INTEGRAL – ESA's Gamma-ray Observatory Mission

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Talk Outline

- Introduction
- Mission Description
- Instruments
- Coded Mask Imaging
- Examples of INTEGRAL data
- Using INTEGRAL

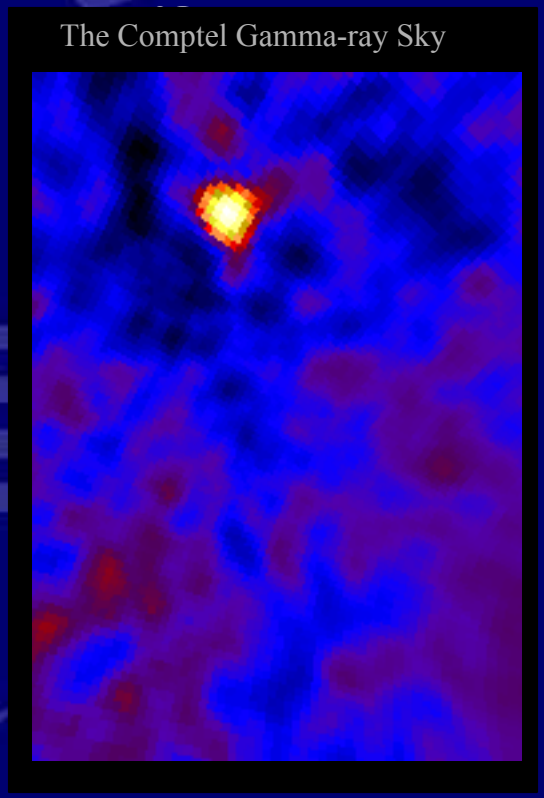
INTEGRAL under Thermal Vacuum testing at ESTEC

The Gamma-ray sky before INTEGRAL

Optic al

X-ray

Gamma-



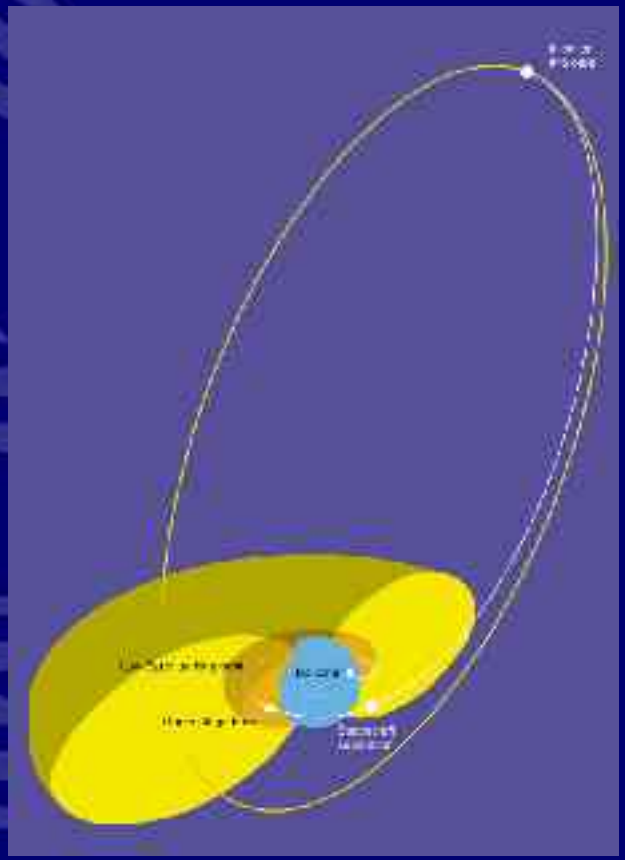
The INTEGRAL Mission

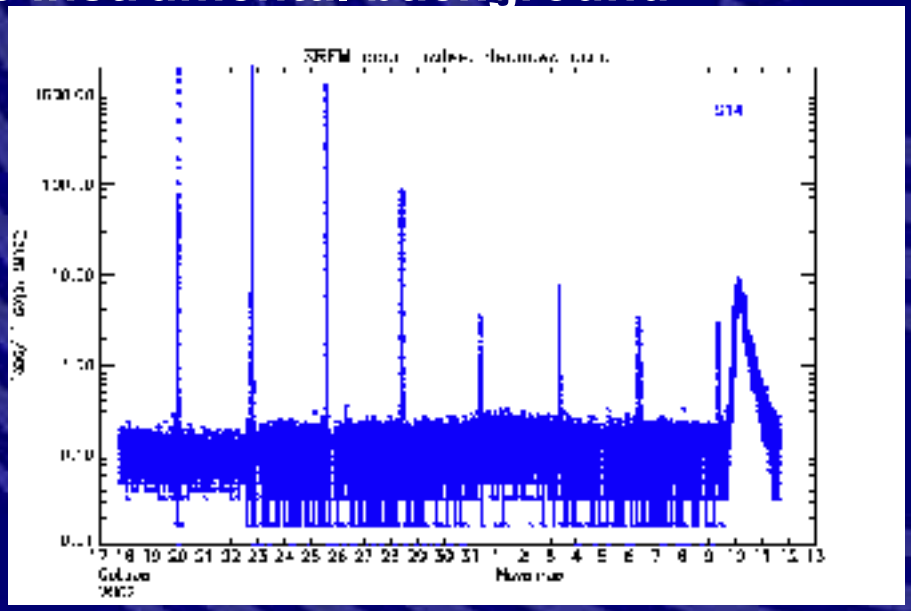
- INTEGRAL is ESA's gamma-ray observatory mission launched on 2002 October 17 on a Proton rocket. ESA led mission in collaboration with Russia and the USA.
- ESA's 2nd gamma-ray mission (COS-B, 1975), joined XMM-Newton in orbit.
- SPC approved a rolling 4-year mission extension until at least 2008 December.
  AWG has recommended further extension up to 2010 (again to be confirmed).
- Spacecraft, instruments and ground segment are all operating extremely well. Consumables for >15 years operations.
- Highly eccentric 72 hour orbit. Perigee 9 000 km, apogee 150 000

2002 October 17, Baikonur, Kazahkstan

The INTEGRAL Mission

- Four perigee raise burn maneuvers and one apogee adjust maneuver by INTEGRAL's on-board propulsion system
- Perigee raised from 651 km to 9050 km – important to minimize the instrumental background





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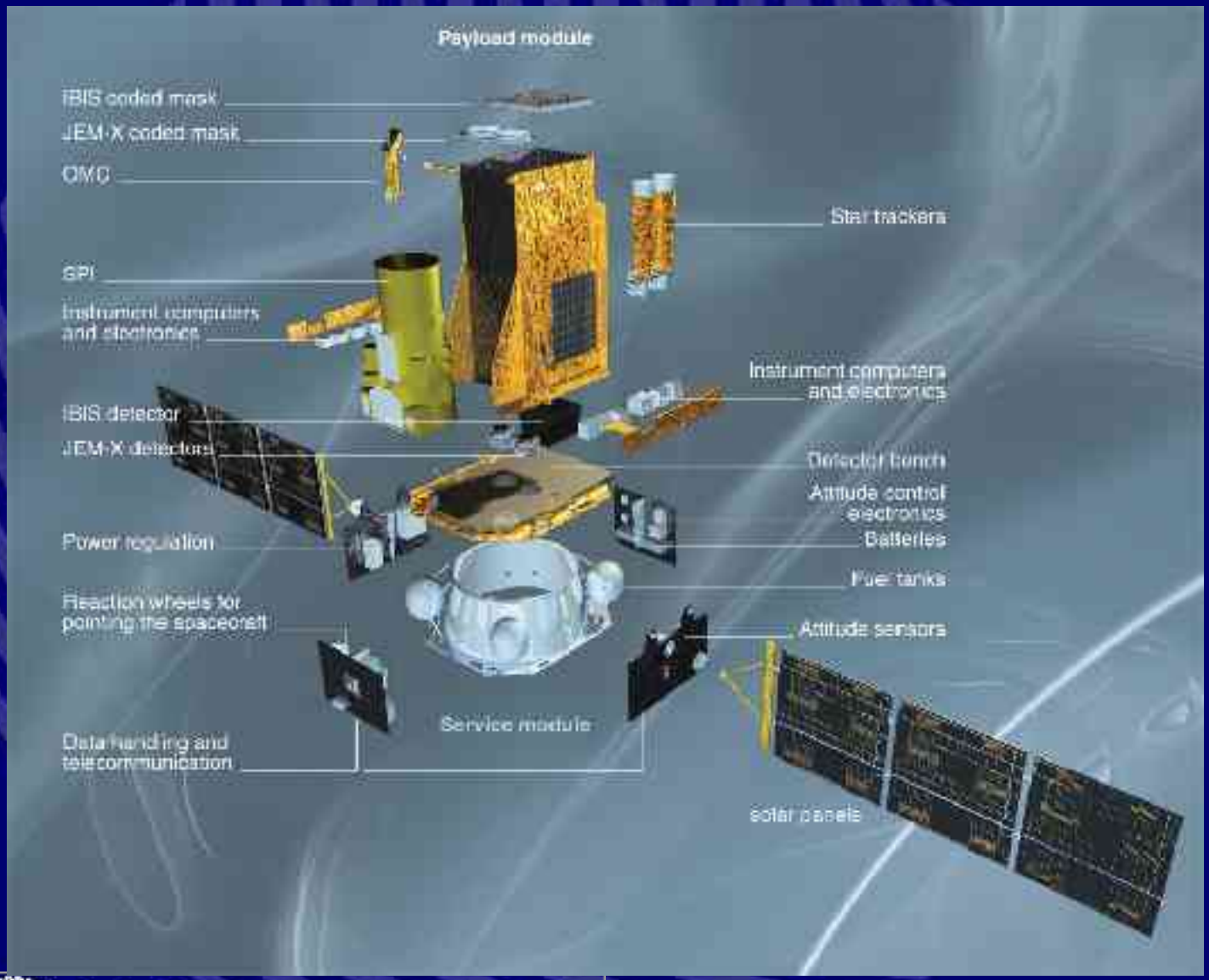
INTEGRAL in a Nutshell



- 4 tonnes
- 5 m high
- 16 m span solar panels.

The Payload

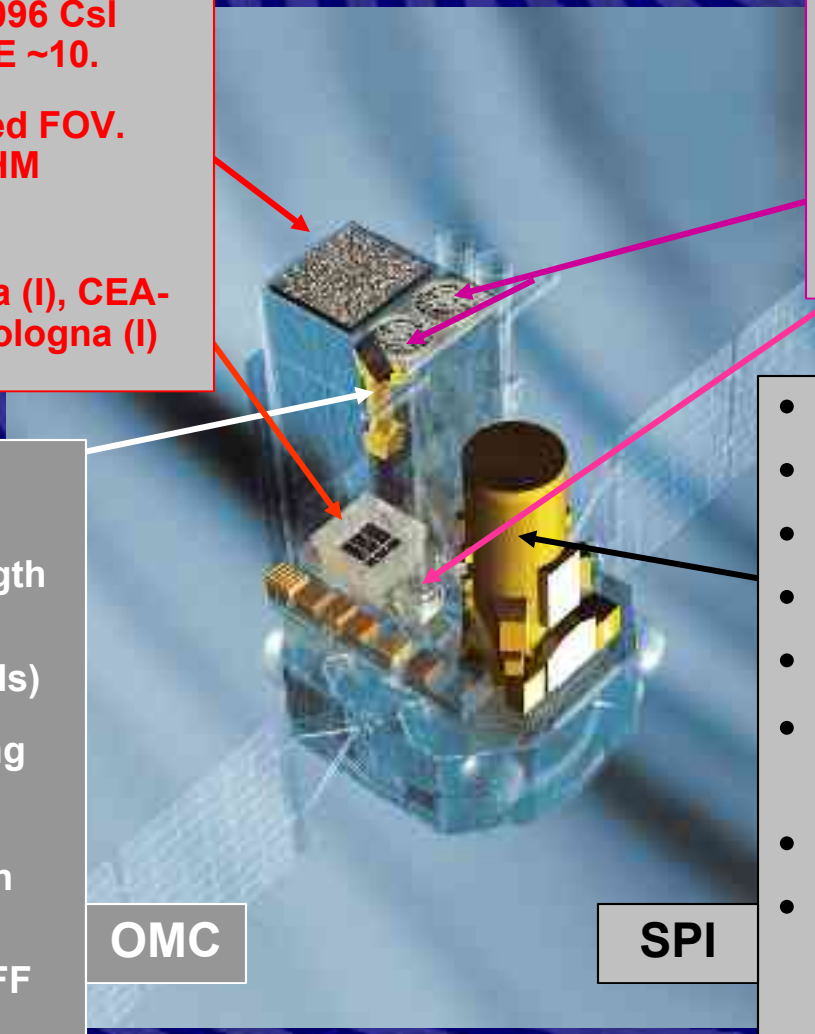
- Two main gamma-ray instruments:
  - IBIS – Imager
  - SPI – Spectrometer
- Two supporting monitoring instruments:
  - JEM-X – X-ray monitor
  - OMC – Optical monitor

IBIS

- Accurate point source imaging and location.
- Broad lines and continuum.
- 15 keV – 10 MeV
- 16384 CdTe (ISGRI), 4096 CsI (PICsIT) detectors. E/ΔE ~10.
- 9°x 9°degree fully coded FOV. Angular resol 12’ FWHM
- 630 kg
- PI Institutes: IAS Roma (I), CEA-Saclay (F), ITESRE –Bologna (I)

JEM-X

- Source identification and monitoring in X-rays
- 3 –35 keV X-ray monitoring
- Microstrip Xe gas detectors
- 5° degree FOV with 3’ spatial resolution
- Energy resolution of 15% at 10 keV
- 65 kg
- PI institute: DSRI (Dk)



OMC

- Optical monitoring of high-energy sources
- 500 – 600 nm wavelength range
- CCD (2048 x 1024 pixels)
- 5° x 5° FOV, 20” imaging
- 17 kg
- Sensitivity: 18.2 mag in 1000 s
- PI Institute: INTA/LAEFF (Esp)

SPI

- Fine spectroscopy of narrow lines
- Diffuse emission on > deg scales.
- 20 keV to 8 MeV
- 19 Ge detectors @ 90 K,
- E/ΔE ~500.
- 16° fully coded FOV. Angular resolution 2° FWHM
- 1300 kg
- PI Institutes: CESR Toulouse (F) and MPE Garching (D)

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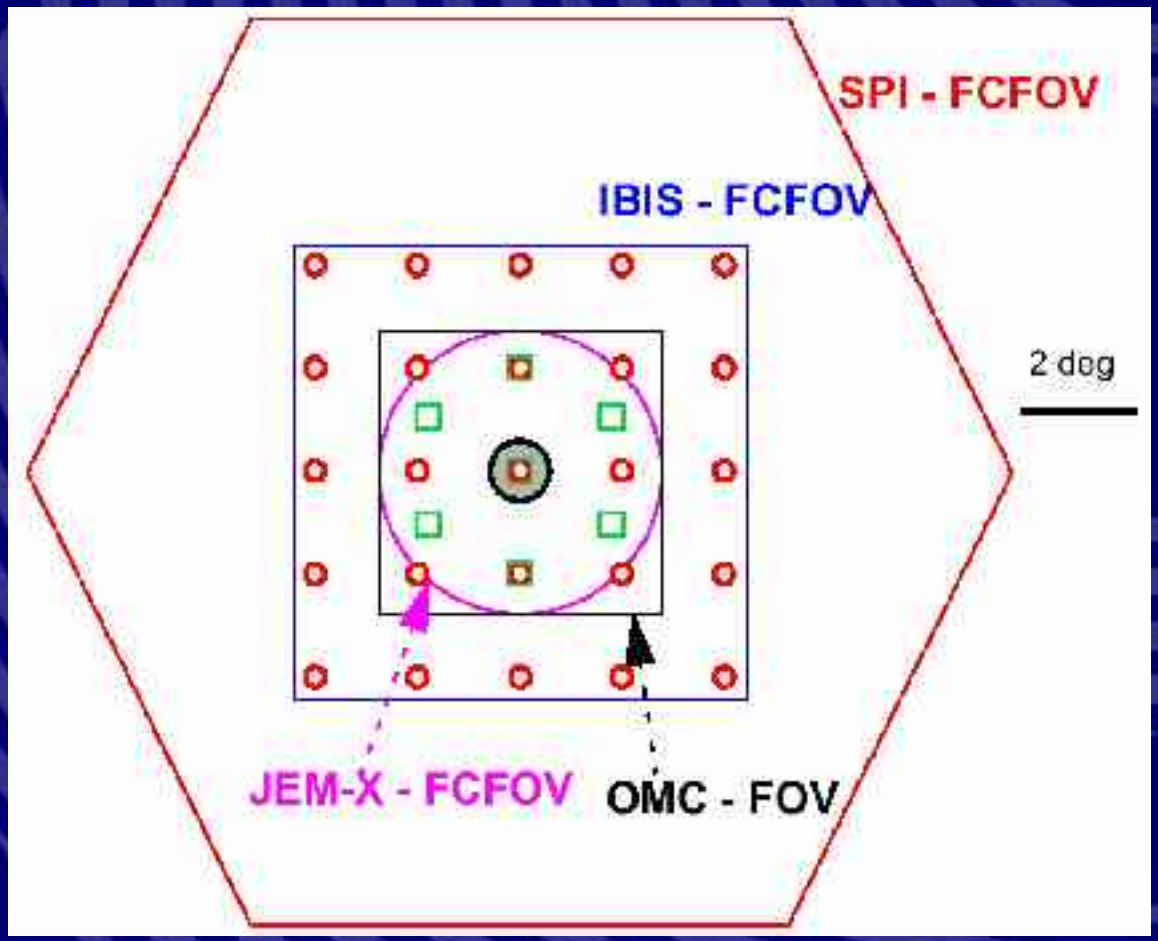
INTEGRAL fields-of-view



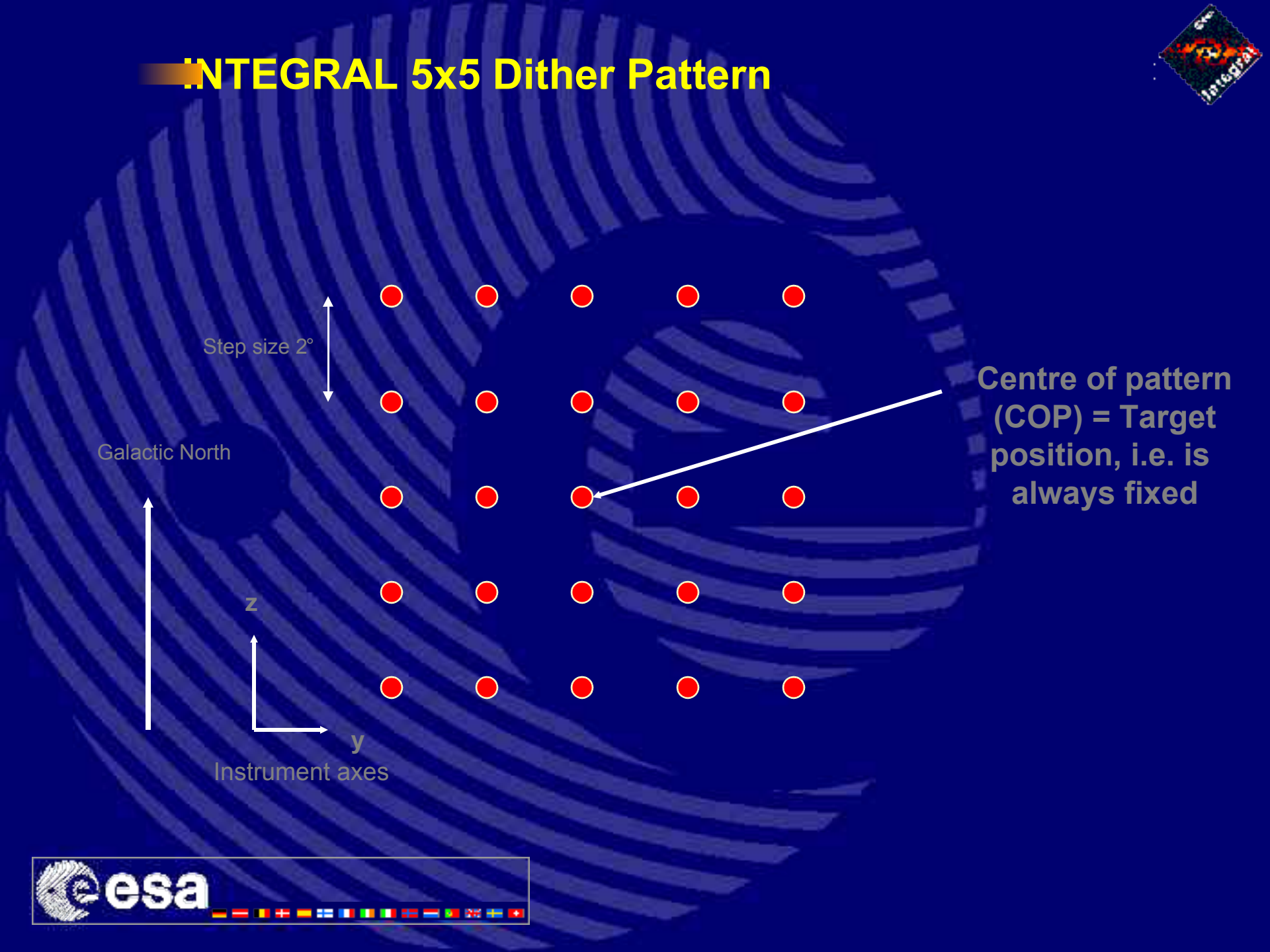
Fully coded fields of view :

- IBIS : 9°
- SPI : 16°
- JEM-X : 4.8°
- OMC : 5°

Dithering patterns:

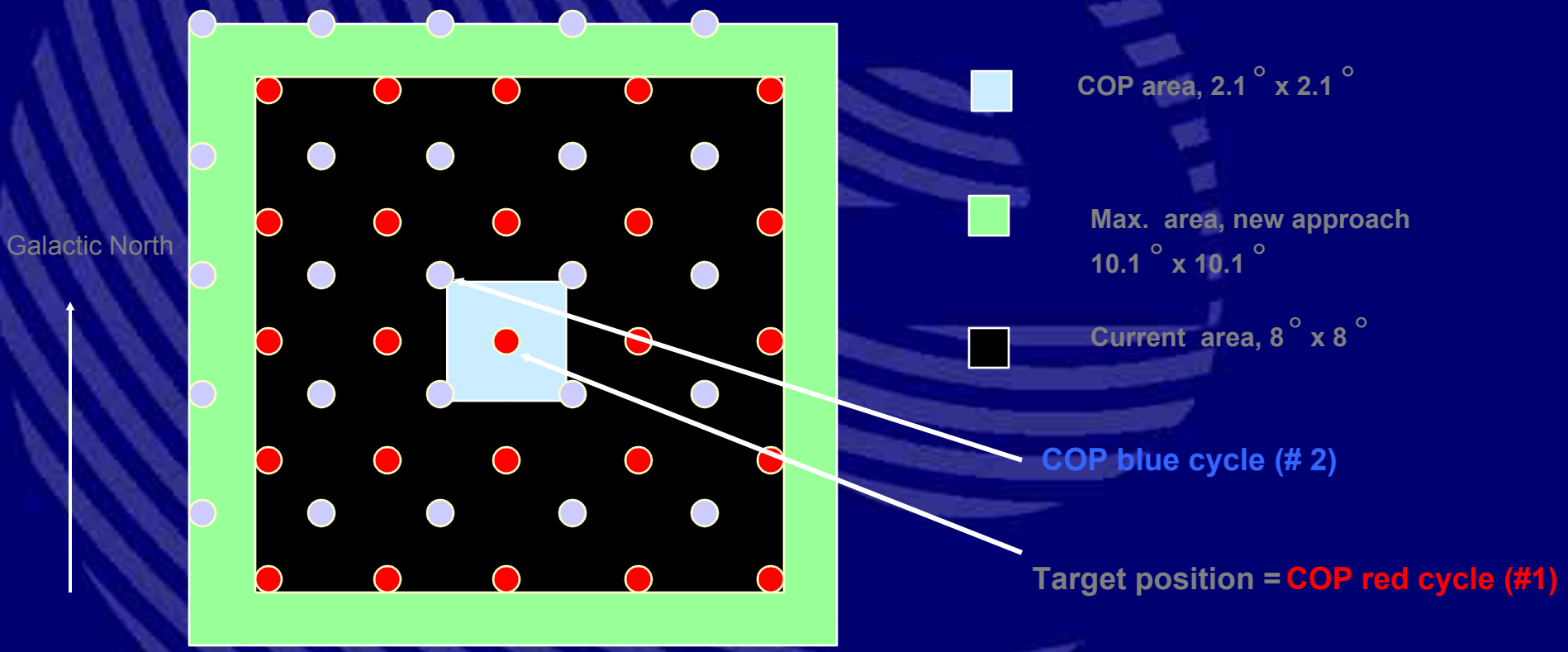
- staring
- 7 point hexagonal
- 5 × 5 rectangular

INTEGRAL 5x5 Dither Pattern

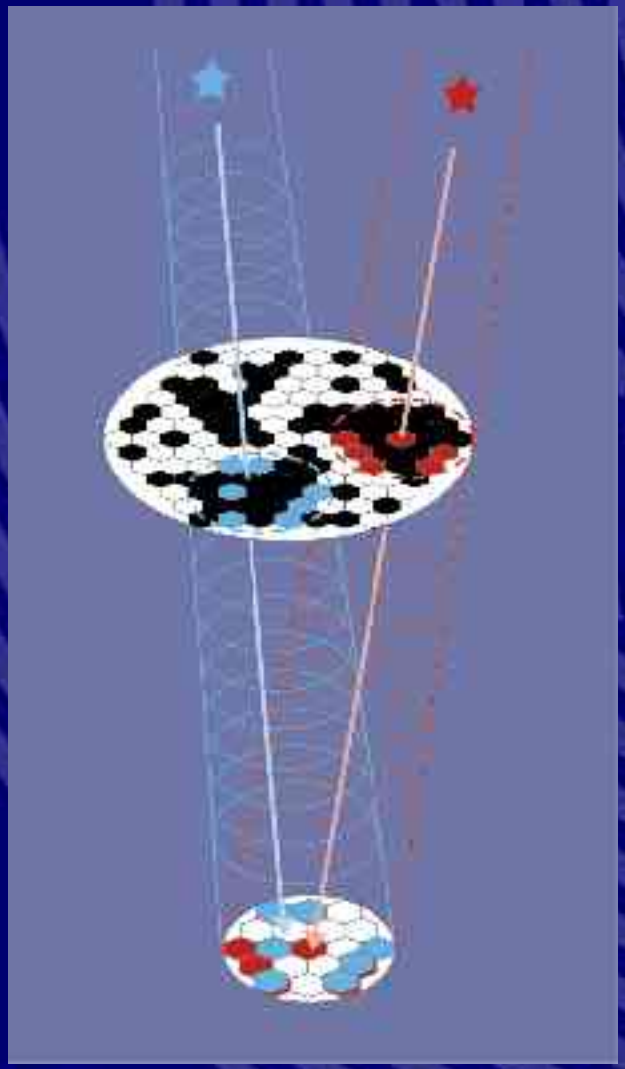


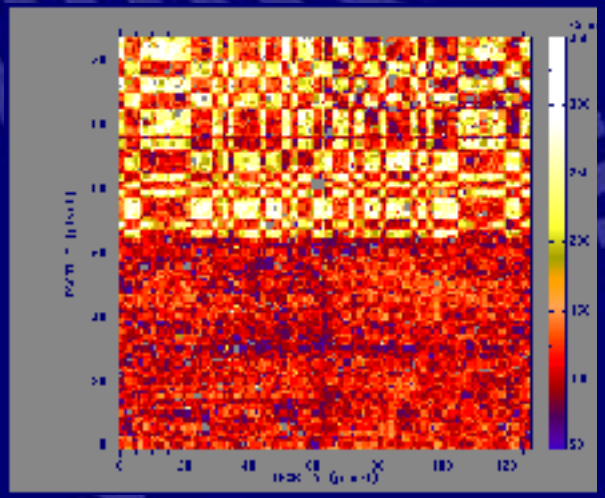
Centre of pattern (COP) = Target position, i.e. is always fixed

INTEGRAL 5x5 Modified Dither Pattern

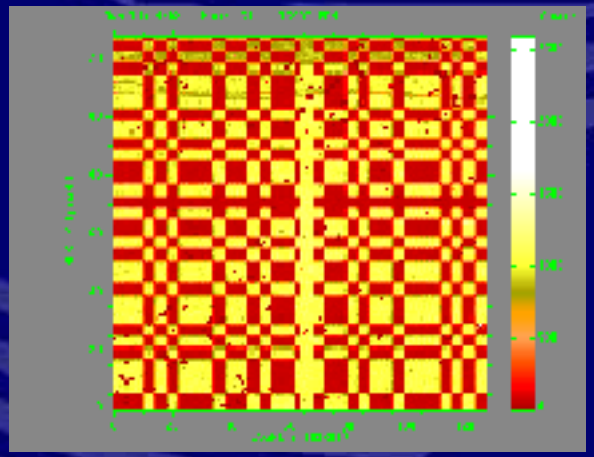


Coded aperture mask imaging (SPI, IBIS and JEM-X)





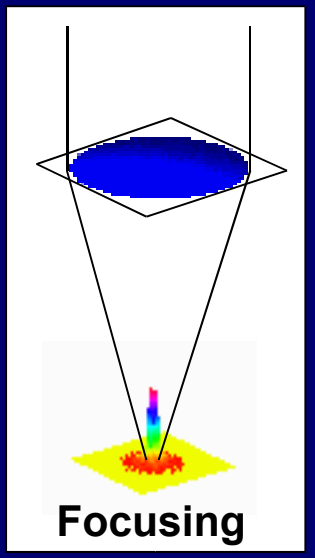
IBIS off-axis Crab shadowgram

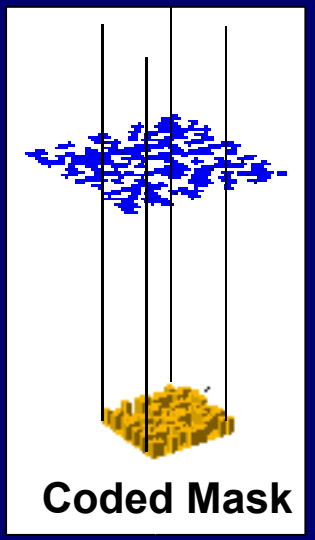


IBIS fully-coded Crab shadowgram

Coded mask imaging – some background

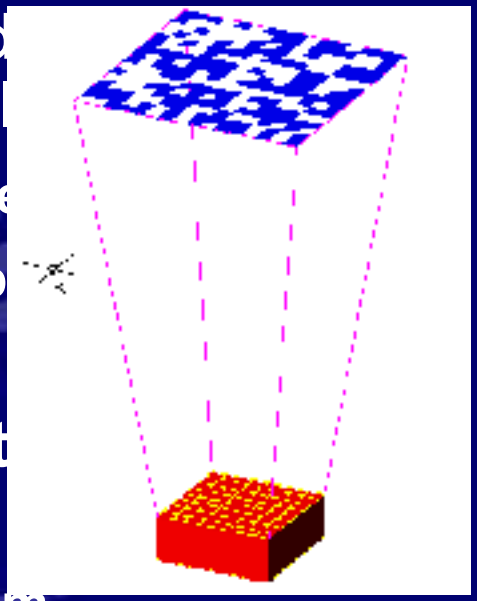
- Worst imaginable PSF
  - Fills detector plane for a point source
    ⇒ Multiple sources are normally entangled!
  - Also background relevant in whole detector!
- So why bother?
  - Images in energy range too high for focusing and too low for Compton or Tracking.
  - Wide fields of view and very good angular resolution.
  - Best energy resolution.





Coded mask imaging – design choices

- 'Optimum' design with mask larger than d
  and cyclically replicated mask pattern (IBI
  - Perfect reconstruction in Fully Coded FOV (ide
  - ***But*** 'ghosts' in Partially Coded FOV and sharp
    distinction between fully and partially coded.
- 'Simple' design with mask equal to detect
  and no repetition (JEM-X comes close):
  - Reconstruction quality drops off gradually from
    on-axis position.
  - No 'ghosts' in PCFOV.
- Special design, not adapted to simple reconstruction (SPI)
  - Broad sky pixels adapted to map diffuse emission.
  - Fewer detector than sky pixels $\Rightarrow$ requires 'dithering' to solve for sources.



Coded mask imaging – reconstruction methods

- Correlation of mask pattern and detector plane.
  - Measure of similarity of shadowgram with projected mask pattern.
  - Relatively easy to implement, fast with use of FFTs.
  - Always works to produce some image.
- Backprojection of events to sky
  - Roughly equivalent to correlation methods.
  - Much faster for few photons.
- Aperture Response, Pixel Illumination Function
  - (Pre-)calculate relation between sky positions (selected or all) and detector pixels.
  - Can be very precise, but for full image either slow or huge calibration files.
- Widespread improvement: Iterative Removal of Sources

Coded mask imaging – real life issues

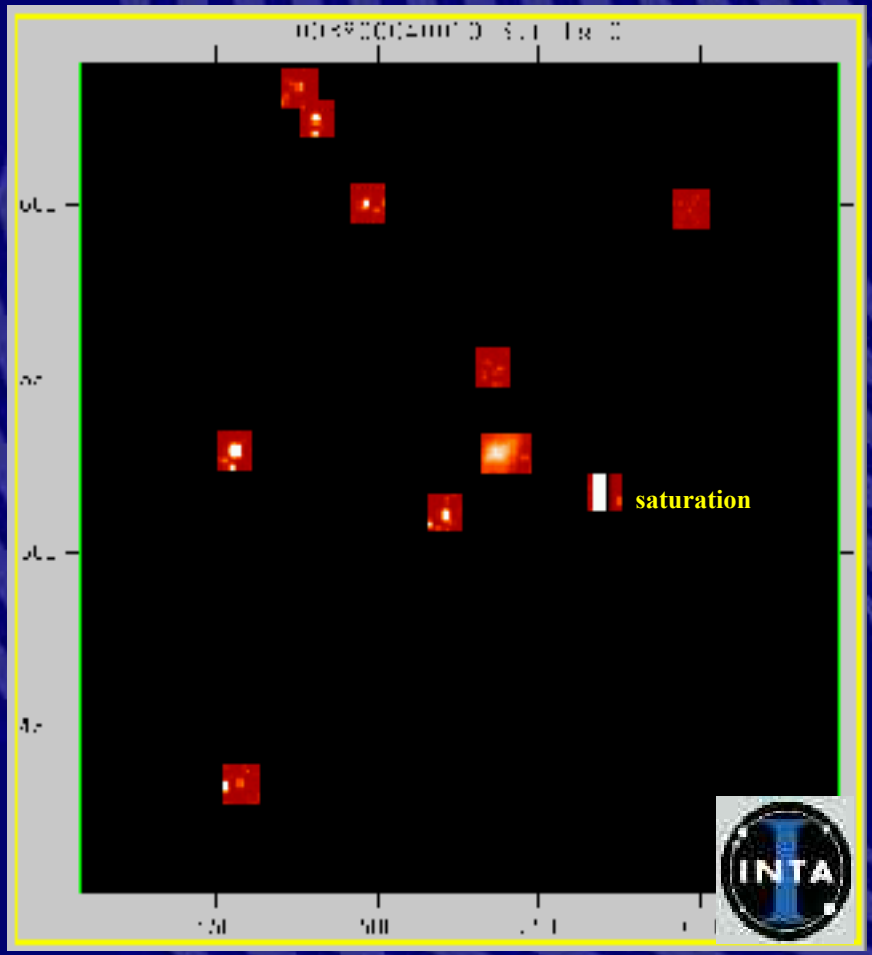
- Non cyclic masks
- Mask closed element absorption
- Mask open element transparency
- Mask element thickness
- Obstructions in mask plane
- Detector finite position resolution
- Detector efficiency non-uniformities
- Detector response dependent on off-axis angle
- Detector background non-uniform
- Gaps in the detector plane
- Dead/inactive pixels in the detector plane
- Shielding (collimation) imperfect
- Obstructions between detector and mask
- Leaks onto detector from far outside the fov

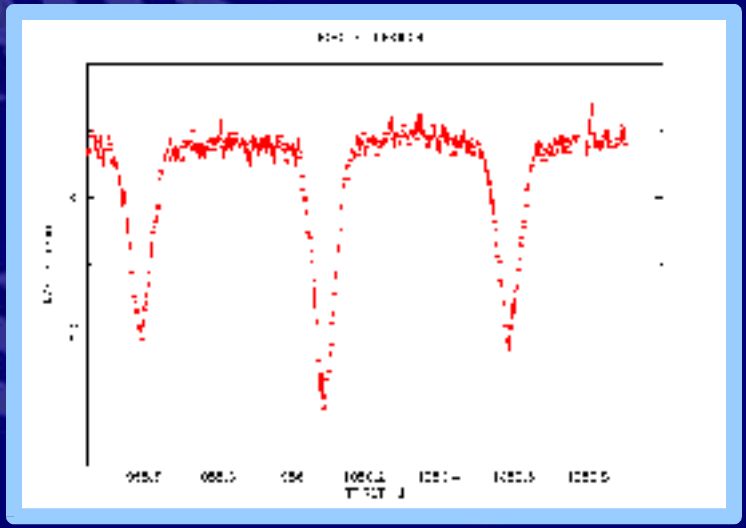
Mask

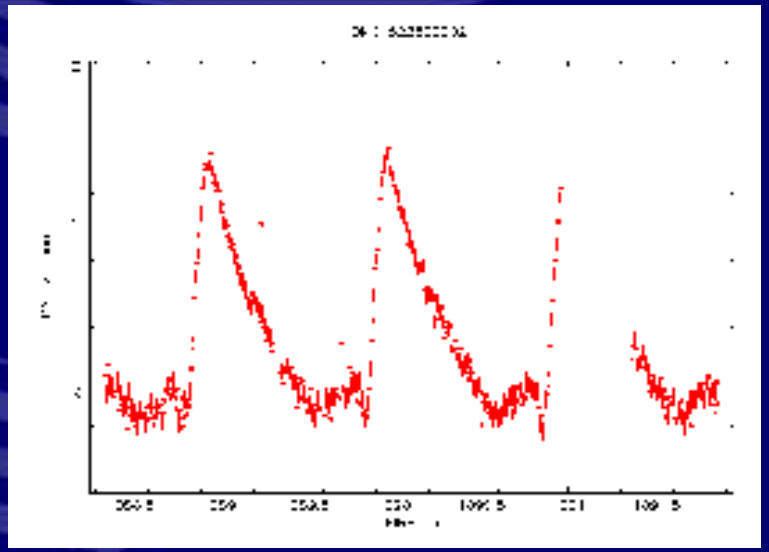
Detector

Other

OMC Produces Lightcurves of Selected Objects

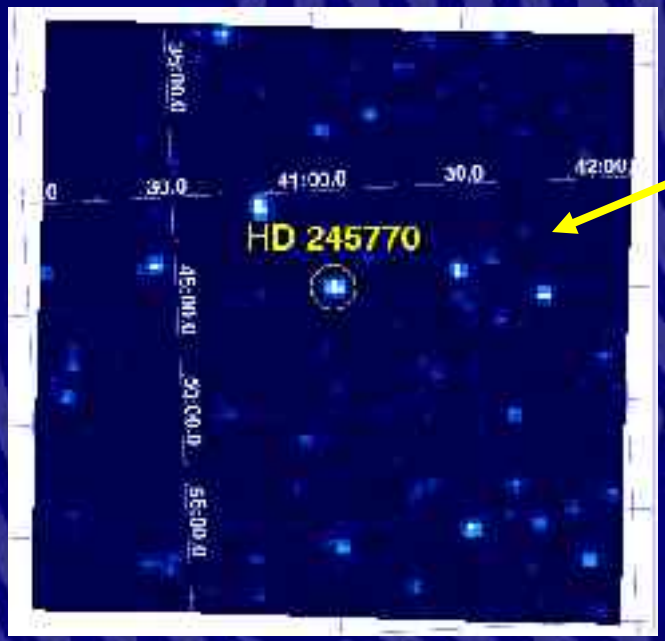






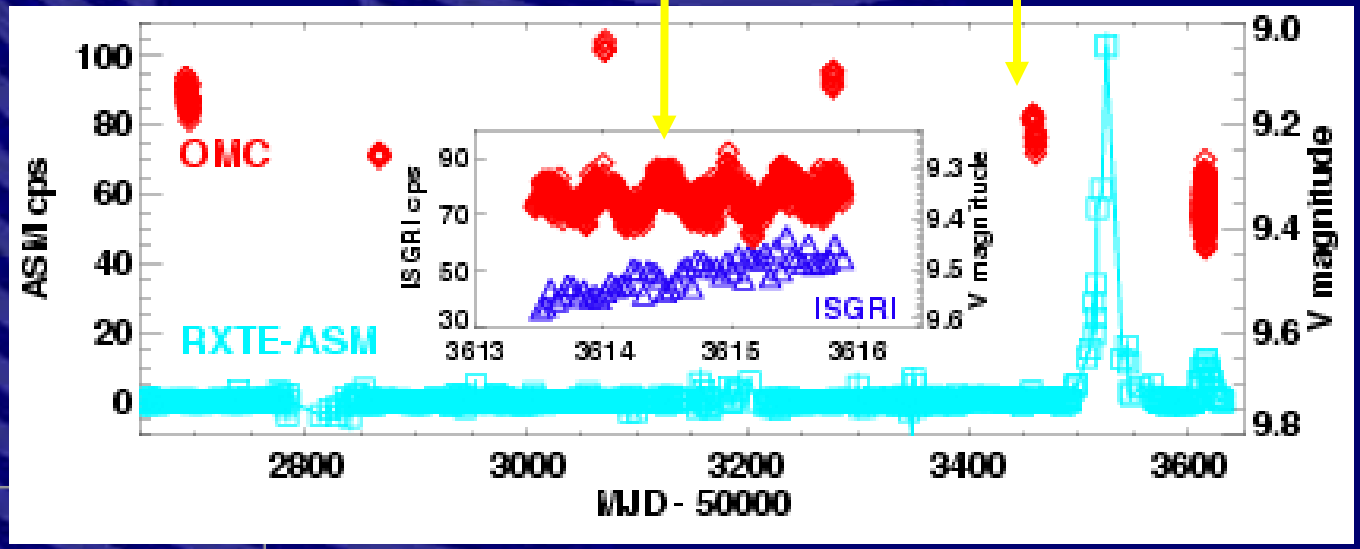
Credit: M. Has-Hesse

OMC Results for the recent ToO on 1A0535+262



- Larger Trigger Mode image, as source was blacklisted and detected by IBAS.

- Long-term OMC lightcurve shows optical fa before X-ray outburst.
- Short-term lightcurve during observation sh variability of Be companion star.

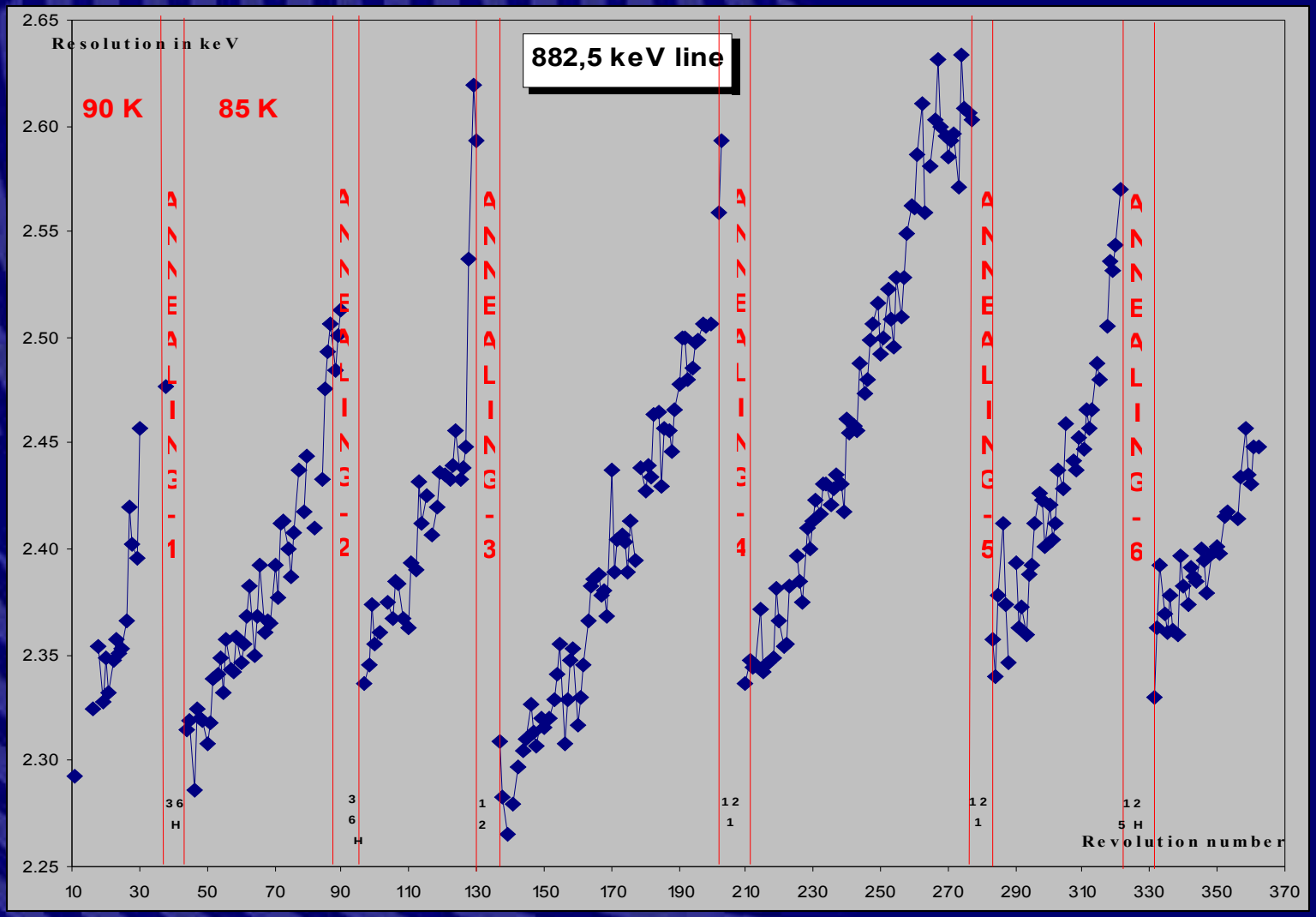


INTEGRAL Status

Instrument Anomalies

- SPI detector #2 failed in 2003 December.
- SPI detector #17 failed on July 17 (2 out of 19 detectors have now failed). It is yet unclear whether both events are linked to the annealing which preceded the failures in both cases by 2-3 weeks. Investigations continue.
- To first order these reduce the SPI effective area by 2/19.
- Soon after launch it was noticed that some of the anodes of the JEM-X detectors were being damaged. This effect was minimised by lowering the HV settings. Subsequently, it was noticed that the overall gain was increasing. To keep the gain within a narrow range of values, the settings are regularly reduced.
- Subsequently, only one of the two JEM-X units is operated at any one time (except for calibration observations). Currently this is JEM-X1.
- To first order this is a sqrt(2) reduction in sensitivity

SPI: Ge-detector energy resolution against time

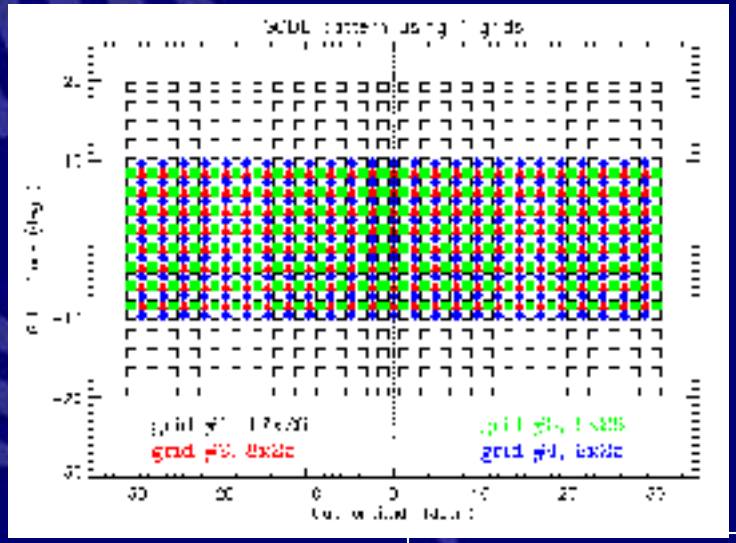


Energy Resolution (keV)

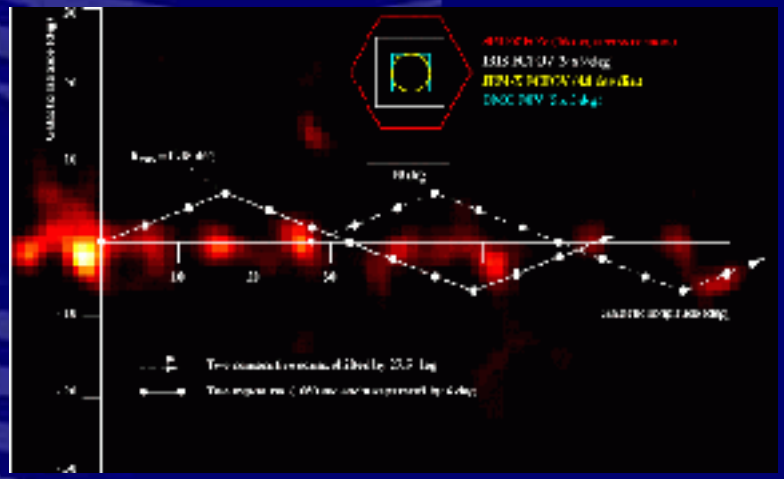
Revolution Number

Observing Programme

- INTEGRAL can observe between 50 and 130 degrees from the Sun.
- In AO-1, 35% of the observing time – the Core Programme – was reserved for the INTEGRAL Science Working Team. This decreased to 30% during AO-2 and 25% thereafter.
- Rest of the observing programme is open worldwide with Russian observers guaranteed 27% of the time (in return for the Proton launch)
- Core Programme observations are mainly regular Galactic Plane Scans and Galactic Center Region Deep



GCDE Pointing Pattern

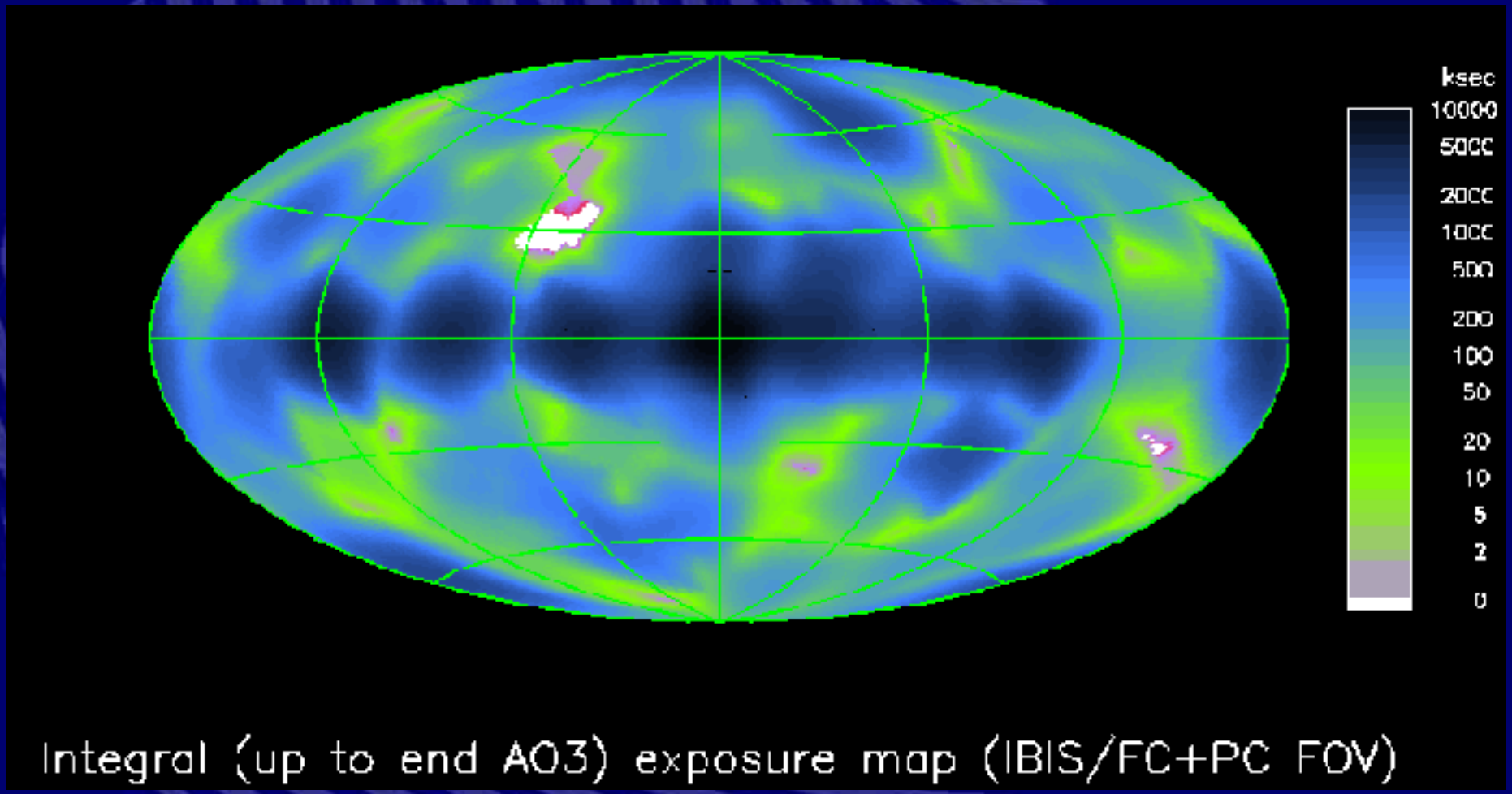


Observing Programme

INTEGRAL Pointing observation plans are available on the ISOC WWW:

Rev	Start time (UTC)	End time (UTC)	Exposure time (s)	Source	Ra (J2000)	Dec (J2000)	Pattern	PI	Proposal
366	2005-10-12 09:20:17	2005-10-13 11:0[illegible].53	13600	Gal. Bulge region	17h45m36.00	-28d56m00.0	HEX	Erik Kuulkers	20200109
366	2005-10-12 12:27:28	2005-10-13 16:19:31	97076	SS433	19h11m49.56	-04d58m57.8	5x5	Anatoly Cherepashchuk	20200086
366	2005-10-13 16:43:51	2005-10-14 15:39:15	81609	SS433	19h11m49.56	-04d58m57.8	5x5	Anatoly Cherepashchuk	20200086
366	2005-10-14 16:[illegible]:28	2005-10-14 21:53:08	6961	SS433	19h11m49.56	-04d58m57.8	5x5	Anatoly Cherepashchuk	20200086
367	2005-10-15 [illegible]:[illegible]:20	2005-10-15 14:38:33	23000	GPS			GPS	ISWT	20300316
367	2005-10-15 15:07:49	2005-10-15 21:49:09	24000	GPS			GPS	ISWT	20300316
367	2005-10-15 22:13:31	2005-10-16 00:57:23	9600	GPS			GPS	ISWT	20300316
367	2005-10-16 01:22:20	2005-10-16 09:04:02	12000	Gal. Bulge region	17h45m36.00	-28d56m00.0	HEX	Erik Kuulkers	20200109
367	2005-10-16 [illegible]:[illegible]:46	2005-10-16 16:27:46	37177	SS433	19h11m49.56	-04d58m57.8	5x5	Anatoly Cherepashchuk	20200086
367	2005-10-16 19:[illegible]:29	2005-10-16 22:52:58	20602	SS433	19h11m49.56	-04d58m57.8	5x5	Anatoly Cherepashchuk	20200086
367	2005-10-16 22:56:27	2005-10-17 09:48:49	34006	GRS 1915+105	19h15m11.50	+10d56m44.3	HEX	Ignacio Rodriguez	20200120
367	2005-10-17 09:50:56	2005-10-17 16:46:40	24670	SS433	19h11m49.56	-04d58m57.8	5x5	Anatoly Cherepashchuk	20200086
367	2005-10-17 19:50:28	2005-10-17 21:48:07	6934	SS433	19h11m49.56	-04d58m57.8	5x5	Anatoly Cherepashchuk	20200086
368	2005-10-18 [illegible]:[illegible]:42	2005-10-19 02:42:39	36003	GRS 1915+105	19h15m11.50	+10d56m44.3	HEX	Ignacio Rodriguez	20200120
368	2005-10-19 09:39:14	2005-10-19 16:20:50	23977	Gal. Bulge region	17h45m36.00	-28d56m00.0	HEX	Erik Kuulkers	20200109
368	2005-10-19 [illegible]:[illegible]:[illegible]	2005-10-19 19:[illegible]:27	27700	SS433	19h11m49.56	-04d58m57.8	5x5	Anatoly Cherepashchuk	20200086
368	2005-10-19 16:13:40	2005-10-20 06:06:08	53605	SS433	19h11m49.56	-04d58m57.8	5x5	Anatoly Cherepashchuk	20200086
368	2005-10-20 19:23:52	2005-10-20 21:2[illegible]:3[illegible]	6934	SS433	19h11m49.56	-04d58m57.8	5x5	Anatoly Cherepashchuk	20200086

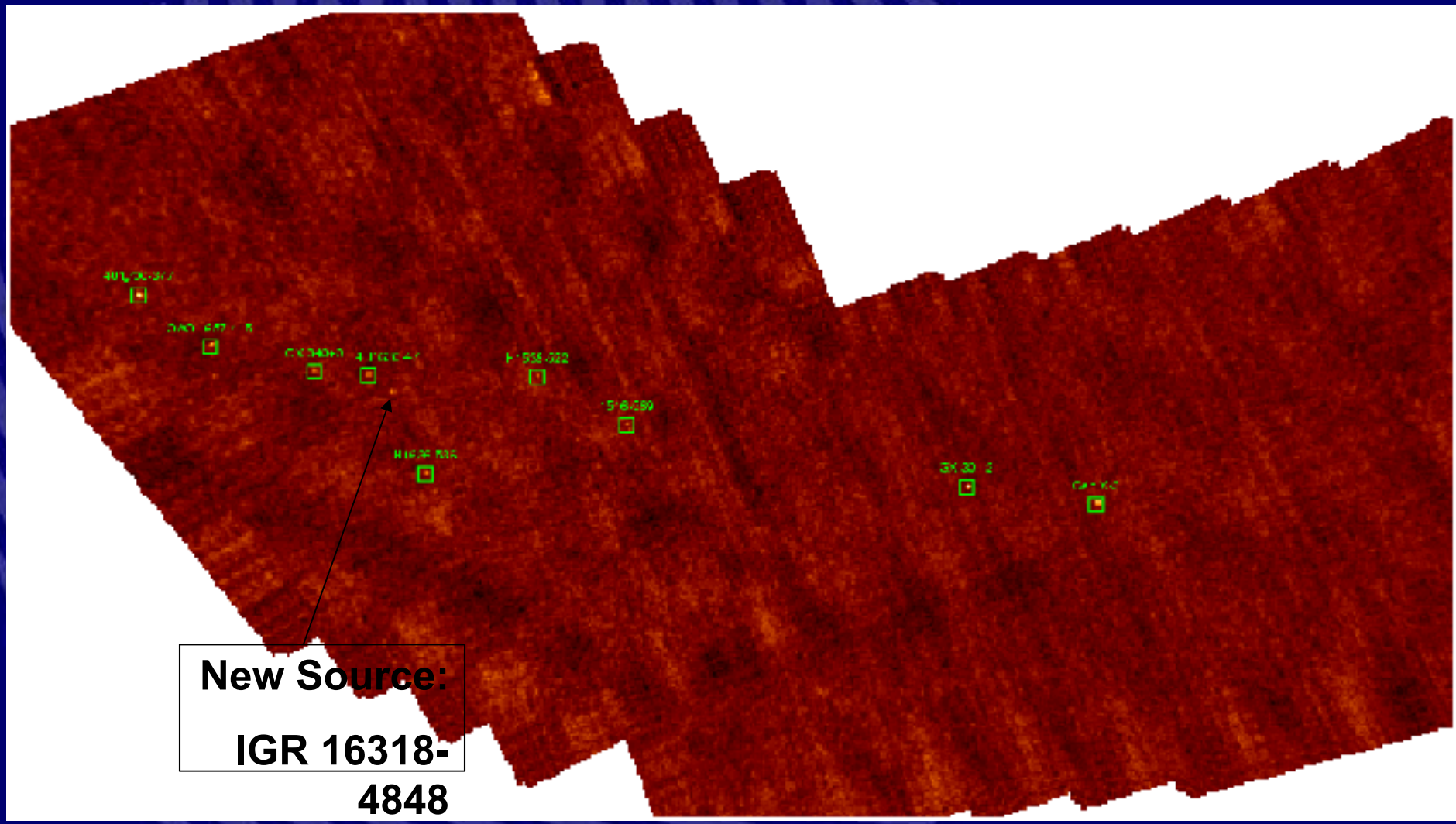
Observing Programme



Applying for INTEGRAL observations

- AO-4 preparations are underway! Tentative schedule:
  - March 3rd to April 21st – Proposal submission.
  - May 30th to June 2nd – TAC Meeting.
  - Aug 17th – Start of AO-4 observations.
- Target of Opportunity observations are always possible, even without an accepted proposal
  – if they can be accommodated.

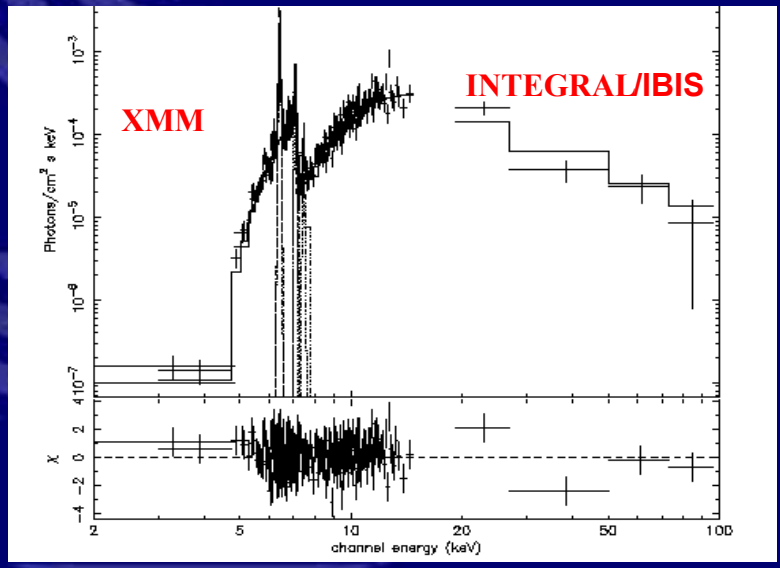
IBIS / ISGRI Galactic Plane Scans



January 2003

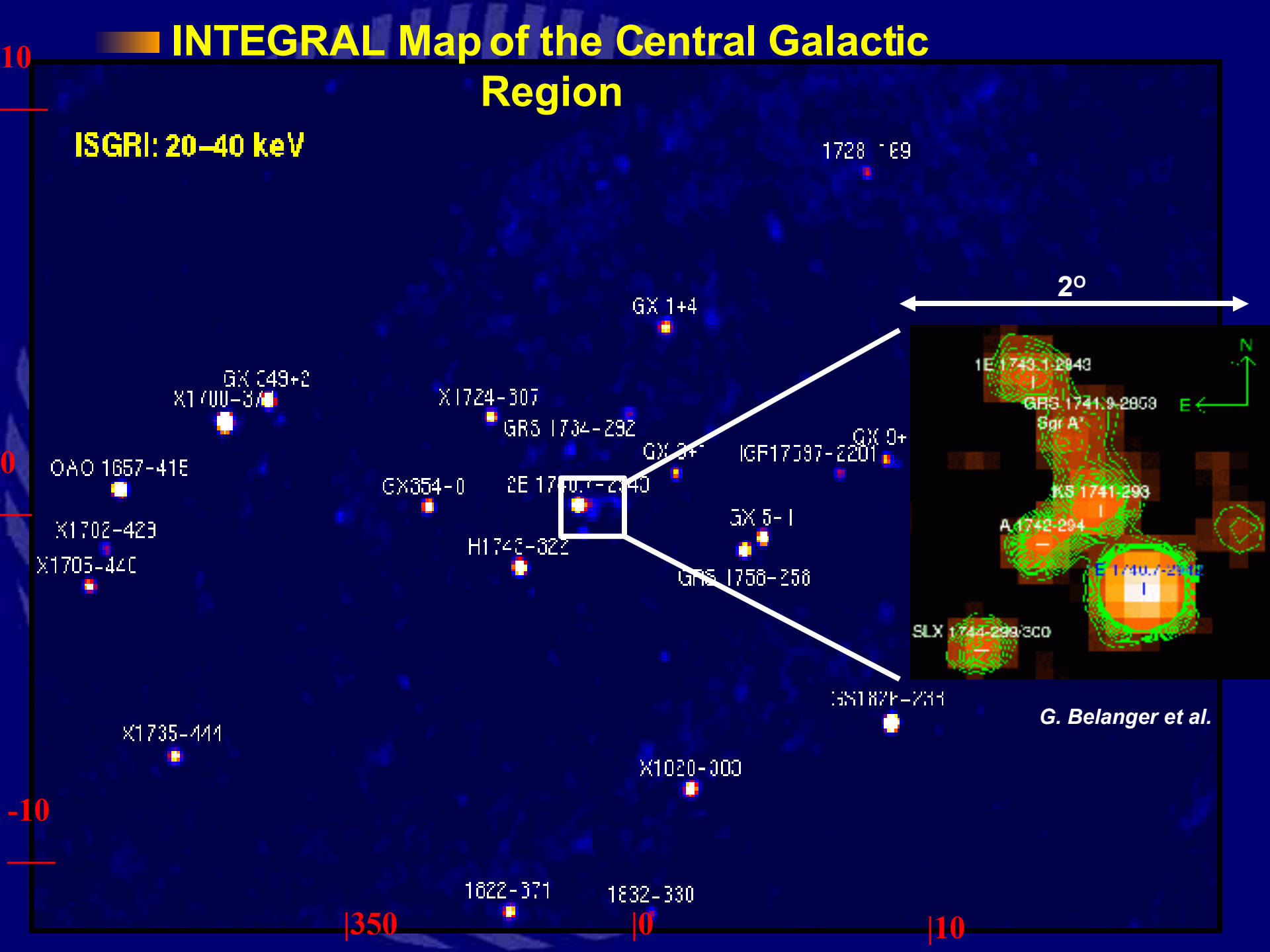
INTEGRAL detects highly absorbed X-ray binaries

- INTEGRAL has detected a new class of highly absorbed ($N_H > 10^{24}$)high-energy galactic sources.
- It is likely that IGR J16318-4848 is a HMXRB where the compact star is enshrouded by a thick accretion flow or stellar wind from the sgB[e] companion.
- INTEGRAL has detected a number of similar sources in the Norma arm tangent – the region with the highest OB-star formation rate in the



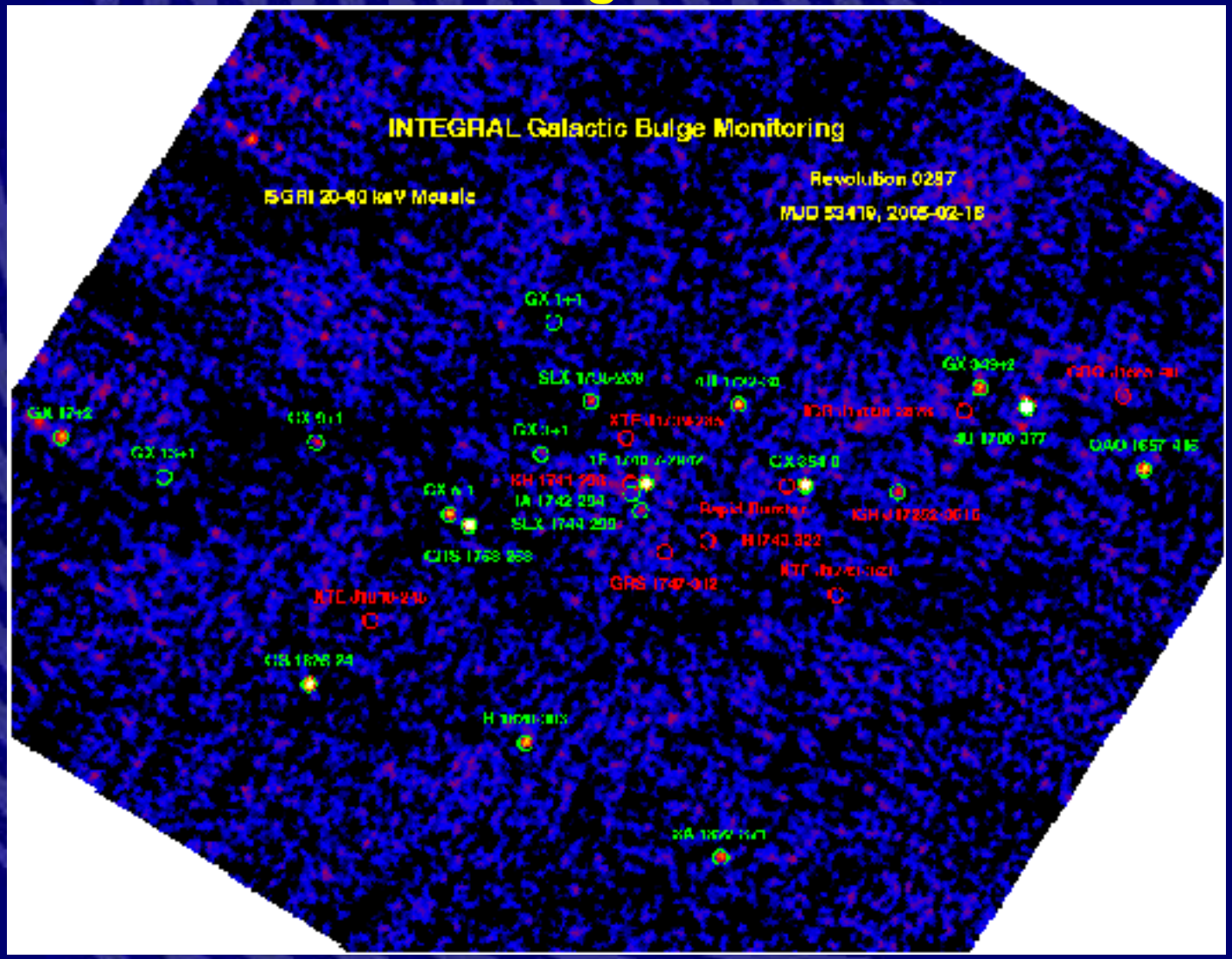
R. Walter et al. (2003)

INTEGRAL Map of the Central Galactic Region



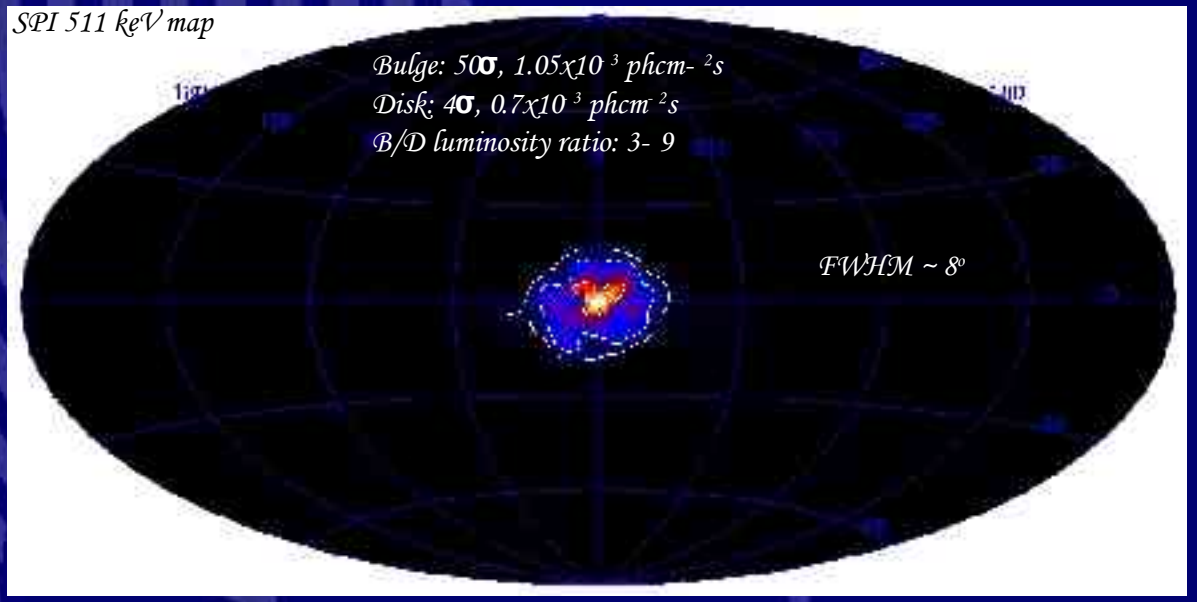
G. Belanger et al.

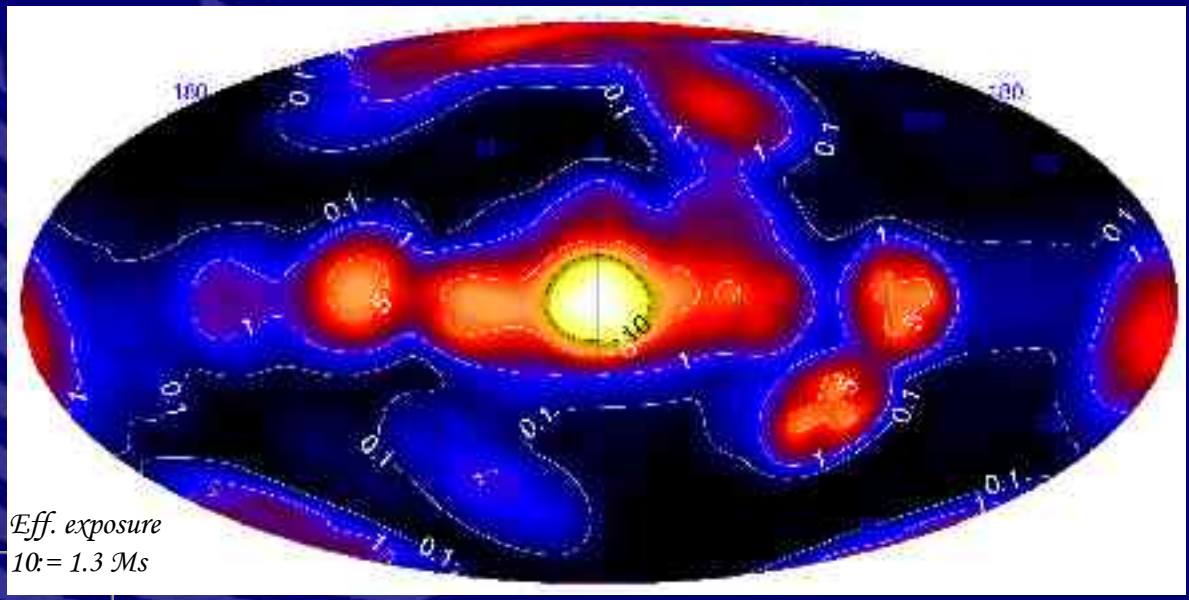
INTEGRAL Monitoring of the Galactic Bulge



INTEGRAL 511 keV All-Sky Map

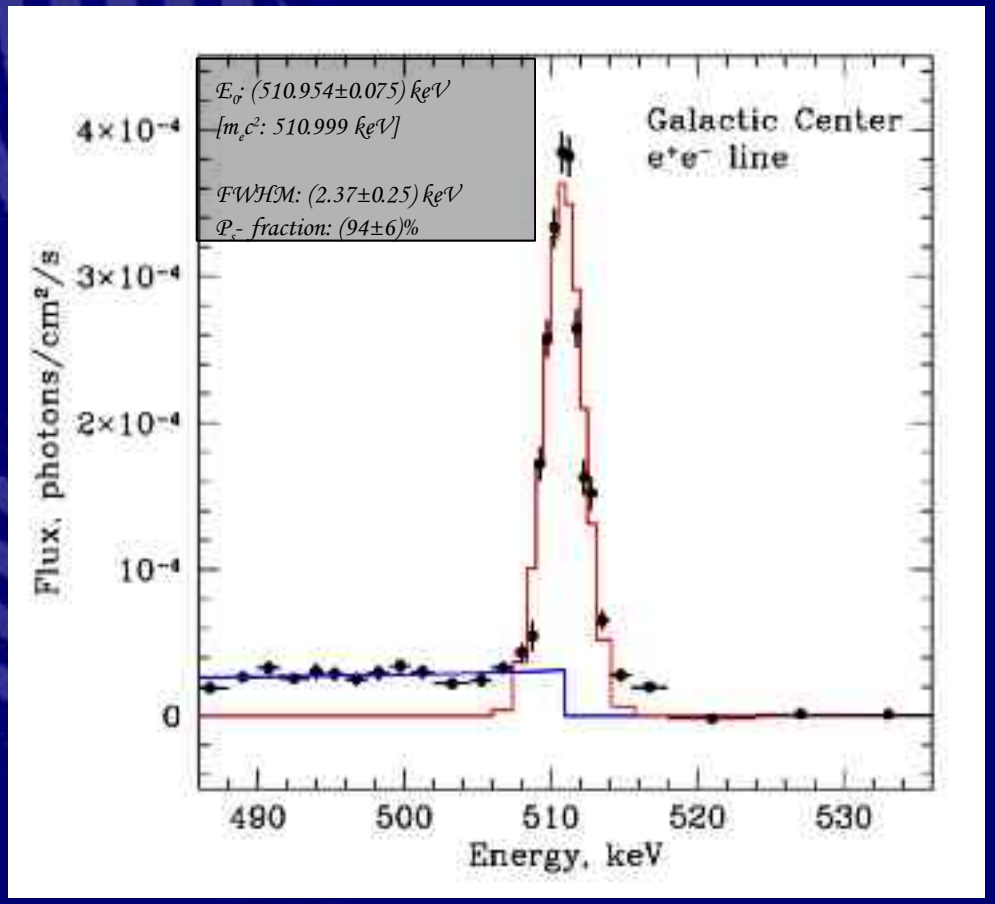
- Bulge/Disk luminosity ratio (3-9) severely constrains on principal positron source
- Bulge: Old stellar population: SN Ia + possibly Novae and/or LMXB; or possibly light Dark Matter.
- Disk: well explained by β+ decay of 26Al and 44Ti
- No point source contribution (> 10-4 cm2/s)
- No local (?) 511 keV "annihilation



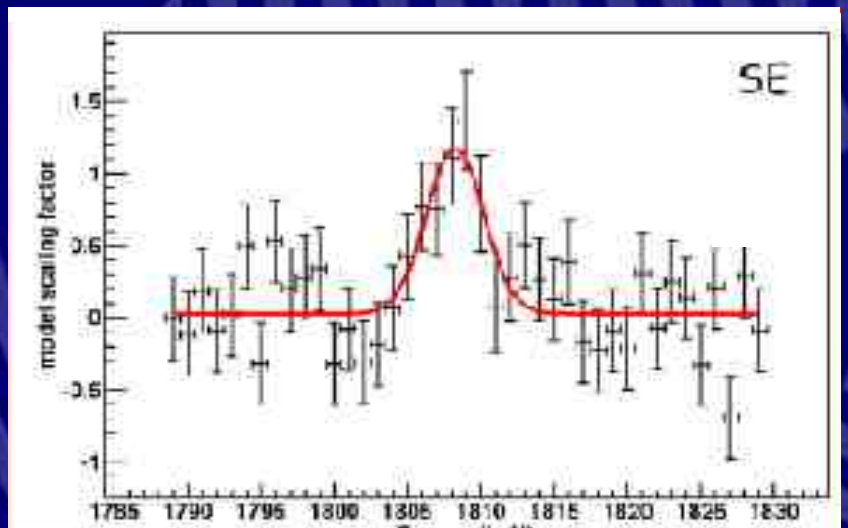


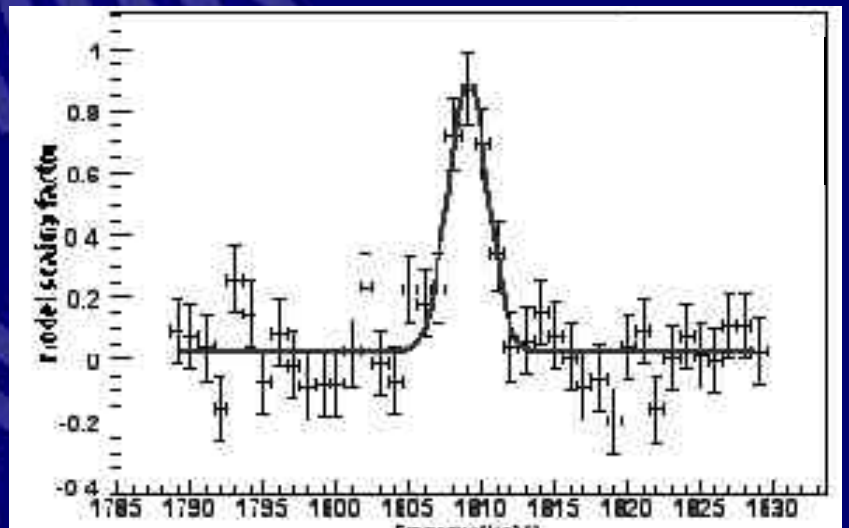
Galactic Center 511 keV Line Spectrum

- Line is unshifted (v < ~30 km/s)
- No fast expansion (v < 800 km/s)
- Brightest γ-ray line: still 2.5% of background @ 511 keV !
- INTEGRAL results most stringent constraints on temperature and ionization state of ISM: annihilation line is compatible with single-phase warm ISM



^{26}Al line emission from the Cygnus X region





Credit: J. Knoedlseder/ R. Diehl

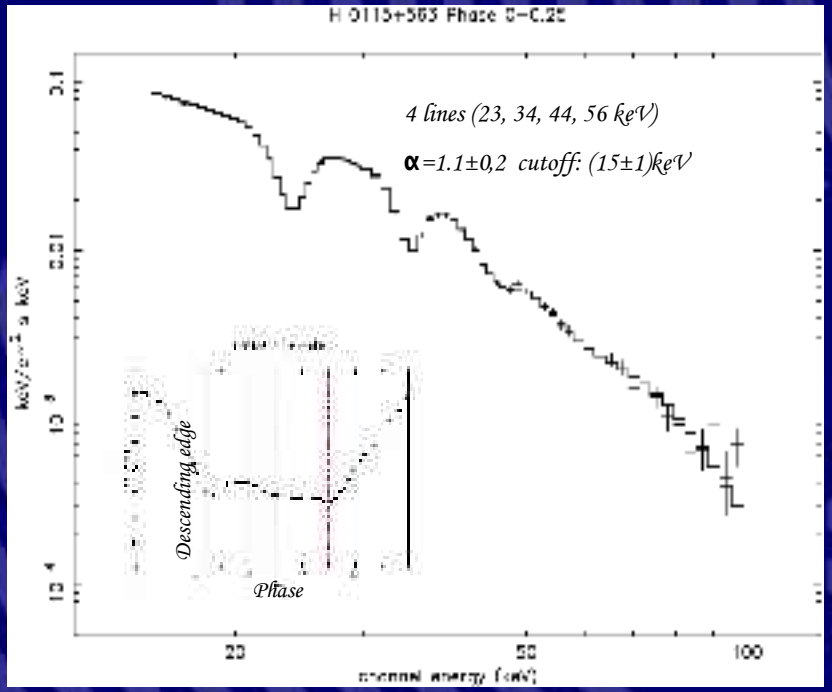
- INTEGRAL: first time precise energy determination of 1809 keV line from Cygnus region:

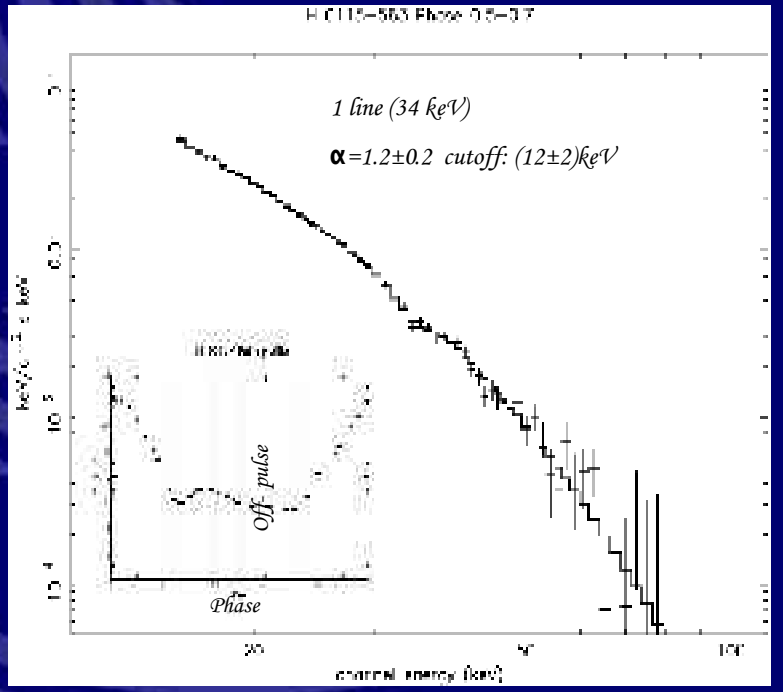
  E = 1808.4±0.3 keV,

  ΔE= 3.3 ± 1.3 keV (vdoppler: 550 ± 210 km/s)

- Broadening of line not due to galactic rotation (~ 10's km/s), so do we see evidence of turbulent motions in hot superbubbles ?

Cyvlotron line studies

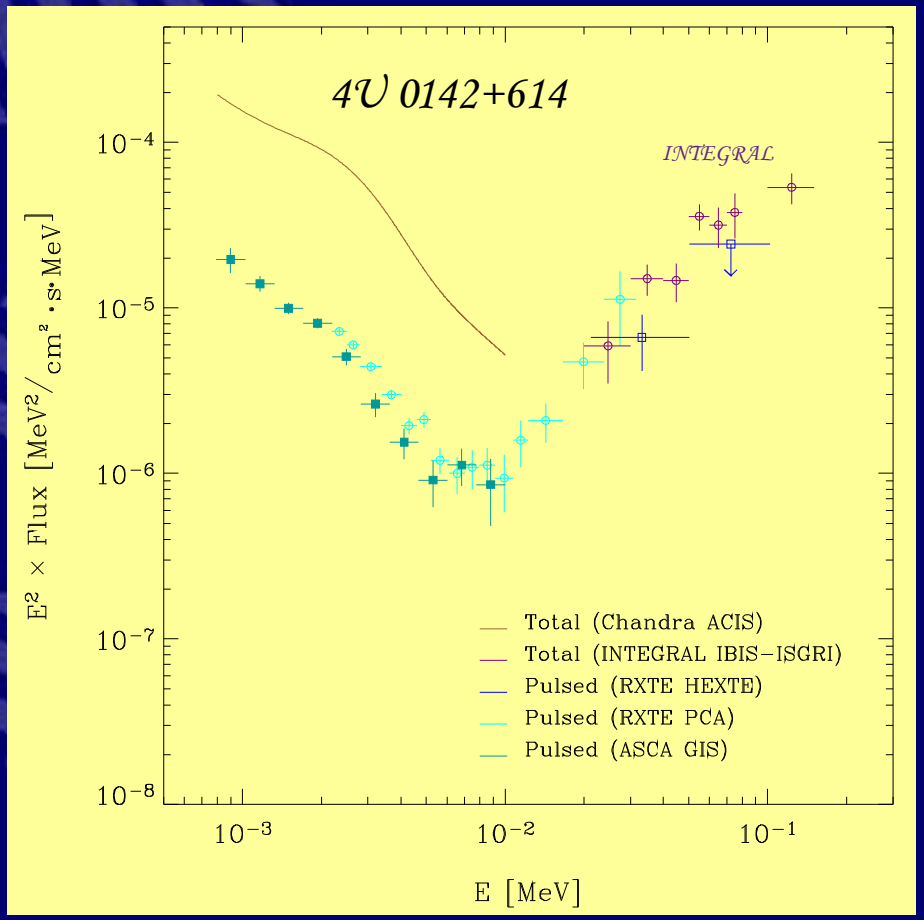




- X0115+63 = NS + Oe9 @ 7 kpc; Outburst: Sep 2004, Pspin ~ 3.6 s
  INTEGRAL: highest resolution observation of cyclotron line ever.
- Line energy = f(phase) suggests different B-field in emission regions

Anomalous X-ray Pulsars

- Hard spectral tails have been discovered for 4 AXP's as a surprise: 1E1841-045; 1RXS J1708-4009; 4U0142+614; 1E2259+586.
- Unpredicted by current theory for AXP's. Energy window (>10 keV) proves to be an important diagnostic to study magnetars
- The hard (PL) spectral (pulsed) tails must have a magnetospheric origin, not powered by the spin-down
- Spectra must break/bend towards CGRO energies, but still no signs of break in the 100-300 keV window

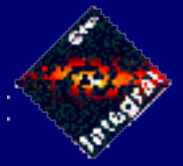


Using INTEGRAL Data

- For a start look at what exists already, e.g.:
  - Public data archive at ISDC (with copy at ISOC)
  - “The INTEGRAL Sky” Web page at ISDC.
  - INTEGRAL Bright Source Catalog (GSFC, ISDC)
  - Galactic Bulge Monitoring pages (ISDC).
  - Accreting X-ray Pulsar Monitoring pages (Warwick, links from ISDC or ISOC).
- Select and download data, ***learn to use OSA***

  and start ‘playing’!
- Don’t forget – there are four instruments and each one may have something interesting for you!

Using INTEGRAL



Finally, enjoy the Workshop!

esa