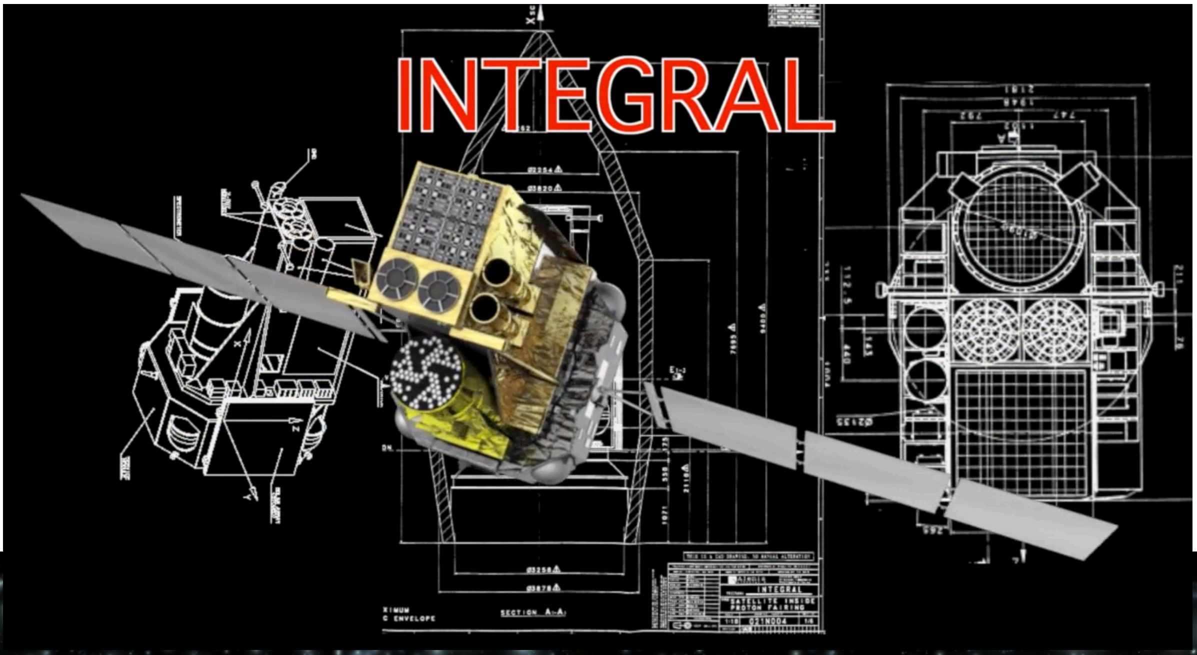
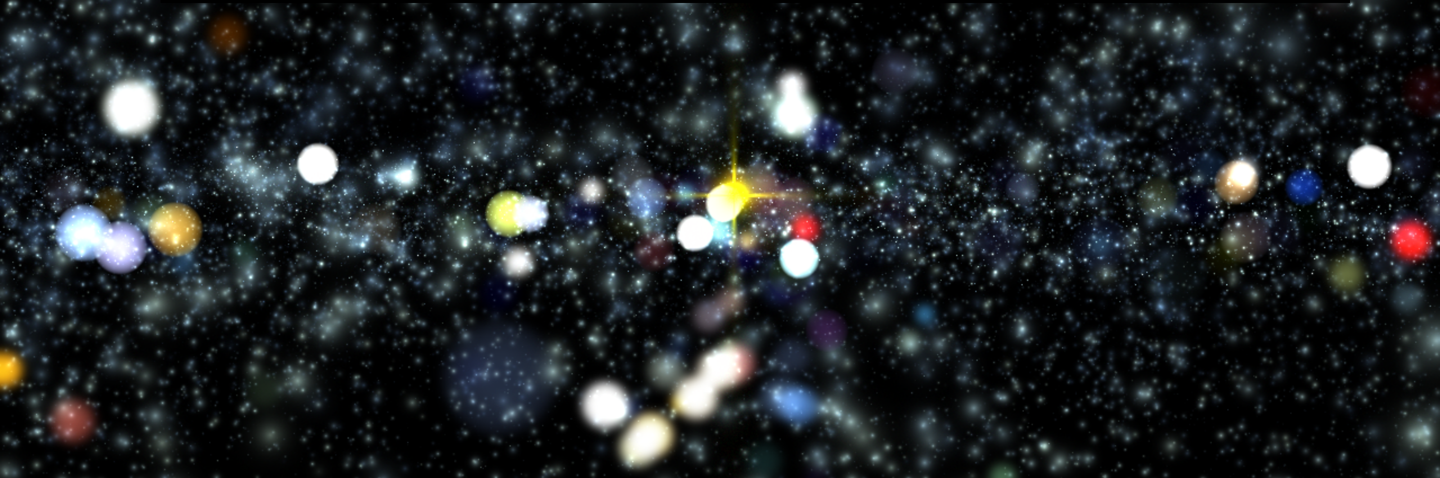
The International Gamma-Ray Astrophysics Laboratory

Mission Extension 2014: INTEGRAL Science Case

Appendix





Compiled by the INTEGRAL Users Group

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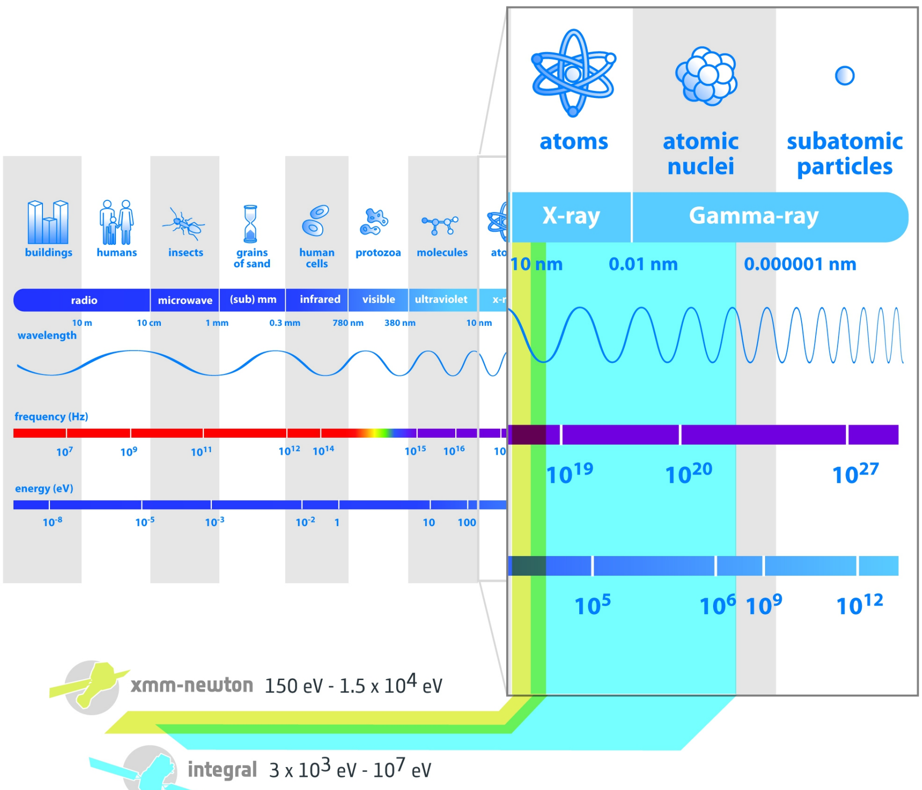
The INTEGRAL extension case and this Appendix is available for download at
http://www.cosmos.esa.int/web/integral/teams-iug

INTEGRAL mission extension 2014 - Appendix

This appendix contains extra information to support the 2014 *INTEGRAL* mission extension case. It is divided in 4 parts:

- Figures, mostly recent, highlighting the scientific areas showing *INTEGRAL's* strengths and uniqueness.
- *INTEGRAL* mission impact and metrics.
- *INTEGRAL* instruments parameters.
- List of theses based upon *INTEGRAL* results.

The *INTEGRAL*-related refereed and non-refereed publications are based on the ADS database, and can be found via:
http://adsabs.harvard.edu/cgi-bin/nph-abs_connect?library&libname=Integral&libid=450176be03



Top: A scheme of the electromagnetic spectrum highlighting the high-energy regions observed by ESA's *INTEGRAL* and *XMM-Newton* space observatories. [Credits: ESA/ AOES Medialab]

Appendix cover page, bottom image: The 4th soft γ-ray source catalogue, released in 2010, obtained with *INTEGRAL*/IBIS/ISGRI, contains more than 700 high-energy sources detected in the energy range 17-100 keV, including both transients and persistent objects. For ~300 sources which are a member of our Galaxy (including black-hole and neutron star X-ray binaries, cataclysmic variables, and other exotic objects), we know the distance. These sources can thus be represented in a 3D fashion. When *INTEGRAL*'s 10 years in space was celebrated, movies including a 3D-view of our Galaxy as seen by *INTEGRAL*, were released. In the image we are facing our Sun (the tiny yellow blob just above the centre of the image) from *behind* the Galactic Centre . Many of the sources are annotated with (part of) their astrophysical name. The size and colours of the fuzzy spheres are based on the intensities in the 17-35-60-100 keV bands. [Credits: ESA/C. Carreau & E. Kuulkers]

γ-ray line spectroscopy – I: SN2014J

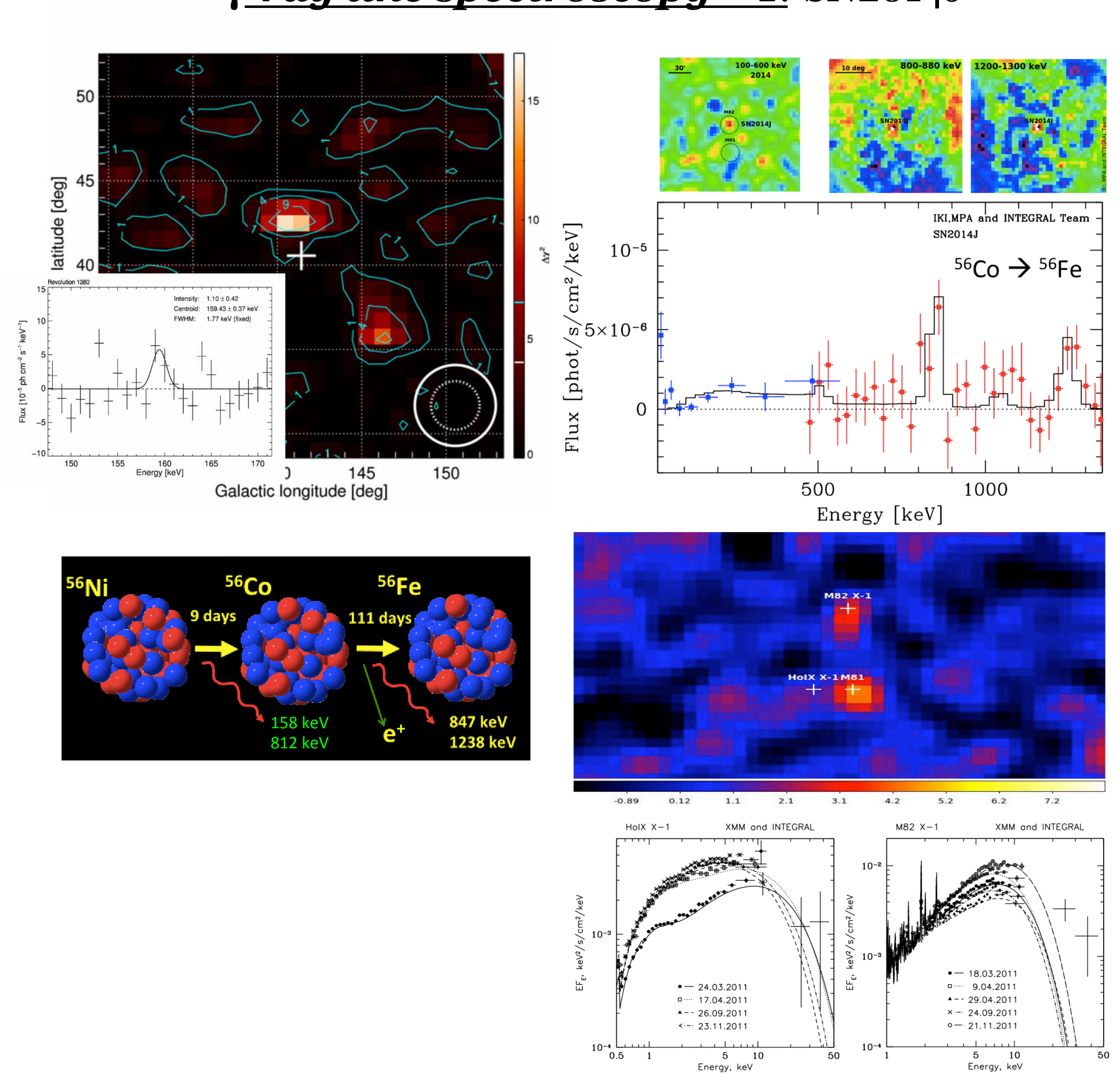


Figure 1: *Top left:* The *INTEGRAL*/SPI spectrum of SN2014J around 158 keV about 2 weeks after the explosion, with the detection of the ^{56}Ni decay line, is shown in the lower left. The origin of the signal agrees within the measurement error with the position of the SN (indicated by the cross in the map of the observed sky region). The map shows the point source significances across the field of view observed in a 10 keV wide energy band including the 158 keV line. The circles in the lower right of the map show the instrumental point source size (68% contours dashed, 90% contour solid). [Figure adapted from R. Diehl *et al.* 2014, Science 345, 1162] *Top right:* The bottom part shows the *INTEGRAL*/SPI spectrum (red points) of SN2014J over the period 50-100 days after the explosion. The ^{56}Co decay lines at 847 and 1238 keV are seen. Blue points show ISGRI/IBIS data for the same period. The flux below ~60 keV is dominated by the emission of M82 itself (as seen in 2011 during M82 observations with INTEGRAL, see the figure shown at the bottom of this page). The black curve shows a fiducial model of the SN spectrum for day 75 after the explosion. Figure adapted from E. Churazov *et al.* 2014, Nature 512, 406] *Lower left:* Decay chain of ^{56}Ni, indicating the decay times and expected decay line energies. *Lower right:* Top panel shows the *INTEGRAL*/IBIS/ISGRI images of the M81 group of galaxies, which contains two bright ULXs, Holmberg IX X-1 and M82 X-1. The deep (~6 Ms) observations resulted in just a weak detection of M82 X-1 and non-detection of Ho IX X-1 at energies above 20 keV. Together with *XMM-Newton* data a clear cut-off at energies above 10 keV in the spectra of both ULXs (bottom panels) can be derived. [Figure adapted from S.Y. Sazonov *et al.* 2014, Astronomy Letters, 40, 65]

γ-ray line spectroscopy – II: ^{26}Al

1809 keV Line Width → ^{26}Al at ~175 km s^{-1}

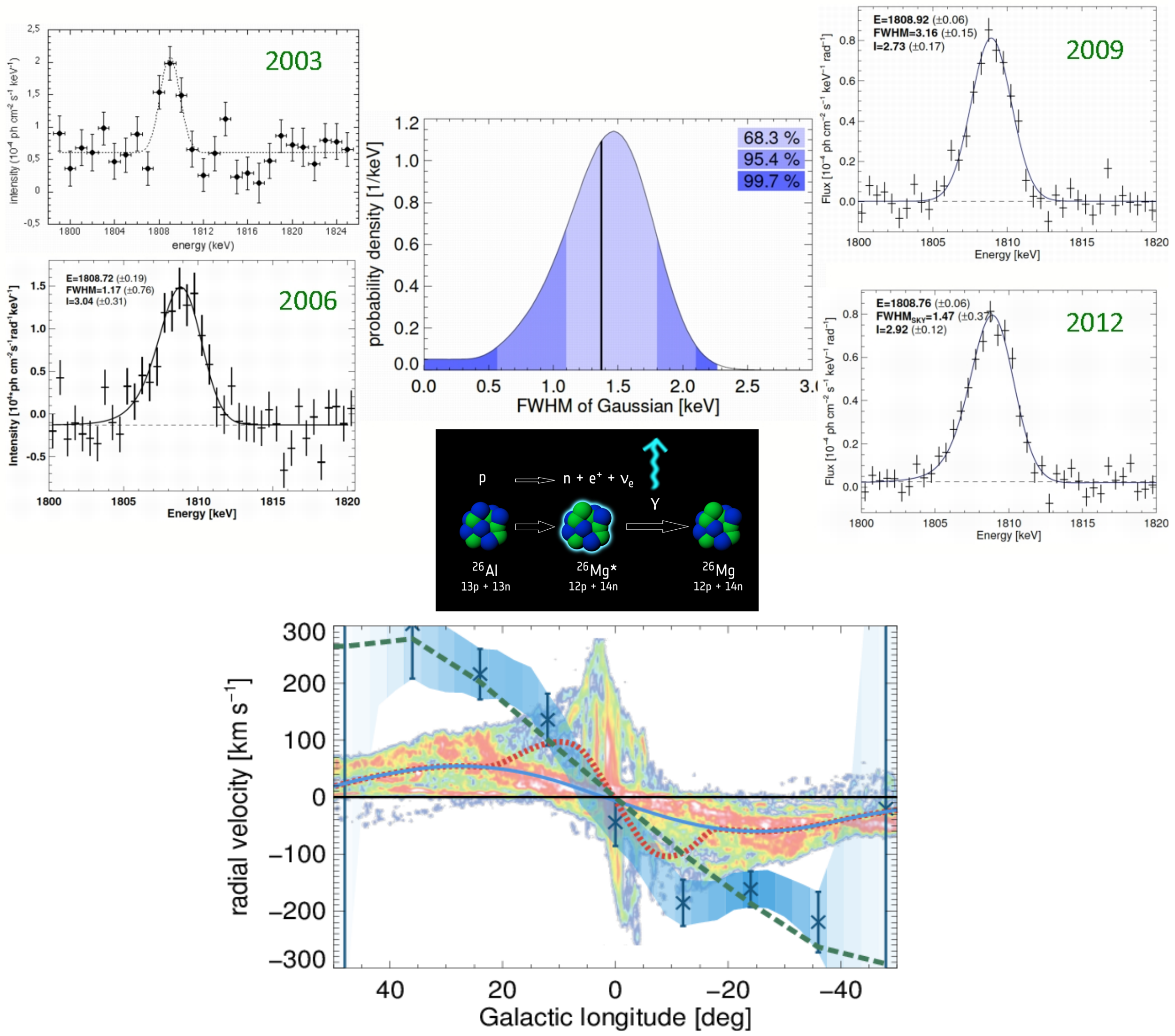


Figure 2: *Top figure:* The width of the γ-ray line from the decay of ^{26}Al in the Galaxy's interstellar medium as measured with *INTEGRAL*/SPI. The central figure shows the probability distribution for the line width from interstellar motion through Doppler shift, which is modeled as a Gaussian, and added to the instrumental line width through convolution. Probability regimes, which correspond to 1σ, 2σ, and 3σ are indicated by colour shading. The measured value of 1.4 keV corresponds to a velocity of (175 ± 45) km s^{-1}. The graphs on the left and on the right sides show how the ^{26}Al line measurements improve with exposure, showing the spectra around the 1808.63 keV line from ^{26}Al as derived in successive analyses over the years. [Credits: SPI Team, K. Kretschmer & R. Diehl] *Bottom figure: INTEGRAL*/SPI measurements of the speed at which hot gas ejected by massive stars in the inner regions of the Milky Way moves, using the Doppler shift of the γ-rays emitted by radioactive ^{26}Al. The velocities (crosses, including error bars) are compared with other objects in our Galaxy. For comparison, different models are shown (blue solid, red dotted, and green dashed lines), as well as the velocity information from molecular gas as seen in CO (colour scale overlay). This shows that a large fraction of this hot gas can move at high speed for a long time and therefore over long distances before it is stopped when it encounters other gas. From this, it is deduced that the massive stars that eject the ^{26}Al are probably located on the leading edge of the spiral arms, and blow most of their ejecta over large distances into the regions between the spiral arms. [Figure adapted from K. Kretschmer *et al.* 2013, A&A 559, A99]

γ-ray line spectroscopy – III: 511 keV

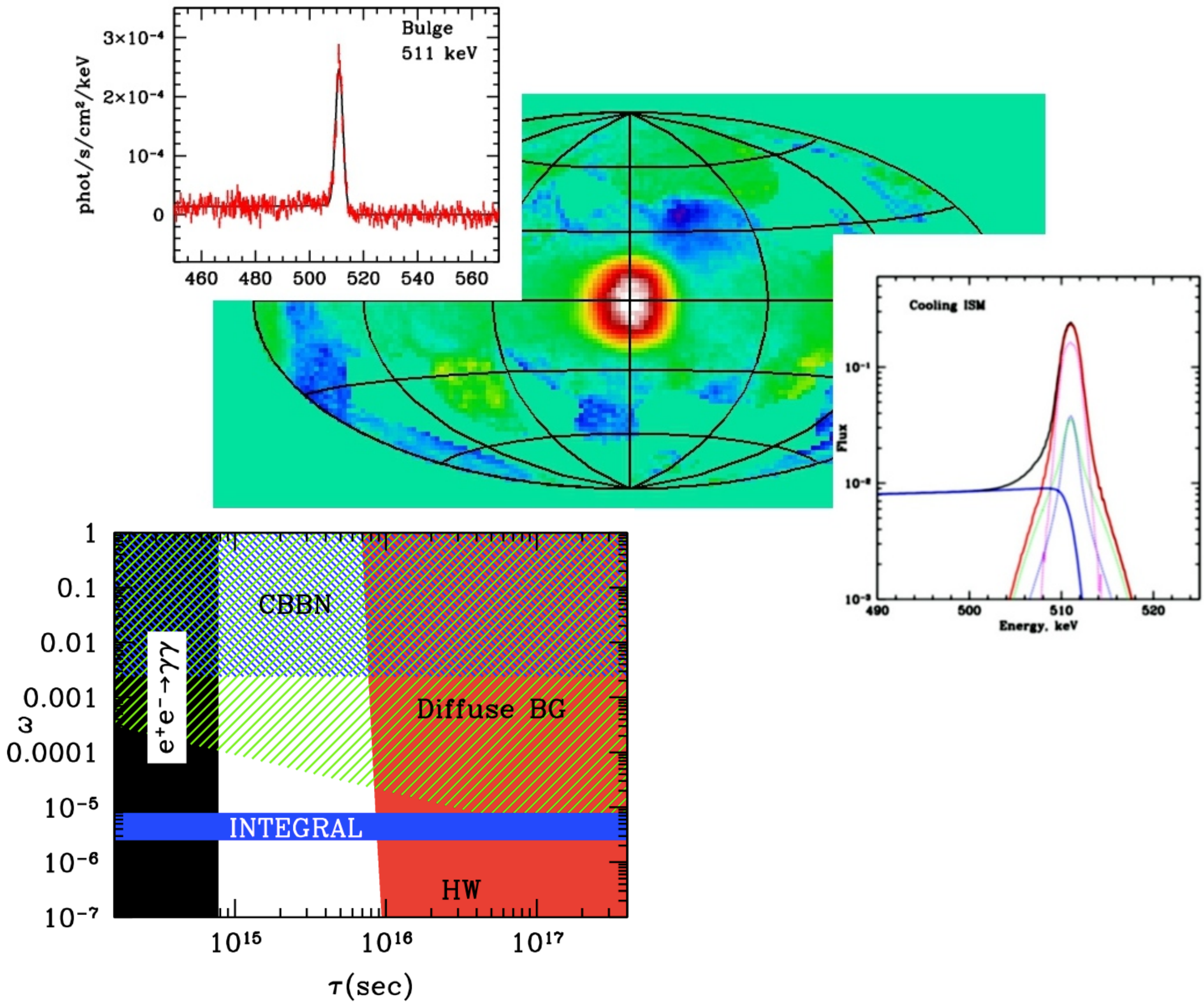


Figure 3: *Top:* Copious production of positrons is taking place in the Galactic Centre (GC) region. *INTEGRAL* sees strong emission from an area of a few degrees around the dynamic centre of our GC (middle image; 508—514 keV), where every second about 10 billion tons of positrons are colliding with electrons and annihilating. The observed γ-ray glow has a unique spectrum, which consists of a narrow line at 511 keV - signature of cold electron-positron annihilation, and a broad continuum, indicating that most positron-electron pairs form atoms of positronium before annihilating (top left image). The bottom right image shows a predicted model spectrum resulting from the cooling process of positrons in the ISM. [Figure adapted from E. Churazov *et al.* 2011, MNRAS 411, 1727] *Bottom:* One of the origins of the GC positrons include enigmatic dark matter particles. This figure shows the constraints on the charged unstable dark matter component, X (which decays into a stable component, the dark matter as of today, and positrons), from Heavy Water (HW), Catalyzed Big Bang Nucleosynthesis (CBBN) and the diffuse γ-ray background. The CBBN constraint applies only to the symmetric scenario (relic abundances of positively and negatively charged X are the same). The region labeled $e^+e^- \rightarrow \gamma\gamma$ would produce positrons early enough that the high background electron density would lead to complete annihilation and therefore no residual signal. Shaded regions are excluded. The horizontal blue band denotes the region in parameters space that would produce a 511 keV flux consistent with that observed by *INTEGRAL*. [Figure from L. Boubekeur *et al.* 2012, PhRvD 86, 103520]

Hard X-ray line spectroscopy: Cas A & SN1987A

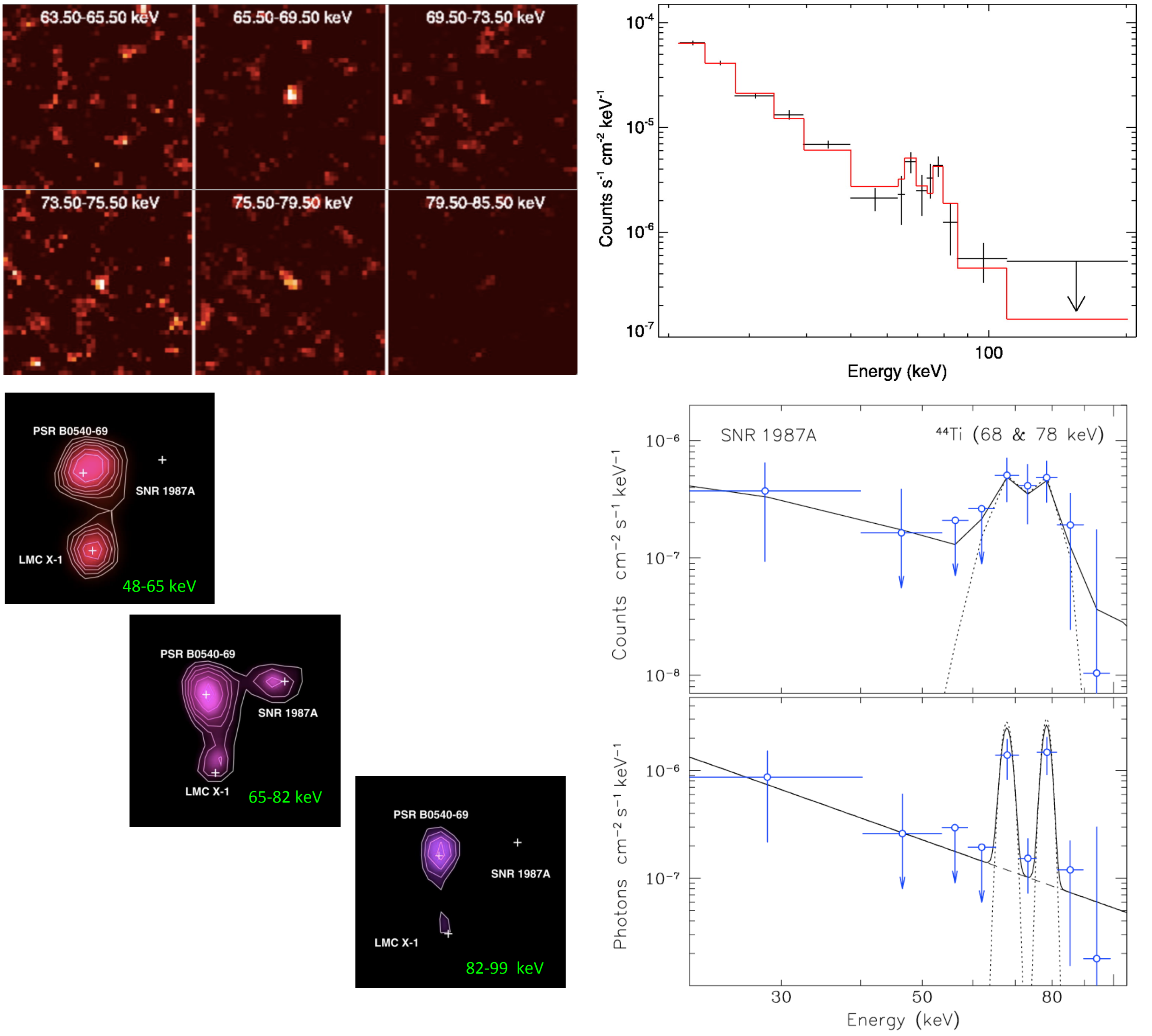


Figure 4: *Top:* (Left) *INTEGRAL*/IBIS/ISGRI flux images (2.5°×2.5°) centered on Cas A in 6 energy bands. The linear scale is the same for all images. Note that the noise in the images depends on the energy bandwidths. (Right) IBIS/ISGRI spectrum of Cas A and the best-fit model (solid red line), showing the 67.9 and 78.4 keV ^{44}Ti decay lines. The upper limit above 110 keV is given at the 3σ confidence level. [Figures from M. Renaud *et al.* 2006, ApJ 647, L41] *Bottom:* (Left) IBIS/ISGRI hard X-ray images (1.5°x1.5°) indicating the detection of ^{44}Ti decay emission lines from SN1987A. The maps show the signal-to-noise ratio contours in 3 energy bands based on a total exposure of ~6.0 Ms. Two well-known sources, PSR B0540-69 and LMCX-1, are clearly seen in all 3 images; SN1987A is only confidently detected in 65-82 keV, containing the 67.9- and 78.4-keV direct-escape lines of radioactive decay of ^{44}Ti. (Right) IBIS/ISGRI hard X-ray spectrum of SN1987A. Top panel: observed (count) spectrum together with the simulated response curves. Bottom panel: unfolded (photon) spectrum. In each panel, open circles show the spectra, dotted curves show the fit with two Gaussian lines at 67.9 and 78.4 keV, and solid curves show a similar fit which includes an additional power-law continuum with photon index = 2.1. It is expected that ^{44}Ti is produced inside the SN core, which is expanding with velocity v ≤ 1, 700 km s^{-1}; thus, the internal width of the lines (that is, their width before smoothing due to the finite energy resolution of the instrument) is unlikely to exceed E ≈ 0.4 keV. The upper limits are 1.7 (90% confidence); error bars on the other points are 1σ. [Figures adapted from S.A. Grebenev *et al.* 2012, Nature 490, 373]

Polarisation: Cygnus X-1, GRB061122 & Crab

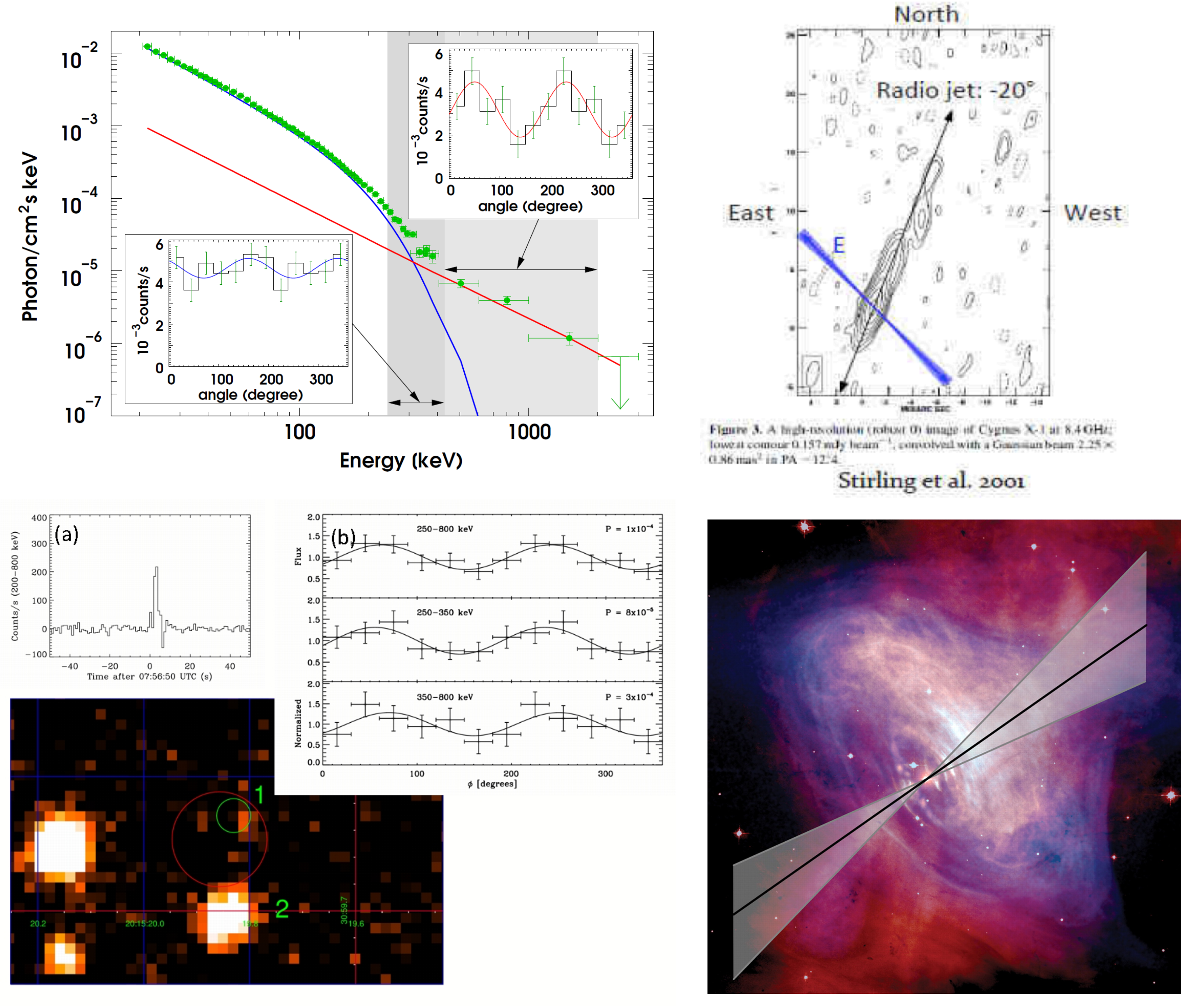


Figure 5: *Top Left: INTEGRAL*/IBIS/ISGRI spectrum of Cygnus X-1 (green points). The blue curve describes the spectrum between 20-400 keV; the red line describes the data between 400-2000 keV. The two insets show the polarization signal at 250-400 keV (bottom left) and at 400-2000 keV (top right). In the 250-400 keV band, the measured signal is consistent with a flat signal, indicating that the emission is only weakly polarized or not polarized at all; in the 400-2000 keV band the signal shows a significant modulation, consistent with a high degree of polarization. The detection of polarization above 400 keV indicates that emission at these energies derives from non-thermal radiation processes that take place in the jets, such as synchrotron or inverse Compton emission. [Figure adapted from P. Laurent *et al.* 2011, Science 332, 438]. SPI confirmed the γ-ray polarization (E. Jourdain *et al.* 2012, ApJ 761, 27). *Top right:* The polarization vector (blue), inferred from *INTEGRAL*/SPI measurements, is superimposed on a high-resolution radio (8.4 GHz) image. [Credits: SPI team] *Bottom left:* (*a*) *INTEGRAL*/IBIS light curve of GRB061122. IR J-band image of the GRB 061122 field; the red circle represents the *Swift*/XRT error box, while the smaller green circle represents the optical afterglow error box. Object 1 has been identified as the GRB host galaxy candidate. (*b*) Polarigrams of GRB061122 in different energy bands. The chance probability of a non-polarized (<1%) signal is reported in each panel. [Figure adapted from D. Götz *et al.* 2013, MNRAS 431, 3550] *Bottom right:* Composite image of the Crab from *Chandra* (X-ray, blue) and the *Hubble Space Telescope* (optical, red). The polarization vector, inferred from *INTEGRAL*/SPI measurements, is superimposed. [Figure from A.J. Dean *et al.* 2008, Science 321, 1183]

Surveys: LMXBs, HMXBs, SFXTs, AGN and diffuse emission

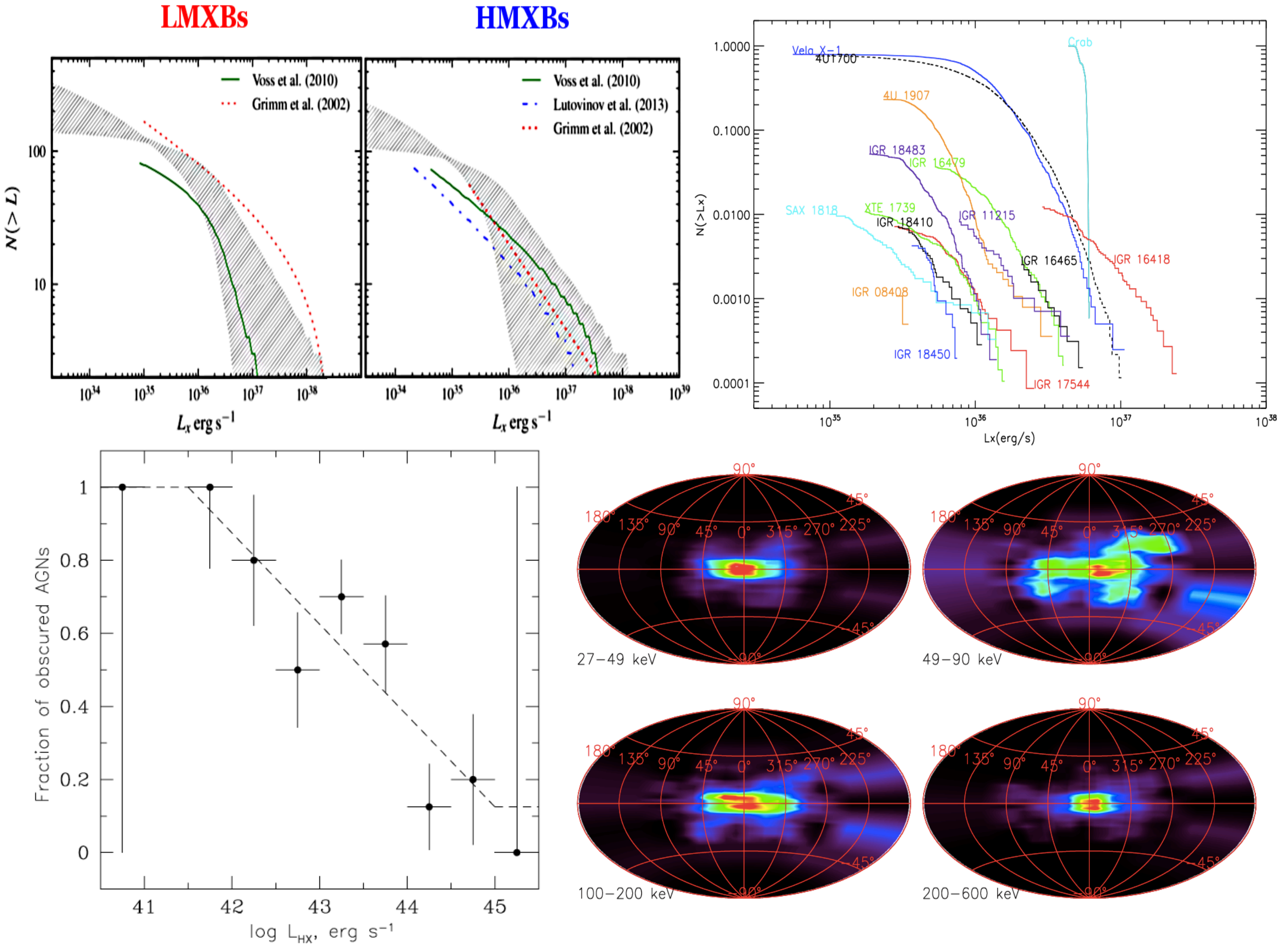


Figure 6: *Top left:* The X-ray luminosity function, XLF, is usually derived from the observed flux distribution of X-ray binaries with known distances. Incompleteness effects must then be corrected for. To overcome this, one can also model the observed flux distribution of XRBs. The two panels show the cumulative luminosity functions for LMXBs (left) and HMXBs (right) using the *INTEGRAL*/IBIS/ISGRI 9-year survey (hatched areas; this is the most sensitive hard X-ray survey to date). Best-fit estimates, published in the literature, are also shown for reference. [Figure adapted from V. Doroshenko *et al.* 2014, A&A 567, A7] *Top right:* Cumulative luminosity distributions for supergiant fast X-ray transients in the IBIS/ISGRI 17–50 keV band. Each curve has been normalized to the total exposure time of the specific source. The duty cycles, the highest values in the y-axis, are with respect to the whole *INTEGRAL* archive. [Figure from A. Paizis & L. Sidoli 2014, MNRAS 439, 3439] *Bottom left:* Fraction of obscured (absorption column, $N_H > 10^{22}$ cm^{-2}) AGNs in the local universe as a function of hard X-ray (17-60 keV) luminosity, L_{HX}, based on the *INTEGRAL* sample. Error bars represent the Poisson uncertainty associated with the number of objects in a given bin. The lowest and highest luminosity bins contain just one source each (NGC 4395 and IGR J09446-2636, respectively). The approximate description of the observed trend is shown by the dashed line. [Figure from S. Sazonov *et al.* 2012, ApJ 757, 181] *Bottom right:* Diffuse emission intensity all-sky maps. The SPI energy bands are (top left) 27–49 keV, (top right) 49–90 keV, (bottom left) 100–200 keV, and (bottom right) 200–600 keV. The original images have pixels of different sizes and are first downsampled to a common pixel size of 3°×2.6°; thereafter they are smoothed by a 3×3 pixel boxcar. The "diffuse" emission energy is minimal in the 50–100 keV band. [Figure from L. Bouchet *et al.* 2011, ApJ 739, 29]

Imaging/monitoring: Galactic Center region

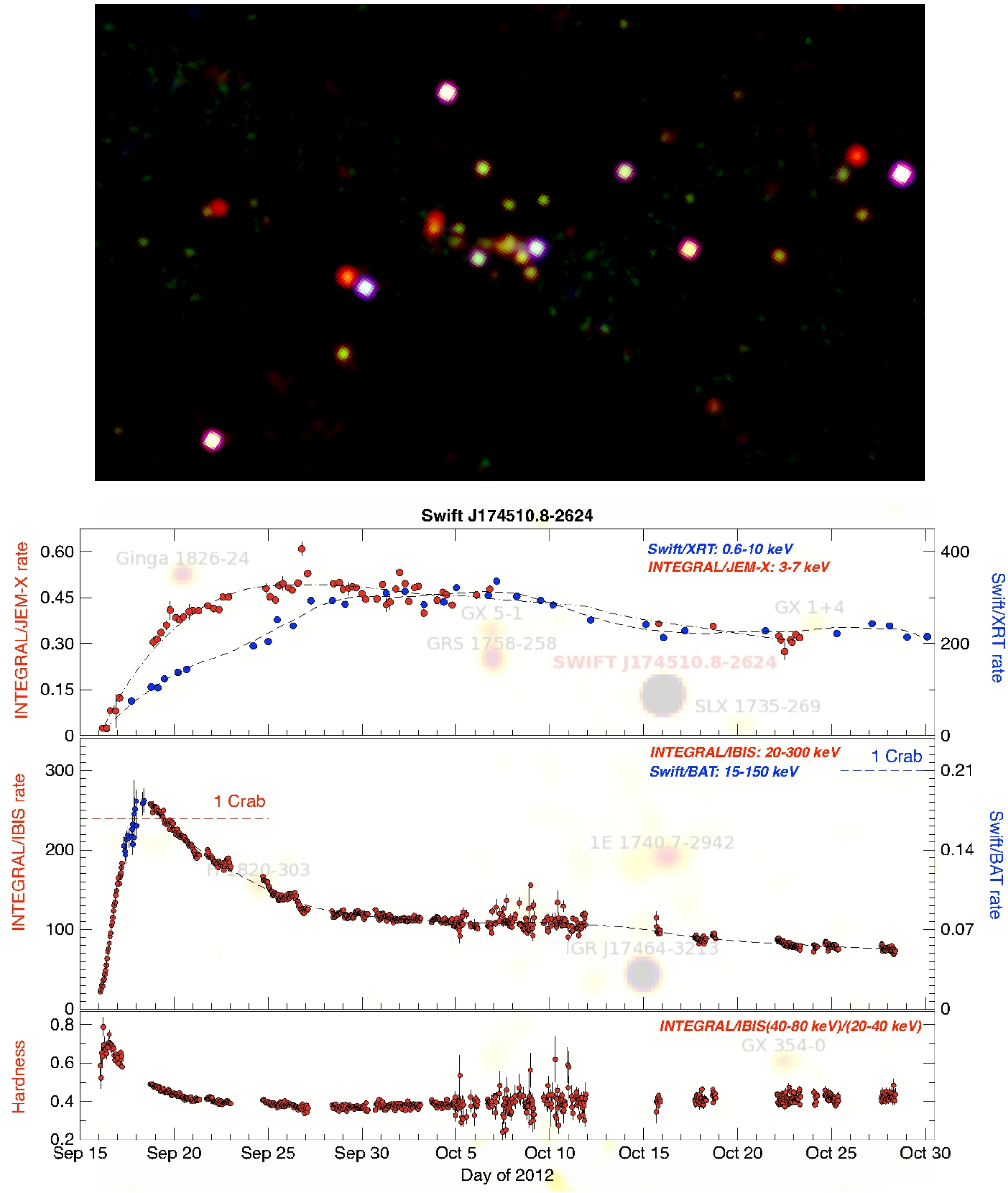


Figure 7: *Top:* 25°x15° IBIS/ISGRI map around the Galactic Center (GC) in "true colours". The Galactic map is a mosaic of the AO-4 and AO-5 GC Key Programme data. "True colour" describes the image composed of three layers: red, green, and blue, that correspond to three energy bands: 20-35, 35-60, and 60-100 keV. The Crab would look white, i.e., with equal contribution from each of the bands. This allows to see the hardness of the sources with respect to the Crab's spectrum. A Gaussian smoothing filter with a radius of 3 pixels was used. [Credits: G. Bélanger, ESA/ISOC] *Bottom:* In September 2012, a new transient black-hole binary was discovered by the *Swift* satellite: Swift J174510.8-2624. Located close to the GC, it was observed serendipitously by *INTEGRAL* and was seen to brighten rapidly. A dense observing campaign with *INTEGRAL* was triggered, featuring a near-continuous pointing for two full weeks. The source was also monitored by *Swift* and ground-based telescopes from optical to radio. *XMM-Newton*, *Chandra* and *Suzaku* observations were also made. Shown is the time evolution of Swift J174510.8-2624 as observed by *INTEGRAL* and *Swift*. Top panel: light curve from the *Swift*/XRT (blue) and *INTEGRAL*/JEM-X (red). Middle panel: *INTEGRAL*/IBIS/ISGRI light curve (red); note that the source flux exceeded the Crab level. Bottom panel: evolution of the ratio between the hard (40-80 keV) and soft (20-40 keV) bands in IBIS/ISGRI, a crude measure of the hardness of the spectrum. The image vaguely visible in the background is the IBIS/ISGRI map of the field. [Credits: T. Belloni, INAF-OAB, Italy]

INTEGRAL: Synergy with other missions

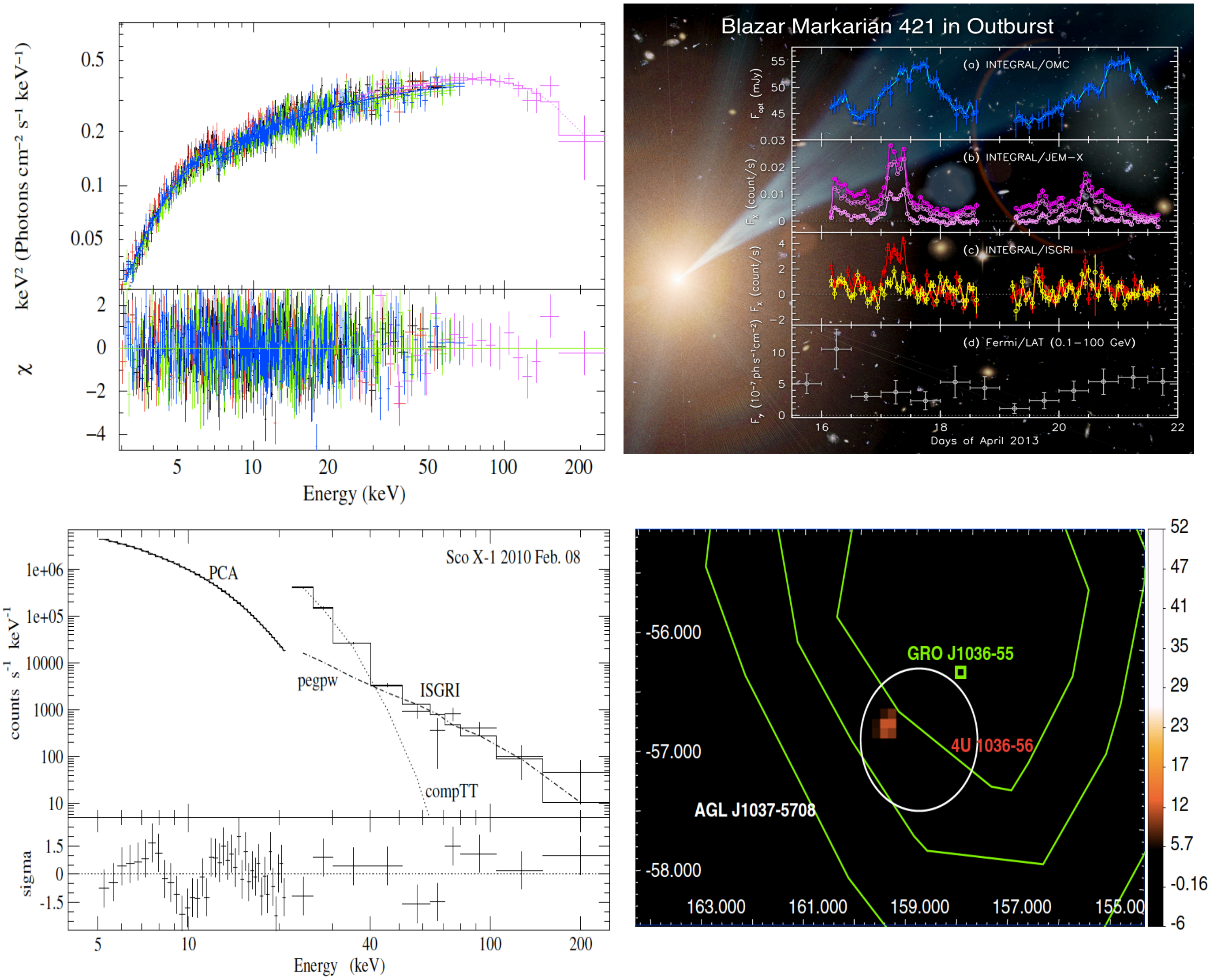


Figure 8: *Top left:* Unfolded spectrum of the persistent black-hole binary and microquasar in the Galactic Center region, 1E1740.7-2942 ('the Great Annihilator'), during a low/hard state observed by *INTEGRAL* and *NuSTAR*. A disk-black-body plus a comptonization model is used to fit the data. *NuSTAR*/FPMA: black and green, for different epochs; *NuSTAR*/FPMB: red and dark blue, for different epochs; *INTEGRAL*/IBIS/ISGRI: magenta. [Figure from L. Natalucci *et al.* 2014, ApJ 780, 63] *Top right:* Multi-wavelength light curves of the blazar Mkn421 in 2013: (*a*) OMC photometry; (*b*) JEM-X count rates, at 3-5.5 keV (light green), 5.5-10.25 keV (green), and 10.25-26 keV (dark green); (*c*) IBIS/ISGRI count rates at 20-40 keV (light blue) and 40-100 keV (dark blue); (*d*) Fermi-LAT fluxes binned with 12-hr time-resolution. The background of the image is an artist representation of a blazar. [Figure adapted from E. Pian *et al.* 2014, A&A, in press] *Bottom left:* Joint *RXTE*/PCA and *INTEGRAL*/IBIS/ISGRI observation of Sco X-1. The spectrum was fitted by a comptonization model plus a power-law component. Also displayed are the relative contributions (at the IBIS part of the fit) from the two components. [Figure from T. Maiolino *et al.* 2013, A&A 551, L2] *Bottom right:* Mosaic image of the 4U 1036–56 sky region, derived by combining all *INTEGRAL*/IBIS/ISGRI data (18–60 keV). The significance level is given by the color scale. Corresponding significance and colour can be found in the right colour bar. The position of the transient *AGILE* source AGL J1037–5708 is plotted with its 95% error region (white). Another transient source, GRO J1036–55, is also shown in this sky region with its 1σ, 2σ, 3σ uncertainty location (green). The x- and y-axes are Right Ascension and Declination in units of degrees. [Figure from J. Li *et al.* 2012, ApJ 761, 49]

INTEGRAL sources: Follow-up

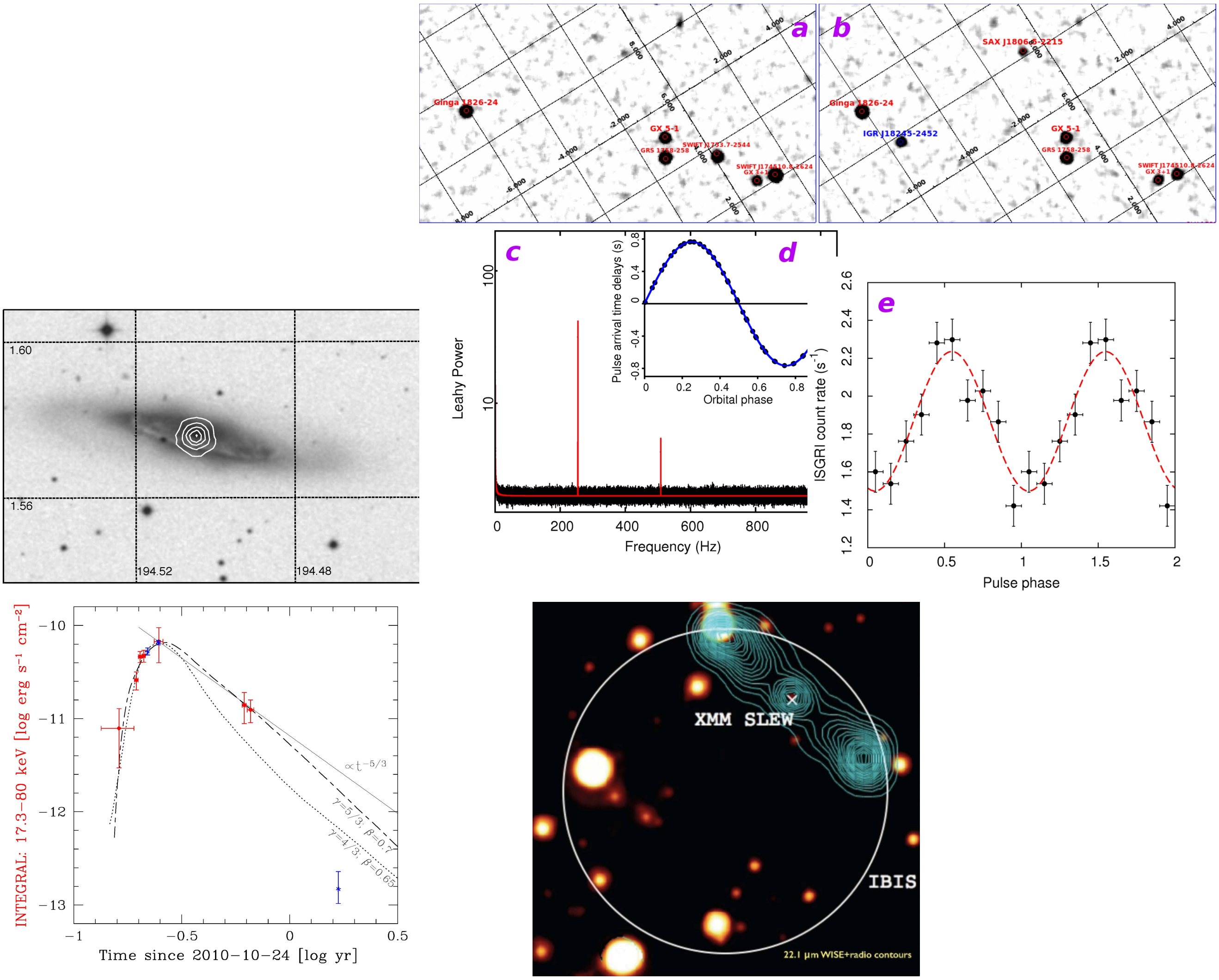


Figure 9: *Top:* IGR J18245-2452 is an X-ray transient discovered by *INTEGRAL* on 28 March 2013 in the globular cluster M28. (*a*) and (*b*) show *INTEGRAL*/IBIS/ISGRI images of the sky before and after the switch on of the X-ray transient, respectively. Follow-up observations with *XMM-Newton* identified it as an accreting millisecond X-ray pulsar spinning at a period of 3.9 msec. The power density spectrum of the X-ray emission observed by *XMM-Newton*, and the 11 hr orbital modulation of the coherent signal of the pulsar are given in (*c*) and (*d*), respectively. (*e*) shows the 20-60 keV pulse profile accumulated by IBIS/ISGRI. Cross-referencing with catalogues of radio rotation-powered pulsars, it was realized that the source had already been seen in 2006 as a radio pulsar. Even more surprising, as the X-ray emission faded, it took just a couple of days for the radio pulsar to reactivate its rotation powered emission. [Figure adapted from A. Papitto *et al.* 2013, Nature 501, 517] *Bottom left:* IGR J12580+0134 was discovered at the beginning of 2011 in NGC 4845, a galaxy never detected in the X-rays before. The top image shows an optical image of NGC 4845 with X-ray contours showing the position of the source as observed by *XMM-Newton*. At the bottom, the light-curve observed by *INTEGRAL*/IBIS/ISGRI (red), *XMM-Newton*/EPIC-pn and *Swift*/XRT (blue). The long-short dash line indicates the prediction of hydrodynamical simulations for the disruption of a sub-stellar object by a massive black hole, whereas the dotted line shows what would be expected for a disrupted star. The most probable mass of the disrupted object is 14-30 Jupiter mass. Only a small fraction (about 10%) of that mass did fall into the black hole. [Figure adapted from M. Nikołajuk & R. Walter 2013, A&A 552, A75] *Bottom right:* IGR J17488–2338 has been optically identified as a broad-line AGN at z~0.24. The source is classified as an intermediate-power Fanaroff-Riley II radio galaxy with a linear size of 1.4 Mpc. The image shows IR 22.1 micron WISE image with radio 1.4 GHz NVSS contours superimposed; the white circle corresponds to the *INTEGRAL*/IBIS/ISGRI error circle; the white cross marks the position based on *XMM-Newton* slew data. The source is extremely bright in the X/γ-rays: among a set of 25 radio galaxies detected so far by *INTEGRAL*, this is the brightest object in the sample. [Figure adapted from M. Molina *et al.* 2014, A&A 565, A2]

INTEGRAL: Sky coverage

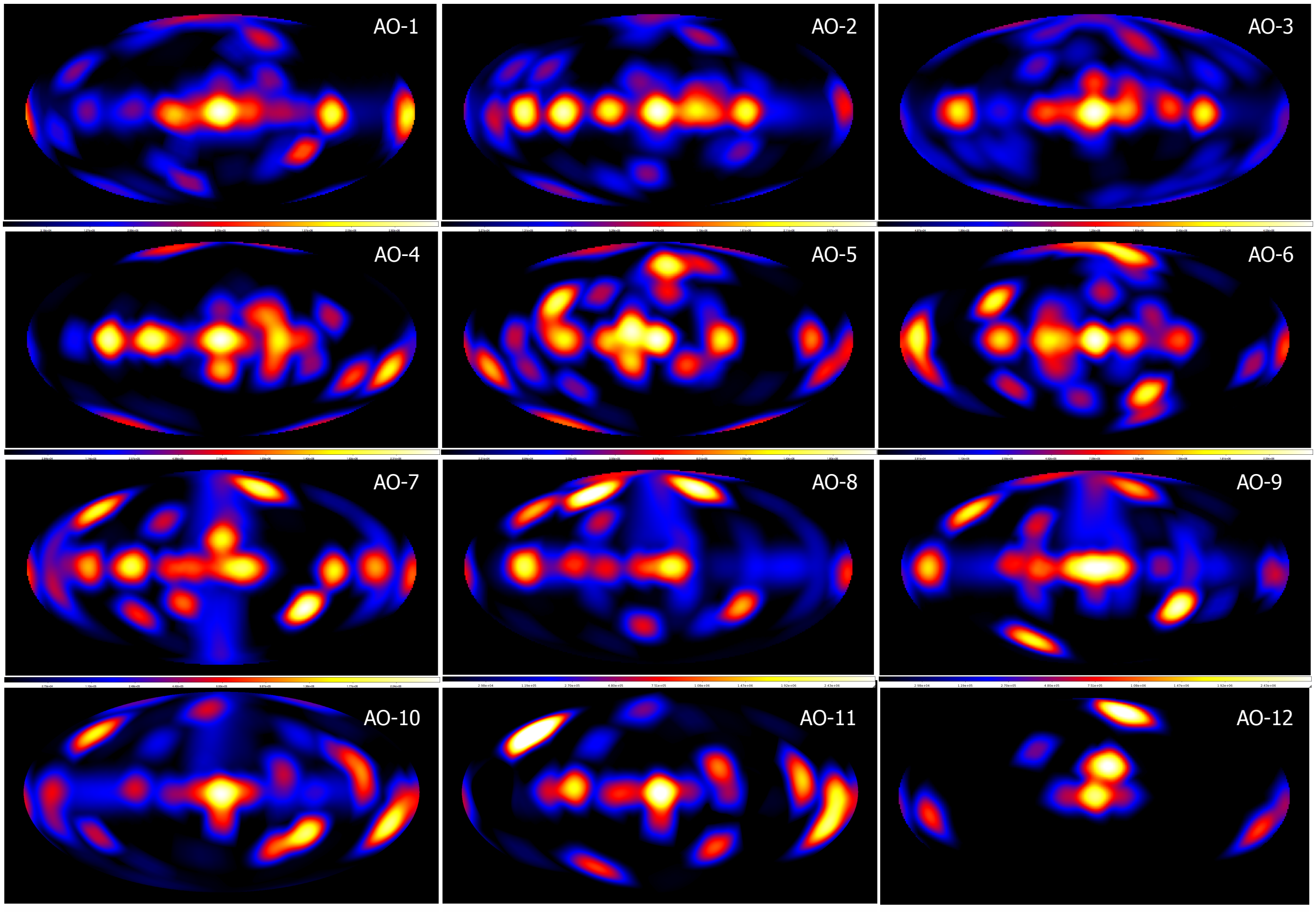


Figure A1: *INTEGRAL* sky exposure maps (IBIS, partially coded FOV) per AO in Galactic coordinates for AO-1 (2003) to AO-11 (extrapolated up to end of 2014), and tentative AO-12 (only approved pointings for 2015). Exposure scale: 0 to ~3 Ms.

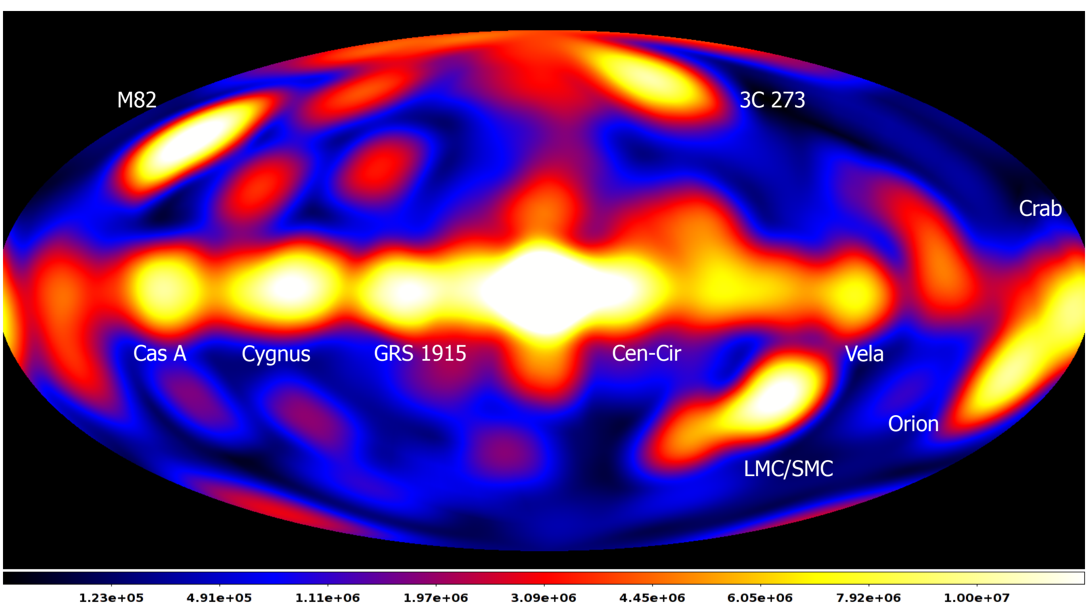


Figure A2: Integrated exposure map (IBIS, partially coded field of view) in Galactic coordinates from AO-1 until AO-11 (from 30 December 2002 until 31 December 2014). The maximum exposure in the GC area is ~ 35 Ms. Units of exposure are in [s].

INTEGRAL: Publications & over-subscription

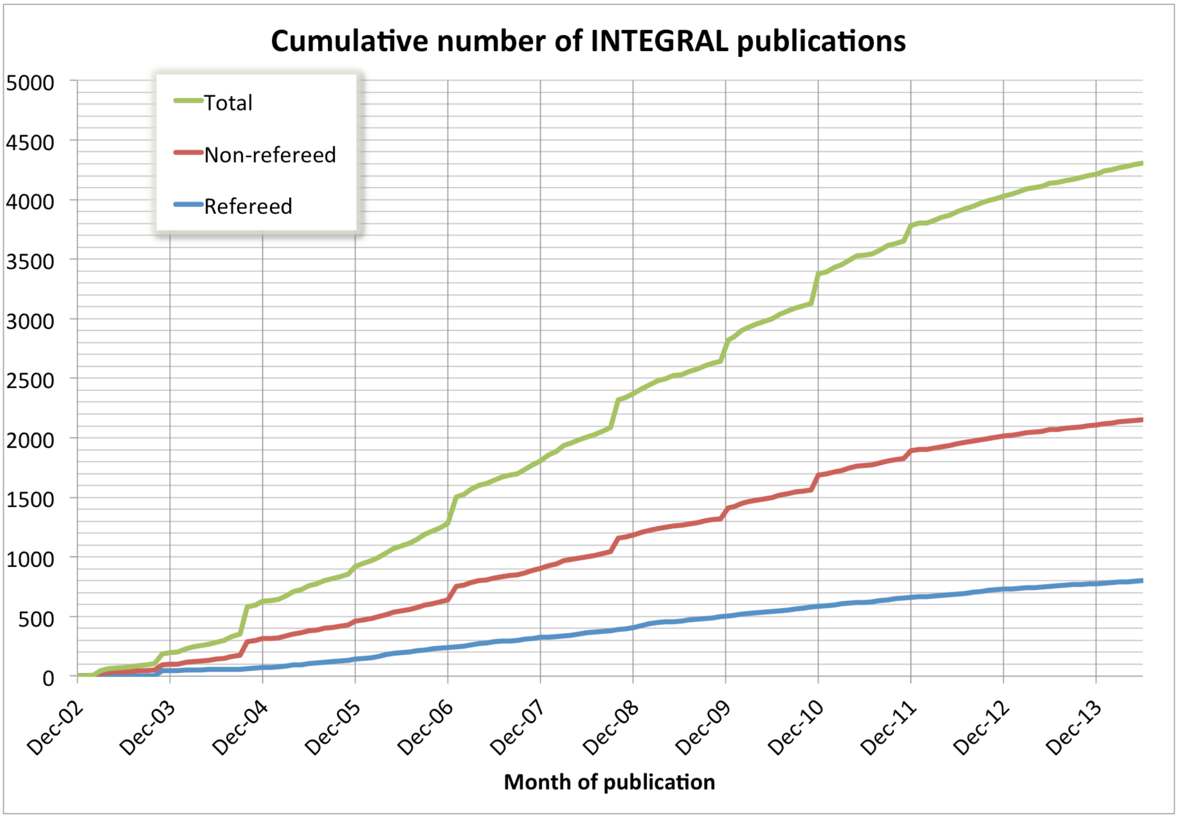


Figure A3: *INTEGRAL* scientific publications (801 refereed papers, 1351 non-refereed papers, 2152 in total), from launch (October 2002) until July 2014. [Derived from http://adsabs.harvard.edu/cgi-bin/nph-abs_connect?library&libname=Integral&libid=450176be03]

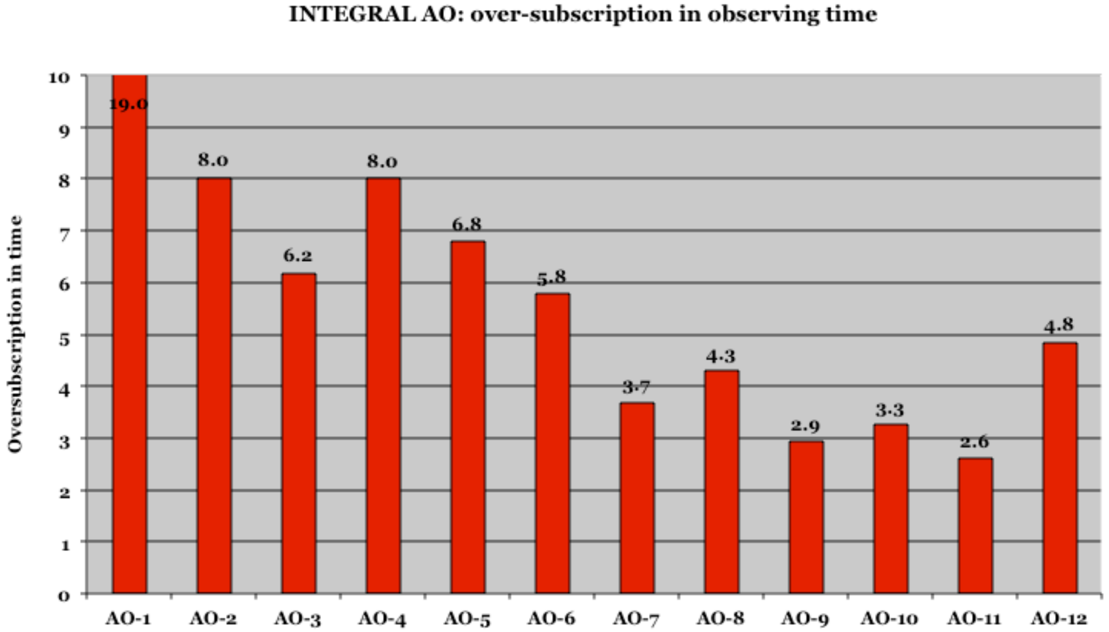
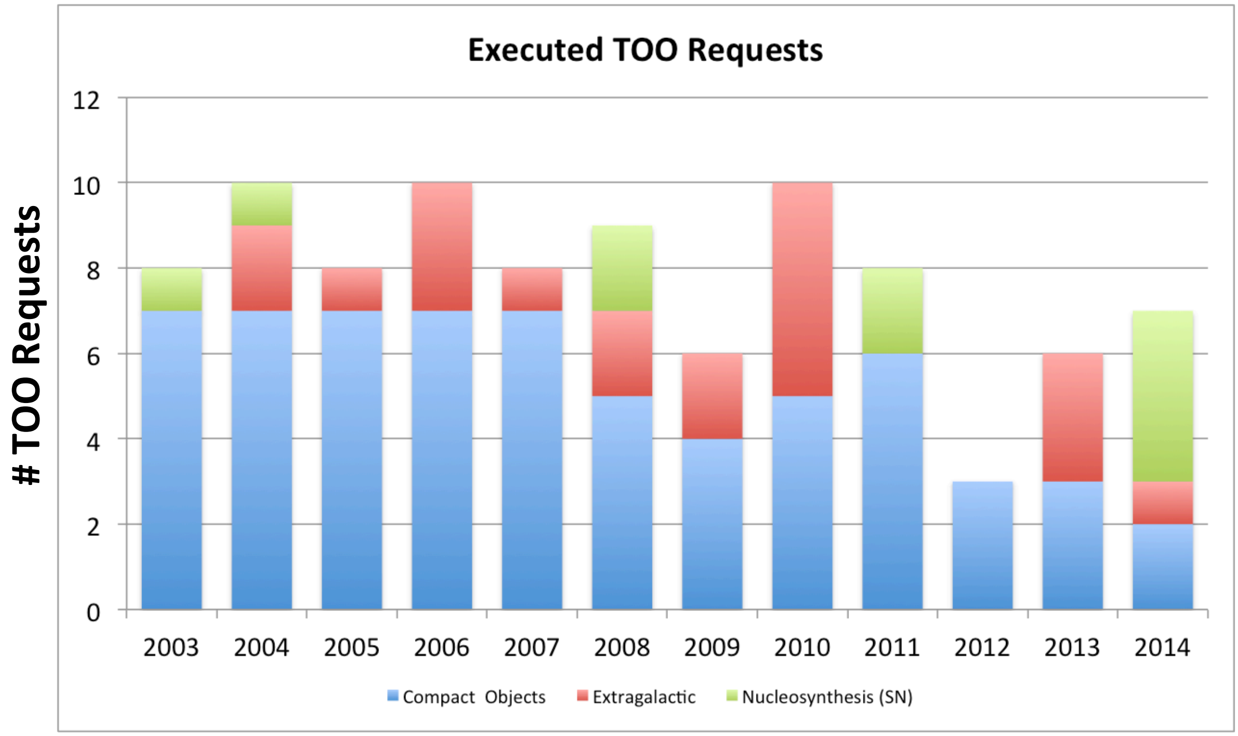


Figure A4: The over-subscription of *INTEGRAL* observing time remains at a high value reflecting the continued interest of the science community. AO-12 will be from 1 January to 31 December, 2015.

INTEGRAL: Targets of Opportunity facility



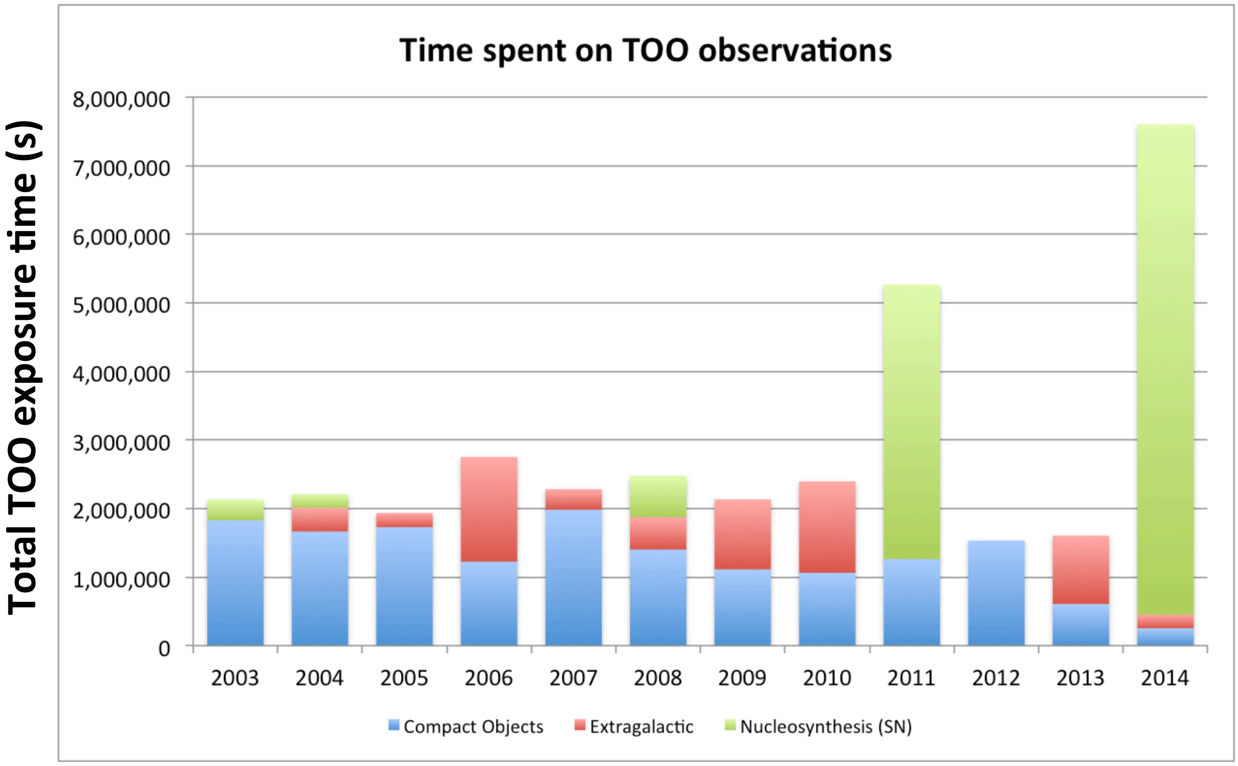


Figure A5: *INTEGRAL* dedicates about 10% of its observing time to unexpected, transient, events in the Universe. *Top:* Number of Target of Opportunity (ToO) requests per year, since launch, specified per scientific category. *Bottom:* Total exposure time in seconds spend per year, since launch, on ToO observations, specified per scientific category.

INTEGRAL: SPI annealing and key parameters

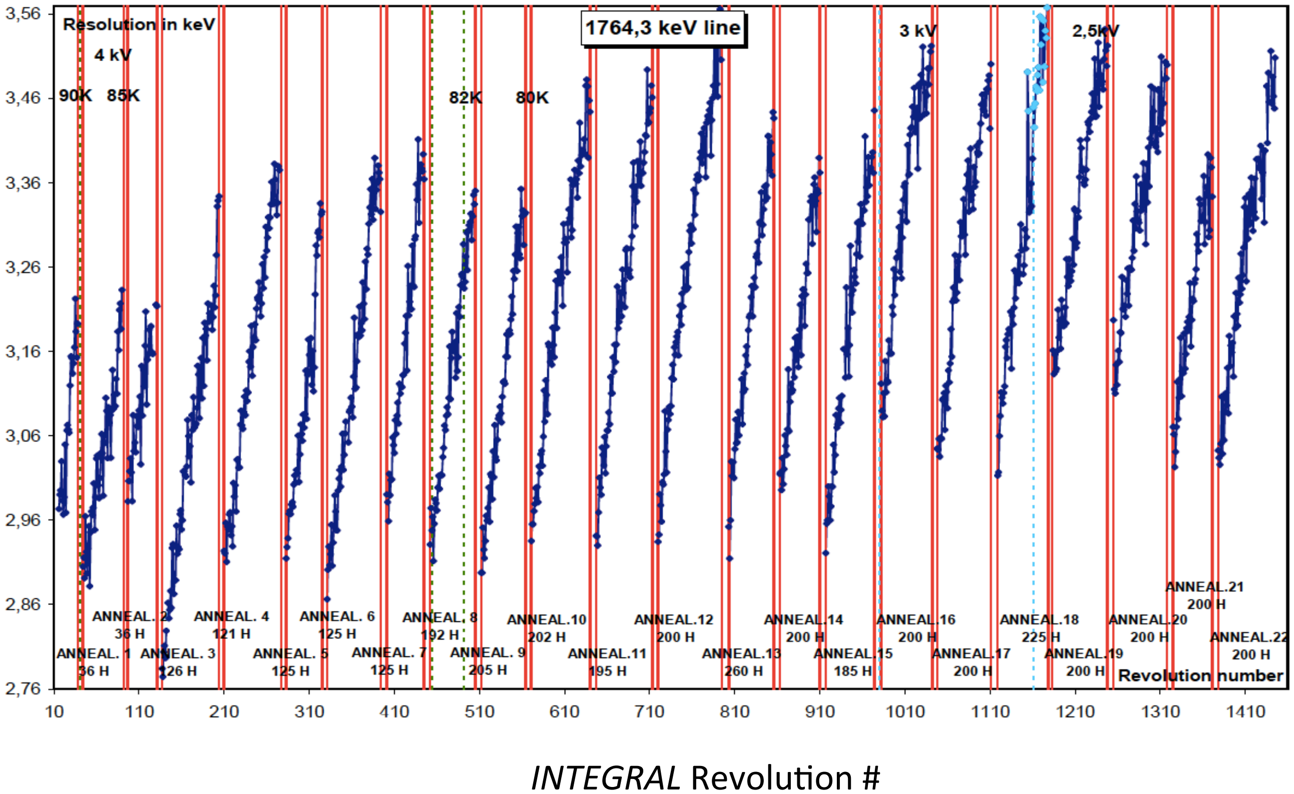


Figure A6: Evolution of the SPI energy resolution at 1764.3 keV since end of commissioning phase (orbital revolution #10). Until September 2014, twenty-three annealing cycles (red vertical bars) have been successfully performed consistently recovering the nominal pre-launch energy resolution.

Table 1: *INTEGRAL* science and payload: complementarity

Instrument	Energy range	Main purpose
Spectrometer SPI	18 keV - 8 MeV	Fine spectroscopy of narrow lines
		Study diffuse emission on >1° scale
Imager IBIS	15 keV - 10 MeV	Accurate point source imaging
		Broad line spectroscopy and continuum
X-ray Monitor JEM-X	3 - 35 keV	Source identification
		X-ray monitoring of high-energy sources
Optical Monitor OMC	500 - 600 nm (V-band)	Optical monitoring of high-energy sources

INTEGRAL: Instrument key parameters - II

Table 2: Key parameters for SPI & IBIS

Parameter	SPI	IBIS
Energy range	18 keV - 8 MeV	15 keV – 10 MeV
Detector	19 Ge detectors[iv] ($6\times6\times7$ cm^3), @ 85K	16384 CdTe detectors ($4\times4\times2$ mm^3), 4096 CsI dets ($8.55\times8.55\times30$ mm^3)
Detector area (cm^2)	500[v]	2600 (CdTe), 3000 (CsI)
Spectral resolution (FWHM)	3 keV @ 1.7 MeV	8 keV @ 100 keV
Field of View (fully coded)	16° (corner to corner)	8.3° × 8.0°
Angular resolution (FWHM)	2.5° (point source)	12'
Source location (radius)	< 1.3° (depending on source strength)	30"@100 keV (50σ source) 3' @100 keV (5σ source)
Absolute timing accuracy (3σ)	~130 μs	~90 μs
Mass (kg)	1309	746
Power [max/average] (W)	385/110	240/208

Table 3: Key parameters for JEM-X and OMC

Parameter	JEM-X	OMC
Energy range	3 keV – 35 keV	500 nm - 600 nm
Detector	Microstrip Xe/CH_4-gas (1.5 bar)	CCD + V-filter
Detector area	500 cm^2 for each of the two JEM-X detectors	CCD: (2055 × 1056) pixels Imaging area: (1024 ×1024)
Spectral resolution (FWHM)	3.6 keV @ 22 keV	--
Field of view (fully coded)	4.8°	5.0° × 5.0°
Angular resolution (FWHM)	3'	23"
10s source location (radius)	1' (90% confidence, 15σ source)	2"
Absolute Timing accuracy	~1 ms	> 3 s
Mass (kg)	65	17
Power [max/average] (W)	50/37	26/17

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