Caliste-3D CZT: Development of a New Generation of Gamma-ray Imager Spectrometer to meet the Sensitivity Challenge of Space Astronomy Telescopes in the MeV band.

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Context

High-energy astrophysics in the spectral band from **0.1 to 1 MeV** suffers from insufficient detection sensitivity in existing observatories. Also **polarimetry** in this energy band has yet to be implemented on a large scale dedicated instrument.

This energy band is associated with the **non-thermal universe** where we can probe how matter behaves around **black holes** and **neutron stars** systems. It also allows to observe supernovae and their remnants to and look for **nucleosynthesis**. Polarimetry can help to characterize the **magnetic field topologies** as well as determine the **emission mechanisms**.

PHEMTO [1] is a current M8 ESA proposal for high energy astrophysics observations. It will operate between 1–600 keV and have a focusing system for x-ray and gamma-rays (req. ΔxΔy ~100 μm on CZT).

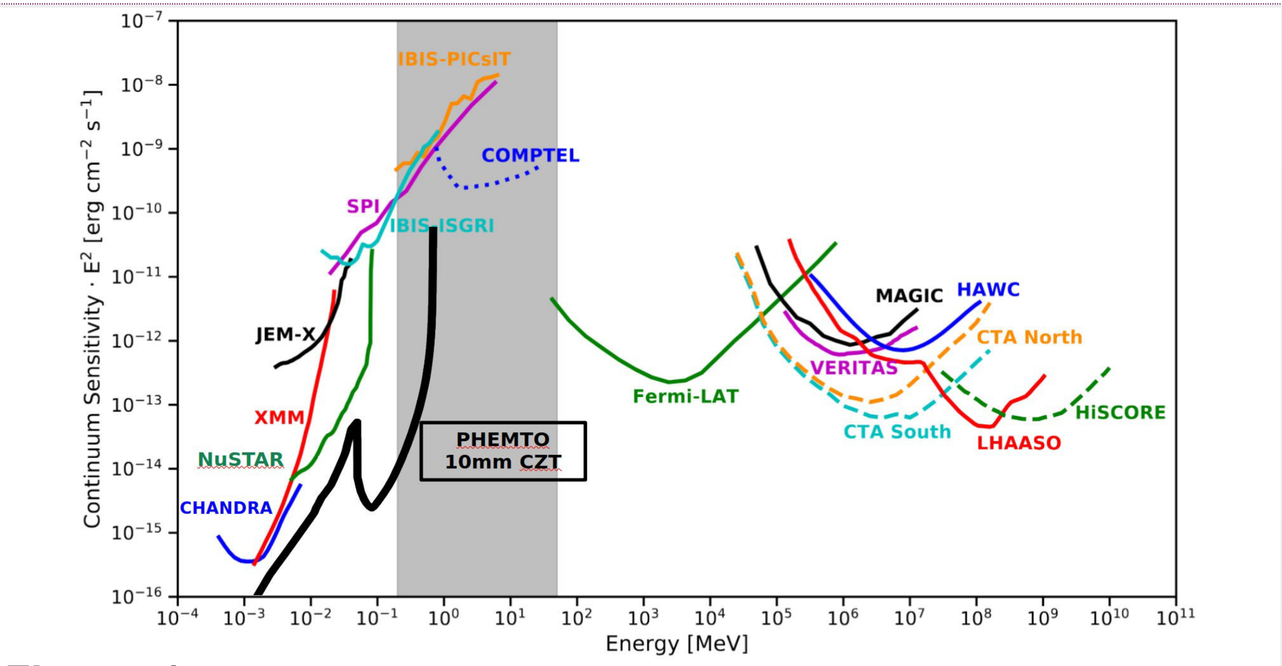

Figure 1: PHEMTO sensitivity, 10 mm CZT detector and the most sensitive high energy astrophysics instruments. Adapted from [2].

State of the art and key questions

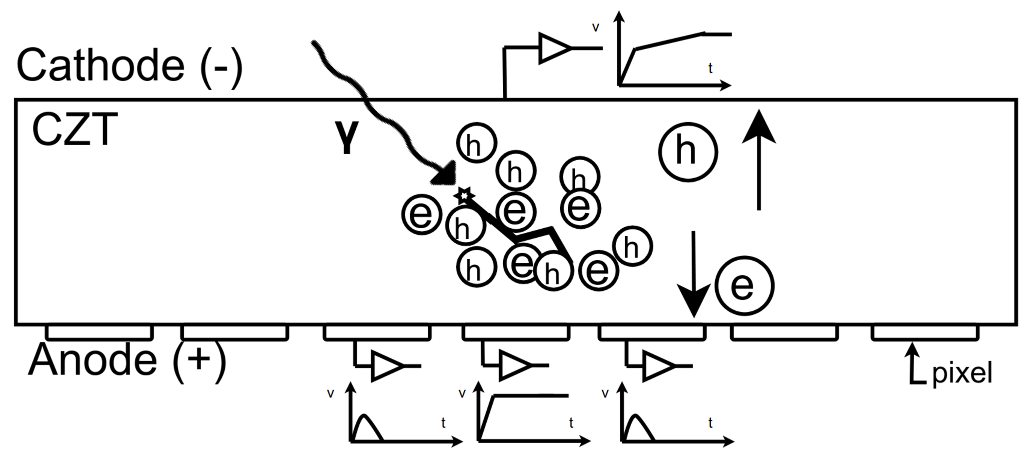

Figure 2: Principle of photon interaction in a CZT pixel detector.

Pixel detectors are easily scalable due to planar configuration. 3D interaction position determination can used to compensate thick CZT spectra, reaching energy resolution of **0.31% at 662 keV** [3]. Also, probing neighbor pixel induced transient signal allows spacial resolutions **ΔxΔy <0.1 mm** for pixel pitch of 0.8 mm [4] .

In this PhD we will design a new device based on the Caliste technology, developed at CEA-Irfu (Figure 4), in order to implement **new signal probing techniques**, Figure 2. We will develop a **detector mathematical model** [5] to correct for charge loss. With this we aim to achieve on a **single device** state of the art spectral, position and polarimetric performances.

Key questions:
What is the best readout strategy to infer event position in 3D?
Can we maintain low energy threshold (2 keV) with dynamic range up to 2MeV?

Work Plan

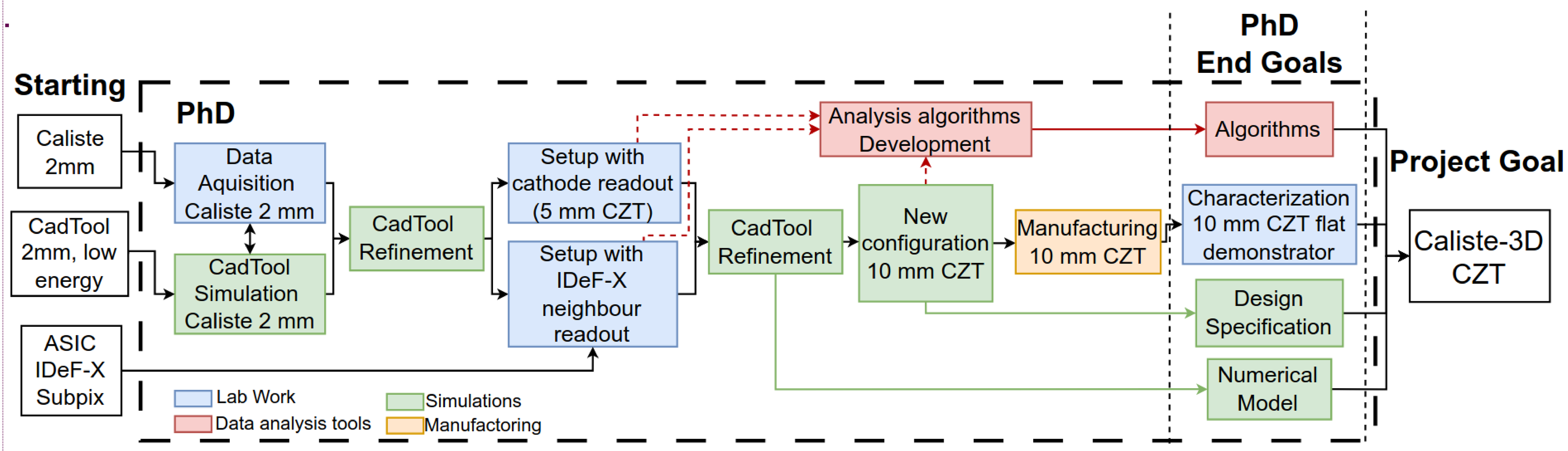

Figure 3: PhD workflow diagram.

Approach:

- Use readably available Caliste to adjust CadTool for high energy;
- Develop lab setup with Caliste and 5 mm CZT to probe cathode signals;
- Use readably available IdeF-X subpix ASIC for 5 mm CZT characterization;
- Use real data for CadTool simulation validation [5];
- Design new 10 mm CZT detector configuration;
- Specify new 10 mm CZT ASIC requirements.

End goals:

- Combine state of the art spectral, imaging, polarimetric capabilities in a **single device**:
  Energy resolution **< 0.31% @ 661 keV** [3];
  ΔxΔy < 0.1 mm for pixel pitch 0.8 mm [4];
  < 2 keV threshold and up to 2 MeV;
  < 1 mm ³ polarimetry;
- Design of sensor:
  Scalable and compatible with space environment (**power**, radiation and thermal cycle);
  Heritage of Caliste technology (Solar Orbiter).

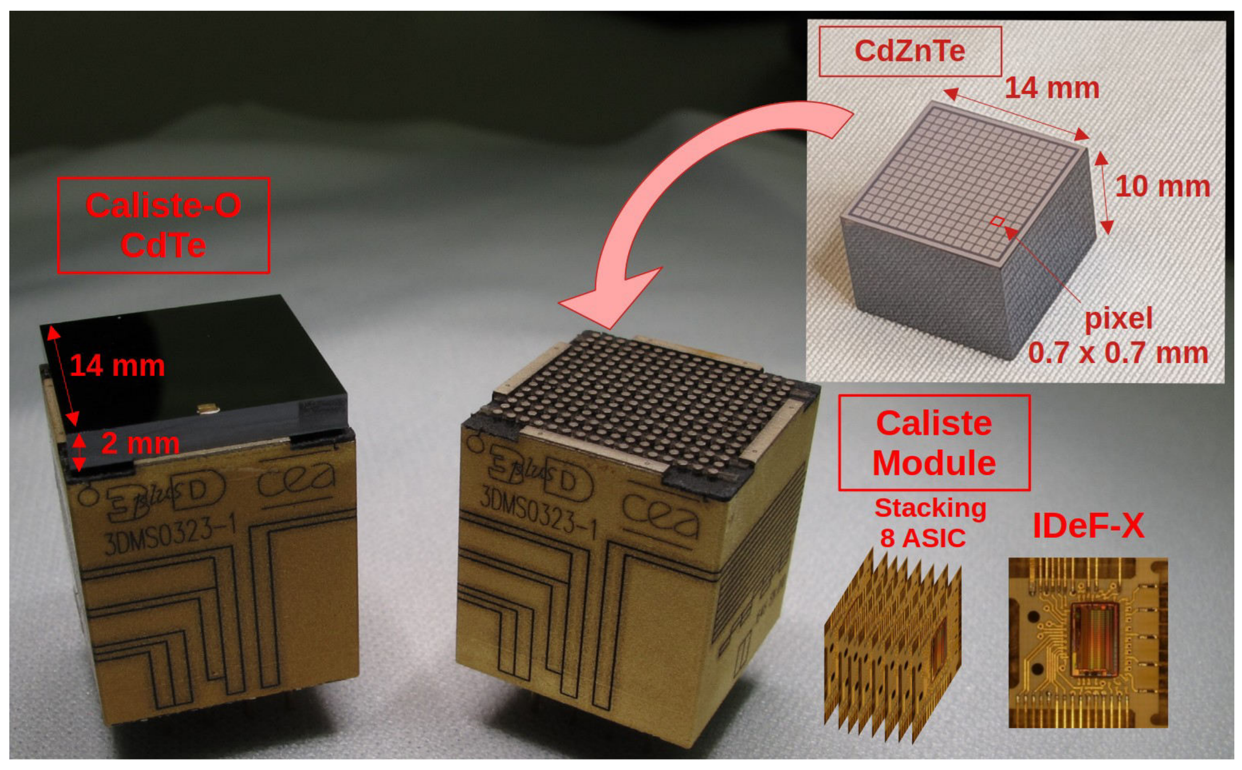

Figure 4: Caliste-O configuration available on lab. Thick CZT to be bonded to Caliste module for Cathode readout.

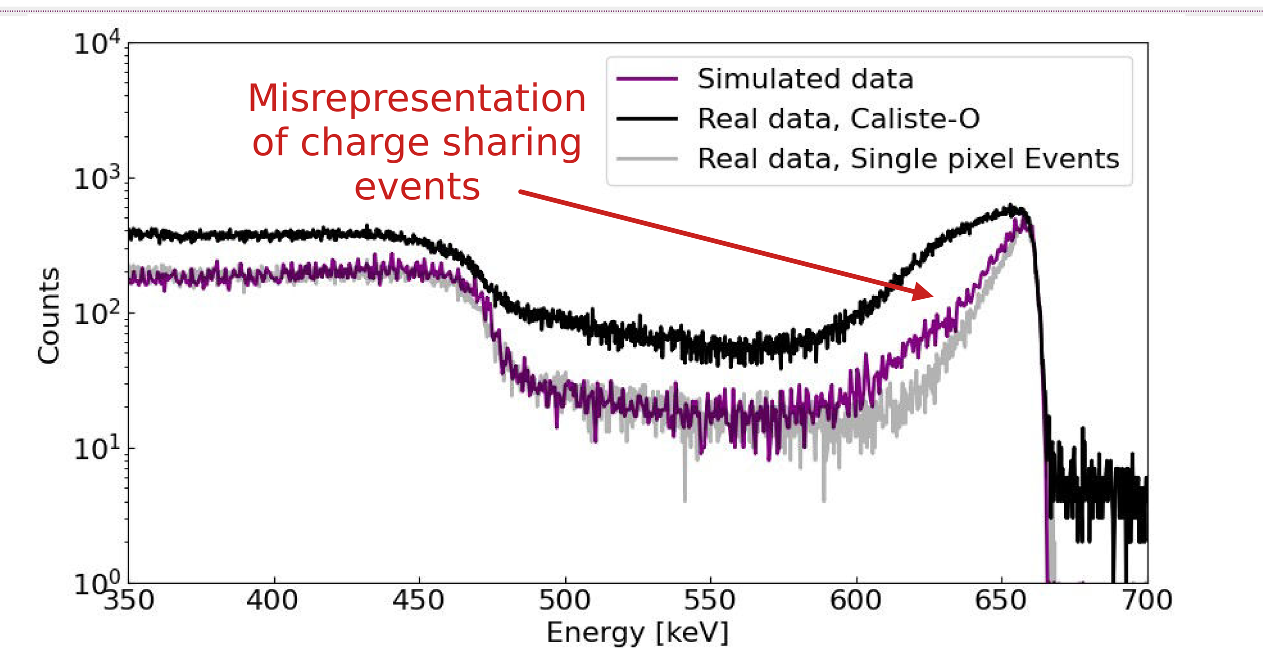

Figure 5: Cesium-137 spectra. Black, real data, all events. Gray real data, single pixel events. Purple, CadTool simulated data.

Preliminary work and next steps

Done

- Preliminary **PHEMTO sensitivity simulations** with MEGAlib, Figure 1, and preliminary definition of PHEMTO alternative CZT detector configuration.
- **High energy spectral response** simulation using CadTool. Used to compare with real on-lab detector configuration data acquisition, Figure 5. To understand if current **charge carrying model** is representative for high energy photons.
- Extracting **induced charge transient signals** from CadTool simulations.

Next Steps

- Optimize CadTool charge cloud generation and transportation model for high energy events.
- Create test plan for cathode readout laboratory test bench.
- Assemble test bench with existing Caliste module and implement cathode readout.
- Develop cathode probe data analysis/calibration pipeline.

References:

[1] P. Laurent et al., 'PHEMTO: the polarimetric high energy modular telescope observatory', Exp. Astron., vol. 51, no. 3, pp. 1143–1173, June 2021.
[2] G. Lucchetta, M. Ackermann, D. Berge, and R. Bühler, 'Introducing the MeVCube concept: a CubeSat for MeV observations', J. Cosmol. Astropart. Phys., vol. 2022, no. 08, p. 013, Aug. 2022.
[3] Y. Zhu and Z. He, 'Performance of Larger-Volume 40 × 40 × 10- and 40 × 40 × 15-mm3 CdZnTe Detectors', IEEE Trans. Nucl. Sci., vol. 68, no. 2, pp. 250–255, Feb. 2021.
[4] L. Ocampo Giraldo et al., 'Study of sub-pixel position resolution with time-correlated transient signals in 3D pixelated CdZnTe detectors with varying pixel sizes', Nucl. Instrum. Methods Phys. Res. A, vol. 884, pp. 136–139, Mar. 2018.
[5] github.com/hallaire/CadTool_SSD