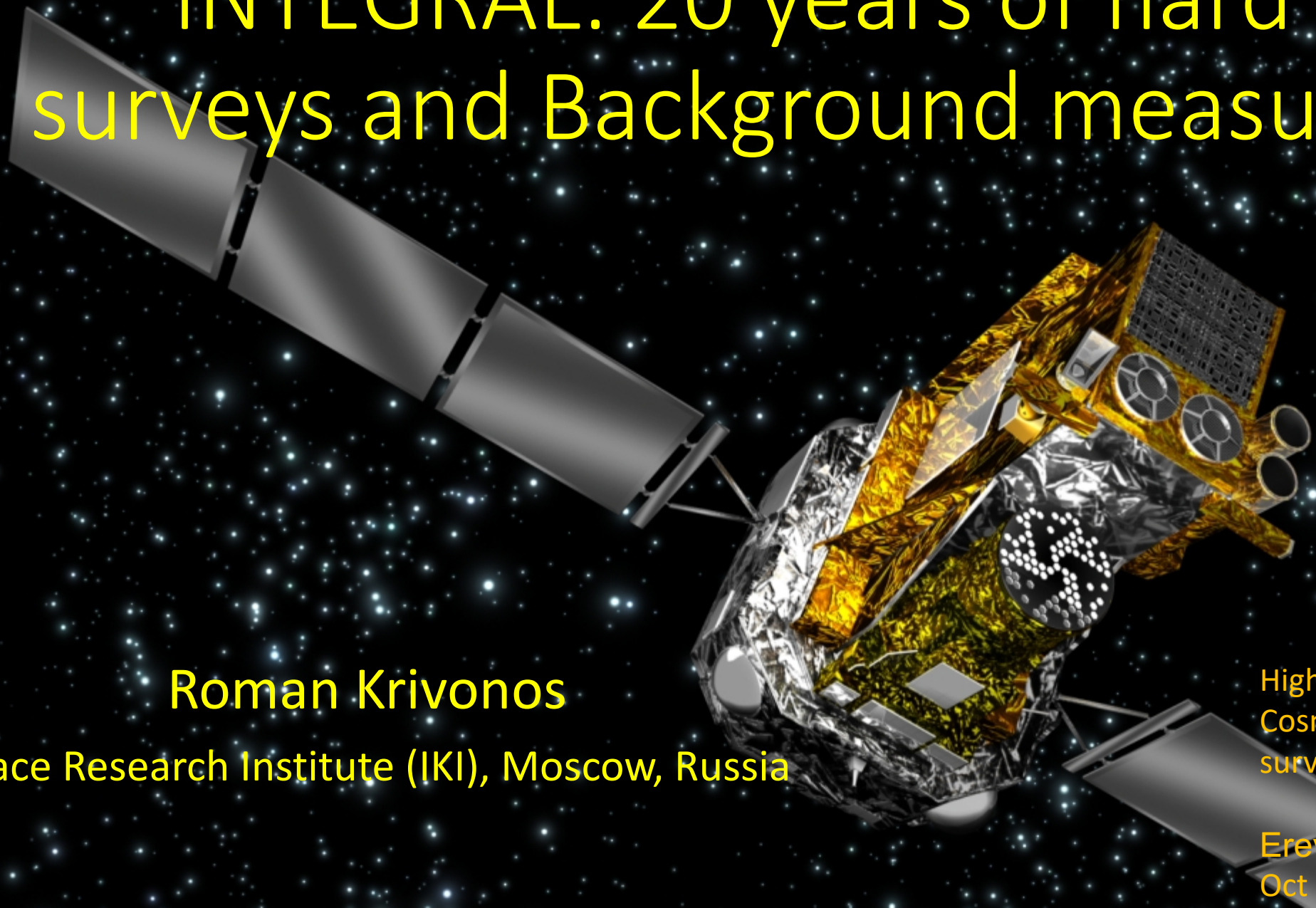
INTEGRAL: 20 years of hard X-ray surveys and Background measurements



Roman Krivonos

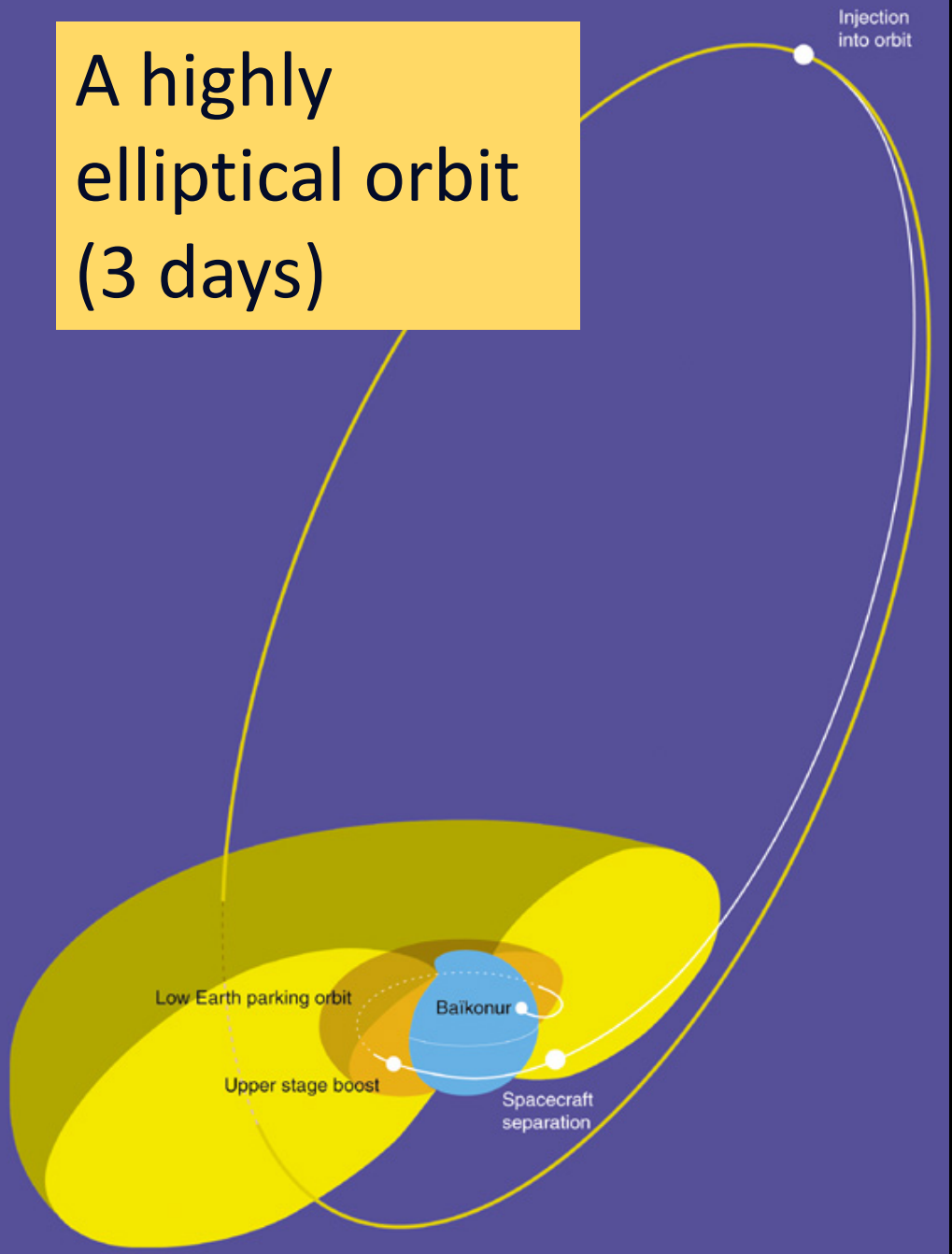
Space Research Institute (IKI), Moscow, Russia

High Energy Astrophysics and Cosmology in the era of all-sky surveys

Erevan, Armenia
Oct 7 – 11, 2024

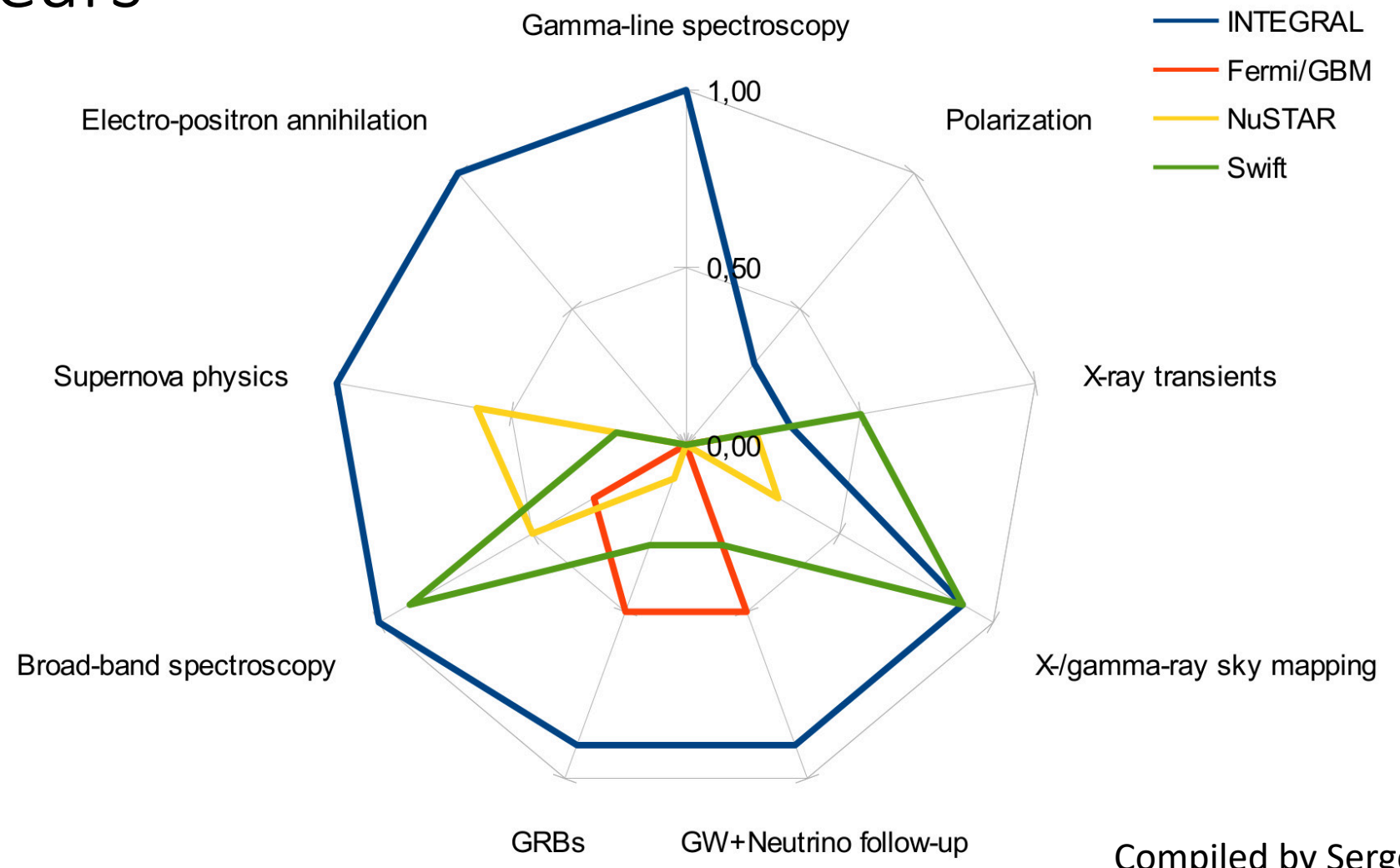
INTEGRAL was launched by a Proton rocket on 17 October 2002 from the Baikonur in Kazakhstan.

A highly elliptical orbit (3 days)




IBIS – 20 keV to 10 MeV
FOV **30x30** deg
resolution 12’
JEM-X
3-35 keV
FOV **13x13** deg
resolution 3’
SPI – 20 keV – 8 MeV
FOV **32x32** deg,
resolution 2.5 deg

INTEGRAL contribution in different fields of astrophysics after 20 years



Compiled by Sergey Grebenev

Outline of the talk

- INTEGRAL performance for surveying the hard X-ray sky
- Part 1. Extragalactic source population
  - Properties of AGN population
  - AGN spatial distribution in the local Universe
  - Cosmic X-ray Background
- Part 2. Milky Way galaxy
  - Cataclysmic Variables
  - Galactic Ridge X-Ray Emission
  - LMXB population
  - HMXB population

Coded-mask telescope **IBIS** onboard INTEGRAL: hard X-ray surveys constitute one of the main goals of the mission

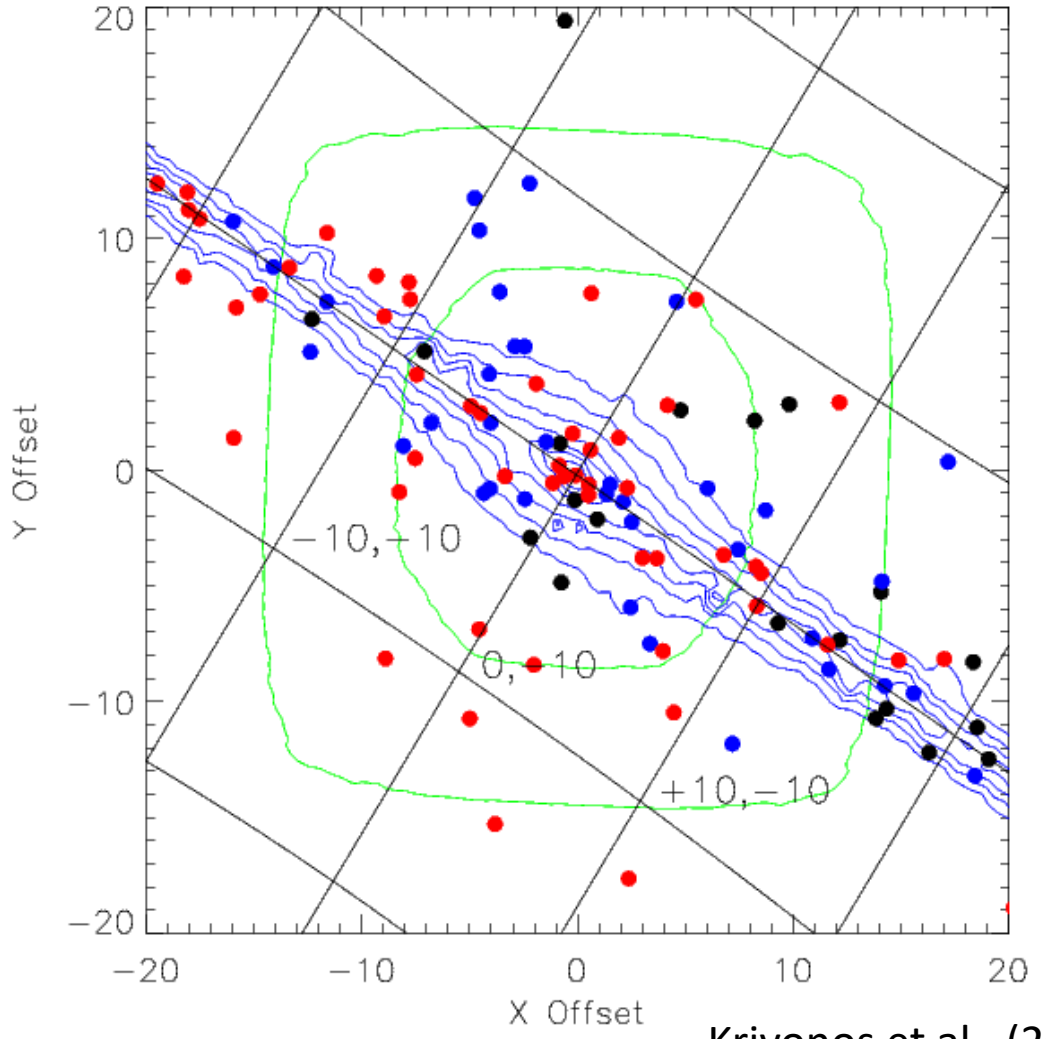
- Large FOV

- Ability to localize point sources

- High sensitivity (17 – 500 keV)

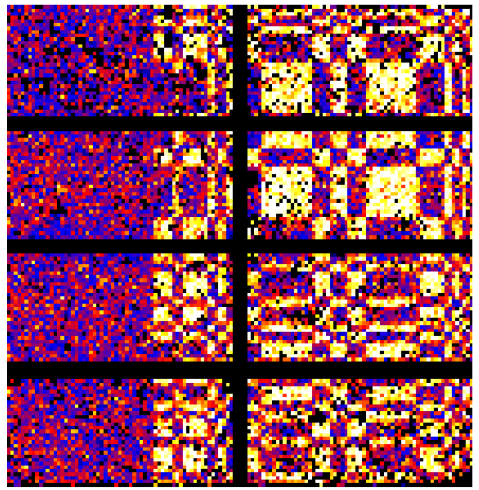
- 3-day orbit for long uninterrupted observations

Galactic Center region

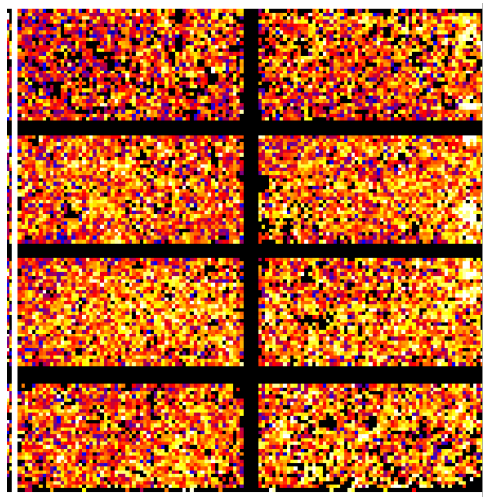


Krivonos et al., (2010)

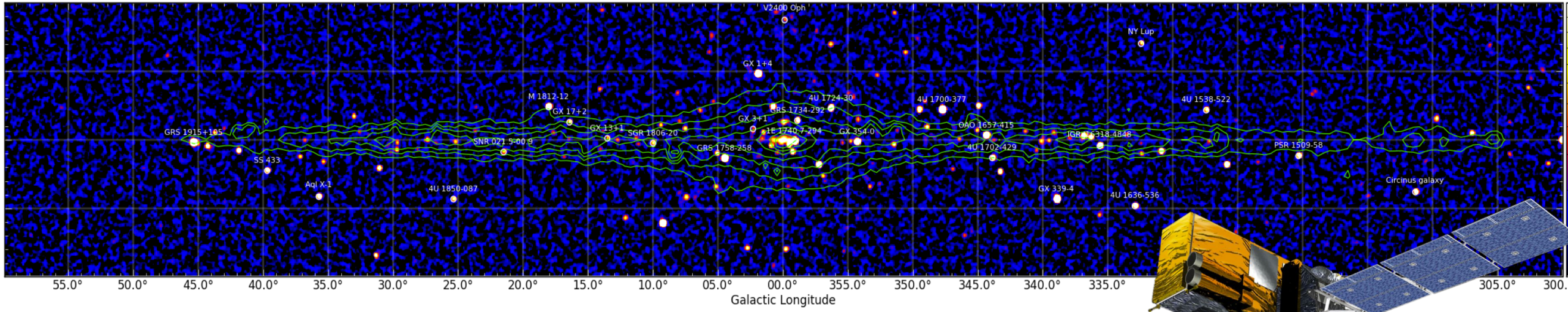
IBIS/ISGRI raw detector images



Ideal case

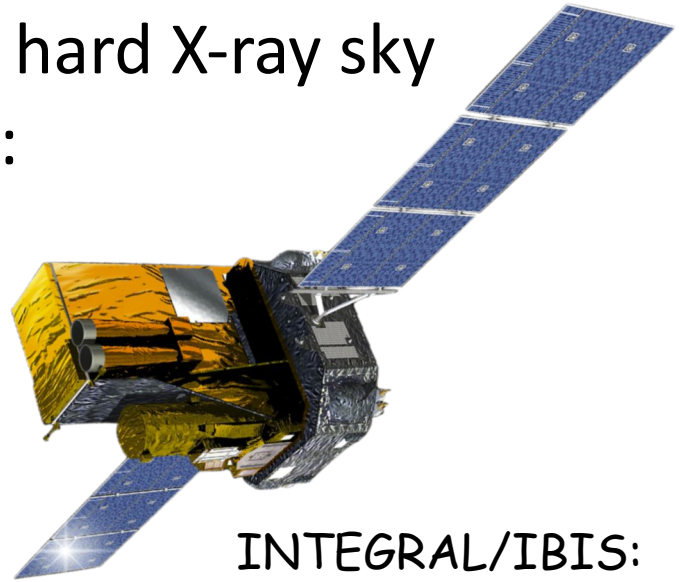


Galactic center

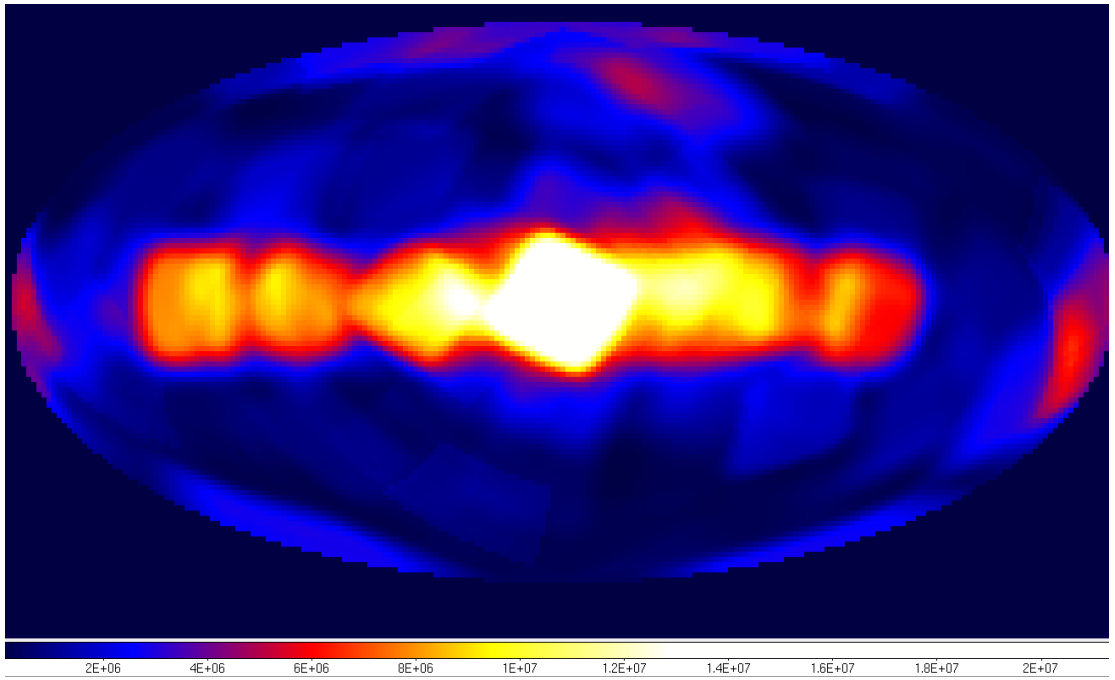


- Systematic study of the source populations
- Search for new phenomena
- year-long snapshot of the whole Galaxy
- The Milky Way is a unique galaxy where we can detect X-ray objects with the lowest possible luminosities.
- Population studies for Galactic and extragalactic X-ray emitters
- Providing new information (targets) for multi-wavelength follow up

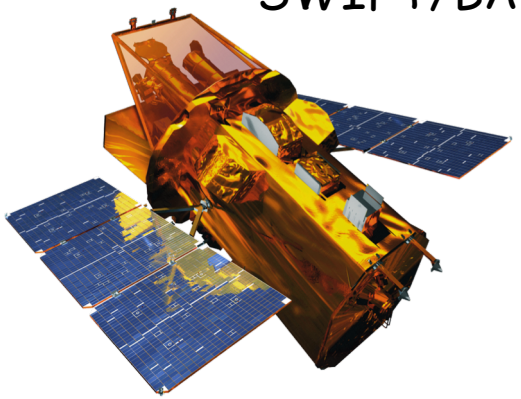
Two main hard X-ray sky observers:

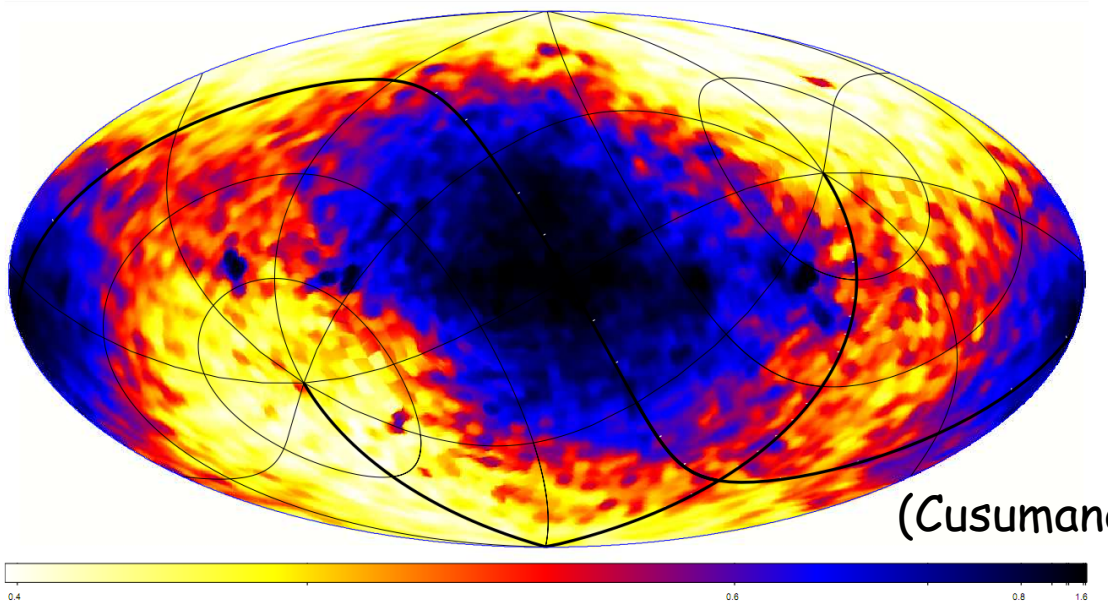


INTEGRAL/IBIS:



SWIFT/BAT:





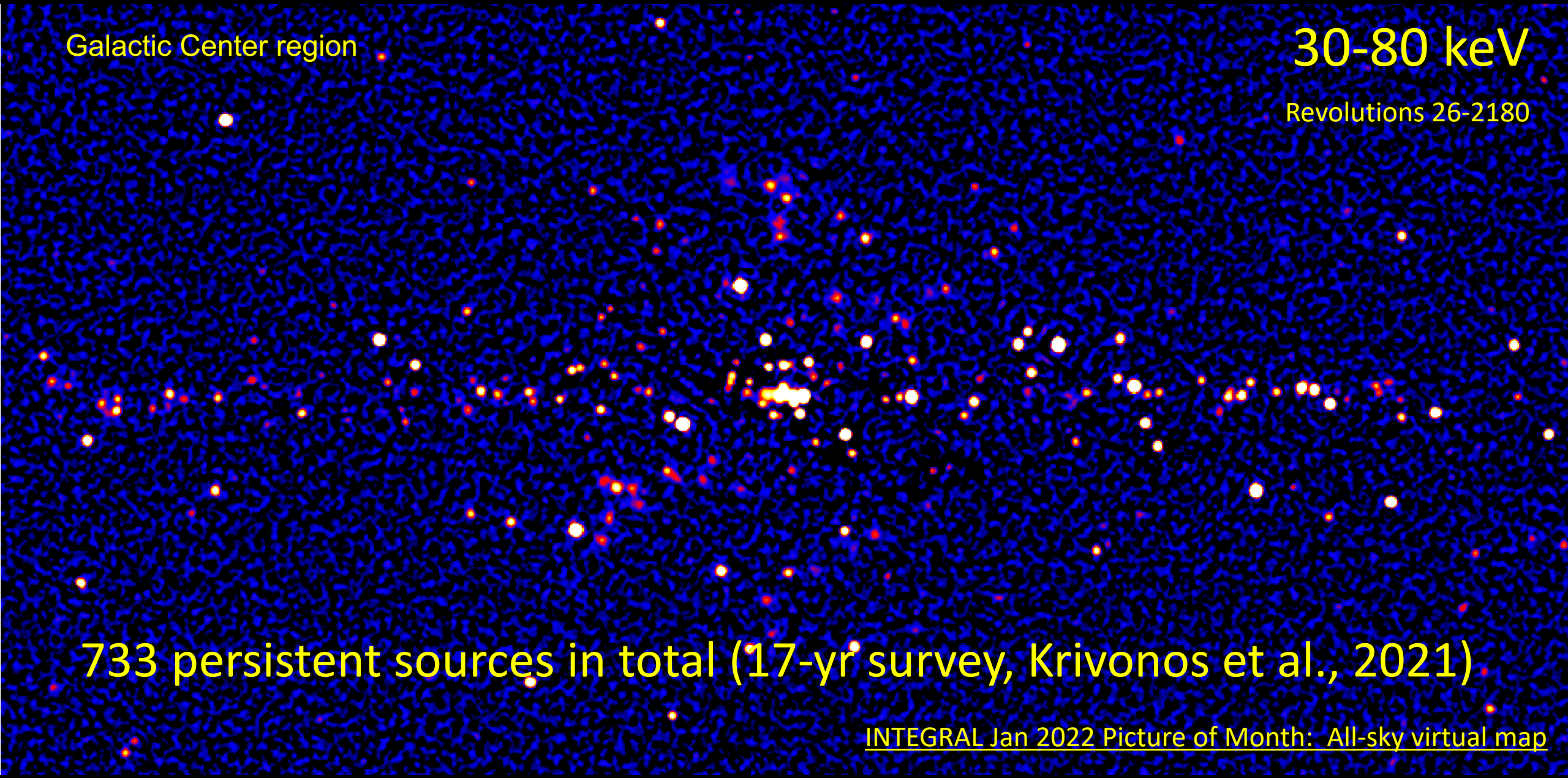
(Cusumano et. al., 2009)

List of 23 INTEGRAL X-ray surveys from 2003 to 2017 (~1.6/year)

Paper by	*INTEGRAL* telescope	ΔE [keV]	Sensitivity [mCrab (σ)]	Sky coverage	Total number of sources	IGR sources[c]	Completeness[d]
Winkler et al. (2003b)	IBIS/ISGRI	15 – 40	36[a] (5σ)		110	10	
	SPI	20 – 40	62[a] (5σ)		33	3	
	JEM-X	5 – 20	20[a] (5σ)		50		
Revnivtsev et al. (2004b)	IBIS/ISGRI	18 – 60	1 – 2	~ 900 deg^2	60	5	10/60
Molkov et al. (2004)	IBIS/ISGRI	18 – 60	1.4	35° × 40°	28	7	7/28
Bird et al. (2004)	IBIS/ISGRI	20 – 100	~ 1		120	5	28/120
Krivonos et al. (2005)	IBIS/ISGRI	20 – 50	~ 1 (4σ)	40° × 40°	13	5	5/13
Revnivtsev et al. (2006)	IBIS/ISGRI	17 – 60	0.8 – 1 (5σ)	50° × 50°	46	20	13/46
Bouchet et al. (2005)	SPI	20 – 150		100° × 50°	63	8	
Bird et al. (2006)	IBIS/ISGRI	20 – 100	~ 1	~ 50%	209	56	~ 75%
Bazzano et al. (2006)	IBIS/ISGRI	100 – 150	~ 2 (4σ)	~ 50%	49		100%
Bird et al. (2007)	IBIS/ISGRI	17 – 100	~ 1	~ 70%	421	167	~ 75%
Krivonos et al. (2007)	IBIS/ISGRI	17 – 60	~ 1	100%	403	137	48/403
Kuulkers et al. (2007)	IBIS/ISGRI	20 – 60,	1[b] (3σ)		76	18	
		60 – 150	3[b] (3σ)		76	18	
	JEM-X	3 – 10,			18		
		10 – 25			18		
Paltani et al. (2008)	IBIS/ISGRI	20 – 60	0.5 (5σ)	2500 deg^2	34	34	~ 100%
Krivonos et al. (2010b)	IBIS/ISGRI	17 – 60	0.26 (5σ)	100%	521	212	38/521
Bird et al. (2010)	IBIS/ISGRI	17 – 100	< 1	100%	723	378	~ 70%
Krivonos et al. (2012)	IBIS/ISGRI	17 – 80	~ 0.2 (4.7σ)	$\|b\|$ < 17.5°	402	180	~ 92%
Grebenev et al. (2013)	IBIS/ISGRI	20 – 60	~0.5 (4.5σ)	640 deg^2	21	4	90%
	JEM-X	3 – 20	~0.5 (5σ)	~100 deg^2	10	0	100%
Krivonos et al. (2015)	IBIS/ISGRI	100 – 150	~ 2 (4σ)	100%	132		100%
Grebenev et al. (2015)	JEM-X	5 – 25		$\|l, b\|$ < 20°	105	24	
Bird et al. (2016)	IBIS/ISGRI	17 – 100	< 1	100%	939	~ 560	
Tsygankov et al. (2016)	IBIS/ISGRI	64.6 – 82.2	~ 0.7 (4.7σ)	$\|b\|$ < 17.5°	1		
Mereminskiy et al. (2016)	IBIS/ISGRI	17 – 60	~ 0.18 (4σ)	4900 deg^2	147	37	25/147
Krivonos et al. (2017)	IBIS/ISGRI	17 – 60	~ 0.15 (4.7σ)	$\|b\|$ < 17.5°	72	72	46/72

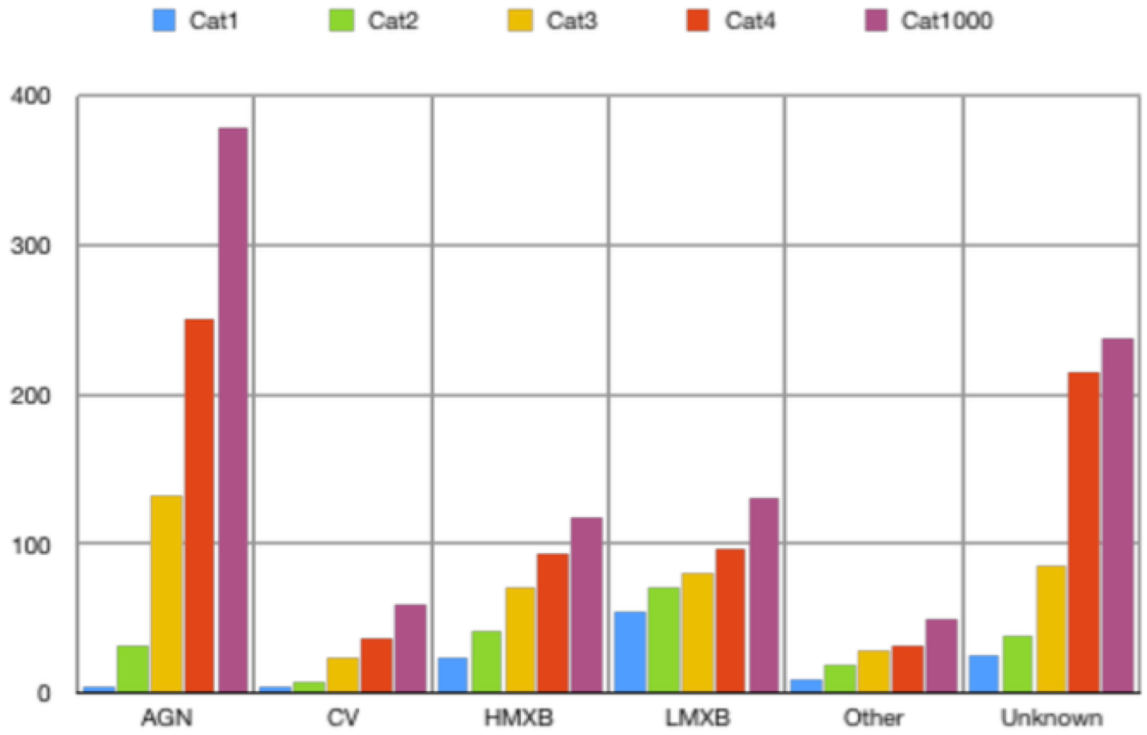
INTEGRAL is a surveying machine

INTEGRAL “15-year reviews” Krivonos et al., (2021)


Galactic Center region
30-80 keV
Revolutions 26-2180
733 persistent sources in total (17-yr survey, Krivonos et al., 2021)
INTEGRAL Jan 2022 Picture of Month: All-sky virtual map

Evolution of source type and number with time, as published in A. J. Bird catalogs

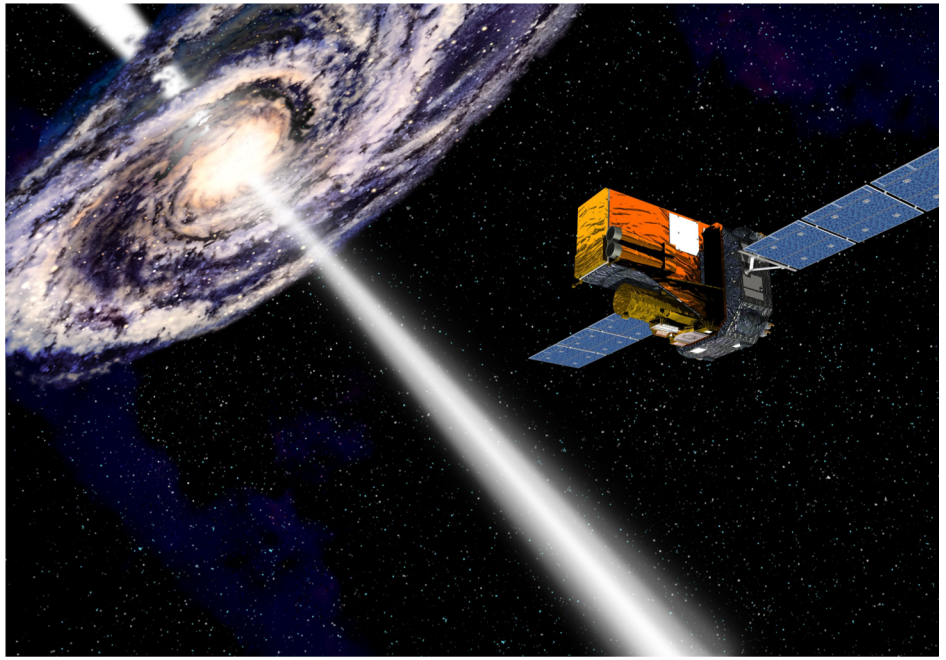
Bird et al., 2004; 2006; 2007; 2009; 2016;



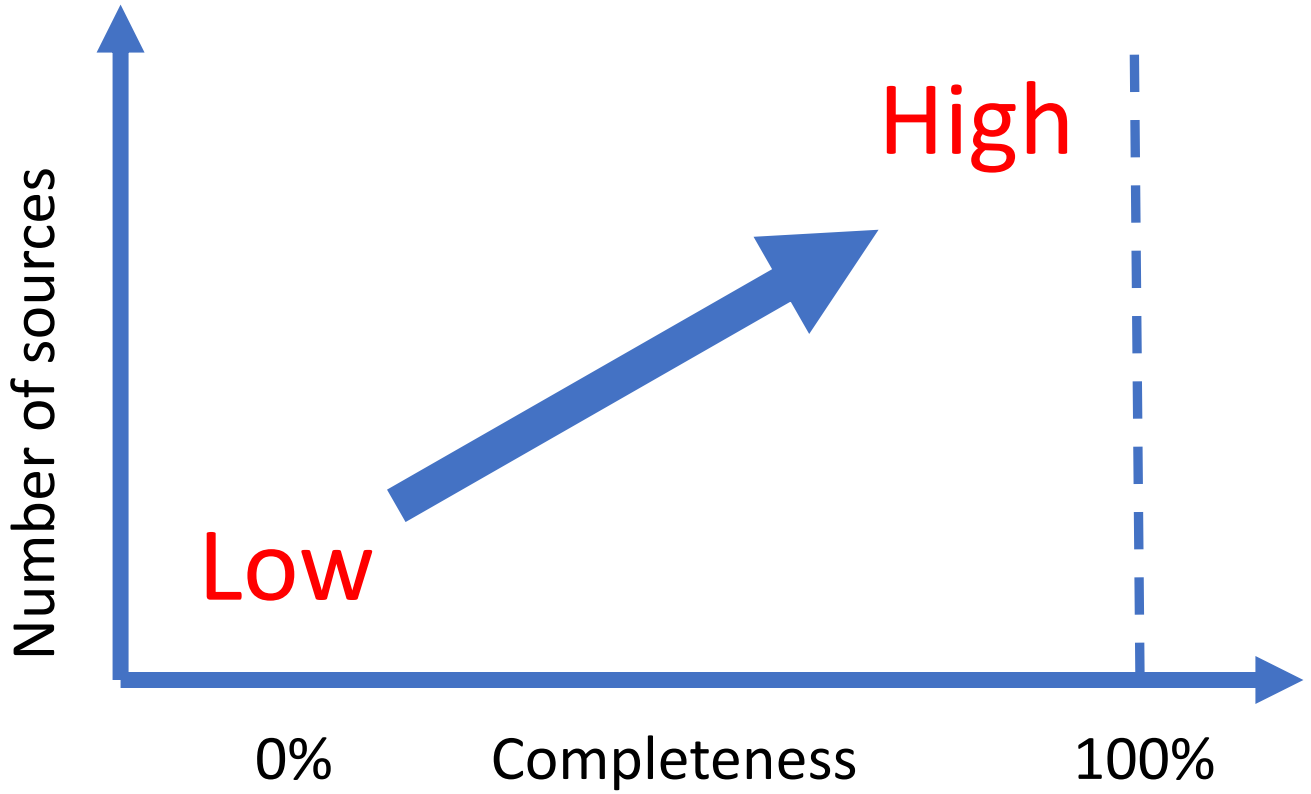
INTEGRAL “15-year reviews” Malizia et al., (2021)

Part 1. Extragalactic source population

- Hard X-ray band is most appropriate for AGN population studies since it is almost unbiased against obscuration
- INTEGRAL plays a key role in detecting AGNs **in the Galactic Plane**, while Swift/BAT is more effective at higher Galactic latitudes

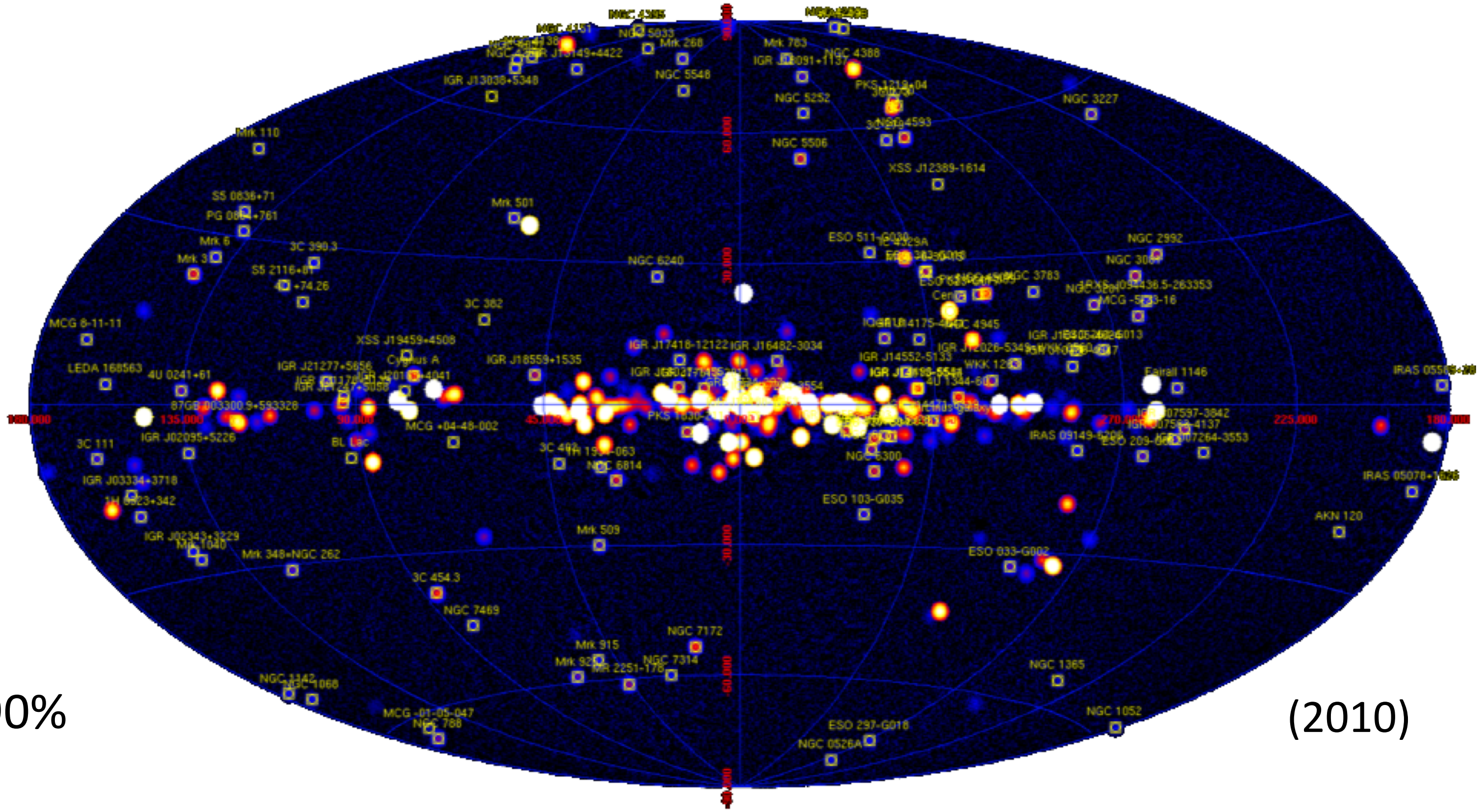


The importance of X-ray surveys for population studies



Brief source detection statistics after 15-17 years

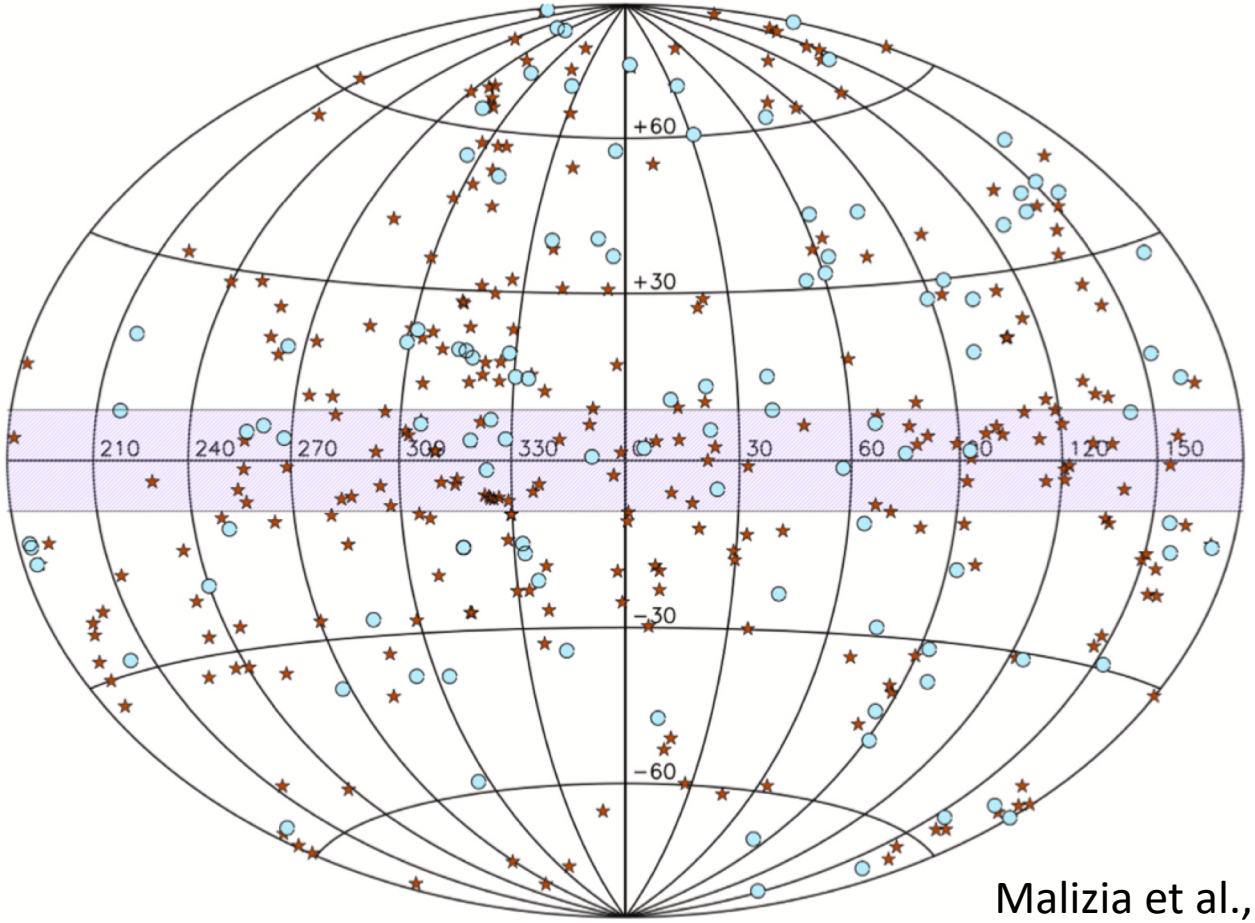
- ~1000 in 17-60 keV
- ~700 in 30-80 keV
- ~100 in 100-150 keV
- ~25 in 150-300 keV



(2010)

Completeness of INTEGRAL surveys is ~90%
(raises at extragalactic to ~97%)

AGNs detected by the INTEGRAL/IBIS surveys for the first time (17-60 keV)



Malizia et al., (2016)

107 new AGNs studied in Malizia et al. (2016) taken from the INTEGRAL/IBIS survey by Bird et al., (2016) (stars)

AGNs detected in previous INTEGRAL/IBIS surveys (circles)

INTEGRAL AGN types and properties

Malizia et al., 2021

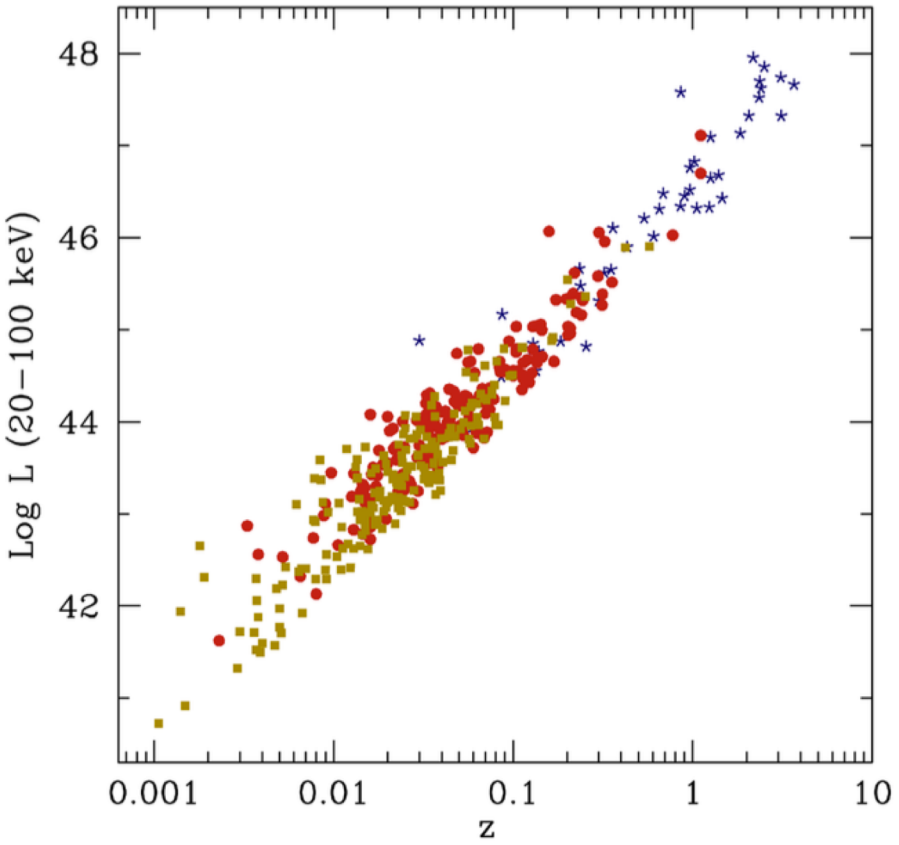
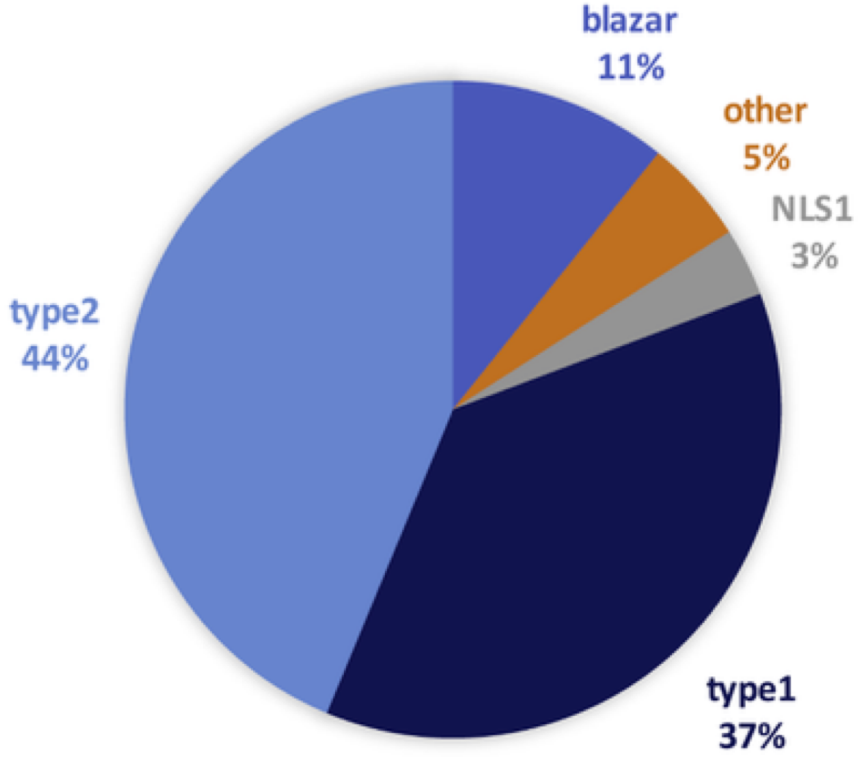


Fig. 3. Observed hard X-ray (20-100 keV) luminosity versus redshift for the whole *INTEGRAL* AGN sample. Gold filled circles are narrow line AGN, red filled squares are broad line AGN and blue stars are balzars.

INTEGRAL AGN sample spans a large range in source parameters:

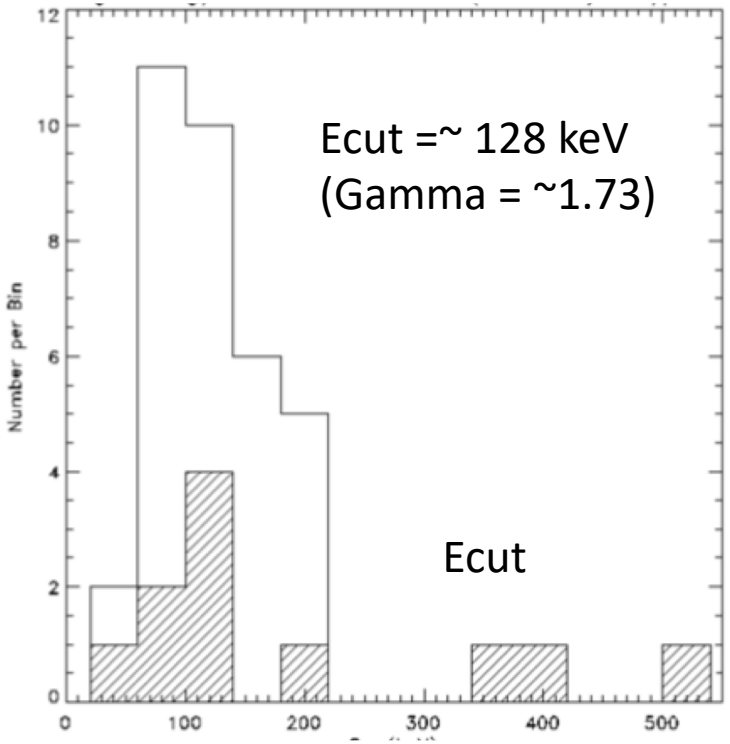
- redshift up to 3.7 with median z=0.035
- luminosity Log10 from 40.23 to ~48 with mean 44



INTEGRAL AGN types and properties

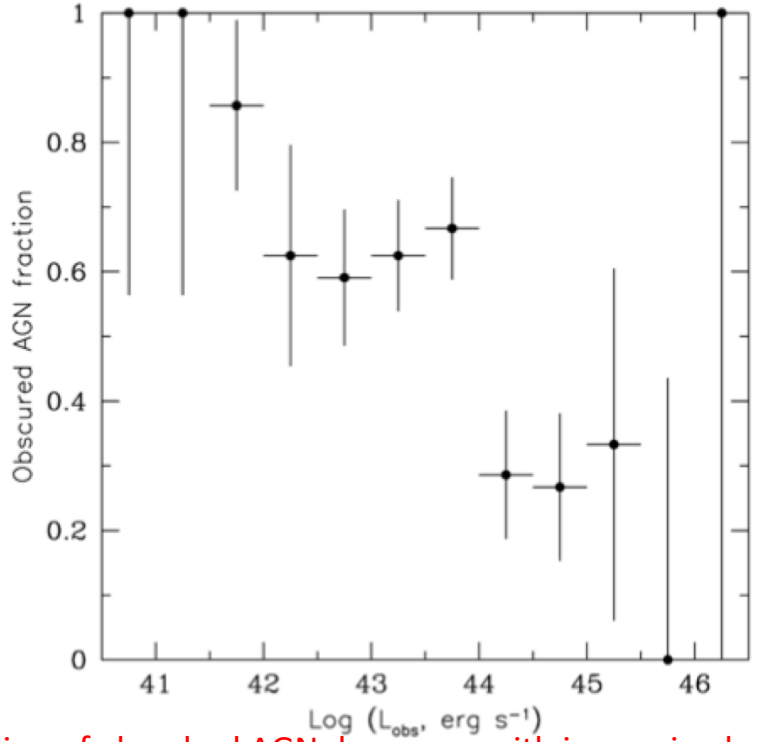
Malizia et al., 2021

AGN Sy1 high-energy cut-off distribution

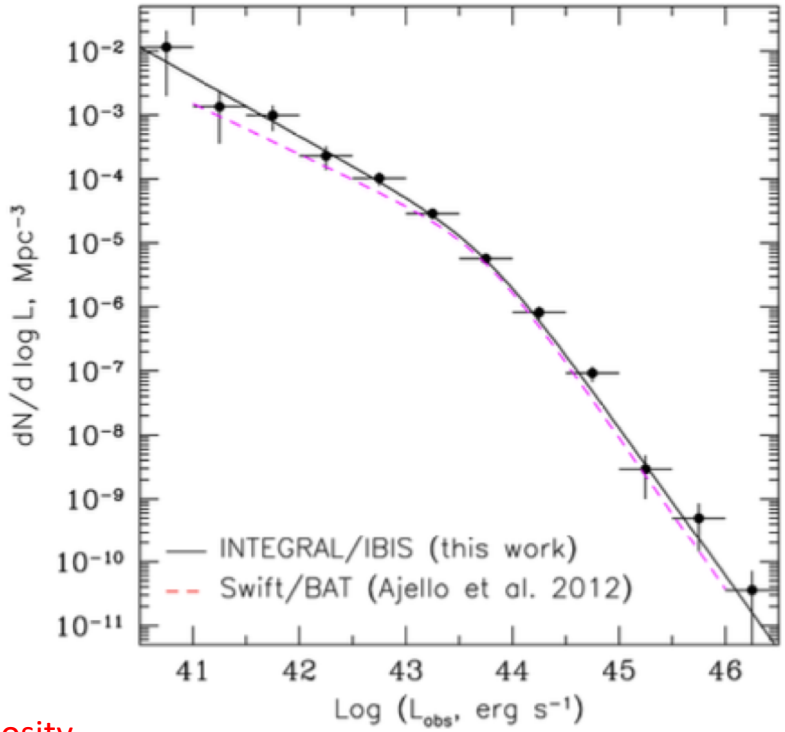


hatched – lower limits of Ecut

Observed fraction of absorbed AGN as a function of observed luminosity (Sazonov et al., 2015)



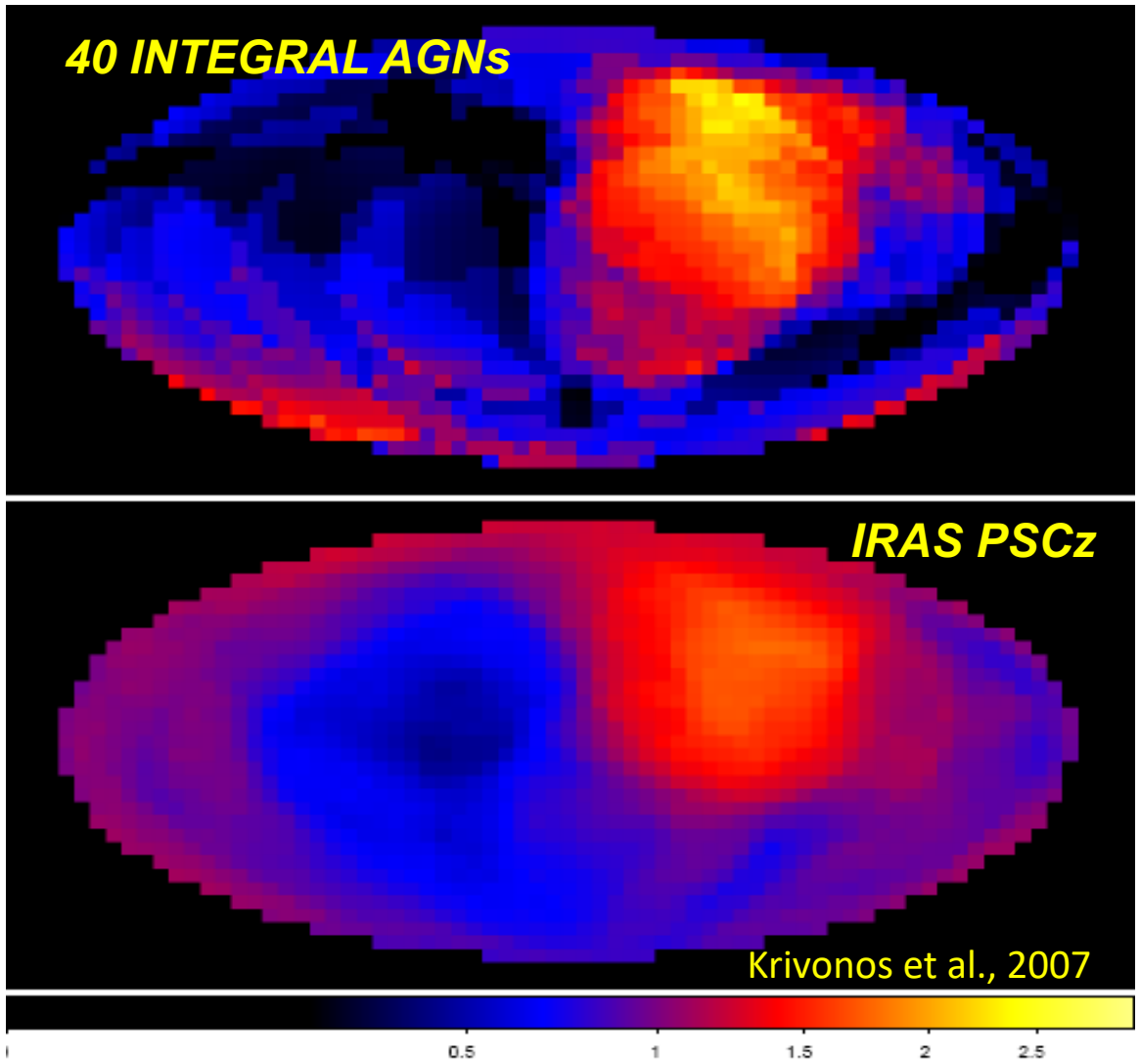
Observed hard X-ray luminosity function of local AGN (Sazonov et al., 2015)

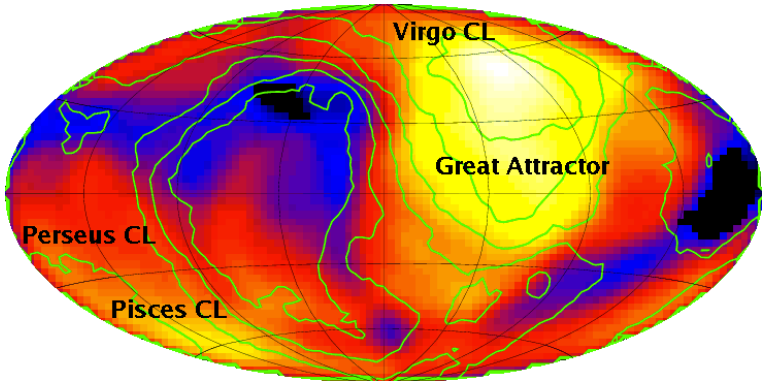


fraction of absorbed AGN decreases with increasing luminosity

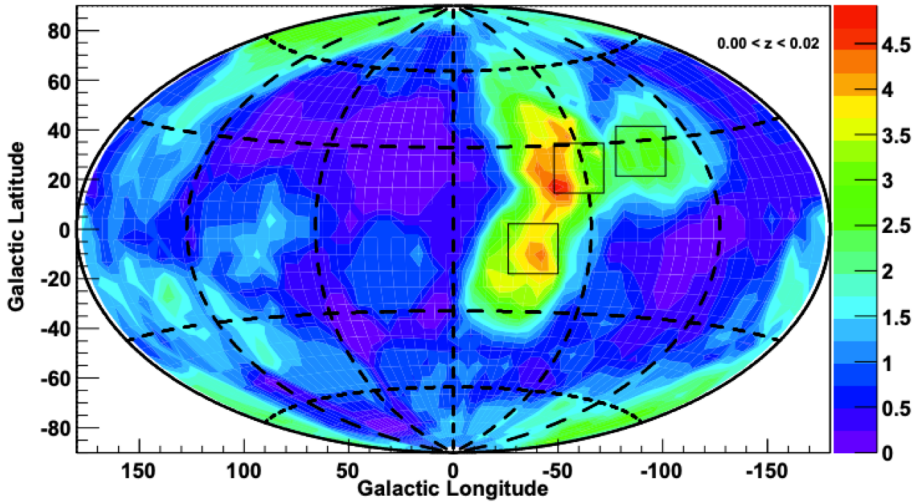
Probing large scale structure of the local universe

Volume density excess of nearby AGN population (<100 Mpc)



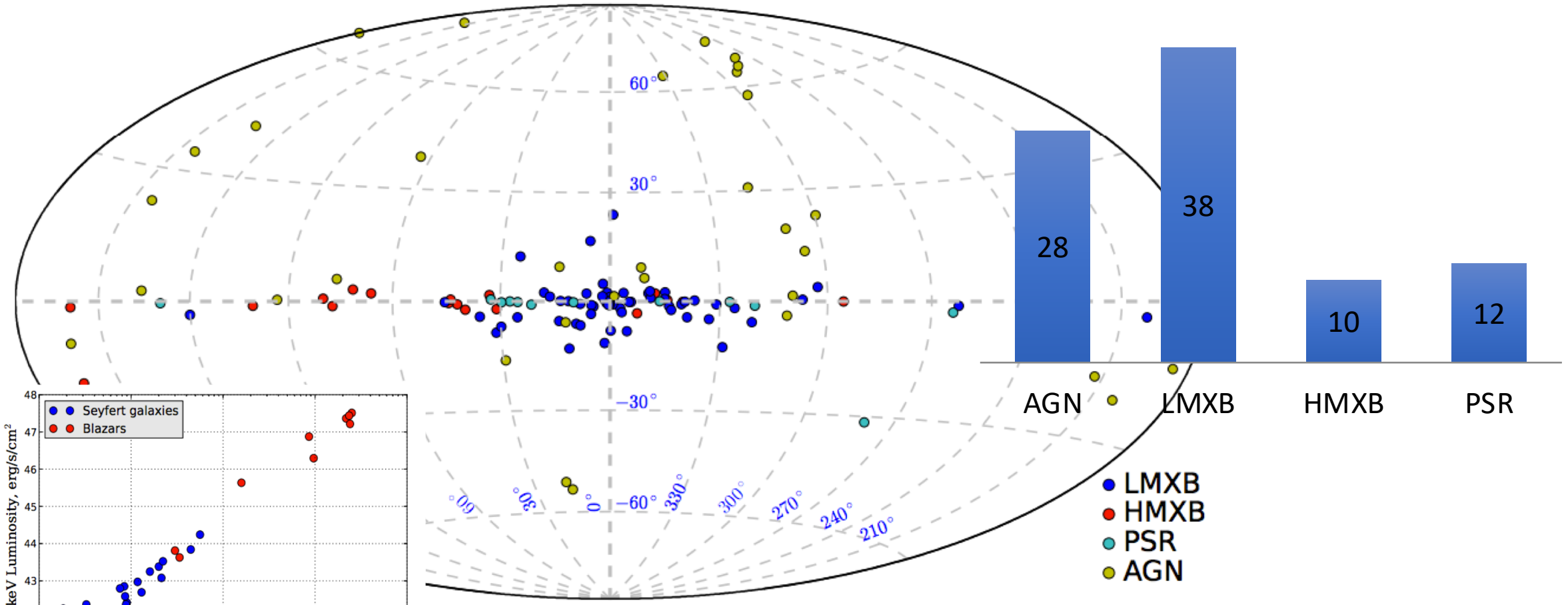


INTEGRAL POM April 2007



60m Swift/BAT survey, Ajello et al., 2012

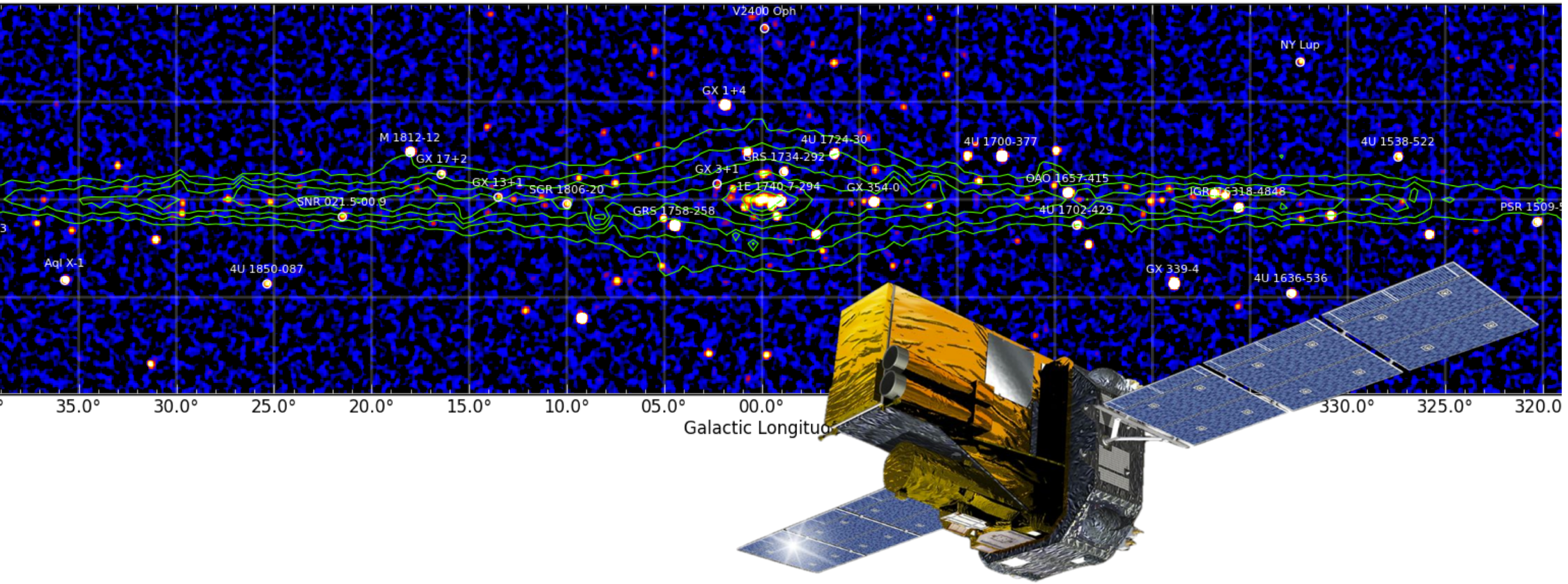
101 INTEGRAL/IBIS sources in **100-150 keV**



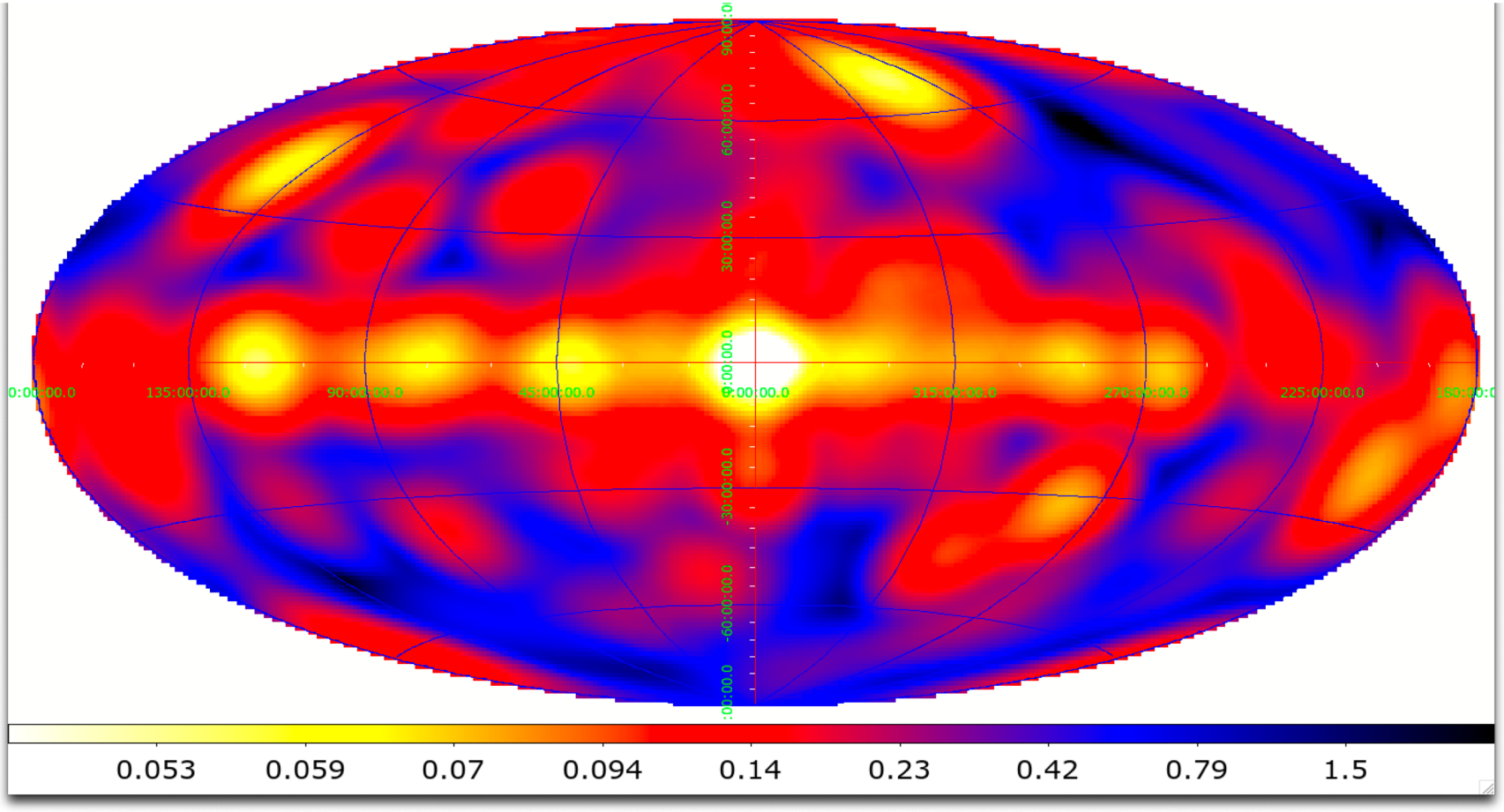
100% completeness

25 sources in **150-300 keV**

Part 2. Milky Way galaxy



17-60 keV IBIS/ISGRI 17-year sensitivity map in mCrab units (1 sigma)

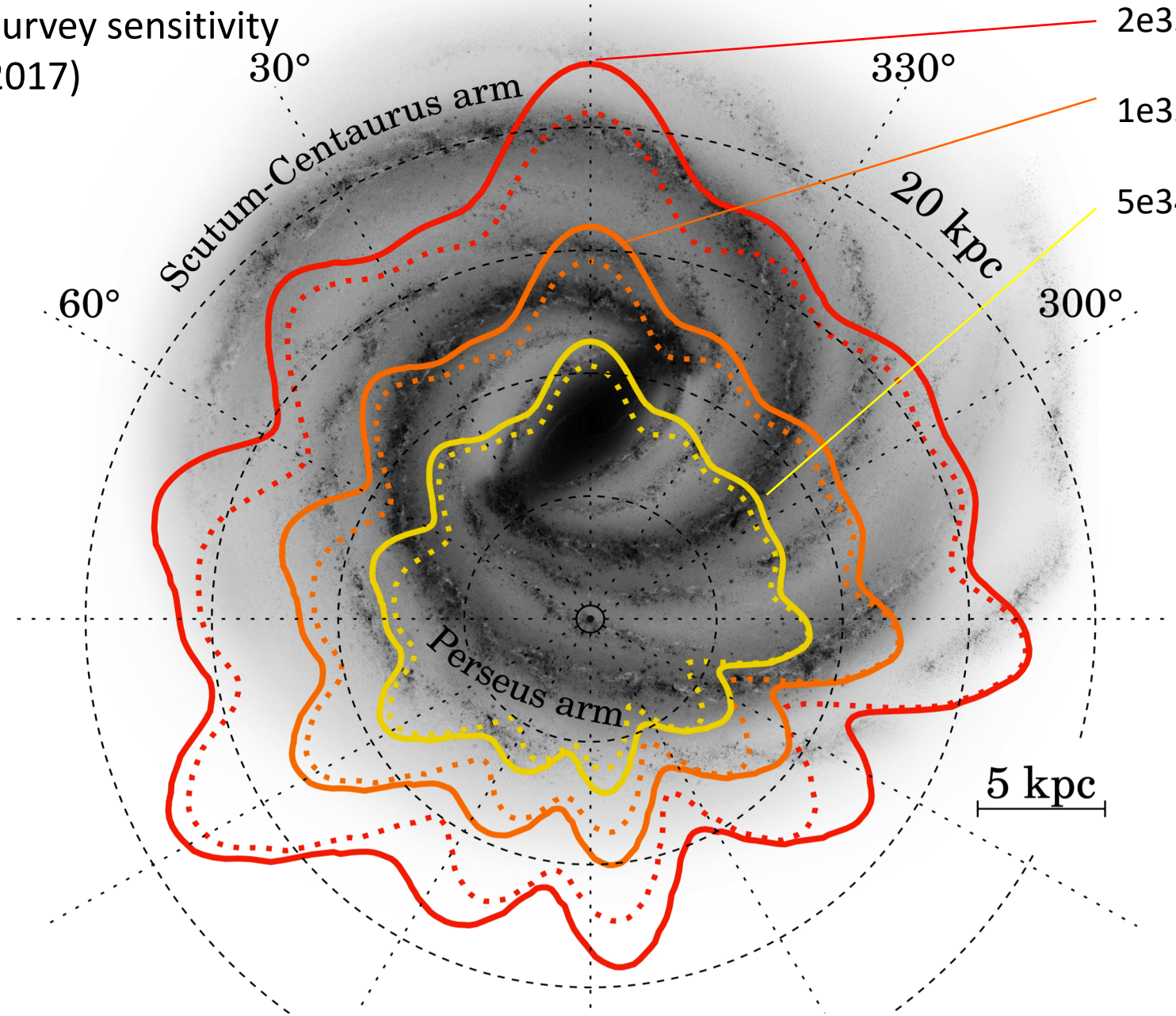


Sky 10% -- 0.27 mCrab (4.5 sigma)
Sky 90% -- 1.67 mCrab (4.5 sigma)

1 mCrab sensitivity is achieved for 73% of the sky

Krivonos et al., (2022)

14-year INTEGRAL survey sensitivity
(data up to mid of 2017)



2e35 erg/s “high L”

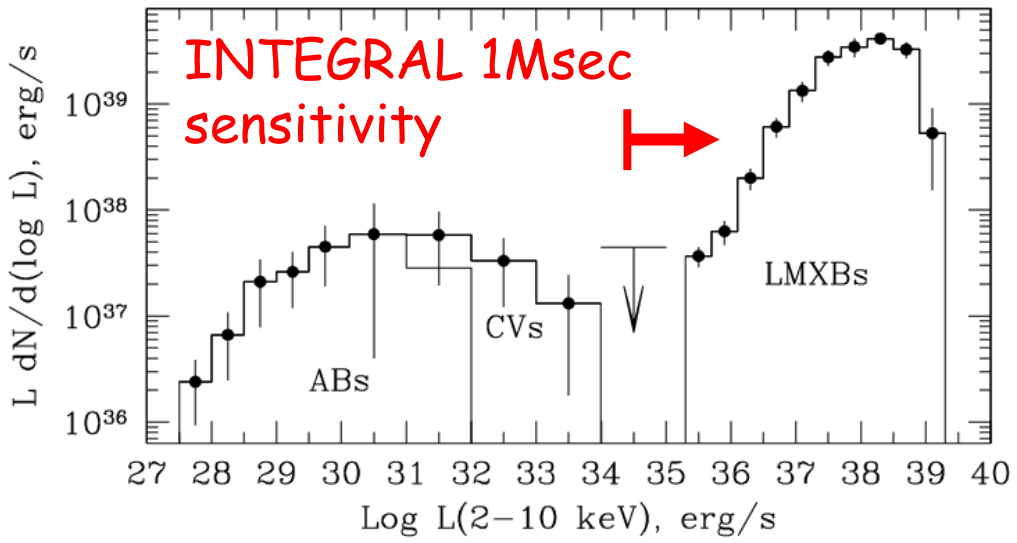
1e35 erg/s “mid L”

5e34 erg/s “low L”

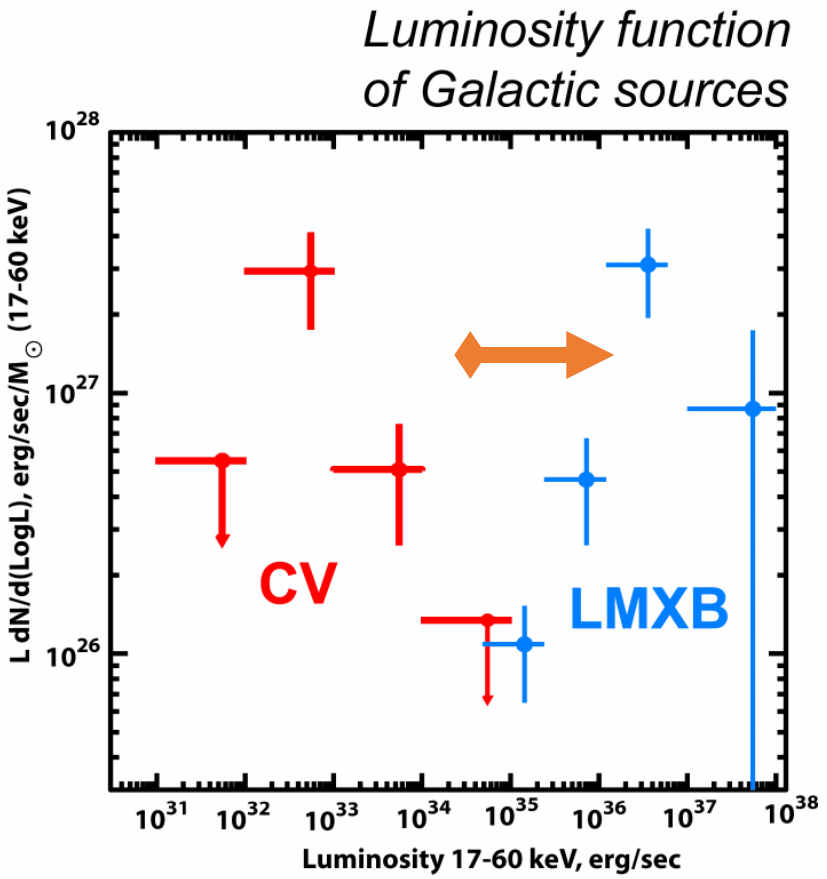
Krivonos et al., (2017)

Survey: galactic LF

INTEGRAL Galactic survey probes the low end of the LF: L_{lim}=4e34 erg/s @8.5 kpc



Sazonov et al. 2006



Revnivtsev et al. 2008

INTEGRAL 17-year survey

Source statistics by type

Type	Count (Notes)
LMXB	146
HMXB	115
X-ray binary (unclassified)	1 (SWIFT J1858.6-0814)
CV	78
Star	4
Symbiotic Star	1 (RT Cru)
Magnetar	5
SNR, SNR/Pulsar	25
Molecular cloud	1 (Sgr B2)
Galactic Center	1 (Sgr A*)
Supernova Type 1	1 (AT2018cow)
ULX	2
Seyfert galaxy	331
AGN (unclassified)	40
Blazar	54
Galaxy cluster	8
Unidentified	122

Galactic: 376 (incl. MCs)

Extragalactic: 437 (start to dominate)

49 persistent

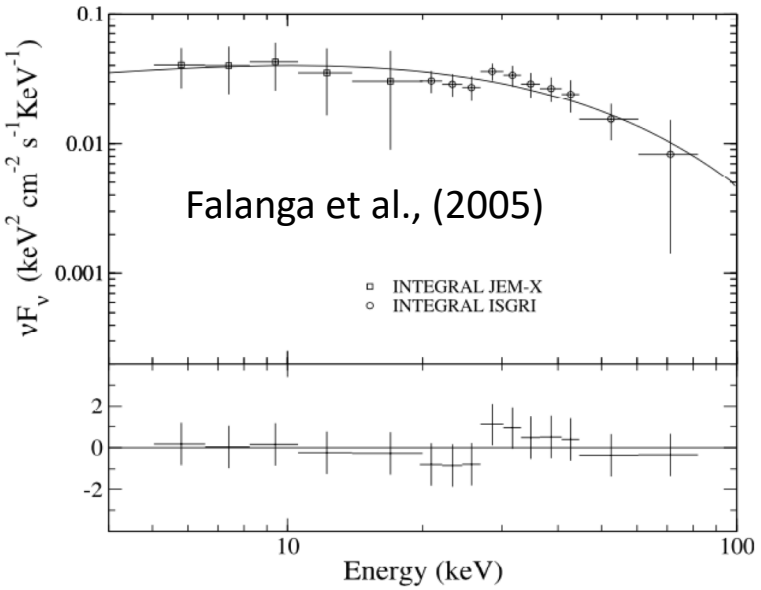
new X-ray source candidates

(S/N > 4.5 sigma)

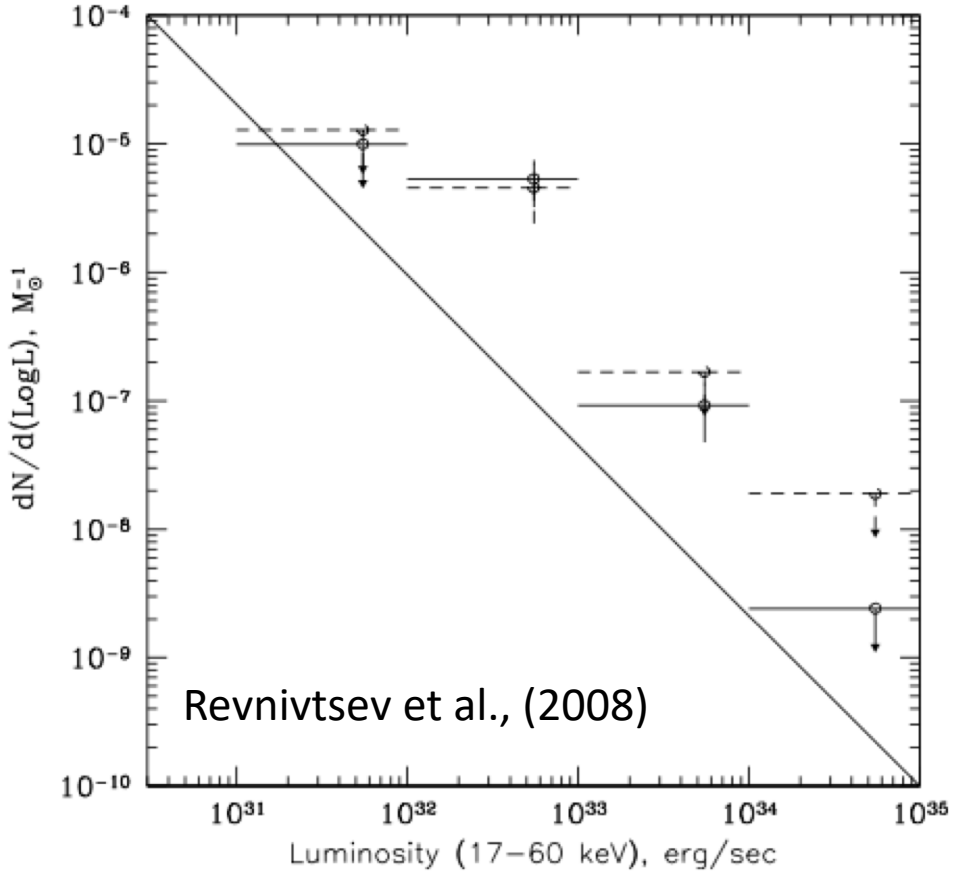
in hard X-ray domain

Galactic CV population as seen with INTEGRAL ("15-year reviews" Lutovinov et al., 2021)

25 WD mass estimates with INTEGRAL data have been made, see Table 2 in Lutovinov et al., (2021)

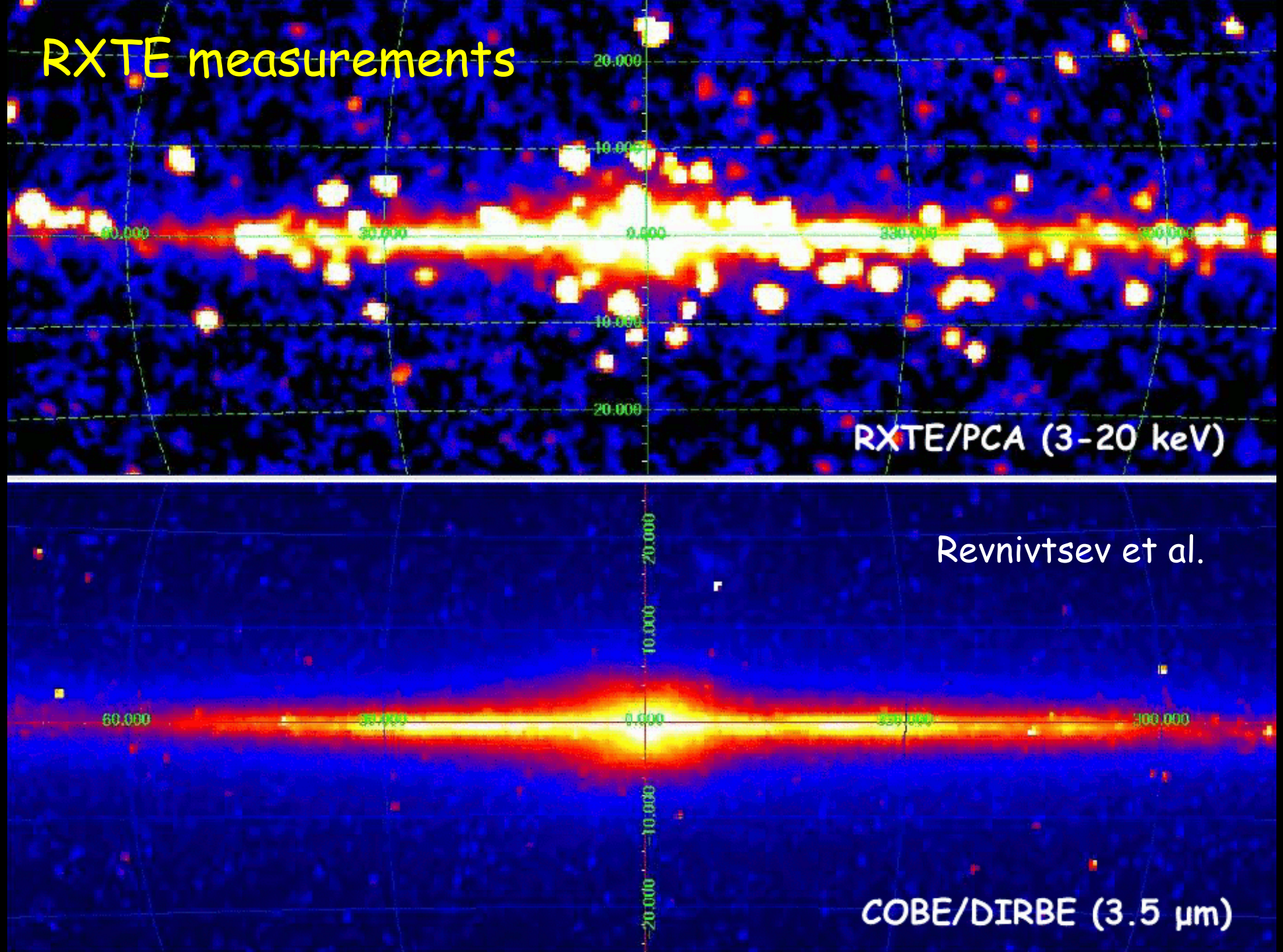


First CV LF in hard X-rays



- ✓ CV space density near the Sun
- ✓ Galactic scale height ~130 pc
- ✓ Total X-ray luminosity density near the Sun
  - ➢ consistent with **GRXE**, as confirmed by INTEGRAL itself (Krivonos et al., 2007) and NuSTAR, see Perez et al., (2019)

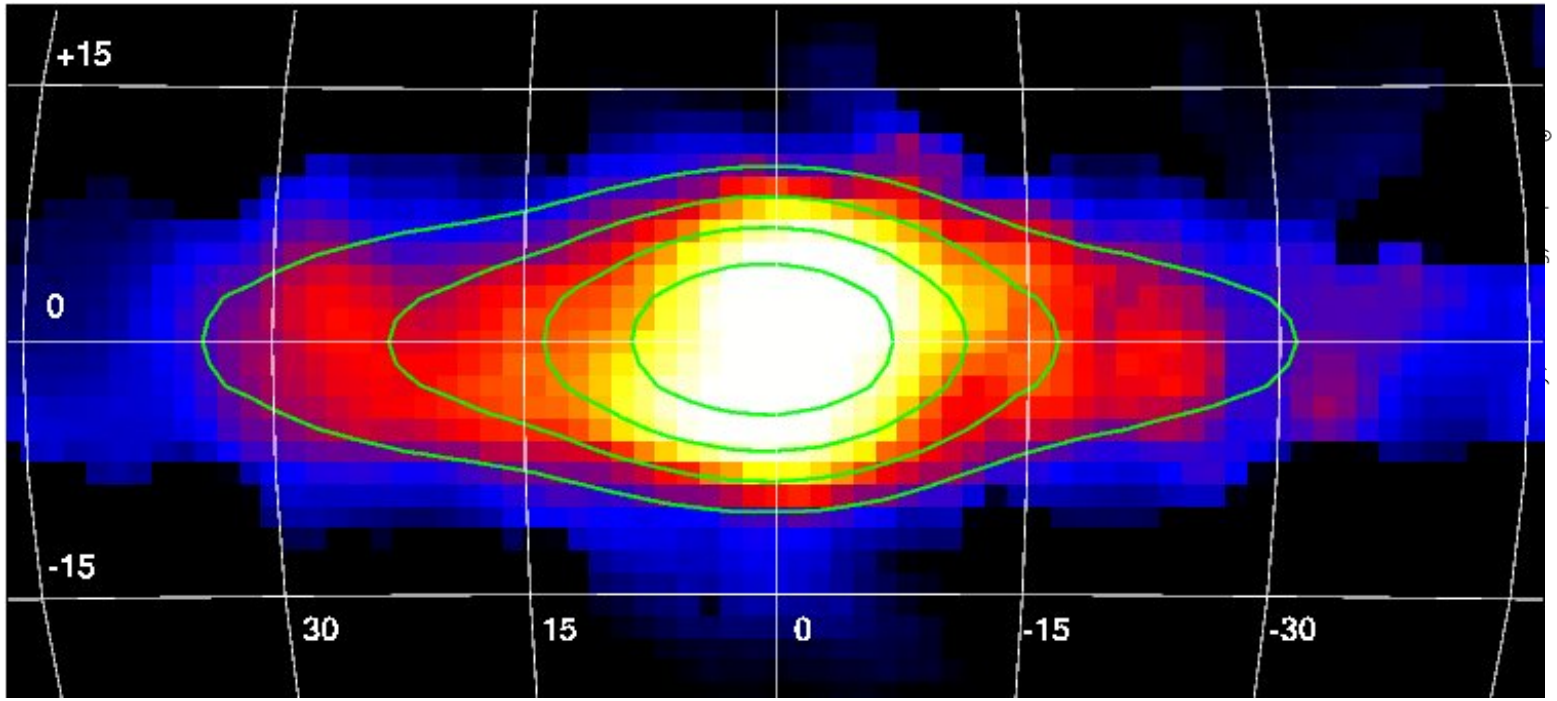
Confirmed later by Swift/BAT, see Pretorius & Mukai (2014)


RXTE measurements
RXTE/PCA (3-20 keV)
Revnivtsev et al.
COBE/DIRBE (3.5 μm)

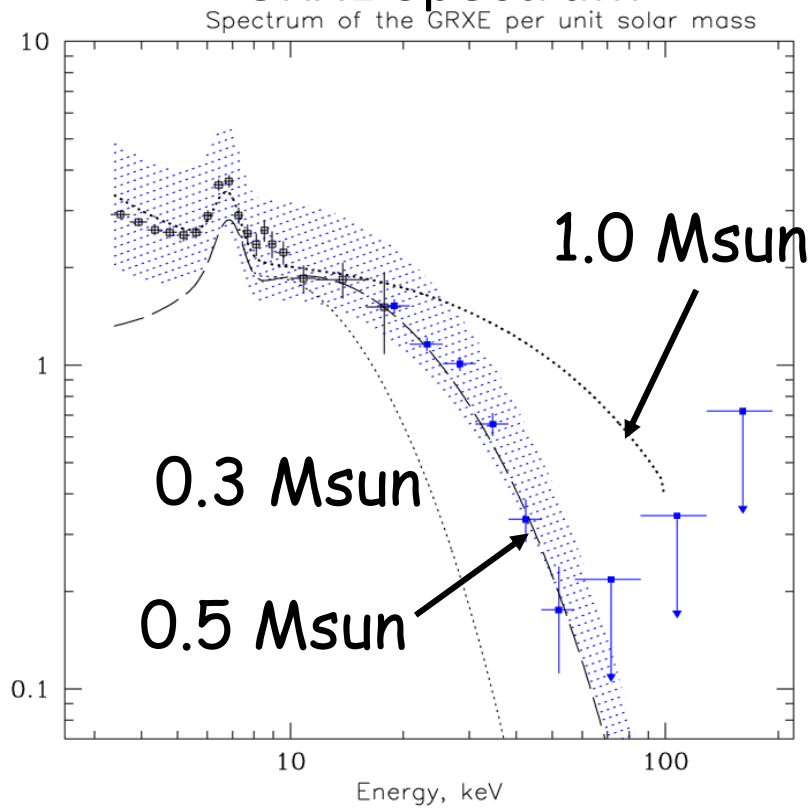
Galactic Ridge X-ray Emission with INTEGRAL

GRXE 17-60 keV map

Krivonos et al., 2007



GRXE Spectrum



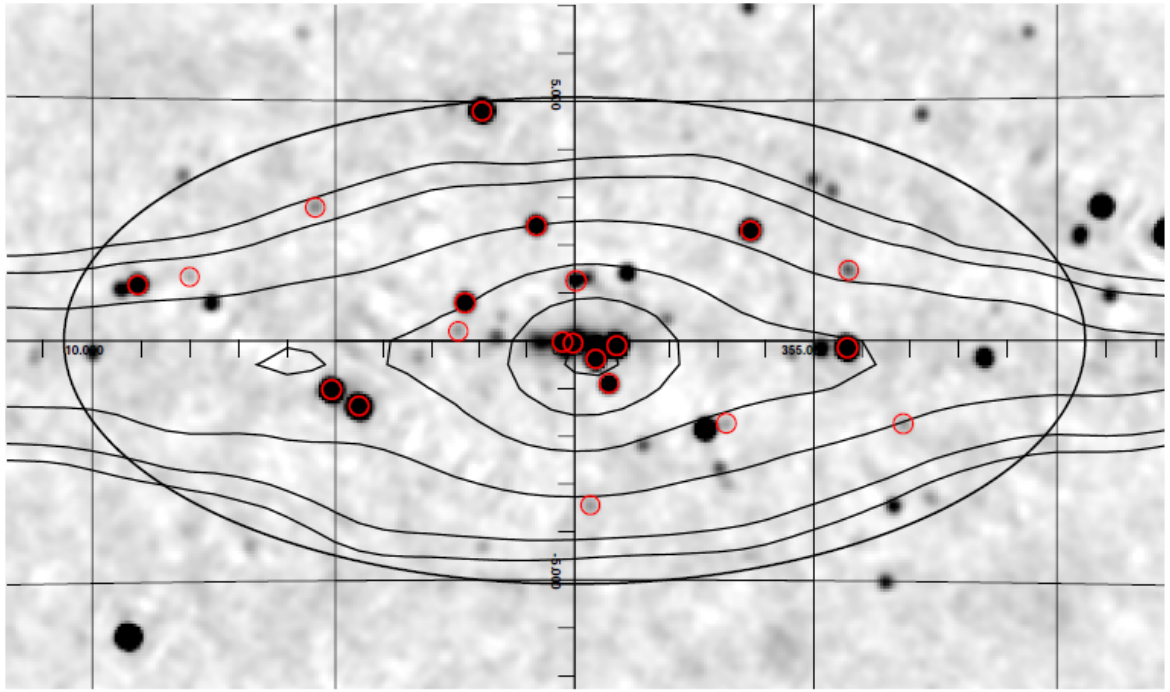
Galactic X-ray Background properties is fully consistent with local CV population

See recent update in arXiv:2409.20058 (Krivonos et al., 2024)

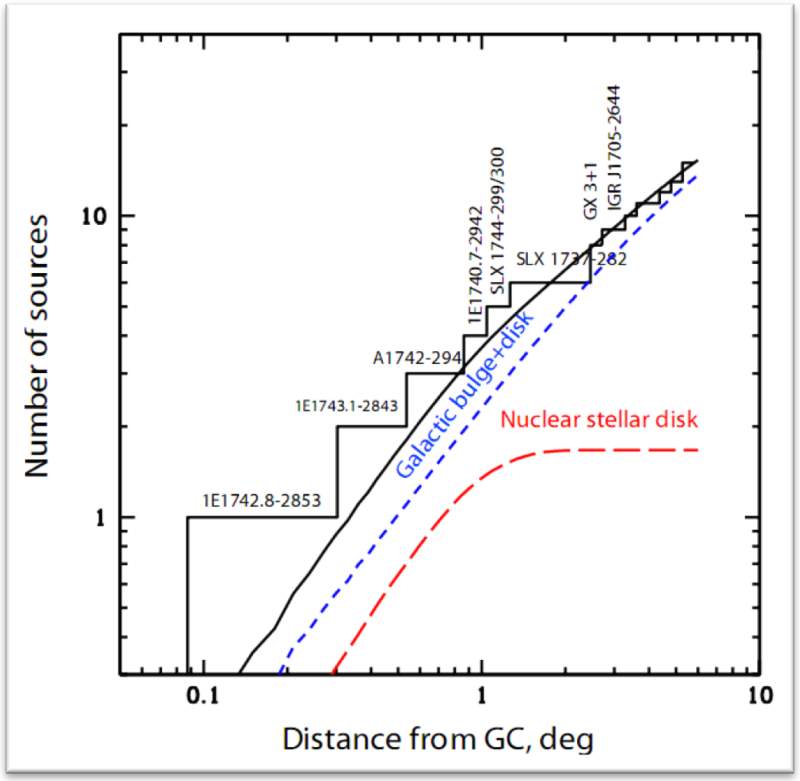
- High energy cutoff found ~50 keV
- accreting WD mass ~0.5-0.7 Msun

Low-Massive X-ray Binaries

in Bulge



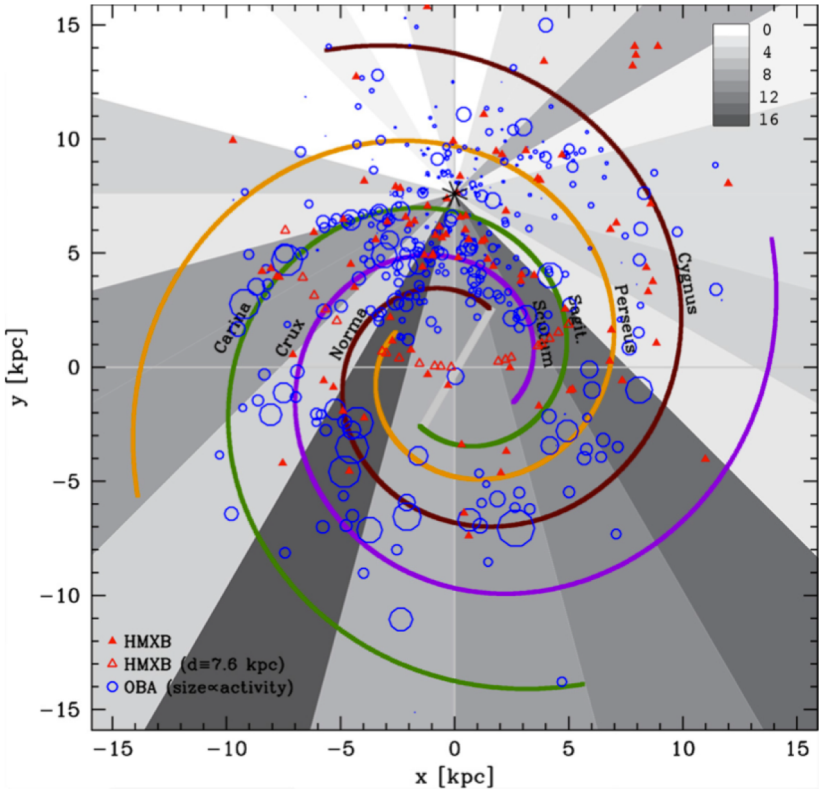
Revnivtsev et al., 2008



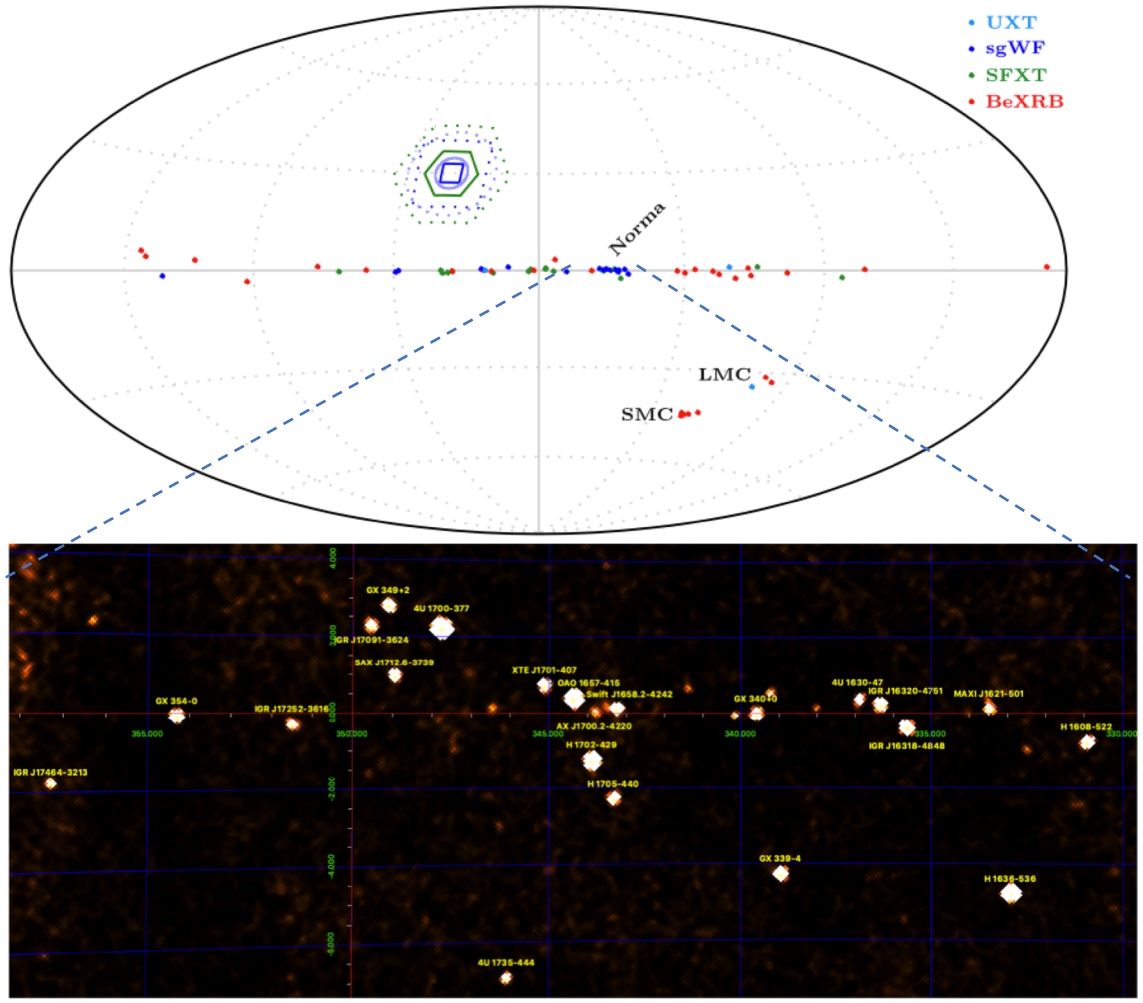
The distribution of persistent LMXBs over the angular distance from the Galactic Centre closely follows the distribution of stellar mass in the bulge within 10 deg

Galactic HMXB Population as seen with INTEGRAL

INTEGRAL “15-year reviews” Kretchmar et al., (2021)



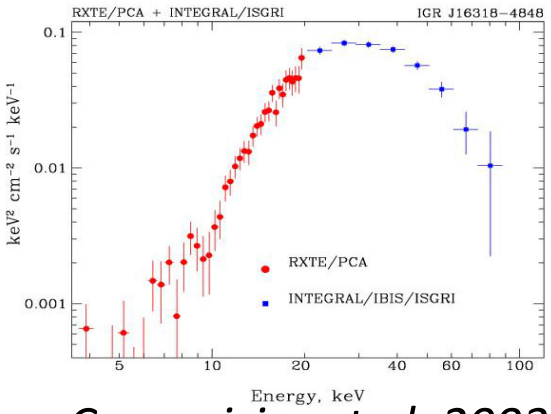
Kretchmar et al., (2021) – updated
Bodaghee et al., (2012) -- original



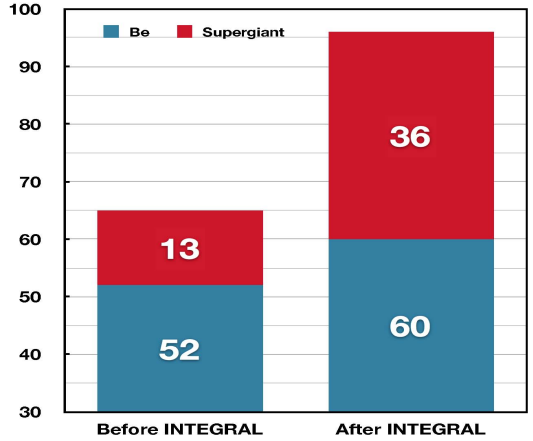
Norma Spiral Arm

Population of HMXBs in the Milky Way

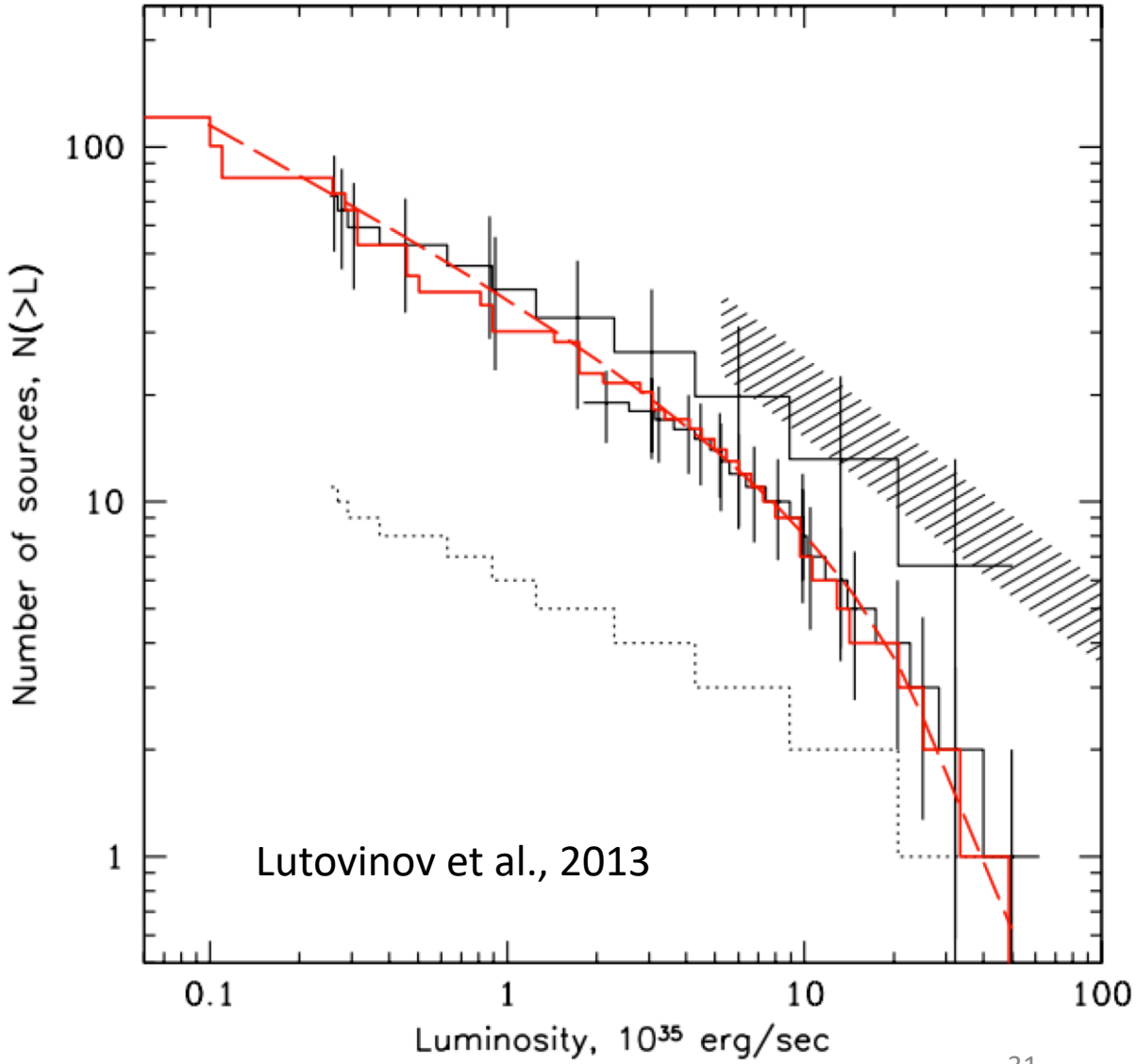
IGR J16318-4848



Courvoisier et al. 2003

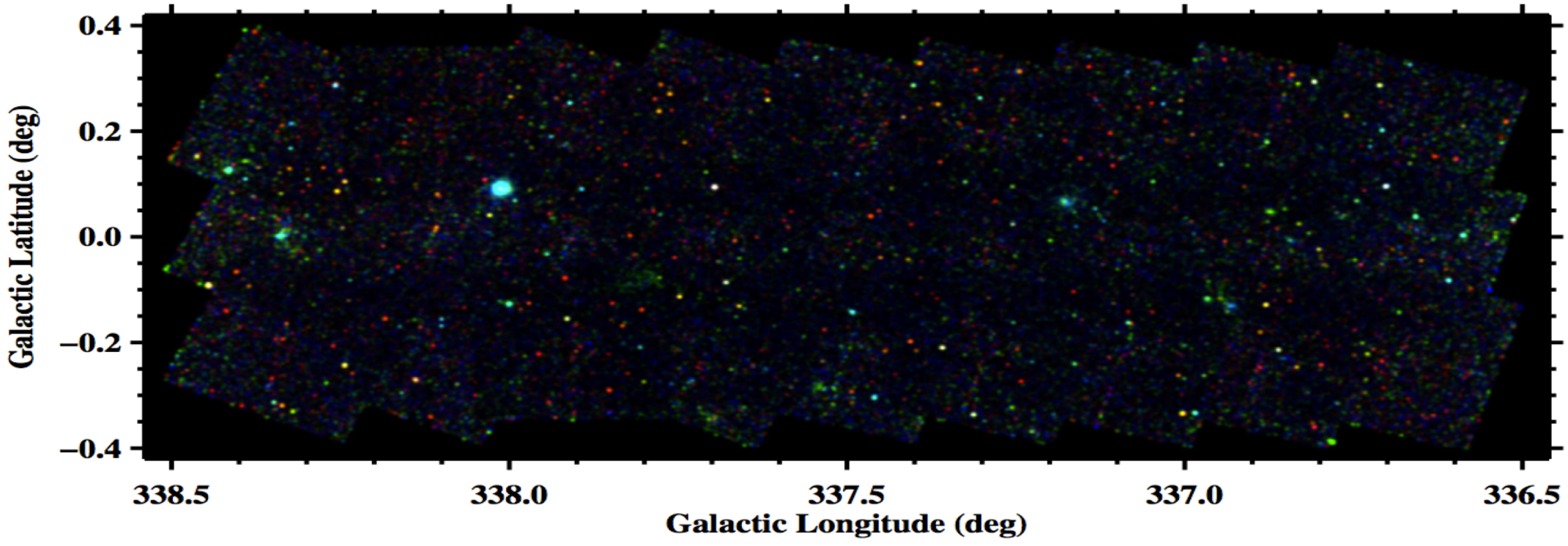


Walter et al. 2015



Chandra deep field in Norma Spiral Arm

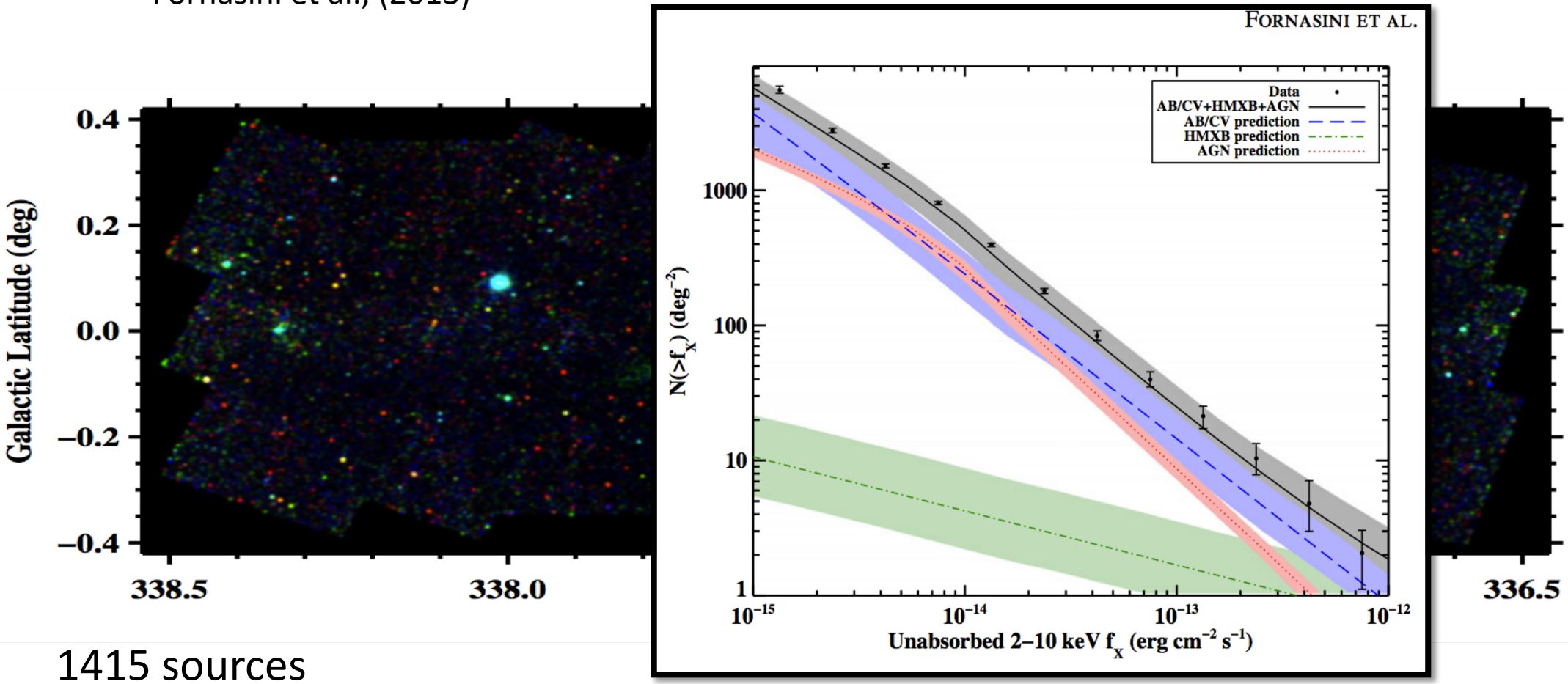
Fornasini et al., (2013)



1415 sources

Chandra deep field in Norma Spiral Arm

Fornasini et al., (2013)



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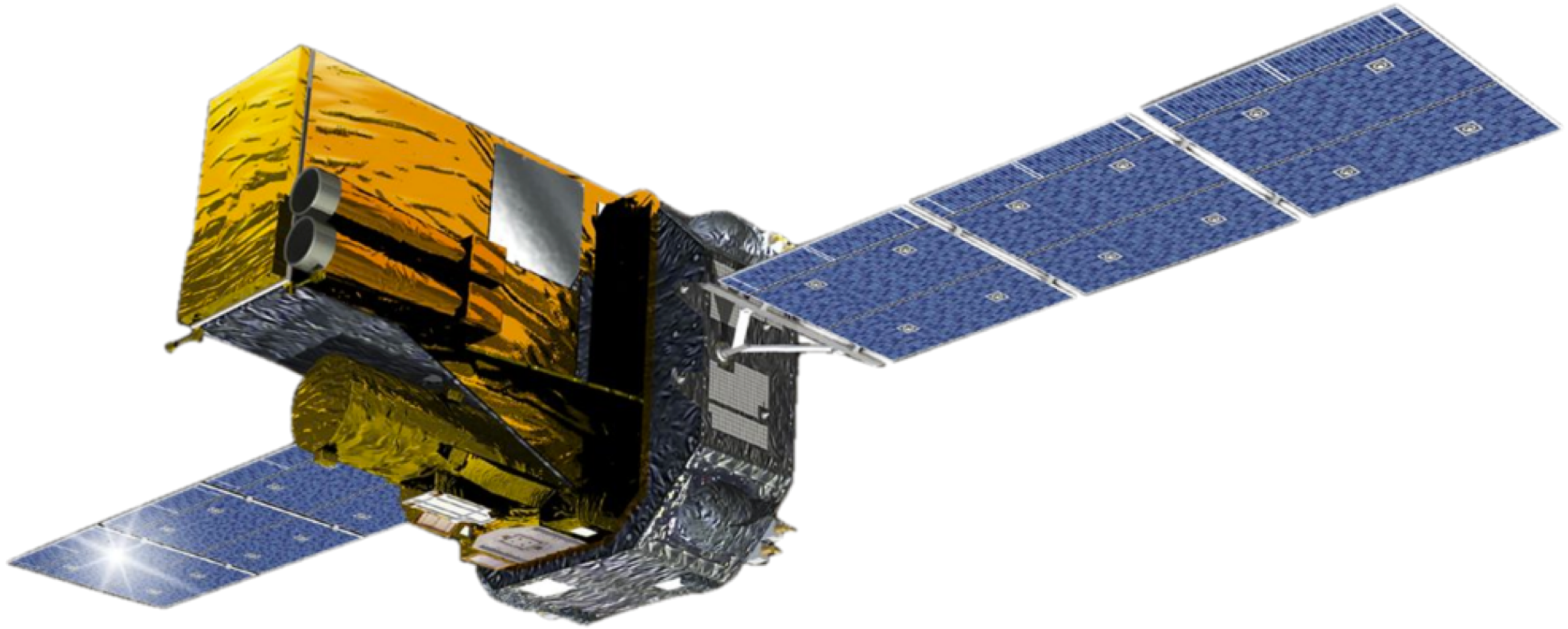

Спасибо за внимание !!!

Thanks for your attention !!!

Շնորհակալություն ուշադրության համար !!!