

# Hunting for elusive multi-messenger transients with INTEGRAL

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Recent years were marked by breakthrough observations of new multi-messenger and multi-wavelength transients, often unveiling unanticipated and puzzling phenomena. Likely associated with most energetic processes in the dense region at the heart of peculiar supernovae, mergers of compact objects, or tidal disruption events, these events expose unique signatures in hard X-ray and gamma-ray emission.

I highlight recent pioneering observations of short energetic transients made with INTEGRAL, which is especially well-equipped to observe unpredictable, short-lived, and energetic hard X-ray and gamma-ray transients. It carries a collection of detectors that monitor the entire hard X-ray sky with over 80% duty cycle and is able to re-point to perform deep and sensitive hard X-ray observations of any large selected sky region. I discuss the observations of gamma-ray bursts, in particular in association with the gravitational wave events and high-energy neutrinos, and review how INTEGRAL observations of fast hard X-ray transients help to reveal mechanisms of the peculiar supernovae. Finally, I will discuss how the recent discoveries in the domain of multi-messenger transients were made possible by a global effort to achieve a new degree of automation and interoperability.

*The New Era of Multi-Messenger Astrophysics - Asterics2019*

*25 - 29 March, 2019*

*Groningen, The Netherlands*

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## 1. Introduction

Recent emergence of rapid optical and radio surveys accelerated the development of time domain astronomy. Furthermore, observations of gravitational waves and neutrinos enabled breakthrough multi-messenger observations of fundamental physical processes in space. Short and energetic events are generally easier to separate from the background than persistent sources, which is why the first truly multi-messenger signals were also detected as transient events.

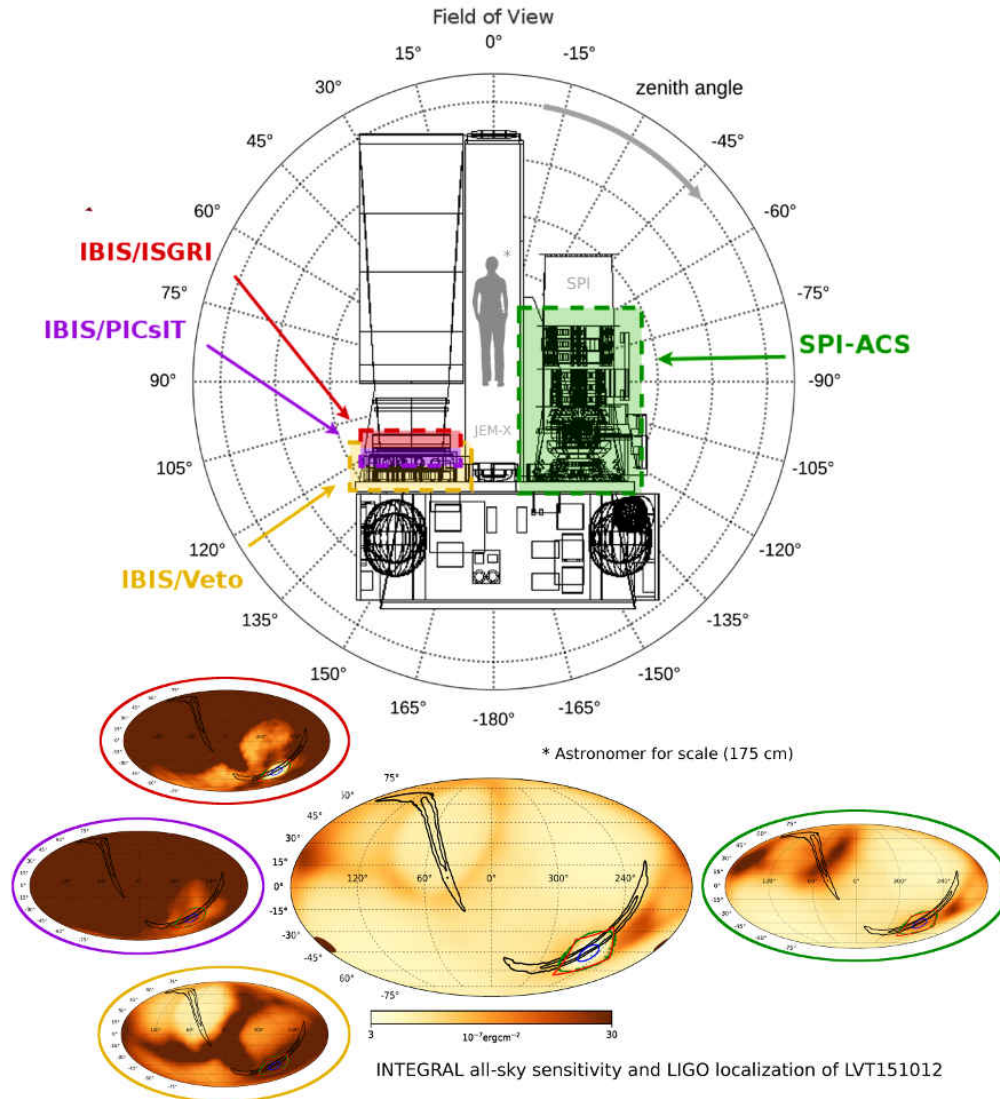
The properties or even the nature of these new transient sources often remain uncertain, typically hinting towards particularly energetic transformations of compact objects: peculiar supernovae, mergers of compact objects, or tidal disruption events. An important perspective on these events is given by hard X-ray and gamma-ray emission: it tends to reveal a distinct emission component that points to the most dense and energetic regions at the heart of the source.

In this paper we highlight recent pioneering observations of short energetic transients made with INTEGRAL, which is especially well-equipped to observe unpredictable, short-lived, and energetic hard X-ray and gamma-ray transients. It carries a collection of detectors that monitor the entire hard X-ray sky with over 80% duty cycle and are able to re-point to perform deep and sensitive hard X-ray observations of a large selected sky region.

## 2. INTEGRAL observatory

International Gamma-Ray Astrophysics Laboratory [INTEGRAL 1] is an M-class ESA mission, operating since 2002. It is equipped to study hard X-ray and gamma-ray emission in the energy range from 3 keV to more than 10 MeV. Photons in this energy range are typically produced in dense and energetic regions, through synchrotron radiation, Compton scattering, nuclear decays, etc. Due to particularly low cross-section, this emission can reach out from the deepest regions of compact sources. On the other hand, photons with these energies are also particularly hard to intercept and characterize. INTEGRAL relies on a collection of heavy detectors, with large stopping power. To distinguish emission from different sources it employs a set of coding masks, projecting thoroughly designed patterns on the detectors. The coded masks are only projected within limited Fields of View (within  $1000 \text{ deg}^2$ ), but due to exceptional penetrating power of photons above 100 keV, they reach the same detectors from any direction in the sky. Sometimes a nuisance this also implies that INTEGRAL has exceptional grasp of hard X-ray emission from any position in the sky. All-sky observations are especially important when the sources appear unexpectedly at random sky positions, preventing any scheduled observations with sensitive narrow-field instruments. Since multiple INTEGRAL instruments can be used in this fashion, it is possible to reconstruct sky direction by exploiting difference of sky sensitivity between different detectors. [2].

In addition, owing to its highly elongated orbit, INTEGRAL does not suffer from any occultation by the earth, unlike every one of the near-Earth spacecraft (like Fermi, AGILE, or Swift). INTEGRAL instruments are online up to 85% of the time, just to give a sufficient margin to avoid the damaging the instruments in the radiation belts.



**Figure 1:** Schematic view of the INTEGRAL spacecraft, highlighting the all-sky instruments. A typical astronomer is shown for scale inside JEM-X monitor. The bottom panel shows contribution to the all-sky sensitivity to any gamma-ray counterpart from GW151012 from different all-sky detectors on-board INTEGRAL (note the color coding matching the top panel), [see 2, for detailed study]

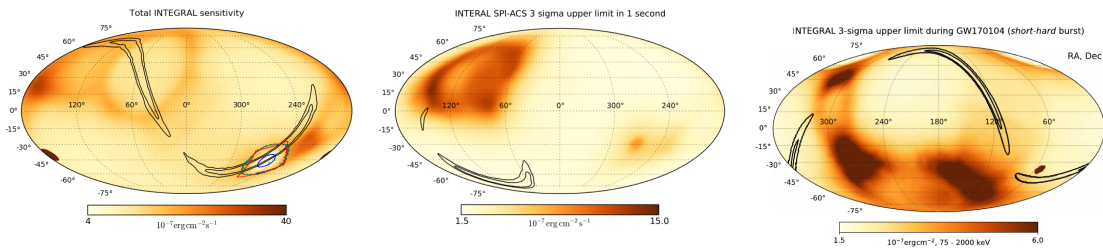
### 3. Observations of GW transients

Since 2015 LIGO detector network (later joined by also by Virgo) has been making ground-breaking observations of gravitation wave sources. The most clear GW signal events is emitted in short bursts just before coalescence of compact binary objects, such as black holes and neutron stars. It is not currently possible to pinpoint the distant compact binary before its collapse, and the localization provided by the GW network is still rather uncertain. This implies that the best observations close to the time of the events come from detectors which do not need to be pointed to a particular source, observing the whole sky at once. As described in the previous section,

INTEGRAL, fits these requirements exceptionally well. From the very first GW detection, INTEGRAL has been performing unique and vital observations of the first GW transients - Binary Black Hole mergers. No gamma-ray signal was found by INTEGRAL from any of the BBH mergers [2, 3, 4, 5] (see Fig. 2). A report of a low-significance gamma-ray counterpart of GW150914 by Fermi/GBM [4, 6, 7, 8] sparked considerable interest in a possibility that such counterparts might be real, despite any prior expectations. Implications of the INTEGRAL upper limits on the Fermi/GBM observations remain uncertain, owing to challenges in characterizing and comparing such a low-significance event between two instruments with only partially overlapping energy ranges.

The capacity of INTEGRAL to detect gamma-ray counterparts of the GW sources was highlighted by the detection of the first GRB associated with a GW burst, GRB170817A Fig. 3. Owing to its superior sensitivity and nearly uninterrupted observations, INTEGRAL was essentially guaranteed to observe it, while even Fermi/GBM, although being more sensitive than SPI-ACS to softer events, almost missed it due to the SAA passage (contributing to its 50% duty cycle).

First detection of GRB-GW source exceeded all but most optimistic expectations: it was thought that most of the short GRBs occur relatively large distances, well outside LIGO/Virgo reach. Instead, GRB170817A was a very nearby, very sub-luminous event. It did not quite fit in the basic GRB framework, and required extensions involving low-power wide-angle outflow, such as part of the structured jet, a cocoon inflated by propagation of a "normal" ultra-relativistic GRB jet [9, 10, 11], or even delayed activity of a long-living remnant of the merger - likely a young magnetar [12, 13, 14].



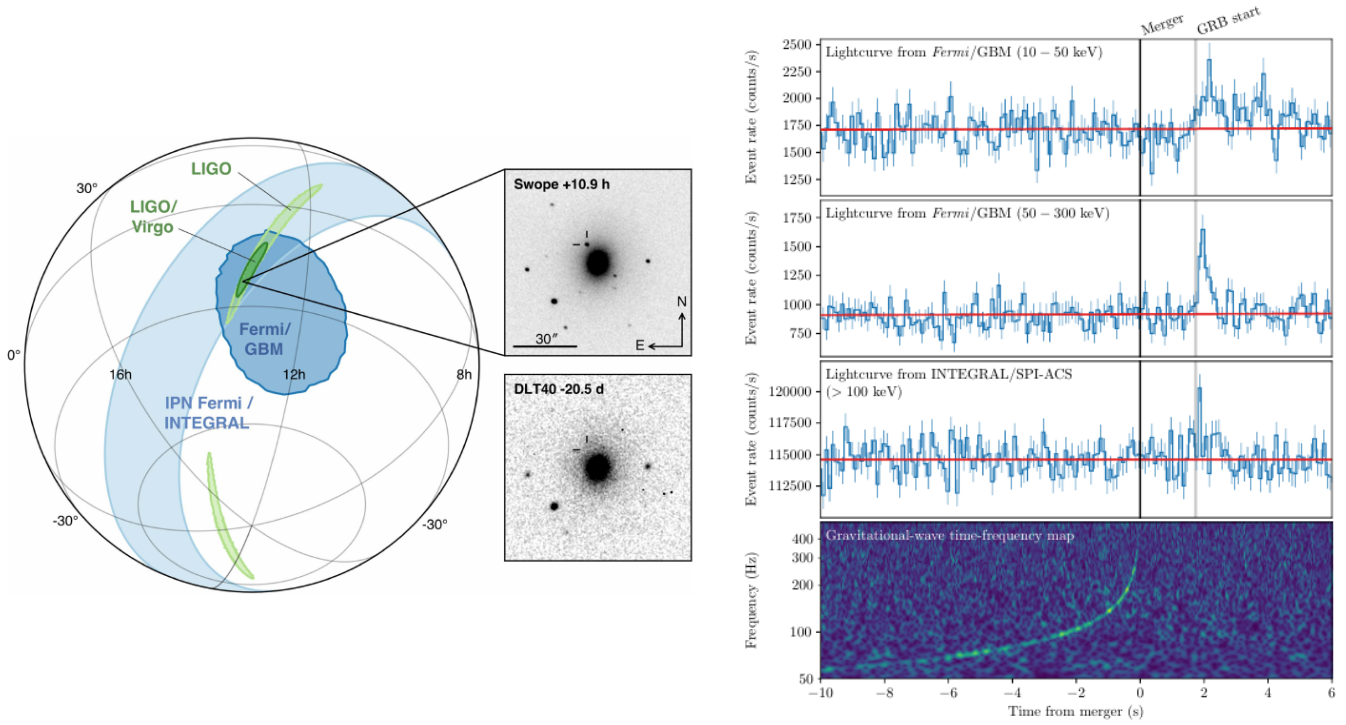
**Figure 2:** INTEGRAL upper limits on gamma-ray counterpart of several BBH mergers found by LIGO in real-time during O1 and O2 [2, 3, 4, 5].

#### 4. INTEGRAL detection of Hard X-ray component in AT2018cow

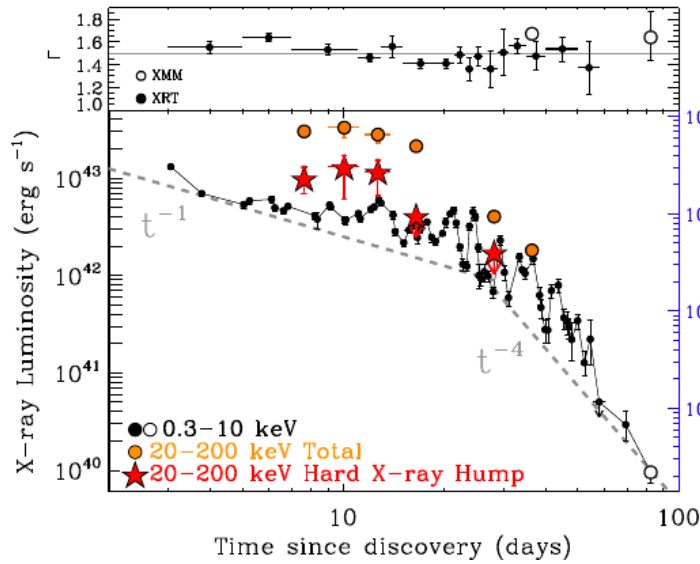
Although the pivotal role of INTEGRAL in observations of short impulsive gamma-ray transients has been firmly established, the searches of slowly decaying weak hard X-ray sources with its pointed coded mask instrument were always seen more in an explorative perspective. Until recently, no stellar-scale object has been detected from distances at which any GRB or GW sources are found. This has changed last year, when a coordinated real-time effort enabled the detection of AT2018cow, likely an exceptionally fast and luminous supernovae at 60 Mpc [18, 19, 21, 20, 22].

#### 5. Conclusions

Recent progress highlighted role of hard X-ray and soft gamma-ray emission in revealing inner workings of the relativistic sources of multi-messenger signals. More fruitful observations



**Figure 3:** INTEGRAL and Fermi observation of GRB170817A, coincident with GW170817 [15, 16, 17]



**Figure 4:** INTEGRAL, Swift, and NuSTAR observations of AT2018cow [18, 19, 20].

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are being collected as multi-wavelength and multi-messenger observations are reaching new and puzzling kinds of sources. INTEGRAL features sufficient sensitivity to remain on the forefront of these synergistic studies for the years to come.

It is remarkable and important to note that recent discoveries in the domain of multi-messenger transients were made possible by a global effort to achieve a new degree of automation and interoperability, in which INTEGRAL is among the frontrunners, owing to the multiple synergistic efforts and developments maintained by Department of Astronomy at University of Geneva (in particular CDCI [23, 24]) as well as ESAC <sup>1</sup>.

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