The Role of Multi-wavelength sky surveys in the identification of High-Energy Sources

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Fermi-LAT Collaboration

LOFT Science Team

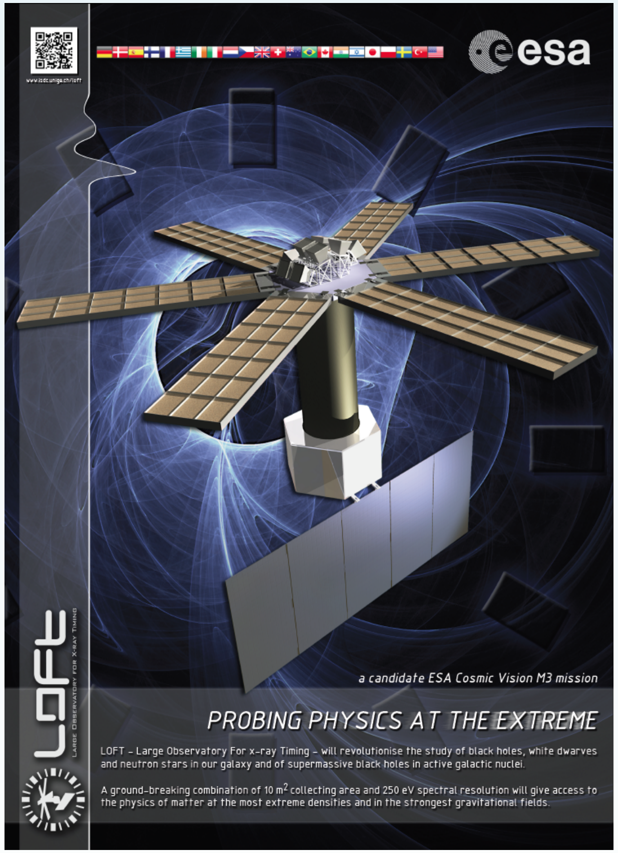
Fermi Gamma-ray Space Telescope

LOFT Large Observatory For X-ray Timing

Science from the Next Generation Imaging and Spectroscopic Surveys, ESO Garching, 15-18 Oct.2012

Fermi

LOFT


esa
a candidate ESA Cosmic Vision M3 mission
PROBING PHYSICS AT THE EXTREME
LOFT – Large Observatory For x-ray Timing – will revolutionise the study of black holes, white dwarves and neutron stars in our galaxy and of supermassive black holes in active galactic nuclei.
A ground-breaking combination of 10 m2 collecting area and 250 eV spectral resolution will give access to the physics of matter at the most extreme densities and in the strongest gravitational fields.
LOFT
LARGE OBSERVATORY FOR X-RAY TIMING

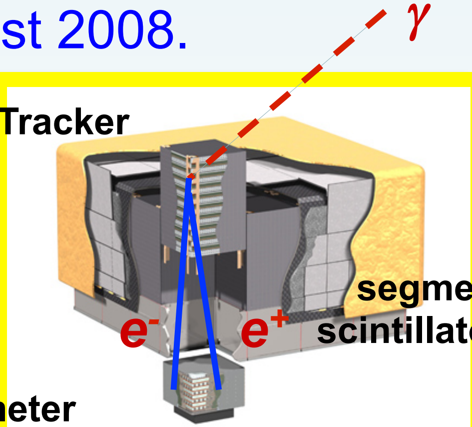
The *Fermi* Gamma-ray Space Telescope

- PI: Peter Michelson (Stanford University), 2011 Rossi Prize of the AAS High-Energy division

- Launched on June 11th 2008 from Cape Canaveral. Circular orbit, Low Earth Orbit (LEO) 565 km, 96m period, 25.6° inclination (Atwood et al. 2008).

- Science operations started August 2008.

LAT (Large Area Telescope)
- *3000 kg*
- ***20 MeV - 300 GeV***
- ***≈0.1° positioning***
- *8250 sq deg FOV ~**1/5 of the sky***
- *ΔE/E ≈0.1@ 200 MeV*



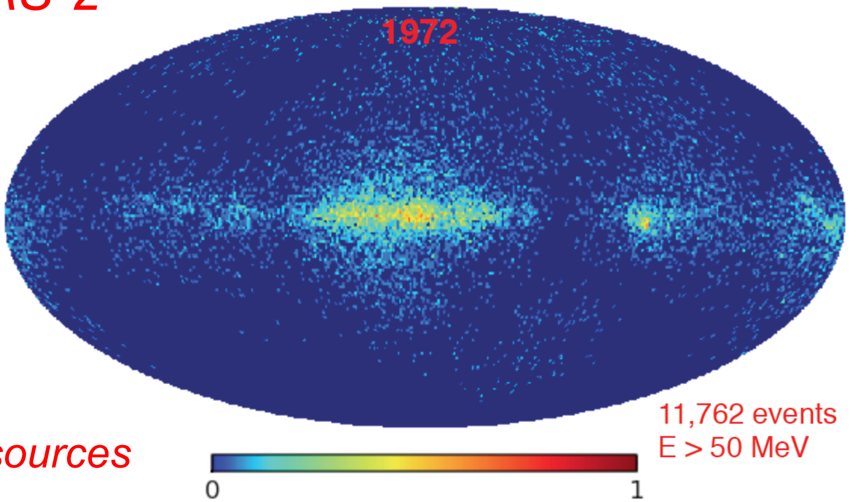
- Largest energy range and spatial resolution than any other γ-ray satellite ever

- All LAT observations in **survey mode. 3 hours/scan**

- Mission lifetime till 2015 (expected)

The history of Gamma-ray astronomy at a glance

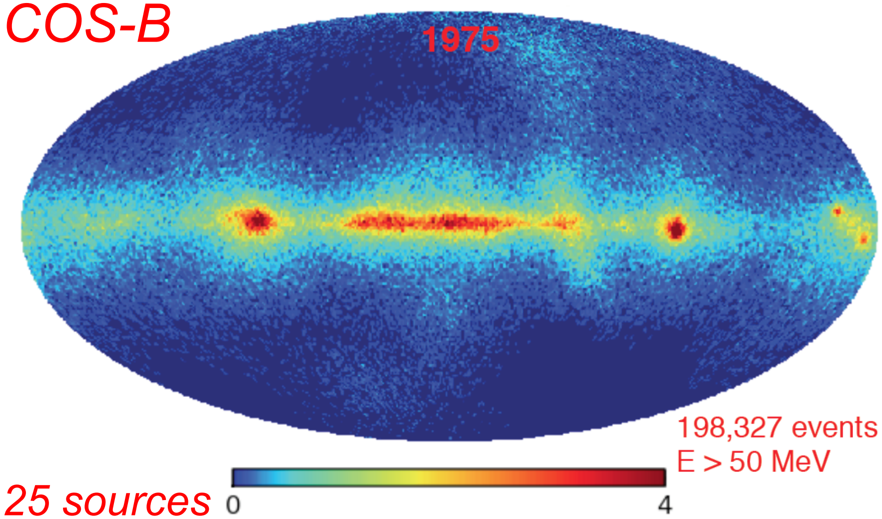
SAS-2



3 sources

11,762 events
E > 50 MeV

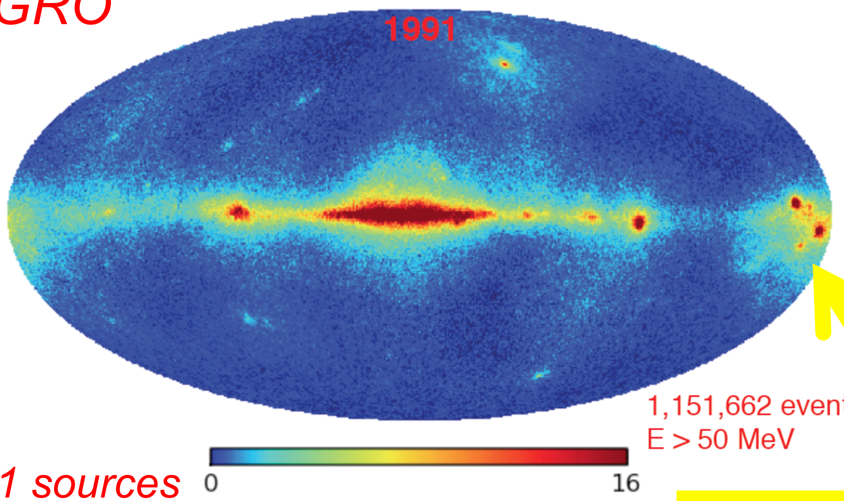
COS-B



25 sources

198,327 events
E > 50 MeV

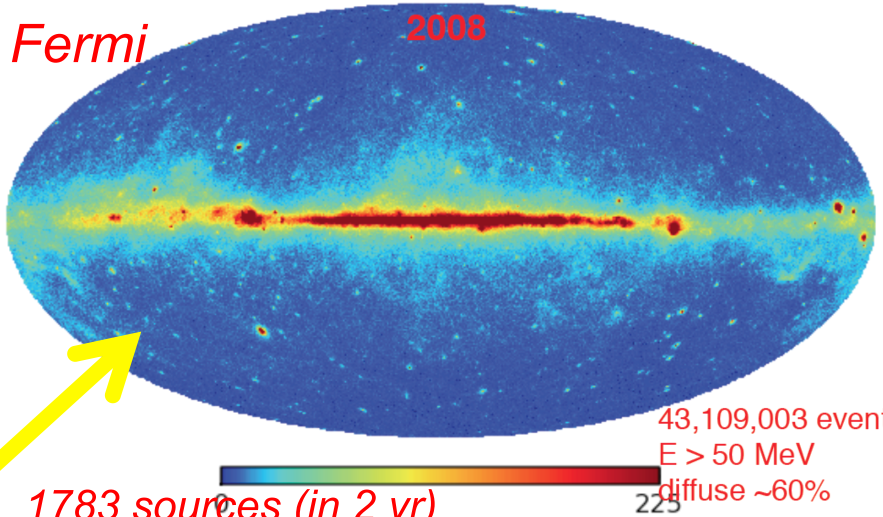
CGRO



271 sources

1,151,662 events
E > 50 MeV

Fermi



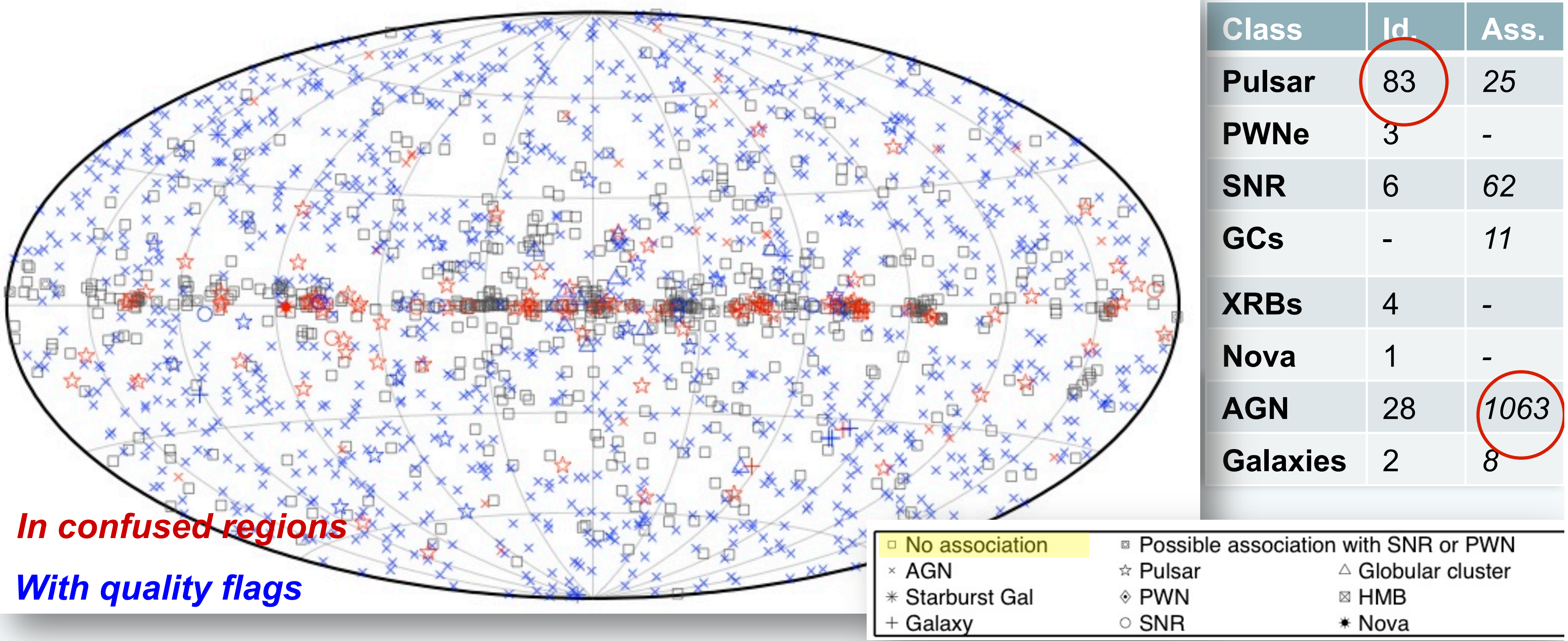
1783 sources (in 2 yr)

43,109,003 events
E > 50 MeV
diffuse ~60%

x50 sensitivity improvement
x10 positioning improvement

The 2nd Fermi LAT γ-ray source catalogue (2FGL)

- ❑ Produced out of the first two years of operation (Nolan et al. 2012)

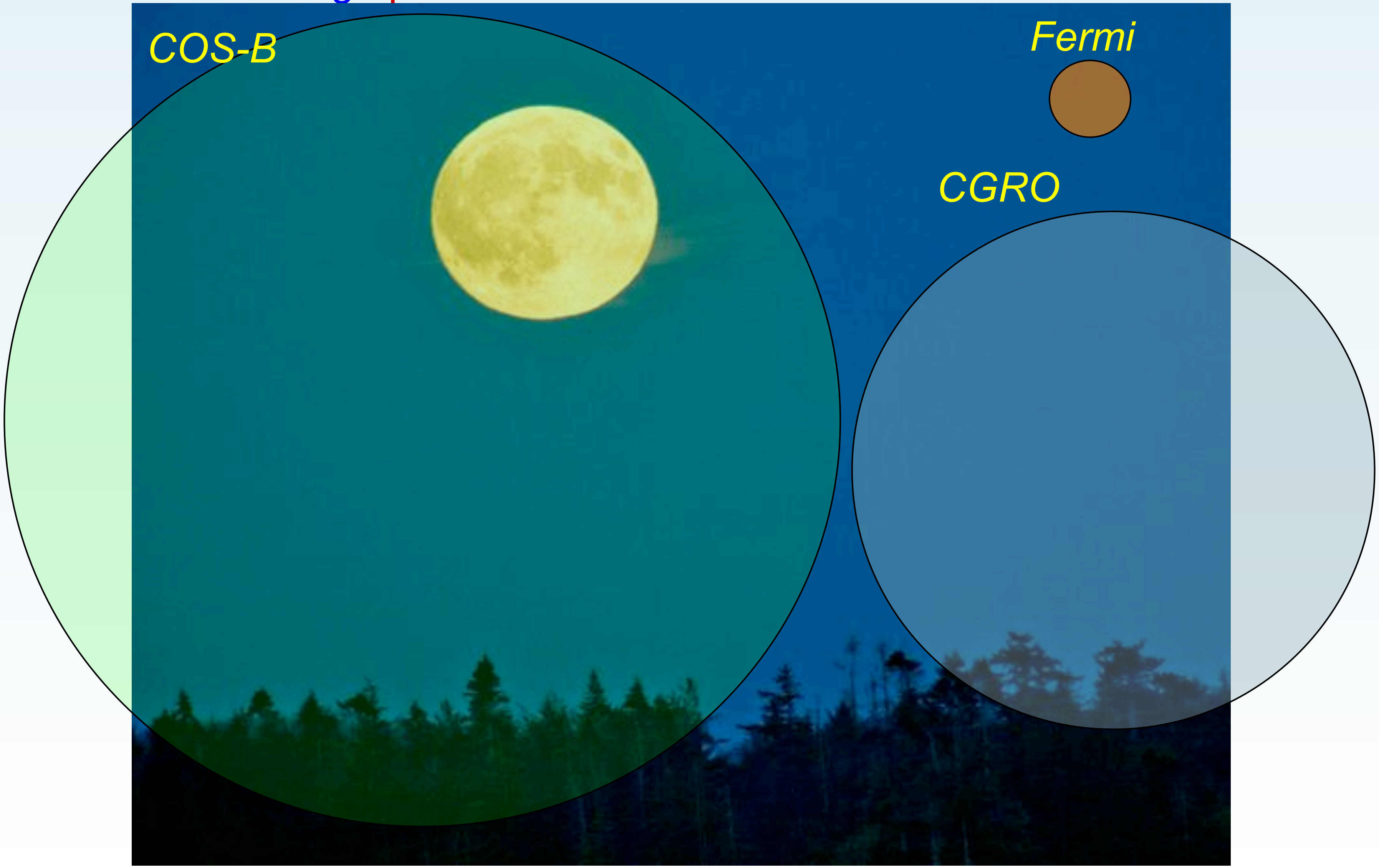


Class	Id.	Ass.
Pulsar	83	*25*
PWNe	3	-
SNR	6	*62*
GCs	-	*11*
XRBs	4	-
Nova	1	-
AGN	28	*1063*
Galaxies	2	*8*

- ❑ **1783** sources detected
- ❑ **127** sources identified
- ❑ **1169** only associated (i.e. *not identified yet*)
- ❑ **577** sources in the 2FGL catalogue remains unidentified/unassociated
- ❑ **The vast majority of LAT sources is still unidentified !**

Gamma-ray Source Identification problem

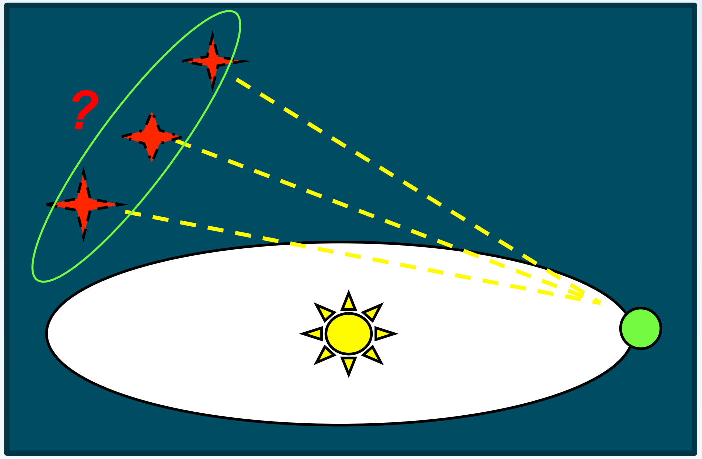
- Uncertainty on Gamma-ray photons positioning prevents a direct source identification through position match → associations must be taken with care



Source Identification and Source Association

- **Identification**: Correlated radio/optical/X-ray **variability** (AGNs, Novae), **orbital modulation** (XRBs), **pulsation** (pulsars), **extension** (SNR,PWN)

- Multi-λ observations not always simultaneous



- Fermi is not sensitive to orbital variability shorter than 3 hrs

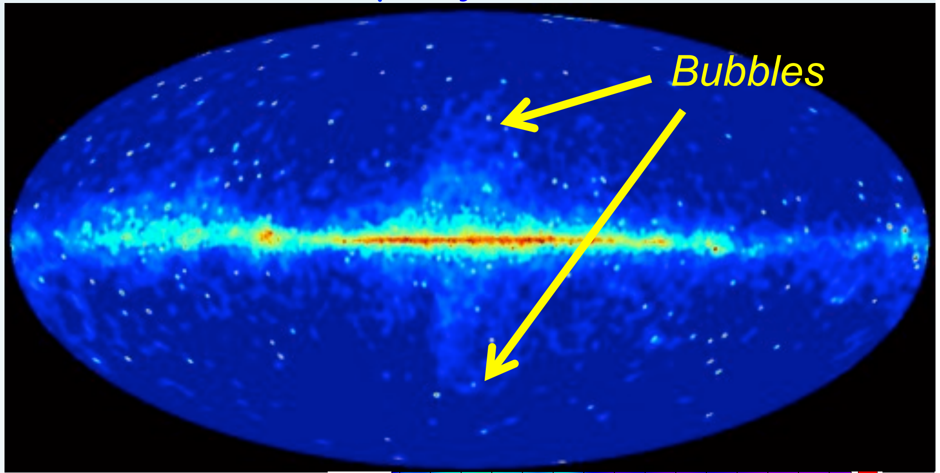
- Not all pulsars can be identified via γ-ray timing
  - ☹ ***~1/3*** *are radio-silent → no radio position or period*
  - ☹ *Not always enough photons for a blind search*
  - ☹ *Several scans needed for fainter sources*
  - ☹ *Troublesome to phase-connect multi-epoch scans*

- **Association**: Cross-matches with master catalogues based on figure of merit, chance coincidence probability

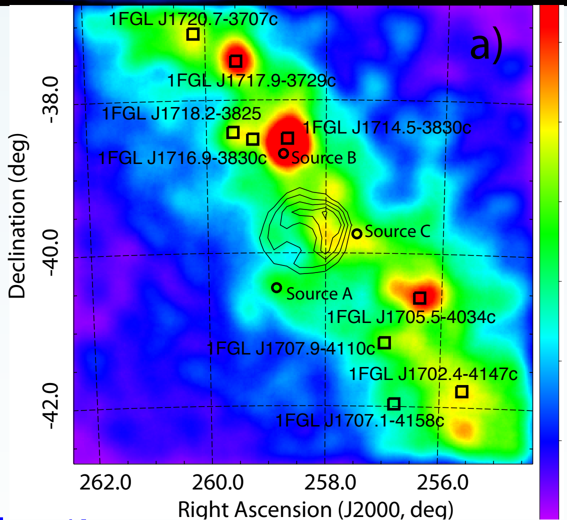
- Master catalogues may be inhomogeneous, outdated, incomplete → biased classification. Unassociated does not mean unidentified

The γ-ray source nature

- ❑ Understanding the nature of the unidentified Galactic γ-ray sources is a major challenge.
  - ✓ Model high-energy non-thermal emission mechanisms
  - ✓ Discovery of new source populations
  - ✓ Study the Galactic γ-ray background
  - ✓ CR contribution, CR sources, ISM properties



- ❑ Modeling of the diffuse emission needs accounting for discrete sources
- ❑ Contribution of known sources can be accounted for but that of *unresolved sources*, or sources *at or below the detection limit*, is more tricky

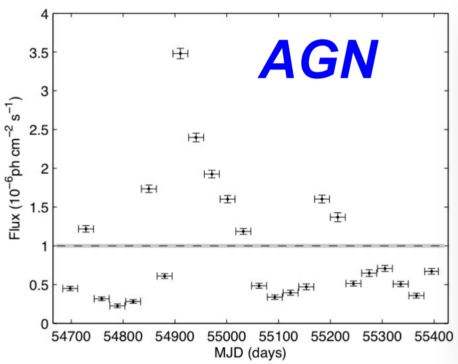


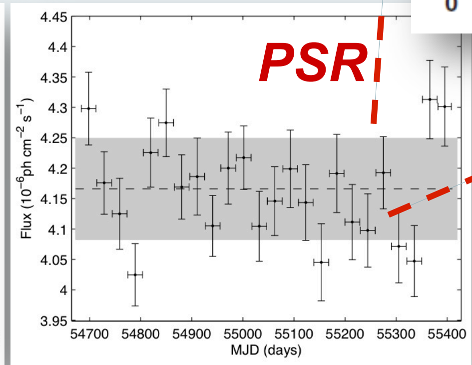
- ❑ Population synthesis models ← γ-ray source identification
- ❑ Modeling of the "true" Galactic γ-ray background → better source detection

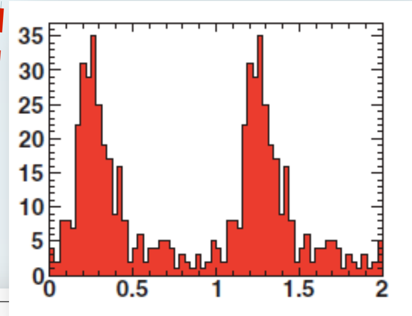
Identification via Statistical Classification

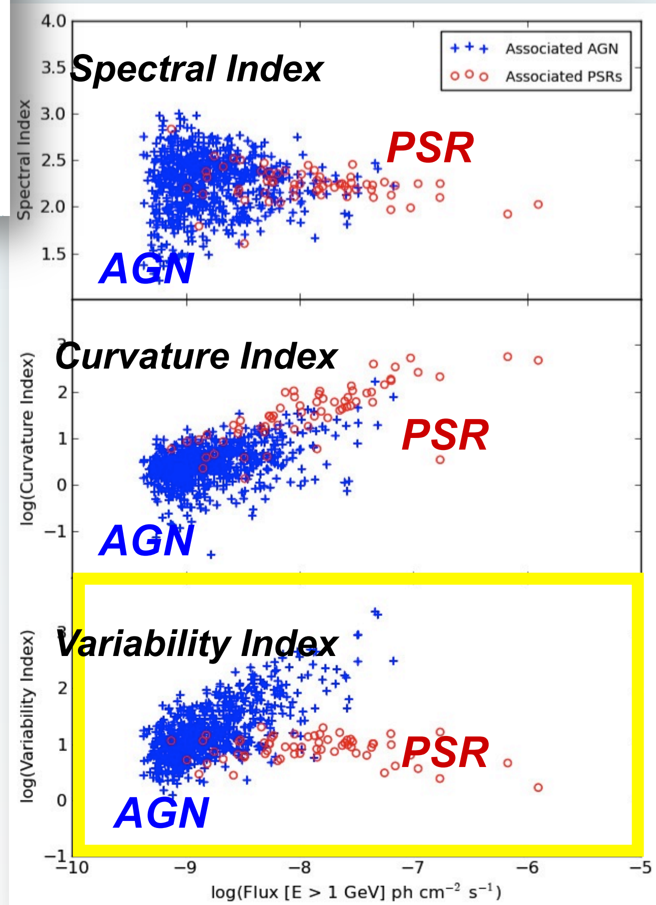
- Source classification with decision-tree and linear regression techniques based on γ-ray source characteristics (variability, spectrum)

- Templates from γ-ray sources in the 1FGL catalogue which are either *identified* or *associated* (Ackermann et al., 2012)







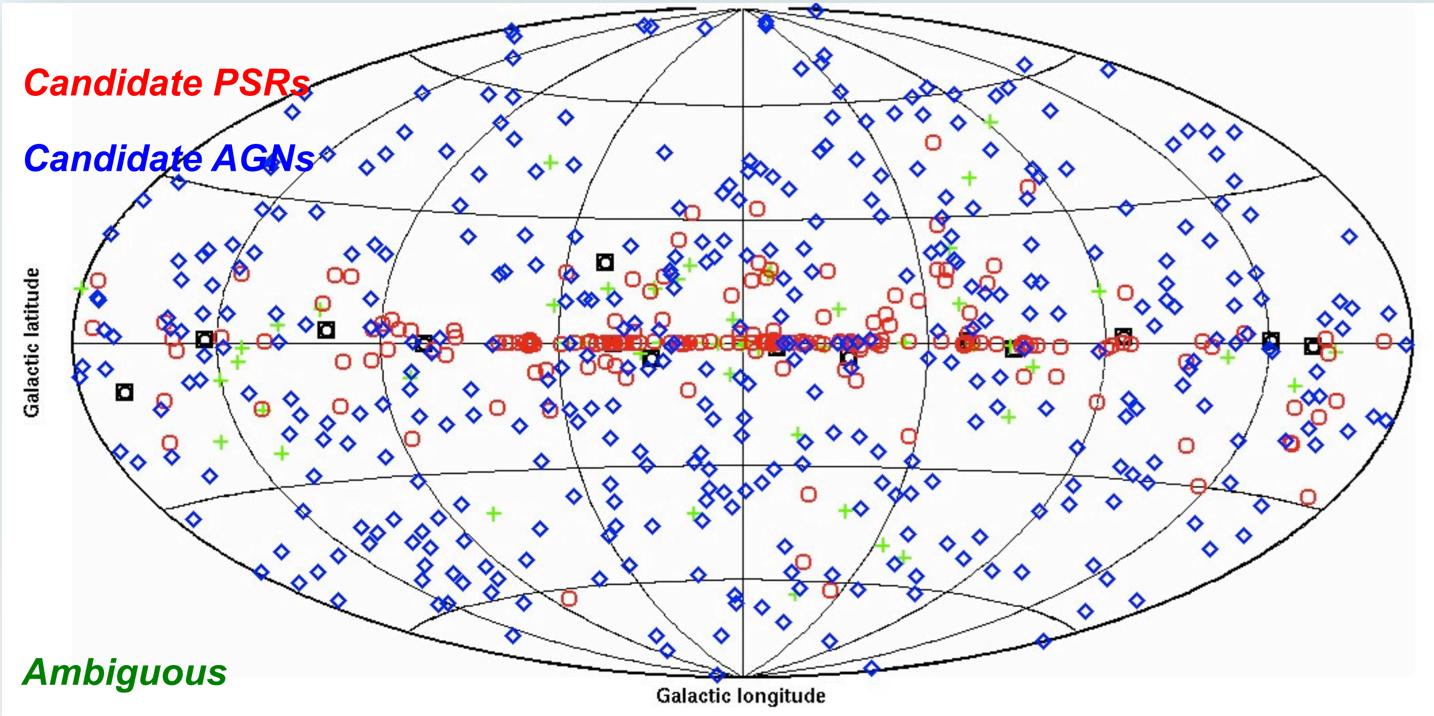


- Pulsar and AGN templates used as a reference

- Variability index is the most efficient discriminator

Statistical Classification results

- **221** AGN-like; **134** pulsar-like sources; **275** sources unclassified (**43%**).



- Pulsars vs. AGNs classification ! Some sources might not be pulsars or AGN, but belong to **new classes !**
- **Method still under test!**
- Multi-wavelength follow-ups are needed to validate classification methods, solve ambiguous cases, define new classification templates
- Multi-wavelength phenomenology must be part of the classification criteria

Multi-wavelength Identification

X-ray map of the γ-ray error box

Test X-ray positions for γ-ray timing of pulsar candidates

Opt(IR) map of the X-ray sources

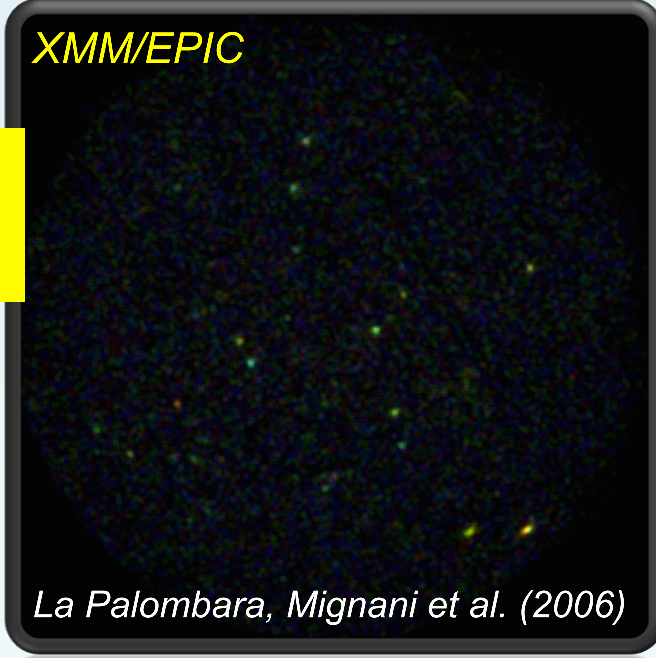
X-ray/Opt source classification

- *X-ray spectrum, variability, periodicity*
- *$N_H \Rightarrow$ galactic/extragalactic*
- *HR = $[cr_{E1}-cr_{E2}]/[cr_{E1}+cr_{E2}]$*
- *Opt/IR SED, variability, periodicity, proper motion*
- ***F_X/F_{opt}** $\Rightarrow$ characteristic of the X-ray source*
- *X-ray/optical extension/morphology*

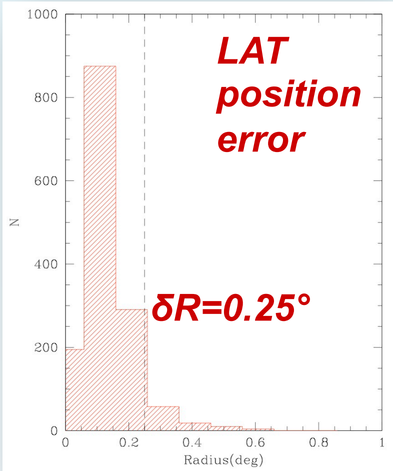
X-ray counterpart classification

γ-ray source identification

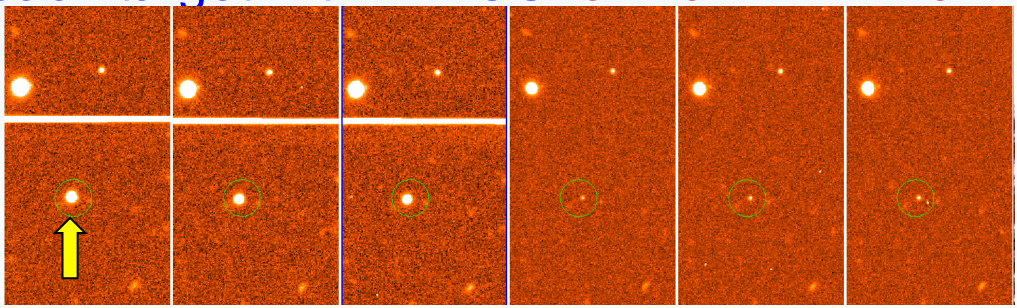
Mignani 2009



XMM+VLT Identification Survey



- Quick look follow-up (~5ks) with the Swift/XRT
- Deep (>30ks) XMM follow-up on selected targets based on position accuracy (δR<0.12°), brightness
- Priority to non "problematic" sources (not extended/confused, faint)
- Both sources with AND without a candidate statistical classification
- Deep (4hrs) VLT BVI follow-up of each target with VIMOS. δR<0.12° → max 4 pointings per target
- 11 sources observed so far (Mignani et al. 2012).

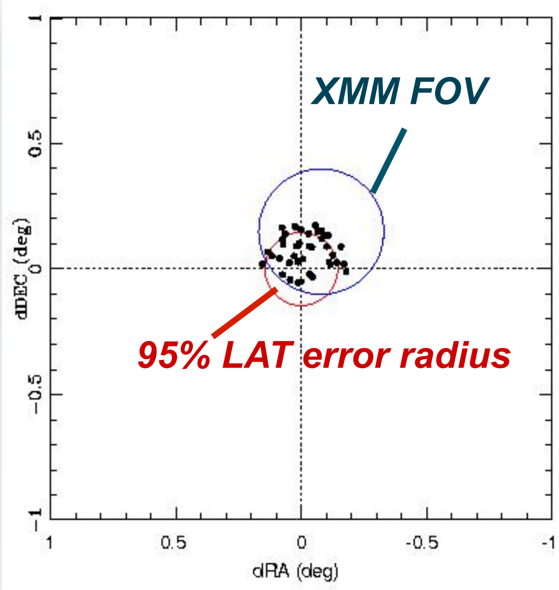


Identification of 1FGL J2339.7–0531 as a binary ms-pulsar through its optical variability

Archive Surveys

- Complete coverage of all unassociated/unidentified LAT sources unfeasible on GO time.
- **577** unidentified LAT sources → **>17 Ms** with XMM
- Exploitations of X-ray DBs and source catalogues for a serendipitous survey *(in progress)*
- **174** LAT sources with *at least partial* X-ray coverage
- Optical coverage even sparser
- Probability of chance overlap with an LAT+XMM field is small.
- Optical FOVs (< 10'x10') → partial overlaps
- Colour coverage + limiting flux may not be adequate

Mission	LAT match
XMM	41
Chandra	42
ROSAT	112
Swift	6
Integral	14

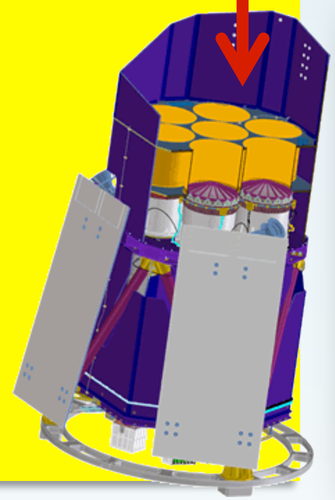


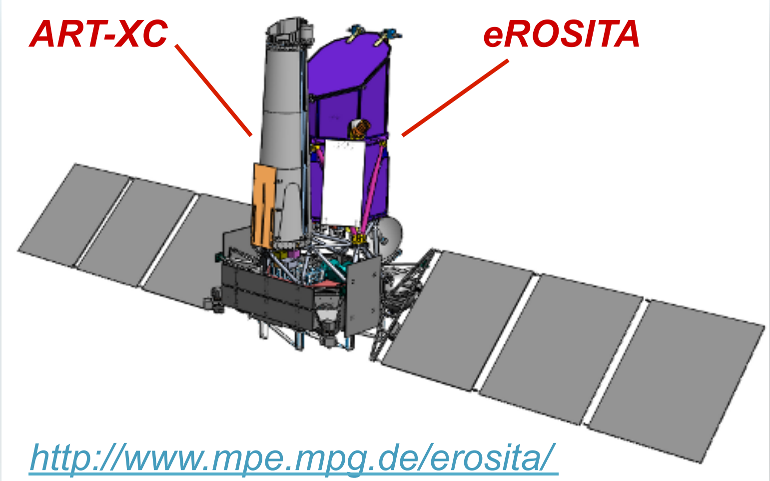
X-ray Surveys

See A. Merloni's talk

- *eROSITA* is the next Wide Field X-ray Telescope, lead by MPE (Garching). It will fly on the Russian satellite *Spectrum-Roentgen-Gamma (SRG)*

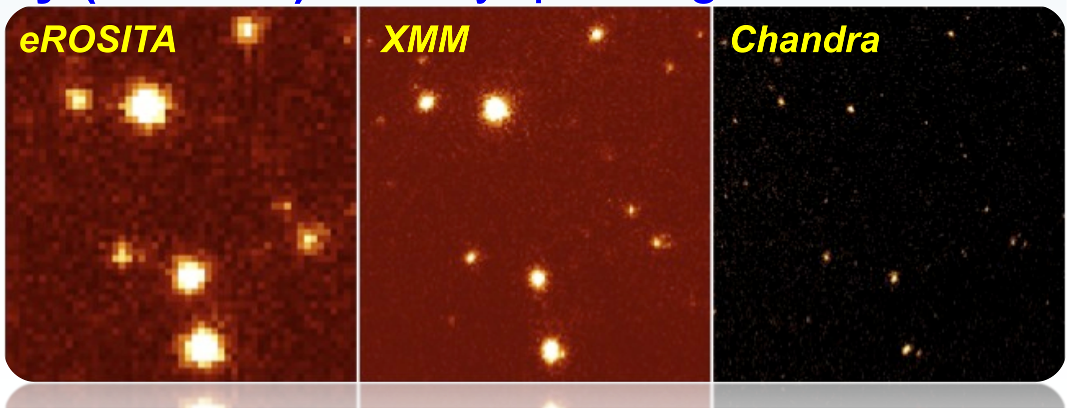
- *7 X-ray telescopes*
- *54 nested Wolter-1 mirrors (36cm)*
- *XMM pn-CCD detectors*
- ***0.5 – 10 keV***
- *Effective area 0.24m^2 @ 1keV*
- *<15" positioning@1kev (on axis)*
- ***1°x1° FOV***
- *$\Delta E/E \approx 1.38$ @ 6 keV*





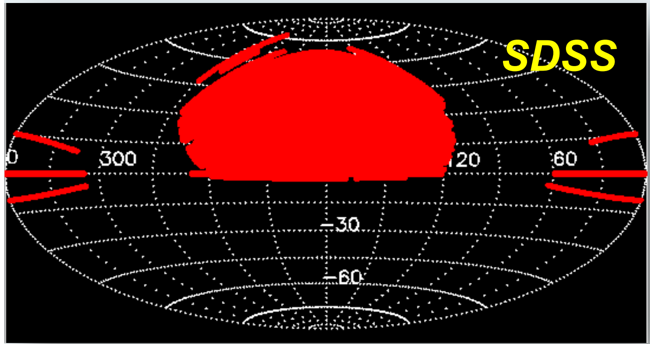
- *SRG* to be launched in 2014 with a Soyus-2 rocket from Baikonur. L2 orbit. >7 yr life time, of which **4 yr survey (8 scans)** and 3 yr pointings

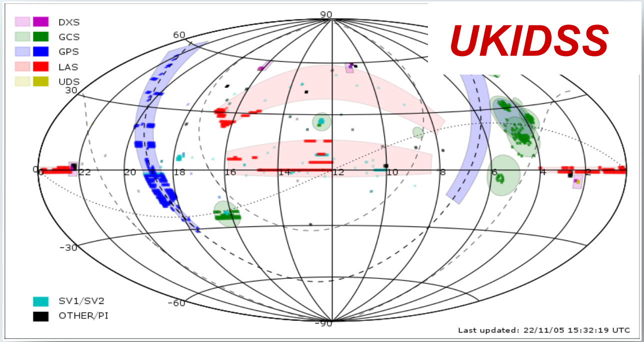
- *eROSITA* will perform the first **multi-epoch** 0.5-10 keV all-sky survey with a factor of **30** deeper flux limit than the RASS



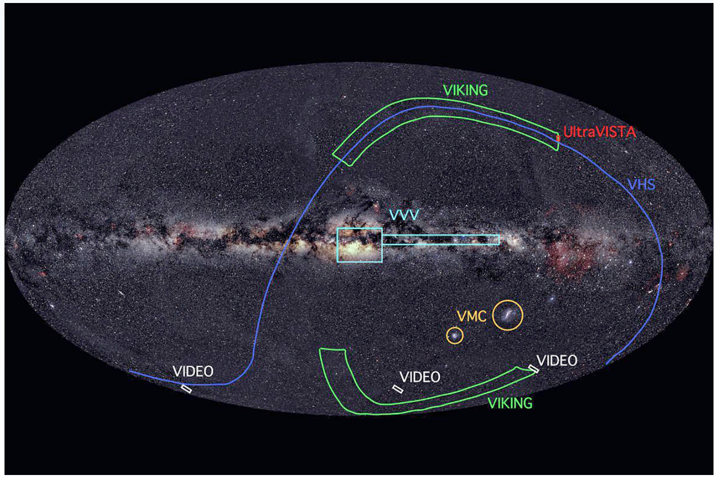
Optical Surveys

- Current surveys (*SDSS, UKIDSS, VISTA, VST*) + object catalogues are the best option for a systematic optical coverage of Fermi/LAT error boxes
- Coverage vs deepness: Not all-sky coverage and inhomogeneous sensitivity





- VST and VISTA will cover the entire southern hemisphere
- VVV: each region observed 100x over ~5 yr
- X-ray transient monitoring in the Galactic plane
- Help from spectroscopic surveys (PESSTO, 4MOST, MOONS) for X-ray counterpart classification

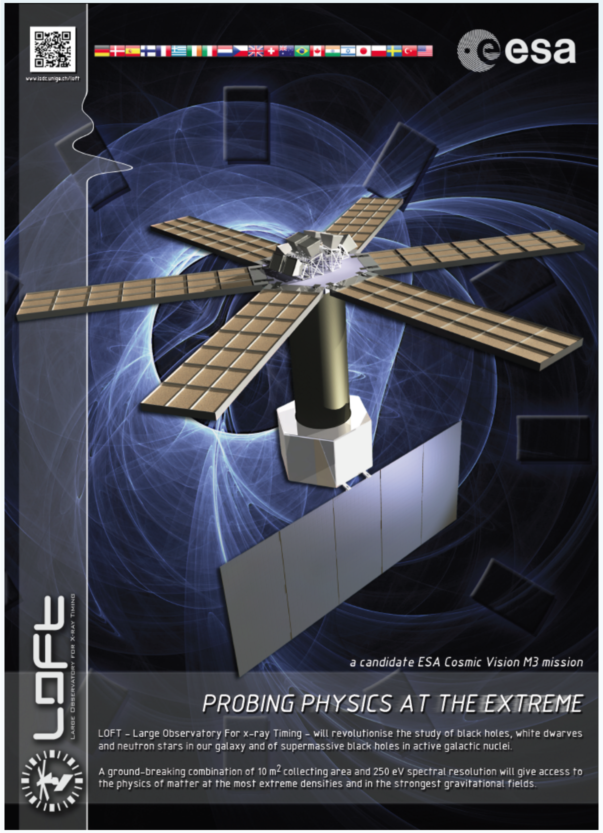


Number crunching

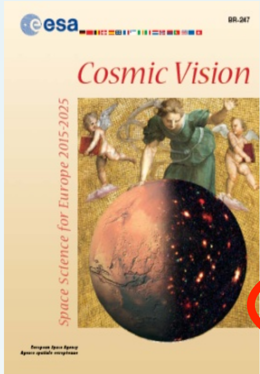
- Multi-λ identification of *Fermi* sources must be fully automatic
- Advanced multi-λ catalogue matching
- Advanced data products from single catalogues (e.g. optical classifications)
- Advanced classification tools using multi-λ information (flux, spectrum, extension, variability, classification)
- Adaptable to new classification criteria for new source classes
- Help from VO tools and survey classification technologies

See P.-C. Zinn's talk

LOFT: the Large Observatory for X-ray Timing



Feroci et al. (2012), arXiv:1209.1497



3. What are the fundamental physical laws of the Universe?

3.1 Explore the limits of contemporary physics

Use stable and weightless environment of space to search for tiny deviations from the standard model of fundamental interactions

3.2 The gravitational wave Universe

Make a key step toward detecting the gravitational radiation background generated at the Big Bang

3.3 Matter under extreme conditions

Probe gravity theory in the very strong field environment of black holes and other compact objects, and the state of matter at supra-nuclear energies in neutron stars

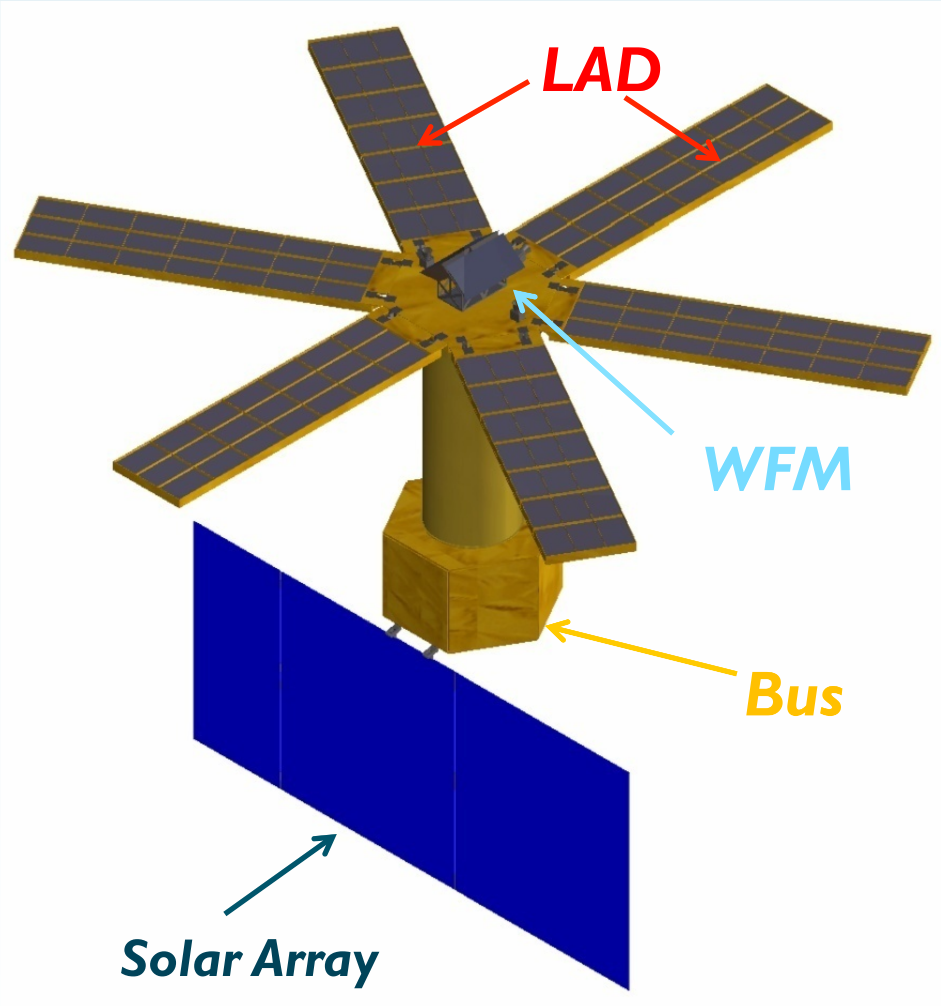
LOFT Science Team composed of >240 scientists from:

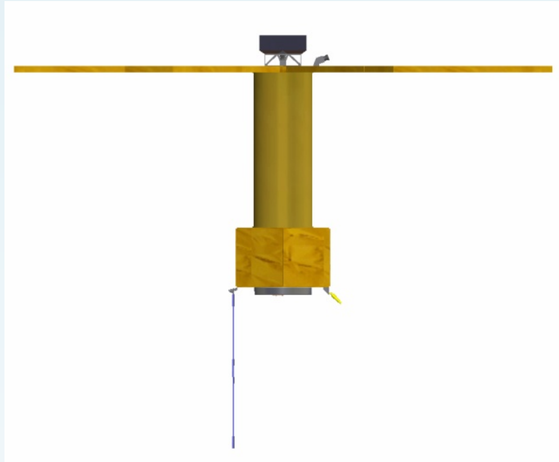
Australia, Brazil, Canada, CzechRepublic, Denmark, Finland, France, Germany, Greece, Ireland, Israel, Italy, Japan, the Netherlands, Poland, Spain, Sweden, Switzerland, Turkey, United Kingdom, USA

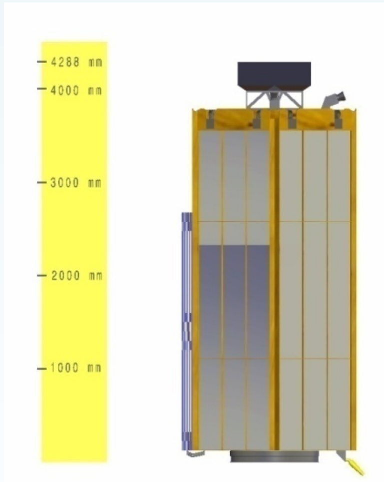
LOFT Consortium: national representatives:

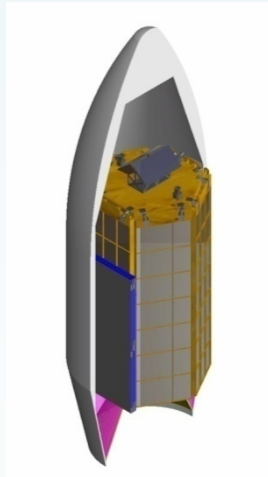
Jan-Willem den Herder	*SRON, the Netherlands*
Marco Feroci	*INAF/IAPS-Rome, Italy*
Luigi Stella	*INAF/OAR-Rome, Italy*
Michiel van der Klis	*Univ. Amsterdam, the Netherlands*
Thierry Courvousier	*ISDC, Switzerland*
Silvia Zane	*MSSL, United Kingdom*
Margarita Hernanz	*IEEC-CSIC, Spain*
Søren Brandt	*DTU, Copenhagen, Denmark*
Andrea Santangelo	*Univ. Tuebingen, Germany*
Didier Barret	*IRAP, Toulouse, France*
Renè Hudec	*CTU, Czech Republic*
Andrzej Zdziarski	*N. Copernicus Astron. Center, Poland*
Juhani Huovelin	*Univ. of Helsinki, Finland*
Paul Ray	*Naval Research Lab, USA*
Joao Braga	*INPE, Brazil*
Tad Takahashi	*ISAS, Japan*

The LOFT satellite



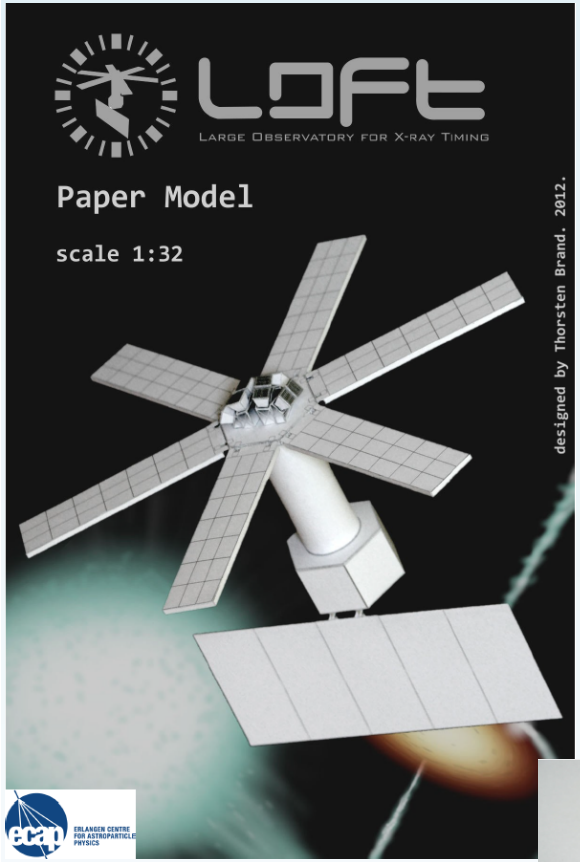




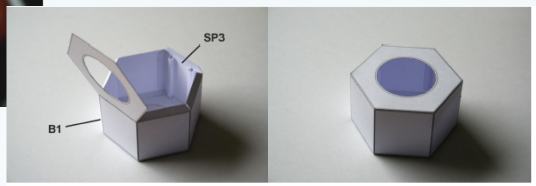


http://www.isdc.unige.ch/loft

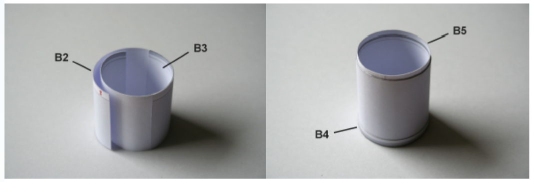
Feroci et al. (2012), arXiv:1209.1497



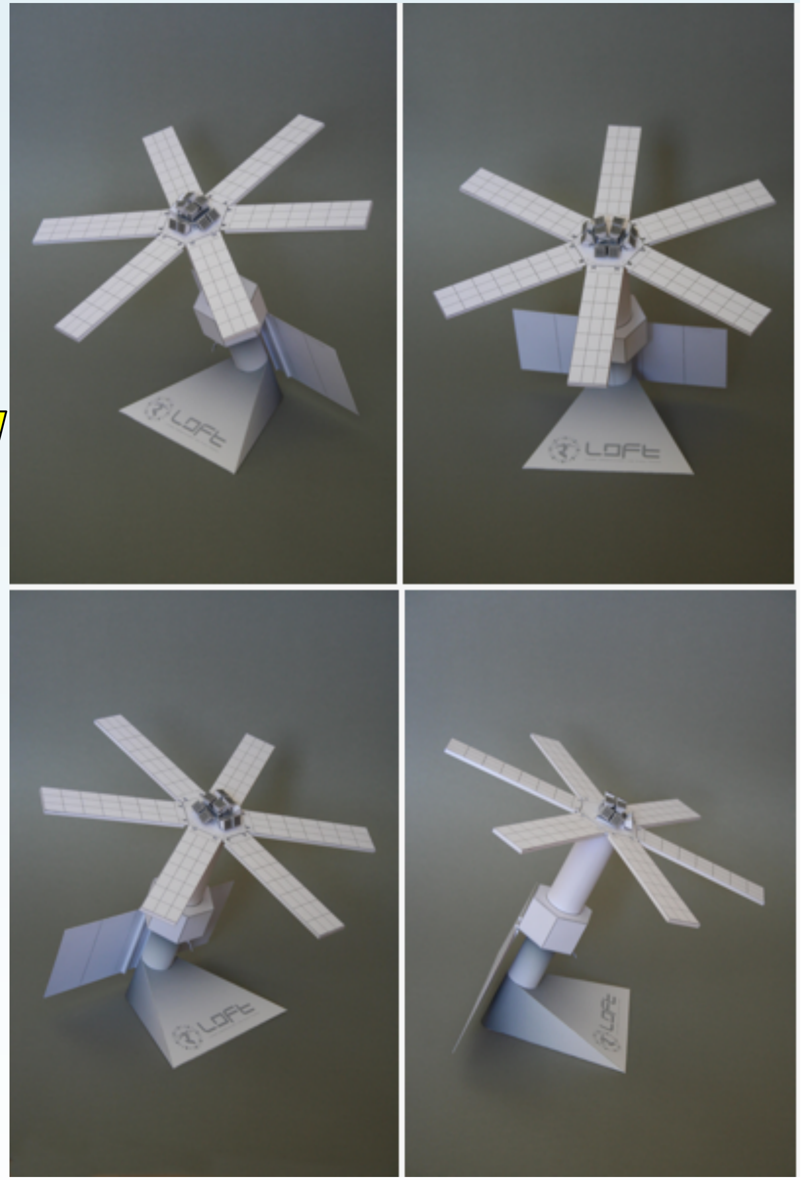
BUILD YOUR OWN 100 cm^2 LOFT!



The hexagonal Bus is built up from part **B1**. Glue the folded part **SP3** to the inside of the face above the red holes, forming two channels.

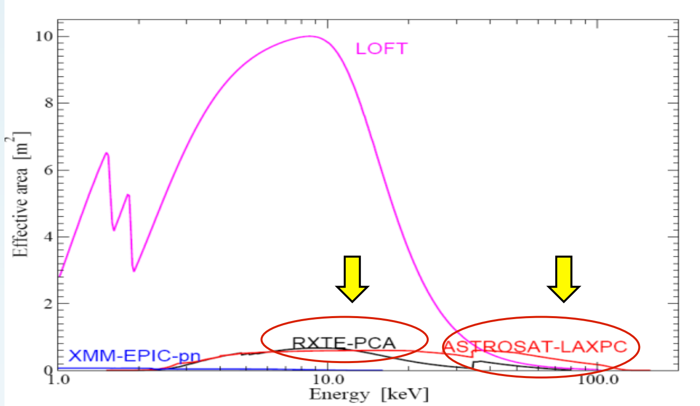


Roll parts **B2** and **B3**, and glue them to a cylinder with **B3** in the inside. Be careful with their orientation: the grey joiner stripe for **B5** has to be on the opposite end of the cylinder than the white stripe for **B4**. Afterwards, glue **B4** and **B5** to these stripes.

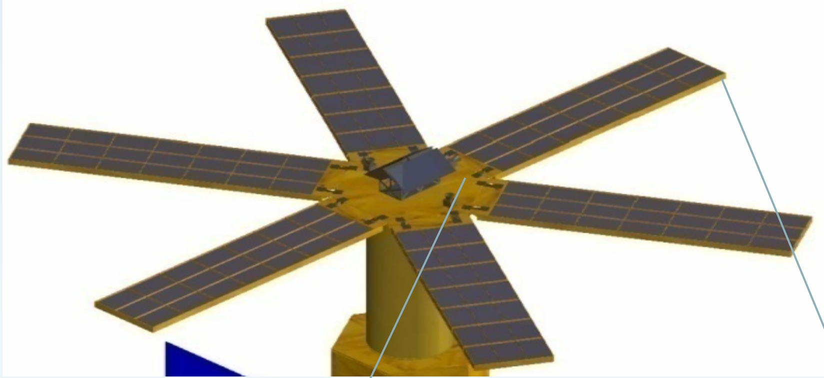


http://www.isdc.unige.ch/loft/index.php/multimedia/122

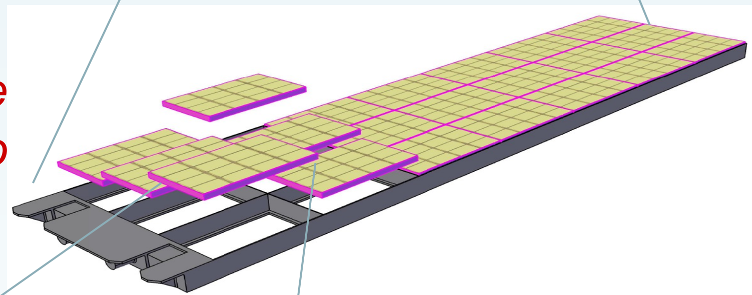
The Large Area Detector (LAD)

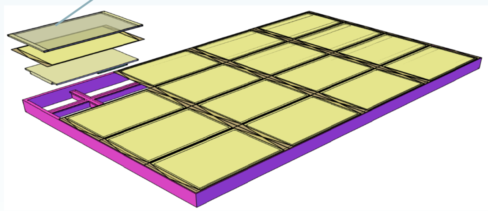


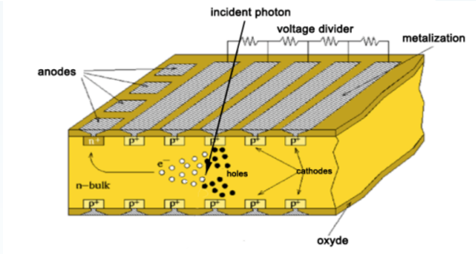
LAD – Large Area Detector	
Effective Area	4 m^2 @ 2 keV 8 m^2 @ 5 keV 10 m^2 @ 8 keV 1 m^2 @ 30 keV
Energy range	2-30 keV primary 30-80 keV extended
Energy resolution FWHM	260 eV @ 6 keV 200 eV @ 6 keV (45% of area)
Collimated FoV	1 degree FWHM
Time Resolution	10 µs
Absolute time accuracy	1 µs
Dead Time	<1% at 1 Crab
Background	<10 mCrab (<1% syst)
Max Flux	500 mCrab full event info 15 Crab binned mode



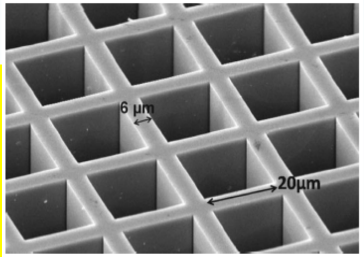
6 petals
21 module
16 detecto



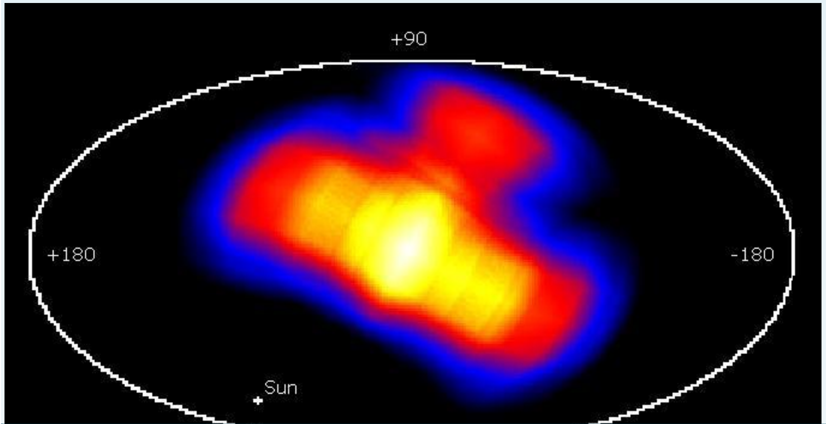


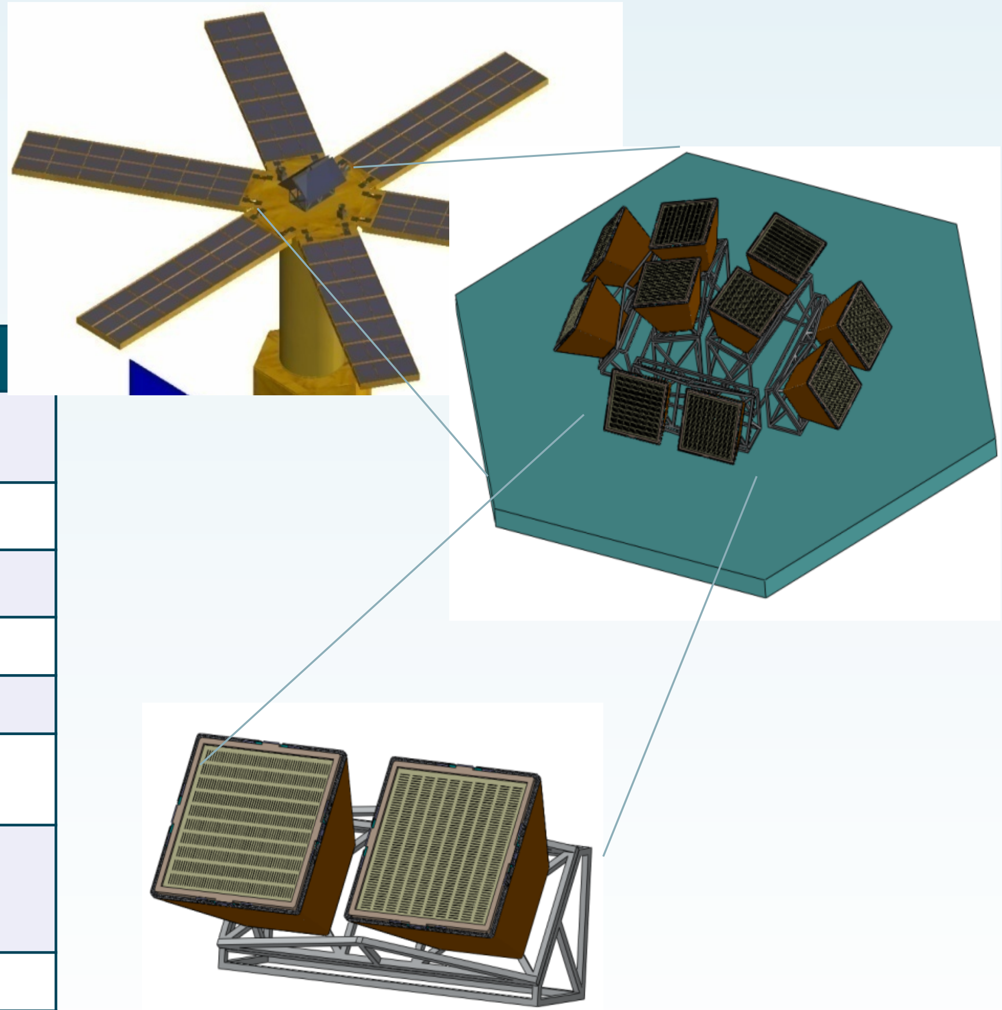


Large-area Silicon Drift Detectors and coded masks.



The Wide Field Monitor (WFM)

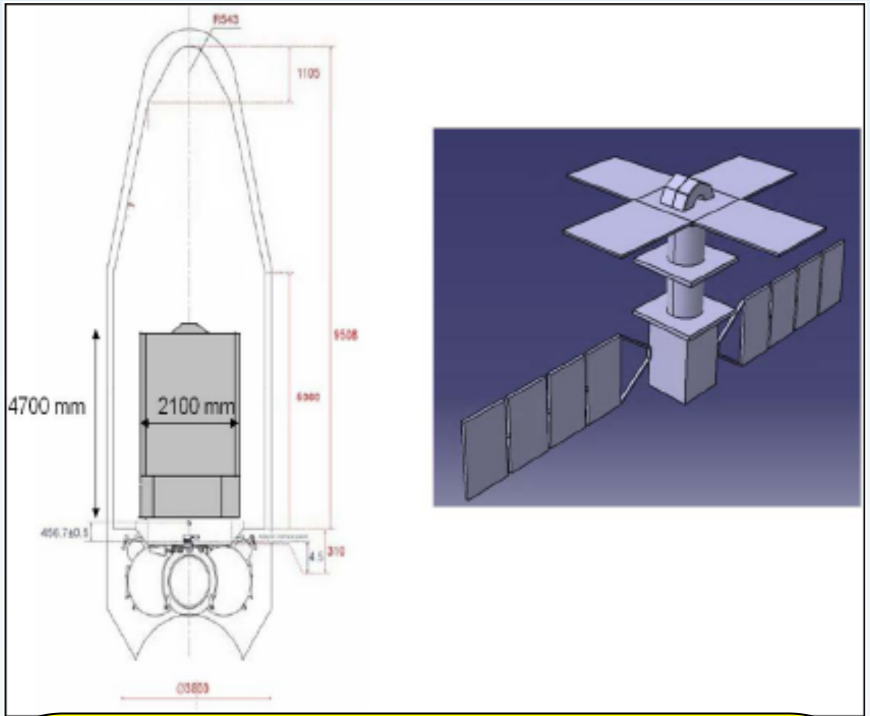




WFM- Wide Field Monitor	
Energy range	2-50 keV primary 50-80 keV extended
Active Detector Area	1820 cm^2
Energy resolution	300 eV FWHM @ 6 keV
FOV (Zero Response)	180°x90° + 90°x90°
Angular Resolution	5' x 5'
Point Source Location Accuracy (10-σ)	1' x 1'
Sensitivity (5-σ, on-axis) Galactic Center, 3 s Galactic Center, 1 day	 270 mCrab 2.1 mCrab
Standard Mode	5-min, energy resolved images
Trigger Mode	Event-by-Event (10μs res) Realtime downlink of transient coordinates

Mission Timelines

- ❑ Launch date: 2022-2024 time frame
- ❑ Soyuz launcher
  - ➢ huge mass margin,
  - ➢ large volume margin,
  - ➢ configuration optimization
- ❑ 4+1 years mission lifetime
- ❑ ESA M3 missions Assessment study extended
- ❑ Down selection of the 4 M3 missions (LOFT, ECHO, Marco Polo, STE-QUEST) + Plato by end 2013.



❑ ***Pointing:***
- ➢ *3-axis stabilized*
- ➢ *LAD accessible sky >75%(G)*
- ➢ *Galactic Centre visibility >65% (G)*
- ➢ *ToOs : within 8 working hrs*

❑ ***Low-Earth Orbit** (equat.. 550 km, <2°)*

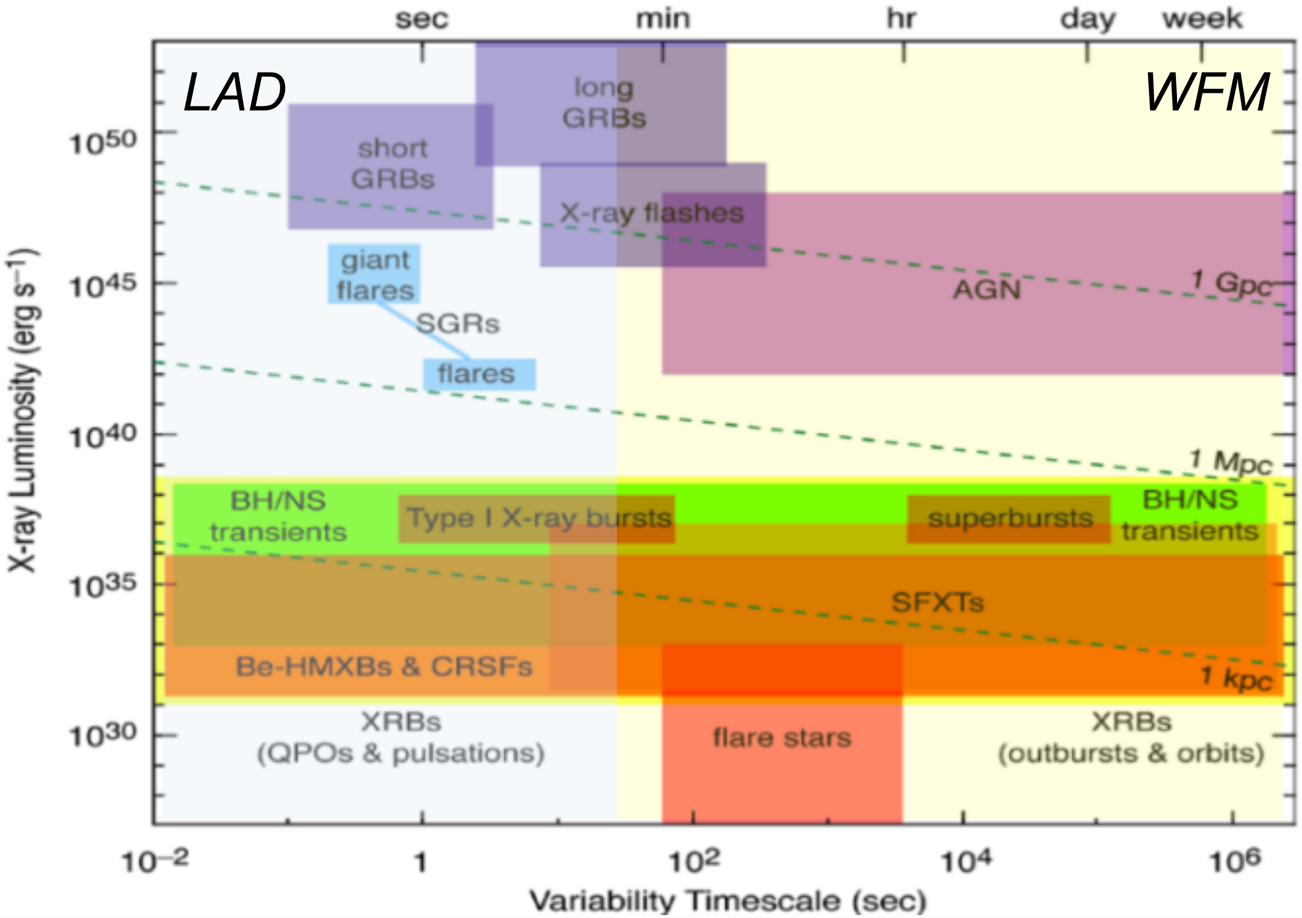
❑ ***Data and Telemetry**:*
- ➢ *Downlink per orbit: 6.7 Gbit*
- ➢ *Flex TM share between LAD and WFM*
- ➢ *Fast delivery of transient coordinates*

The LOFT Science

- LOFT is specifically designed to exploit the diagnostics of very rapid and long-term X-ray flux and spectral variability in compact objects.

The LAD will study sub-ms QPOs and ms/s pulsations In XRBs, BHc, ULXs, pulsars, and magnetars

The WFM will discover X-ray transients and impulsive events and monitor spectral changes over ~1/3 of the sky



- The LAD will observe in pointing mode and the WFM in survey mode

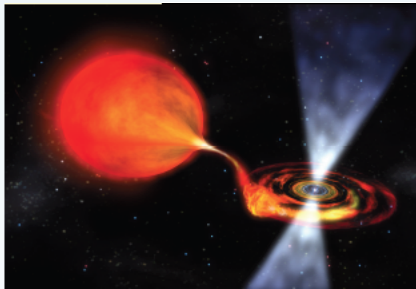
LOFT/WFM

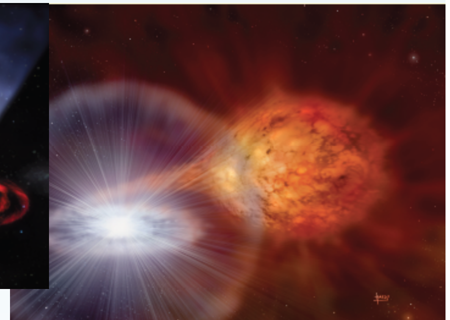
- The WFM will expand on the legacy of the *RXTE*/All Sky Monitor but with a **x20** larger collecting area
- The WFM will monitor variable X-ray sources detected by *eRosita* and *NuSTAR*
- WFM will trigger optical follow-up
- Synergies btw X-ray/optical observations

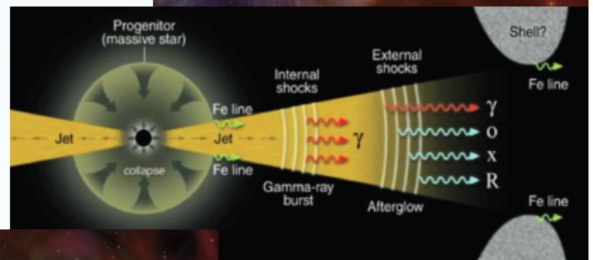
  Discovery of X-ray transient optical counterparts

  Monitor X-ray/optical variability on day-to-yr scales

  Correlate X-ray/optical variability and spectral changes
- Probe emission physics on a much broader sample
- **Optical survey telescopes will work in perfect synergy with the WFM**







Building on current facilities

- Time-domain is a consolidated parameter space in optical astronomy
- Several small-to-mid class survey telescopes already operational
- Current survey telescopes will build an enormous multi-band data base of variable and transient objects over large fractions of the sky.
- No simultaneity with WFM observations but this data base is an important reference for a posteriori cross-matching and optical identification of X-ray transients detected by the WFM
- New technologies tested, e.g. *VOEvent*, *SkyAlert*, to automatically trigger follow-ups
- New technologies developed for automated transient classifications based on light curves, colours, etc.

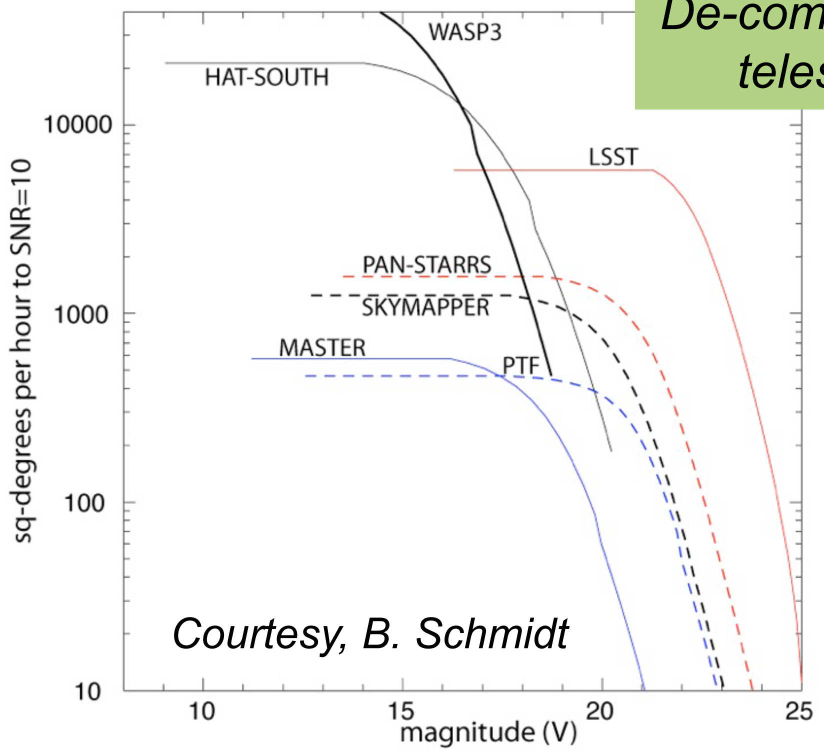
Survey Telescopes

- ★ Planetary Transits
- ★ Microlensing
- ★ Variable Stars
- ★ Asteroids
- ★ Galactic transients
- ★ Extra Galactic Transients
- ★ Cosmology

Robotic and not

Most telescopes are small (and cheap)

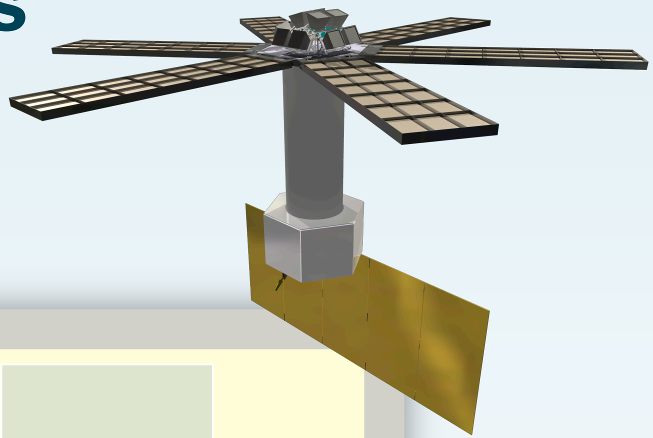
Option for 2020s De-commissioned telescopes

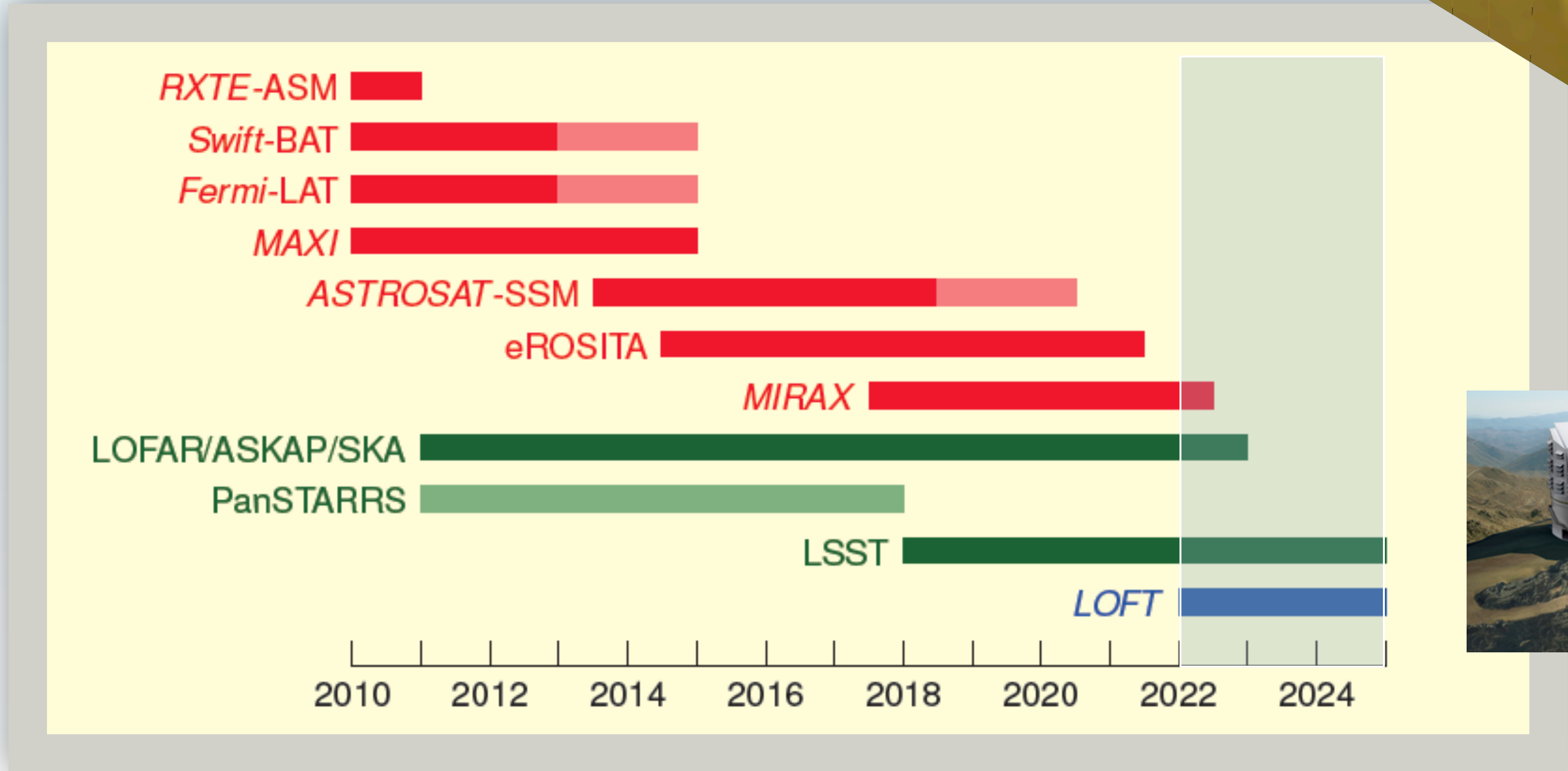


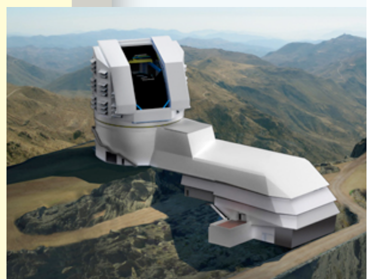
ESO 1m Schmidt

	□ deg	D(m)
UK/Palomar Schmidt	36	1.2
SDSS	1.5	2.2
CFHT+MegaCam	1.0	3.3
Palomar +PTF	6.6	1.2
PanStarrs	7.0	1.4
SkyMapper	5.2	1.1
OGLE IV	1.4	1.2
DECCAM	2.9	3.5
Subaru+HyperSup	1.8	7.2
VST	1.0	2.5
GMT + MACHO	1.1	1.1
MASTER	8.0	0.4
ROTSE	13.7	0.45
WASP-3	964.0	0.2
HAT-South	384.0	0.18
LaSilla QUEST	8.1	1.0

LOFT/WFM and Multi-λ Synergies







Summary and Conclusions

I. X-ray and optical/IR surveys are a crucial ingredient in the identification **of the hundreds of unidentified** γ-ray sources detected by *Fermi*

II. e-ROSITA will be fundamental to cover all the *Fermi/LAT* error boxes

III. With the VST and VISTA imaging surveys, as well as with current/future spectroscopy surveys, ESO will play a major role in the optical/IR coverage of the *Fermi/LAT* error boxes

IV. The synergy with synoptic survey telescopes, such as the LSST, will add great value to the *LOFT* program and ideally complement WFM observations