Monitoring of X-ray binaries and novae with the Burst Alert Telescope on board the *Swift* satellite

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Outline

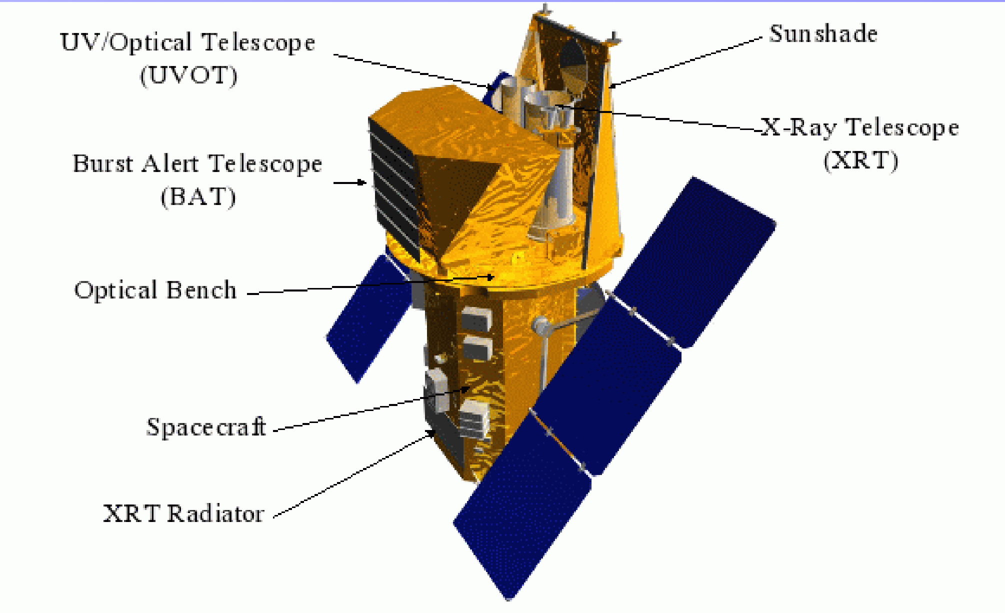
1. The Burst Alert Telescope on board *Swift*
2. The BAT survey data exploitation: a pipeline for temporal and spectral analysis of known sources. Tests with the Crab and GRO J1655-40
3. Application to some astrophysical sources:
   - IGR J08408-4503: a new recurrent supergiant fast X-ray transient
   - 4U 1954+319: a new symbiotic low mass X-ray binary system
4. Search for prompt gamma-ray emission from novae:
   - Detection of RS Ophiuchi
   - Classical novae: expected rate of detection of novae with BAT
5. Conclusions and plans for future work

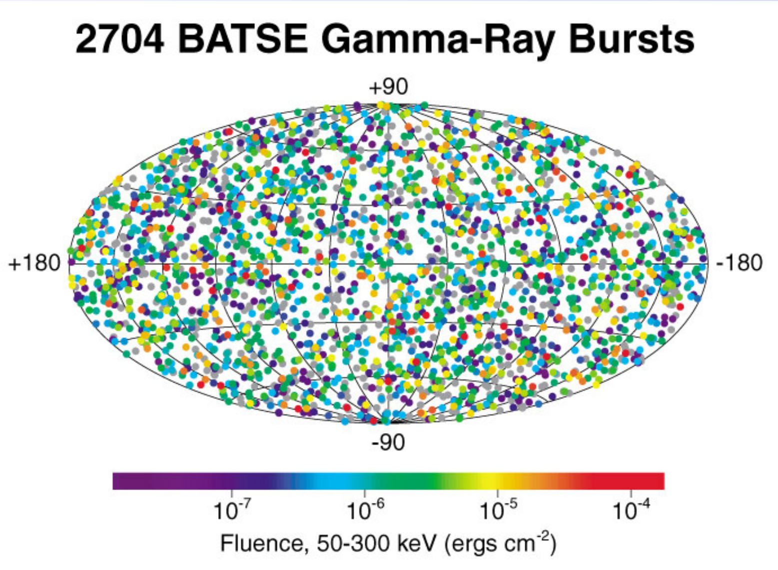
The *Swift* mission

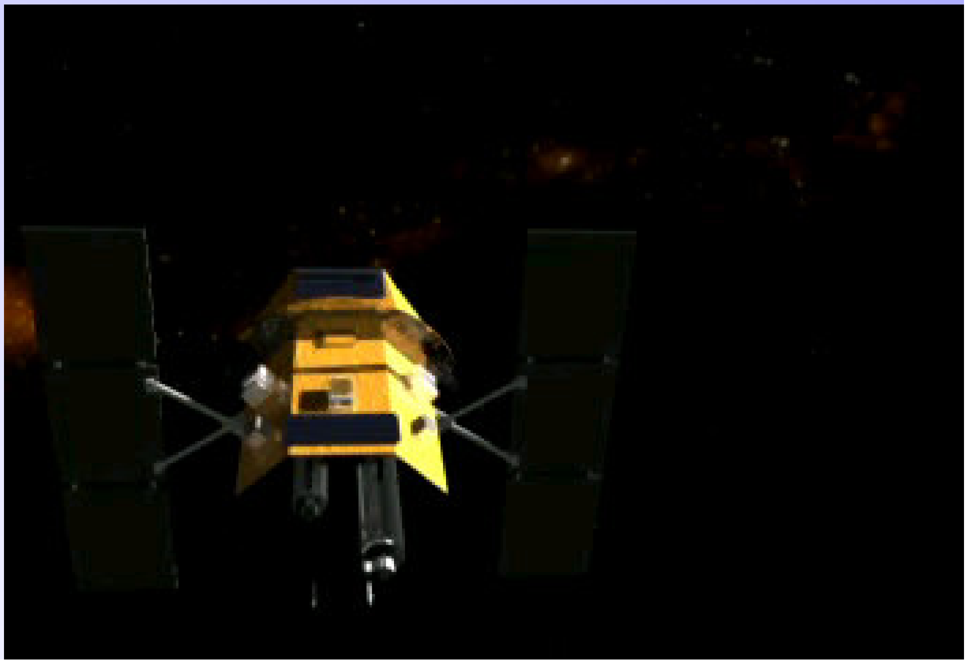
- Launched on November 2004
- USA / UK / ITALY collaboration

The first aim of *Swift* is the detection of Gamma-Ray Bursts (GRBs) and the following multi-wavelength study with all the instruments on board (rapid follow-up)

GRBs are rapid (from a few milliseconds up to several minutes) bright gamma-ray transients uniformly distributed, appearing at a rate of ~1/day







The *Swift* mission

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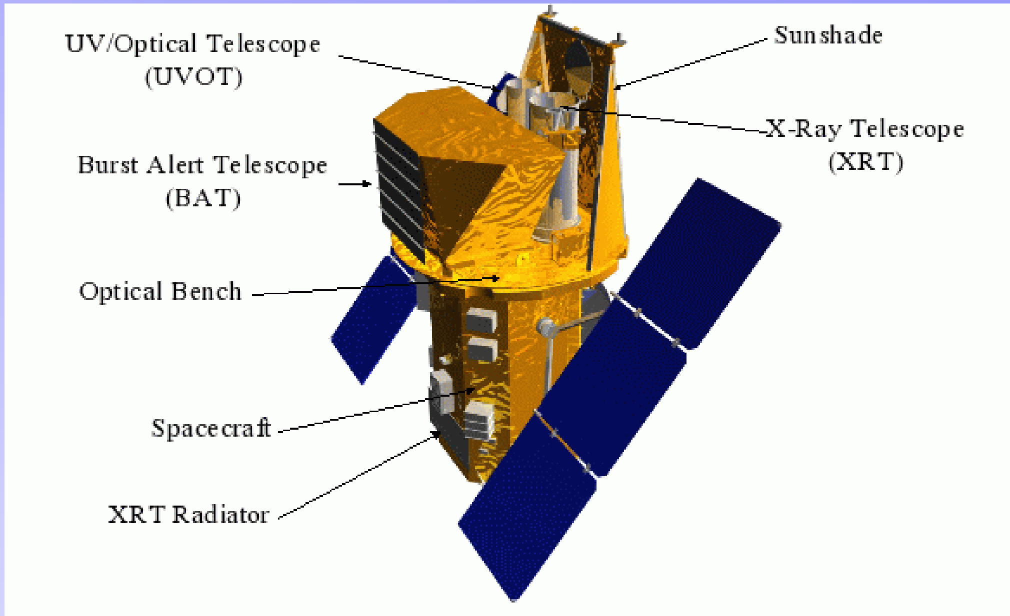


Other scientific objectives of *Swift*/BAT (**SECONDARY SCIENCE**):

1. The most sensitive all-sky survey ever made in the hard X-ray band
2. Rapid reaction science

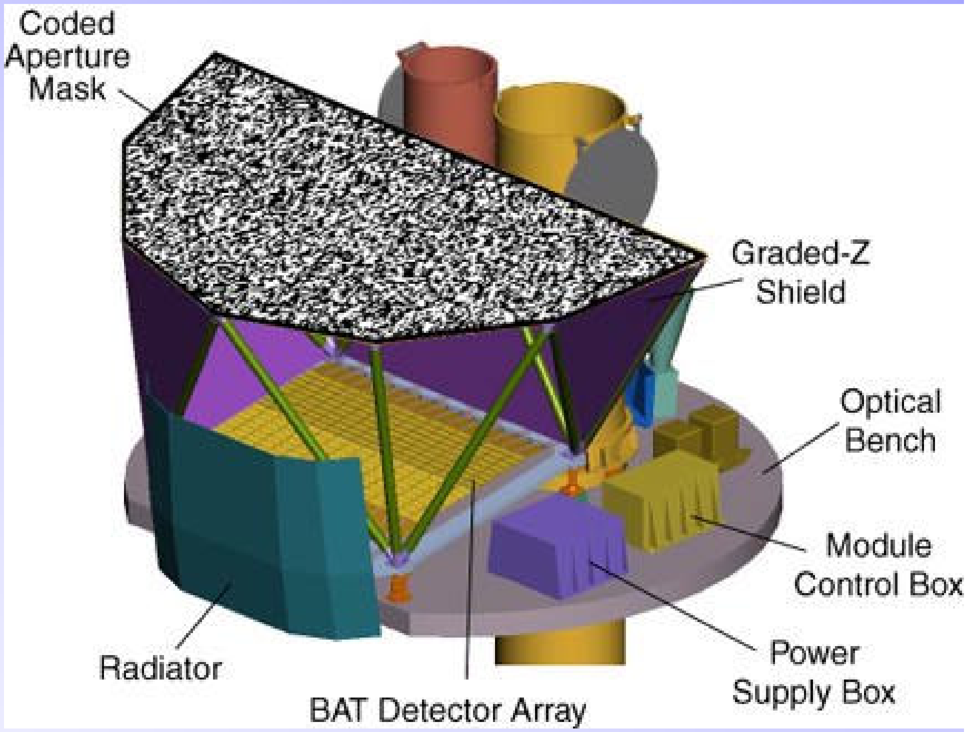
Gehrels et al. (2004), ApJ 611, 1005

The Burst Alert Telescope on board *Swift*

BAT is a coded mask instrument: a mask is mounted ~1m above a detector plane composed of 32768 CdZnTe elements (5200 cm^2) sensitive in the 14-200 keV band

BAT is the key instrument to detect GRBs

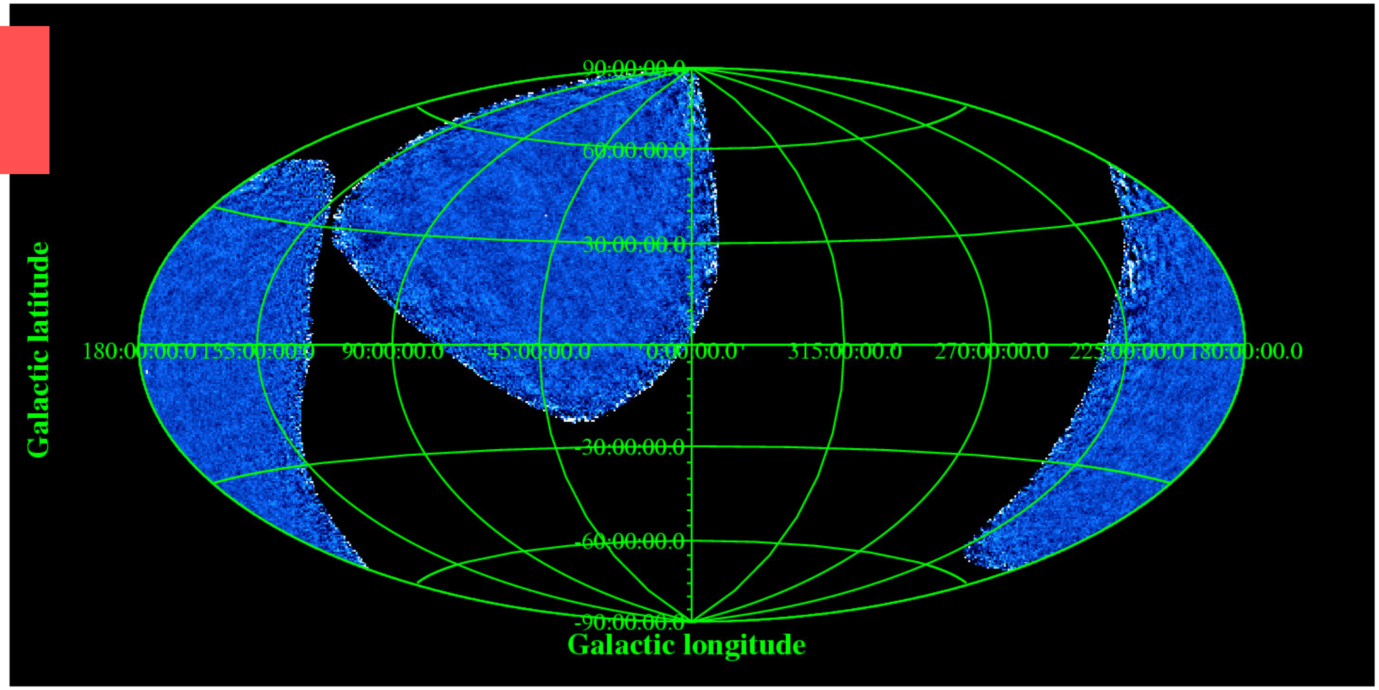
BAT in a nutshell	
Collecting Area	5200 cm^2
Detector	CdZnTe
Detection Elements	32768
Detector Unit Size	4 mm x 4 mm x 2mm
Detector Operation	Photon by photon (burst mode); Detector plane histogram (survey mode)
Field of View	1.4 sr (partially-coded)
Telescope PSF	20 arcmin (FWHM)
Sky coverage / orbit	50 %
Energy Range	14-200 keV

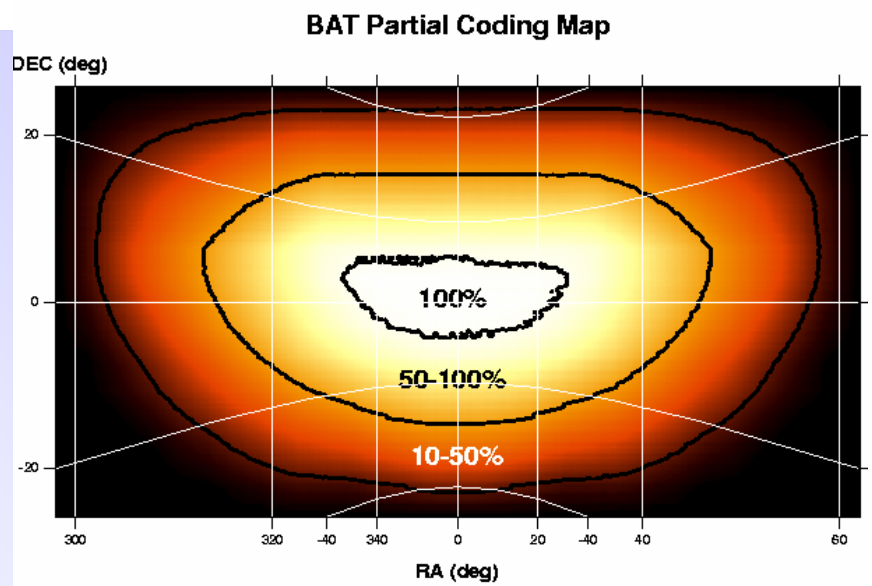


The Burst Alert Telescope on board *Swift*

2 BAT pointings

A huge field of view





Field of View = 1.4 sr (partially-coded)

Sky coverage / orbit = 50 %

Outline of the BAT data

BAT pointing (survey mode)

Detector count rates searched on board for transients (ring buffer ~10 min, different timescale/energy bands)

Trigger

Image

GRB Alert

BAT repointing

Event file

GRB Science

No triggers

Interesting known source

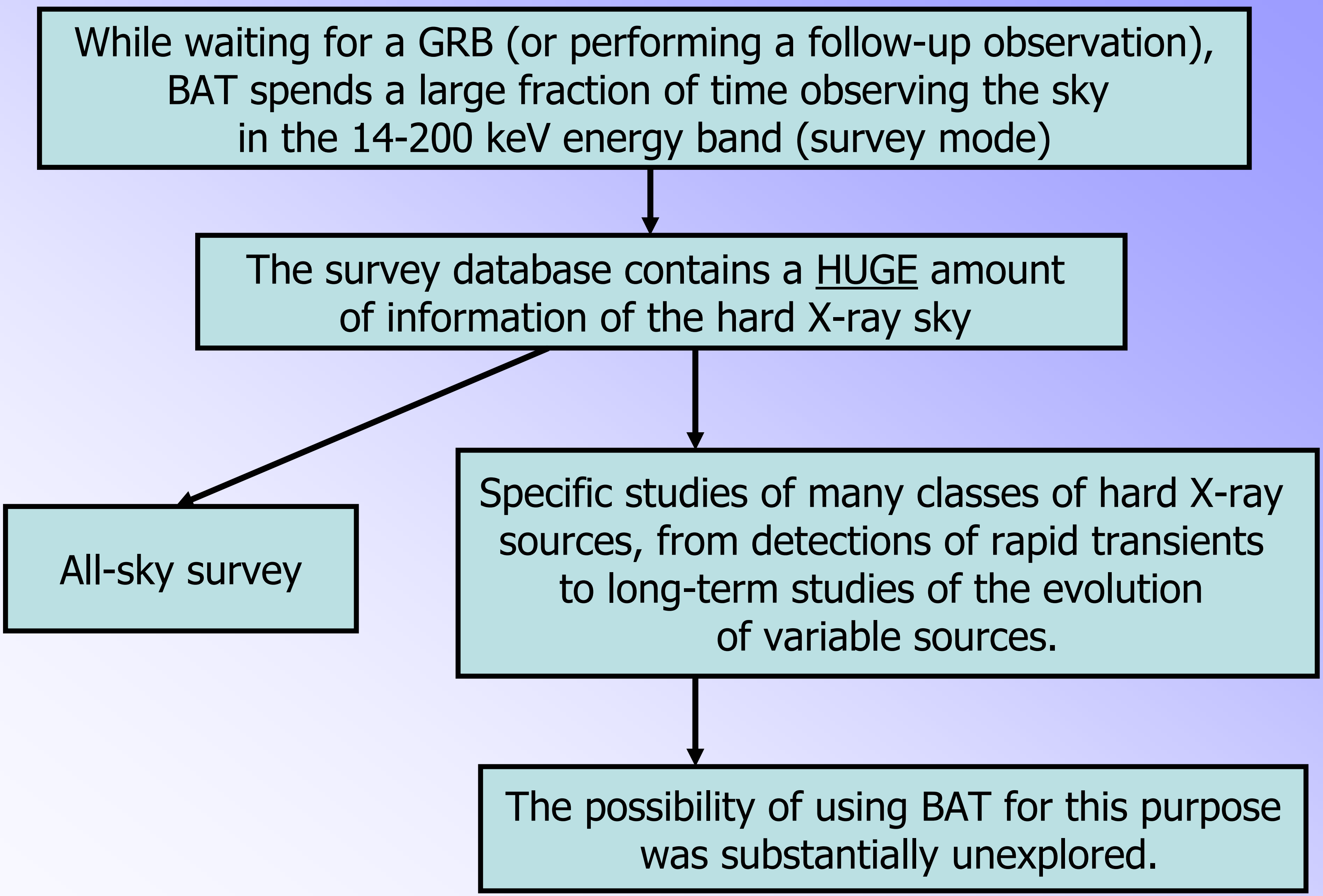
DPH file

Detector Plane Histograms (DPHs):

- 3D histograms: 2 spatial dimensions (detector plane) + 1 spectral (80 energy channels)
- Typical integration time of 450 s or less, depending on operational reasons (telemetry availability, slews, SAA …)

Secondary Science

The Secondary Science



The BAT survey data exploitation: a pipeline for temporal and spectral analysis

Public tools for DPH analysis available at
http://heasarc.nasa.gov/docs/swift/analysis/
but BAT survey data analysis is not supported

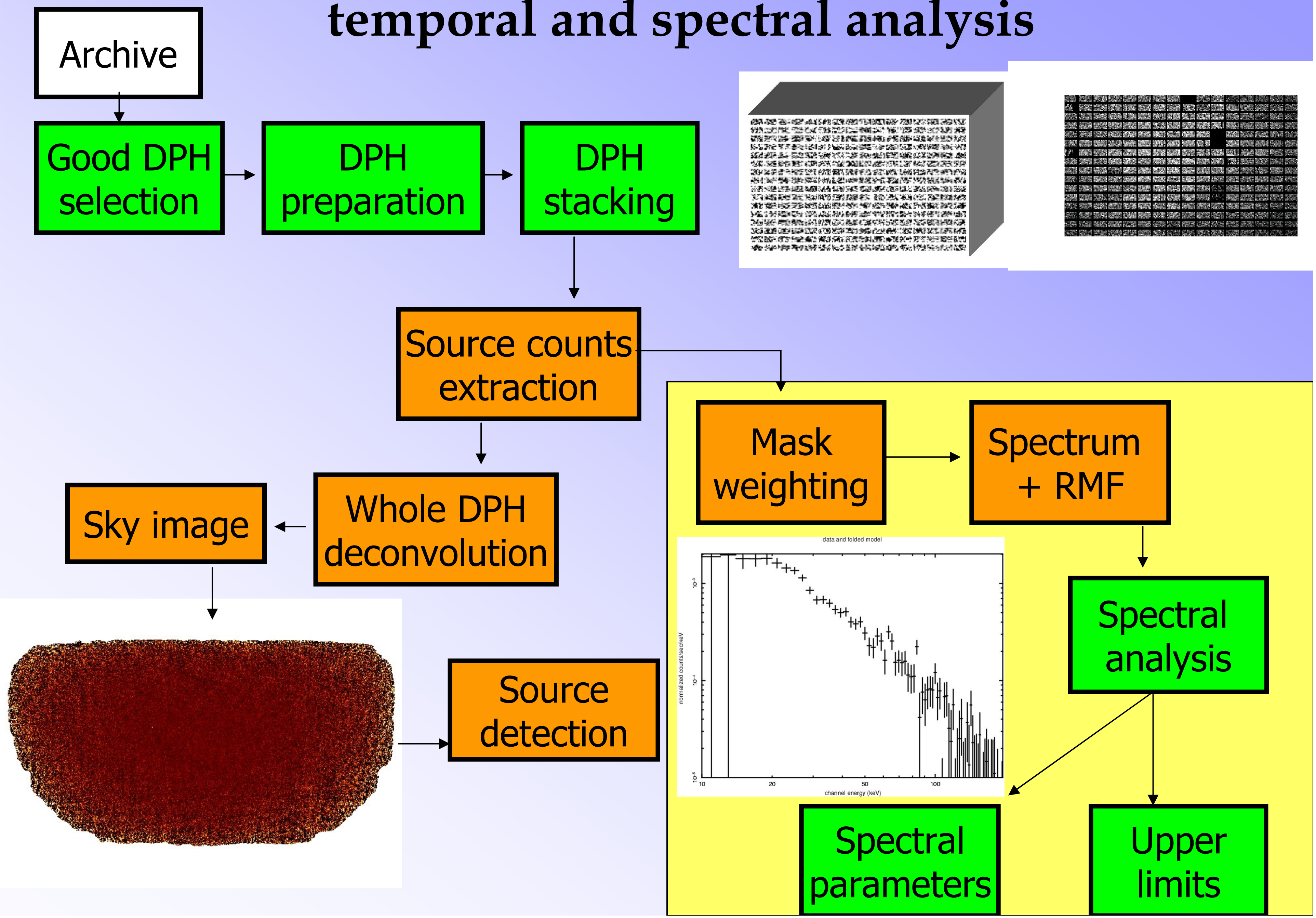
↓

Implemented a pipeline which combines opportunely the public tools to reduce data and extract spectral information of known sources

This pipeline was successfully used to study:

1. The Crab and the microquasar GRO J1655-40 (calibration test): Senziani et al. (2007), A&A 476, 1297
2. The SFXT IGR J08408-4503: Gotz et al. (2007), ApJ 655L, 101
3. The Symbiotic LMXB 4U 1954+319: Mattana et al. (2006), A&A 460L, 1M

The BAT survey data exploitation: a pipeline for temporal and spectral analysis



Evaluation of source flux: mask weighting

Select a position on the sky and extract a spectrum from DPH

1. Generate weighting map for selected direction
2. Extract bkg-subtracted spectrum
3. Generate ad-hoc response matrix
4. Include appropriate systematics
5. Spectral modelling (Xspec)

The Crab dataset

4626 DPHs retrieved from archive

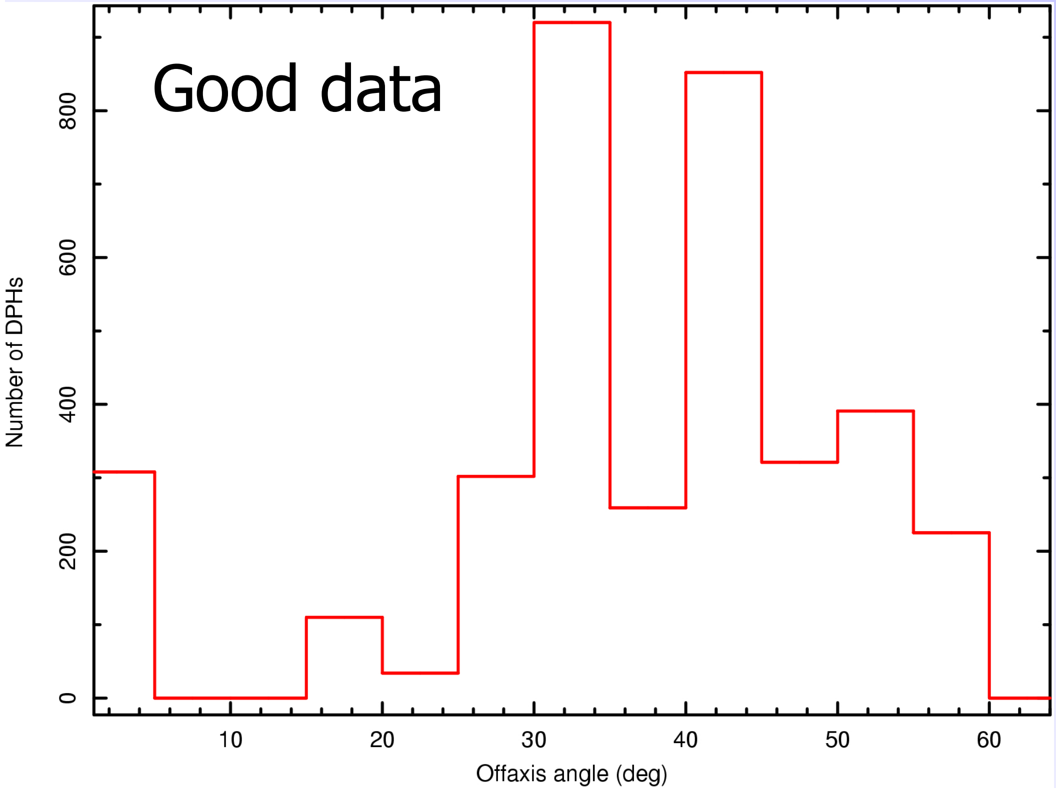
2005/01/01 - 2005/06/31

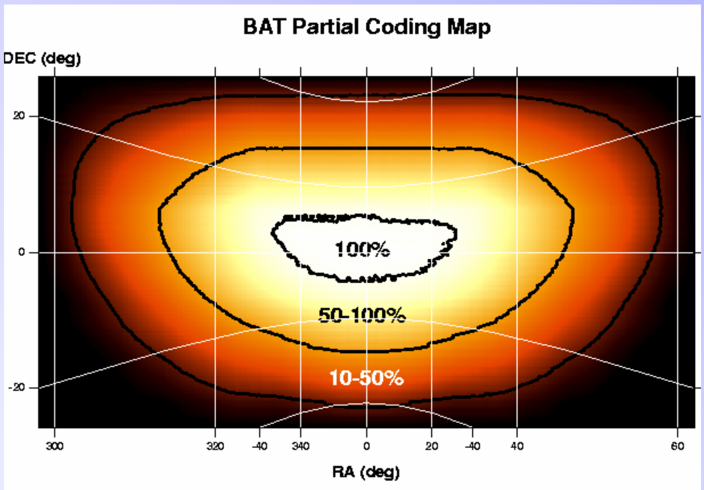
~3600 good DPHs - 1.2 Ms total

~1000 DPHs discarded (~20%)

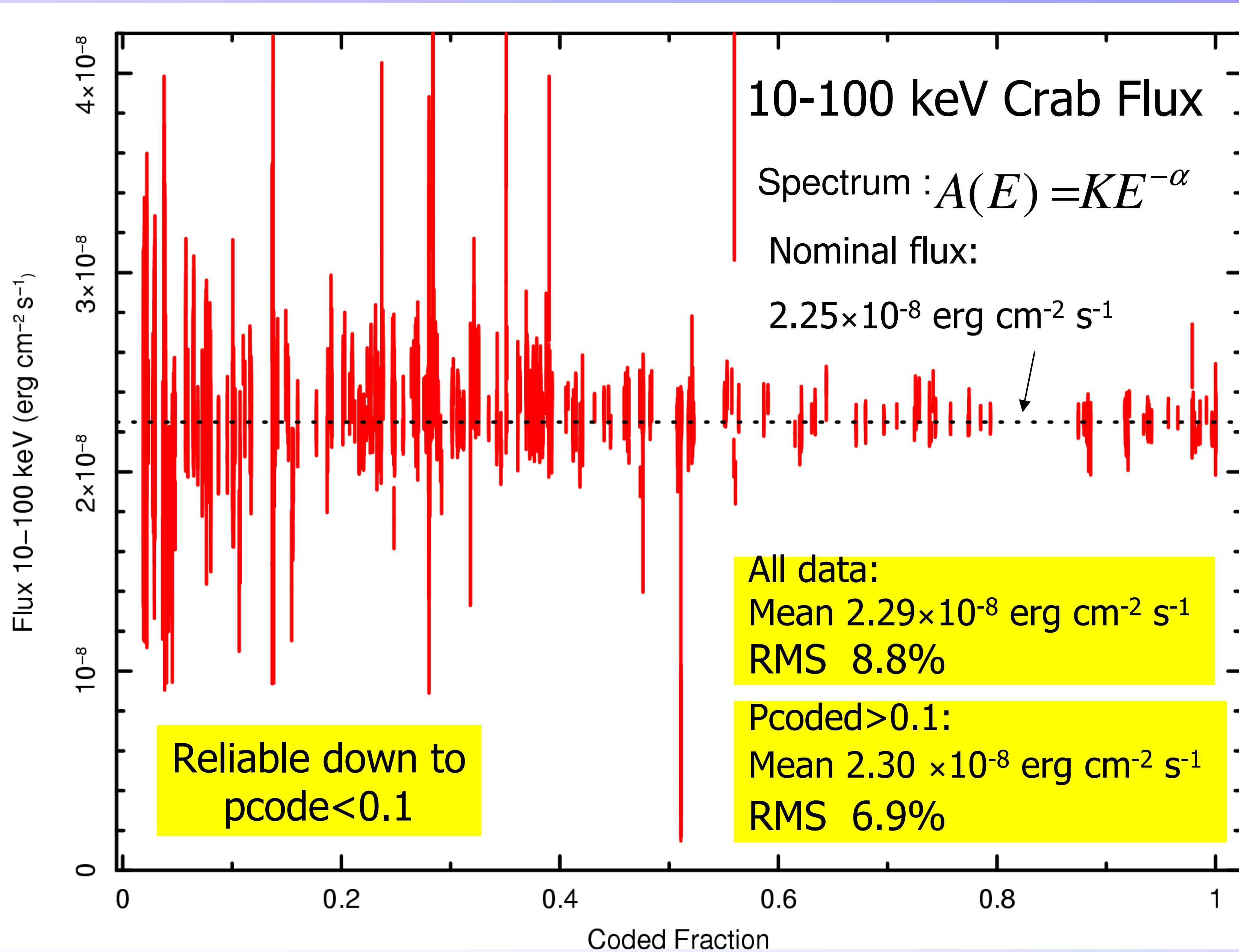
Discarded DPHs:

# detectors not enabled	36
Earth contamination + SAA	121
Star tracker unlocked	264
Pointing unstable	317
High bkg count rate	328
Earth/Moon/Sun source occultation	297

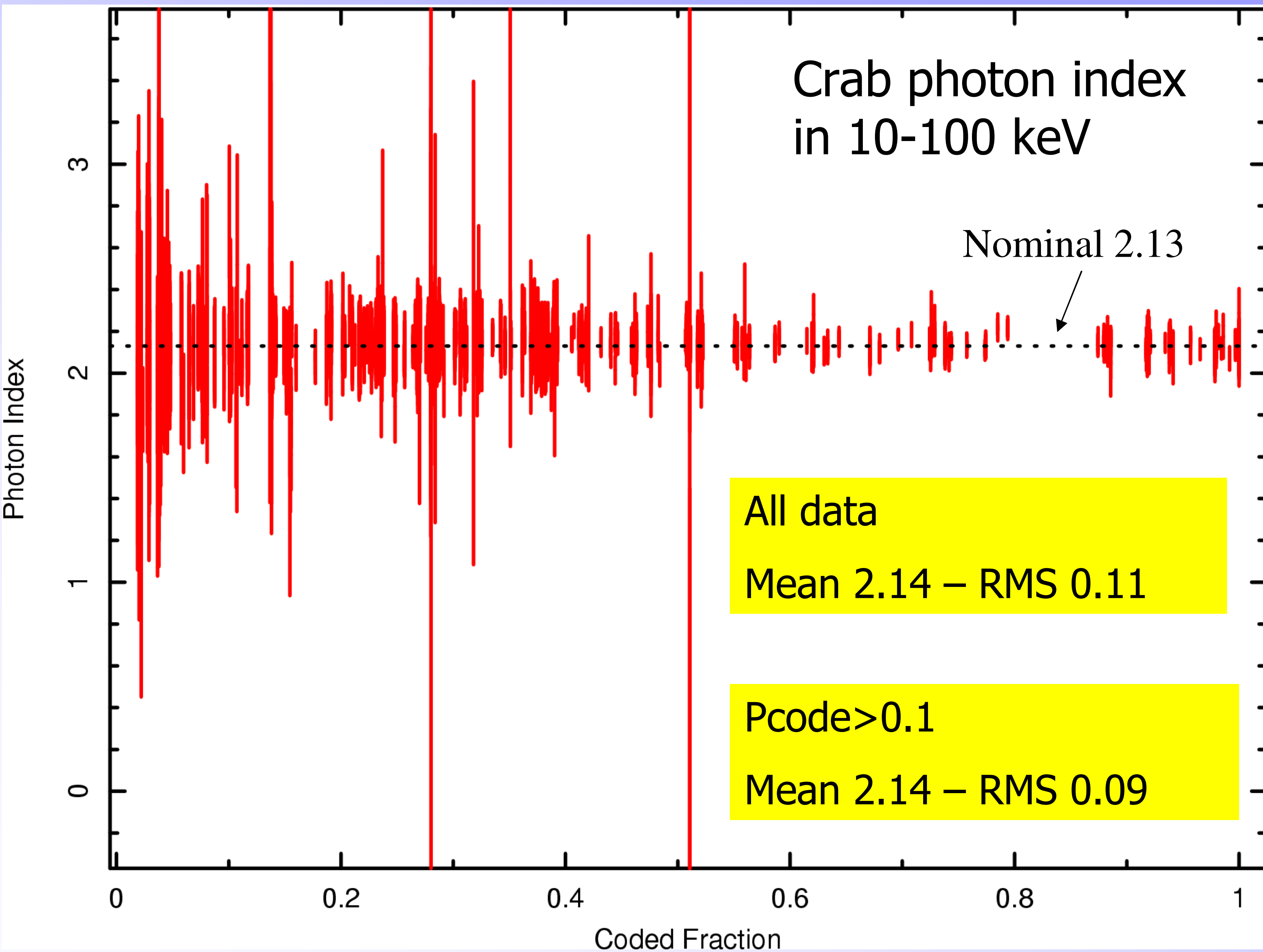




Mask weighting: results



Mask weighting: results



A further step: DPH stacking

- Typical DPH exposure: ~5 min
- Good DPHs may be merged to increase statistics
- Careful check of attitude is crucial

A test with the Crab

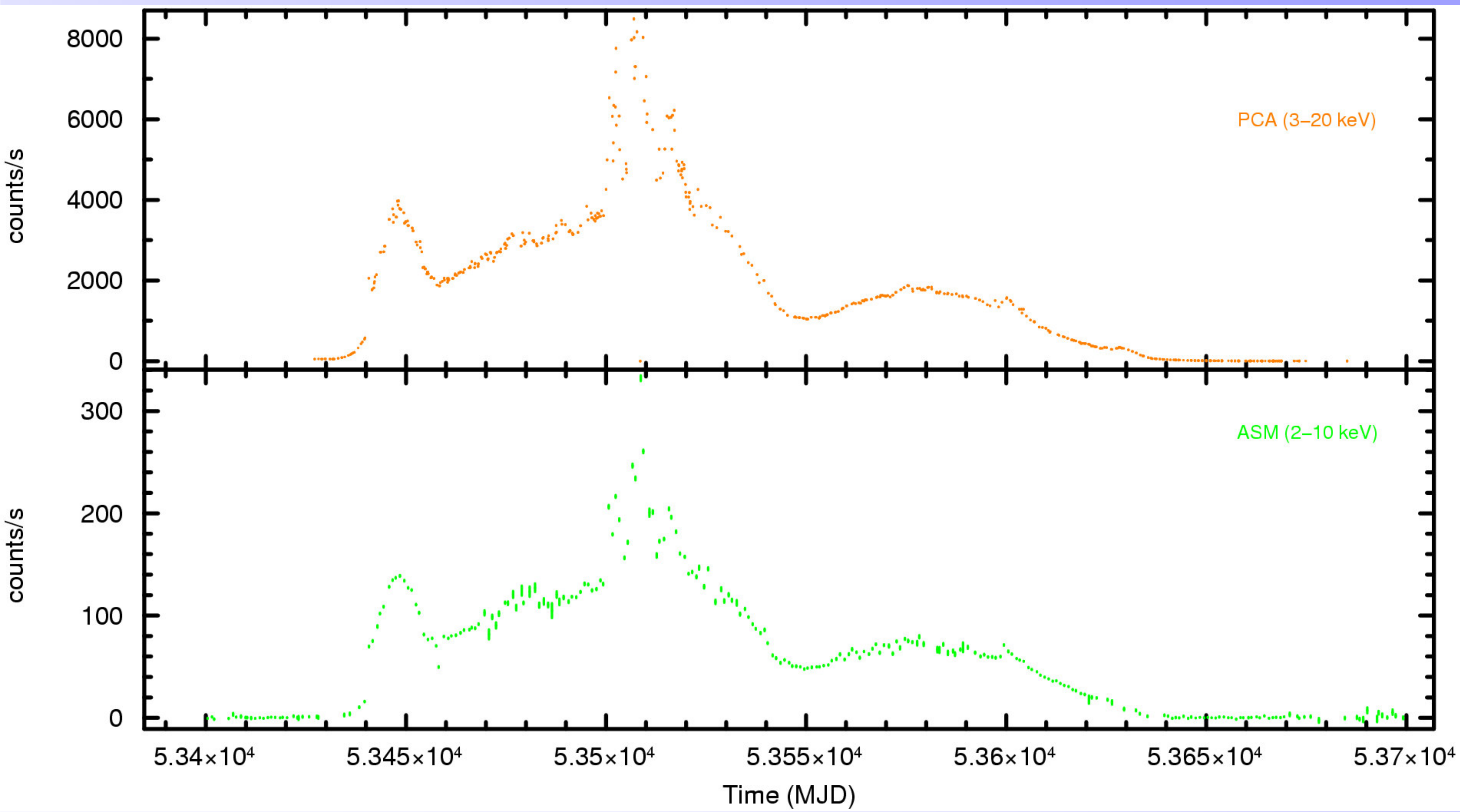
Coded Fraction	Offset	Flux loss
1	3 arcmin	1.9%
1	5 arcmin	5.7%
0.5	2.7 arcmin	5.2%
0.5	4 arcmin	19.4%
0.1	2 arcmin	7.7%

To be conservative,
we stack DPH
if coordinate differ
by <1.5 arcmin

The 2005 outburst of GRO J1655-40

Source strongly variable both in flux and in spectral shape

Monitoring campaign with RXTE: cross-calibration!



GRO J1655-40: the BAT dataset

Retrieved data between 2005/01/22 and 2005/11/11

8724 DPHs - 6644 good (~2.0 Ms total)

- 2080 discarded (23.8%)

The RXTE dataset*

490 observations – 2005/02/26 – 2005/11/11

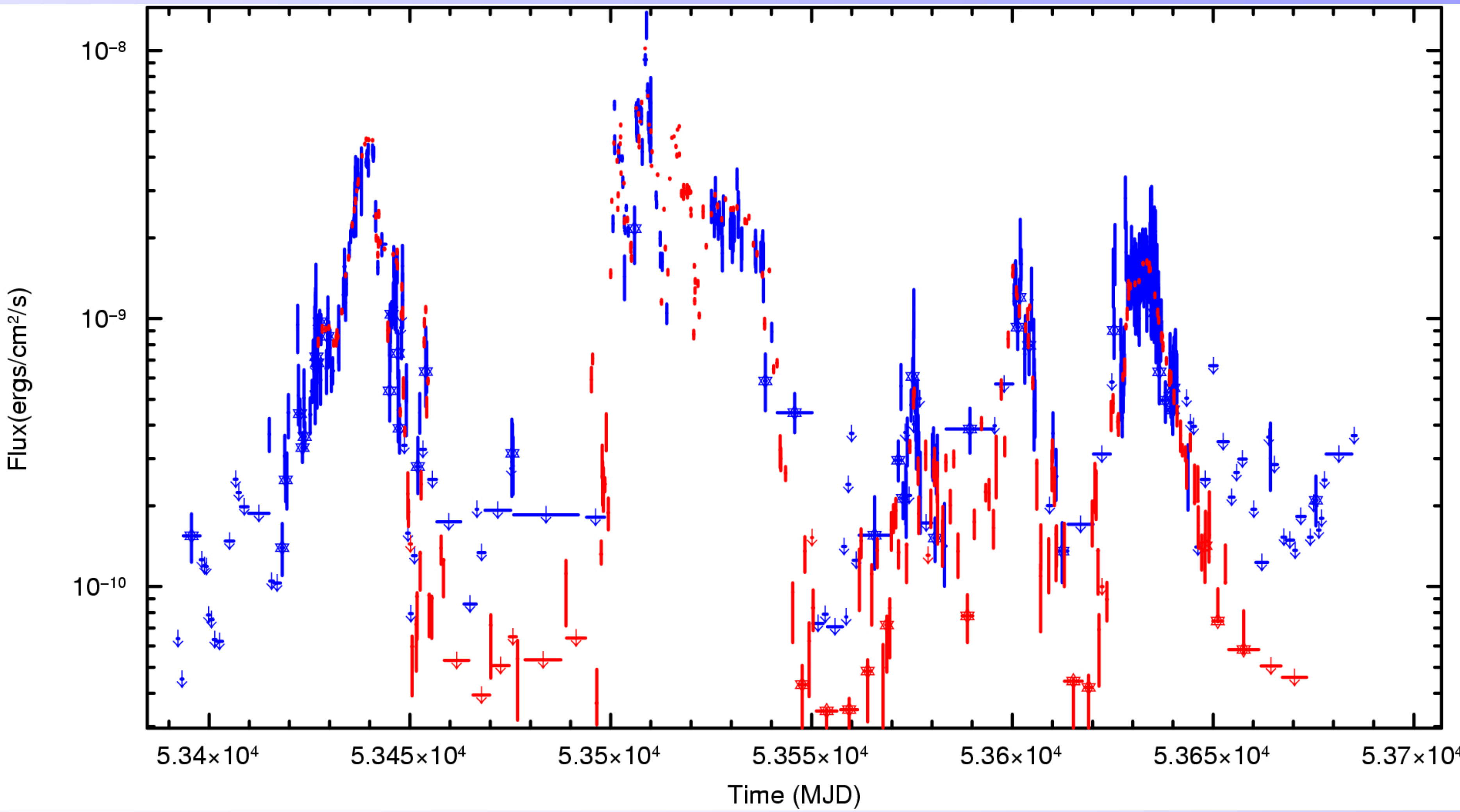
~1.5 ks each - ~665 ks total (HEXTE)

*retrieved from http://tahti.mit.edu/opensource/1655/

BAT vs HEXTE

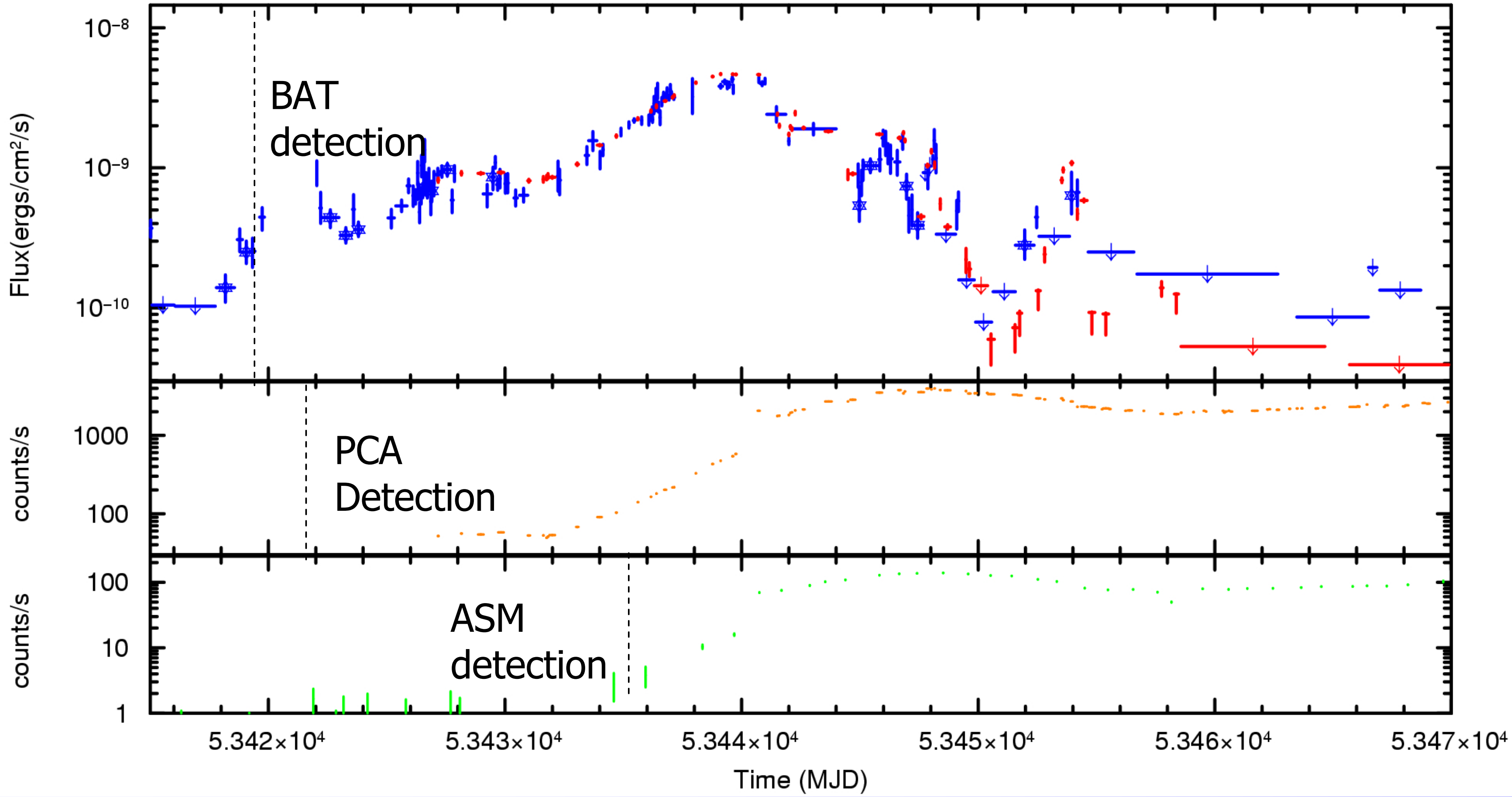
Flux in 30-100 keV

Independent spectral analyses



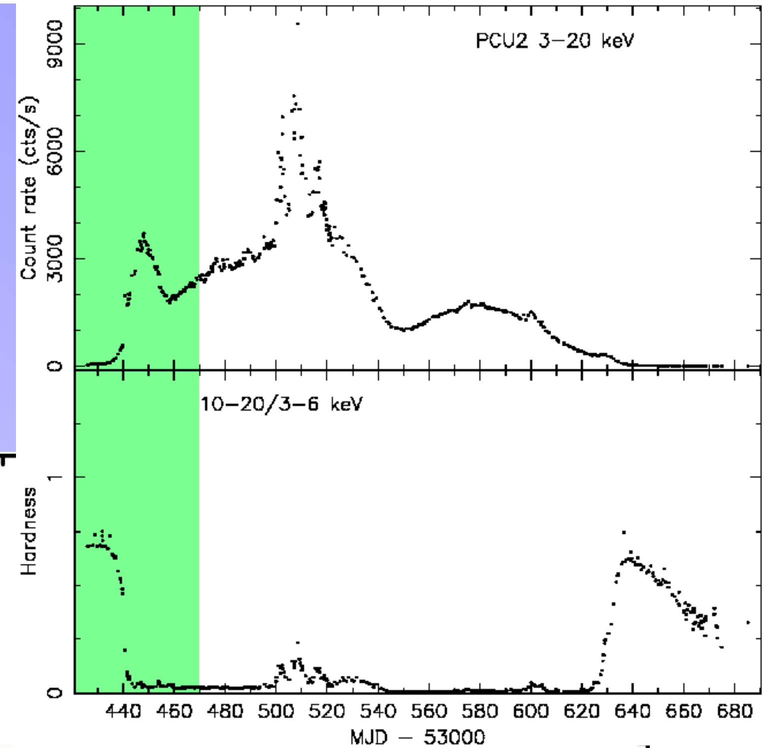
The rise and the first peak

- Source activity first noticed with PCA bulge scan (ATel 414)
- BAT would have detected the source serendipitously ~3 days before
- ASM detection ~20 days later

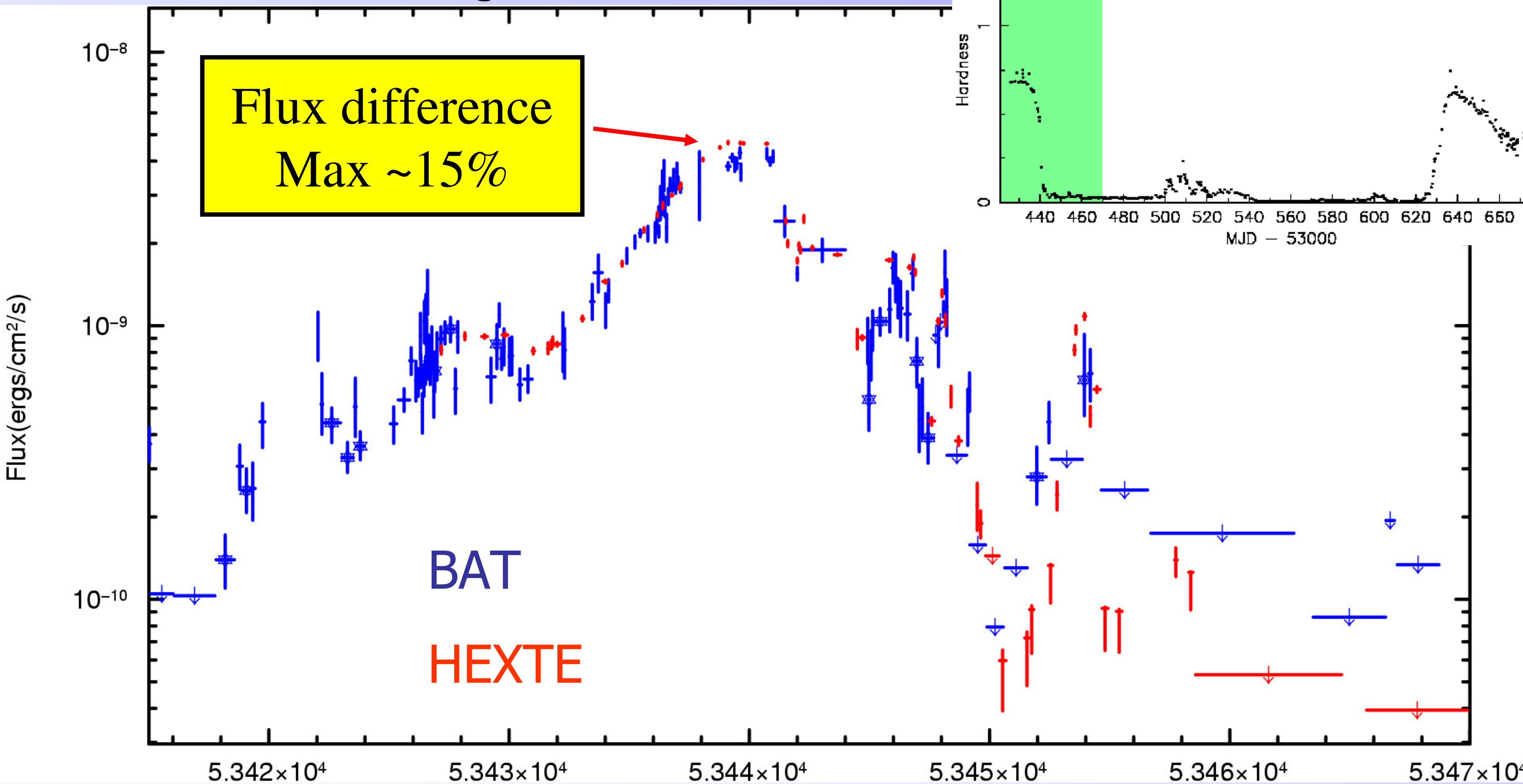


The rise and the first peak

PCA light curve

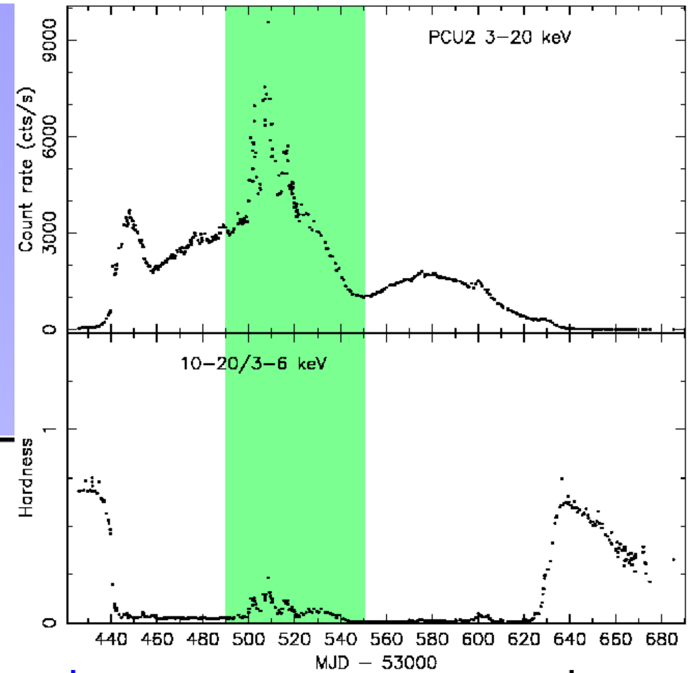


BAT and HEXTE light curves

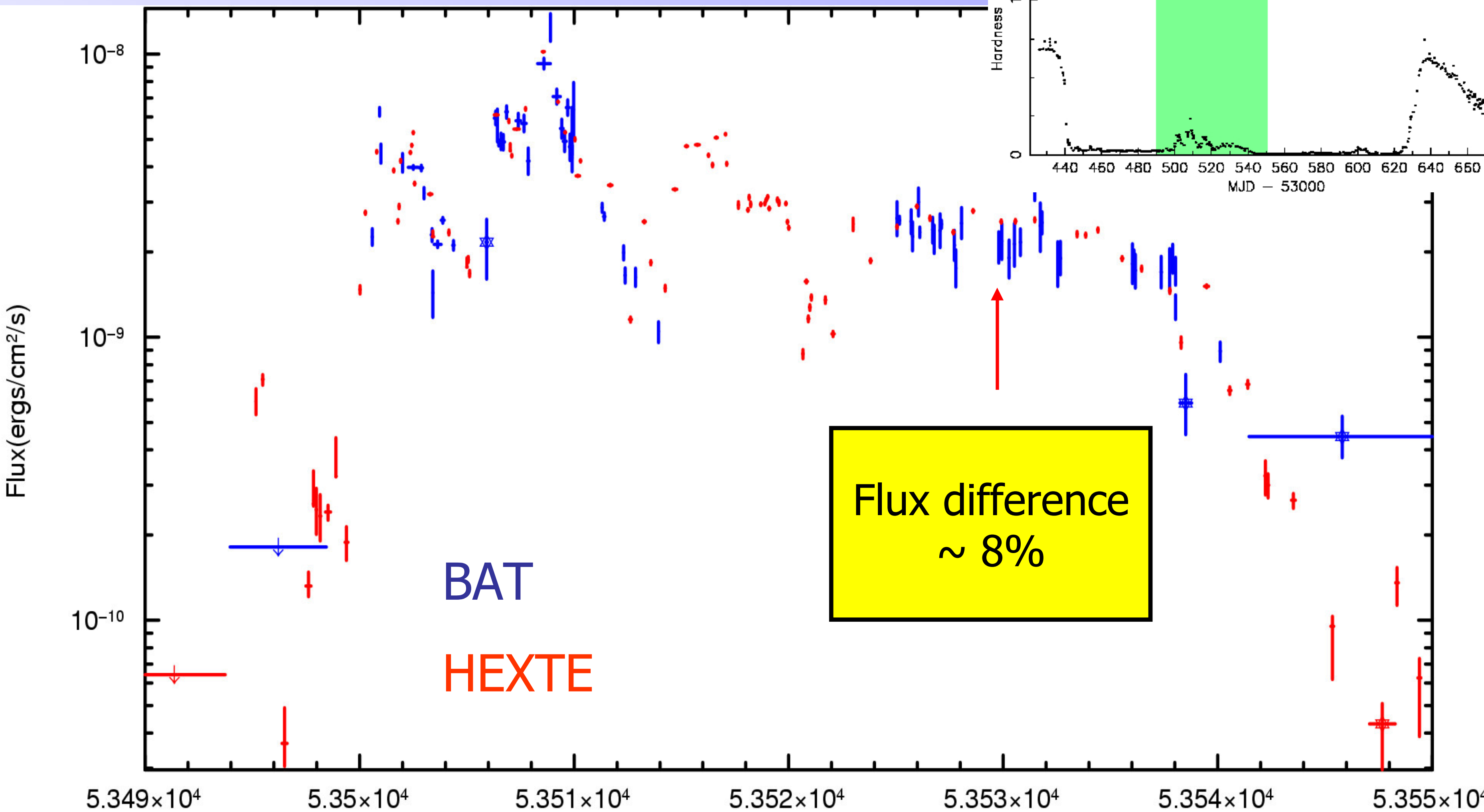


The very high state

PCA light curve

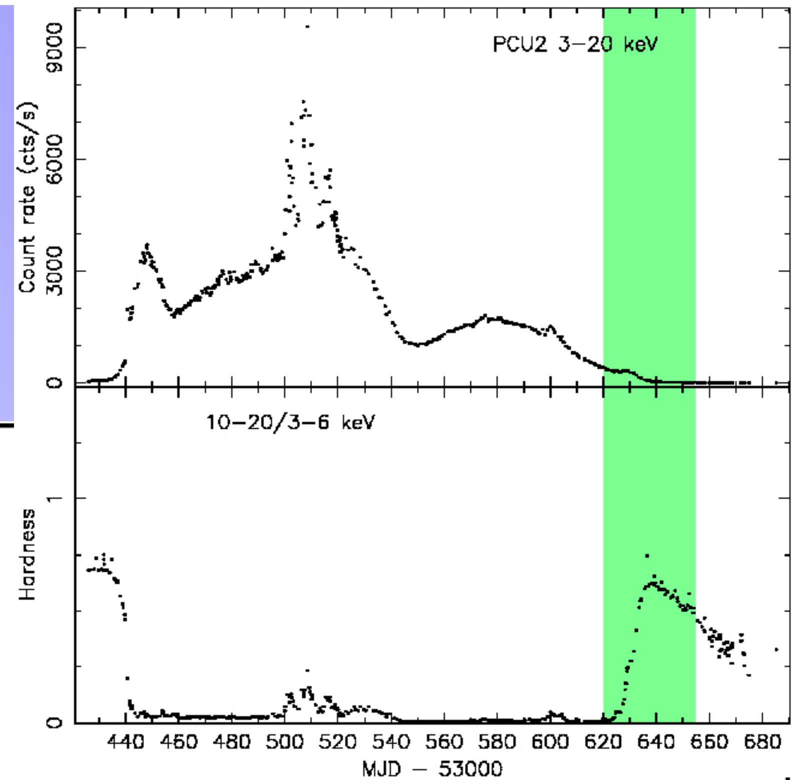


BAT and HEXTE light curves

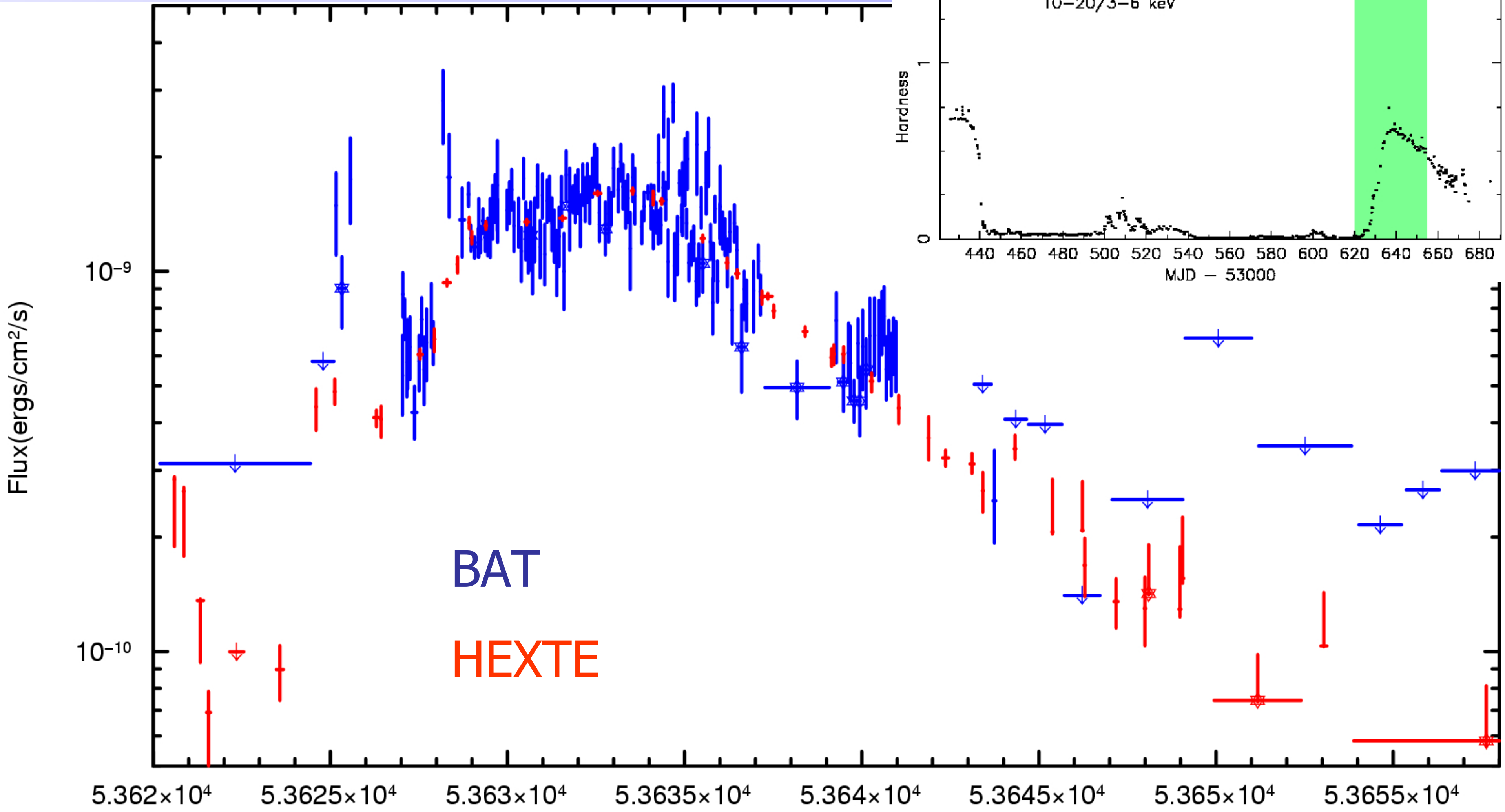


The end of the outburst

PCA light curve



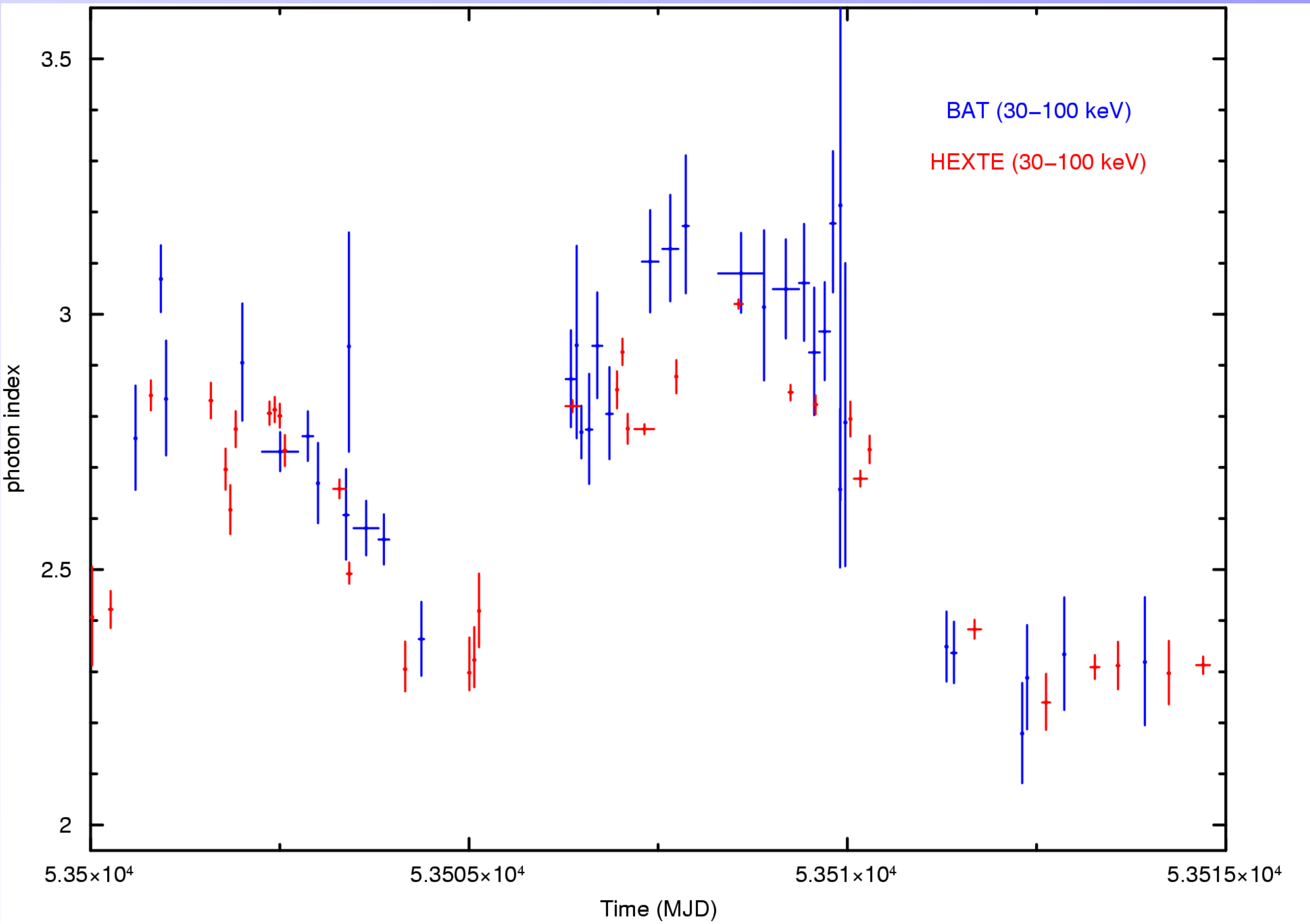
BAT and HEXTE light curves



The pipeline sensitivity

- Generally, a good agreement (within errors) is found when the *S*/*N* in BAT spectra is greater than 4
- The actual flux yielding such a *S*/*N* obviously depends on the position of the target within the FOV
- In one hour exposures, the 3σ sensitivity with our approach is ~10–20 mCrab for an on-axis source, a factor ~10 worse at a coded fraction of 0.2
- If the target lies within the half-coded region, our approach yields significant spectral measurements (consistent with HEXTE) in the 30–100 keV range down to (5–6) $\times 10^{-10}$ erg cm^{-2} s^{-1}, or ~50 mCrab

Spectral shape: the very high state



Monitoring of hard X-ray sources

We have a pipeline that can follow the evolution of both the temporal and spectral behavior of a source

The huge amount of survey data serendipitously collected while waiting for GRBs can be exploited using our pipeline

Monitoring of hard X-ray sources

- Probably next year the RXTE mission will finish, thus BAT will continue the monitoring of the sky in the 14-200 keV energy band
- Although this project is part of the “Secondary Science” program of *Swift*, it will be of great interest for hard X-ray astronomy

IGR J08408-4503: a new recurrent supergiant fast X-ray transient

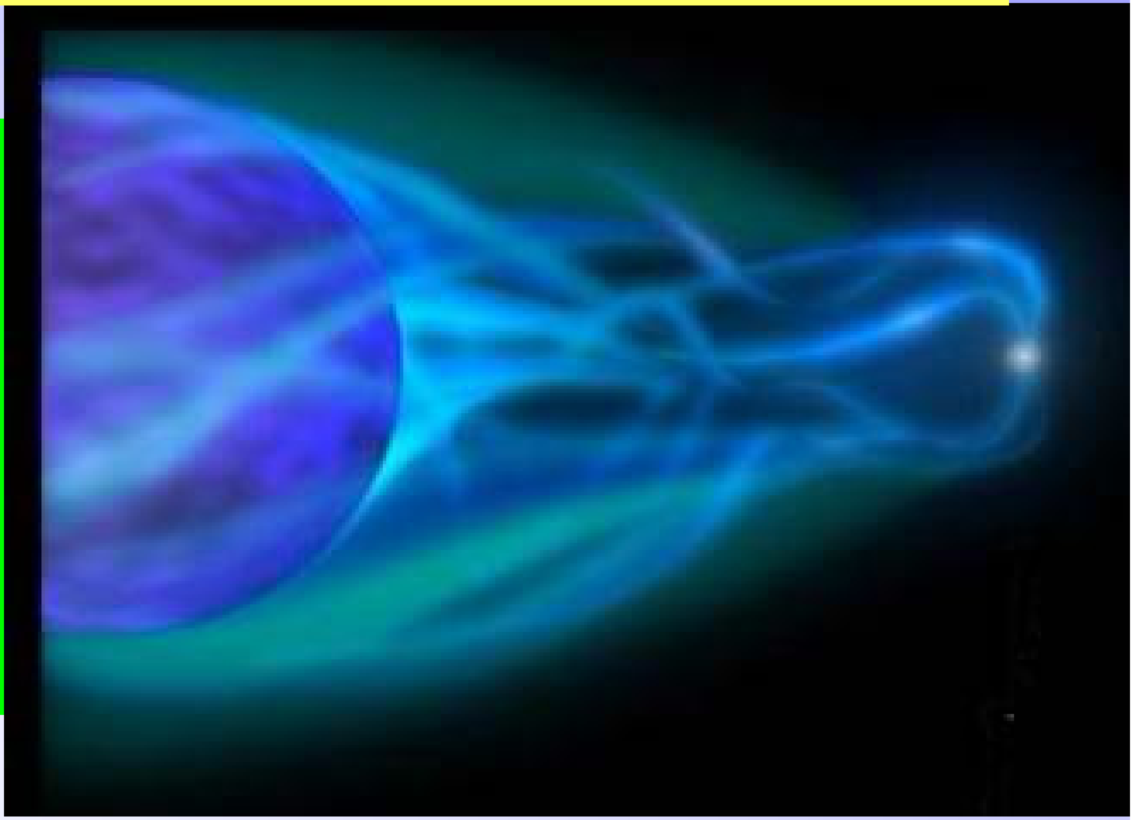
The Supergiant Fast X-ray Transients (SFXTs)

- SFXTs have been discovered only recently as a new class of X-ray sources
- They consist of a wind-accreting compact object and an OB supergiant donor star
- Most of the time is spent in a quiescent state (X-ray luminosity of 10^{32}-10^{33} erg/s)

- Sporadic, aperiodic (except IGR J11215-5952) outbursts, reaching luminosities of 10^{36}-10^{37} erg/s

- Strong flaring activities characterized by very short timescales (from minutes to hours)

- Origin of the outbursts unknown (clumpy wind …)



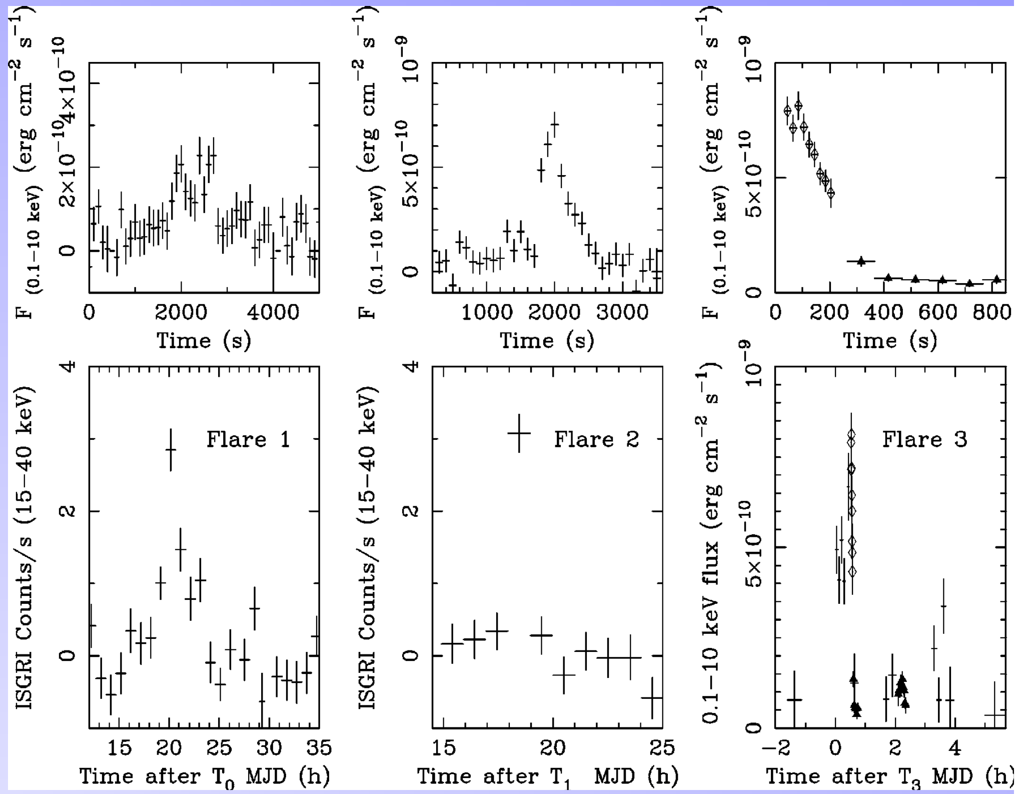
IGR J08408-4503: a new recurrent supergiant fast X-ray transient

IGR J08408-4503

• We studied the 3rd flare with BAT and XRT

• No evidence for periodicity

• N_H ~10^{21}cm^{-2} during the 3rd outburst, compatible with the total Galactic absorption in the same direction as estimated from the HI maps



Gotz et al. (2007), ApJ 655L, 101

• Not consistent with a clumpy wind scenario

• Probably sudden accretion onto the magnetic poles of matter previously stored in the magnetosphere during the quiescent phase

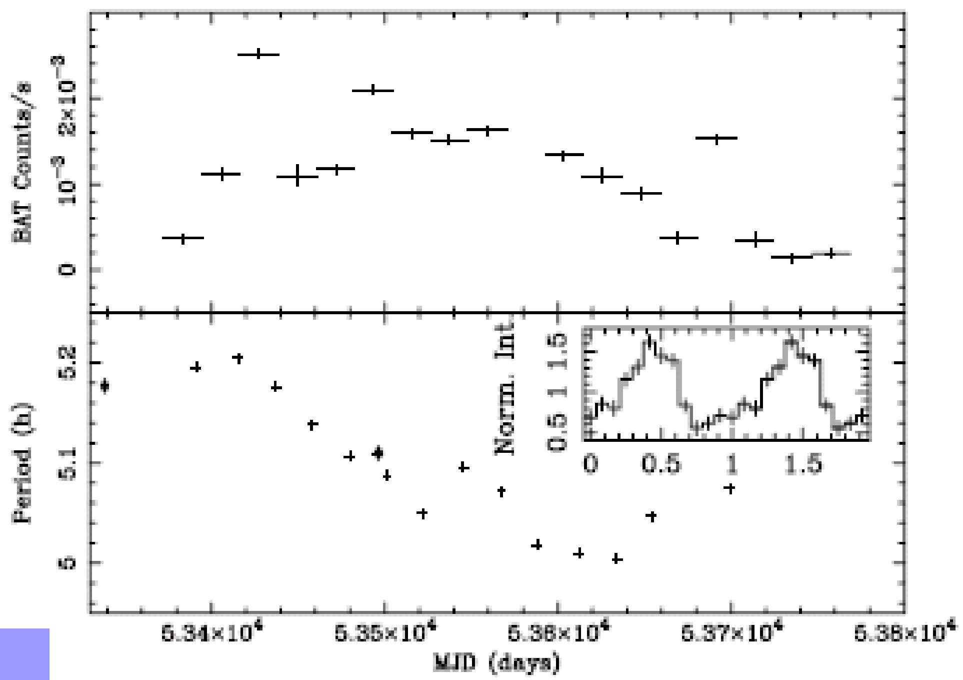
4U 1954+319: a new symbiotic low mass X-ray binary system

4U 1954+319

- The third LMXB hosting a NS and a late type giant companion: Symbiotic X-ray binary, the probable progenitors of most wide-orbit LMXBs
- Detected a periodic signal (~5.09 h) quasi-monotonically decreasing (Corbet et al. 2006)

BAT observations

- BAT lightcurve of ~1yr in the 15-50 keV band used for timing analysis
- Periodic signal confirmed (~5.17h): THE SLOWEST NS SPIN PERIOD OBSERVED
- Spin-up time scale (*P*/*P_dot*) of ~25 years
- Local episodes of spin-down
- Using the standard accretion torque models a value of B~10^{12} G was derived



Mattana et al. (2006), A&A 460L, 1

Interpretation

- NS spin period of 5h can be reached in ~8.5 × 10^9 yr, the age of the companion star
- Spin-up trend coupled with the increase of the accretion rate (red giant phase)

Search for prompt gamma-ray emission from novae

Originally novae were stars which became visible to naked eye where no star was known before and lasting some days before vanishing

Thanks to the progress in astronomical instrumentation now we can study their progenitors

However, a multi-wavelength study of a nova depends on its discovery which typically still occurs at **optical wavelengths**

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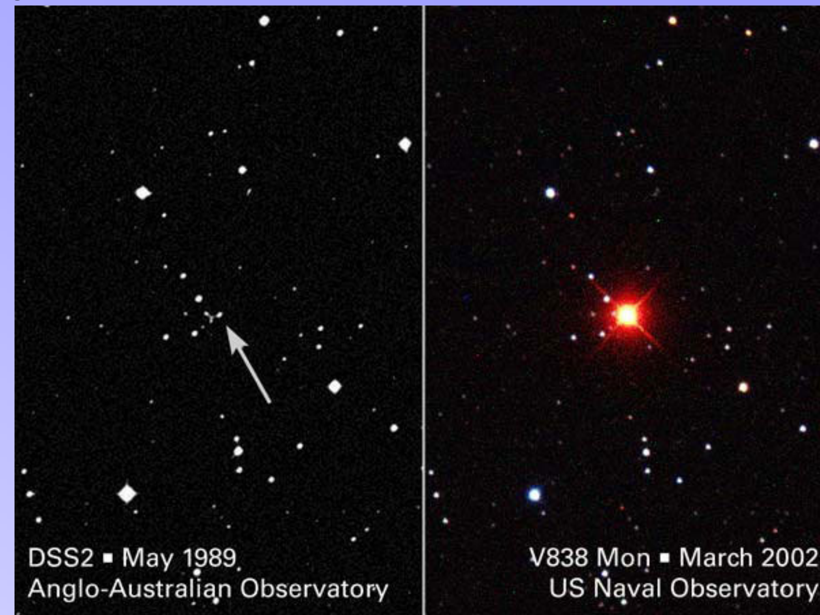
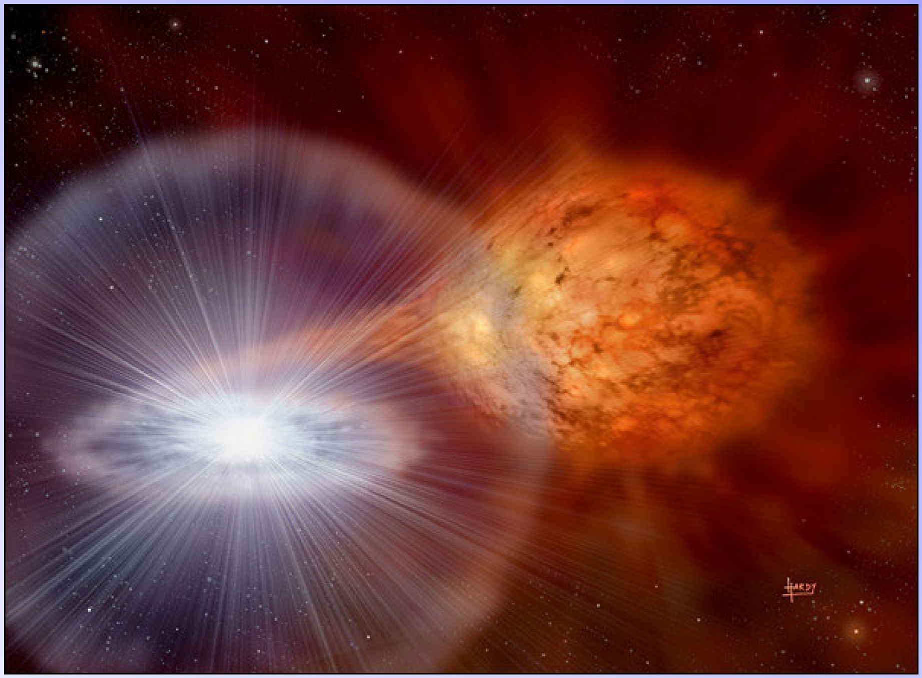
Amateurs astronomers are of crucial importance



Model

Novae are grouped in the cataclysmic variables class (CVs)

Accreting White Dwarf



Companion star

Matter accumulates on top of the WD (envelope) until it reaches critical conditions and consequently erupts (Thermonuclear Runaway) causing the emission of light at different wavelengths and ejection of a fraction of the accreted mass

After that, the nova returns in its normal state until the accreted material on top of the WD is enough to enable a further eruption (10^4-10^5 yrs for CNe, tens of years for RNe).

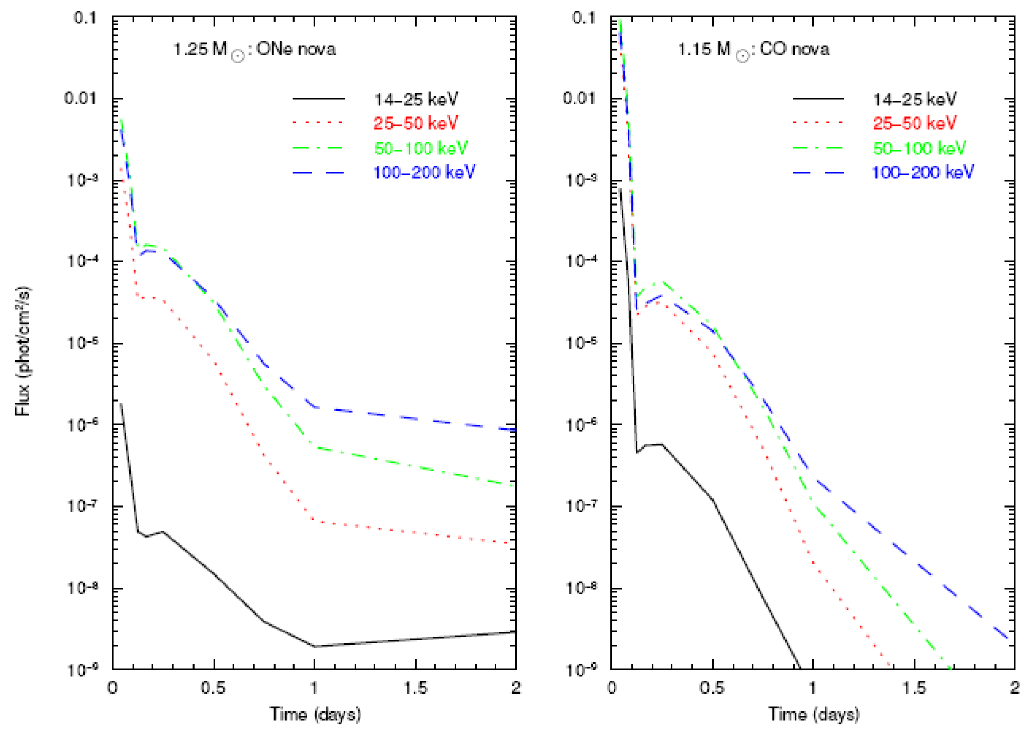
Credit: Dr Andrew Beardmore, **University of Leicester**

Model

During a nova eruption the hydrogen burning produces several short-lived β+-unstable nuclei (^{13}N, $^{14-15}O$, $^{17-18}F$).

Their decay results in:
- prompt gamma-ray emission (511 keV line + Comptonization down to few tens of keV)
- envelope expansion
- mass ejection

^{13}N (τ=862 s) and ^{18}F (τ=158 min) are the most important contributors of the gamma-ray emission since they decay when the envelope is becoming transparent.



Courtesy of M.Hernanz

The instruments used in the past did not detect gamma-rays from novae mainly because none was sufficiently sensitive and complete in coverage → WE TRIED WITH BAT

Search for prompt gamma-ray emission from novae

BAT is a suitable telescope to search for prompt gamma-rays from novae. In survey mode BAT can monitor a given source about every day with a time resolution which is typically 300s.

Search for new transients in the data

Retrospective search from the direction of known novae

Performed a retrospective search in the BAT data archive for gamma-ray emission from a sample of 18 novae detected visually from the Swift launch (November 2004 – March 2007)

- BAT data selection: for each nova, all data having the nova in the FOV and with time comprises between 20 days before and 20 days after the discovery time
- Data reduction performed with Prof. Skinner's pipeline (public tools + non-standard products)
- Energy bands: 14-25, 25-50, 50-100, 100-200 keV
- Timescales: "DPH by DPH",1h,3h,6h,12h,24h

RS Ophiuchi

We detected the Recurrent Nova RS Ophiuchi in the 14-25 keV energy band

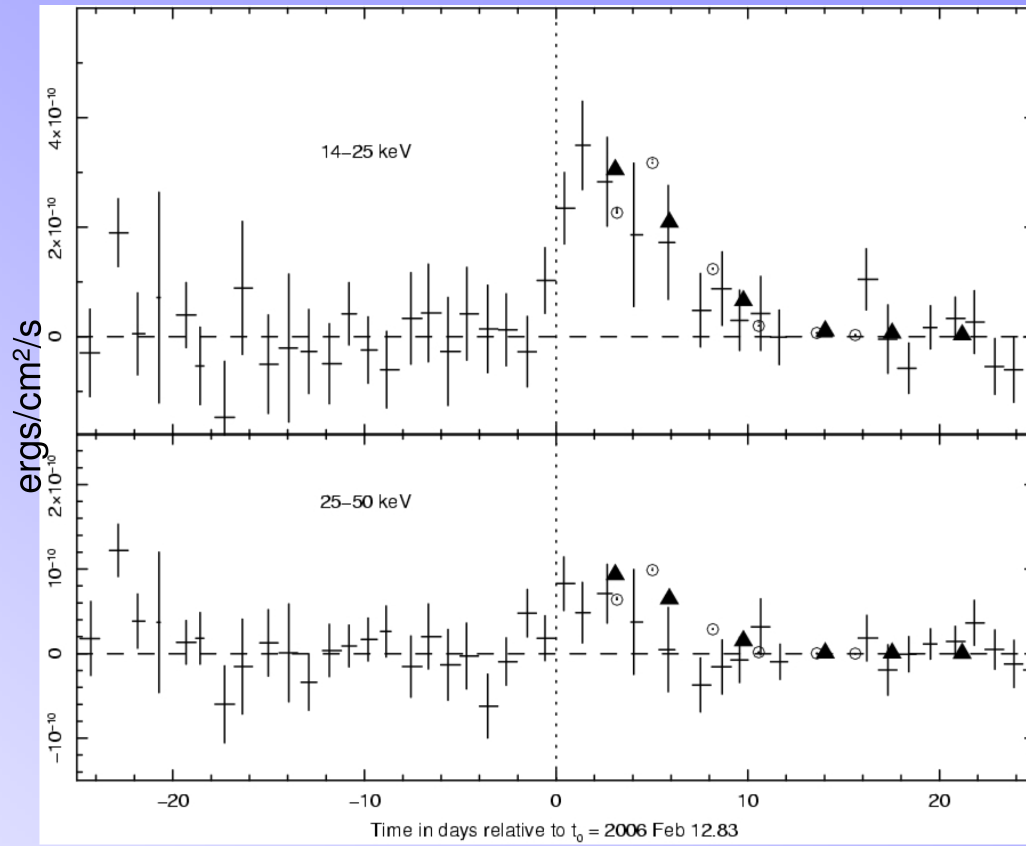
Emission due to the shock between the ejecta and the dense red-giant wind from the companion

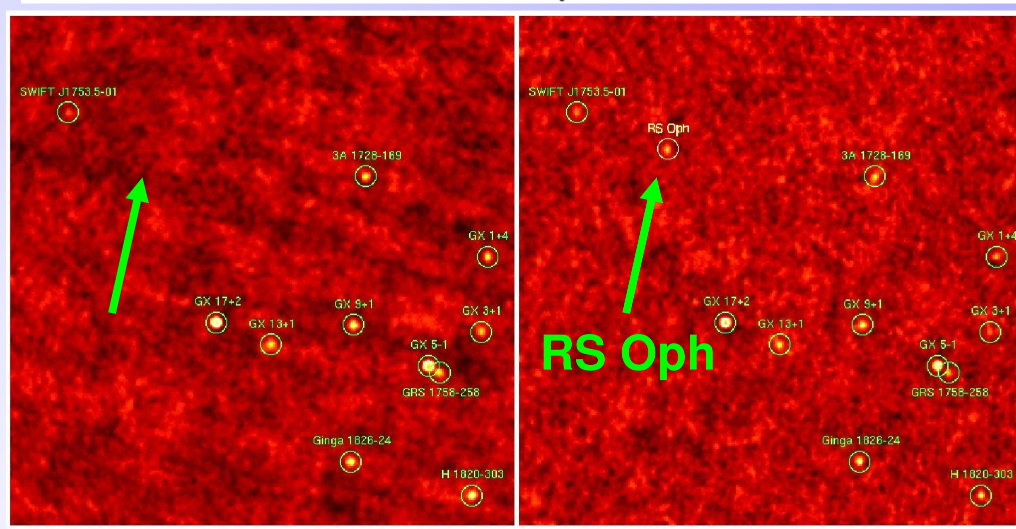
XRT and PCA spectra well described by a bremsstrahlung model (emission from a high temperature thermal plasma), consistent with the emission produced by the shock-system

On day 3:

- kT ~ 8-9 keV
- v_{ej} ~ 2500 km/s
- N_H ~ 5.5 x 10^{22} cm^{-2}

Bode et al. (2006), ApJ 652, 629





Results for the other 17 Classical Novae

- No evidence was found for prompt gamma-ray emission from any of the 17 classical novae
- The distribution of the complete ensemble of S/N measurements (750000 points) agrees very well with a random distribution around zero

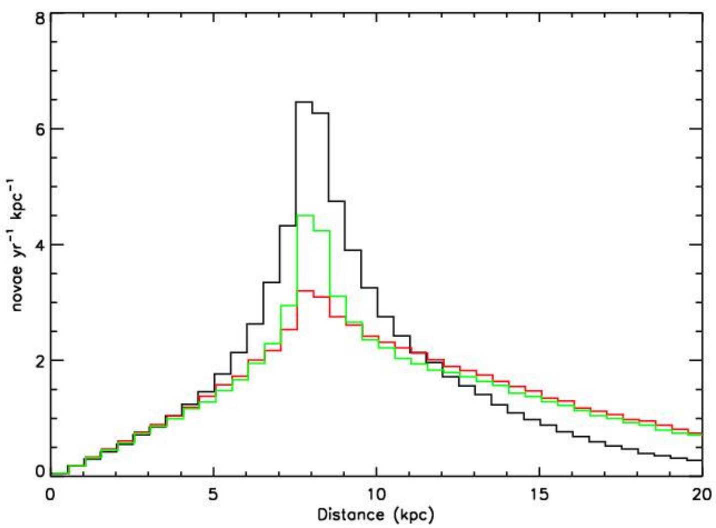
We therefore conclude that in each case either the expected gamma-ray emission from the novae occurred when the object was not in the BAT FOV or the distance was too large for the predicted emission to be detected

- For each nova we estimated upper limits which were used to estimate the maximum distance out to which they should have been detectable (for probabilities P that the peak of emission occurred when BAT was observing the nova of P=10% and P=50%)
- We found that BAT can see up to a distance of 2-3 kpc (P=10%).

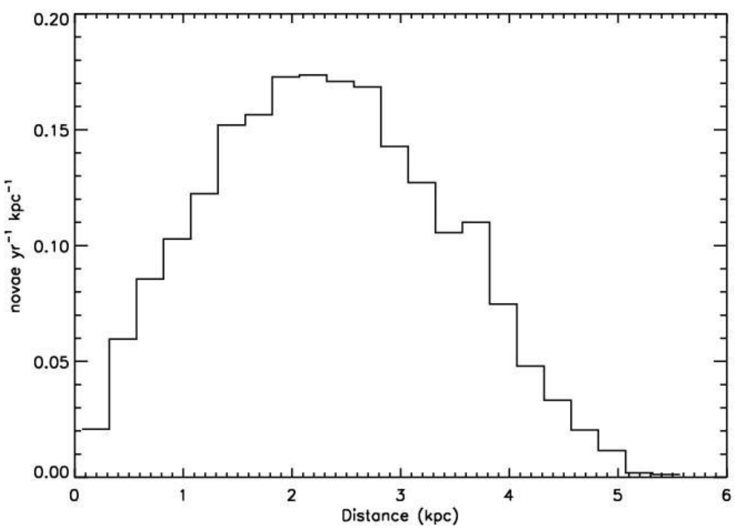
The distances estimated with the AAVSO lightcurves of each nova are too large compared with those estimated with BAT, thus the non detections are not surprising

Expected rate of detection of novae with BAT

Virtual novae simulated with a Monte Carlo approach assuming:
- 3 different models of the spatial distributions in the Galaxy
- A rate of novae in the Galaxy of 35/y (Shafter, 1997)



Expected rate of detection of novae with BAT calculated with the simulated sample of novae assuming:
- The predicted gamma-ray fluxes
- The ideal 5σ BAT sensitivity
- The real BAT observing sequence during the first 2.28 yrs



If Swift will be operating for 10 yrs (as predicted), we expect to detect 2-5 novae during the mission

Senziani et al. , in progress

Conclusions

- Huge database of BAT "Survey" data substantially unexplored

- We developed an ad-hoc pipeline for BAT "Survey" data reduction and analysis, aimed at spectral monitoring of bright sources

- Calibration of such pipeline with the Crab and with GRO J1655-40 shows that BAT is a very powerful all-sky hard X-ray monitor, with a sensitivity (1 hour) of 20 mCrab for an on-axis source (or 50 mCrab half-coded)

- We used our pipeline to study two very peculiar Galactic accreting sources
    - IGR J08408-4503 , a new member of the SFXTs
    - the Symbiotic Low-mass X-ray Binary 4U 1954+319, hosting the neutron star with the slowest spin period known

- A different pipeline for BAT Survey data analysis was developed by Prof.Skinner at CESR. We used such a pipeline in order to study gamma-ray emission from novae
    - we detected emission from RS Oph, but this is due to shocks between the ejecta and the dense stellar wind from the red-giant companion
    - we searched for emission from known novae, but only upper limits were obtained
    - we estimated 2-5 new detections in 10 years of BAT data

Plans for future work

- We will start a systematic analysis of BAT Survey data using our pipeline for spectral monitoring, focusing on different classes of Galactic sources (peculiar objects; microquasars; standard LMXB)

- The search for prompt gamma-rays from novae will continue in the future both by retrospectively searching in the BAT data once the novae are discovered optically and by searching for new transients in the images of the whole archive

- We are implementing and testing a new pipeline aimed at stacking BAT data with different pointings. This will allow to detect and study much fainter sources (current capabilities: <5mCrab in 1 month)

- Such a new pipeline, coupled to our first one, will have very interesting potentialities. In particular, we will use BAT for simultaneous follow-up studies of high energy gamma-ray sources detected by AGILE and GLAST

Acknowledgments

- I would like to thank Gerry Skinner and all the CESR group not only for the scientific training but also for their helpfulness and friendship

- A special thank to Prof. Bignami and Dr. Caraveo for the possibility they offered me, Tomaso Belloni and all the friends of Milano

- I would like to address a special thank to the Pavia BAT team (ADL, Gio and Mario) and to all the astrophysicists of Pavia for the pleasant days spent all-together