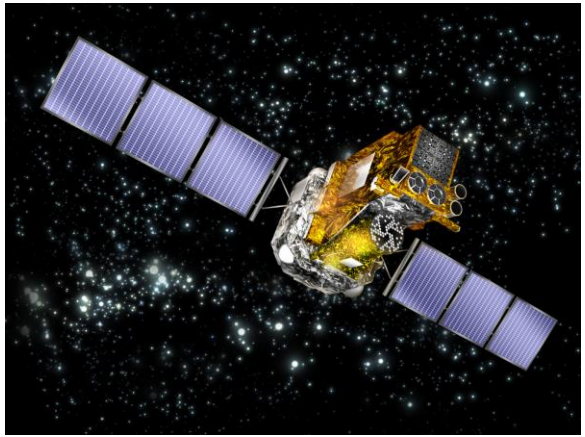
Multi-Messenger astronomy with INTEGRAL



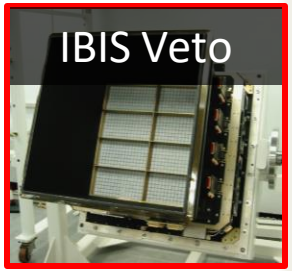
Open access to a full review paper:
https://doi.org/10.1016/j.newar.2020.101595

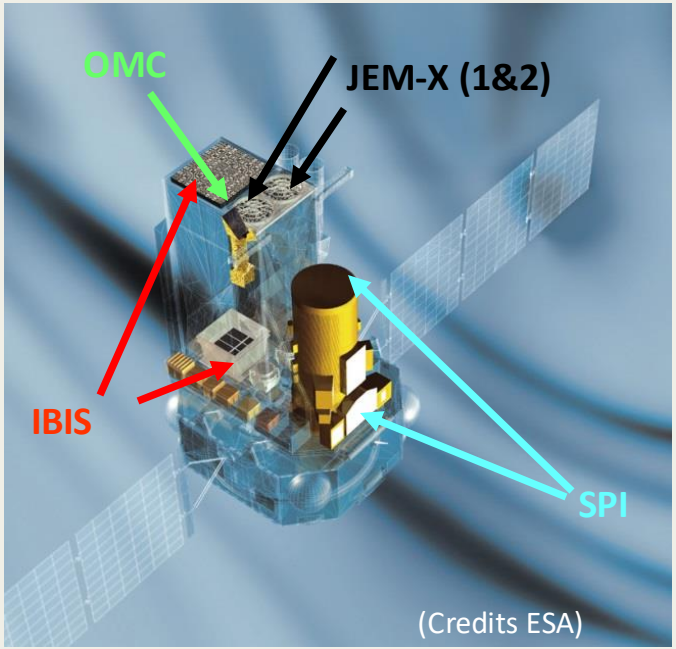
Carlo Ferrigno for the INTEGRAL multi-messenger collaboration
https://www.astro.unige.ch/cdci/integral-multimessenger-collaboration

INTEGRAL in a nutshell

Launched in 2002, it carries 4 co-aligned instruments: 3keV – 8 MeV plus V optical

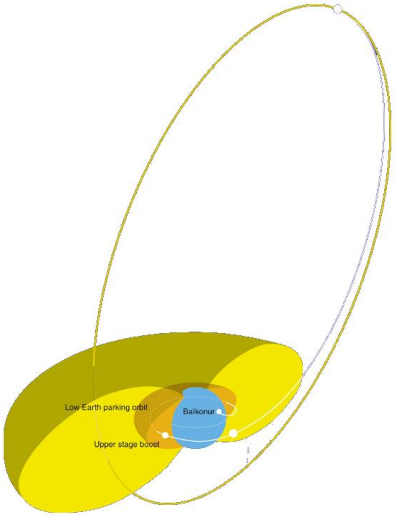
Pointed instruments are complemented by active shields in searching for serendipitous gamma-ray flashes.



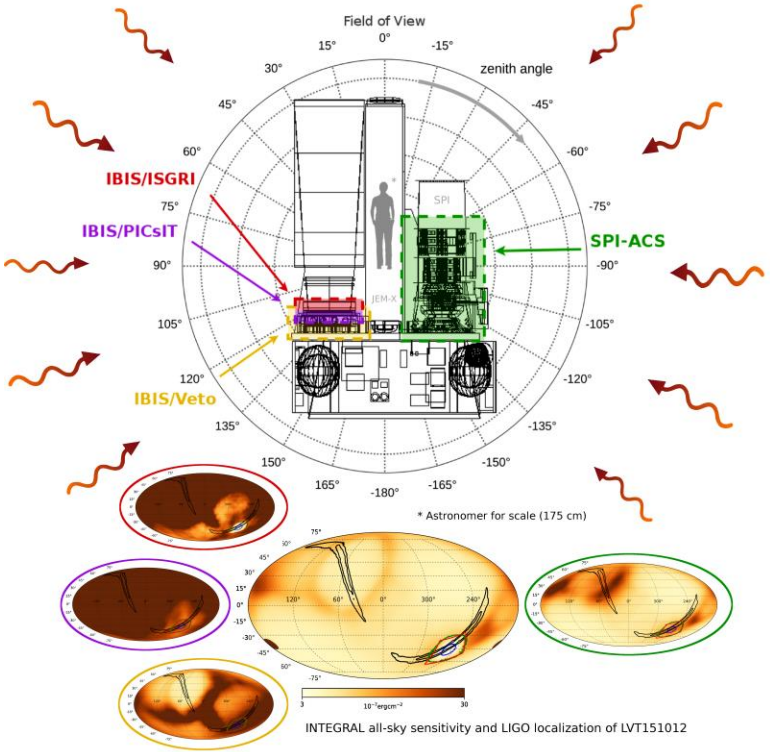


SPI Anti-Coincidence System

An efficient full-sky monitor

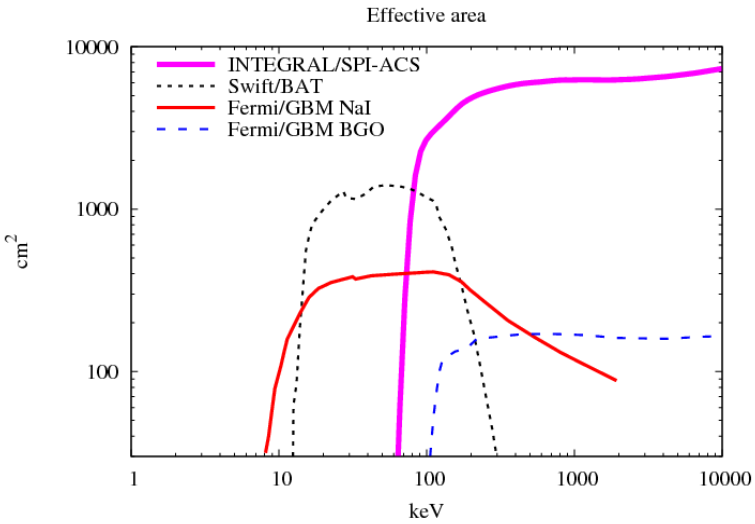


- Uninterrupted, unocculted, omni-directional response for 85% of the 2.7-days orbit
- Combining the off-axis response of all detectors, it is possible to enhance sensitivity
- 30x30 degrees field of view with higher sensitivity.



Adapted from Savchenko et al. 2017

An efficient full-sky monitor

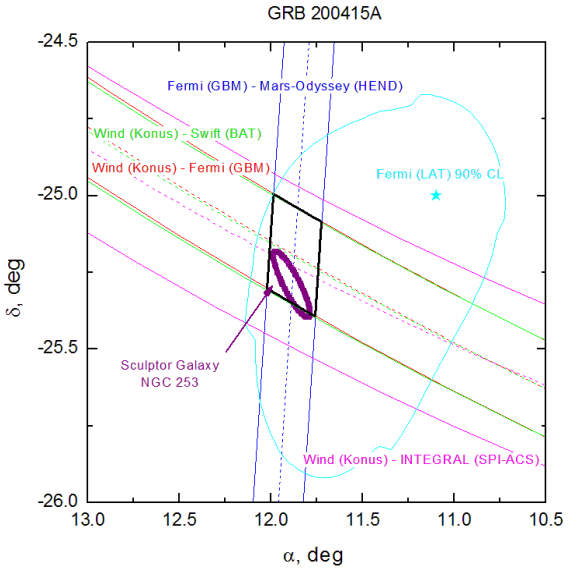


- The SPI-ACS has large effective area, and sensitivity on the most of the sky, but no localisation.
- It has a stable background, which is, however, a high and affected by short (~0.1 s) spikes induced by cosmic-ray hits.
- INTEGRAL is not triggering on board, but it downloads data in real time to ground.
- Since the start of mission, data stream of SPI-ACS and IBIS are scanned for gamma-ray bursts and alerts distributed (IBAS system).
- SPI-ACS: 200 GRBs per year: localisation by triangulation in InterPlanetary Network (IPN)
- 6-10 GRBs/year detected and localised (3') by IBIS

Interplanery network (IPN)

- IPN uses spacecraft in both Earth-orbit and elsewhere in the solar system to establish the locations of gamma-ray bursts and magnetar flares through triangulation.
- GRB 200415A was localised in the nearby Sculptor galaxy at 3.5 Mpc and classified as a giant magnetar flare with $L=10^{46}$ erg/s

- Kevin Hurley (1942-2021) pioneered the whole multi-mission localizations with IPN also, and worked on improving various gamma-ray instruments for multi-instrument use.
- He pushed to have the 50 ms counter on SPI-ACS to be used for triangulation.

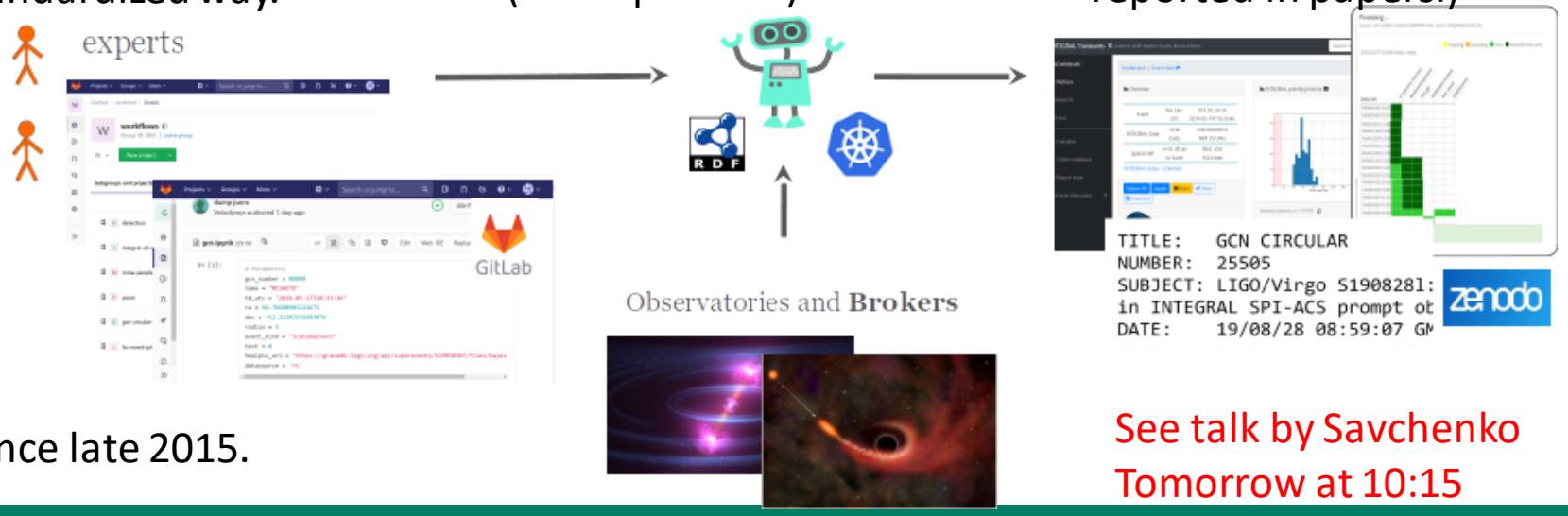


Architecture of our transient analysis

Experts can develop test, and integrate the scientific workflows in a reproducible and standardized way.

We developed a fully automated triggered analysis to react to neutrino, gravitational waves, and (when possible) FRB.

Distribute standard results in Data Papers/Publications. Use these as base for further robust knowledge (to be reported in papers.)



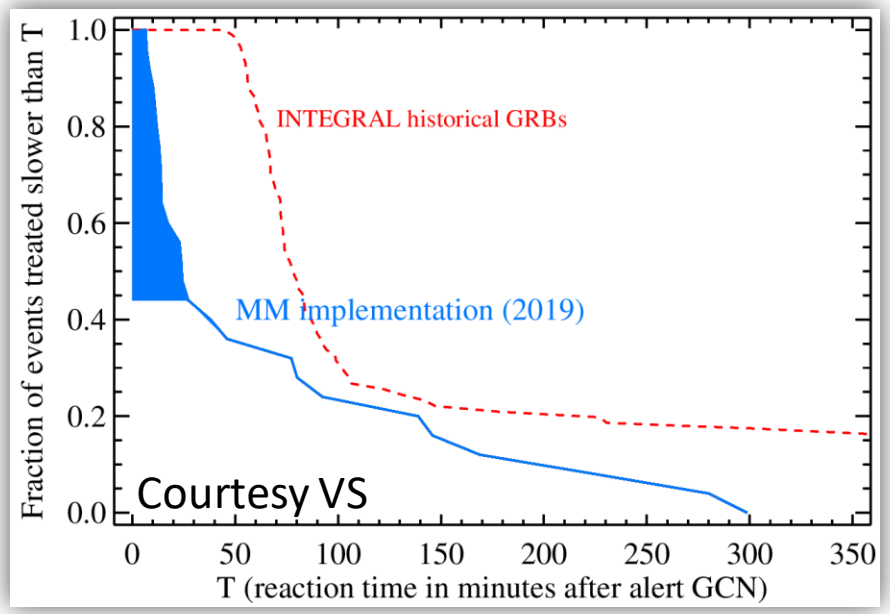
Since late 2015.

See talk by Savchenko
Tomorrow at 10:15

Expecting the unexpected

The INTEGRAL Multi-Messenger team and on-line computing interface

- Since 2011 – we scanned offline for known events in near real time, and since 2018 - scanned for known events in real time (within 20s)
- Fast-responding infrastructure with built-in intelligence: development 2017-2019
- Shared effort among the instrument teams
- Round the clock scientists on shift
- Results ready in one click: fully automatized data analysis and circulars to GW, neutrino, or any other alerts (LSST, SKA, ...)

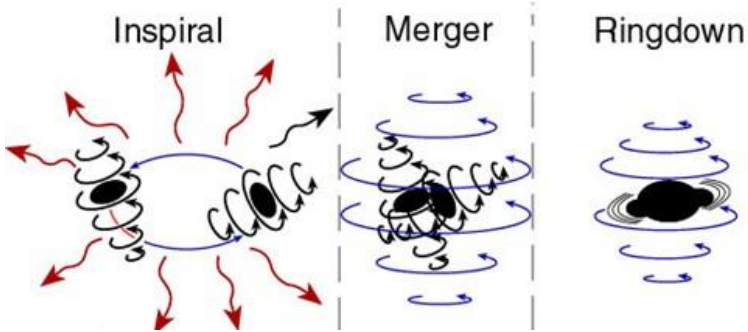


☛ **For 60% of MM events 3x faster response compared to historical GRBs**

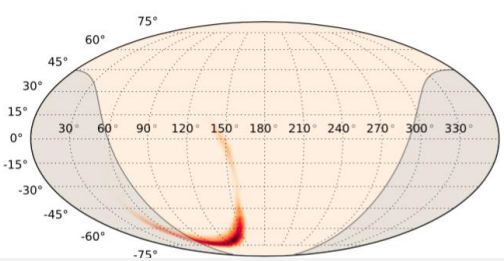
Upper limits on BH-BH mergers

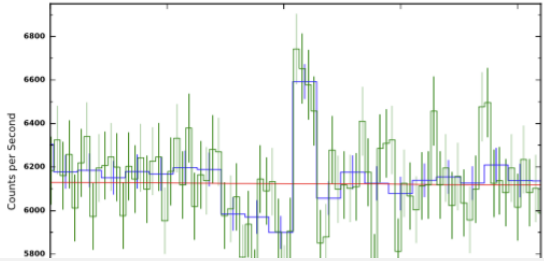
- 61 upper limits with fluence from 1.3e-07 and 5.3e-07 erg/cm^2
- 11 times INTEGRAL was inactive at the time of the event (15%)
- 2 pointed follow-up

- Our results on LIGO/Virgo O1 O2, and O3 are consistent with the expectation that no matter in involved in the merging on black-holes and, therefore, not electromagnetic emission is possible.

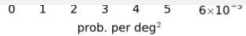


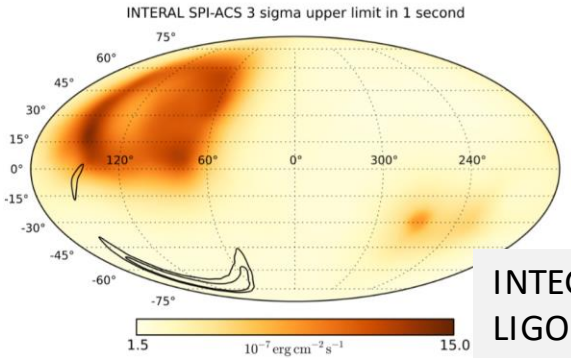
GW 150914: the first of many upper limits on BH-BH mergers

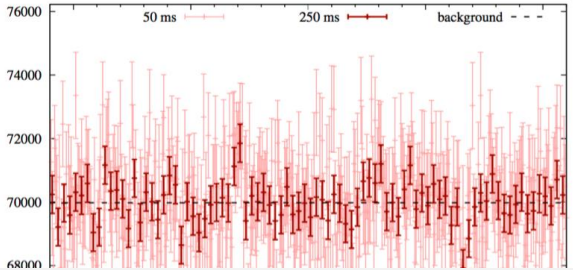




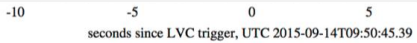
Fermi-GBM 75% of LIGO localisation (Connaughton et al, 2016, 2018)





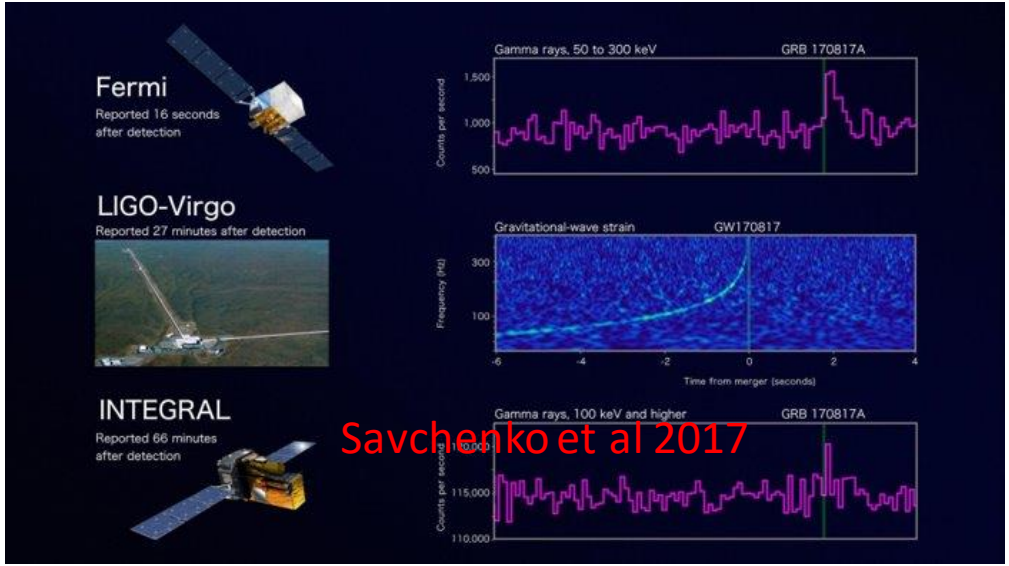


INTEGRAL SPI-ACS 100% of LIGO localisation (Savchenko et al. 2016)

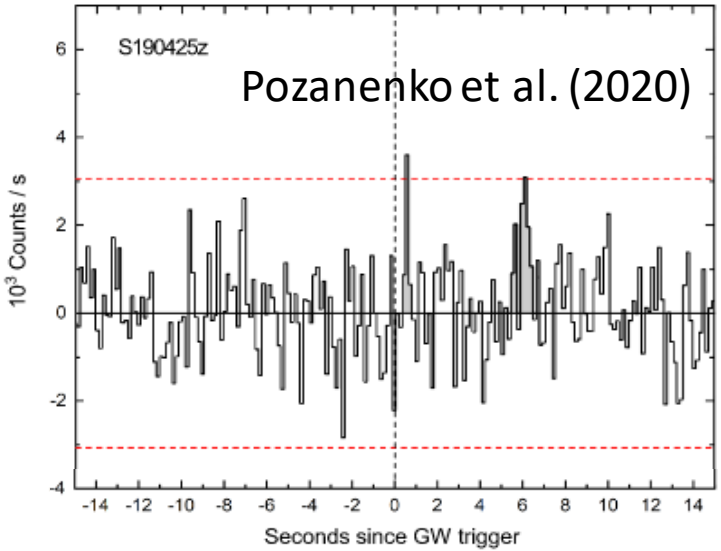


- GW150914 was due to the merging of two 30 solar masses Black Holes, localised within 620 deg^2 at 90% c.l.
- Fermi-GBM reported a marginal excess 0.4s after the merging (0.22% FAP)
- INTEGRAL set upper limits on EM emission to be <10^{-6} the GW energy for a limiting fluence of 10^{-7} erg/cm^2
- Only a corner of parameter space allows the GBM excess to be compatible with INTEGRAL data.

Binary neutron star mergers



On 17 August 2017, INTEGRAL and Fermi-GBM detected a short faint gamma-ray burst following the merging of two neutron stars.
It was an off-axis GRB and constrained alternative theories of gravity as well as Lorentz invariance.

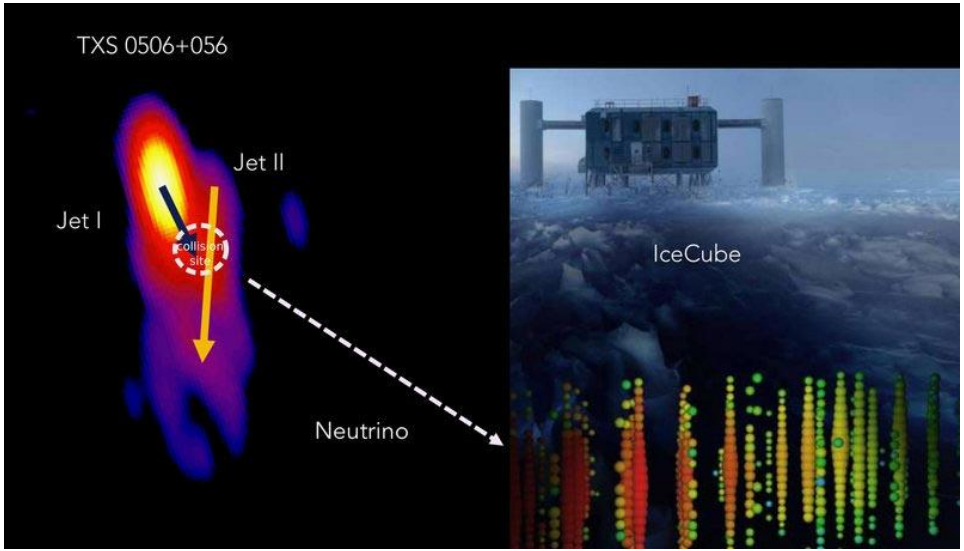


On 25 April 2019, gravitational waves were detected from the merging of two objects, whose total mass exceeded 3.3 Suns. The only, speculative, counterpart was reported by INTEGRAL.

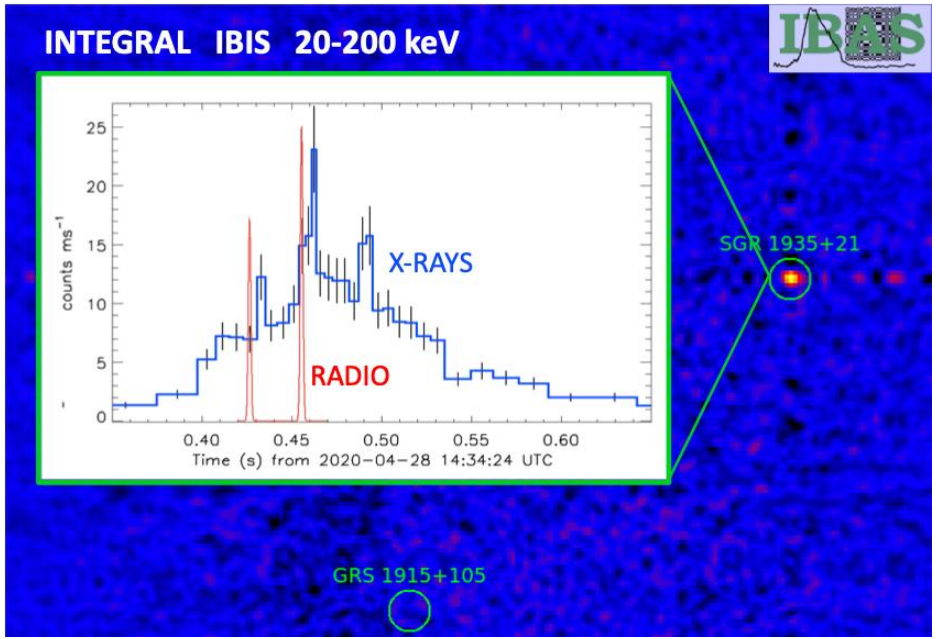
ICECUBE and ANTARES neutrino serendipitous observations

- 52 upper limits with fluence from 1.8e-07 and 5.2e-07 erg/cm^2
- 5 times INTEGRAL was reported to be inactive at the time of the event (8%)
- 2 pointed follow-up without notable source behaviors

- INTEGRAL provided spectral contraints on the blazar TXS 0506+056 candidate source of a high-energy neutrino detected by IceCube in 2017

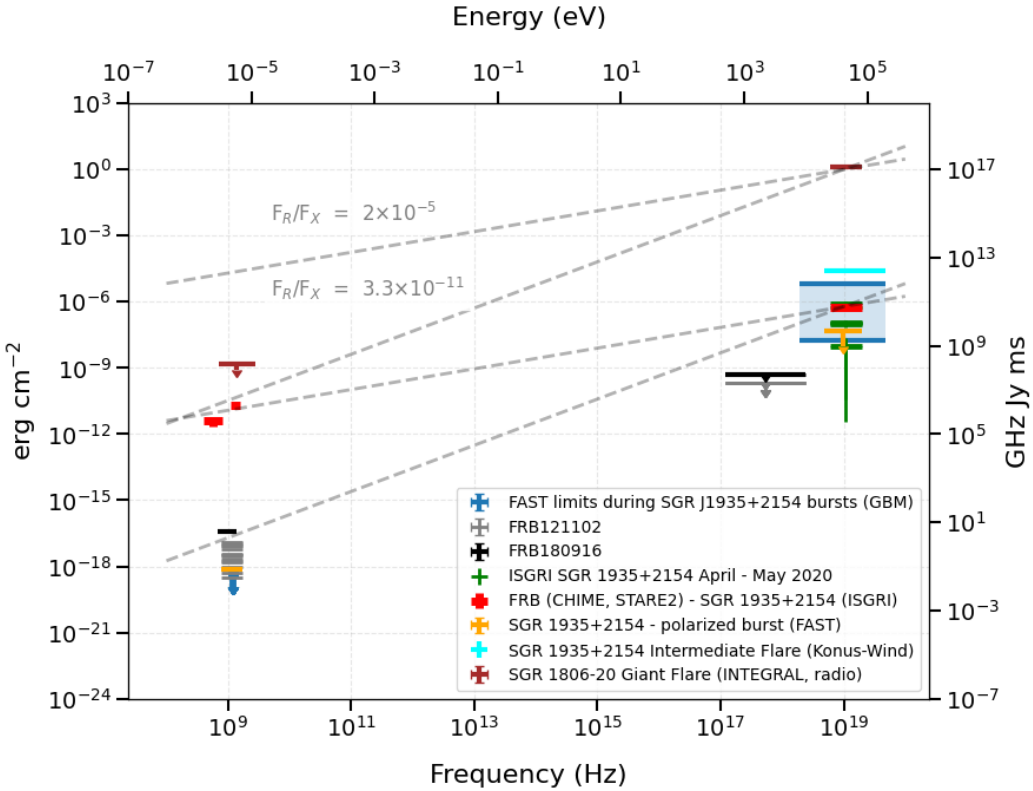


A magnetar flare produced a galactic Fast Radio Burst



- On 28 April 2020, INTEGRAL detected a hard X-ray magnetar flare that was in the field of the IBIS detector,
- A low-latency automatic alert was sent **5.5 s after the event**. We were the first to associate the FRB and the X-ray flare in the morning of 29 April.
- CHIME and STARE2 radiotelescopes detected a double peaked fast radio burst
- Direction and timing show that both X-rays and radio waves come from the magnetar SGR 1935+21.
- It is the first time that a Galactic Fast Radio Burst is observed.

A rare phenomenon



- The ratio of radio to X flux is from 2e-5 of the detection to 1e-11 of several upper limits.
- It is necessary to continue exploring the parameter space with the new wealth of FRB detectors to understand when and why emission is panchromatic.

Conclusions

- INTEGRAL detected the first GRB coincident with a neutron star merger using SPI-ACS on 17 August 2017. Owing to the coincident detection with Fermi-GBM and LIGO/Virgo, and the subsequent kilonova, the era of multi-messenger astronomy was opened.
- Upper limits on the hard X-ray emission of 85% of gravitational waves and neutrino events were consistently produced over the first three LIGO-Virgo observing runs.
- A Magnetar flare was detected in temporal and spatial coincidence with a Fast Radio Burst confirming the hypothesis of magnetars being at the origin of (at least some) FRBs.
- INTEGRAL will operate *at least* until March 2023 and it might cover part of O4 from LIGO/Virgo. Further extension of INTEGRAL is asked to ESA.
- *Open access to the full review paper: https://doi.org/10.1016/j.newar.2020.101595*