INTEGRAL observations of gravitational wave events

C. Ferrigno

On behalf of the INTEGRAL Multi Messenger Collaboration

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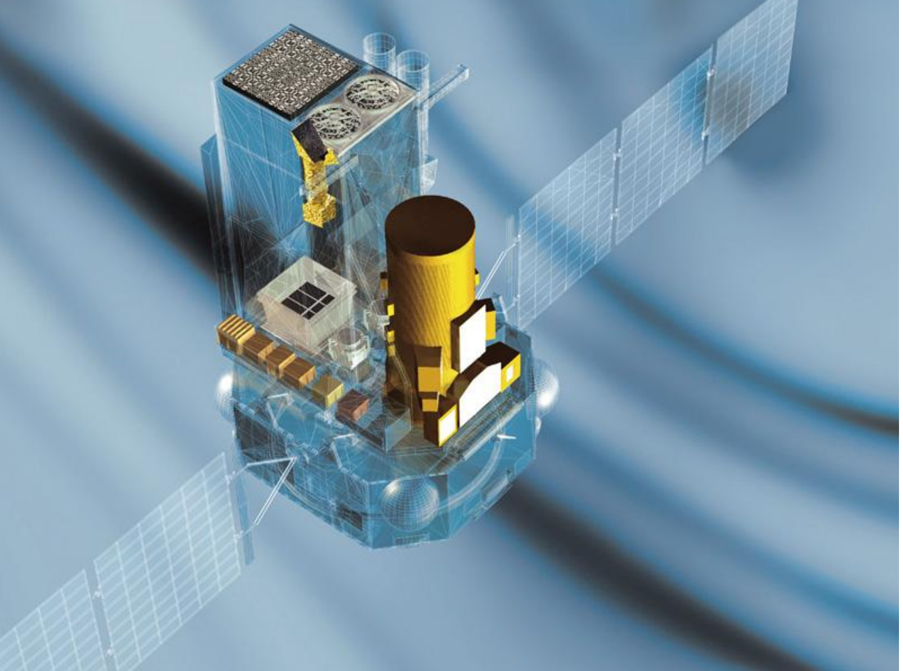
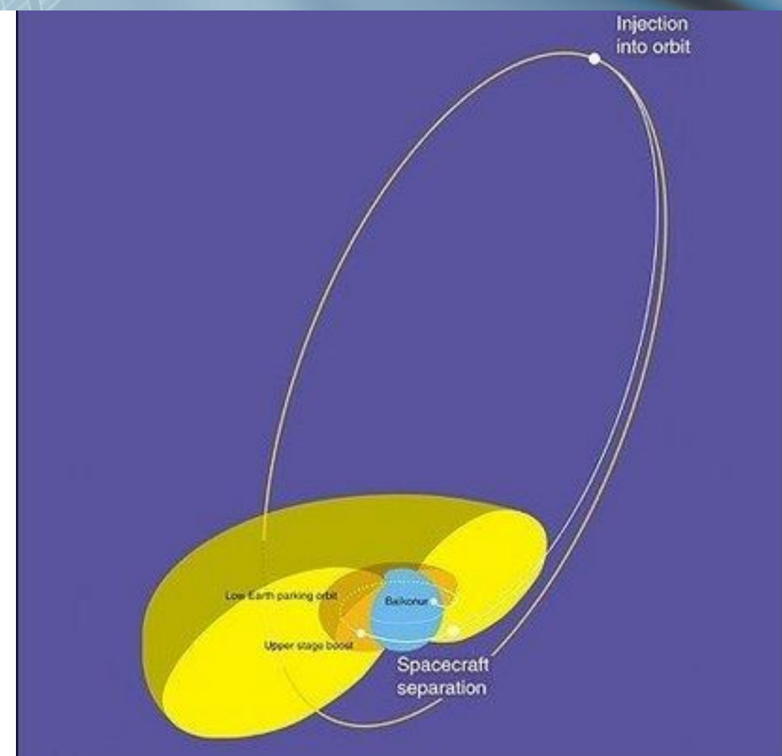




INTEGRAL

hard X-ray and soft gamma-ray observatory

2002 - **, operations currently approved until December 2022

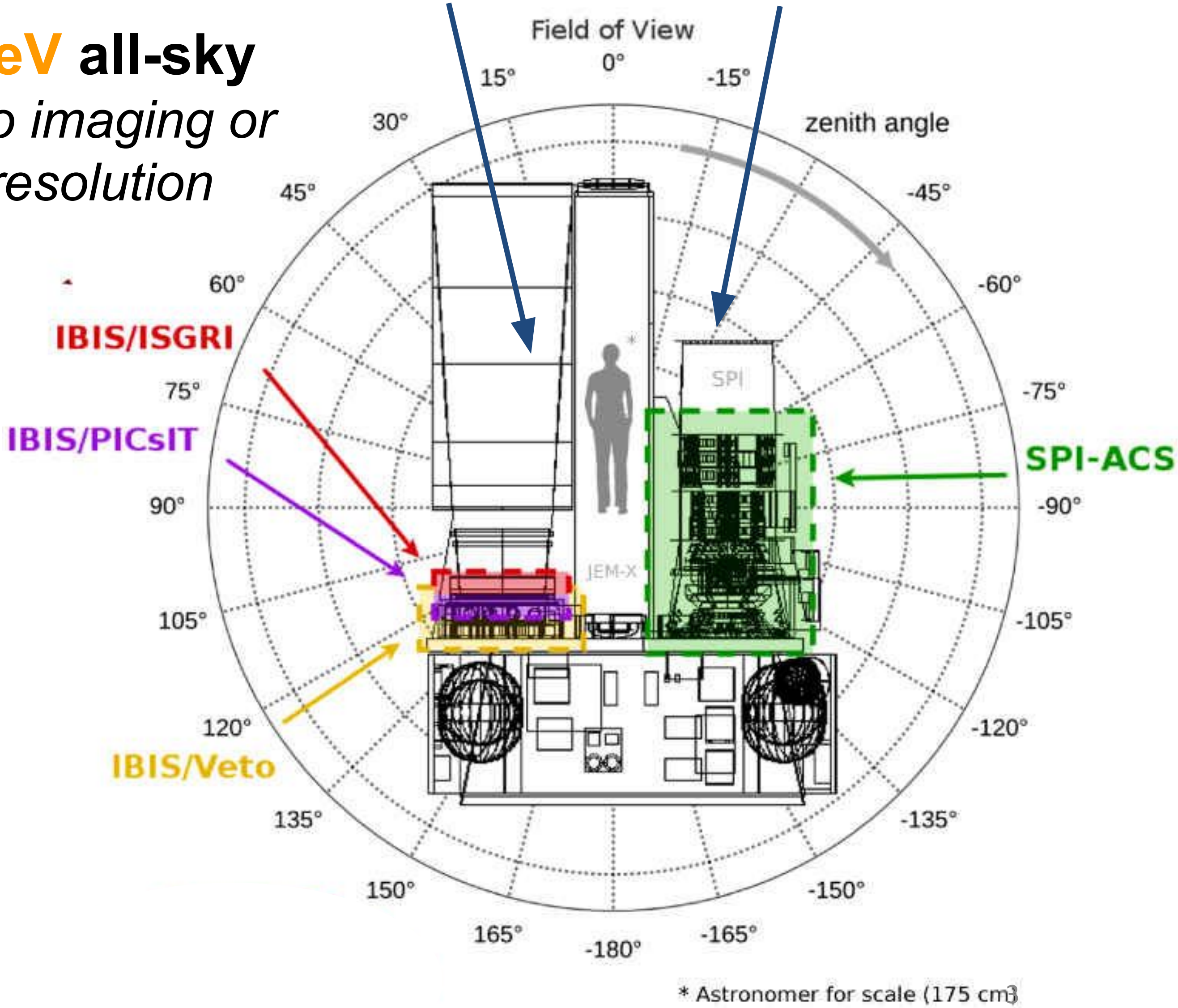
2.7 days orbit with 85% useful observing time above radiation belts

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

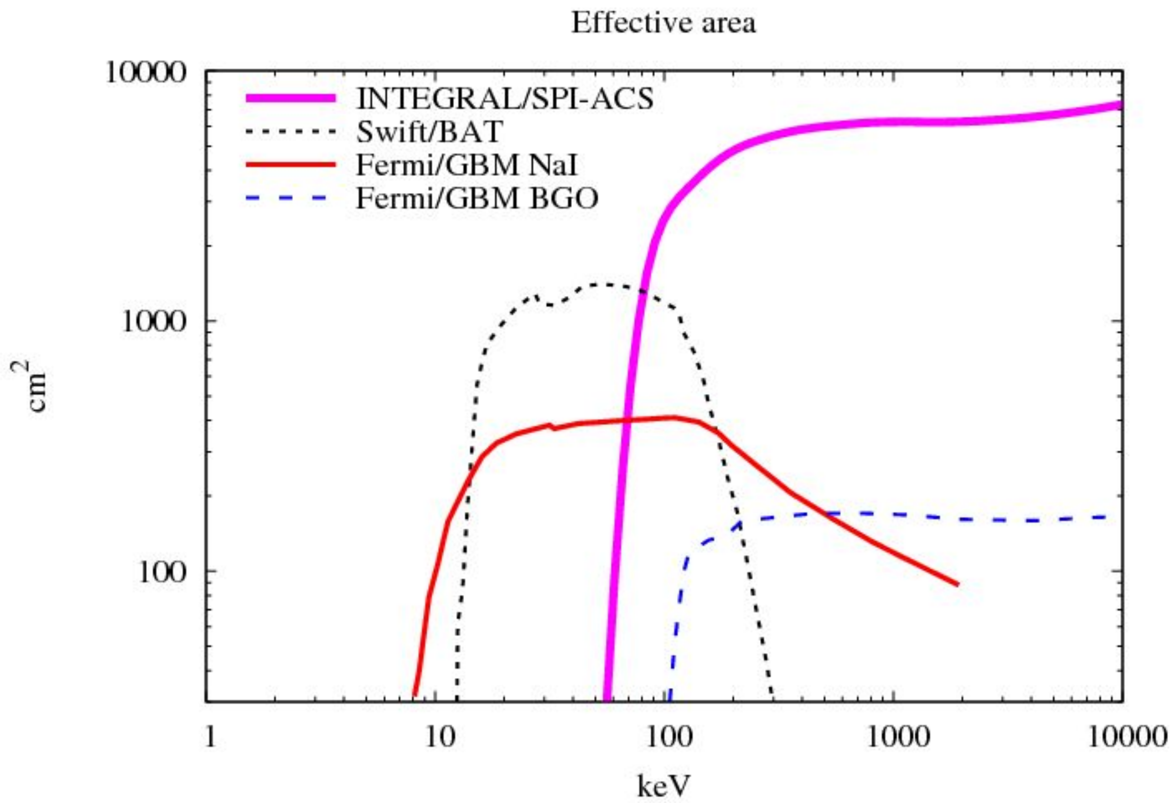
3 - 8000 keV pointing field of view (from 3x3deg at 3-30 keV to 30x30deg above 25 keV)
sub-arcmin imaging, good spectral resolution

> 100 keV all-sky
almost no imaging or spectral resolution



VS+ 2017

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

		E_{GW} (Mo)	D (Mpc)	Upp Lim 75-2000 1 sec	$E_{1keV-10MeV} / E_{GW}$	
150914	BBH	3.1	430	< 1.3 10e-7	< 7 10e-7 (best limit)	GBM burst not seen in SPI/ACS **Pointed follow-up**
151012	BBH	1.5	1060	< 1.3 10e-7	< 9 10e-6	Announced 6 months later
151226	BBH	1	440			Perigee
170104	BBH	2.2	960	< 2 10e-7	< 8 10e-6	AGILE/MCAL event not seen in SPI/ACS
170608	BBH	0.9	320	< 4.3 10e-7	< 1 10e-6	
170729	BBH	4.8	2750			
170809	BBH	2.7	990			Perigee
170814	BBH	2.7	580	< 2.1 10e-7	< 2 10e-6	Pointed follow up
170817	BNS	0.025	40	1.4 10e-7		Burst detected **Pointed follow-up 6d long**
170818	BBH	2.7	1020			
170823	BBH	3.3	1850			Perigee

GW 170817

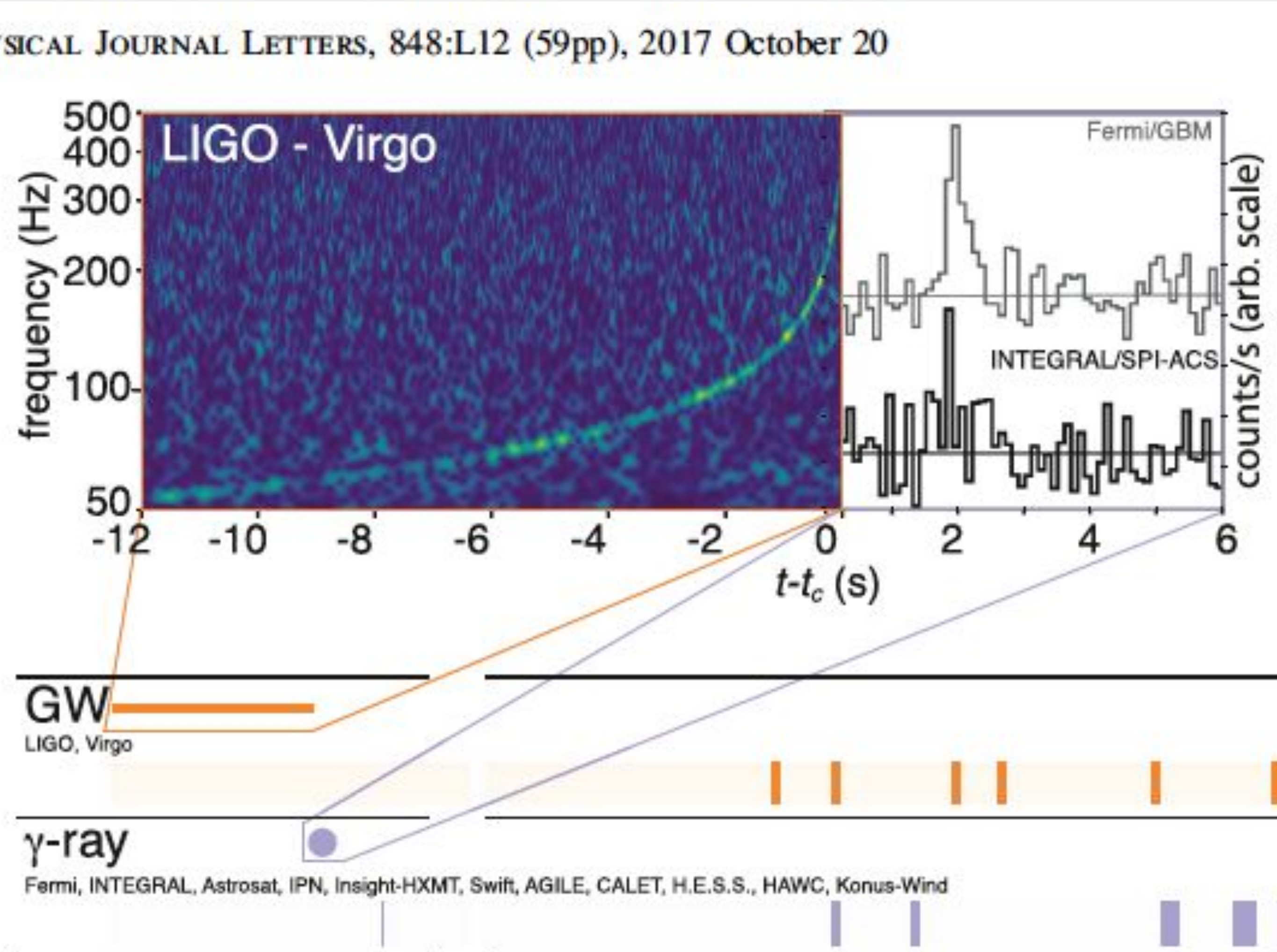
BNS at 42Mpc

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 4.2 σ 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

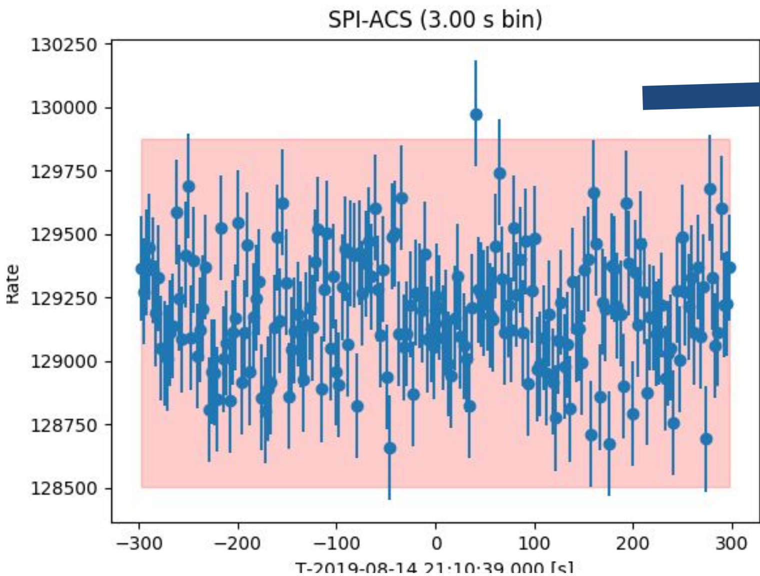
Automatic reception of alerts triggers an automatic pipeline that:

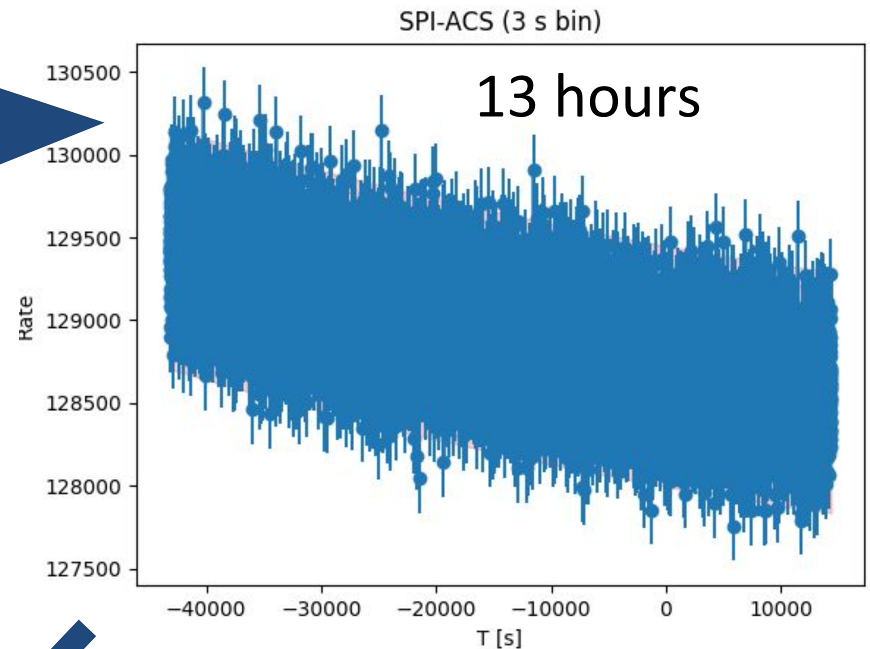
1. bins the lightcurve at different time scales;
2. computes (running) mean and variance;
3. searches in a +/- 300s range time bins with signal in excess of a certain S/N (e.g., 3) [and computes likelihood to be a cosmic ray interaction].
4. counts how many similar excesses happen in the light curve 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.

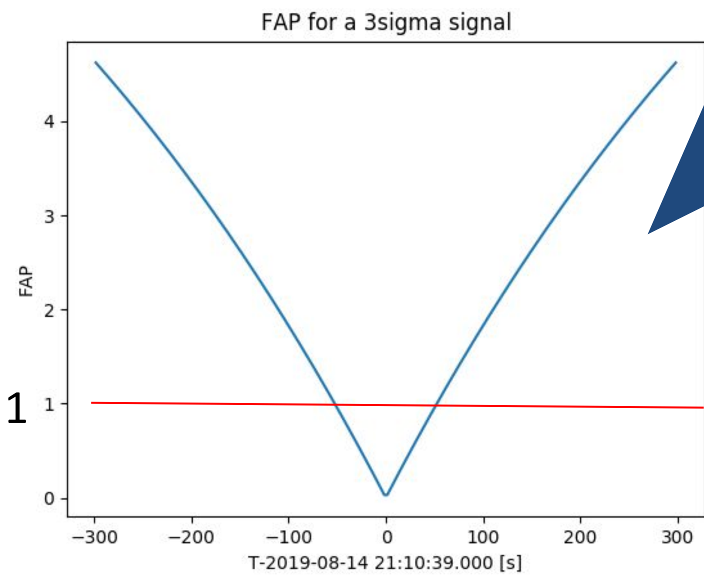
Simplified for clarity

+/- 5min

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…

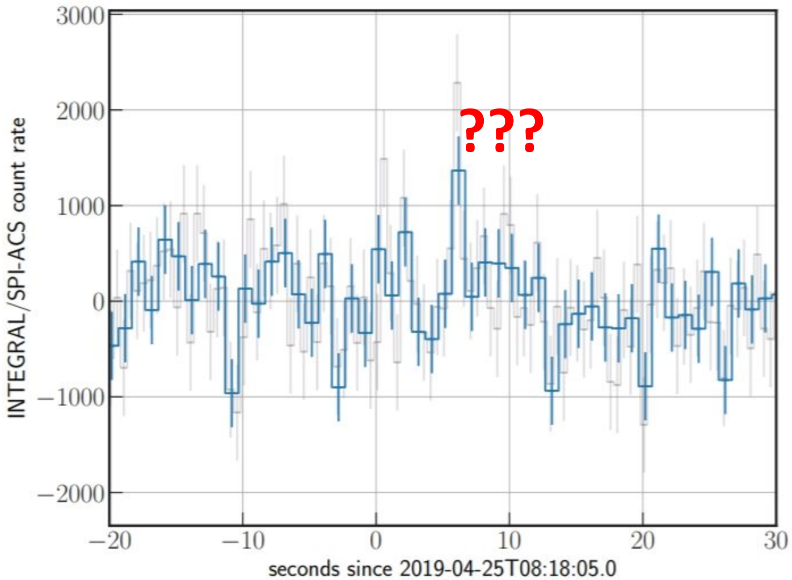
		90% error region	D Mpc	erg/cm2 75-2000 1 sec	E gamma	
S190408an	?	387	1473	< 2.5 10e-7	< 7 10e49	Pointed follow-up
S190412m	BBH	156	812	< 2.9 10e-7	< 3 10e49	
S190425z	BNS	7461	156	< 4.0 10e-7	< 1 10e48	Excess has S/N 3.7 on a 1 s timescale and happened 6 s after the GW. The association significance is 1.5 sigma. **Pointed follow-up**
S190426c	NSBH ?	1131	377	< 1.7 10e-7	< 3 10e48	Terrestrial origin ?
S190503bf	BBH	448	421	< 2.4 10e-7	< 5 10e48	
S190510g	BNS	1166	277			perigee
S190512at	BBH	252	1388			perigee
S190513bm	BBH	691	1987	< 2.6 10e-7	< 1 10e50	
S190517h	BBH	939	2950	< 2.7 10e-7	< 3 10e50	
S190519bj	BBH	967	3154	< 2.9 10e-7	< 4 10e50	
S190521g	BBH	765	3931	< 2.3 10e-7	< 5 10e50	
S190521r	BBH	488	1136	< 4.0 10e-7	< 7 10e49	
S190602aq	BBH	1172	797	< 3.8 10e-7	< 3 10e49	

19 BBH + 3 BNS + 2 BHNS in O3 so far…

		90% region	D Mpc	erg/cm2 75-2000 (1s)	E gamma	
S190630ag	BBH	8493	1059	< 1.9 10e-7	< 2.5 10e49	
S190701ah	BBH	67	1045	< 1.6 10e-7	< 2 10e49	
S190706ai	BBH	1100	5700	< 1.7 10e-7	< 7 10e50	
S190707q	BBH	1375	818	<2.6 10e-7	<2 10e49	
S190718y	terrestrial	7246	227	<2.5 10e-7	<1.5 10e48	
S190720a	BBH	1461	1061	< 1.510e-7	< 2 10e49	
S190727h	BBH	841	2022	< 1.8 10e-7	< 1 10e50	
S190728q	MassGap	543	795	< 2.6 10e-7	< 2 10e49	One marginal event (S/N 5.22, FAP 3.27 equivalent sigma) at 0.05s time scale at T0+201.01.
S190814bv	NSBH	38	276	< 3 10e-7	< 2 10e48	Unlikely associated event FAP 4%, S/N=4 at 3s scale, at T0+41s LX=1.8+/-0.4+/-0.6 10e49 erg/s
S190828j	BBH	603	2280	< 1.7 10e-7	< 1 10e50	
S190828l	BBH	948	1600	< 1.8 10e-7	< 5 10e49	
S190901ap	BNS	13613	242	<1.7 10e-7	<1.2 10e48	2 s scale, T-T0=17.2 s, S/N=3.7 FAP=3.4%

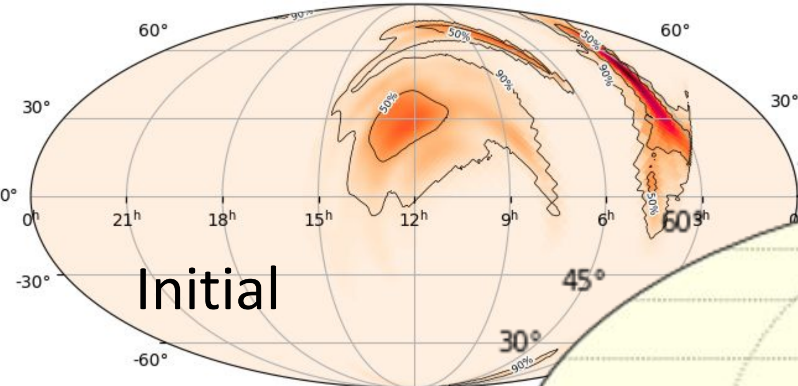
GW 190425z: a binary neutron star merger in LIGO-Virgo O3 at 150 Mpc

Martin-Carillo et al 2019, Savchenko et al 2019, Minaev et al 2019: discussed a weak, poorly associated possible counterpart in SPI-ACS

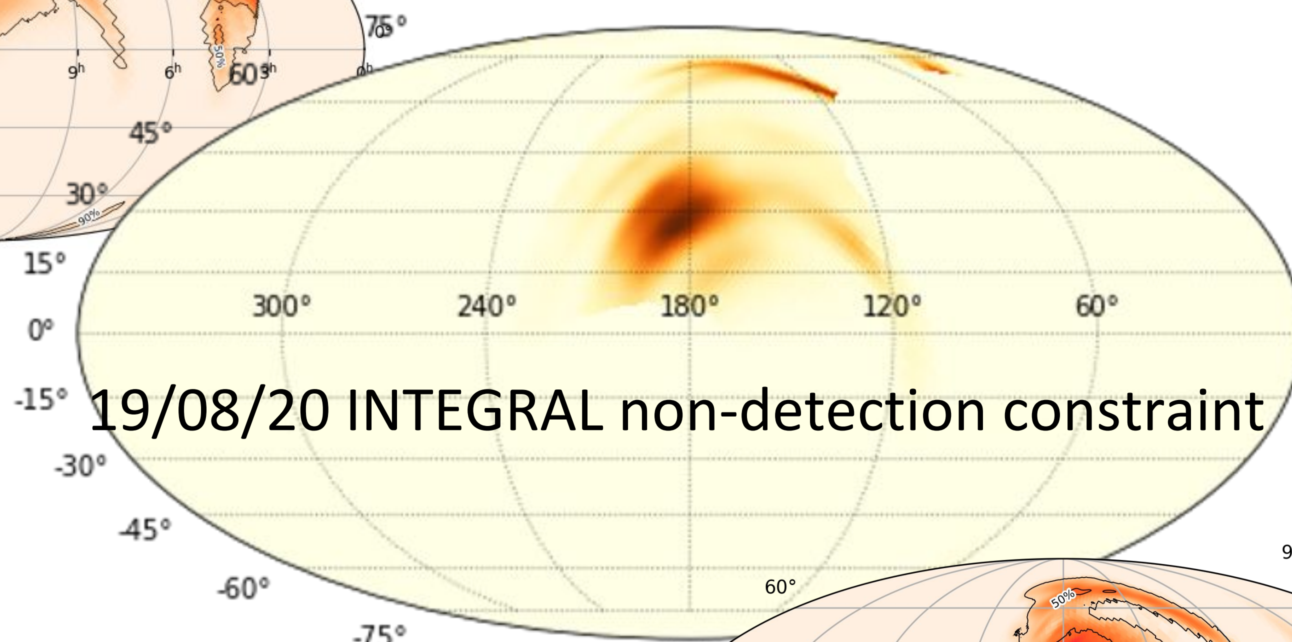


Excess has S/N 3.7 on a 1 s timescale and happened 6 s after the GW. The association significance is 1.5 sigma, making it unlikely to be correlated. Compared to GW170817, the timescale is 3 times larger, delay larger, and S/N lower.

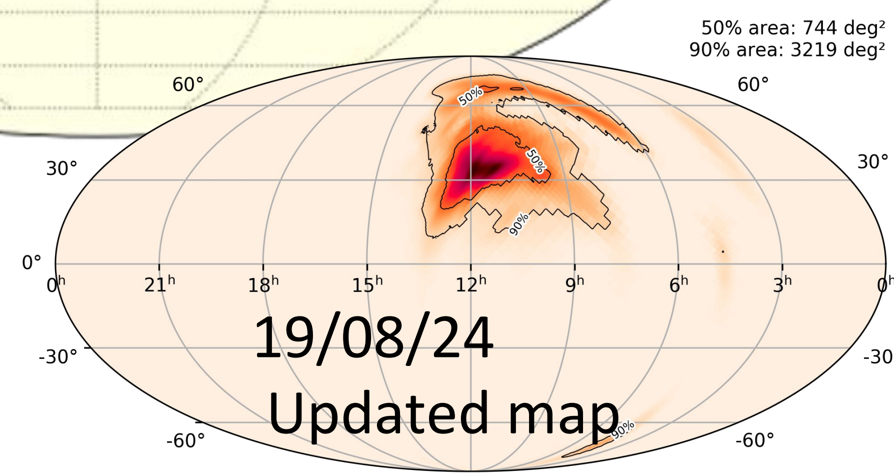
Fermi GBM-190816: discovery and localization of subthreshold GRB-GW candidate



Initial



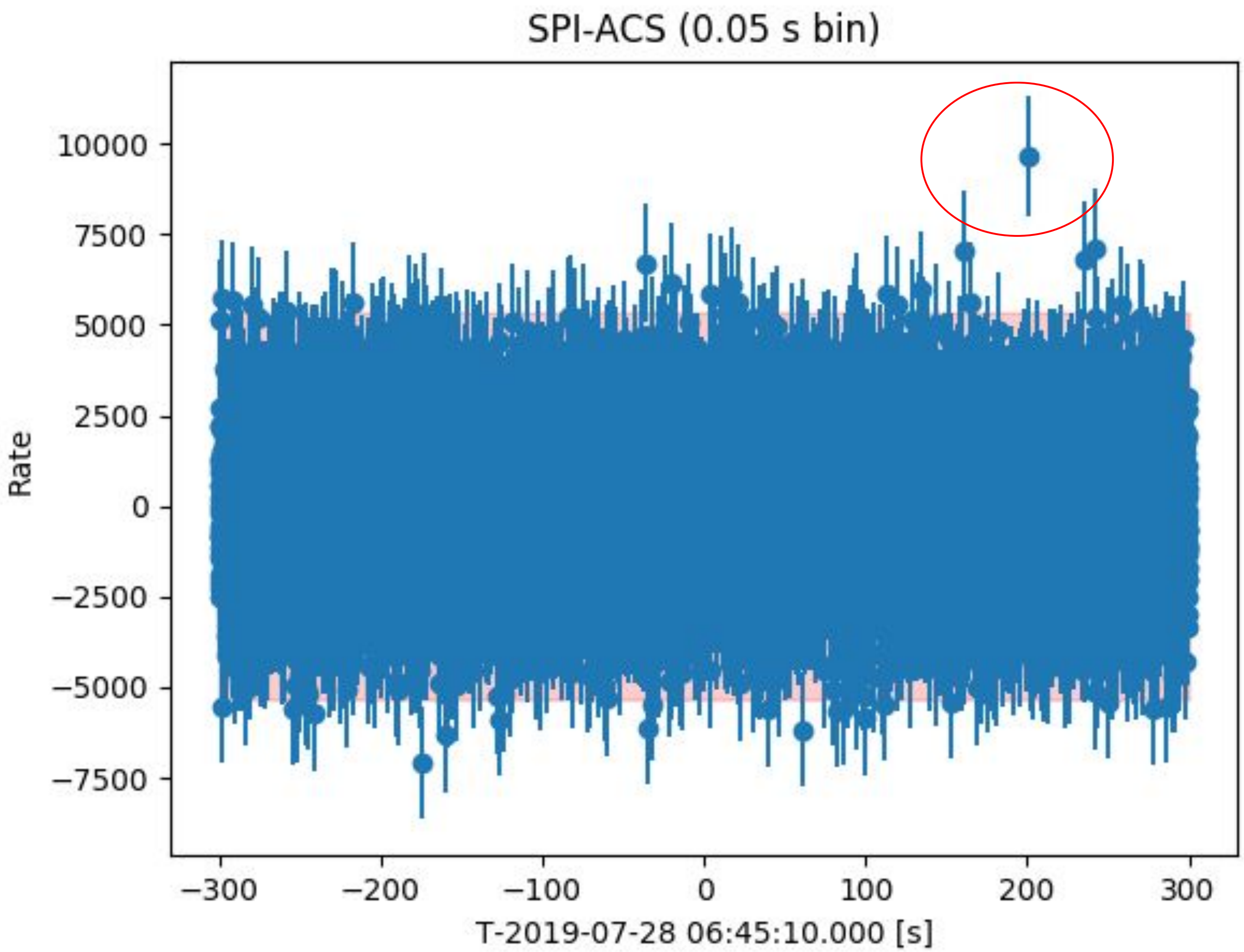
19/08/20 INTEGRAL non-detection constraint



19/08/24
Updated map

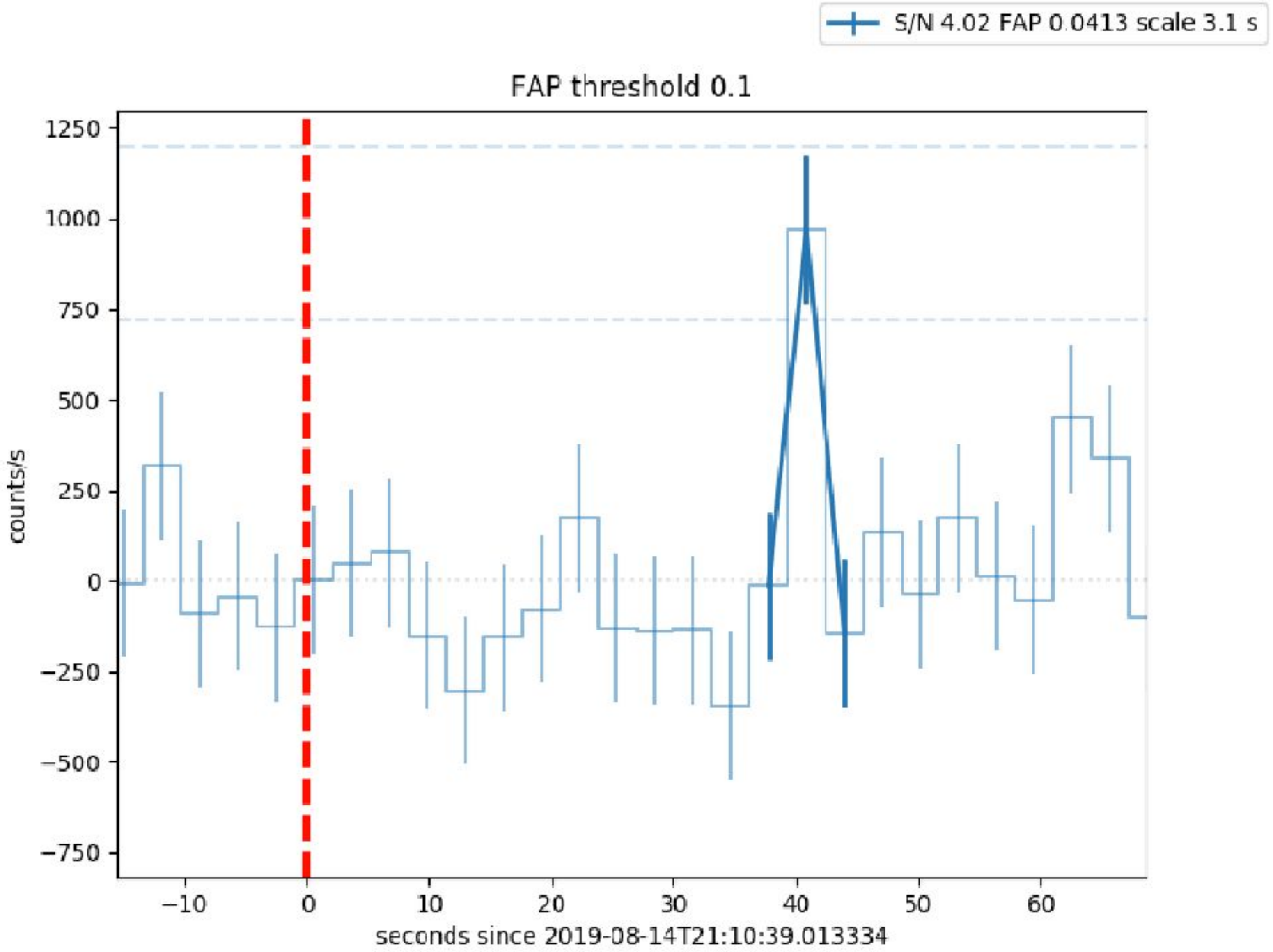
INTEGRAL non-detection favors the region found in the independent refinement by Fermi-GBM and LIGO-Virgo teams.

S190728q Mass Gap

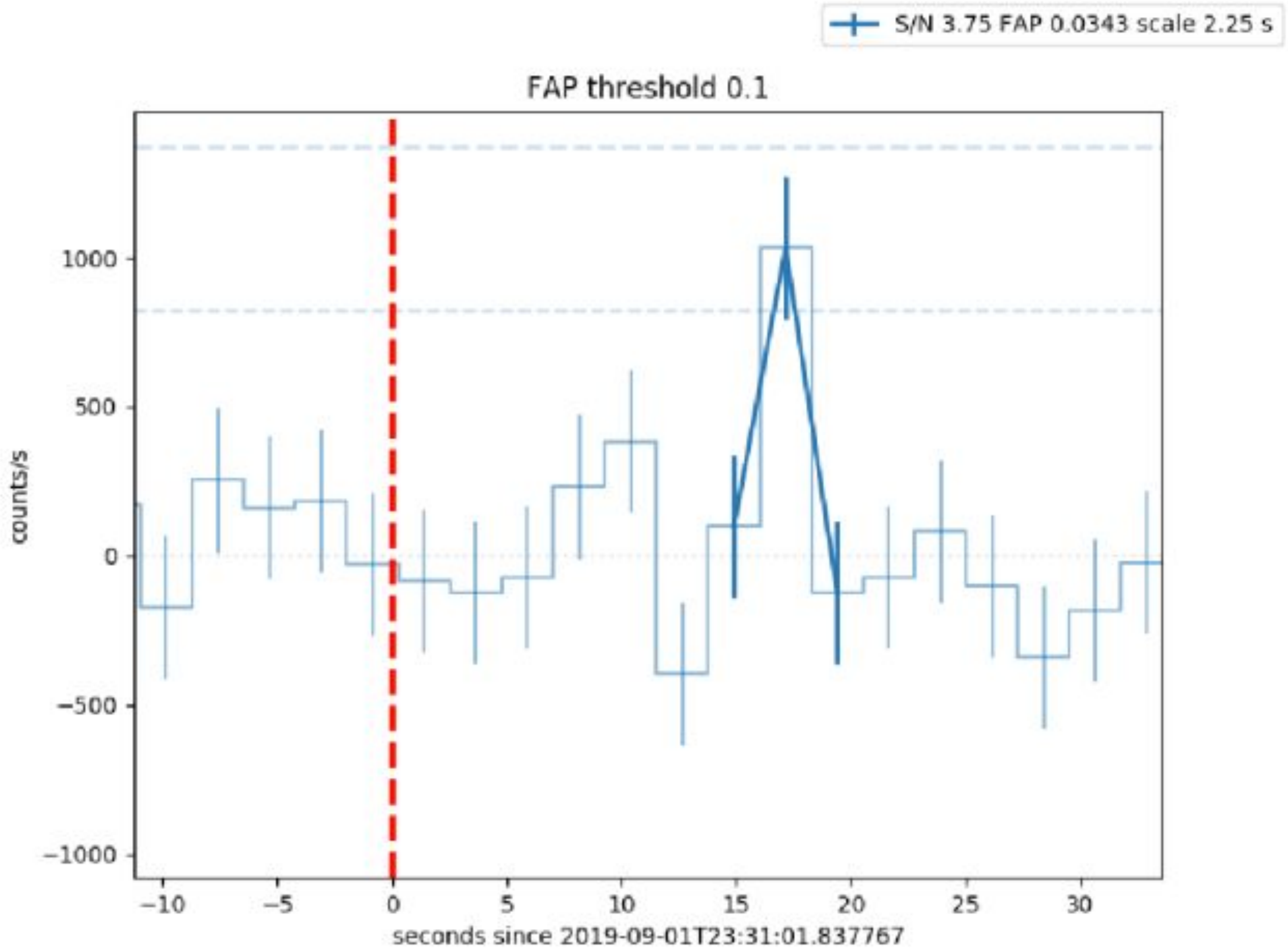


Marginal event:
S/N 5.22, FAP 3.27
equivalent sigma)
0.05s time scale at
T0+201.01 s

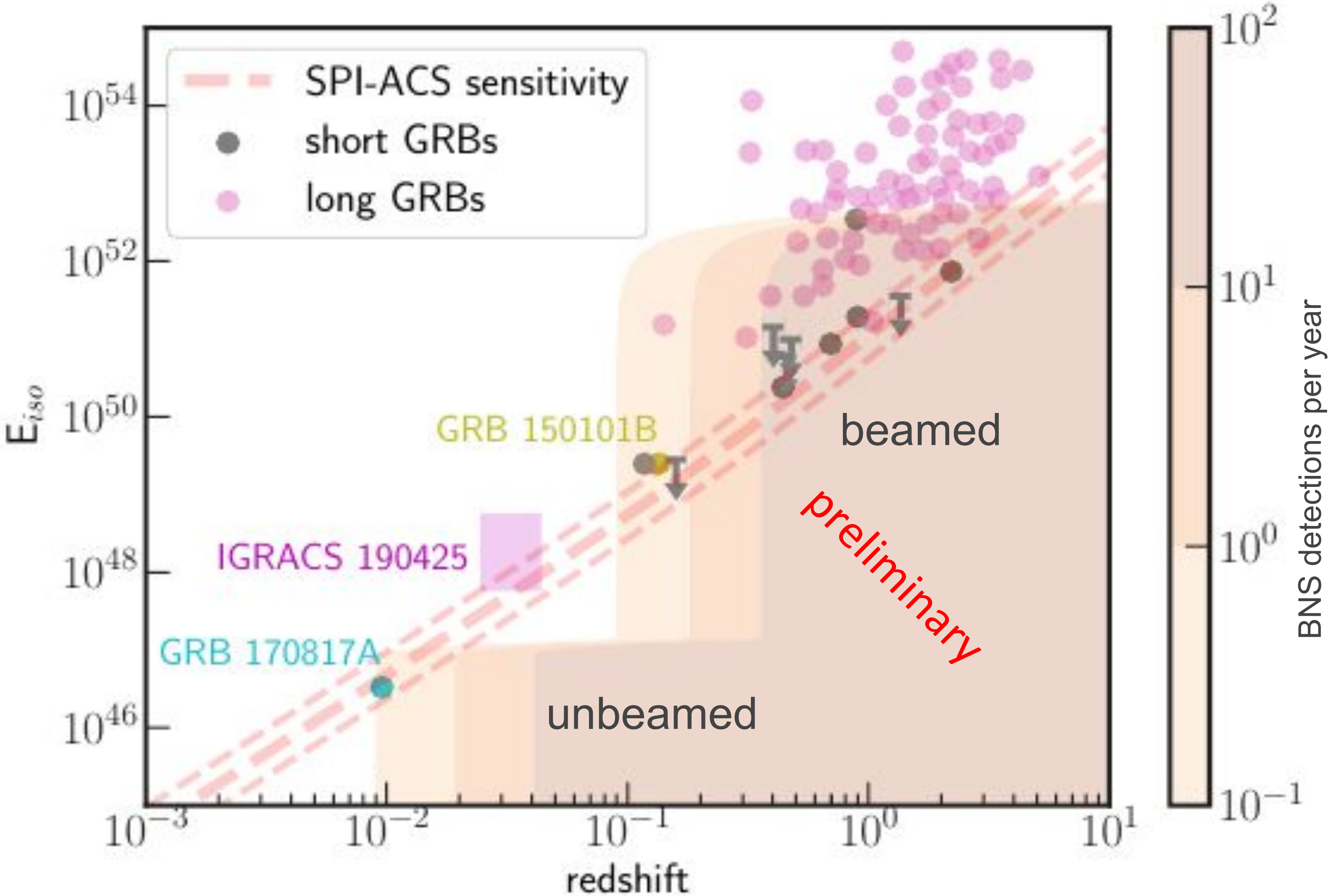
S190814bv NSBH



S190201q NSNS



GRB jet structure and future GRB-GW observations



VS+2019, in prep

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

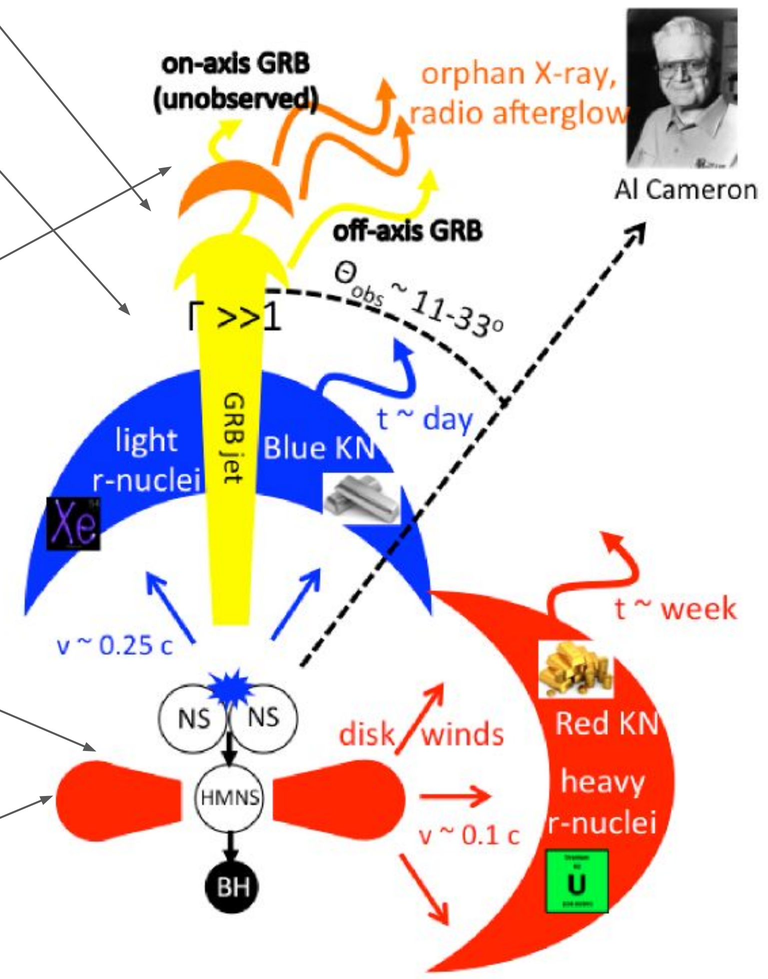
Structured Jet Internal Dissipation: weak prompt GRB (**Found**)

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?...

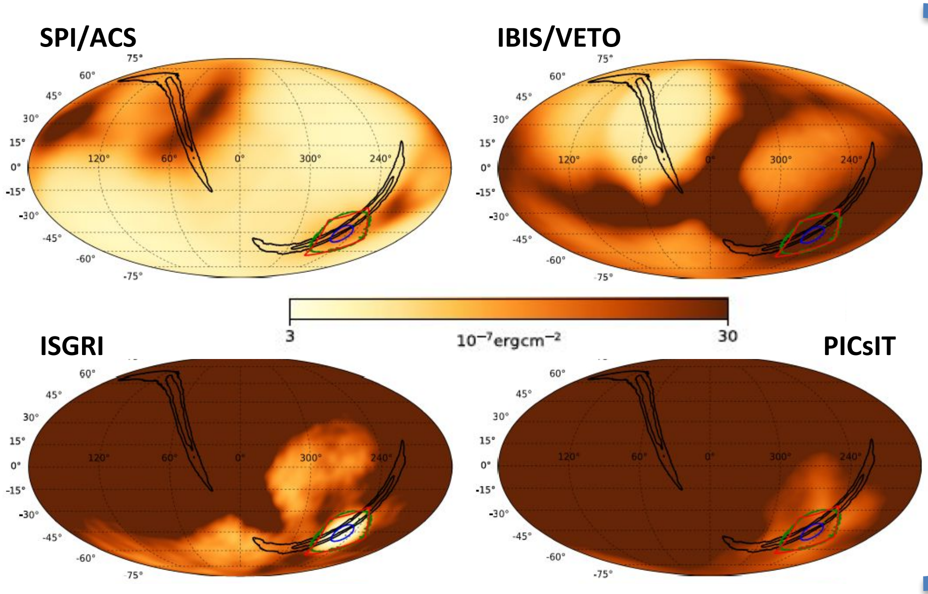


SUMMARY

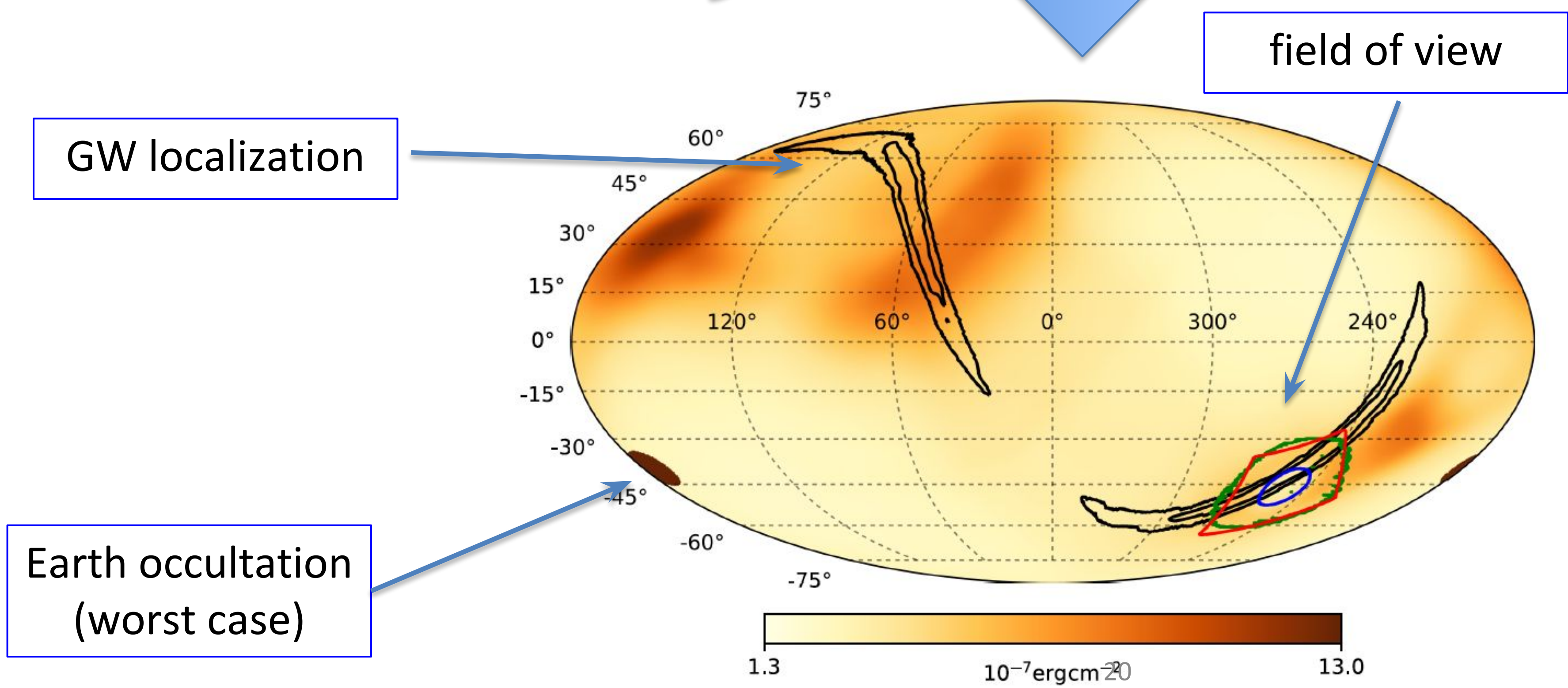
- INTEGRAL unique capabilities for multi-messenger prompt observations and follow-up
  - 85% duty cycle: uninterrupted 2.7-day long observations in stable background
  - Highly competitive all-sky sensitivity, down to 10^{-7} erg cm^{-2} s^{-1} (75 - 2000 keV) with complementary role of every instrument
  - 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 seeked to find new events in hard X-ray, especially in early data (T_0 ..).

EXTRA SLIDES

Sensitivity maps (light color is best)

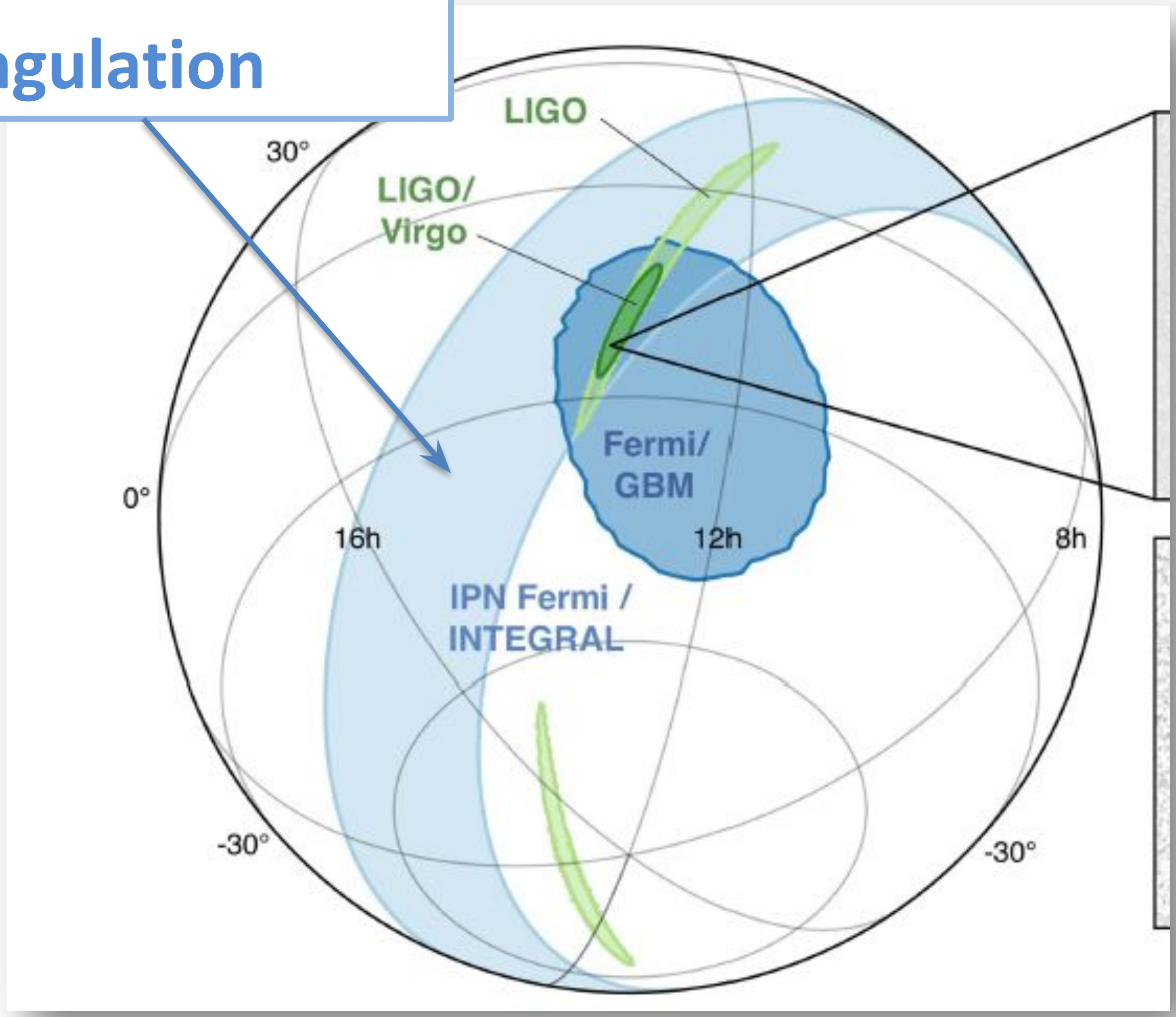


Best all-sky sensitivity by combining all instruments



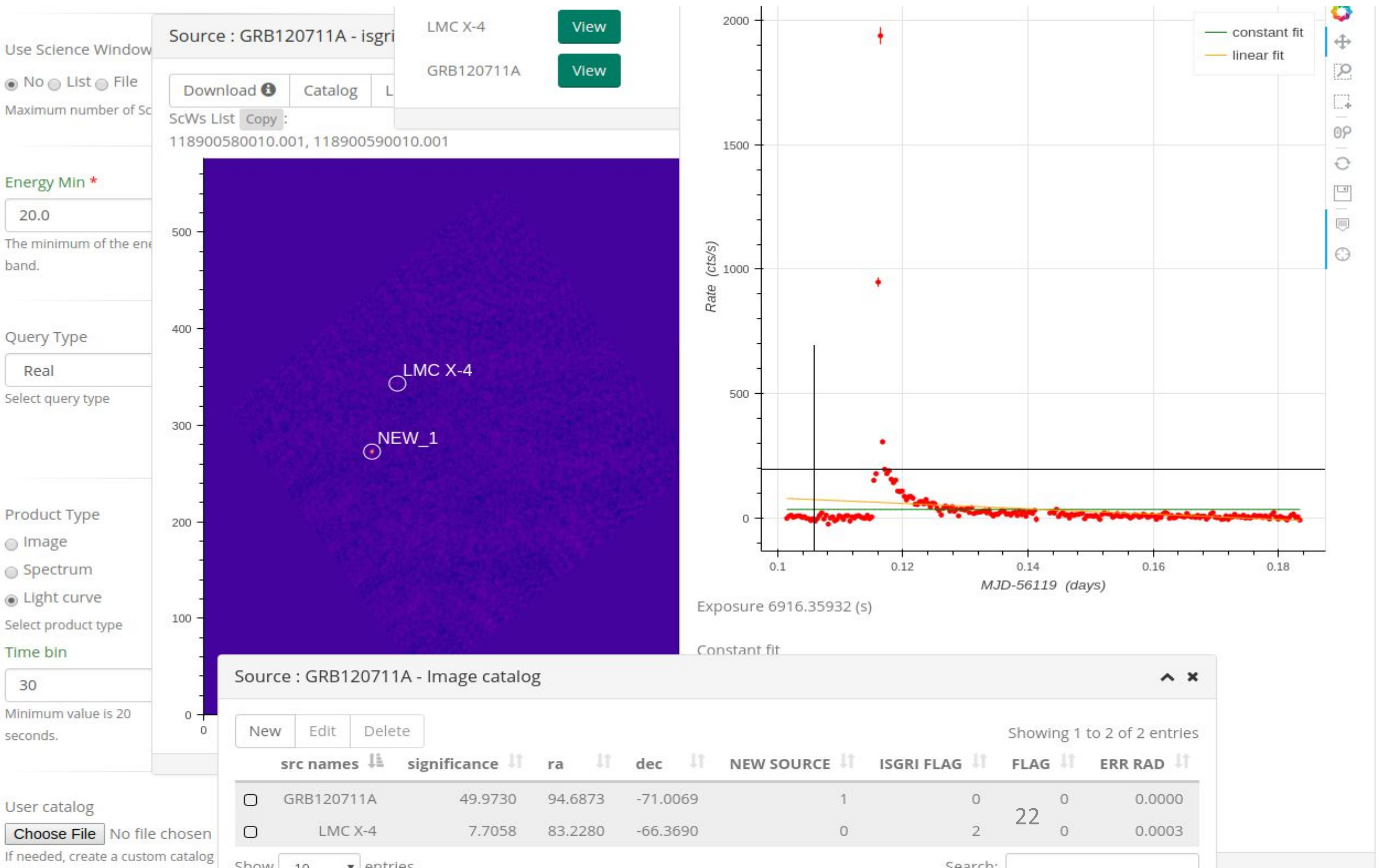
GW 170817

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



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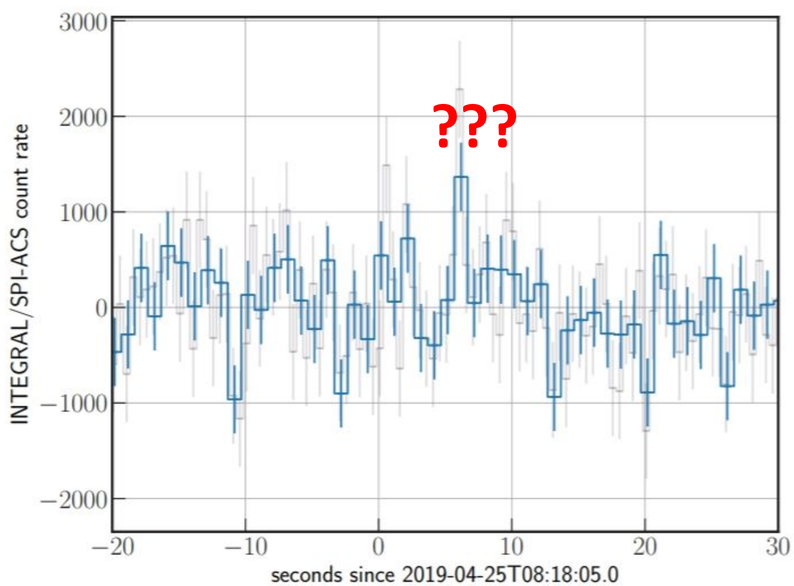
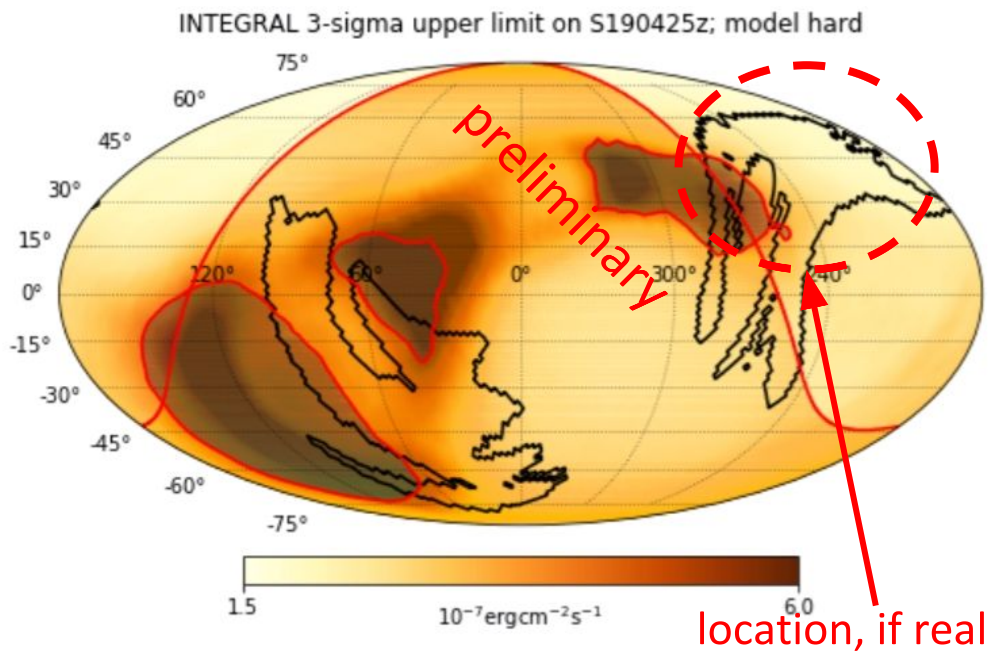
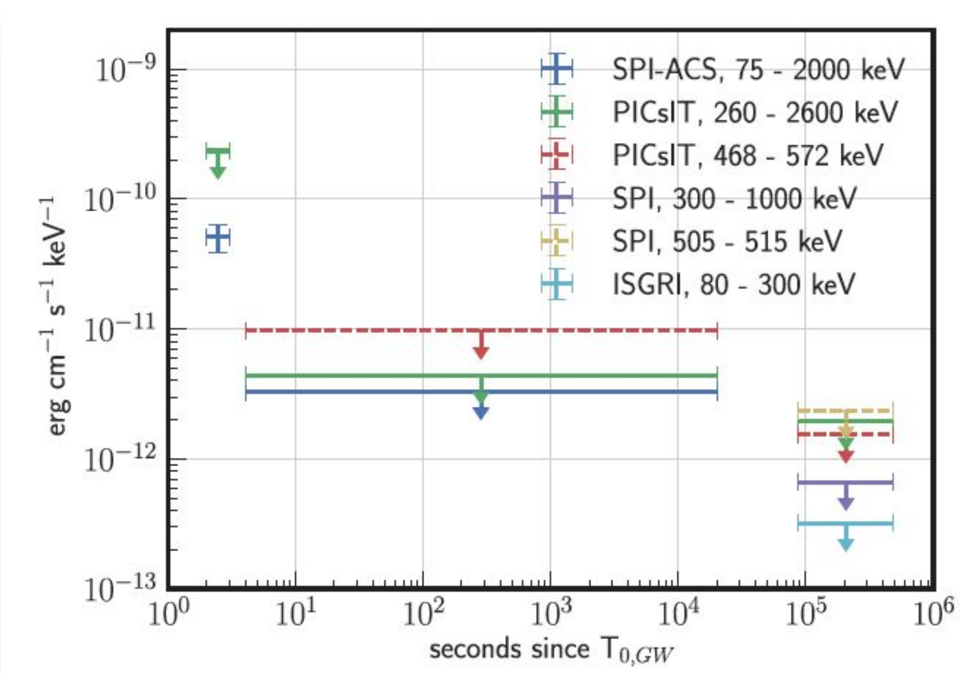
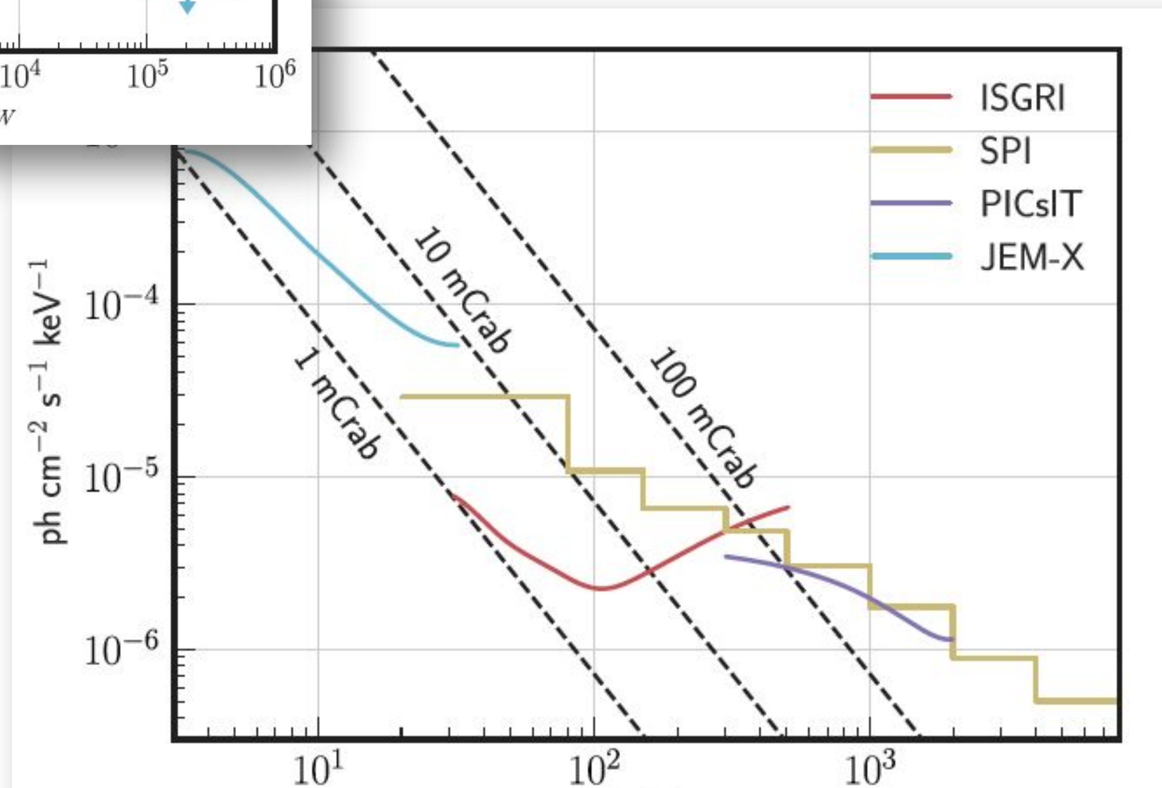




Excess has S/N 3.7 on a 1 s timescale and happened 6 s after the GW. The association significance is 1.5 sigma, making it unlikely to be correlated.
Compared to GW170817, the timescale is 3 times larger, delay larger, and S/N lower.
Assuming it is real, the comparison with Fermi-GBM and Konus-Wind upper limits would help to constrain the localisation within the LIGO-Virgo map.

FOLLOW-UP POINTING (GW 170817)

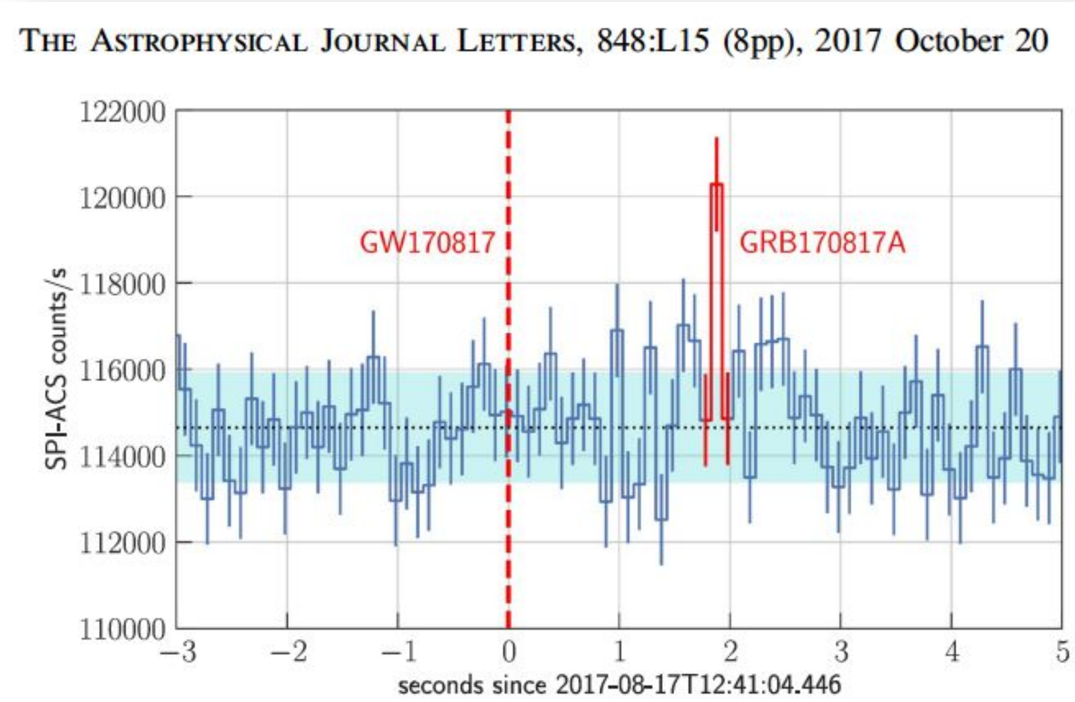


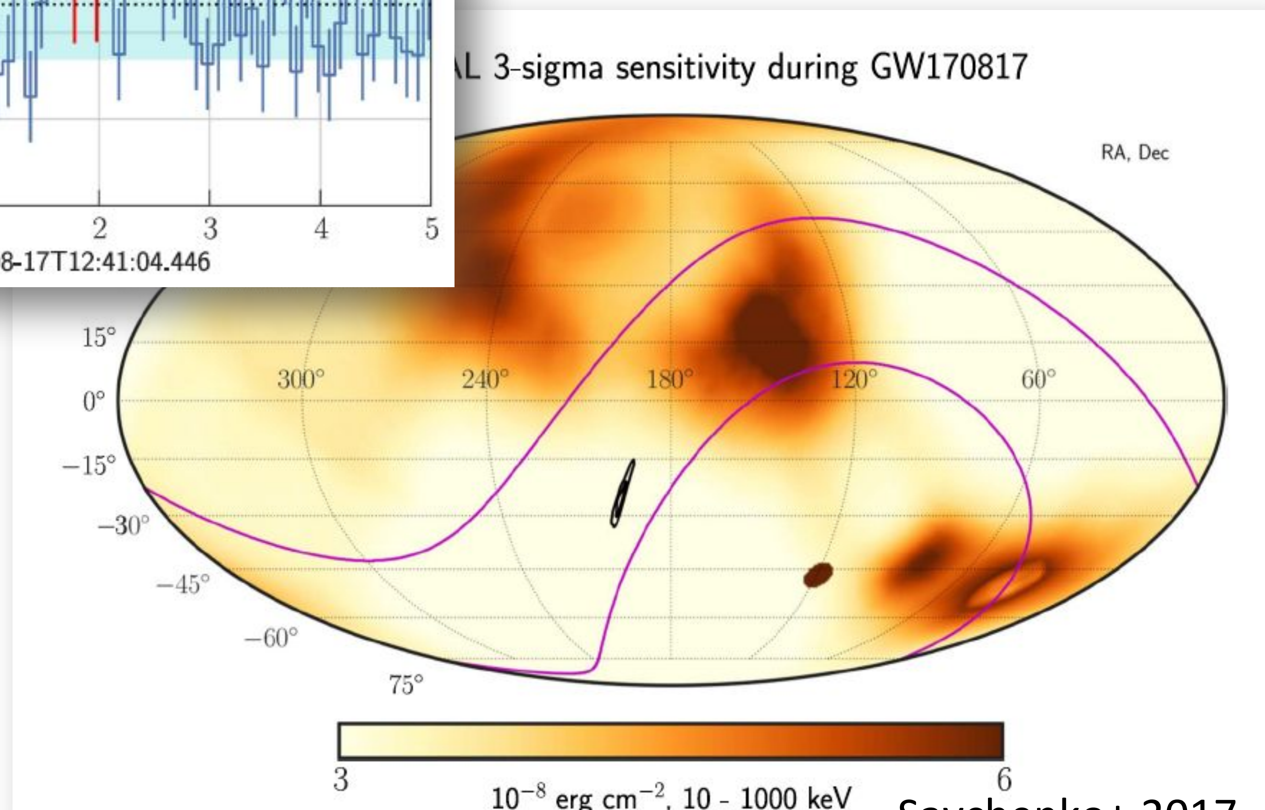


These follow-up can constrain the presence of magnetar flares in the hours after the event.

VS+2017

GW 170817
PROMPT EMISSION

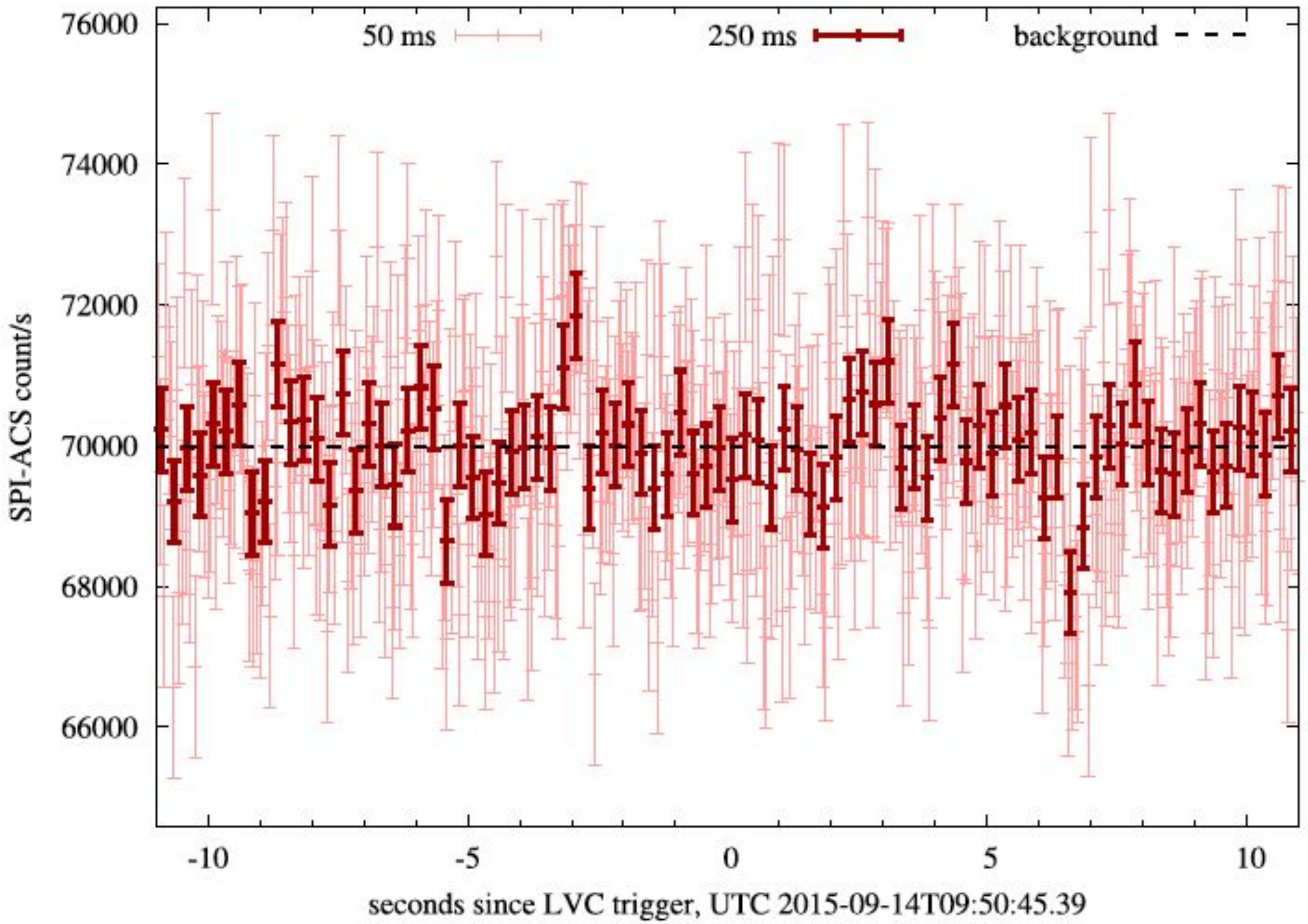




Savchenko+ 2017

GW 150914

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

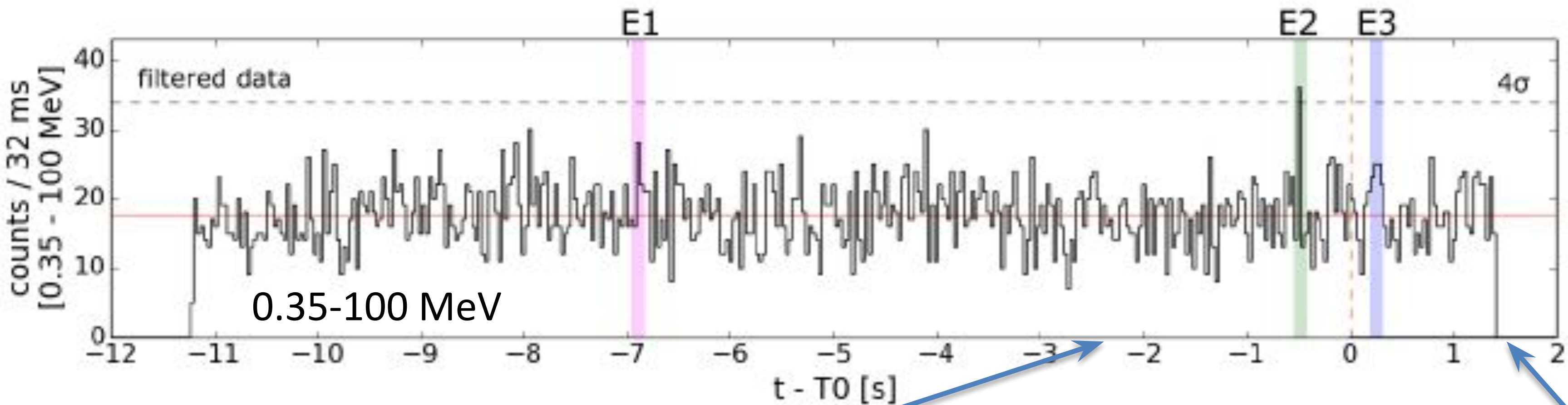


Savchenko+ 2016

GW 170104

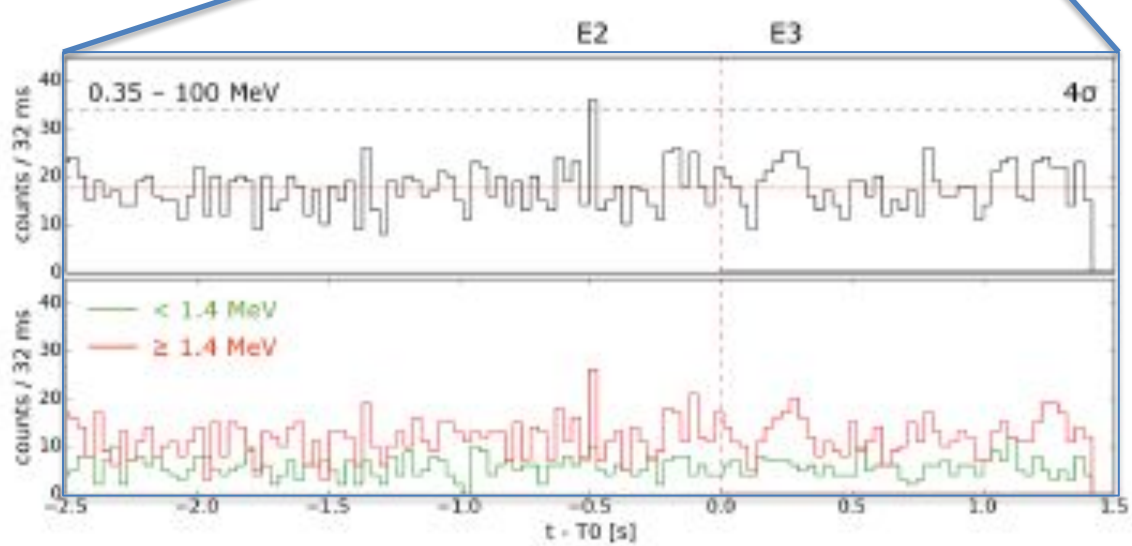
Interesting event in AGILE/MCAL 0.46 s before T_o

(Verrecchia+ 2017)



E2 post-trial coincidence probability between 2.4σ and 2.7σ

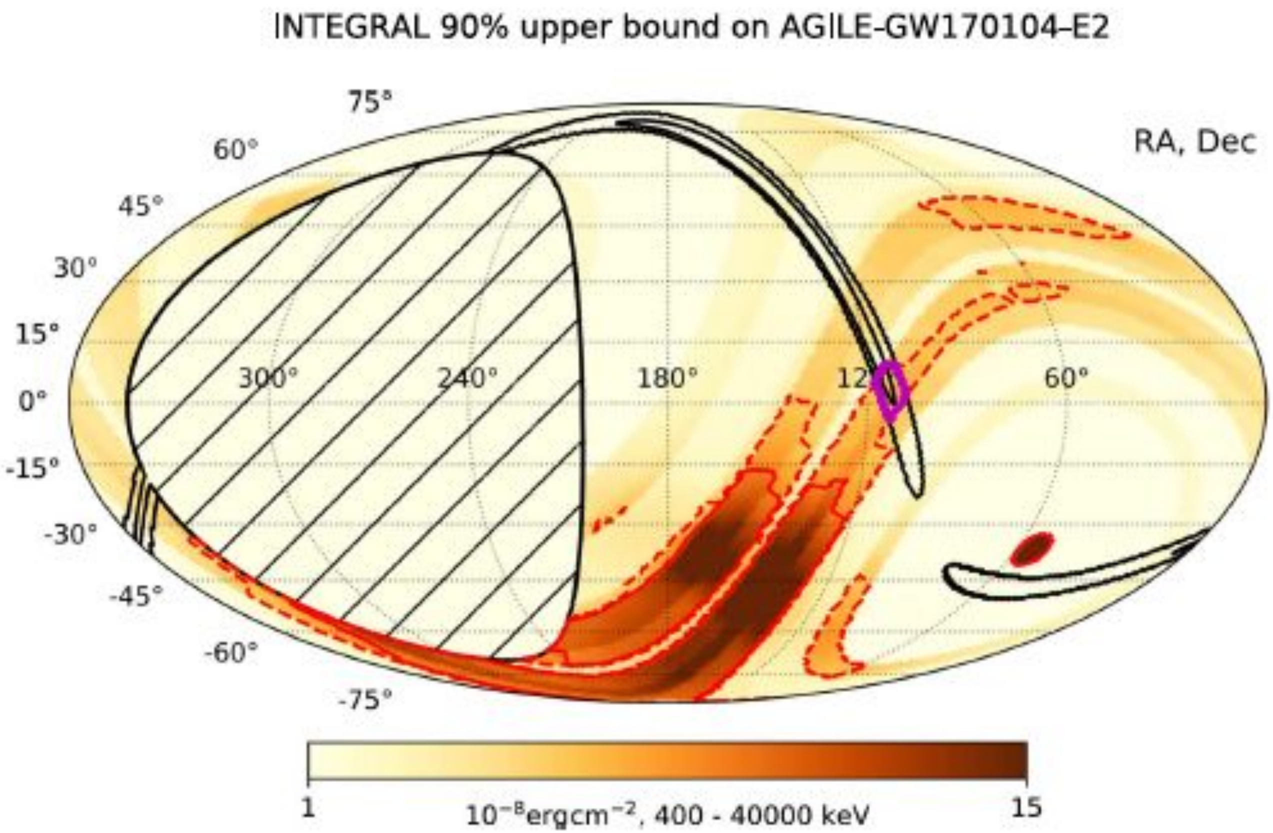
Fluence ~10^{-7} erg/cm^2
(0.4-40 MeV)



GW 170104

SPI/ACS ul on possible AGILE event

(for PL spectrum with slope -2)



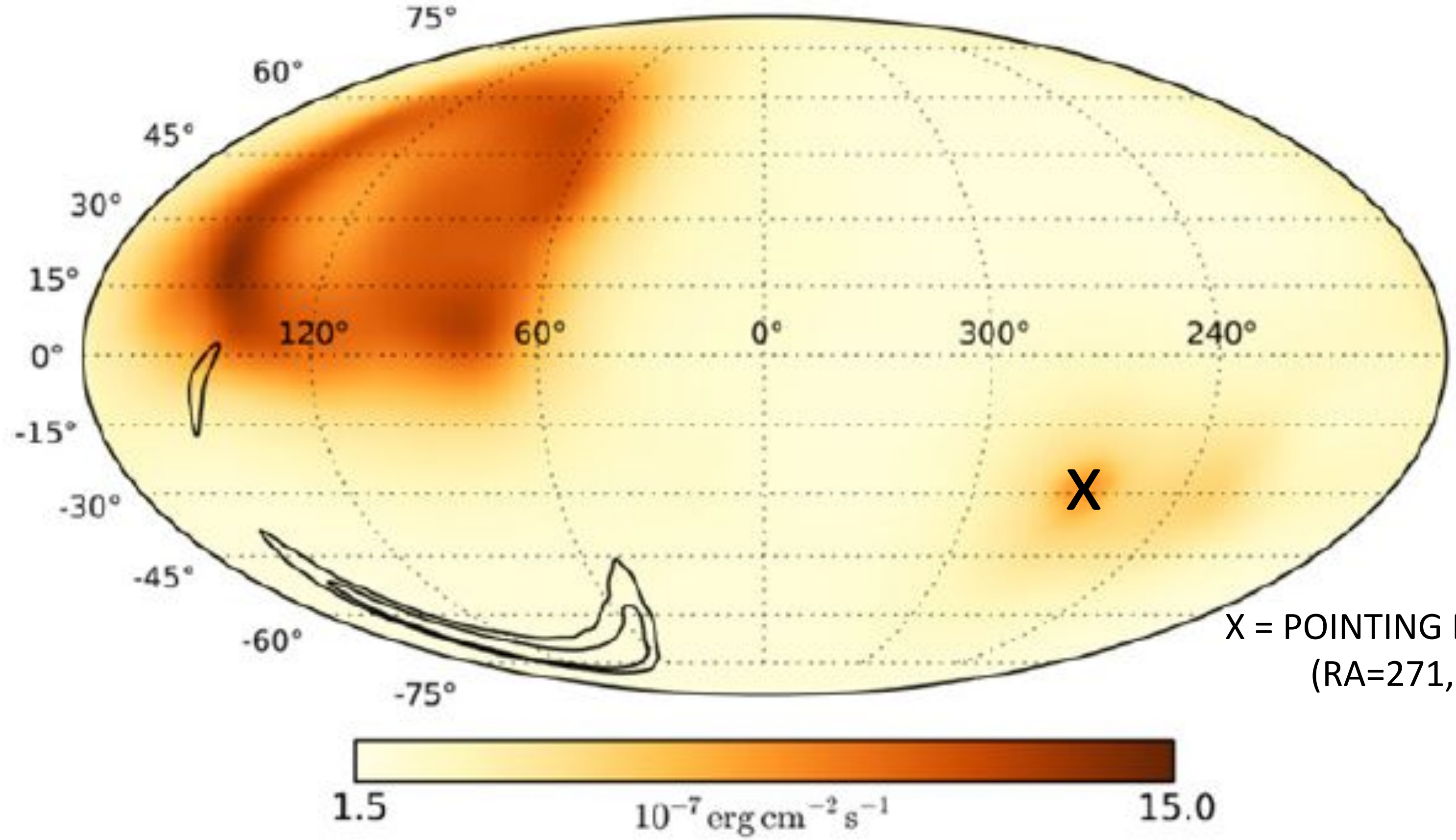
Only within red contours u.l. compatible with AGILE event fluence

Savchenko+ 2017b

GW 150914

SPI-ACS 3σ upper limit in 1 second

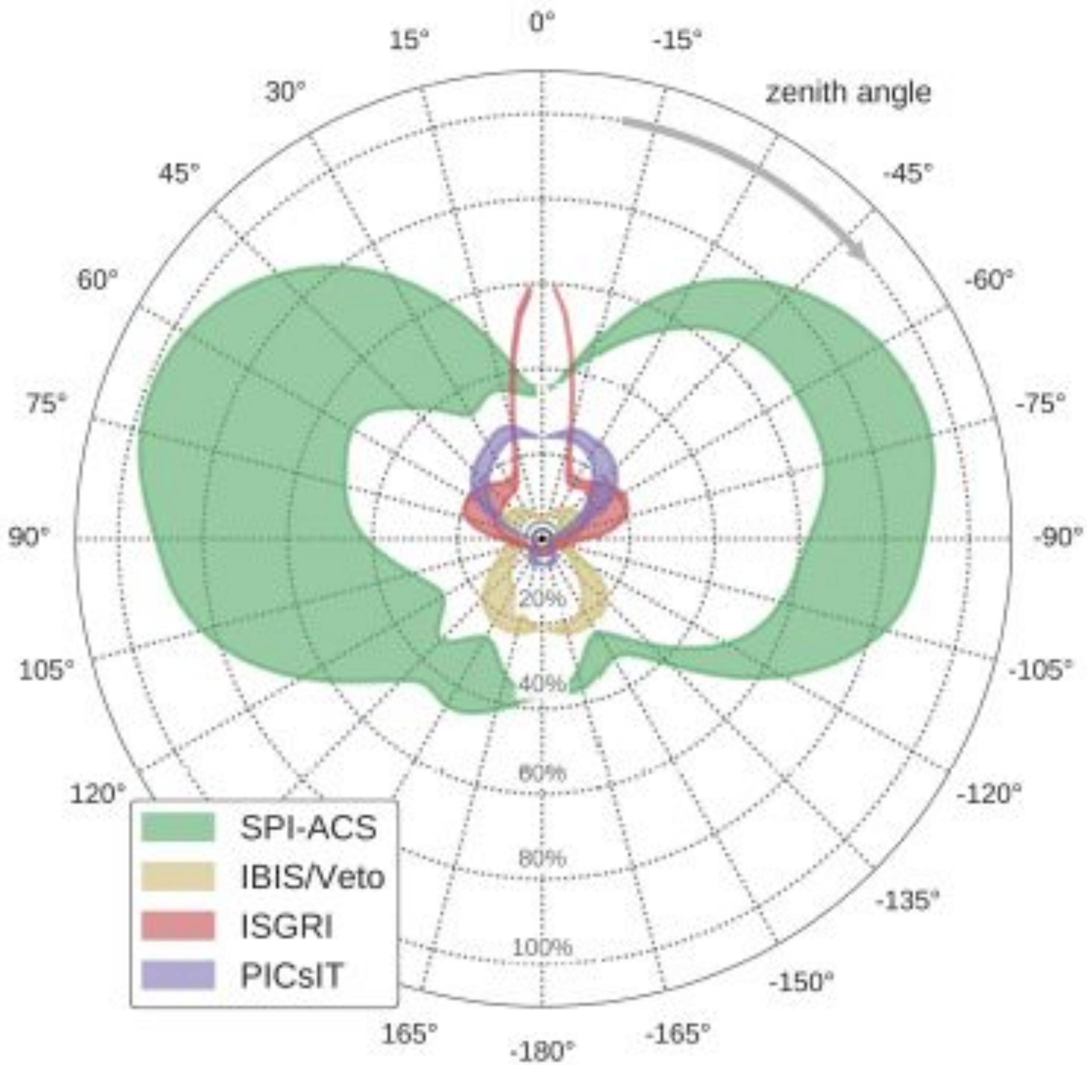
$F_{75\text{-}2000} < (1.2 - 1.7)\ 10^{-7}$ erg/cm^2 for 95% of error region



X = POINTING DIRECTION
(RA=271, DEC=-31)

for $\alpha = -0.5$, $\beta = -2.5$, E_p=1.5 MeV

Relative sensitivity as a function of zenith angle

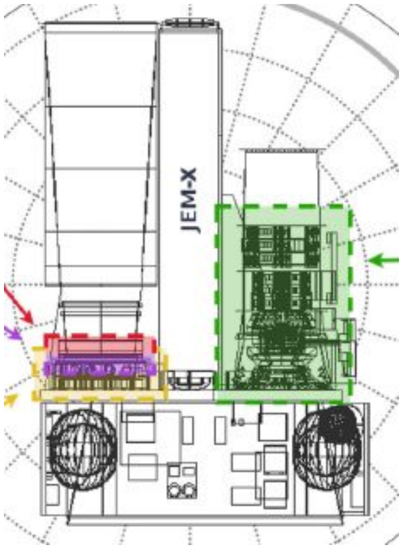


Savchenko+ 2017

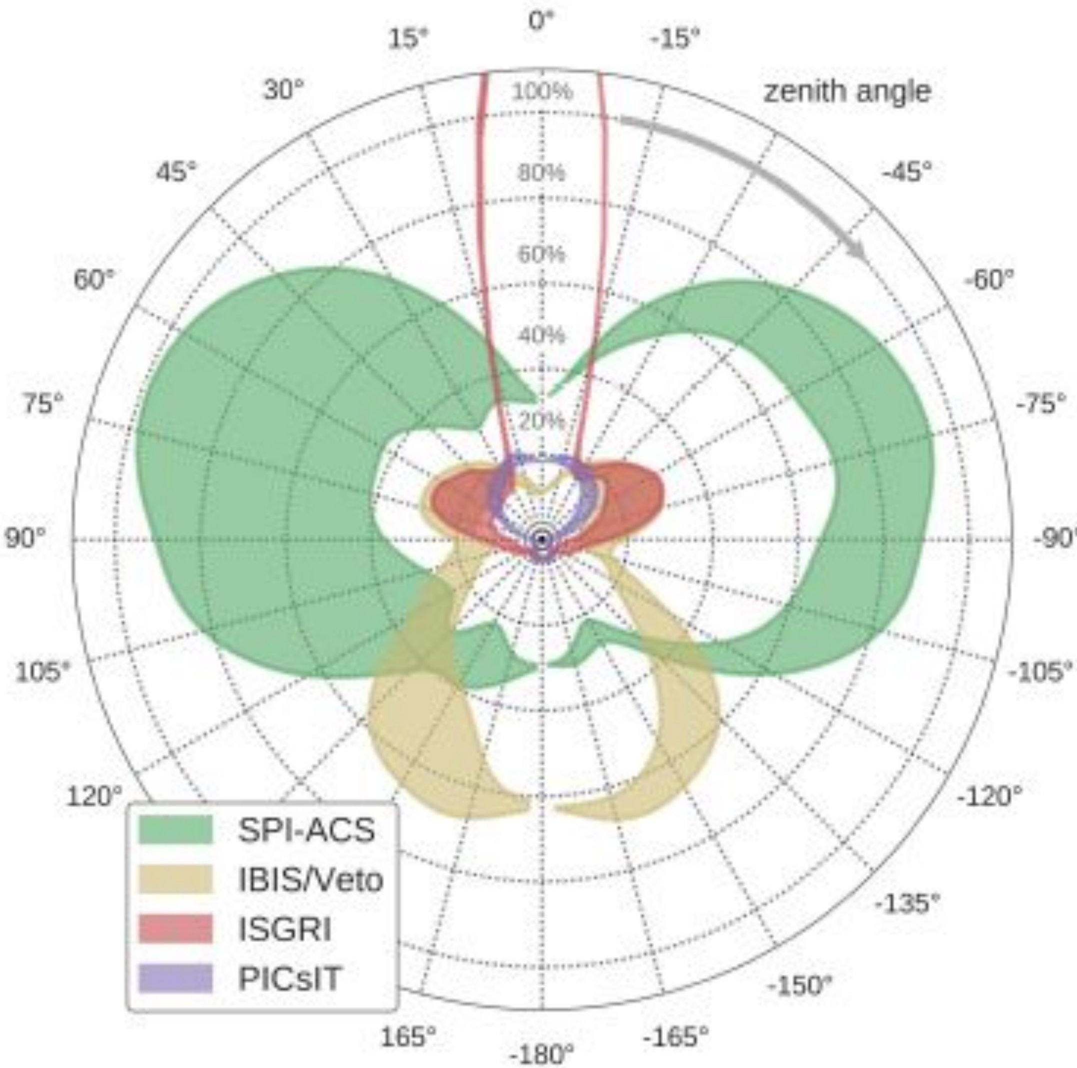
Short hard burst

1 sec

CPL $\alpha=-0.5$ Ep=600 keV



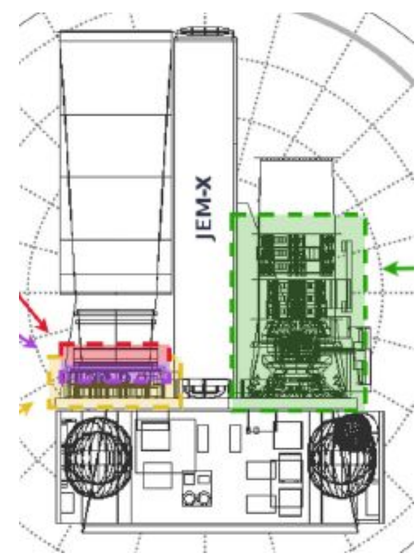
Relative sensitivity as a function of zenith angle



Long burst

8 sec

$\alpha = -1$ $\beta = -2.5$ Ep=300 keV



Savchenko+ 2017