INTEGRAL observations of gravitational wave events

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On behalf of the INTEGRAL Multi Messenger Collaboration

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2002 - **, operations currently approved until December 2022

2.7 days orbit with 85% useful observing time above radiation belts

Only very small fraction of sky occulted by Earth

All data transmitted to ground in real time and analysed for GRB within a few seconds
3 - 8000 keV pointing field of view (from 3x3deg at 3-30 keV to 30x30deg above 25 keV)

sub-arcmin imaging, good spectral resolution

> 100 keV all-sky
almost no imaging or spectral resolution
Challenges of all-sky detection with INTEGRAL SPI-ACS

- Exceptional GRB detection capability
- Poor localization and spectral characterization
- We do not usually send GCN circulars with SPI-ACS detections
- We **opted for interoperability**, joining observations with other missions, e.g. by **IPN triangulation**.
- Full public data available through an **online analysis, APIs**.
## 10 BBH + 1 BNS in LIGO/Virgo O1 & O2

<table>
<thead>
<tr>
<th>Date</th>
<th>Event Type</th>
<th>$E_{GW}$ (Mo)</th>
<th>D (Mpc)</th>
<th>Upper Limit 75-2000 1 sec</th>
<th>$E_{1keV-10MeV} / E_{GW}$</th>
<th>Notes</th>
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<tbody>
<tr>
<td>150914</td>
<td>BBH</td>
<td>3.1</td>
<td>430</td>
<td>&lt; 1.3 $10^{-7}$</td>
<td>&lt; 7 $10^{-7}$ (best limit)</td>
<td>GBM burst not seen in SPI/ACS Pointed follow-up</td>
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<td>151012</td>
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<td>1.5</td>
<td>1060</td>
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<td>&lt; 9 $10^{-6}$</td>
<td>Announced 6 months later</td>
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<td>151226</td>
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<td>440</td>
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<td>&lt; 2 $10^{-7}$</td>
<td>&lt; 8 $10^{-6}$</td>
<td>AGILE/MCAL event not seen in SPI/ACS</td>
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<td>170608</td>
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<td>170809</td>
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<td>170814</td>
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<td>170817</td>
<td>BNS</td>
<td>0.025</td>
<td>40</td>
<td>1.4 $10^{-7}$</td>
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<td>Burst detected Pointed follow-up 6d long</td>
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<td>170823</td>
<td>BBH</td>
<td>3.3</td>
<td>1850</td>
<td></td>
<td></td>
<td>Perigee</td>
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</table>
GW 170817

BNS at 42Mpc

INTEGRAL short GRB was 2 s after the GW and lasted 0.1 s

S/N = 4.7

Association significance with GW is 3.2σ and 4.2σ with the Fermi-GBM GRB

Fluence (1.4 ± 0.4 ± 0.6) × 10-7 erg cm-2 (75-2000 keV)

LVC, Fermi, INTEGRAL 2017; Goldstein+ 2017; VS+ 2017
Targeted search of excesses in INTEGRAL detector light curves

Automatic reception of alerts triggers an automatic pipeline that:
1. bins the lightcurve at different time scales;
2. computes (running) mean and variance;
3. searches in a +/- 300s range time bins with signal in excess of a certain S/N (e.g., 3) [and computes likelihood to be a cosmic ray interaction].
4. counts how many similar excesses happen in the light curve extending the time range to days
5. computes the False Alarm Probability as function of Delta T0 and S/N [plus CR likelihood].
6. Correct for number of trials.
Pedagogical example

- close to T0, it is unlikely to find events with high S/N, extending the range, it is more likely to find such an event
- FAP decreases dramatically for a higher S/N event
### 19 BBH + 3 BNS + 2 BHNS in O3 so far...

<table>
<thead>
<tr>
<th>Event</th>
<th>Type</th>
<th>Distance (Mpc)</th>
<th>90% Error Region</th>
<th>Energy (erg/cm²) 75-2000 1 sec</th>
<th>Gamma E</th>
<th>Follow-up Notes</th>
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<tr>
<td>S190408an</td>
<td>?</td>
<td>387</td>
<td>1473</td>
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<td>S190412m</td>
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<td>BNS</td>
<td>7461</td>
<td>156</td>
<td>&lt; 4.0 10e-7</td>
<td>&lt; 1 10e48</td>
<td>Excess has S/N 3.7 on a 1 s timescale and happened 6 s after the GW. The association significance is 1.5 sigma. <strong>Pointed follow-up</strong></td>
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<td>S190426c</td>
<td>NSBH ?</td>
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<tr>
<td>Event</td>
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<td>Distance</td>
<td>Redshift</td>
<td>1s Flux</td>
<td>100s Flux</td>
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<td>242</td>
<td>&lt;1.7e-7</td>
<td>&lt;1.2e48</td>
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</tr>
</tbody>
</table>

One marginal event (S/N 5.22, FAP 3.27 equivalent sigma) at 0.05s time scale at T0+201.01.

Unlikely associated event FAP 4%, S/N=4 at 3s scale, at T0+41s LX=1.8+/−0.4+/−0.6 10e49 erg/s

2 s scale, T-T0=17.2 s, S/N=3.7 FAP=3.4%

19 BBH + 3 BNS + 2 BHNS in O3 so far...
GW 190425z: a binary neutron star merger in LIGO-Virgo O3 at 150 Mpc


Excess has S/N 3.7 on a 1 s timescale and happened 6 s after the GW. The association significance is 1.5 sigma, making it unlikely to be correlated. Compared to GW170817, the timescale is 3 times larger, delay larger, and S/N lower.
Fermi GBM-190816: discovery and localization of subthreshold GRB-GW candidate

INTEGRAL non-detection favors the region found in the independent refinement by Fermi-GBM and LIGO-Virgo teams.

19/08/20 INTEGRAL non-detection constraint

19/08/24 Updated map
Marginal event: S/N 5.22, FAP 3.27 equivalent sigma) 0.05s time scale at T0+201.01 s
S190814bv NSBH

FAP threshold 0.1

Counts/s

Seconds since 2019-08-14T21:10:39.013334
as O3 advances, the prospects for joint detections can be revised. 
see also Hosseinzadeh et al 2019, Saleem et al 2019
Possible Hard X-ray emission from BNS mergers

Internal GRB Jet Dissipation: regular prompt GRB

Structured Jet Internal Dissipation: weak prompt GRB (Found)

External GRB Jet Dissipation: hard X-ray afterglow

Radioactive decays of heavy elements in gamma-ray lines

Metastable merger product: young magnetar, re-energising the outflow

anything else?...
SUMMARY

• INTEGRAL unique capabilities for multi-messenger prompt observations and follow-up
  – 85% duty cycle: uninterrupted 2.7-day long observations in stable background
  – Highly competitive all-sky sensitivity, down to $10^{-7}$ erg cm$^{-2}$ s$^{-1}$ (75 - 2000 keV) with complementary role of every instrument
  – Sensitivity for broad and narrow gamma-ray lines in follow-up observations

• Detection of GW170817

• In O1-O2, limits for 19 (out of 24) events (with whole error region coverage)

• Fast pipeline processing and efficient team organized for rapid reaction.

• New ideas are sought to find new events in hard X-ray, especially in early data ($T_0$ .. ).
EXTRA SLIDES
Best all-sky sensitivity by combining all instruments

Sensitivity maps (light color is best)

GW localization

Earth occultation (worst case)
GW 170817

Fermi + INTEGRAL Triangulation
GRBs in the IBIS field of view

about 6 times per year, we detect a GRB in the Imager field of view and we can provide immediate localisation at 3 arcmin plus spectra
GW 190425z: a binary neutron star merger in LIGO-Virgo O3 at 150 Mpc


Excess has S/N 3.7 on a 1 s timescale and happened 6 s after the GW. The association significance is 1.5 sigma, making it unlikely to be correlated.

Compared to GW170817, the timescale is 3 times larger, delay larger, and S/N lower. Assuming it is real, the comparison with Fermi-GBM and Konus-Wind upper limits would help to constrain the localisation within the LIGO-Virgo map.
These follow-up can constrain the presence of magnetar flares in the hours after the event.

VS+2017
GW 170817
PROMPT EMISSION
GW 150914

SPI-ACS light curve (>75 keV) around GW150914 trigger time

Savchenko+ 2016
GW 170104

Interesting event in AGILE/MCAL 0.46 s before $T_0$
(Verrecchia+ 2017)

E2 post-trial coincidence probability between $2.4\sigma$ and $2.7\sigma$

Fluence $\sim 10^{-7}$ erg/cm$^2$
(0.4-40 MeV)
GW 170104

SPI/ACS ul on possible AGILE event
(for PL spectrum with slope -2)

Only within red contours u.l. compatible with AGILE event fluence

Savchenko+ 2017b
GW 150914

SPI-ACS 3σ upper limit in 1 second

$$F_{75-2000} < (1.2 - 1.7) \times 10^{-7} \text{ erg/cm}^2 \text{ for } 95\% \text{ of error region}$$

for $$\alpha = -0.5, \ \beta = -2.5, \ E_p = 1.5 \text{ MeV}$$
Relative sensitivity as a function of zenith angle

Short hard burst

1 sec
CPL $\alpha = -0.5$  $E_p = 600$ keV

Savchenko+ 2017
Relative sensitivity as a function of zenith angle

Long burst

8 sec

$\alpha = -1 \quad \beta = -2.5 \quad E_p = 300 \text{ keV}$

Savchenko+ 2017