collimators, coded masks and all sky monitors

P. Laurent

CEA/DRF/IRFU/SAp

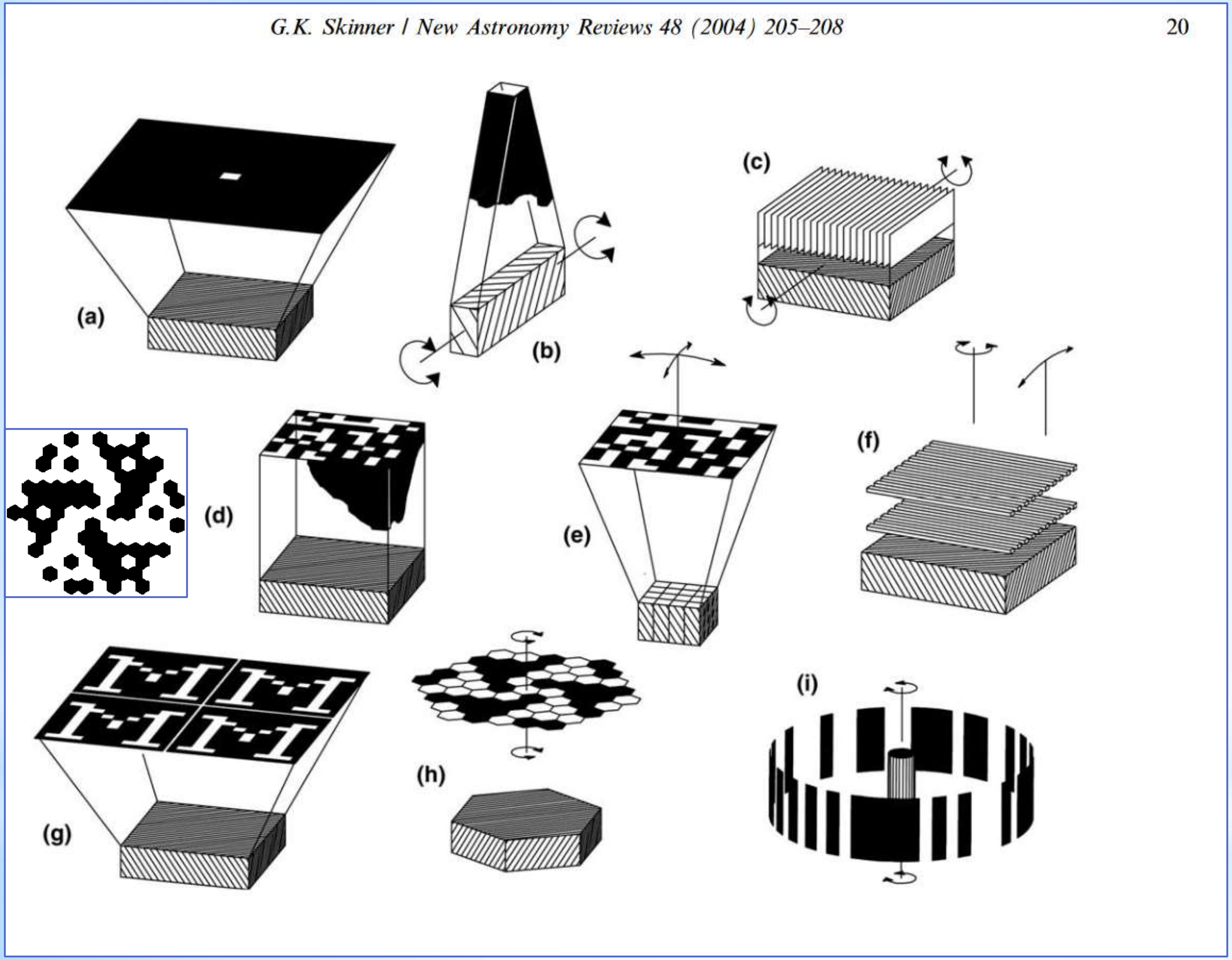
(with the help of F. Lebrun and A. Goldwurm)

Content

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

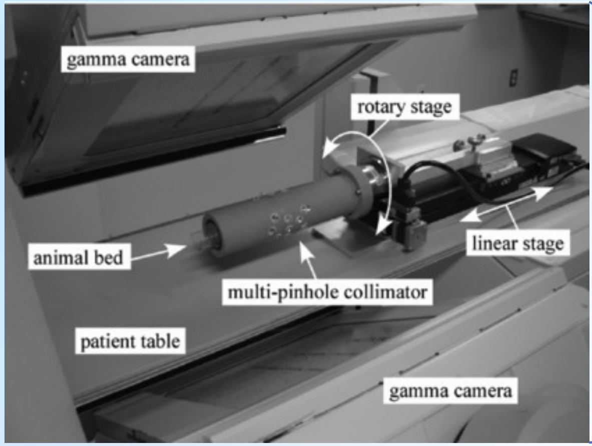
*PART 2

Many types of coded masks …



(a) pinhole camera,
(b) one-dimensional scanning pinhole camera (Ariel 5 ASM),
(c) collimated detector (OSSE),
(d) coded mask camera (Sigma, IBIS)
(e) coded mask with dithering (SPI)
(f) rotation-modulated collimator (RHESSI),
(g) cyclic coded mask (SL2 XRT),
(h) cyclic rotating coded mask (GRIP),
(i) cyclic temporal coding (TGRS).

Coded masks in “every day life”

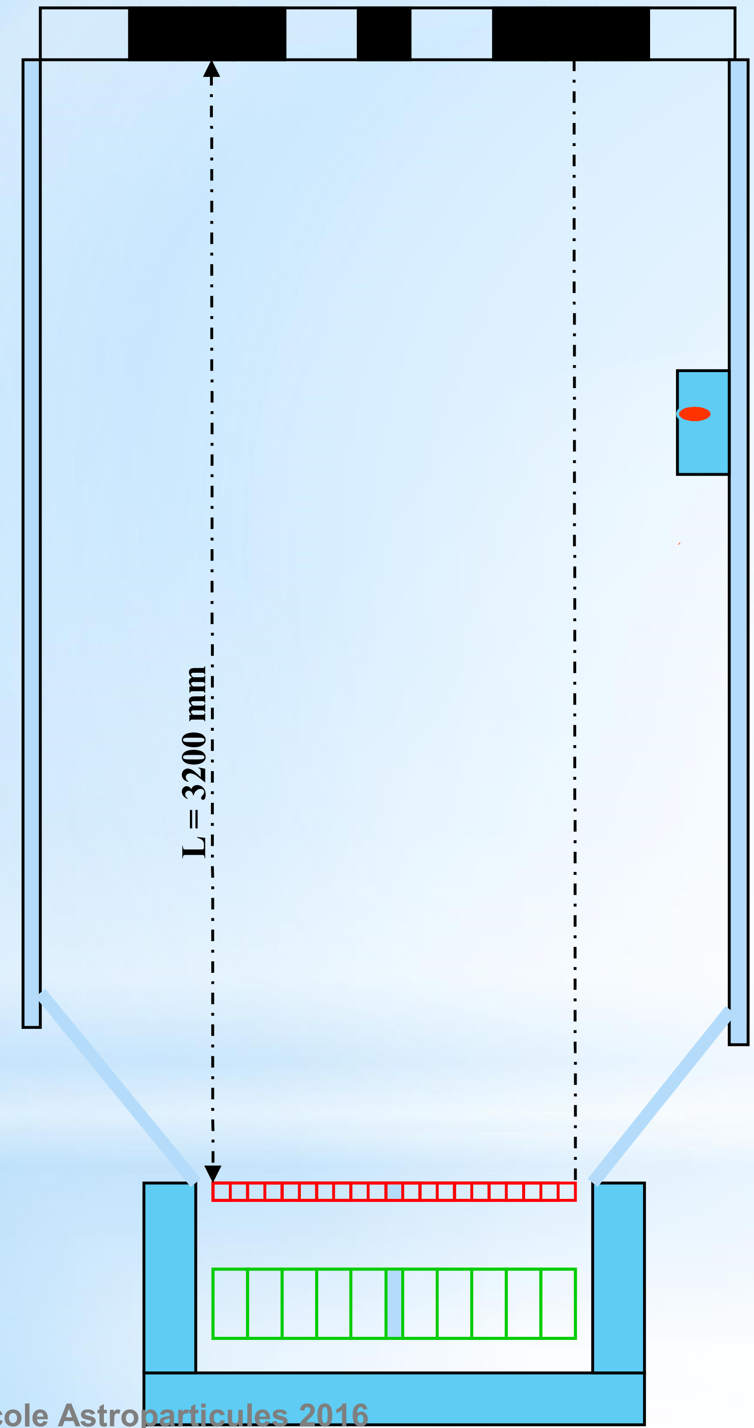


Homeland security

Pet SCAN

*INTEGRAL/IBIS DATA ANALYSIS

The Coded Mask IBIS Telescope



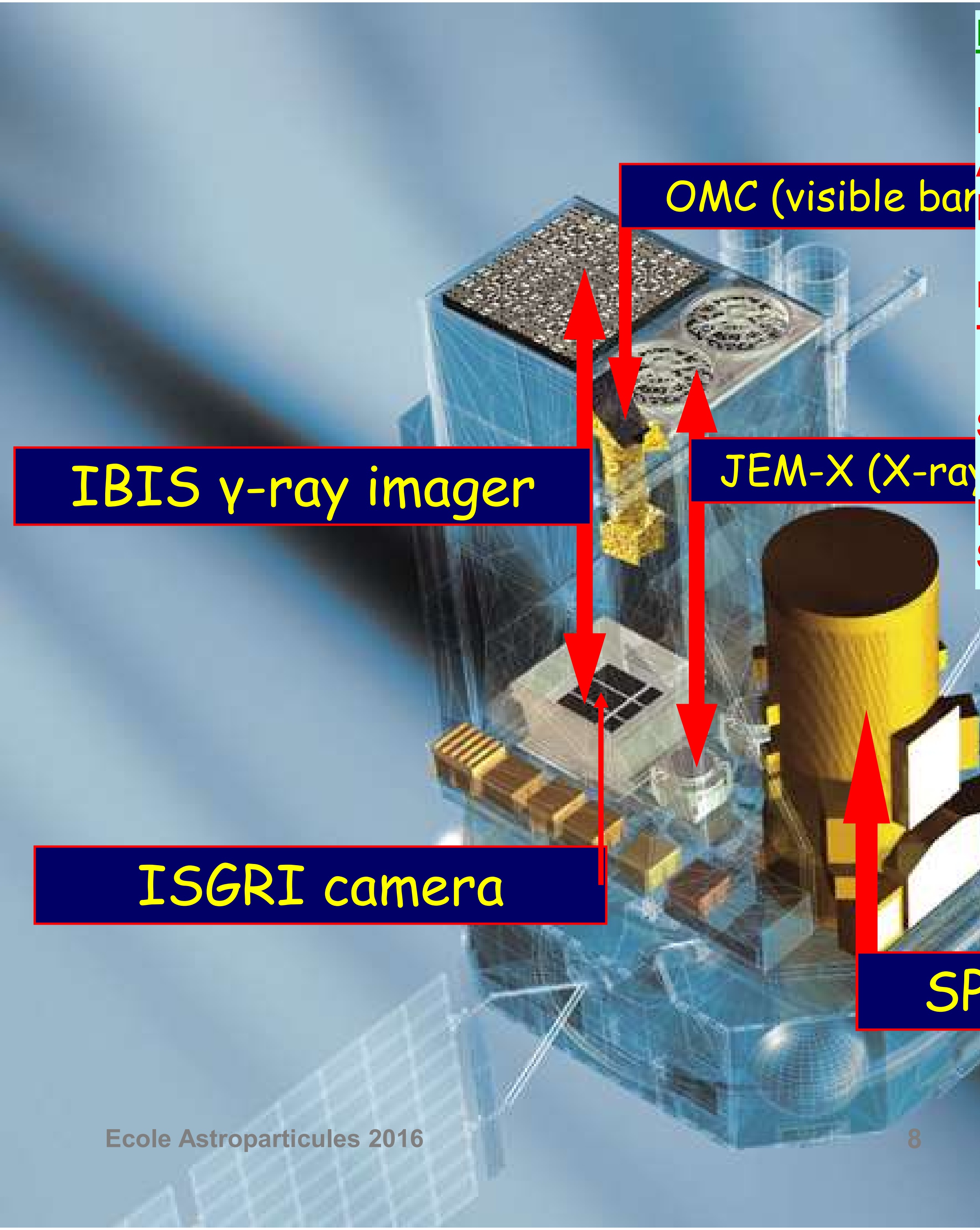
Mask :
53 x 53 MURA basic pattern,
95 x 95 W elem. of size 11.2 x 11.2 mm^2
at a distance L = 3.2 m from the detector

Positional Detectors :
ISGRI : 128 x 128 pix
PICsIT : 64 x 64 pix bars
Some dead-zones, off pixels

Shielding system, Veto and CU :
Passive (tube, hopper)
Veto Unit : 16 BGO mod
Calibration Unit : ^{22}Na Source

Imaging properties :

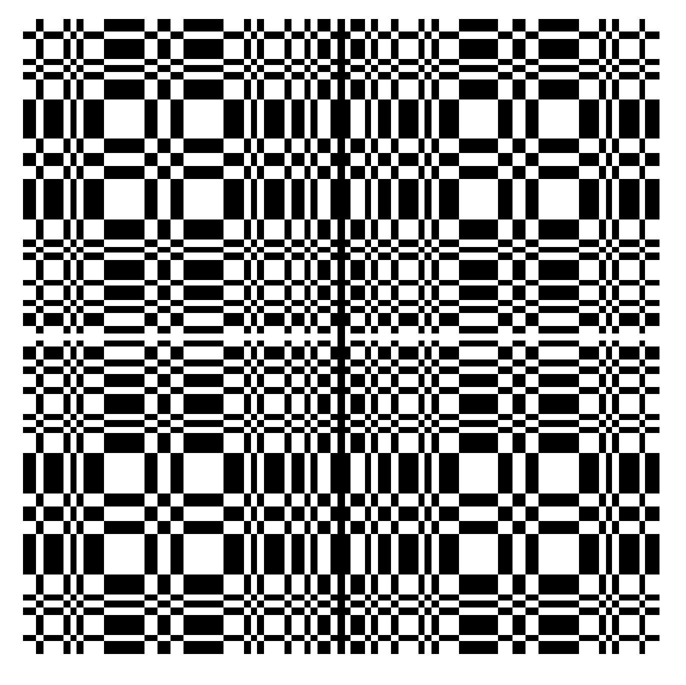
FCFOV	9° x 9°
FC+PCFOV	29° x 29°
Angular Resolution	12’
ISGRI/PICsIT pixels	5’ / 10’



IBIS / ISGRI Performances

Energy Band		20 keV-1 MeV
Angular Resolution		12’
FOV	at 100% s.	9° x 9°
	at 0 sensitivity	29° x 29°
Point Source Location Err.		30” (S/N~30)
Temporal resolution		60 μs
		100 keV
Sensitivity (ph cm^{-2} s^{-1} keV^{-1})		4 10^{-7}
(for 10^6 s, 3σ, ΔE=E)		1 mCrab
Narrow line sens. (cm^{-2} s^{-1})		10^{-5}
Spectral resolution		8 keV

IBIS Mask, Veto and Calibration Unit



MASK
MURA basic pattern 53 x 53
Total number of W el. 95 x 95
El. Dimension = 11.2 x 11.2 mm^2
El. Thickness = 16 mm
Transparency: 60% @ 20 keV
82% @ 60 keV

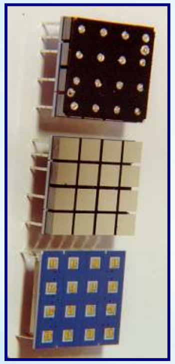
Veto system
Anticoincidence system around the 2 detector layers, made of 16 BGO modules viewed by 32 PMT

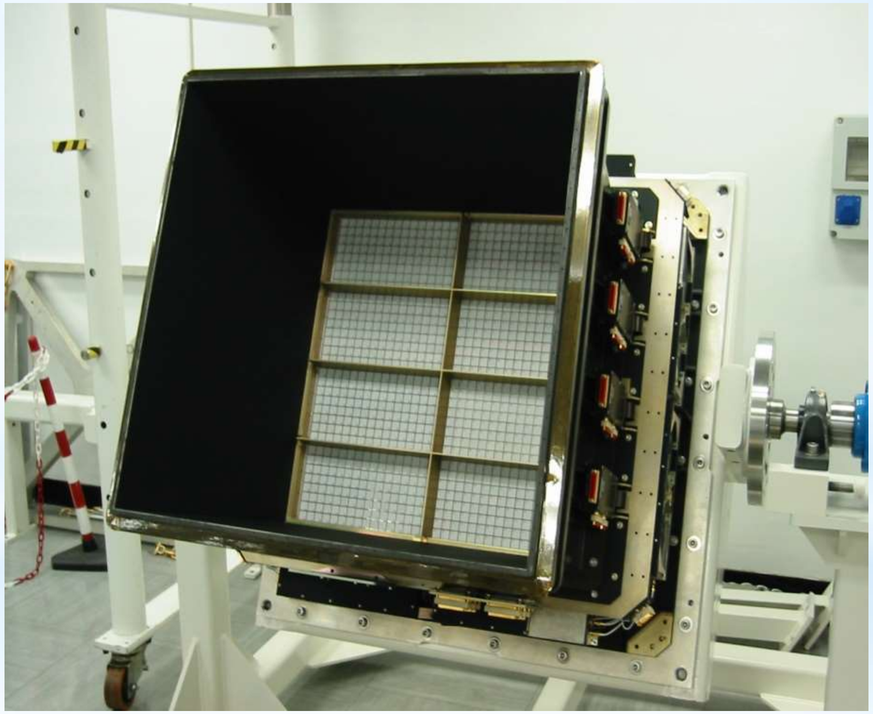
Calibration Unit
A source of ^{22}Na which emits two 511 keV photons in opposite directions is placed on the passive shield tube.
It is viewed by a BGO+PMT module which detects one of the 511 keV photons. CU tagged events are used to measure 1% gain variations in PICSIT pixels on time scales of few hours

ISGRI : The Soft Gamma-Ray Imager

New-generation gamma-camera of Cadmium Telluride (CdTe), semiconductor with high Z (48-52) working at room temperature.

128 x 128 = 16384 pixels (4 x 4 mm^2, 2 mm thick) in 8 modules
Energy range : 20 - 1000 keV
Spatial resolution : 4.6 mm (separation of pixel centers)





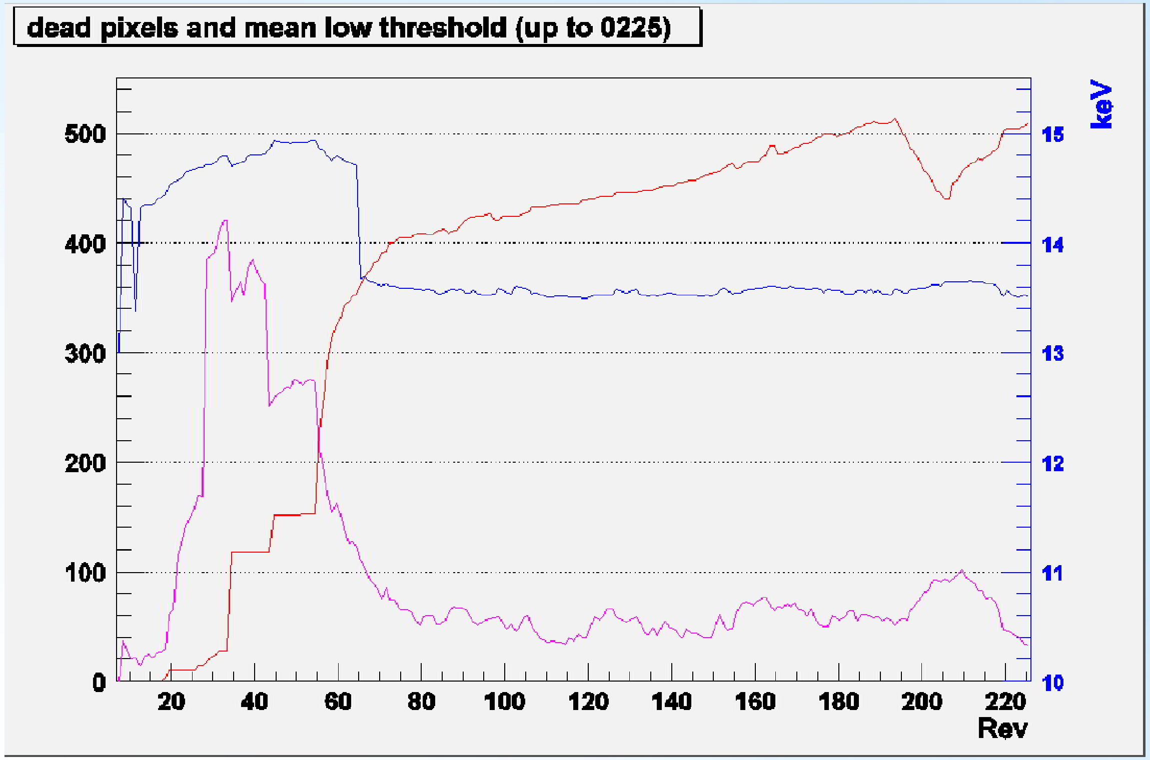
The ISGRI Noisy pixels

The ISGRI CdTe pixels are not all stable.

In spite of strong selection during manufacturing about 5% of them suffer from intrinsic noise.

An on-board s/w detects and switches OFF noisy pixels, then periodically resets them ON.
The very bad ones are set off in the Context (worked out each revolution)
Pixels low-energy thresholds are changed first to make them stable.

Monitoring of the instrument parameters (HK rate-meters) will provide GTI, status of pixels and dead-times



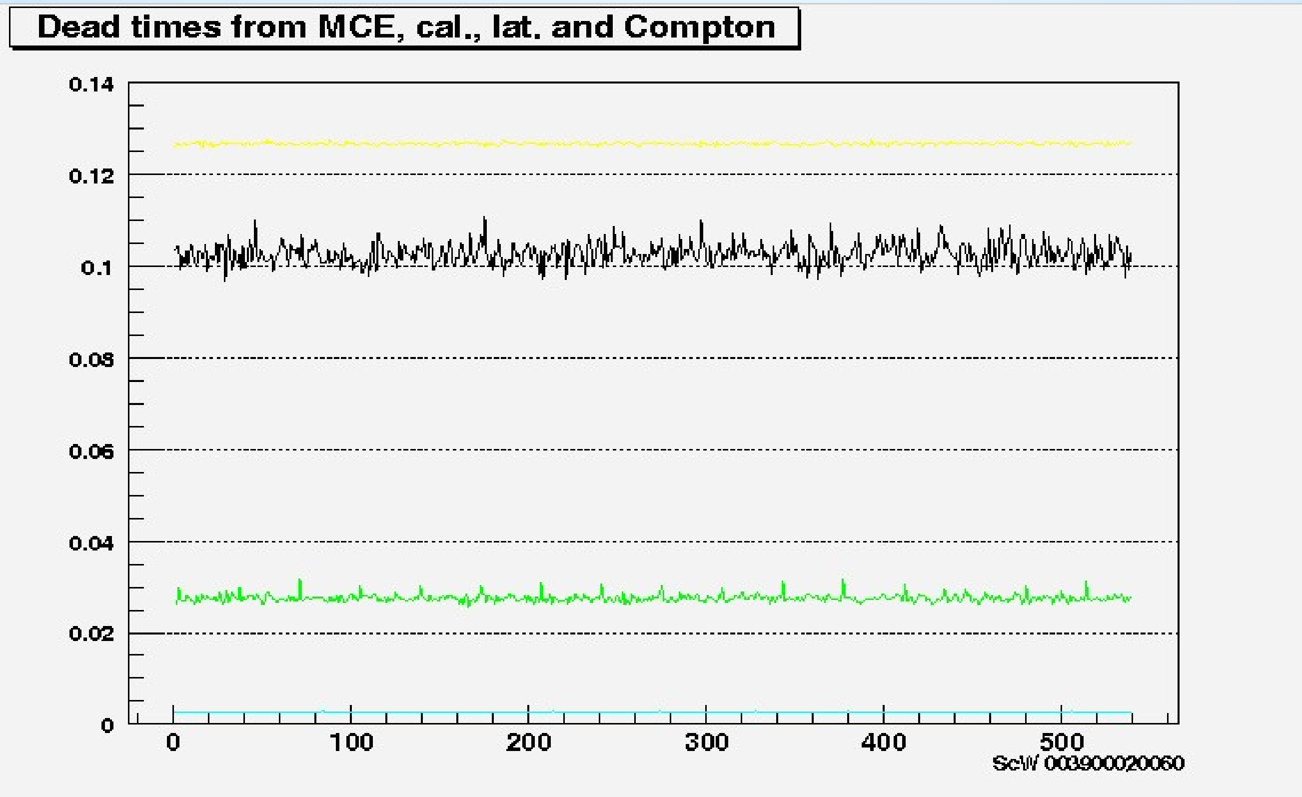
ISGRI dead-pixels and threshold evolution

ISGRI dead pixels

ISGRI average low-en threshold

ISGRI max low-en threshold

Computation of ISGRI dead times



ISGRI deadtimes due to different effects

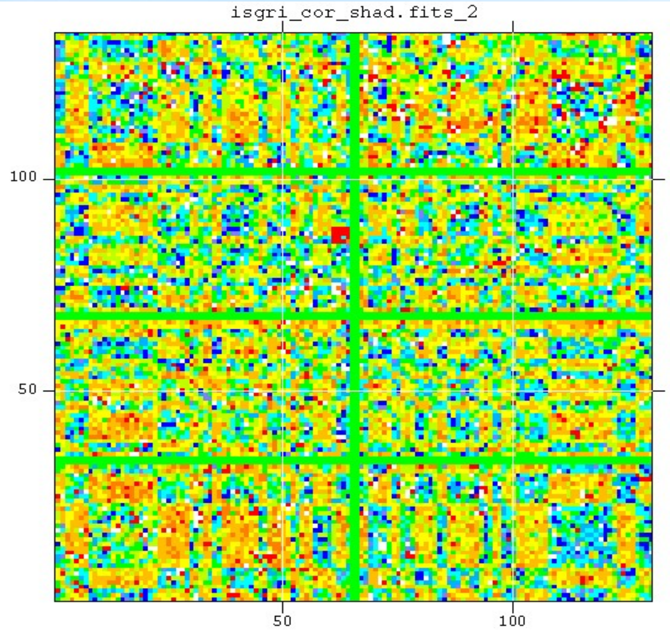
____ ISGRI deadtime

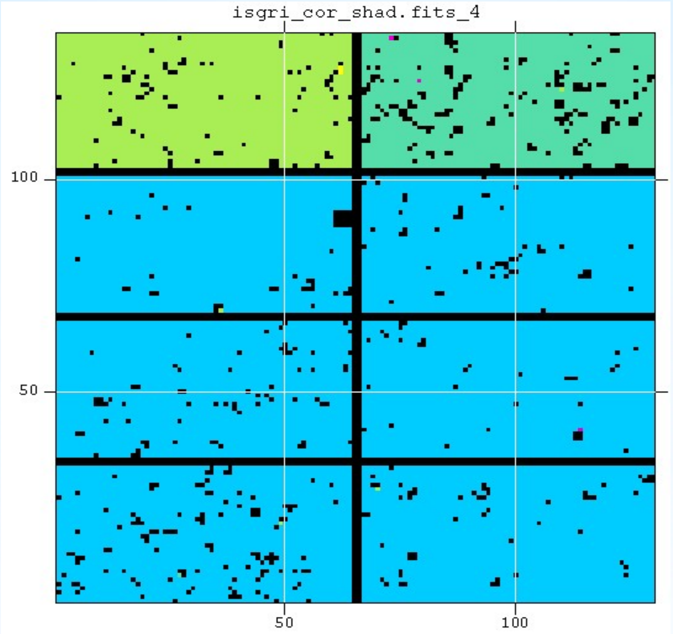
___ Random-coincidence Veto DT

____ Random coincidence CU

___ Random-coincidence Compton DT

Shadow Build – Uniformity Correction





- Event binning in images 128 x 128 pix
- Efficiency images
- Enlarging images (dead z.) 130 x 134 pix
- Correction with Det-Unif.

& Background maps

$$\mathbf{D' = (D/E - bB) / U}$$

$$\mathbf{b = \langle D/E\rangle / \langle B\rangle}$$

User GTI

Rise time bands

Energy bands

ISGRI Contexts (pixels off, low-energy thresholds)

Dead-Times (per each module)

GTIs per module

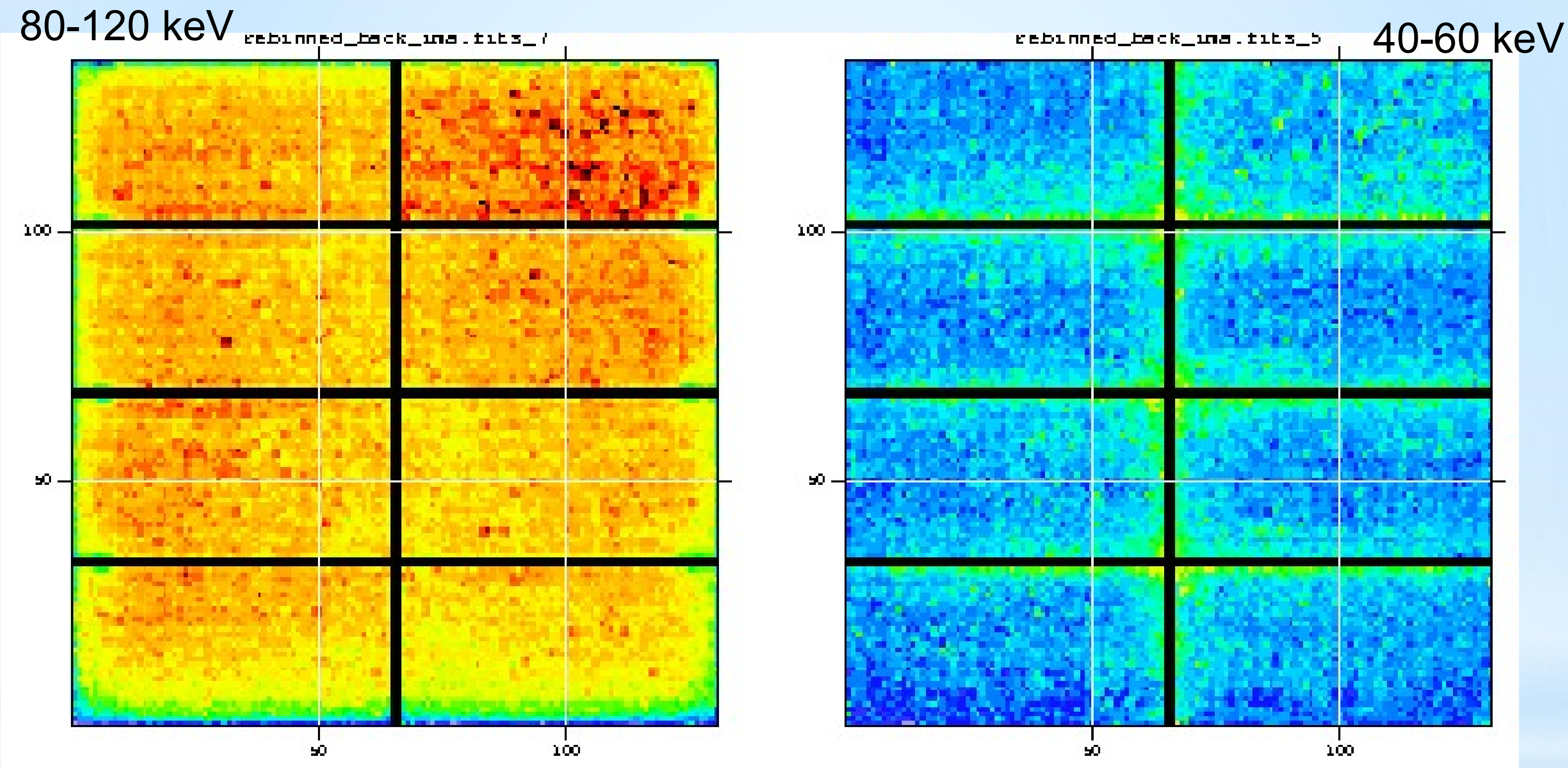
Maps of “variable” pixels off (HK3)

Background maps

Uniformity maps

Binning to energy bands

Background Correction Maps

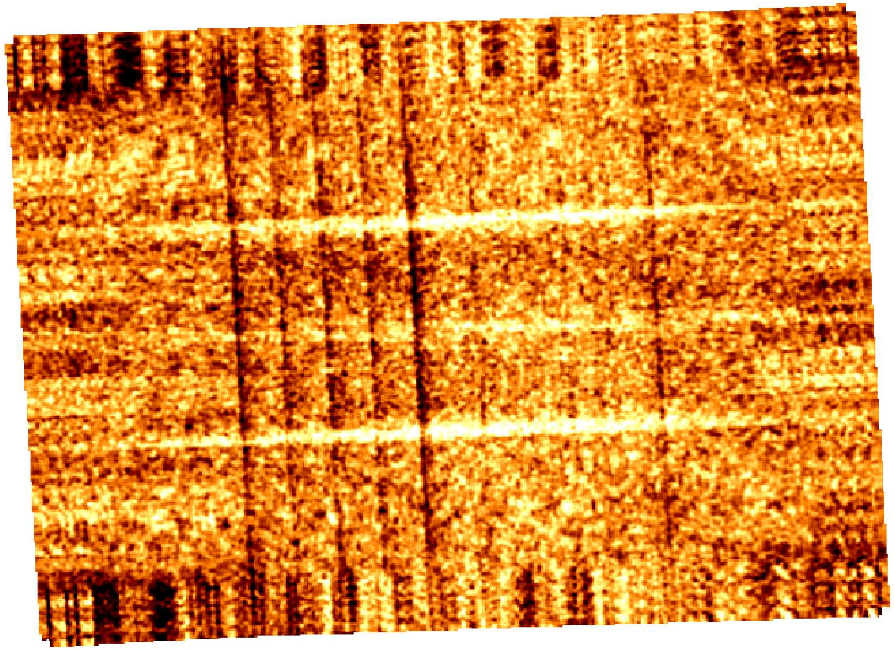


Background images are built from large sample of empty field or high latitude pointing observations. Images are corrected for efficiency.

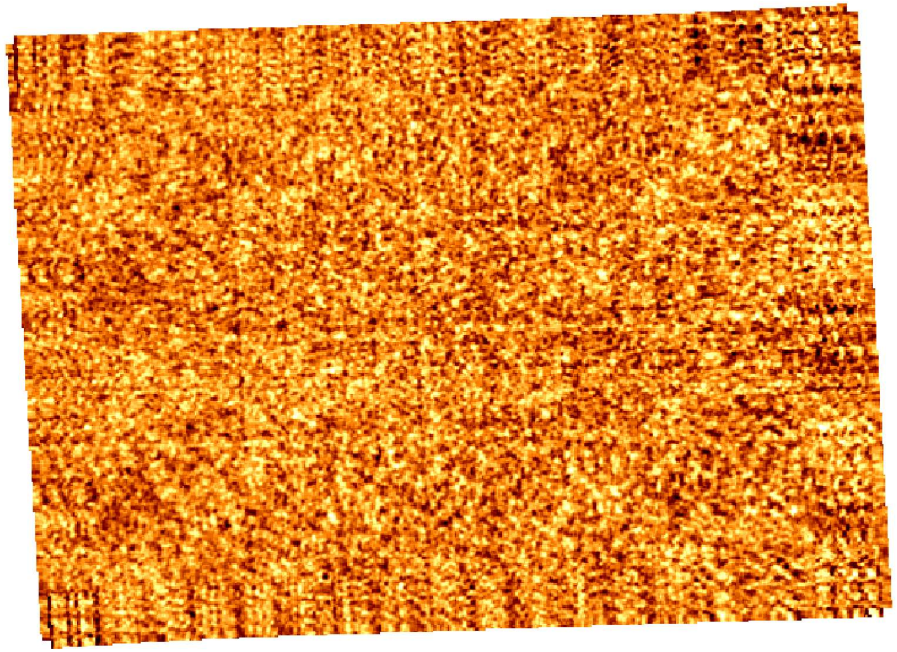
256 BKG correction shadowgrams (130 x134) for 256 energy channels.

Effect of Background Correction (100-200 keV)

un-corrected



corrected

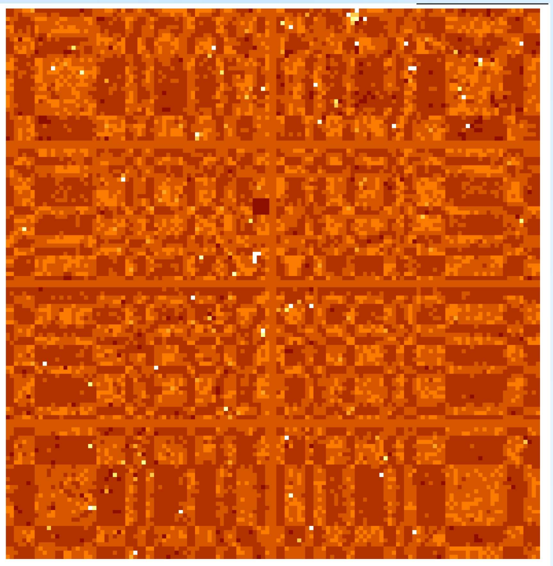


Mosaic of Galactic Center sky images before and after ubc correction

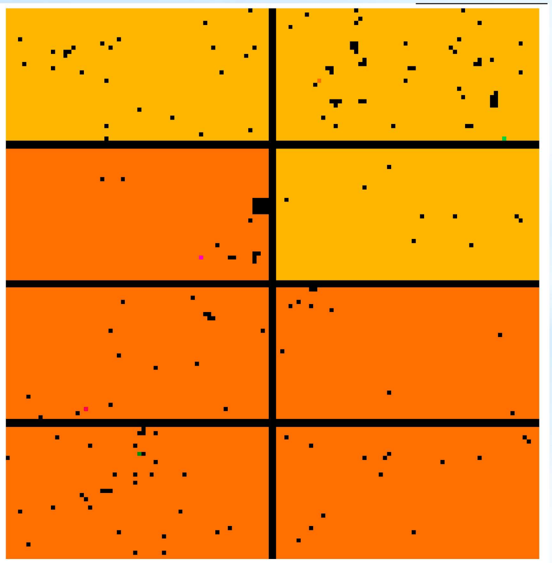
Some residual bkg noise present because correction maps are not perfect

One way to “measure” the “residual” bkg structures is to determine the ratio of the variance in the image to the computed variance (or look at the distribution)

Sky-Image reconstruction : input & decoding arrays

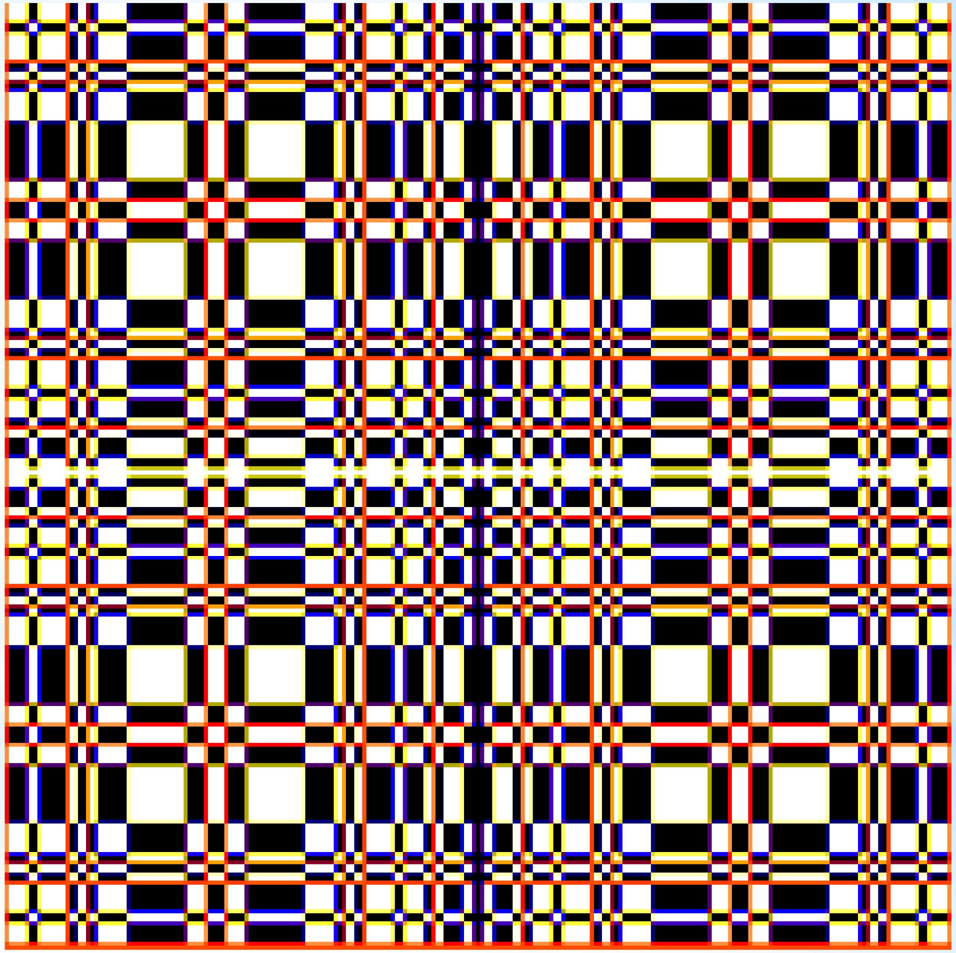


D



W

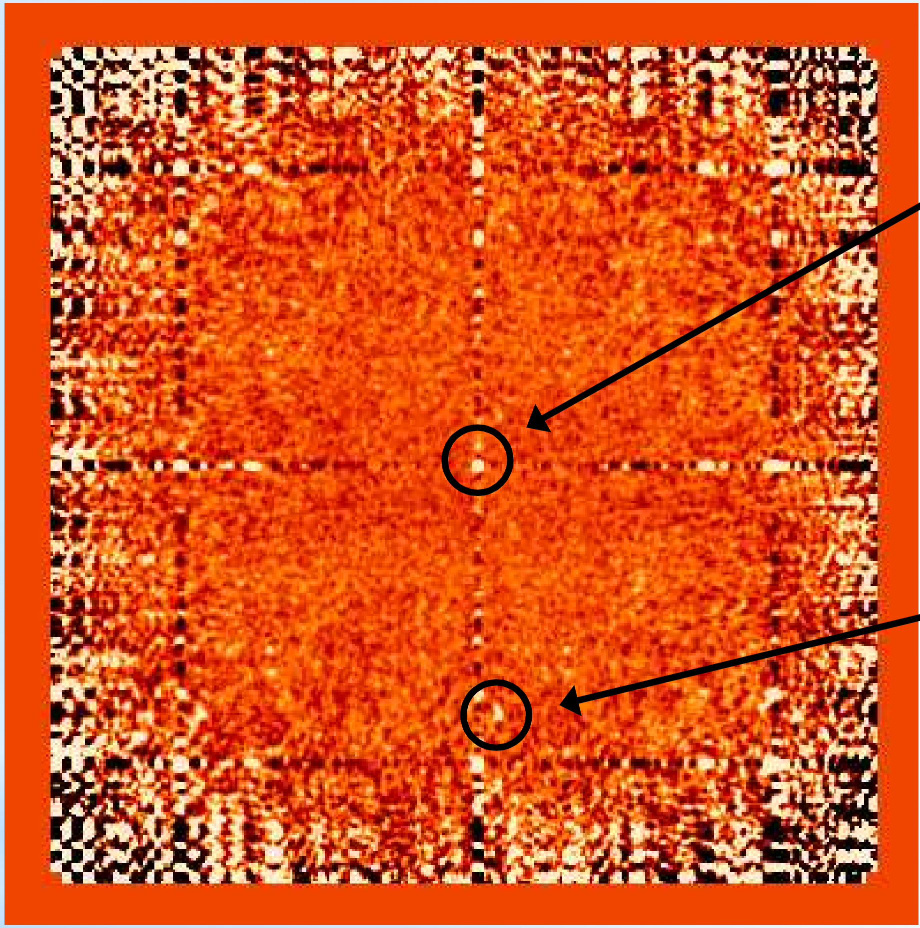
- Decoding array obtained from the projection of the mask on the detector pixel grid (G between -1. and +1.) => a kind of "DPSF convolved" balance fine cross-correlation



G

Sky-Image reconstruction : iterative procedure

Decoding: 400 x 400 pix sky maps



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

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

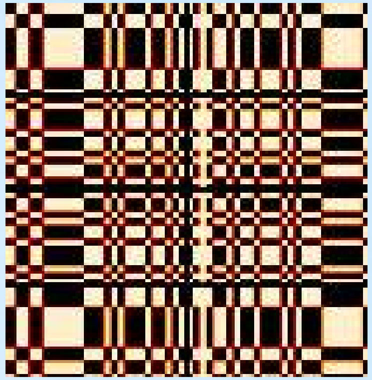
$$V_{ij} = \sum D_{kl} (W_{kl} G^{+}_{i+k,j+l})^2 + b_{ij}^2 \sum D_{kl} (W_{kl} G^{-}_{i+k,j+l})^2$$

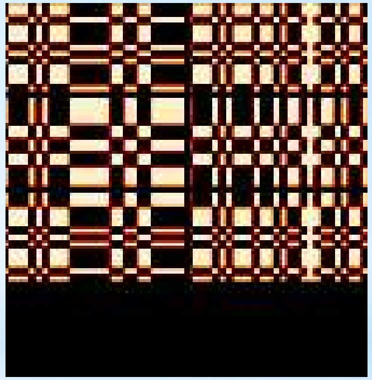
Source Detection

Excess 1
Position (SPSF fit)
Identification
→ Modelling

Excess 2
Position (SPSF fit)
Identification
→ Modelling

Source Modelling

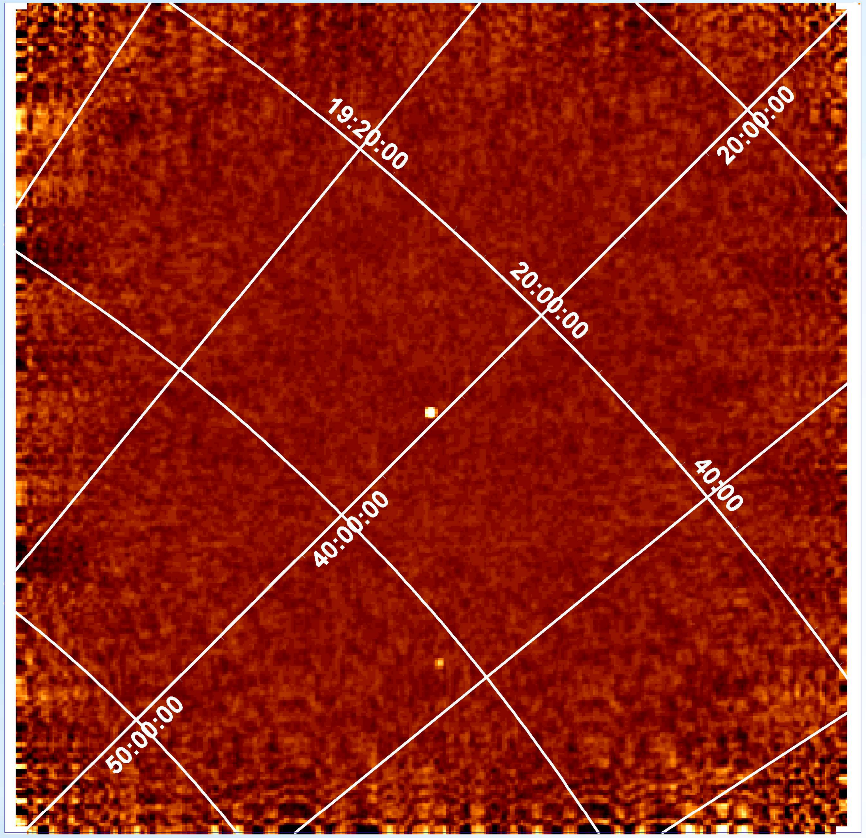


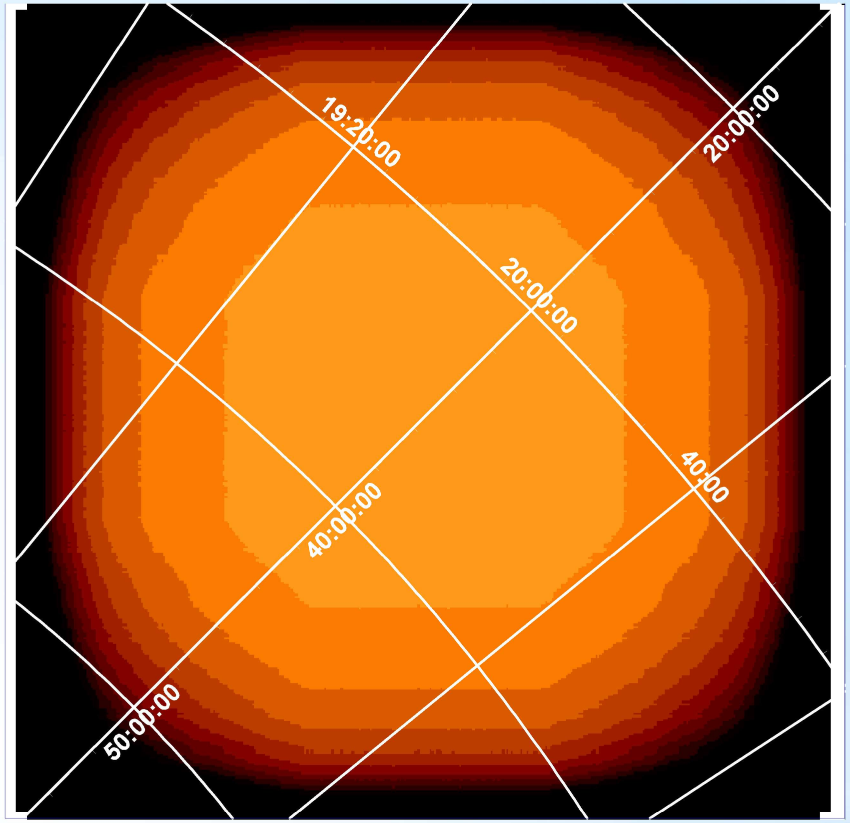


Ghosts Cleaning

Source models are decoded, normalized and subtracted from the sky image

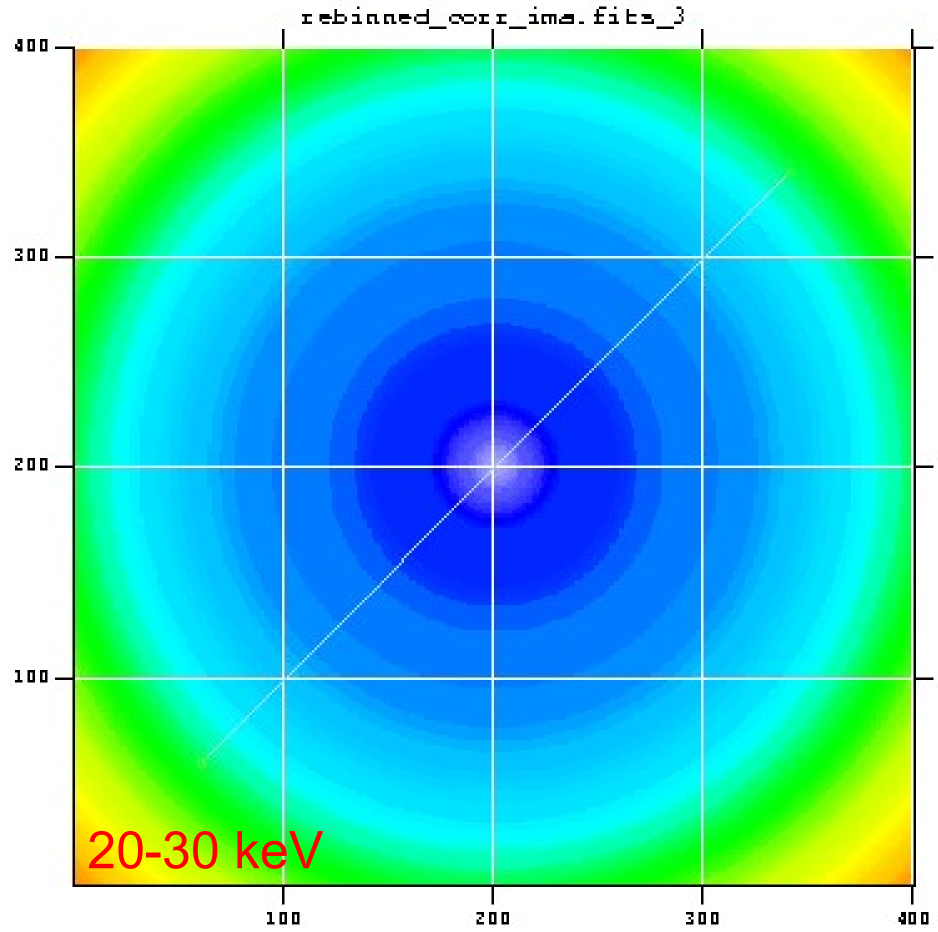
ScW Reconstructed Sky-Images

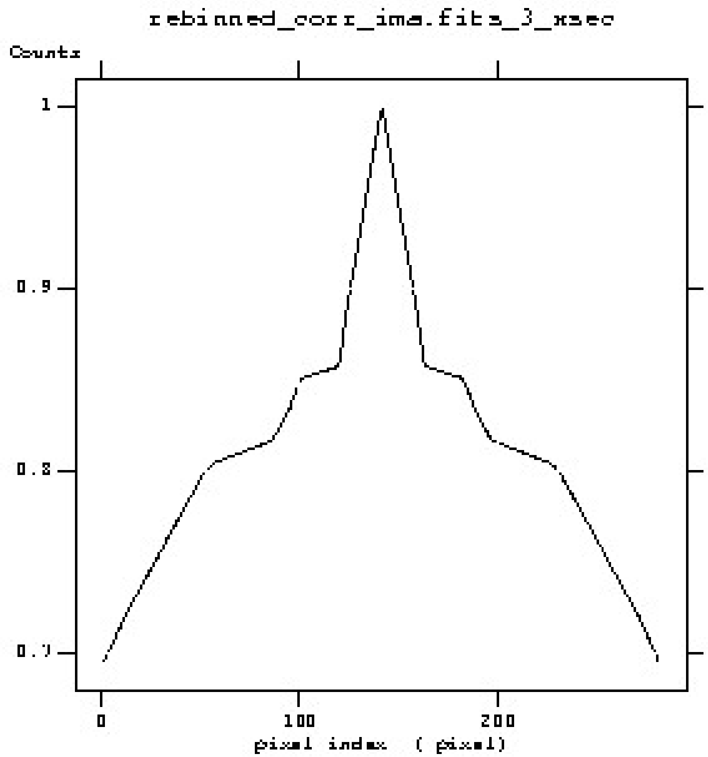




- Reconstructed images (400 x 400 pix of size ~ 5' x 5') are in intensity (I) units (cts/s) renormalized to FCFOV corrected for "off-axis" effects, with variance (V) and SNR = I / SQRT(V) images (+ Effective exposure and/or ghost residual images)
- Parameters of "analyzed" sources are reported in output : fine position, model-flux
- Flux is given by the intensity at the source pixel (**not the integral of the peak!**)
- New excess must be well above 3 sigma to be really significant : rather ~ 5-6 sigma

Off-Axis Correction Maps

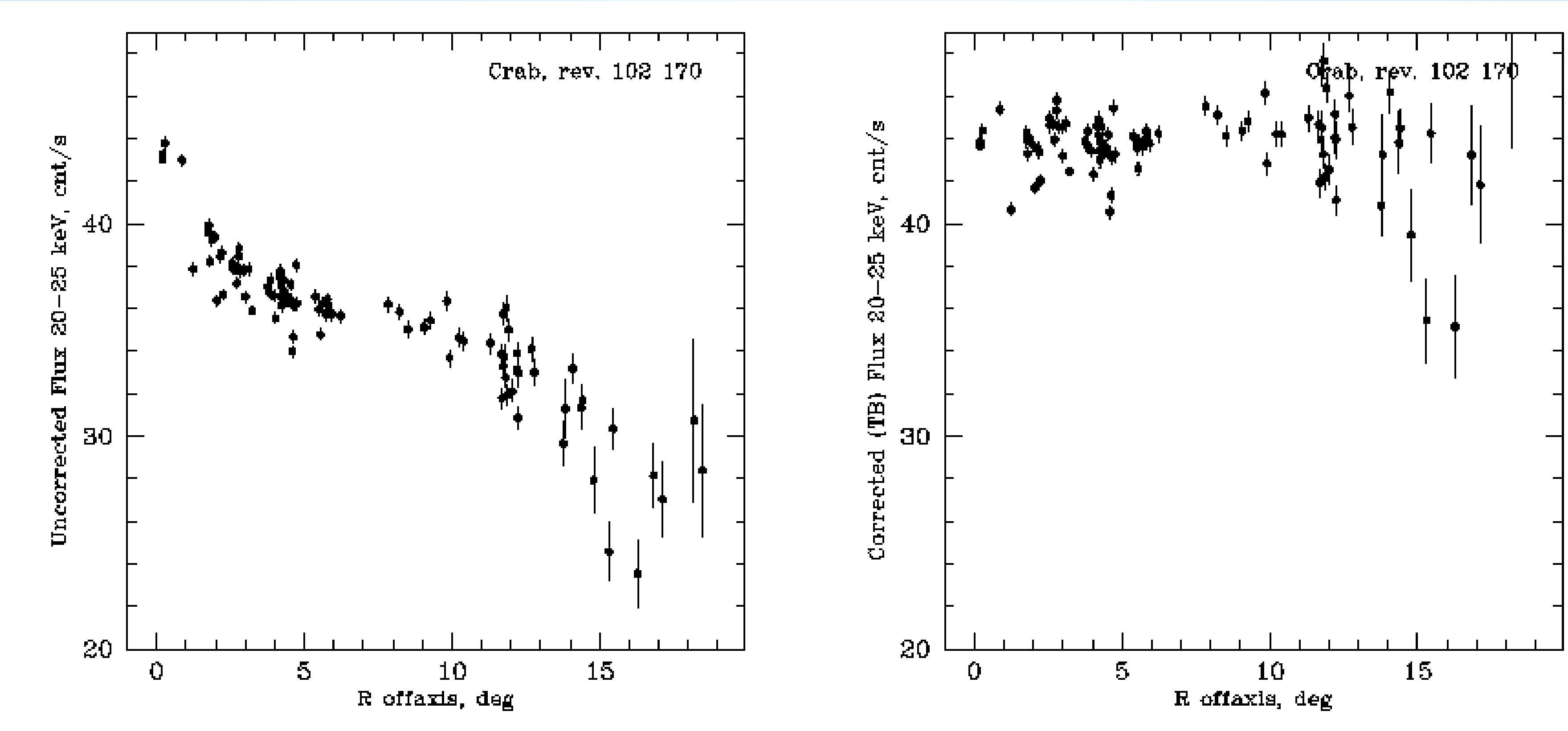




Dependence with the off-axis position of the opacity of the mask support structure is not modeled: correction after image reconstruction

256 Off-axis correction maps (400 x 400 pix) for 256 energy channels.

Off-Axis Correction

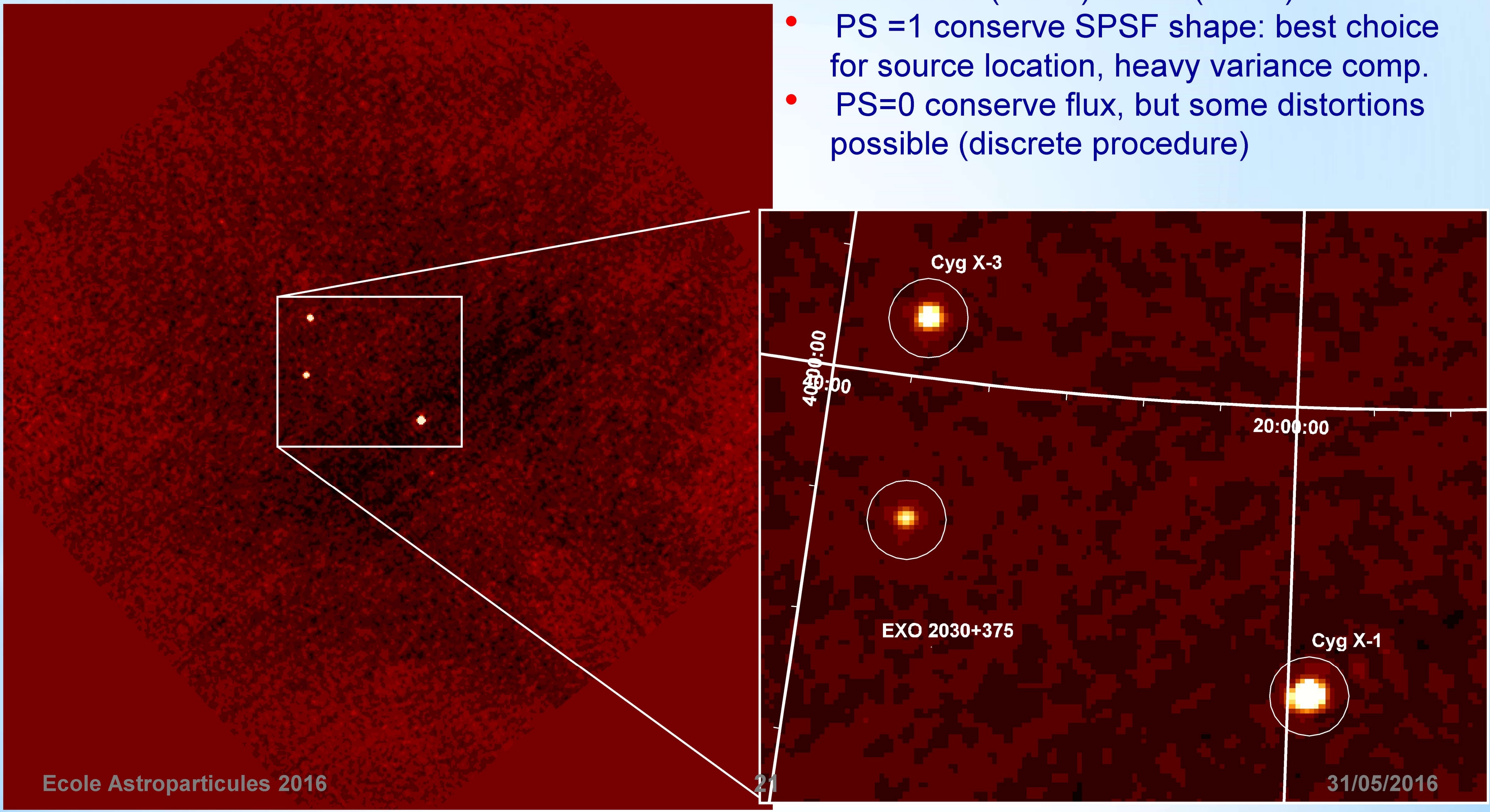


Dependence with the off-axis angle is corrected at the first order. Systematic scatter remains in the low energy bands due to not perfect modeling of mask support

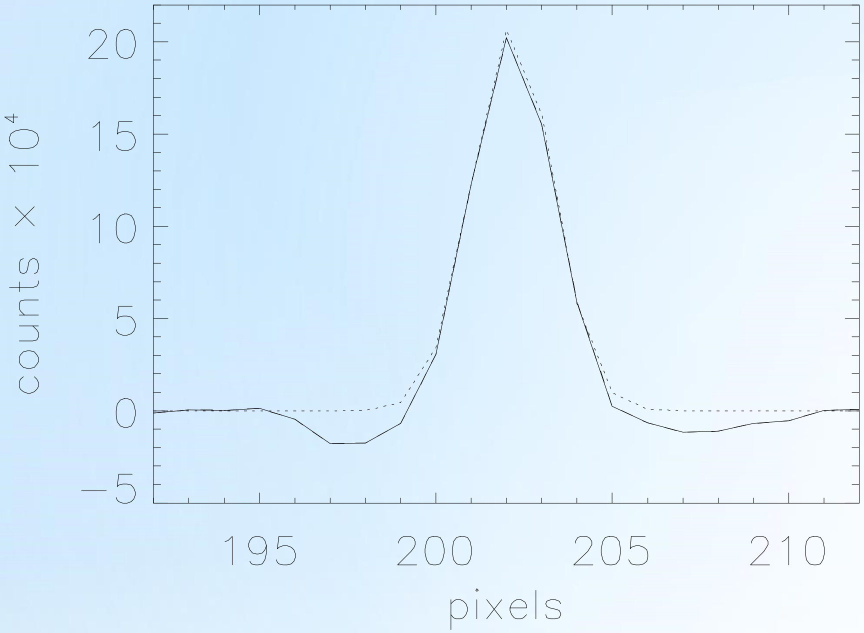
On the Crab : ~ 4% Max Dev. for 5 x 5 dithering on axis

Weighted Sum of Reconstructed Sky-Images in Mosaics

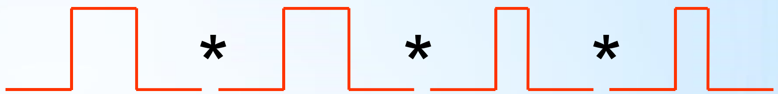
- Two way to rotate image: pixel values are distributed (PS=1) or not (PS=0)
- PS =1 conserve SPSF shape: best choice for source location, heavy variance comp.
- PS=0 conserve flux, but some distortions possible (discrete procedure)



IBIS/ISGRI System Point Spread Function and Source Location



For our decoding the FCFOV SPSF (in absence of coding noise) is given by :



≈ **G**(w)

with **G** a bidimensional Gaussian of width $w^2 = (w_M{}^2 + w_p{}^2) \sim 2.6$ pix ~ 13'

We fit the image sector around the source peak with a function given by

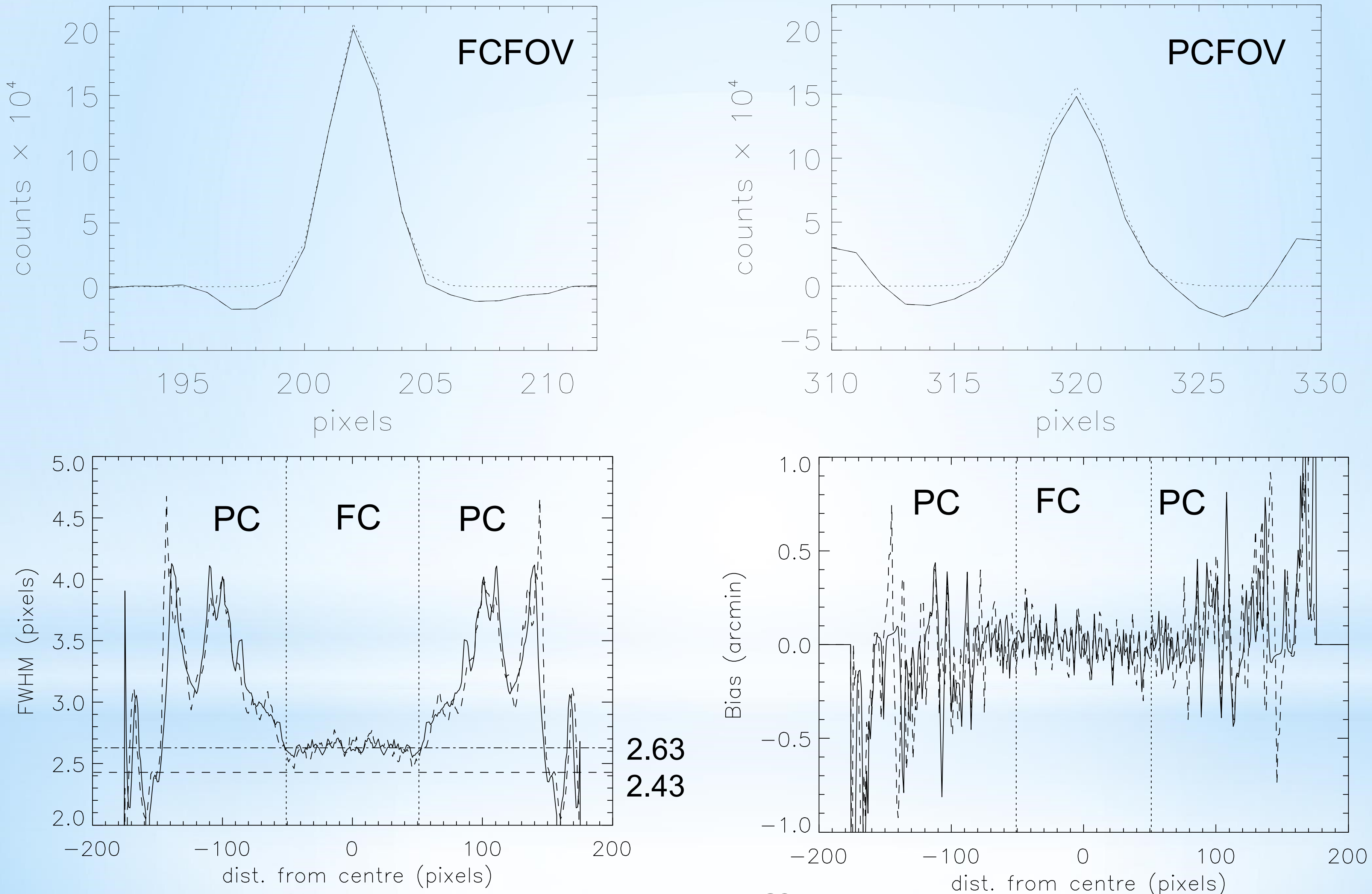
SPSF(y,z)= I_s **G**(y,z,y_s,z_s,w_y,w_z) + B

by chi-square minimization

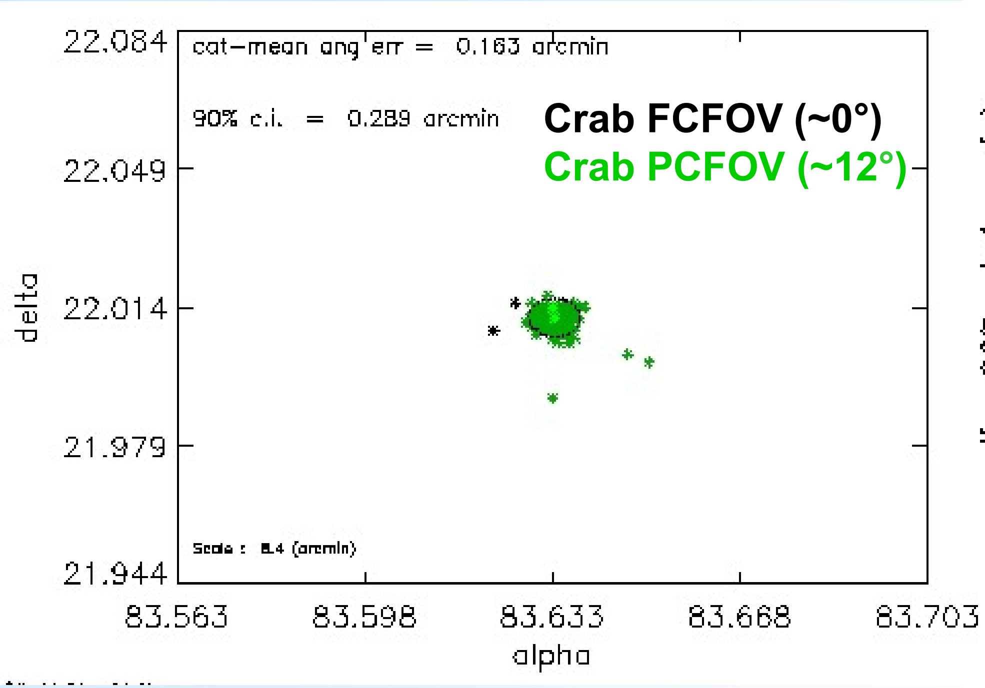
and determine the parameters

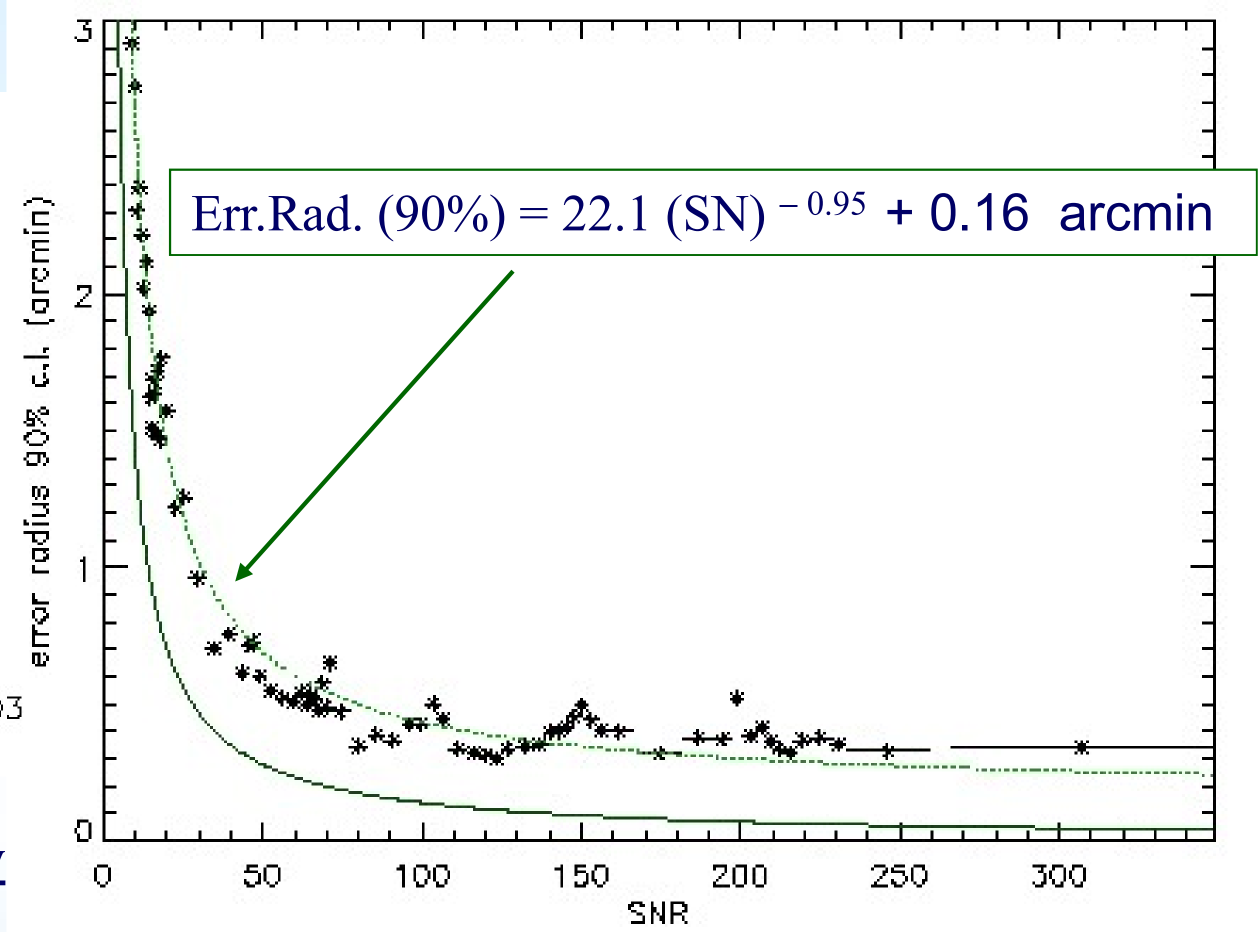
I_s = source intensity
$y_{s,}$, z_s = source position
B = local background
(w_y,w_z = widths of the Gaussian)

IBIS/ISGRI SPSF and Source Location



ISGRI In-Flight Point Source Location Accuracy





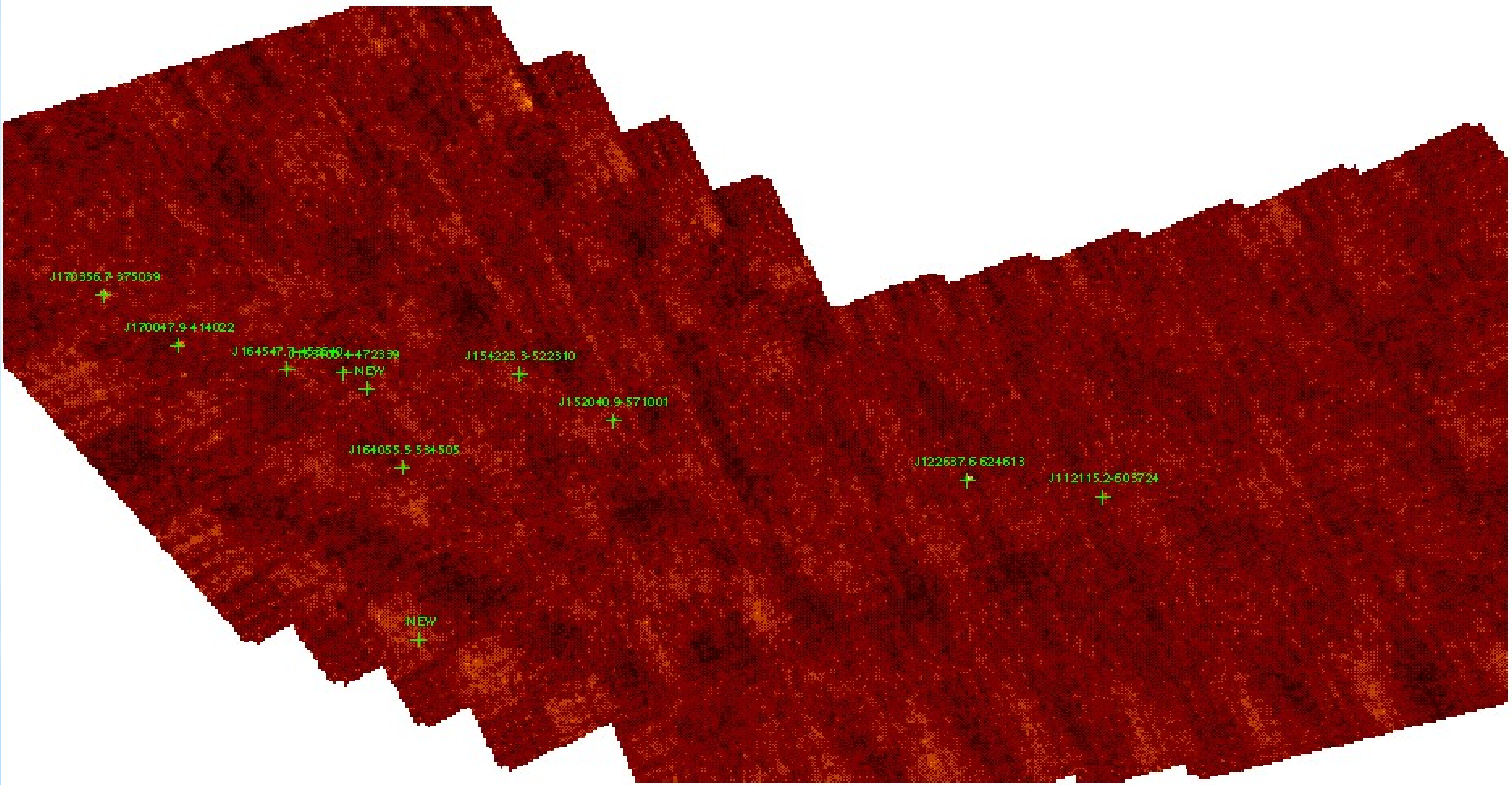
IBIS/ISGRI Source Location Accuracy

- Reconstructed positions for the Crab in FCFOV and PCFOV
- Measured 90 % confidence level radius error vs. statistical source S/N

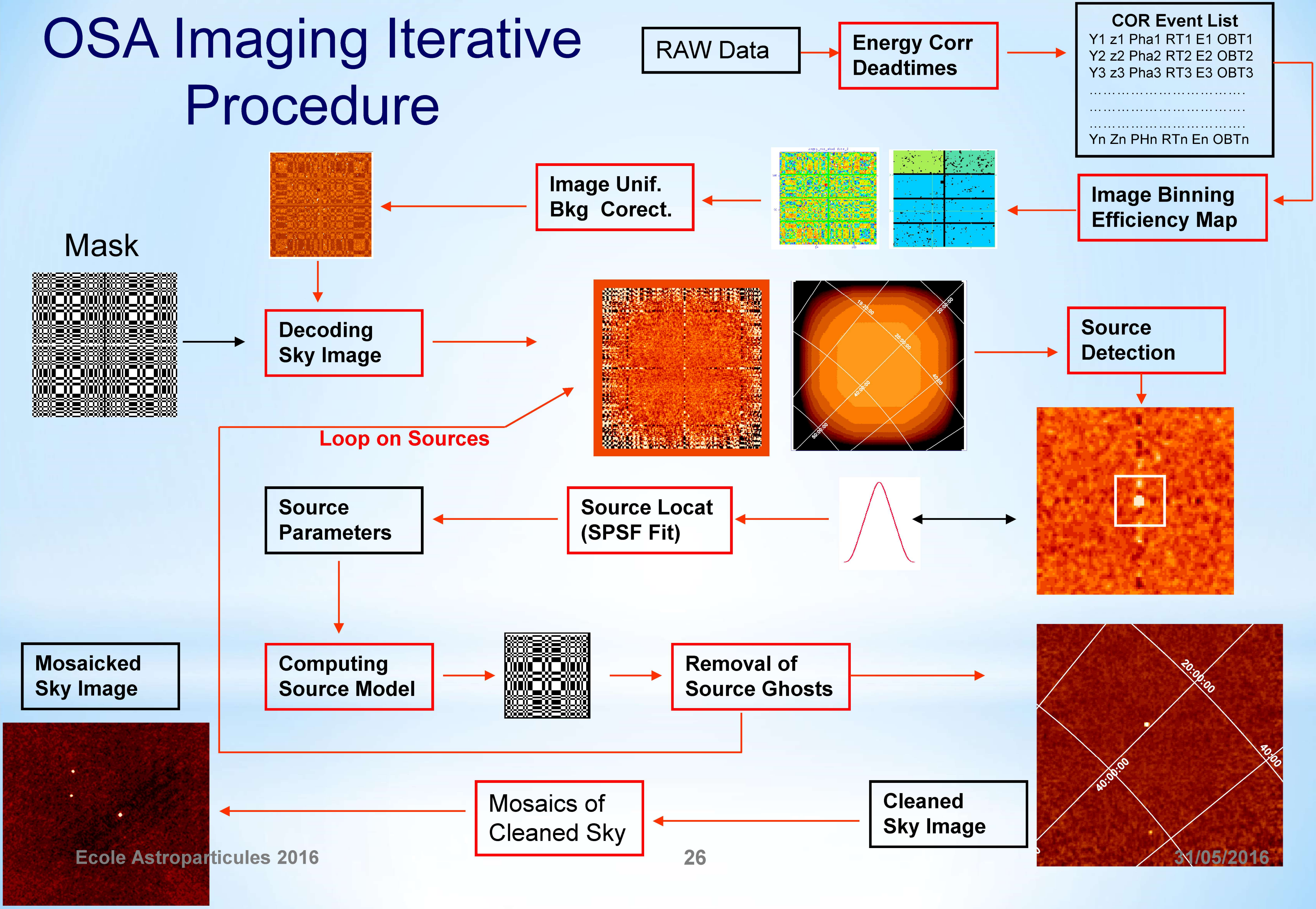
  Data: ~ 2000 computed offsets (Crab, Cyg X-1, Cyg X-3), E ~ 20-400 keV, Axis dist. ~ 0° - 14°

  Comparison with the theorical curve (perfect system) (Gros et al. 2004)

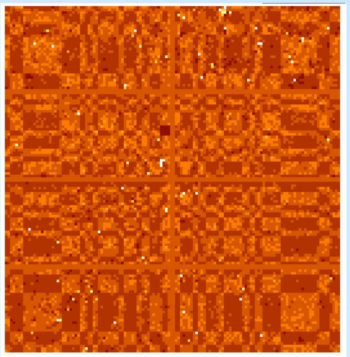
Mosaic of IBIS images



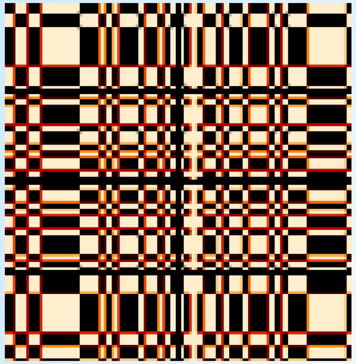
OSA Imaging Iterative Procedure



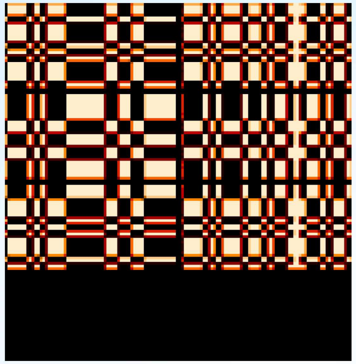
IBIS/ISGRI Spectral Analysis



D



M_1



M_2

For each active source in the FOV of the ScW (see results of imaging) we define (for given position) a model of the source contribution in the energy band (called PIF).

We can fit the detector image D with a detector model function DM including the models Ms for each active source and the Background B (including efficiency image E)

$$\mathbf{DM}(y,z,e)= \sum I_i \mathbf{M_i}(y,z,y_i,z_i,e)\, E + bB(e)E$$

by Least Squares or Maximum Likelihood

and determine the parameters
I_i intensity source i (i=1,..,n)
b = background intensity
for each energy
⇒ SOURCE & BKG SPECTRA

References

Coded mask imaging:

Fenimore & Cannon,1979 & 1981, App. Opt.
Gottesman & Fenimore, 1989, App. Opt.
Skinner, G.K., 1984, NIMA, Vol. 221, No. 1, p. 33
Skinner, G. K., 1995, Experimental Astronomy, Volume 6, p1

IBIS data analysis concepts:

Goldwurm et al., 2003, A&A, 411
Gros et al., 2003, A&A, 411

IBIS/ISGRI in-flight calibrations, responses, performances:

Terrier et al., 2003, A&A, 411

ALL SKY MONITORS

Why an All Sky Monitor (ASM) ?

- Hard X-ray, gamma-ray sky is very variable and sources can be ON or OFF at any moment. So, it is needed to have a regular survey the sky in order to be ready when an interesting source is switching on.

- Most of the high sensitivity, high angular resolution telescopes have a small field of view, so they cannot perform this survey.

- A telescope with a large FOV, which survey a large part of the sky, even with limited imaging capabilities, is therefore often required in space missions.

- Often, they are "secondary" instruments (monitors) in these missions, so they have to be simple and cheap (often, 1D coded mask).

Why an All Sky Monitor ?

An ASM will be used then to:

- Monitor the hard X-ray sky: it will localize the sources detected in its wide FOV, and possibly trigger main instruments observation, possibly after repointing.
- Alert other space or ground-based observatories in case of peculiar events (black hole spectral state change, GRB, pulsar glitch, novae, supernovae …).
- Follow-up peculiar transient events detected by other observatories (GRB, gravitational waves, …)
- Follow-up the X-ray variability of compact sources, from stellar mass black holes, pulsars to white dwarves.
- Map the hard X-ray sky in our Galaxy between 2 and 200 keV; Time resolved spectroscopy.

PAST AND PRESENT ALL SKY MONITORS

The GRANAT/WATCH telescope (1989 – 1997)

- The Four WATCH instruments, designed by the Danish Space Research Institute, were in operation on the Granat observatory starting in January 1990.

- The instruments could localize bright sources in the 6-180 keV range to within 0.5° using a Rotation Modulation Collimator.

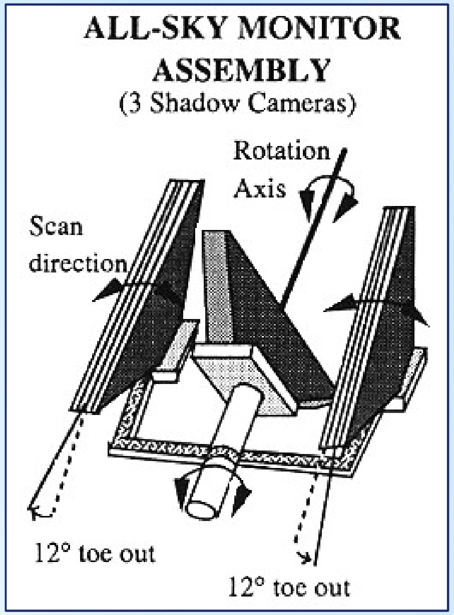
- Taken together, the fields of view of the instruments covered ~75% of the sky.

Circular No. 5590 Central Bureau for Astronomical Telegrams
INTERNATIONAL ASTRONOMICAL UNION

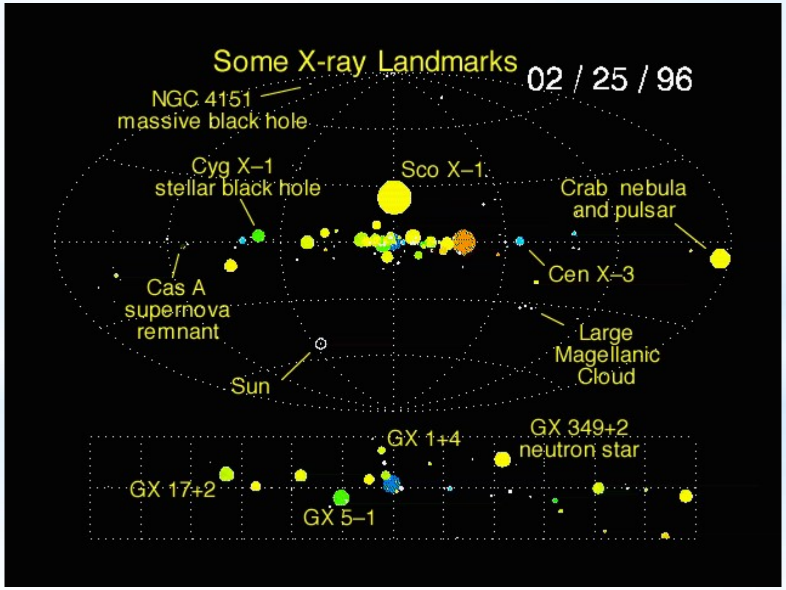
GRS 1915+105 A. J. Castro-Tirado, S. Brandt, and N. Lund, Granat WATCH team (Danish Space Research Institute, Lyngby; and Space Research Institute, Moscow), report: "A new x-ray transient in Aquila has been discovered in data obtained by the WATCH all-sky monitor on Granat on Aug. 15. The source strength is about 300 mCrab. The source has been localized to the following position: R.A. = 19h14m.9, Decl. = +10 28' (equinox 1950.0), with a probable error radius 0.5 deg. Follow-up observations are encouraged."

The RXTE/ASM monitor (1995 – 2012)

The RXTE/ASM consists of three wide-angle shadow cameras equipped with proportional counters with a total collecting area of 90 cm^2.



- Energy range : 2 - 10 keV
- Coverage : 80% (orbit)
- Spatial resolution : 3' x 15'
- FOV : 6° x 90°

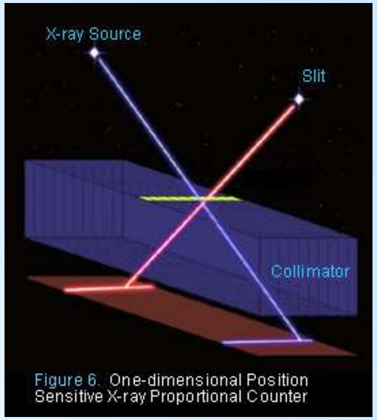


The MAXI monitor (2009 –)

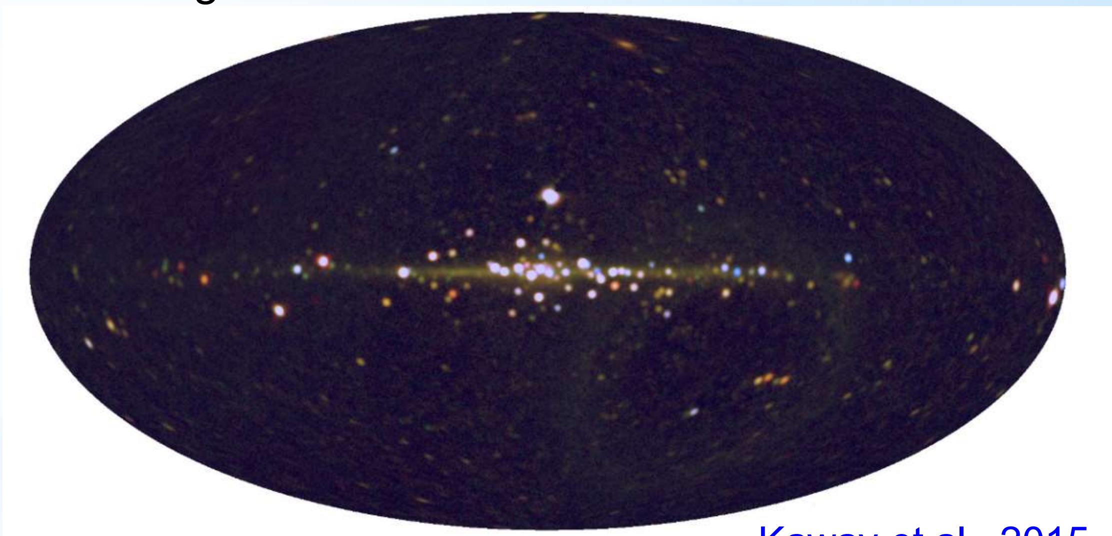
MAXI is an ASM (0.5 – 30 keV) which has been installed on the International Space Station **Kibo** Japanese module in 2009.

- It is equipped with two types of cameras as detectors: a gas slit camera with proportional counters and an X-ray CCD slit camera with an X-ray CCD.

- Images are made with a 1D slit. The over dimension is got temporally along the orbit (as in ASM).



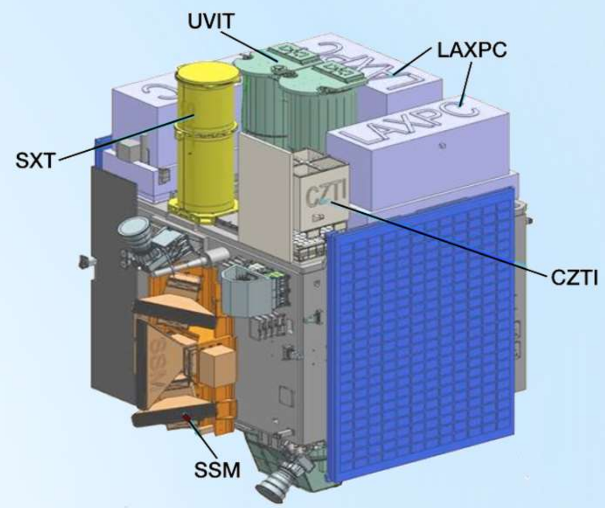
- Energy range : 0.5 - 30 keV
- Coverage : 80% (orbit)
- Spatial resolution : 30'
- FOV : 3° x 80°



Kaway et al., 2015

The ASTROSAT/SSM monitor (2015 –)

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.



The Scanning Sky Monitor (SSM) consists of three one-dimensional position-sensitive proportional counters with coded masks.

- Energy range : 2 - 10 keV
- Coverage : 80% (orbit)
- Spatial resolution : 3' x 15'
- FOV : 6° x 90°