Wide band Laue lenses: development status and their scientific prospects in Hard X and soft astronomy

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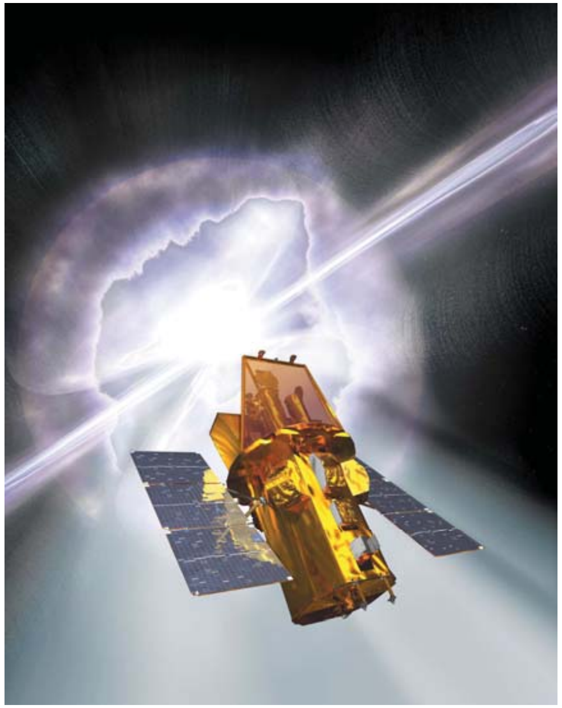
on behalf of the “LAUE” Collaboration

Perspective in Hard X-ray astronomy

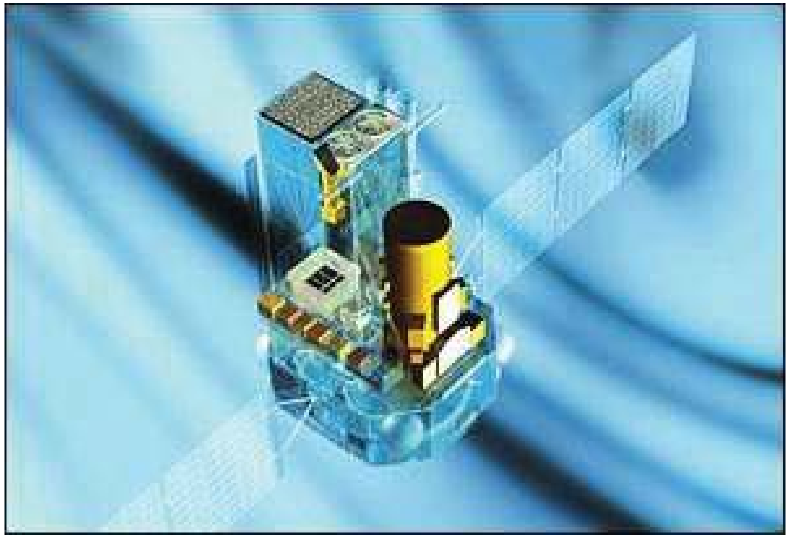
Physics Dept., Diderot University, Paris, 13-14 January 2013

Introduction 1/2



- Hundreds of hard X-ray sources discovered with INTEGRAL and Swift surveys.
- Polarized photons above 400 keV discovered;
- Asymmetric distribution of the 511 keV line in the GC.

- Requirement of order of magnitudes more sensitive instruments for deep studies of the discovered sources and new phenomena.

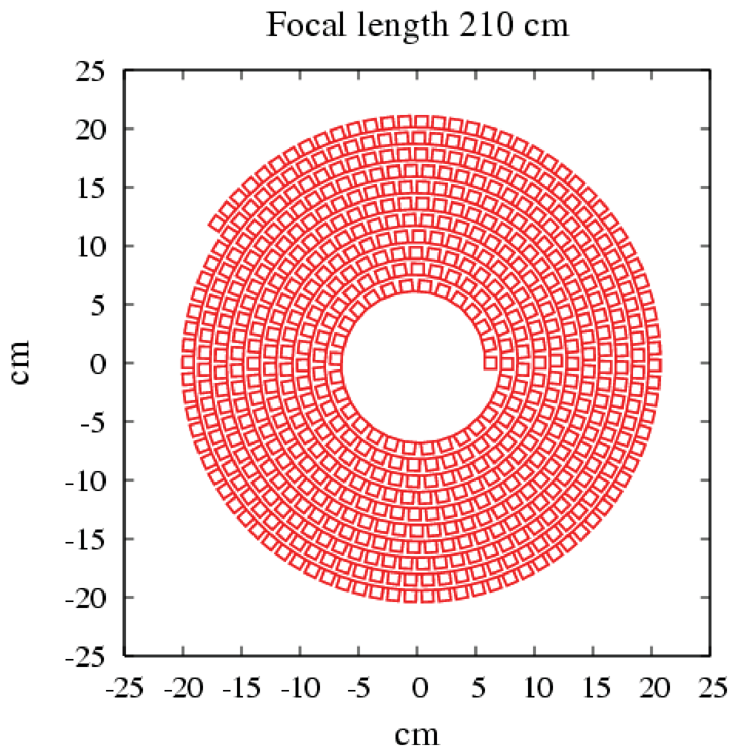


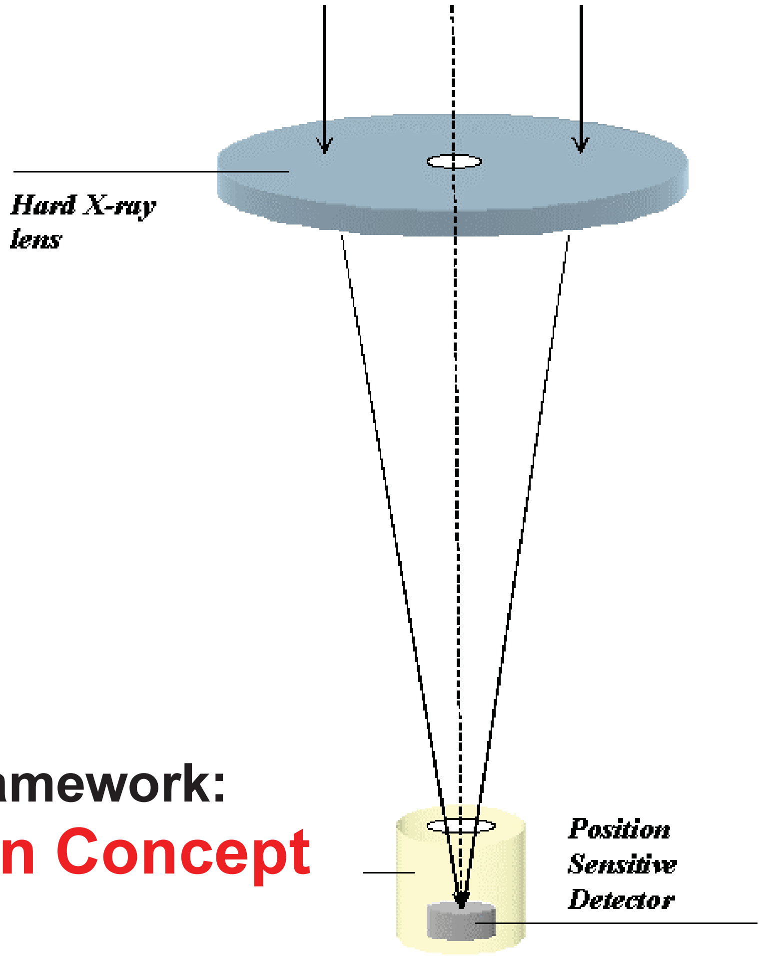
Introduction 2/2

- The only viable way is the use of hard X—ray focusing telescopes.
- NuSTAR is the first mission with focusing hard X-ray telescopes, with sensitivity two orders of magnitude better. However:
  - Hard X—ray passband limited (<80 keV) with maximum sensitivity around 30 keV.
- Extension to higher energies is crucial to settle many open issues (see later)

- **Requirements for hard X-/soft gamma-ray telescopes (>80/100 keV):**
  - **Continuum sensitivity at least two orders of magnitude better than that of INTEGRAL at the same energies:**
    - **Goal: a few x10^{-8} ph/(cm^2 s keV) in 10^5 s,** .
      i.e. **10^{-15} erg/(cm^2 s keV);**
  - **Much higher line sensitivity (Goal: 10^{-5} ph/cm^2 s in 10^5 s in the case of a narrow line);**
  - **Much better (< 1 arcmin) imaging capability.**
  - **Reliable Polarisation measurement capability**

Our proposal: a wide band Laue lens



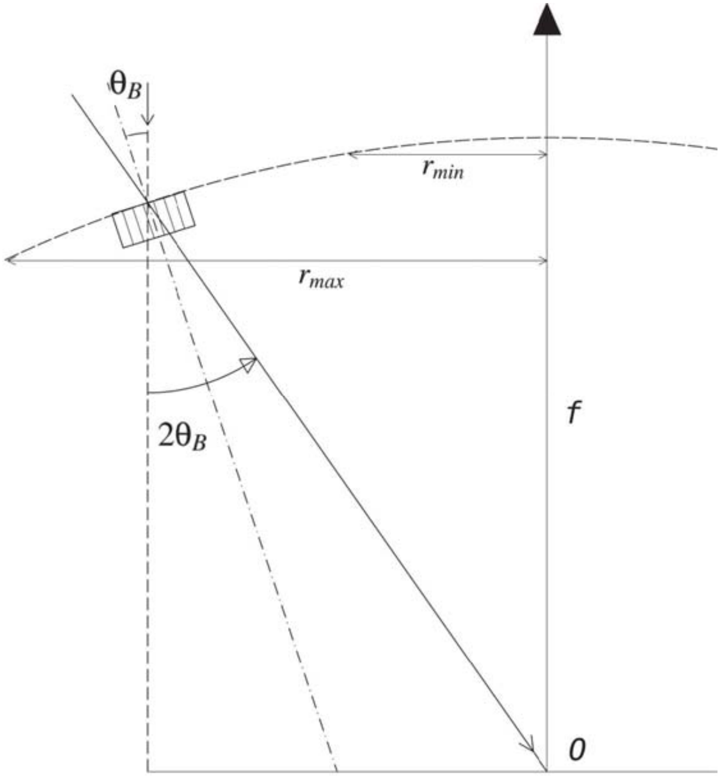


First proposal in the ESA M2 Call framework:

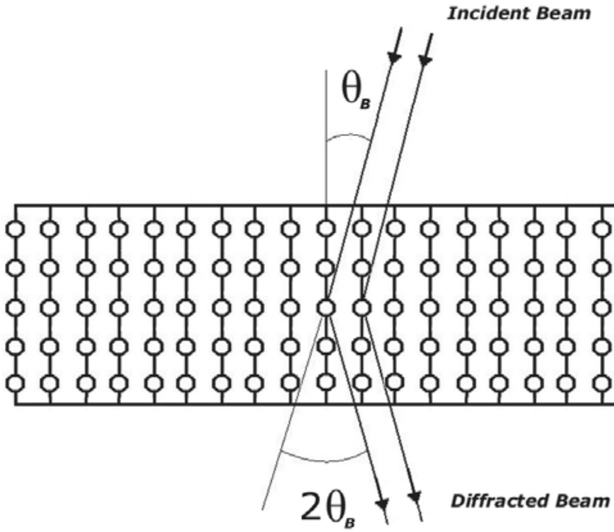
GRI (Gamma Ray Imager) Mission Concept

- Wide band and Nuclear line Laue Lens (200 keV-1000 keV) +
- High energy Multilayer Mirrors (10-300 keV)
- Focal lenght: 80 m
- Formation flight (two satellites)

Laue lens principle



- Laue lens surface is spherical
- Curvature radius 2x Focal length

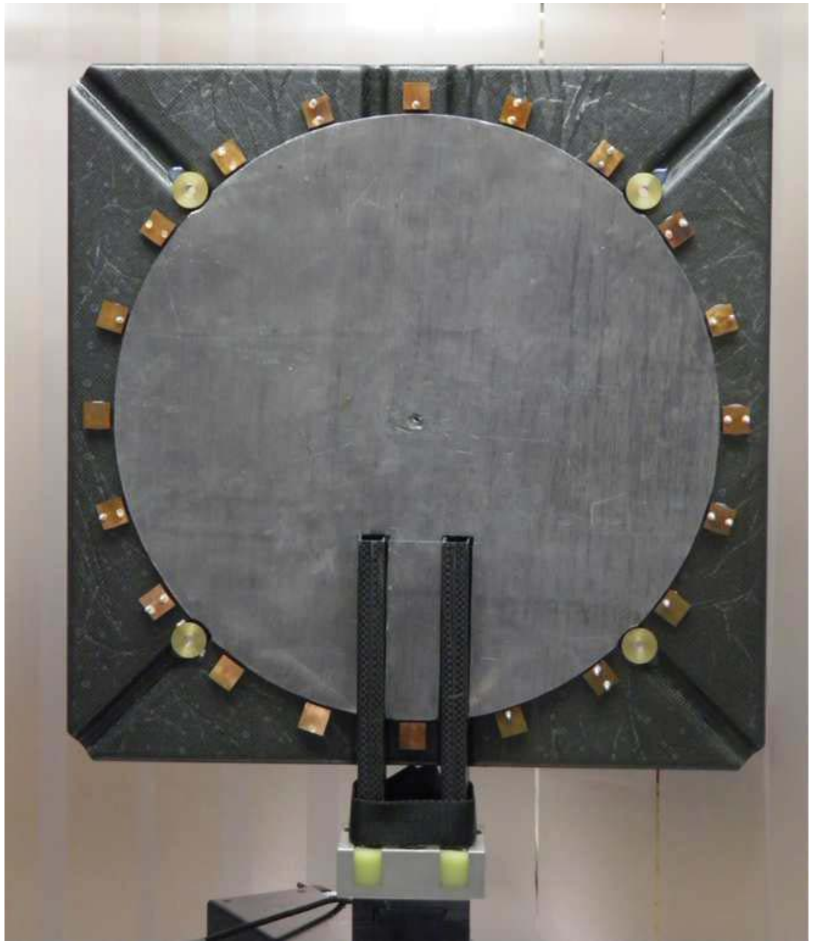


- Bragg diffraction in transmission configuration
- Mosaic/bent crystals to extend the passband and get a smooth dependence of the lens effective area with energy;
- Material and lattice planes properly chosen to maximize reflectivity.

First experience: the HAXTEL project

- Multistep building approach;
- 6 m focal lengt*h;*
- Flat mosaic crystals of Cu (111);
- Mosaic spread of a few arcmin.

Frontera et al. 2008

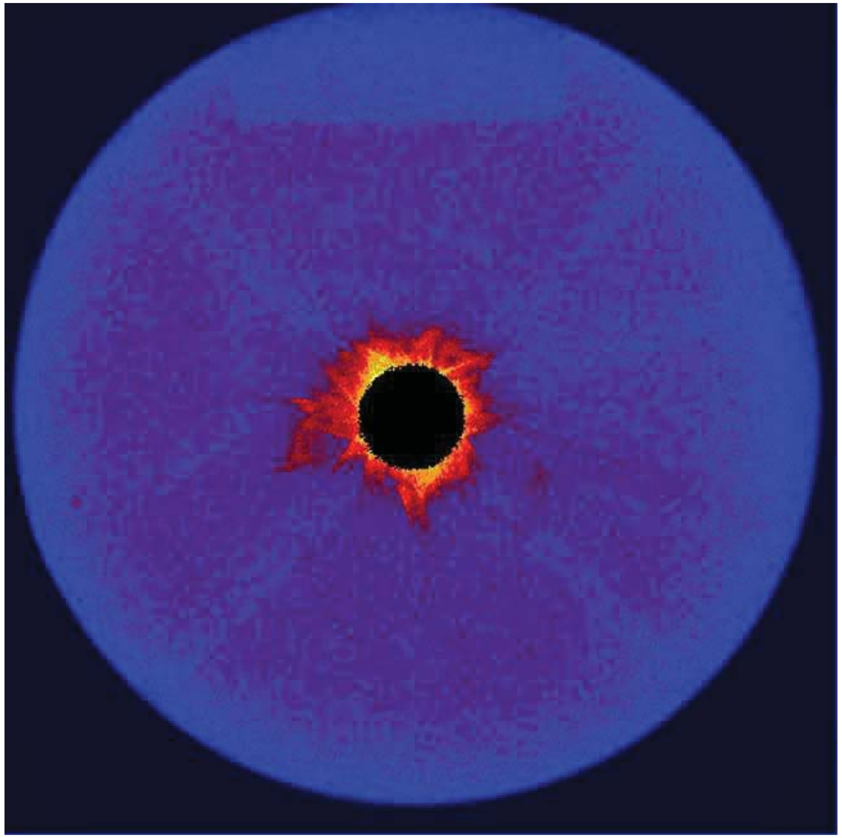


Virgilli et al. 2011

HAXTEL results

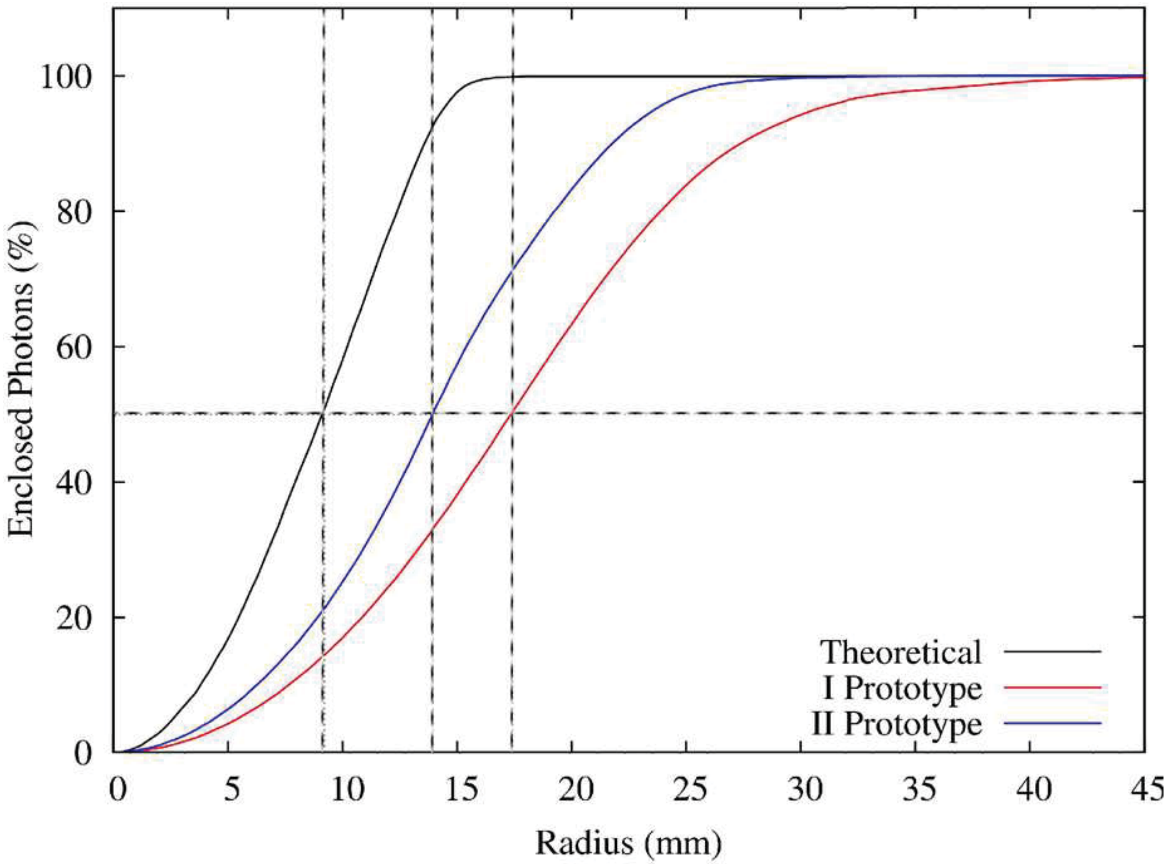
- Cu mosaic crystals: 15x15x2 mm^3
- Expected PSF diameter is the Cu crystal diagonal (black circle)

1st prototype



2nd prototype

1st prototype vs. 2nd prototype



A PSF improvement obtained, <u>but not sufficient !</u>

A new assembling technology was needed in particular for long focal lengths.

Laue Project

(funded by ASI in 2010)

Main goals:

- More accurate assembly technology for long focal lengths. Required cumulative error budget <10”;
- Better reflection efficiency and better focusing;
- Development of a 20 m FL lens petal;
- Feasibility and accommodation study of a space lens made of petals.

Laue Consortium:

- Scientific Institutions:

  UNIFE, INAF/IASF-Bologna, CNR/IMEM-Parma;
- Industry:

  DTM-Modena, TAS I-Milan and Turin.

Possible configuration of a space lens made of petals

From the feasibility study performed by Thales-Alenia Space- Italy – Branch of Turin

New approach

- **For an accurate assembly technology:**
  - Development of an apparatus that would allow to correctly orient and fix each crystal to the lens frame under the control of a gamma–ray beam.
  - Fixed lens petal;
  - Movable gamma–ray beam remaining parallel to the lens axis.

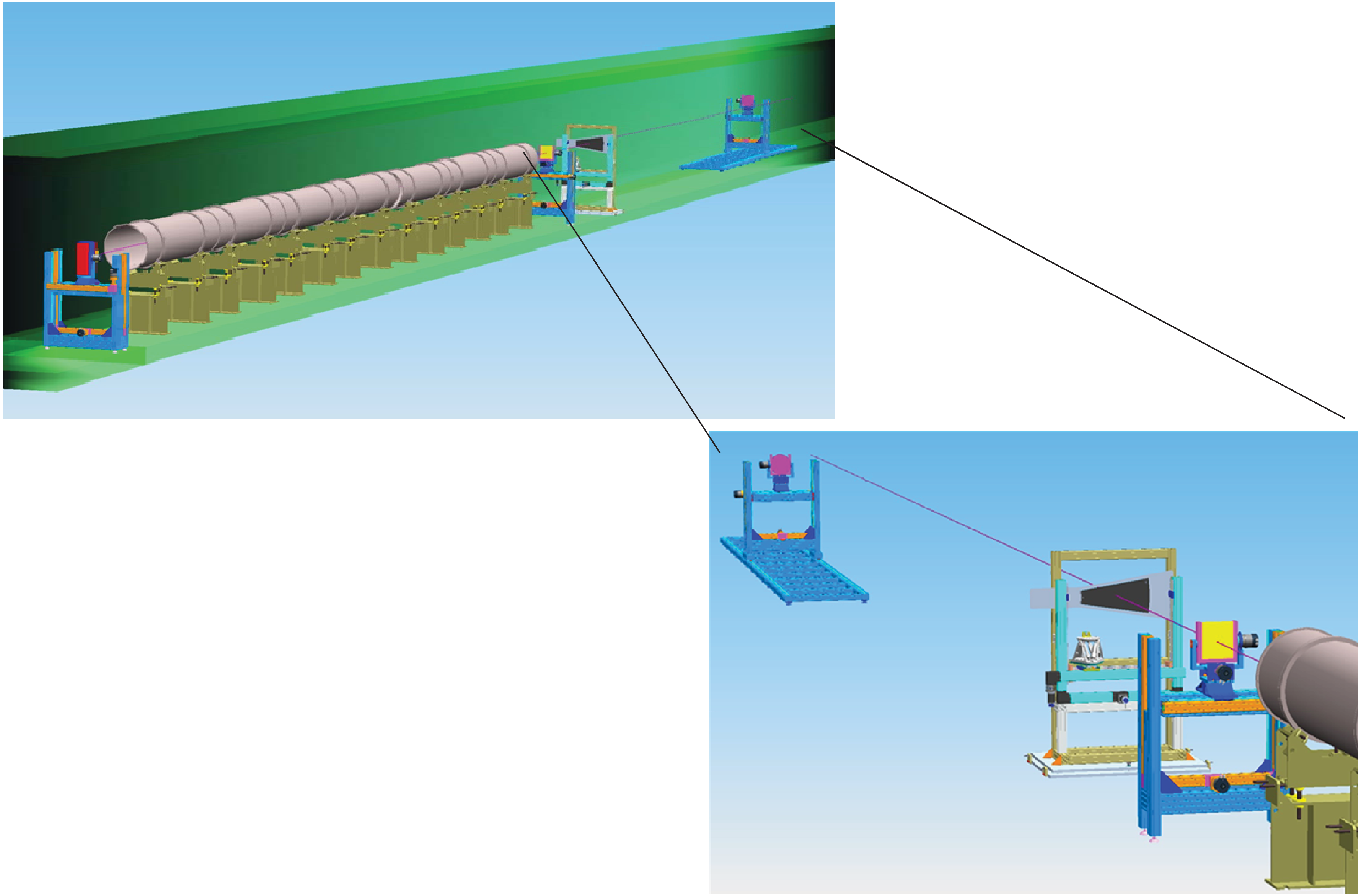
- **For a higher reflection efficiency and better focusing:**
  - development of bent crystals.

Apparatus location: the LARIX lab of the University of Ferrara

The LARIX A facility
and
The Console Room

The LARIX tunnel

Developed Apparatus



A collimated and movable gamma-ray source

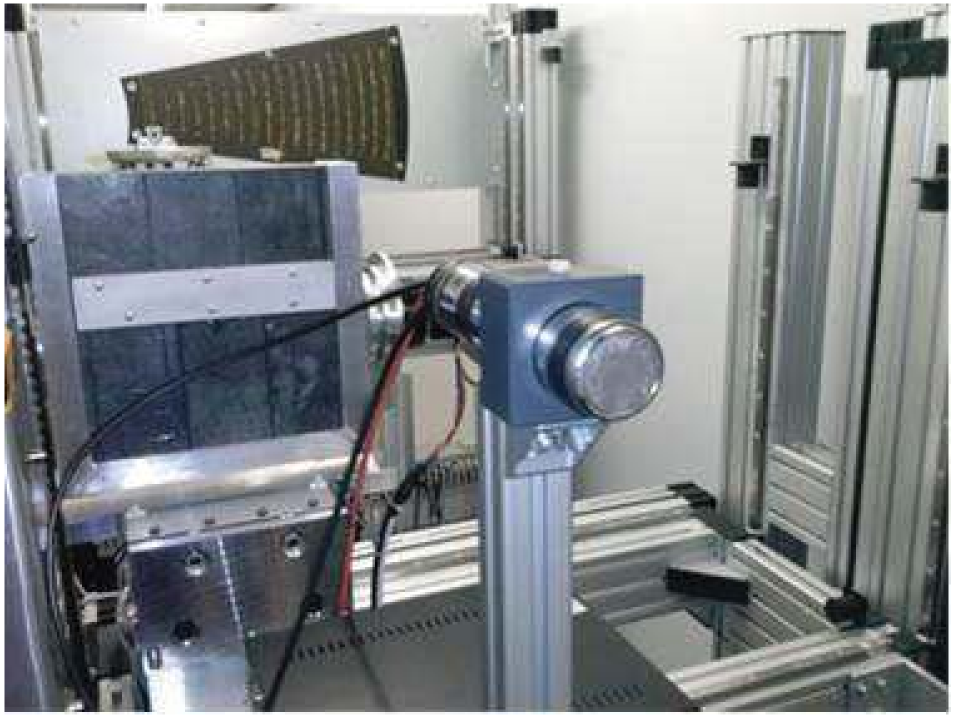
Emax =300 keV
Collimation: 20 arcmin
Translation along (y,z), Rotation around y,z

Beamline

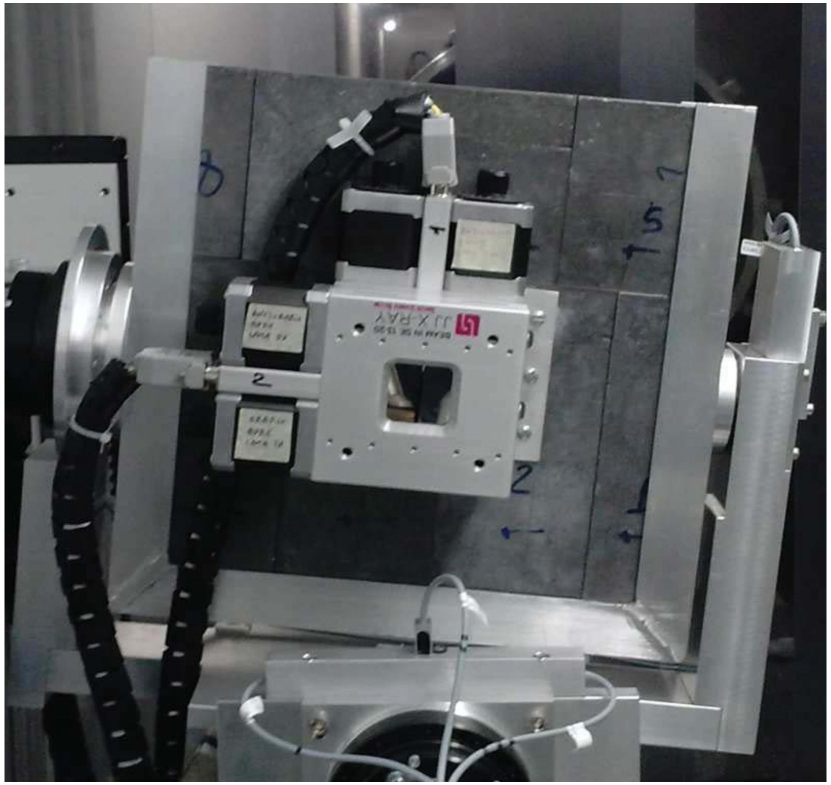
- A beam-line 21 m long, 60 cm inner diameter, under vacuum (0.1 mbar). Initial design 70 m.

Gamma-ray monitor of incident radiation

- Positioned at the end of the beamline to monitor gamma-ray beam intensity and stability.



Motorized collimator equipped with a slit

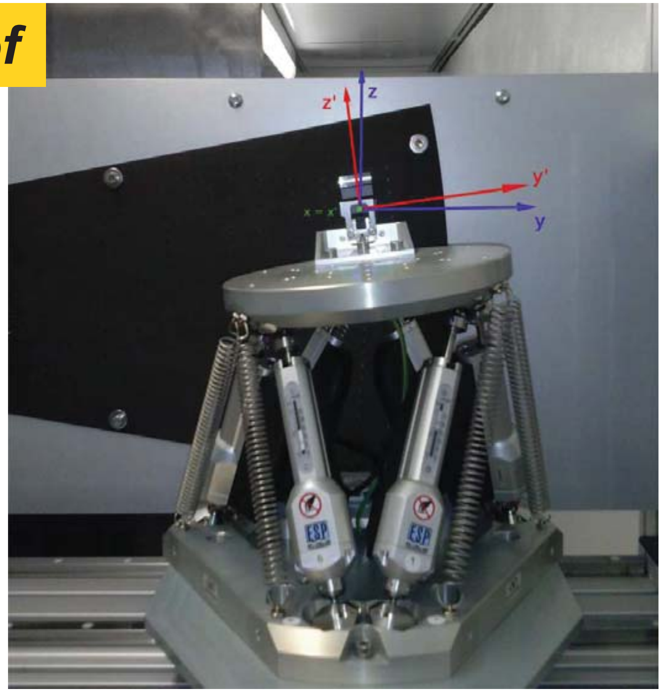


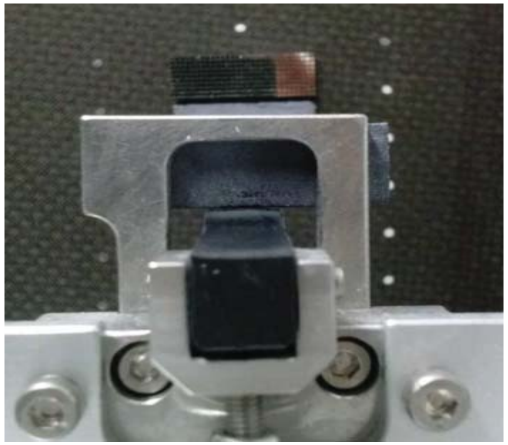
- Slit with Tunsten Carbide (4 independent blades);
- 6 d.o.f. for the correct orientation of the beam in front of each crystal

Collimator carriage

Hexapod: the crystal holder and fine positioner

Hexapod: 6 *dof*

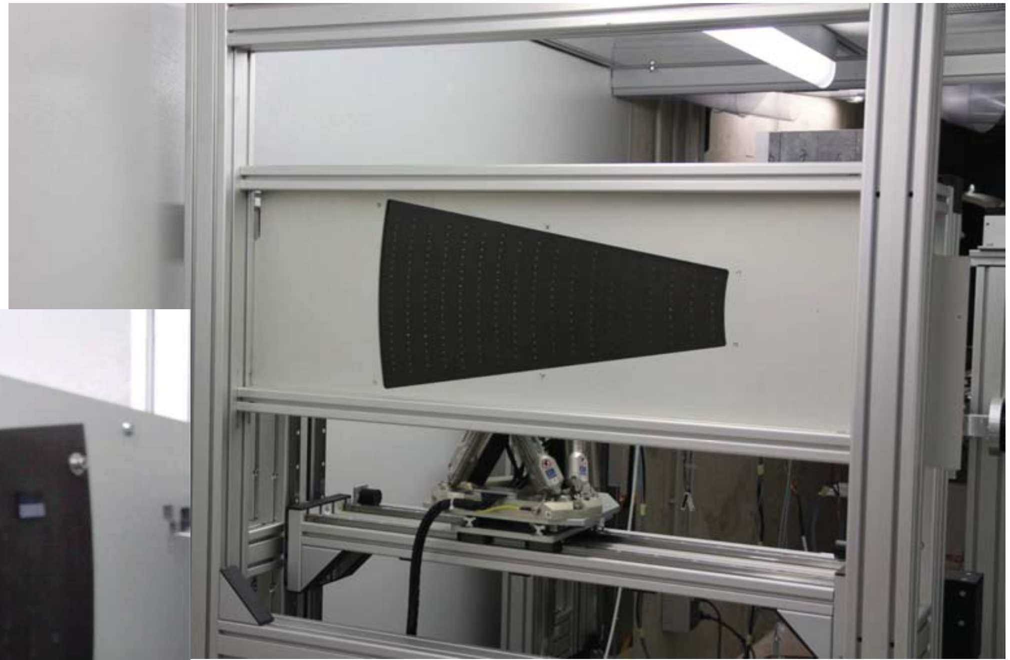




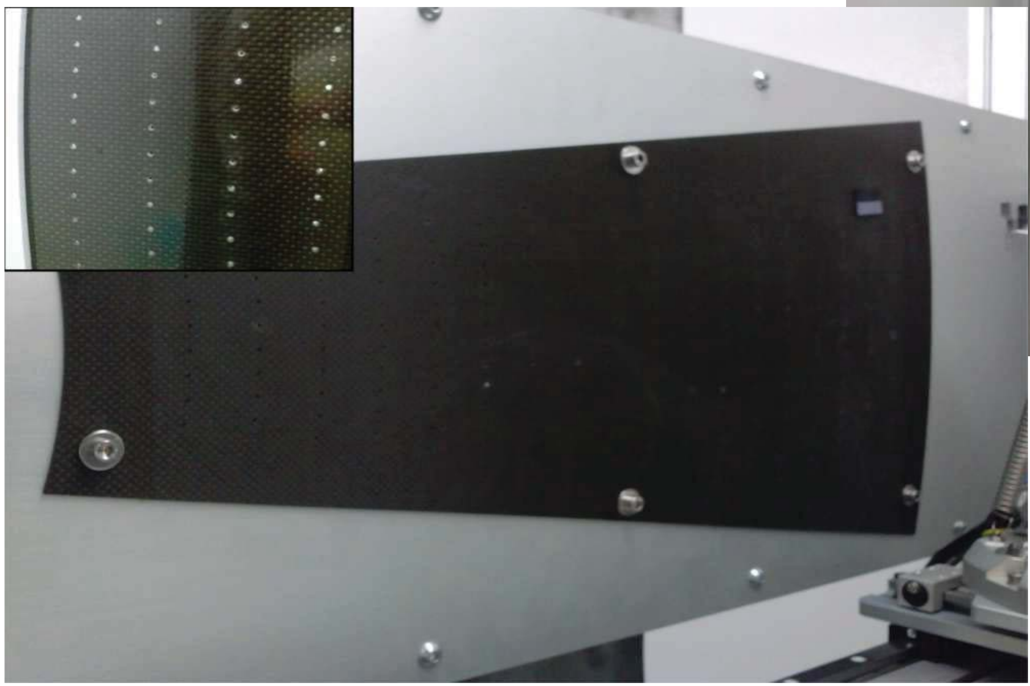
Holder: 3 out of 6 side of the crystal are kept free

Petal frame

The petal frame is made of carbon fiber (thickness 2.3 mm)



Back of the petal frame, where resin is injected.



Temperature and humidity controlled clean room

Inside the clean room:

- Final collimator with slit
- Lens petal to be assembled

Focal Plane Detectors

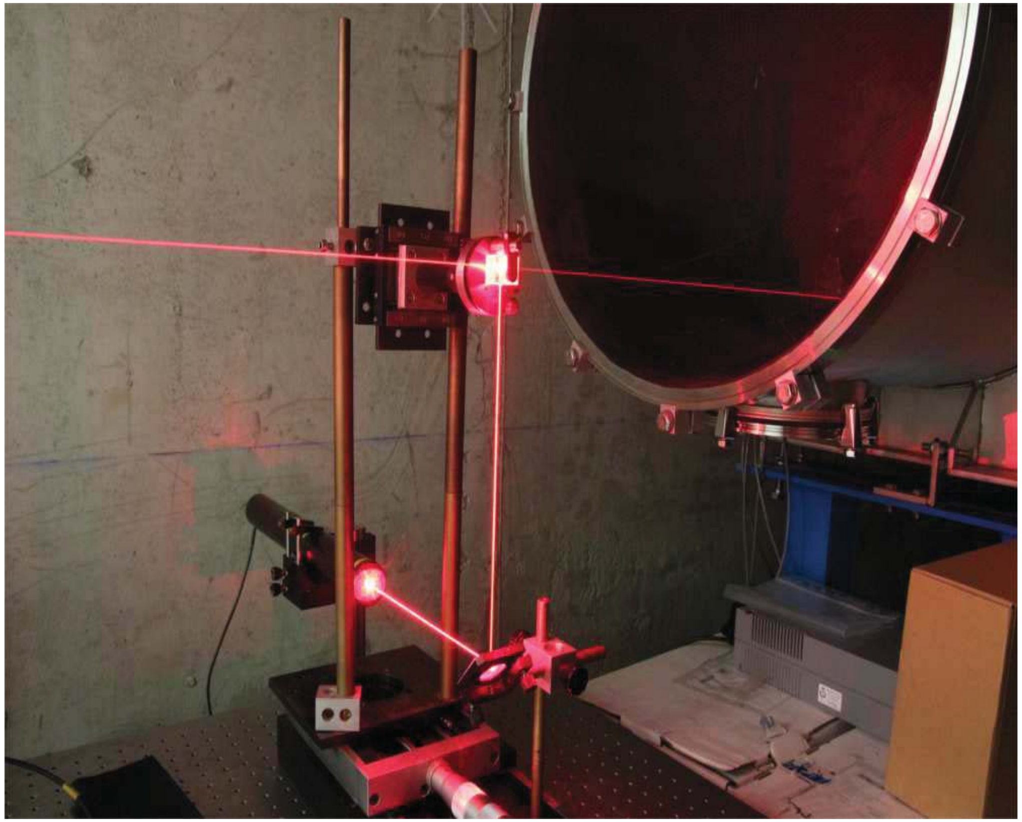
- **X-ray imaging detector:**
  - flat panel based on a CsI (0.8 mm thick) scintillator coupled with Si PD array (TFT)
  - 200 µm spatial resolution over 20x20 cm^2 active area

- **Cooled HPGe spectrometer:**
  - Spectral recontruction precision: 200 eV @ 200 keV.
  - 5 cm diameter and 2.5 cm thickness

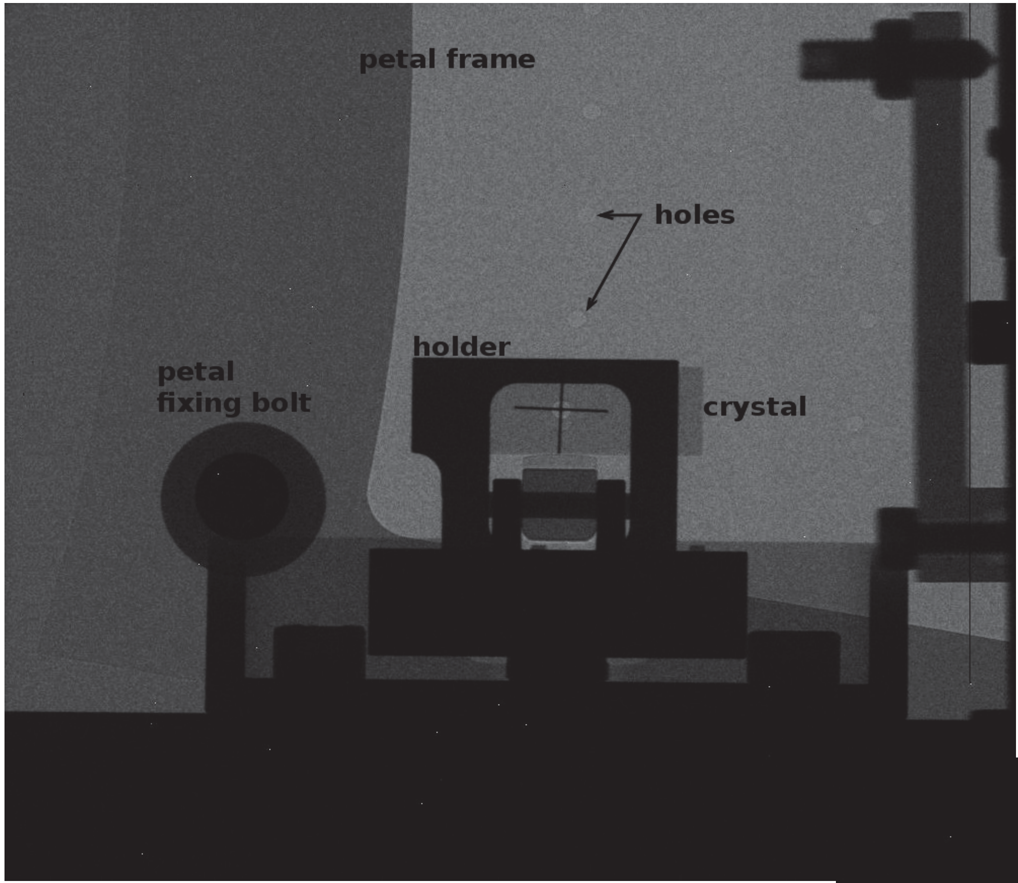
Optical Facility Alignment

<u>**REQUIREMENT:**</u> **The X-ray beam must be kept parallel to itself and to the lens axis.**

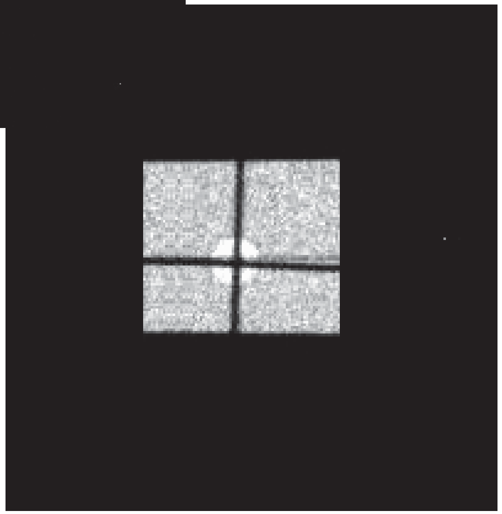
CONSTRAINT: The beam-line is fixed, then all the other subsystems must be aligned with respect to the beam-line.

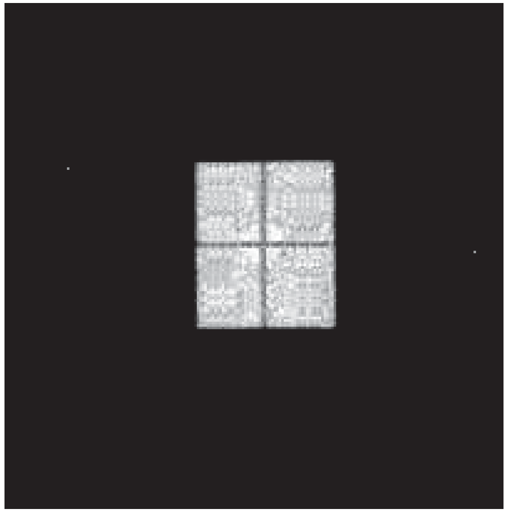


Gamma-ray fine alignment



Two Tunsten crosses were used to fine tuning the alignment (crystal + collimator cross)

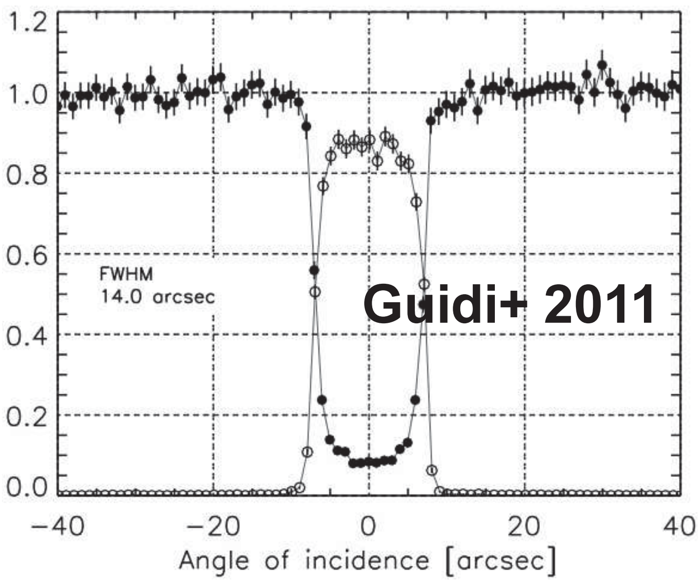


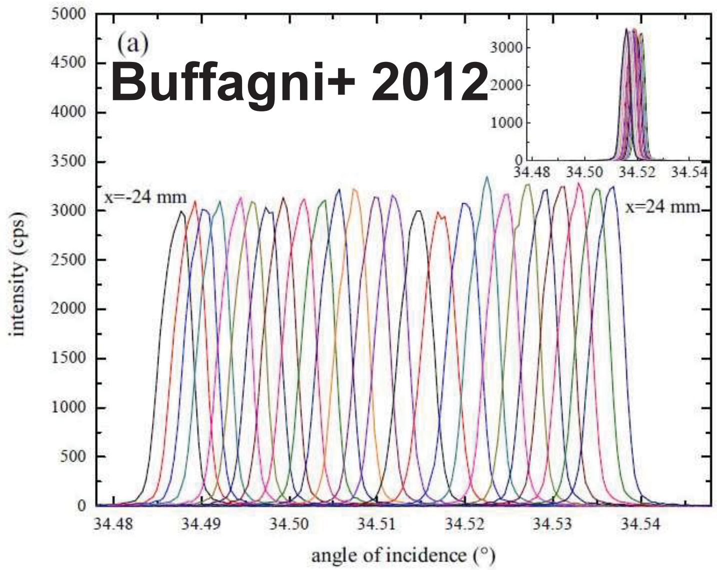


Bent crystals

- Diffraction efficiency overcome the theorical limitation of 50% for Mosaic Crystal;
- Each crystal become a focussing element for a defined energy band because its surface follow the theorical laue lens curvature;

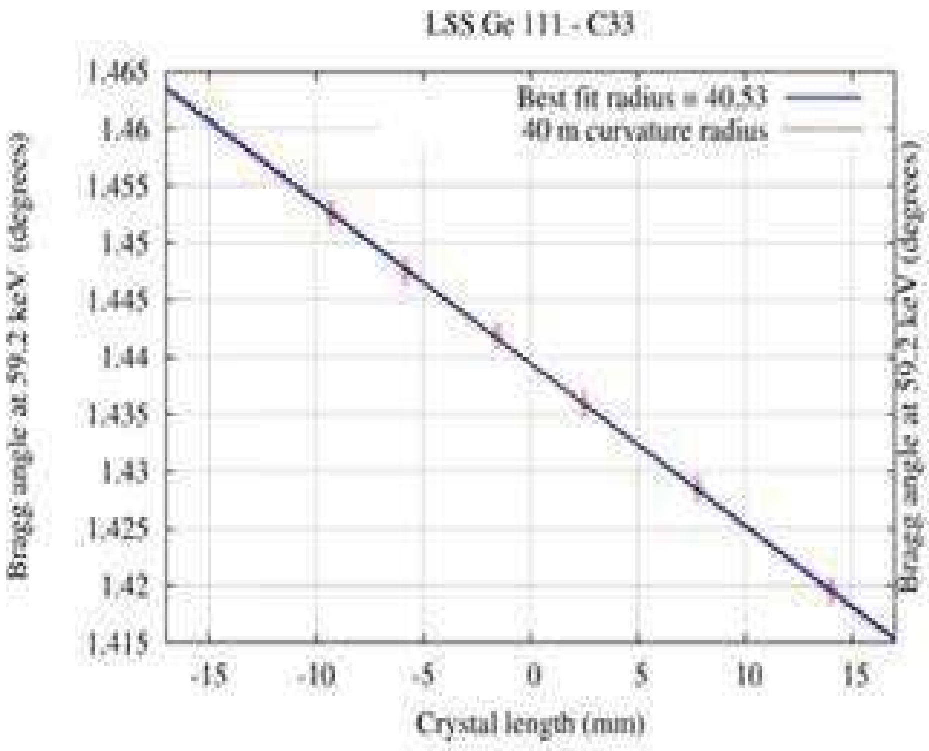
- Bent samples of perfect Ge(111) developed at UNIFE: curvature is obtained using mechanical indentation.
- Bent samples of mosaic GaAs (220) 25 arcsec spread, developed at IMEM- Parma: curvature obtained using sand paper lapping.

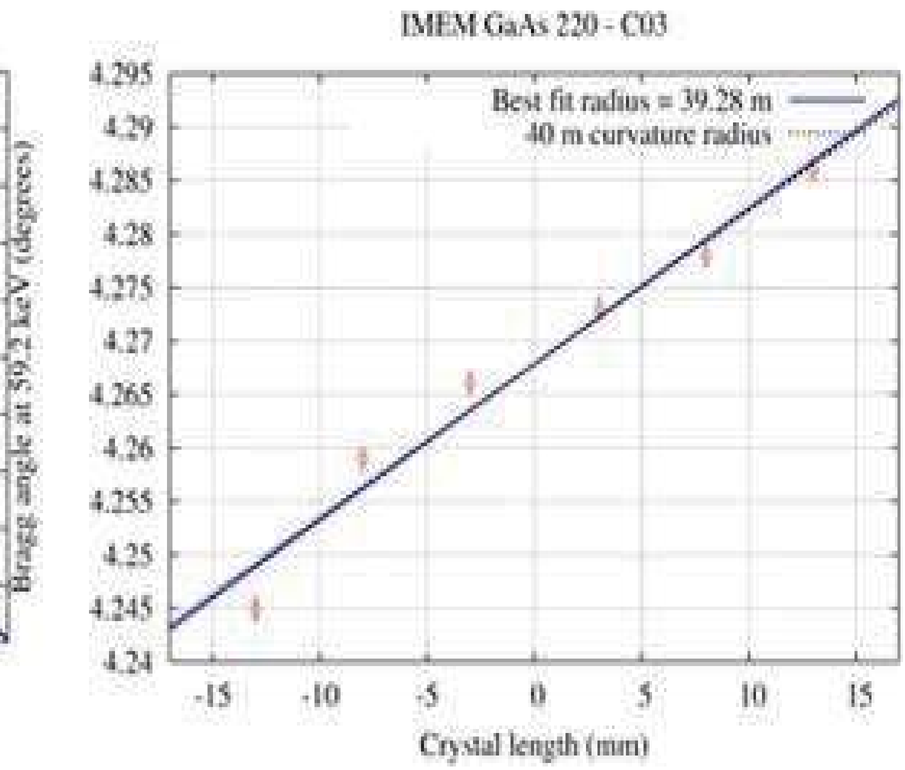




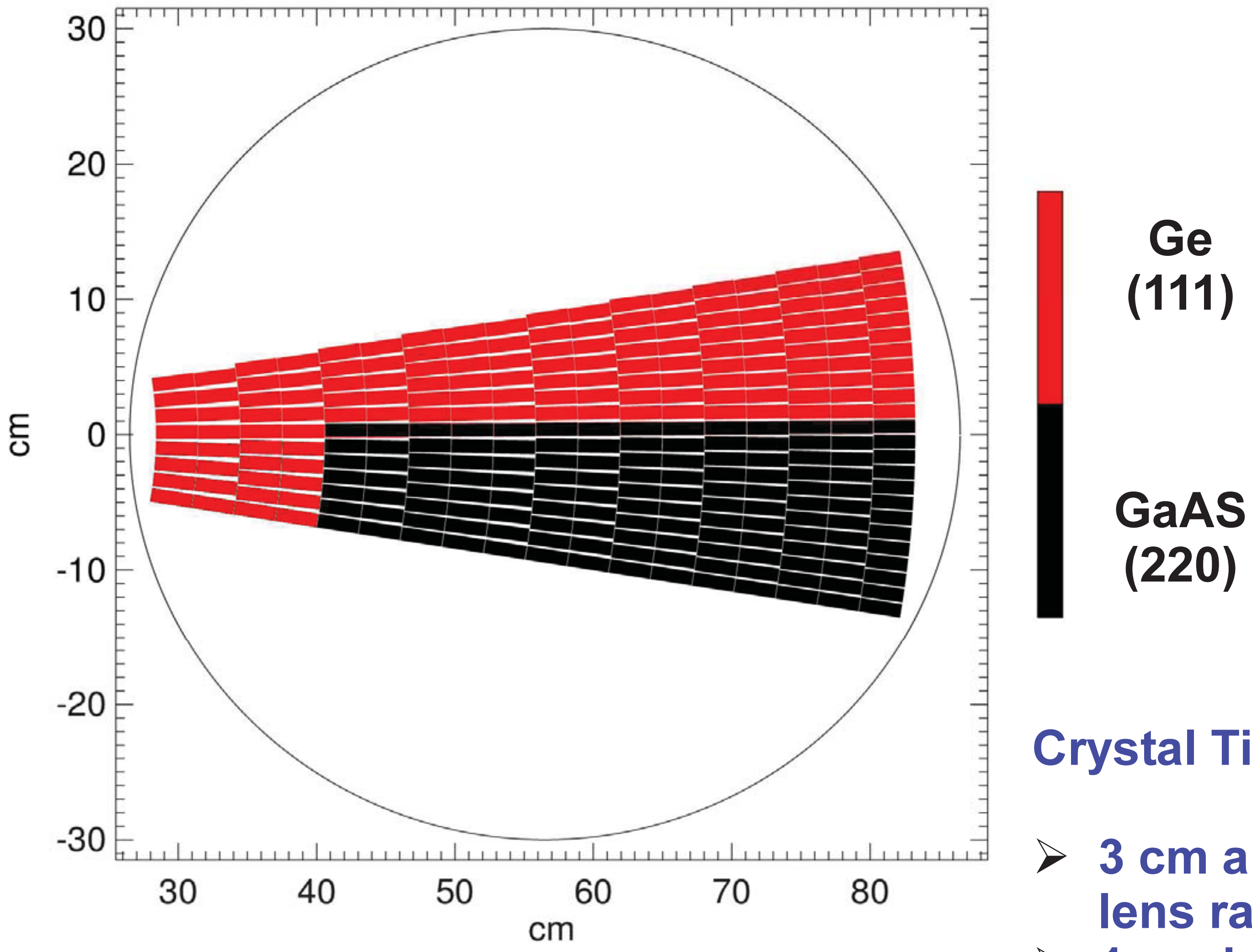
Production of bent crystals for LAUE project

- Production of 300 crystal tiles of Ge (111) and GaAs (220)   2 mm thick.
- Curvature of the produced crystals tested in the LARIX facility at 59.2 keV monochromatic line ($K\alpha_1$ fluorescente line of the W anode of X—ray tube).





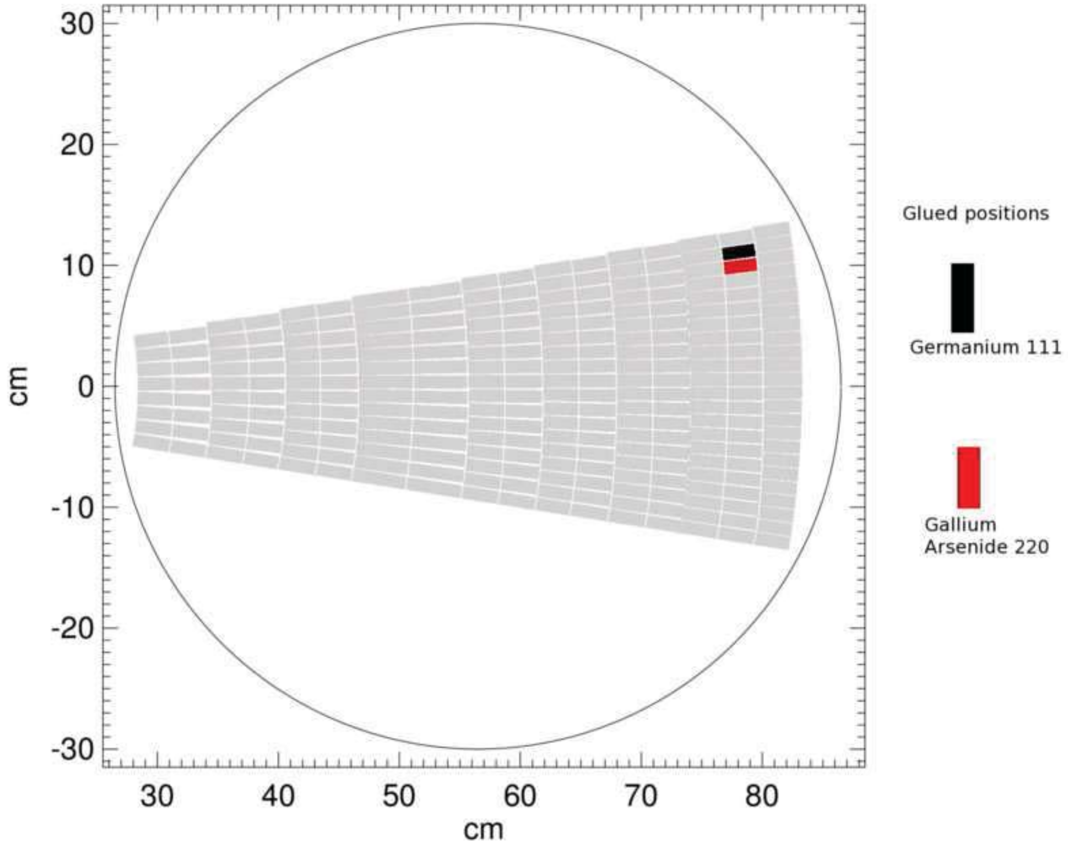
Designed lens petal



Crystal Tiles dimensions:

- 3 cm along the laue lens radius;
- 1 cm in the orthogonal direction;
- 2 mm thick.

First assembling test



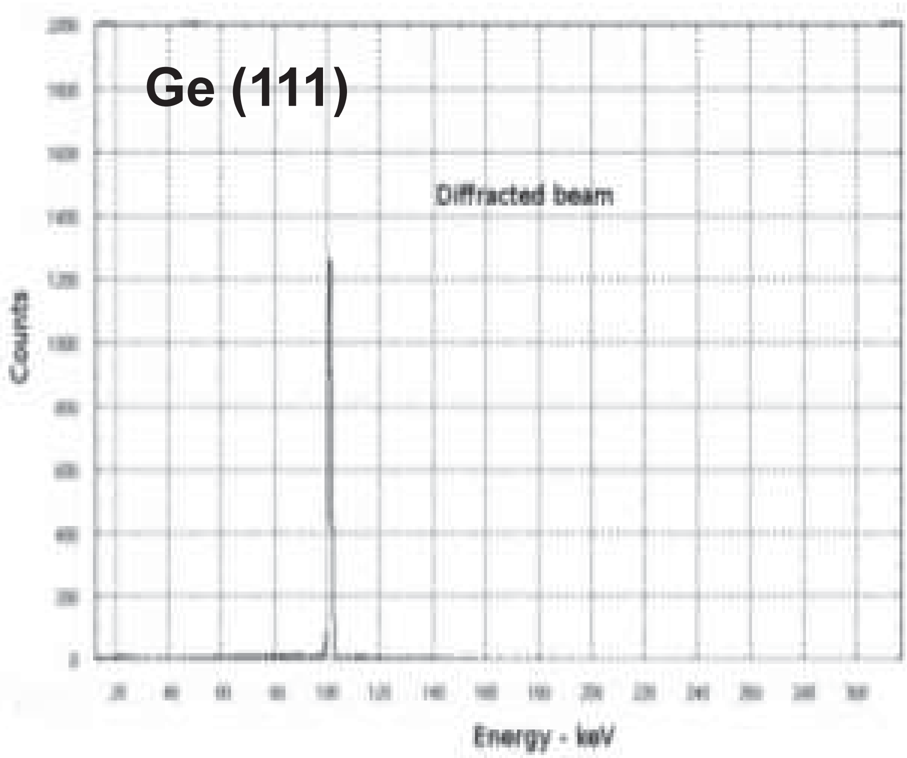
Two tiles to test:

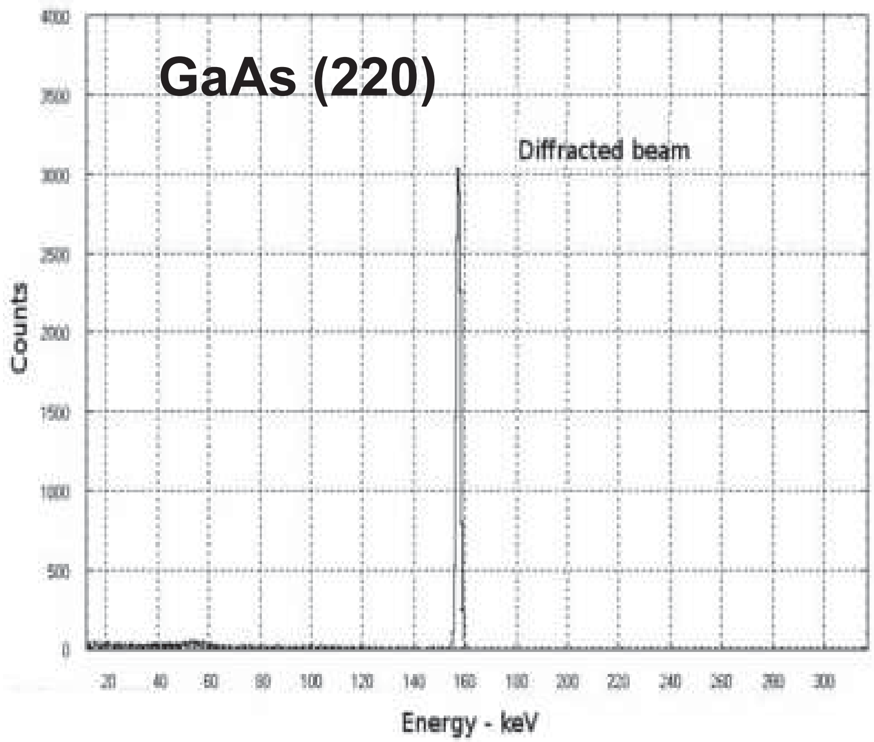
- ❑ **Positioning capability;**
- ❑ **Resin/Gluing effect.**

Expected diffracted energy centroid:

- **Ge(111): 96.14 keV;**
- **GaAs(220): 157.10**

First positioning results



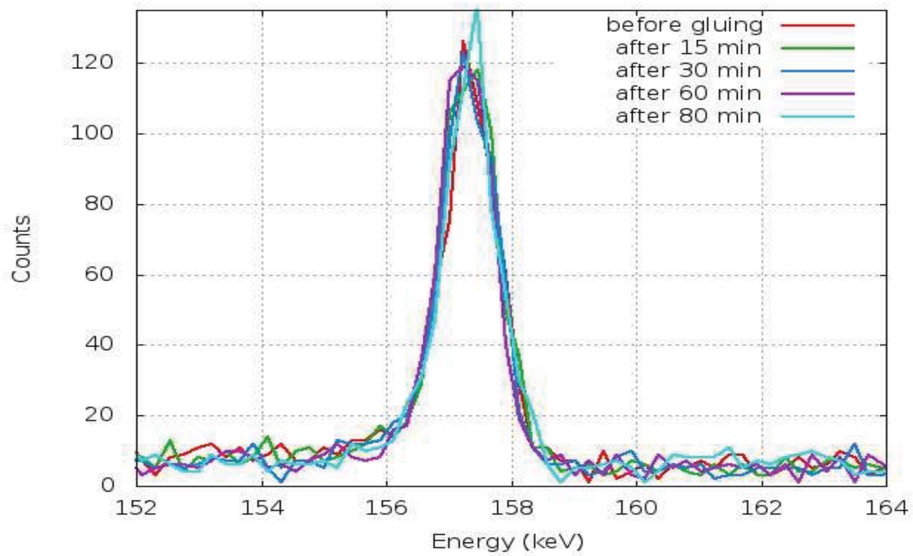


Diffratcted spectra by crystal tiles in the two test positions on the laue lens petal

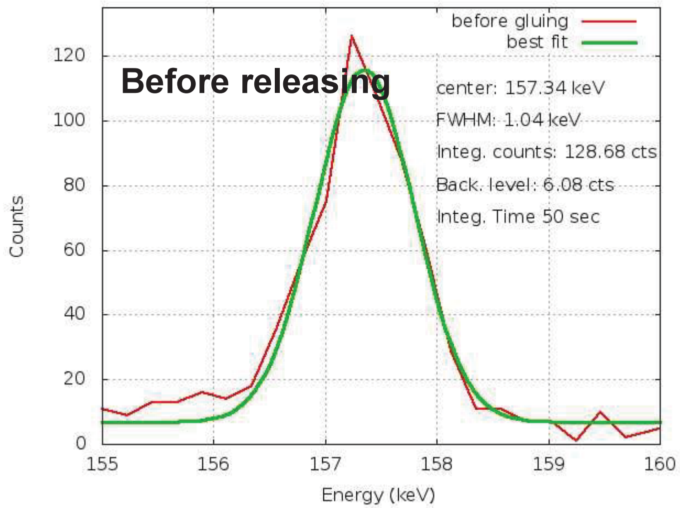
Beam spot: 0.5 mm (Y) x 6 mm (Z)

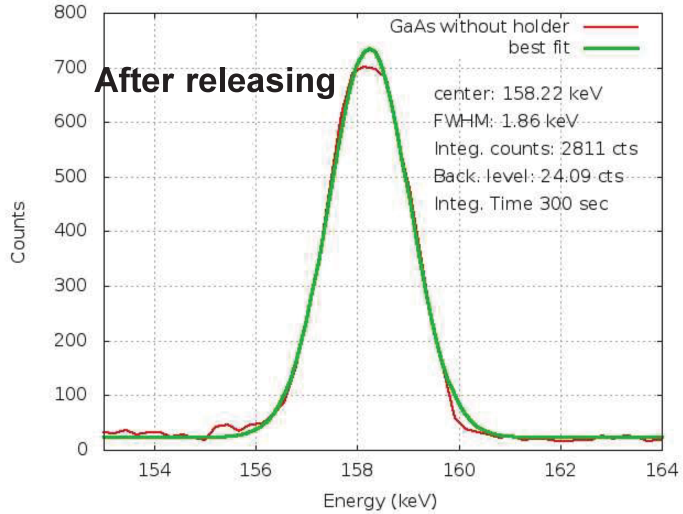
Beam centre: centre of crystal tile

Resin/Gluing impact



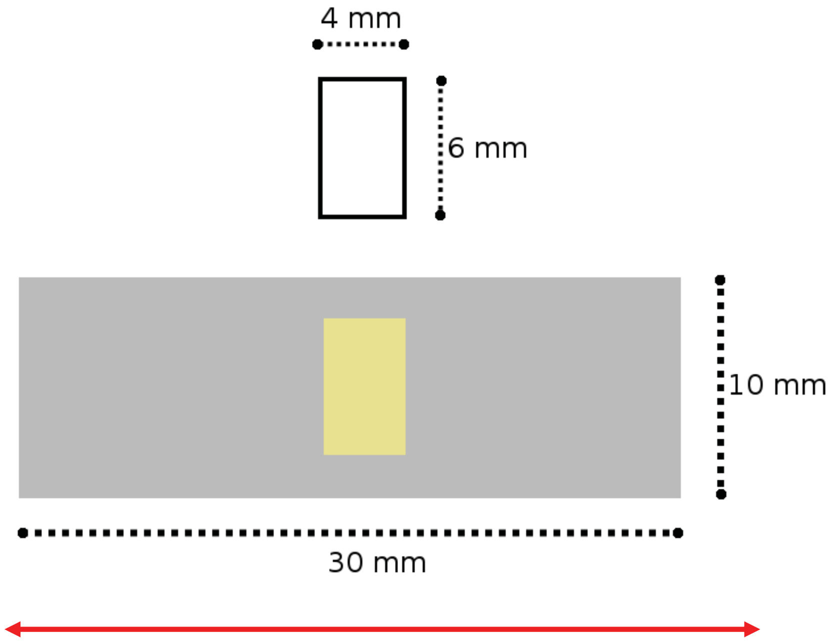
GaAs (220) @ 157 keV , during polimerization



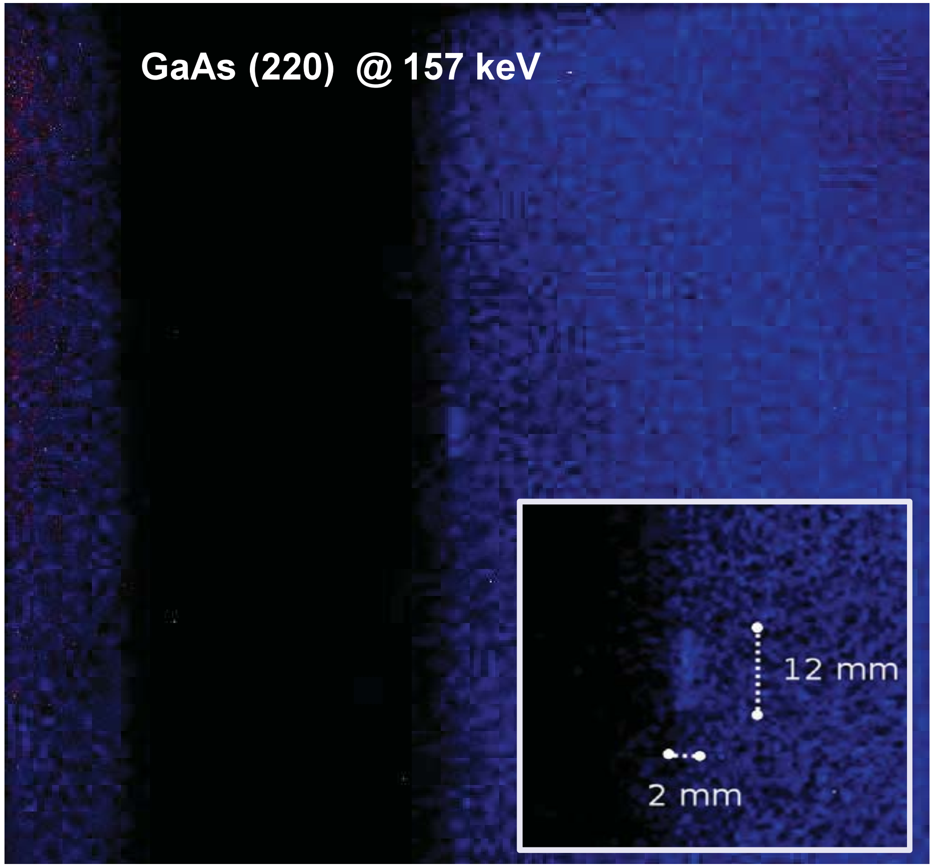


Noted systematic misalignement (< 1 keV → 20 arcsec)that is being taken into account for the petal assembling

First imaging results



Laue lens petal radius direction



Bent crystal Focusing effect observed as expected:

- **2 mm in the Laue radius direction instead of 8 mm expected because of beam divergence and focal length**
- **12 mm in the orthogonal direction: amplification due to beam divergence and focal length.**

Ge(111) vs GaAs (220)

Parameter	Value	
	case of GaAs(220)	case of Ge(111)
Focal length	20 meters	20 meters
Energy range	89 - 308keV	88 - 290keV
Subtended angle	18	18
No. of Rings	33	20
Minimum radius	41.71 cm	27.67 cm
Maximum radius	137.71 cm	84.67 cm
No. of crystal tiles	913	343
Crystal dimension	30mm x 10mm x 2mm	30mm x 10mm x 2mm
Crystal mass (total)	2.5gm x 913 = 2282.5 gm	2.07 gm x 343 = 710 gm

Laue Lens final configuration and dimension strongly depend on the crystal tiles materials and distribution.

The Laue lens configuration for a given energy range and focal length can be optimized choosing crystal materials and their distribution on the lens surface.

e.g., in table Germanium lens is much more compact

Expected performance of a lens made of petals

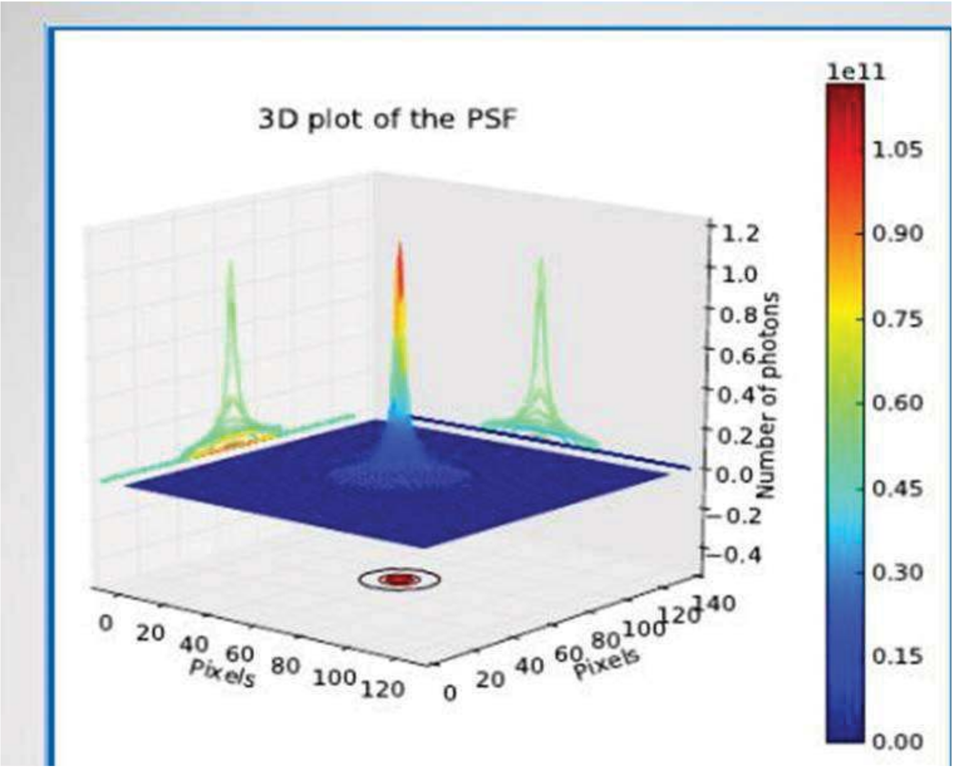
Case Study:

- Bent crystal tiles 2mm thick
- Material: Ge (111):
- Crystal-tile geometric surface: 30x10 mm^2
- Gap between crystal tiles: 0.1 mm
- Passband: 90-670 keV
- Focal length: 20 m.
- 28 rings, 9341 crystals
- Inner diameter: 25 cm
- External diameter: 190 cm
- Weight: 19 kg (crystal) + ~10 kg (carbon fiber support frame)

NOTE1: Pass band could be extended down to 60 keV increasing external diameter to 240 cm, still compatible with a Proton faring.

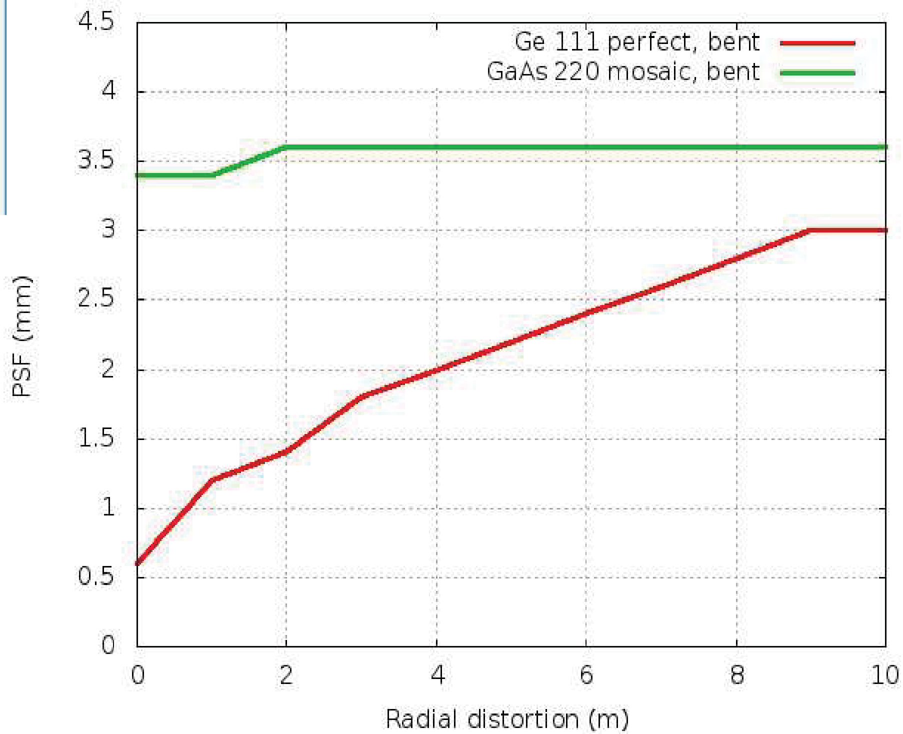
NOTE2: The low energy limit can be tuned with a coaxial ML mirrors telescope that can be arranged in the free inner Laue lens hole (PheniX+wide band Laue: i.e. a «GRI reloaded»)

On-axis PSF and its dependence on radial distortion



On-axis PSF for Ge(111) with no radial distortion.

(distorsion = discrepancy between tile real curvature and theoretical one).



FWHM PSF vs. radial distortion for Ge and GaAs

Focal plane detector

Basic Requirements:

- ❑ 2D-space resolution: $\leq$ 0.3 mm
- ❑ High absorption efficiency : >80 % (total)
- ❑ Good spectroscopy: 1% at 500 keV

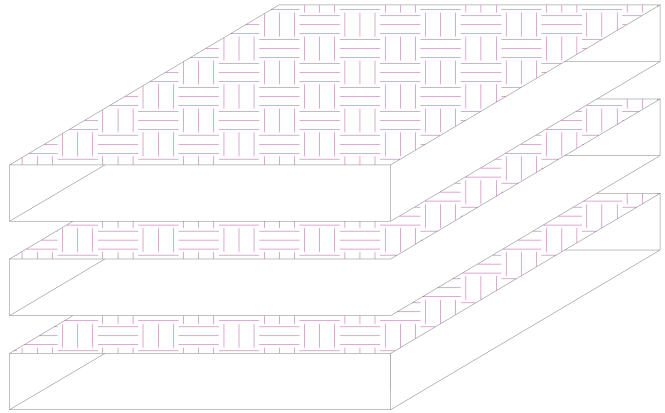
Advantages of a 3D position sensitive spectrometer:

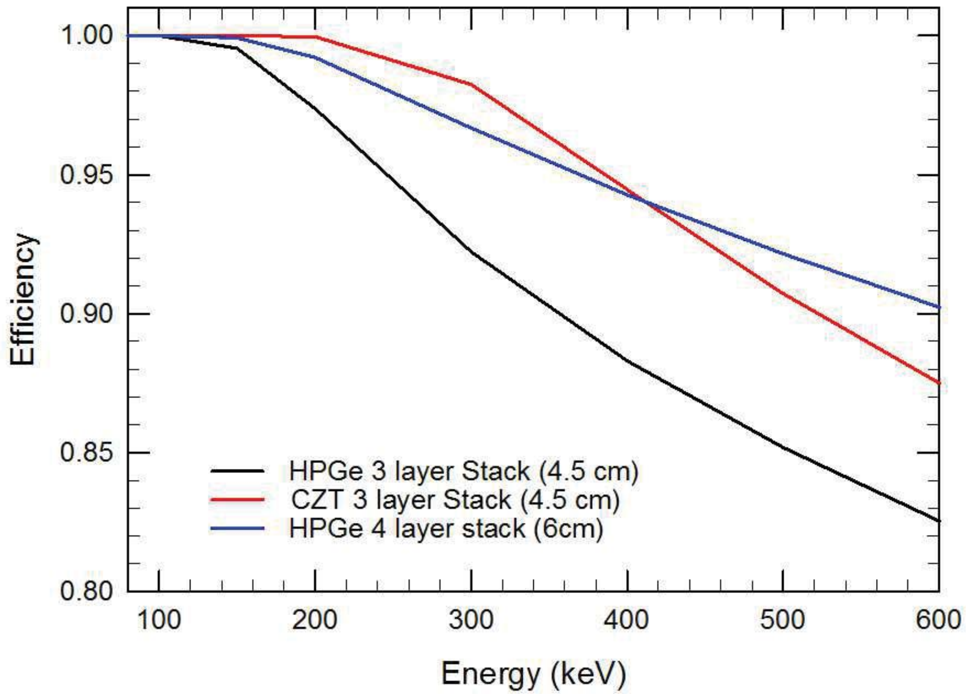
- ❑ better background rejection, improvement of source detection efficiency.
- ❑ High sensitivity to the photon linear polarization.

Possible focal plane detector

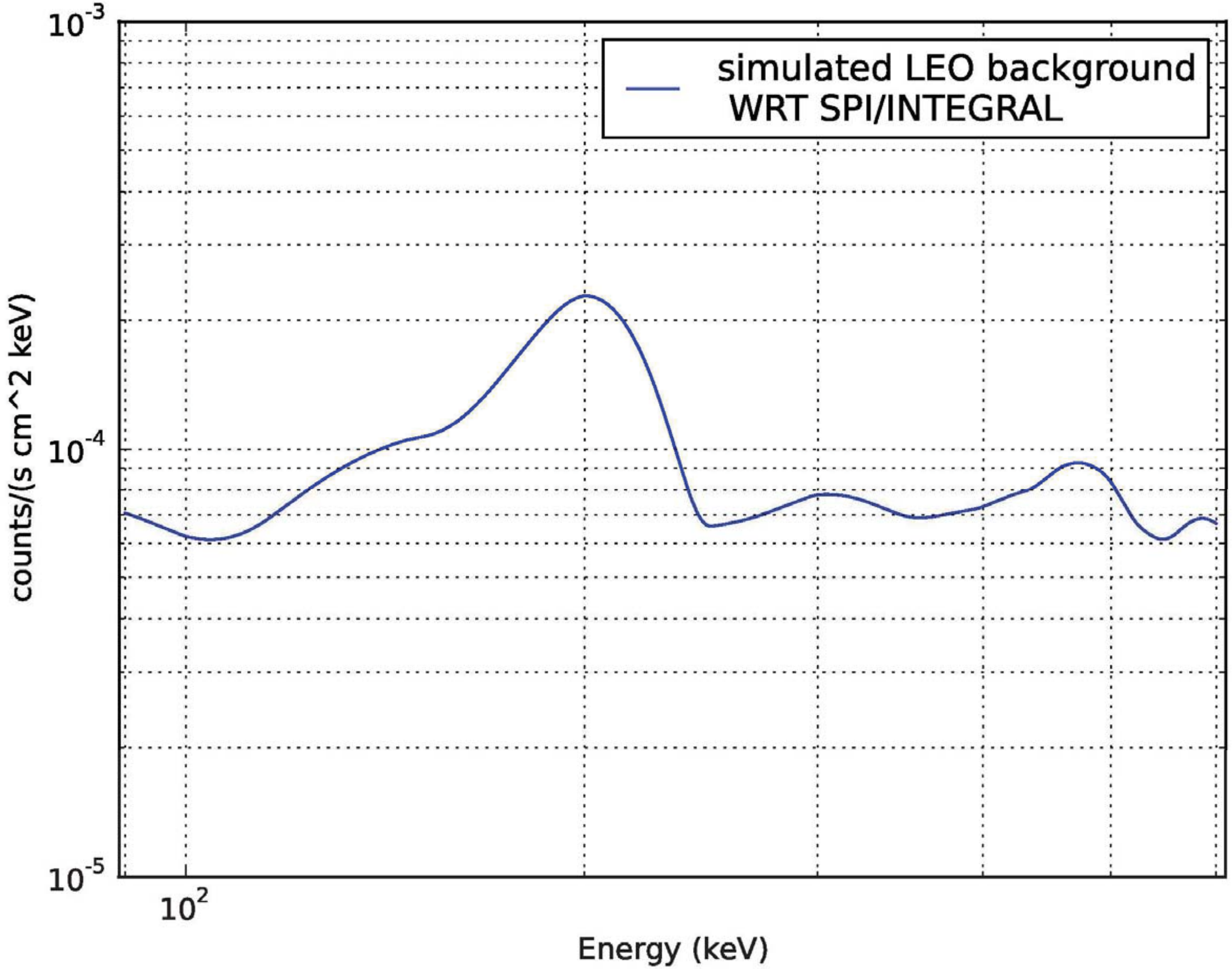
Stack of 3D spectroscopic imager layers

Focal plane characteristics	
Material	HPGe or CZT
Layer thickness	15 mm
Number of layers	3
Layer area	6x6 cm^2
(X,Y) resolution	0.3x0.3 mm^2
Z resolution	0.5 mm

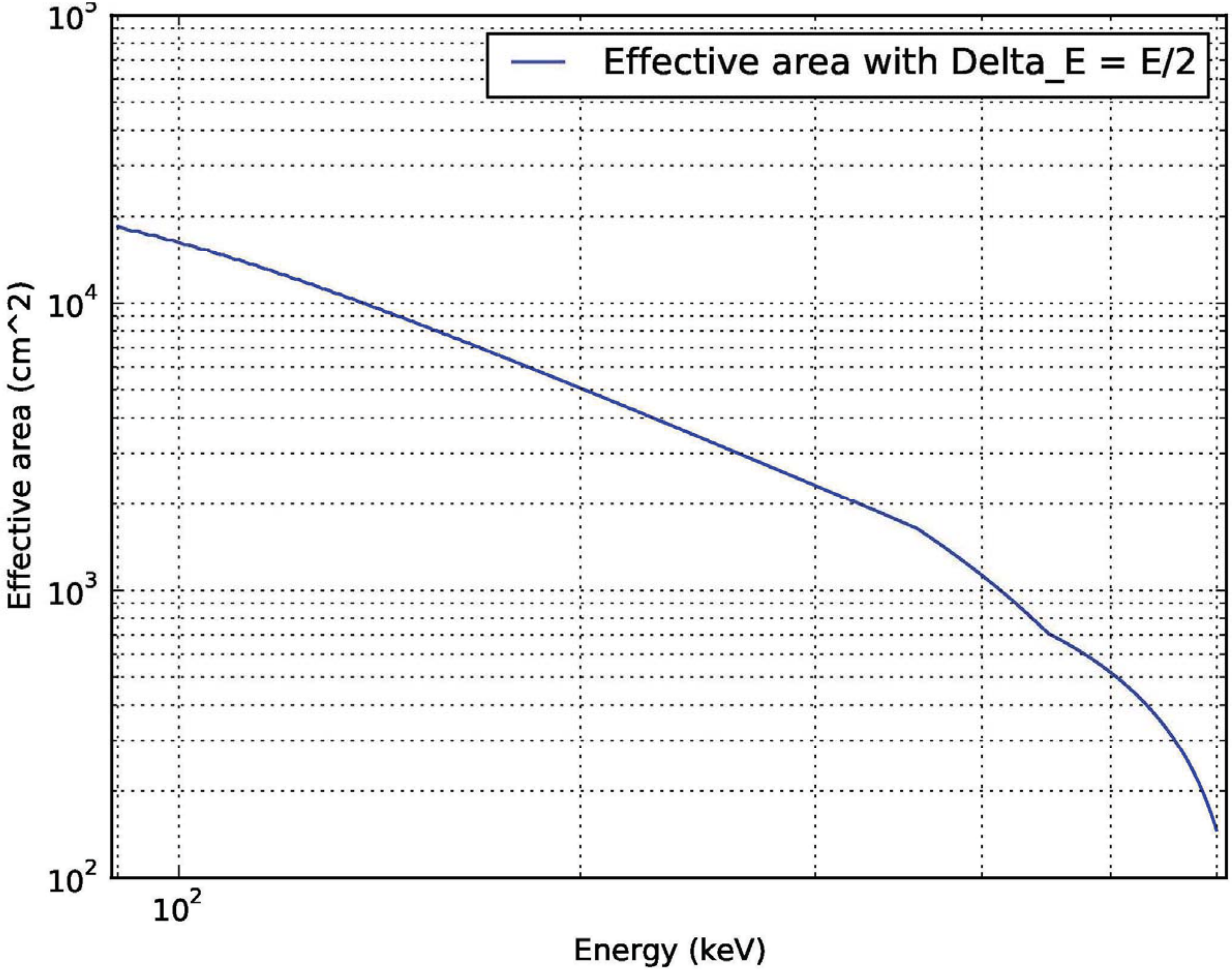




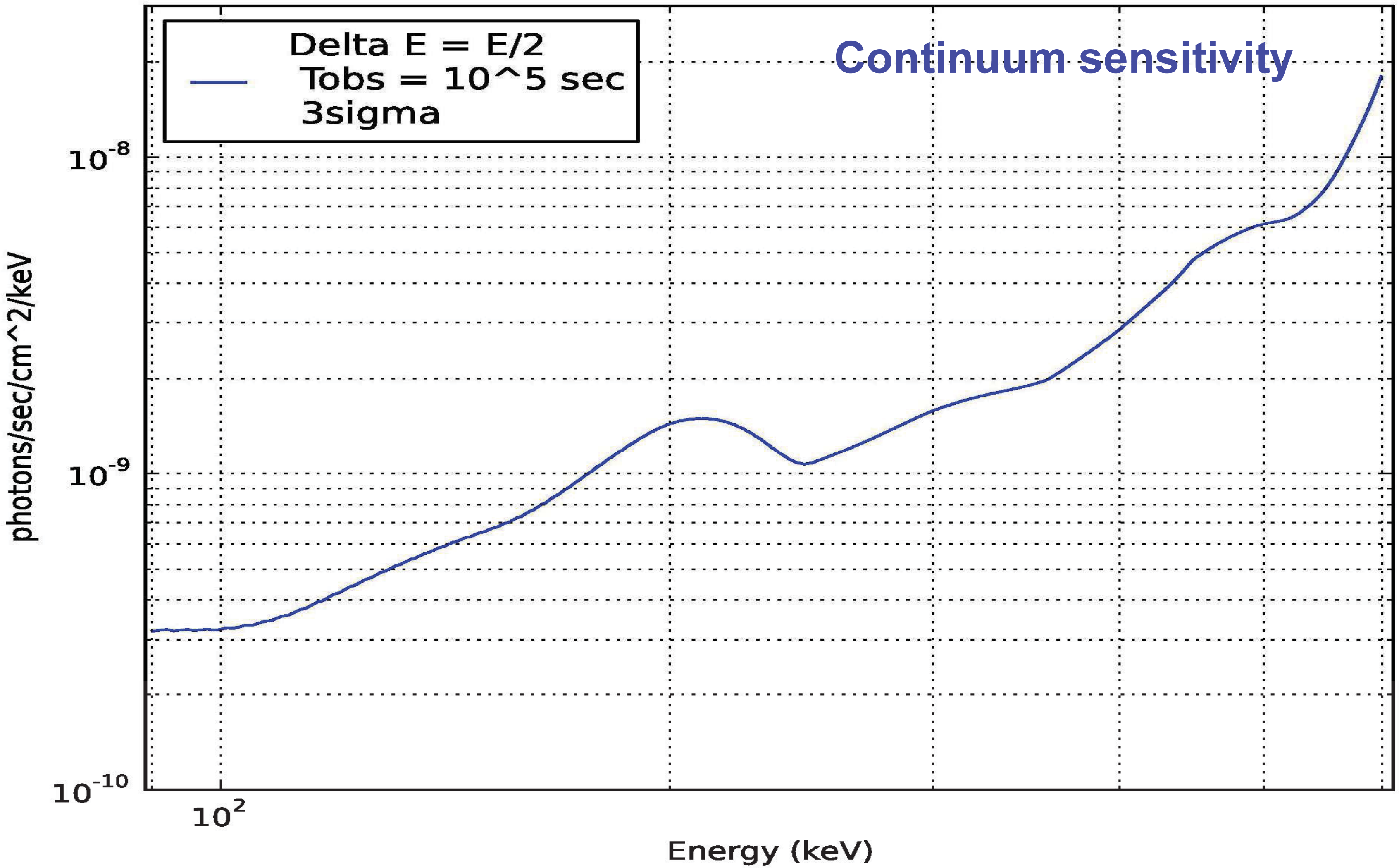
Expected Background (HPGe focal plane)



Lens effective area of a Ge(111) lens



Expected on-axis sensitivity (3σ) in 10^5 s



Energy flux sensitivity:

1.5 $\times 10^{-13}$ erg/cm^2 s (@ 300keV)

Conclusions I

- A new apparatus has been developed for building Laue lenses with long focal lengths (20 m)
- For the first time bent crystals have been developed and used for a wide band lens petal.
- An industrial study shows the feasibility of a lens made of petals.
- [High performance spectroscopic imager are really needed: different technologies are available now!]
- The energy band beyond 70-100 keV is crucial for settling many key-importance open issues.
- The pass-band of Laue lenses can extended down to 30-40 keV with an outer radius of less than 2 m for 20 m FL, and 1.5 m for 15 m FL.
- Concrete prospect for proposing a broad band satellite mission based on Laue lenses plus a multilayer optics.