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Constraining the rate of supernova shock break-out events

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IUSS
Scuola Universitaria Superiore Pavia

Exploring the X-ray Transient and variable Sky

EXTraS is an **FP7 project** which has explored for 3 years (2014-2016) the serendipitous content of the ***XMM-Newton*** archive in the time domain.

The results are available at: ***http://www.extras-fp7.eu/***

The EXTraS consortium is formed by:
INAF *(PI: Andrea De Luca)*, **IUSS Pavia**, **CNR – IMATI Genova**, **University of Leicester** (UK), **MPE** and **ECAP (**Germany)

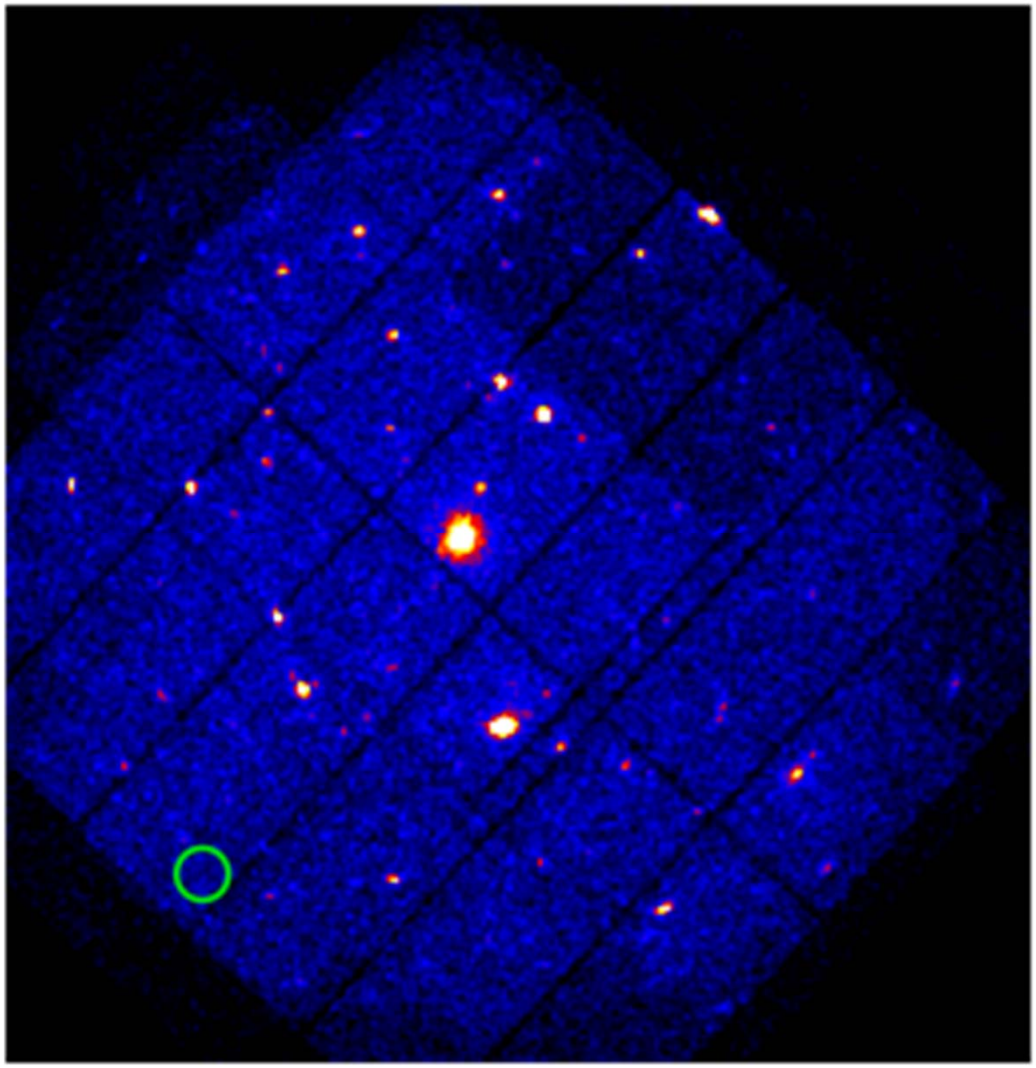
IUSS Pavia had the responsibility to search for new **transient** X-ray sources, detected only for a small fraction of the full observation

The EXTraS transient pipeline

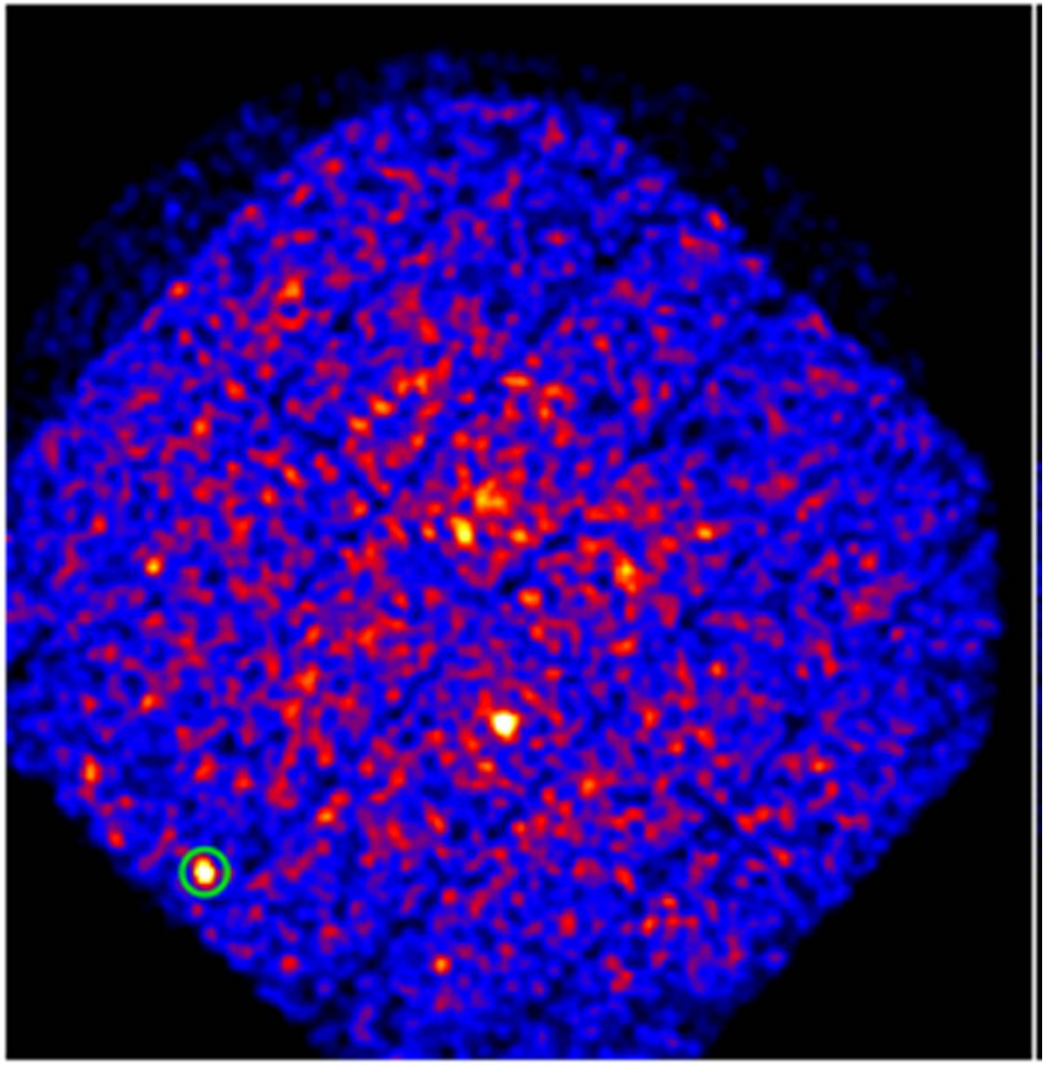
- **Source detection** on images with **variable** time bins (<5 ks), identified through a **Bayesian Blocks** (BB, *Scargle 1998*) analysis of detector cells with ~PSF size
- **Transient candidates** are the point sources detected in sub-observations but not in the full observation
- **Visual screening** of transient candidates in the detector cells that triggered the BB interval
- **130** high significance new **transients** were discovered (and publicly released) in the analysis of **7,811 observations** (3XMM DR5 catalogue: Feb 2000 – Dec 2013)

Testing and systematic data processing on different ***computer clusters*** *(24-2,000 cores) at IUSS, INAF (IASF-Milano; OA Trieste), CINECA (PICO), Leicester University*

The shortest transient in EXTraS analysis



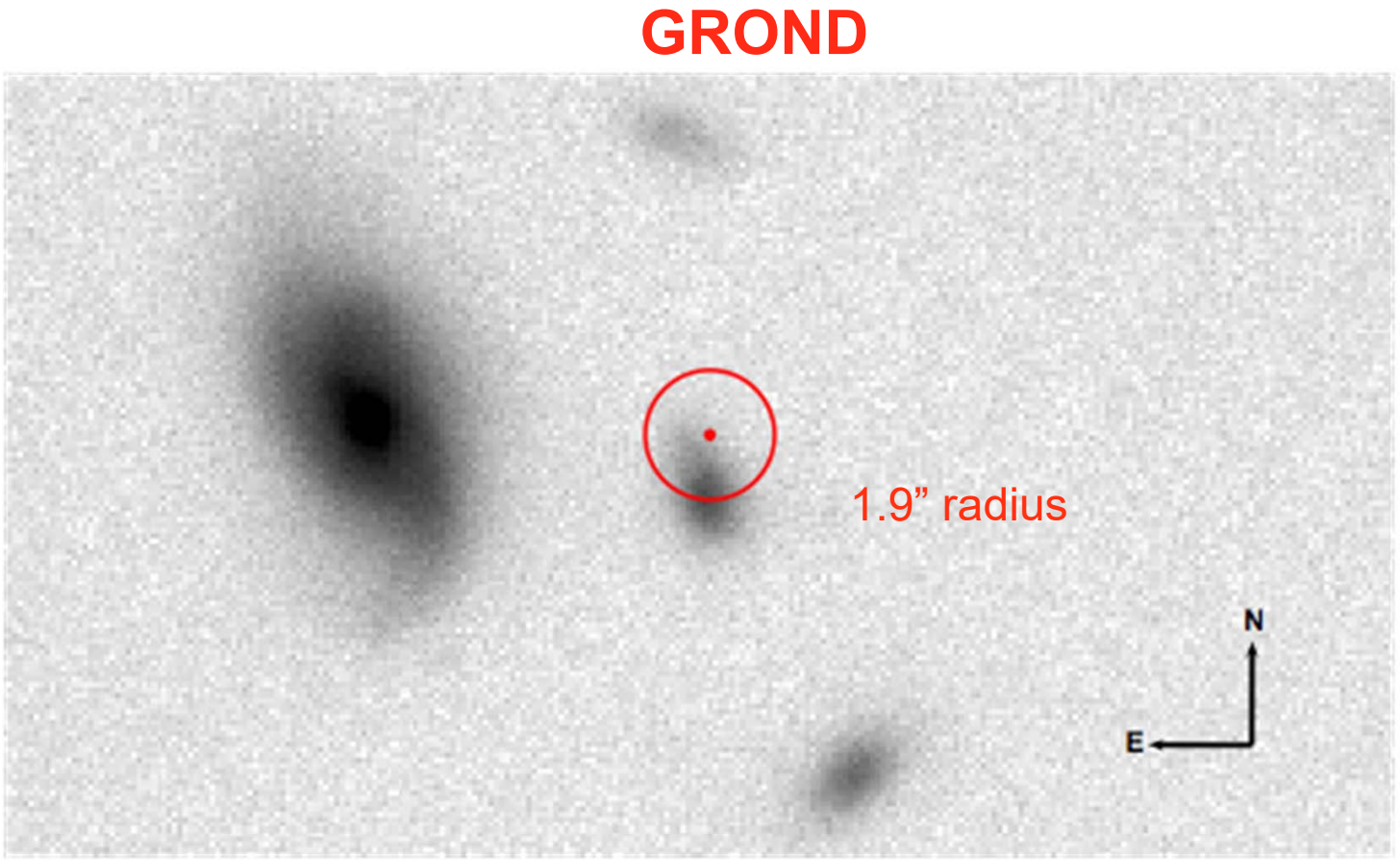
Full observation (net exposure >20 ks)



Time interval: 315 s

Follow-up optical observations

From CTIO* optical high resolution spectrum we derive a redshift of z = 0.092 ± 0.003, corresponding to a distance of 424 Mpc



* (COSMOS spectrograph at the Blanco Telescope of the Cerro Totolo Inter-American observatory)

Comparison with a SN X-ray flare

The flare energy and duration are very similar to those of the X-ray transient associated to **SN2008D**, observed by **Swift/XRT** and interpreted as the emission from the **shock break-out** of a **core-collapse supernova** *(Soderberg et al. 2008)*

	SN 2008D	***EXTraS transient***
d	*27 Mpc (z=0.006494)*	*424 Mpc (z=0.092)*
Fluence	2.3×10^{-7} erg cm^{-2}	8×10^{-10} erg cm^{-2}
Total energy	2×10^{46} erg	1.7×10^{46} erg
Peak luminosity	6.1×10^{43} erg s^{-1}	4.3×10^{43} erg s^{-1}

Event rate and pipeline sensitivity

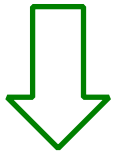
To determine the **event rate** we need to estimate the **sensitivity** of the EXTraS detection pipeline for this kind of events at different distances

Many **instrumental effects** and **observation properties** can strongly affect the pipeline sensitivity: background, interstellar absorption, off-axis angle, chip gaps and defects, bright (diffuse) X-ray sources, instrument settings...

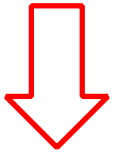
To estimate the sensitivity, we **simulated** transients with same spectrum and lightcurve as **SN2008D**, but with different fluxes and positions, added the simulated events to **real PN data** and then **run the EXTraS pipeline** on the merged event files

The CHIPP proposal

We submitted a CHIPP proposal to **simulate and analyse** a large number of **SN2008D-like transients** on the largest possible sample of 3XMM-DR5 observations



We obtained **30,000 cpu hours** on the OA Catania cluster



Since these resources were smaller than our initial requests, we also used our **local (small) clusters** at IASF-Milano (for the **simulations**) and at IUSS Pavia (to **reprocess** ~15% of the observations that exceeded the memory limit)

Analysis and results

After **data transfer** and **software installation** and testing (**no problems**, thanks to previous IASF-Milano experience on the OA Catania cluster), the **data analysis** was performed in August 2017 (**very smooth**, most jobs submitted and checked from smartphone, on holydays)

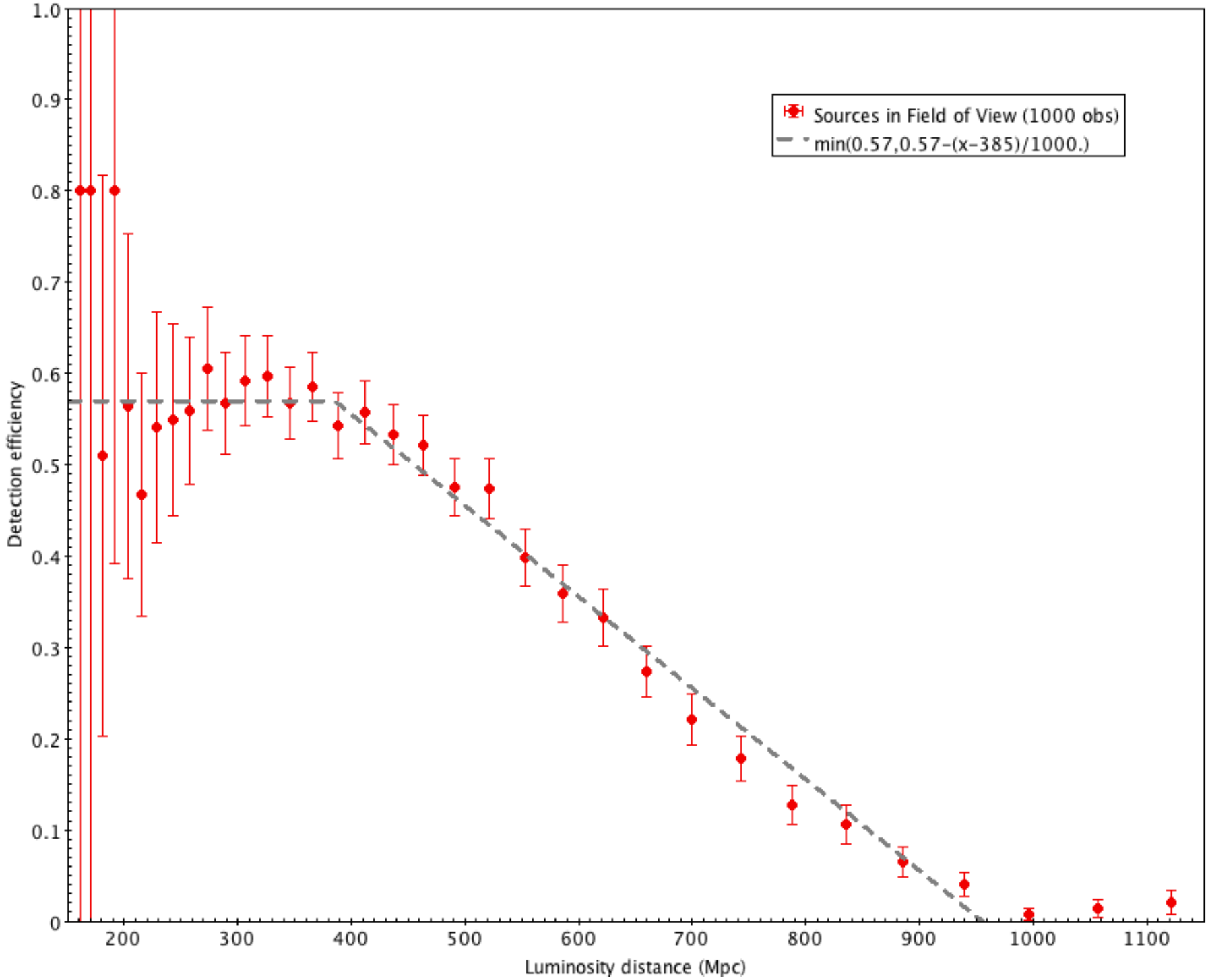
Using **33,100 cpu hours** of CT cluster and local resources, we analysed ~3500 (**>50%**, randomly selected) 3XMM DR5 **observations** with PN data, containing **~92,000 simulated transients**, **~40%** of which were **detected** by the pipeline

Well characterized detection fraction in **0.4-1 Gpc** range. **Rate** consistent with **all CC SNe** (uncertain due to single detection)

Conclusions and future prospects

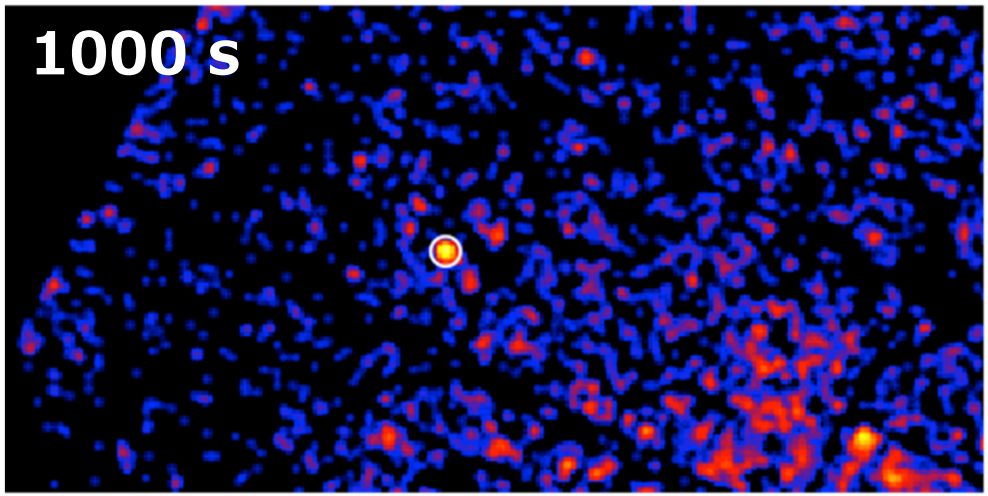
- Our experience with **CHIPP** has been **very positive**, mainly thanks to the support from **OA Catania staff** and **our previous experience** with the same cluster and CINECA (very similar environment)

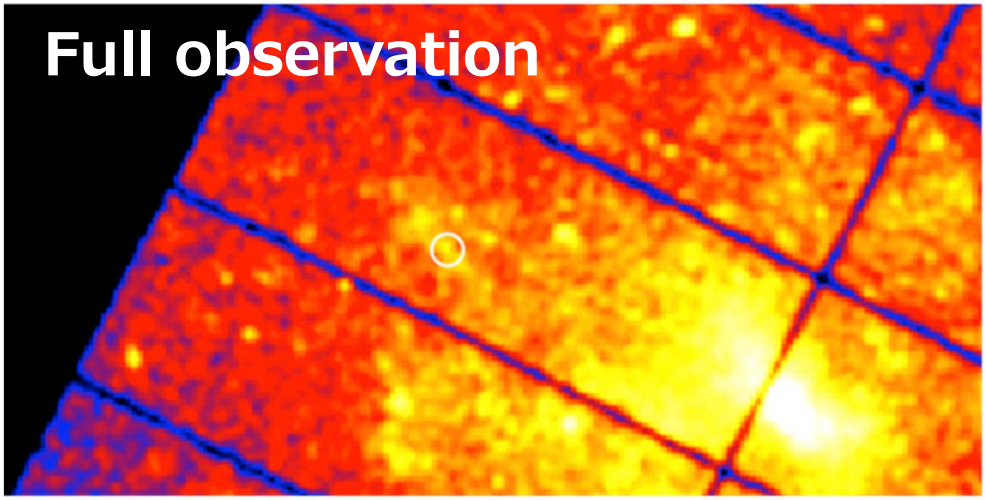
- We **achieved the goal** of our CHIPP project (results will be **published** soon), but we would like to **continue along the same research line** (*ULTraS* project just funded within "Accordo Attuativo ASI-INAF n. 2017-14-H.0"):
  - Extend EXTraS analysis to **more recent observations**
  - Extend **simulations** to **MOS** cameras and other **transient classes** (e.g., stellar flares)
  - Automatic transient **candidate screening** and **astrophysical classification** with neural network algorithms


Sources in Field of View (1000 obs)
min(0.57,0.57-(x-385)/1000.)
Detection efficiency
Luminosity distance (Mpc)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
200
300
400
500
600
700
800
900
1000
1100

What is a transient?

In this context, we define as a **transient** an X-ray source that is **detected during part of an EPIC observation, but NOT in the full observation** (i.e., in the 3XMM catalogue for the same observation)





The search algorithm

- **Source detection** on images with **variable** time bins (<5 ks), identified through a **Bayesian Blocks** (BB, *Scargle 1998*) analysis of detector cells with ~PSF size

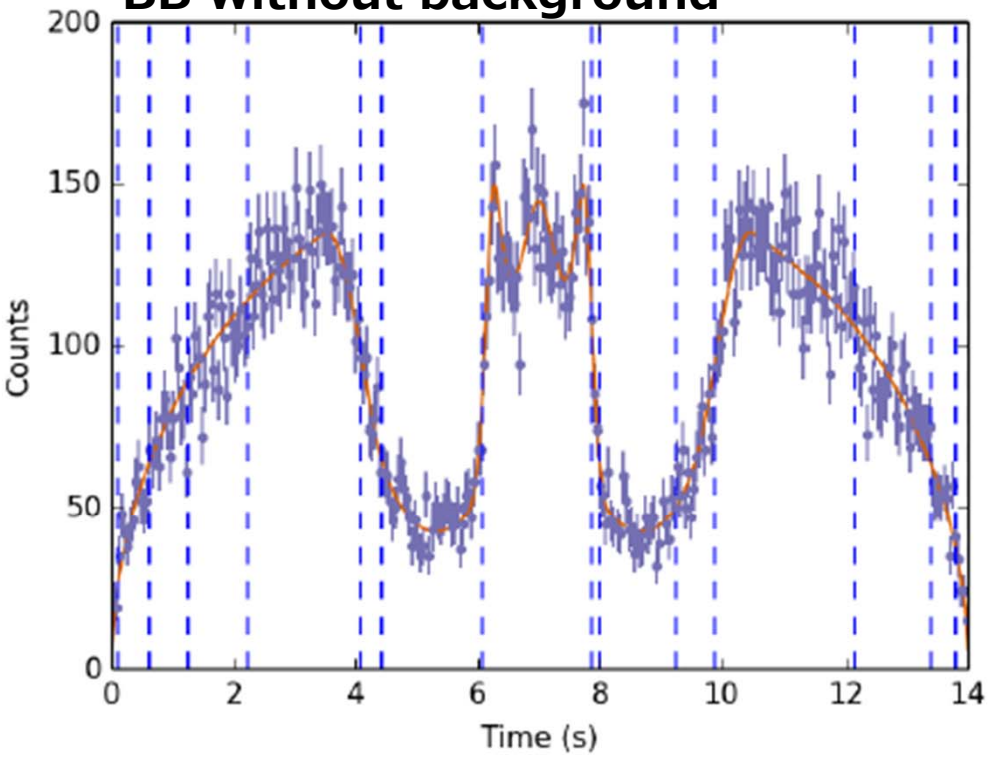
- **Transient candidates** are the point sources detected in sub-observations but not in the full observation

- **Manual screening** of transient candidates in the detector cells that triggered the BB interval

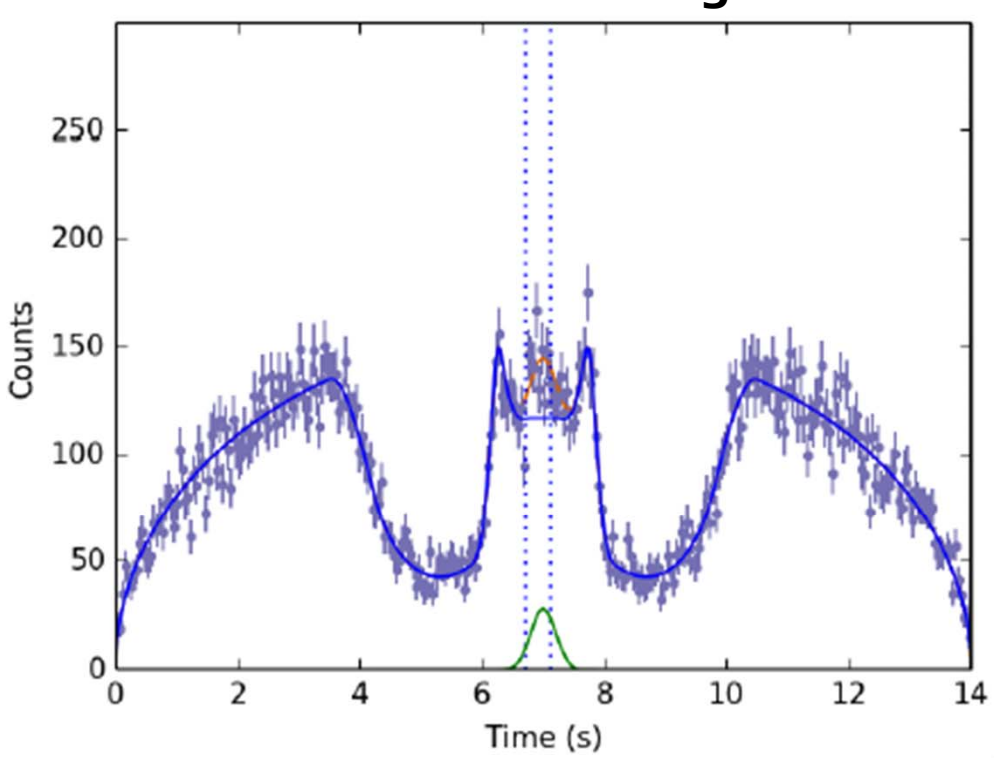
BB with variable background

The XMM background is **time variable** due to soft proton flares ⇒ the algorithm creates a new **Bayesian Block** when it detects a significant excess with respect to the local **background**

BB without background



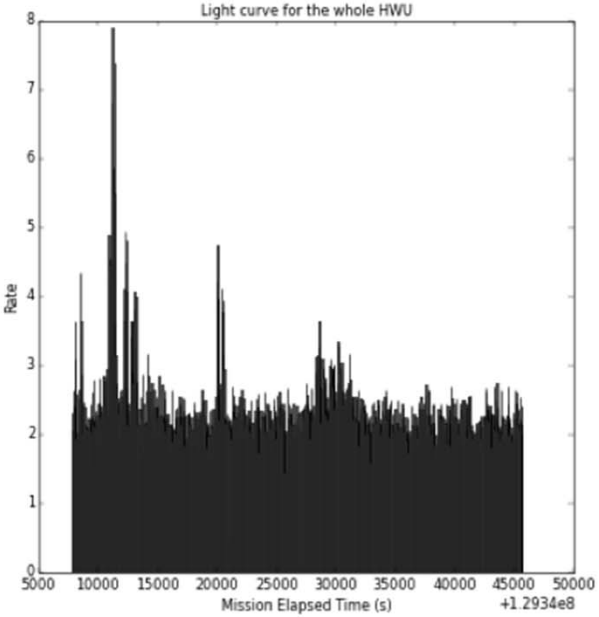
BB wrt a variable background

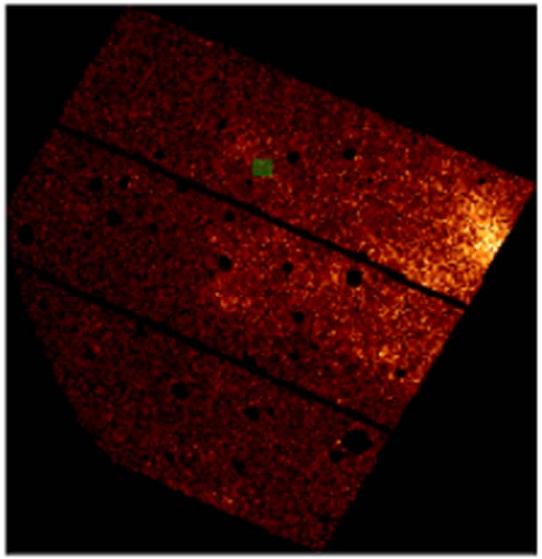


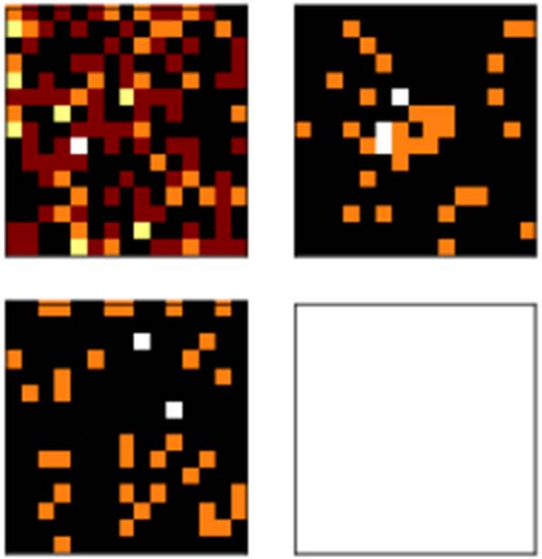
The BB algorithm

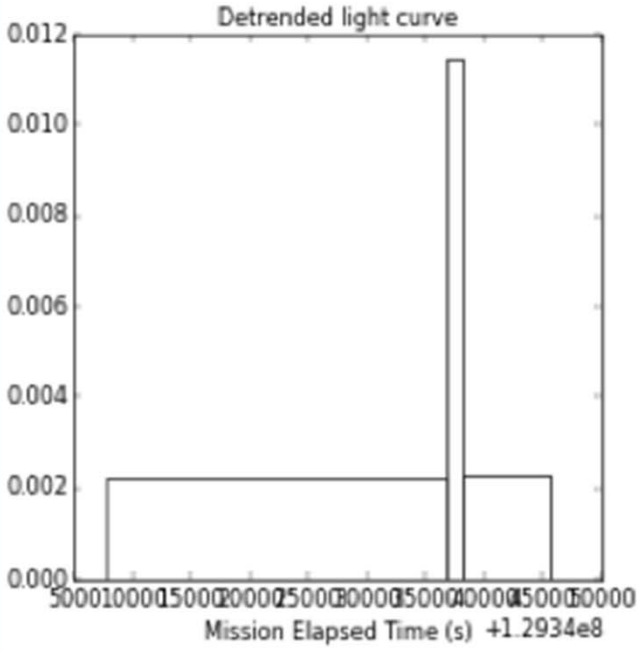
- To avoid contamination from variable sources, we **exclude** regions around **3XMM sources**

- **Spatial analysis** to select only time intervals with point source candidates









Close-to-source algorithm

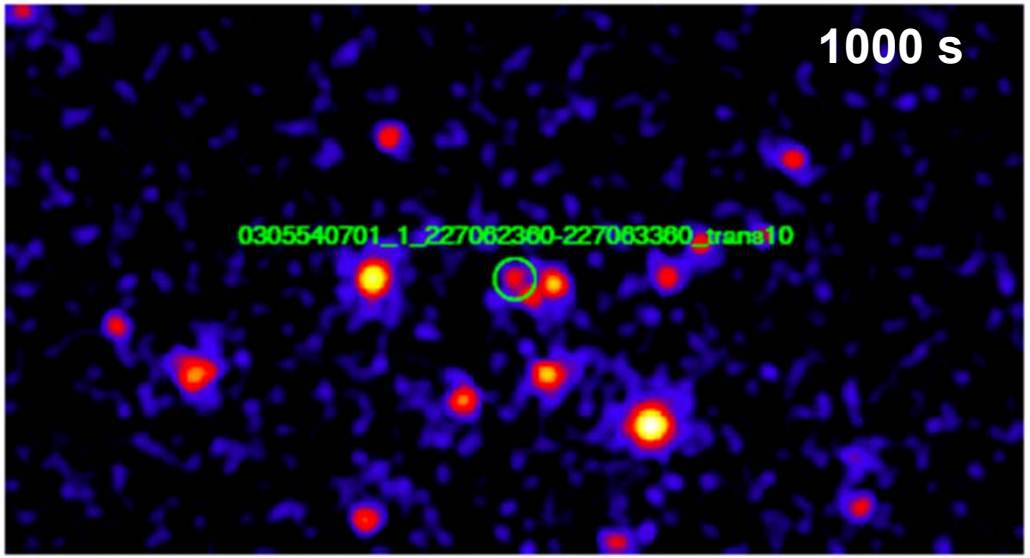
- Regions **close to 3XMM sources**, excluded from BB analysis, are analysed using **fixed time intervals** (1000 s; adiacent intervals are merged if the rate excess becomes more significant)

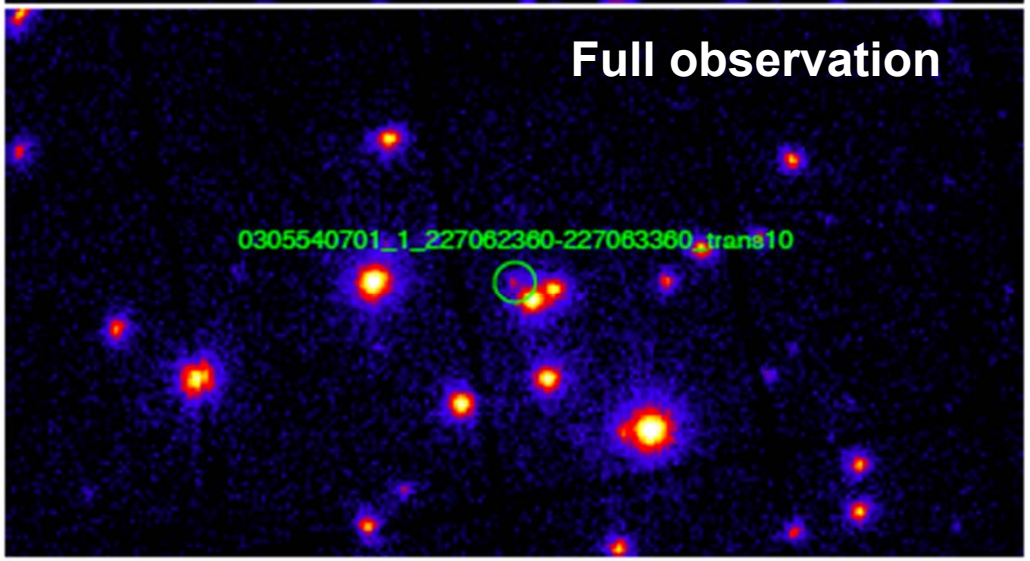
- After the time interval selection, the analysis continues as for the intervals selected through the BB algorithm (**source detection, comparison with 3XMM, manual screening**)

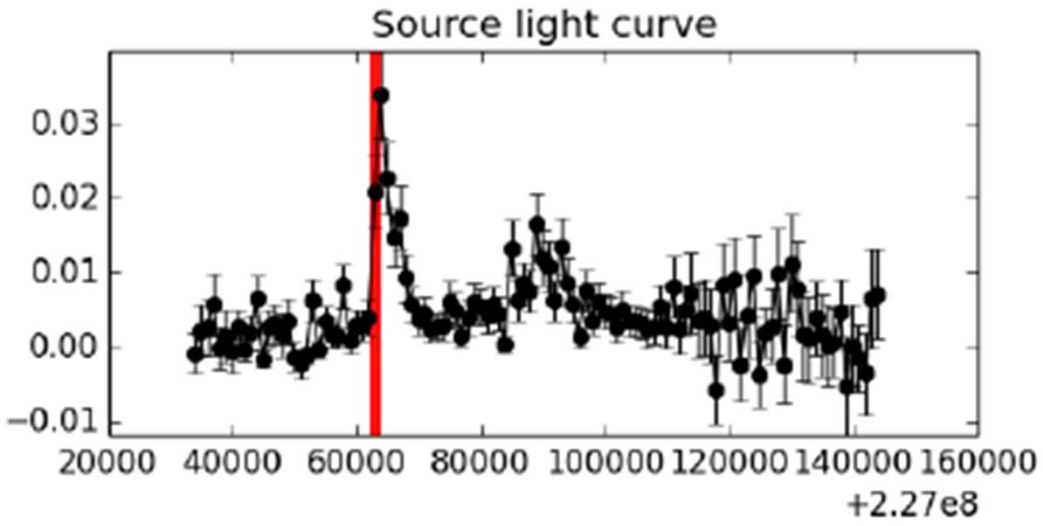
- These transients are tipically located in **crowded fields** (e.g., stellar clusters, nearby galaxies) and might contaminate **lightcurves** of 3XMM sources

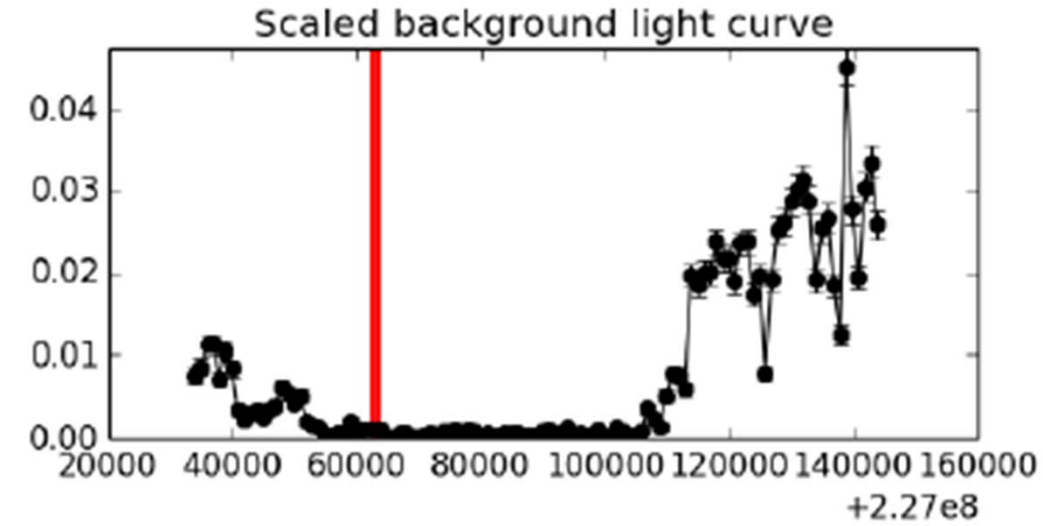
Transients close to 3XMM sources

EXAMPLE: rho Ophiuchi pointing









Post-processing screening

A **manual screening** of transient candidates is required to filter out spurious detections:

- **instrumental flares**, due to **bright/flickering pixels** or high energy **particles;**
- **displaced sources**, due to **unstable attitude** or **moving targets** (Solar System objects);
- **contaminating sources**, such as very **bright and/or extended sources**, **Out of Time** events, stray-light **rings;**
- **optical loading** due to very **bright stars** and/or wrong optical blocking filter

Systematic pipeline processing

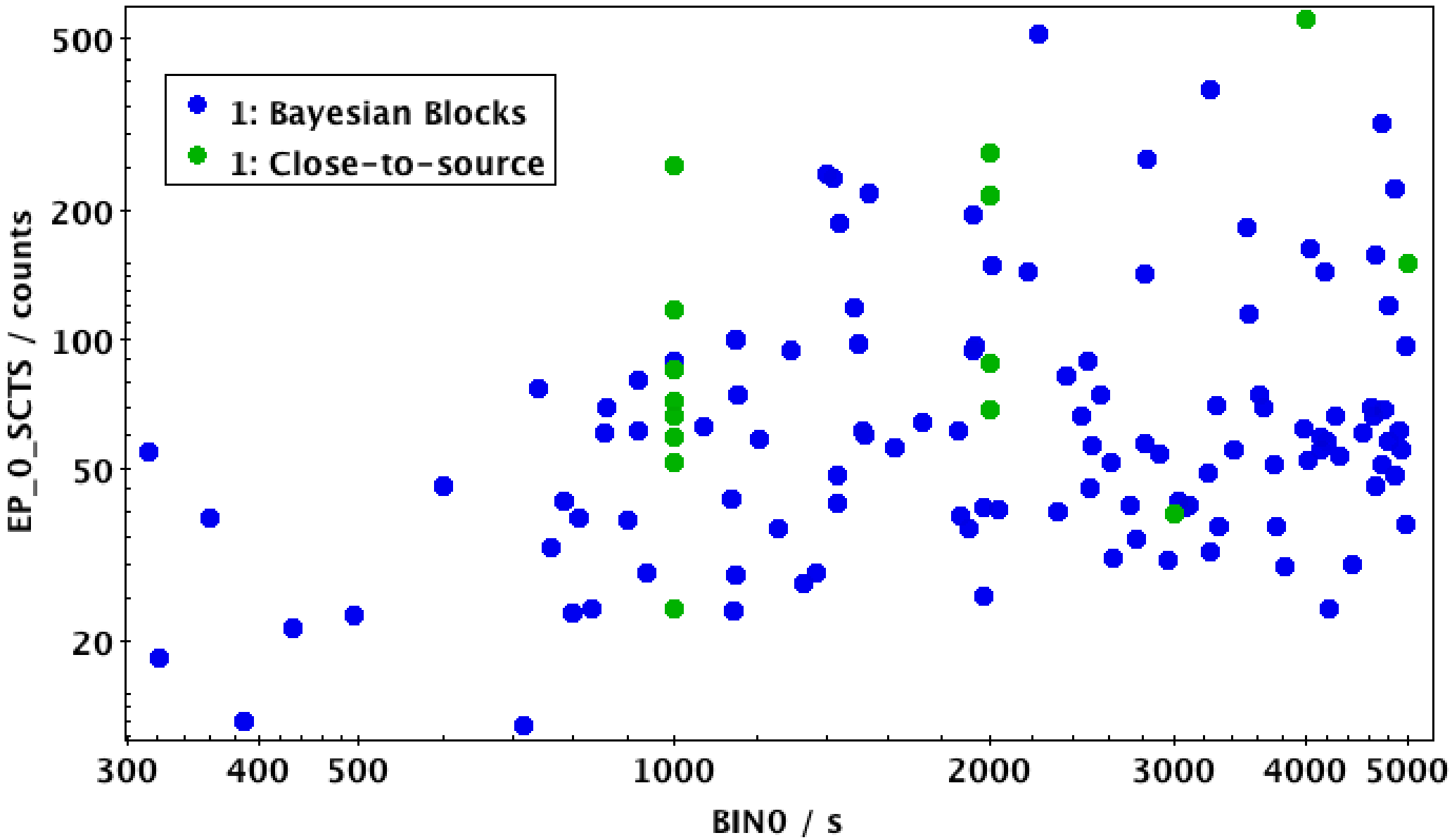
- The pipeline was run (several times!) on **7,811 observations** (3XMM DR5)
- Testing and systematic data processing on different **computer clusters** (24-2,000 cores) at IUSS, INAF, CINECA, Leicester University
- Manual **screening** performed at IUSS by different persons, including comparison of results obtained with different pipeline versions

Publicly available products

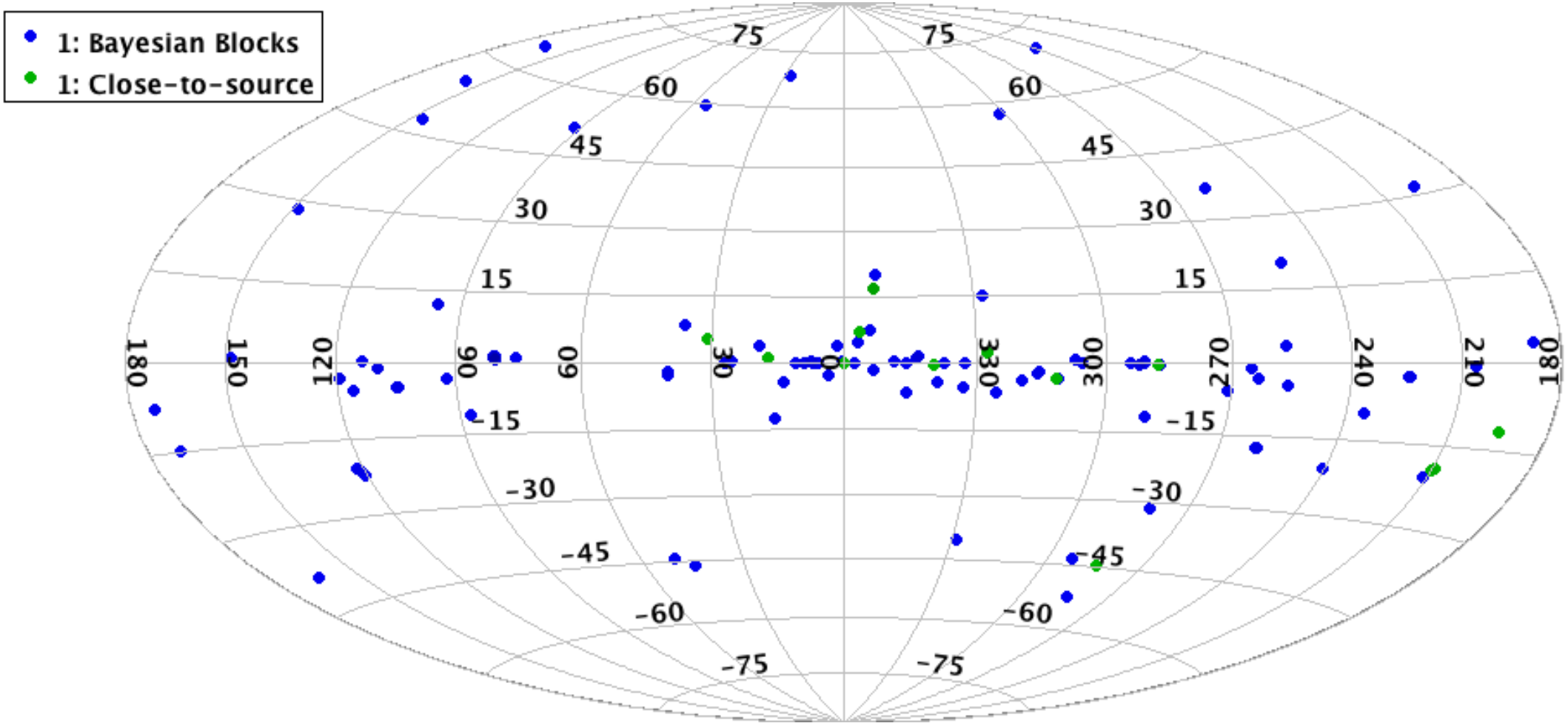
https://www88.lamp.le.ac.uk/extras/query/extras_transients

- **Transient catalogue** (FITS): 130 **sources** and 186 **columns** (time interval properties + 3XMM-like parameters for the most significant time interval)
- **For each transient**: **images** (FITS and PNG with region files), **exposure** and **background** map (FITS), **region files** (.reg/ds9, 20” circles) of the transient and the other detections in the most significant time interval

Transient counts and duration



Transient sky distribution



105/130 transients have |b|<20°

Event Rate

- **Serendipitous** discovery
- Sky coverage of the EXTraS survey corresponds to the **full sky** observed by the PN instrument **for ~8 minutes**
- How to estimate the **sensitivity** of the EXTraS search for transients

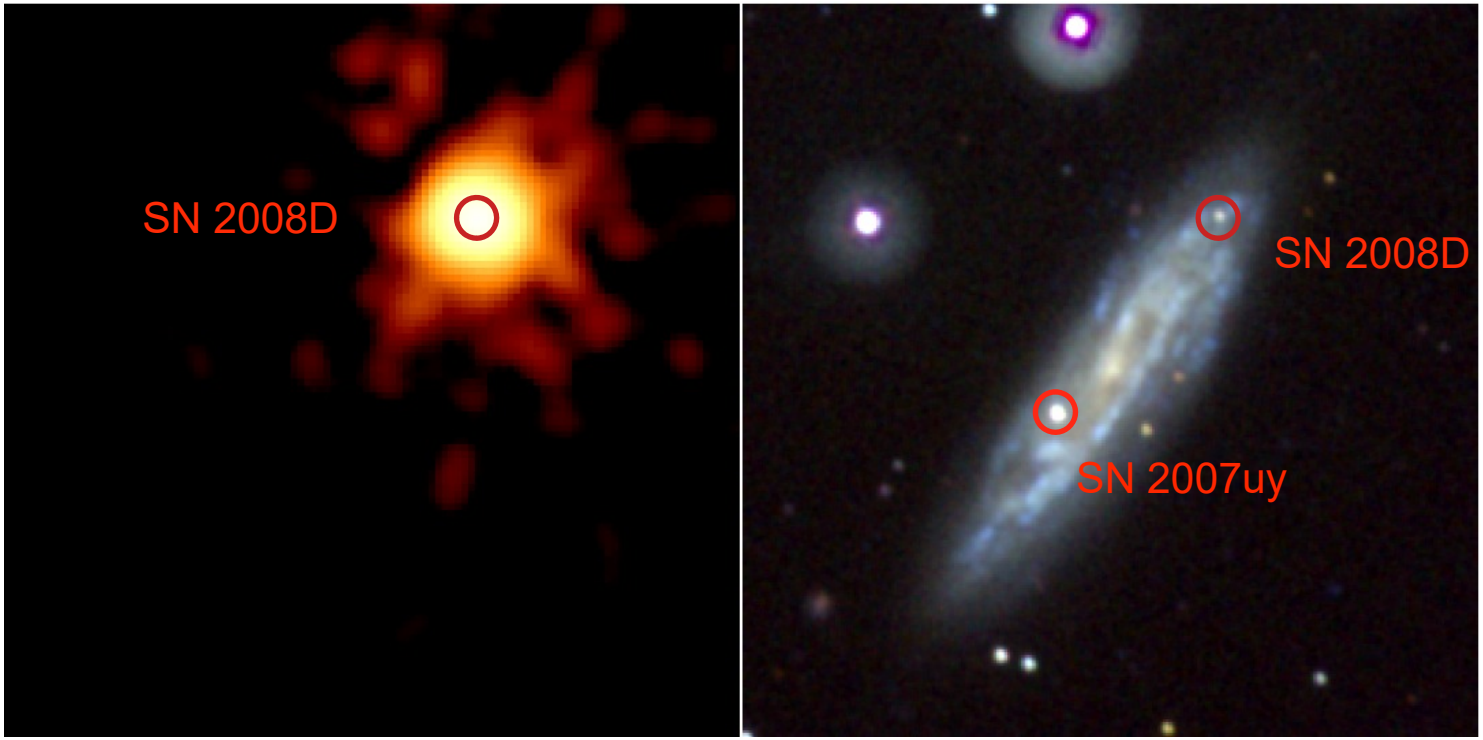
From this single detection, the *(preliminary)* event rate is **1.3×10^5 yr^{-1} Gpc^{-3}**, consistent with Sorderberg et al. (2008) and a factor ~2 larger than core-collapse SN rate (~6×10^4 yr^{-1} Gpc^{-3}).

Optical SN searches might have missed a significant fraction of core-collapse SNe

Supernova association

Being discovered in archival data, no follow-up optical observations to **search for a supernova**; no sufficiently deep archival optical observations; outside OM FoV during *XMM-Newton* observation

SN2008 was discovered during the observation of a SN-rich galaxy, whereas our discovery is serendipitous



http://www.nasa.gov/centers/goddard/news/topstory/2008/swift_supernova.html

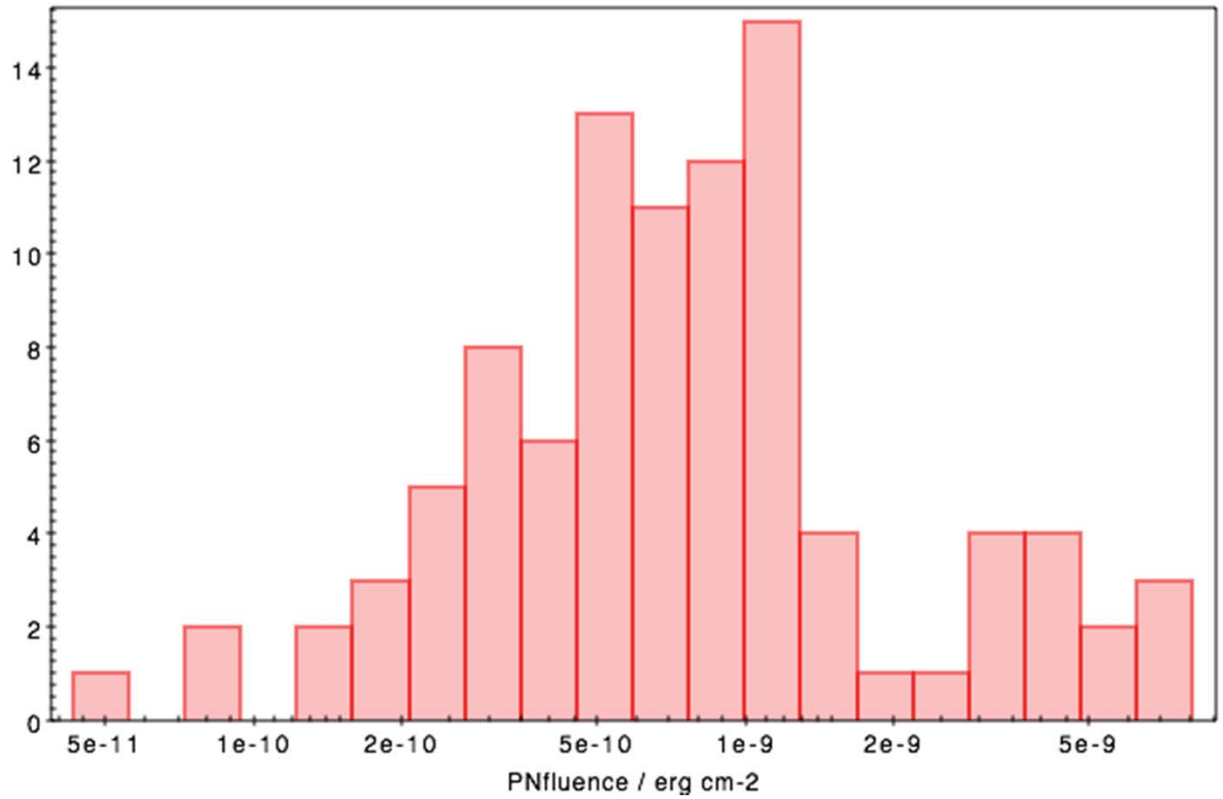
Other interpretations for the transient?

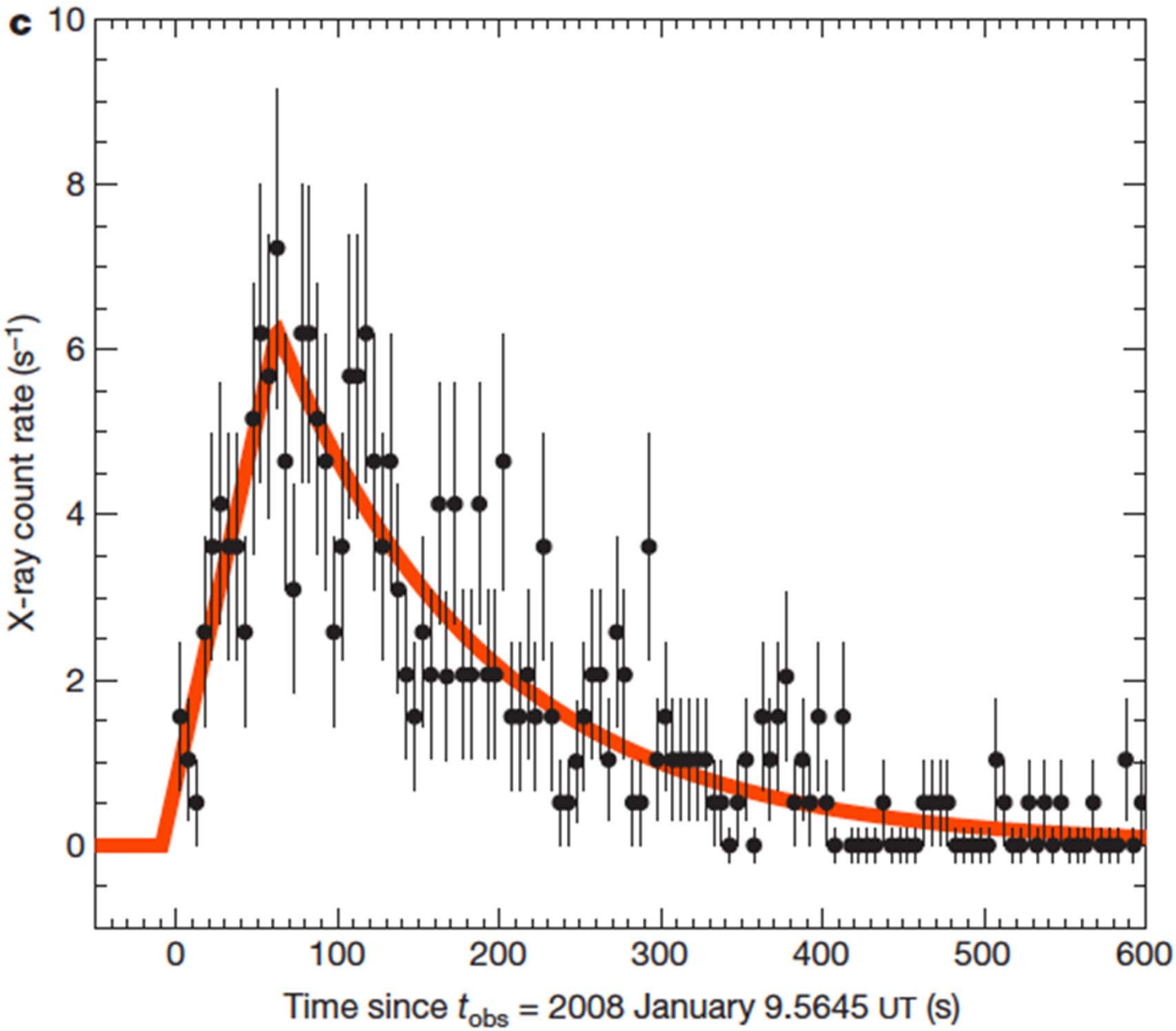
Galactic source → NO: low probability of chance alignment with galaxy (~10^{-3}) and evidence for $N_H > N_{H,Gal}$

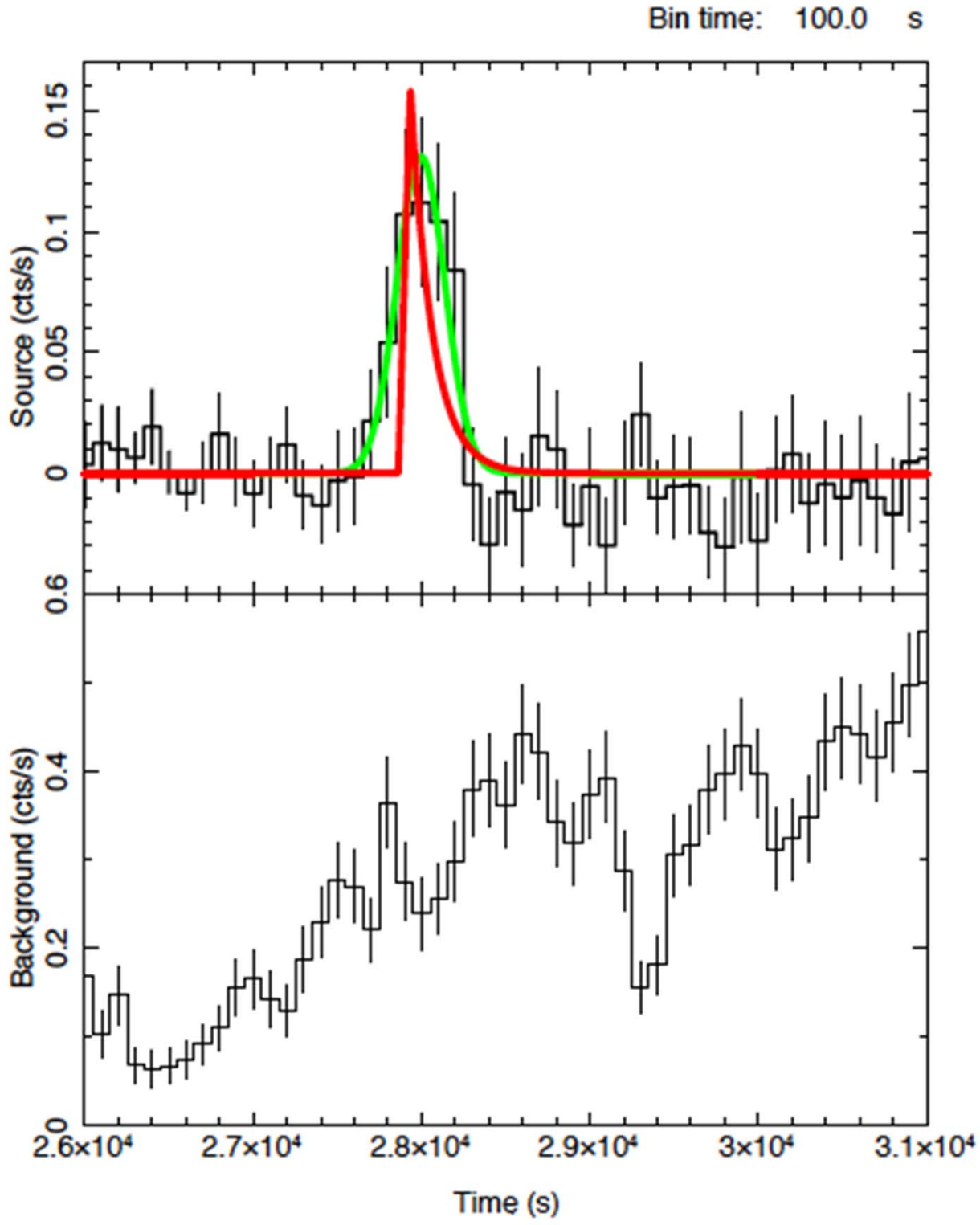
Flare from an AGN → NO: no evidence for AGN activity

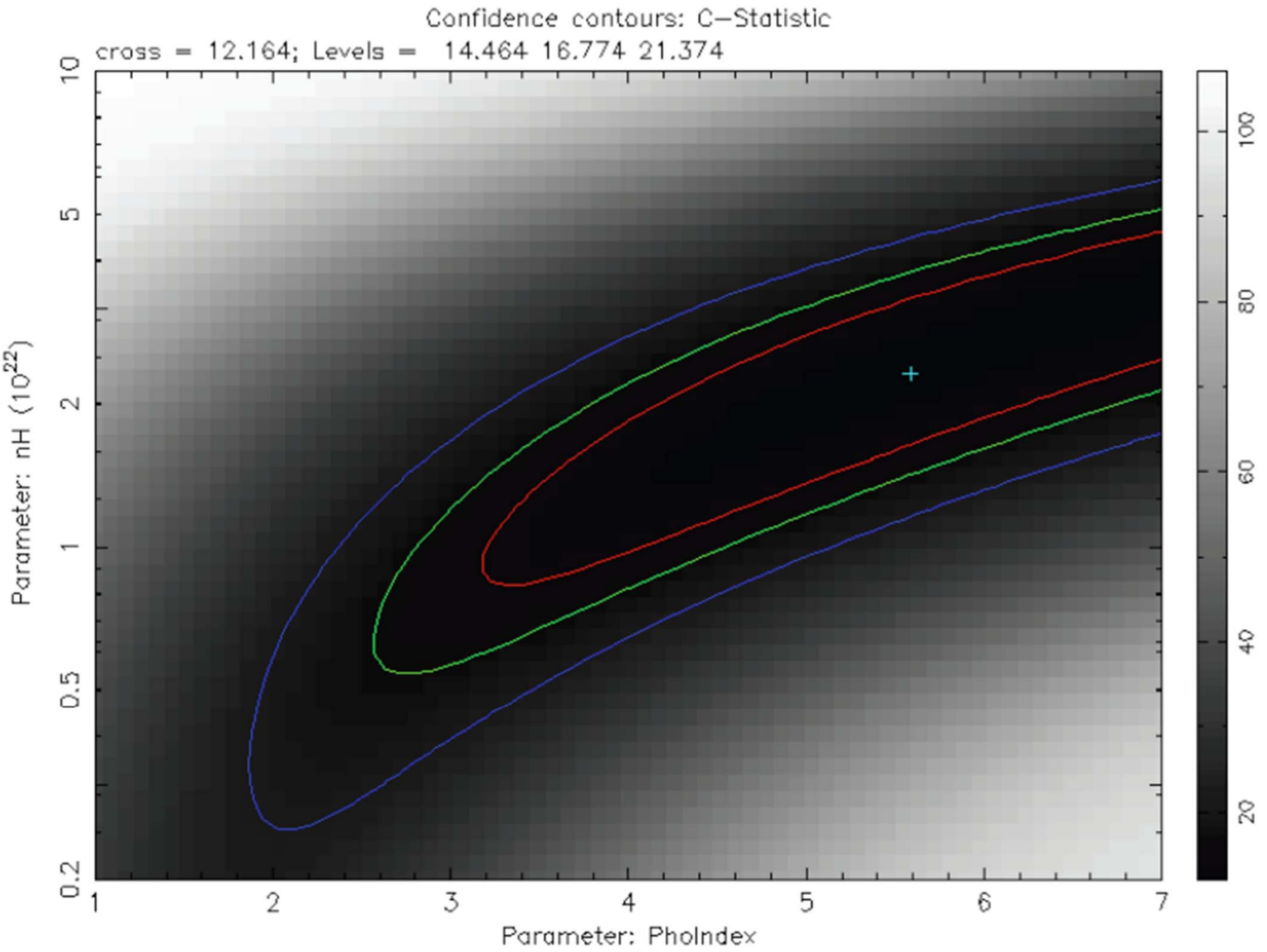
Magnetar → NO prompt: too long (>100 s vs <1 s)
→ NO tail: too bright (10^{46} erg vs 10^{44} erg)

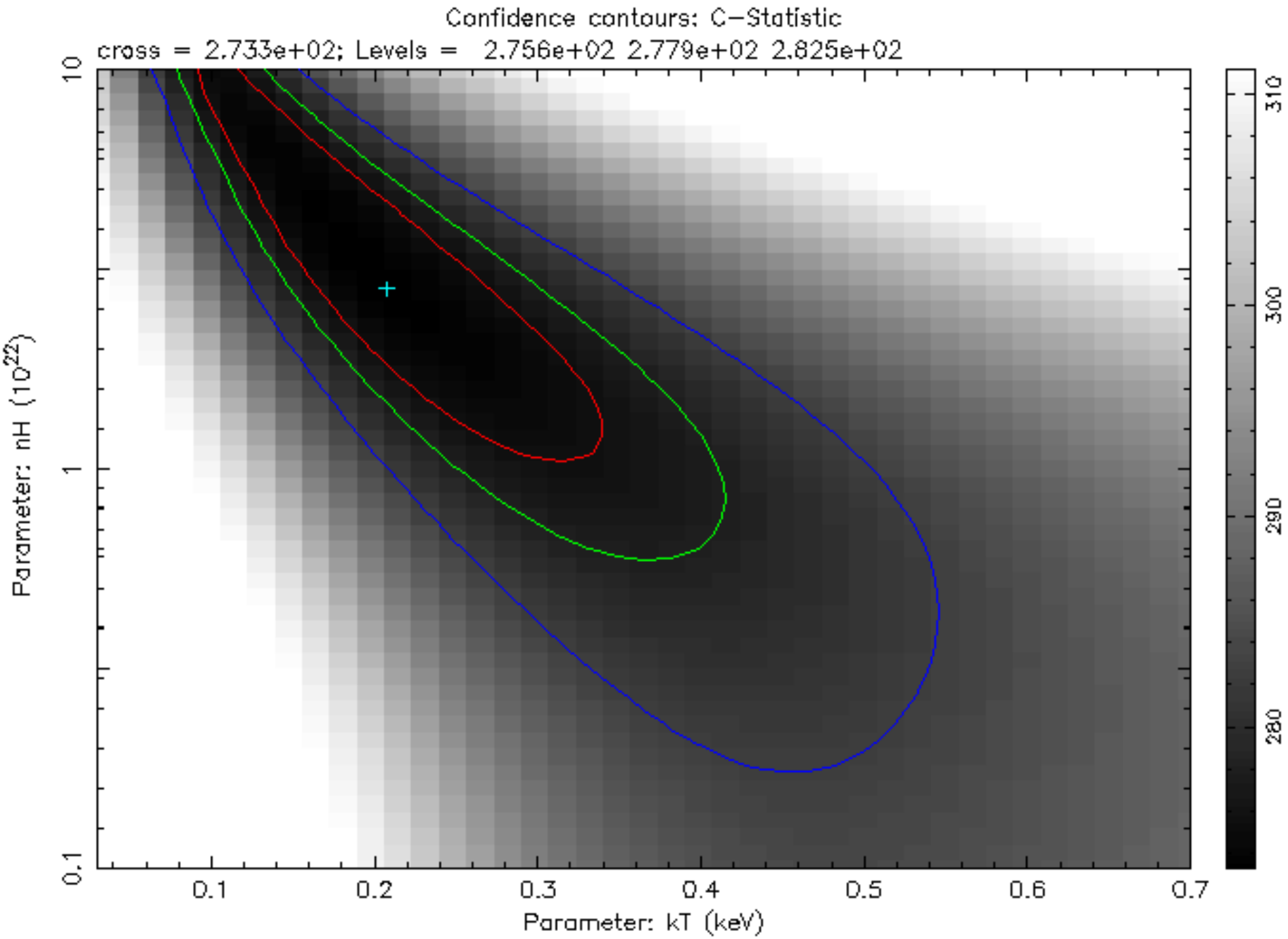
Distribution of fluences



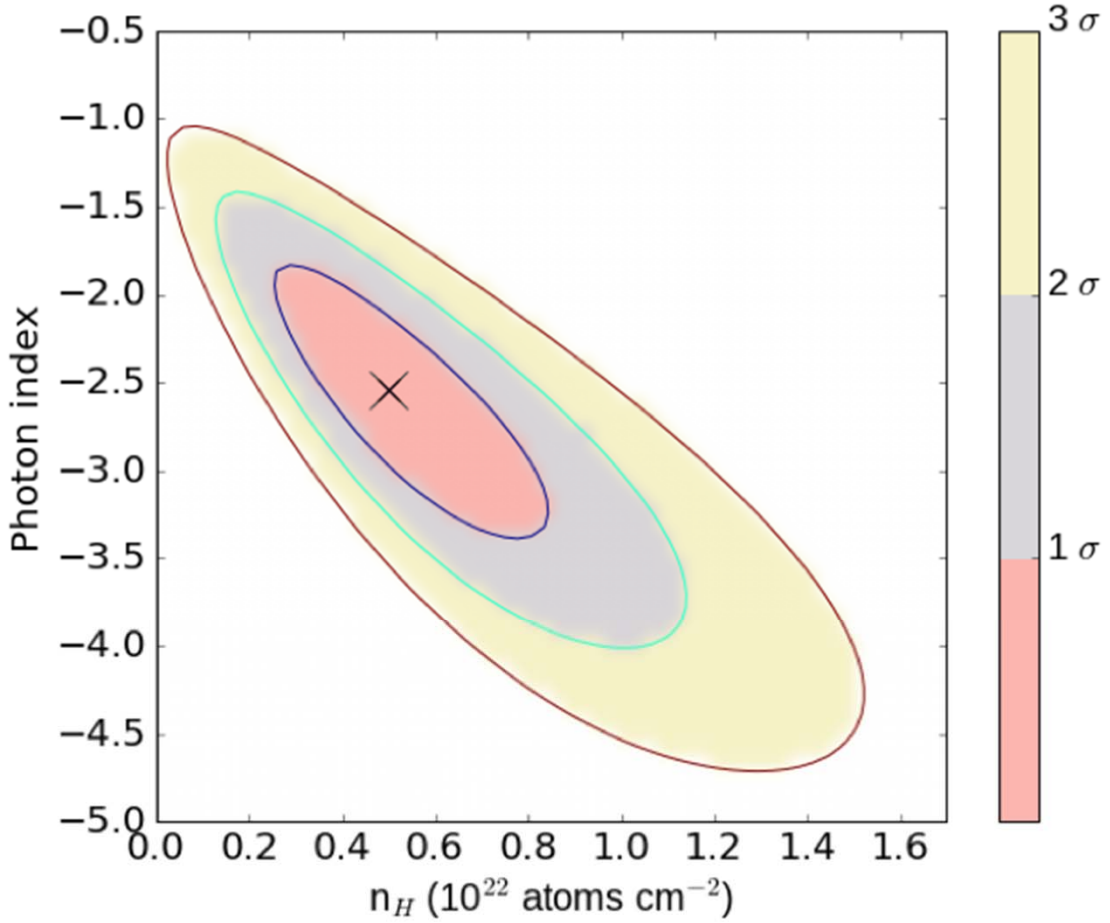

c
10
8
6
4
2
0
X-ray count rate (s⁻¹)
0
100
200
300
400
500
600
Time since t_{obs} = 2008 January 9.5645 UT (s)


Bin time: 100.0 s
Source (cts/s)
0.15
0.1
0.05
0
0.6
Background (cts/s)
0.4
0.2
0
2.6×10⁴
2.7×10⁴
2.8×10⁴
2.9×10⁴
3×10⁴
3.1×10⁴
Time (s)


Confidence contours: C−Statistic
cross = 12.164; Levels = 14.464 16.774 21.374
Parameter: nH (10^{22})
0.2
0.5
1
2
5
10
Parameter: PhoIndex
1
2
3
4
5
6
7
20
40
60
80
100


Confidence contours: C−Statistic
cross = 2.733e+02; Levels = 2.756e+02 2.779e+02 2.825e+02
Parameter: nH (10^{22})
10
1
0.1
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Parameter: kT (keV)
310
300
290
280

X-ray properties



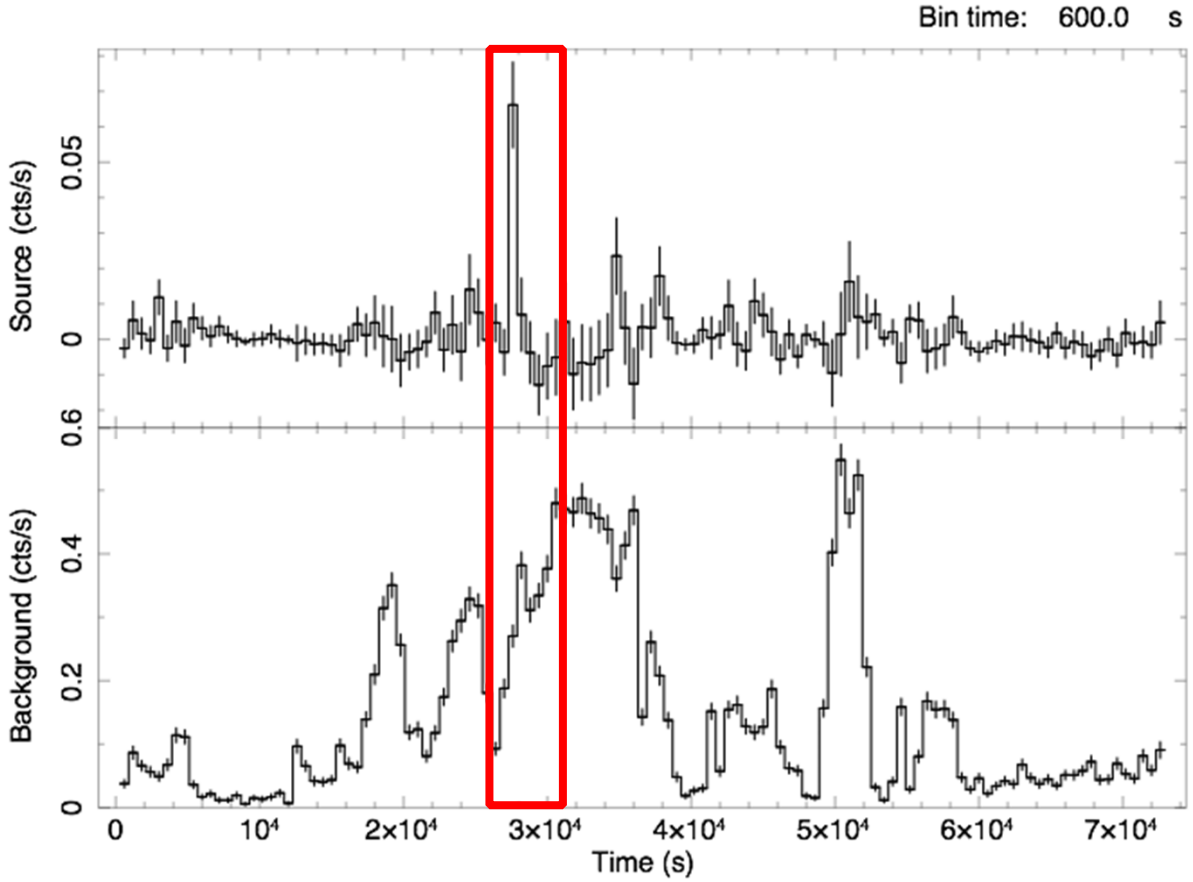
- X-ray spectrum (background-subtracted, in the 315 s interval)
- With a power-law model absorbed both in our Galaxy (N_H=3x10^{20} cm^{-2}) and in host galaxy: Γ~1.5 and >3σ evidence for excess absorption in the host galaxy
- Fluence: 8x10^{-10} erg cm^{-2}
- Energy: 1.7x10^{46} erg (d=424 Mpc)

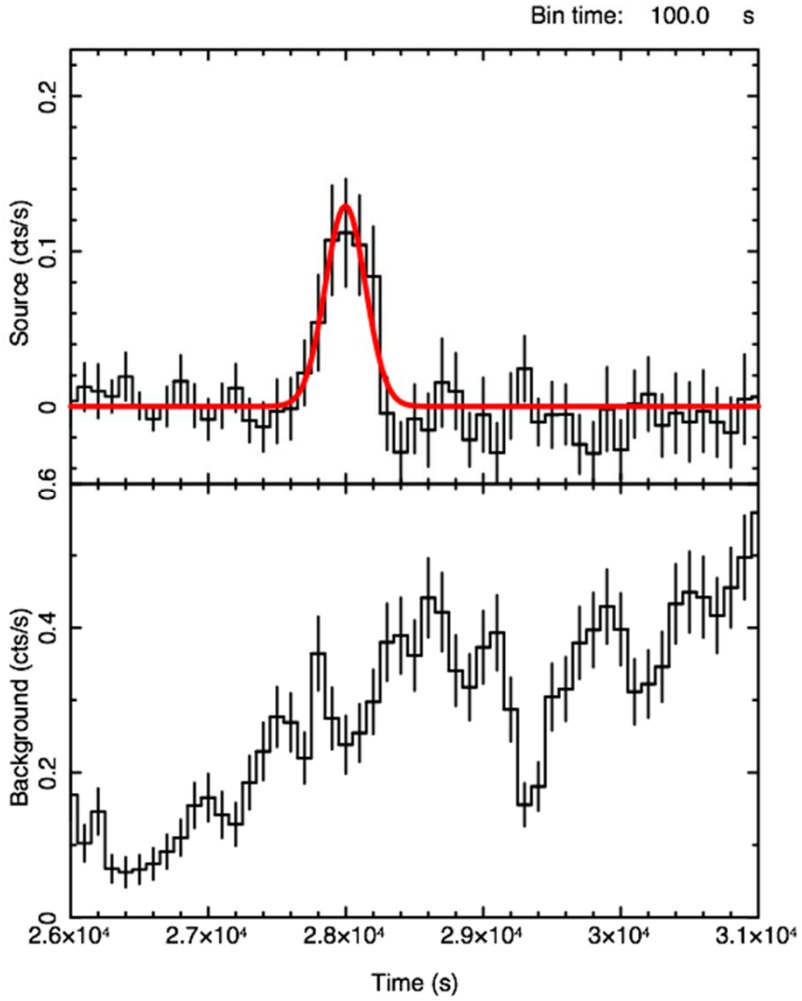
Within the EXTraS project we found a new X-ray source that could be detected only in a ~5 min interval of a long observation. Thanks to its position we identified it as a star-forming galaxy at redshift $z = 0{,}092 \pm 0{,}003$.

Its luminosity and spectral/timing properties make it a perfect analogue of the X-ray transient associated to SN2008D.

Our transient, therefore, was interpreted as an X-ray emission from a supernova shock break-out, but at a 15 times larger distance; we could then set tight constraint on the supernova rate in the local Universe up to z~0.1

X-ray light curve





47 total counts by integrating the Gaussian profile