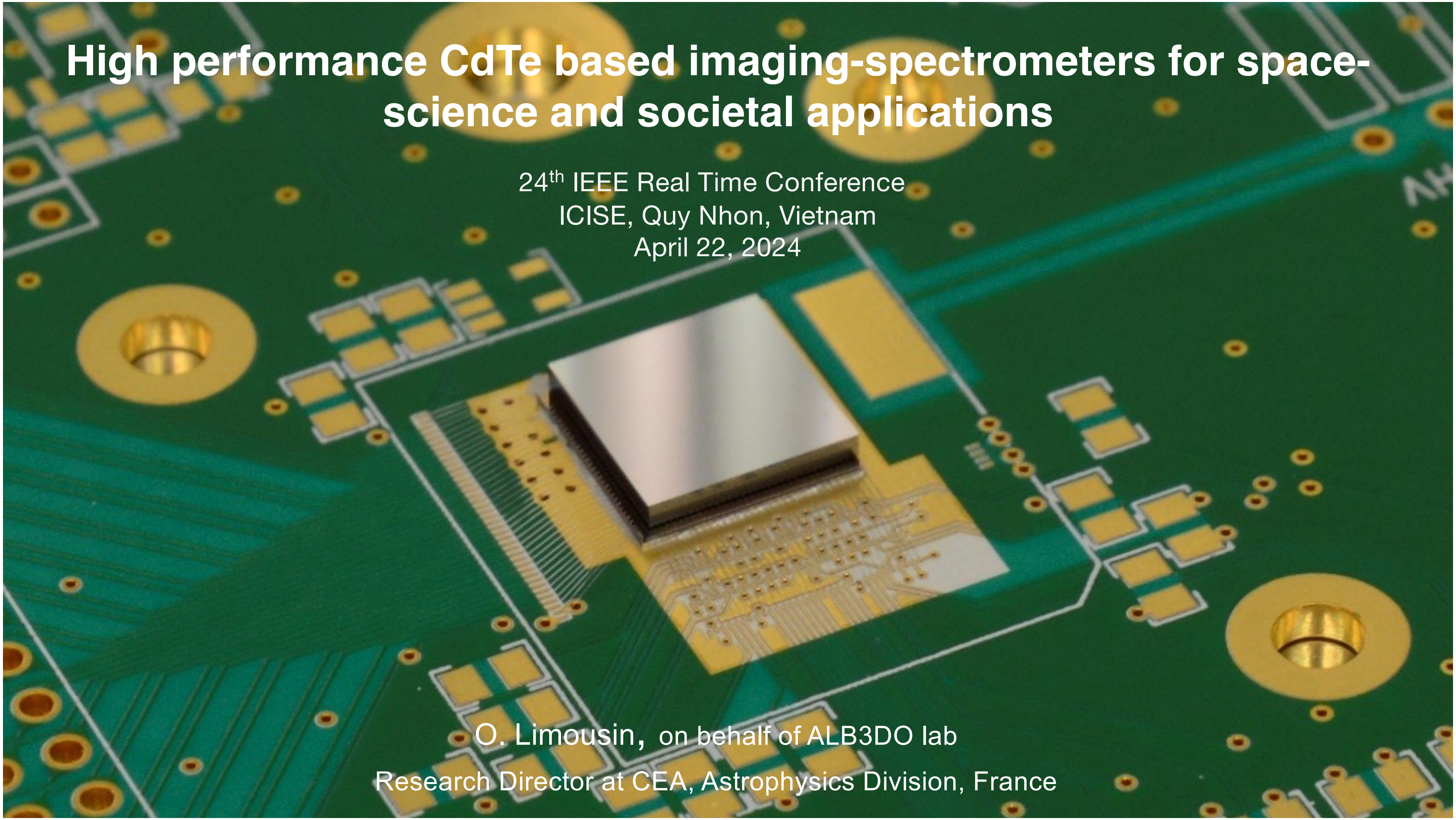


High performance CdTe based imaging-spectrometers for space-science and societal applications

24th IEEE Real Time Conference
ICISE, Quy Nhon, Vietnam
April 22, 2024

O. Limousin, on behalf of ALB3DO lab
Research Director at CEA, Astrophysics Division, France

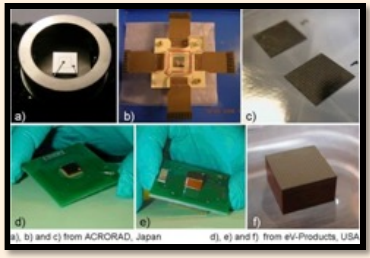
Thanks for your invitation in Vietnam …

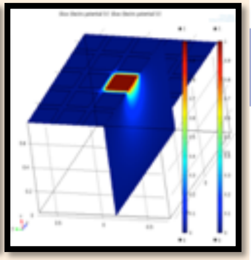
Special thanks to

- Patrick Le Du
- Martin Grossmann Handschin
- Masaharu Nomachi
- David Abbott
- Real Time 2024 organizers

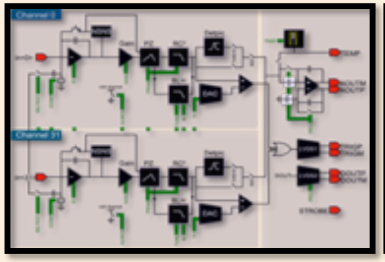
Who are we?

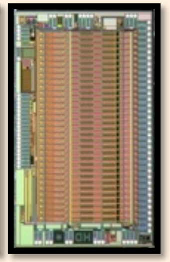
CdTe detectors design, modelisation and simulations



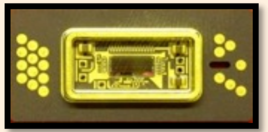


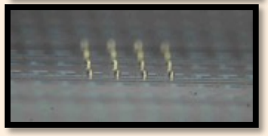
ASIC, Design, tests

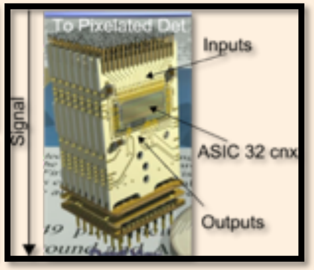




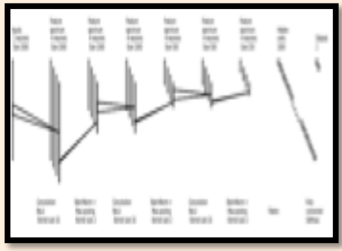
Hybridization

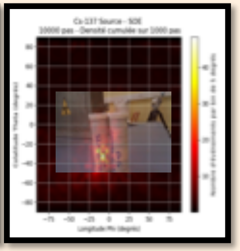




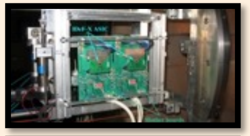


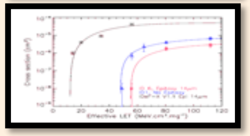
Data Analysis methods And reconstruction

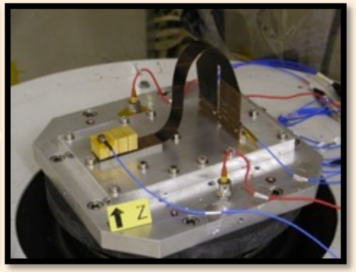




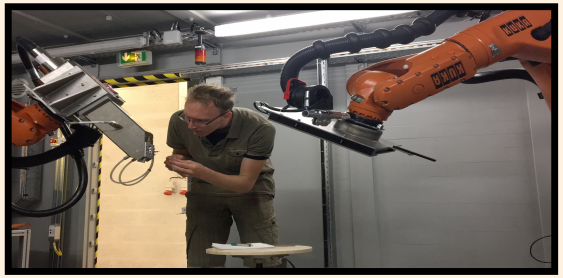
Space Qualification



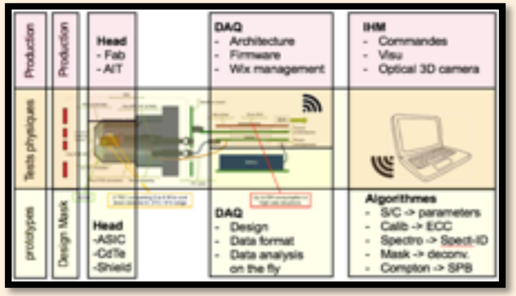




Experimentation



System

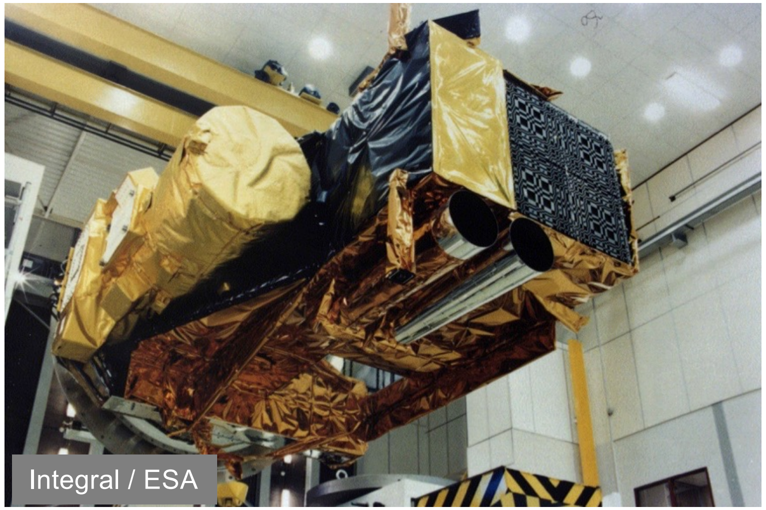


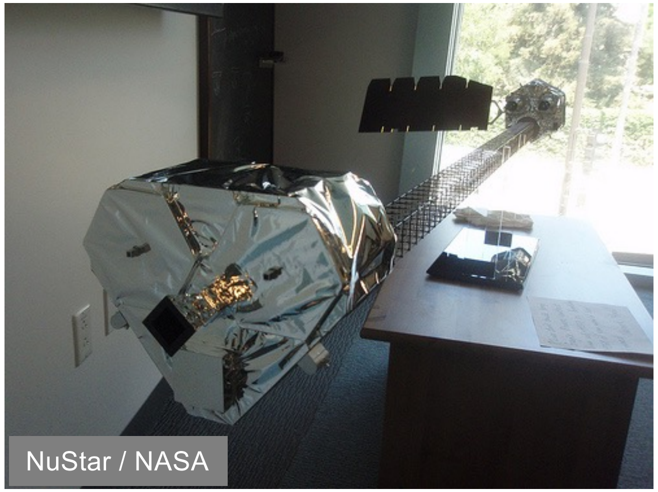
Our motivation (obsession…) is

Sensitivity

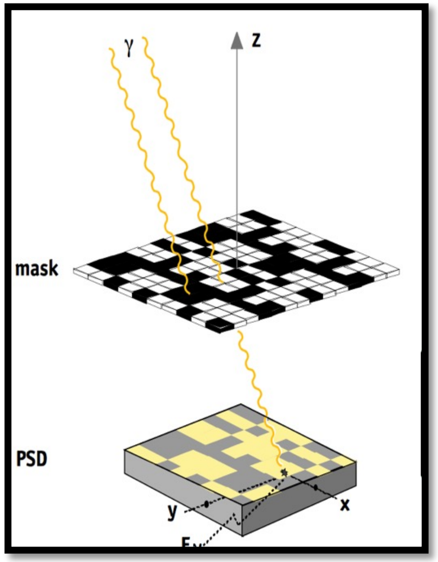
In Hard X-rays

Imaging spectroscopy for astrophysics


Integral / ESA

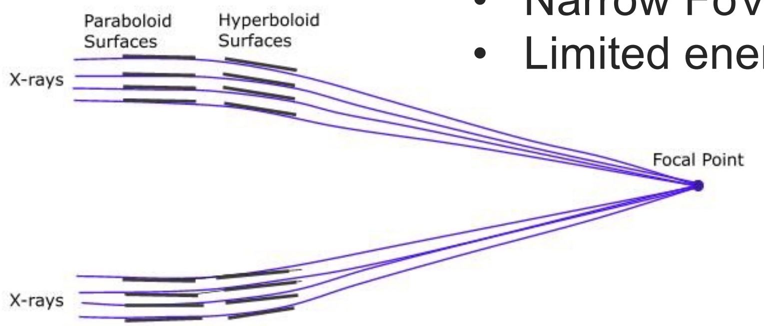

NuStar / NASA


Astro-H / JAXA

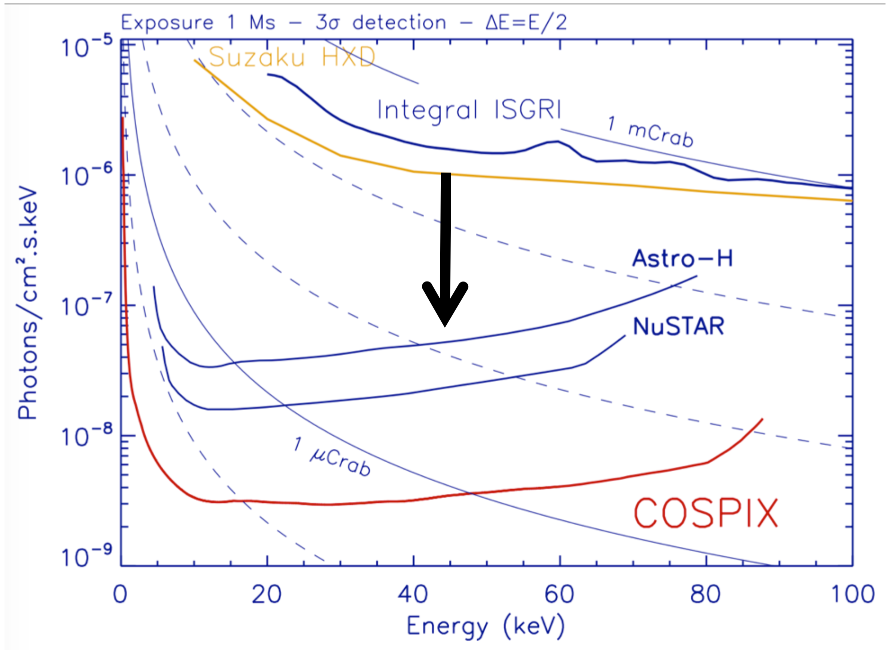


Coded Mask:
- Wide FoV
- Modest Angular resolution
- High Dynamic range in E
- Limited sensitivity

Grazing incidence mirrors
- High Angular resolution
- Narrow FoV
- Limited energy range



Imaging spectroscopy for astrophysics



Huge constraints on the detector design
Use of CdTe HXR detectors

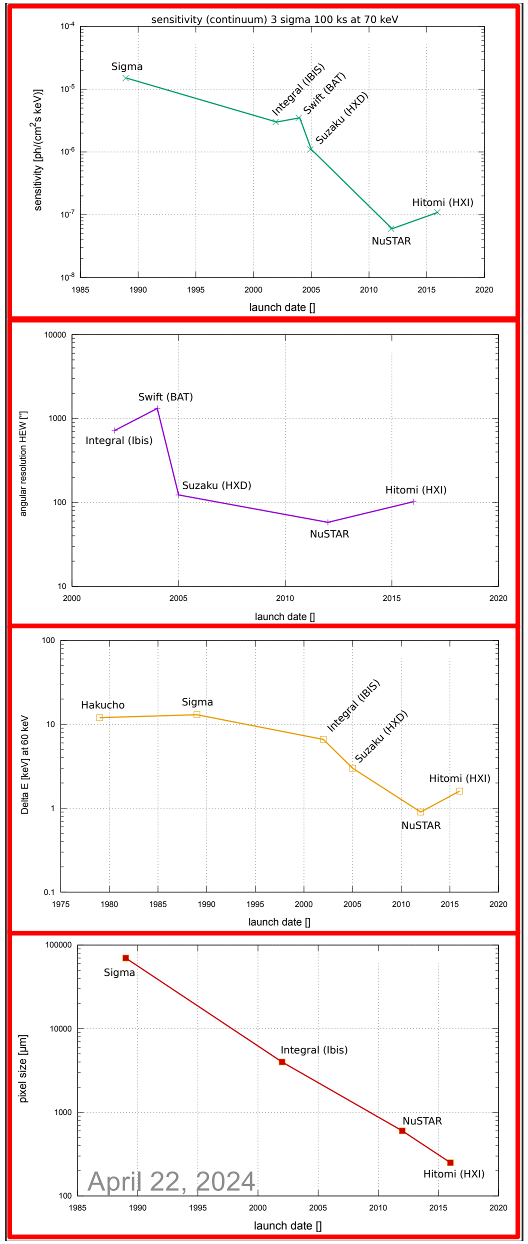
Trends is as usual … smaller is better

Most progress in sensitivity in HXR will come from direct focusing/imaging, and good observing conditions

Anyhow … all HXR instruments need <u>detectors</u> with:

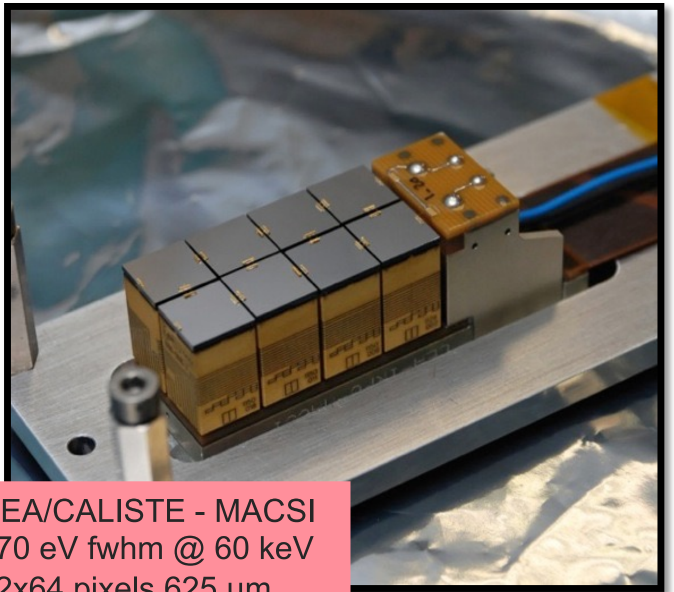
- High spatial resolution
- High efficiency
- High speed
- High stability
- High reliability
- High dynamic

- Low noise
- Low threshold
- Low mass
- Low volume
- Low Power



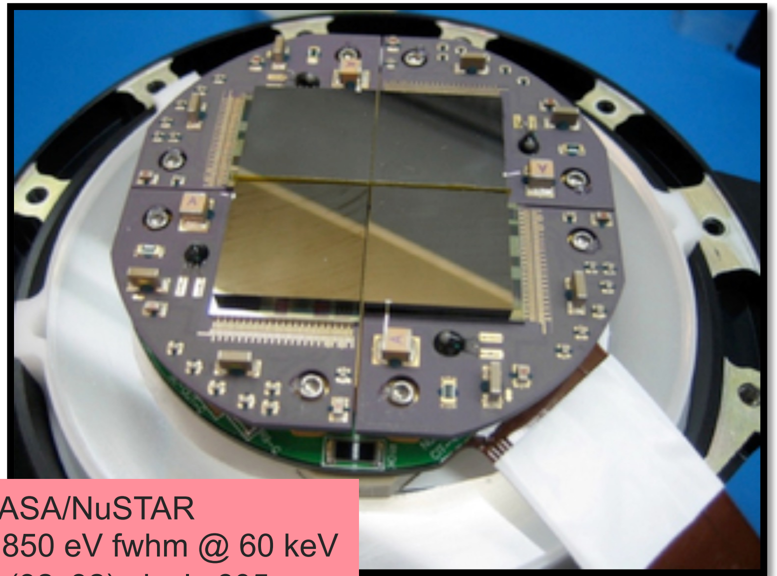
A Worldwide challenge for CdTe and CZT detectors

Fine pitch



CEA/CALISTE - MACSI
670 eV fwhm @ 60 keV
32x64 pixels 625 µm

Limousin+14

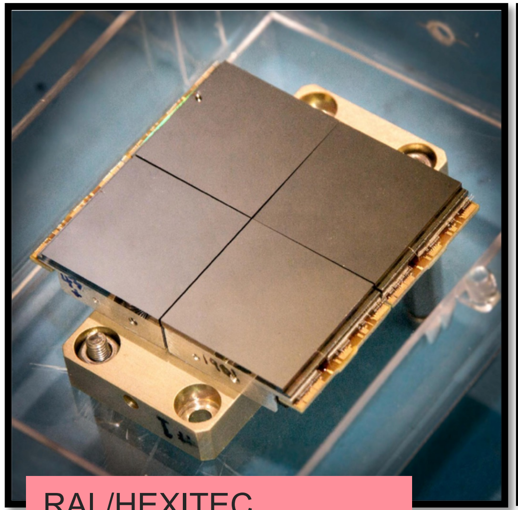


NASA/NuSTAR
~ 850 eV fwhm @ 60 keV
4x(32x32) pixels 605 µm

Harisson+13

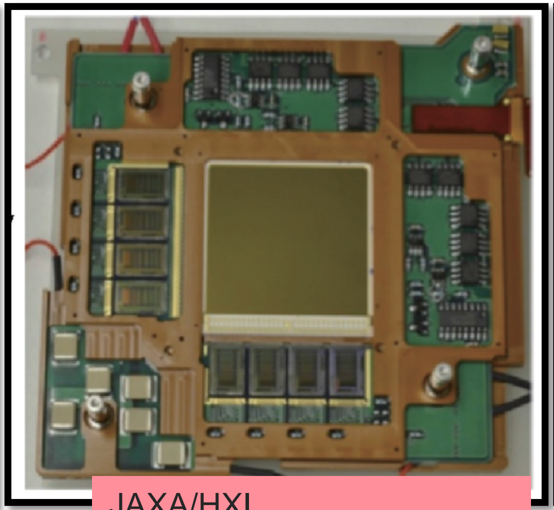
A Worldwide challenge for CdTe and CZT detectors

Very Fine pitch



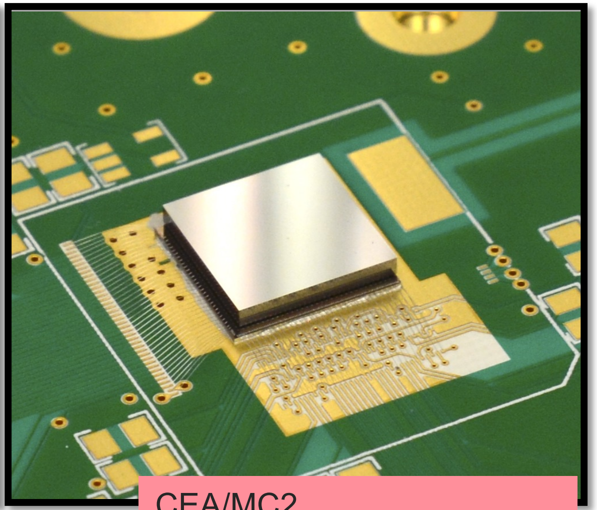
RAL/HEXITEC
~1 keV fwhm @ 60 keV
4x(80x80) pixels 250 µm

Jowitt+21



JAXA/HXI
~2 keV fwhm @ 60 keV
128x128 pixels 250 µm

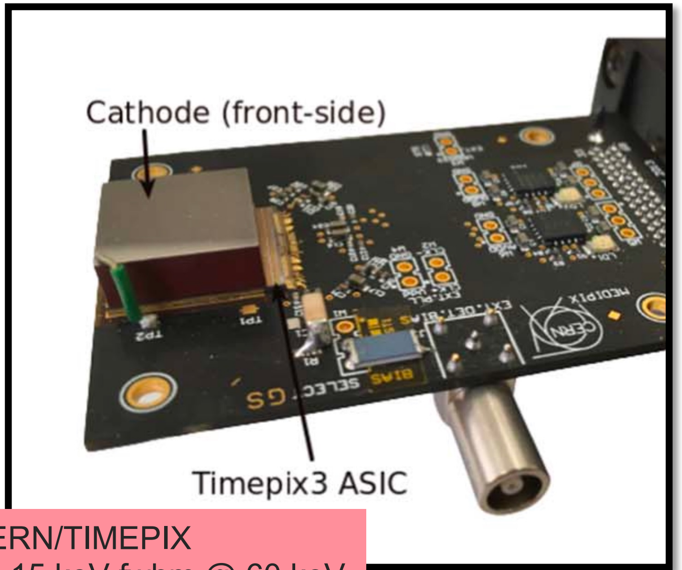
Hagino+21



CEA/MC2
~ 0.95 keV fwhm @ 60 keV
32x32 pixels 250 µm

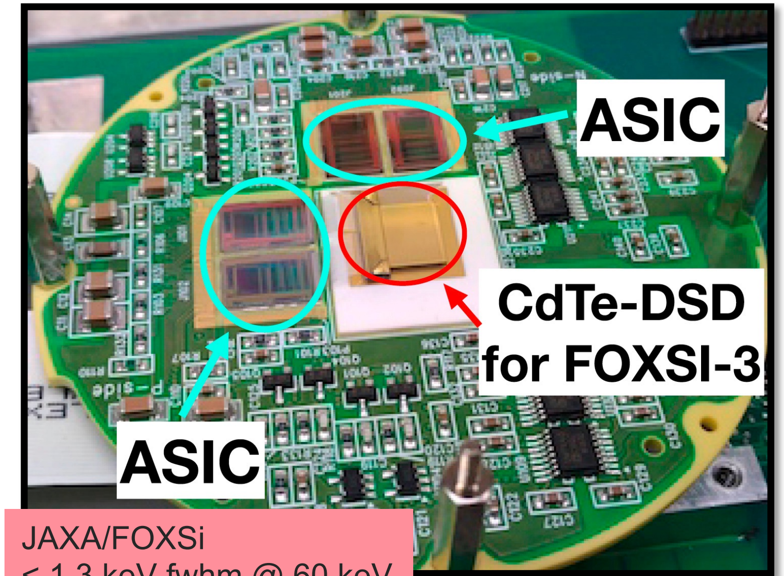
Allaire+23

A Worldwide challenge for CdTe and CZT detectors



CERN/TIMEPIX
~8-15 keV fwhm @ 60 keV
(26x256) pixels 55µm

Smolyanskiy+24



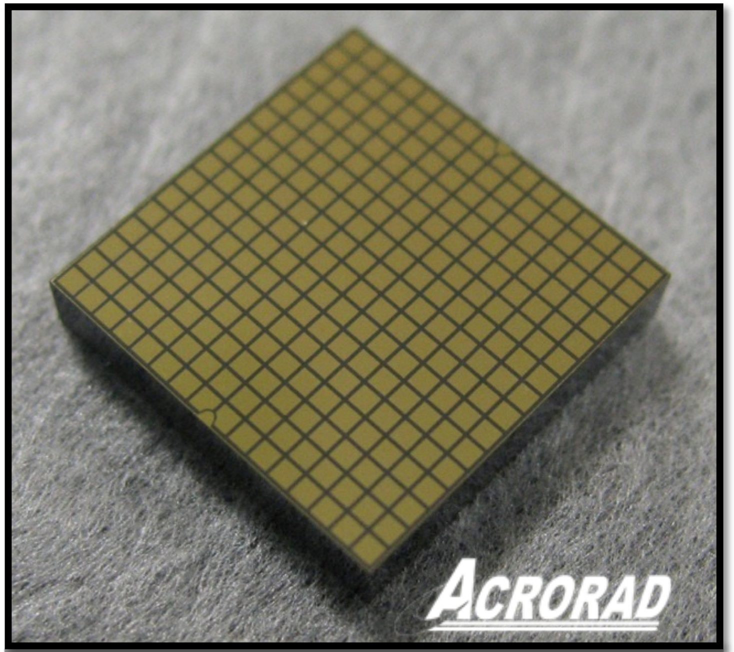
JAXA/FOXSi
< 1.3 keV fwhm @ 60 keV
128x128 pixels 60 µm

Furukawa+19

3D approach / CdTe Schottky: main properties

Imaging a PSF with

- 1 cm^2 monolithic CdTe
- 16 x 16 pixels
- 625 µm pitch, 100 µm interpixel gap
- Guard is 20 µm width
- 1mm thick for hard X-Ray domain is fine



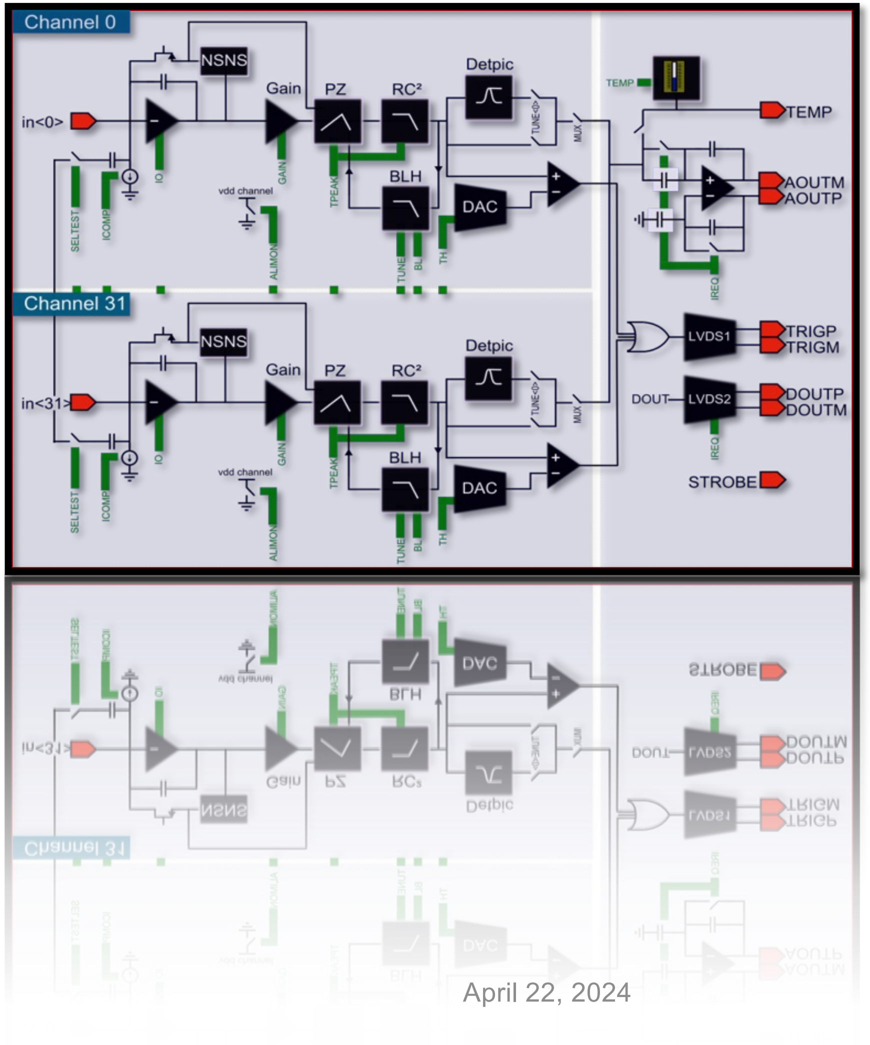
Measuring the energy accurately

- Al Schottky contacts
- Low leakage current (< 1pA at 0°C / 300V)
- Detector stray capacitance is very low (<50 fF)
- Complete charge collection

3D approach / IDeF-X HD ASIC main properties

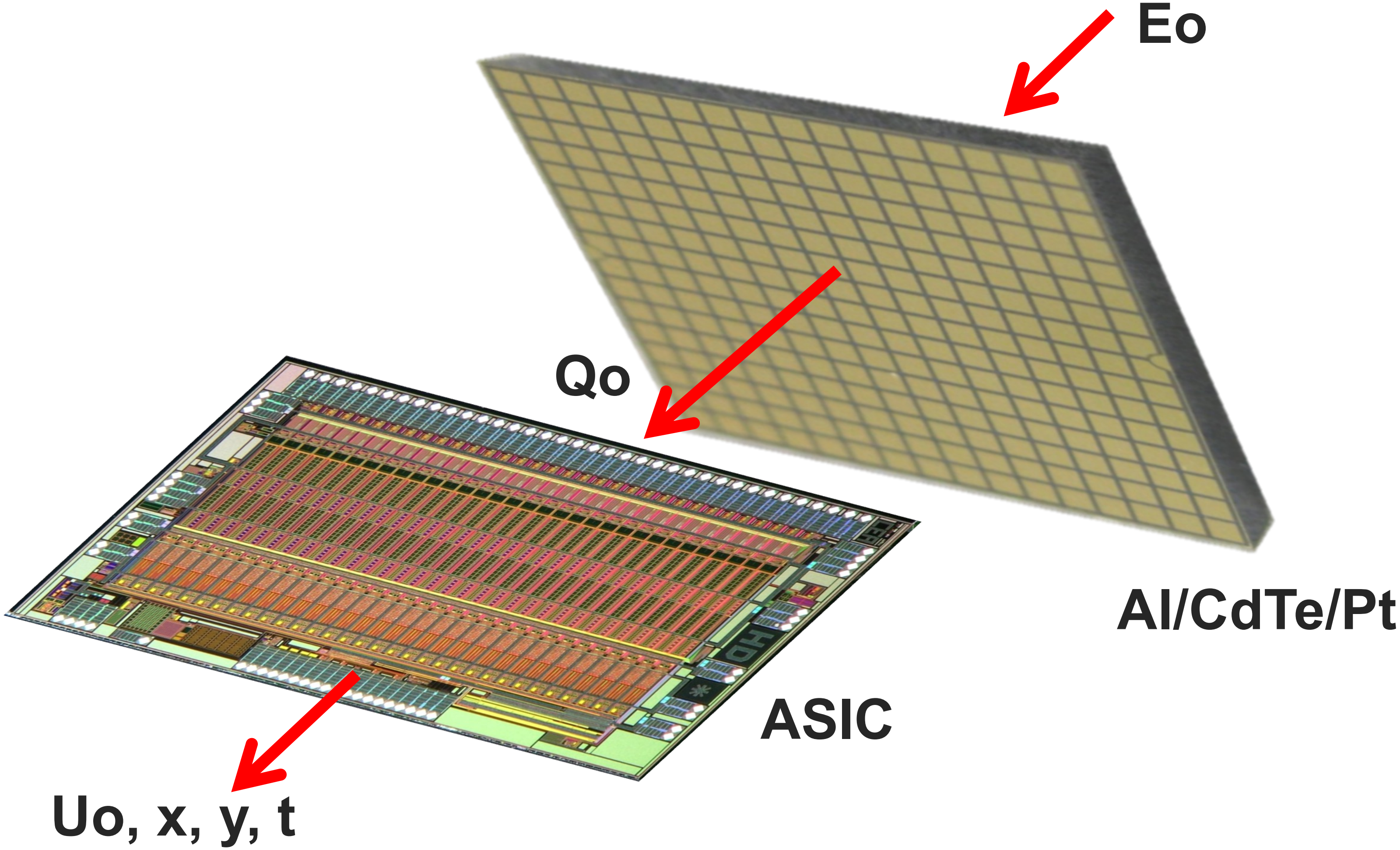
Full custom ASIC (family) developed at CEA

- CMOS AMS 0.35 µm, Area: 5.8 x 2.5 mm²
- 32 channels
- Individual tunable threshold
- Tunable shaper and gain
- Base line holder
- Absolute on-chip thermal sensor
- 800 µW/channel
- Multi ASIC digital interface
- High impedance output buffers
- Radiation hard (> 100 krad, Latch up free)



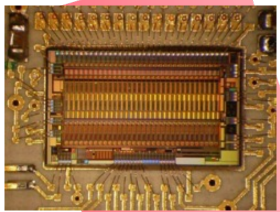
Low noise down to 33 el. rms floor

3D approach / Vertical Interconnexion concept



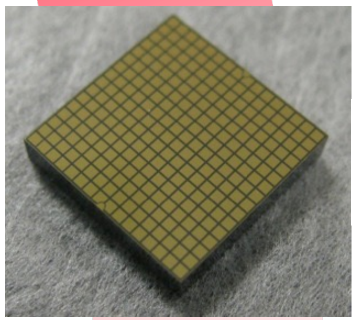
3D approach / Caliste HD: hybridization technology

IDeF-X HD ASIC
32 analog channels

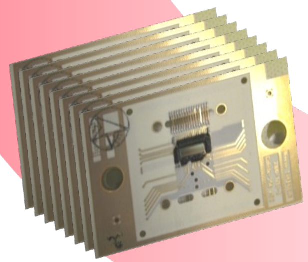


Mounting on PCB

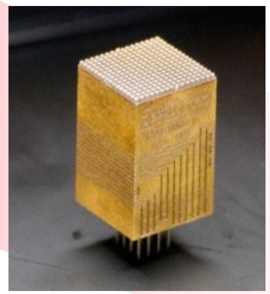
CdTe 256-pixel detector
Schottky type



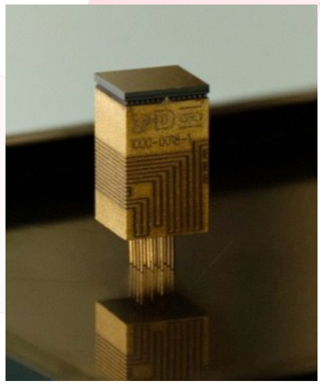
8 ASIC stack
perpendicular to the detection surface



Top surface preparation

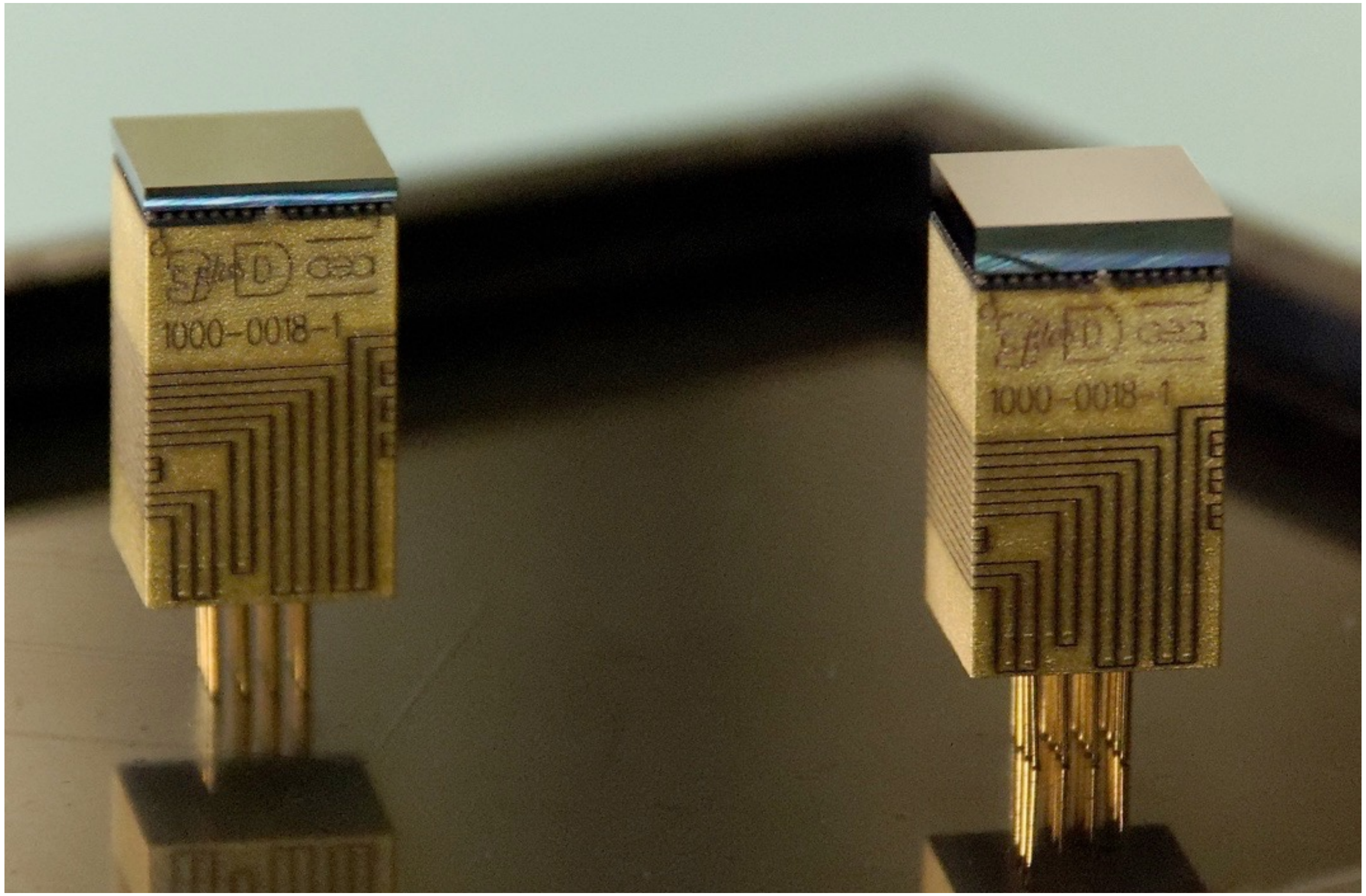


Electrical body
with a 4 x 4 pin grid array



Caliste-HD camera

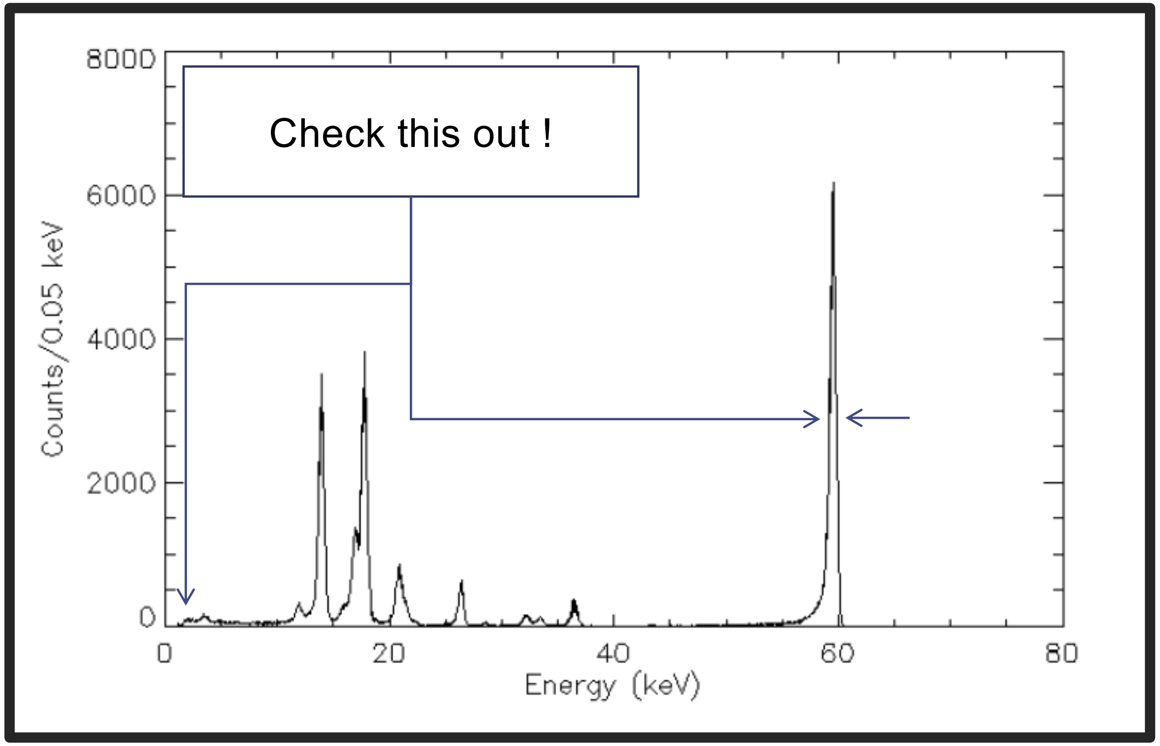
3D approach / Caliste concept



Caliste-HD, 1 and 2mm thick CdTe crystals, 256 pixels, 625µm pitch

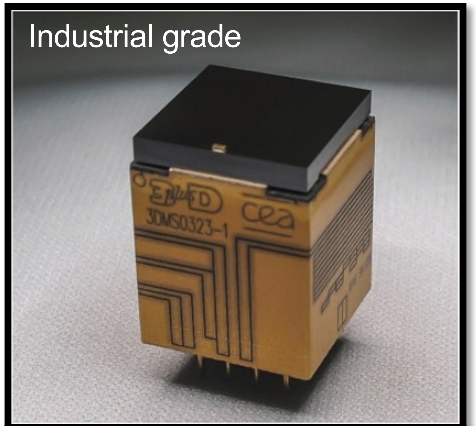
3D approach / Caliste-HD spectral response

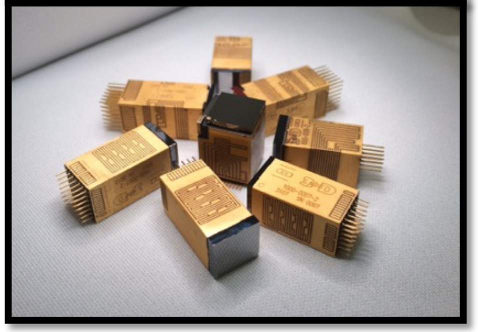
- -4°C / 400V
- **256 pixels** 562 eV FWHM at 13.9 keV
- **666 eV FWHM at 59.5 keV**
- **1.2 keV low threshold**
- **1 MeV dynamic range**



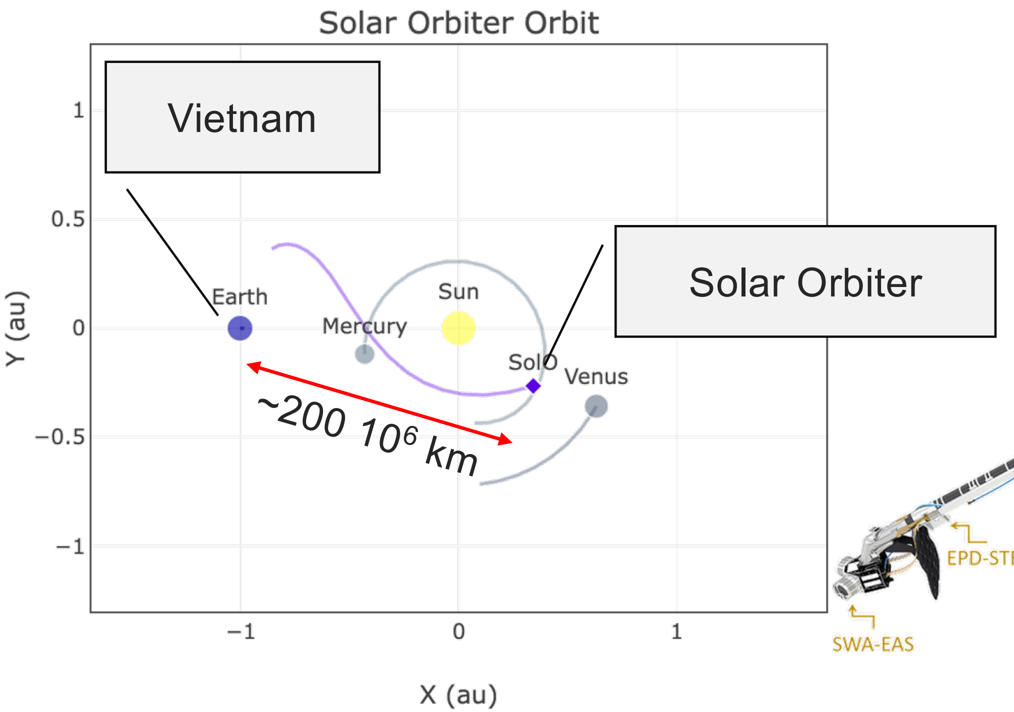
Caliste SiP 3D Modules family so far

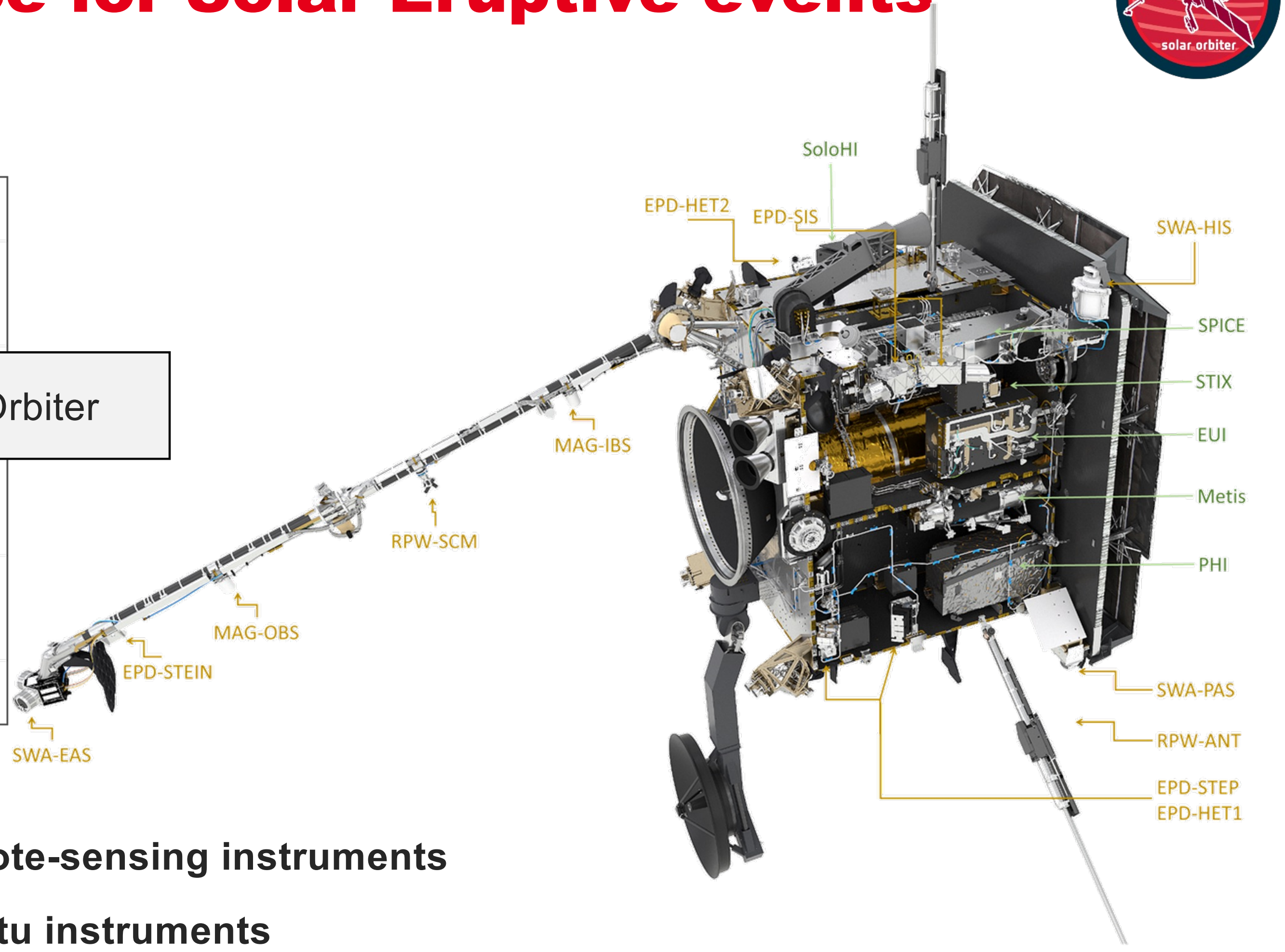
Parameters	Caliste-64	Caliste-256	Caliste-HD	Caliste-SO	Caliste-O
Years of development	2005-2007	2008-2009	2010-2011	2011-2013	2014-2017
Pixel array	8 × 8	16 × 16	16 × 16	4 × 3	16 × 16
Pixel pitch	900 µm	580 µm	625 µm	2150/4550 µm	800 µm
Guard ring width	900 µm	100 µm	20 µm	500 µm	500 µm
Front-end electronics	IDeF-X V1.1 (16 channels)	IDeF-X V2 (32 channels)	IDeF-X HD (32 channels)	IDeF-X HD (32 channels)	IDeF-X HD (32 channels)
Number of ASIC	4	8	8	1	8
Interface	7 × 7 PGA	7 × 7 PGA	4 × 4 PGA	2 × 10 SOP	7 × 7 PGA
Power consumption	200 mW	800 mW	200 mW	20 mW	200 mW
Energy range (keV)	2 to 250	1.5 to 250	1.5 to 1000	1.5 to 1000	1.5 to 1000
Energy resolution (FWHM at 60 keV)	900 eV	860 eV	670 eV	1000 eV	1000 eV
Dimensions w/o CdTe (mm³)	10×10×18.6	10×10×20.7	10×10×16.5	11×12×15.65	15×15×16.5
CdTe or CZT Dimensions (mm³)	10×10×(0.5 – 2)	10×10×(0.5 – 2)	10×10×(0.5 – 2)	10×10×1	15×15×(0.5-2)
Radiation Hardness TID (krad) SEU (MeV.cm².mg⁻¹) SEL (MeV.cm².mg⁻¹)	 >300 ~9 12	 >300 ~9 56	 >300 ~9 >110	 >300 ~9 >110	 >300 ~9 >110





Application in Space for Solar Eruptive events observations



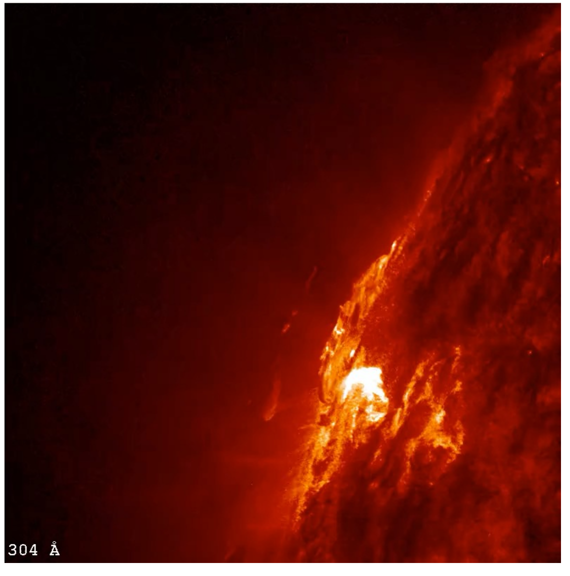


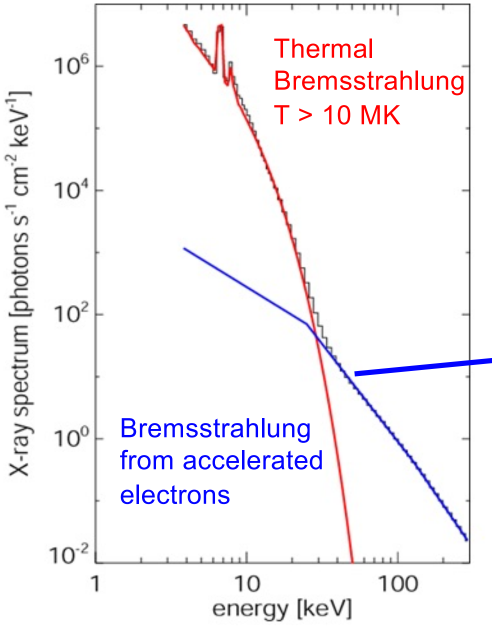
- **6 remote-sensing instruments**
- **4 in-situ instruments**

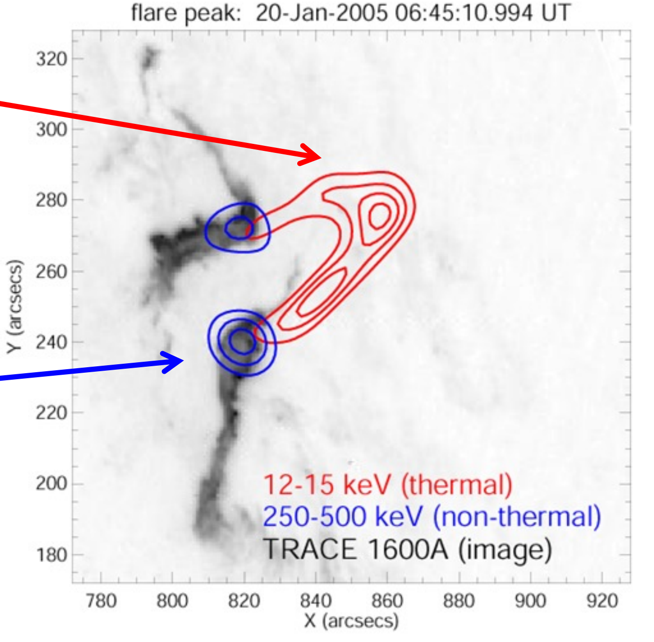
STIX Science goals

- **STIX: Spectrometer Telescope Imaging X-rays**
- **By detecting X-rays from 4 to 150 keV, STIX determines the intensity, the location, the timing, the spectra of accelerated electrons near the Sun.**

Energy range	4-150 keV
Angular resolution	7” to 180”
Spectral resolution	~1 keV @ 6 keV
Time resolution	down to 0.1 s
FOV	2° x 2°

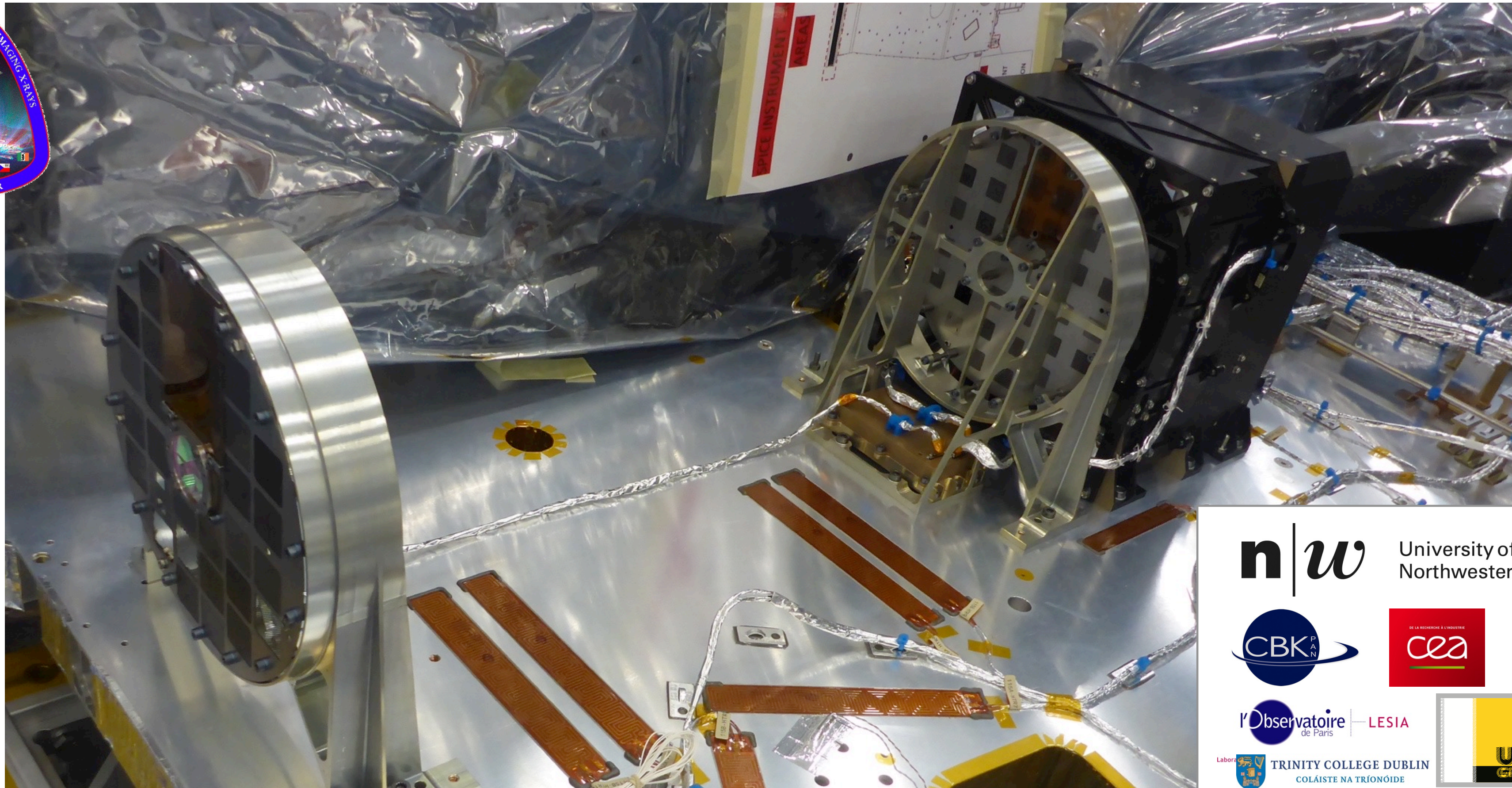






Hard X-ray Spectrum and Image from RHESSI

Application in Space for Solar Eruptive events observations



University of Applied Sciences Northwestern Switzerland

CBK PAN

cea

AIP

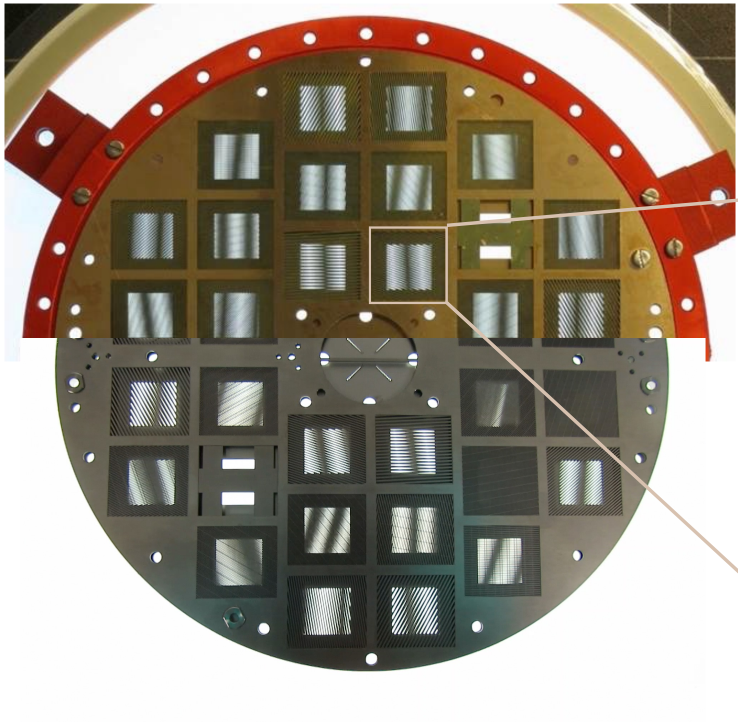
l'Observatoire de Paris — LESIA

TRINITY COLLEGE DUBLIN
COLÁISTE NA TRÍONÓIDE

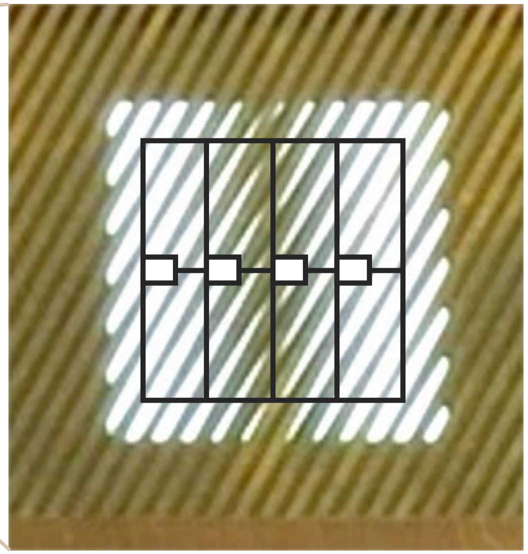
UNI GRAZ

UNIVERSITÀ DEGLI STUDI DI GENOVA

Imaging technique: Fourier Imaging Spectroscopy

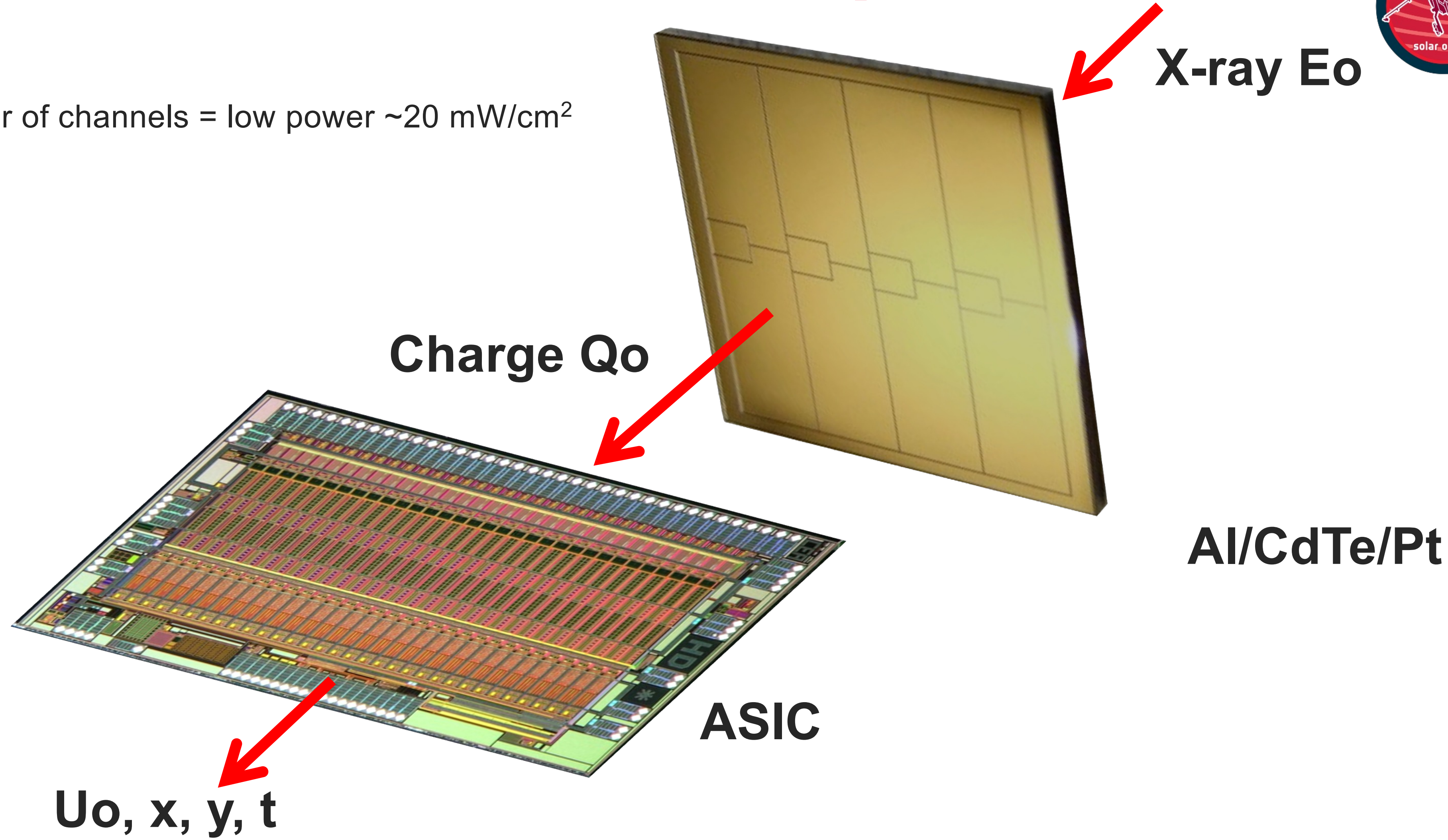


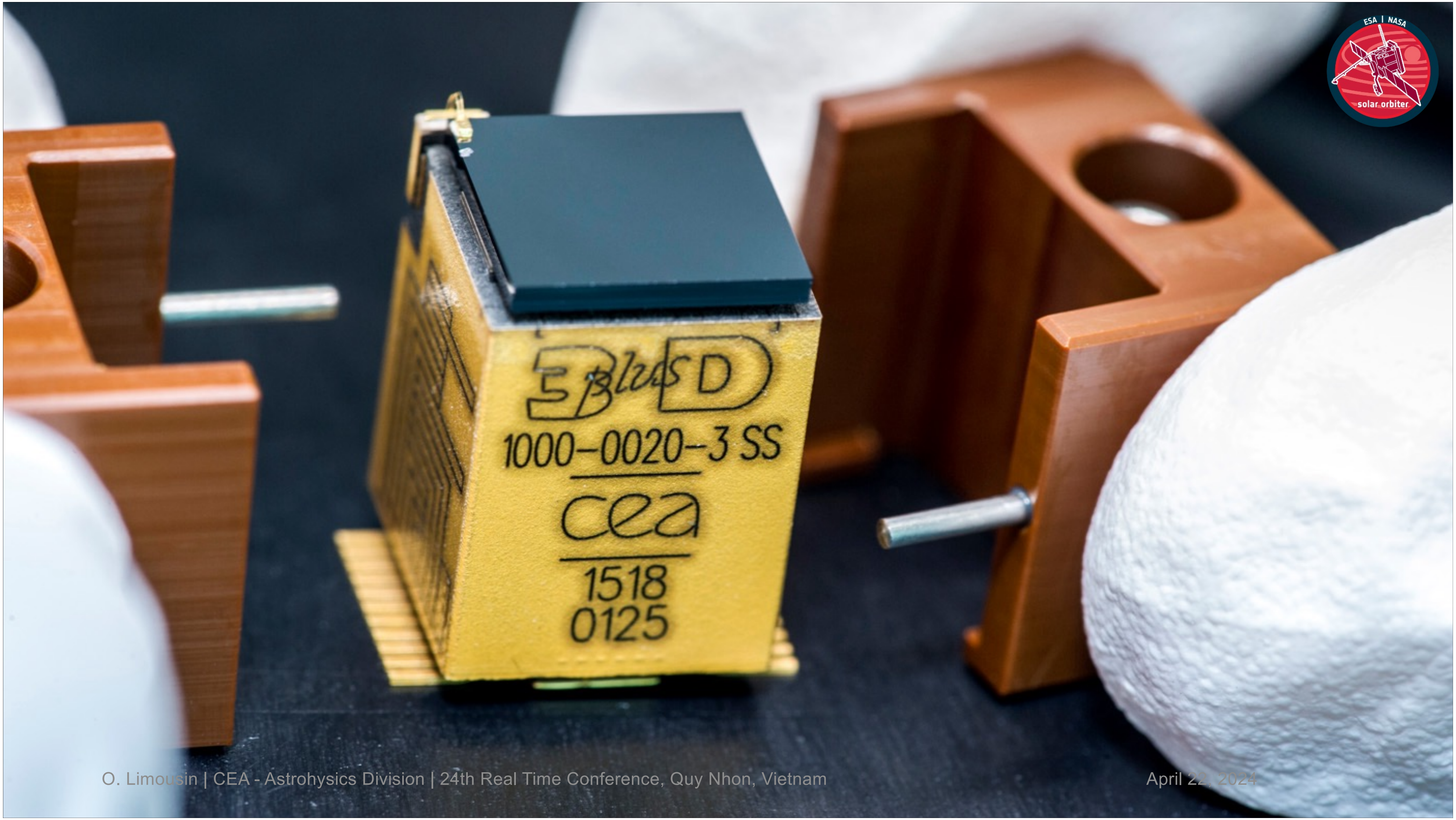
- 4 bands to measure the amplitude and the phase of the visibility
- 8 pixels for redundancy
- 12 pixels with 4 small pixels for high count rate capability

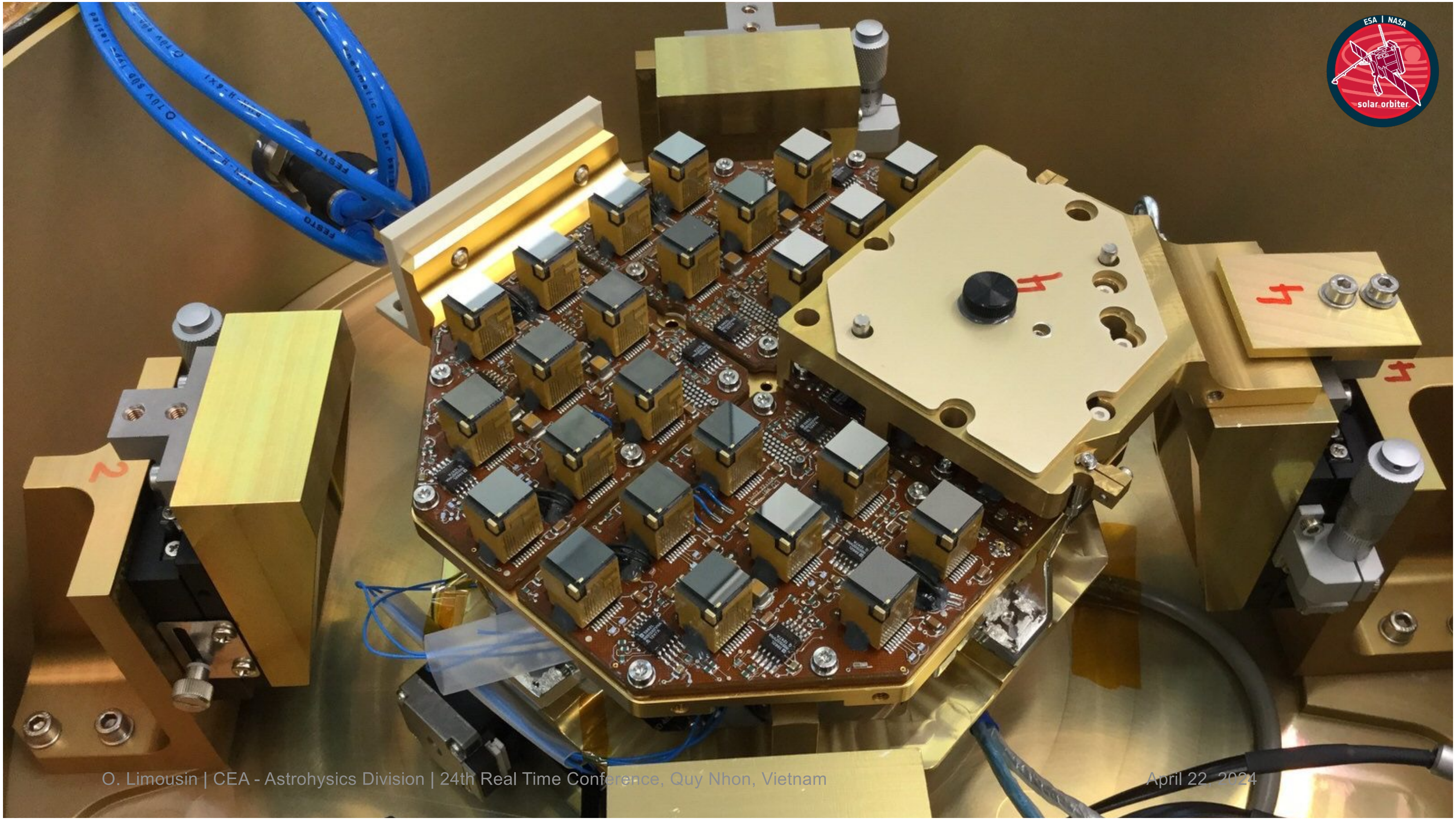


Vertical Interconnexion concept

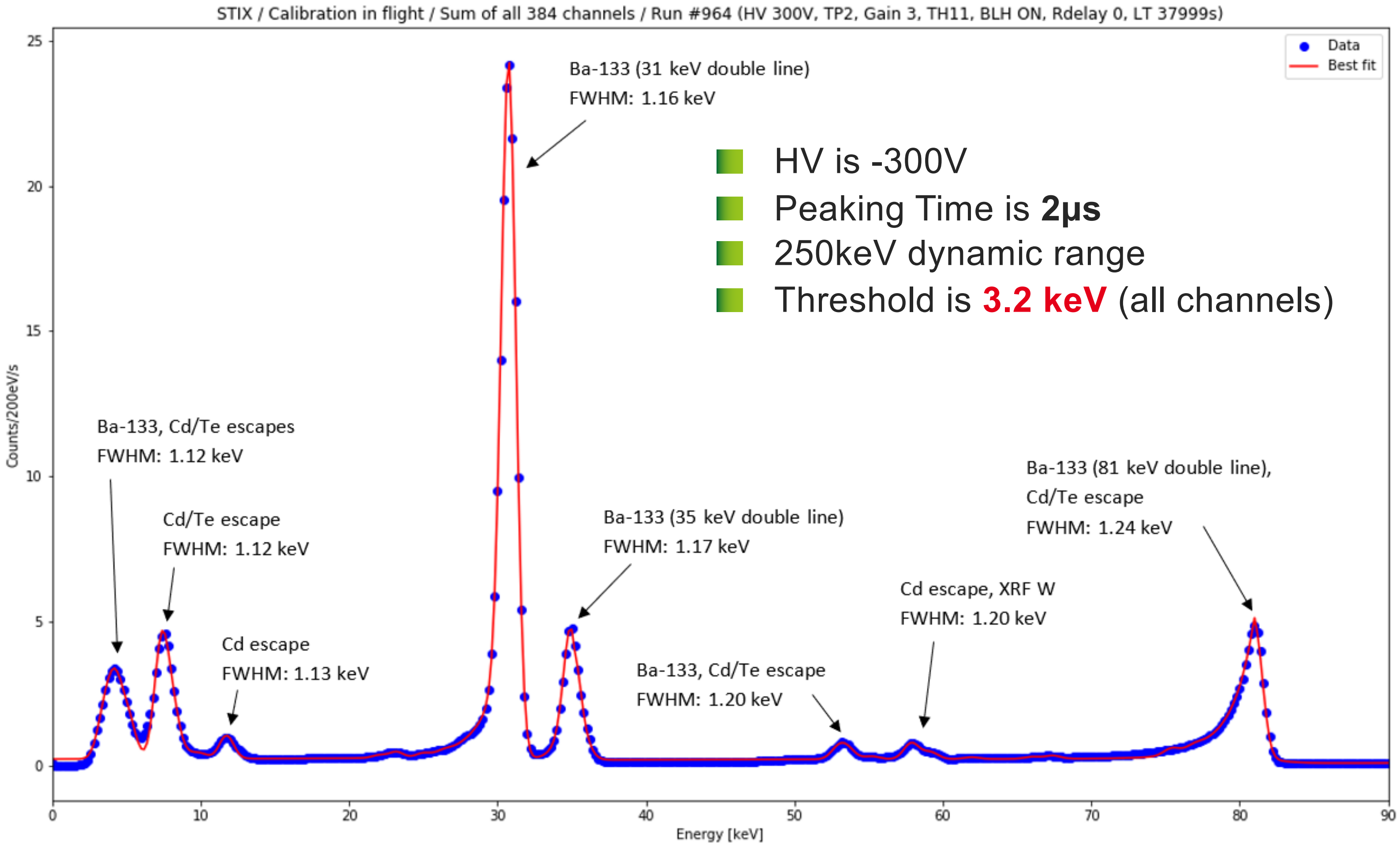
Small number of channels = low power ~20 mW/cm^2




ESA | NASA
solar orbiter
3plusD
1000-0020-3 SS
cea
1518
0125


ESA | NASA
solar orbiter
2
4
4
4

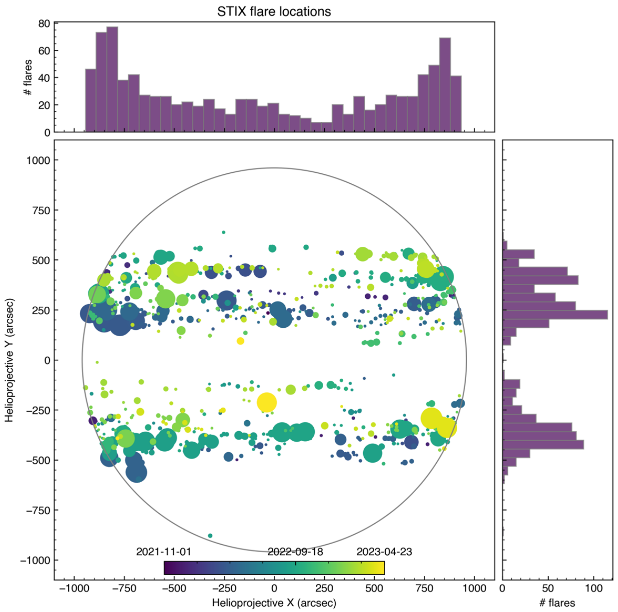
Performance in flight on board Solar Orbiter

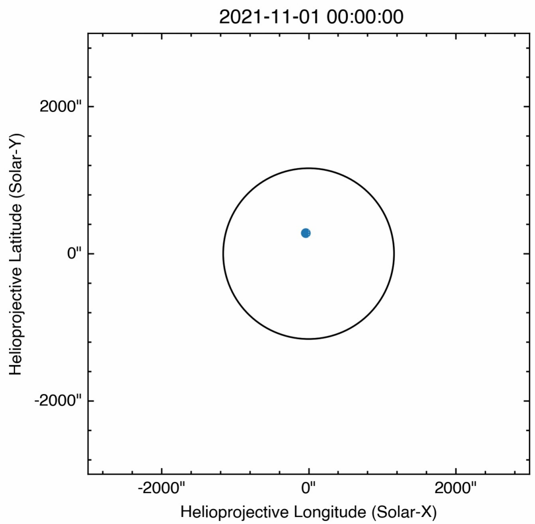


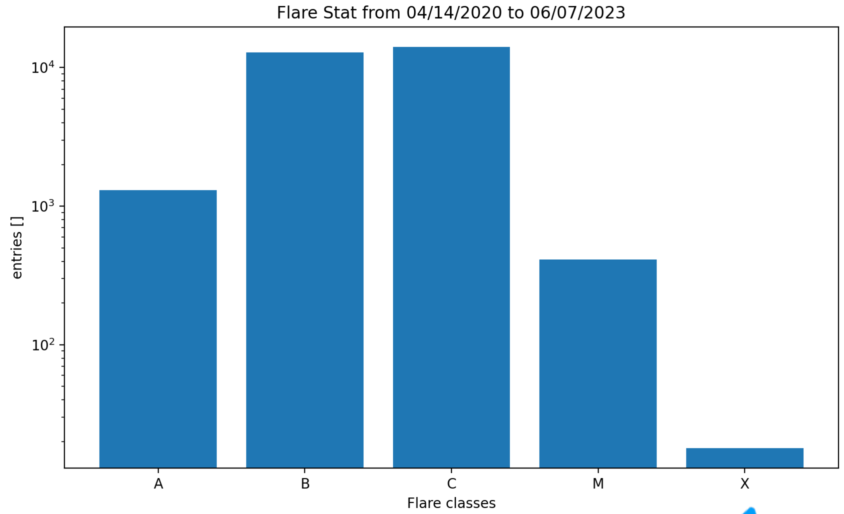
- HV is -300V
- Peaking Time is **2µs**
- 250keV dynamic range
- Threshold is **3.2 keV** (all channels)

STIX successfully operating 24/7 since 2021

50,000+ Flares since then







*courtesy of Laura Hayes, ESA

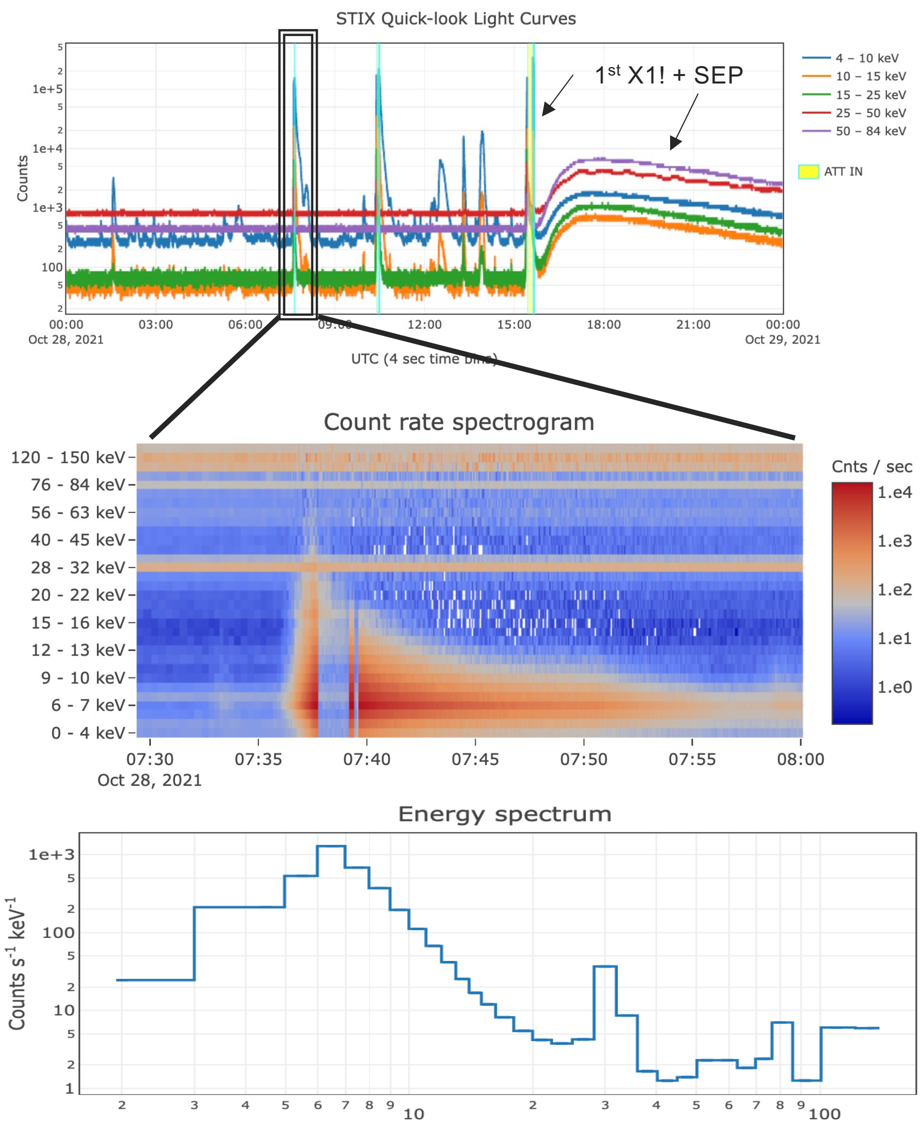
My favorite ones …

STIX Operation mode

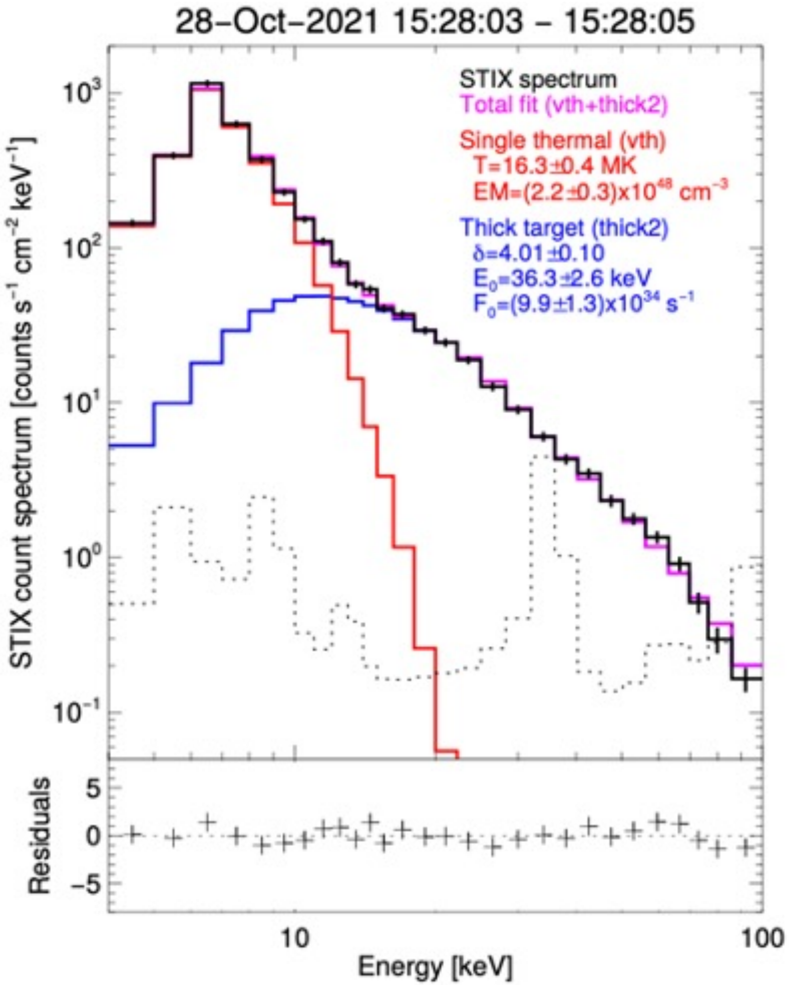
- Quick-Looks are sent down automatically
  - Select Event period of time
  - Energy range
  - Time resolution
  - Data type (Full or spectrograms)
  - Send the data request (Weekly)

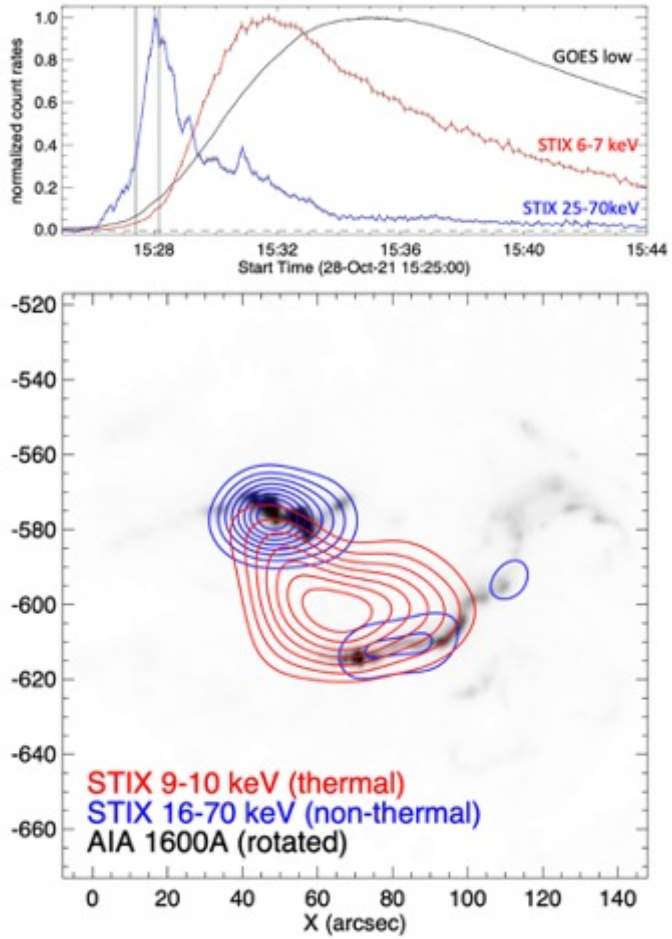
- Internal memory of STIX holds up to ~6 months of data

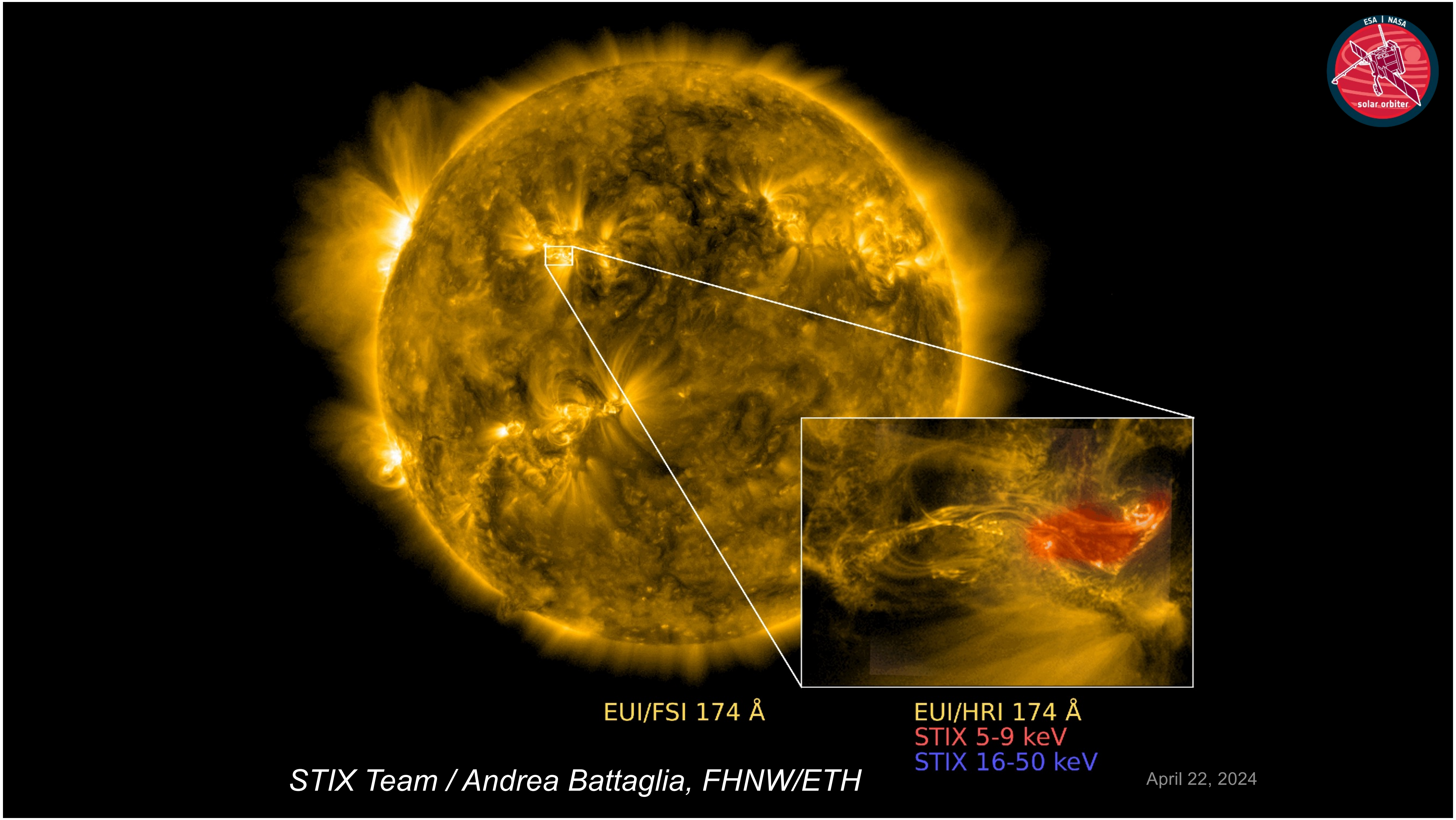
- Be patient … (6 weeks approx.)
  - Take your data
  - Play with it!



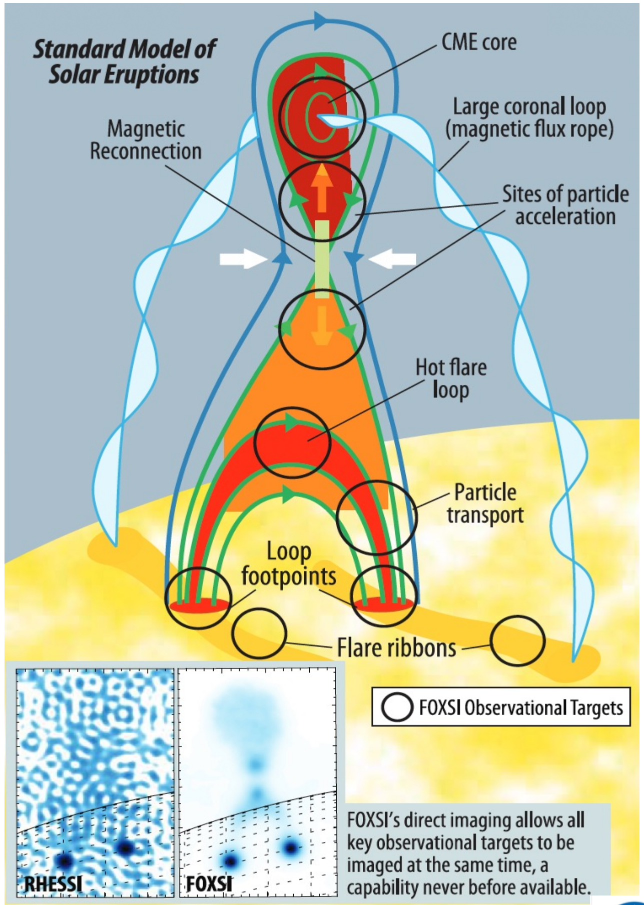
Performance in flight on board Solar Orbiter



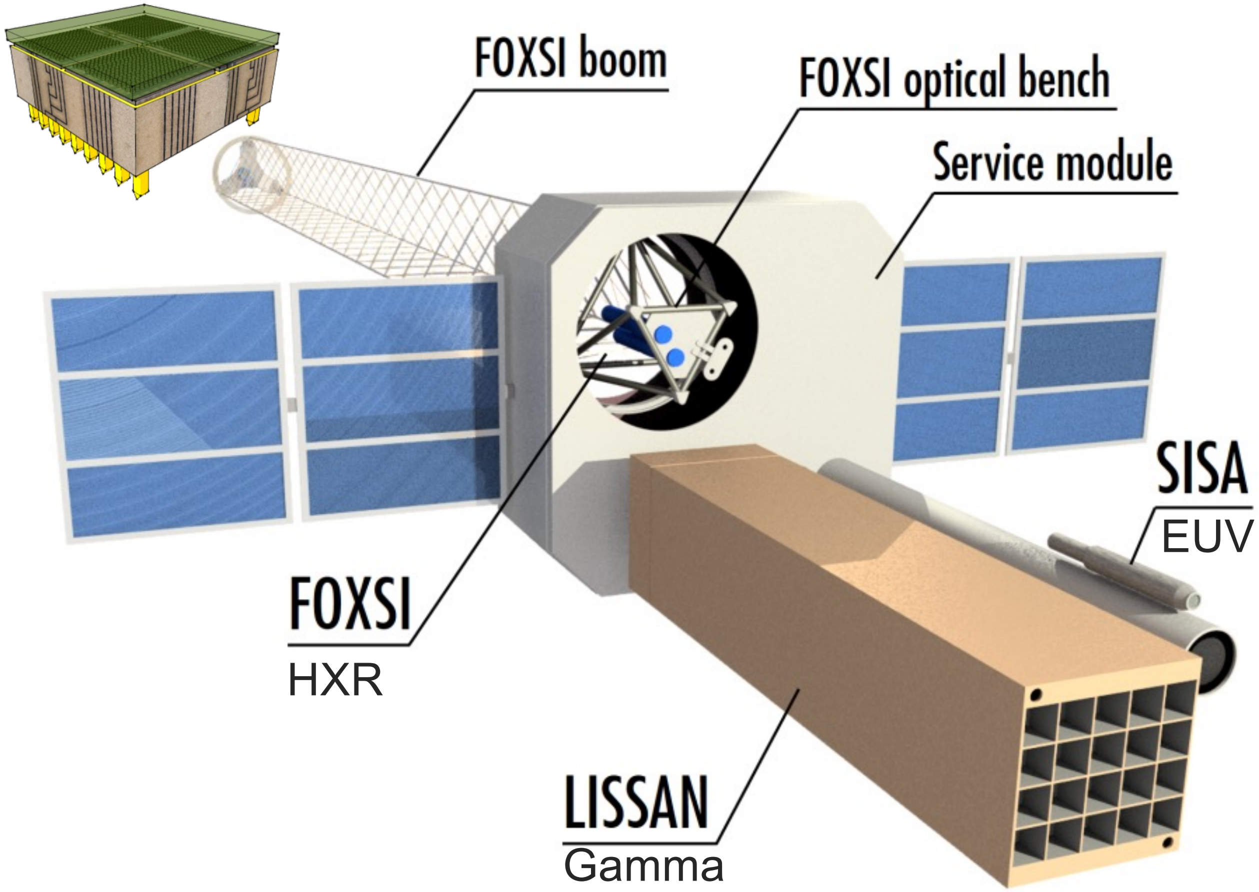



ESA | NASA
solar orbiter
EUI/FSI 174 Å
EUI/HRI 174 Å
STIX 5-9 keV
STIX 16-50 keV
STIX Team / Andrea Battaglia, FHNW/ETH
April 22, 2024

What should we do next for space science: SPARK

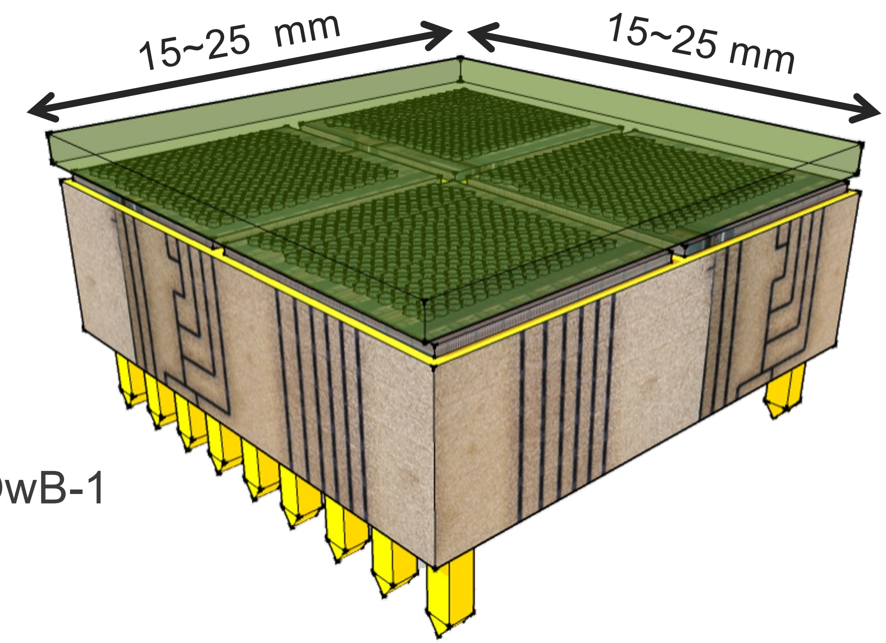


Courtesy of Steven Christe, NASA/GSFC



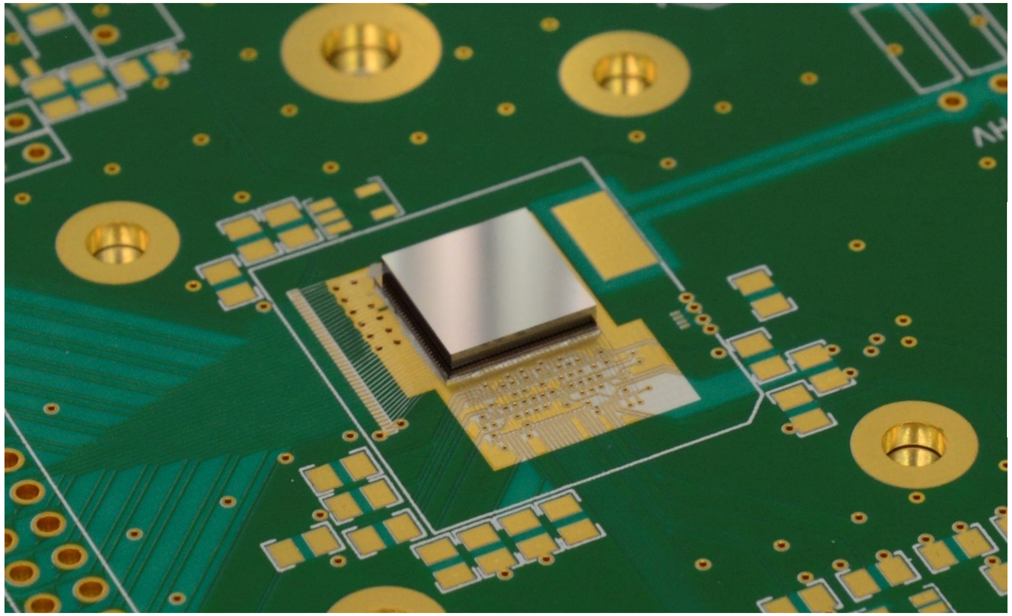
Caliste-MC2 concept

- Reach the Fano limit for ultimate energy resolution
- Smaller pixels (Pay attention to spilt events …. ~100-200 µm minimum)
- Larger area
- Higher counting rate capability
- **More advanced packaging**
- **More advanced embedded functions**



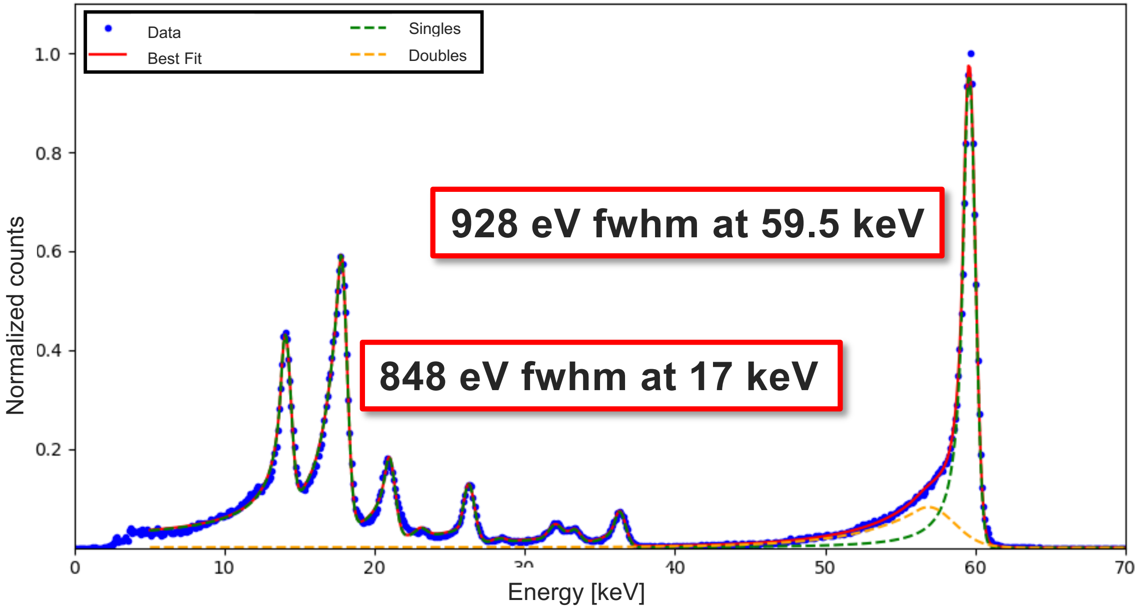
- 3D integration
- Modular approach, $(64 \text{ to } 96)^2$ fine pitch CdTe
- Flip chipped to a mosaic of 2D-ASIC D^2R_x
- Stacked to a
  - Fully parallel high speed A/D converter – OwB-1
  - Filter stage
  - I/O's

Detector performance demonstration



Caliste-MC2-1K prototype (flat configuration)

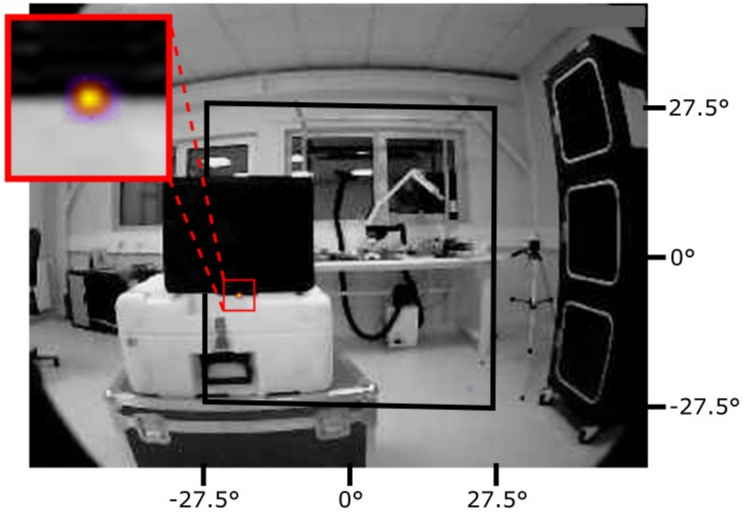
Allaire+23

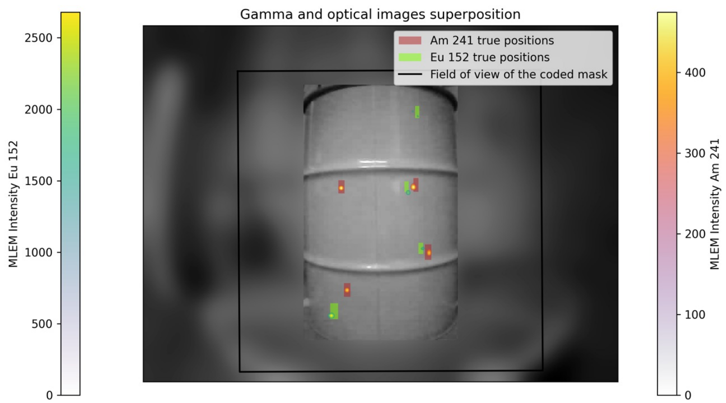


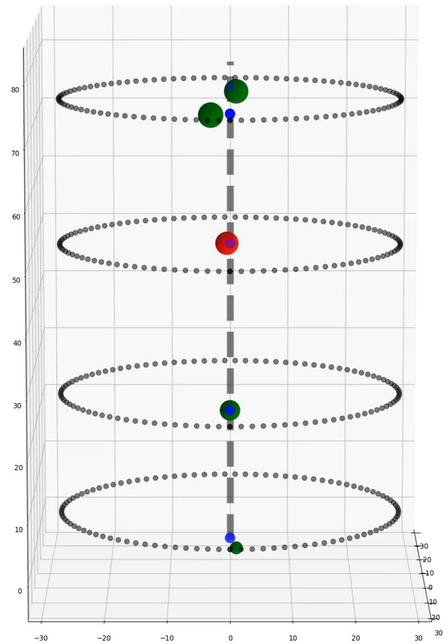
^{241}Am, T = +4,0°C, HT = 400 V, Sum of all channels

Spid-X Gamma camera for nuclear monitoring

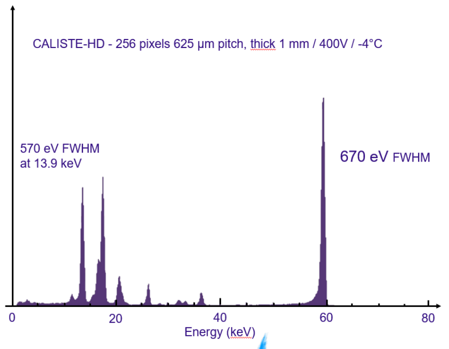
Spid-X Industrial demonstrator
Caliste-O technology embedded

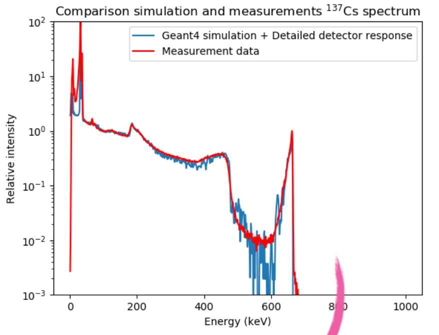


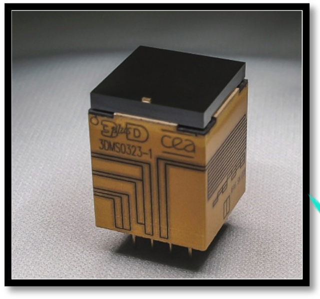




Spid-X for nuclear monitoring







Energy Calibration

- Fine Mesh ECC Algorithm (see poster D. Maier et al.)

Learning flow

- Detector simulation
- Synthetic Source Mixture Database
- Training neural networks

Data Acquisition

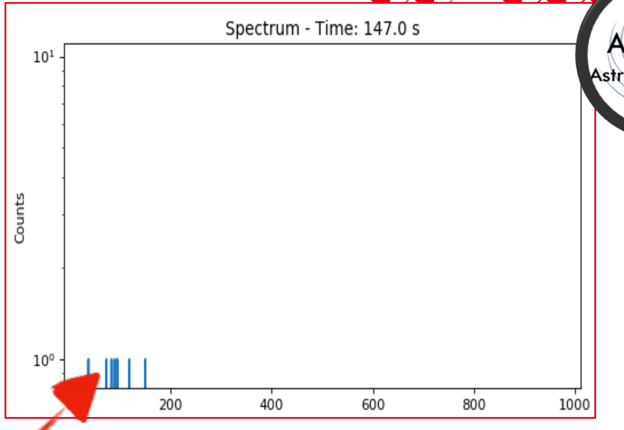
- Caliste Detector
- Event Energy Calibration

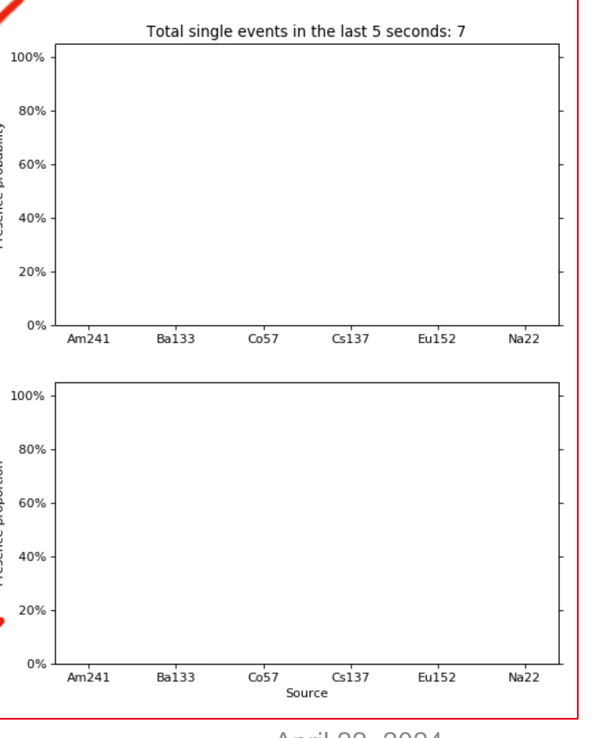
Real-Time processing

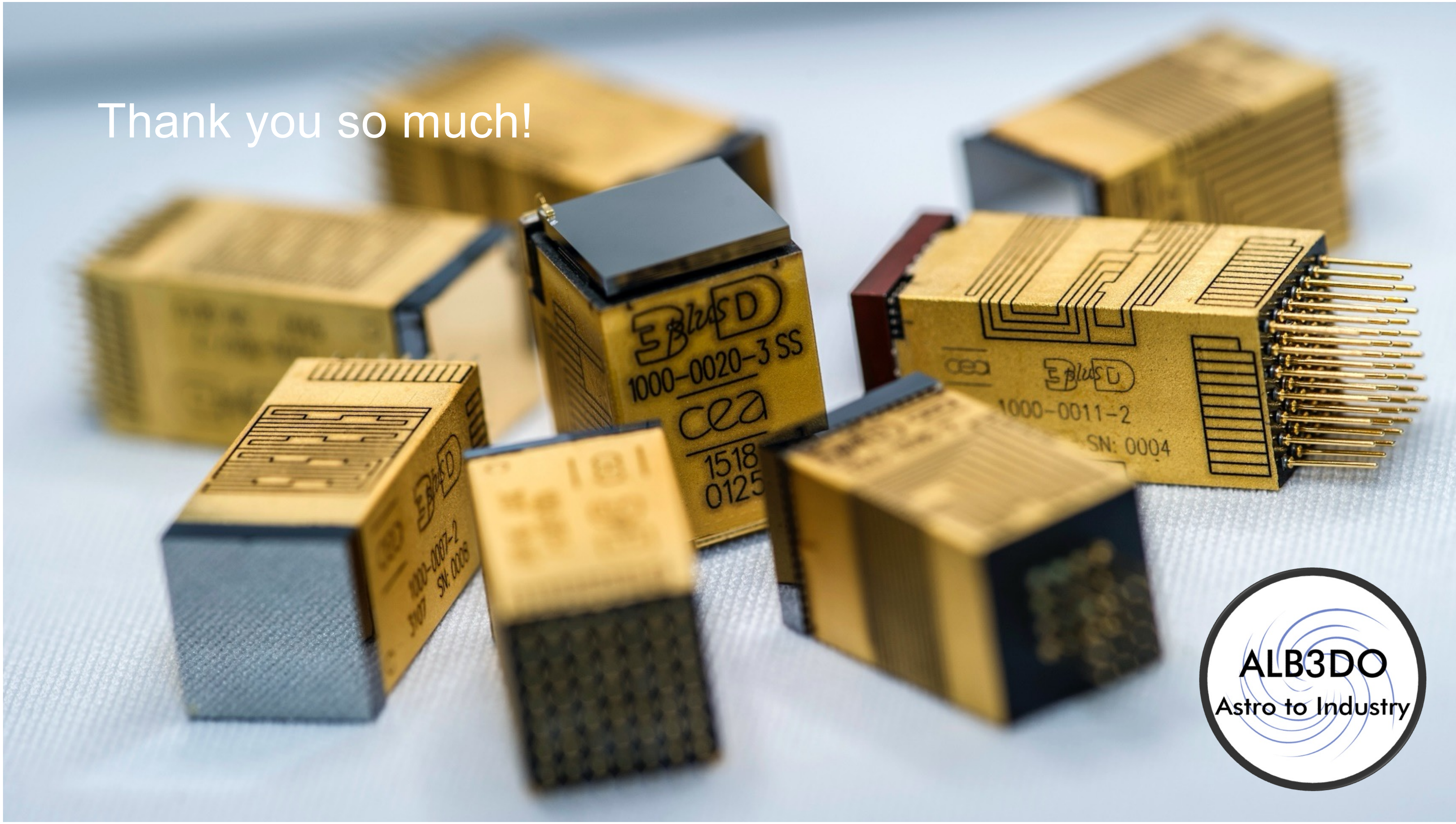
- Energy Spectra build-up
- Radio-elements Identification and Proportion by BCNN

Algorithm output

- Identified sources list
- Identification confidence level
- Proportions of identified sources in a mixture
- Uncertainties estimates of source proportions






Thank you so much!
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cea
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SN: 0004
ALB3DO
Astro to Industry