Experimental High Energy Astrophysics - Challenges for the new Decade
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Experimental maturity for proposing an entirely focusing broad band X-/γ-ray mission

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Key scientific issues in X- and γ-ray astronomy (>70/100 keV)

- Physics in the presence of super-strong magnetic fields (magnetars);
- High/Soft and Very Soft state of Galactic BHBs;
- Opens issues for AGNs, such as the origin and the distribution of power-law indices of each population and of high energy cut-offs, the luminosity function of each population with energy.
- Origin of Cosmic X-ray Background (CXB);
- Role of non-thermal mechanisms in extended objects (e.g., Galaxy Clusters);
- Determination of the antimatter production processes and its origin.

Requirements for a next decade hard X-/γ-ray mission

- Sensitivity up two orders of magnitude better than INTEGRAL at the same energies, achieved in a shorter time scale (10^5 s)
- A much better (< arcmin) imaging capability;
- Broad band (a least 2 decade of energy: 1-600 keV)
- Polarimetric capabilities

The need of such breakthrough in hard X- and soft γ-ray astronomy has been well recognised at European level (ESA Cosmic Vision 2015-2025 Document BR-247);

Readiness for a next decade hard X-/γ-ray mission (1-600 keV)

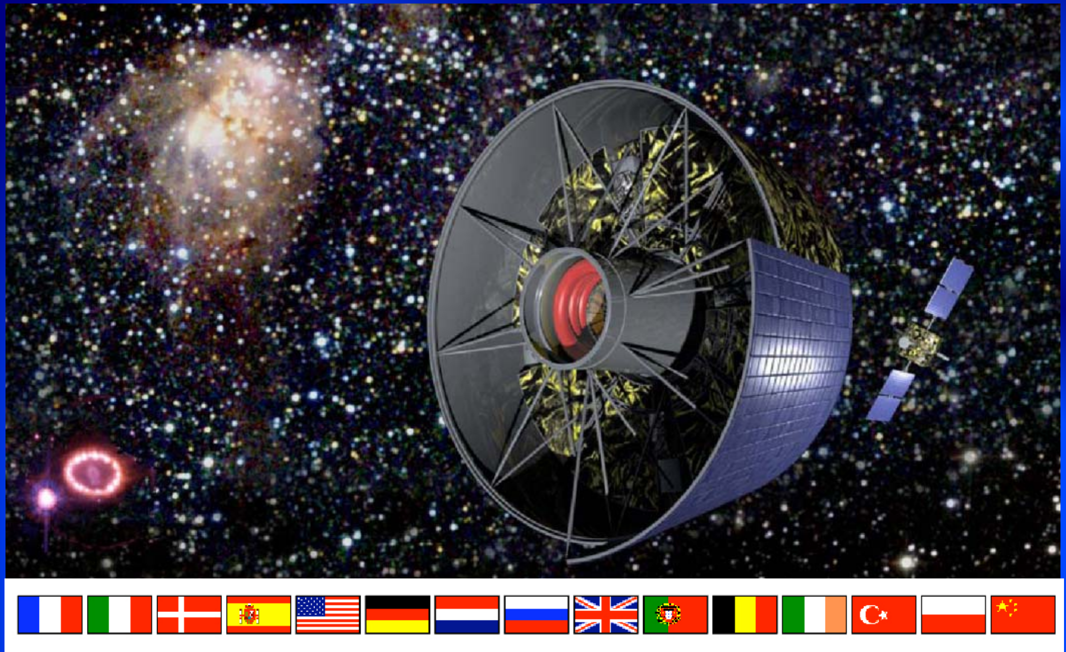
In the medium X-ray energy band (up to 70–80 keV) technology is really mature (Multilayer mirrors). Telescopes are being tested in space with NUSTAR (2011), ASTRO-H (2014).

Different european groups involved (Denmark, Italy) in Multilayer mirror developments.

Need to extend the energy band up to 500/600 keV with similar performance in order to solve the addressed scientific problems.

A challenging answer to these requirement is to implement also at this energy band proper focussing optics based on **Laue lens.**

GRI – a great european experience 1



GRI Mission profile:

❖ Formation flying mission composed of two spacecrafts: the Optics Spacecraft carrying the Laue lens and the Detector Spacecraft .

❖ Both satellites will be kept actively in formation at a focal distance of 100 m.

❖ Launched by a single Soyuz Fregate-2B rocket into a 20000 /183000 km HEO orbit.

GRI Payload profile

Novel focusing optics to concentrate high-energy photons over the range 10 keV- 1.3 MeV: a Laue crystal lens with a single-reflection multilayer-coated mirror.

❖ The Laue crystal lens efficient throughout the 200 keV - 1.3 MeV energy range.

❖ The multilayer mirror cover the 10 keV - 250 keV hard X-ray band.

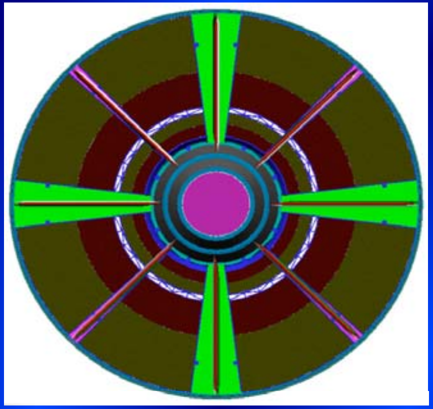
❖ Angular resolutions of 30” (Laue lens) and 10” (Multilayer mirror)

❖ FOV of 5’.

❖ The Laue lens and the Multilayer mirror optics were coaxial

❖ Focal plane detector: 4 stacked layers of pixel CZT sensors): Top layer optimized for ML mirrors, 3 thick (2 cm) bottom layer optimized for Laue lens.

GRI – a great european experience 2

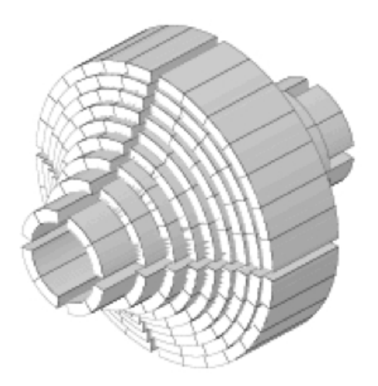


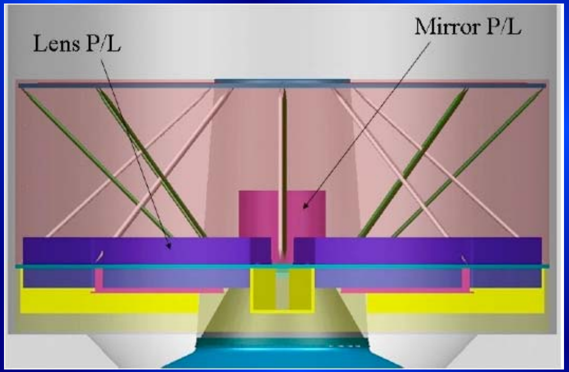
Laue Lens Optics

- Mosaic crystals of different materials (Cu[111,200,220], SiGe[111], Ge[311,400] on concentric rings around the optical axis
- Laue Lens structure in 8 petals unit on a SiC support, each one divided in 22 crystal holder subsector.
- Inner radius 0.65 m, external radius 1.8 m
- 28000 mosaic crystals, each one 15x15 mm^2.
- Laue lens total mass: 500 kg

Multilayer Mirror Optics

- High performance Si-pore optics developed by ESA for XEUS to realize a light-weight mirror substrate on which depth graded multilayer coatings will be applied which act as broad band Bragg reflector;
- With respect to XEUS: (a) single reflection instead of approximated Wolter geometry, (b) 10” angular resolution required instead 2”
- 86 petal units on a CeSiC support for a total mass of 85 Kg.





The Optics Spacecraft concept is based on XEUS heritage. It consists of a thrust cone, four equipment radius, four stiffening radius, eight sets of reinforcement rods and an external cylindrically drum.

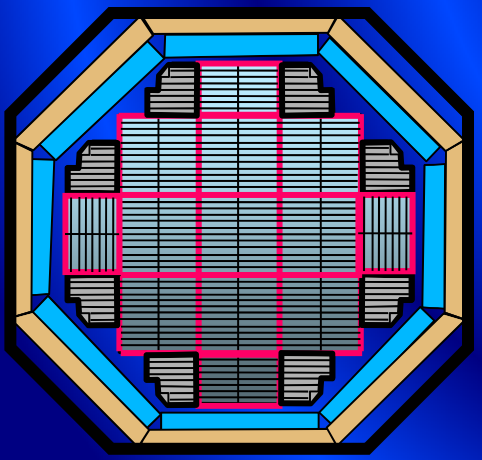
This configuration allow the launch of both S/C (optics and focal plane in a stacked configuration on the same launcher.

GRI – a great european experience 3

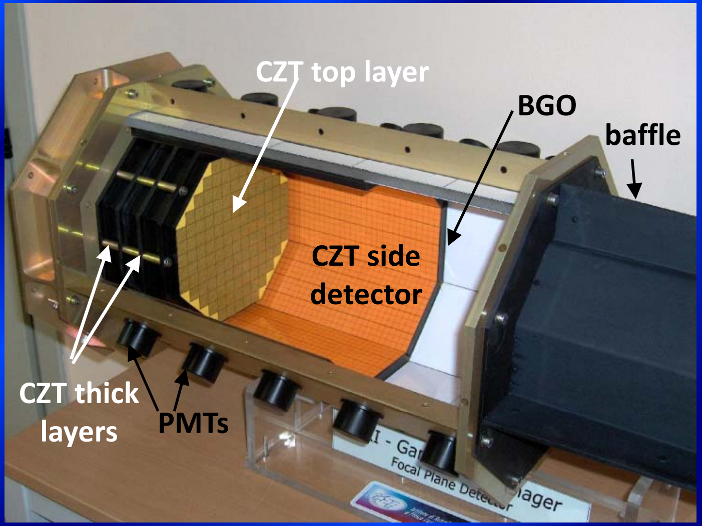
Focal Plane Detector

The GRI focal plane detector is based on a position sensitive spectrometer made of **4 stacked layers (mosaic of segmented CZT sensors)** , surrounded by CZT side walls.

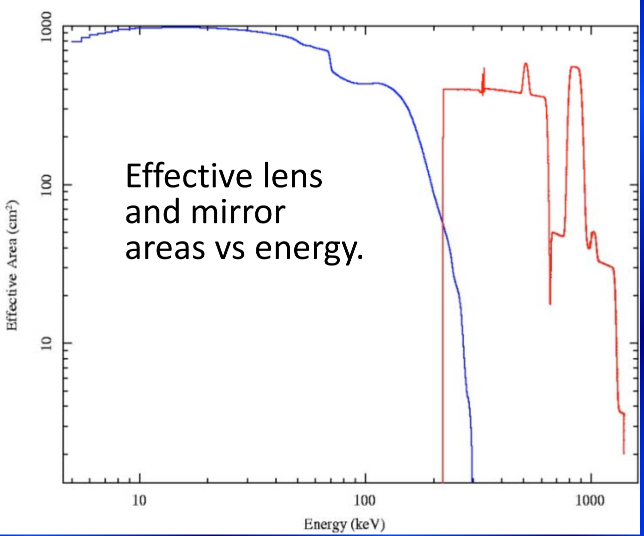
- The multilayer mirrors detector: the 5 mm thick top layer, optimized for photoelectric absorption in the 10-250 keV band;
- The Laue lens detector : the three bottom layers, each one 20 mm thick in **PTF configuration with drift strip anodes and segmented cathode**, to grant a total detection efficiency >75% for photons below 1 MeV.
- The side wall detectors to collect scattered photons from the primary beam in order to maximize the full energy absorption efficiency. The thickness is 10 mm.
- The detector is surrounded by a segmented veto shield made of 44 BGO modules.
- On top of the detector, a baffle (a graded passive shield) to efficiently reduce the diffuse cosmic background up to 100 keV.



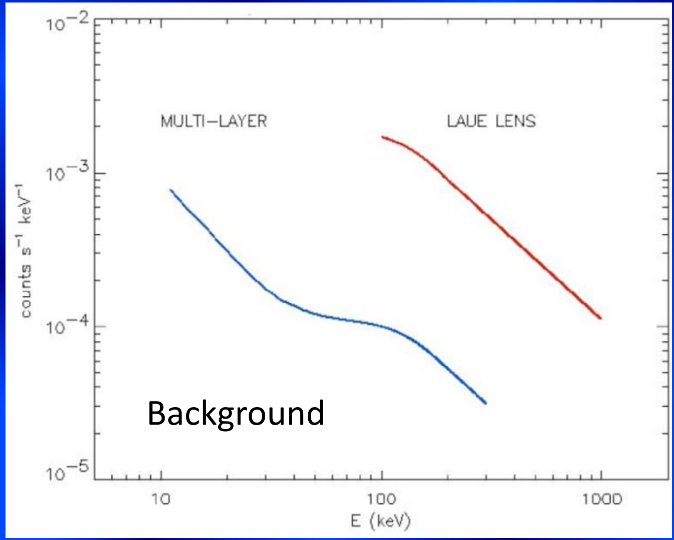
- Top layer: 129 crystals, 33024 pixels of 0.8×0.8 mm^2
- Bottom layers: 688 crystals, 8384 pixels of 1.6x1.6 mm^2
- Side walls: 1344 crystals, 4032 pixels of 6.4×6.4 mm^2
- Mass: 100 kg
- Volume: 35 cm (ø) x 43 cm (H)
- Required Power: 170 W

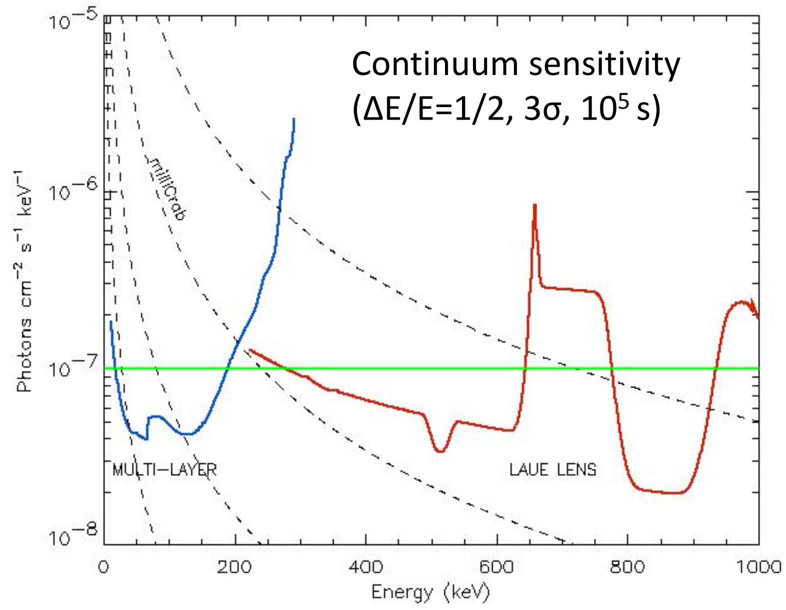


GRI – a great european experience 4



Expected GRI performances





Parameters	*Requirement*	*Goal*
Energy coverage	20 - 900 keV	10 – 1300 keV
Continuum sensitivity (ΔE/E=1/2, 3σ, 10^5 s)	10^{-7} ph·cm^{-2}·s^{-1}·keV^{-1}	3×10^{-8} ph·cm^{-2}·s^{-1}·keV^{-1}
Line sensitivity (ΔE/E=3%, 3σ, 10^5 s)	3×10^{-6} ph·cm^{-2}·s^{-1}	10^{-6} ph·cm^{-2}·s^{-1}
ΔE (FWHM)	3%	0.5%
FoV (ø)	5’	10’
Angular resolution	60” (LL)/10”(ML)	30”/10”
Timing	100 μs	100 μs
Polarimetry (MDP, 3σ)	5% (100 mCrab)	1% (100 mCrab)

GRI – a great european experience 4

The GRI proposal was not selected mainly for technological readiness problems:
"In summary, it was felt that the **scientific (***not well exploited the imaging capabilities at the quoted sensitivity***)** and **technical (***Laue lens feasibility not clearly demonstrated***)** concept of GRI is currently not yet ripe for making this a good candidate for a launch in 2017".

.... But now

❖ the new ESA call is for an M-class mission to be scheduled from 2022!

.........and.........

Laue lens development activities in Italy 1

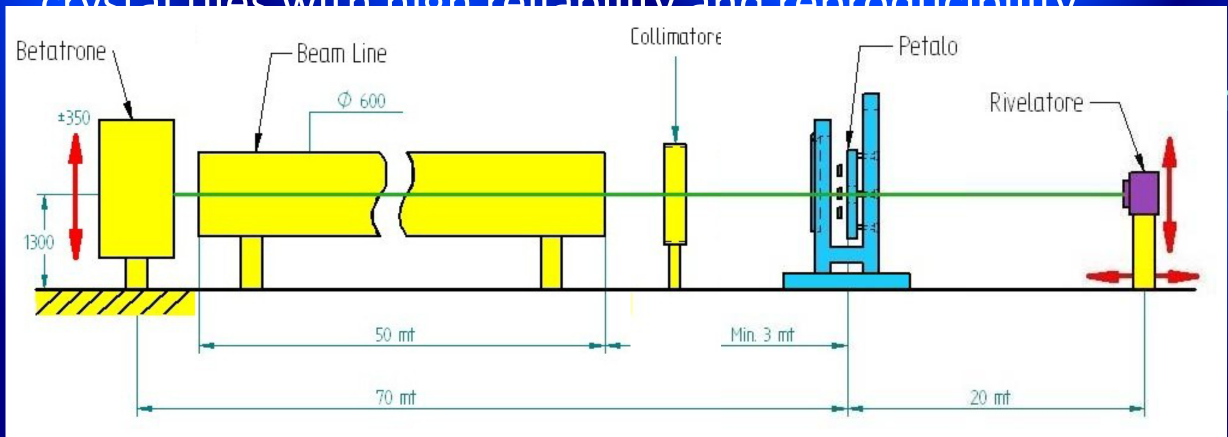
...... since the GRI proposal (2006) different R&D and technological activities have been carried out on wide band Laue lens development and associated detectors

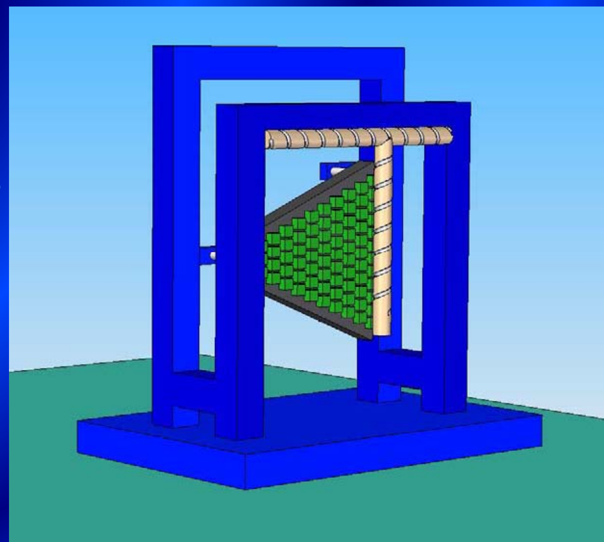
❖ First images of a Laue lens prototype based on Cu mosaic crystals built at the Ferrara university and tested by the LARIX beam (previously presented by E. Virgilli). The crystal assembling developed technology is suitable for low (<10 m) focal lengths Laue lens.

❖ Study of different materials for optimizing the Laue lens collecting area as function of energy (CESR/ Toulouse, ILL/Grenoble, IMEM/CNR-Parma)

❖ Development of bent crystals (LSS/University of Ferrara)

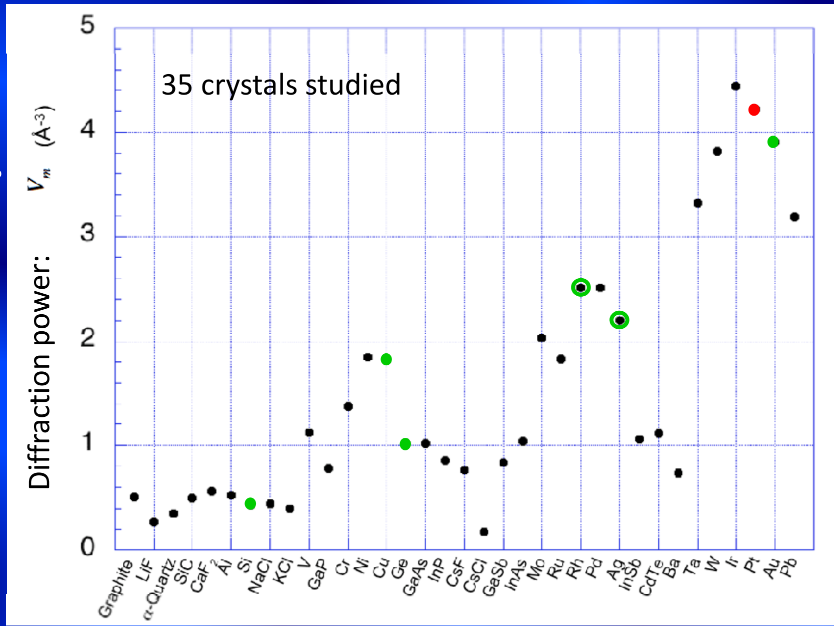
❖Development of an industrial technology for assembling crystal tiles with high reliability and reproducibility





Laue lens development activities in Italy 2

Study of different materials performance as Laue diffracting elements and suitable for mosaic crystals or bent crystal development.

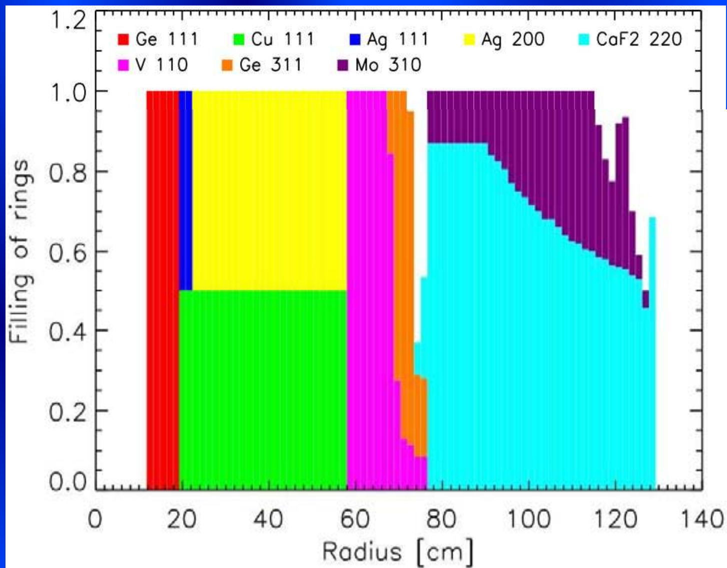


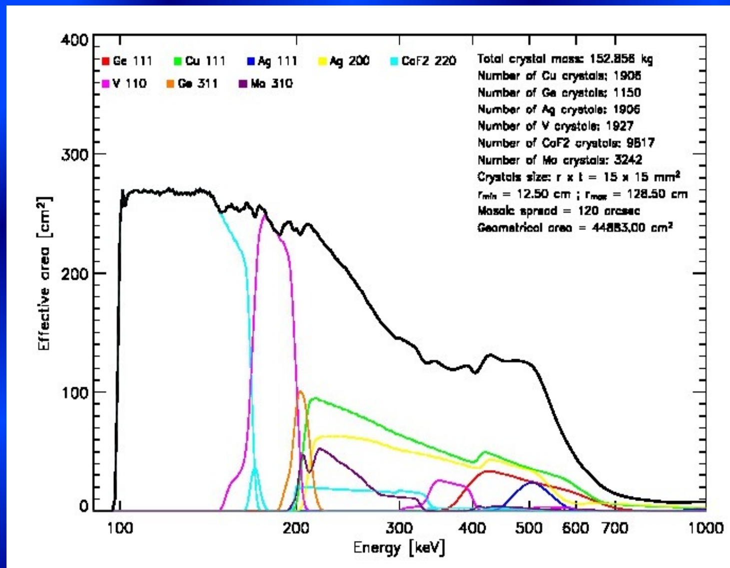
Potentially suitable materials:

- ❑ Pure elements
- ❑ Two-components crystals (GaAs, CdTe, …).

⇒ Crystals made of more than two components are not interesting because their crystal cell is large which decreases strongly the diffraction efficiency

Study of a 20 m FL Laue lens made of mosaic crystals (Barriere et al. 2009)





Laue lens development activities in Italy 3

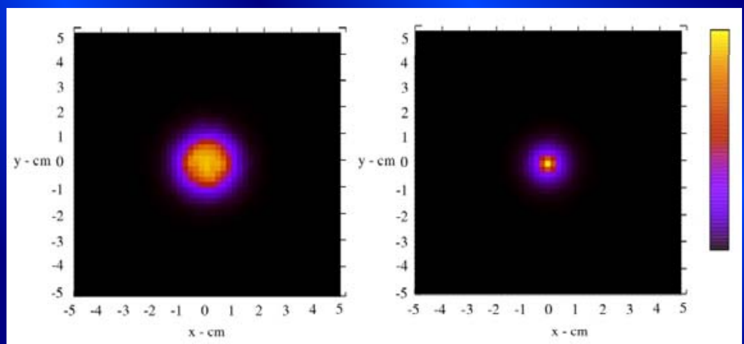
Bent crystal development for Laue lens application, a real breakthrough for Laue lens based instrument feasibility (E. Virgilli presentation):

- Perfect crystals can be used as grown (e.g. Si, Ge, GaAs and others) because the final orientation of crystalline planes for diffraction is generated and controlled by the bending process.
- Achievable (measured) 100% diffraction efficiency, while for mosaic crystals the theoretical limit is 50% (usually rather low): i.e. at minimum a gain of a factor 2 in collecting area.
- The crystal tiles curvature can be tuned to the Laue lens curvature therefore the expected PSF decrease (the tiles dimensions are not anymore a limiting factor) drastically in size, i.e. Large sensitivity improvement (>10).
- No limit on the crystal tiles dimension: improvement on the achievable filling factor and simplification of the assembling process (large tiles can be used).

15 m Focal Length, Energy range: 70 – 300 keV, internal mosaicity 30”

Flat Crystals
tile size 15 x 15 mm

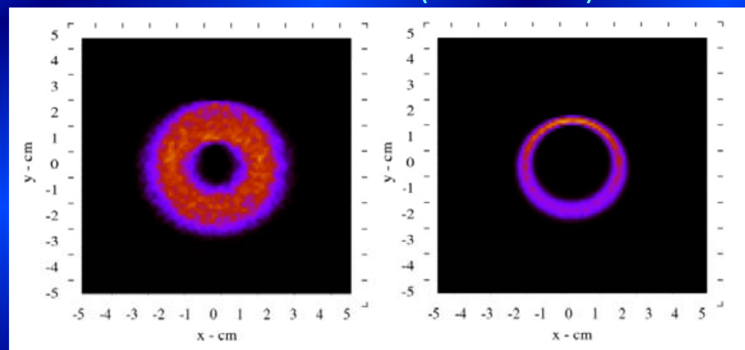
Curved Crystals
(Rc = 30 m)



On Axis

Flat Crystals
tile size 15 x 15 mm

Curved Crystals
(Rc = 15 m)

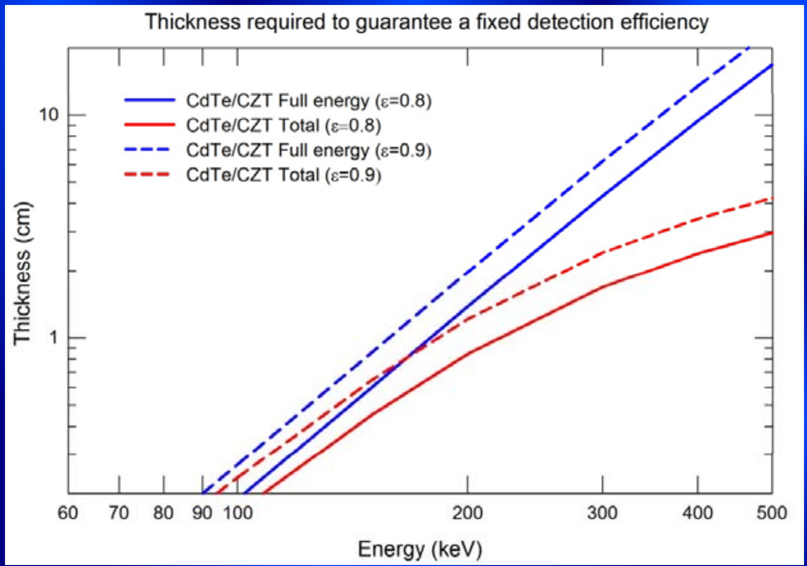


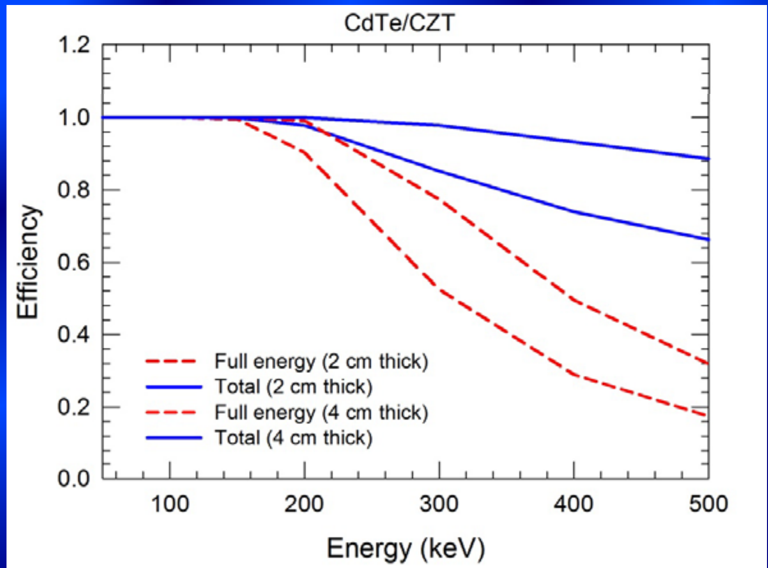
3’ off Axis

Focal plane detector requirements

- ➢ High detection efficiency (> 80%) up to the highest Laue lens pass energy;
- ➢ Spatial resolution: typically 1-2 mm for mosaic crystal based lens, 0.2-0.4 mm for bent crystal based optics, the difference depending on the PSF diameter;
- ➢ Good energy resolution: few % at 100 keV.
- ➢ Operating in coincidence mode between each pixel: maximize overall efficiency, allow polarimetric measurements and background rejection technique implementation.

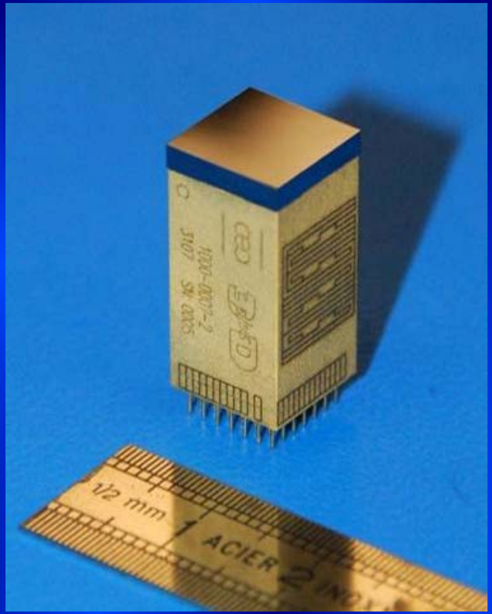
- ❑ High Z room temperature solide state detector: CZT/CdTe
- ❑ Stack and highly segmented detectors for 3D spatial resolution.
- ❑ Techniques for spectroscopic performance improvement (e.g. electrode configurations and deep sensing methods, schottky devices, ……..)



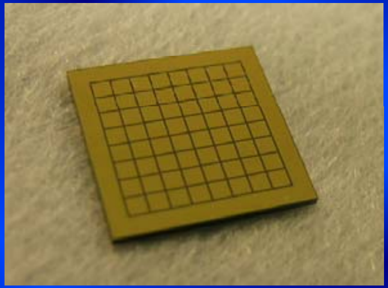


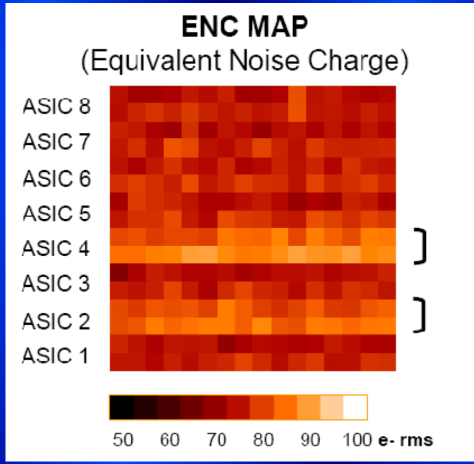
Focal plane detector technologies 1

Multilayer focal plane: the case of Simbol X.
A heavy technological development by CEA/Saclay to produce a high integrated module (Caliste 64/256) to be used as the sensitive unit of the Simbol X focal plane. (Limousin et al.)



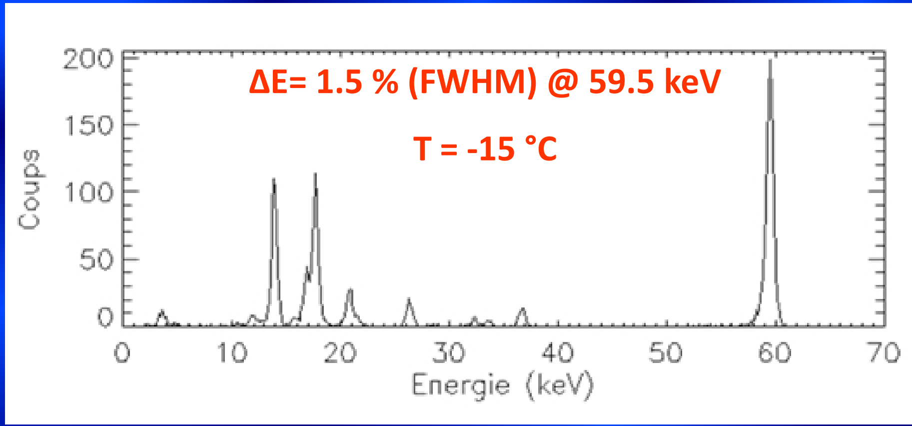
Pixel Shottky CdTe detector:
10x10x1-2 mm^3
Final pixel scale 0.6x0.6 mm^2
Operating temperature: -20°/-10 °





The IDEFIX ASIC: a Low noise readout 16 channels electronics: average r.m.s. 80 e $^-$

Summed spectrum of all the Caliste 256 pixels

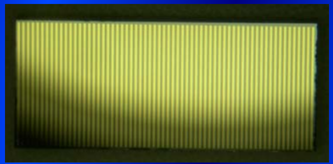


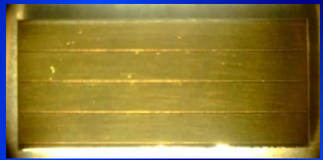
Focal plane detector technologies 2

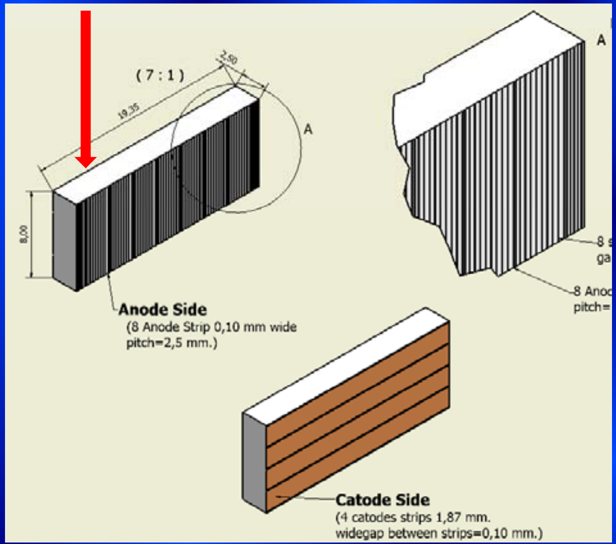
Laue lens focal plane suitable technologies:

3D CZT thick detector development for a GRI type focal plane (IASF, Italy and DTU space Denmark)

Use of PTF and drift strip configuration to achieve high detection efficiency with a low number of layer and improving the spectroscopic response

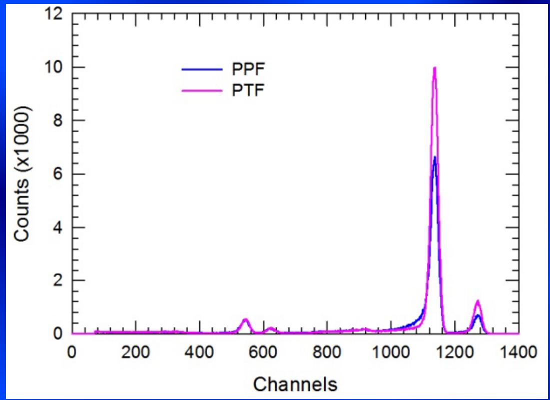


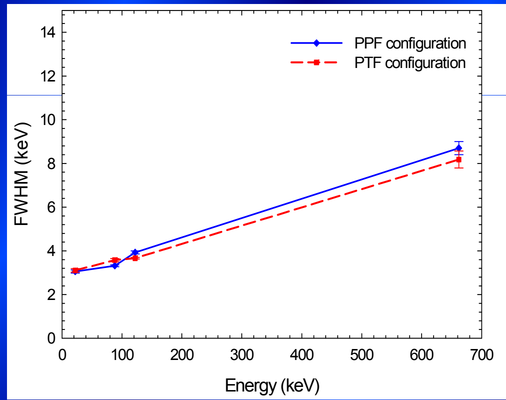




The anode has a drift strip configuration, while the cathode is segmented ortogonally to anode giving the third spatial coordinate .

The detector is equivalent to a stack of thin layers .



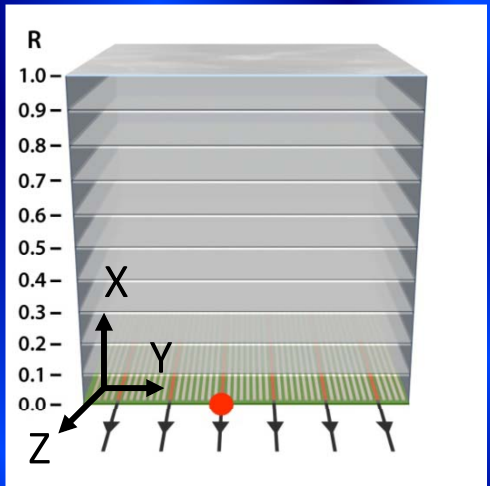


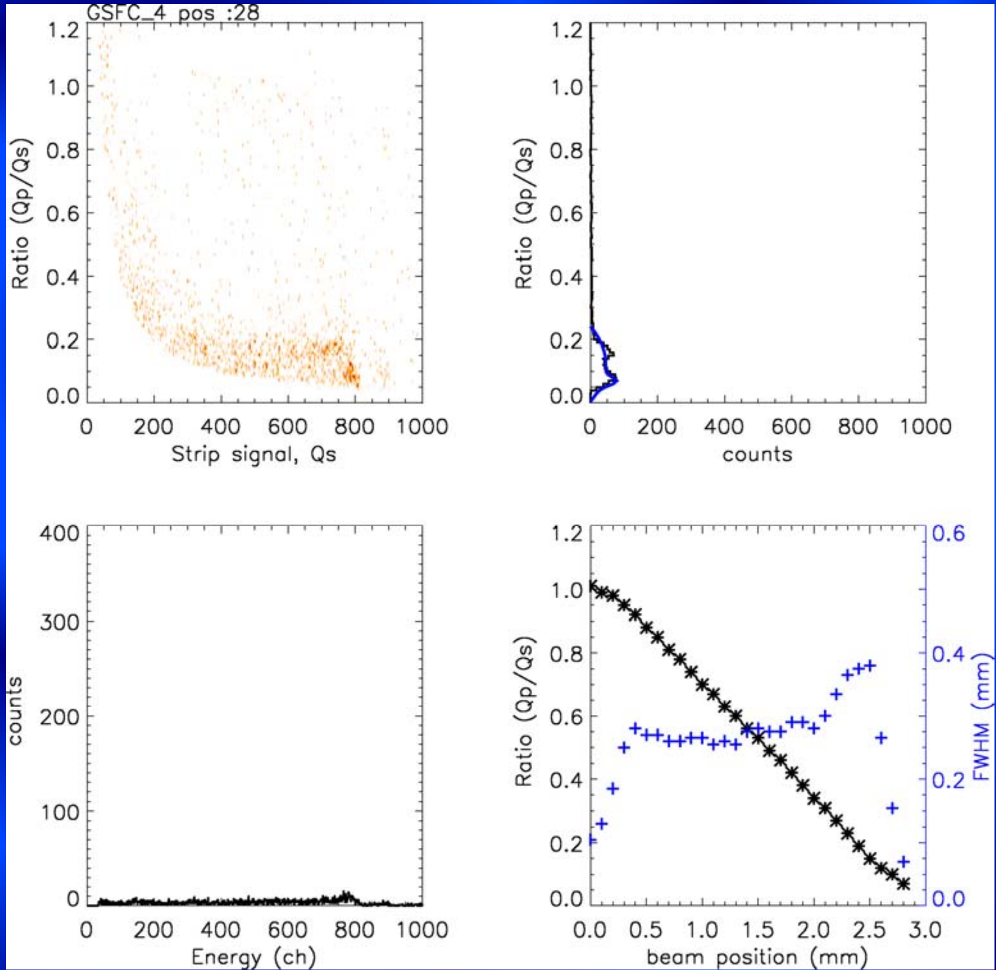
The energy resolution iis not anymore dependnet on the photon interaction position as demonstrated by the absences of low tails in potopeak shape

Focal plane detector technologies 4

Drift strip CZT detectors as (3D) fine spatial resolution sensors for hard X- and soft γ-rays

Recent measurements at ESRF confirm that a spatial resolution of ~ 0.1 mm can be achieved across the electrodes distance using the ratio between cathode and anode signals (Qp/Qs)

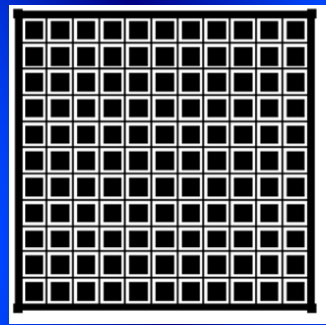




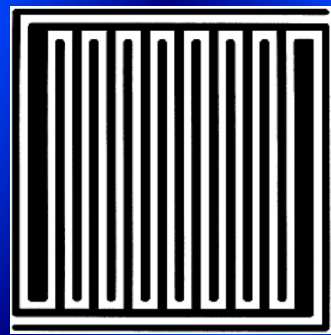
Focal plane detector technologies 3

Other sensor configuration can be used to obtain thick 3D position sensitive detector suitable to operate between 70 up to 600 keV with good energy resolution and high detection efficiency.

❖ 3D thick (up to 10 mm) Combining 2-D position sensing using a pixel anode array yielding good energy resolution from the small pixel e¤ect , and the depth sensing technique though the ration between cathode and anode signal for electron trapping corrections.



❖ The coplanar-grid technique consists of a detector anode equipped with a pair of interleaved grid electrodes and a full area electrode on the cathode side. 3D spatial resolution can be achieved with 2D coplanar anode strucure



NOTE: all the reported configuration use the interaction depth sensing through the cathode/anode sign al ratio: i.e. the third spatial dimension does not imply increasing the readout electronics channels.

Polarimetry: the ultimate dimension

❖ Polarimetry is a very important observational parameter for high energy astrophysics. Therefore the capability to perform accurate polarimetric measurement of high energy cosmic sources fluxes shall be included in future space instrumentation.

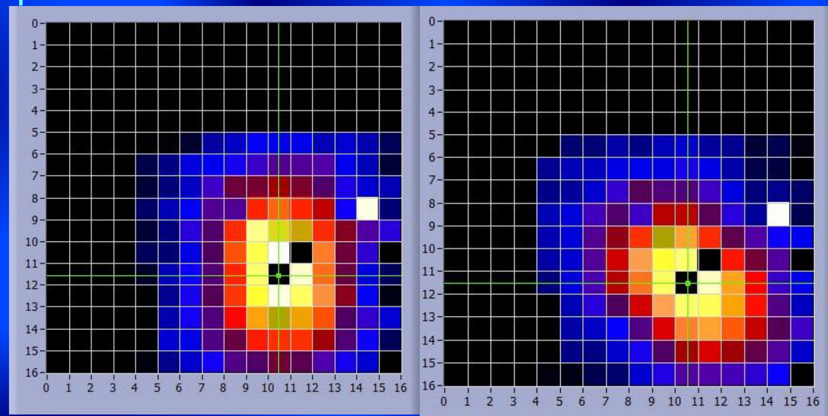
❖ Every segmented detector can be operated as a scattering polarimeters.

❑ The quality (modulation factor Q) of a detector operated as a scattering polarimter depend on pixel size , i.e. on the segmentation level of a detector

❑ The MDP depend also on the compton scattered detection efficiency and on related background count rate.

For ~2 mm spatial resolution scale as in the GRI design the Q factor = 0.3-0.4

The POLCA experiments at ESRF with a 5 mm thick CZT detector with 2.5x2.5 mm^2 pixels. E = 200 keV, scattering map with detector inclined 0°, and 45° with respect to the beam polarisation direction



GRI-MDP for a 100 mCrab source (3σ)	
Time	50-500 keV
10^4 s	10%
10^5 s	3%

The improvement in the PSF size with new bent crystal in Laue Lens construction require a more fine spatial resolution of the focal plane increasing its polarimetric expected performance:

- **Q factor increase**
- **better identification of good compton scattered events**

The Laue lens payload

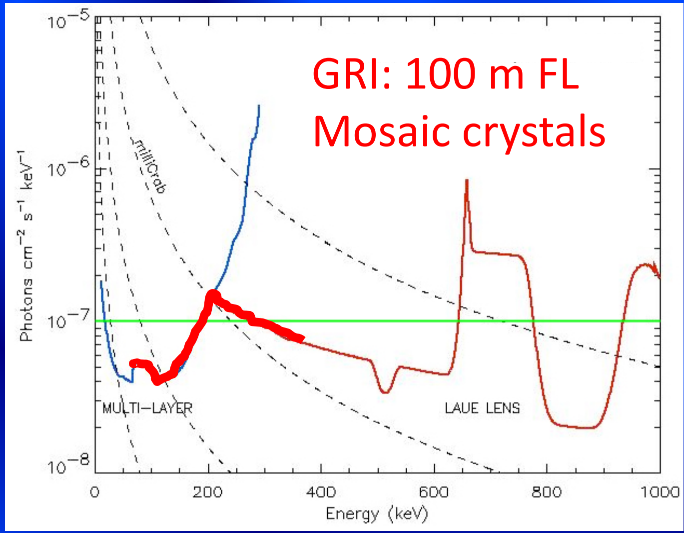
With the improvement achievable using bent crystal as laue diffracting elements medium/low focal lens configuration can be considered for a next decade wide band focusing hard X ray telescope.

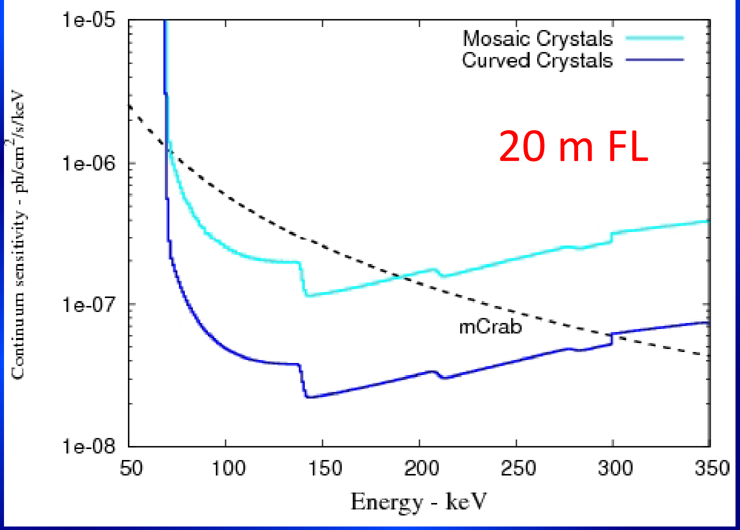
Cu[111] crystals of 15x15 mm^2

N.B. With bent crystals the number of crystal tiles can be strongly decreased

Focal Lentght	15 m	20 m
Energy Band	70-400 keV	70-400 keV
Internal radius	25 cm	29 cm
External radius	120 cm	140 cm
Tiles Ring number	53	70
Crystal number	12890	22680
Crystal weight	78 kg	130 kg

Continuum sensitivity (3σ, 10^5 s, $\Delta E=E/2$)





A focussing hard X-/γ-ray space mission for the next decade

❑ The current status of technological development guarantee the feasibility of a focusing telescope covering the band 1-500/600 keV based on two main payload:

- a multilayer mirror telescope operating up to 70/80 keV;
- a wide band laue lens telescope covering the 70-500/600 keV energy range.

NB. the implementation of bent crystals in the laue lens will allow a much better tuning between the two instrument in term of sensitivity, field of view and angular resolution.

❑ This type of mission will be "focussed" on deep study of the physics processes and the environment characteristics that are responsible of the hard X –ray emission from cosmic source. This instrument will be mainly a "diagnostic" probe for known hard X- and soft γ-rays

❖ The Multilayer telescope and the Laue lens could be coaxial: i.e. the ML can use the empty Laue lens inner circle if compatible (as in GRI).

❖The proposed payload is compatible with available launchers;

❖ The propose payload does not require formation flight;

❖ Which kind of orbit is required? This is TBD depending on constraints on the expanding structure used to achieve the required focal lenght

❖ There is the need for a complementary wide field instrumentation? We consiThe laue lens focal plane can be operated as a compton telescope with large field of view.

Conclusion

The needed know-how and experiences are currently available at several research groups in different European countries.

The history of science give several examples in which it was necessary to bet on new ideas and technologies even if they was not really mature in order to made progress and breakthrough to solve a particular problem. As a relevant example I would like to remind that at the begin of the BeppoSax story has been decided to bet on grazing incidence technique to focus soft X ray even if this technology was at this time at a very preliminary stage (and in fact only 10 years later grazing incidence focusing will become a "standard" for soft X ray astronomy: the XMM/AXAF era)

We believe that we have to use the same attitude for the opportunity that ESA will give to our community with the incoming Call for a M class mission for 2022.

Dear colleagues and friends what do you think about ?

May we start a discussion on such type of proposal?