INTEGRAL highlights and perspectives for GW counterparts search

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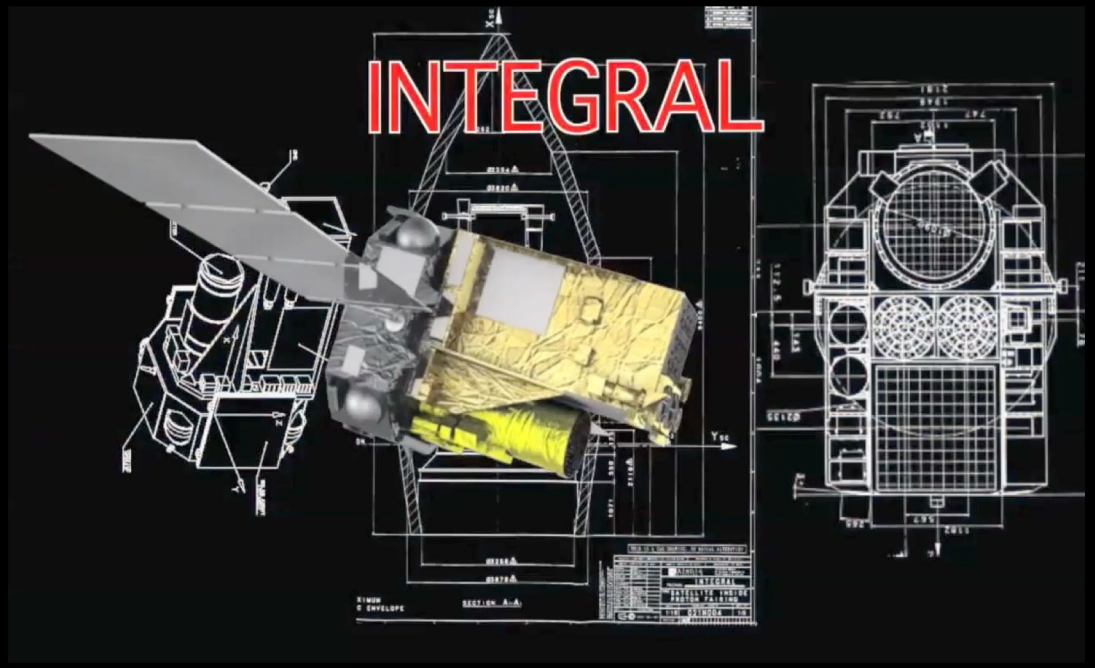
on behalf of the INTEGRAL GW Team

Ligo-Virgo MoU 5/4/2014

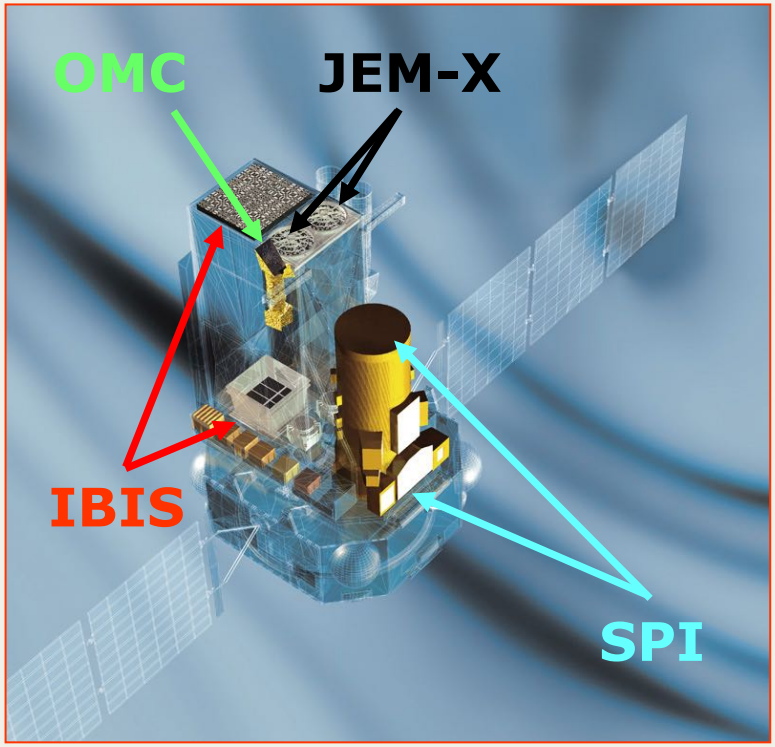


RICAP2018, University Roma TRE, Rome
Physics Department, 4-7 September, 2018


Cos-b
August 1975
Exosat
May 1983
BEPPO-SAX
April 1996
XMM-Newton
December 1999
Integral
OCTOBER 2002
Swift
November 2004
Agile
April 2007
Fermi
June 2008
Athena
CTA
From BeppoSAX increasing the energy range in the last 20 years → XMM → INTEGRAL → AGILE → and near future ATHENA and CTA to exploit high energy gamma ray science
Italy-Europe has a four decades worldwide record of success in the field of high energy astrophysics

The ESA Gamma-Ray Observatory

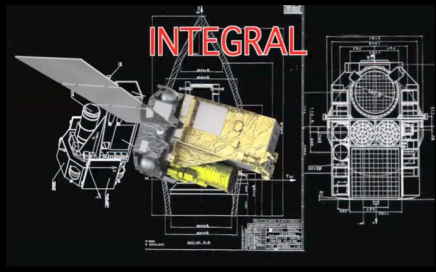
- **INTE**rnational **G**amma-**R**ay **A**strophysics **L**aboratory
  - Medium-sized mission (Horizon 2000) - Launched 17 October 2002
  - Highly elliptical orbit (~72 hrs); 58 hrs of continuous science



- **4 instruments:**
  - **IBIS**: imaging
  - **SPI**: spectroscopy
  - **JEM-X**: X-ray monitor
  - **OMC**: optical monitor

- ***All operating simultaneously***
  - IBIS, SPI, JEM-X: large FOV

INTEGRAL: ESA International Gamma Ray Observatory
16 ° years of scientific success → Heading 2020



INTEGRAL main features:

- ✓ 3 keV-10 MeV energy range with unprecedented sensitivity
- ✓ Wide FoV:≈ 100-1000 deg^2 plus..
- ✓ Allsky monitor capability in the range 80 keV - 2.5 MeV
- ✓ High time resolution <120 μs absolute
- ✓ Arc min angular accuracy and keV energy resolution
- ✓ Unique polarimetry capabity
- ✓ Long uninterrupted observations 2.7days, 6 h perigee passage
- ✓ Real-Time GRB transmission to ground and web delivery →

17TH/10
16 YEARS
BIRTHDAY!

INTEGRAL is the link between soft X-ray and high energy γ-ray science

So far > 1100 INTEGRAL papers published

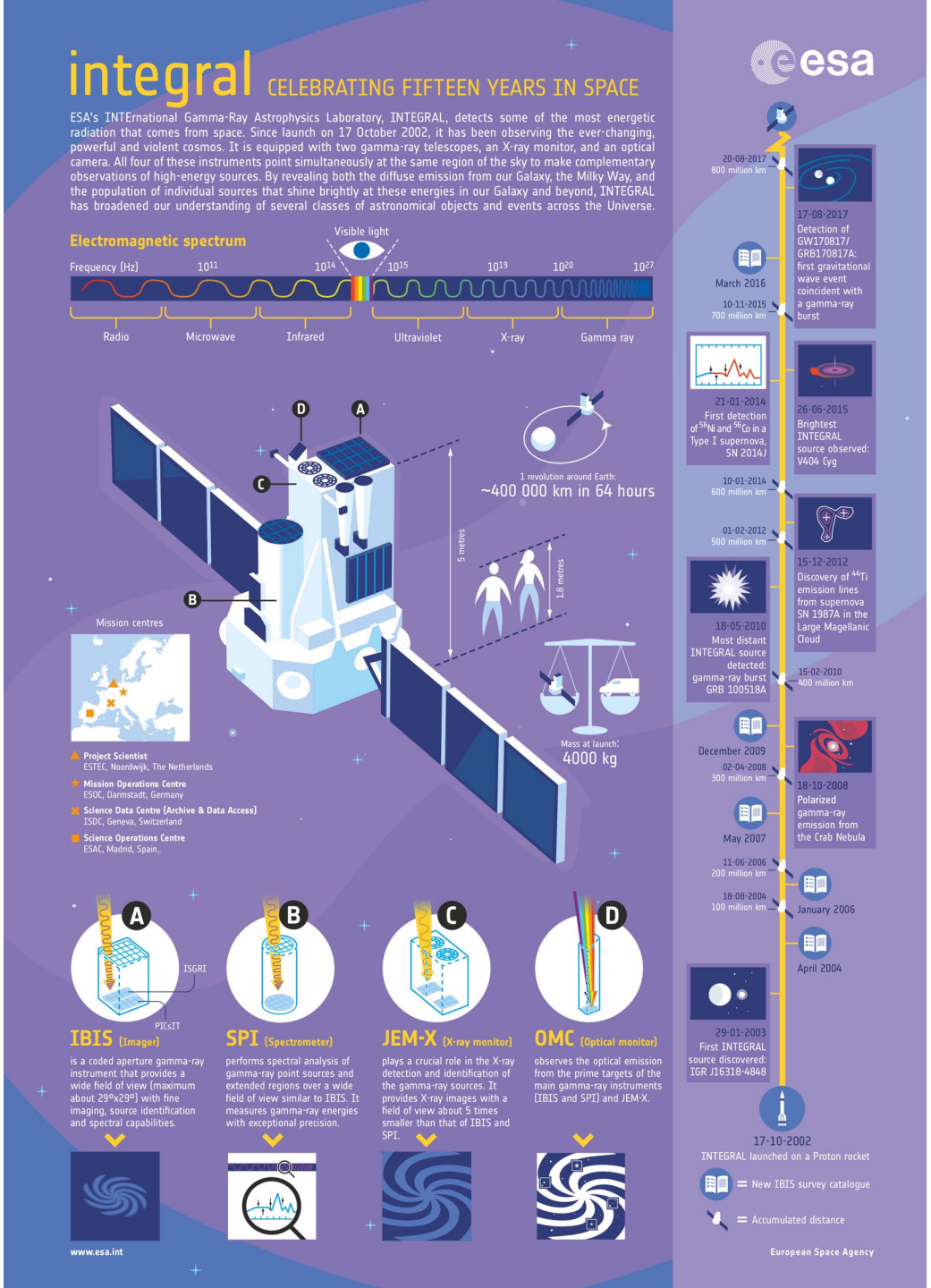
102+7 on-going PhD thesis (15+1 Italy)
and 110+ press release

RELEVANT STEPS/FACTS

Instruments characteristics

Surveys

MAIN scientific results



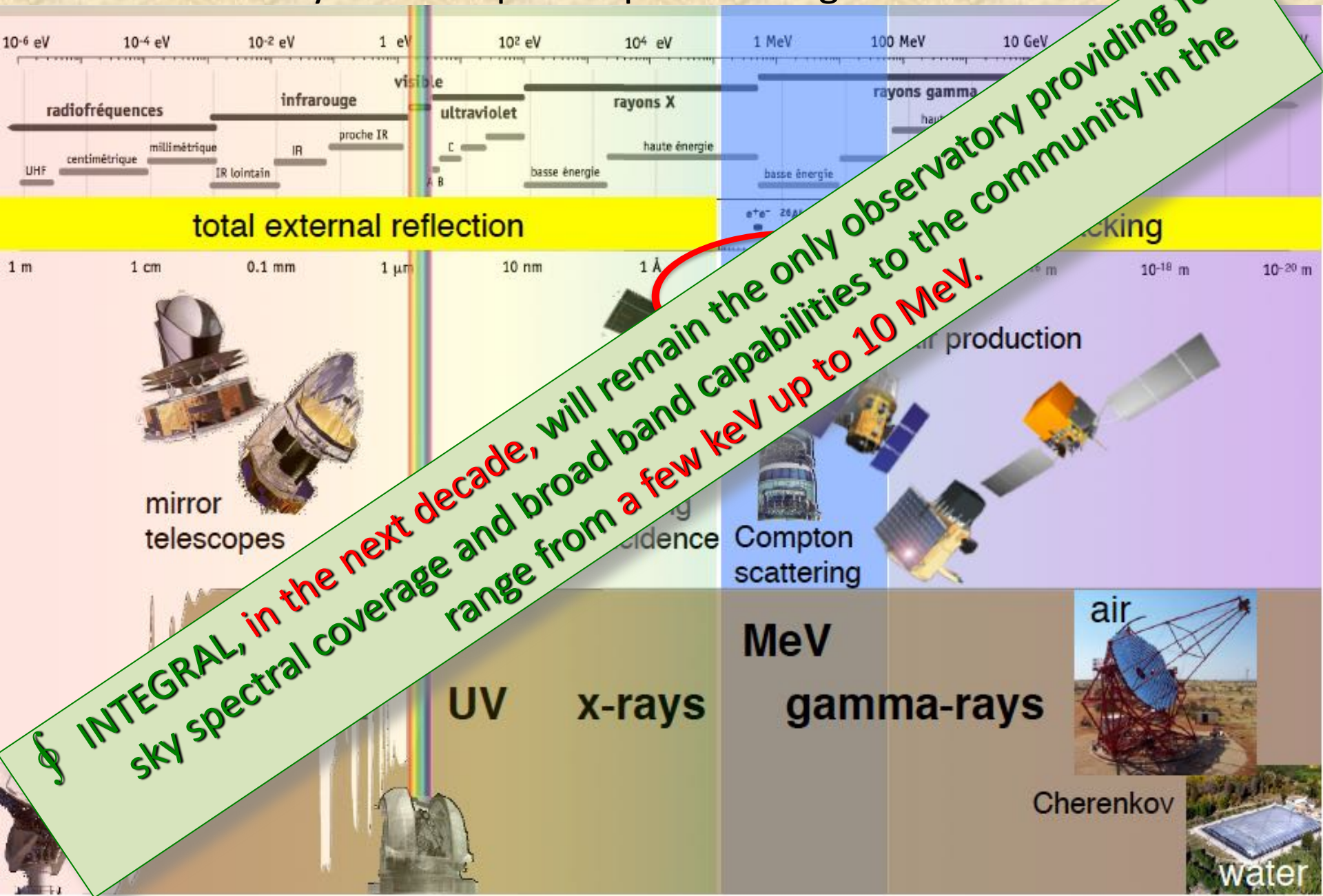
IUG
INTEGRAL Confirmation & Extension

- **INTEGRAL continues to address key questions from ESA's Cosmic Vision 2015-2025 plan: '*What are the fundamental physical laws of the Universe?*' and '*How did the Universe originate and what is it made of?*'**

- **INTEGRAL's operations have been approved in November by ESA SPC until the end of 2019 with indicative extension up to 2020 suggested in Decemeber 2017. FINAL decision expected in November 2018 after revision of IUG new docuement includin MEOR reccomandation. (see next slide)**

- **Note that the number of publications in 2017, 2016 and 2015 increased by ~25% with respect to 2014; this is possibly due to the unsolicited time made available to follow up on rare events (ToO) and immediate public availability of the data**

High-energy X/γ-rays probe the extreme, non-thermal Sky with basically no absorption up to the edge of the Universe



Key science capabilities

➢ γ-ray line spectroscopy & imaging

- Nucleosynthesis: lines from elements formed in massive stars, SNe & (X-ray) novae
- Positrons in the Galaxy: annihilation with electrons (511 keV emission)

INTEGRAL will remain the *only* observatory allowing these studies

➢ γ-ray polarimetry

- Unique diagnostic of the photon source process (magnetic fields)
- Neutron stars, black holes, pulsars, magnetars, gamma-ray bursts

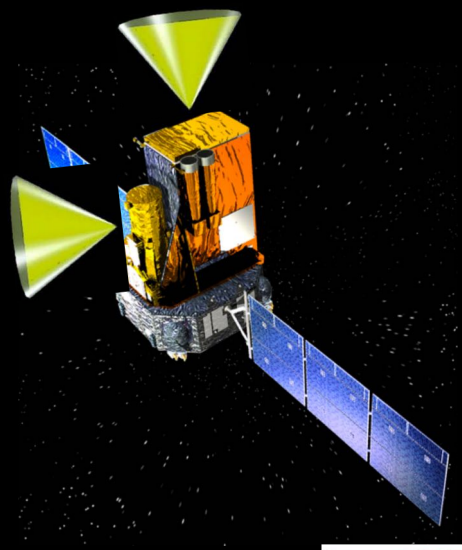
➢ Large FOV (~900 square degrees) + arcmin localisation

- Omni-directional view through shields

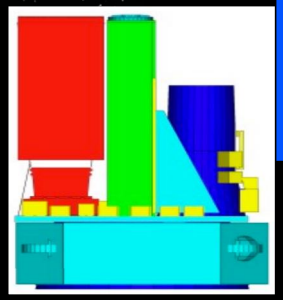
INTEGRAL to hunt γ-ray transients

The SPI/ACS detectors view ~4π solid angle of the sky.
E>75 keV, Tres=50ms
Effective area: up to $1m^2$

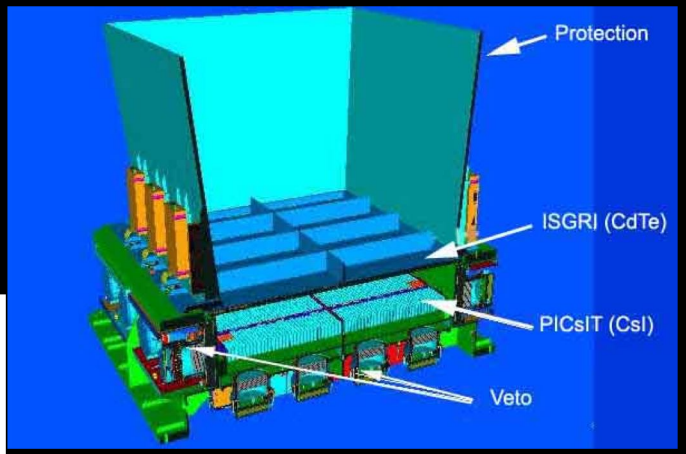
The IBIS detectors ISGRI and PICsIT have max sensitivity to directions normal to SPI/ACS factor of 5 at least



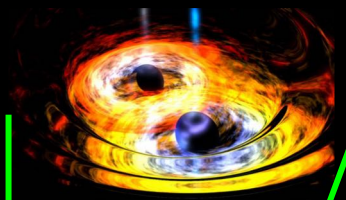
The sensitivity to a gamma-ray transient depends on sky position and its evaluation must take into account the payload and satellite masses distribution



Outside the IBIS FOV (~30x30 deg^2) the ISGRI and PICsIT detectors also view ~4π up to 2.6 MeV.
PICsIT: T_res=15.6ms
Effective area up to ~$900cm^2$



INTEGRAL has two independent instruments with all-sky area coverage in the range 70 keV- 2.6 MeV
SPI-ACS: 91 BGO units 5-8 cm thick
IBIS-VETO: 16 BGO units 2 cm thick
providing about 6,000 cm² sensitive area or 12,000 cm³ volume s

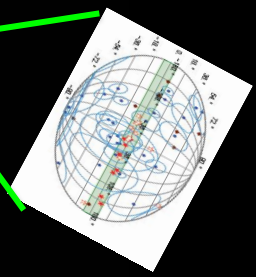


Gravitational Wave Triggers

Sky angle not covered by the SPI-ACS and IBIS-VETO

153.000 km

Almost the full Sky is covered by the SPI-ACS and IBIS-VETO 21 out of 27 hours due to TLM off at perigee passage
Full corage to GW & HE Neutrino's triggers

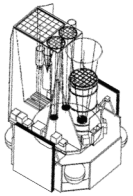


Neutrino's counterpart search

4π of the sky: expect the unexpected

Shields of SPI & IBIS

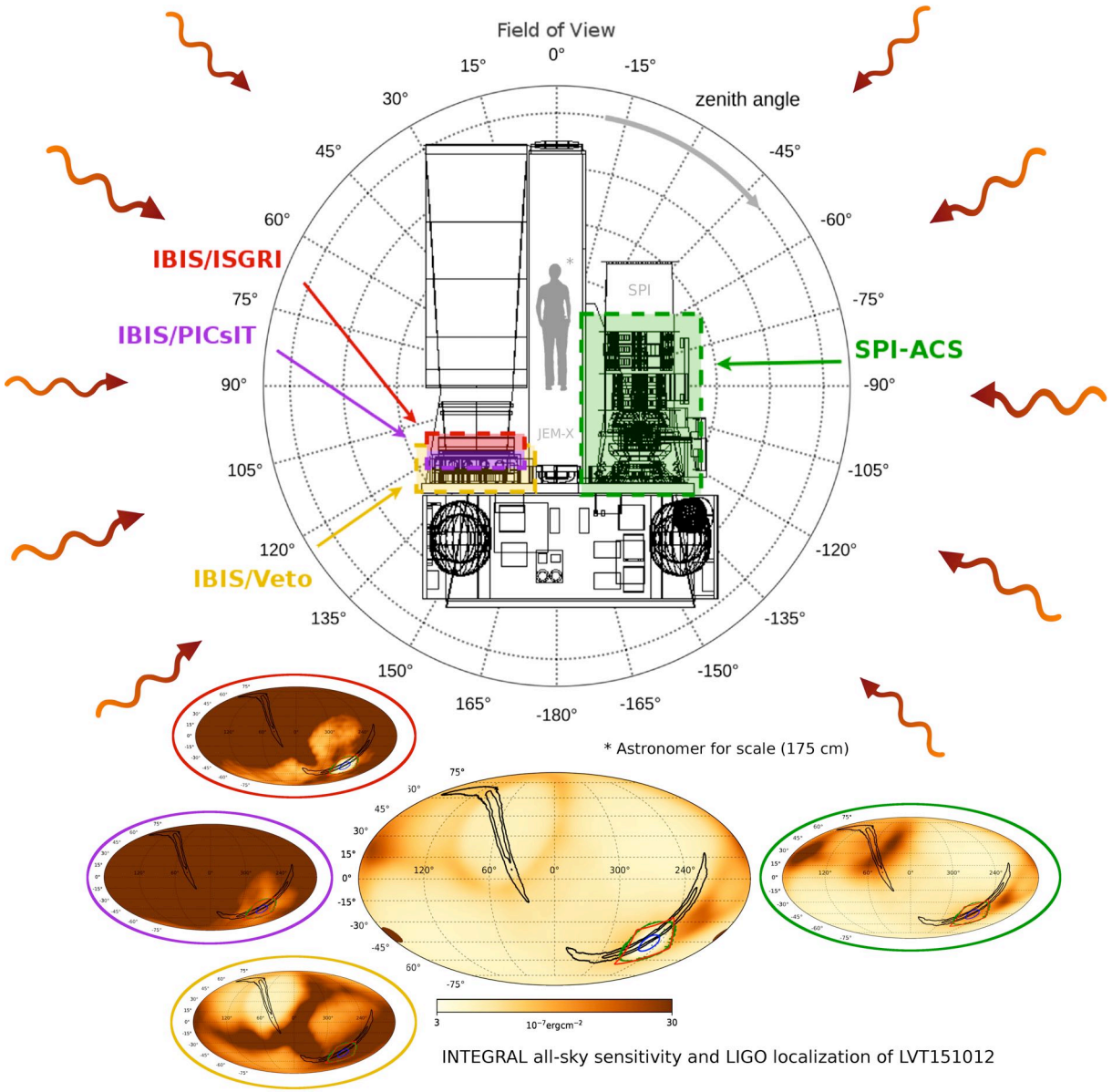
- **SPI/ACS:**
  >75 keV, 50 ms - Effective area: ~1 m^2
- **IBIS/PICsIT**
  ~0.25-2.6 MeV, 15.6 ms - Effective area: ~900 cm^2



Thanks to the Anti-Coincidence Shields (ACS) of SPI & IBIS it will ***immediately*** detect high-energy photons from *any* event at ***any direction on the sky***

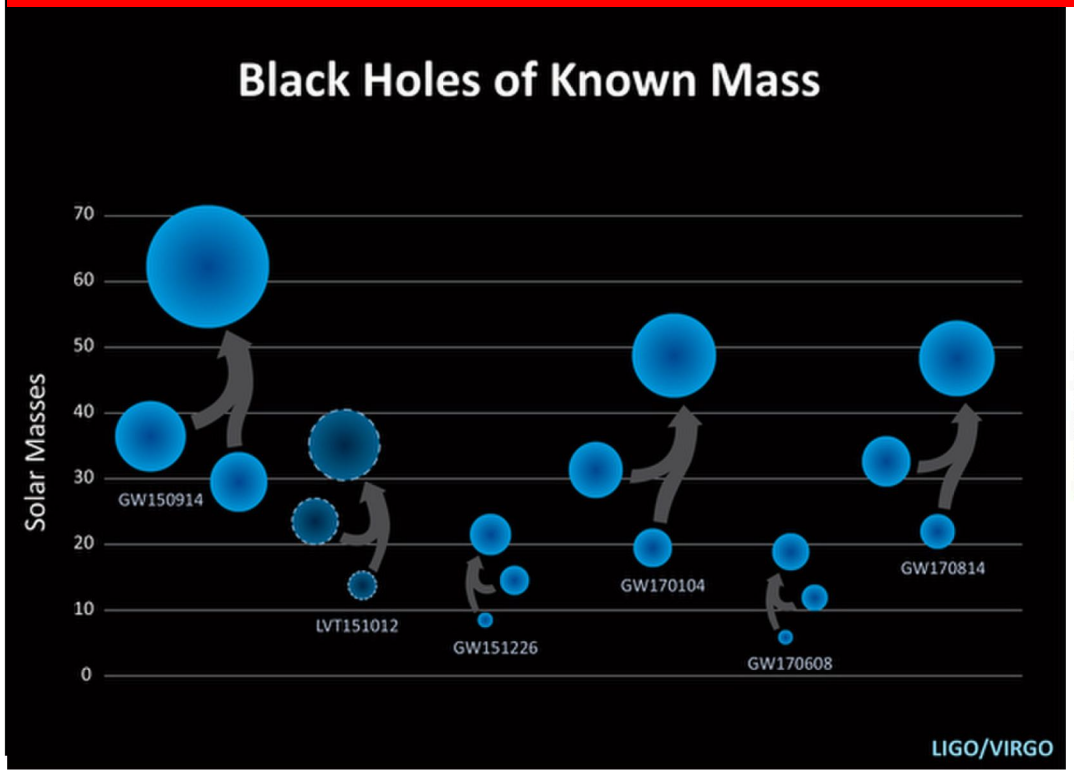
- **Omni-directional view!**

- **γ-ray burst (GRB)** detections by INTEGRAL so far, on average:
  - ~200 per year in the ACS of SPI
  - ~5 per year in Field of View of IBIS & SPI

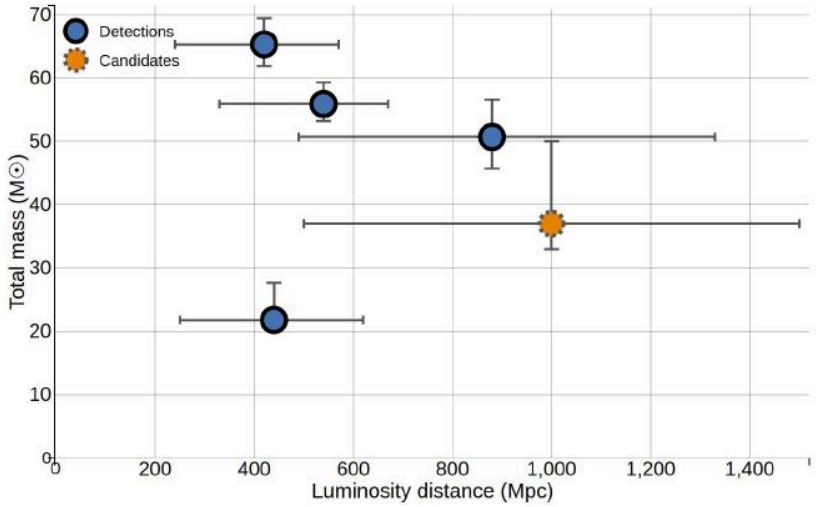


INTEGRAL all-sky sensitivity and LIGO localization of LVT151012

In fact, INTEGRAL has observed 5 out of 6 BH-BH mergers

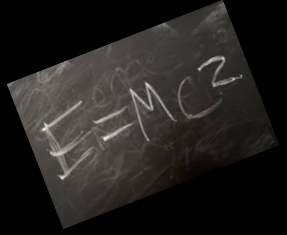


LIGO/Virgo network discovered an unexpectedly larger population of heavy BBH, observable up to **1500 Mpc**

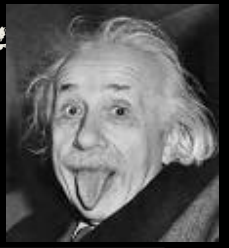


http://chrisnorth.github.io/plotgw/

LIGO-VIRGO detection	INTEGRAL Observation
GW150914	Savchenko et al., ApJL, 820, 2, L36, 2016, Abbot et al., ApJL, 826, L13, 201
	Abbot et al., ApJS., 225, 8A, 2016
LVT151012	Savchenko et al., A&A, 603, A46, 2017
GW151226	Missed, pergee passage
GW170104	Savchenko et al., ApJL, 2017
GW170814	Savchenko et al., GCN
GW170817 NS-NS Inspiral	Savchenko et al., ApJL 848, L15, 2017, Abbott et al., ApJL 848, L12, 2017
	Abbott et al., ApJL 848, L13, 2017



However , one of the main expected sou
of GW is the inspiral of binary NS:
GW170817 = GRB170817A
is the text book case!!



LIGO-Virgo Black Holes

X-ray Binary
Black Holes

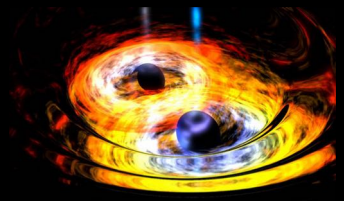
Small BH, or
Massive NS (EoS still realistic?),
New physics object?.....

Known Neutron Stars

LIGO-Virgo Neutron Stars

Credits: LIGO-VIRGO Collaboration

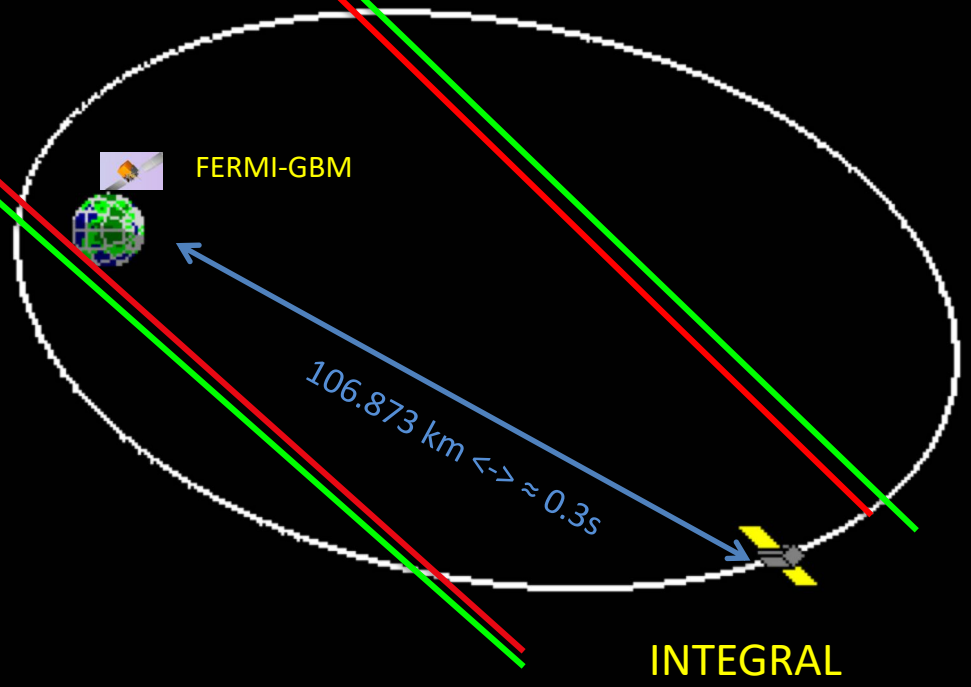
P. Ubertini, IAPS-INAF



Direzione di arrivo del segnale Gravitazionale (GW) dalle due stelle di neutroni che si fondono (NS-NS)

Arrival sequence of the Signals:

- Virgo (Pisa)
- FERMI LEO
- Geo Centre
- LIGO Livingston
- LIGO Hartford
- INTEGRAL HEO



P. Ubertini, IAPS-INAF

Till the 17 August 2017 theer were only GW detection from BBH mergers with only upper limits in the EM domain… no astrophysical signals apart GWs me lag report of the events GW170817/GRB170817A

... And then there was LIGO/Virgo; and there were Fermi and INTEGRAL ...

Gamma rays, 50 to 300 keV

GRB 170817A

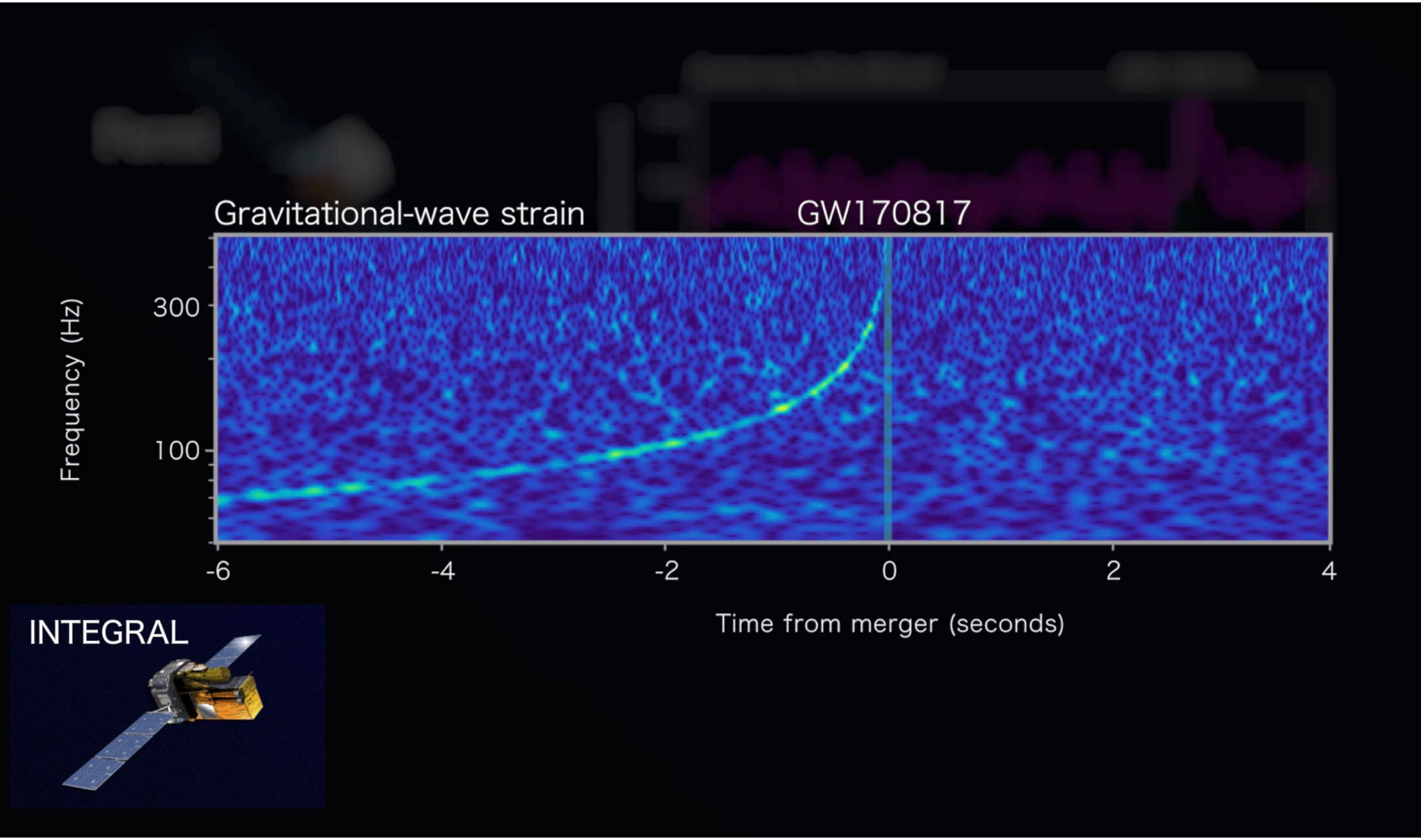
Counts per second

1,500

1,000

500

LIGO-Virgo


Gravitational-wave strain
GW170817
Frequency (Hz)
300
100
-6
-4
-2
0
2
4
Time from merger (seconds)
INTEGRAL

FERMI-LVC-INTEGRAL time lag report of the events GW170817/GRB170817A

Fermi

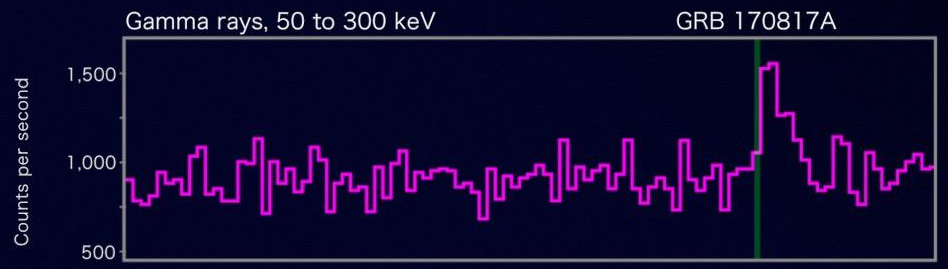
Reported 16 seconds after detection

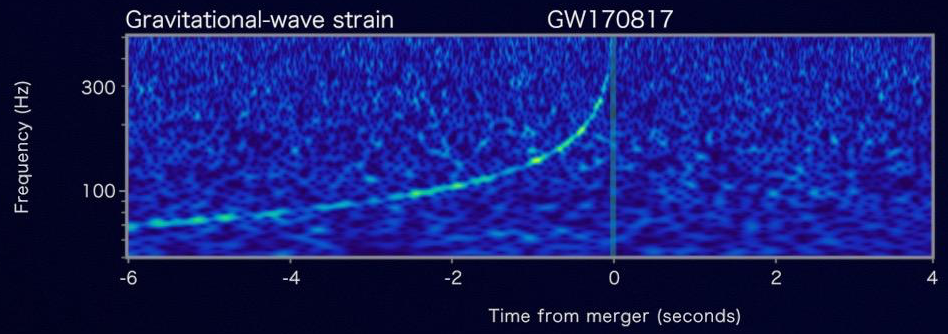
LIGO-Virgo

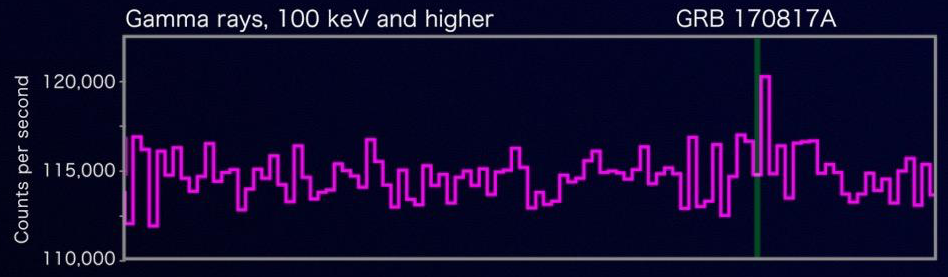
Reported 27 minutes after detection

INTEGRAL

Reported 66 minutes after detection







Current Work

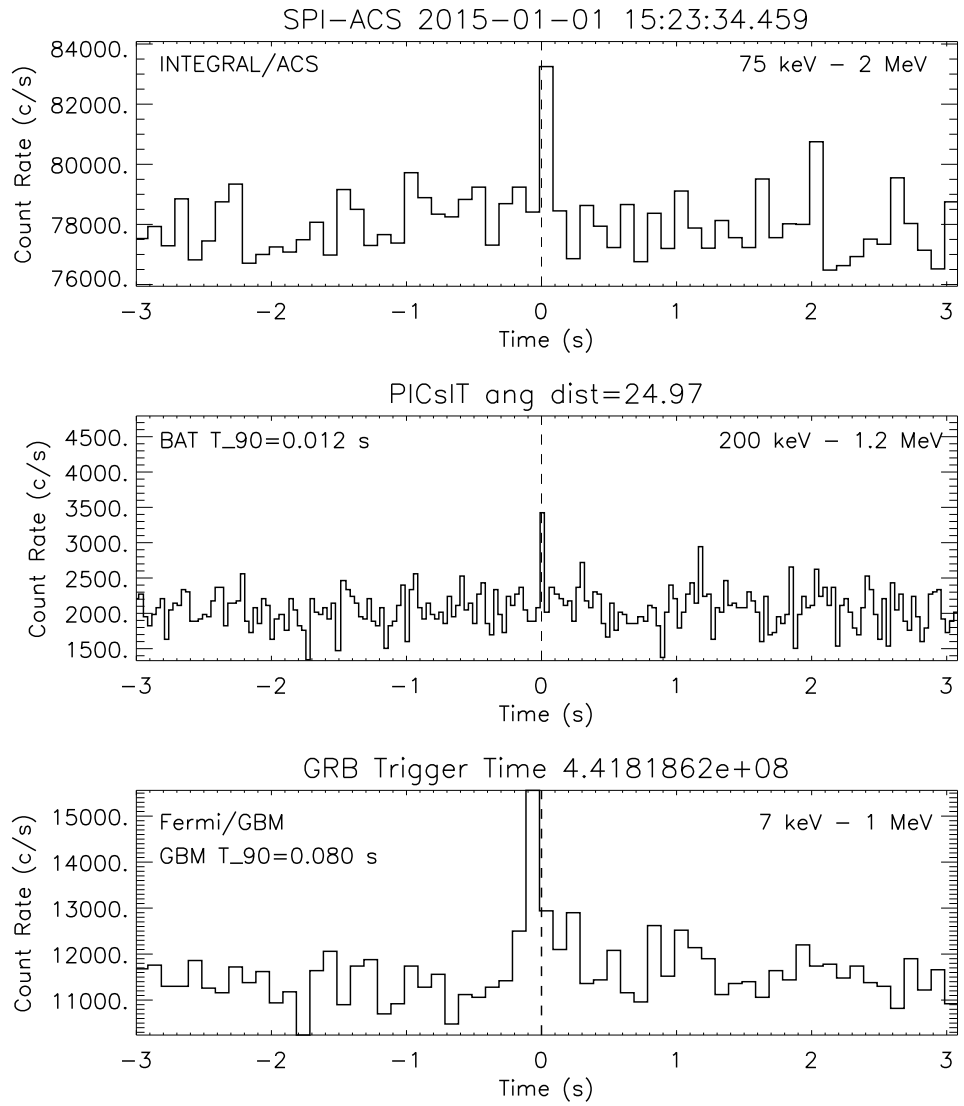
- **Common search of under-threshold Ligo-Virgo signals coincident with INTEGRAL sGRBs**

- **Search for past *INTEGRAL*/PICsIT GRBs previously reported by other instruments, focus on short GRBs:**
  the GRB1150101 case: a GW170817 extra luminous gemini?

- **Spectral analysis of soft gamma-ray spectrum above ~300 keV to extend *Fermi*/GBM results**

- **Search of *INTEGRAL*/PICsIT and SPI/ACS data for faint SGRBs below trigger threshold**

LAST NEWS

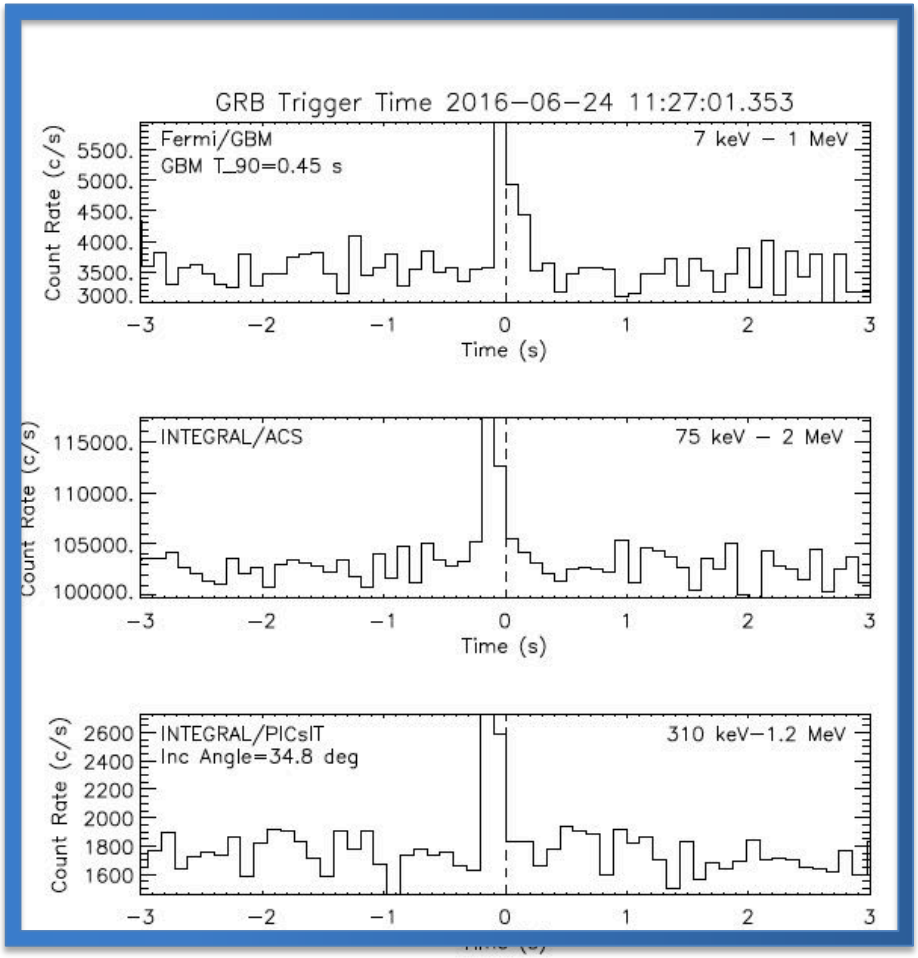


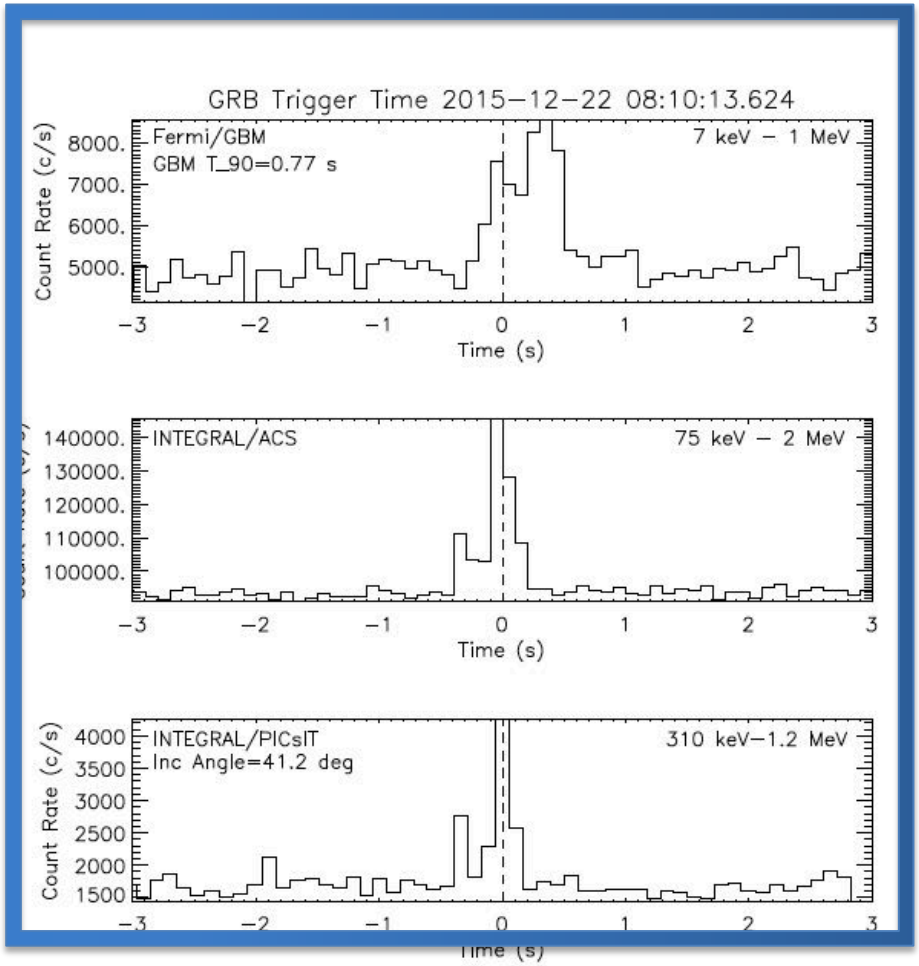
Motivated by the submitted paper on astroph, (Troja et al. 2018, arXiv:1806.10624) suggesting that GRB150101B is a kilonova event comparable to GW170817/GRB170817A (but at cosmological distance and without the observations of a gravitational-wave trigger) we performed analysis of archival PiCsIT data.

We confirm the independent detection by SPI-ACS and IBIS/PICsIT of a short duration (~0.012 sec) event, consistent with that reported in Troja et al.

The signal in SPI-ACS (75 keV-10 MeV) and in IBIS/PICsIT (200 keV-1.2 MeV) has a S/N of 5.1, and 4.2, respectively. From the SPI-ACS observation, we estimate a 75 keV-2 MeV fluence of GRB150101B in the time interval T_0-0.05s - T_0+0.1s of $(1.3 \pm 0.3)^{-7}$ erg/cm^2, assuming a simple power-law spectrum with a slope of 1.2 (as measured by Swift/BAT and Fermi/GBM). Analysis is on-going to constrain any possible soft gamma-ray afterglow with contemporaneous INTEGRAL observations.

SGRBs seen by INTEGRAL & *Fermi*/GBM:
the accurate measurement of arrival time with INTEGRAL, FERMI, SWIFT, AGILE
allows to get informations on arrival direction of GWs:

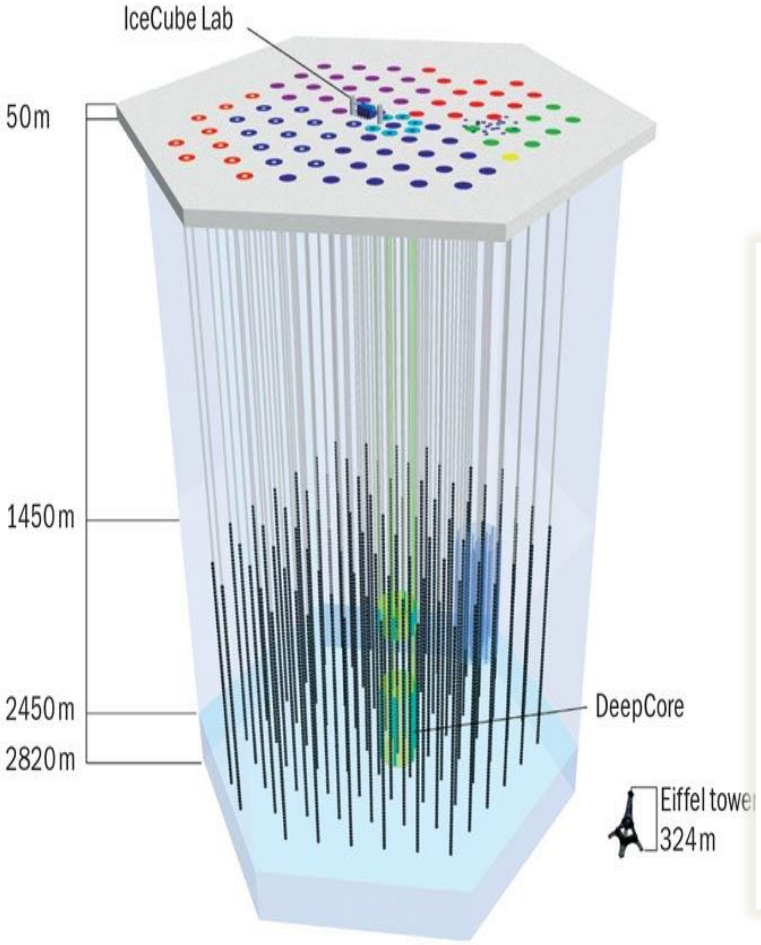




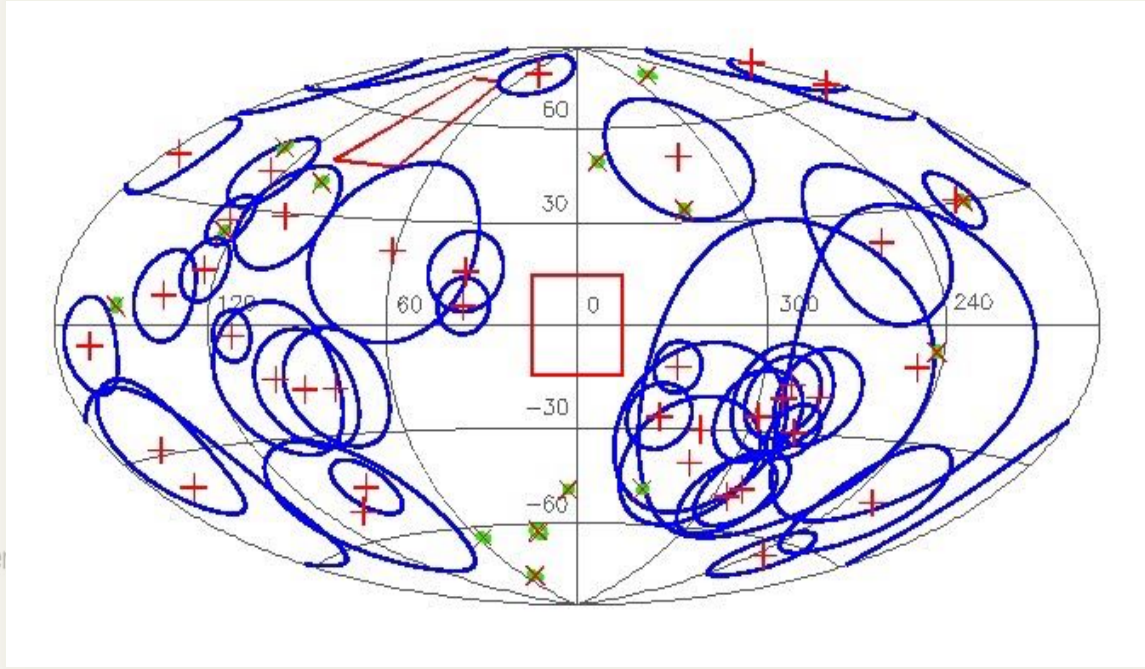
Neutrino events

@ Ultra High Energy, search for:
- places of HE Cosmic Ray acceleration (GRBs?,AGN?)
- Dark Matter decay

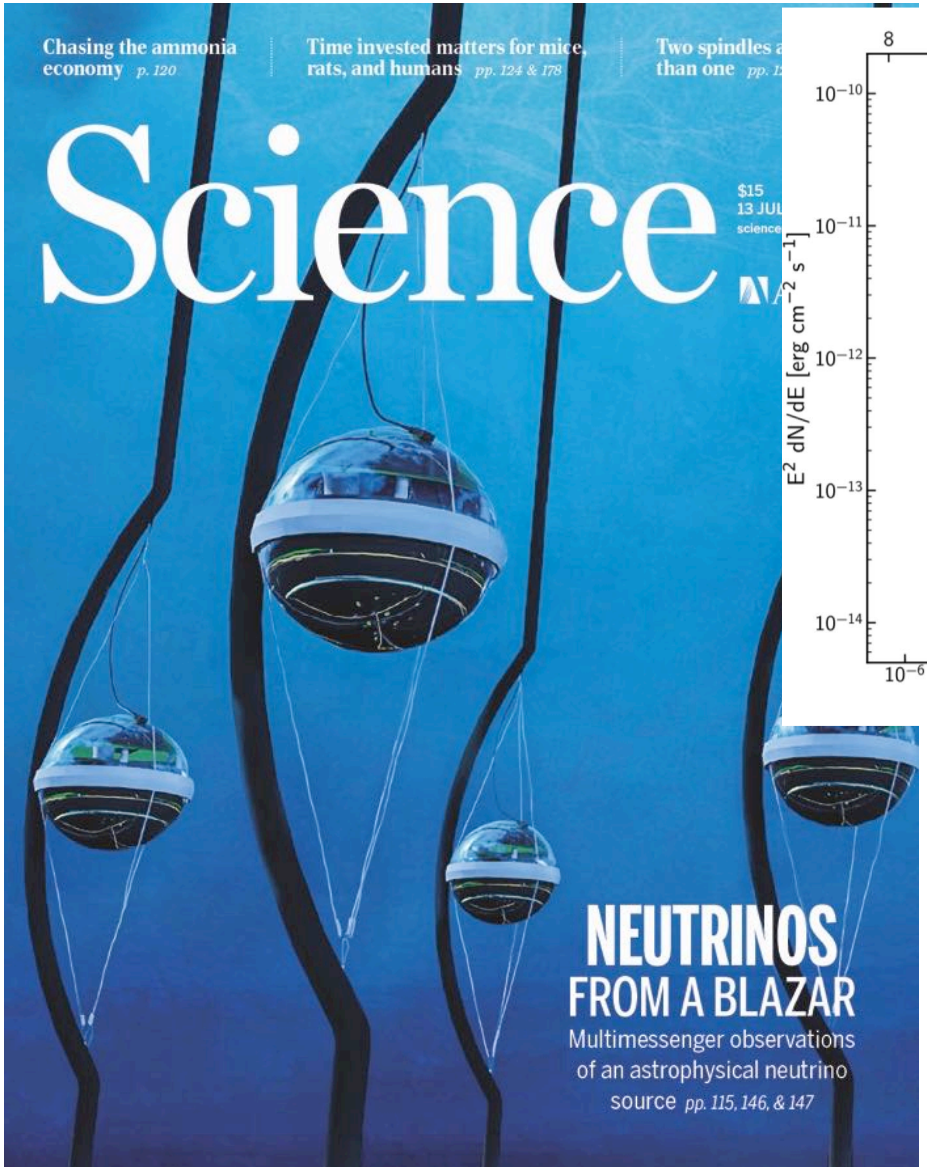
Arrival directions of ≈40 neutrinos observed in 3y by the IceCube detector, Aartsen et al. 2014

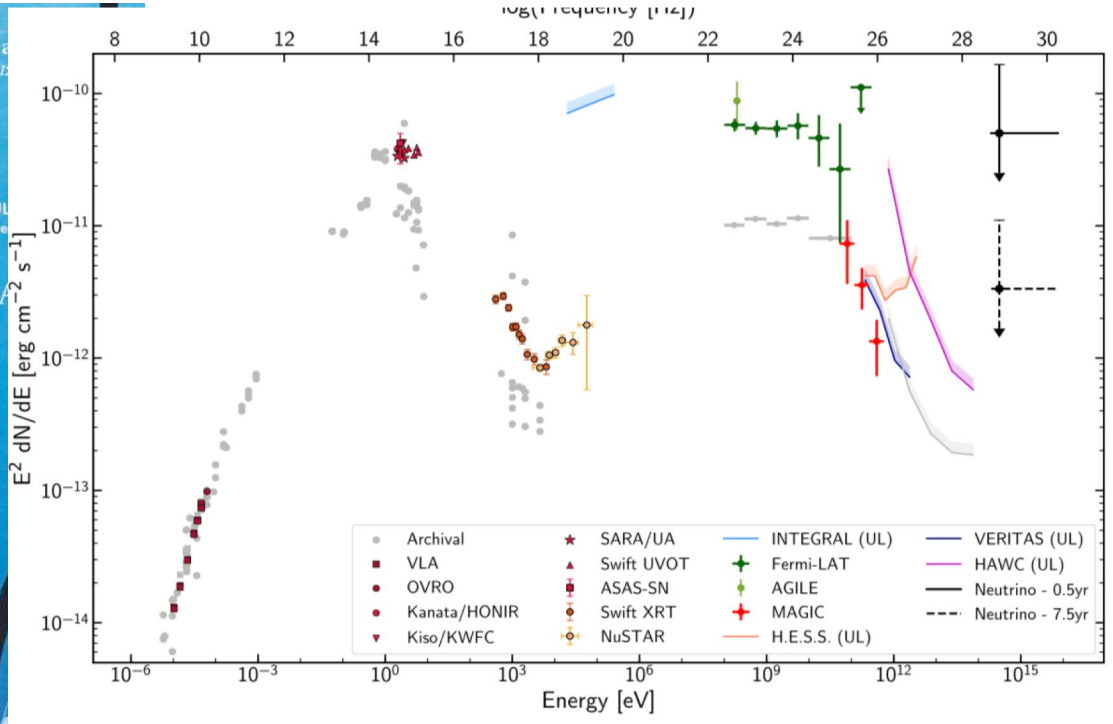


IceCube high-energy e-neutrino events (blue) and muon events (green crosses)
54 events in 2010−2014



INTEGRAL and Neutrinos

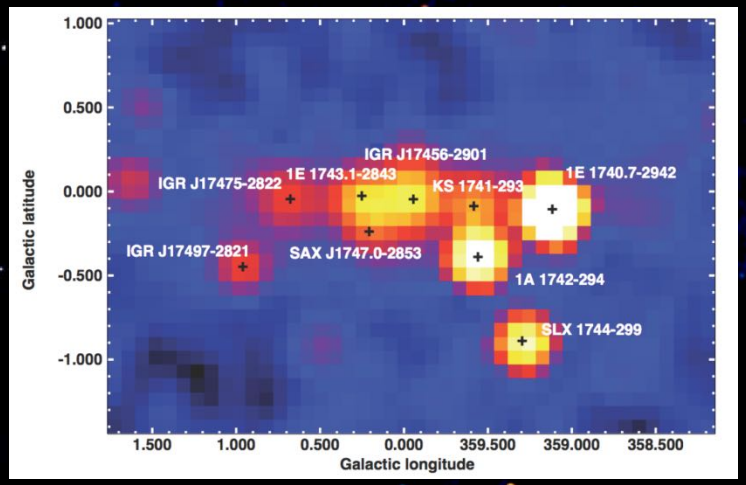




INTEGRAL contributed with upper limit in the range 20-250 keV during the pointings devoted to NGC2110 (P.I. F. Panessa) and the team was included in the Multimessenger papaer on Science on July 13 2018. (Science, 361, 146)

IBIS SURVEY: the first 1000 orbits

120 Ms data,75000 pointings:
~ 300 new detections of which more than 100 are NEW sources



Bird et al., 2016 ApJS

The headline results

- **939 sources listed**
  - **881 at above 5 sigma (secure)**
  - **58 between 4.5 and 4 sigma (used with caution)**

- **307 new (!!!) sources wrt cat 4**
  - **60 already reported IGR detections**
  - **127 listed in other X-/hard-X catalog**
  - **120 reported for the first time**

In total 600 new hard X-ray emitters discoverd since 2003 and more than 250 firmly identified.

New follow-up programs started with XRT/SWIFT and Optical/ NIR

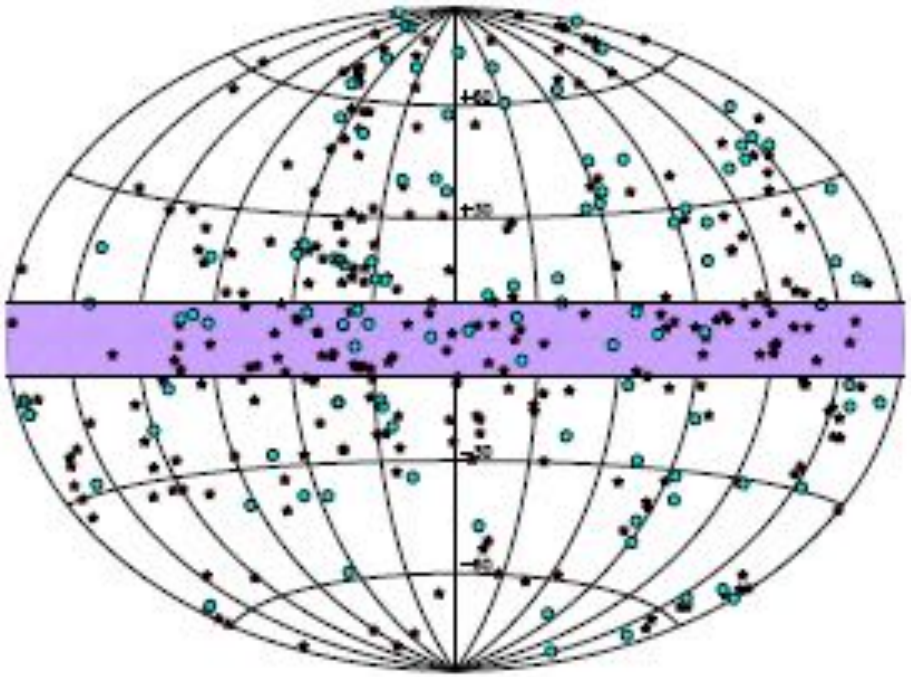
WHAT ARE THEY

Type	cat4		cat1000 new		cat1000 overall	
	Src	%	Src	%	Src	%
AGN	250	40%	119	39%	369	39%
?	100	16%	119	39%	219	23%
LMXB	106	17%	23	7.5%	129	14%
HMXB	96	15%	20	6.5%	116	12%
CV	42	7%	14	5%	56	6%
SNR	10	2%	0	<1%	10	1%
XB	6	<1%	3	1%	9	1%
PSR	5	<1%	3	1%	8	1%
Cluster	4	<1%	3	1%	7	1%
PWN	5	<1%	0	<1%	5	1%
SGR	2	<1%	1	<1%	3	<1%
AXP	2	<1%	0	<1%	2	<1%
GRB	1	<1%	1	<1%	2	<1%
RSCVn	1	<1%	1	<1%	2	<1%
Mol cloud	1	<1%	0	<1%	1	<1%
XP	1	<1%	0	<1%	1	<1%
Total	632		307		939	

Source types number for:

- **confirmed cat 4 sources (left)**
- **New cat 1000 sources (centre)**
- **Complete cat 1000 list**

IBIS AGN



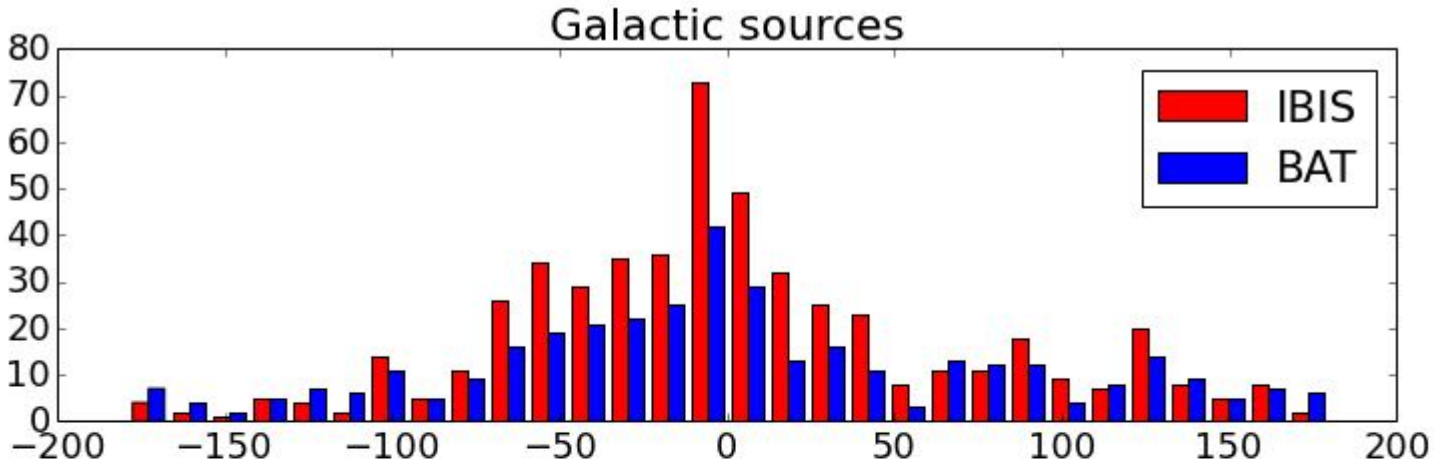
Complete sample of INTEGRAL emitters firmly associated with AGN represent the NEW for which the optical & spectral characterization has been obtained:

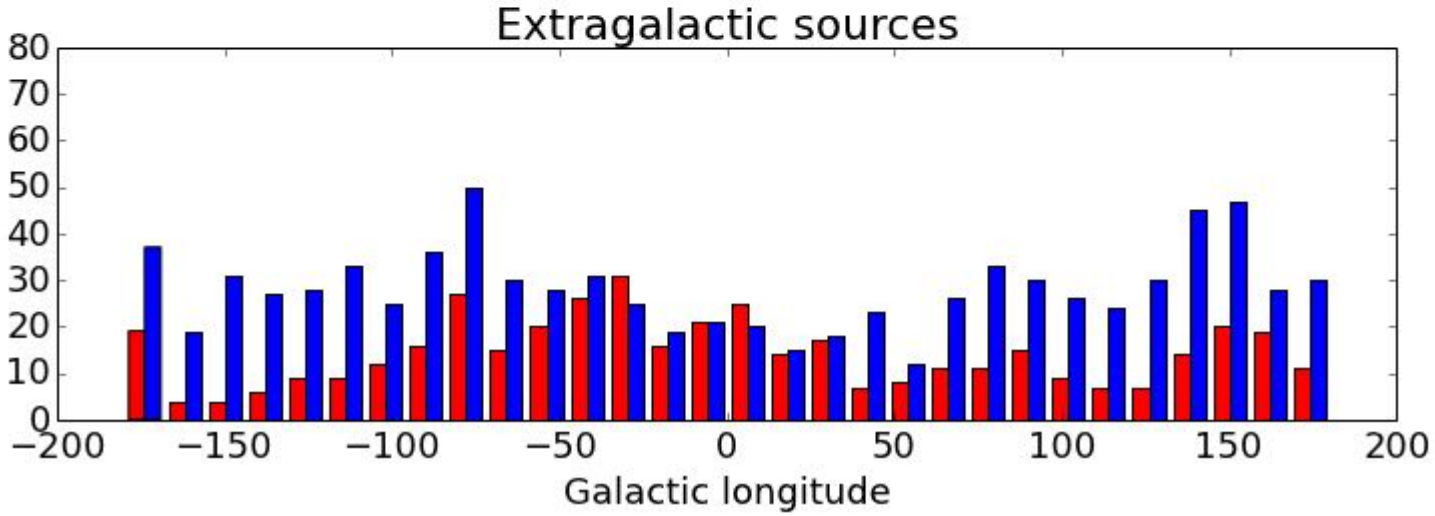
34 broad line or type 1 AGN, 47 narrow line or type 2 AGN, 18 Blazar and 8 still remain unknown.

X-ray coverage using data from Swift/XRT, XMM and NuSTAR

Malizia et al., 2016

Comparison with SWIFT/BAT





565 correlations within 400"

245 galactic
319 extragalactic

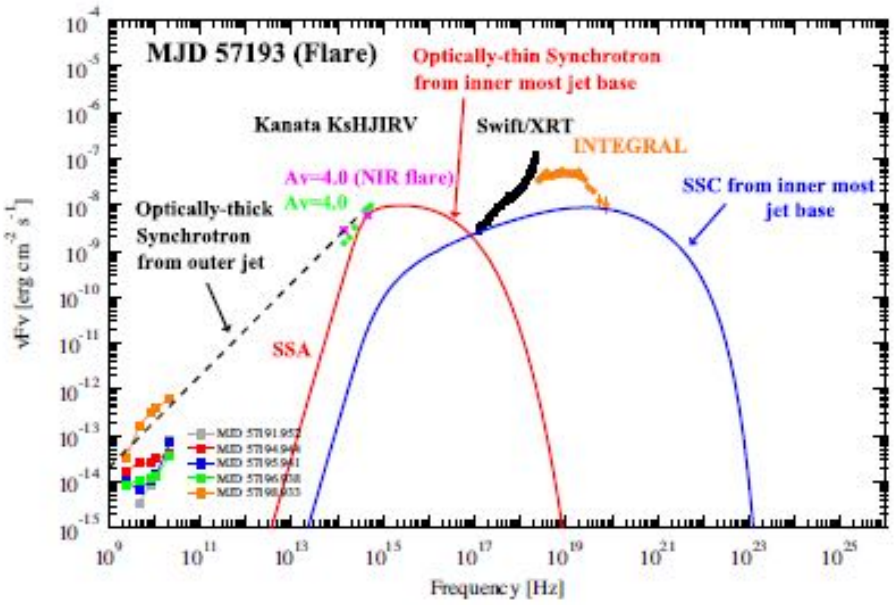
IBIS data from cat 1000

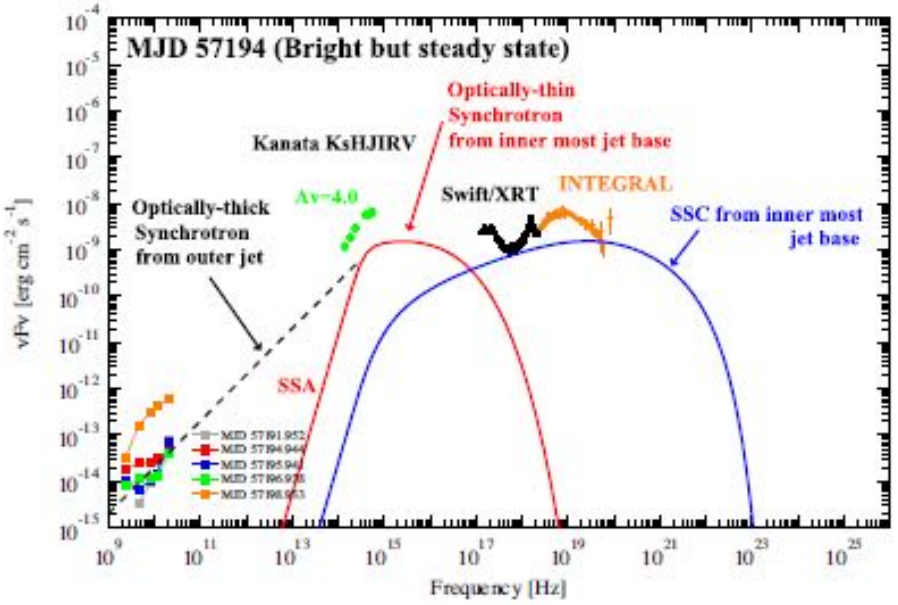
BAT data from Baumgartner 2013

Example of list content

Name[a]	RA	Dec	Error[b]	F20-40[c]	F40-100[c]	Type[d]	Vari[e]	Signif[f]	Exposure[g]
GX 301-2	186.657	-62.771	0.18	192.3±0.1	20.6±0.2	HMXB, XP, T		2074.5	3702
Detected as a persistent source in the 17-30 keV band.									
XSS J12270-4859	187.008	-48.893	2.30	1.6±0.2	1.5±0.3	LMXB, MSP		11.7	1313
1RX J122758.8-485348	*Detected as a persistent source in the 18-60 keV band.*								
3C 273	187.278	2.052	0.32	13.2±0.1	17.0±0.2	AGN, Sy1, QSO		173.8	3589
Detected as a persistent source in the 18-60 keV band.									
IGR J12319-0749	187.977	-7.816	3.97	0.8±0.1	<0.4	AGN, QSO, Blazar		6.4	2004
Detected as a persistent source in the 18-60 keV band.									
Mrk 771	188.039	20.125	4.01	0.6±0.1	<0.4	AGN, Sy1	Y	6.3	2072
SWIFT J1232.1+2009	*Detected in a 468.4 day outburst from MJD=55010.4.*								
XSS J12303-4232	188.054	-42.295	4.86	0.8±0.2	<0.8	AGN, Sy1.5		5.1	756
SWIFT J1232.0-4219	*Detected as a persistent source in the 18-60 keV band.*								
IGR J12341-6143	188.467	-61.796	3.98	<0.2	<0.3	?	Y	6.3	3470
Detected in a 0.9 day outburst from MJD=54649.9.									
RT Cru	188.728	-64.566	0.76	4.1±0.1	2.5±0.2	XB, Symb		44.3	3395
IGR J12319-6431	*Detected as a persistent source in the 18-60 keV band.*								

EXAMPLE of SINEGY and Models





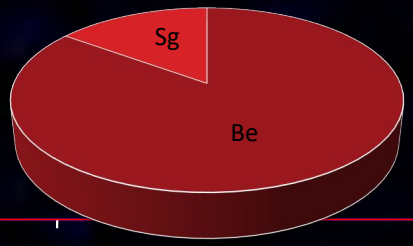
Broadband spectra of V404 Cyg during the orphan NIR flare and a relatively faint and steady state by including quasi-simultaneous Swift/XRT and INTEGRAL fluxes. A single-zone synchrotron plus inverse-Compton model has been used as in modeling of blazars, constrained the parameters of a putative jet. Because the jet synchrotron component cannot exceed the Swift/XRT disk/corona flux, the cutoff Lorentz factor in the electron energy distribution is constrained to be $<10^2$, suggesting particle acceleration is less efficient in this microquasar jet outburst compared to AGN jets. (Tanaka et al., 2016)

Supergiant Fast X-ray Transients: a new class of HMXBs discovered by INTEGRAL

mostly along the Galactic Plane

HMXBs before the INTEGRAL era

- ~60 HMXBs known in our Galaxy before the launch of INTEGRAL in 2002 (Liu et al. 2000)
- HMXBs classified into two groups: (depending on the evolutionary state of the donor star):
  - **85% Be HMXBs**
  - **15% Supergiant HMXBs (SGXBs)**

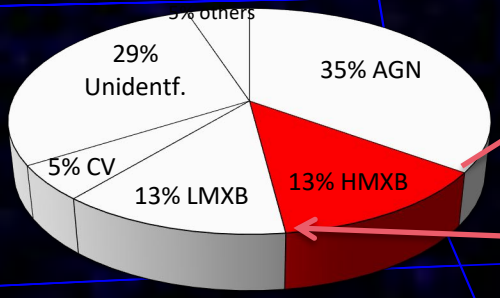


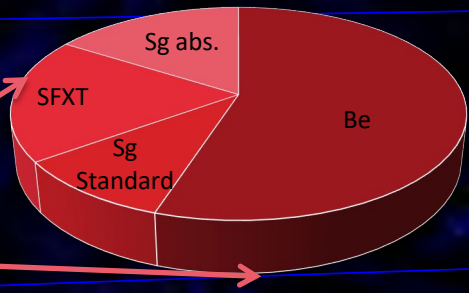
150.000

HMXBs in the INTEGRAL era

INTEGRAL doubled the number of known HMXB with two new classes:

- highly obscured HMXB
- supergiant fast X-ray transients





Supergiant HMXBs (SGXBs)

- massive O,B star evolved in the **supergiant phase**

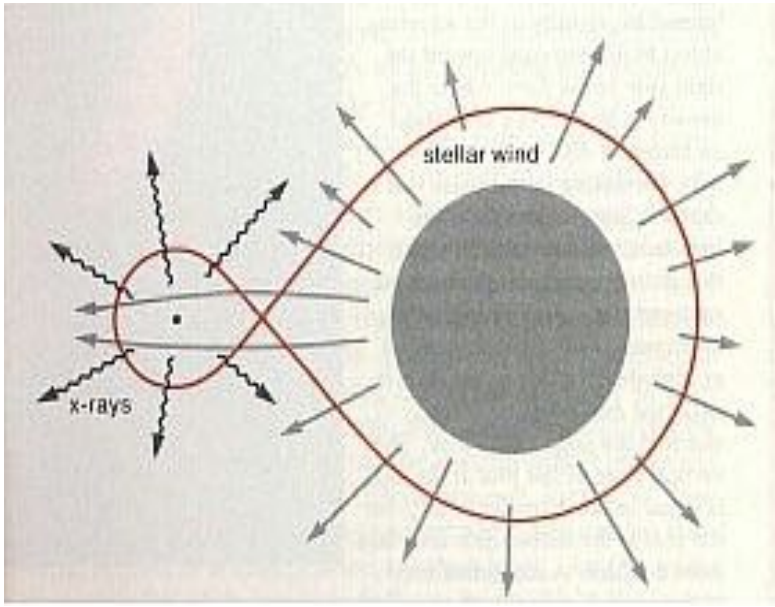
  T ~ 20,000 - 40,000 K, dense stellar wind (10^{-6} - 10^{-8} Mo, 1,000 - 2,000 Km/s)

- **SGXBs were believed to be rare objects, only a dozen SGXBs discovered in 40 years of X-ray astronomy!** (Liu et al. 2000)

- circular **($e \leq 0.1$)** and short orbits **($R < 2R_*$)** with periods ~ **2-12 days**

- usually **wind-fed:** bright and **persistent** X-ray sources with $L_x \sim 10^{36}$ erg s^{-1} and variability up to ~ 20, intrinsic aborsption $N_H \sim 10^{22}$ cm^{-2}

- rarely **Roche lobe overflow:** bright and **persistent** X-ray sources with $L_x \sim 10^{38}$ erg s^{-1}, no variability

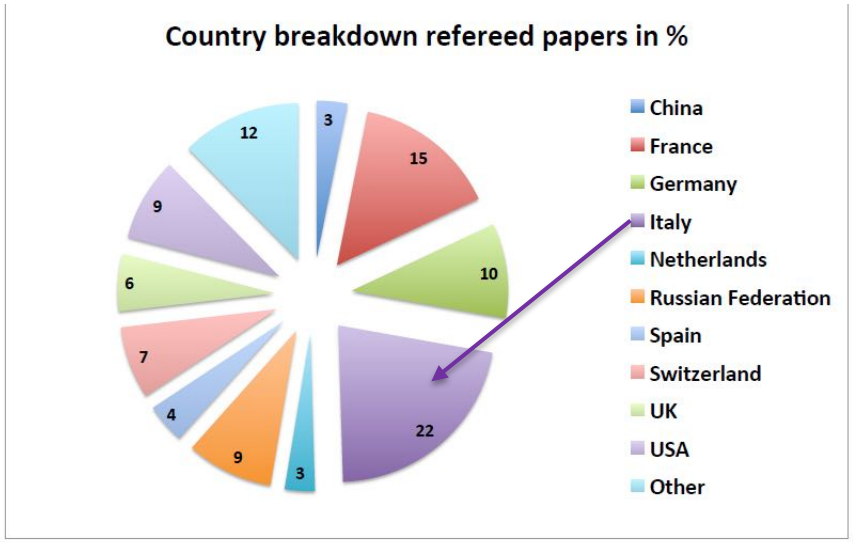


INTEGRAL

….after more than 15 years of operation

the science return continues at a high pace, building an impressive legacy

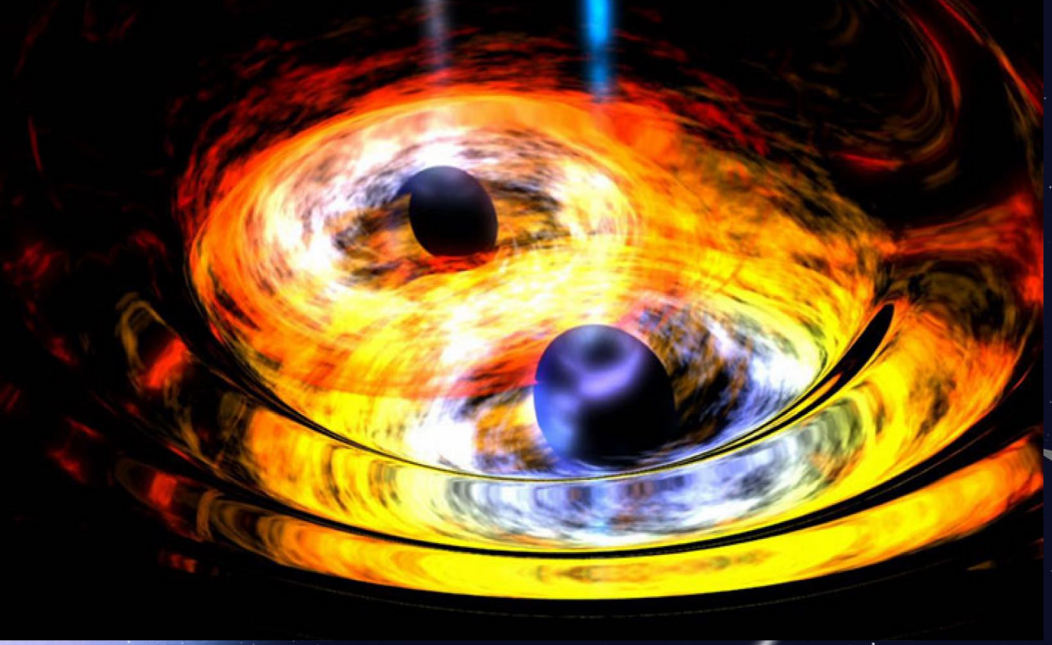
- discovering **600+ new high energy sources**,
- **decay lines of radioactive isotopes from extragalactic supernovae (SNe)**,
- **pioneering γ-ray polarization studies**,
- shedding **new light on the enigmatic positron annihilation in the Galactic centre region**, which is potentially linked to dark matter decay.
- detection of new kinds of non-electromagnetic signals in the form of **gravitational waves (GW) and possibly (ultra-)high-energy cosmic neutrinos and FRBs**

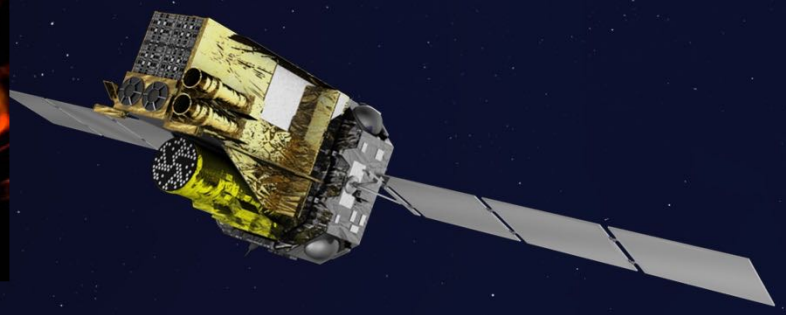


Up to now:

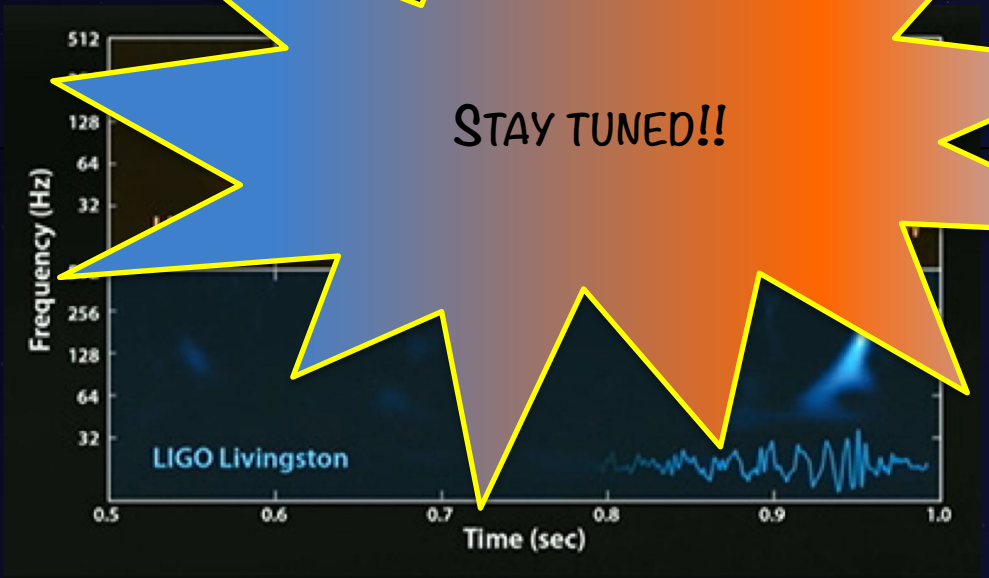
- **1140 refereed papers**
- **111 press releases**
- **'Official Conferences' every 2 years plus Workshops on specific topics every other year**

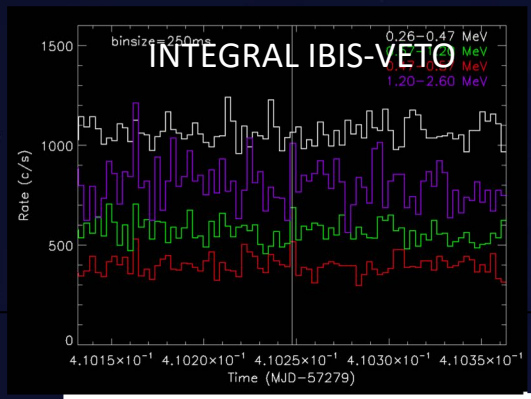
as for the end of 2014

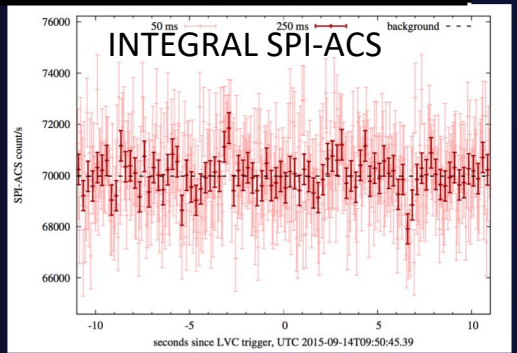




STAY TUNED!!


512
128
64
32
256
128
64
32
Frequency (Hz)
LIGO Livingston
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)


INTEGRAL IBIS-VETO
binsize=250ms
0.26–0.47 MeV
MeV
MeV
1.20–2.60 MeV
1500
1000
500
0
Rate (c/s)
4.1015×10⁻¹
4.1020×10⁻¹
4.1025×10⁻¹
4.1030×10⁻¹
4.1035×10⁻¹
Time (MJD−57279)


INTEGRAL SPI-ACS
50 ms
250 ms
background
76000
74000
72000
70000
68000
66000
SPI-ACS count/s
-10
-5
0
5
10
seconds since LVC trigger, UTC 2015-09-14T09:50:45.39

CONCLUSIONS

- After 14 years of successful operation INTEGRAL is still in NOMINAL condition as launched
- Just after the detection of GW150914 the operation mode has been changed to IMMEDIATELY follow-up the NEXT GW trigger expected in O2 (November on)
- INTEGRAL is observing the whole sky in the range 50KeV-10MeV, searching for GW and HENs
- Highly competitive all-sky sensitivity, down to 10^{-7} erg cm^{-2} s^{-1} (75 KeV- 2.5 MeV) with IBIS-VETO and SPI-ACS
- Operations recently optimised to detect 'cosmic' electromagnetic counertpart of HE Neutrino events
- Core science and Legacy deep programs are continuing, with a target to be operative till 2020... (re-entry 2029).

looking forward to have Athena and eLISA!!

Summary

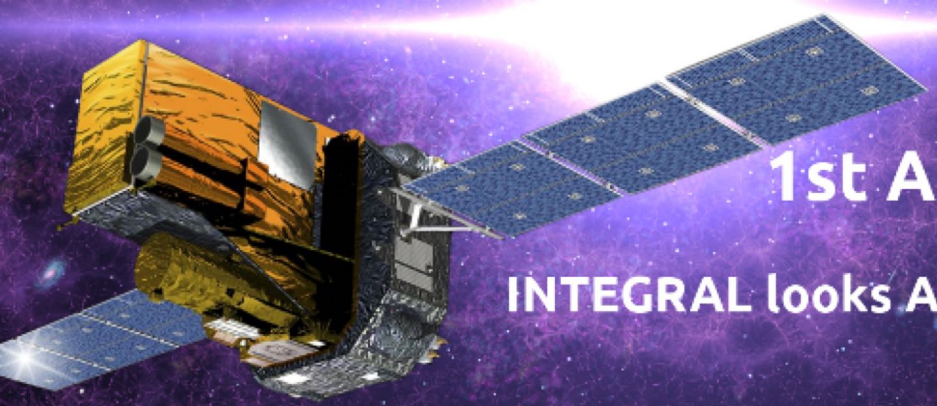
INTEGRAL followed-up **full GW localization region 5 out of 6 reported events**, as expected with 85% duty cycle. **Combination of the high duty cycle and high sensitivity is unique, and allowed us to contribute to the first joint GRB-GW Detection**

Detection of a GRB from an off-axis merger implies much more frequent GRB-BNS associations, which might happen **regularly in O3,** the bright triggers will be most probably **immediately public**

Early GRB-GW detection: be **prepared for unexpected optimistic scenario**!

Multimessenger observations open possibilities for studying processes in energetic events involving compact objects, implications that go beyond BNS mergers.

Neutrino follow-ups remain very promising and tentative MM detections might soon reach the level of solid evidence



12th INTEGRAL Conference
1st AHEAD Gamma-ray Workshop

INTEGRAL looks AHEAD to Multi-Messenger Astrophysics

11-15 February 2019 - Geneva, Switzerland

Thanks for your attention!