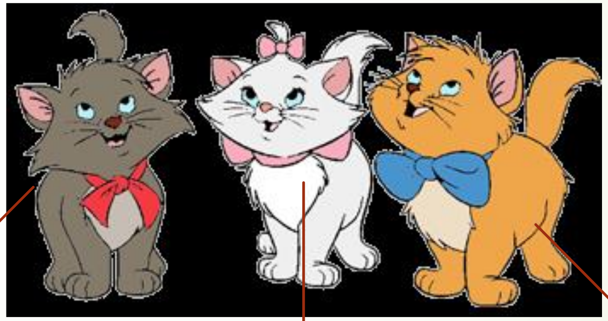


Approved & future projects

- Since 1992, several small R&D projects funded by CNR, ASI, and INAF.
- High performance 3D Cadmium-Zinc-Telluride spectro-imager for X and gamma-ray applications (3CaTS) by INFN (2016)
- 3D-CZT Module for spectroscopic imaging, timing and polarimetry in hard X-/soft gamma-rays satellite mission (3DCaTM) by ASI/INAF (**Studi di Astrofisica delle Alte Energie e di Fisica Astroparticellare Bando "Future Missioni", 2018**)
- Increase of the Technological Readiness Level for the realization of hard X-/soft Gamma-ray Laue optics (TRILL) by ASI/INAF (**Studi di Astrofisica delle Alte Energie e di Fisica Astroparticellare Bando "Future Missioni", 2018**)
- COMPET-01, COMPETITIVENESS OF EUROPEAN SPACE SECTOR: TECHNOLOGY AND SCIENCE - H2020

3CaTS goal

To develop and realise an innovative fully functional **highly segmented** prototype of a CZT detector to evaluate its performance as an **RT spectrometer** with **3D spatial resolution** capabilities suitable for different spectroscopic **imaging applications** in the range from a few tens of **keV up to 1 MeV**



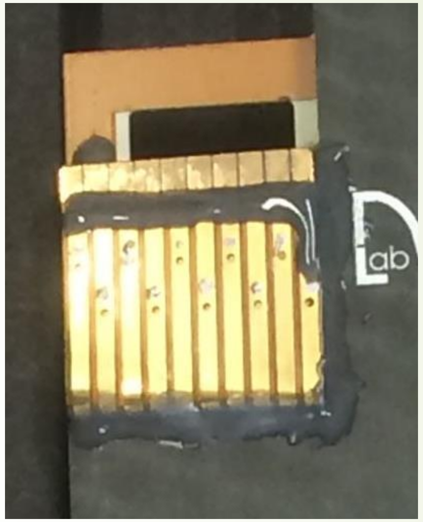
medical imaging (BNCT)

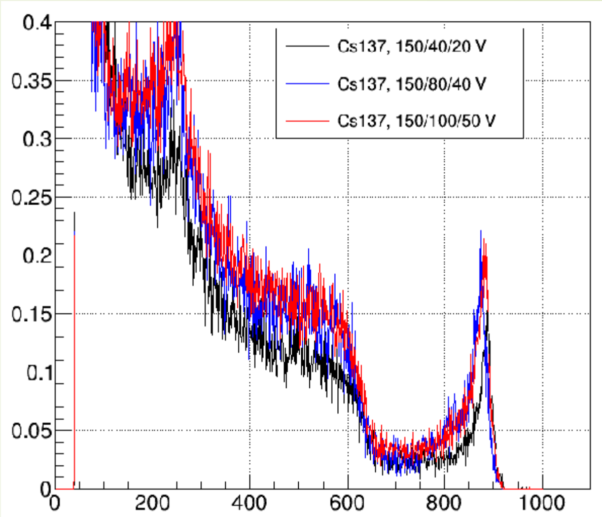
fine spectroscopy for fundamental physics

hard-X and soft-γ ray astronomy

3CaTS detector

- 3D-CZT single unit:
- **20x20x5 mm³**
- planar transversal field (PTF),
- orthogonal strip electrodes (12 + 10)
- contact pitches of 2 mm (cathode) and 1.6 mm (anode, 1 central read-out strip + 2 drift strips/side)
- strip wide: 150 micron
- Gap: 250 micron

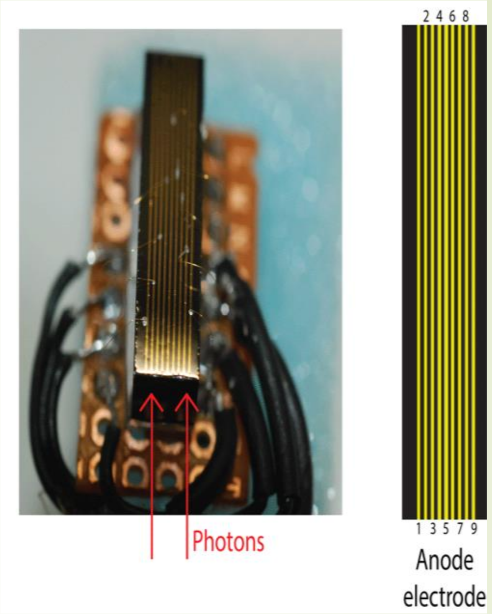


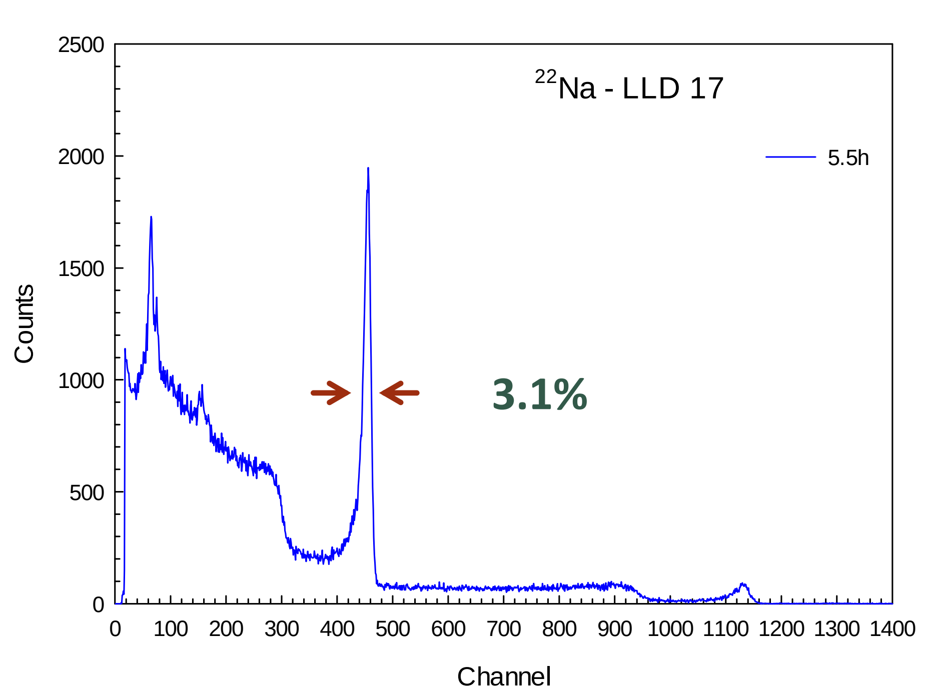


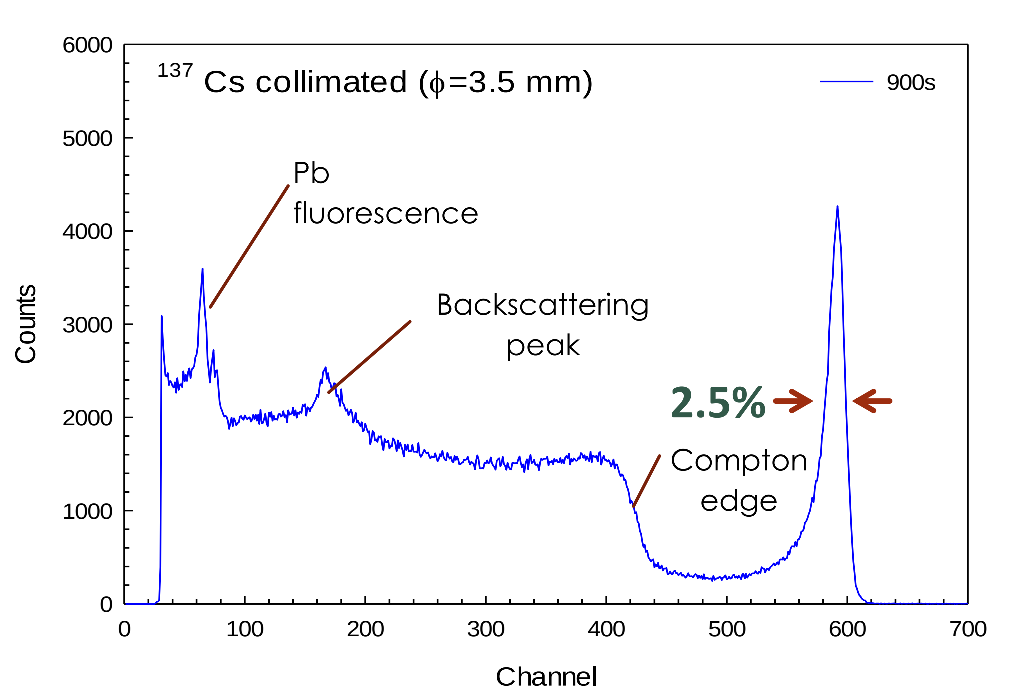
- Limited number of read-out channels (22) with intrinsic spatial resolution of 1.6mm x 2mm x 5mm; improvable by using reconstruction methods up to 0.2x0.3 mm^2 in the photon incident plane and 0.6 mm in depth.
- The sensor will be coupled to a digital multichannel electronics based on digital pulse processing.

Detector prototype

- ❑ 3D-CZT single unit:
- ❖ **5x5x20 mm³**,
- ❖ planar transversal field (PTF)
- ❖ 1 cathode (5x20 mm)
- ❖ 1 anodic strip + 4 drift strips/side
- ❖ strip wide: 150 micron
- ❖ Gap: 250 micron







3DCaTM goal

- Development of a representative 3D new generation detection system prototype for high performance imaging, spectroscopy, timing and polarimetry operating between 5 keV and 1 MeV. This demonstrator includes two main subsystems:
  - The demonstrator detector is based on a 20×20×20 mm^3 CZT module, realized by stacking four 20×20×5 mm^3 3D CZT PTF drift strip sensors, coupled with 7 CSP boards for a total of up to 100 readout channels.
  - A Digital Pulse Processing electronics system to handle in real time all the preamplified signals.
- A fully digital approach will be implemented in a 3D spectro-imager to exploit its performance in term of spectroscopy (< 1% FWHM at 511 keV), 3D spatial resolution (<300 μm), polarimetry (Q > 0.5), timing (<10 ns) and Compton imaging capabilities (<10 degrees). **Only with 100 readout channels.**

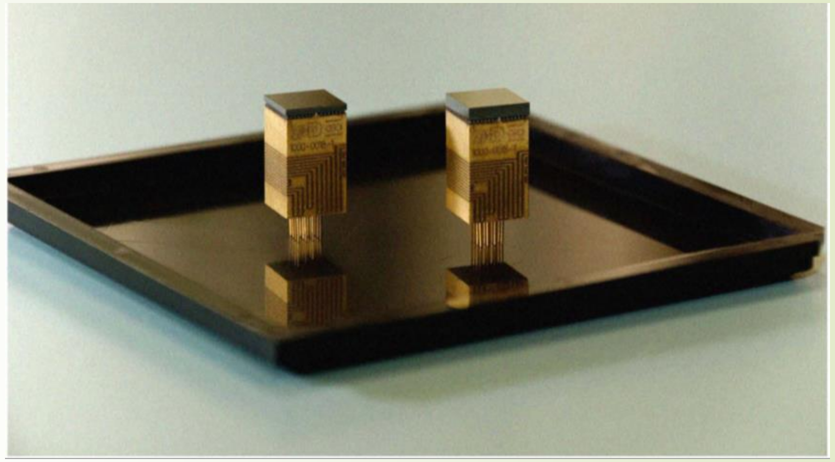
The target is to improve the TRL from the current level 3 to level 5

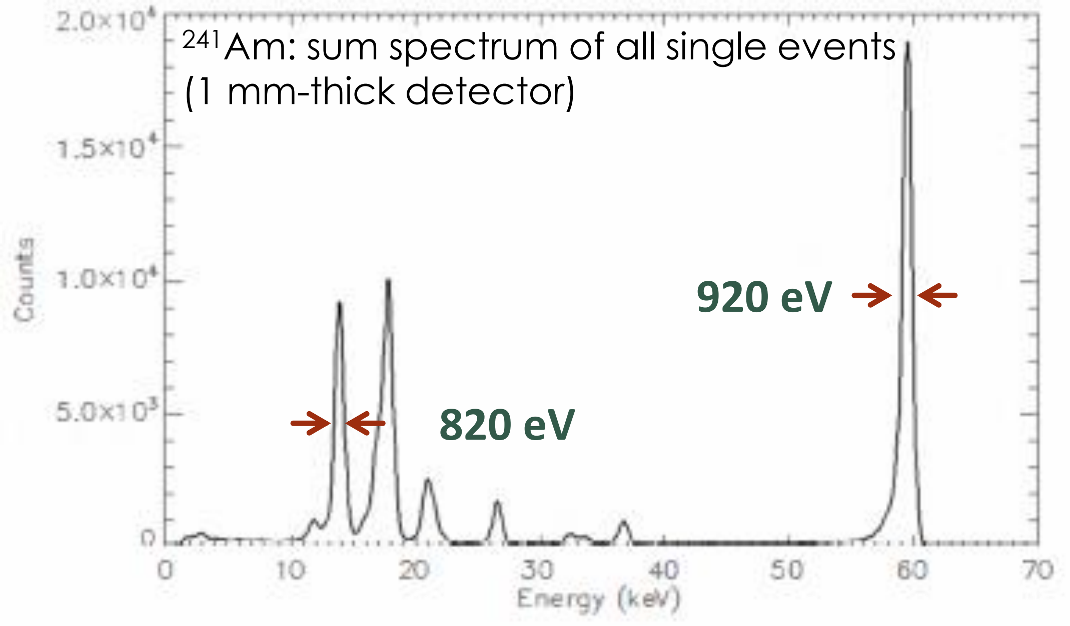
TRILL: the focal plane detector

- **Caliste –O** by CEA/Saclay:

  Second generation of portable gamma camera based on Caliste CdTe hybrid technology

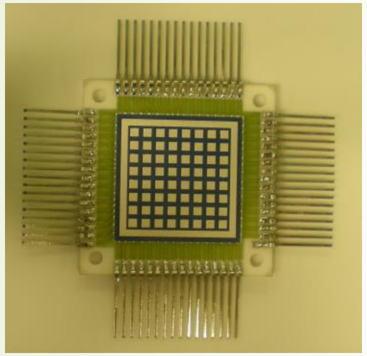
- 16 × 16 Schottky CdTe pixels
- Area: 14.2×14.2 mm^2
- Thickness: 1- 2mm thick
- Detector coupled to 8 full-custom front-end ASICs
- Pitch: 0.8 mm
- low-level threshold: ~ 1. 5 keV
- Total power: 0.2 W



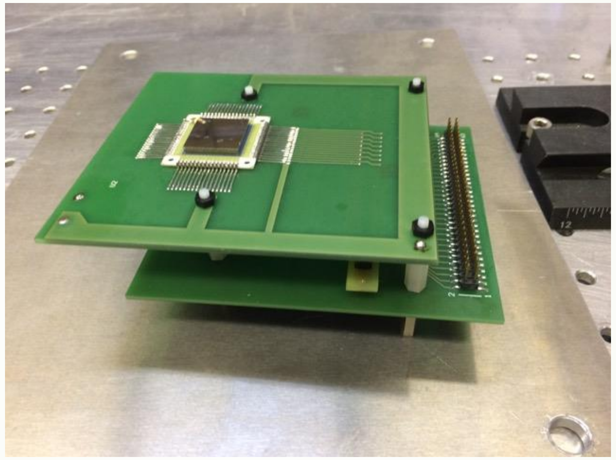


Next Generation Spectro-imager Polarimeters

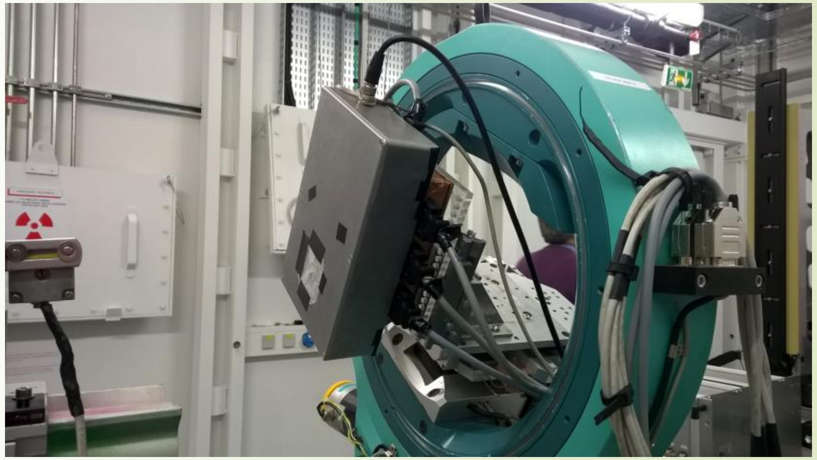
- Compton spectro-imager based on 2 CdTe pixelized detectors when used as a **Compton polarimeter**.



Single detector



2 layers



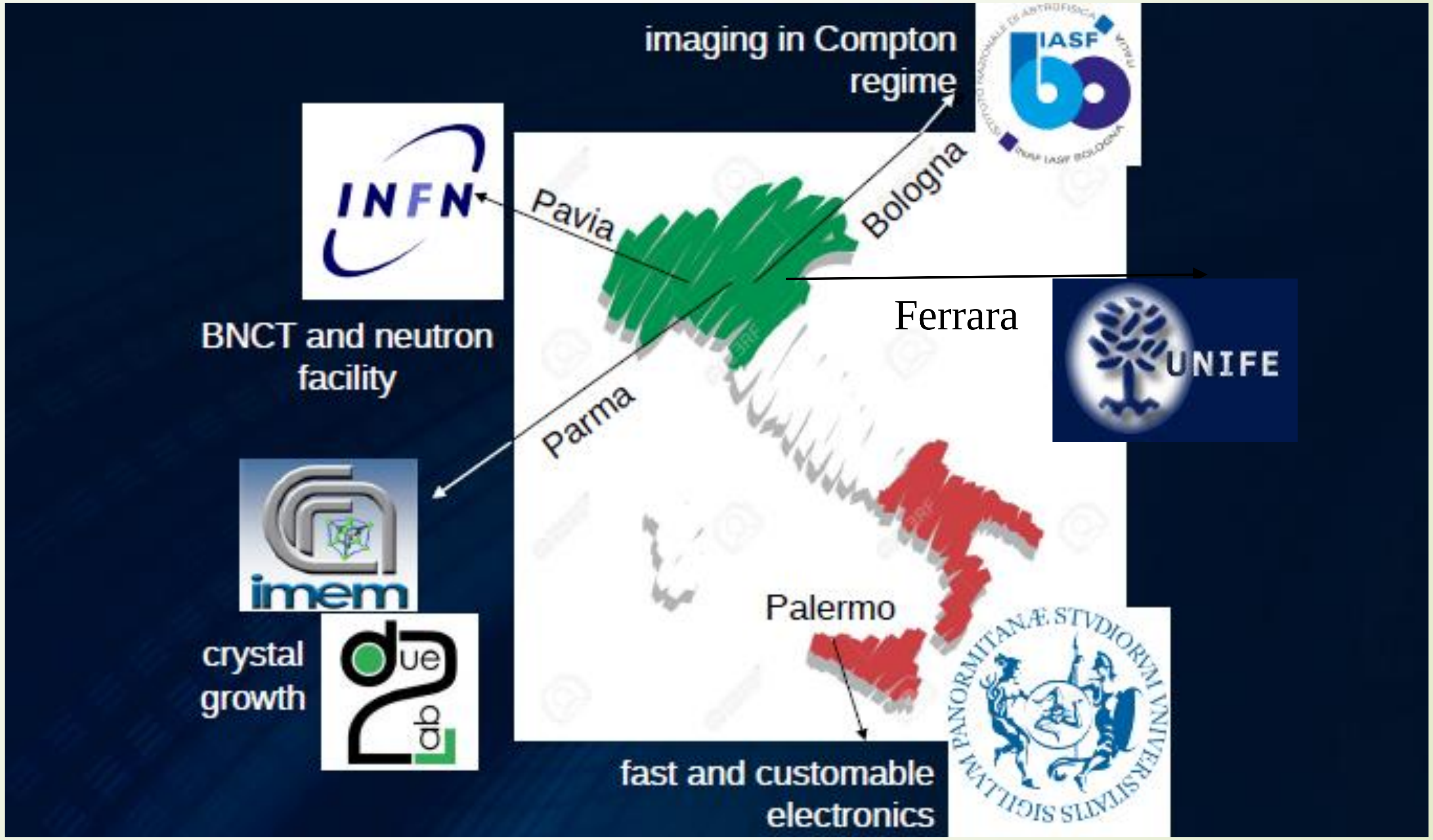
Test campaign at ESRF (Grenoble) to evaluate the tracker polarimetric performance

- The results provide some important inputs for the next Gamma-ray Space telescopes that require highly segmented and 3D detection system: eASTROGAM and H2020 AHEAD project configurations (ASTENA).

Critical issues for R&D activities

- Lack of Electronics engineers/physics and/or technicians, i.e. need of expensive external expertise.
- Laboratory basic instruments obsolescence. R&D activities are supported with no long-term strategy and with loans that generally do not allow investment in basic laboratory equipments (e.g. H2020 project).
- Currently lack of a short-mid term reference space mission. ASTENA is only a mission concept for a long term implementation feasible in a 30-40 years scale.

Thanks a lot!


imaging in Compton regime
IASF
INFN
Pavia
Bologna
Ferrara
UNIFE
BNCT and neutron facility
Parma
imem
crystal growth
due lab
Palermo
fast and customable electronics
PANORMITANÆ STVDIORVM VNIVERSITATIS SIGILLVM