The STATiX view of the transient X-ray sky

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First Results from the SRG/eROSITA All-Sky Survey:
From Stars to Cosmology (15-20 September 2024)

IAASARS

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H.F.R.I. Hellenic Foundation for Research & Innovation

Introduction

- The X-ray sky is highly variable at multiple time scales.
- Serendipitous **sort transients** can be easily **missed in the background** noise:
  - Shock-wave breakouts (SBO) from supernovae (*Soderberg+2008*)
  - Merging of compact stellar objects (*Bauer+2017*, *Xue+2019*, *Sarin+2021*)
- Previous efforts for systematic searches:
  - EXTRaS (*De Luca+2021*)
  - EXOD (*Pastor-Marazuela+2020*), EXODUS
  - Chandra Fast transients (*Yang+2019*, *Quirola-Vásquez+2022*)
  - SBO candidates (*Alp & Larsson 2020*)
  - ...

Introduction

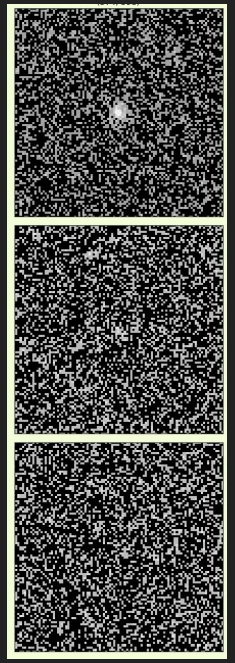
- Our goals:
  - Source detection algorithm considering **spatial and time information**
  - Robust and **usable** source detection **pipeline**
  - Timing information for all sources

Denoising for source detection

2D vs 2D+1D MSVST

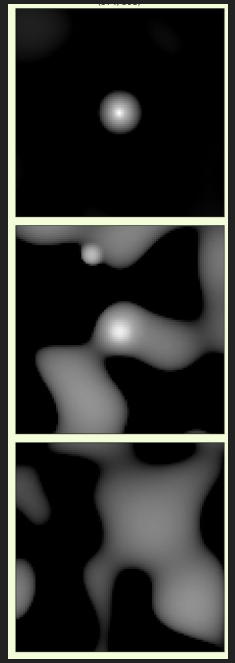
Multi-Scale Variance Stabilization Transform ***(Zhang et al. 2008, Stark et al. 2009)***

Original image



Data cube
32 time frames

2D MSVST



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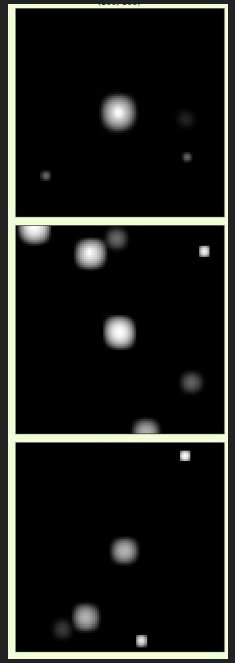
max_scalexy = 4
sigma_level = 4

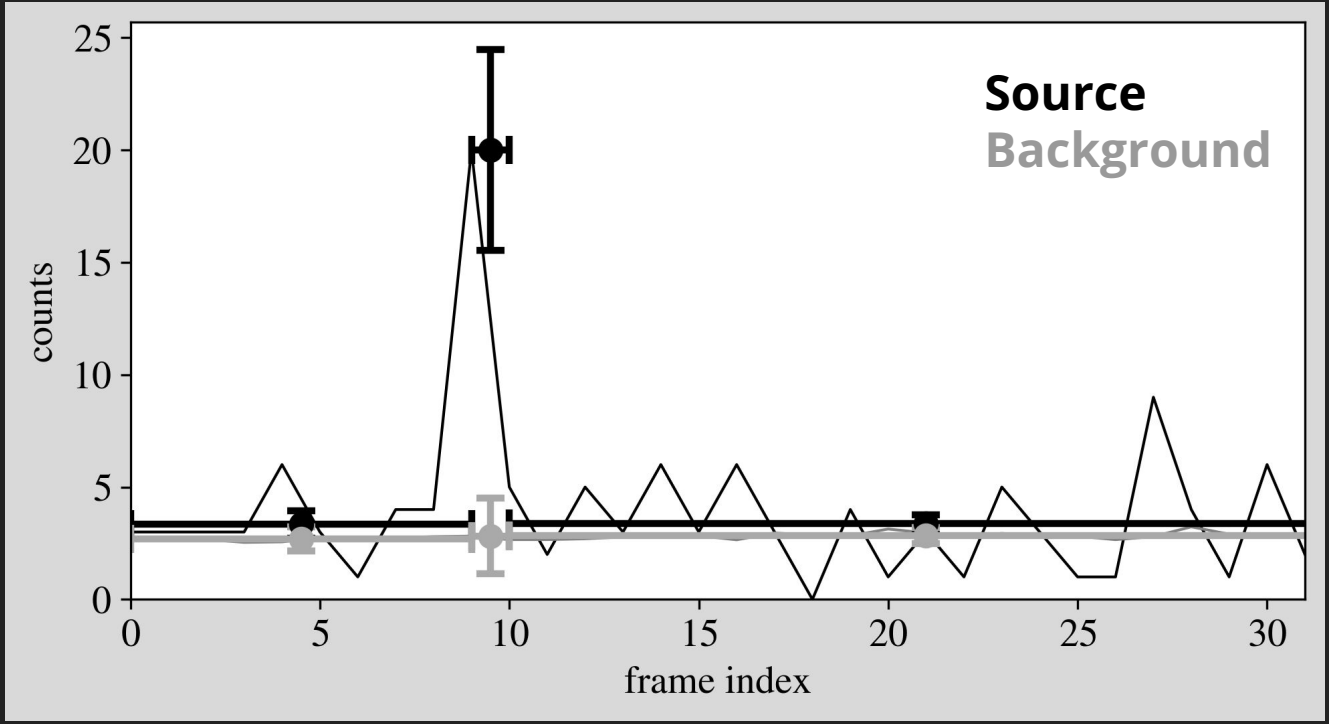
2D+1D MSVST



min_scalexy = 1
max_scalexy = 4
min_scalez = 1
max_scalez = 5
sigma_level = 5

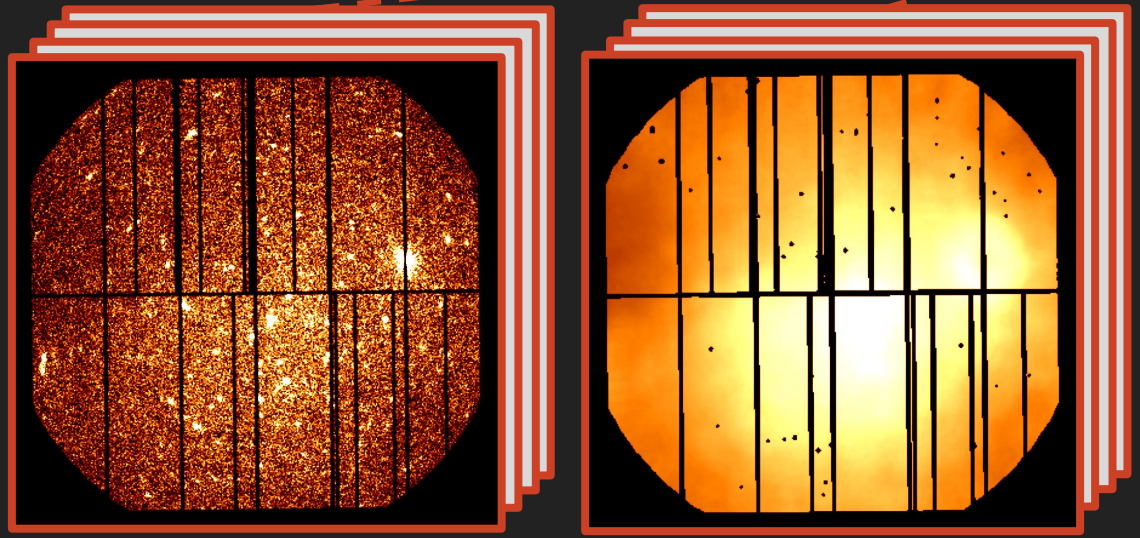
Time behaviour characterization

Bayesian Blocks (*Scargle et al. 2013*)

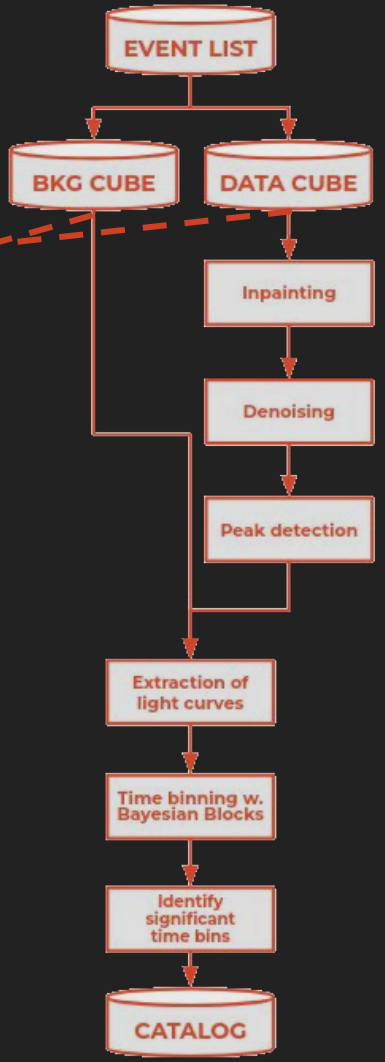


STATiX

Space and Time Algorithm for Transients in X-rays (Ruiz et al. 2024)



2D projection along the time axis for the initial data and background cubes. Each cube contains 32 time frames.
[XMM-Newton Obs.Id. 0305970101]



https://github.com/ruizca/statix

STATiX

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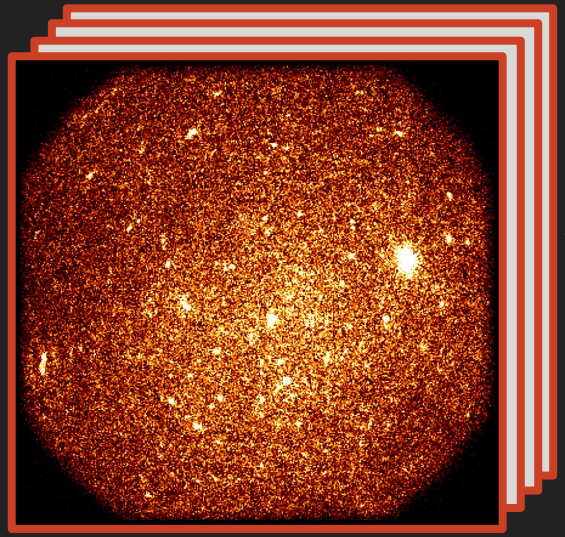
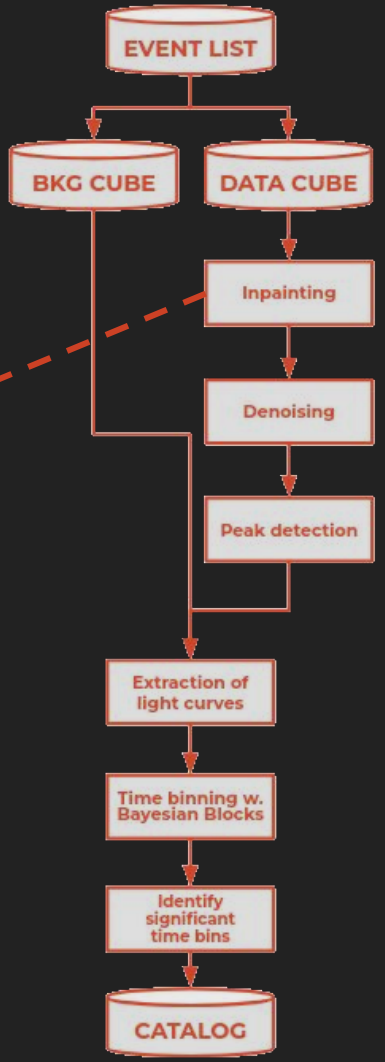


2D projection of the inpainted data cube.



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STATiX

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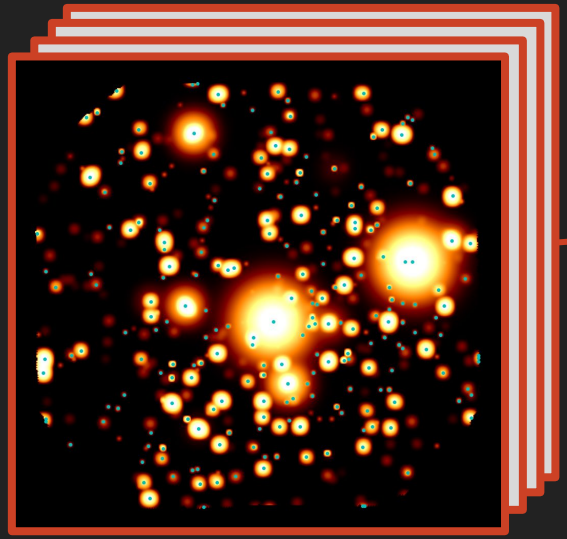
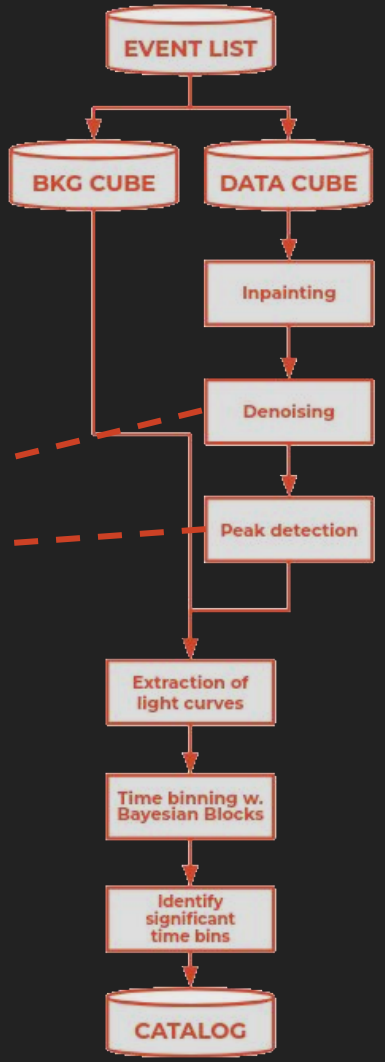


2D projection of the denoised data cube using MSVST. Blue dots mark the source candidates detected with a simple peak detection algorithm.



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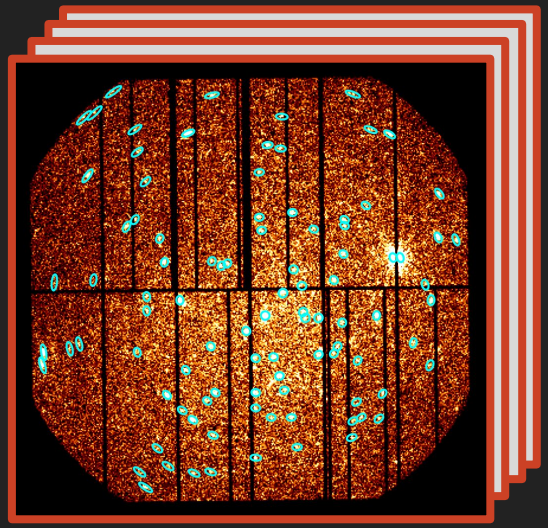
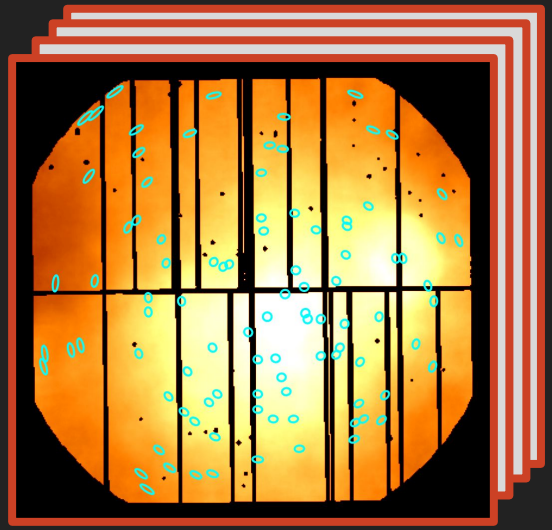
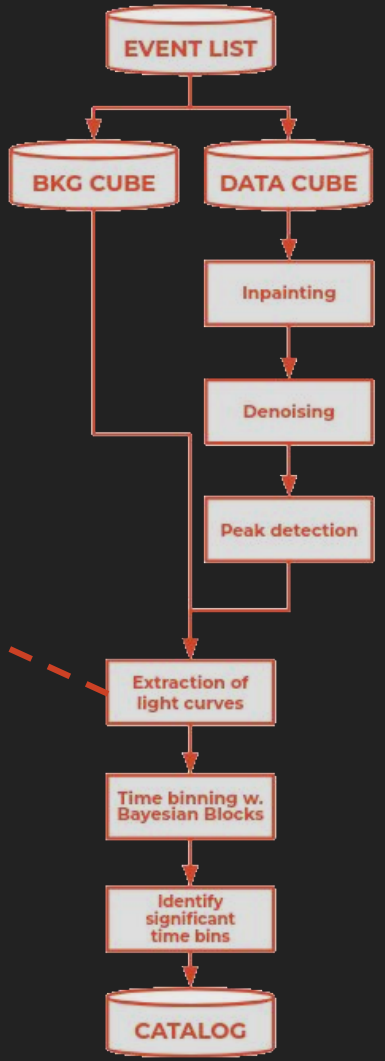
Space and Time Algorithm for Transients in X-rays (Ruiz et al. 2024)





2D projection of the data and background cubes.
Ellipses show the counts extraction regions for statistically significant source candidates after the light-curve analysis.



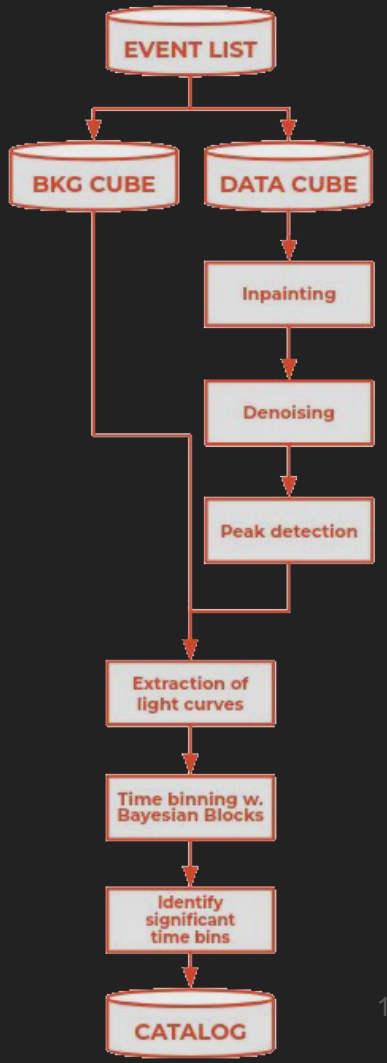
https://github.com/ruizca/statix

STATiX

Space and Time Algorithm for Transients in X-rays
(***Ruiz et al. 2024***)

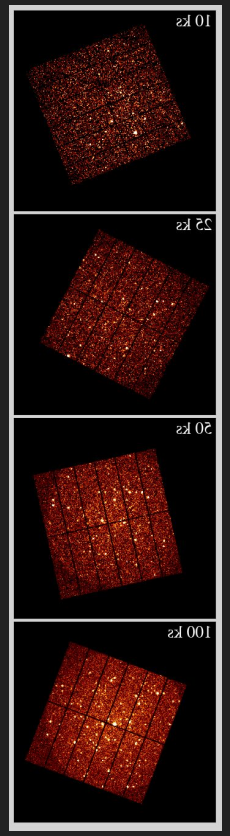
FINAL CATALOGUE

- Positions
- Fluxes
- Light-curves (Bayesian Blocks and unbinned)
- Statistical significance

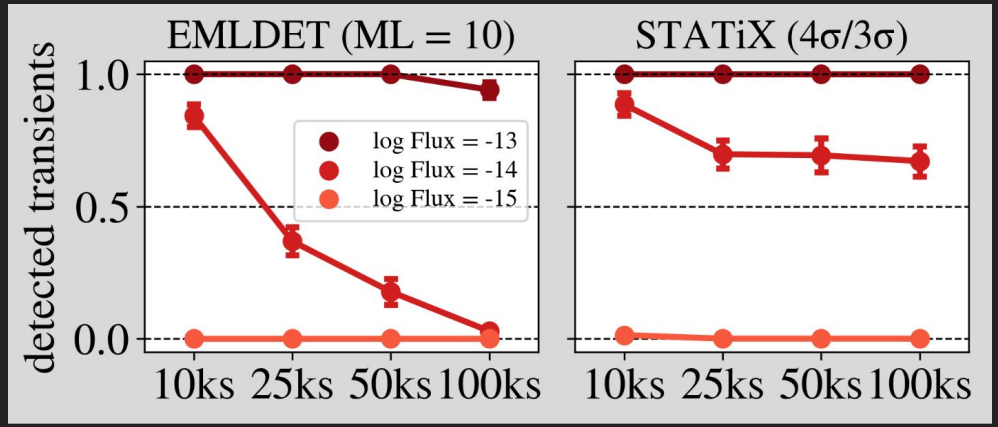


https://github.com/ruizca/statix

STATiX: Testing via simulations



- 1000 realistic XMM-Newton simulations using SIXTE *(Dauser et al. 2019)*: constant-flux sources + 5 ks transient.
- **We found completeness and false detection rates comparable to EMLDETECT.**
- **Higher detection rate of transients** for long exposure time observations.

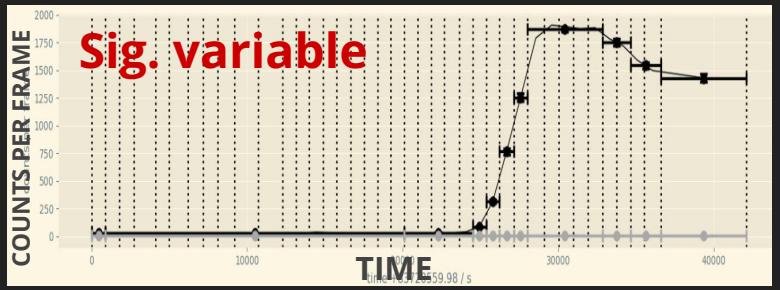


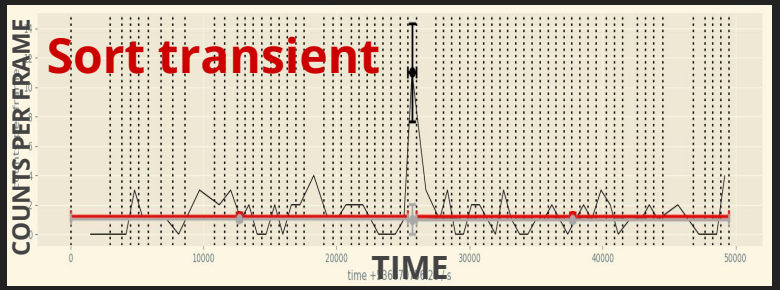
https://github.com/ruizca/sixtexmm

Applying STATiX to the XMM archive

Preliminary results (~1000 observations)

- Identification of sources with interesting time behaviour:
  - **Significantly variable (~500 sources):**
    - Three or more BB
    - $CR_{min} + 3\sigma_{min} < CR_{max} - 3\sigma_{max}$
  - **Sort transients (~50 sources):**
    - Three BB
    - $\Delta T_{min} < 5$ ks
      $\Delta T_{min} << \Delta T_{max}$



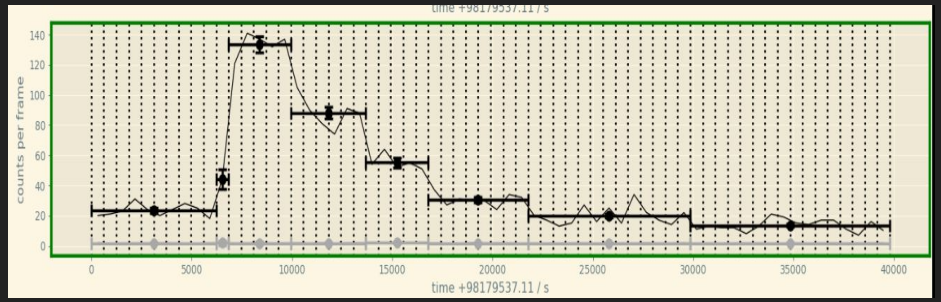


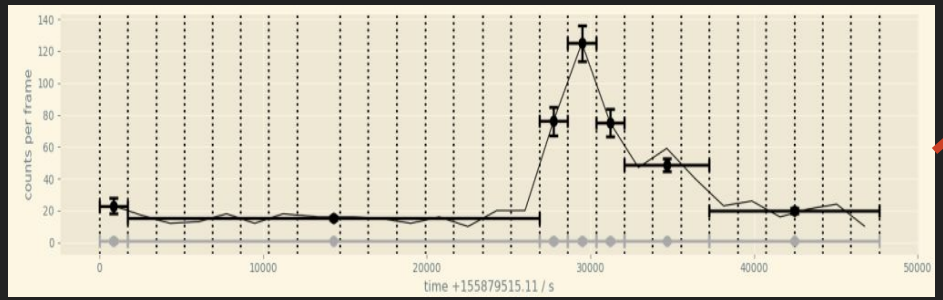
- Search for multiwavelength info:
  - Optical/IR imaging and counterparts.
  - X-ray/optical/IR long-term light-curves (RapidXMM, ZTF, PanSTARRS, CATWISE)
  - Spectra (SDSS, LAMOST)

Applying STATiX to the XMM archive

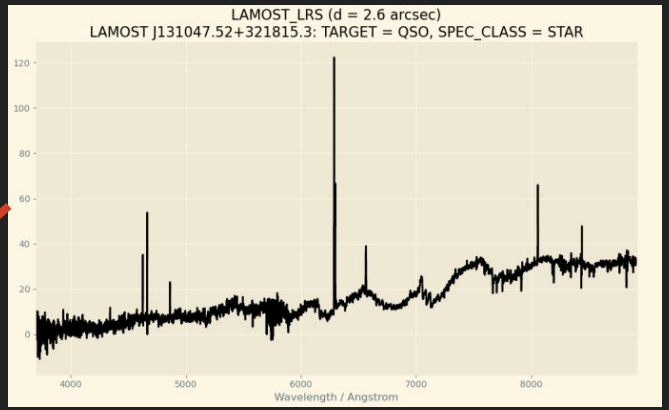
Preliminary results (1000 observations)

Light-curves examples





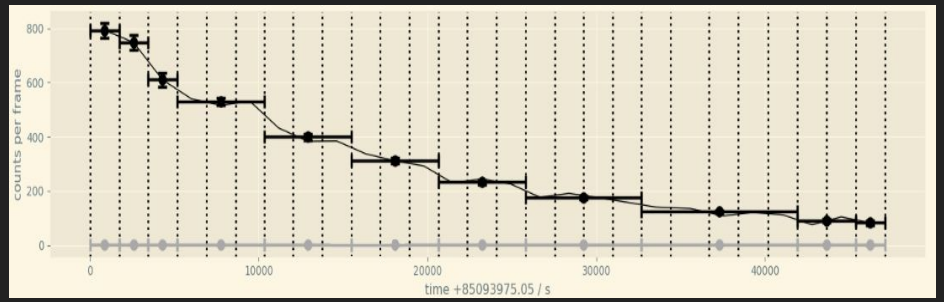
Flaring stars (~70%)

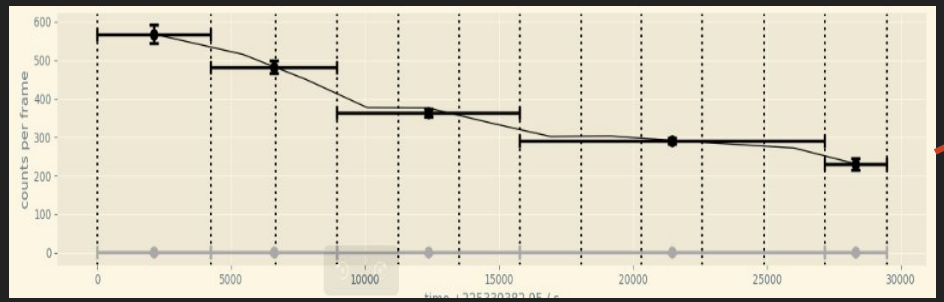


Applying STATiX to the XMM archive

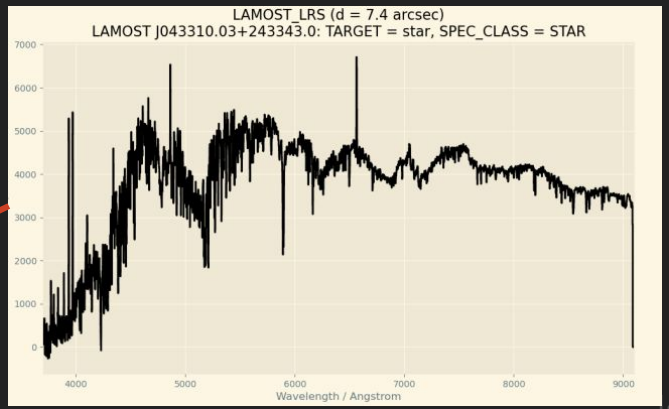
Preliminary results (1000 observations)

Light-curves examples





Slow decay
(tail of stellar flares)

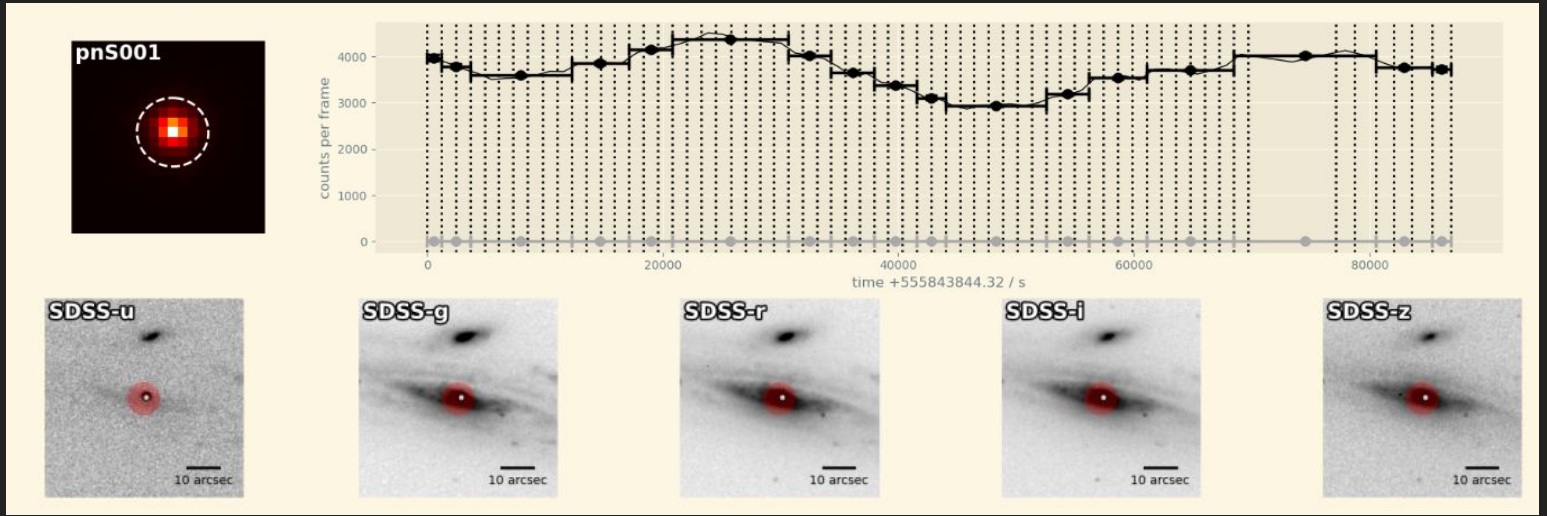


Applying STATiX to the XMM archive

Preliminary results (1000 observations)

Light-curves examples

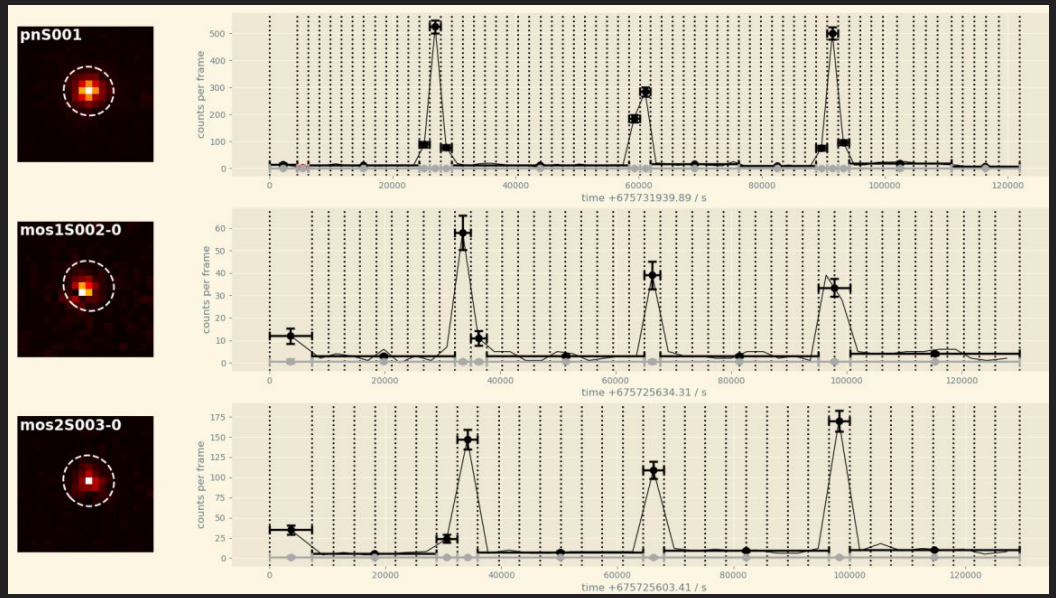
Oscillations



Applying STATiX to the XMM archive

Preliminary results (1000 observations)

Light-curves examples



Known QPEs

GSN 069 (***Miniutti+2013, 2023***)
XMM Obs.Id 0851180401

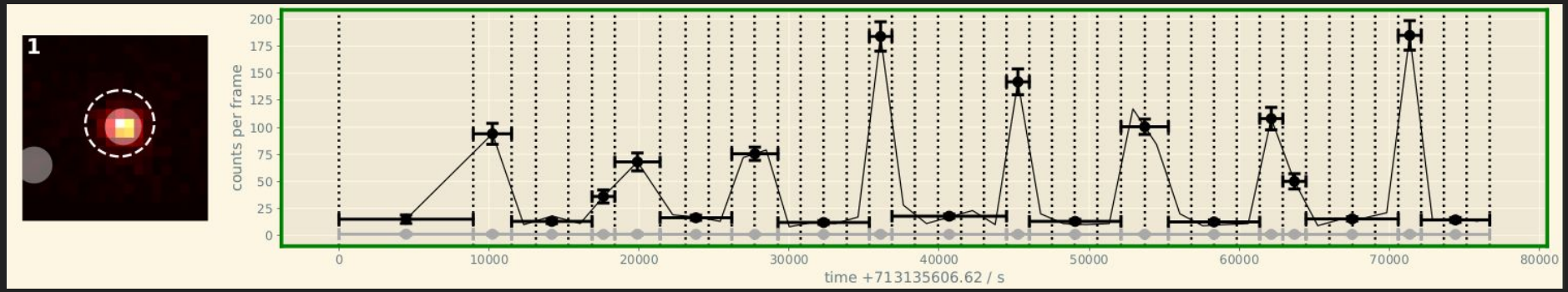
Applying STATiX to the XMM archive

Preliminary results (1000 observations)

Light-curves examples

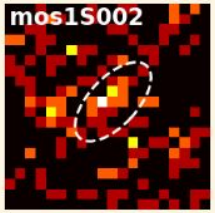
Known QPEs

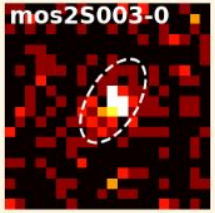
eRO-QPE2 (***Arcodia+2021***)
XMM Obs.Id 0872390101

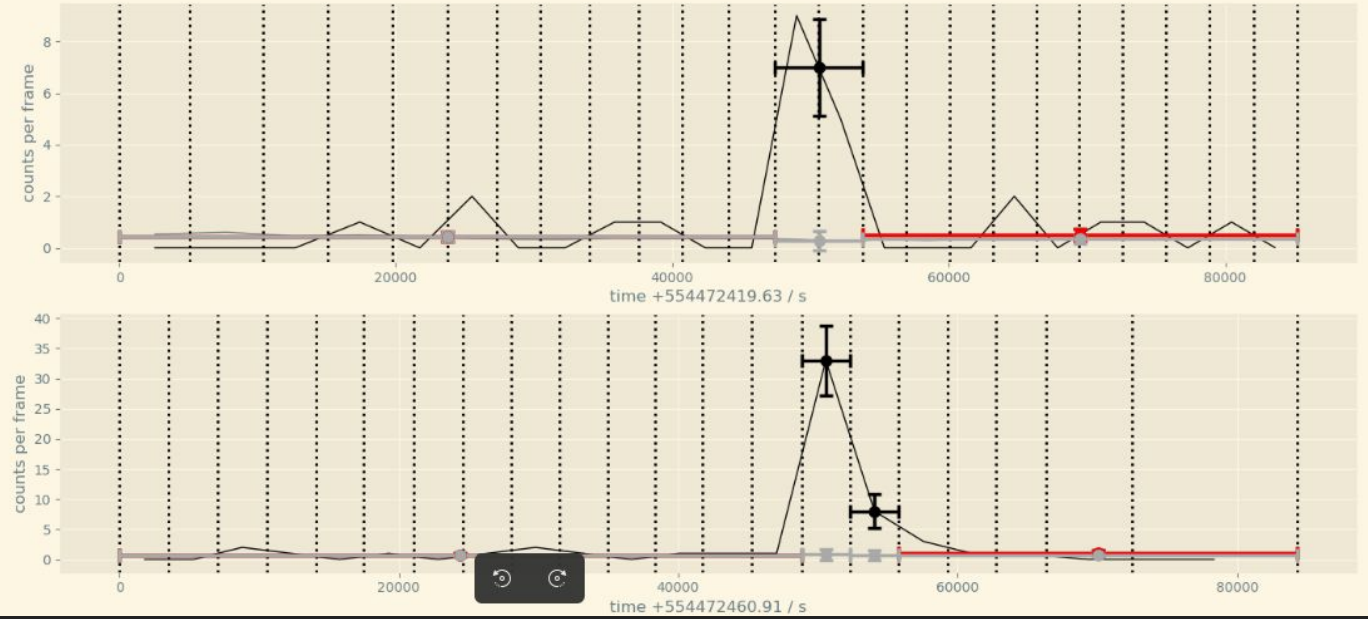


Applying STATiX to the XMM archive

Preliminary results (1000 observations)

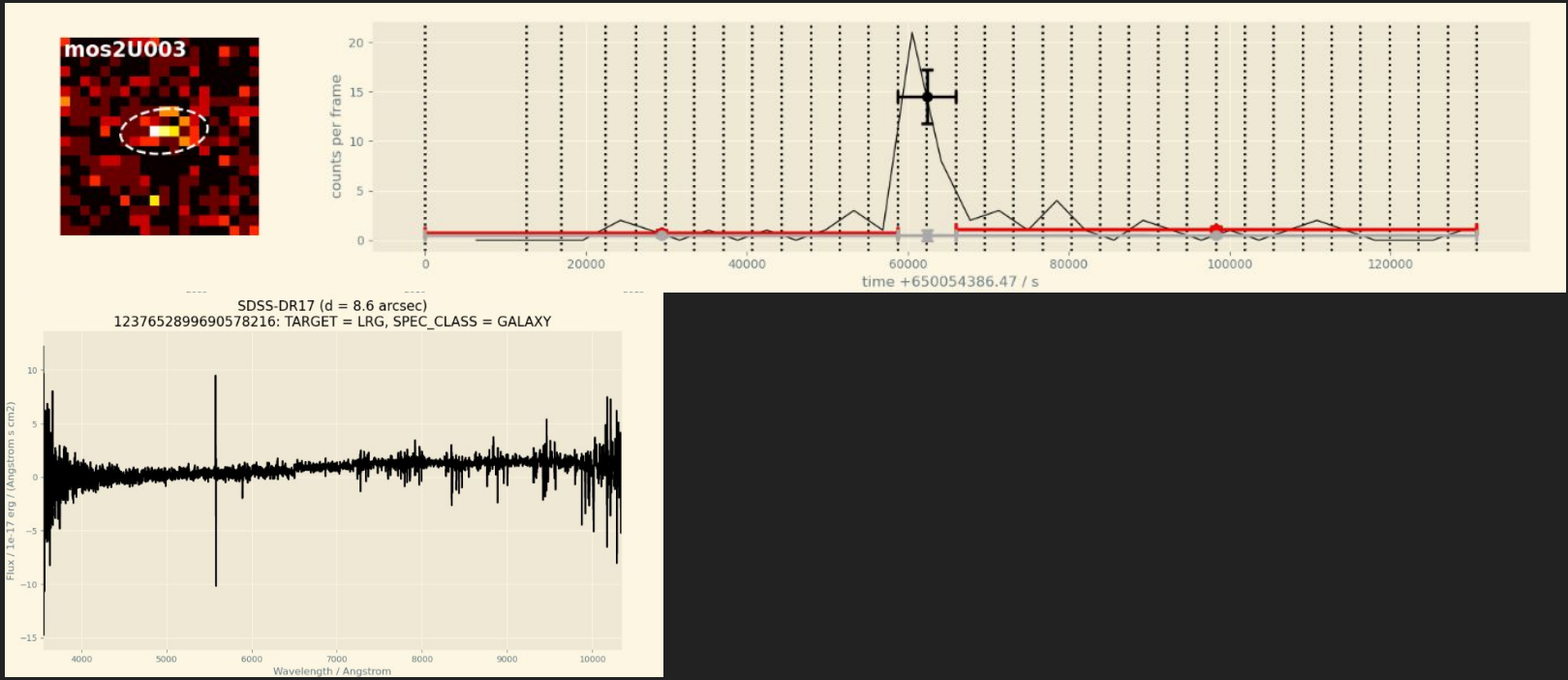






Applying STATiX to the XMM archive

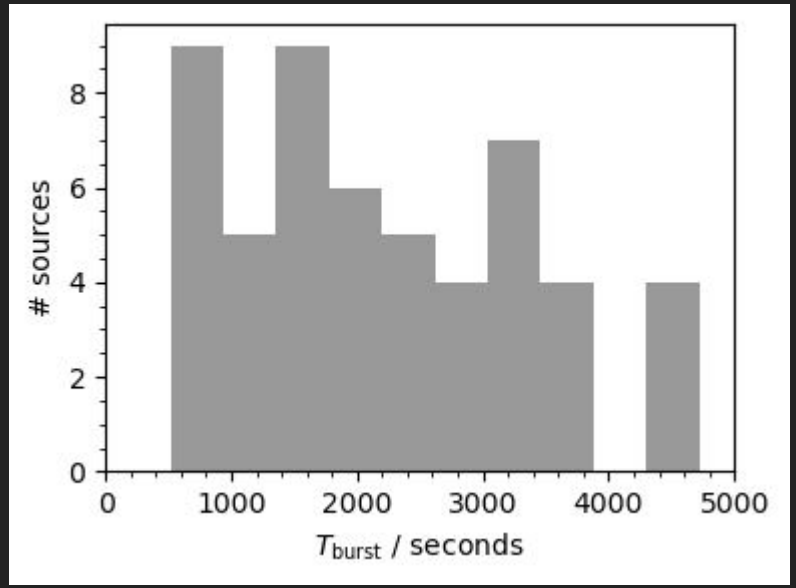
Preliminary results (1000 observations)



Applying STATiX to the XMM archive

Preliminary results (1000 observations)

Duration distribution of sort burst



Summary

- **STATiX** is a fully functional, open **3D algorithm for X-ray source detection**, with performance comparable to EMLDETECT for constant sources.

- While very **efficient for the detection of transient sources**, it also very useful for fast detection of sources with interesting time behaviour.

- We are currently processing the whole XMM-Newton archive, finding a rich and complex variety of light-curve patterns in X-ray sources: Sort transients, QPEs, flaring stars, etc.

- Future work:
  - Robust identification of interesting candidates
  - Development of tools for light-curve classification/identification.

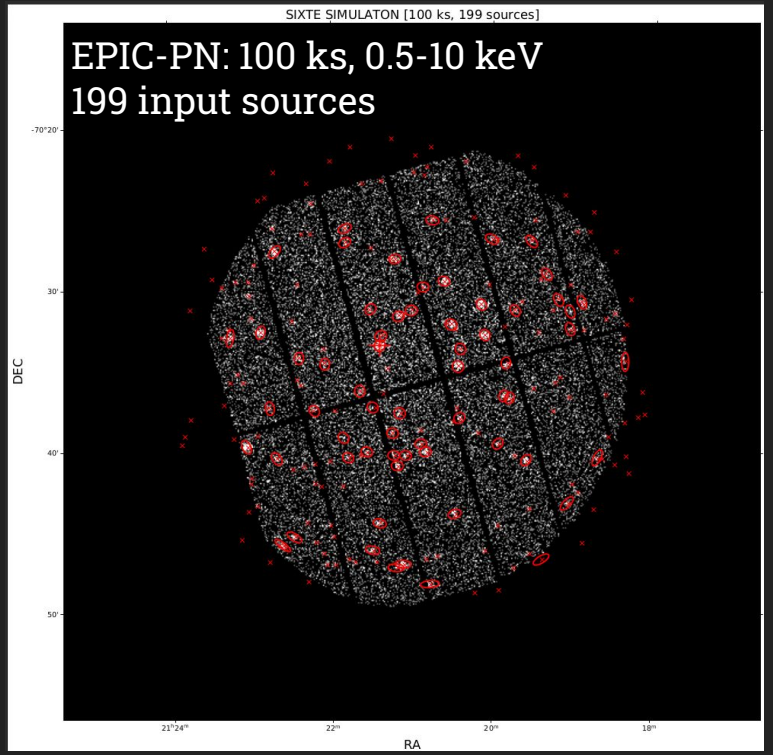
Backup slides

MSVST for X-ray source detection

- MultiScale Variance Stabilization Transform (Stark et al. 2009).
- 2D+1D **denoising** algorithm based on wavelets.
- Two key ideas:
  - **2D + 1D:**
    - Disentangle spacial and time/energy dimensions.
    - Apply IUWT to 2D image, and then 1D IUWT to all wavelet coefficients.
  - **Variance stabilization:**
    - Transform poisson noise to gaussian noise.
    - Allows to apply “simple” thresholding for denoising.

MSVST applied to XMM-Newton simulations

More realistic SIXTE simulations

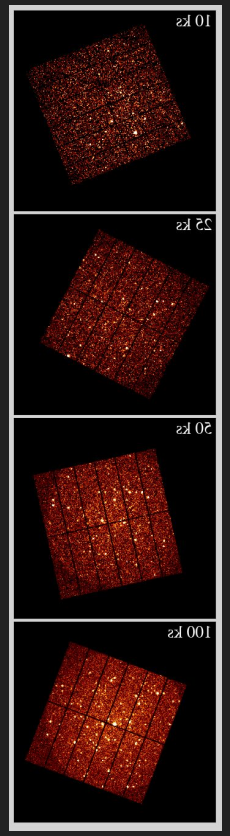


40 SIXTE simulations for XMM-Newton observations:

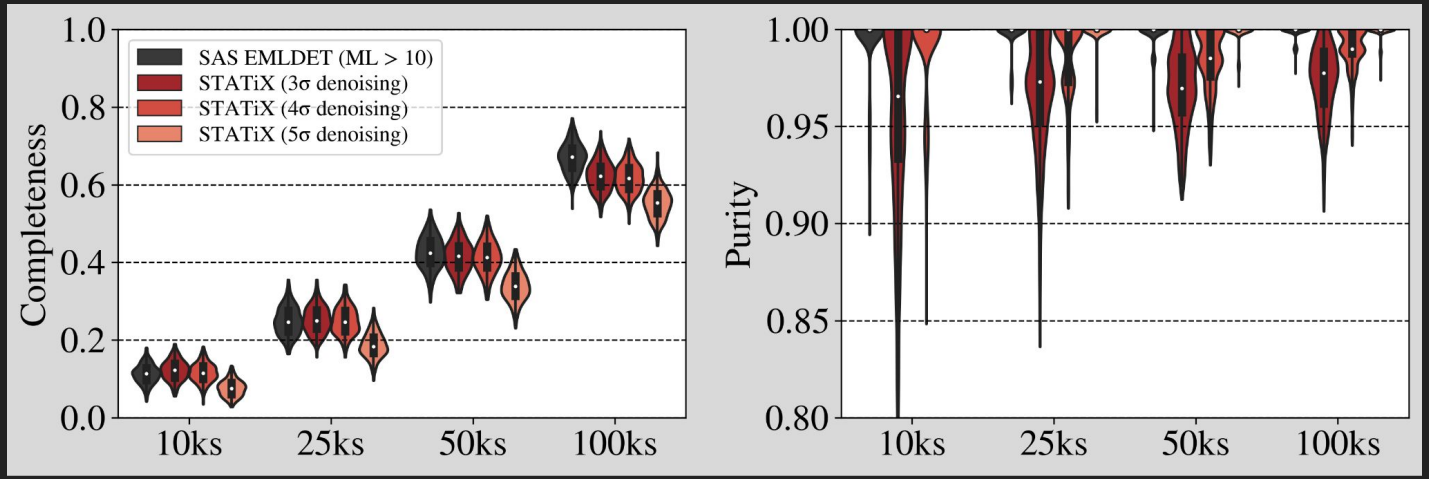
- Replicate geometry of EPIC-PN detector.
- Vignetting effects included.
- Random orientation of the detector.
- Exposure times: 10ks, 25ks, 50ks, 100ks.
- Sources randomly distributed in the FoV.
- Source flux distribution following an scaled logN-logS.
- Astrophysical background + particle background.

Data analyzed using SAS-EMLDetect
and our 2D+1D MSVST algorithm.

STATiX: Testing via simulations

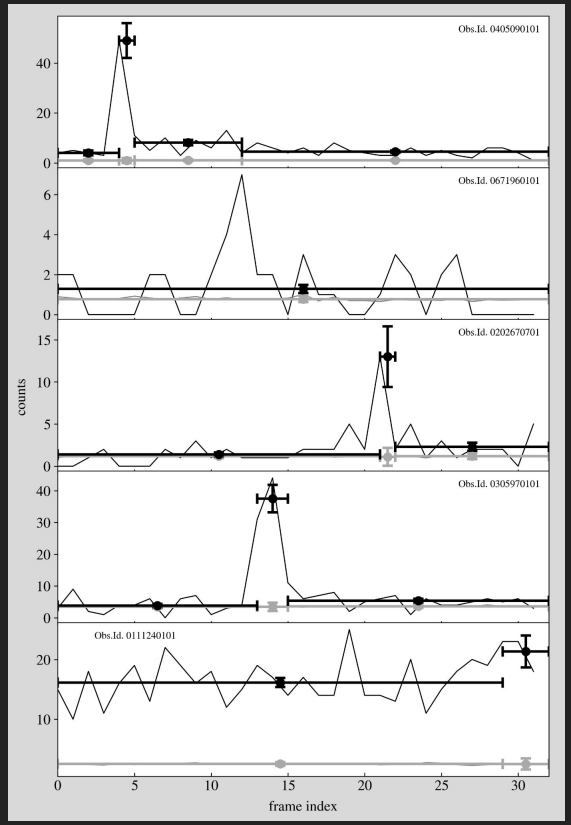


- 1000 realistic XMM-Newton simulations using SIXTE *(**Dauser et al. 2019**)*
- Constant-flux sources + 5 ks transient



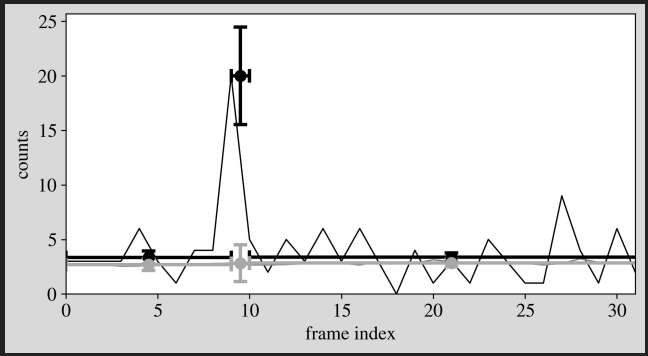
`https://github.com/ruizca/sixtexmm`

STATiX: Testing with EXTRaS transients



- Seven *XMM-Newton* observations containing eight **EXTRaS transient** candidates (***De Luca et al. 2021***) suitable for being analyzed with STATiX:
  - Clean exposures times > 50 ks
  - Transient source not overlapping any high particle background time interval.
- Detection of **5 out of 8 (~60%)** EXTRaS transients using a **4σ denoising threshold**.
- Up to **7 out of 8 (~90%)** using a **3σ threshold**.
- We also detected a new transient candidate in these observations not identified by EXTRaS.

STATiX: Testing with EXTRaS transients



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Applying STATiX to the XMM Archive

- Code upgrades:
  - Support for EPIC-MOS data.
  - **Number of frames** in data cubes calculated to **optimize** performance of MSVST (dependent on exposure time and background level).
  - Filtering of high-background time intervals using vargrowth algorithm.

- Selection of XMM-Newton exposures:
  - EPIC scientific exposures in imaging modes.
  - Exposure times greater than 20 ks.
  - Final selection (as of March 2024):
    ~23,500 exposures, corresponding to **~8200 XMM observations**