The INTEGRAL search for 511 keV annihilation line from Galactic X-ray binaries

G. De Cesare

IASF-INAF, Rome

giovanni.decesare@iaps.inaf.it

P. Laurent(1), L. Titarchuk(2)

(1) CEA/DSM/IRFU/APC CEA Saclay, France

(2) Physics Dpartment, University of Ferrara, Italy

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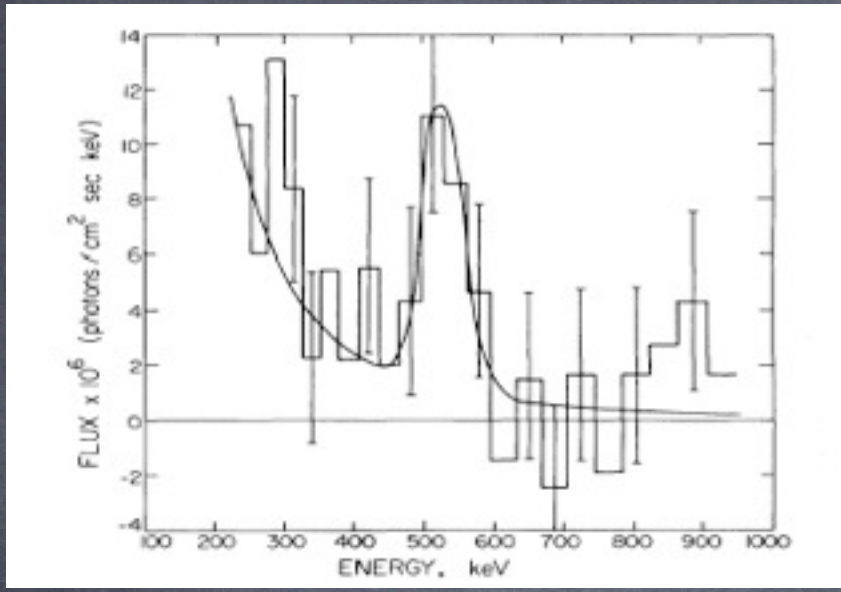
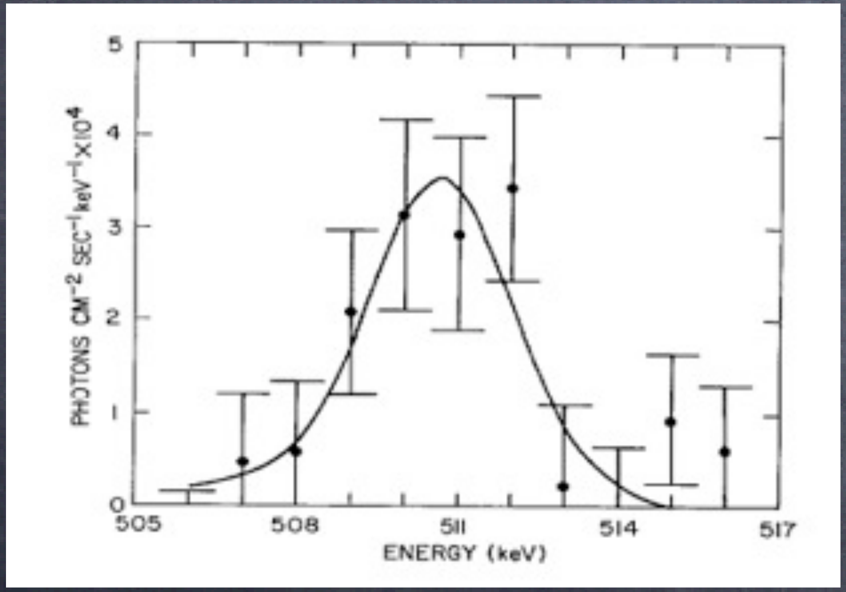
Outline

- Galactic positrons as revealed by 511 keV annihilation line (first detection in 1972)
- The INTEGRAL gamma-ray observatory, launched in October 17 2002
- 511 keV emission line from X-ray binaries: scientific motivations
- 511 keV emission line from X-ray binaries: data analysis
- A short discussion
- Conclusion

Galactic positrons as revealed by 511 keV annihilation line
First detection



The 511 keV emission from positrons annihilation from the direction of the Galactic center was first discovered in the early 1970s, by balloon-born detectors with low energy resolution (Johnson et al. 1972)



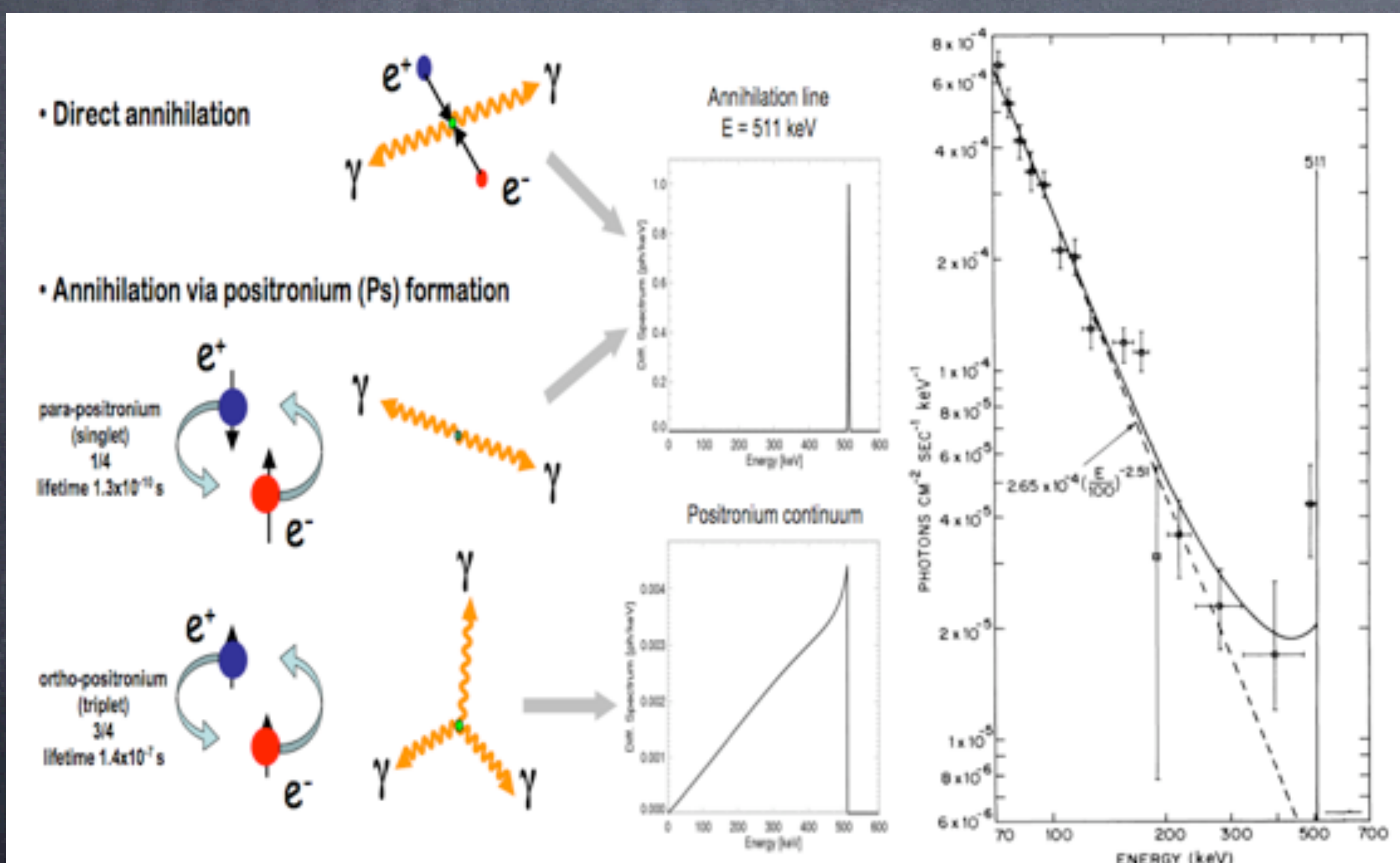
The line was clearly identified a few years later with high energy resolution Ge detectors (Leventhal et. al., 1978)

Galactic positrons as revealed by 511 keV annihilation line
The positronium

Annihilation of positron can take place by direct annihilation in two opposite 511 keV photons or by formation of prositronium atom. The positronium can be formed with two total spin (S) state:

S=0 para-positronium -> two 511 keV photons (25 %)

S=1 ortho-positronium -> three photon with an energy up to 511 keV (75 %)



Leventhal 1978

By measuring the intensities of the 511 keV line and of the Ps continuum one can derive the fraction of positrons that annihililate by positronium formation:

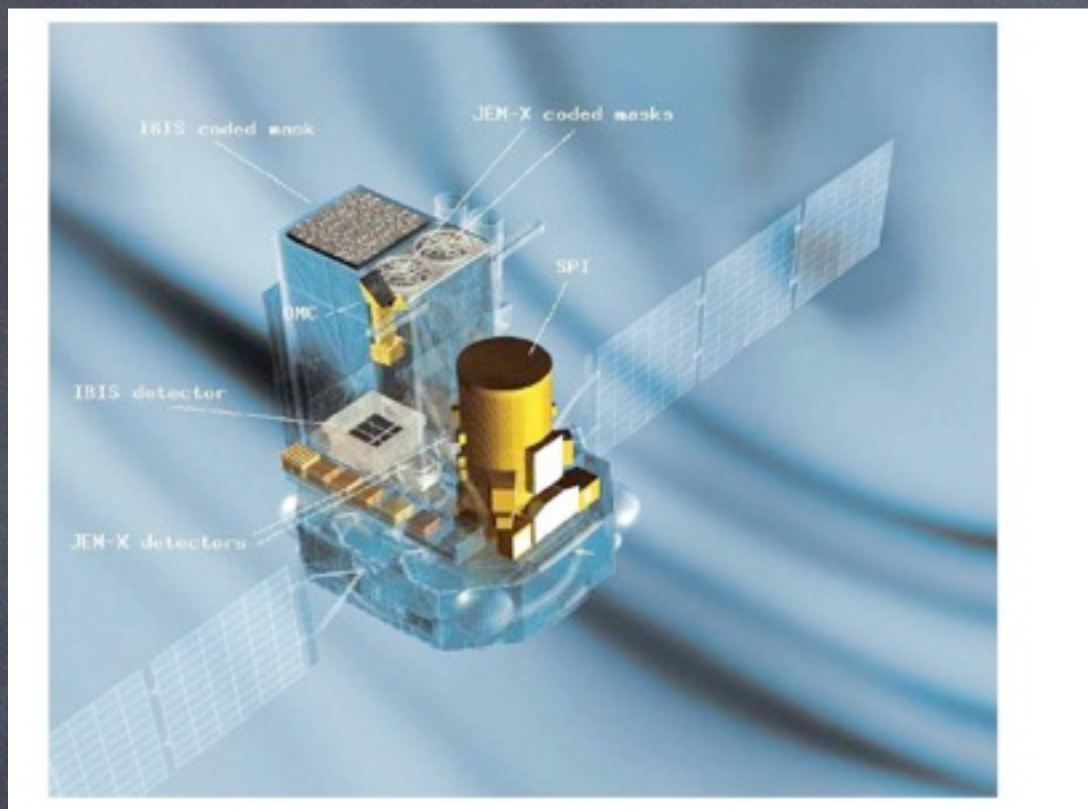
$$I_{3\gamma} \propto \frac{3}{4} 3 f_{P_s}$$

$$I_{2\gamma} \propto 2(1 - f_{P_s}) + \frac{1}{4} 2 f_{P_s}$$

$$\downarrow$$

$$f_{P_s} = \frac{8 I_{3\gamma}/I_{2\gamma}}{9 + 6 I_{3\gamma}/I_{2\gamma}}$$

The INTEGRAL gamma-ray observatory

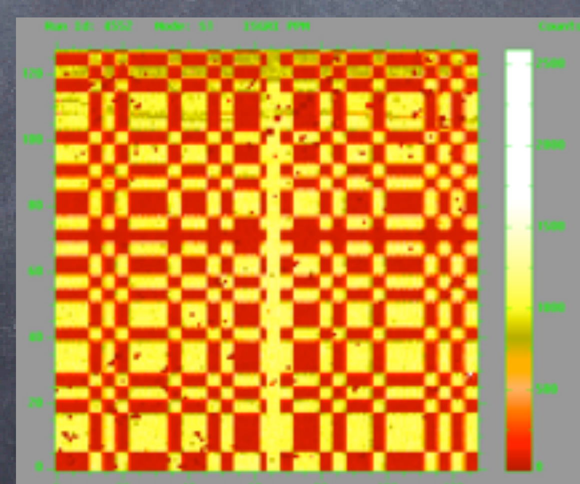


INTEGRAL was launched by PROTON from Baikonur in Kazakistan on 17th October 2002.

SPI High resolution spectroscopy (~ keV @ 500 keV) with moderate angular resolution (2 degree)

IBIS: Fine imaging (angular resolution = 12') with low resolution spectroscopy (~ 30 keV @ 511 keV)

SPI: 19 Ge detectors



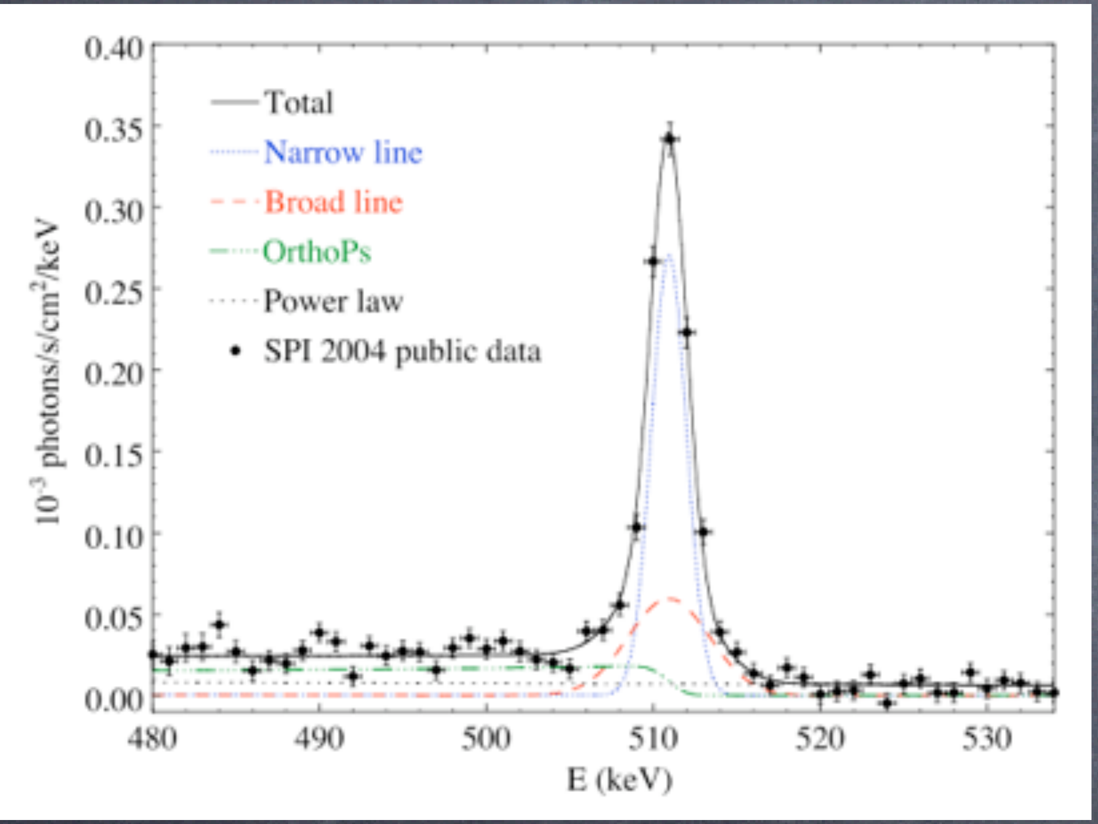
IBIS/ISGRI count map ("shadowgram") obtained with a 60 keV source

IBIS/ISGRI: 16384 CdTe detectors

The INTEGRAL gamma-ray observatory
511 keV line measured by the spectrometer SPI

At 511 keV we detect 10^{-3} phs cm^{-2} s^{-1} ~ 2 x 10^{43} e^{+} s^{-1} in the GC

Jean et al. 2006

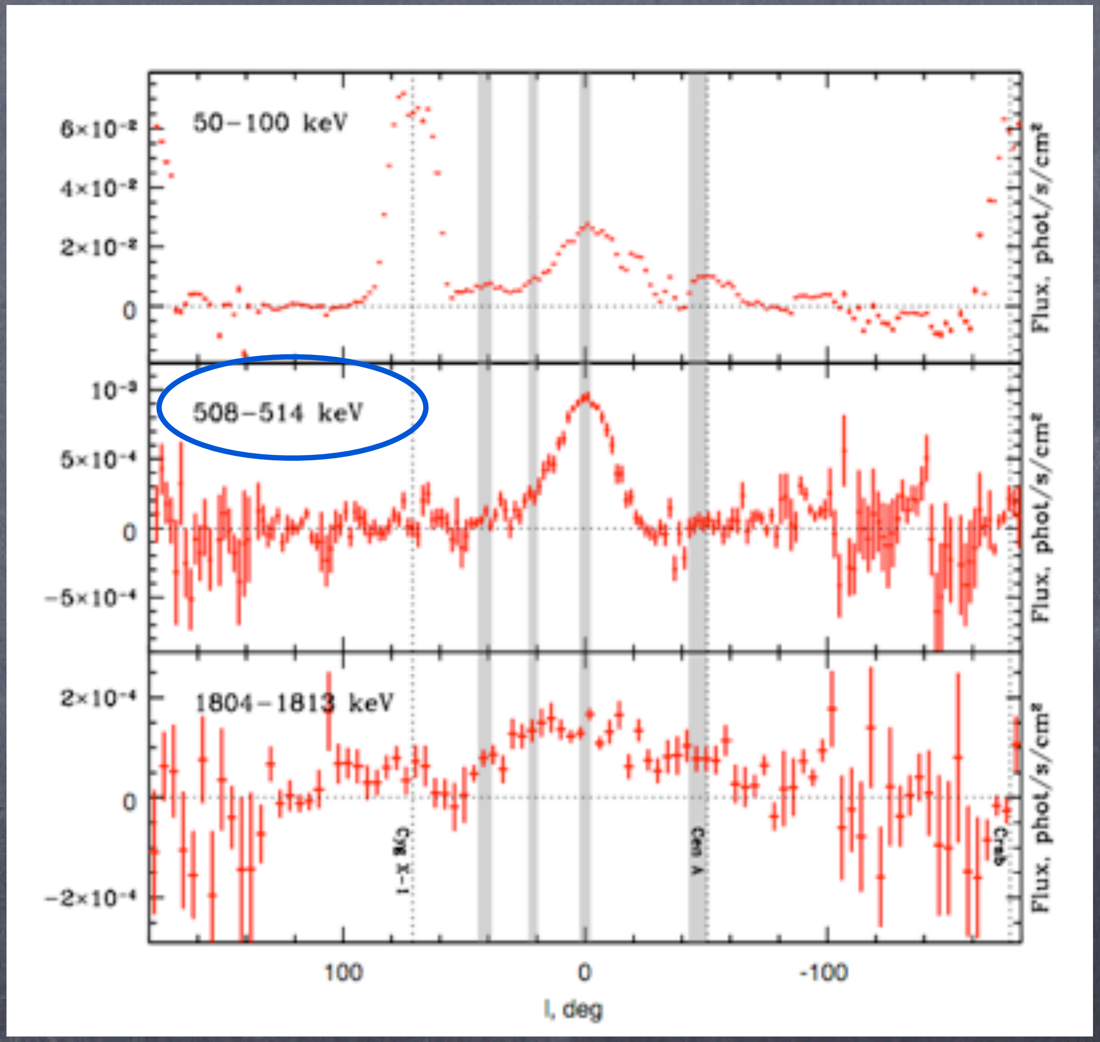


Narrow line FWHM = (1.3 ± 0.4) keV

Broad line FWHM = (5.4 ± 1.4) keV

Positronium fraction = (96.7 ± 2.2) %

Churazov et. al 2011



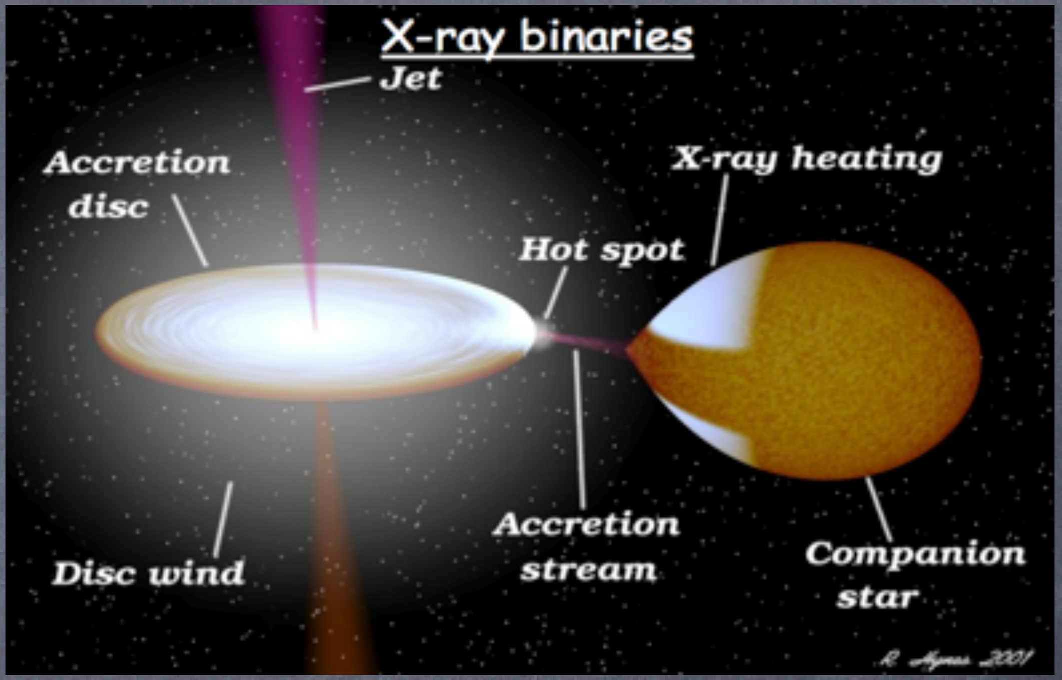
SPI flux profile along the Galactic plane in 3 energy band obtained with a simple scan.

511 keV emission from XRBs

Scientific motivations

Basically, an X-ray binary (XRB) is a stellar size machine that convert gravitational energy into electromagnetic power by accreting materials from a companion star into a compact object (first detection of Sco X- 1 in 1962 by Giacconi).

Companion star: Low Mass (LM), High Mass (HM)
Compact Object: Neutron Star or Black Hole
Phenomena: Spectral States, QPOs, jets, ecc...



The observed distribution of LMXRBs in the Galaxy is strongly peaked towards the central regions, similar to that of the 511 keV emission. In terms of total energy the LMXBs population could explain the 511 keV flux.

$$f_{SPI}(511\,keV) = 10^{-3}\,\frac{ph}{cm^2\,s}$$

$$E_{e+} = 511\,keV = 10^{-6}\,erg$$

$$n = 2 \times 10^{43}\,e^{+}\,s^{-1}$$

$$L_{511\,keV} = 2 \times 10^{37}\,erg/s$$

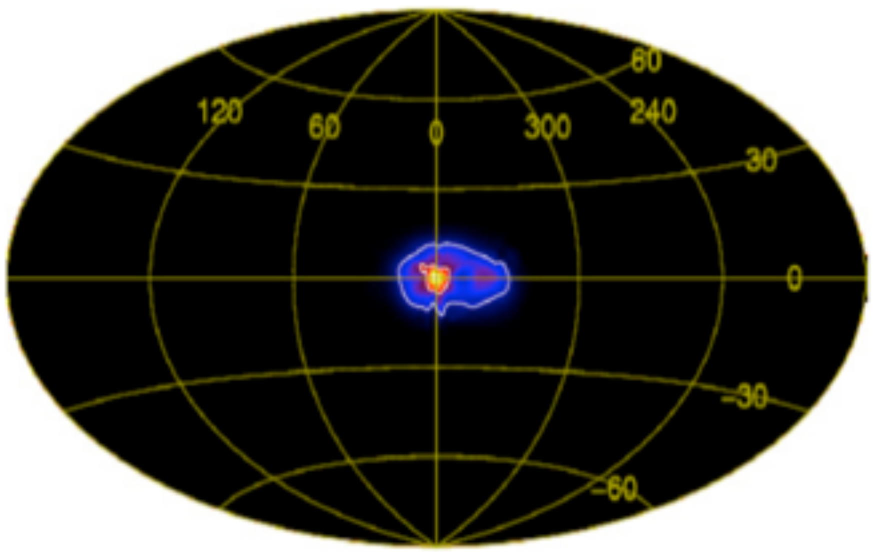
This value is 50 times lower than the total luminosity of the LMXBs (Grimm et al., 2002)

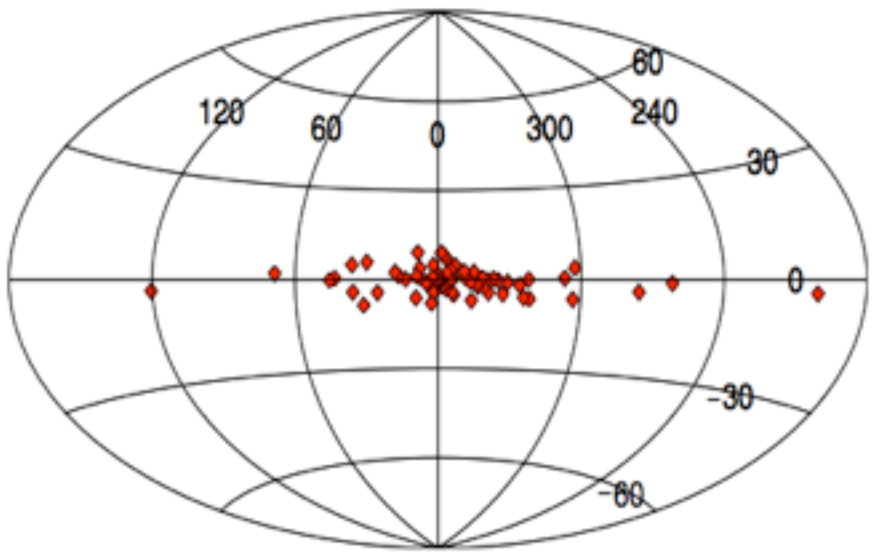
$$L_{tot}(LMXB) = 10^{39} erg/s$$

511 keV emission from XRBs

Scientific motivations

Some evidence of an asymmetry of the 511 keV emission along the Galactic longitude, possibly correlated with the spacial distribution of the hard X (E > 20 keV) LMXBs detected by the imager IBIS aboard INTEGRAL, has been reported by Weidenspointner et al., 2008





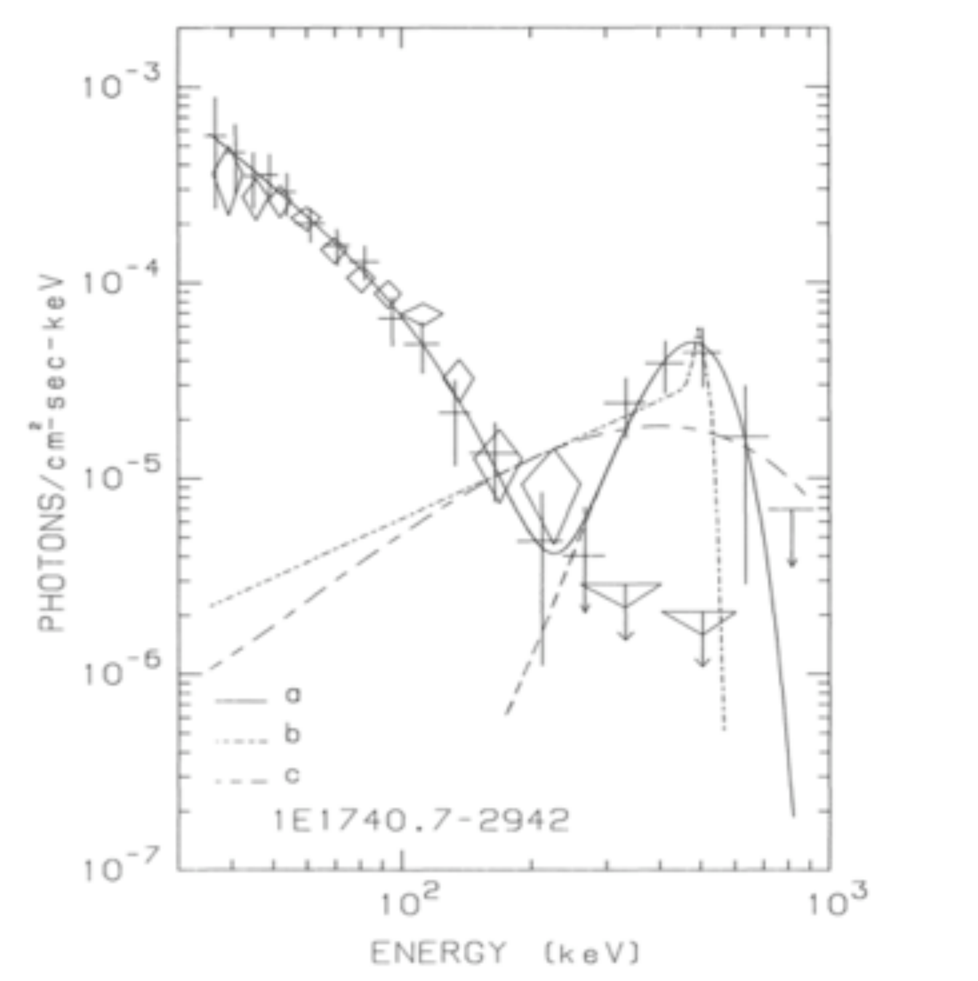
The SPI sky map in the 511 keV electron-positron annihilation line and the sky distribution of the hard X (E > 20 keV) LMXBs detected by IBIS

But a different analysis of the same SPI data do not confirm this asymmetry (See Bouchet et al., 2008, Churazov et al., 2011)

511 keV emission from XRBs

Scientific motivations

During the 1990 October 13 the SIGMA telescope, aboard the GRANAT space observatory, discovered that the microquasar 1E 1740.7-2942 was exhibiting a remarkable transient feature in its emission spectrum (See e.g. Bouchet et al. 1991), possibly associated with a very broad 511 keV line emission



This transient feature appeared during a 13 hours observation and then possibly in two further occasions but at a less significant level.

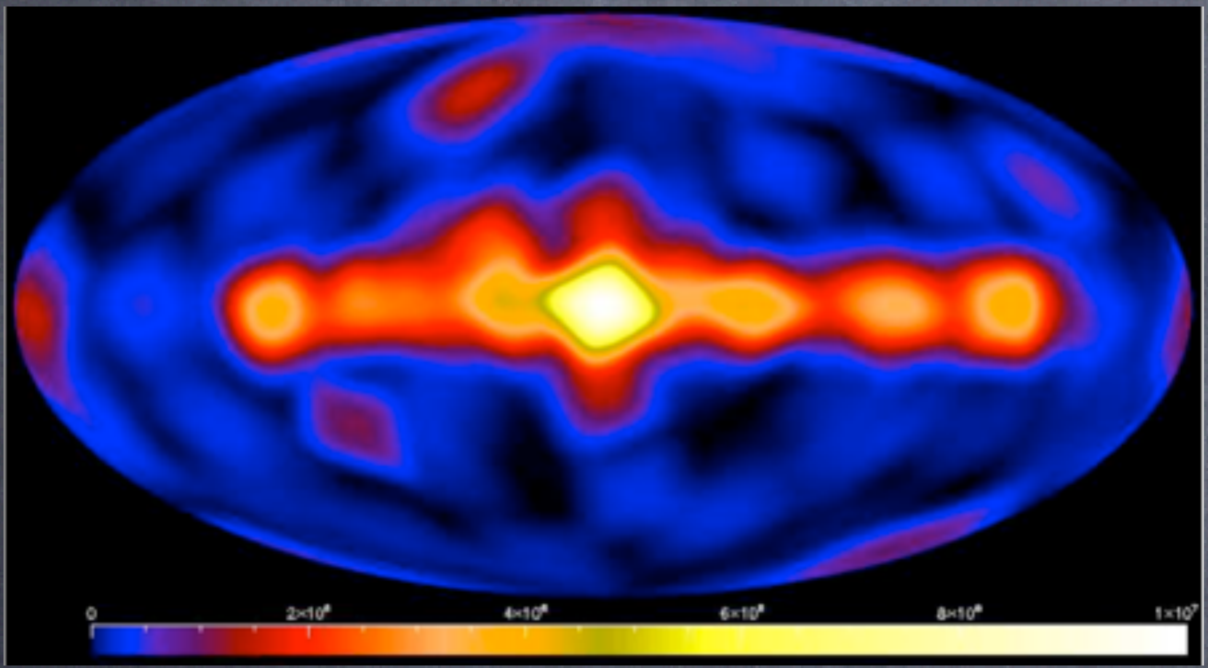
But note that this 511 keV feature was not confirmed by OSSE data analysis (Jung et al. 1995).

The 1E 1740.7 position is about 1 degree from the Galactic center. It is reported in the INTEGRAL/IBIS in hard X catalogue with a flux of (29.8 ± 0.1) mCrab (A.J. Bird, 2007)

511 keV emission from XRBs: data analysis

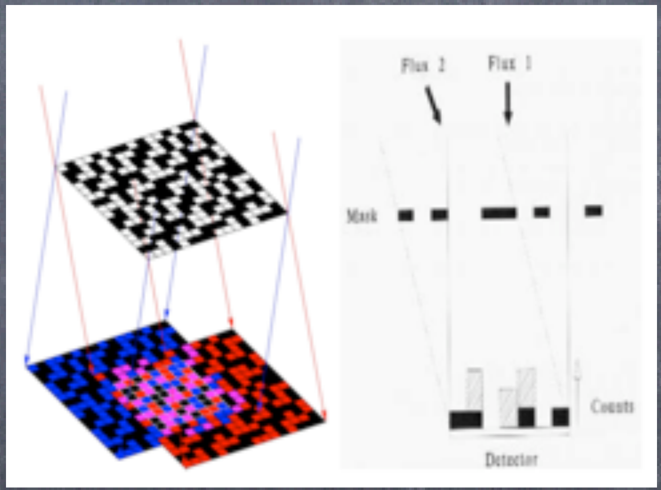
The data sample and standard analysis

With our sample, we reach a 10 Ms exposure in the Galactic center region. The data set consists in about 5 year of observations, including all the IBIS data accumulated until April 2007.



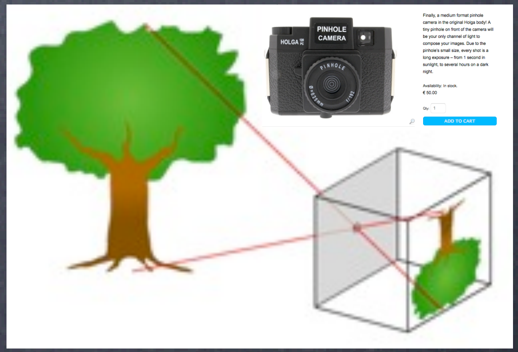
The exposure map for the IBIS 511 keV all sky survey. The maximum exposure (10 Ms) is obtained in the Galactic bulge (yellow and white colors)

The IBIS data set consists in a large set of small pointing observations, each producing an image with an exposure of about 2000 seconds. Thus, a sky map can be obtained by overlapping a sample of these small images. Our data set includes about 40 000 ScWs



Coded mask imaging

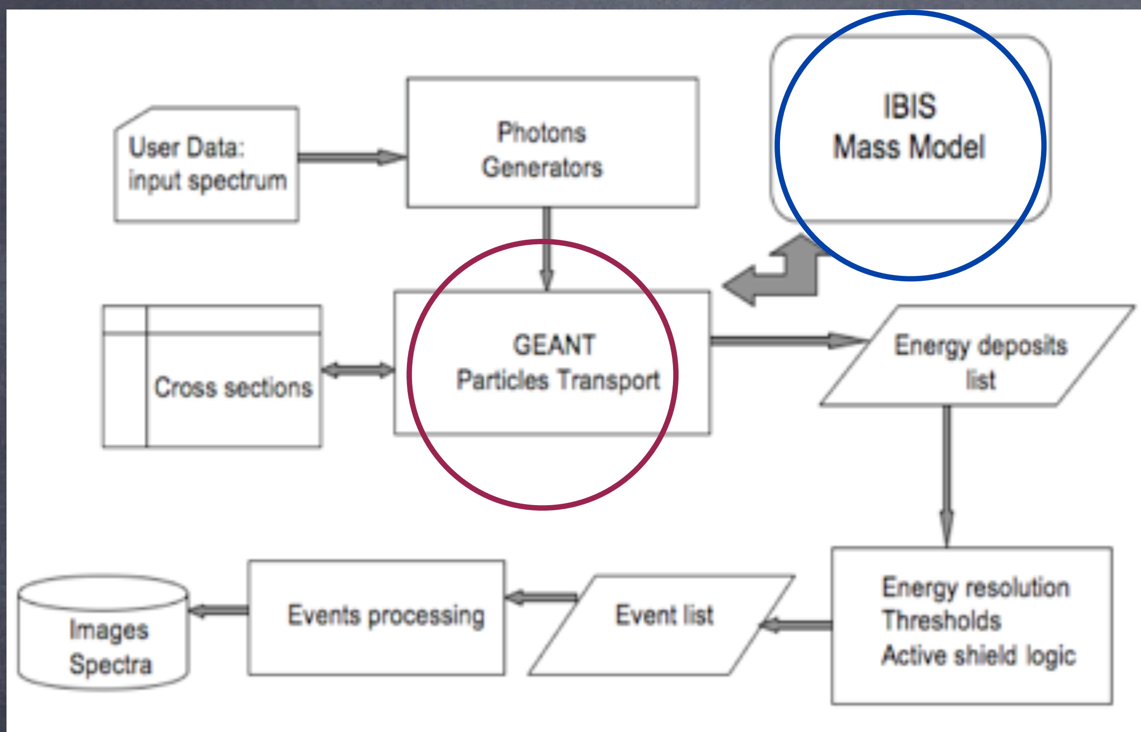
Pro: large field of view
Con: high background



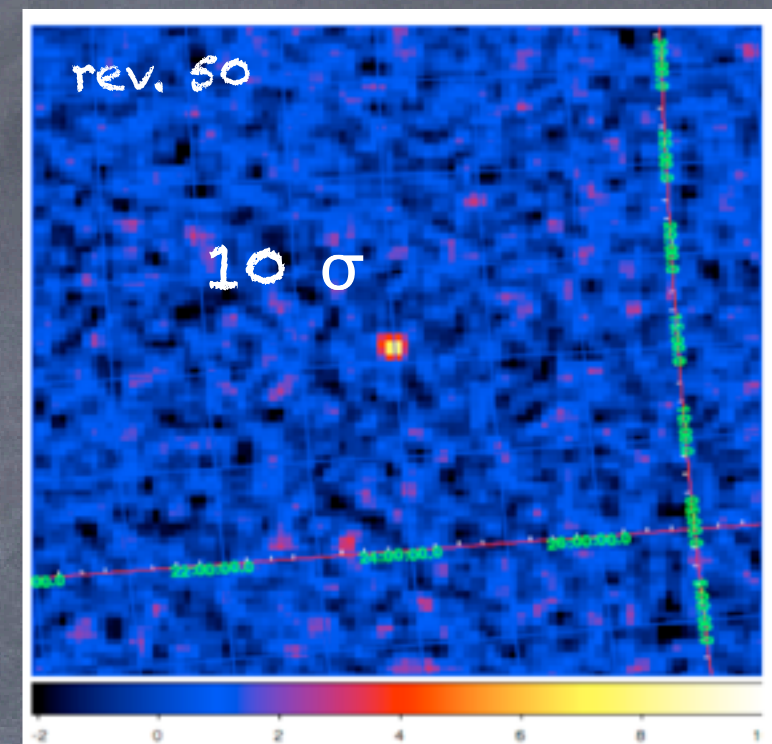
A pinhole camera concept

511 keV emission from XRBs: data analysis

Monte Carlo simulation: a 511 keV lne source



The flowchart of IBIS Monte Carlo. The code is based on the CERN GEANT library to reproduce the interaction of the gamma-rays with IBIS detectors and passive materials.

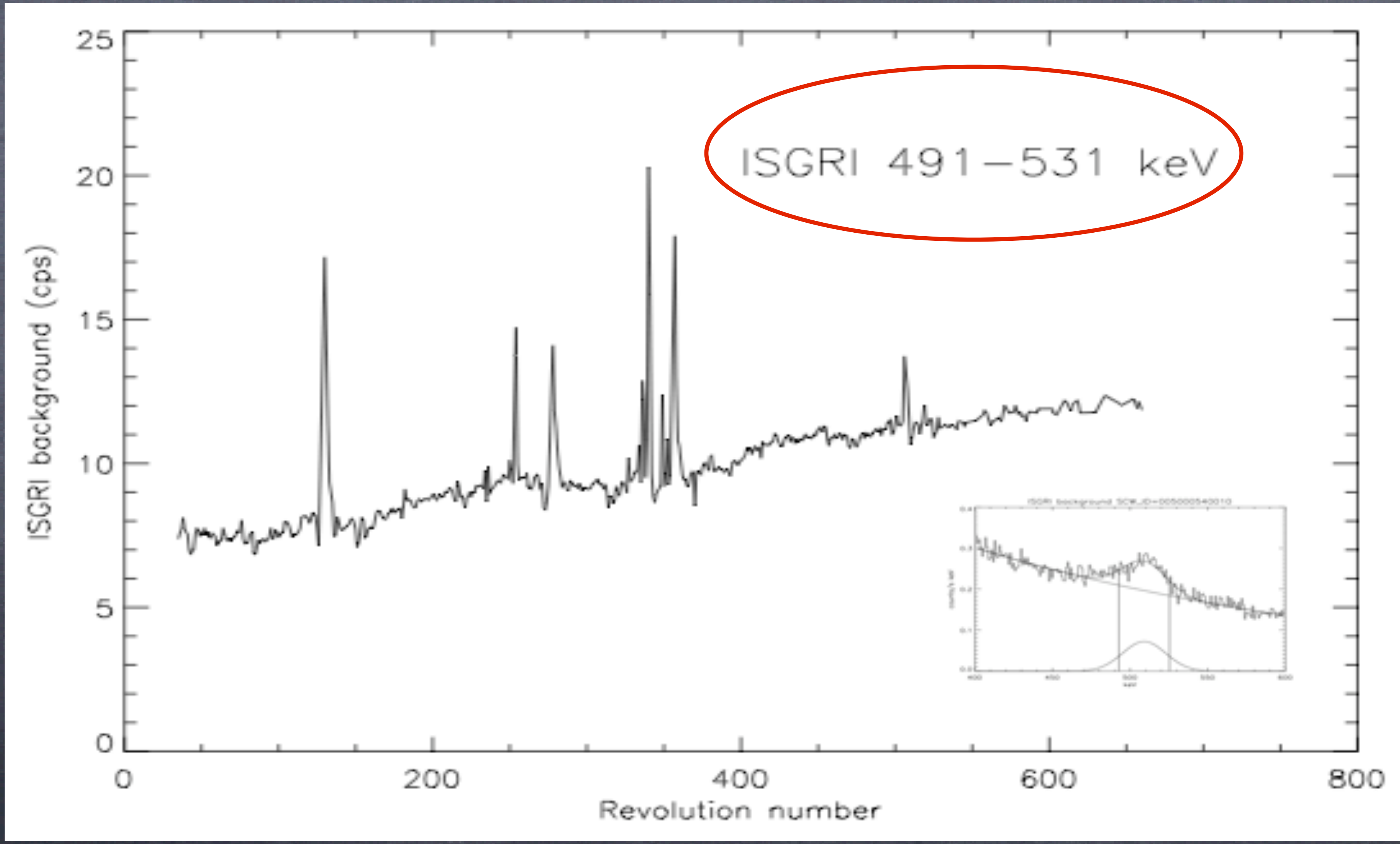


A realistic simulation of short (30 min) observation of a 511 keV strong point source as seen by IBIS. This image is obtained adding to the real data the photon list generated by the IBIS Monte Carlo and then processing the result with the standard analysis software until the image level.

511 keV emission from XRBs: data analysis

IBIS background

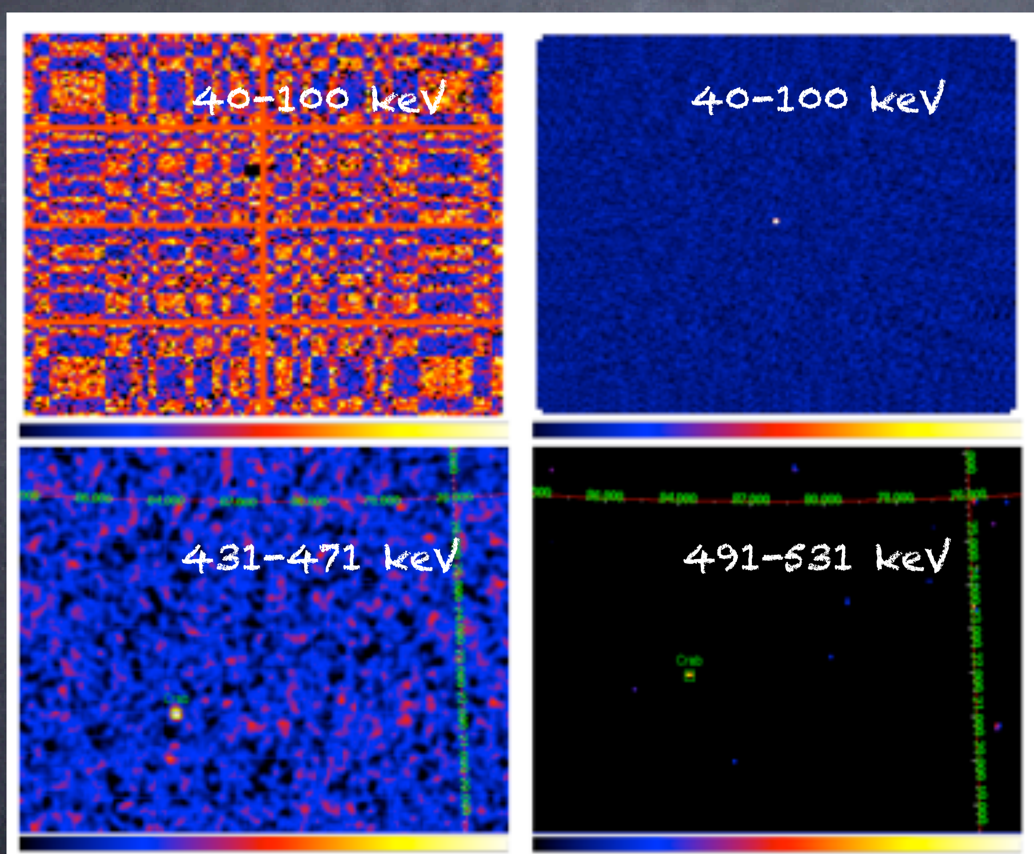
The 511 keV line sensitivity, i.e. the minimum flux detectable at a low significance level, basically depends on the (high) background count rate and on the (low) effective area.



511 keV emission from XRBs: data analysis

The 511 keV line sensitivity: Crab detection

The Crab nebula continuum emission in 511 (491-531) keV band is detected at 3.8 sigma. This significance is in agrement with the signa that we expect from the IBIS Monte Carlo simulation.



The Crab nebula as detected by IBIS/ISGRI in the soft gamma-ray domain with a 3 Ms of exposure.

Energy (keV)	signal (σ)	counts/s
20 – 40 keV	8372	157.527 ± 0.019
40 – 100 keV	5360	93.984 ± 0.017
100 – 300 keV	1250	17.608 ± 0.014
431 – 471 keV	9.5	$(3.0 \pm 0.3)\ 10^{-2}$
491 – 531 keV	3.8	$(1.2 \pm 0.3)\ 10^{-2}$
551 – 591 keV	not detected	–

$F_{Crab}(491-531\,keV) = (6.8 \pm 0.5) \times 10^{-4}\,ph\,cm^{-2}\,s^{-1}$ *measured by SPI*

$S_{2\sigma}^{Crab}(511\,keV) = (2.0 \pm 0.7) \times 10^{-4}\,ph\,cm^{-2}\,s^{-1}$

Data : ISGRI *exposure* $= 10\,Ms$

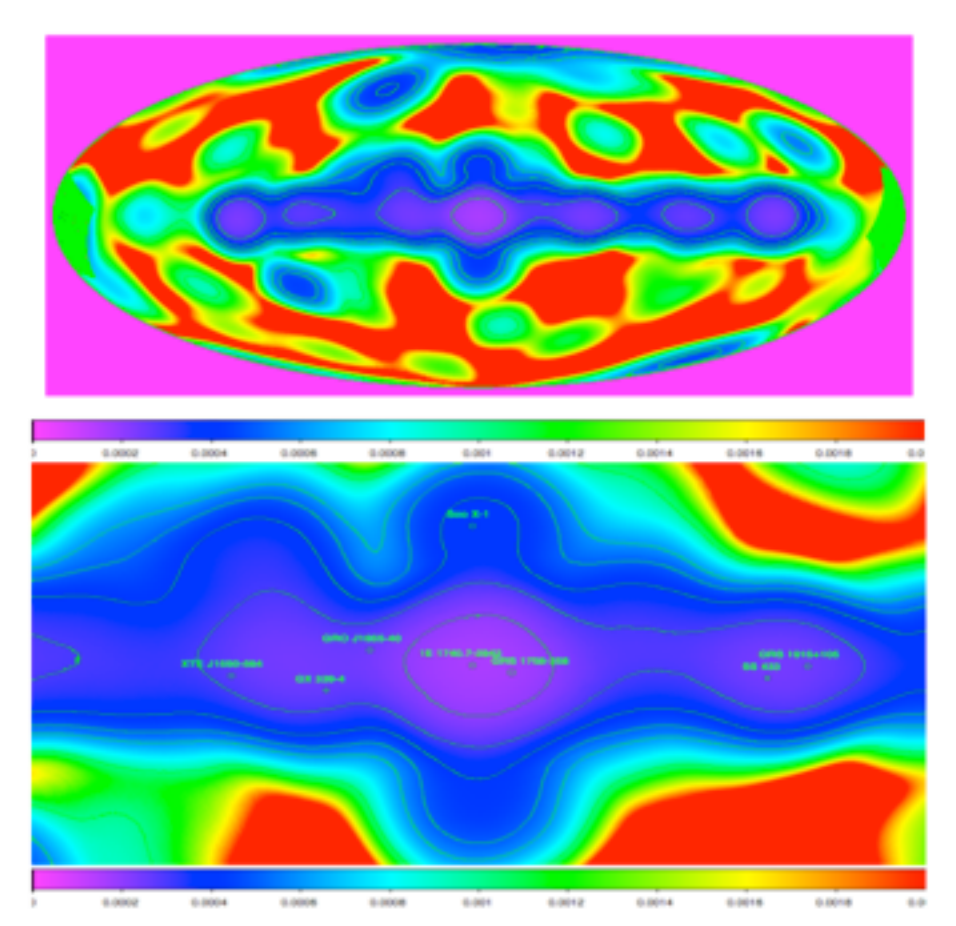
Method : Crab data

The IBIS 511 keV sensitivity as estimated with the Crab data

511 keV emission from XRBs: data analysis

The 511 keV broad line sensitivity map

Processing 5 year of IBIS data we do not find at 511 keV (491-531 keV) full sky map any evidence of point source.



With an exposure of 10 Ms, the best 511 keV flux limit in this map is $1.6\ 10^{-4}$ ph cm^{-2} s^{-1} for 1 E 1740.7-2942 and GRS 1758-2258, the two IBIS microquasars located near the center of the Galaxy. For the sources with lower exposure, as for example Sco X-1 that has a flux upper limit of $3.7\ 10^{-4}$ ph cm^{-2} s^{-1}, our observations gives a less tight constraint on the 511 keV emission.

511 keV emission from XRBs: data analysis

LMXBs 511 keV narrow line upper limits

A possible correlation between this source distribution and the SPI 511 keV map was pointed out by Weidenspointner et al., 2008

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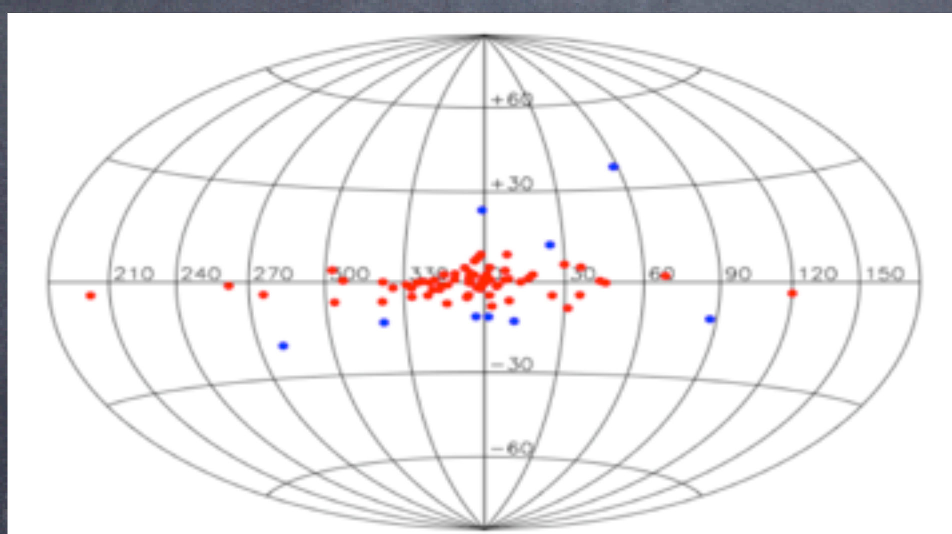

Sky distribution of the the LMXBs detected by IBIS above 20 keV. The red point corresponds to the LMXBs with |b| < 10 degrees, while for the blue ones |b| > 10 degrees.

Table 4.4. 511 keV 2σ steady flux upper limits for the hard X (E > 20 keV) LMXBs reported in the 3rd IBIS catalogue of galactic latitude absolute value $|b| < 10\,degrees$

Source name	R.A. (deg)	Dec (deg)	Error[a] (arcminutes)	F_{20-40}[b] (mCrab)	F_{40-100} mCrab	2σ flux limit[c] ($10^{-4}\,ph\,cm^{-2}\,s^{-1}$)
IGR J00291-5934	7.253	59.566	0.5	4.6 ± 0.1	5.1 ± 0.2	2.4
4U 0614+091	94.280	9.139	0.8	26.8 ± 0.7	22.1 ± 1.1	8.7
4U 0836-429	129.346	-42.894	0.2	31.2 ± 0.1	26.6 ± 0.2	2.3
4U 0919-54	140.093	-55.191	1.1	4.0 ± 0.2	3.0 ± 0.3	3.0
4U 1246-58	192.410	-59.090	1.6	3.1 ± 0.2	2.4 ± 0.3	3.0
1H 1254-690	194.438	-69.288	1.6	2.5 ± 0.2	< 0.7	3.6
4U 1323-62	201.634	-62.136	0.9	5.9 ± 0.2	$3.5 \pm 0,3$	3.0
Cir X-1	230.172	-57.169	0.4	9.3 ± 0.1	0.6 ± 0.2	2.9
4U 1543-624	236.976	-62.570	1.3	3.4 ± 0.2	0.6 ± 0.3	3.5
XTE J1550-564	237.745	-56.479	0.2	3.4 ± 0.1	55.3 ± 0.2	2.7
4U 1608-522	243.177	-52.424	0.4	13.9 ± 0.1	7.8 ± 0.2	2.5
SWIFT J1626.6	246.648	-51.944	2.0	< 0.3	0.4 ± 0.2	2.5
4U 1624-490	247.013	-49.208	0.7	4.4 ± 0.1	0.4 ± 0.2	2.8
4U 1630-47	248.507	-47.396	0.2	38.9 ± 0.1	32.3 ± 0.2	2.4
4U 1636-536	250.228	-53.753	0.3	38.1 ± 0.1	23.4 ± 0.2	2.6
GX 340+0	251.448	-45.614	0.2	31.9 ± 0.1	1.5 ± 0.2	2.5
IGR J16493-4348	252.375	-43.828	1.7	2.3 ± 0.1	1.6 ± 0.2	2.5
GRO J1655-40	253.504	-39.846	0.6	2.3 ± 0.1	2.7 ± 0.2	2.5
...	...	...	...	...	...	...

[a]Position error expressed as radius of 90 % confidence circle.

[b]Fluxes averaged on the total exposure (Bird et al. 2007):
20-40 keV: $1\,mCrab = 7.57 \times 10^{-12}\,erg\,cm^{-2}\,s^{-1} = 1.71 \times 10^{-4}\,ph\,cm^{-2}\,s^{-1}$
40-100 keV: $1\,mCrab = 9.42 \times 10^{-12}\,erg\,cm^{-2}\,s^{-1} = 9.67 \times 10^{-5}\,ph\,cm^{-2}\,s^{-1}$

[c]The collective flux limit, obtained adding the detected flux from all the sources, is $\sim 2 \times 10^{-5}\,ph\,cm^{-2}\,s^{-1}$

511 keV emission from XRBs: data analysis

Microquasars 511 keV line flux upper limits

The possibility to detect a 511 keV radiation due to the jet positrons hitting the atmosphere of the companion star, in the case of misaligned microquasars, is discussed by Guessoum et al. 2006.

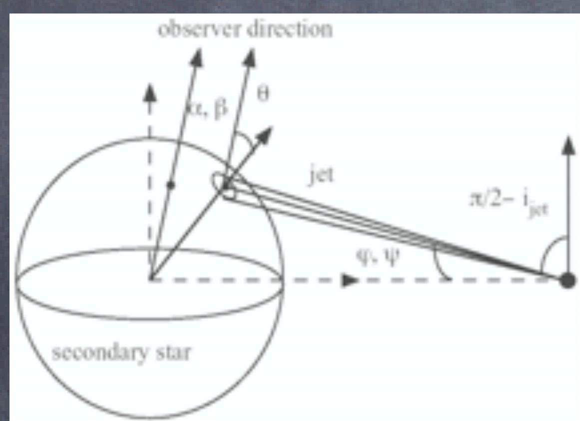

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Table 4.3. 511 keV 2 σ steady flux upper limits for the hard X (E > 20 keV) microquasars reported in the 3rd IBIS catalogue

Source name	R.A. (deg)	Dec (deg)	Error[a]	F_{20-40}[b] (mCrab)	F_{40-100} mCrab	2 σ flux limit[c] ($10^{-4}\,ph\,cm^{-2}\,s^{-1}$)	Type[d]
XTE J1550-564	237.745	-56.479	0.2	34.0 ± 0.1	55.3 ± 0.2	2.7	LMXB
Sco X-1	244.980	-15.643	0.2	685.7 ± 0.3	24.7 ± 0.3	3.7	LMXB
GRO J1655-40	253.504	-39.846	0.6	2.3 ± 0.1	2.7 ± 0.2	2.5	LMXB
GX 339-4	255.706	-48.792	0.3	40.7 ± 0.1	46.7 ± 0.2	2.6	LMXB
1E 1740.7-2942	265.978	-29.750	0.2	29.8 ± 0.1	36.6 ± 0.1	1.6	LMXB
GRS 1758-258	270.303	-25.746	0.3	58.8 ± 0.1	75.3 ± 0.1	1.6	LMXB
SS 433	287.956	4.983	0.5	10.4 ± 0.1	5.2 ± 0.2	2.4	HMXB
GRS 1915+105	288.799	10.944	0.2	296.8 ± 0.1	123.4 ± 0.2	2.5	LMXB
Cyg X-1	299.590	35.199	0.2	763.7 ± 0.2	876.7 ± 0.3	3.0	HMXB
Cyg X-3	308.108	40.956	0.2	196.5 ± 0.2	78.3 ± 0.3	2.6	HMXB

[a]Position error expressed as radius of 90 % confidence circle in arcminutes

[b]Fluxes averaged on the total exposure (Bird et al. 2007):
20-40 keV: $1\,mCrab = 7.57 \times 10^{-12}\,erg\,cm^{-2}\,s^{-1} = 1.71 \times 10^{-4}\,ph\,cm^{-2}\,s^{-1}$
40-100 keV: $1\,mCrab = 9.42 \times 10^{-12}\,erg\,cm^{-2}\,s^{-1} = 9.67 \times 10^{-5}\,ph\,cm^{-2}\,s^{-1}$

[c]The collective flux limit, obtained adding the detected flux from all the sources, is $\sim 10^{-4}\,ph\,cm^{-2}\,s^{-1}$

[d]Type identifiers: LMXB=Low Mass X-ray binary, HMXB=High Mass X-ray binary

Table 4.8. 511 keV 2 σ upper flux limit during the hard X outburst of two microquasars detected by IBIS

Source	Start (MJD)	End (MJD)	ΔT (days)	F_{20-40}[a] (mCrab)	511 keV flux limit ($10^{-4}\,ph\,cm^{-2}\,s^{-1}$)
GRO J1655-40	53424.05	53447.03	22.98	2.3 ± 0.1	7.6
GX 339-4	54127.91	54132.37	4.46	40.7 ± 0.1	15

[a]Mean flux in mCrab in the 20-40 keV band (Bird et al. 2007)
$1\,mCrab = 7.57 \times 10^{-12}\,erg\,cm^{-2}\,s^{-1} = 1.71 \times 10^{-4}\,ph\,cm^{-2}\,s^{-1}$

511 keV emission from XRBs: data analysis
The Galactic Center monitoring

A possible 511 keV emission from the Galactic Center has been also monitored during the INTEGRAL visibility periods at Ms timescale, without finding any signal. The flux upper limit are reported here:

Table 4.7. 511 keV 2σ Sgr A* upper flux limit in the Galactic Center visibility periods.

Period	Start Time (UT)	End Time (UT)	No. ScWs[a]	Sgr A* Exposure[b] (Ms)	Flux limit ($10^{-4}\,ph\,cm^{-2}\,s^{-1}$)
2003 Spring	2003-02-28	2003-04-23	1731	0.650	5.7
2003 Autumn	2003-08-10	2003-10-14	1717	1.872	3.2
2004 Spring	2004-02-16	2004-04-20	1862	1.046	4.5
2004 Autumn	2004-08-17	2004-10-27	2191	1.292	4.3
2005 Spring	2005-02-16	2005-04-28	2144	1.165	4.7
2005 Autumn	2005-08-16	2005-10-26	1667	0.790	5.9
2006 Spring	2006-02-09	2006-04-25	1869	1.501	4.1
2006 Autumn	2006-08-16	2006-11-02	1770	1.080	5.0
2007 Spring	2007-02-01	2007-04-22	985	0.347	9.2

[a]Each ScW lasts about half an hour

[b]Obtained from the exposure map. The exposure map, and in particular the value in the Galaxy depends both on the number of ScWs and the dithering patterns

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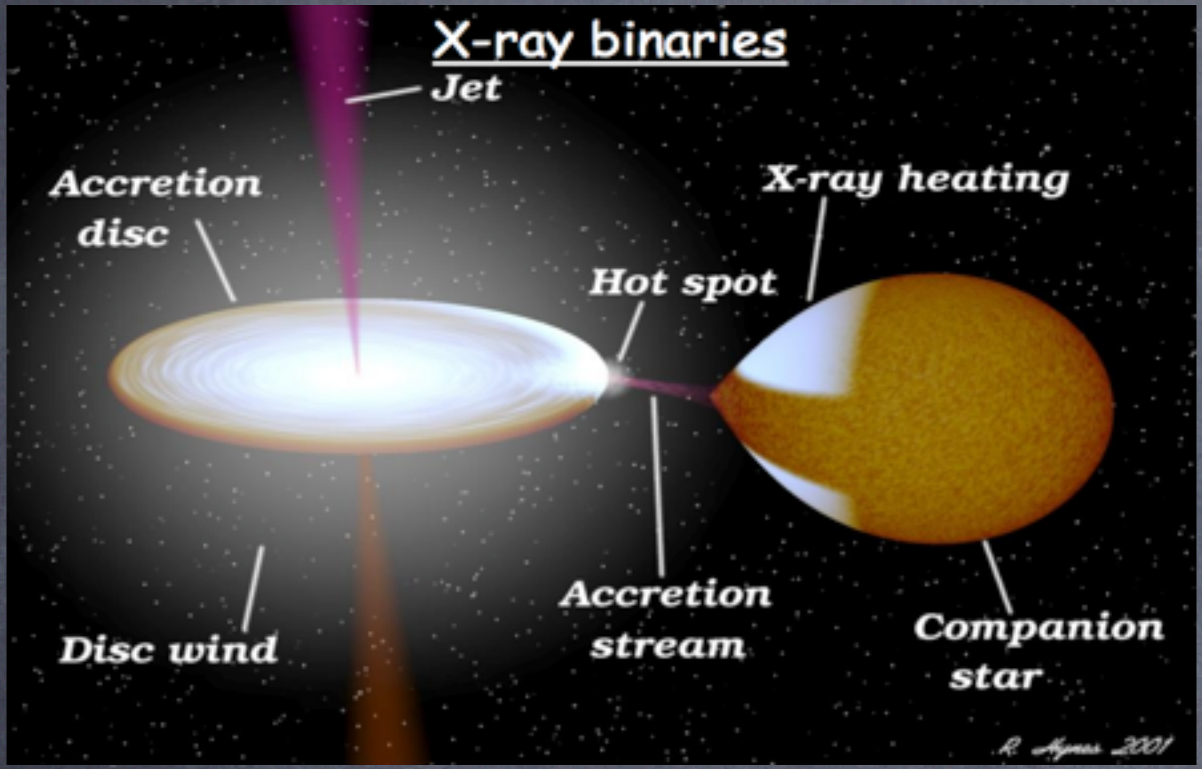
In data analysis a sky map has been generated for each INTEGRAL revolution, therefore also monitoring the IBIS 511 keV sky in day-timescale.

Discussion
How to create e+e- pairs in X-ray binaries?



Electron-positron pairs are created by a 2-steps process:

1. A X-ray photon from the disk is upscattered to high energy E_γ in the corona (Comptonization), very close to compact objects

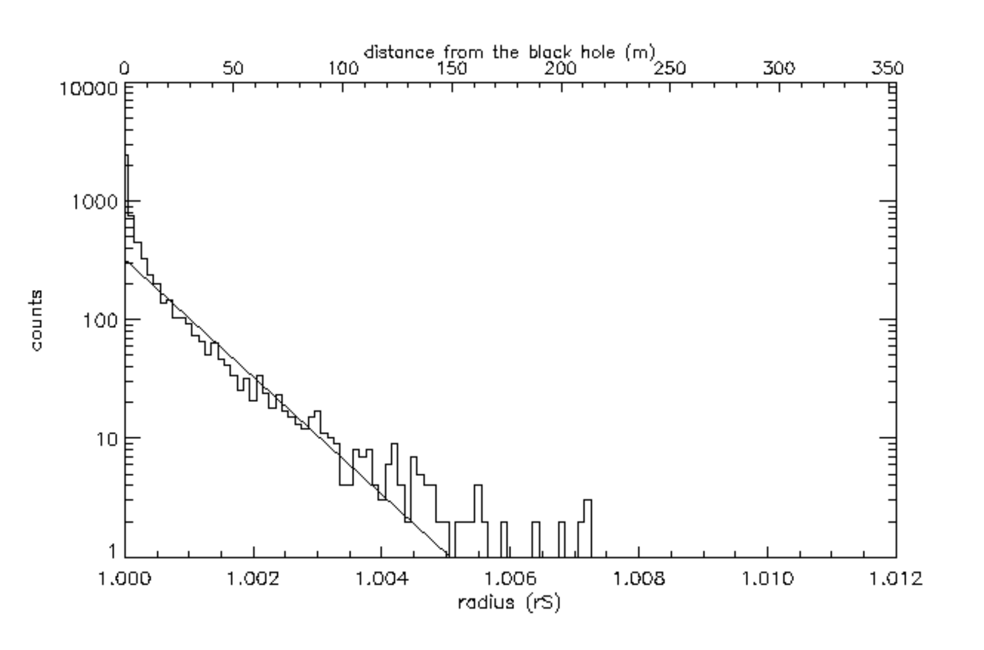
2. Then if $E_X + E_\gamma > 2\ m_e\ c^2$ and $E_X \times E_\gamma > (m_e\ c^2)^2$ this photon can create a pair electron-positron by scattering with another X-ray photon of energy E_X.

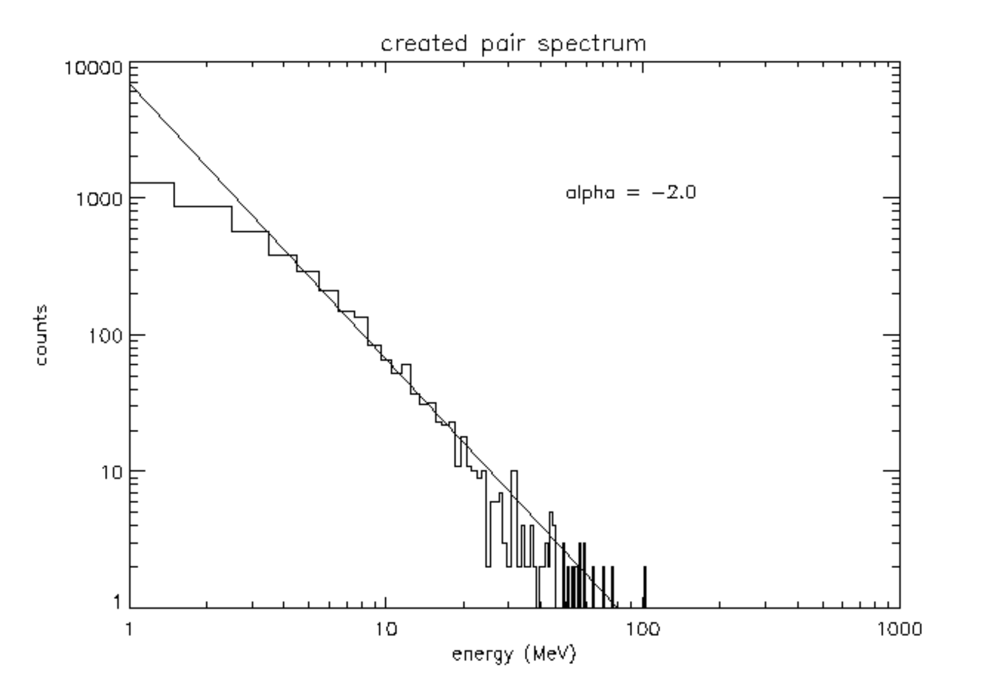
Discussion
What happens to e+e- pairs?

A recent Monte Carlo simulation (Laurent and Titarchuk, in preparation) of the accretion flow in BH XRBs shows that:

1. Most of them fall in the black holes.
2. Other annihilate and create 511 keV photons, which can be observed red-shifted.
3. And other scatter on X-ray photons and create another Comptonization component up to few MeV.

Guessoum, Jean, Prantsoz 2006 suggested that in microquasars a significant fraction of positrons may be channeled out by jets. In this case the 511 keV flux is expected below the INTEGRAL sensitivity.

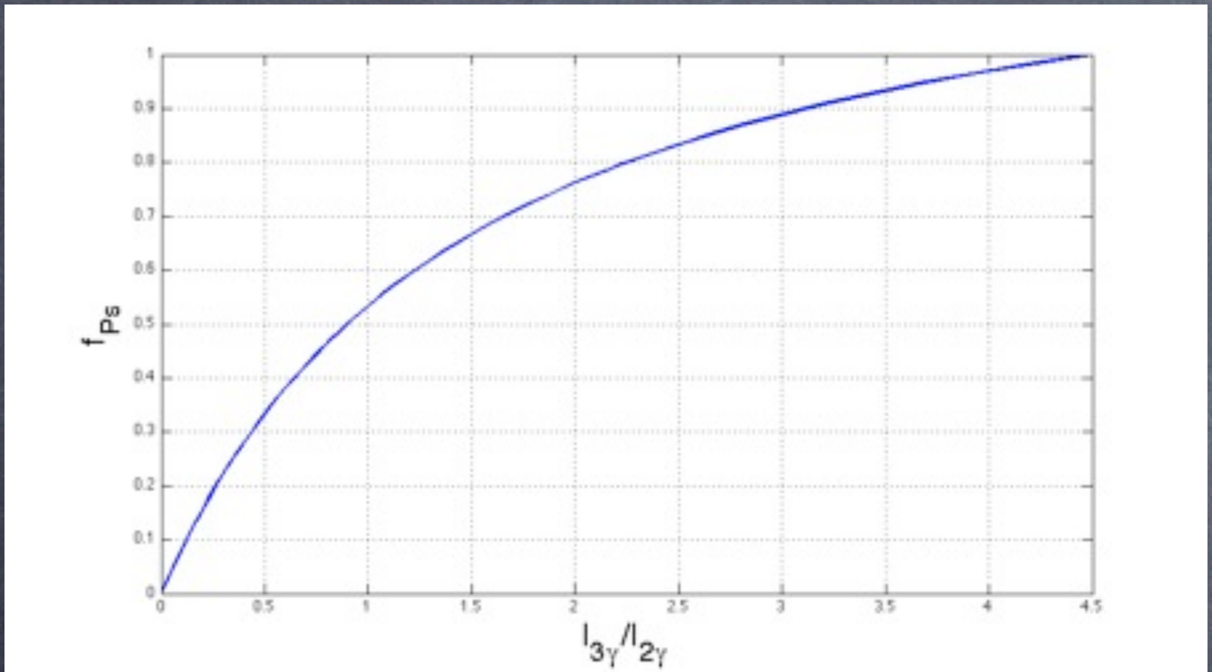




Discussion

Positronium continuum emission and infrared lines

In the INTEGRAL data there is not evidence of soft gamma rays continuum produced in the 3-gamma positronium (Ps) decay. Since the IBIS effective area is high at low energy, if the Ps fraction were 1, this lack of detection would provide strong a constraint of the e+e- annihilation in XRBs. But also note that soft gamma-ray emission in XRBs is dominated by Comptonization.



The signal depends on the positronium fraction, being maximum ($I_3/I_2 = 9/2$) when all the positrons annihilate by the positromium formation, and zero if no positronium atoms are formed.

Since the Ps energy levels to hydrogen once the mass is replaced by $m_e/2$, infrared lines from Ps atoms could also be visible in forthcoming observations (Ellis and Bland-Hawthorn, 2009; Puxley and Skinner 2006).

n	Radiative lifetime τ/s	Singlet Ps Annihilation lifetime T/s	Singlet Ps Ratio T/τ	Triplet Ps Annihilation lifetime T/s	Triplet Ps Ratio T/τ
1	–	1.25×10^{-10}	–	1.41×10^{-7}	–
2	4.26×10^{-9}	10.0×10^{-10}	0.23	1.1×10^{-6}	265
3	8.12×10^{-8}	3.37×10^{-9}	0.041	3.8×10^{-6}	46.9
4	6.17×10^{-7}	8.00×10^{-9}	0.013	9.0×10^{-6}	14.6
5	2.90×10^{-6}	1.56×10^{-8}	0.0053	1.76×10^{-5}	6.03
6	1.04×10^{-5}	2.70×10^{-8}	0.0026	3.05×10^{-5}	2.93

The radiative and annihilation lifetimes of Ps for various energy levels.

Conclusions

- Is there any evidence of 511 keV emission line from XRBs in the INTEGRAL data? NO. By reducing 5 year of the IBIS imager data, we do not find any evidence of 511 keV lines feature from BH sources. The 511 keV broad line upper flux limit are reported by De Cesare, 2011. Basically, we know that in one second, from XRBs we cannot get 2 or more photons in one square meter. The 511 keV narrow line flux upper limits, obtained with the spectrometer data, are reported by Knodlseder et al., 2005.

- Are INTEGRAL results in agreement with XRBs models? YES. The lack of a 511 keV radiation can be explained by that photons related to 511 keV line are reprocessed in the local environment and even if they escape directly to the Earth observer they are seen at much lower energies because the gravitational redshift (Laurent and Titarchuk, in preparation). Guessoum et al. in 2006 suggest that in microquasars a significant fraction of positrons may be channeled out by jets, but at a flux lower than the INTEGRAL upper limits.

- Is it possible to detect the 3 gamma positronium continuum? MAYBE. But so far this signature is not reported in the hard X (soft gamma) XRBs spectra measured by INTEGRAL. The intensity of this component depends on the positronium fraction, being 9/2 of the 511 keV line intensity if all positrons annihilate by formation of positronium atoms. A cool molecular cloud coincident with 1E 1740.7 (Mirabel et al., 1991) might slow down relativistic positrons to the velocity required for Ps formation.

- Is it possible to detect infrared Ps lines? MAYBE. The flux upper limit reported by Puxley and Skinner in 2006 is of the order of 10^{43} ph/s, i.e. the total Galactic positrons flux, but a better sensitivity can be obtained with the recent advances in NIR observations.