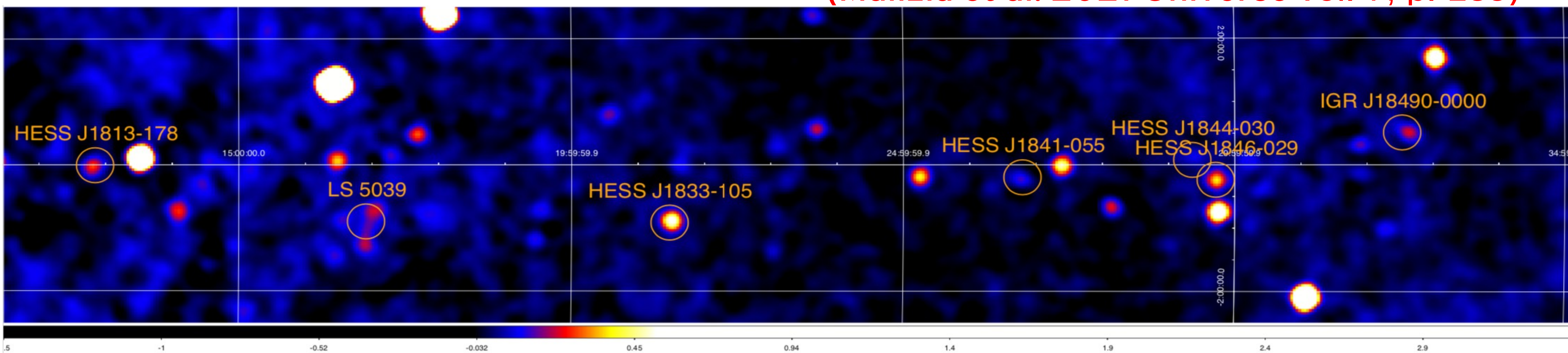
INTEGRAL view of TeV sources: A legacy for the CTA project

(Malizia et al. 2021 Universe vol. 7, p. 135)



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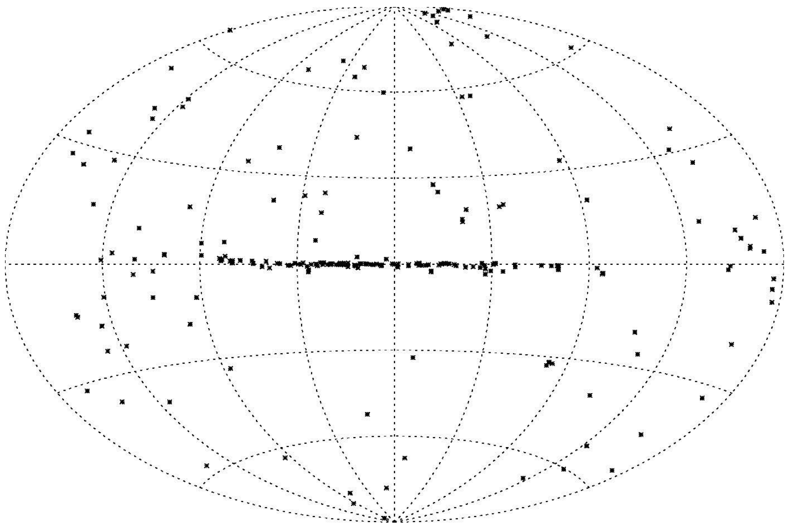
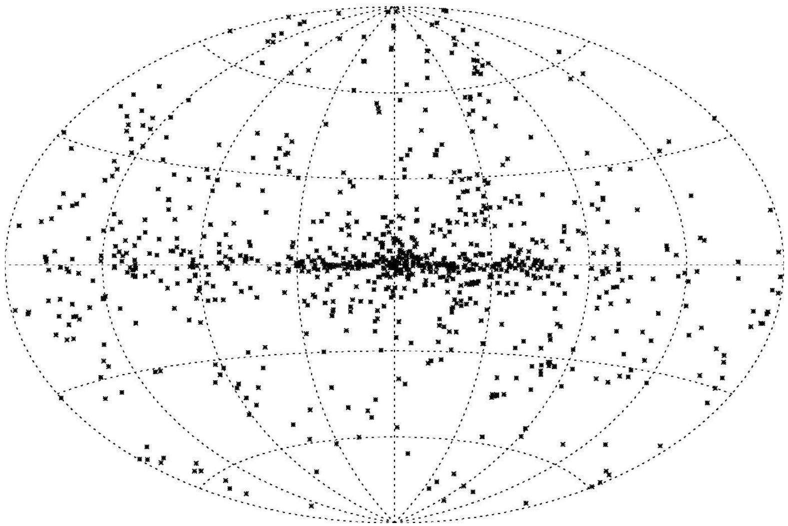
INAF OAS BOLOGNA

Identification of soft γ-ray counterparts of VHE sources

Employing a spatial cross-correlation technique (Stephen et al. 2010; 2011), we compared the *INTEGRAL*/IBIS and TeV all-sky data in search of secure or likely associations.



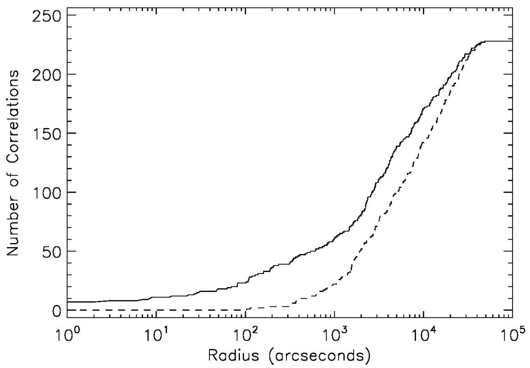
TeV database: TeV on-line catalogue which includes 229 objects (by end of 2020).



***INTEGRAL* database:** 1000-orbit catalogue (Bird et al. 2016) which lists 939 sources detected in the 17-100 keV energy range above 4.5σ.

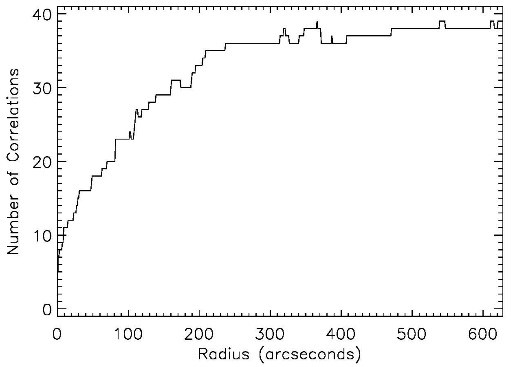
Cross-correlation analysis

The cross-correlation technique consists of calculating the number of TeV sources for which at least one *INTEGRAL* counterpart was found within a specified angular distance.
To have a control group, we then created a list of 'anti-TeV sources', mirrored in Galactic longitude and latitude, and the same correlation algorithm applied.



Solid curve: the number of TeV/*INTEGRAL* spatial correlations

Dashed curve: same correlation with 'fake' TeV sources



The difference between the two curves showing the number of 'excess' correlations.

- Strong correlation out to about 330 arcseconds;
- Only 2 or 3 false associations are expected to be, by chance, coincidence.

INTEGRAL - TeV associations

From the cross-correlation analysis we found a total of 37* TeV sources having a soft γ-ray counterpart in IBIS catalogues.

20% of VHE objects have *INTEGRAL* coverage and useful data over the 20–100 keV band.

37 associations: *all types of VHE objects from galactic to extra-galactic:*

- SNRs
- PSRs/PWN systems
- Binary systems
- AGN of various classifications
- Unidentified sources

(*) the associations grow to 39 considering distances greater than 330 arseconds where some true correlations may still be present.

SNR view at soft γ-ray and TeV energies

INTEGRAL/IBIS offers the opportunity to cover the relatively unexplored soft γ-ray window in at least some bright objects. From the cross-correlation analysis we found 3 SNR-shell associations:

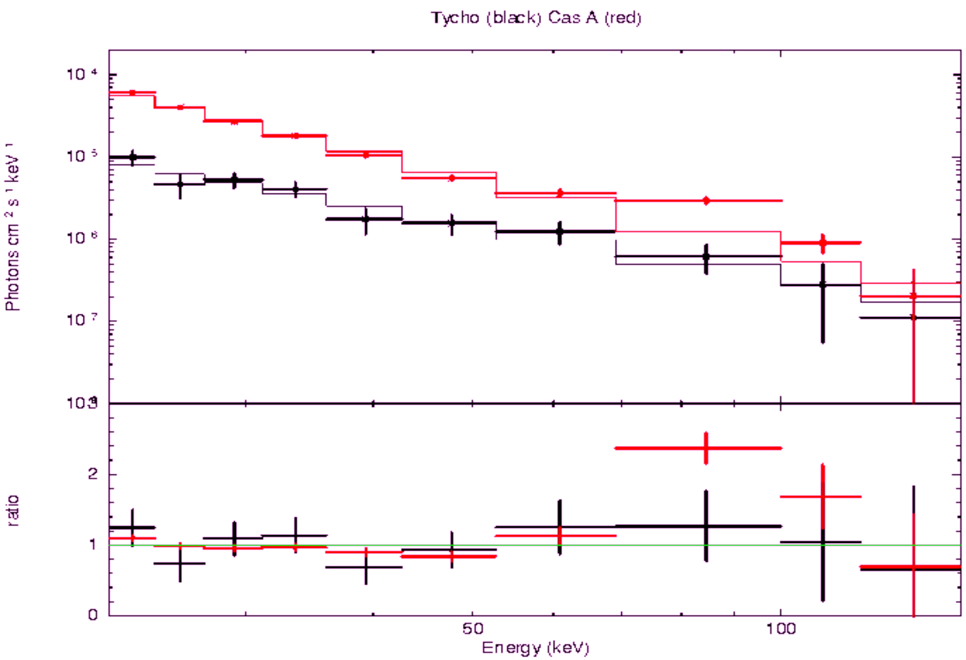
Tycho

Cas-A

RX J1713.7-3946

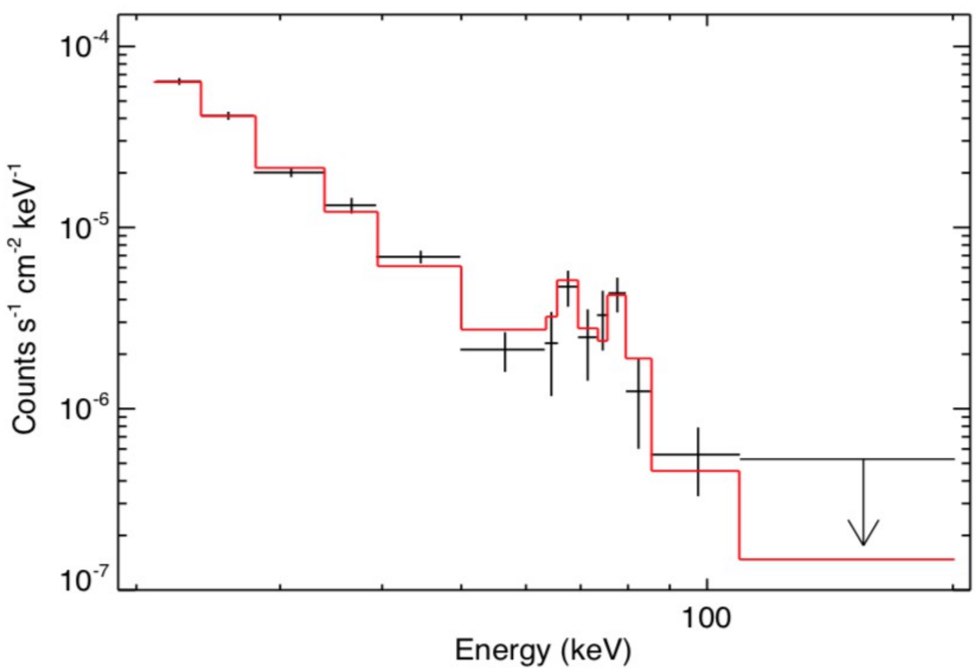
The study of the shape of the broad-band spectrum as well as the morphology of these 3 sources measured by *INTEGRAL*, in conjunction with other observatories, provide clues for our understanding of the details of cosmic rays acceleration and the radiation mechanism at work in the expanding shell of these remnants.

Tycho and CasA



	Gamma	F(20-150 keV)
Tycho	~2.2	~1.2x10^{-11}
Cas A	~3	~4.9x10^{-11}

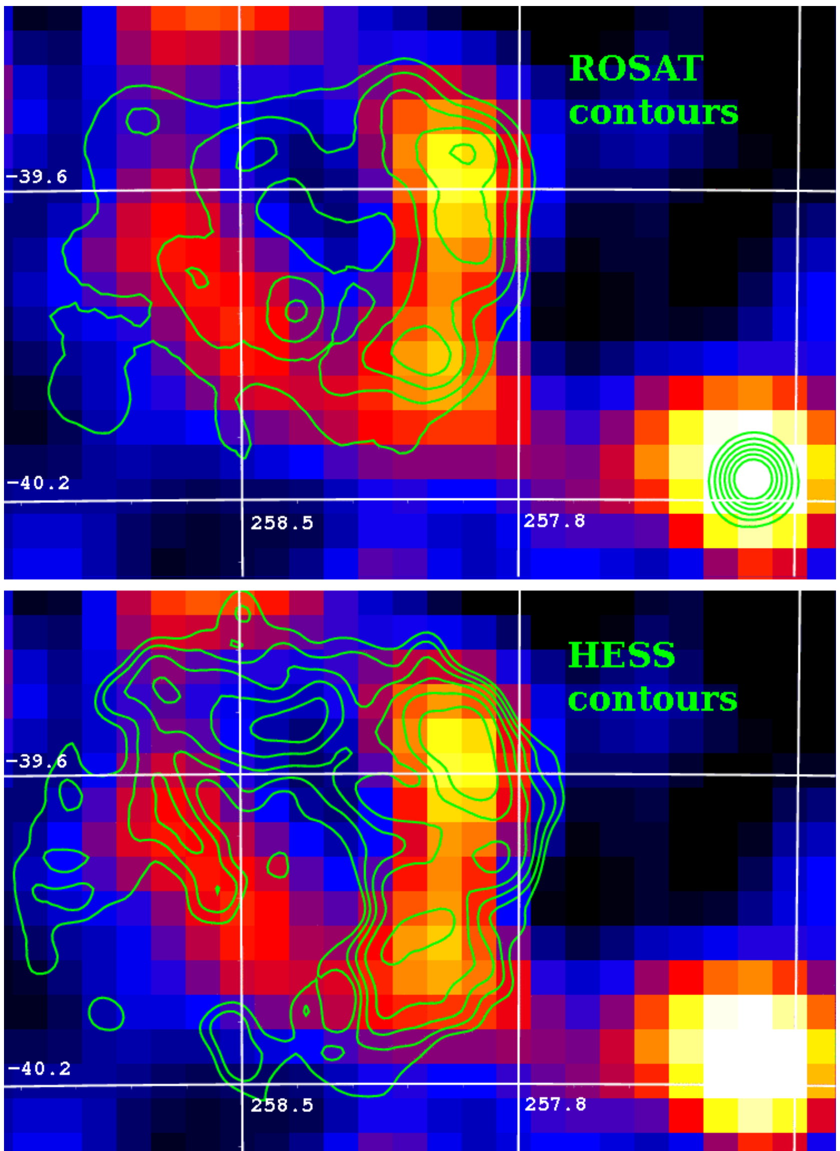
In Cas A: excess around 70-90 keV due to the presence of Titanium-44 (44Ti) decaying lines.



Broad-band spectrum of Cas A (from Renaud et al. 2006): the two 44Ti decaying line was found at 68 and 78 keV.

RX J1713.7-3946

A nice example of the imaging capability of *INTEGRAL* in the case of extended objects, since IBIS has, for the first time, resolved its spatial structure in soft γ-rays (Krivonos et al. 2007).



Colour-coded image obtained in the 17–60 keV energy band: a clear ring-like structure with $\sim$24 arcmin radius is evident.

Also plotted are the ROSAT (upper panel) and HESS (lower panel) contours. It is evident the similarity of the images in soft X-rays, soft γ-rays and energies.

Soft γ-ray pulsars with TeV emission

Among the several pulsars observed at TeV energies, only 2 were detected by *INTEGRAL*: **Vela** and **Crab**.

Vela

- H.E.S.S. observations: presence of an extended emission located south of the Vela pulsar (Aharonian et al. 2006);
- *INTEGRAL* data: detection of a spatially extended emission above 18 keV, after the subtraction of the main radiation from the pulsar (Mattana et al. 2011).

***INTEGRAL* has observed both the pulsar and the Vela-X PWN.**

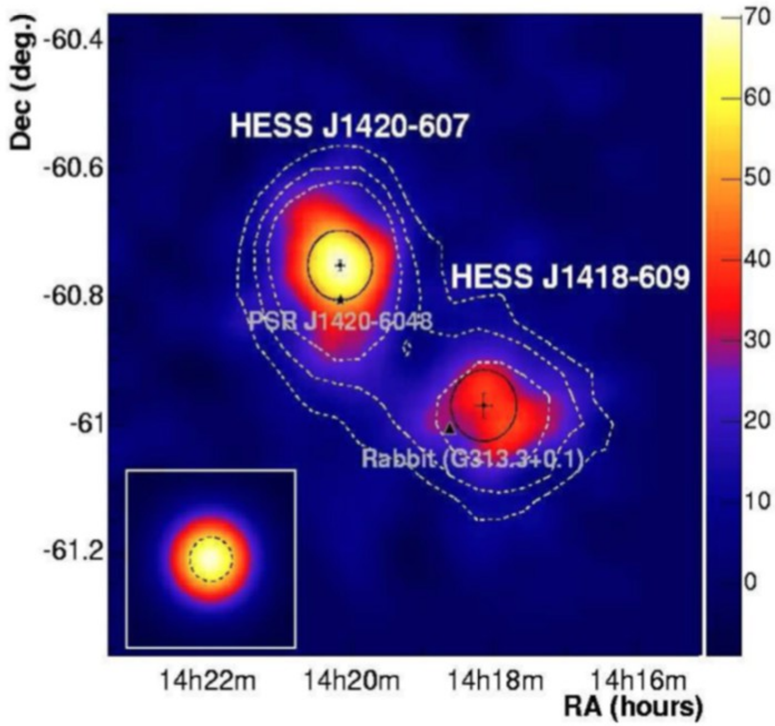
PWNs

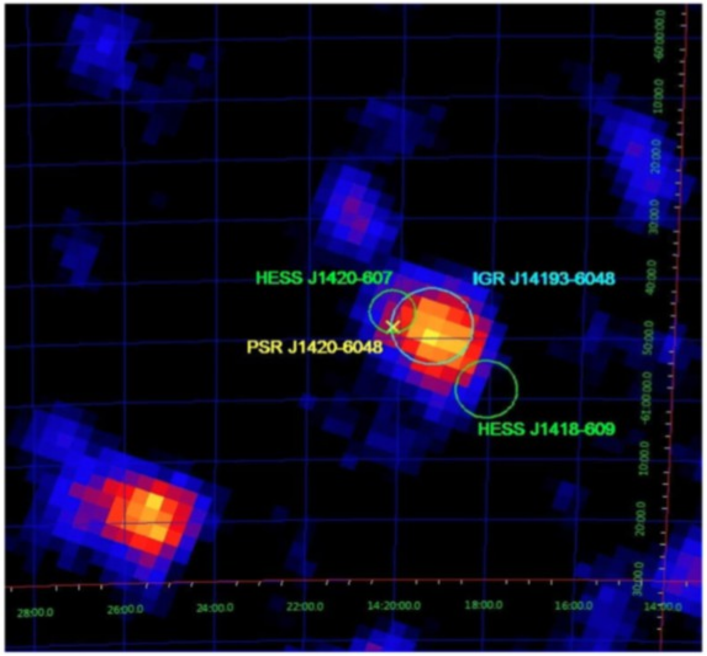
- How many PWNs? ~12;
- Where? Half of the systems are in the Scutum arm region;
- What kind of PWNs? Some complex systems (Vela, IGR J14193-6048/Kookaburra and HESS J1616-508/PSR J1617-5055);
- What about emission?: At soft γ-ray energies, the emission is most likely due to the contribution of both the pulsar and its PWN; at TeV energies the PWN dominates in most objects (except for Crab and Vela, where pulsed emission is observed);
- In the 20–100 keV waveband, the PWN is a significant component of the 20–100 keV emission in approximately half of the systems.

By combining *INTEGRAL* and TeV data allows us to model properly the source SED and estimate fundamental physics parameters since in some systems the synchrotron peak is observed in the X-ray/soft γ-ray domain, while the IC peak is measured in the TeV regime.

Some complex systems

1) IGR J14193-6048/Kookaburra

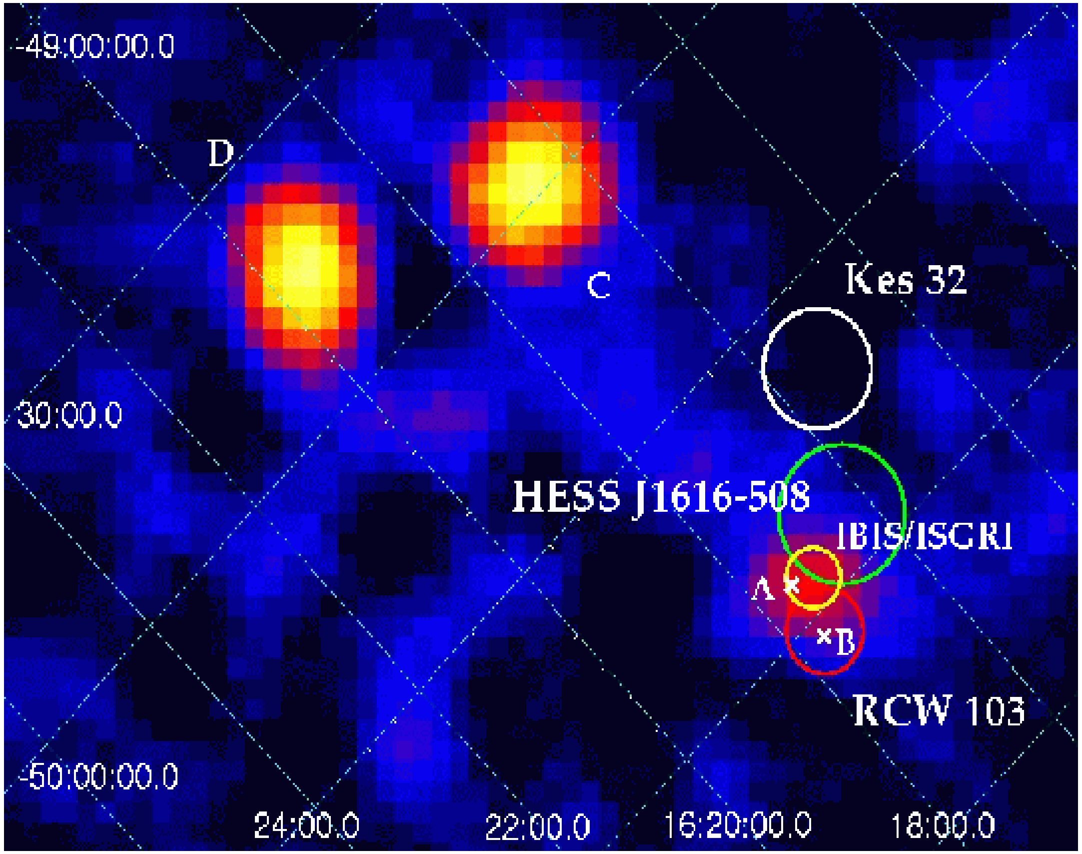




H.E.S.S. observed two close-by, distinct TeV sources in the Kookaburra complex: HESS J1420-607 and HESS J1418-609 (Aharonian et al. 2006).

INTEGRAL detects a source (IGR J14193-6048) in between the two TeV objects, although its position is shifted towards HESS J1420-607. *Chandra* data → PSR J1420-6048 is the likely identification for the *INTEGRAL* source, although its location is barely inside the 99% IBIS error circle (Fiocchi et al. 2010). The association has been confirmed by BAT data (Oh et al. 2018).

2) HESS J1616-508/PSR J1617-5055



PSR J1617-5055 and its PWN are certainly the counterpart of the *INTEGRAL* source, but not necessarily that of HESS J1616-508.

HESS J1616-508 has been identified with a PWN in the TeV catalogue, although it is not firmly associated with any known counterpart at other wavelengths. Based on this, the source can be considered as still unclassified.

Binaries from keV to TeV

- How many binaries at TeV energies? ~11;

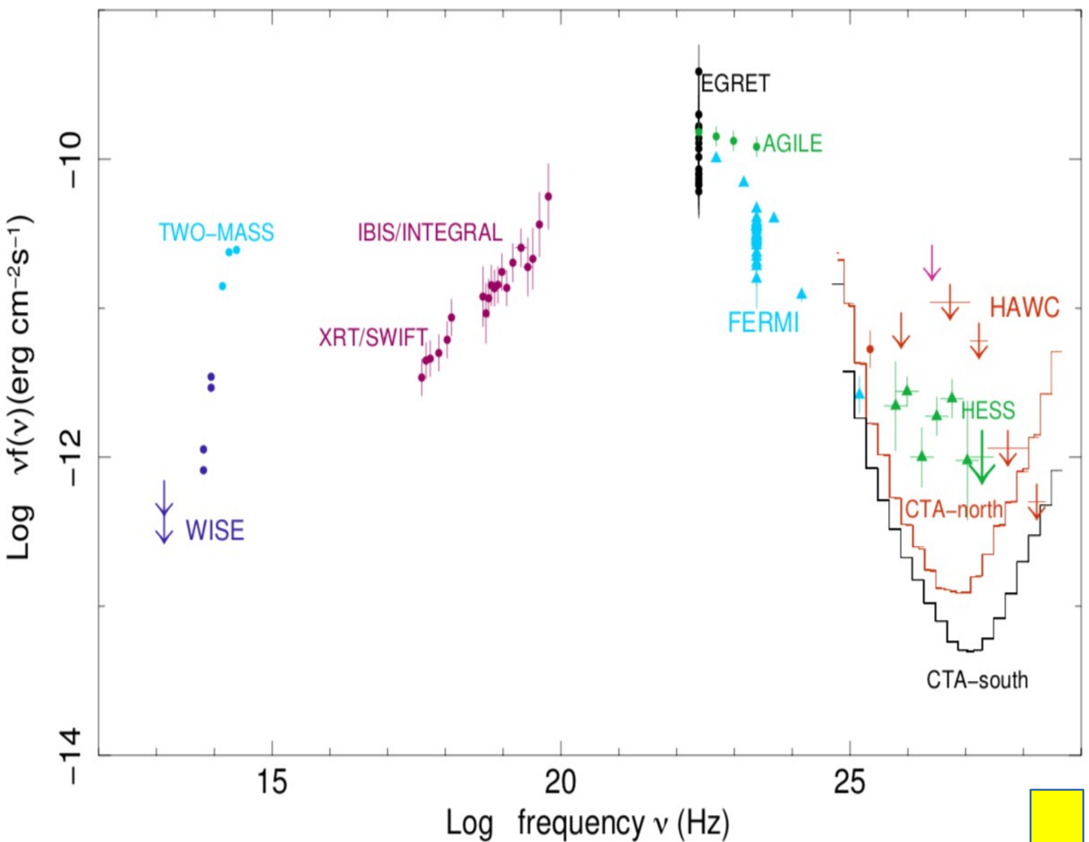
- How many systems from the cross-correlation analysis? 4 objecs: PSR B1259-63, LS 5039, LSI+6103 and Eta Carinae;

- What about TeV emission?: It can have different physical origins: 1) in microquasars the non-thermal particle acceleration processes occur in the jet of an accreting compact object (Zhang et al. 2010; Massi et al. 2015); 2) in the pulsar binaries the particle acceleration is the result of the shock between the stellar and the pulsar winds (Maraschi et al. 1981);

- Future simultaneous observations, including *INTEGRAL* and CTA, will be essential for the study of the physical processes that are responsible for the particle acceleration.

LS 5039

LS 5039 is a variable and periodic γ-ray source, showing the shortest orbital period among the γ-ray binaries (3.9 days).



SED of LS5039 using non-simultaneous data and showing the sensitivity expected from the southern (black line) and northern (orange line) CTA observatories **for 50 h***.

From low to high energy, the data used are from the: 2MASS survey (blue light points), WISE (purple points), EGRET catalog (black points), AGILE catalog (green points), Third *Fermi* catalog (blue light points), HAWC (orange points), and H.E.S.S. (green points).

SED although constructed using non-simultaneous data from radio to VHE, including *INTEGRAL* and CTA data, will be crucial in discriminating the physical process generating the non-thermal photons at high energies.

(*) from https://www.cta-observatory.org/science/cta-performance/, accessed on May 3, 2021).

Soft γ-ray to TeV radiation in *INTEGRAL* AGN

- How many AGNs form the cross-correlation analysis? 17

- What kind of AGNs?

  - 11 are BL Lac objects (9 HBL and 2 IBL);

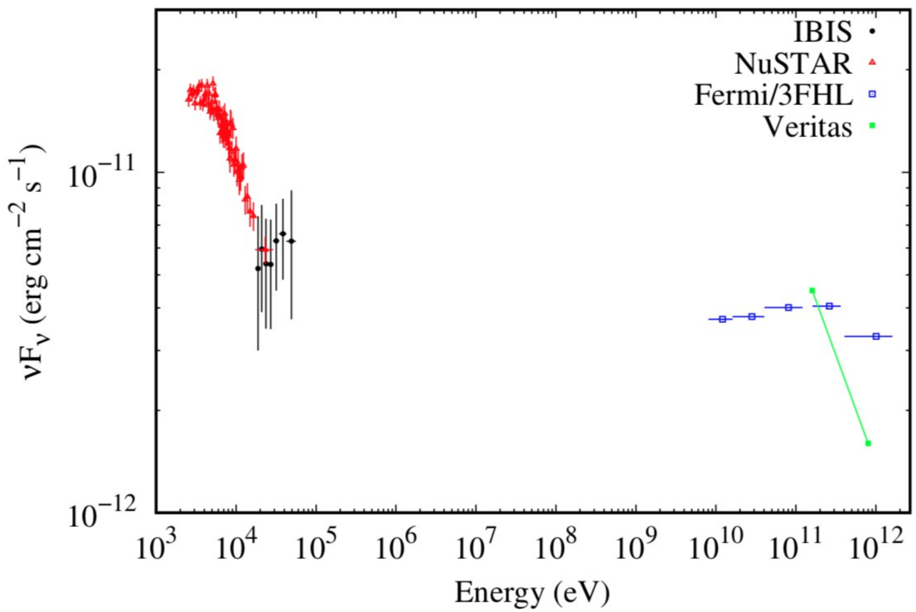
  - 3 Flat Spectrum Radio Quasars or FSRQ (PKS 1510-089, 4C +21.35 and 3C 279);

  - 2 FR I radio galaxies (Cen A and NGC 1275);

  - IGR J20569+4940: this source is now classified as BL Lac, but of unkown class and redshift (Chiaro et al. 2016).

IGR J20569+4940

- It is associated with a *Fermi* source 2FGL J2056.7+4939 (Ajello et al. 2020) and it was found to emit at TeV energies (VERITAS, Benbow et al. 2015);
- It has a bright radio counterpart (NVSS 205642+494005), as typically observed in radio-loud AGNs;
- It is variable both in radio (Ofek et al. 2019) and X-rays (Landi et al. 2010).



Peak in the GeV region?

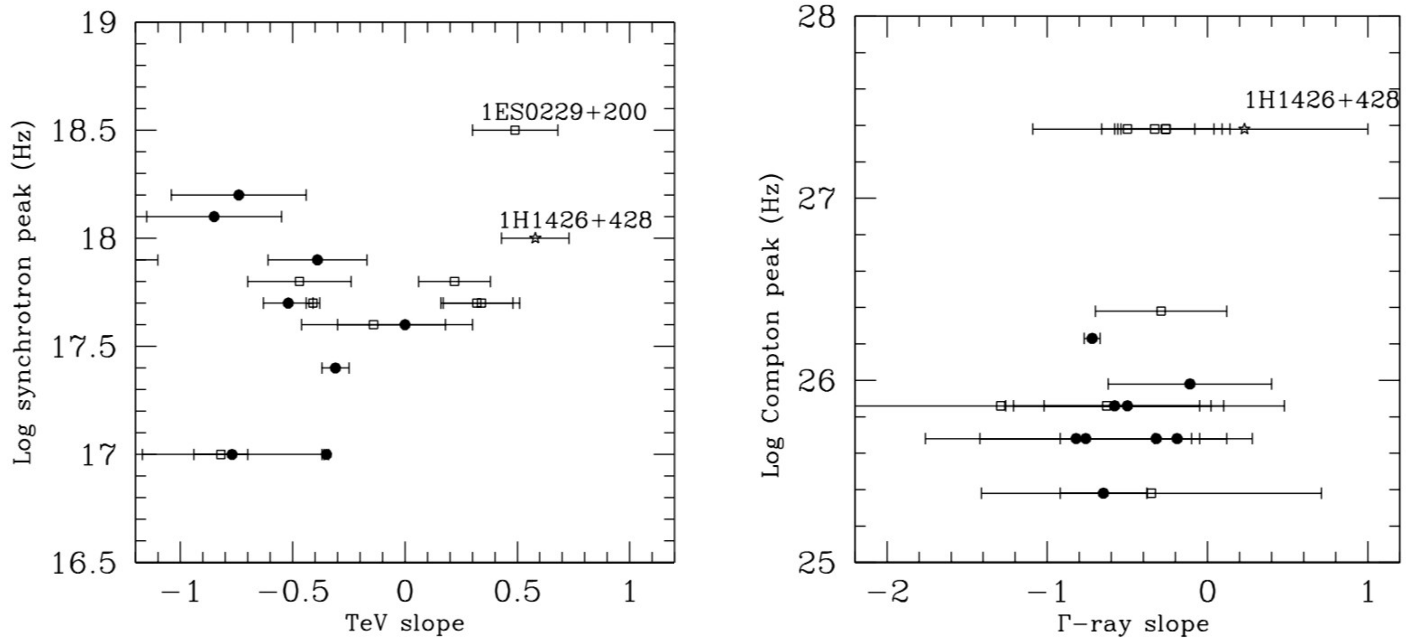
The SED resembles that of IGR J19443+2117 = HESS J1943+213 one of the most extreme high-peaked blazars emitting through the Galactic plane.

IGR J20569+4940 is another example of a high synchrotron peaked BL Lac, as originally proposed by Fan et al. (2016).

INTEGRAL BL Lac

Most of the BL Lac detected by *INTEGRAL*/IBIS belong to the subclass of typical HBL

Synchrotron peak versus TeV slope



Compton peak versus soft γ-ray slope

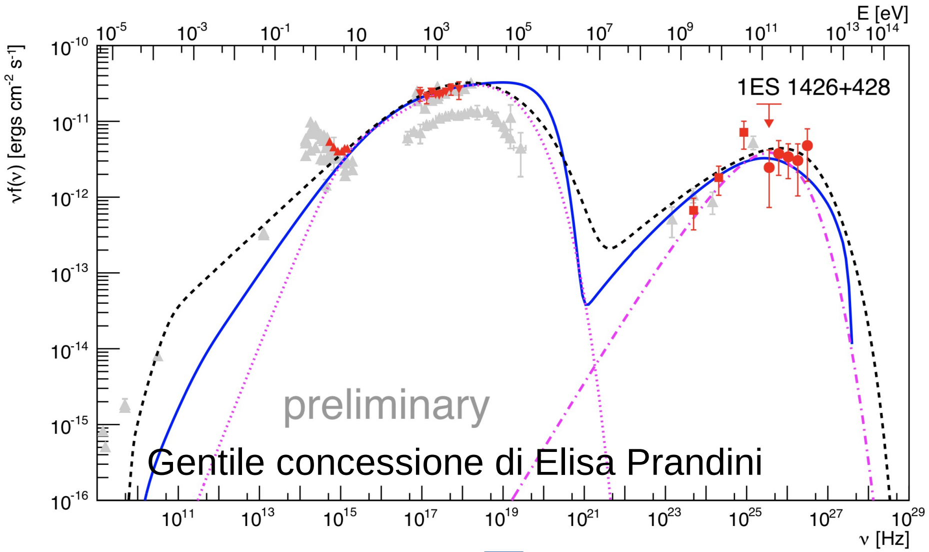
Filled circles and star are HBL objects that are detected by *INTEGRAL* + 8 extra from Foffano et al. 2019.

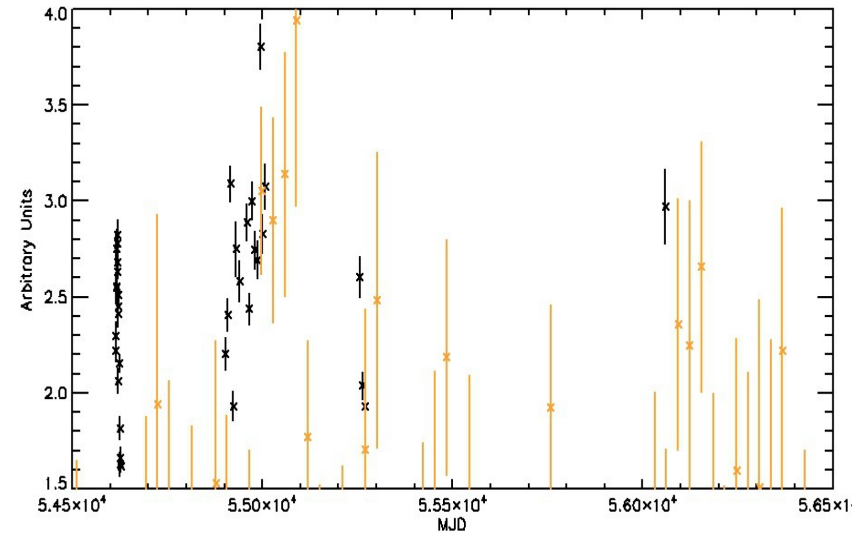
In the Compton peak versus soft γ-ray slope diagram the discrimination between typical and hard-TeV objects is more pronounced. This makes this diagram a more useful one to highlight the most extreme high energy peaked BL Lac objects.

Peculiar case: 1H 1426+428

Its synchrotron peak is located above 100 keV, making it a very rare case of a hard-TeV BL Lac.

1H 1426+428





The SED suggests an extreme location of both synchrotron and IC peak.

Swift/XRT light curve (black points) superimposed on *Swift*/BAT light curve (orange points) showing the flare event (June 2009).

- *INTEGRAL* ToO to detect the source in a high state, so to confirm the presence of the synchrotron peak at around 100 keV. The prompt for our ToO observation will be the soft X-ray trigger provided by either *Swift*/XRT and/or MAXI, which are continuously monitoring the source;

- We have a coordinated campaign with the MAGIC telescope in order to investigate the Compton peak in the TeV regime and the synchrotron one in the hard X-rays.

Future perspectives

- The CTA thanks to its characteristics in terms of energy range, angular resolutions, great pointing flexibility, and global sky coverage, will allow a major leap in the future of GeV/TeV astronomy;

- *INTEGRAL* current and future survey will provide essential information in the analysis of the candidate accelerators;

- *INTEGRAL* will provide information in terms of light curves and spectra, particularly for high energy peaked objects, where it will give a significant contribution in building their spectral energy distributions (SED);

- CTA is expected to discover many new sources, and their identification and study can benefit from *INTEGRAL* current and future survey data, where unidentified and/or poorly known objects are continuously being followed-up in the X-rays and at optical/infrared wavelengths, not only for classification purposes, but also for multiwaveband characterisation.