# INTEGRAL search for electromagnetic counterparts of gravitational wave events

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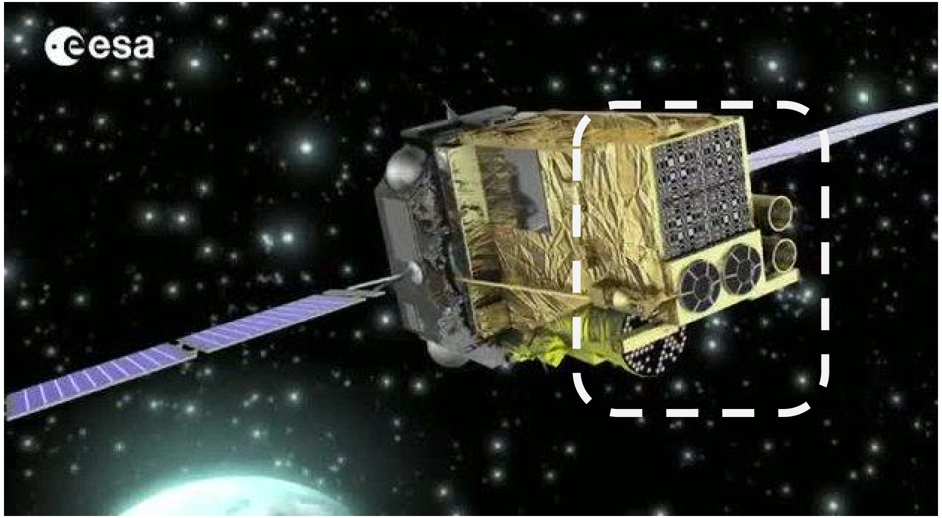
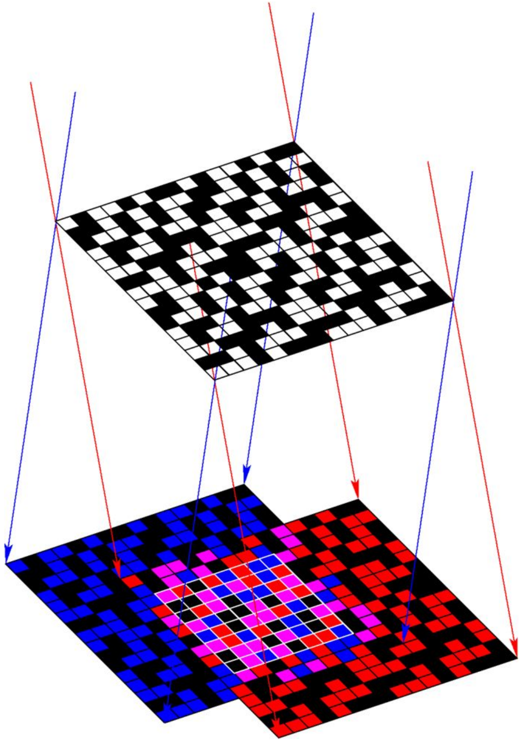
Cohcem 2016

# INTEGRAL: INTErnational Gamma-RAy Laboratory

hard X-ray and low-energy gamma-ray photons can not be easily focused, and Compton or pair production can not yet be used for imaging

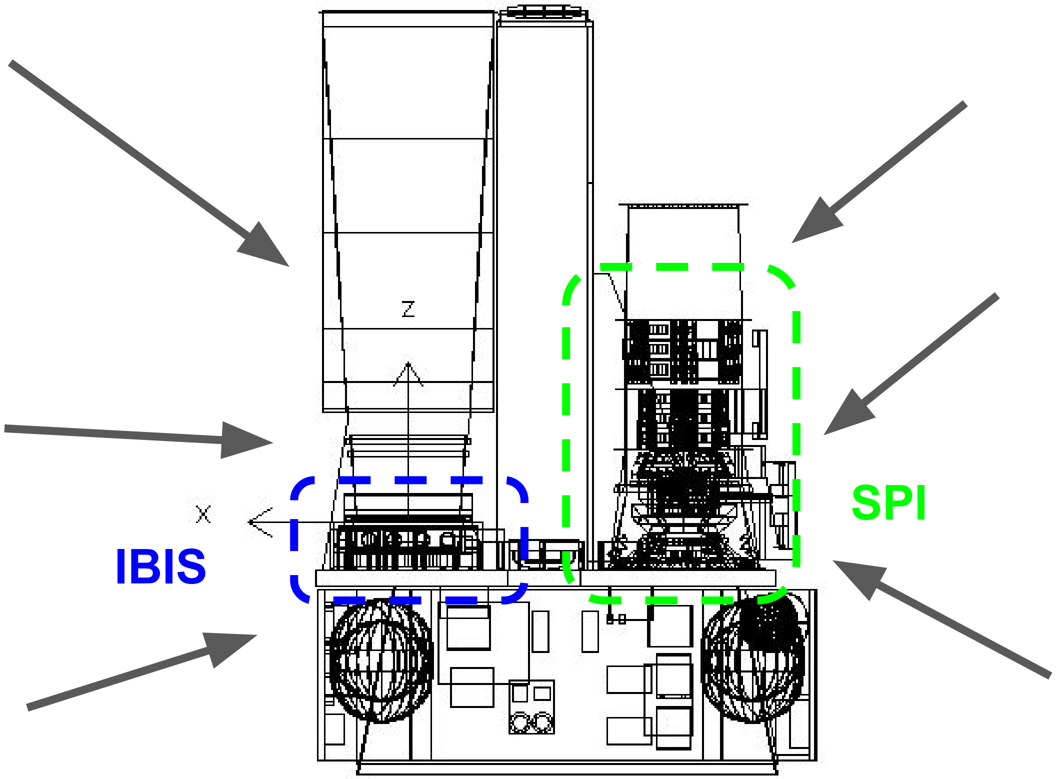
Coded mask combines large FoV (30x30 deg) with reasonable resolution (12 arcmin)



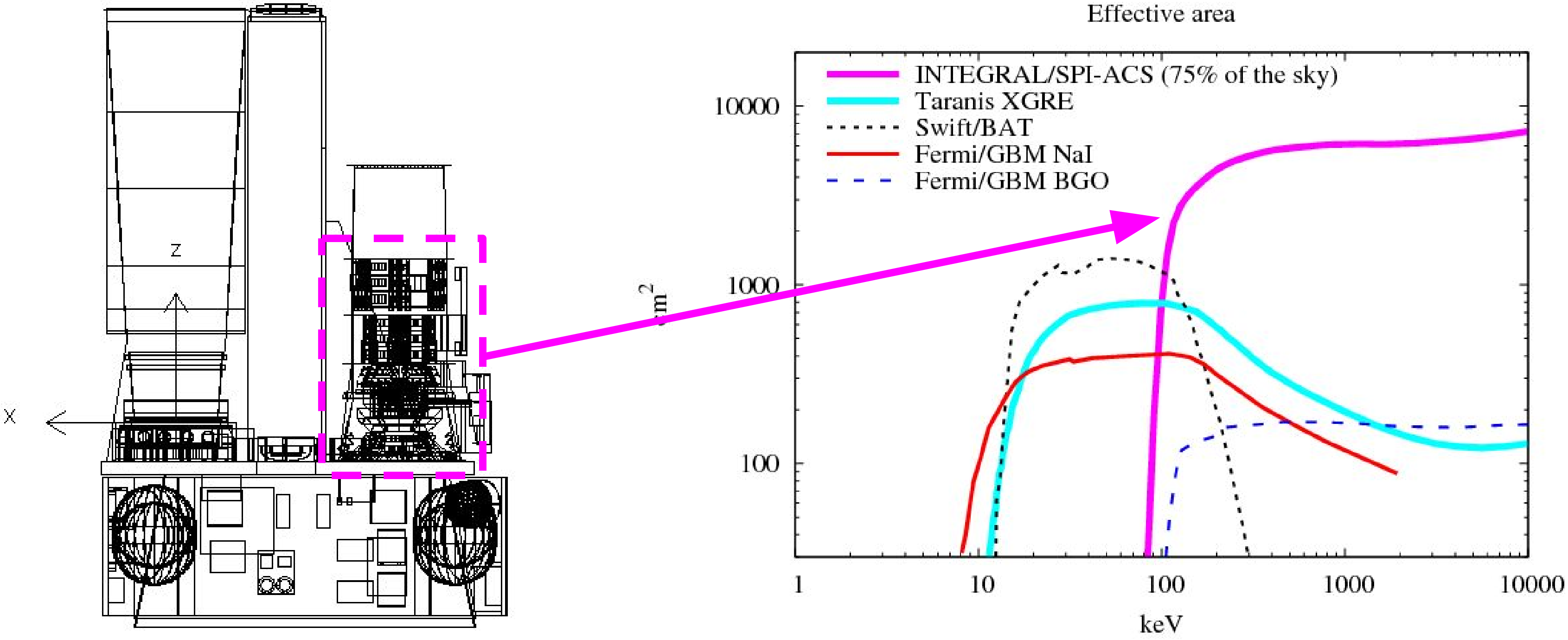
# INTEGRAL:
# all-sky detector

The gamma-ray detectors are the most opaque structures on the spacecraft, meaning that the source photons reach them **from every direction**, although through different amount of the passive material.



# INTEGRAL SPI-ACS

Anti-coincidence shield of SPI, 512 kg of BGO

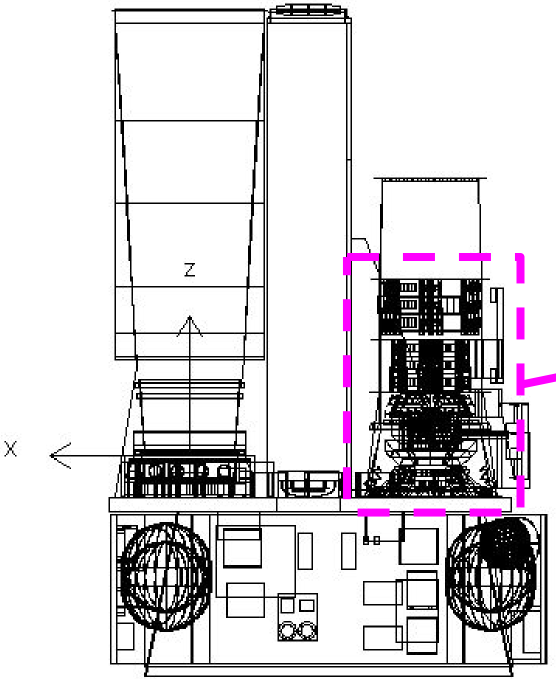


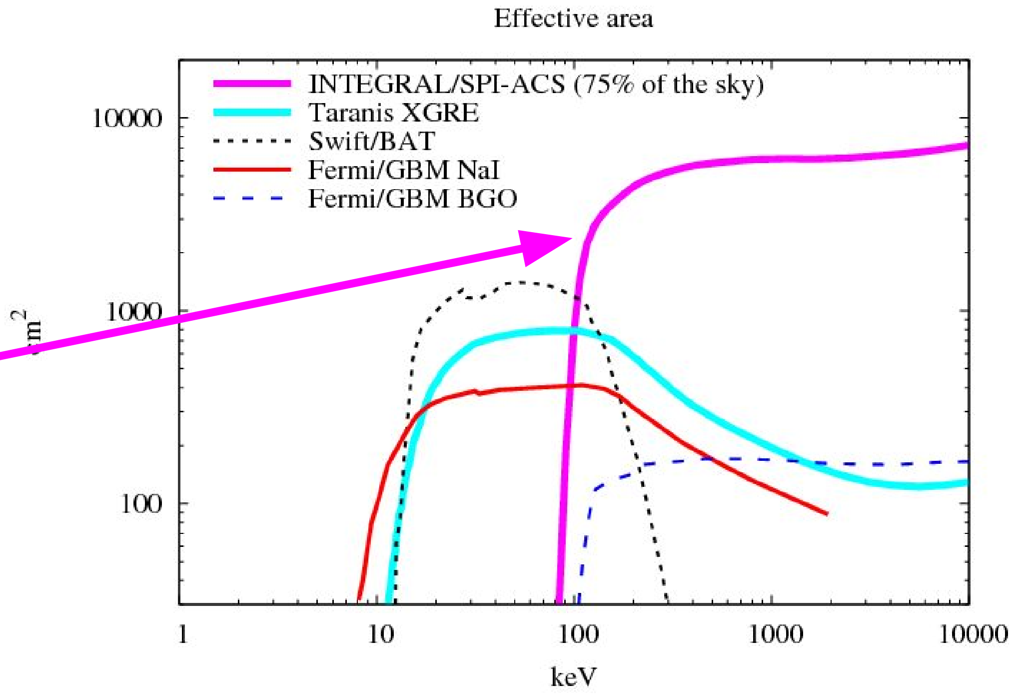

But: not energy resolution or localization capabilities

# INTEGRAL SPI-ACS

Large detector = large background...

Anti-coincidence shield of SPI, 512 kg of BGO



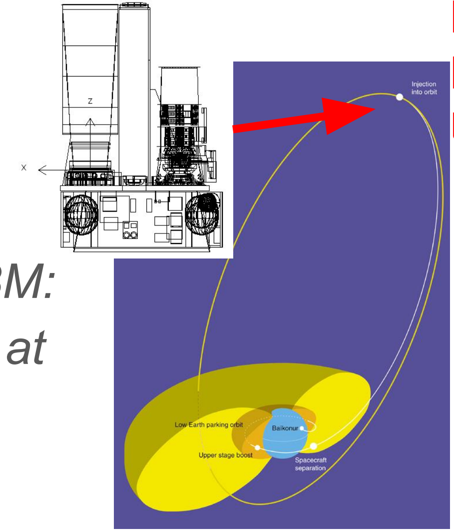

But: not energy resolution or localization capabilities

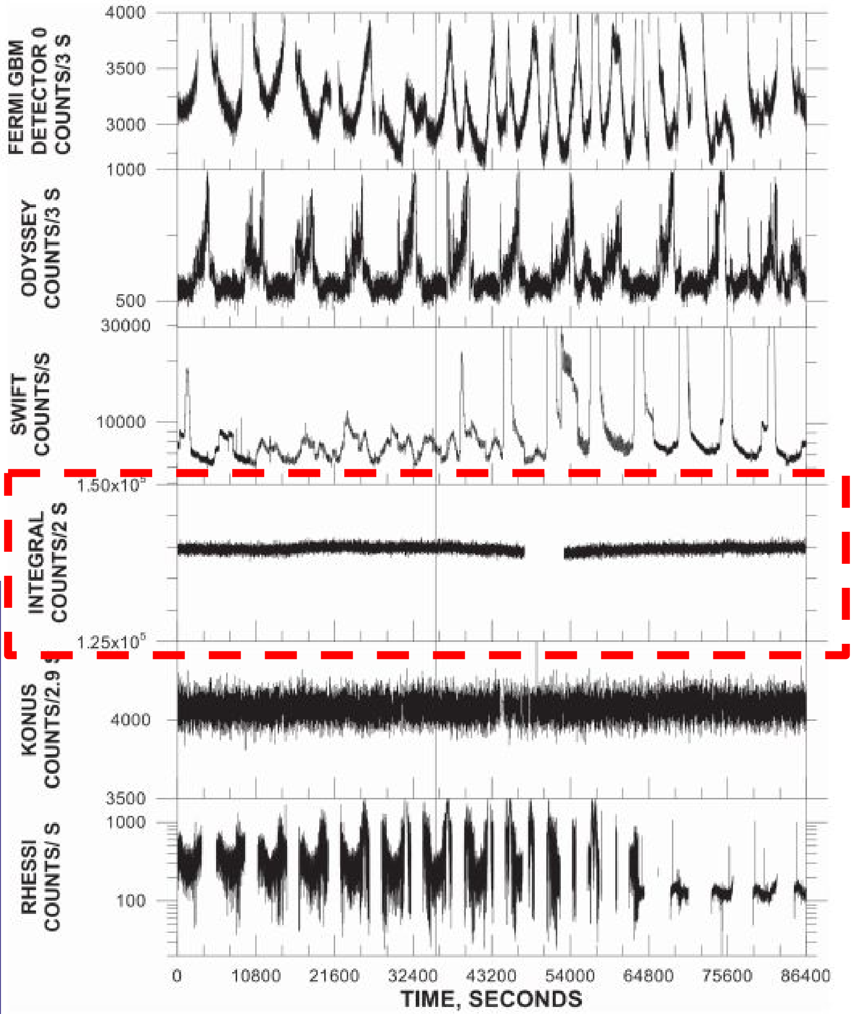
# Background

Owing to very elongated orbit, INTEGRAL features **stable background** on scale of 2 days, 85% (currently) duty cycle, and  all-sky sensitivity

No Earth shadow!

*Compare to Fermi/GBM: duty cycle 50%,  75% at any given moment, unstable background*



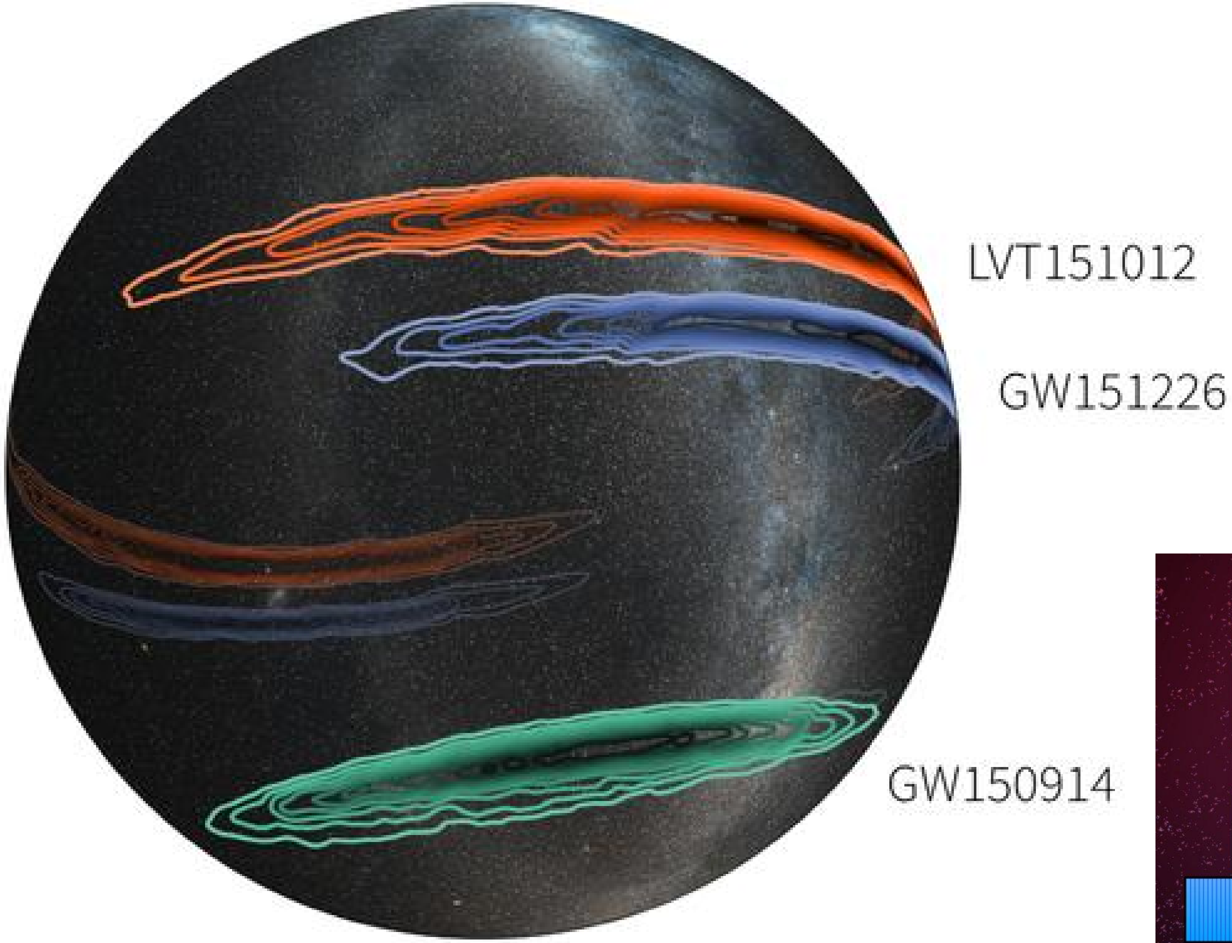




*Hurley et al 2016*

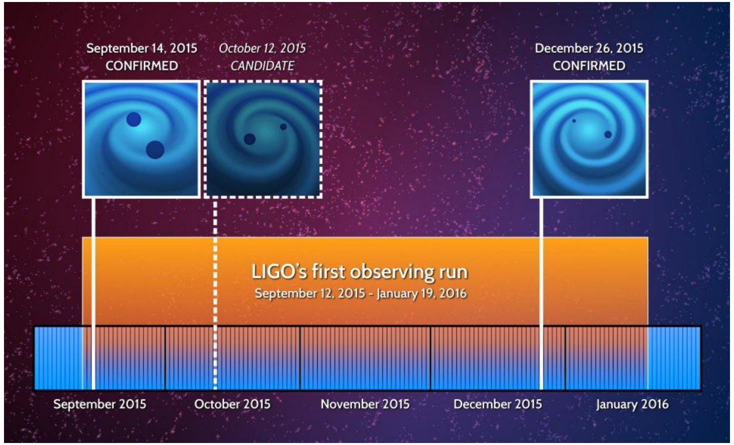
# LIGO O1

In September 2015 LIGO reached next level of sensitivity, and detected 2(+1) binary black hole mergers in 4 month

Virgo will likely join in 2017



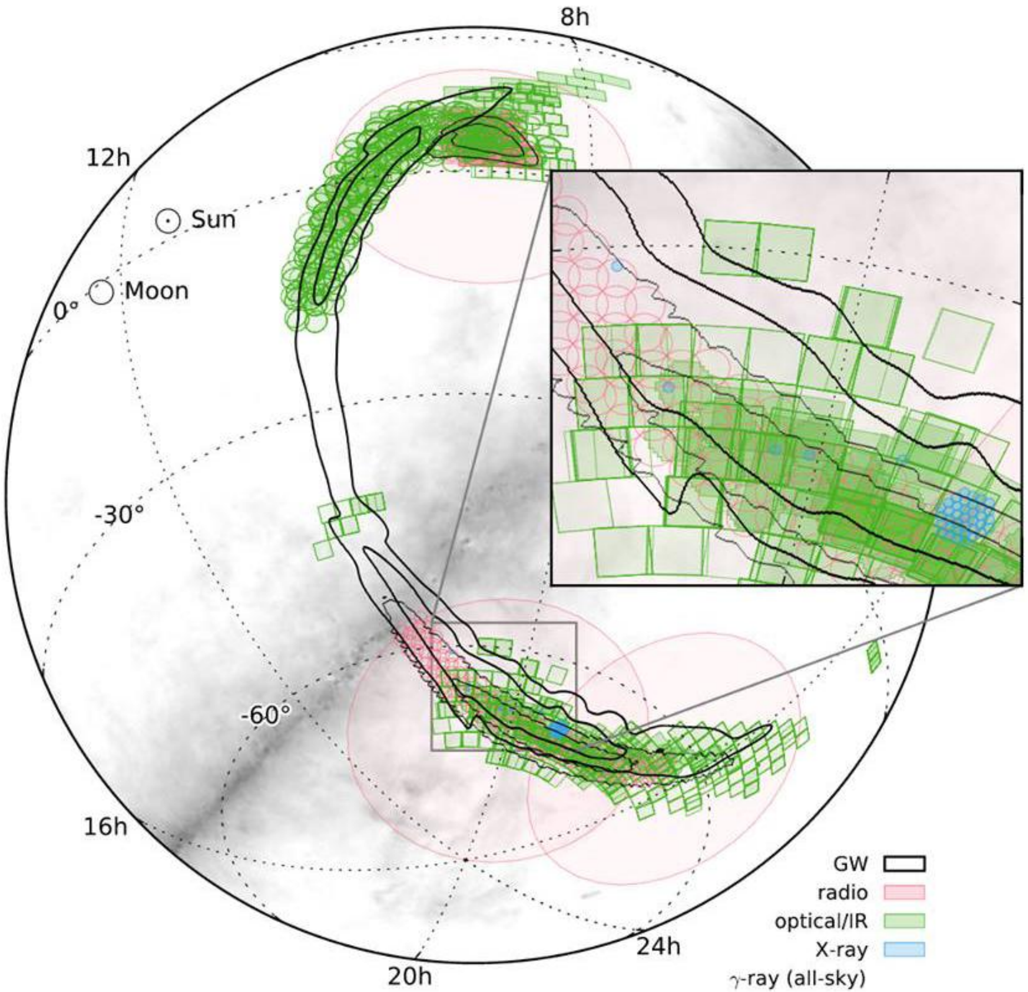

Localization maps



# Electromagnetic follow-up

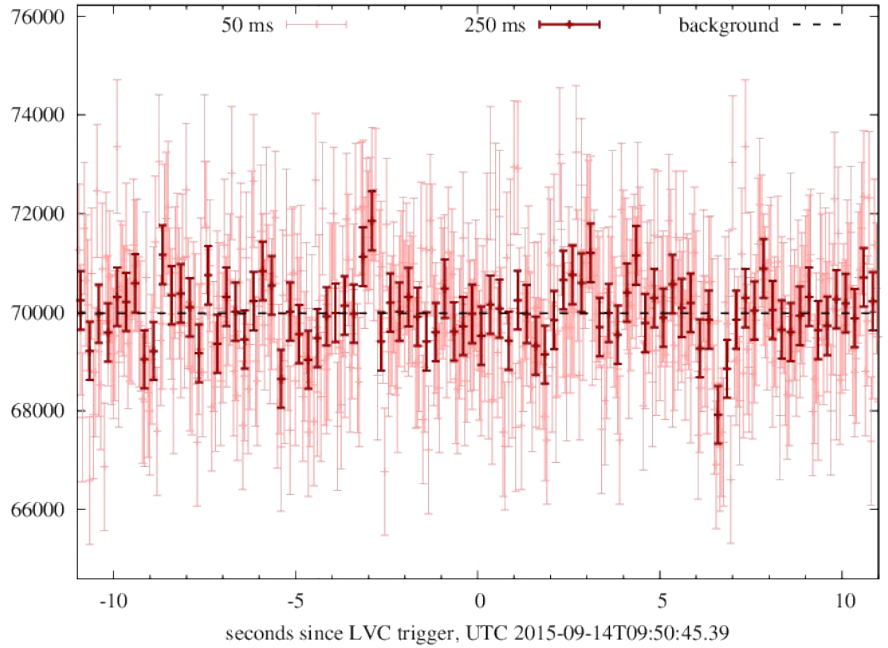
The alerts were promptly distributed to observers from radio to gamma-ray, who made the agreements with LIGO/Virgo collaboration.

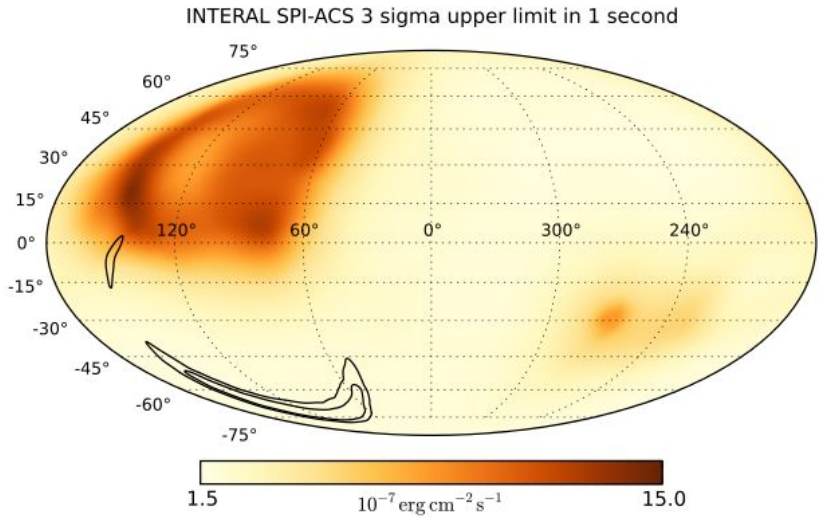
LIGO/Virgo - INTEGRAL MoU was lead by ISDC (Geneva) with collaboration of APC..



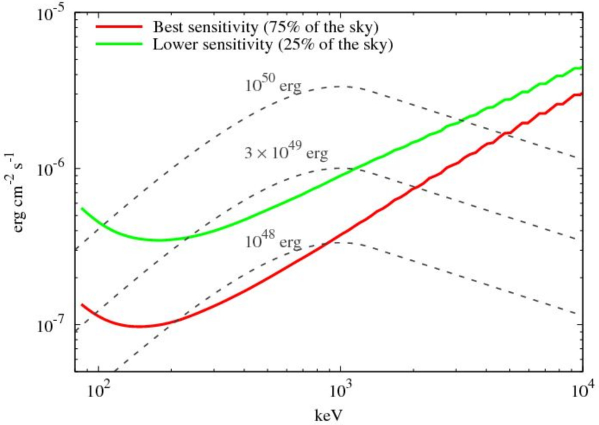

Follow-up of GW150914

# GW150914: upper limit



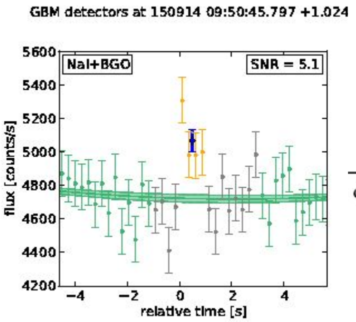




**$10^{-6}$** - ratio of energy in 75-2000 keV to GW



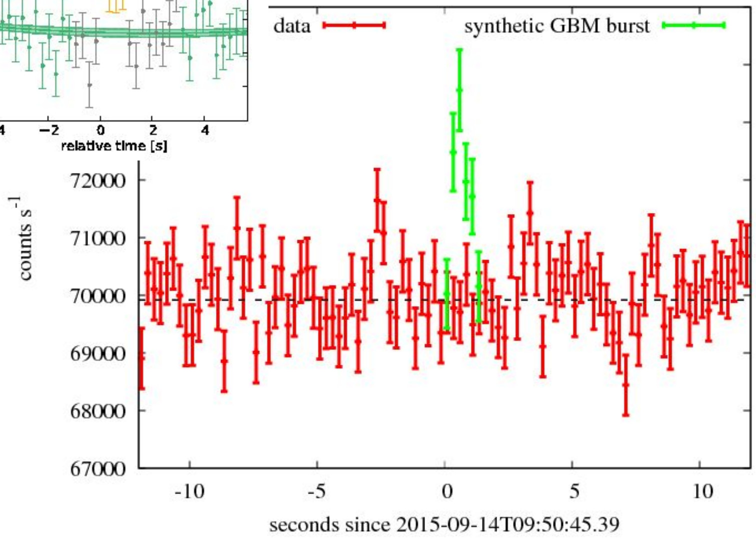

The region was in a very lucky orientation for SPI-ACS! Lucky background conditions too.

# And Fermi/GBM (2.9 sigma)




*Connaughton et al 2016*

It's complicated...

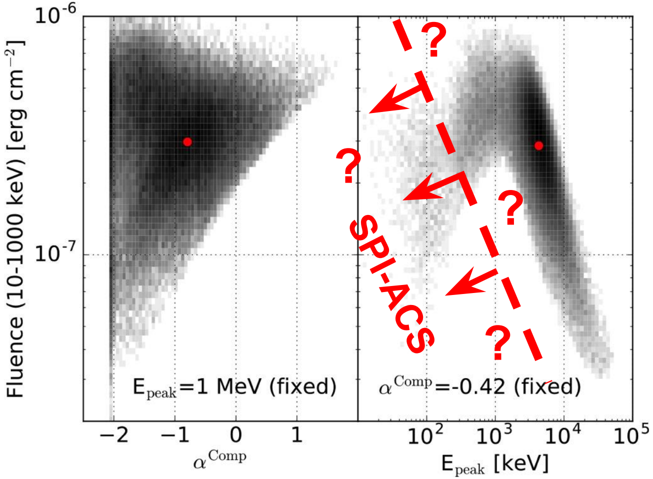



Rescaling real GRB with a moderately hard spectrum assuming **best fit fluence of GBM-GW150914,** resulting in **15 sigma** detection: **good margin**!

Some spectra, soft and weak, could be marginally compatible with SPI-ACS and GBM data, but **the probability is very low**

But, given that the the excess in Fermi/GBM is limited to high energy, soft spectrum implies no detection.

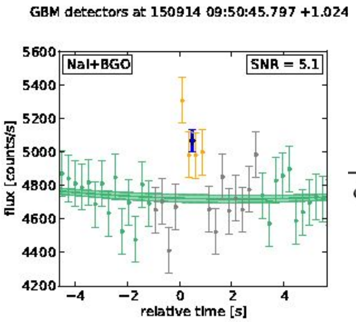
*Greiner et al 2016*




*Veres et al 2016*

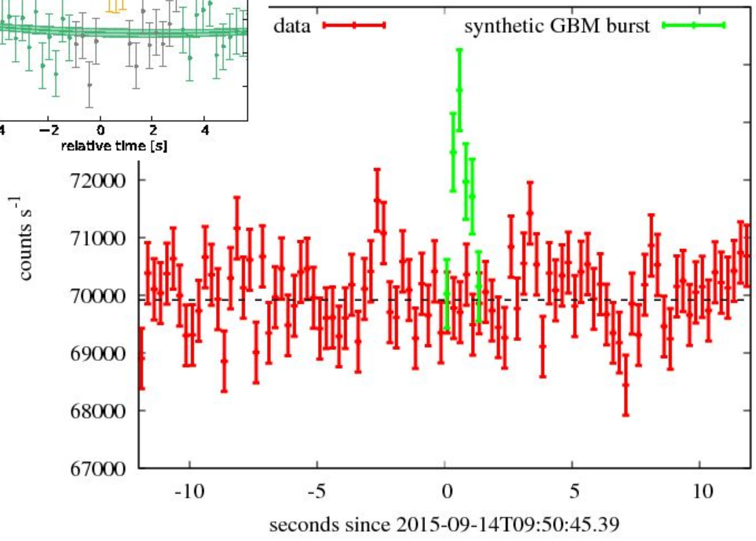
Fully taking into account statistical and systematic uncertainties in the GBM parameter estimation is required. The collaboration is ongoing, **useful for future observations**!

# And Fermi/GBM (2.9 sigma)

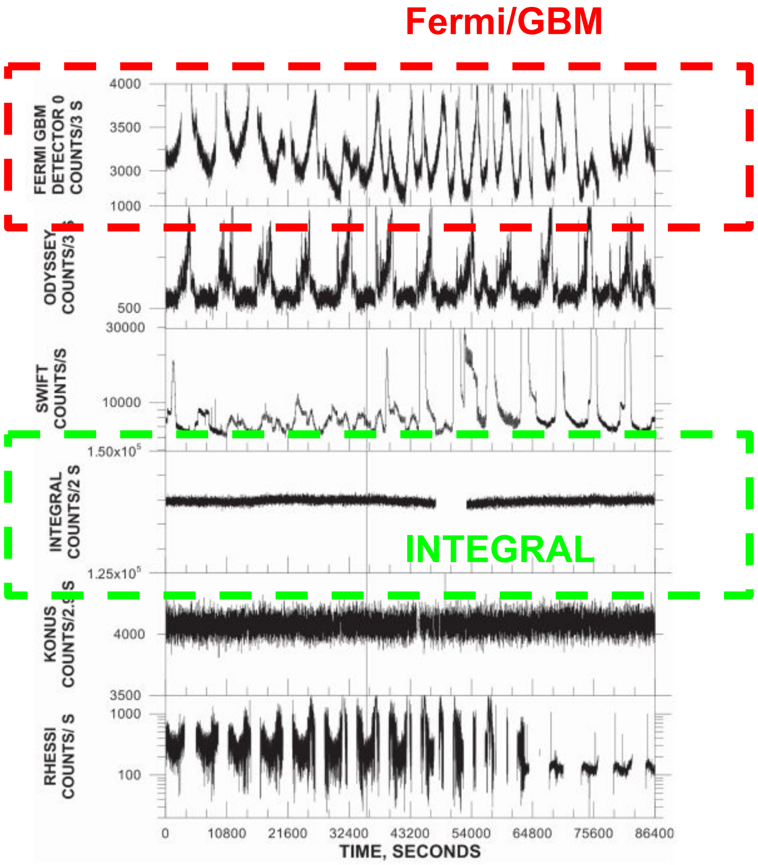



*Connaughton et al 2016*

It's complicated...



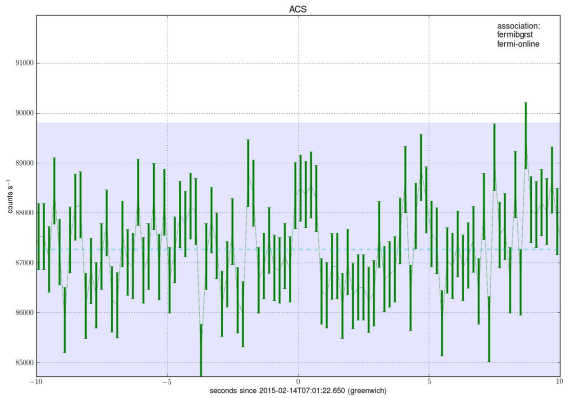

Rescaling real GRB with a moderately hard spectrum assuming **best fit fluence of GBM-GW150914,** resulting in **15 sigma** detection: **good margin**!



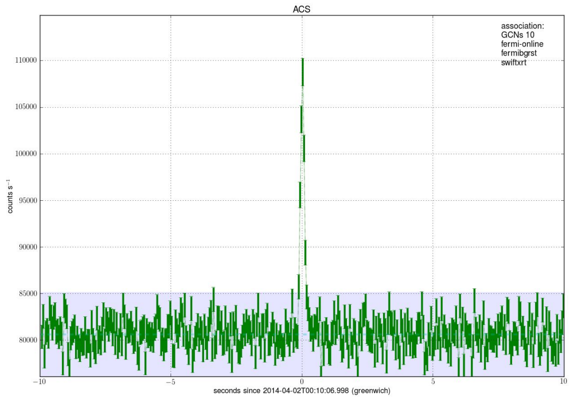

Note strong variations of the Fermi/GBM background on all time scales, resulting in large FAR

# Fermi/GBM sGRB with comparable fluence to GBM-GW

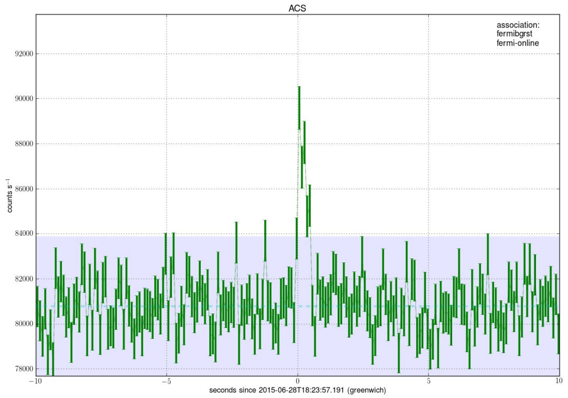
Since the properties of the event are difficult to determine, typical GRBs of the same fluence were suggested as examples




1.9 sigma




28 sigma

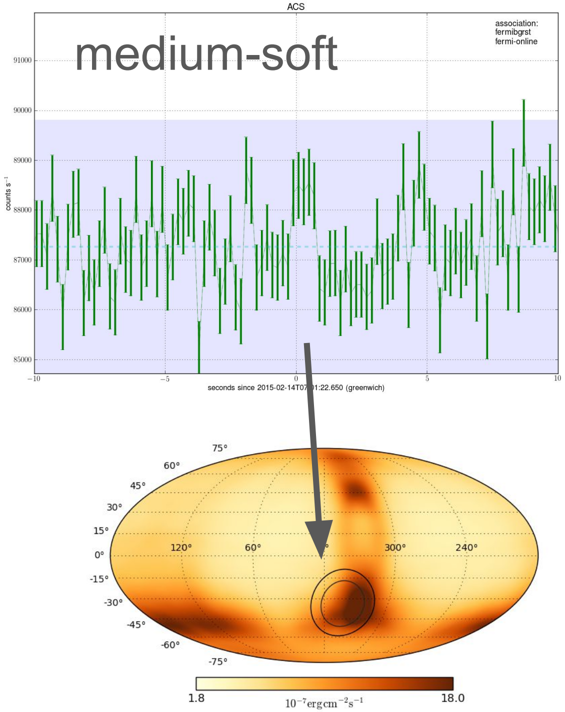


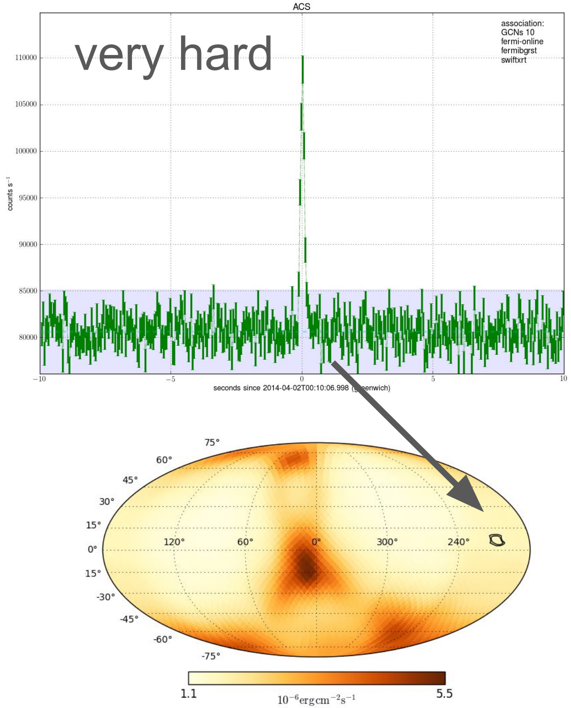

12 sigma

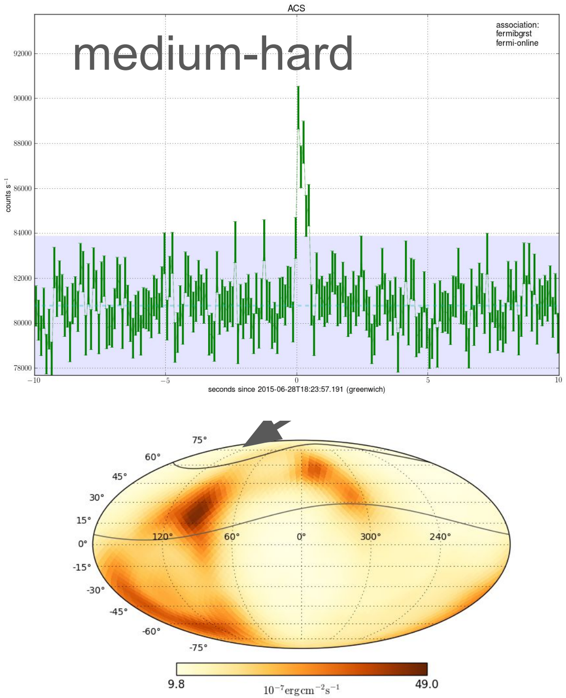
In principle, the events have different spectra and location, but does it really explain the difference?..

# Fermi/GBM sGRB with comparable fluence to GBM-GW

Typical GRBs of the same fluence are compatible between Fermi/GBM and INTEGRAL/SPI-ACS: **understanding of the intercalibration is encouraging!**



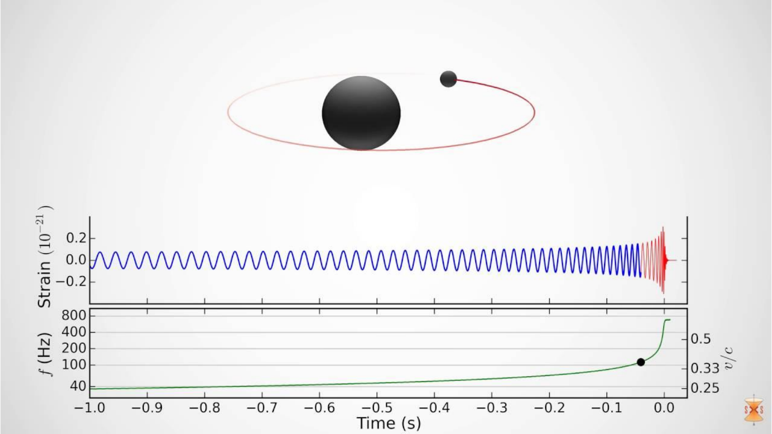



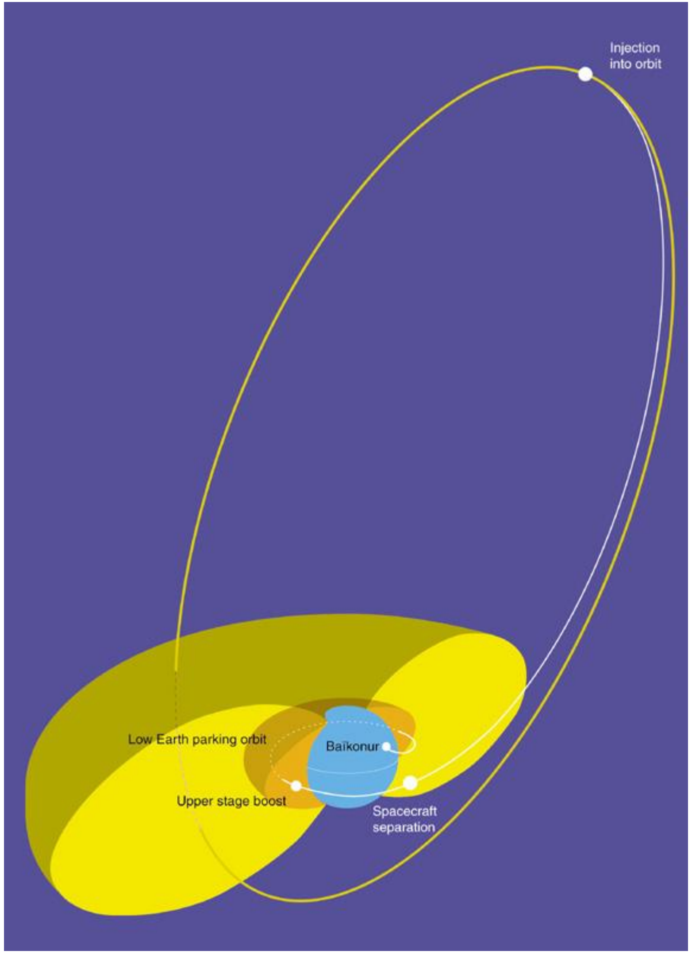
# GW151226?..

No data for hours around the event

With current orbit, duty cycle 85%...



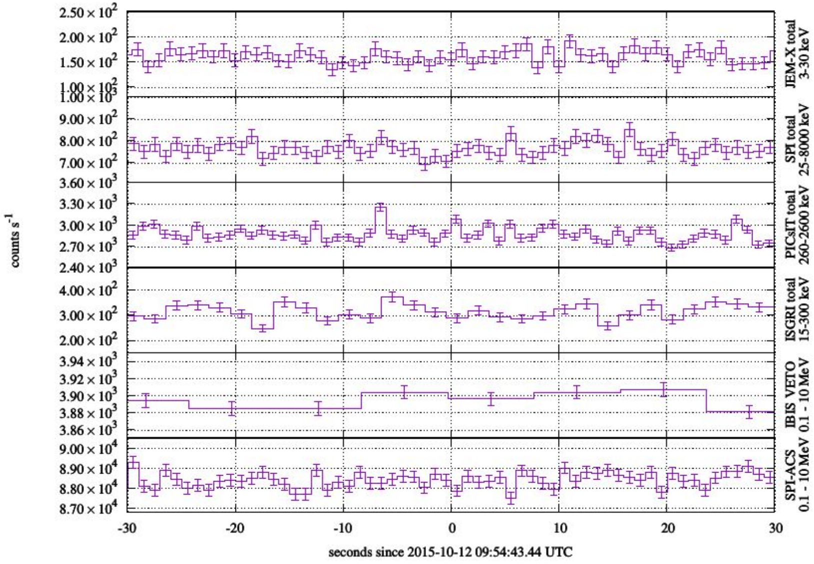

Compare to 50% of Fermi/GBM

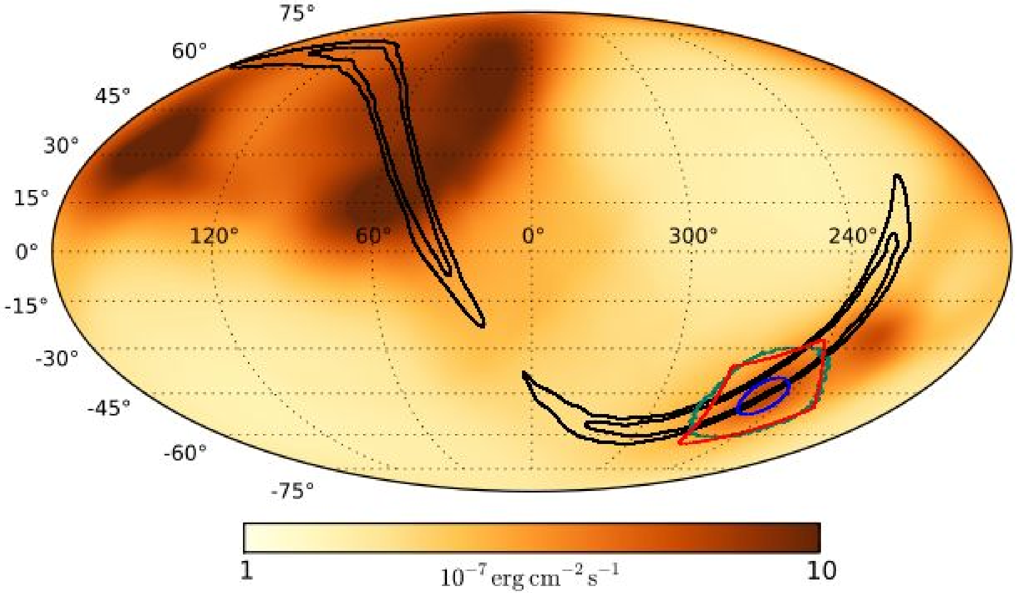


# LVT151012: SNR of 9.6, FAP of 2%

Rare lucky case: peak of the localization is in the FoV

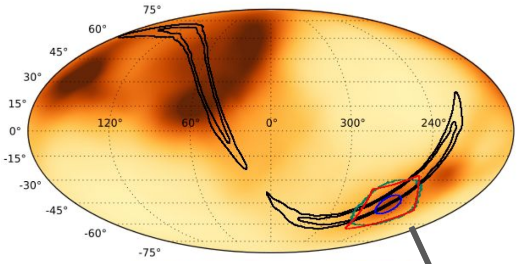
1 second, α=-0.5, $E_{peak}$=600 keV

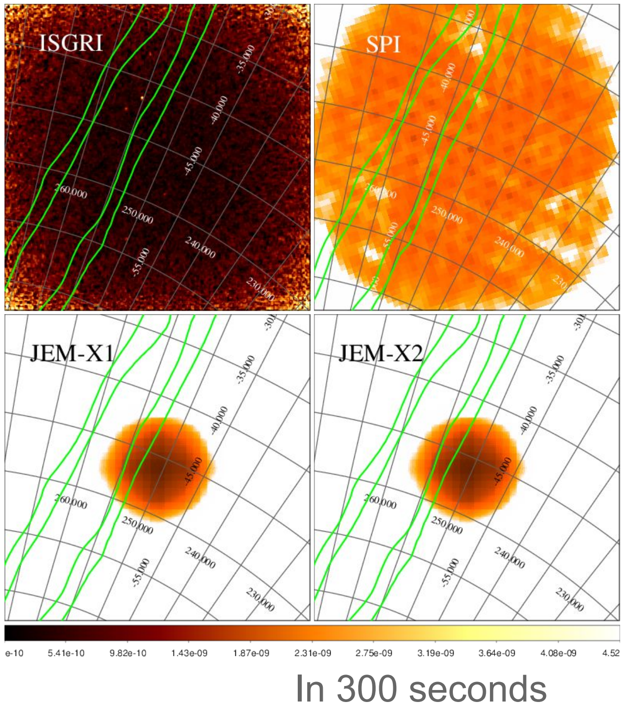


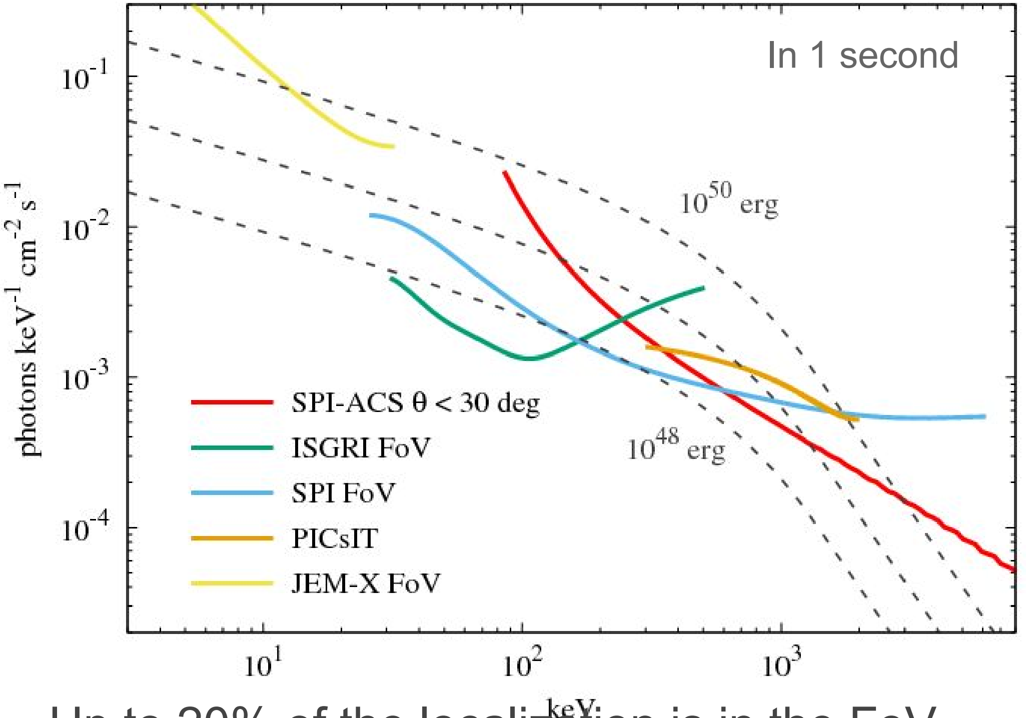




Depending on the true source location, spectrum, and duration, the best limit may come from SPI-ACS, IBIS/Veto, ISGRI, PICsIT, SPI, or JEM-X…. Lucky?..

# LVT151012: Field of View



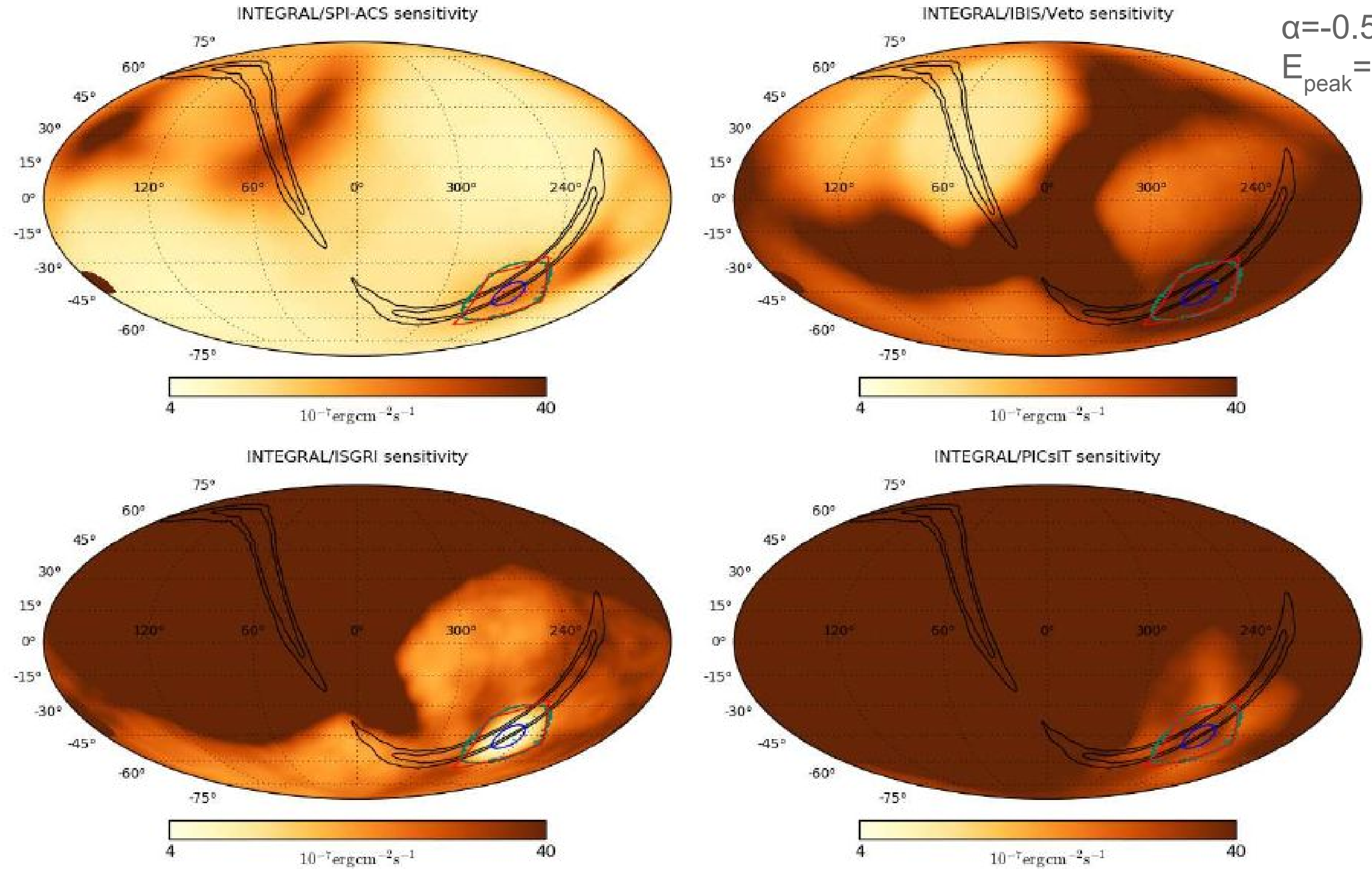




Up to 20% of the localization is in the FoV,
3 orders of magnitude covered.

LVT151012: complicated case: all-sky

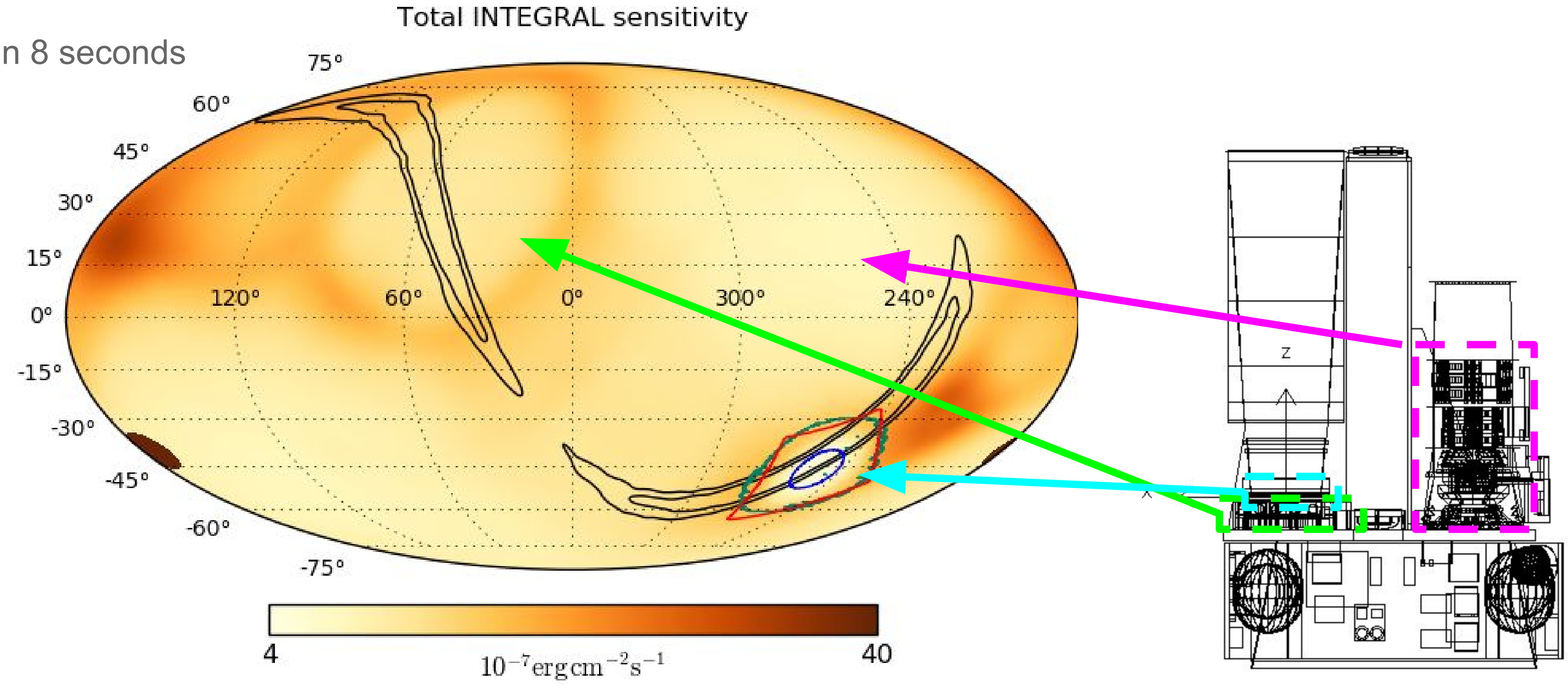
In 8 seconds
α=-0.5
$E_{peak}$=600 keV




Relative contribution of PICsIT and ISGRI reverses for very hard bursts

# LVT151012: complicated case: all-sky

In 8 seconds

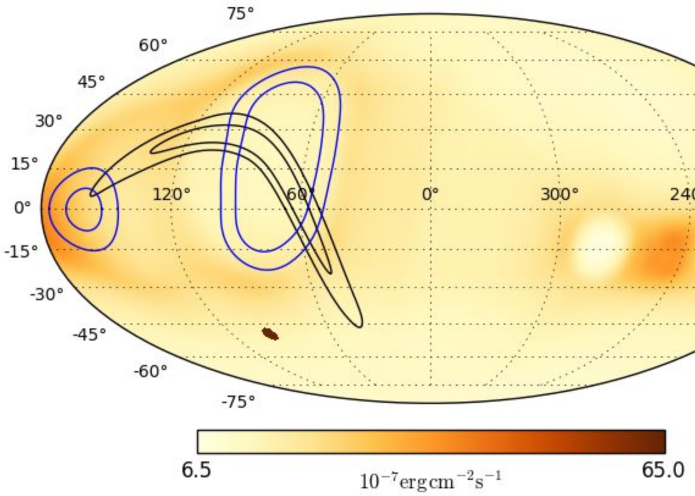


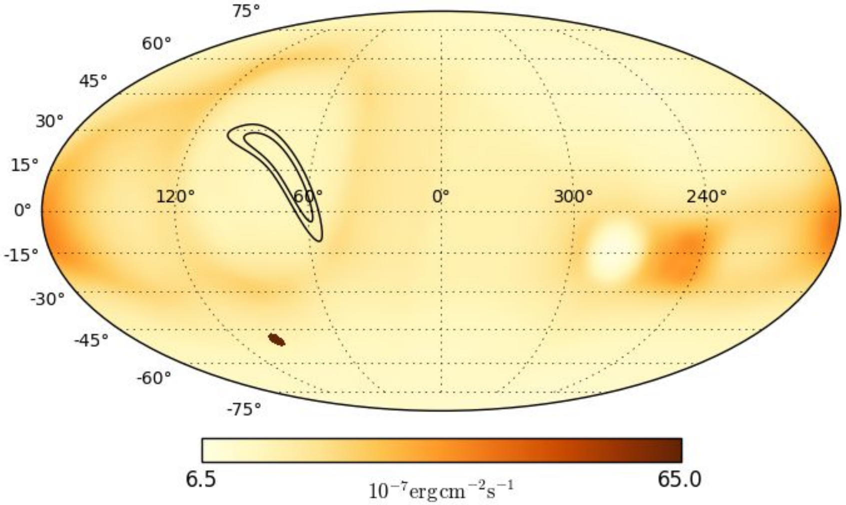

Total sensitivity is within 30% from the best in 95% of the sky, SPI-ACS only - in 75%

# All-sky localization: synthetic NS merger event at 200 Mpc

*Expectations for NS rates in LIGO O2 remain low, even lower are expected GRB rates*

INTEGRAL localization

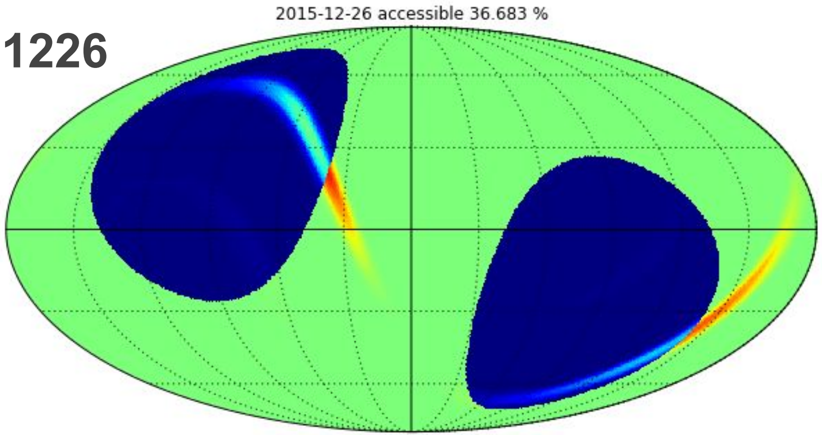


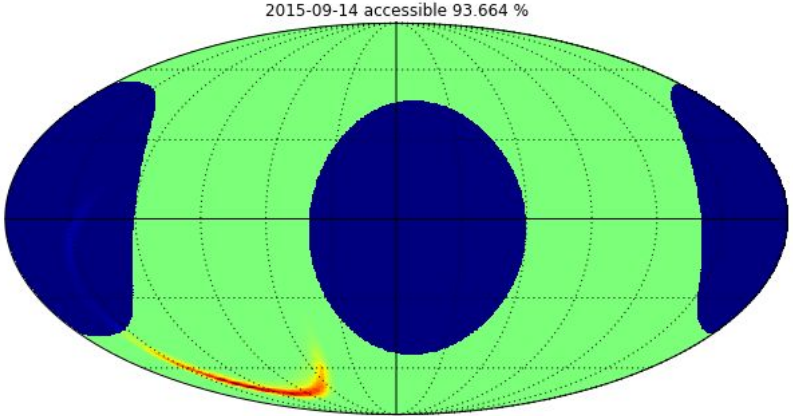




synthetic NS merger event at 200 Mpc

# Pointed follow-up: limitations

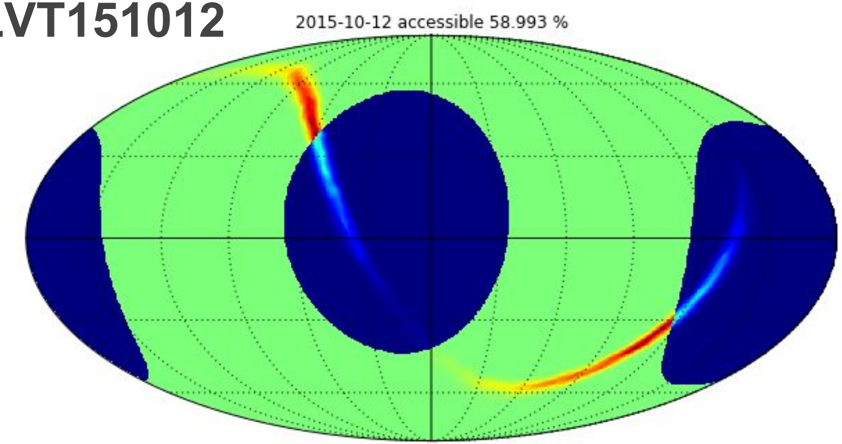
**GW151226**




**GW150914**

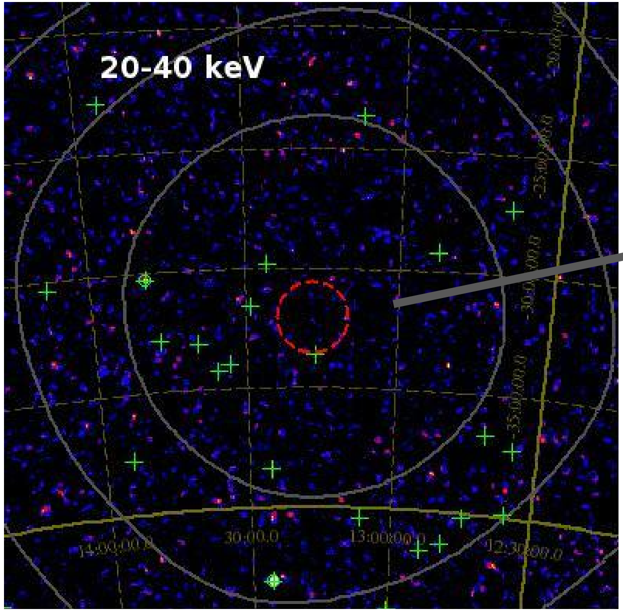
**LVT151012**

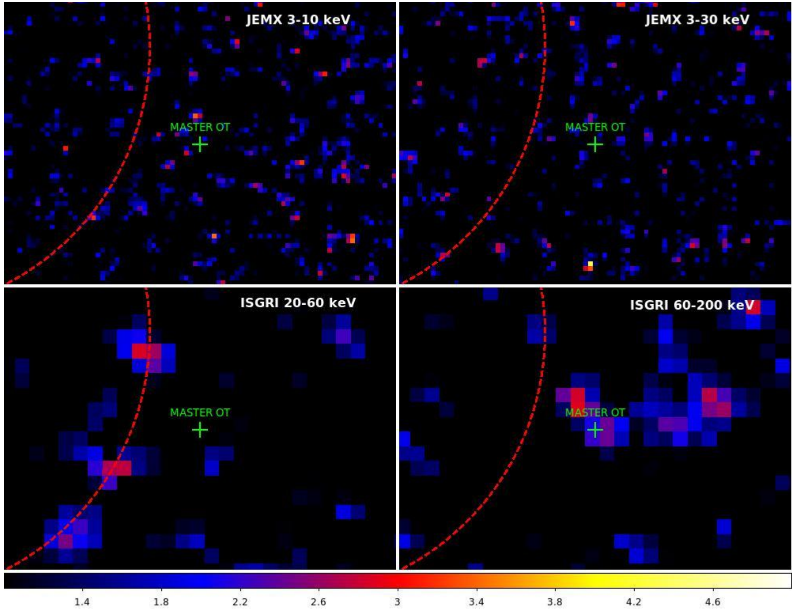



For the actual events, different fraction **36-96%** can be followed-up

# Neutrino follow-up: since April 2016

IceCube 160811




INTEGRAL also recently established MoU with IceCube to follow-up high-energy neutrino events.

Pointed follow-up of an IceCube event, for the same event an optical transient was reported by MASTER

*Tyurina et al 2016*

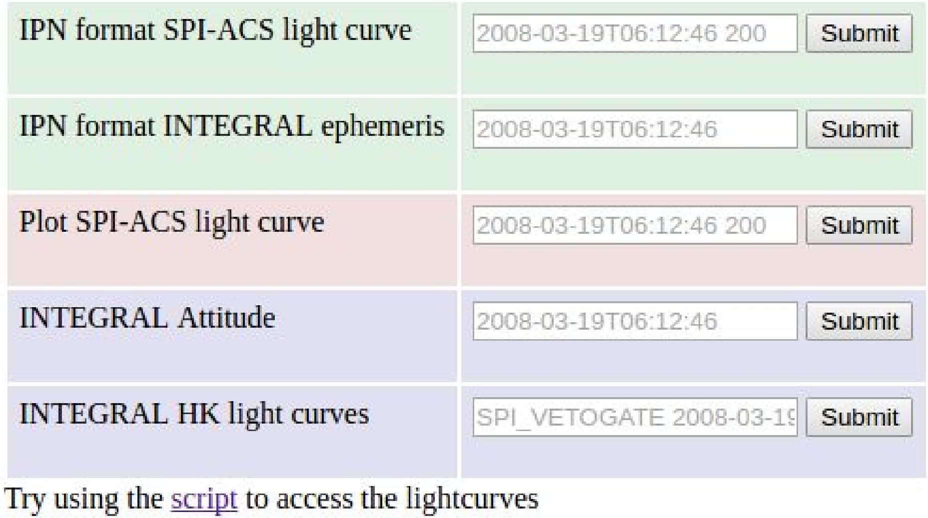
# INTEGRAL SPI-ACS public data service

In 2011, I set up a public service to promptly provide calibrated SPI-ACS data

It was extensively used for years by IPN and Konus colleagues

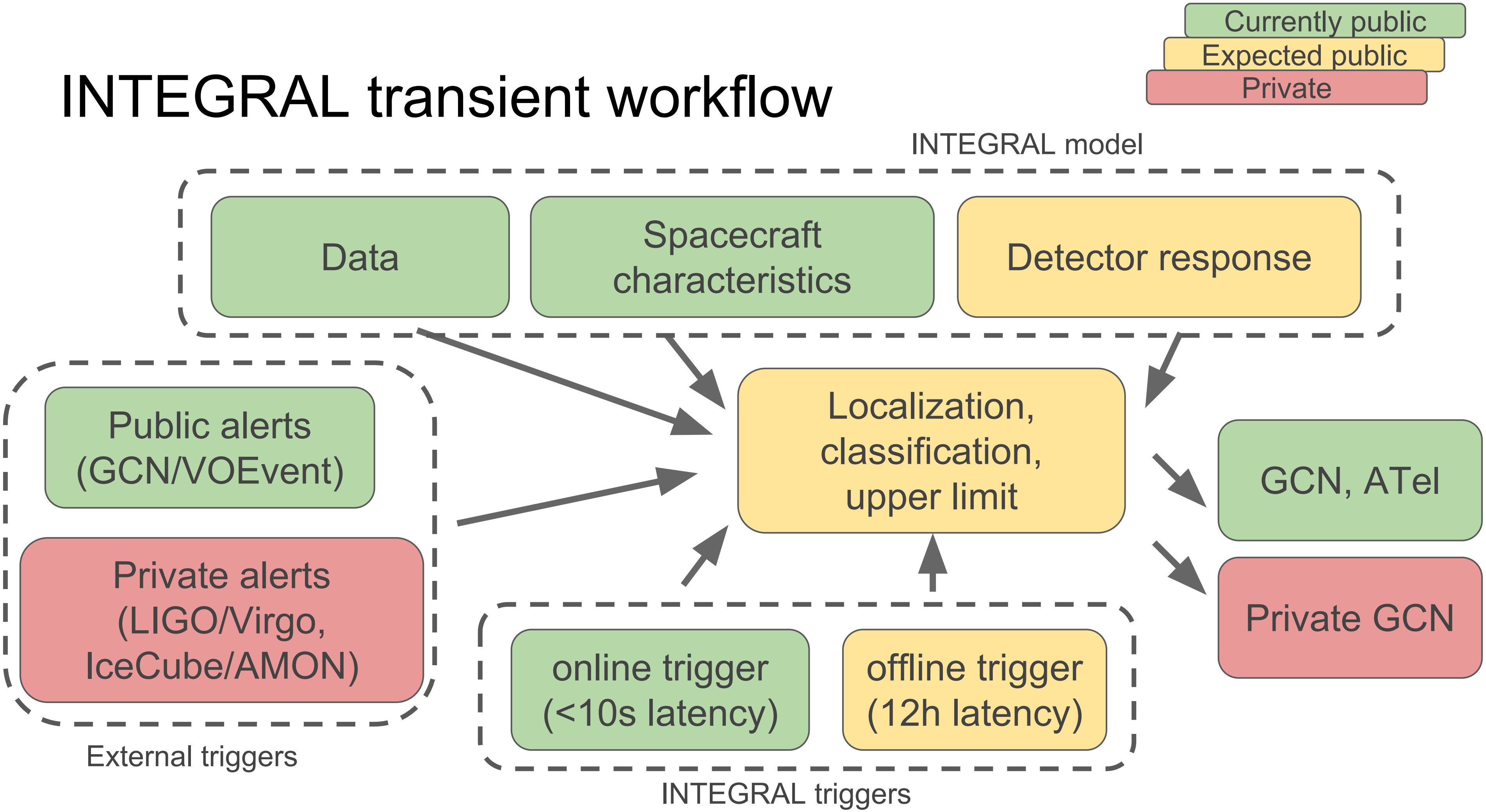
Since 2015, Fermi/GBM team used the service to verify their detections and challenge SPI-ACS

Several other groups started to use it. In total >100 Gb has been served.




Fully scriptable RESTful service, providing various public INTEGRAL data as well as auxiliary information

# INTEGRAL transient workflow

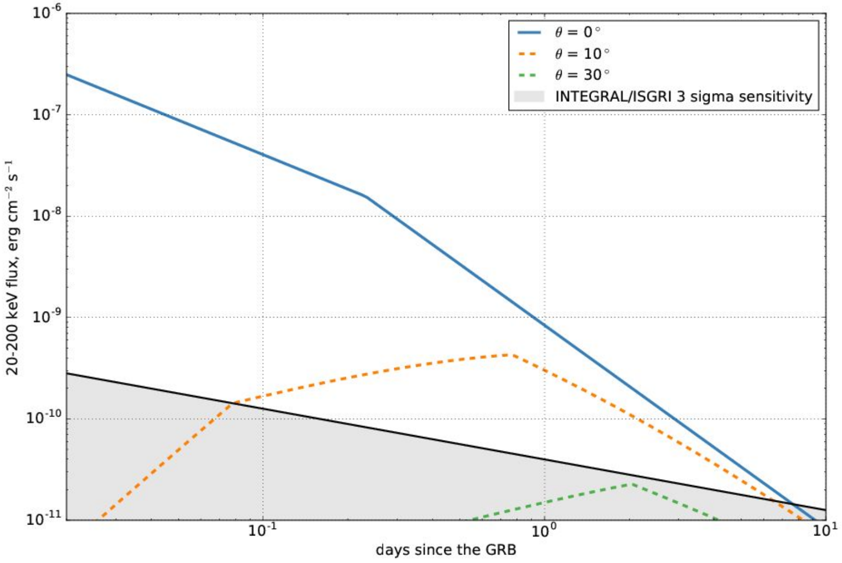


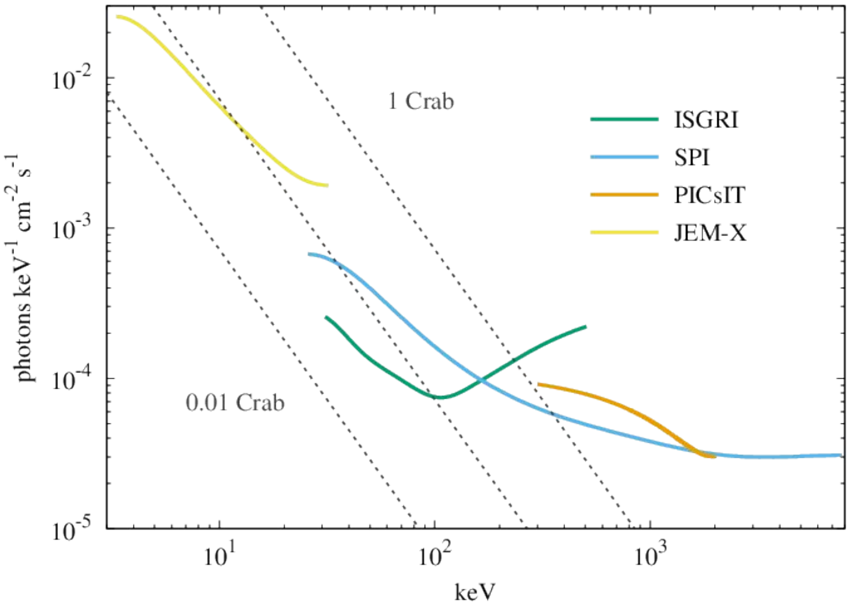
# Conclusions and outlook

- INTEGRAL strengths in multi-messenger follow-up:
  - high duty cycle, uninterrupted 2-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
- Further multi-mission calibration is required to achieve the best results
- Expected number of binary NS in O2 still not guaranteed, 50%, but it is the right time to be ready
- Fermi/GBM possible counterpart triggered a lot of theoretical research on EM counterparts BBH mergers - these sources should be abundant in O2
- Possibility for FoV observations opens interesting new opportunities

# Backup slides

# Perspectives for pointed follow-up



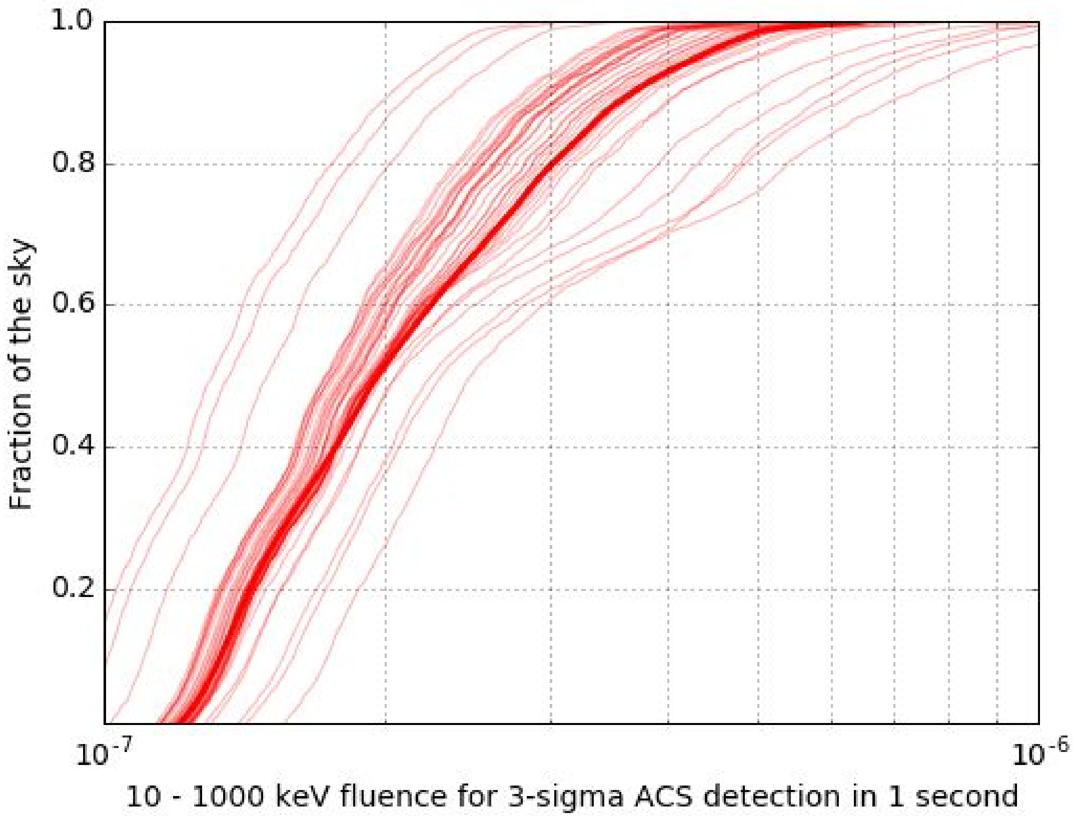




Left: Off-axis afterglow at the distance of LVT151012, prediction based on actual hard X-ray afterglow (Martin-Carillo 2014) and a simple deccelerating jet model (Granot et al 2002)

# Detection limit

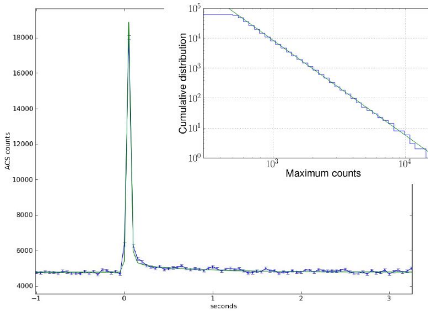
Inhomogeneous sky sensitivity results in a stretched detection threshold.

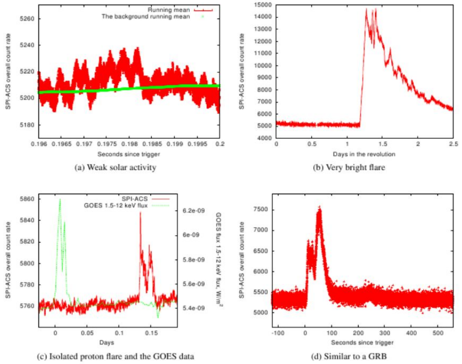
This plot assumes spectra of GBM-detected GRBs, not accounting for GBM selection bias.



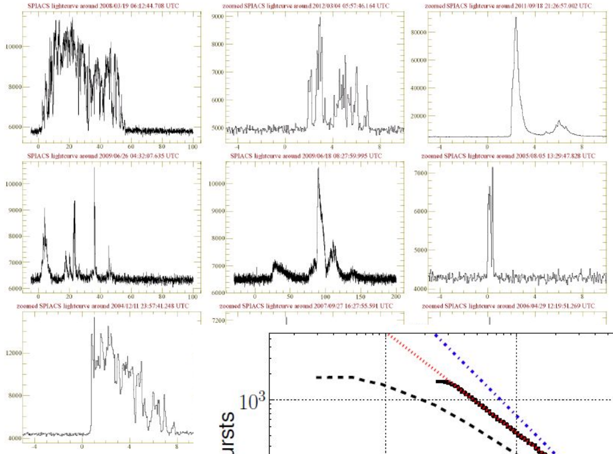
# INTEGRAL SPI-ACS excluding remaining background

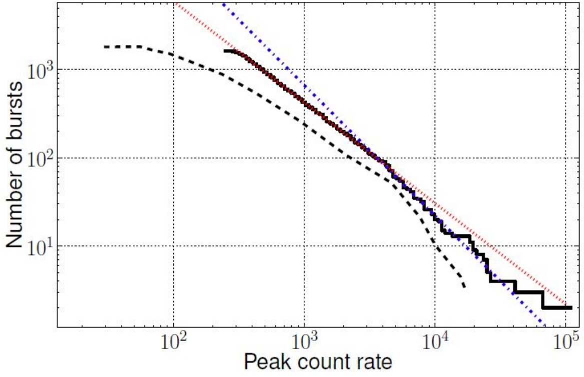
Solar activity in SPI-ACS, particle environment of the satellite. Excluded with GOES, and background stability




High-energy cosmic ray interactions: < 50 ms, 30/day, Identical predictable profiles, can be excluded.



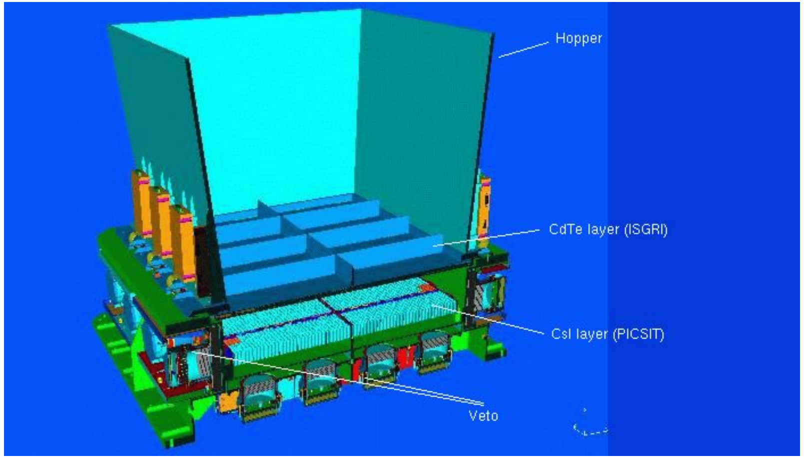


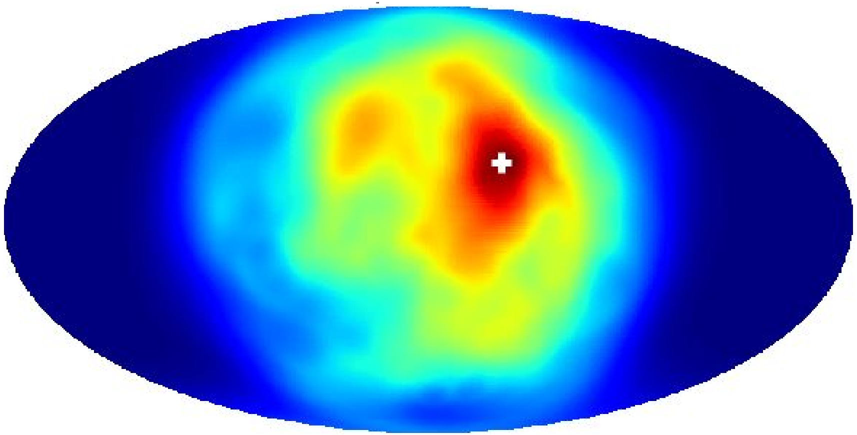

~1 GRB alert in 1.5 days, 50% confirmed

*Savchenko et al 2012*

# IBIS Compton mode

In about **50% of the sky** IBIS Compton mode can be used to measure location of bright bursts with about **5 degree PSF**.



INTEGRAL/IBIS compton mode localization of GRB090902B: 40 degrees off-axis.

# Other INTEGRAL SPI-ACS results

*Hurley et al 2016*

IPN network uses data provided by instrument teams to localize bursts with triangulation, also allows to systematically compare instruments: **compatible with INTEGRAL team result**.

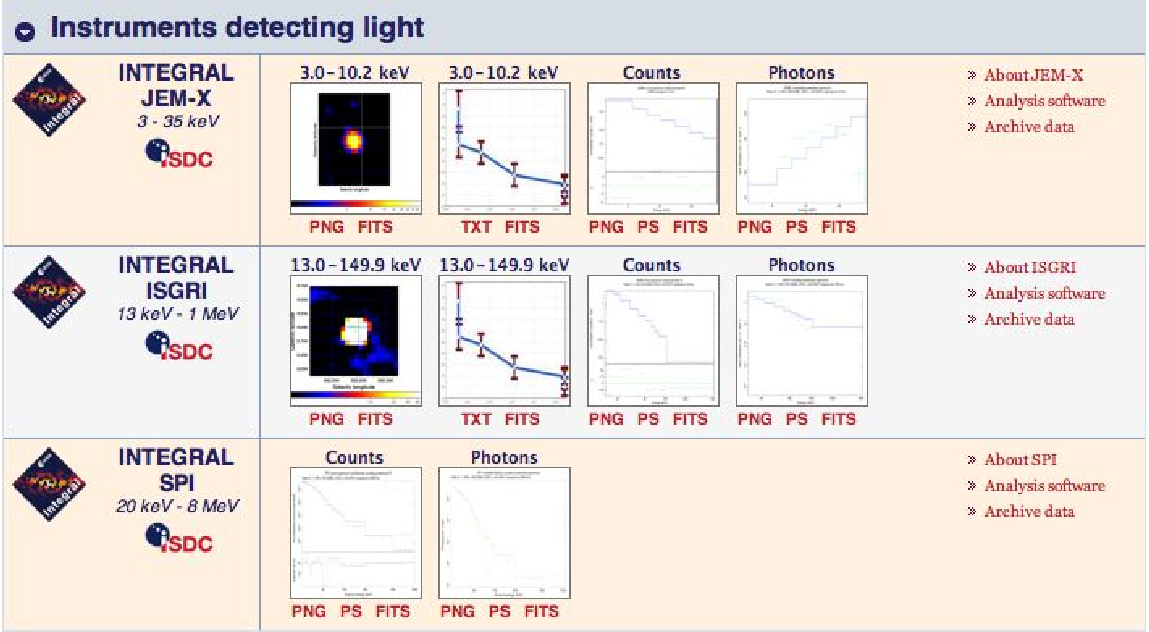
| Instrument | Orbit | Maximum Sky Coverage, % | Duty Cycle, % | Energy Range, keV | Approx. Sensitivities, erg $cm^{-2}$ | Number of GRBs/y |
|---|---|---|---|---|---|---|
| *Odyssey* HEND | 400 km, 93°1 | 72 | 86 | 50–3000 | $7 \times 10^{-8}$, $2 \times 10^{-7}$ | 67 |
| *RHESSI* | 600 km, 38° | 69 | 59 | 30–150 | $5 \times 10^{-8}$, $1.5 \times 10^{-7}$ | 69 |
| *Swift*-BAT | 600 km, 20°6 | 69 | 86 | 15–150 | $10^{-7}$, $5.3 \times 10^{-7}$ | 83 |
| *Konus-Wind* | $1.5 \times 10^6$ km | 100 | 99.4 | 20–1450 | $7 \times 10^{-8}$, $4.3 \times 10^{-7}$ | 169 |
| *INTEGRAL* SPI-ACS | $1.5 \times 10^5$ km, 52°5 | 100 | 94 | ≳75 | $2.5 \times 10^{-8}$, $1.1 \times 10^{-7}$ | 221 |
| *Fermi*-GBM | 530 km, 25°6 | 69 | 83 | 10–1000 | $2.3 \times 10^{-8}$, $2 \times 10^{-7}$ | 248 |

Another alternative analysis of the ACS data, not based on the response model, also suggests **SPI-ACS should have seen the GBM-GW event**

*Pozanenko et al 2016, Huntsville GRB symposium*

# Heavens at ISDC: archival data

http://www.isdc.unige.ch/heavens/



# LIGO/Virgo O2 expectations: binary Neutron Stars

Expectations for NS rates in LIGO O2 remain low, even lower are expected GRB rates, but including low-SNR LIGO events we expect up to 50% chance of a short GRB in coincidence. Every detection will be 50 sigma in SPI-ACS  at least.