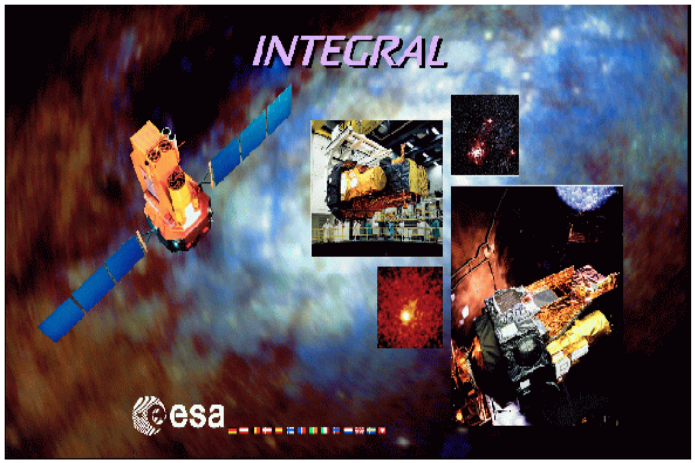


INTEGRAL e l'esplorazione del cielo sopra 10 keV

Loredana Bassani, A. Malizia, V. Sguera, F. Ursini

OBIETTIVI DELL'ATTIVITA' DI RICERCA

Studio e caratterizzazione del cielo sopra 10 keV:

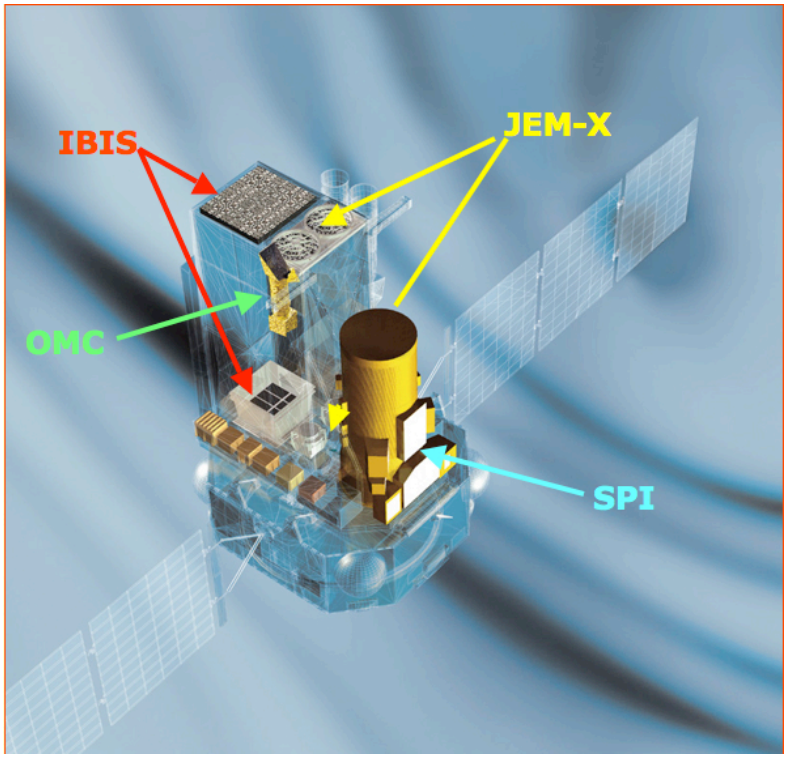
Surveys (incluso follow up X e ottico/IR)

Studio broad band di oggetti individuali o classe di oggetti
Studi di popolazione, studi multibanda
Sinergie tra il cielo soft gamma e il cielo a piu' bassa e a piu' alta energia (GeV e TeV)

L. Bassani	Coordinator
A. Malizia	Surveys +AGN studies (ESA INTEGRAL User Group member)
F. Ursini	X-ray follow up (assegno di ricerca su fondi INTEGRAL)
V. Sguera	Surveys +galactic studies
F. Gianotti	Software engennering (data archive and software)
J. Stephen	Coded aperture imaging and statistical studies
N. Masetti & coll.	Follow up ottico/IR

Main collaborations: IAPS/INAF-Roma (IBIS PI Institute) & Southampton University, UK

ESA INTEGRAL SATELLITE



- IBIS and SPI are the main instruments
  - IBIS optimised for imaging (17keV-10MeV)
  - SPI optimised for spectra (20keV-8MeV)
- IBIS is the primary survey instrument
  - Wide FOV (30x30 degrees)
  - ISGRI detector mainly operates 17-600 keV
  - Sensitivity <0.5mCrab for deep exposures
- JEM-X and OMC are the X-ray and optical Monitors

INTEGRAL launched on October 17, 2002
Operations approved up to 2022, science revision in 2020
Able to operate until 2026

First reseach objective: survey

Quiet demanding task considering:

a) thousends of revolutions, each rev around 100 sw, each sw =2ksec obs,

b) Various survey interactions to include new sources to correct for image ghosts

c) Various energy bands and timescales to consider and maps to analyse.

Some numbers : 100000 sw analysed before filtering

- Various energy bands
  - 5 for source search
  - 10 for spectroscopy

Optimises the search for different underlying spectra

- Various timescales
  - Bursticity (see after)

Optimises the search for different outburst timescales

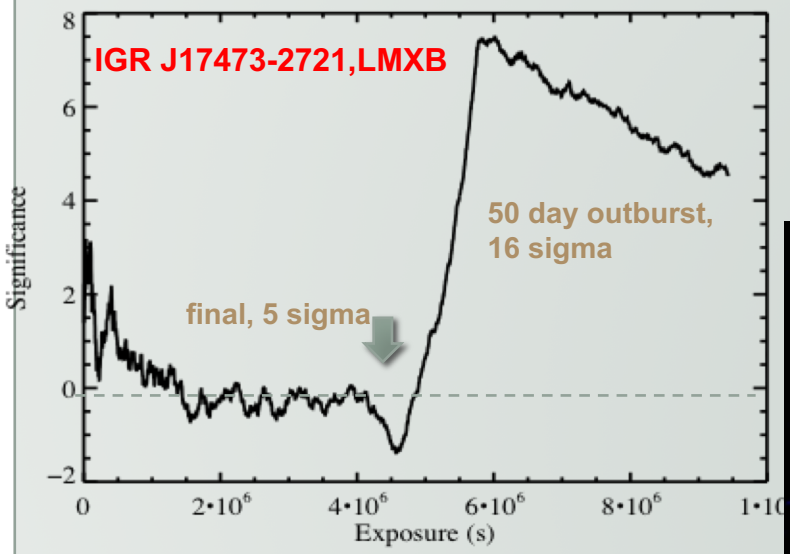
- Various projections/mosaics
  - Galactic centre (all-sky)
  - Galactic anti-centre (all-sky)
  - North and south polar

Optimises the PSF for source search algorithms

We look for persistent but also variable sources

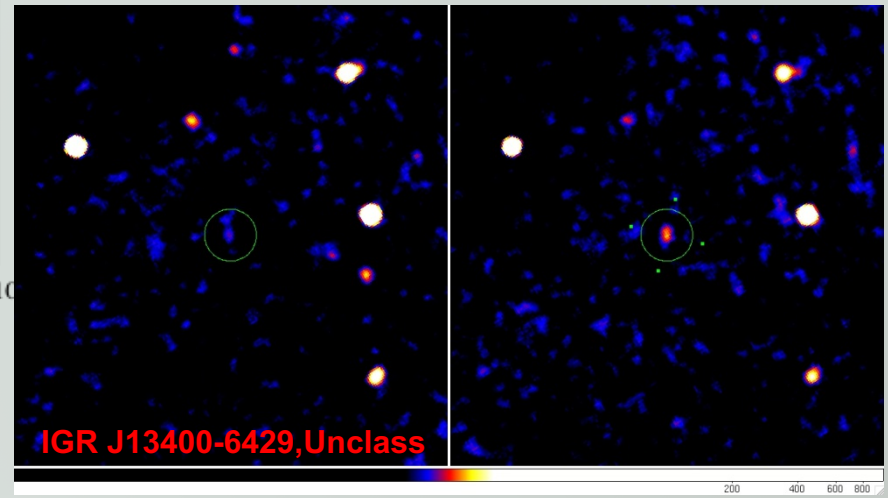
Maximize significance using subset of data (from 0.5days –upwards)

- At the moment works if we know (or suspect) a source is there!
- Make a light curve, and maximize signal/noise

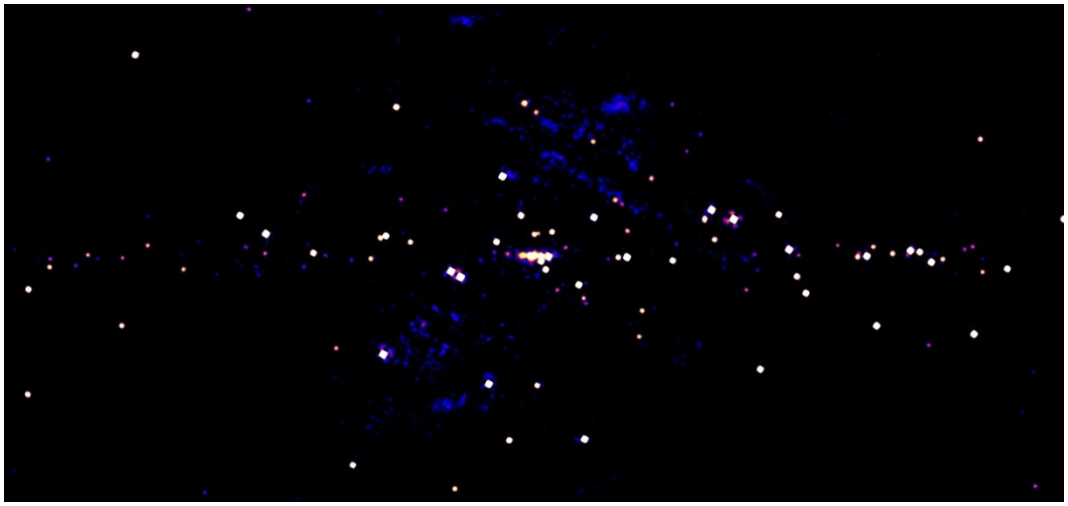


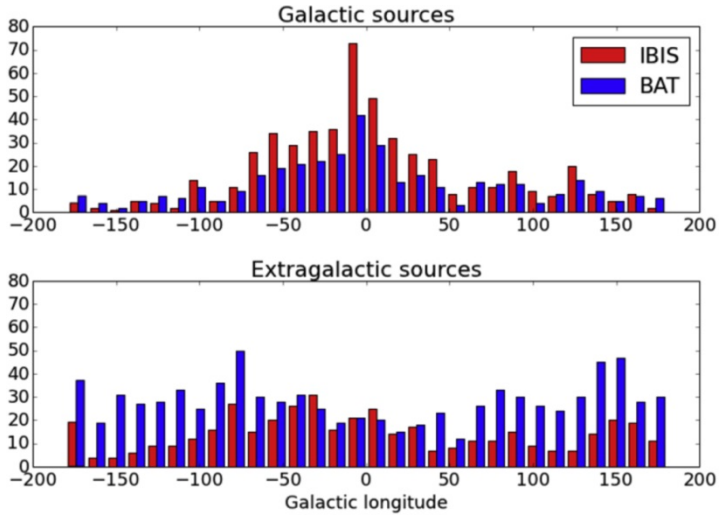
Marginal (4-4.5 sigma) detection in the whole-dataset maps

Over an optimised 500-day period, becomes a robust 7.5 sigma detection.



Surveys Work (done and in progress)





5 Surveys in the 20-100 keV band
Most recent one based on data from 1000 revolutions/observations up Dec 2010 (Bird et al. 2016), around 1000 sources detected

1 survey at high energy (100-300 keV) at the beginning of the survey work (Bazzano et al. 2006)

Working on next 20-100 keV survey covering up to revolution 2000 (200.000 sw!!!), where we intend to use a machine learning approach

High energy (100-300 keV) maps for 1500 revolutions now availble for a high energy survey

Testing new mosaics methods on 1000 revolution data to correct for map distortion

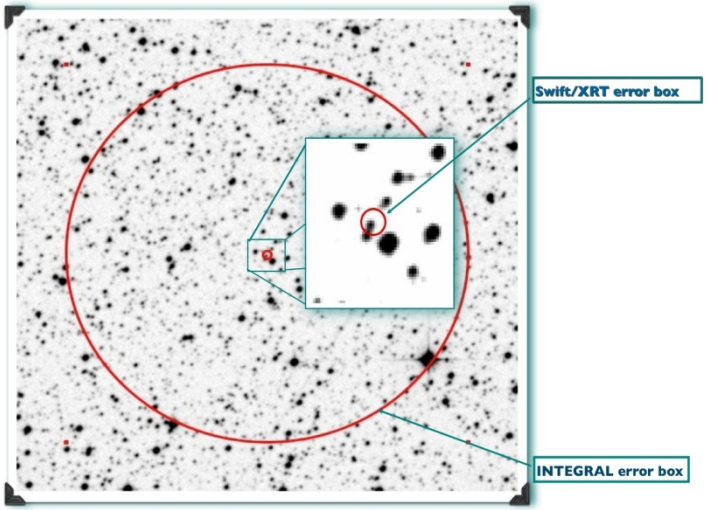
Working at slew survey

Have alreday products related to 1500 revolutions

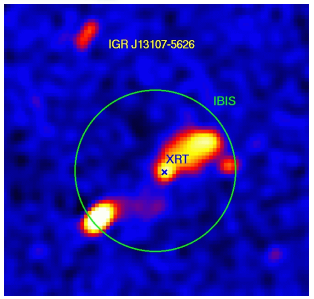
Follow up campaigns

At the beginning 30% of our sources where unidentified/unclassified, now around 20%
need for a large follow up observational campaign

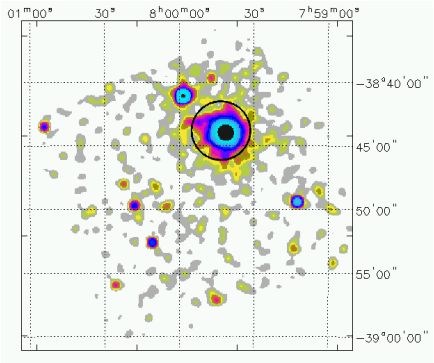
Positioning of likely counterpart(s)
(from arcmin to arcsec arsec location :
a) cross-correlation with availbale catalogues:
X-rays, radio, IR etc with ad hoc tools
b) archival search
c) X-ray follow up-observations



Search for counterparts within arcsec error box on DSS-II-Red and 2MASS surveys



Optical/IR spectroscopy

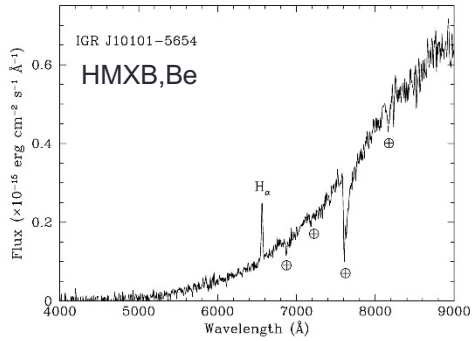


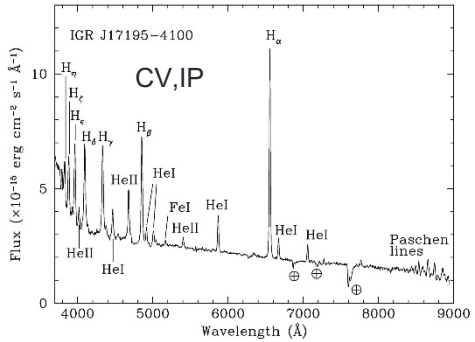
(Warning: Masetti may actually appear older!!)

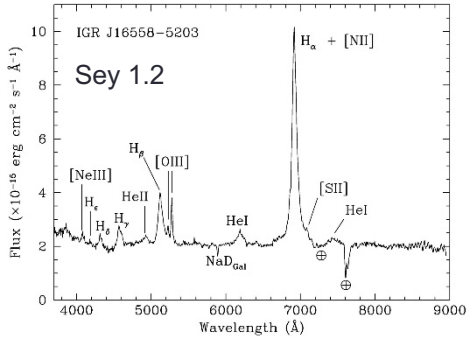
Optical follow up
Responsabile: Nicola Masetti

We started our campaign at the Bologna 1.5m telescope in Loiano in 2004.
3 objects were identified:
- IGR J17303-0601 (**IP CV**)
- IGR J18027-1455 (**Sy1 AGN**)
- IGR J21247+5058 (**Sy1 AGN**)

In order to continue to pursue this identification program, we asked for (and obtained) time at Loiano, Asiago, CTIO, ESO, SPM, SAAO, CASLEO telescopes, and extracted archival objects from the 6dF and SDSS surveys. The result is the classification of more than 200 INTEGRAL sources so far (10 papers published since 2004):







Catalogue of IBIS optical identification on http://www.iasfbo.inaf.it/extras/IGR/main.html

Identification and classification program

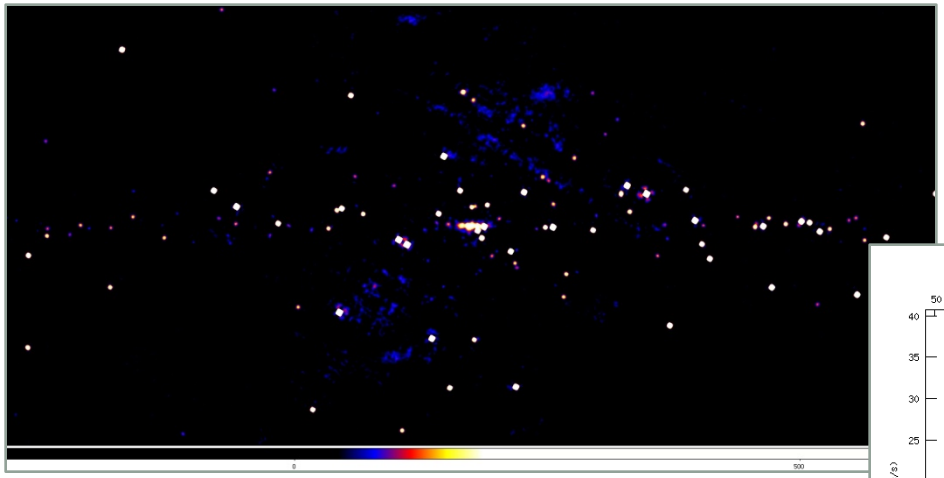
Using tools and expertise developed for INTEGRAL we also identified objects in the Swift/BAT and Fermi LAT surveys. So far we have contributed to the identification and classification of:

- **220 BAT/ sources** (8 papers since 2008)
- **120 LAT sources** (5 papers since 2009)

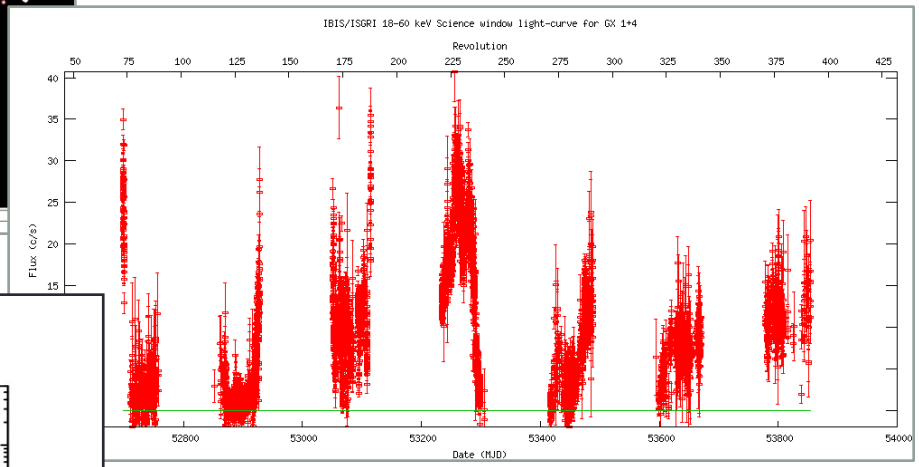
Highlights of this work: discovery of new classes of high energy emitting objects (CV, transitional millisecond pulsars, supegiant fast X-ray transients, high redshift blazars, AGN of unusual type), statistical & population studies, estimates of luminosity functions etc…

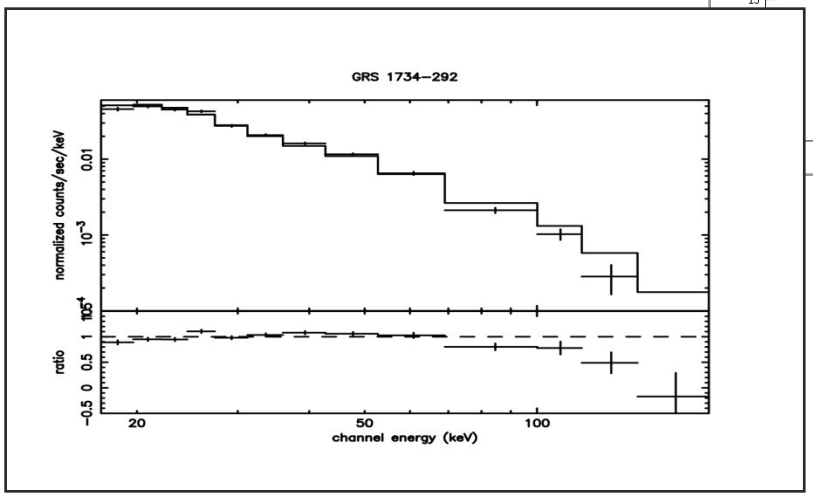
Still a large number of unidentified objects to follow up, particularly in the southern emisphere and with infrared spectroscopy. Number will increase with future surveys. Space for collaboration, student laboratory etc…

Survey products (now for 1500 rev, 16 years of data)



Images in various energy bands





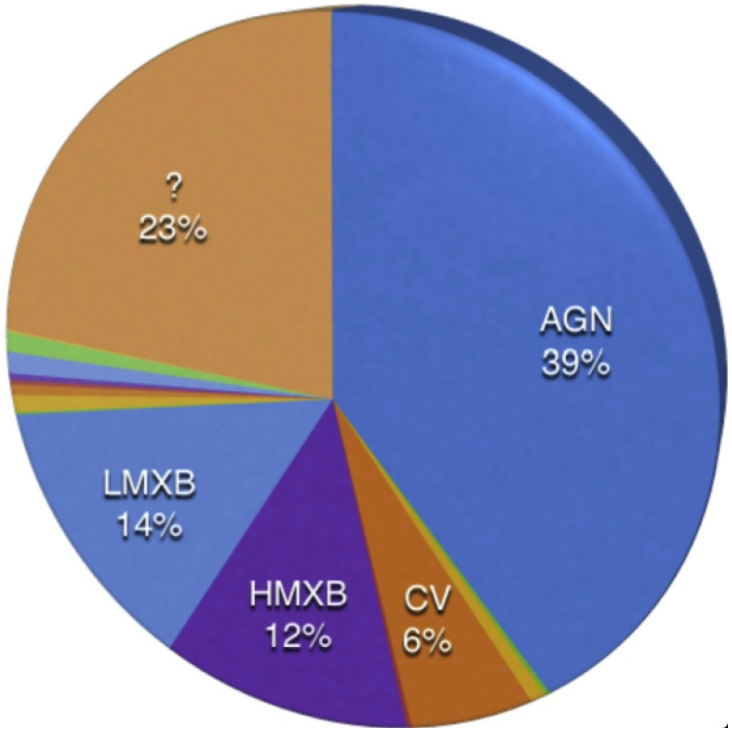
light curve

Average spectrum

for every source of latest catalogue

INTEGRAL Sources

AGN AXP Cluster CV GRB HMXB LMXB Mol cloud PSR PWN RSCVn SGR SNR XB XP ?



X-ray binaries V. Sguera

AGN Radio Quiet A. Malizia
AGN Radio Galaxies F. Ursini

Altro : Cataclysmic Variables
Pulsar/PWN (GeV/TeV)
Magnetars
Blazars
Others

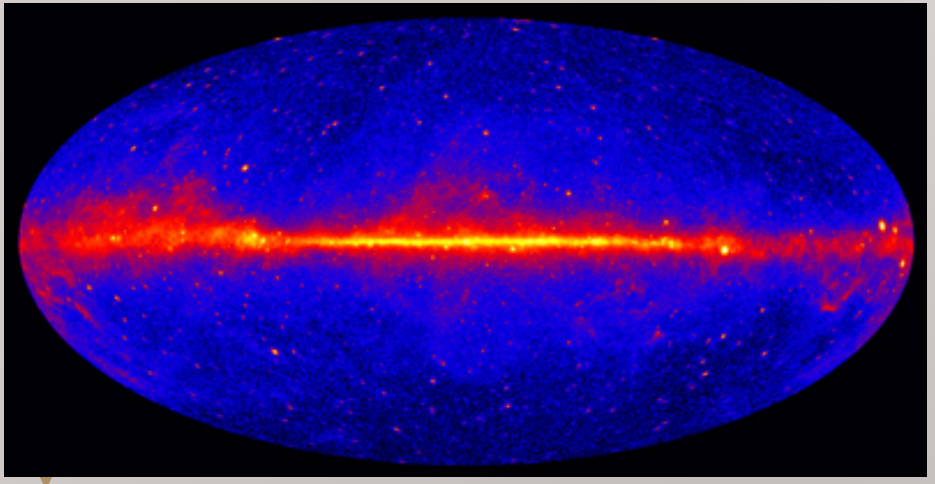
Main Stream proposal on FRB using INTEGRAL Archive

Comparison IBIS (1000 Rev catalogue) versus GeV sky

- Fermi 8 years catalogue 5523 sources >4 sigma(100meV-1TeV)

70 associations found

Most associations are:
Blazars (31),
Other AGN(9),
XB(4),
SNR/PS/PWN(9),
Others (17)



Only 8% of IBIS sources are detected at GeV energies

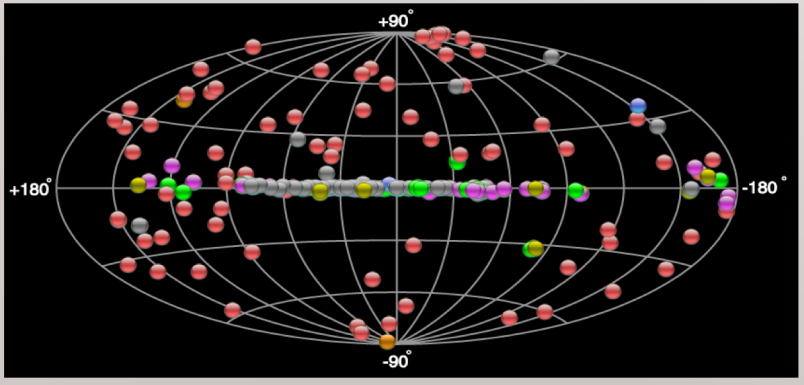
But only less than 1% of Fermi/LAT sources have a IBIS counterpart

Comparison IBIS (1000 Rev catalogue) versus TeV sky

- TeV on line catalogue 217 sources

  30 associations found

  Most associations are:
  Blazars (11, 8 HBL), RG (1)
  XB(5),
  SNR(3)
  PS/PWN (6/7)
  Other (2)

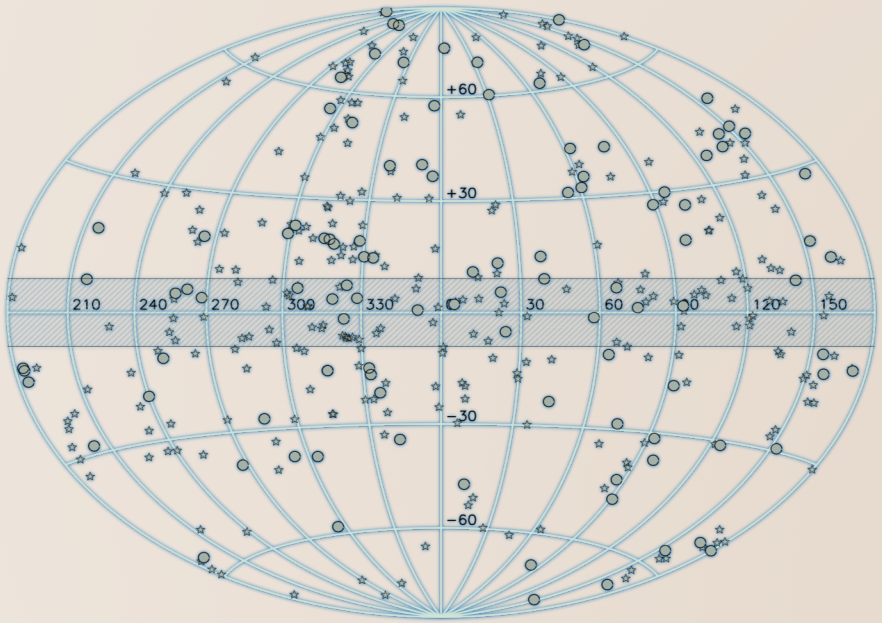


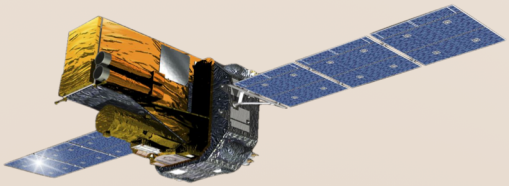
⇨ 3% of INTEGRAL sources have a TeV association

But 14% of TeV have an IBIS counterpart

INTEGRAL legacy important for CTA

INTEGRAL view of the exagalactic Sky (A. Malizia)





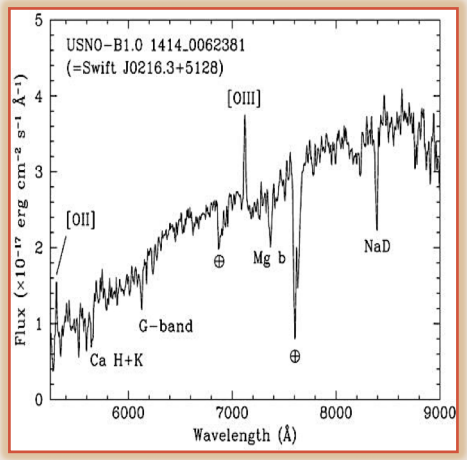
distribution of all AGN (~500) so far detected by INTEGRAL plotted on the sky (Malizia et al. 2012 + 2016).

mainly broad line or type 1 AGN, narrow line or type 2 AGN and blazars (QSO and BL Lac).

There are sources still of unknown optical class but they have been considered AGN since have been associated with galaxies detected in the IR and/or in the Radio band.

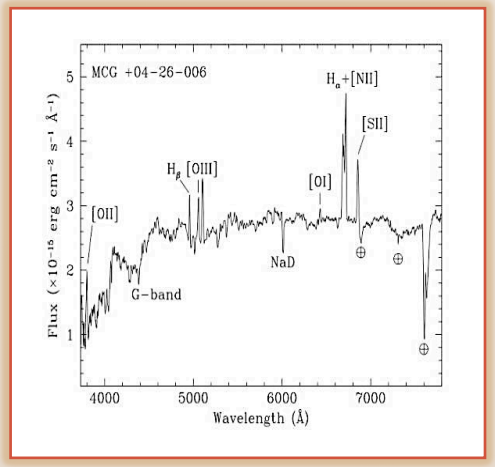
Not AGN population viewed by INTEGRAL

not only Seyfert galaxies

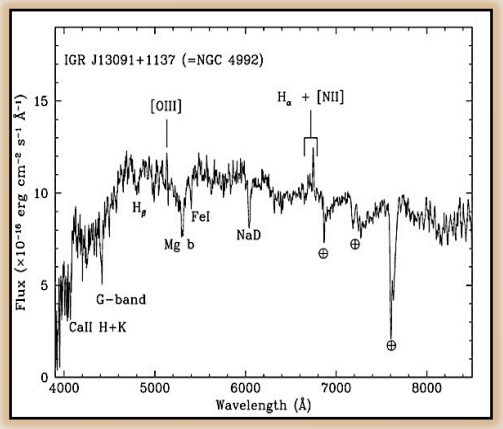


Also a few type 2
QSO $22.2 \leq N_H \leq 23.4$

Few Liners,
all with $N_H \geq 22$
none CT



4 XBONG,
$0.01 \leq z \leq 0.1$,
$N_H \geq 23$



All type of AGN observed in soft X-rays now seen above 20 keV

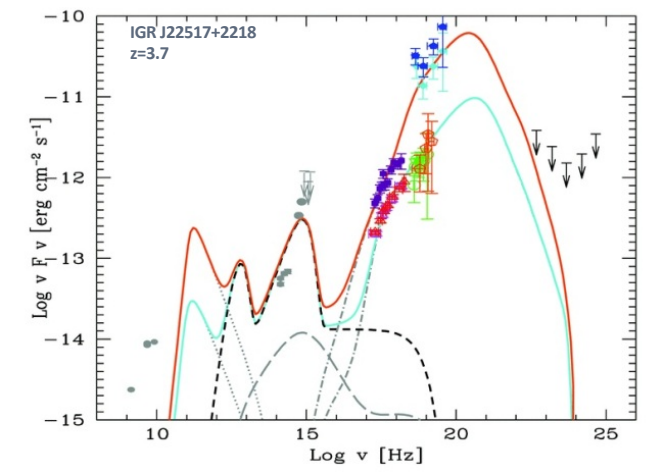
Not only blazar but the most extreme blazars

hard X-rays allow the discovery of:

1) very high power objects, those having:

- more powerful jet
- more luminous accretion disks
- larger black hole masses

MeV Compton peak but redshifted to hard X-ray domain

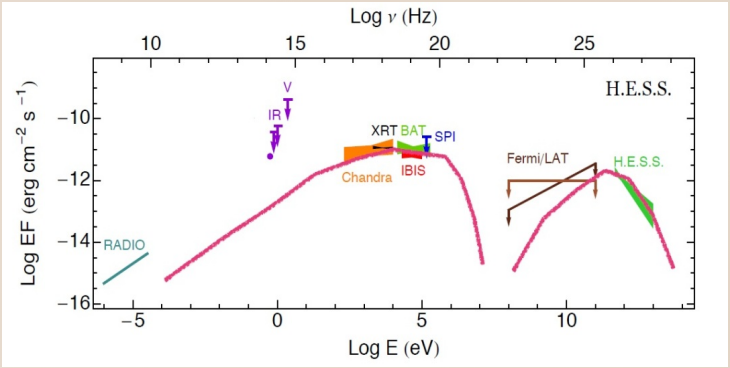


Lanzuisi et al. 2012

2) very LOW power objects, those having

- less powerful jet
- inefficient accretion disks

Hard X-ray Synchrotron peak



AGN SAMPLE characteristics

All the INTEGRAL AGN have been undoubtedly identified through X-ray and optical follow-up observations and they have been fully characterized in terms of their spectral parameters in a broad energy band (2-100 keV).

Table 1: INTEGRAL/IBIS AGNs

Name	RA	Dec	z	Class	$F_H^{\dagger}$	$F_S^{\dagger\dagger}$	Log $N_H^{\diamond}$	Reference
IGR J00040+7020	00 04 01.92	+70 19 18.5	0.096	Sy2	1.47	0.35	22.52 [22.49 – 22.54]	De Rosa et al. 2012
IGR J00158+5605	00 15 54.19	+56 02 57.5	0.169	Sy1.5	<0.66	0.31	**21.50**	Malizia et al. 2011
IGR J00256+6821	00 25 32.50	+68 21 44.0	0.012	Sy2	1.47	0.05	23.60 [22.92 – 23.93]	Landi et al. 2007a
IGR J00333+6122	00 33 18.34	+61 27 43.3	0.105	Sy1.5	1.38	0.68	21.93 [21.65 – 22.11]	Molina et al. 2009
1ES 0033+595	00 35 52.60	+59 50 05.0	0.086	BL Lac	1.83	5.90	21.55 [21.44 – 21.64]	Donato et al. 2005
IGR J00465-4005	00 46 20.68	−40 05 49.1	0.201	Sy2	3.56	0.12	23.38 [23.25 – 23.52]	Landi et al. 2010a
MKN 348	00 48 47.10	+31 57 25.0	0.015	Sy2	10.60	0.44	23.02 [22.93 – 23.10]	Tartarus Database

optical coordinates of counterpart and redshift

IBIS [20-100 keV] flux

X-ray [2-10 keV data]

Most appropriate optical class: cross check NED and Veron-Cetty Veron 13th catalogue
generally preferred the most recent !

In case of mismatch: class criteria Veilleux & Osterbrock (‘87)
line ratio diagnostics of Ho et al. (‘93, ’97) and Kauffmann et al. (2003)

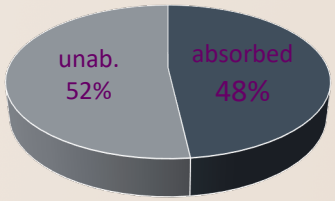
For assigning Seyfert subclasses (1.2, 1.5, 1.8, 1.9): Hα/O[IIII]λ5007 line flux ratio criteria (Winkler ‘92)

CONNECTION BETWEEN OPTICAL CLASSIFICATION AND X-RAY ABSORPTION & POPULATION STUDIES

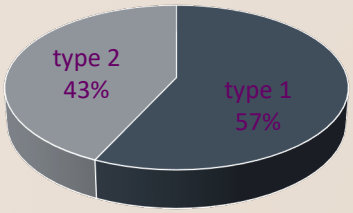
VERIFICATION OF THE AGN UNIFICATION MODEL

(Malizia+ 2012)

X-RAY classification



OPTICAL classification



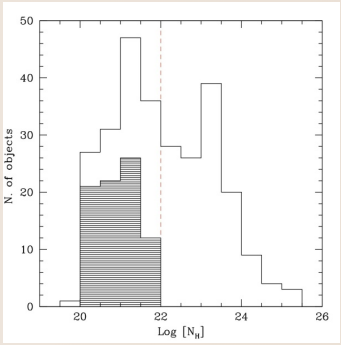
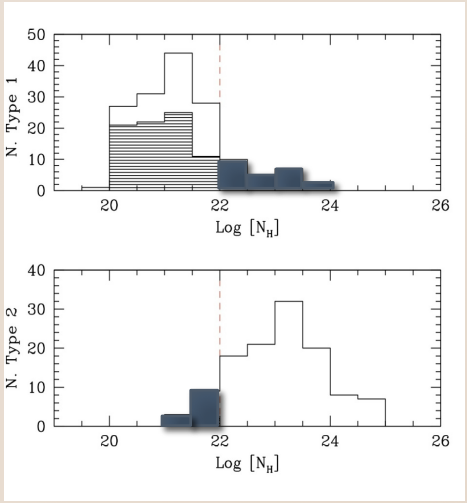
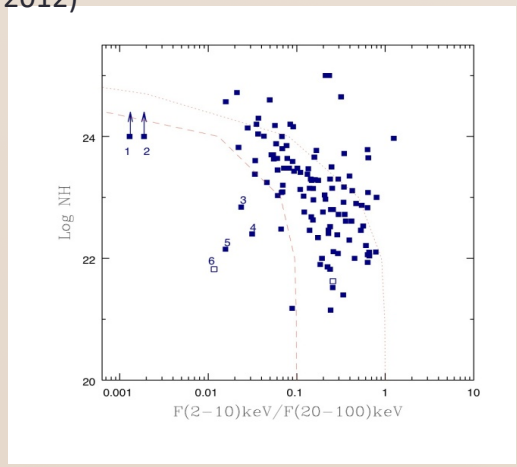


Table 1. Optical classification of sources in the INTEGRAL sample.

Class	Spectral type	Number
Type 1 (57%)	Sy 1	46
	Sy1.2	24
	Sy1.5	45
	Sy1/LINER	3
	NLS1	14
	Blazar	22
Type 2 (43%)	Sy 2	70
	Sy1.9	13
	Sy2/LINER	6
	Radio Gal.	1
	XBONG	5
	LINERs	2
	QSO 2	5
	Compton thick†	16
Total		272

† all the Compton thick sources are Seyfert 2 but one, NGC 1365, which is optically classified as 1.9.





	Opt. type 1	Opt. type 2	Total
Unabsorbed	132	**10**	142 (52%)
Absorbed	**22**	108	130 (48%)
Total	154 (57%)	118(43%)	272

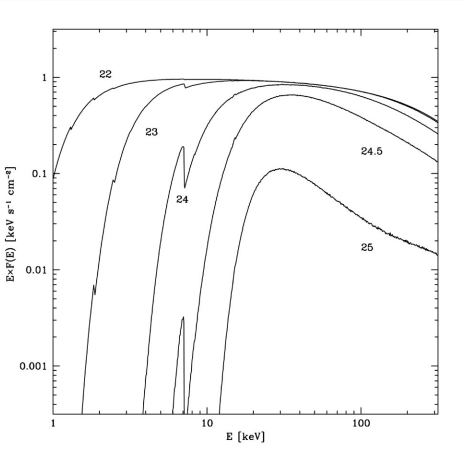
Several CT confirmed

Detailed studies of ABSORBED type1 and UNABSORBED type 2

ABSORPTION PROPRIENTIES

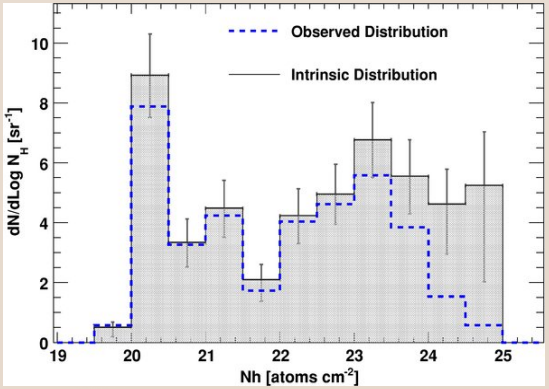
Using a complete sample of AGN, INTEGRAL for first estimated the TRUE FRACTION OF ABSORBED AND CT (Malizia et al. 2009)

Reduction of hard X-ray flux as a function of column density



Range NH (Log)	Flux Reduction	Number missed‡
24-24.5	8%	0.5
24.5-25	25%	3
25-25.5	64%	12

loss of about 15 objects above Log(NH) = 24



Abs. AGN 43% → 51%
CT AGN 7% → 21%

INTEGRAL results have been confirmed by Swift/BAT

Adopting a similar correction, also Burlon et al. (2011) found a fraction of CT AGN~ 20% using a BAT sample of AGN!!

BROAD BAND SPECTRA

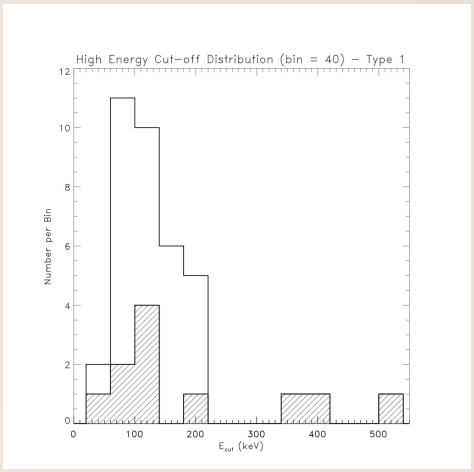
Newton-XMM + INTEGRAL-IBIS +*Swift*-BAT:
NOT contemporaneous but cross correlations between instruments OK

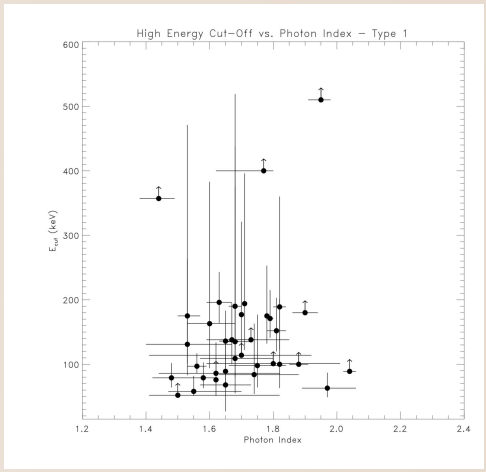
confirmed by simultaneous XRT+NuSTAR data

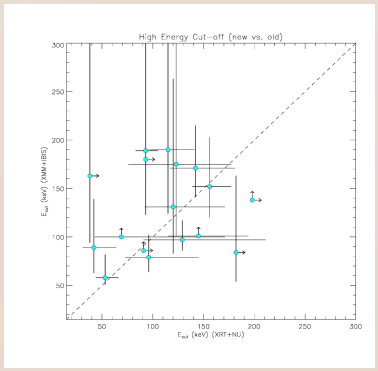
Molina+2018, MNRAS submitted

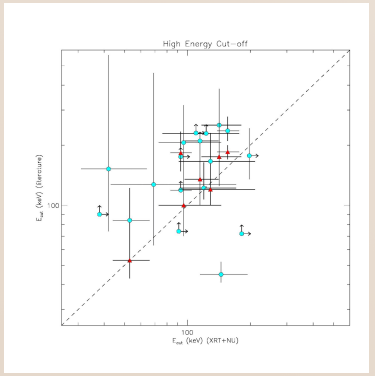
Spectral parameters (e.g . photon index and cut-off) well constraned

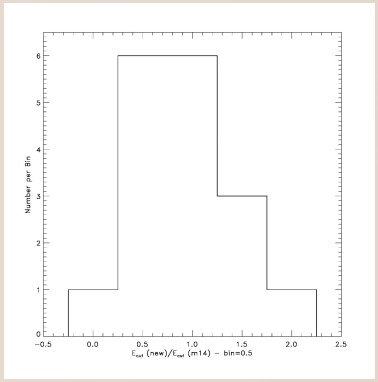
FIRST CUT OFF constrain in broad line Sey (Malizia+2014)

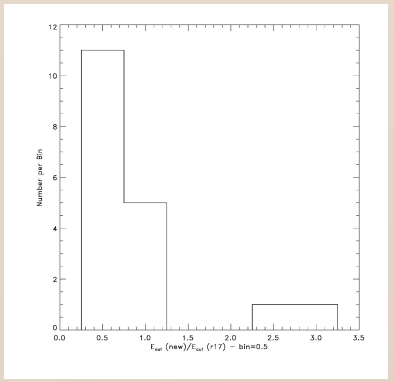












Sey 2 (absorption → more complex) need to be deep investigated

XMM+NuSTAR TO DO

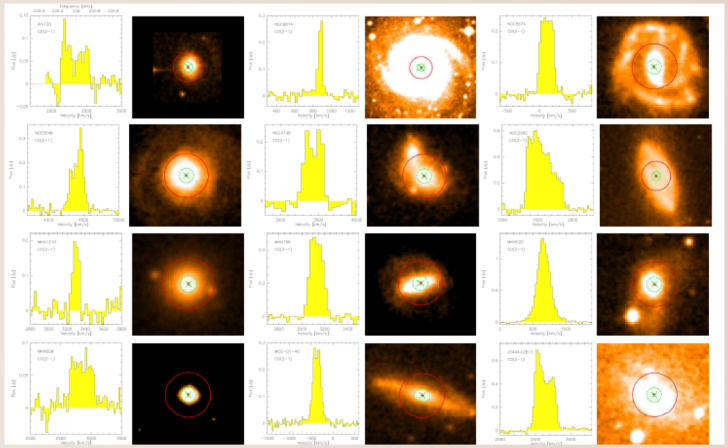
Ibisco survey(☆)

(coll. Trieste: Feruglio/Fiore)

Unbiased survey of H_2 reservoirs & outflows in AGN host galaxies

60 Hard X-ray 20-100 keV AGN from the IBIS INTEGRAL AGN survey
(unbiased against nuclear obscuration)

$L_x > 10^{43}$ erg/s
$z < 0.05$
Accurate BH masses
M* , SFR



@IRAM 30m: Measure CO (1-0) & (2-1)
70 hours survey completed 2017 - 80% detection rate
(Feruglio in prep.)

@ALMA band 6: map CO with 50 pc resolution
P.I. Feruglio (cycle 5)

@INTEGRAL, NuSTAR, XMM: X-ray spectra - P.I. Malizia
⟹ Lx, N_H, $\dot{M}_{ACC}$ + WA

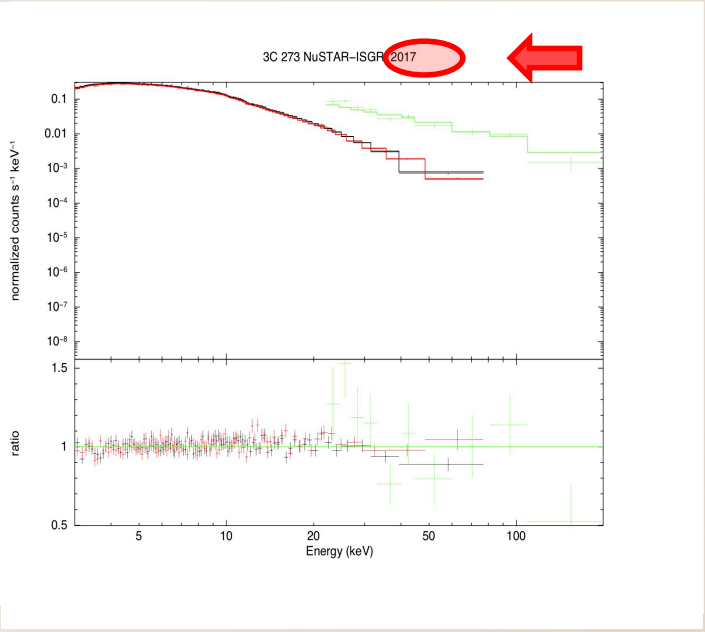
NLS1 done (Molina+2018) BUT all the rest TO DO

(☆) reaches fainter flux limits than BASS survey - Sample of NLSy1

Cross-calibration of INTEGRAL with NuSTAR and XMM nearly simultaneous observations

in coll. with Lorenzo Natalucci (IAPS) + IACHEC

Campaigns on 3C273



NuSTAR-INTEGRAL joint fitting (3-110 keV)

model: wa_g*cflux*po

Year	Instrument	Γ	$F_{20-40keV}$ (10^{-11}erg cm^{-2}s^{-1})	$\Delta\chi^2$
2012	FPMA	1.674±0.005 (1.669÷1.679)	$6.42^{+0.05}_{-0.04}$ (6.38÷6.47)	0.994
	FPMB	1.664±0.005 (1.659÷1.669)	6.697±0.05 (6.648÷6.748)	
	ISGRI	$1.646^{+0.20}_{-0.19}$ (1.456÷1.846)	$6.418^{+0.77}_{-0.73}$ (5.688÷7.186)	
2015	FPMA	1.727±0.01 (1.717÷1.738)	4.478±0.07 (4.412÷4.545)	1.009
	FPMB	1.706±0.01 (1.695÷1.716)	4.663±0.07 (4.592÷4.735)	
	ISGRI	$2.861^{+1.79}_{-1.05}$ (1.811÷4.646)	$5.85^{+3.28}_{-2.24}$ (3.612÷9.135)	
2016	FPMA	1.606±0.007 (1.599÷1.613)	12.578±0.127 (12.451÷12.705)	1.096
	FPMB	1.609±0.003 (1.602÷1.617)	$12.735^{+0.127}_{-0.14}$ (12.595÷12.862)	
	ISGRI	$1.743^{+0.18}_{-0.17}$ (1.570÷1.928)	$11.927^{+1.258}_{-1.203}$ (10.724÷13.185)	
2017	FPMA	1.700±0.01 (1.690÷1.710)	5.531±0.08 (5.45÷5.612)	1.046
	FPMB	1.651±0.01 (1.641÷1.661)	6.046±0.09 (5.957÷6.139)	
	ISGRI	$1.724^{+0.31}_{-0.28}$ (1.444÷2.033)	$6.367^{+1.18}_{-1.37}$ (5.267÷7.545)	

model: const*wa_g*po

Year	Γ	$C_{FPMA/ISGRI}$	$C_{FPMB/ISGRI}$	$F^{ISGRI}_{20-40keV}$ (10^{-11}erg cm^{-2}s^{-1})	$F^{FPMA}_{20-40keV}$ (10^{-11}erg cm^{-2}s^{-1})	$F^{FPMB}_{20-40keV}$ (10^{-11}erg cm^{-2}s^{-1})	$\Delta\chi^2$
2012	1.669±0.003	$0.995^{+0.07}_{-0.06}$	$1.024^{+0.07}_{-0.06}$	6.49	6.46	6.65	0.994
2015	1.739±0.012	$1.196^{+0.411}_{-0.244}$	$1.211^{+0.416}_{-0.247}$	3.74	4.47	4.53	1.012
2016	1.608±0.005	1.069±0.06	1.087±0.06	11.73	12.54	12.75	1.094
2017	1.677±0.007	$0.861^{+0.09}_{-0.07}$	$0.88^{+0.09}_{-0.08}$	6.62	5.70	5.84	1.055

XMM-NuSTAR joint fitting (3-10 keV)

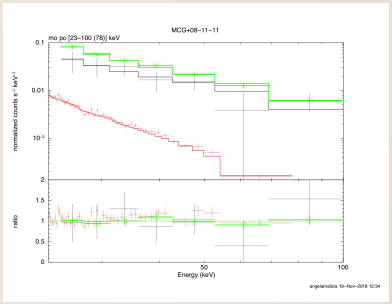
model: const*wa_g*po

Year	Γ	$C_{FPMA/XMM}$	$C_{FPMB/XMM}$	$F^{XMM}_{2-10keV}$ (10^{-11}erg cm^{-2}s^{-1})	$F^{FPMA}_{2-10keV}$ (10^{-11}erg cm^{-2}s^{-1})	$F^{FPMB}_{2-10keV}$ (10^{-11}erg cm^{-2}s^{-1})	$\Delta\chi^2$
2012	1.667±0.02	1.095±0.02	1.115±0.02	6.926	7.588	7.724	0.987
2015	1.693±0.01	1.019±0.01	1.023±0.01	6.15	6.27	6.30	1.021
2016	1.567±0.01	1.093±0.01	1.113±0.01	12.95	14.17	14.42	1.131
2017	1.541±0.01	1.10±0.01	1.114±0.01	6.53	7.18	7.27	1.116

- NuSTAR vs INTEGRAL good agreement confirmed within ~10% (mostly limited by the low statistics)
- epic PN spectra significantly harder than NuSTAR in the 2017 observation
- epic-PN flux normalisation lower than NuSTAR (~10%).

Spectra & light curves

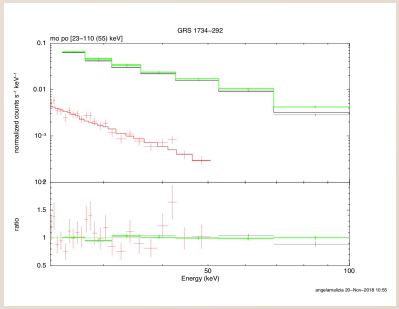
MCG+08-11-11



$\Gamma_{NuSTAR\ \_\ A}$ = 1.94 [1.90772 1.98356]
$F_{20\text{-}100\ keV}$ = 1.78 x 10^{-10} ergs/cm²/s

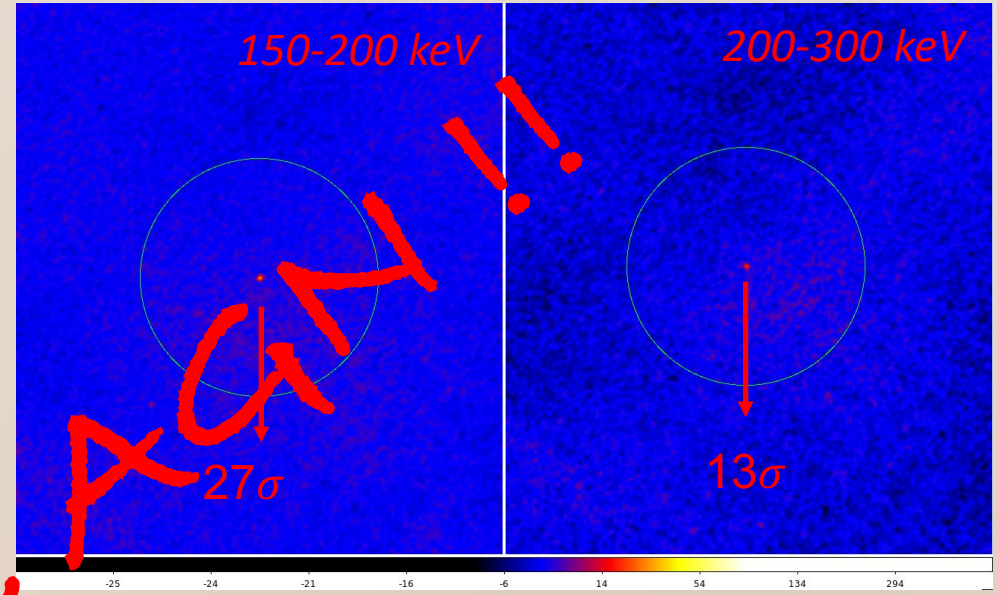
$\Gamma_{cat1500}$ = 1.95 [1.88934 2.01904]
$F_{20\text{-}100\ keV}$ = 2.02 x 10^{-10} ergs/cm²/s

GRS 1734-292



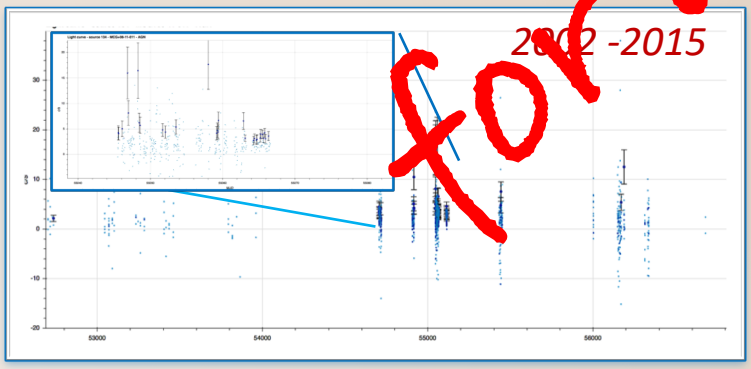
$\Gamma_{NuSTAR\ \_\ A}$ = 2.10 [1.87659 2.34096]
$F_{20\text{-}100\ keV}$ = 1.0 x 10^{-10} ergs/cm^2/s

$\Gamma_{cat1500}$ = 2.16 [2.12103 2.20531]
$F_{20\text{-}100\ keV}$ = 9.5 x 10^{-11} ergs/cm^2/s

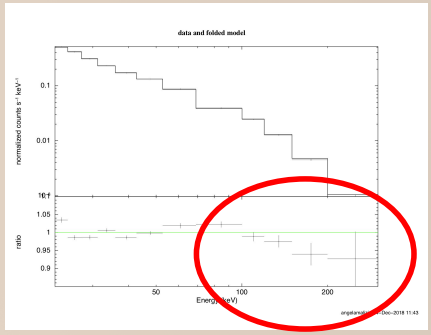


for all AGN!!

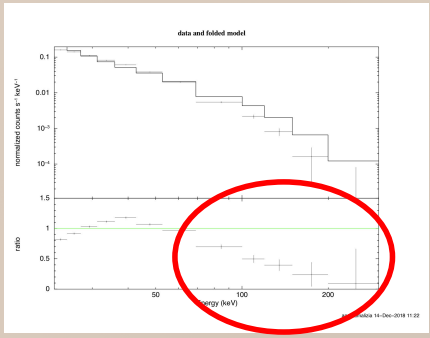
MCG +08-11-11 - 20-100 keV



CEN A



Circinus Galaxy

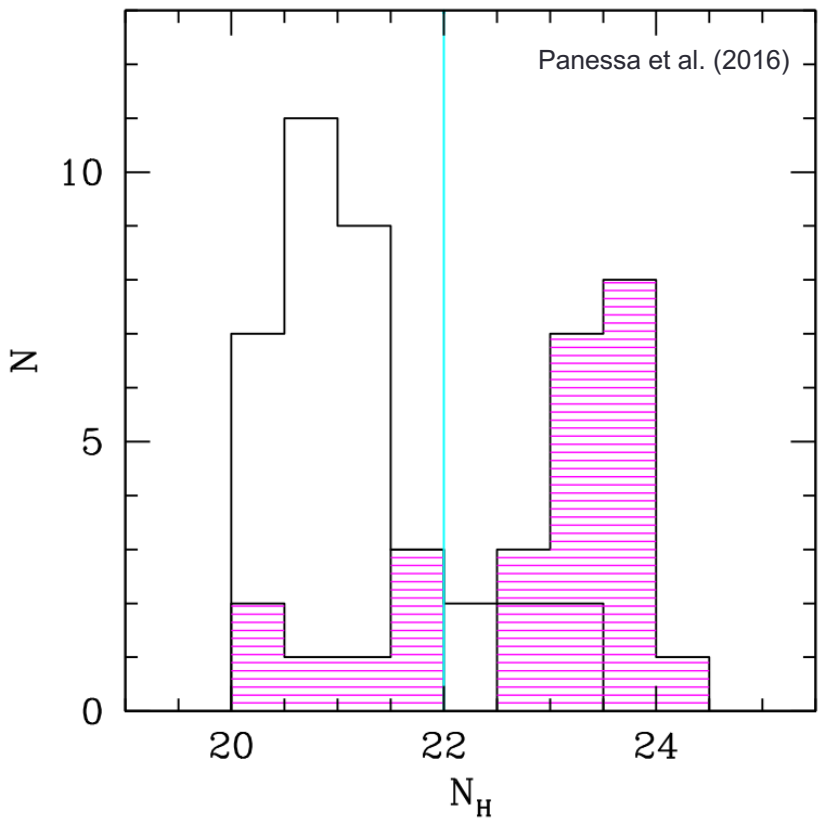


Radio galaxies above 20 keV

- First sample of radio galaxies selected in the hard X-rays by Bassani et al. (2016): ~70 sources from the INTEGRAL and Swift/BAT surveys
- Goal: multi-wavelength characterization of the sample
- Collaboration with:
  - INAF/IAPS Roma: F. Panessa, G. Bruni (radio properties and follow-up) et al.
  - INAF/IRA Bologna: D. Dallacasa, T. Venturi et al.

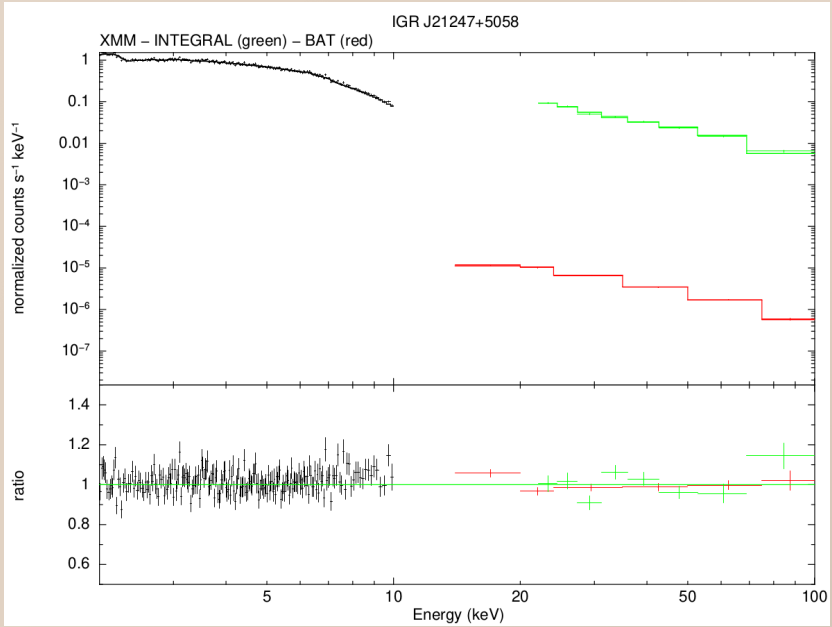
X-ray characterization of the sample

X-ray absorption: similar to radio-quiet AGN...



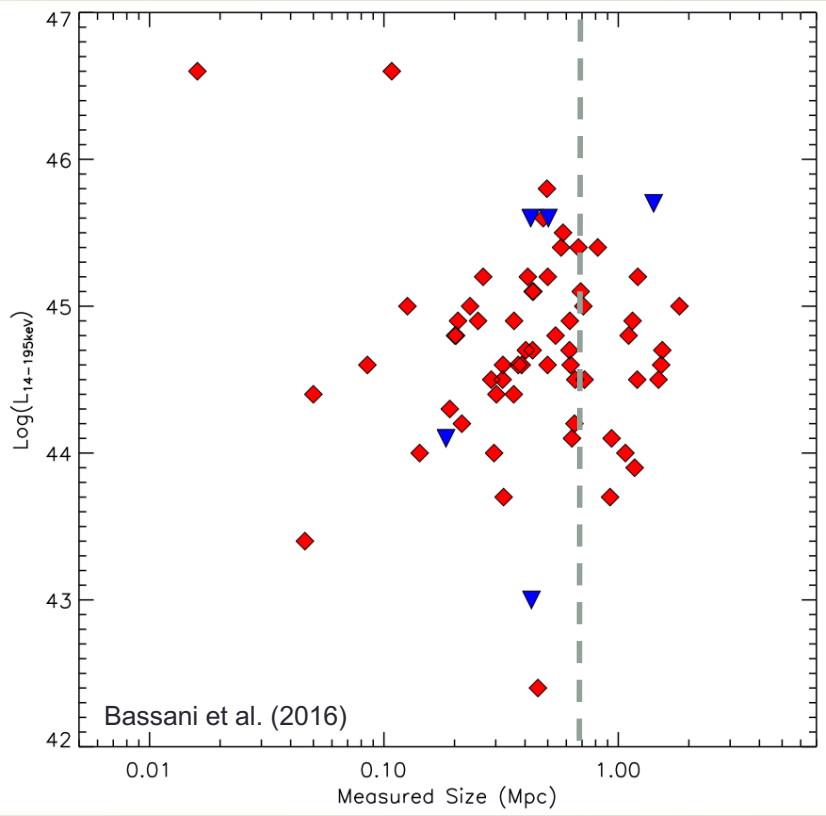
… but no evidences for Compton-thick sources (Ursini et al. 2018)

Broad-band studies including Swift/XRT, XMM, Chandra (ongoing)

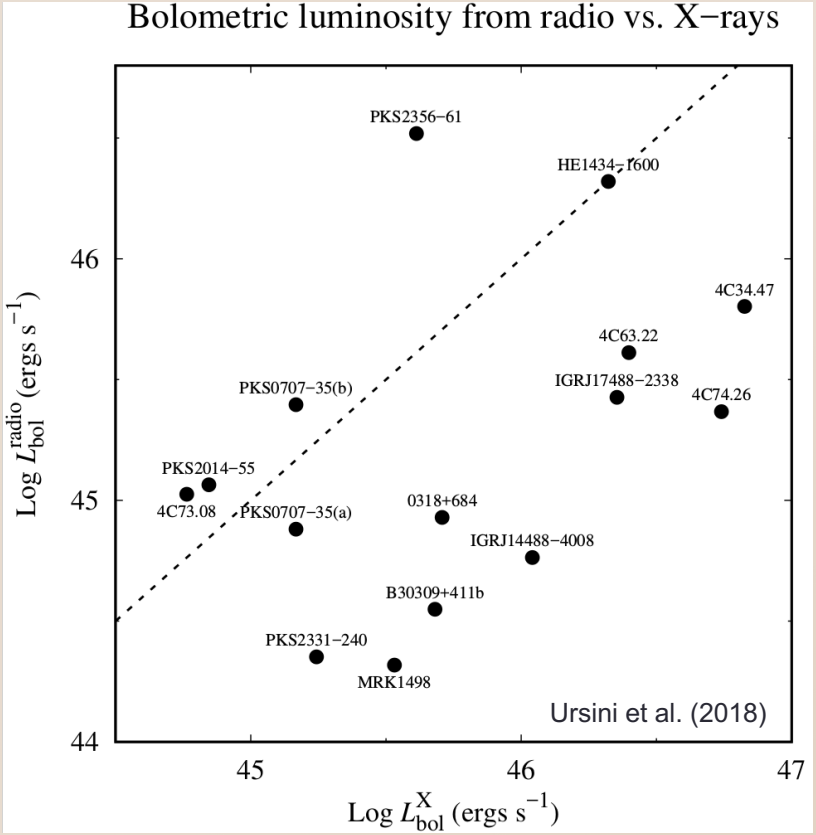


Giant radio galaxies

A large fraction (20%) are giants (size >0.7 Mpc)...



… Ideal to study past activity (radio lobes) vs present activity (X-rays)



Giant radio galaxies

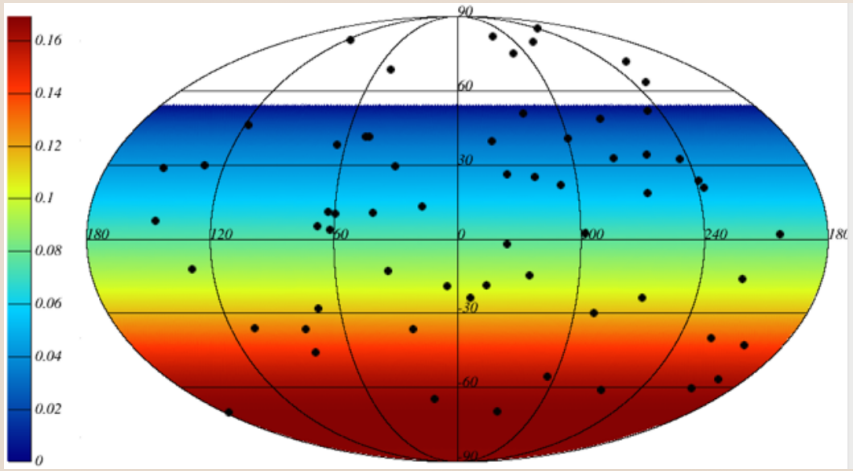
- Future: LOFAR Key Science Project

"Radio restarting activity in AGN and its duty cycle"

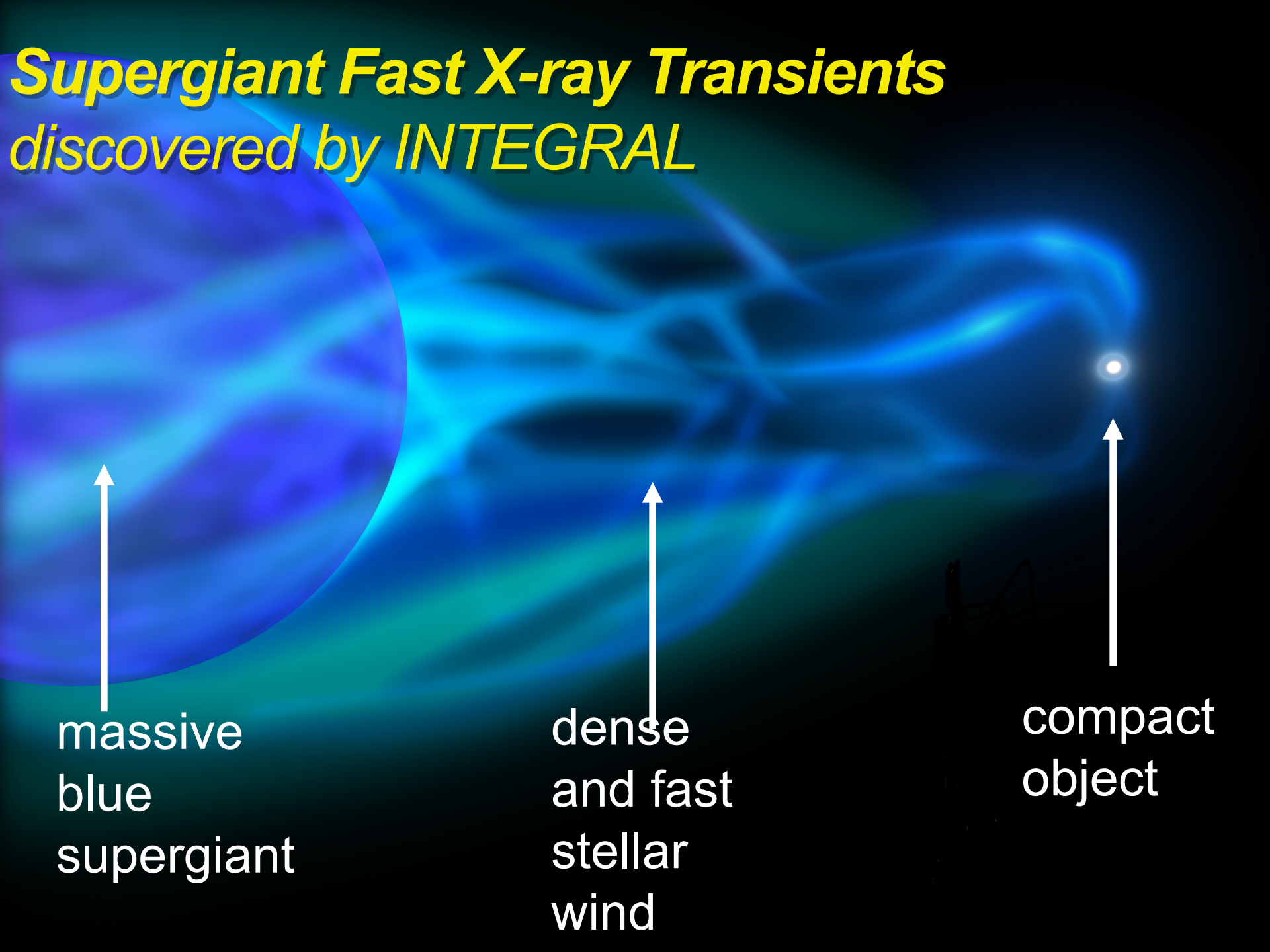
- PI: F. Panessa, Co-Is: L. Bassani (OAS), G., Bruni, F. Ursini (OAS), M. Brienza, A. Capetti, E. Caroli (OAS), D. Dallacasa, M.T. Fiocchi, F. La Franca, T. Venturi, P. Ubertini, E. Chiaraluce

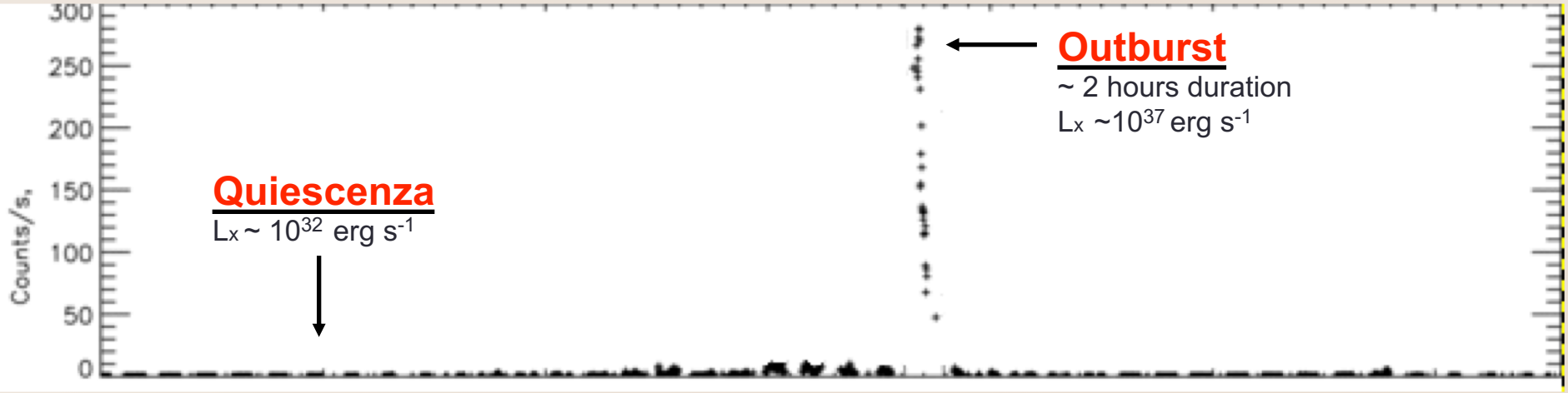
Other projects

- ANTARES: search for correlations with neutrino events (55 objects in the FOV of ANTARES, ~35 events expected)



Supergiant Fast X-ray Transients
discovered by INTEGRAL





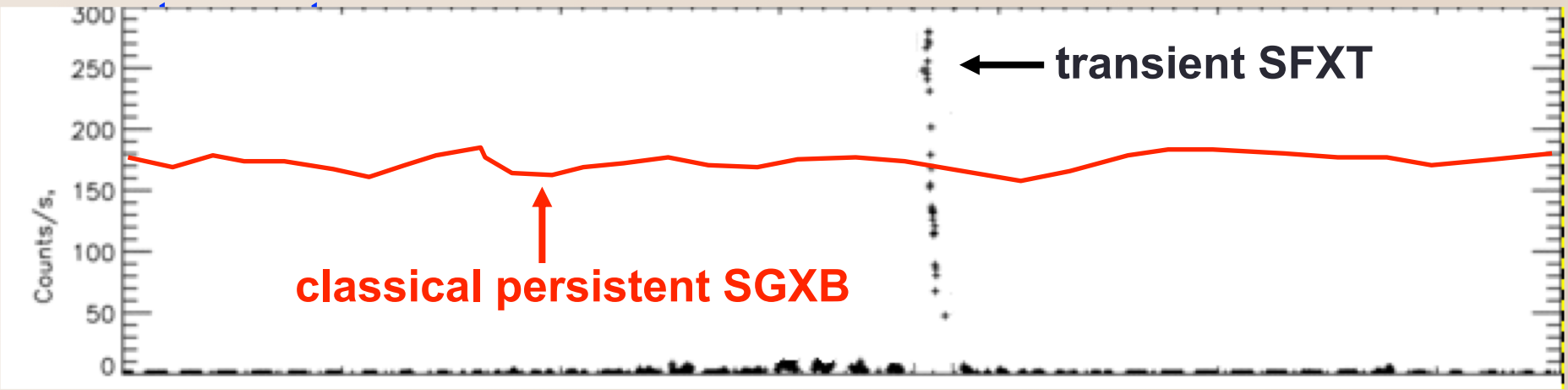
SFXTs are among the most extreme Galactic transients in term of :

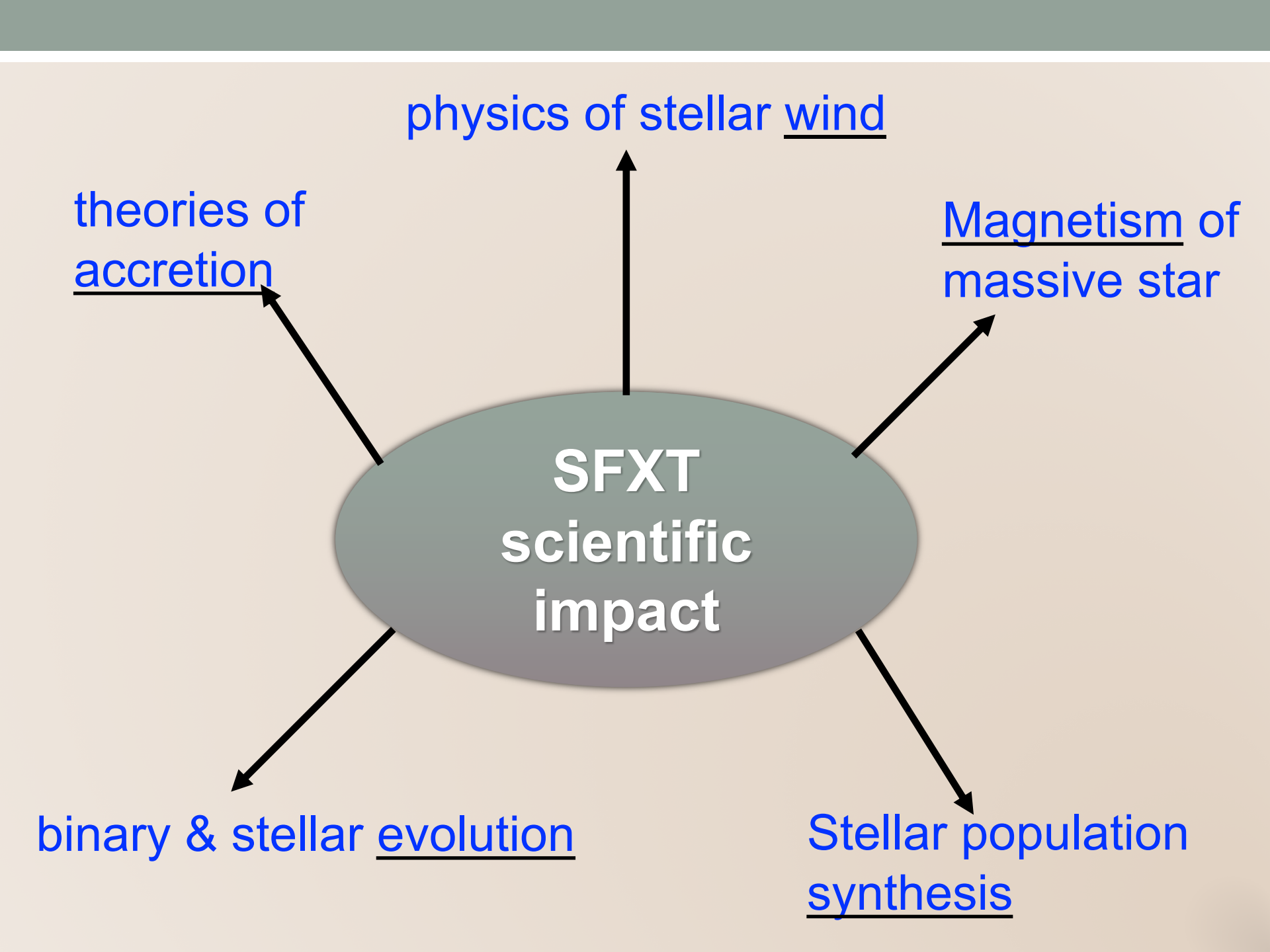
- duration (0.5 - 2 h)
- energetic (10^{36} - 10^{37} erg s^{-1})
- dynamic range (5 orders of magnitude)
- duty cycle (0.01% - 3%)

SFXTs: major questions

(1) which are the physical reasons behind their peculiar behavior & which is the accretion mechanism at work (alternative to the standard Bondi - Hoyle - Lyttleton)

(2) why their X-ray behaviour is **completely different** from that of their **parent population of classical persistent Supergiant High Mass X-ray Binaries** having identical "ingredients", i.e. blue supergiant +




physics of stellar wind
theories of accretion
Magnetism of massive star
SFXT scientific impact
binary & stellar evolution
Stellar population synthesis

Our studies are mainly focussed on:

- ✓ **cyclotron lines** in broad band 0.2-100 keV spectra
- ✓ **orbital characteristics** (i.e superorbital and orbital periods, eccentricity)
- ✓ **X-ray pulsations** from the neutron star
- ✓ **Cumulative distribution function** of outbursts' luminosity
- ✓ **Discovery of new SFXTs (~ 15 firm objects to date)**

Mandatory for population studies, i.e. **formation rate of SFXTs** ⟶ rate of neutron stars mergers which produce gravitational waves and short GRBs

Main collaborations:

- IASF Milano

- IAPS Roma

- Gruppo alte energie
  Universita' di Southampton (UK)

On future perspectives…

Are SFXTs the prototype of a new class of Galactic MeV - TeV and/or radio transients?