collimators, coded masks and all sky monitors

P. Laurent

CEA/DRF/IRFU/SAp

(with the help of F. Lebrun and A. Goldwurm)

Content

- Collimator concept
- Coded mask imaging
- Past and present coded mask missions
- The INTEGRAL/IBIS/ISGRI data analysis
- All sky monitors

*PART 1

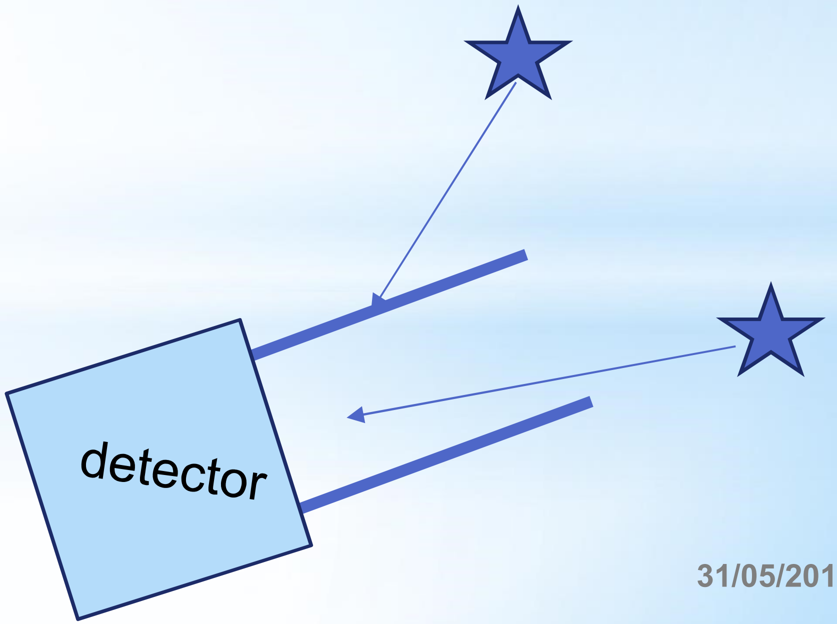
*COLLIMATORS

Collimators concept

Basics

- Telescopes working in the hard X-ray/ soft γ-ray regime use collimators, especially those observing at very low energy where the photoelectric effect dominates all the other type of interactions.

- Indeed, contrarily to higher energy phenomena (Compton scattering, pair creation) photoelectric effect does not provide intrinsic information on the detected photon direction.



Collimators concept

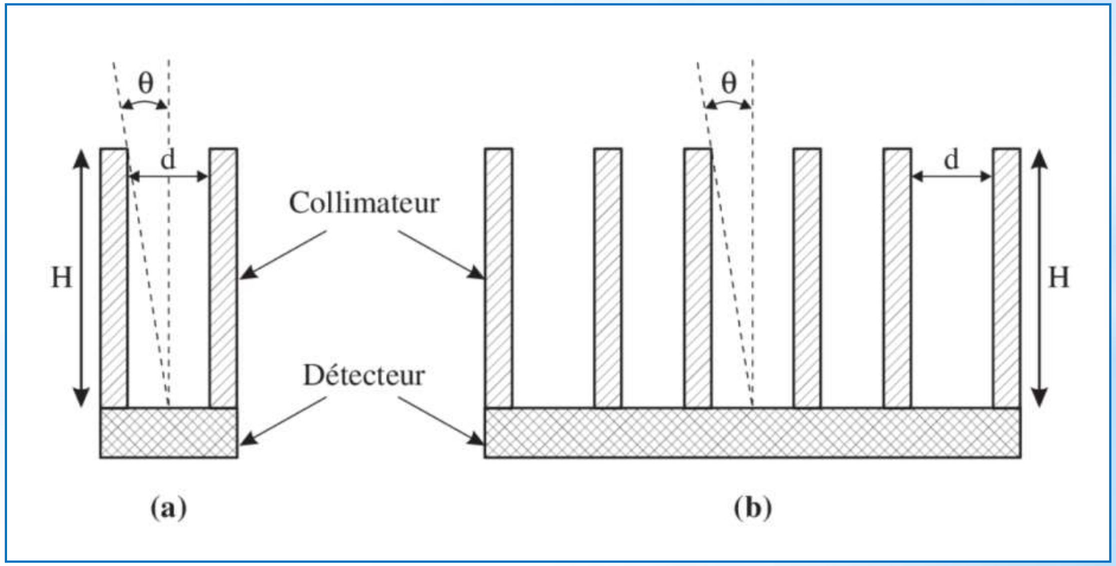
Basics

- Also, if we except hard X-ray mirrors or devices based upon the Laue diffraction, it is quite impossible to bend the trajectory of γ-ray photons.
- Hard X-ray imaging systems are then all based upon the shielding of a certain photon direction in order to privilege another one.
- A collimator is without any doubt the most simple of those devices used to determine the photons incident direction:
    - it is a tube whose walls can absorb the γ-ray photons, and which is placed in front of the detector, in the direction we wish to observe.
    - Any photon travelling more or less along this direction hits the detector and can be recorded. The other ones are absorbed by the walls.

Collimators concept

Basics

- We may also put on the top of the detector a multiple-aperture collimator such as the one shown below.
- The shielding should be maximized to stop photons outside the field of view.
- In the other hand, in order to minimize the shaded surface, the walls thickness has to be as low as possible, which implies the use of high-Z elements.



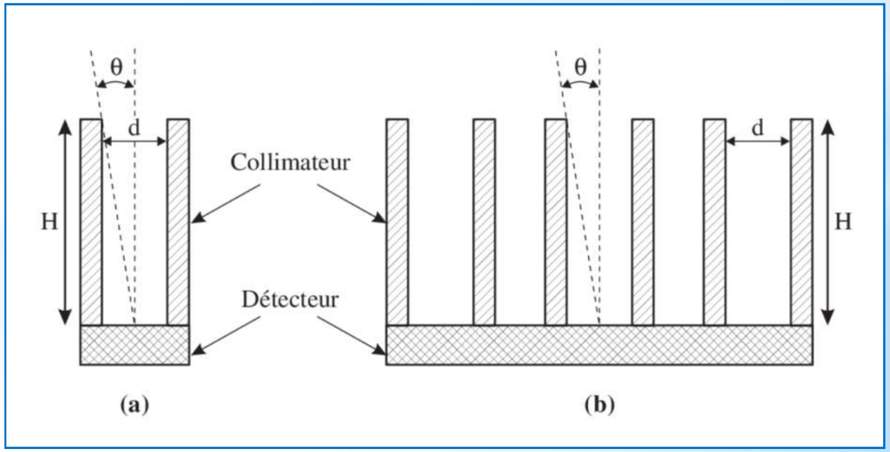
Collimators concept

Basics

If we supposed the wall totally opaque to γ-rays the point spread function of such a multiple-aperture telescope is represented by a triangle-shaped function, whose total width at half maximum θ is given by:

$$\boldsymbol{\theta = Arctg(\frac{d}{2H})}$$

where H is the collimator height and d the distance between the walls. The measurement of the photons direction is all the more precise as θ is small which leads to high collimators for a given detector area.



Collimators concept

Main properties and limitations

- The localization accuracy of such systems is generally poor. In practice, these devices can achieve a point source localization accuracy around one degree for bright sources.

- If the position of the source we want to observe is already known, it is possible to suppress the underlying background by using the "on-off" method, whose principle is the following:

  1. We make a first observation "on" by pointing the considered source. The measured count rate n_{S+B}, is then the sum of the source and background count rates.
  2. We make then a second "off" observation, looking nearby the source in a region supposed not to contain any other sources. This observation give the value of the background count rate n_B.

$\Rightarrow$ The source count rate n_S is then obviously given by the difference of the two previous measurements.

Collimators concept

Main properties and limitations

This method suffers from two main problems:

1. The measurement of the source count rate will be altered if there is one or many unknown sources in either the "on" or the "off" field. This problem is even stronger with high sensitivity telescope where the probability to have a weak source in the field is higher.

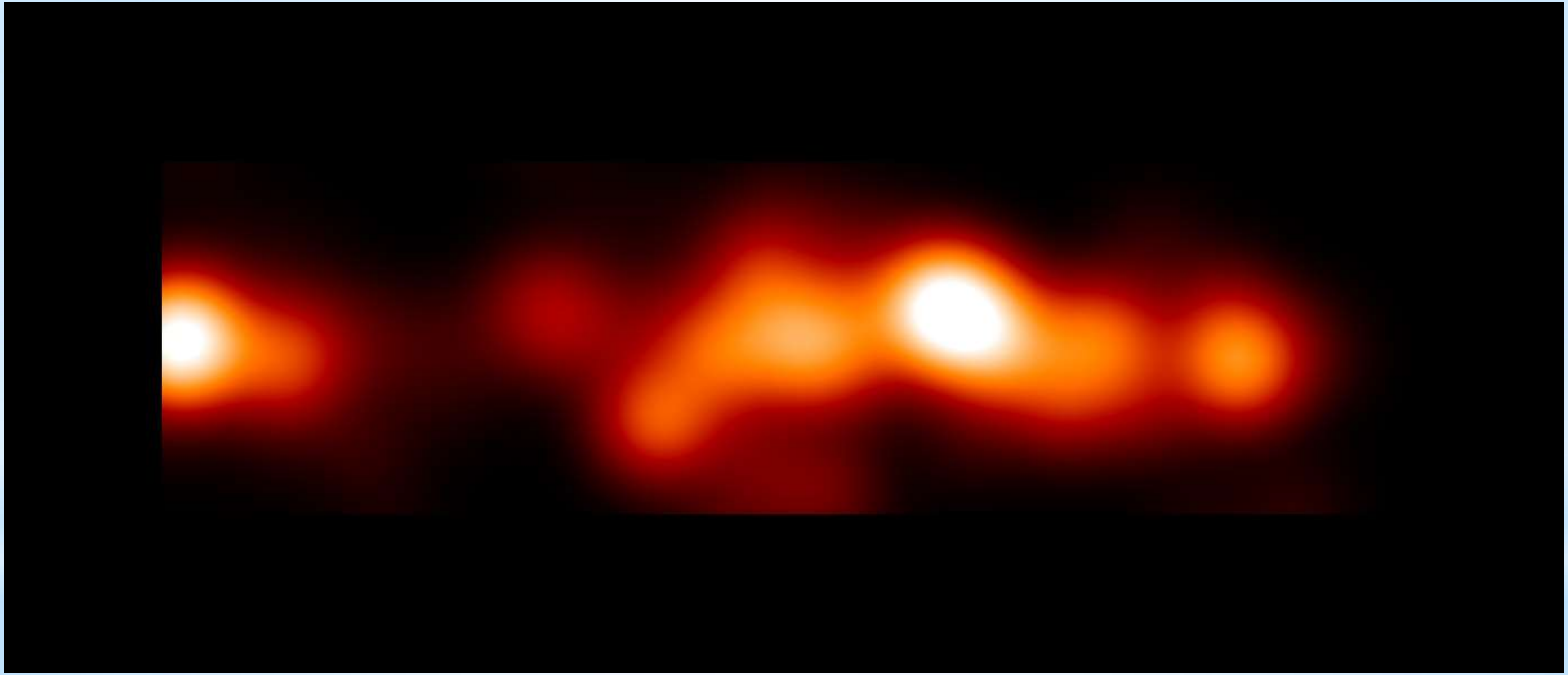
2. Background has to be estimated very precisely in order to correctly remove it. This implies long observations of the "on" and "off" field, of the order of several hours, even days, in order to obtain high statistics. On the other hand, the background in space evolves on much shorter timescales.
   $\Rightarrow$ The background measured during the "off" observation is then different from the one underlying the source flux measured during the "on" observation, which then lead to an erroneous estimate of this source flux.

Collimators concept

The GRO/OSSE experiment

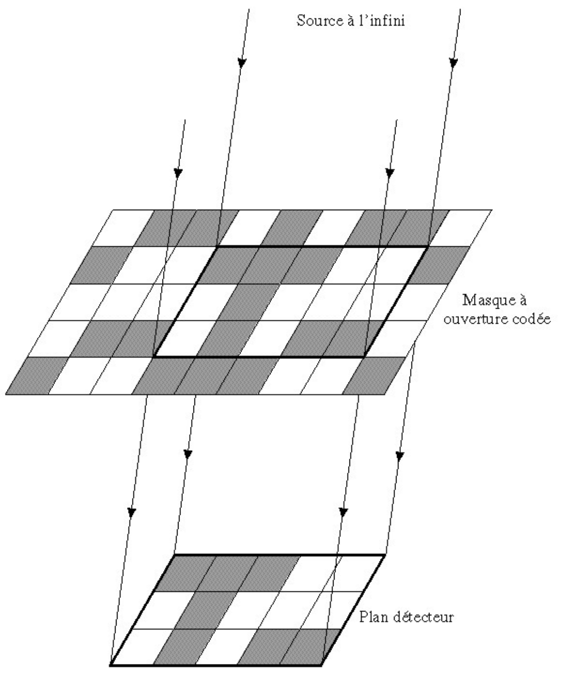
- Despite those limitations, collimators were well in use in the beginning of the nineties, as their relatively easy conception enable the fabrication of very large telescopes.
- It was the case of the OSSE experiment (*Oriented Scintillation Spectrometer Experiment*) inboard the *Compton* Gamma Ray Observatory, put into orbit on April 1991.
- With a total mass of 1814 kg, this huge γ-ray spectrometer was composed by large area NaI scintillator, associated with a multiple aperture collimator.
- It had a rectangular field of view of $11.4° \times 3.8°$ (Johnson *et al.*, 1993).

OSSE image of the Galactic Centre
60 keV , resolution: 7°
(4.7° x 11.3°)



CODED MASK IMAGING

Coded Mask Imaging : Concept



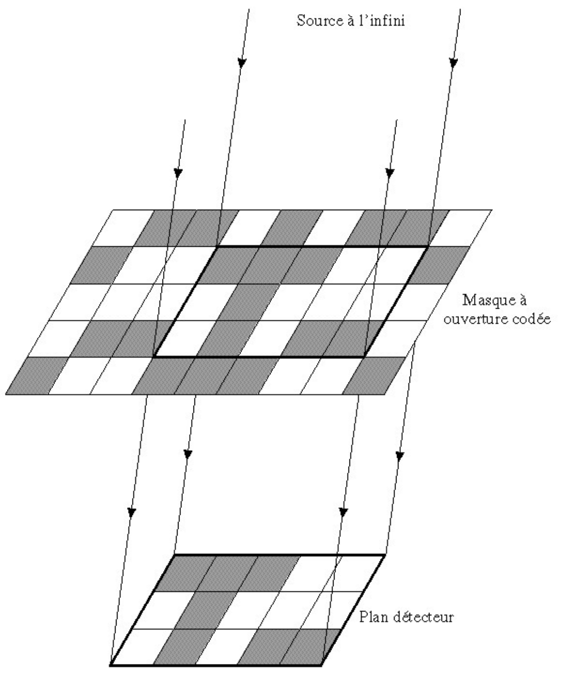
Coded Aperture Systems are based also on shielding. It employs a **mask** of opaque and transparent elements to modulate sky radiation before it is recorded by a **position sensitive detector**.

Sources project patterns of the mask on the detector, and an image can then be reconstructed by correlation with the known mask pattern.

To reconstruct a sky image, the **mask pattern** must be such that:

- the projected shadow by any given source must be unique to avoid "ghosts".

- the match between shifted patterns must be as poorest as possible to avoid false detection.



Coded Mask Imaging : Concept

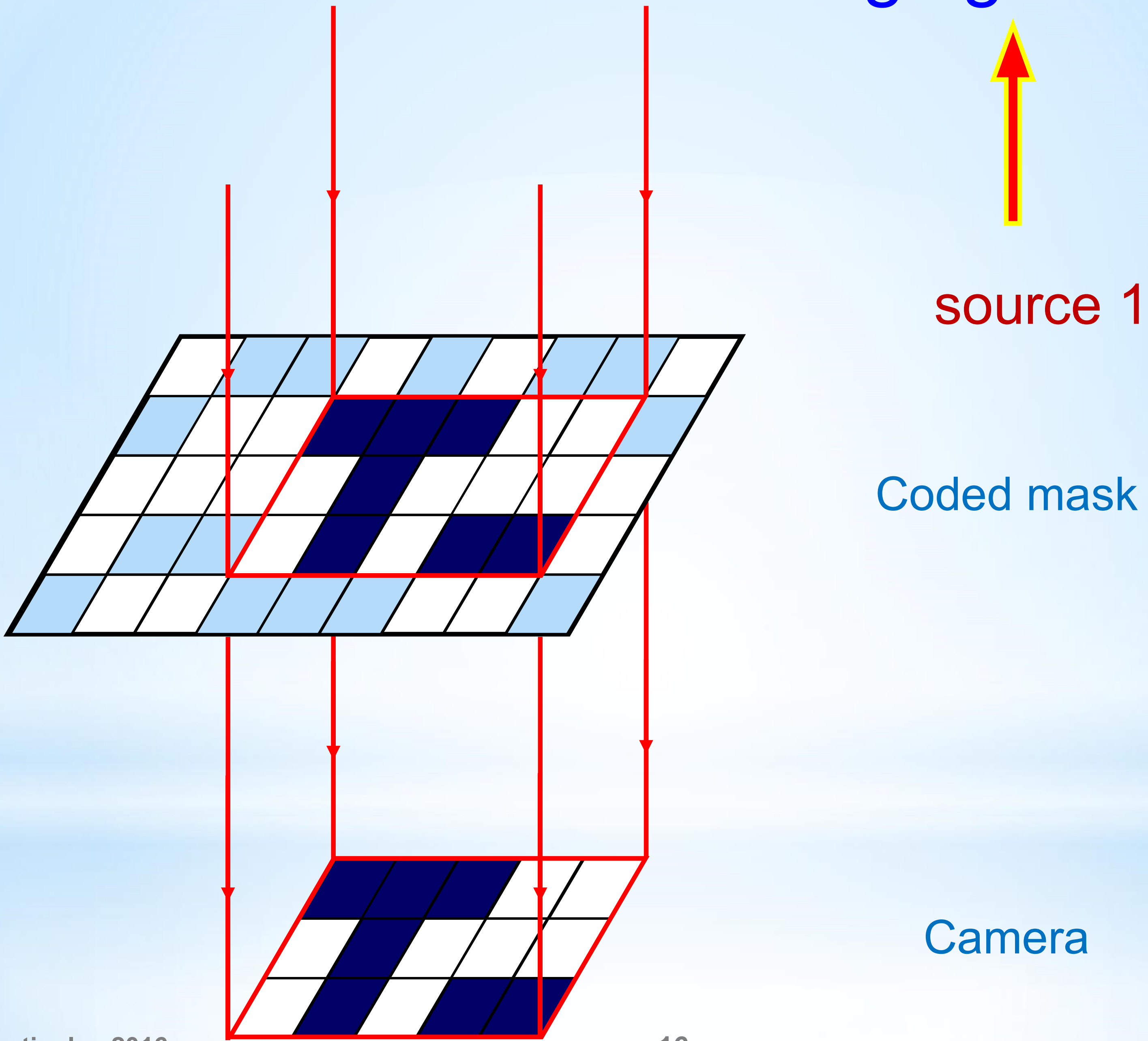
Advantages :

- Angular resolution is given by SIZE of mask elements and by mask-detector DISTANCE. Small mask elements $\Rightarrow$ good angular resolution.
- Large Field of View (FOV) can be obtained.
- Background is measured simultaneously to the source fluxes.

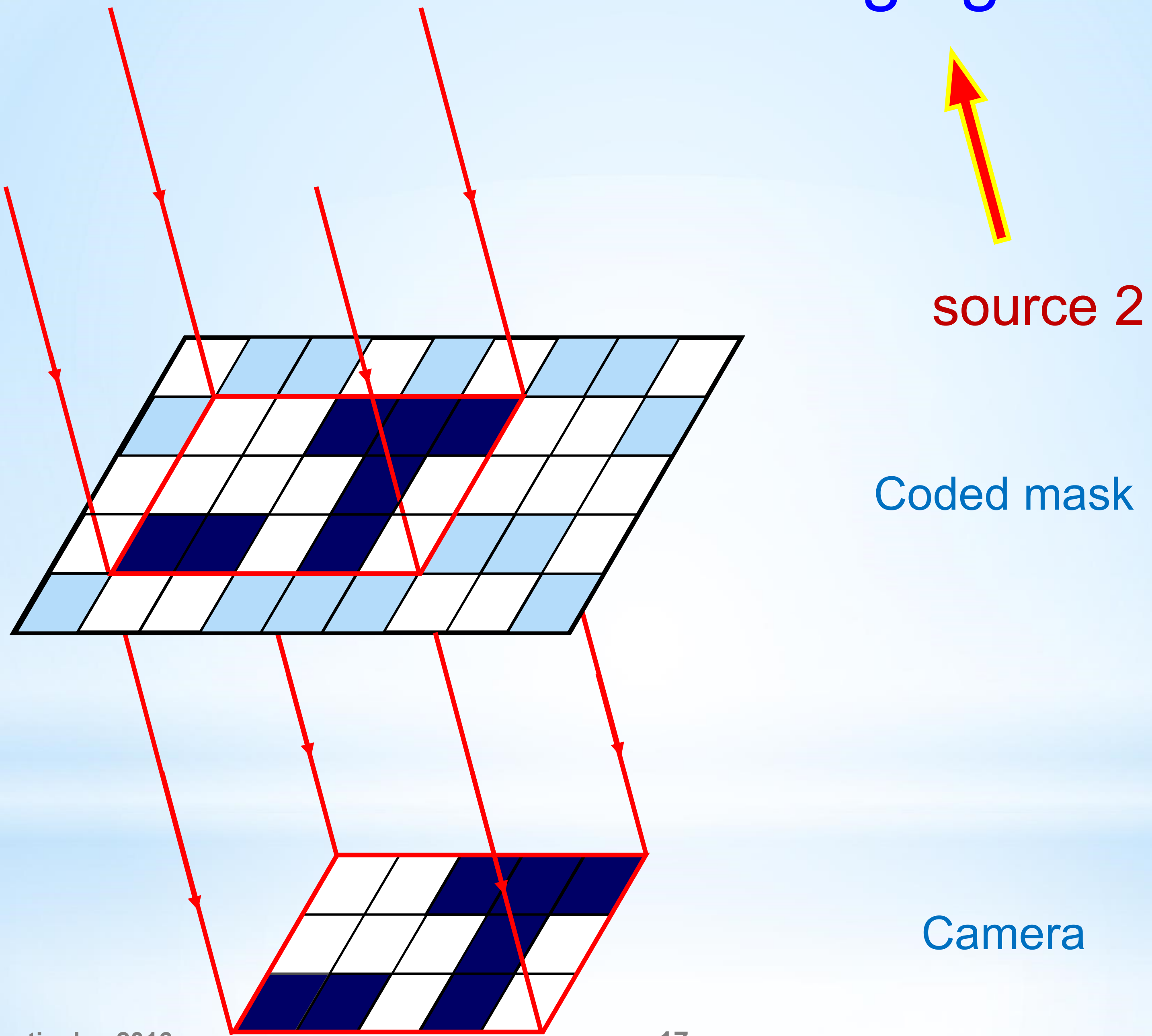
Problems :

- Not-direct imaging, decoding needed (slow processing).
- *Collective / Statistical* imaging, not event by event.

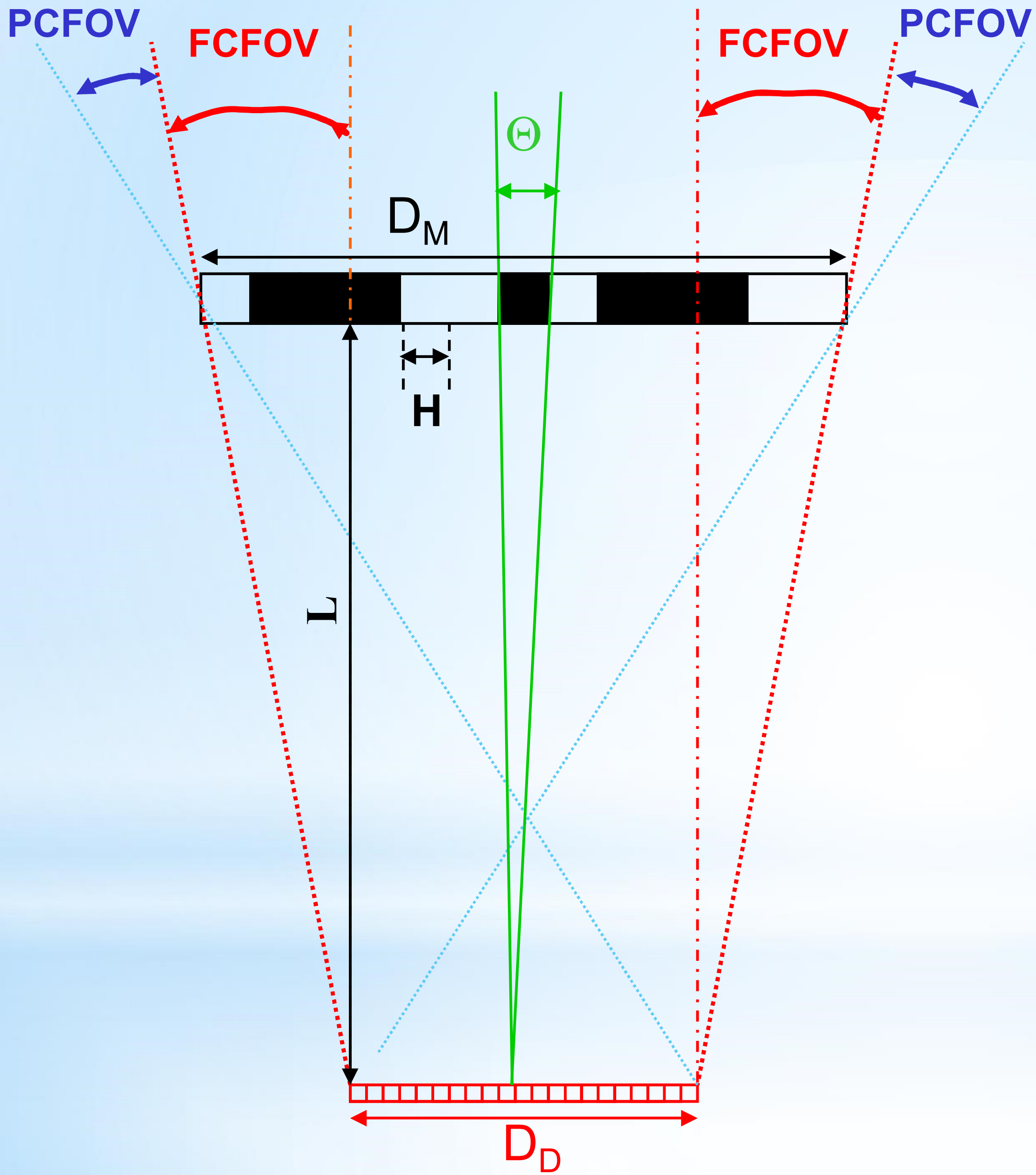
Coded Mask Imaging : Concept



Coded Mask Imaging : Concept



Coded Mask Imaging : Parameters



<u>Mask</u>

Opaque/transparent elements

Mask element size = H

Distance from detector = L

Mask dimension = D_M

<u>Position Sensitive Detector</u>

Dimension $D_D \leq$ mask dim D_M

Pixels size $\leq$ mask element size

<u>Two Fields of View</u>

Fully Coded (sens. ~ const.)

Θ_{FC} = arctg ((D_M - D_D) / L)

Partially Coded (decr. sens.)

Θ_{PC} = arctg ((D_M + D_D) / L)

<u>Angular Resolution</u>

Θ = arctg (H/L)

Coded Mask Imaging : Coding & Decoding

Source flux (S) is modulated by mask (M) before being recorded by a position sensitive detector, the resulting image (D) is, if B is background :

$$D = S * M + B$$

If it exists G such that $G * M = \delta$ (= delta function), reconstructed sky S' is

$$S' = D * G = S * M * G + B * G = S * \delta + B * G = S + B * G$$

S' = S apart from the background term $B * G$, a constant level if B uniform.

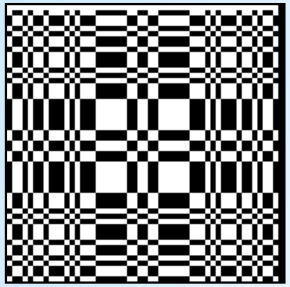
Such array G exists for Uniformly Redundant Arrays (URA), built using cyclic different sets, binary sets with a cyclic autocorrelation function = δ

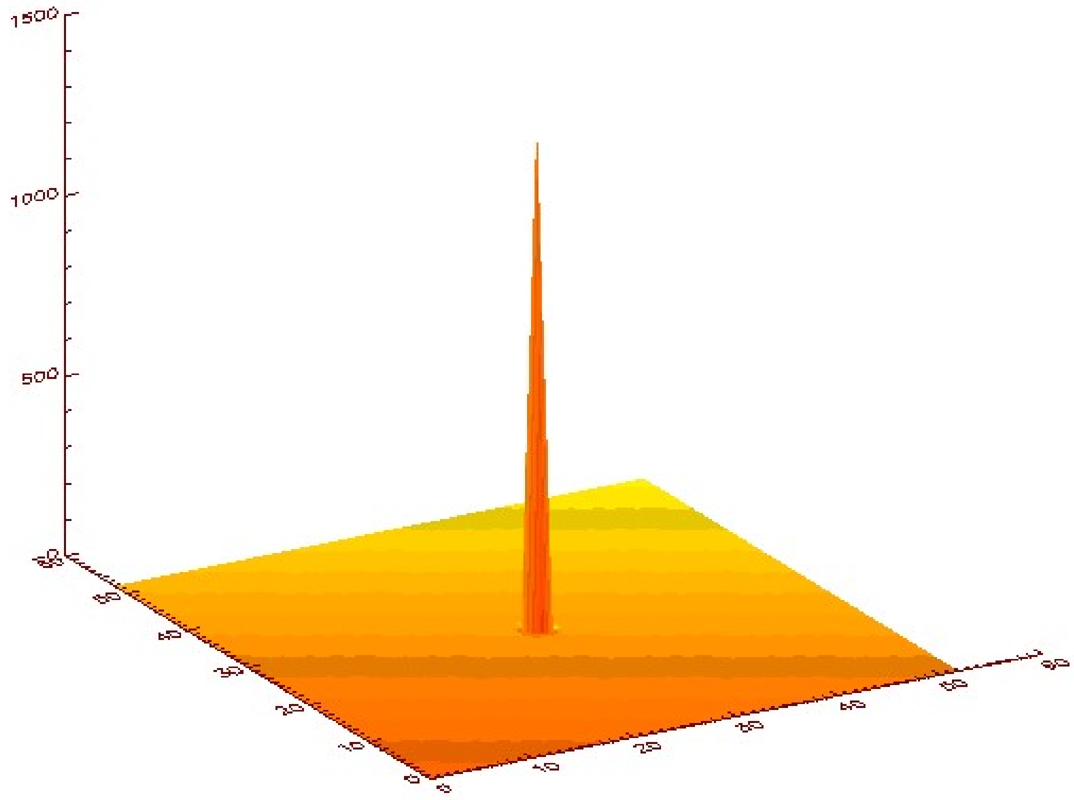
For URA $G = 2M - 1$ (-1 associated to opaque, +1 to transparent elem.).

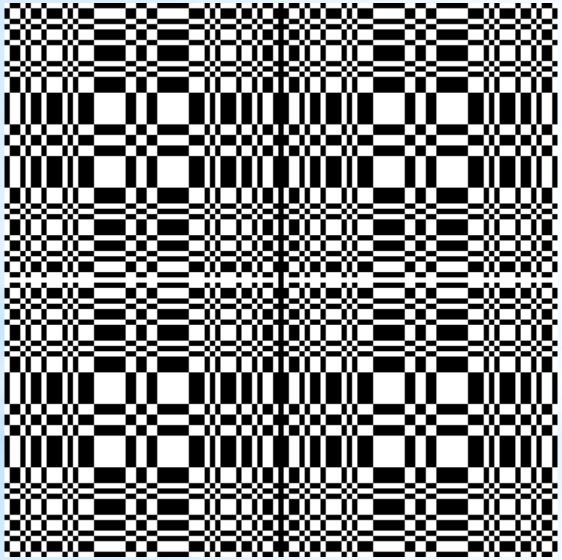
<u>Essential properties for γ-ray imaging</u> :

- Angular resolution increases by varying hole size or mask-detector distance without losing sensitive area (unlike collimators)
- Simultaneous measure of sources and background
- Projected source pattern is unique and provide flat side lobes response
- URAs have half open and half close elements : best S/N condition

Coded Mask Imaging : Optimum System







- A 53 x 53 MURA (Modified URA) Basic Pattern
- The Replicated (2 times - 1) Basic Pattern
- Their cross-correlation : a delta function,
  the Point Spread Function in the FCFOV

Coded Mask Imaging : Errors and Noise

Statistical errors

URA (as Hadamard or other optimum masks) provide best statistical error.
Assuming Poissonian statistics of detector count rates:

V(S') = Total number of detector counts C

Source signal to noise ratio (S/N) for a measured source intensity I_S is then

$$S / N = I_S / V^{1/2} = I_S / (C)^{1/2}$$

However any deviation from optimum system induce systematic errors.

Systematic errors

The worse are those which **depend on the background**.
Condition B = uniform over detector plane is usually not verified.
In this case the decoding procedure magnifies the variations.
=> need to correct the non-uniform background spatial distribution

Other source of systematic noise is the ***non perfect coding*** (side lobes in the PSF) due to non-perfect system (dead zones, geometrical effect, etc.).
Coding noise is proportional to source flux.

In the PCFOV, URA mask properties are not satisfied so there the PSF will have side lobes (8 main ghost peaks + distributed coding noise).

Coded Mask Imaging : Sampling

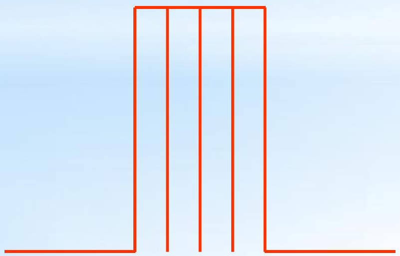
Unless the source is right in the middle of a sky pixels the reconstructed peak will be shared by different pixels and there is a loss of efficiency (we will call this imaging loss). You can perform a SPSF-fit (see below) to recover part of the peak height but a certain loss is inevitable.

To reduce this loss the detector must have spatial resolution better than the mask element size. Detector pixels (resolution) over-sample the mask elements (n x n). In this case the decoding can take the form of

Fine cross-correlation: G and S elements are also sampled in n x n pixels and the correlation run on all them

Delta-decoding : same but G=2M-1 in only1 pix out of the n x n, =0 elsewhere

4 x 4



Decoding Array G

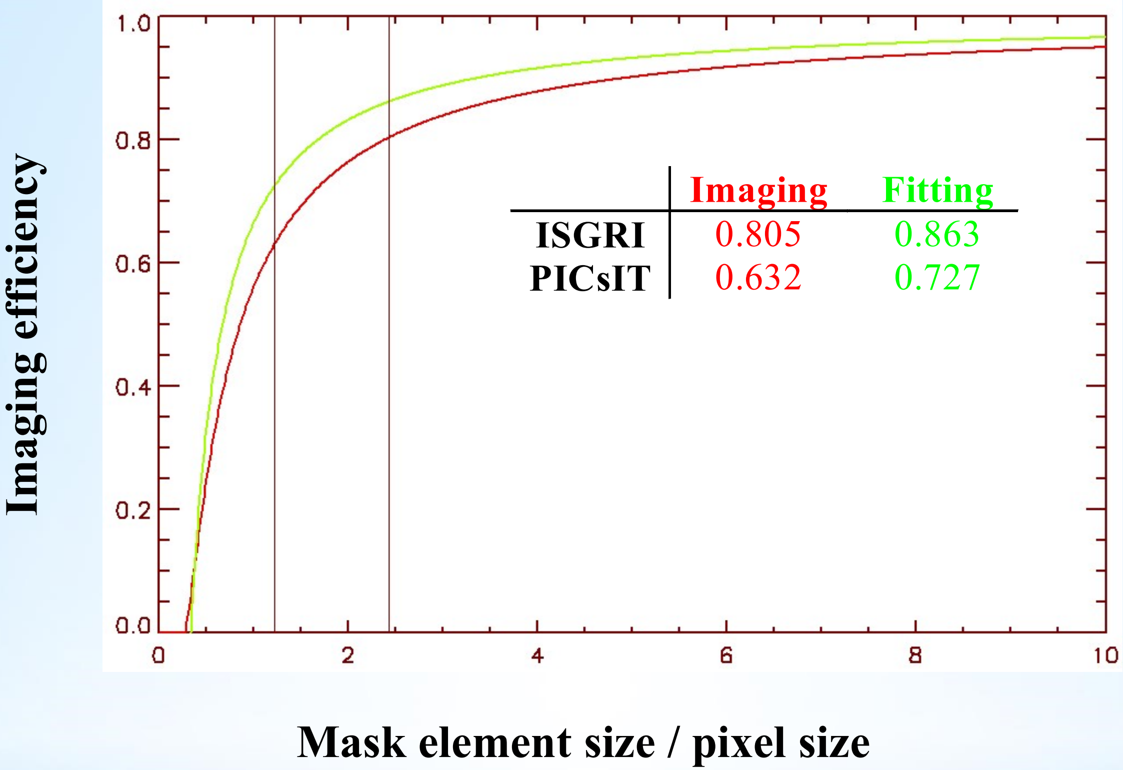
Fine C-C

-1	-1	-1	-1	1	1	1	1
-1	-1	-1	-1	1	1	1	1
-1	-1	-1	-1	1	1	1	1
-1	-1	-1	-1	1	1	1	1
1	1	1	1	-1	-1	-1	-1
1	1	1	1	-1	-1	-1	-1
1	1	1	1	-1	-1	-1	-1
1	1	1	1	-1	-1	-1	-1

Delta-Dec

0	0	0	0	0	0	0	0
0	-1	0	0	0	1	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	1	0	0	0	-1	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0

Coded Mask Imaging : Imaging Efficiency Loss

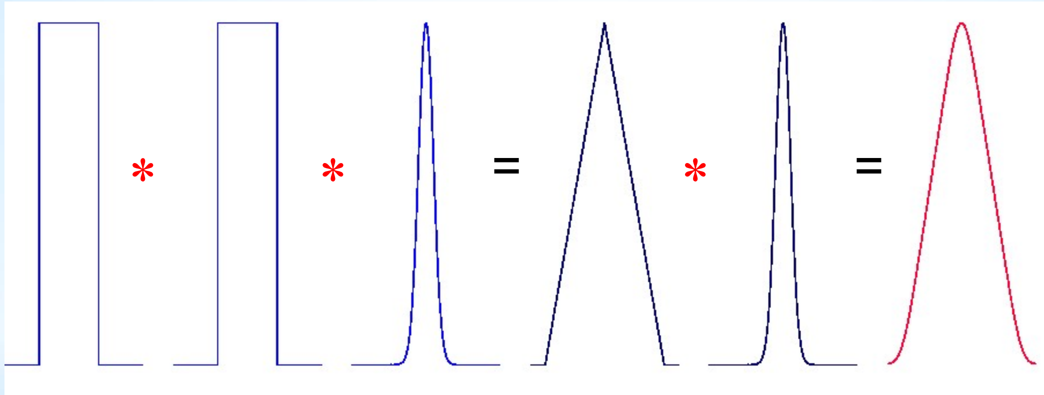


	Imaging	Fitting
ISGRI	0.805	0.863
PICsIT	0.632	0.727

Expected average values of imaging efficiency due to discrete binning as function of the ratio (r) between mask element – pixel sizes for simple fine cross-correlation and for SPSF fitting. Values expected for both IBIS detectors ISGRI (r=2.4) and PICSIT (r=1.2) pixel to mask element size ratios.

Coded Mask Imaging : the SPSF

The final System Point Spread Function (after decoding) of a optimum coded mask system is independent of position in FCFOV and given by the convolution of a block function (describing the peak of the delta function) with a function describing the kind of decoding applied and then with a function which describes the detector spatial resolution.
For example for fine cross-correlation decoding (4 pix per mask el.) and a Gaussian Detector-PSF with σ_d = 0.5 pix the SPSF looks like :



Chi-square fit of the analytical SPSF with a decoded image sector is then employed to obtain fine source location estimate and position error.

Point Source Location Error depends on source signal to noise (SNR) as

$$\mathrm{PSLE} \div 1 / \mathrm{SNR}$$

Coded Mask Imaging : Decoding in PCFOV

Discrete correlation to reconstruct sky image and variance in FCFOV is written using D_{kl}, M_{kl}, S_{ij}, $G_{kl} = 2\,M_{kl} - \mathbf{1}$, array elements as

$$S_{ij} = \sum D_{kl}\, G_{i+k,j+l}$$

$$V_{ij} = \sum D_{kl}\, (G_{i+k,j+l})^2$$

To extend decoding procedure in PCFOV we can use G^+ and G^- arrays defined as $G^+ = M$, $G^- = \mathbf{1} - M$, padded with 0 outside the mask :

$$S_{ij} = \sum W_{kl}\, D_{kl}\, G^+_{i+k,j+l} - b_{ij} \sum W_{kl}\, D_{kl}\, G^-_{i+k,j+l}$$

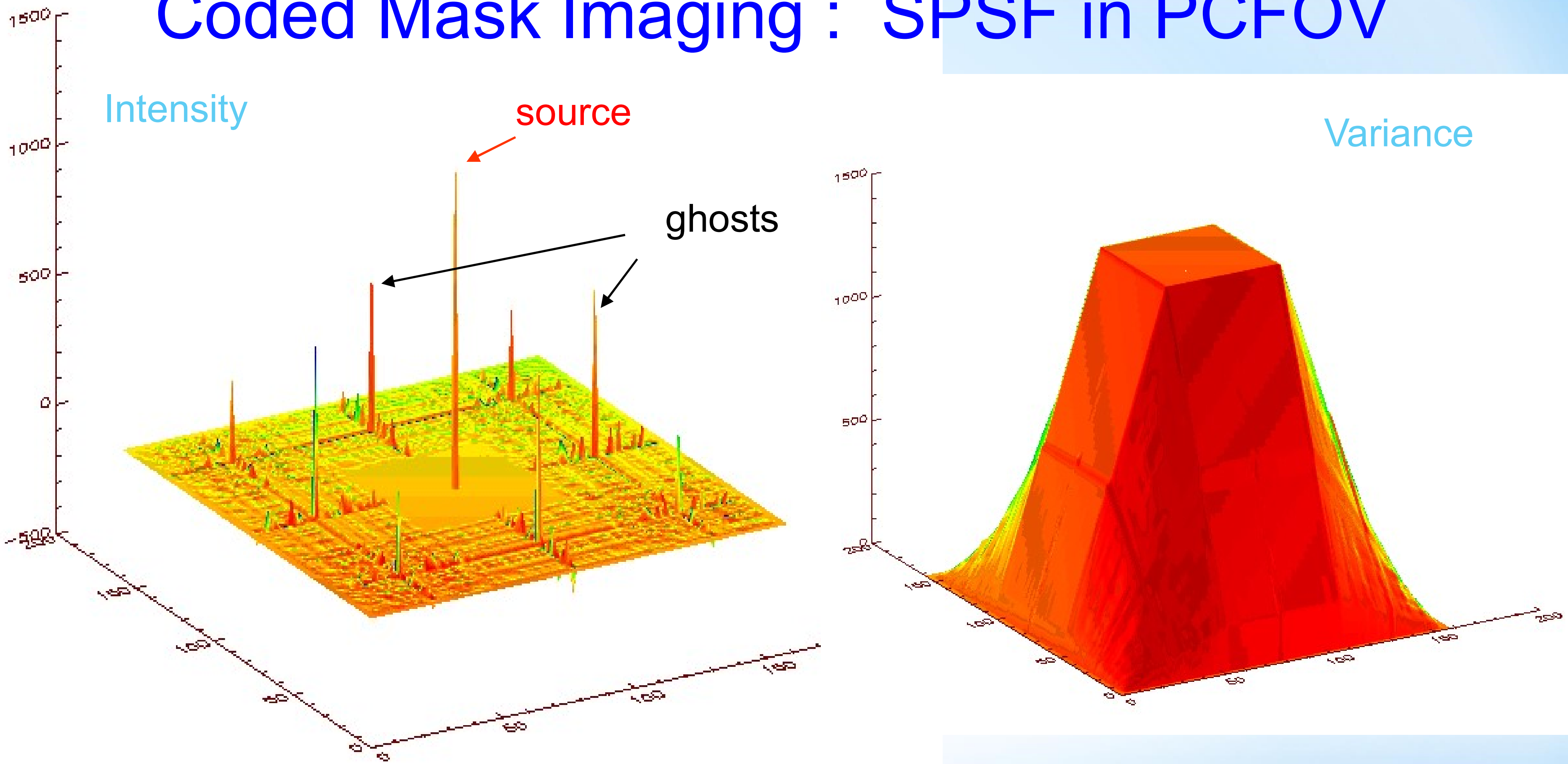
$$b_{ij} = \sum W_{kl}\, G^+_{i+k,j+l} \,/\, \sum W_{kl}\, G^-_{i+k,j+l}$$

$$V_{ij} = \sum D_{kl}\, (W_{kl}\, G^+_{i+k,j+l})^2 + b_{ij}^2 \sum D_{kl}\, (W_{kl}\, G^-_{i+k,j+l})^2$$

Details :

- Weighting array $W_{kl} \neq 1$ can be used to take into account some effects (attitude drifts, IBIS detector dimension > mask pattern, etc.)
- To take into account finite spatial resolution or not exact binning of mask elements (IBIS) G can assume values between +1 and -1
- These operations can be performed in fast way by a combination of array operations and Discrete Fourier Transforms (DFT).

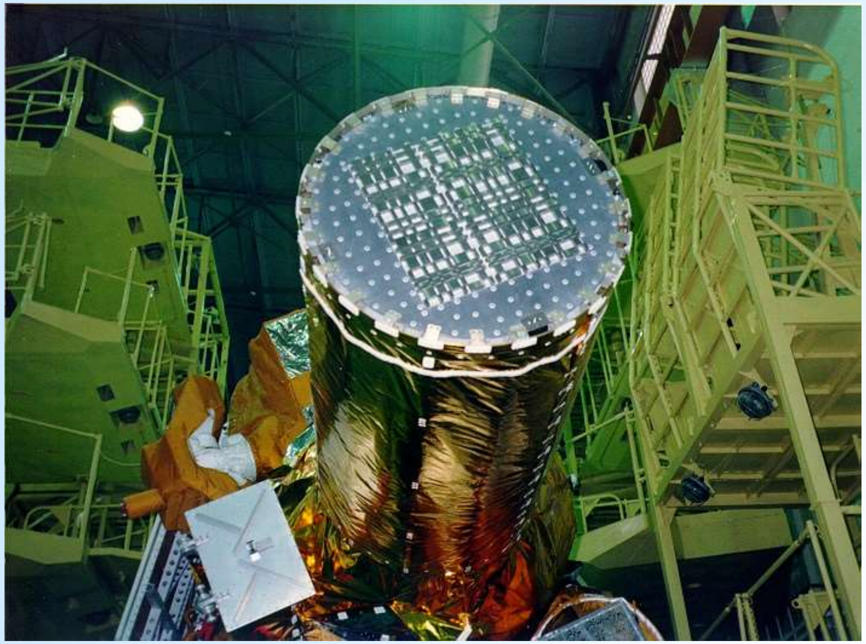
Coded Mask Imaging : SPSF in PCFOV



- Point Spread Function in FC + PC FOV for a 53 x 53 MURA Optimum System and an on-axis source :
  Delta Function in FCFOV + Coding noise in the PCFOV (8 ghosts + noise)
- Variance associated to the reconstructed sky image: constant over the FCFOV decreasing (increasing in relative value) in the PCFOV

PAST, PRESENT AND FUTURE CODED MASK MISSIONS

SIGMA (1989 – 1997)

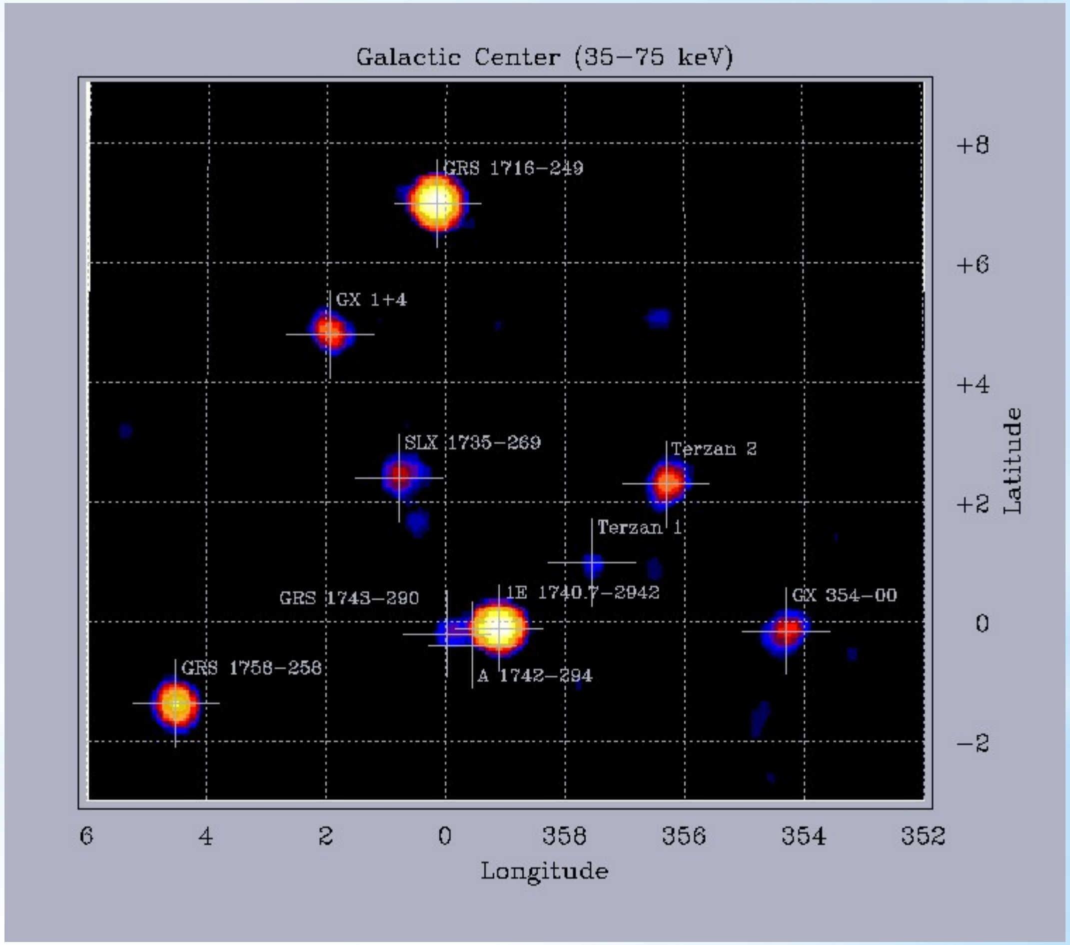


First gamma-ray space telescope with coded mask (URA)

- Anger gamma-camera

  (35 keV – 1,3 MeV)
- ΔE/E (FWHM): ~ 15%
- Sensitivity: 30 milliCrab
- FOV: 4.3° x 4.7°
- Angular resolution: 20'

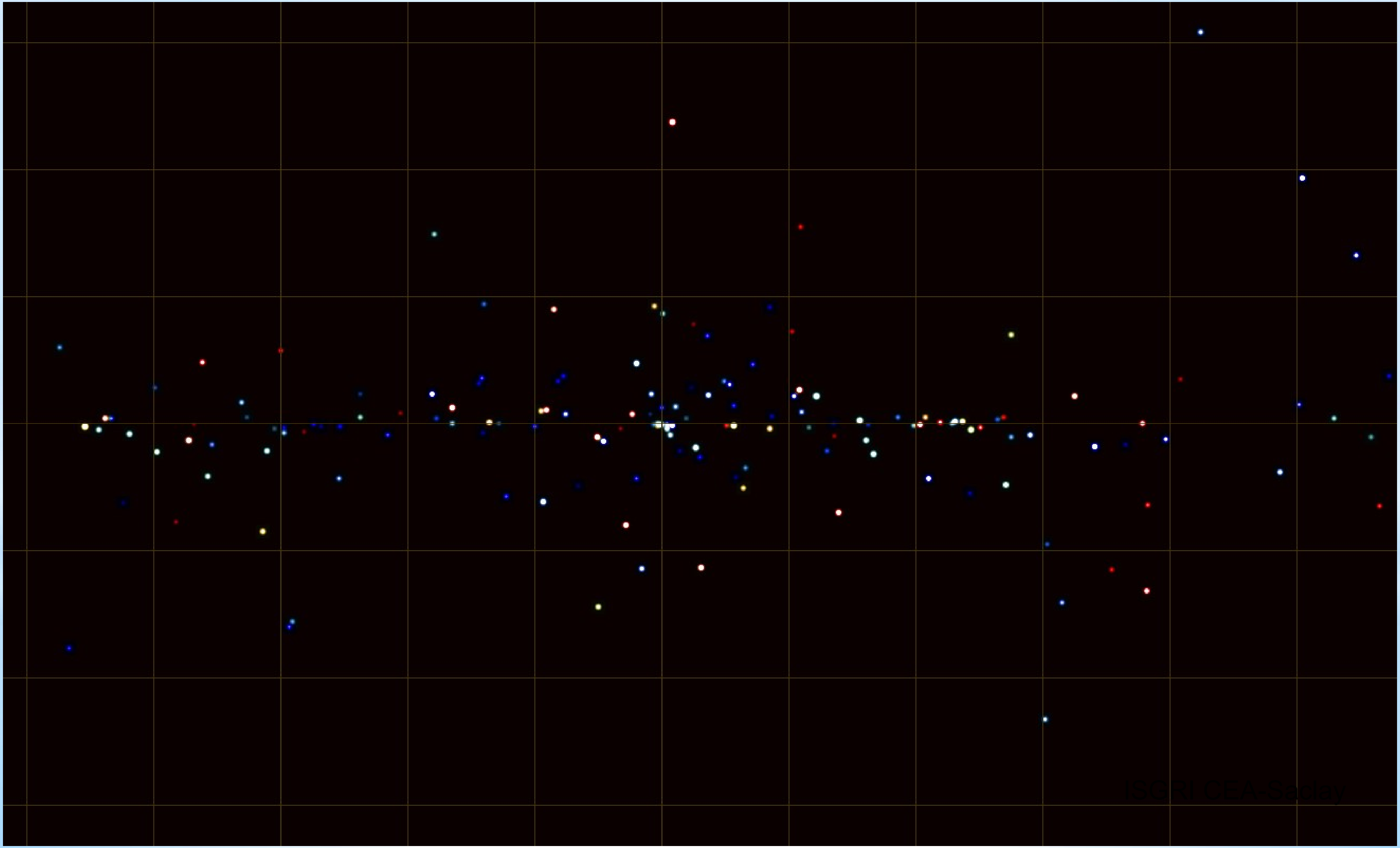
Galactic Centre observations



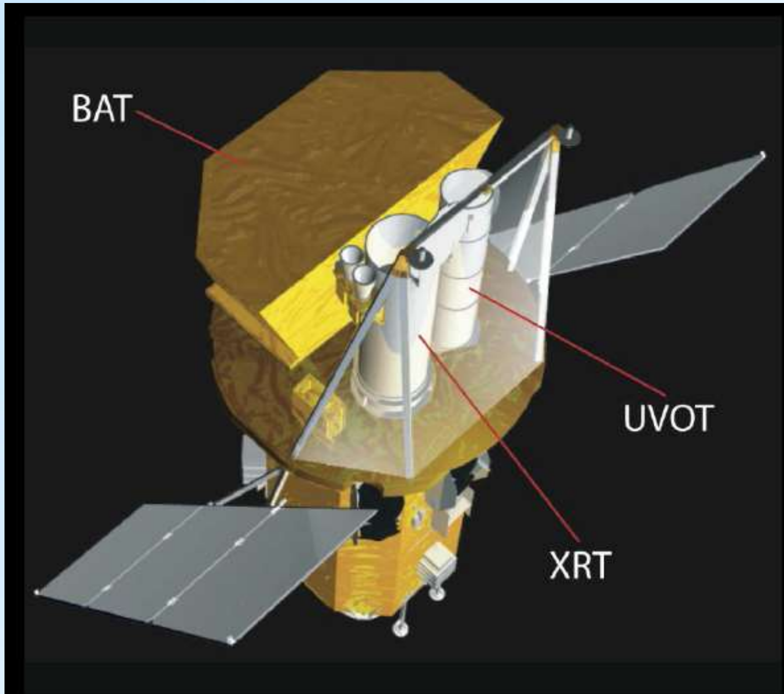
The INTEGRAL mission

- ESA M2 mission
- ESA-RKA-NASA collaboration
- Instruments:
  - IBIS: Italy-France (coded mask)
  - SPI: France-Germany (coded mask)
  - JEM-X: Denmark (coded mask)
  - OMC: Spain (optical)
  - ISDC: Switzerland (data centre)
- Launch : October 2002, from Baïkonour space center
- Observatory mission with annual call for observations

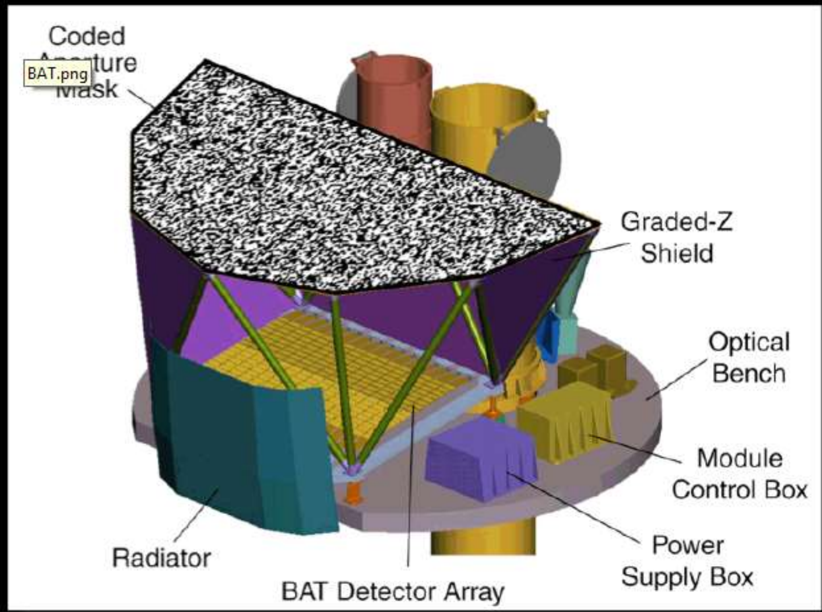
The Galactic centre as seen by INTEGRAL/IBIS (20 – 60 keV)



The Swift/BAT telescope



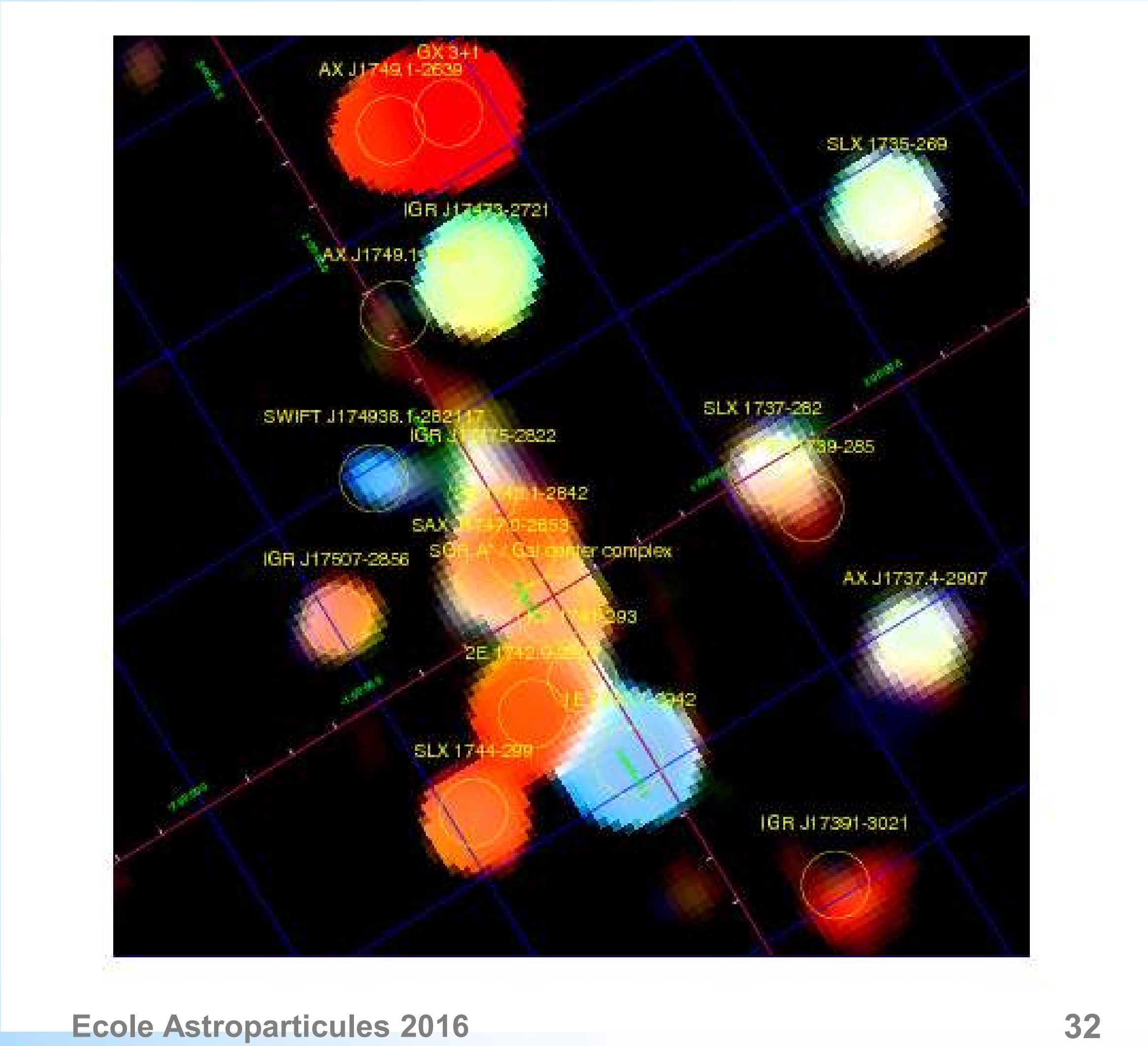
14-195 keV energy range
FOV: 1.94 sr (> 10% coding)
Location resolution ~1.5 arcmin
Detector area: 5200 cm^2
Similar to IBIS – but Swift observing plan leads to more uniform sky coverage



Launched on 2004, october 20th

Krimm, BAT Monitor & Survey

The Galactic centre as seen by SWIFT/BAT (14 – 150 keV)



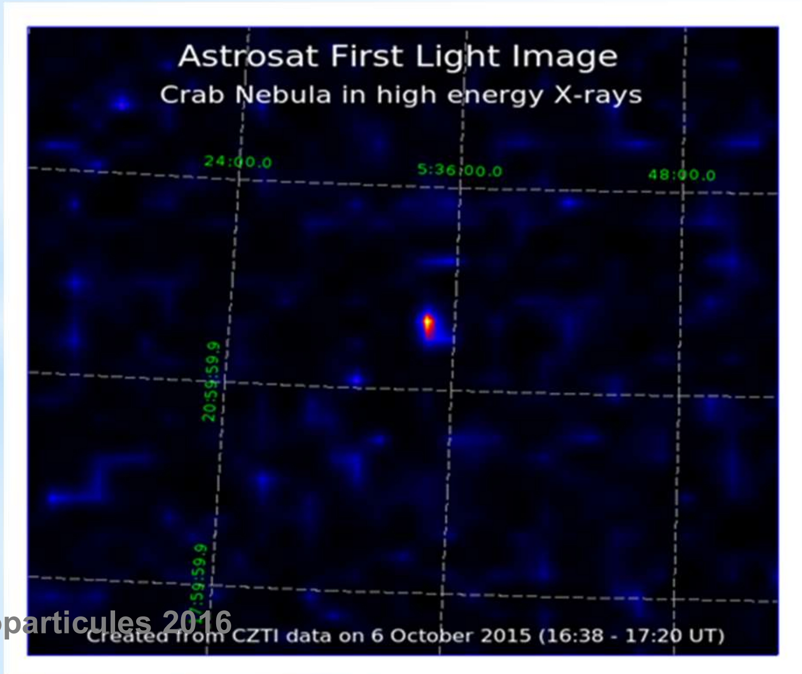
Red : 14 – 24 keV
Green : 24 – 50 keV
Blue : 50 – 150 keV

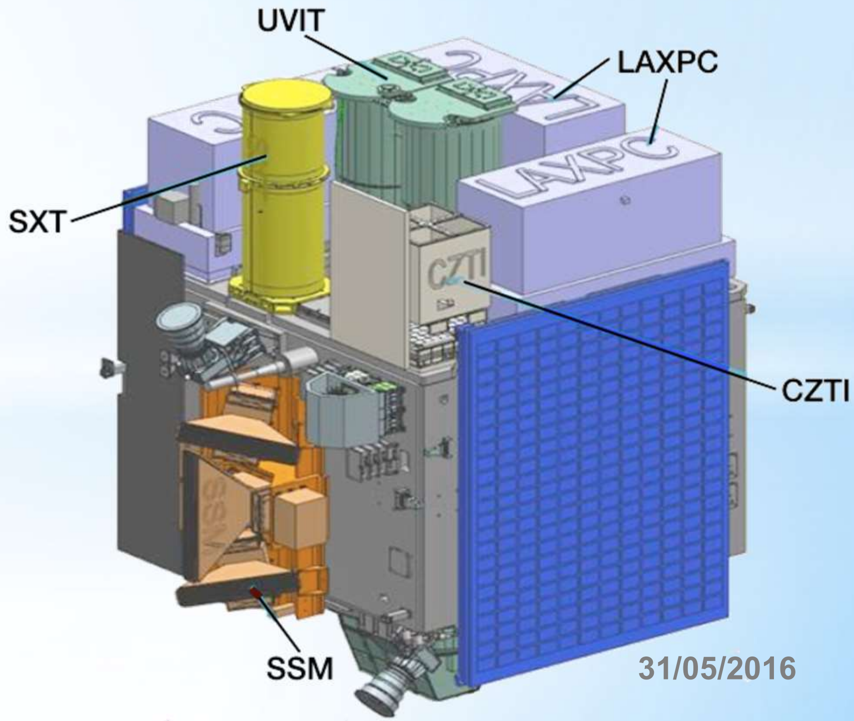
The PSF of BAT in this mosaicked map is 19.5 arcminutes.

The ASTROSAT/CZTI telescope

ASTROSAT is a multi-wavelength astronomy mission on an IRS-class satellite in a 650 km, near-equatorial orbit. It was launched by the Indian launch vehicle PSLV from Satish Dhawan Space Centre, Sriharikota on **September 28, 2015**. The expected operating life time of the satellite will be more than five years.

There is five instruments on board ASTROSAT. The Cadmium-Zinc-Telluride coded-mask imager (CZTI) is covering hard X-rays from 10 to 150 keV, with about 6 deg field of view and 480 cm^2 effective area.

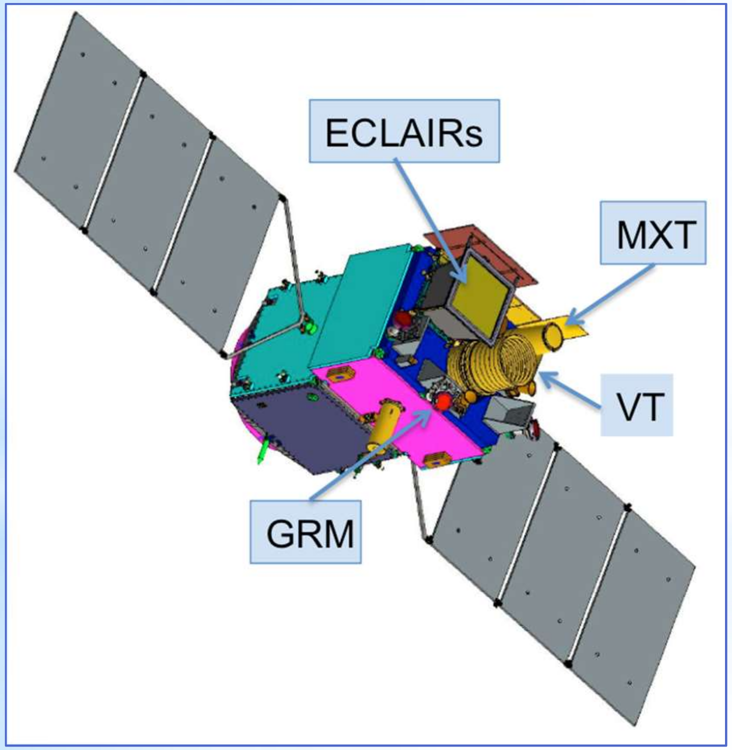




The SVOM/ECLAIRs telescope

SVOM is a French – Chinese mission to be launched in 2021.

ECLAIRs is a wide field of view (~2 sr) coded mask telescope encircled by a graded shield collimator to reduce the cosmic diffuse induced background. It has a useful area 1024 cm^2 and will observe the sky in the 4.0 to 250 keV energy band.



ECLAIRs