



INTEGRAL: past, present and future



SEEKING OUT THE EXTREMES OF THE UNIVERSE

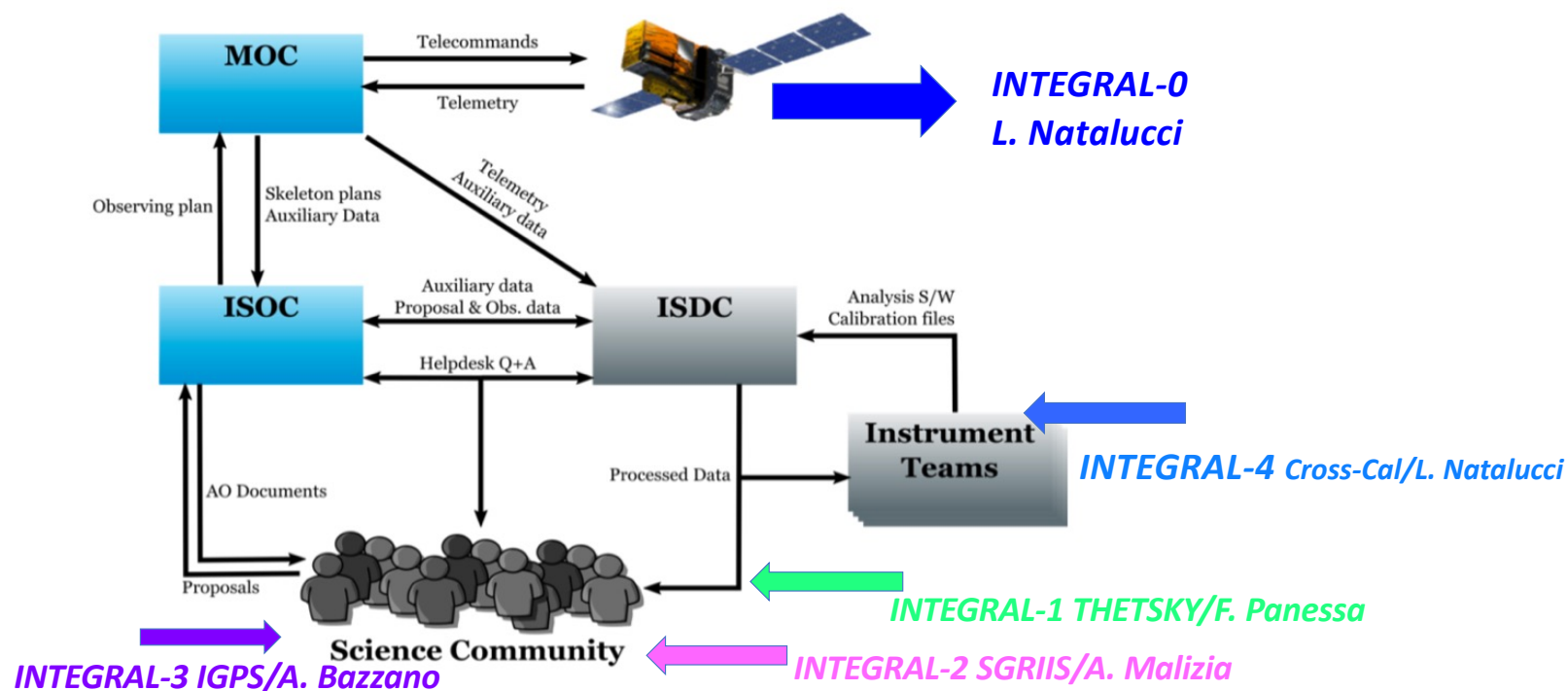
Lorenzo Natalucci for the Italian IBIS Team
INAF/IAPS

Thanks: E. Kuulkers (INTEGRAL PS)

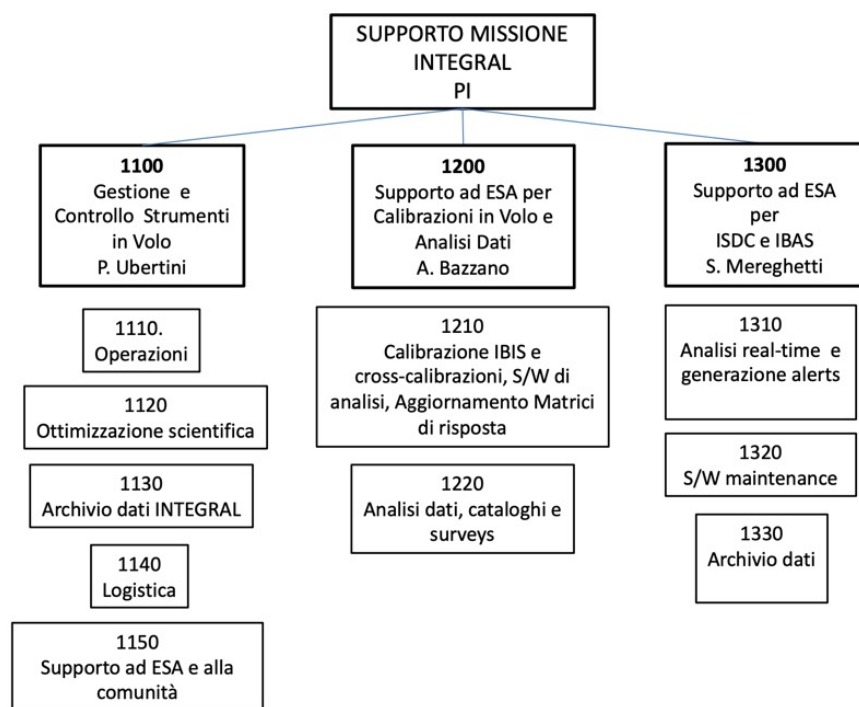
L.Natalucci - Audizioni RSN4, 25-26 Maggio 2021

Schede correlate

- AHEAD2020/L. Piro ← Prompt emission of multi-messenger transients
- MIOHECS/N. Masetti ← Optical source follow-up
- SCOX-0/T. Belloni ← Data exploitation



Attività & Team INAF



IAPS: 3 TI Ricercatori (0.3) , 0.5 TD , 1 AdR, 1 CTER (0.3) , 1 OPERATORE (0.1) + 2 ASSOCIATI (0.5)

OAS: 3 TI RICERCATORI (0.4), 1 AdR + 1 ASSOCIATO (0.2)

IASF-Milano: 2 TI RICERCATORI (0.2)

IASF-Palermo: 1 Associato (0.1)

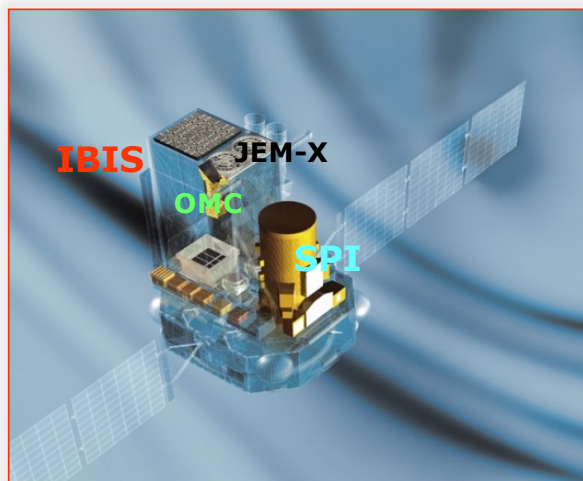
Dedicati a: **Operazioni in volo, Calibrazioni, Cross-Calibrazioni (IACHEC), Inputs per IUG, Data Analysis e Survey**

Attività finanziate con accordo ASI/INAF n. 2019-35_HH.0

The INTEGRAL observatory

➤ **INTE**rnational **G**amma-**R**ay **A**strophysics **L**aboratory

- Medium-sized mission (Horizon 2000) - Launched 17 October 2002
- Highly elliptical orbit (~64 hrs); ~47 hrs of continuous science per orbit



➤ **4 instruments:**

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

➤ **All operating simultaneously**

- IBIS, SPI & JEM-X: large FOV
30°x30° & 7.5°
- Exposure times: hrs-days
- Continuous data stream & fast near-real-time (NRT) access to data

➤ **Payload/instruments: nominal**

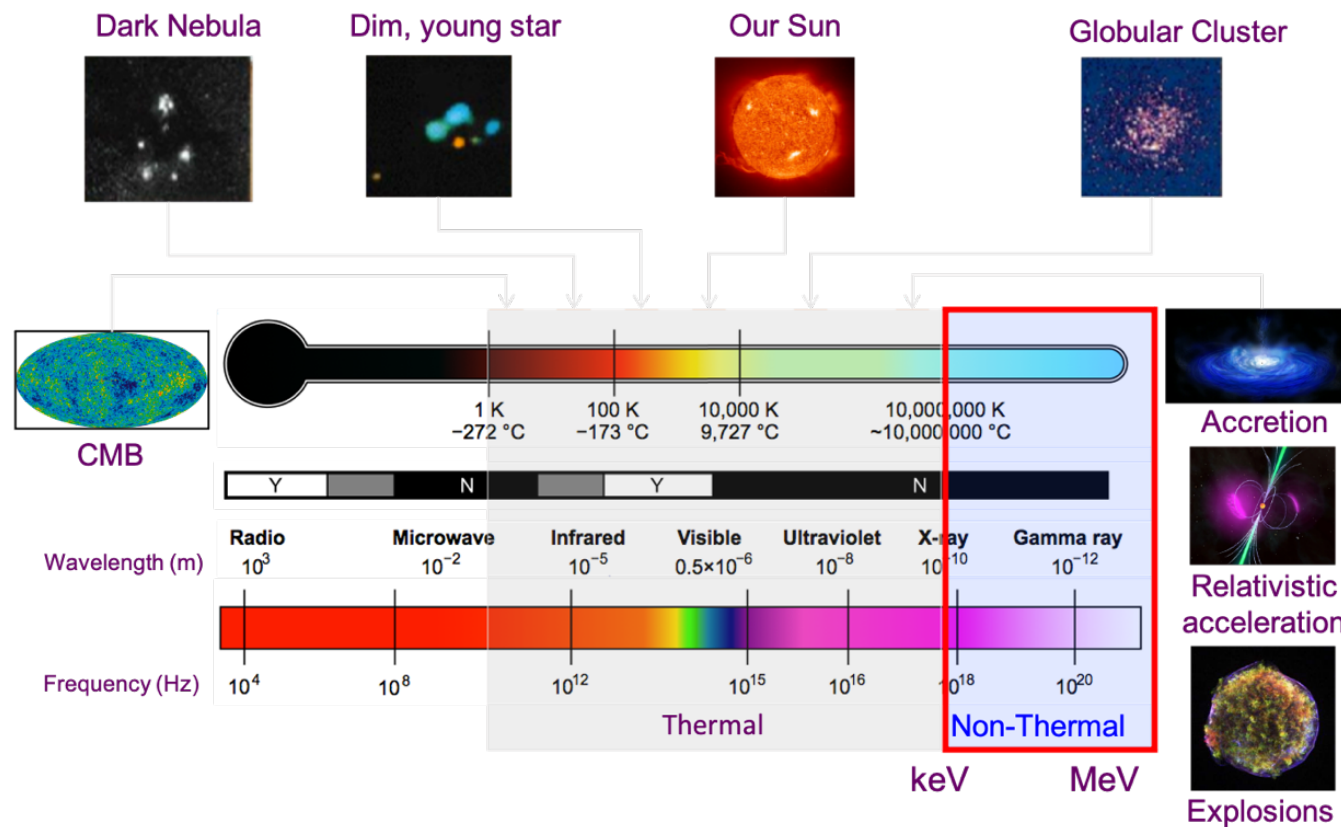
➤ **Mission extended up 31-12 2022**

Possible further extension to cover 2023-2025

INTEGRAL will remain the *only observatory providing 3-keV-10 MeV capabilities to the community in this decade*



Probing the extreme, non-thermal Universe with hard X/soft γ -rays

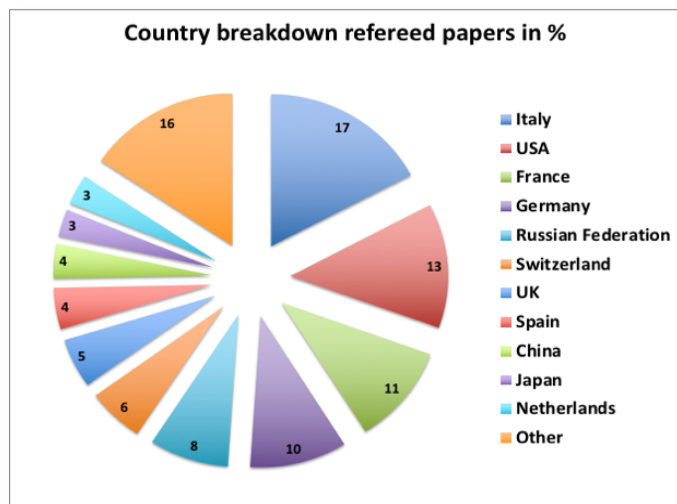


...after >18 years

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

- discovering ~600 new high energy (IGR) sources,
- >300 AGN uniquely identified and spectrally characterised
- 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:



- **1791 refereed papers (April 2021)**
- **300 led by Italian + ~200 as co-authors**
- **120 press release**
- **~200 Atels, GCN (150 in the last 5 years)**
- **'Official Conferences' every 2 years plus Workshops on specific topics every other year**
- **Published 13 reviews on special issue of New Astronomy Rev: INTEGRAL «re-loaded», Survey, LMXBs, HMXBs, BHCs, CVs, Pulsar, AGN, Annihilation, Nucleosynthesis, SNaE, MultiMessenger, Serendipitous science (solar e TGF)**

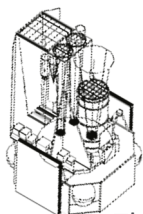
Key science capabilities

- **Large FOV (~ 900 square degrees) + arcmin localisation**
 - X-ray & γ -ray transient discovery space + multi-source monitoring
- **Omni-directional view through shields**
 - γ -ray transients + counterparts of GRBs, GW & high-energy neutrino events, FRBs
- **γ -ray polarimetry**
 - Unique diagnostic of radiation process/source geometry/magnetic field (neutron stars, black holes, pulsars, magnetars, GRBs, blazars)
- **Target of Opportunity capability**
 - allows rapid follow-up observations after alerts from GW, neutrino or EM facilities (response times < day, down to ~ 4 hrs)
- **Synergy**
 - Connects X-ray missions (e.g. eROSITA, HXMT, NICER, NuSTAR, Swift, XMM-Newton) with higher-energy γ -ray facilities (e.g. Fermi)
- **γ -ray line spectroscopy & imaging**
 - Positrons in the Galaxy: annihilation with electrons (511 keV emission)
 - Nucleosynthesis: lines from elements formed in massive stars, SNe & (X-ray) novae

4 π of the sky: expect the unexpected

THETSKY

Shields of
SPI & IBIS



➤ SPI/ACS:

>75 keV, 50 ms - Effective area: $\sim 1 \text{ m}^2$

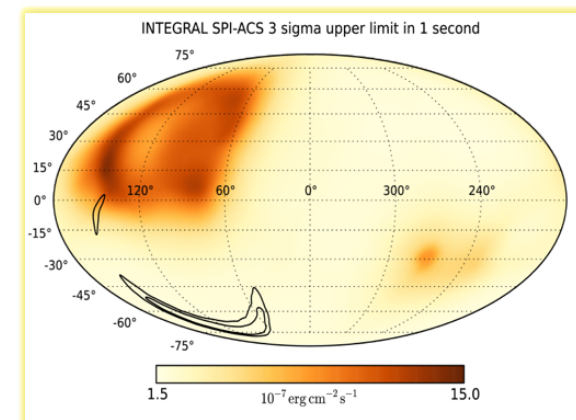
➤ IBIS/PiCsIt/Veto

$\sim 0.25\text{-}2.6 \text{ MeV}$, 7.9 ms - Effective area: $\sim 3000 \text{ cm}^2$

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

👉 Omni-directional view!

GW150914



The entire sky is accessible for continuous observations with a duty cycle of 85% (up to $\sim 2\text{days}/2.7\text{days}$ revolution)

Note:

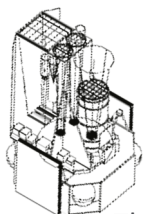
Fermi in LEO $\rightarrow \sim 50\%$ duty cycle, sky partly blocked by Earth



4 π of the sky: expect the unexpected

THETSKY

Shields of SPI & IBIS



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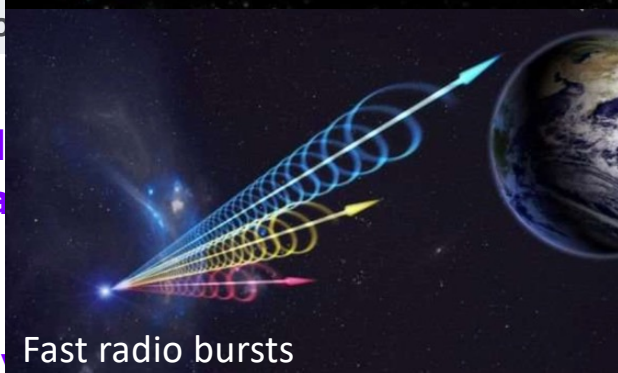
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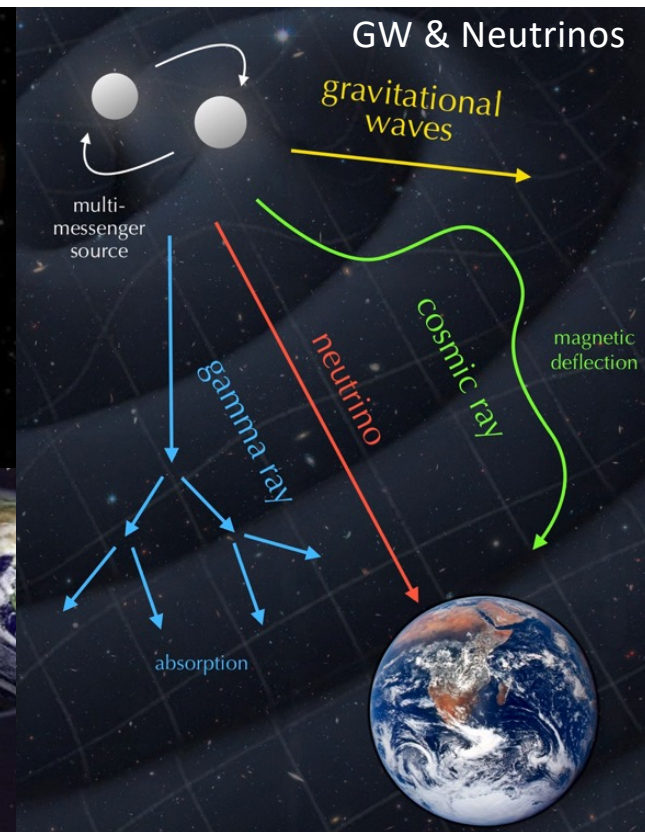
Fermi in LEO → ~50% duty

Tidal Disruption Events



Fast radio bursts

GW & Neutrinos





... now around the clock

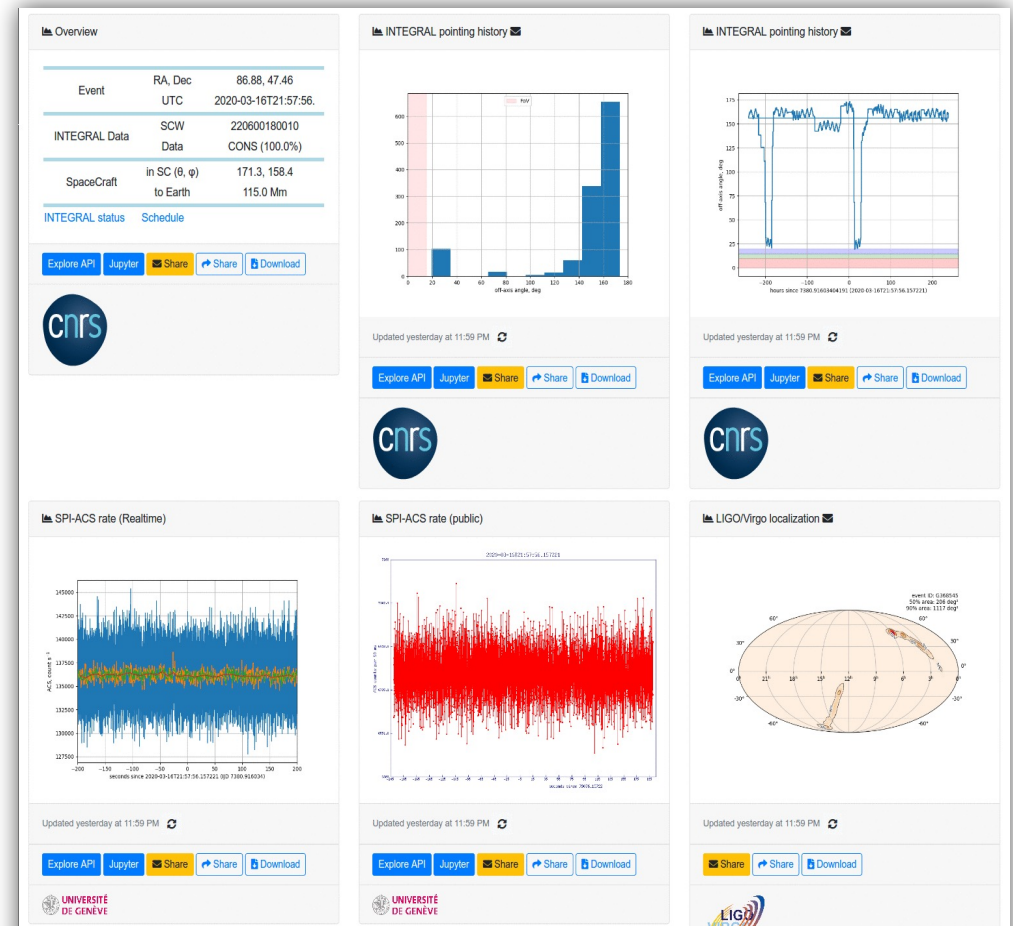


The INTEGRAL Multi-Messenger team and on-line computing interface

- 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, ...)

Courtesy of C. Ferrigno & V. Savchenko

THESKY

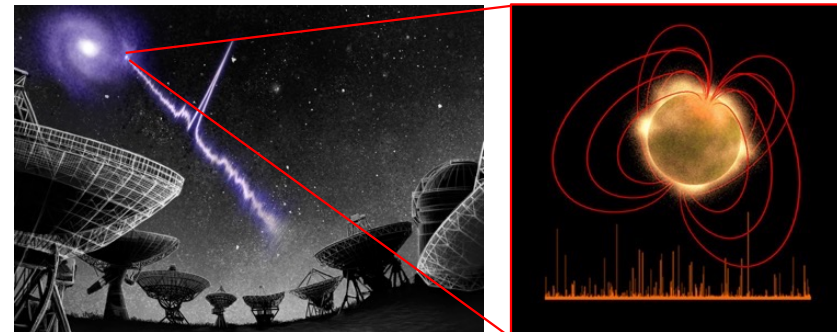
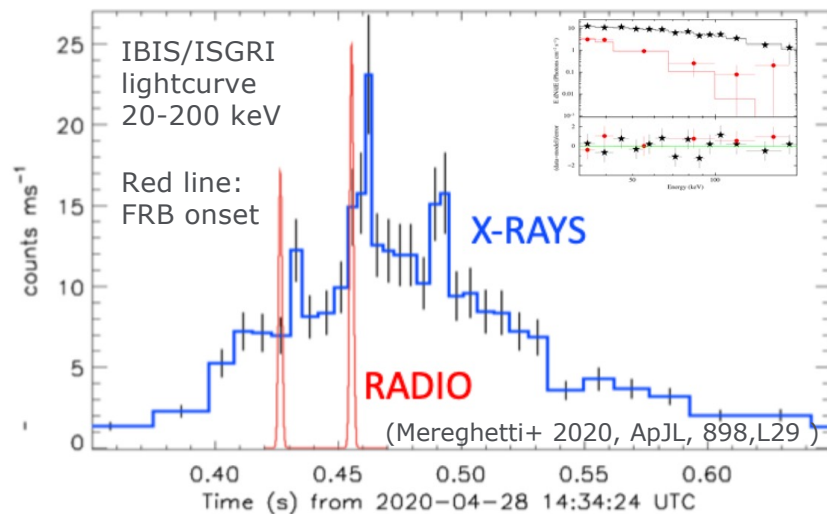


SGR 1935+2154

See Talk by Sandro Mereghetti

Breaking

INTEGRAL discovery of a burst with associated radio emission from the magnetar SGR 1935+2154




Fast Radio Bursts: unknown objects emitting short ($\sim 1-10$ ms) pulses of radio emission with peak fluxes of $\sim 0.1-100$ Jy at GHz

Magnetars: neutron stars powered by magnetic energy dissipation (ms bursts up to 10^{41} erg/s).

INTEGRAL discovers a magnetar flare spatially and temporarily coincident with an FRB. Long sought connection confirmed.

The mCrab transient Universe 1/2

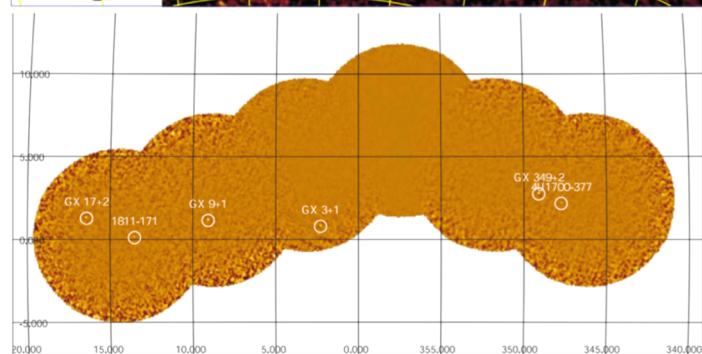
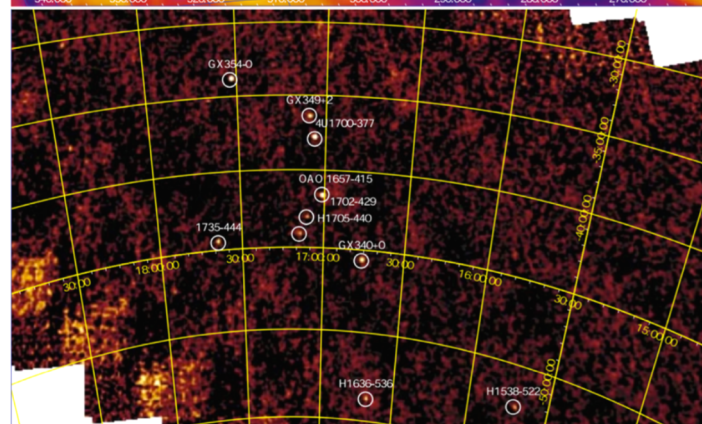
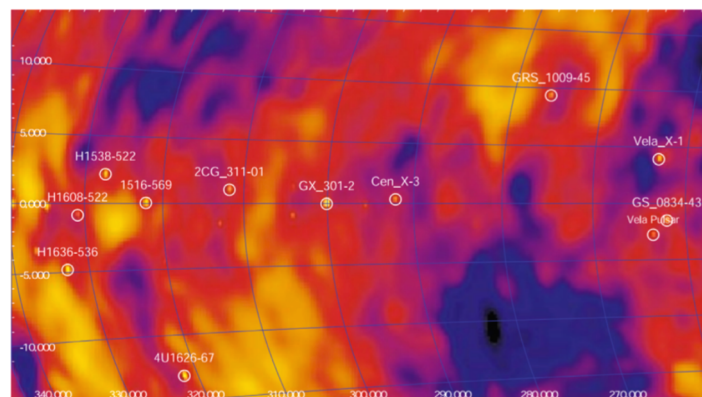


IGPS

INTEGRAL enables
• unique access to the
fast transient
Universe @ mCrab
levels

- Optimal combination of FoV, sensitivity, broad-band coverage
- Long staring observations toward specific regions of the sky

Transient Universe 1/2



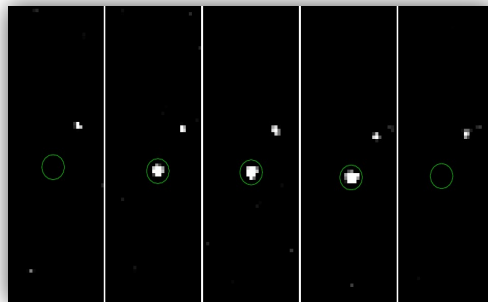
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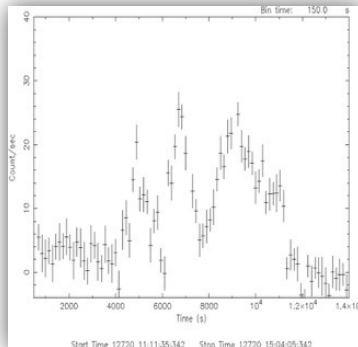
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The mCrab transient Universe 2/2

Supergiant fast X-ray transients: the enigma of clumpy stellar winds

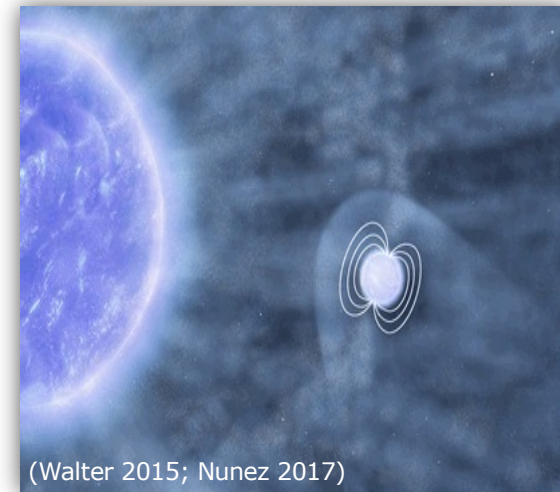
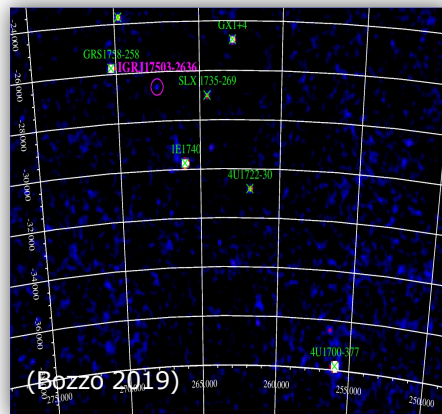


- Discovery (~ 10 -50 mCrab)
- Broad-band characterization
- Duty cycles
- Orbital periods
- Super-orbital periods



(Sguera 2005)

IGR J16418-4532
XTE J1739-302
IGR J17544-2619
SAX J1818.6-1703
IGR J16479-4514
IGR J18483-0311
IGR J18450-0435
IGR J18410-0535
IGR J08408-4503
IGR J11215-5952
IGR J16328-4726
IGR J18462-0223



(Walter 2015; Nunez 2017)

Challenging our understanding of massive star winds and their mass loss rates: wide Astrophysical implications.

Perspectives until 2025



➤ Strong focus on:

ToO capabilities of INTEGRAL in broadest sense:

- The “Multi-messenger astronomies”: [GW events](#), [high-energy neutrino events](#) & [FRBs](#)
 - INTEGRAL prompt & ToO follow-up observations
- ToO time to be awarded to [other transients](#) (~ 3 Msec/year) e.g., Novae, Supernovae, outbursts of Black Holes in X-ray binaries & AGNs (Micro-quasars, Blazars and Quasars seen out to $z=3.6$)

+ Legacy programs in areas for which INTEGRAL was designed:

- (Galactic) [nucleosynthesis](#); synergy with other observatories, like NuSTAR, Swift, XMM-Newton
- Continued [transient hunting](#) in the Galactic Center region and Galactic plane, and its e^+/e^- annihilation emission
- Study of [polarization at gamma-ray energies](#) (100 – 3000 keV) - of relativistic jets of black holes in XRBs and AGNs, and sources like Crab, GRBs, etc. ▫ [synergy with future mission IXPE](#)

+ Additional science:

- [Solar system observations](#): Earth aurora (TBC with *Swarm*, 2nd half of 2021), Jupiter & Moon (community interest for 2021)

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**2023+ :
expect a revolution in
time domain astronomy!**

Synergies

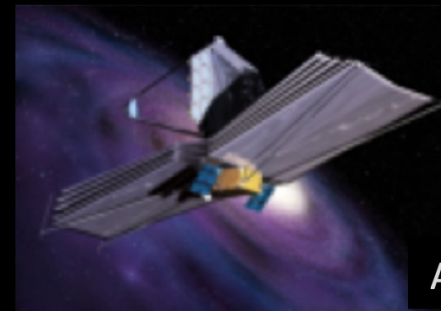
INTEGRAL



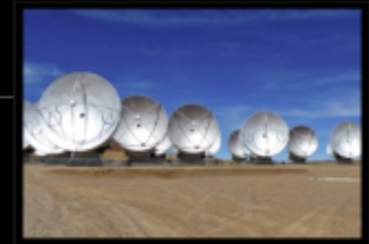
ATHENA 2030



JWST 2022



ALMA



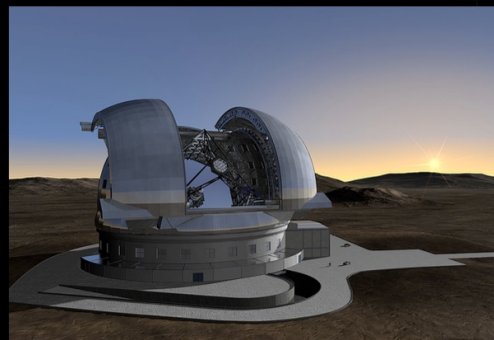
SKA1 2022+ - FAST, China



Roman Space Telescope WFIRST 2025



LSST (2023), ELT 2025, TMT (?) e



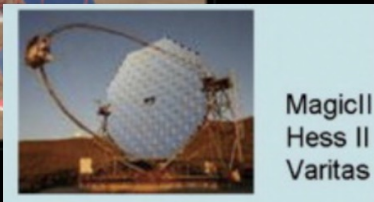
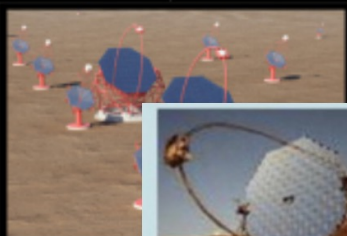
EUCLID 2022



FERM.



CTA 2024



MAGIC II
Hess II
Veritas

Y-RAY

X-RAY

UV

OPTICAL

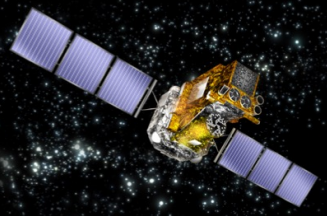
IR

SUBMM

RADIO

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INTEGRAL



ATHENA 2030



JWST 2022



Synergies

INTEGRAL Picture of the Month

FERM.

Roman Space Te



Article

INTEGRAL View of TeV Sources: A Legacy for the CTA Project

Angela Malizia ^{1,*,}, Mariateresa Fiocchi ^{2,†}, Lorenzo Natalucci ^{2,†}, Vito Sguera ^{1,†}, John B. Stephen ^{1,†}, Loredana Bassani ^{1,†}, Angela Bazzano ^{2,†}, Pietro Ubertini ^{2,†}, Elena Pian ¹, and Antony J. Bird ³

¹ INAF/OAS Bologna, Via P. Gobetti 101, 40129 Bologna, Italy; vito.sguera@inaf.it (V.S.); john.stephen@inaf.it (J.B.S.); loredana.bassani@inaf.it (L.B.); elena.pian@inaf.it (E.P.)

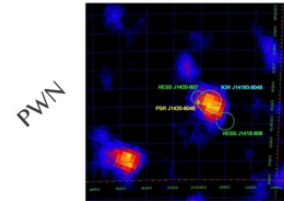
² INAF/IAPS Roma, Via Fosso del Cavaliere 100, 00133 Roma, Italy; mariateresa.fiocchi@inaf.it (M.F.); lorenzo.natalucci@inaf.it (L.N.); angela.bazzano@inaf.it (A.B.); pieter.ubertini@inaf.it (P.U.)

³ School of Physics and Astronomy, University of Southampton, Southampton SO17 1BJ, UK; A.J.Bird@soton.ac.uk

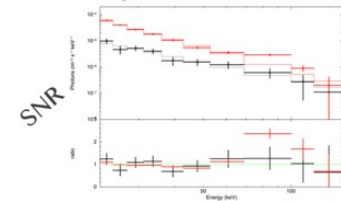
* Correspondence: angela.malizia@inaf.it

† These authors contributed equally to this work.

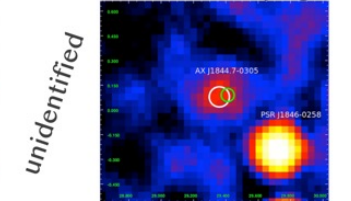
PSR J1420-607



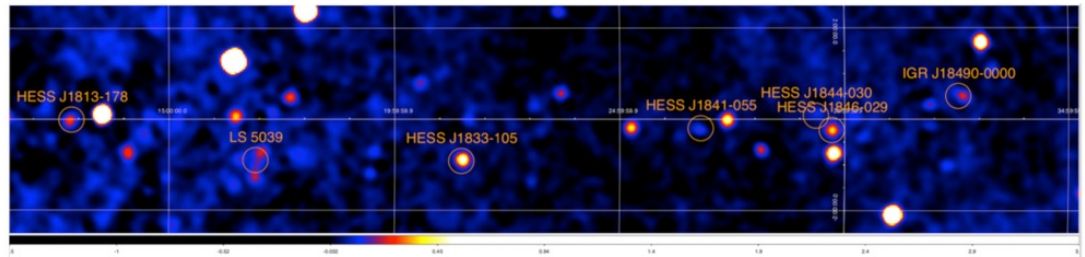
Tycho (black) Cas A (red)



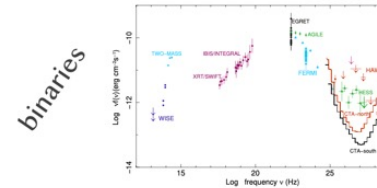
HESS J1844-030 sky region



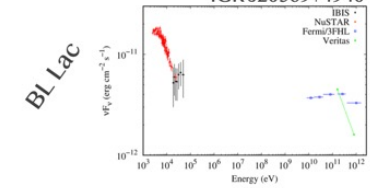
Galactic Plane



LS 5039



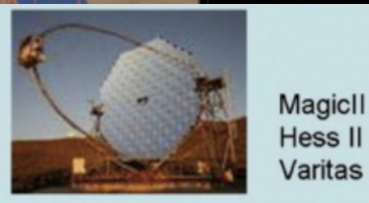
IGR J20569+4940



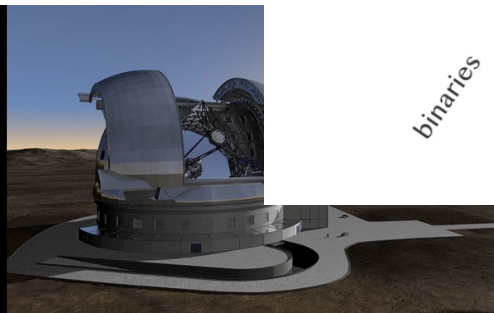
binaries

BL Lac

a



MAGIC II
Hess II
Veritas



Y-RAY

X-RAY

UV

OPTICAL

IR

SUBMM

RADIO

L.Natalucci - Audizioni RSN4, 25-26 Maggio 2021



Fondi

Fondi a sostegno

21. Totale fondi a disposizione (dato aggregato, k€)

Certi 2021	Certi 2022	Certi 2023	Presunti 21	Presunti 22	Presunti 23
150.0	150.0	0.0	0.0	0.0	150.0

Stima fondi acquisiti da INAF (2002-2020): ~8 M€

Costo totale missione: ~700 M€

Costo strumento IBIS: ~100 M€



Leadership INAF

Contributo Italiano alla missione:

- Imager IBIS: PI-ship (IAPS), Sottosistemi PiCslt, Veto, Hopper, Meccanica, Sorg di calibrazione
- Supporto a ESA: Calibrazioni, Operazioni e Mantenimento IBIS, INTEGRAL User Group (IUG), Operational Control Group (IOCG);
- ISDC: Tool IBAS per alert GRB (IASF-MI e supporto iniziale da vari Istituti)
- Spettrometro SPI: Anticoincidenza al Plastico (IASF-MI)
- Jem-X: Facility di calibrazione (UNI Ferrara+ contributi IAPS, OAS e IASF-PA)

Sfruttamento scientifico:

- Dal 2003, 300 articoli su 1791 a primo autore italiano ($\approx 20\%$), più 190 con almeno 1 Co-autore italiano e ~ 200 ATEs. -Mission Scientist: G. Palumbo selezionato da ESA dimesso poi nel 2015
- Uno dei maggiori contributi e ritorno scientifico per INAF è l'attività sulla identificazione delle nuove sorgenti IBIS. Su circa 300 sorgenti, 230 sono state identificate tramite follow-up in banda X (Swift/XRT, XMM e Chandra) e campagne in banda IR/ottico. Rif. schede SGRIIS e MIOHECS.

Critical issues

- Since July 17h, routine operations are done without using thrusters for momentum offload
- **No significant science loss**, only minimum increase of slewing time between targets. The new z-flip strategy fully recovers observational capability
- ToO < 4h are possible

Other issues:

- **Instruments and S/C aging:**

Detectors with highly modular design. No critical under-performance expected.

Batteries: no malfunctions expected in next 5 years.

S/C: full redundancy of subsystems including Power Supply

Orbit: stable (controlled re-entry planned on 2029).

- **Extension beyond 2022 (2023-2025):**

Waiting SPC decision by the first half of 2022.

