The ASTENA Wide Field Monitor-Spectrometer: design and simulations

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Ezio Caroli

on behalf of

the ASTENA/WFM-S Collaboration:

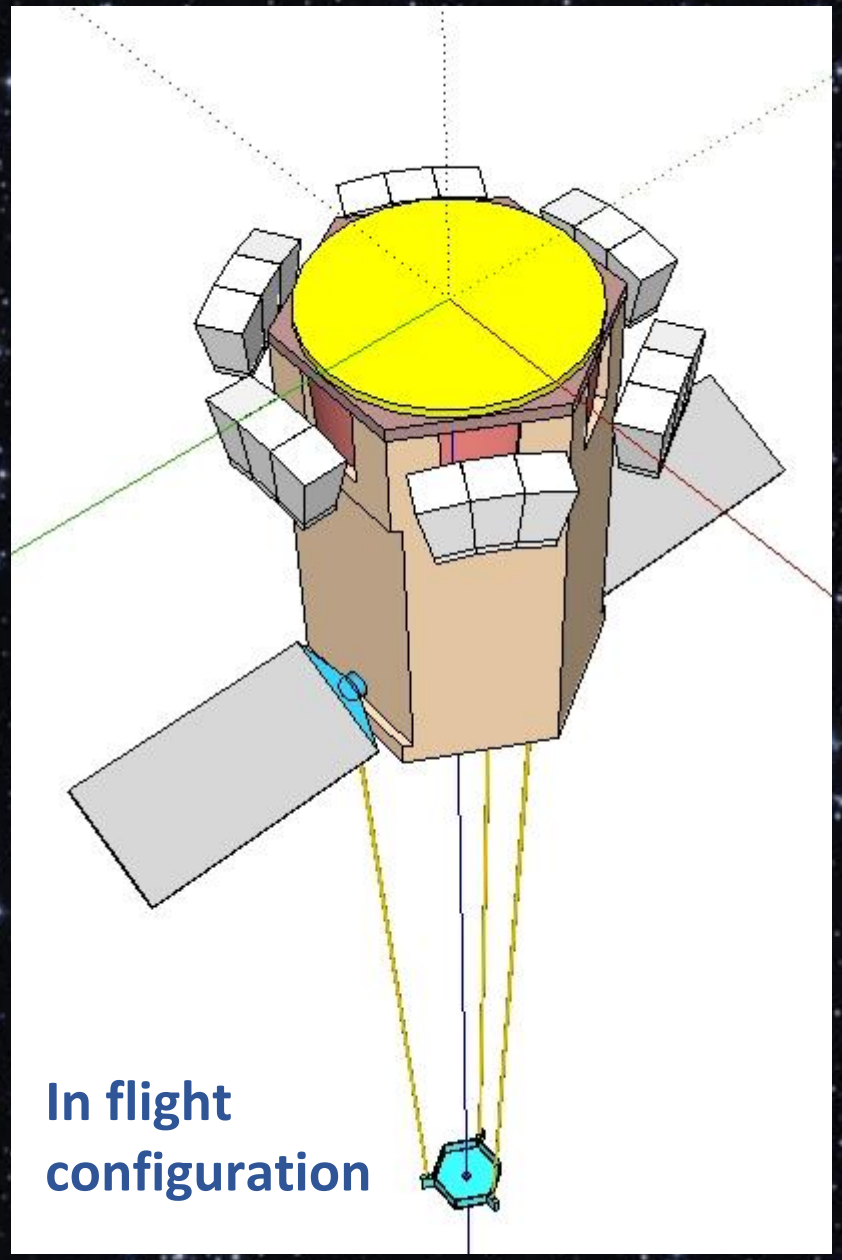
- **University of Ferrara:** P. Rosati (Lead proposer), F. Frontera, C. Guidorzi, E. Virgilli.
- **INAF-IASF Bologna/Palermo**: L. Amati, N. Auricchio, L. Bassani, R. Campana, E. Caroli, F. Fuschino, C. Labanti, A. Malizia, M. Orlandini, J. B. Stephen, S. Del Sordo
- **DTU Space, Copenhagen**: C. Budtz-Jorgensen, 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 2-20000 keV range.

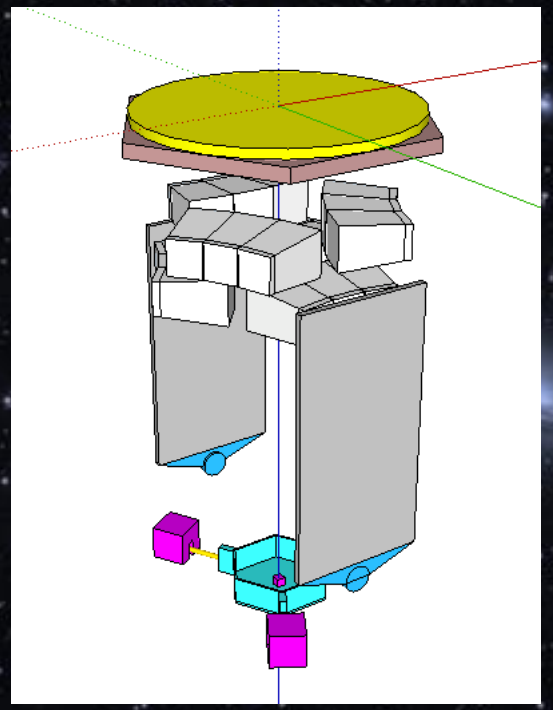
- **A modular wide field monitor/spectrometer (WFM/S),** with a passband from 2 keV to 20 MeV with a GRB localization accuracy of order of **few arcmin** between 1 and 50/100 keV and a FOV of about 1.5 sr.

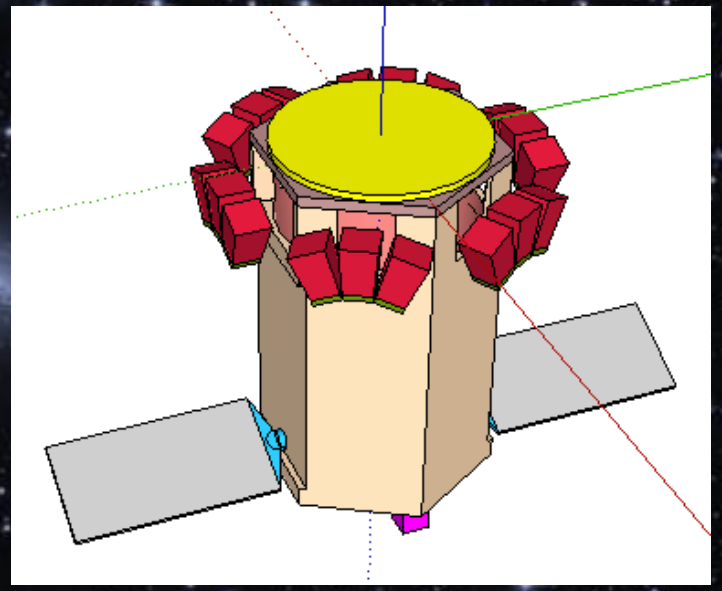
- **A narrow field telescope (NFT),** made of a broad-band Laue lens (50 – 600/700 keV) of 20 m focal length, with a FOV= 2-3 arcmin, and an angular resolution of ≈30".

ASTENA Satellite configuration



In flight configuration





(left) WFM/S closed configuration;
(right) open configuration.

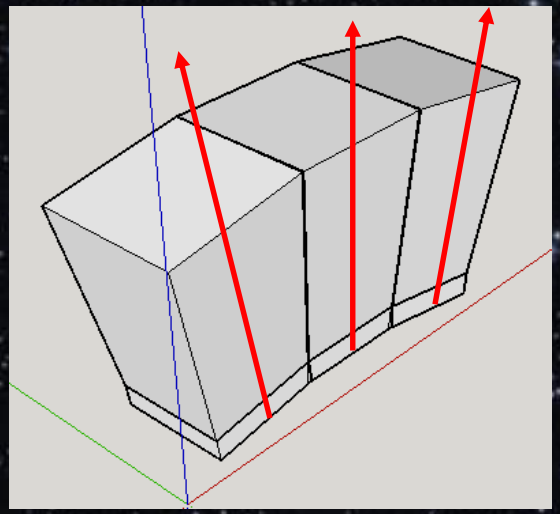
Laue Lens (∅ 3 m), with 20 m focal length

WFM/S (18 modules)

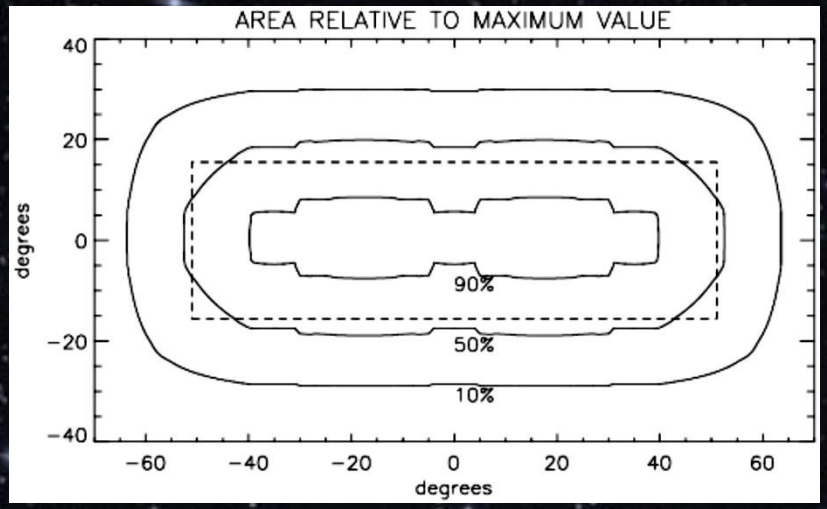
ASTENA WFM/S main characteristics

- **18 identical modules (in 6 blocks)**.
- **WFM/S modules and NFT are partially coaxial**. This configuration guarantees that the NFT field of view is centred in the WFM/S FOV.
- Each module has 4 detection systems based on solid-state detectors and scintillators: **SDD+CsI(Tl)**
- Energy band **2 keV – 20 MeV**
- **Imaging capabilities at low energies** (2–50/100 keV) using a coded mask: FOV of 1.5 sr and angular resolution of few arcmin.
- **Isotropic detection capabilities at high energies** (100 keV – 20 MeV)

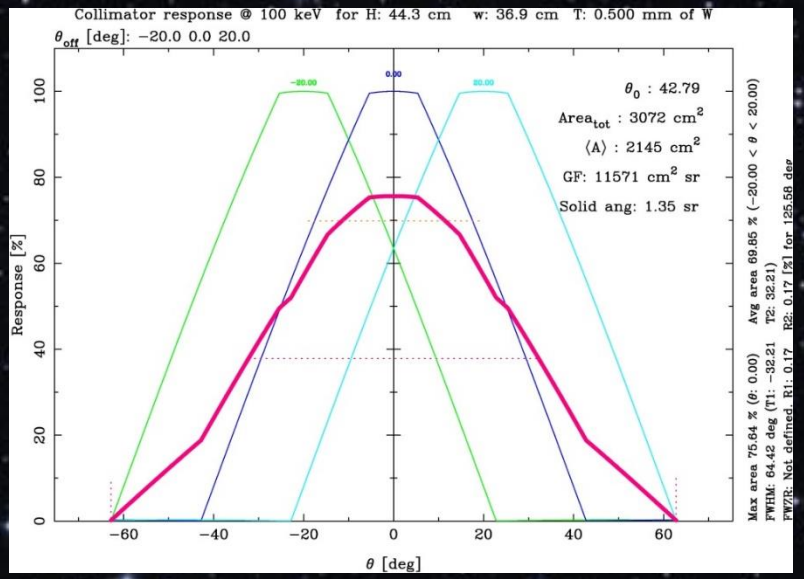
ASTENA : WFM/S Block field of view



The BLOCK WFM/S assembly. The red arrows represent the optical axis of each telescope module



The map of one WFM Block FOV at 100 keV with ± 20° offset of the module optical axes



Profile of the FOV at 100 keV of one Block in the direction that crosses the three telescope modules
The total exposed area is ~3000 cm^2.
The FOV is 1.35 sr.

The Total field of View of the WFM/S (6 Blocks) will be the superimposition of the single Block «elliptic» FOV with each major axis rotated by 60°.

ASTENA-WFM/S: Performance evaluation

- GEANT4 mass model of one WFM/S block (i.e. 3 coded mask telescopes modules): **ready.**
- Implementation in the MEGALIB environment: **starting.**
- **Goals:** WFM/S sensitivity and MDP for different:
  - *shape and dimension of sensitive elements and mask design*
  - *operating parameters, like spatial, energy resolution, and background*
  - *source spectra, direction and duration*

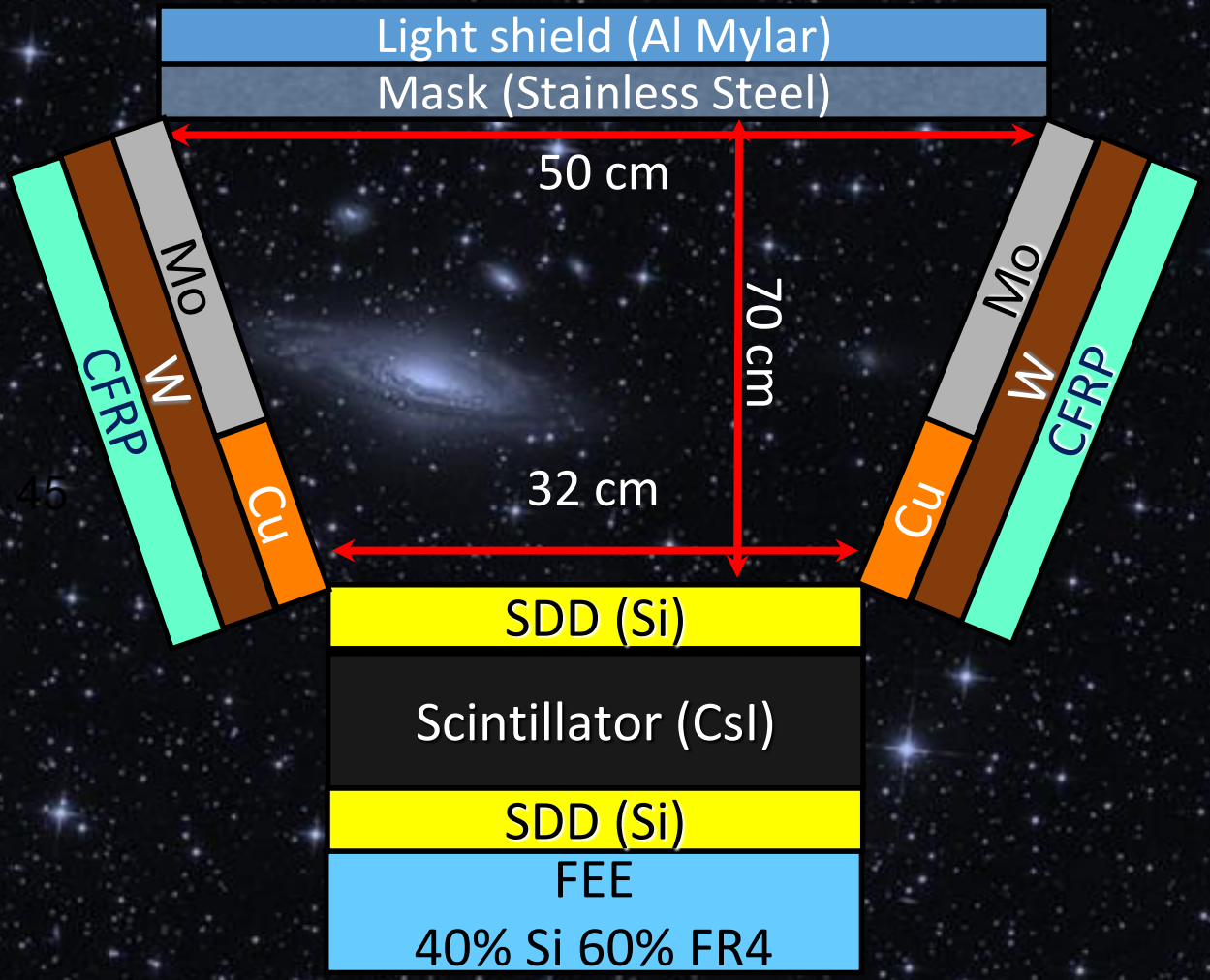
ASTENA : WFM/S Performance evaluation code

Adopted detector response models:

- ❑ Analytical model of spectral resolution of the SSD layers as function of energy
- ❑ Analytical model of spatial resolution of CsI bar elements along axis.
- ❑ Analytical model of spectral resolution of CsI bar elements as function of energy and interaction position along CsI bar axis.

ASTENA-WFM/S GEANT4 Mass Model of a module

Geometry and sizes			
System item	**Thick**	**Unit size**	**Array**
CODED MASK			
Light Shield	0.15 mm	50x50 cm^2	
Mask	0.5-1 mm	5x5 mm^2	100x100
GRADED HOPPER			
Layer1(int)	0.1 mm	50x32x70 cm^2	0.45
Layer2(mid)	0.3-0.5 mm		
Layer3(ext)	2 mm		
DETECTOR SYSTEM			
SDD top	0.45 mm	5x5 mm^2	32x32
Scintillator	50 mm	5x5 mm^2	32x32
SDD bottom	0.45 mm	5x5 mm^2	32x32
FEE	5 mm	32x32 cm^2	



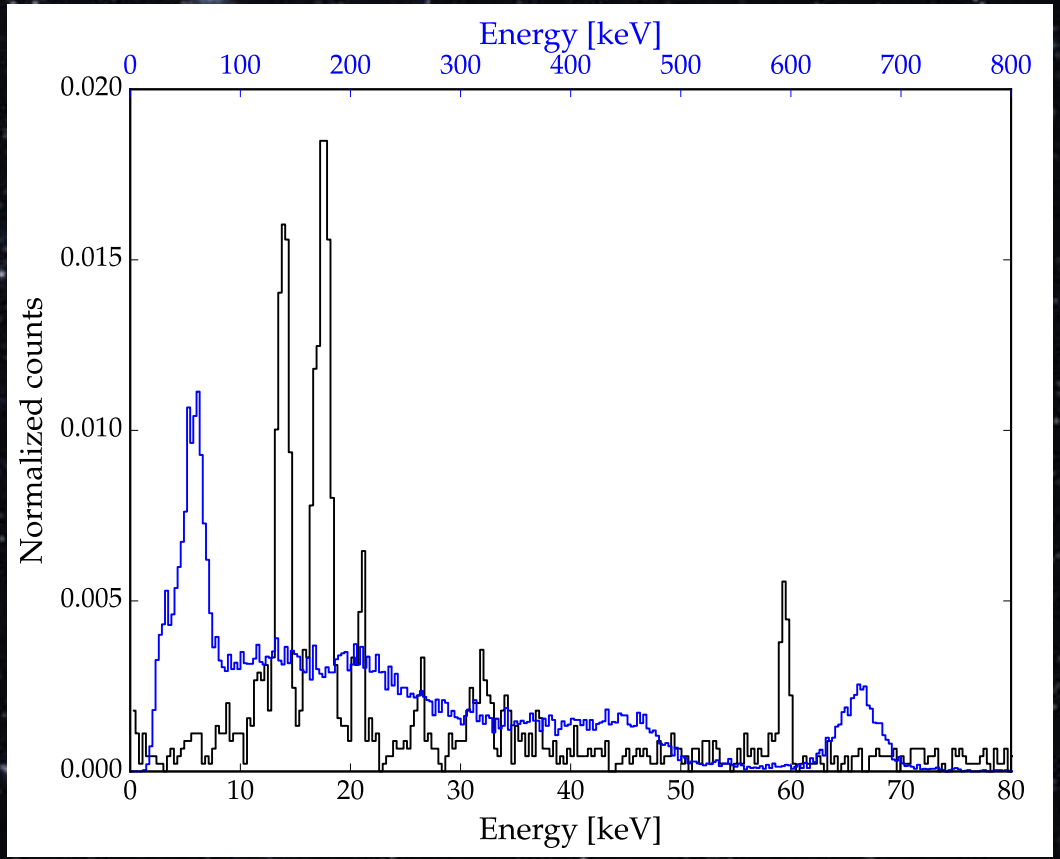
The sizes are the baseline values

WFM/S Detector response model for SDD spectroscopic resolution

Model of the spectroscopic resolution of the SDD layers as function of energy.

The SDD are used as soft X-ray detector and as CsI-scintillator readout.
From experimental spectra acquired using SDD we can extrapolate the model to convert simulated energy deposit in readout signal as function of energy and interaction position (SDD or CsI)

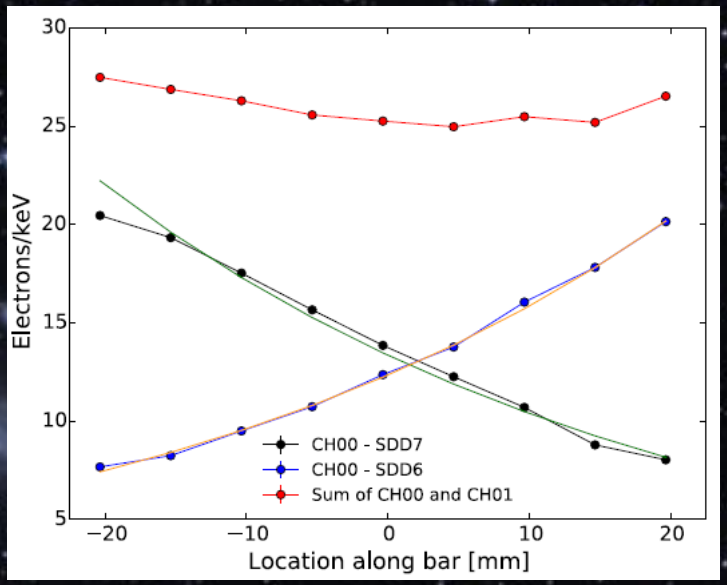
Simultaneous acquisition of a ^{137}Cs plus an ^{241}Am source by SDD.
The black curve (lower x-axis) is the spectrum of X-events (SDD events), while the blue one (upper x-axis) is the spectrum of Cs events detected in the CsI bar unit.



WFM/S Detector response model for CsI spatial resolution

Model of spatial resolution of CsI bar unit sensitive elements along axis.

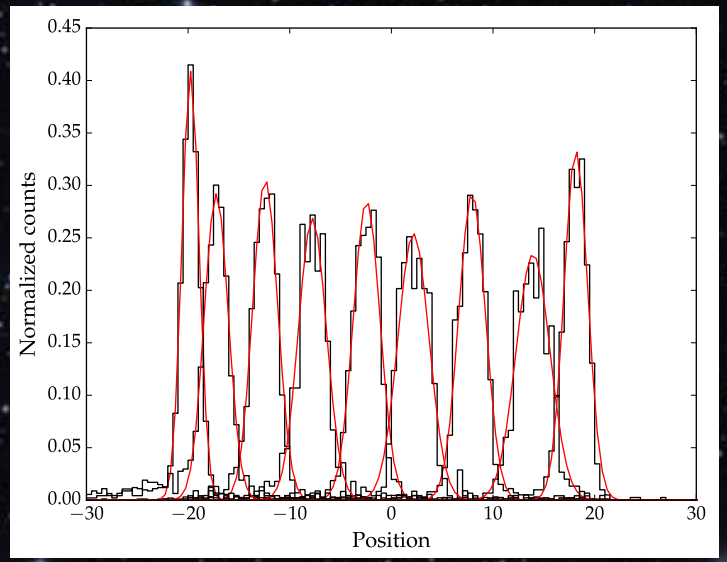
The model is derived from laboratory measurements on CsI bar with the same geometry and dimension.



The reconstruction of the photon interaction position along the bar axis is performed by

$$z = \frac{1}{2\alpha} \ln\left(\frac{S_1}{S_2}\right)$$

Where S_1 and S_2 are the light signal collected by the two SDD at the opposite extreme of each sensitive unit.



(top) Exponential Light attenuation along the bar (top).
(bottom) Reconstructed position for various measurements along the bar. The spatial resolution (FWHM) is ~ 2 mm over 50 mm length.

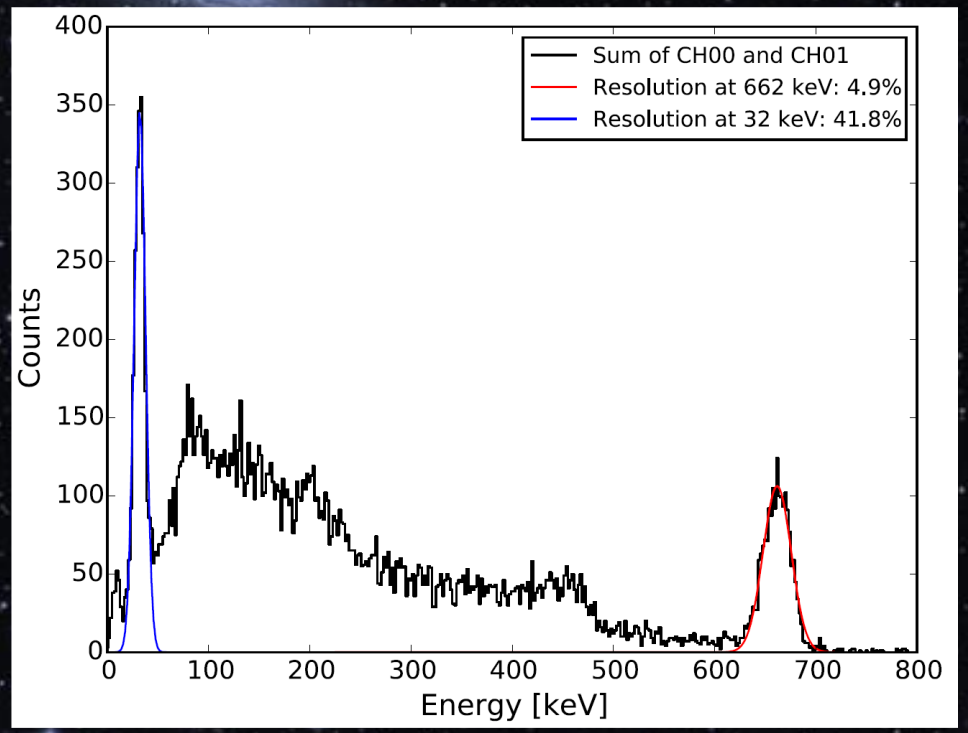
ASTENA : WFM/S Detector response model for CsI spectral resolution

Model of spectroscopic resolution of CsI bar units as function of energy and interaction position along CsI bar axis

The model is derived from laboratory measurements on CsI bar with the same geometry and dimensions:

$$E = k\sqrt{S_1 \cdot S_2} = kE_\gamma e^{-\frac{\alpha L}{2}}$$

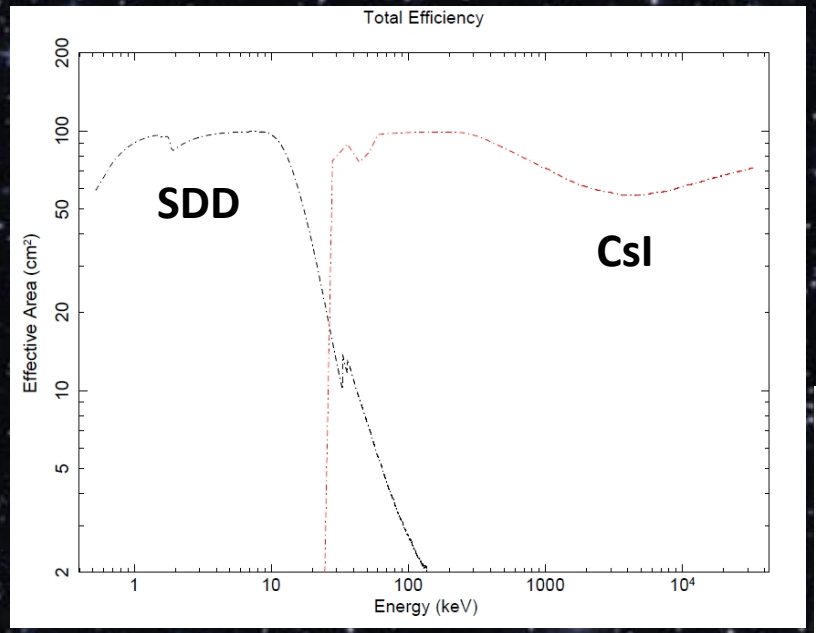
The energy resolution (1σ) as function of the position interaction can be evaluated from the above relation by error propagation



Spectrum of a collimated ^{137}Cs source, placed in the middle of the scintillator bar, acquired summing the scintillation light signals collected by the SDDs at both ends.

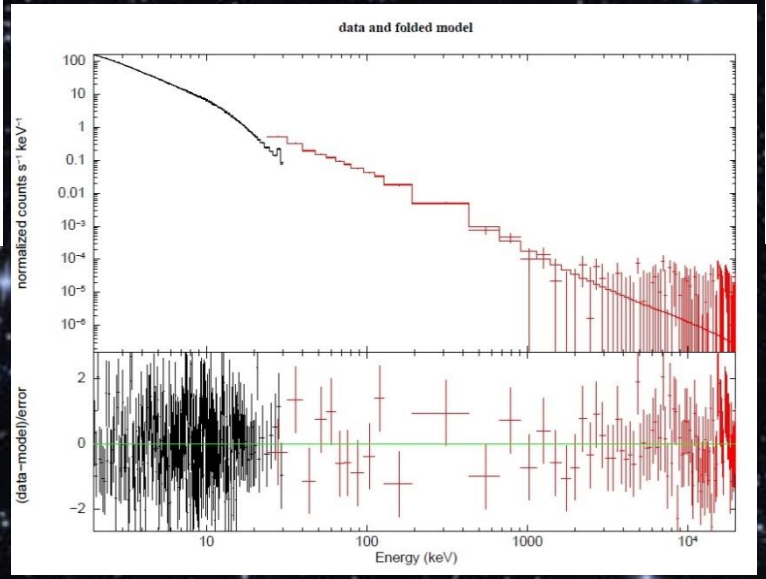
ASTENA : WFM/S GEANT 4 Simulation Results

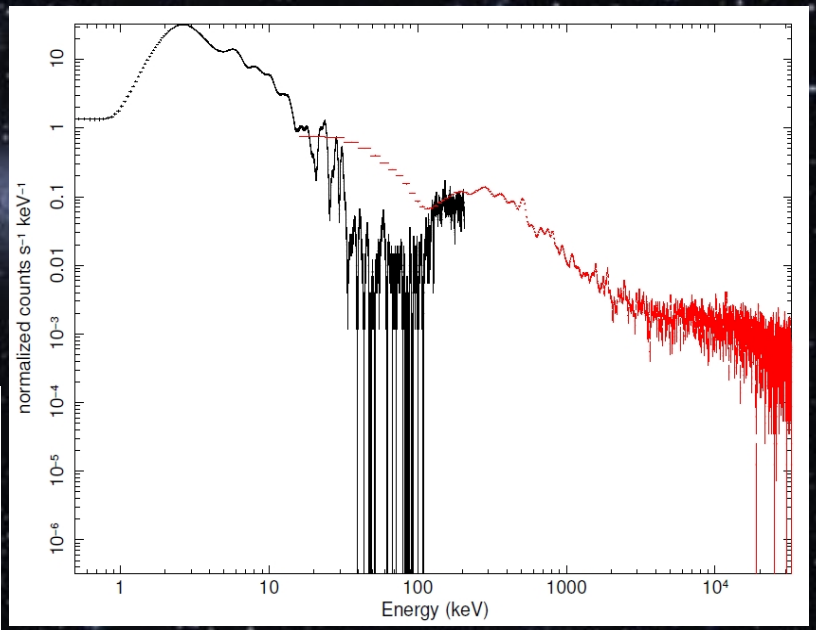
Examples from the Matrix Response obtained with the THESEUS WFM/S Geant4 Mass Model.



One Module effective area

Detected spectra of a GRB with a fluence 20 ph/cm^2 in 50-300 keV (a typical BASTE GRB spectrum)



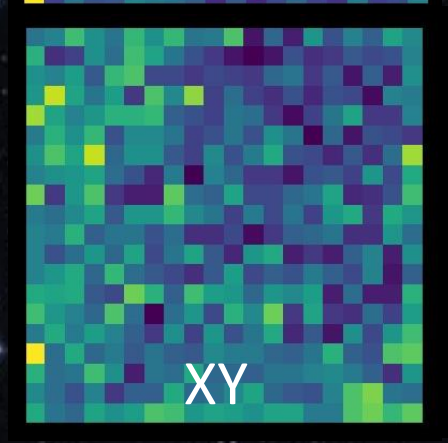


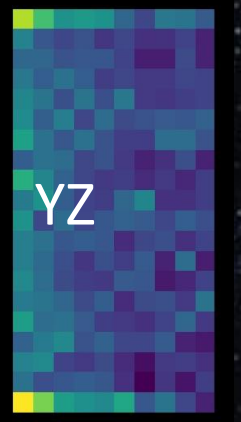
Expected Background, LEO orbit at 550 km, equatorial [5°]

ASTENA : WFM/S GEANT 4 Simulation Results

Examples from the Matrix Response obtained with the THESEUS WFM/S Geant4 Mass Model: the reconstructed spatial distribution of CsI events.

Each CsI bar is dicretized along the main axis in 10 segment of 5 mm (twice the 1 σ spatial resolution. The final CsI detector is therefore a 3D detector with voxel of 5x5x5 mm^3 .

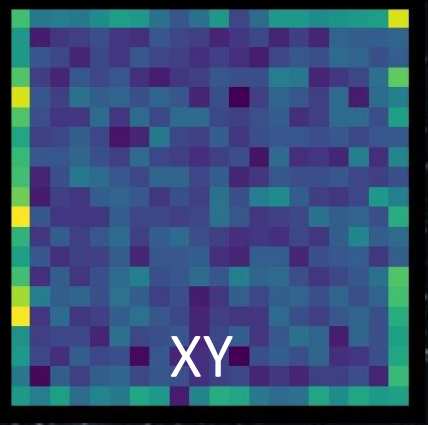




Parallel flux at 1 MeV with two different incoming directions (both external to the Mask FOV):

Left $(\theta,\phi)=(40°, 0°)$

Right $(\theta,\phi)=(70°, 210°)$

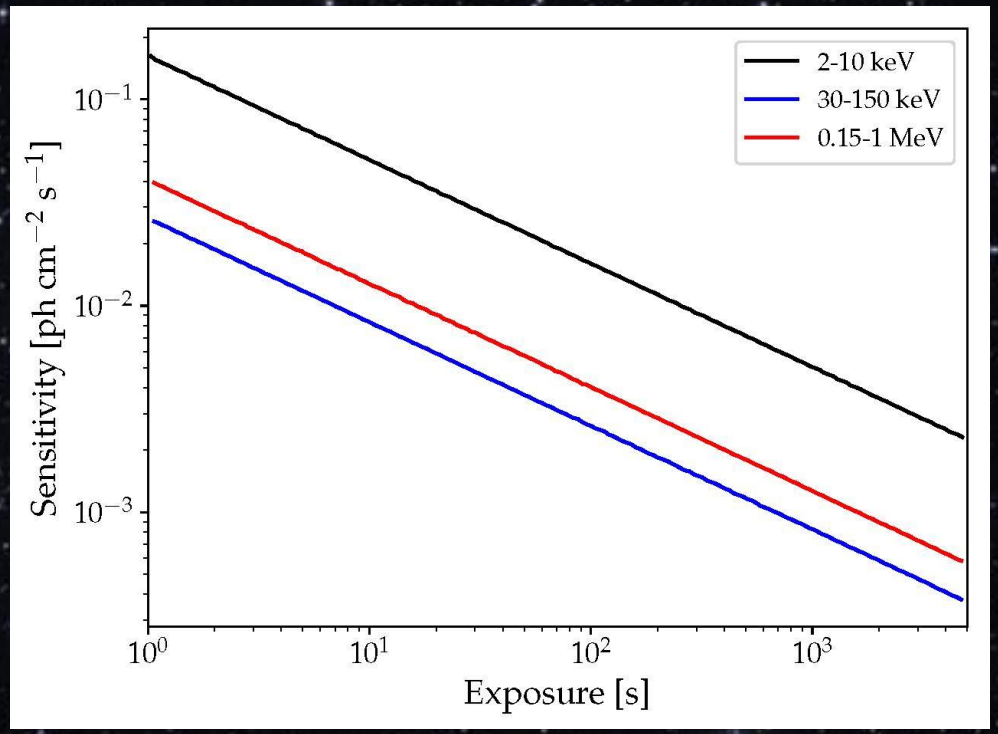


From these counts distribution over the full set of WFM/S modules it will be possible to infer the GRB incoming direction within a certain angular precision

CONCLUSION: ASTENA WFM/S Expected performance

Using a reference background in a LEO orbit the figure shows the expected sensitivity by the ASTENA WFM/S in different energy bands. Sensitivity to GRBs is unprecedented.

This preliminary evaluation is already at least a factor ten (in 1 s integration time) in sensitivy with similar instrumentation currently proposed (Theseus) for GRB science.



NEXT STEPs:

- ❑ Implementation of the GEANT 4 WFM/S block mass model in MEGALIB;
- ❑ Implementation of the detector response models in MEGALIB;
- ❑ Definition of simulation scenarios needed to build the WFM/S response matrix

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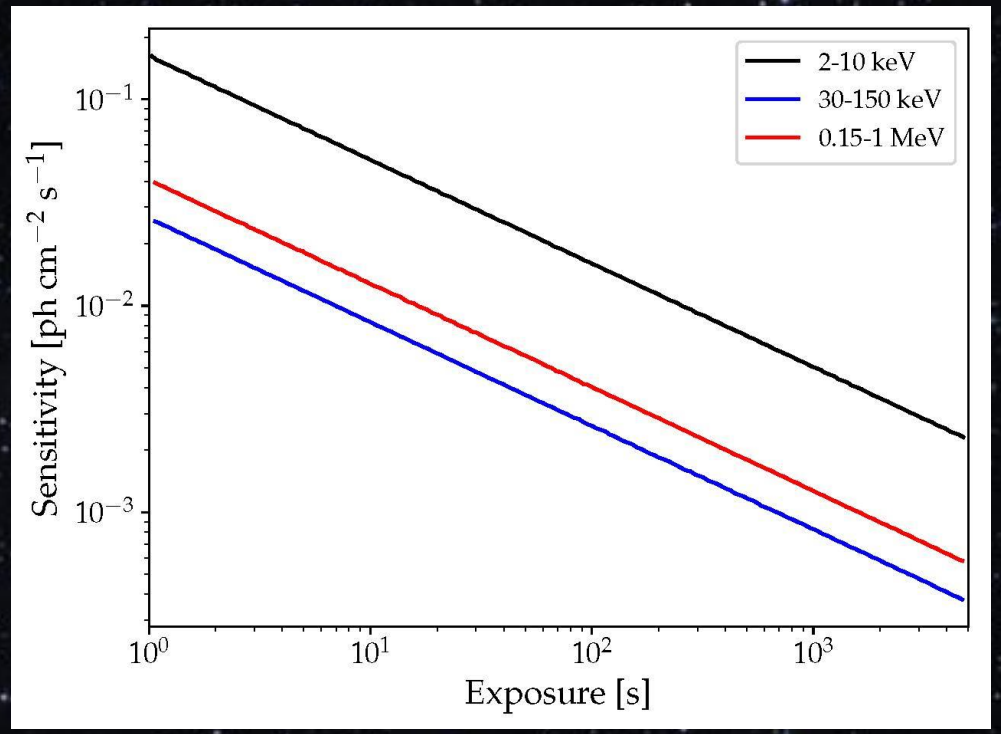
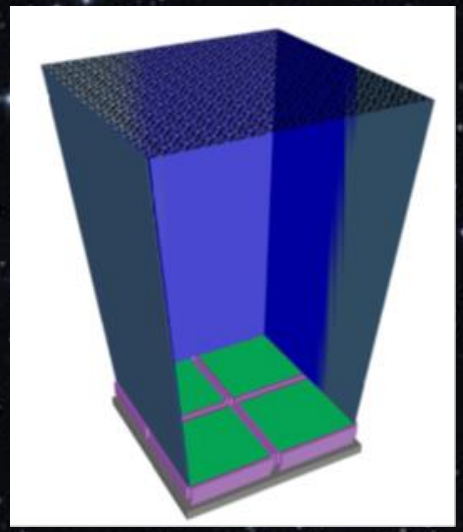


NEXT STEPs:

- ❑ Implementation of the GEANT 4 WFM/S block mass model in MEGALIB (may 2018);
- ❑ Implementation of the detector response models in MEGALIB (may 2018);
- ❑ Definition and run of simulation scenarios needed to build the WFM/S response matrix for GRB's and source survey (june-november 2018);
- ❑ Evaluation of sensitivity, source location accuracy, and MDP (october-december 2018)

ASTENA : WFM/S GEANT4/MEGALIB Monte Carlo Model



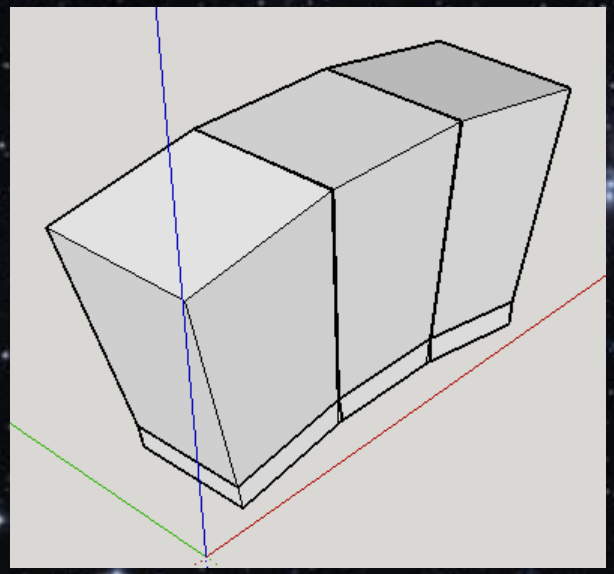
Single coded mask telecope.

Coded mask imaging up to 50/100 keV

Hopper FOV delimiter up to 150 keV

- The mask has a self-support pattern in order to guarantee the maximum transparency of the open elements
- The Hopper walls have graded thickness profile to optimize opacity and weight.

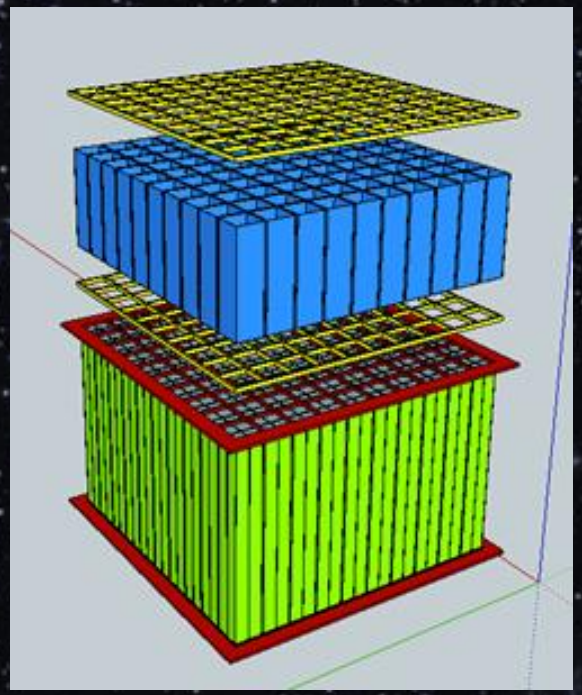
WFM/S module characteristics	
Mask Pattern	Random
Element size	5x5 mm
Pattern Open fraction	30%
Dimension	50 cm x 50 cm
Mask-Detector Dist.	70 cm
Mask Material	Steel
Mask Thickness	0.5-1 mm
Hopper Material	W
Hopper thickness	**0.1-0.5 mm**



WFM/S Block Unit

The relative inclination (offset) between the optical axis of each module shall be optimized to maximize total FOV, but taking into account satellite bus constraints.

ASTENA : WFM/S GEANT4/MEGALIB Monte Carlo Model 1/2



Details of the volumes that are defined in the WFM/S detector array model

WFM/S detector module characteristics	
Energy band	2 keV – 20 MeV
# detection plane arrays	4
# of detector pixels/array	32x32
pixel size/shape	3-5 mm/ Square/Hex
Low-energy detector (2-30 keV)	SDD 450 μm thick
High energy detector (20 keV-20 MeV)	CsI(Tl)/ (3-5 cm thick)
CsI bar element shape	Square/Hex

Material Definition in the MC model

- SSD Top: Silicon layer on a ceramic l layer
- Scintillator bar detector: CsI(Tl)
- SSD Bottom same as SSD top
- FEE: Silicon and FR4 material mixture.