EXOD : EPIC XMM Outburst Detector

Continuing the search for fast transients in XMM-Newton Observations

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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101004168

Presentation Overview

- Introduction
  - Motivation for Transient Searches.
  - Previous Works
  - EXOD : Timeline
- EXOD Method:
  - Detection Algorithm
  - Crossmatching and Post-Processing
- Preliminary Results
- Future Plans

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XMM Archive : A goldmine of data

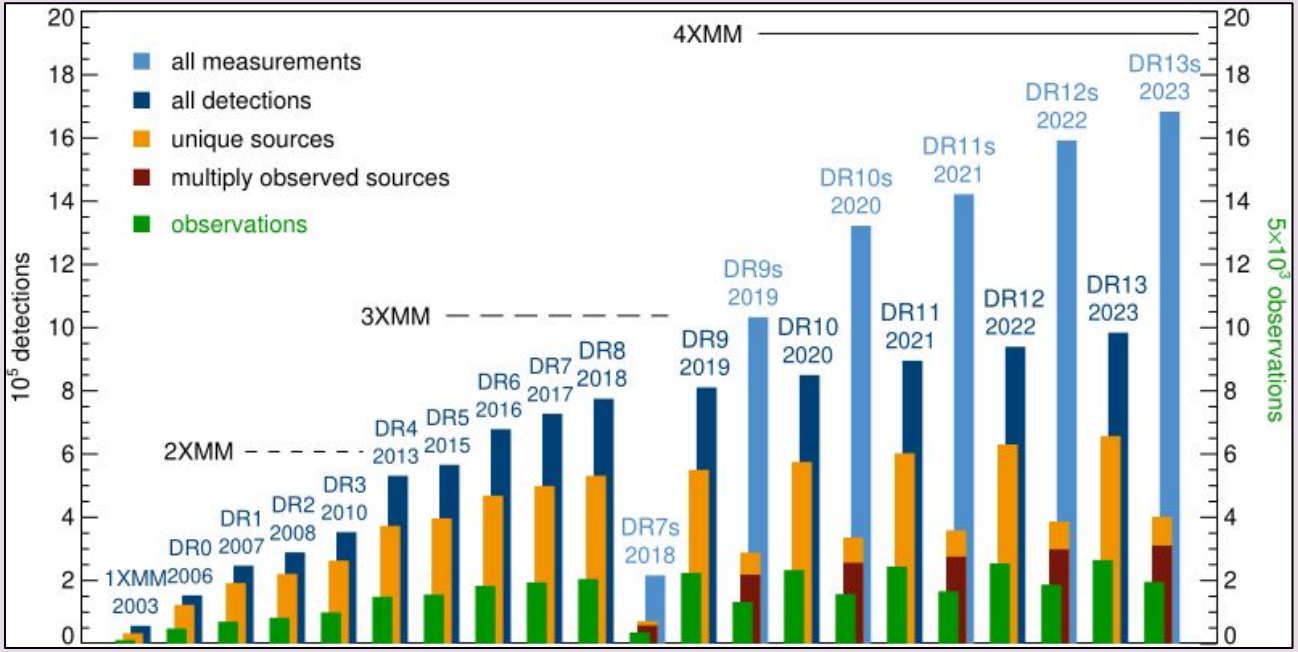
XMM2ATHENA

4XMM-DR13 :

- 23 years of archival data
- ~15000 observations
- 3.2% sky coverage
- 984k detections
- 8.8 years of PN exposure
- 30.4 years combined exposure
- 4207 Earth orbits
- 65 ± 45 detections per observation
- 27,368,678,750 photons (3.37 x 🌍)

The XMM pipeline only searches for variability in sources with >100 photons.

This corresponds to 1/3 of the detections.



Credit: Iris Traulsen

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What can we detect within an observation?

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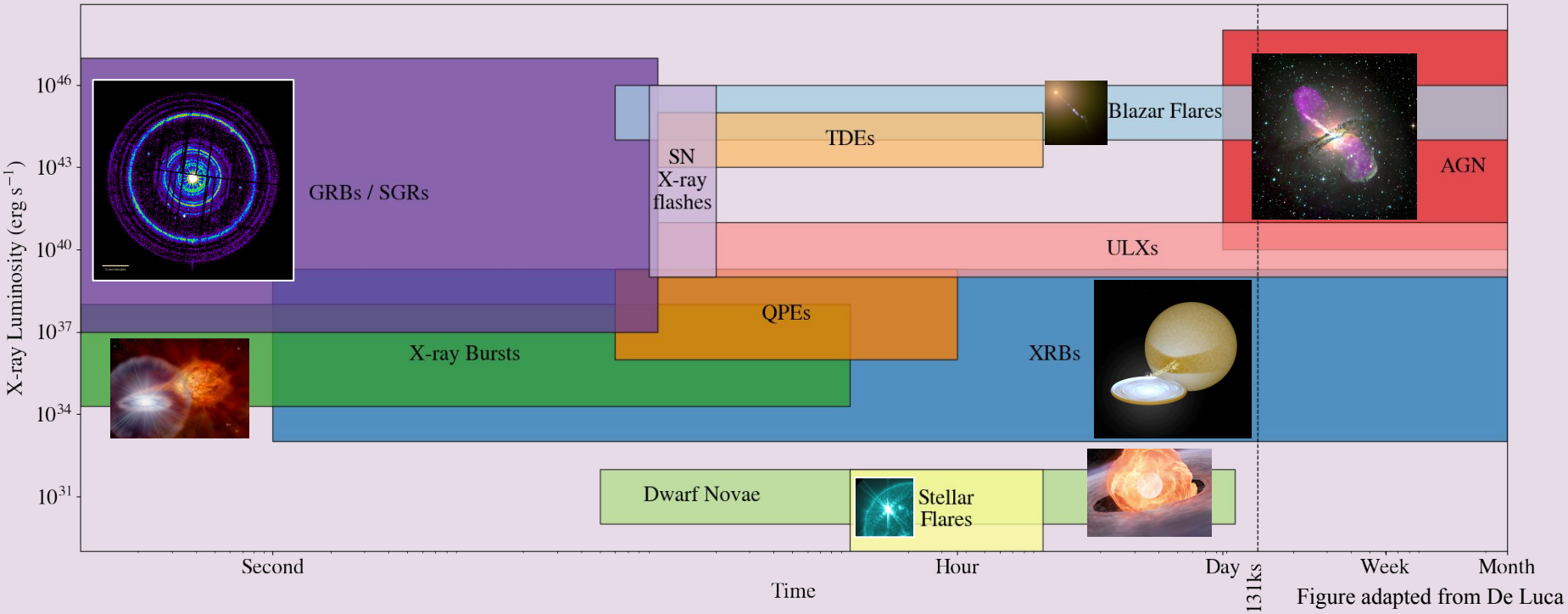

Figure adapted from De Luca

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Previous Publications | XMM Fast X-ray Transients

XMM2ATHENA

1. (Pastor-Marazuela et al. 2020): The **EXOD** search for faint transients in XMM-Newton observations: Method and discovery of four extragalactic Type I X-ray bursters

2. (Alp et al. 2020): Blasts from the Past: **Supernova Shock Breakouts** in the XMM-Newton Archive.
   Included BTIs | 0.3 - 2.0 keV | 5 different timescales 100 - 10,000s log binning

3. (De Luca et al. 2021): **EXtraS**
   Bayesian blocks + Fixed Bins | 3 E bands | Pulsation Searches | Included BTIs
   136 new transients. 900s - 5000s duration

4. (Ruiz et al. 2023): The **STATiX** pipeline for the detection of X-ray transients in three dimensions
   Bayesian Blocks | Inpainting + Denoising using wavelets

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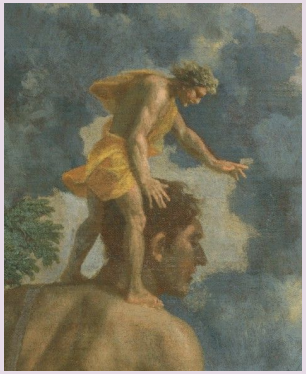
EXOD : Timeline



Variabilitectron - Damien Wojtowicz

Initial Algorithm proof of concept

2017

2018

Variabilitectron v2 - Inés Pastor Marazuela

GTI inclusion, Lightcurve extraction & statistical tests for variability

2019

EXOD - Inés Pastor Marazuela & Florent Castellani

First run on XMM Archive upto 3XMM-DR8 (31 December 2017)

2022

EXODUS - Maitrayee Gupta

Extension for MOS1 & MOS2 & Cross-matching | Source Classification

2023

EXOD 2 - Norman Khan & Erwan Quintin

Full re-write | Modifications to detection algorithm | Performance increases.

GitHub

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EXOD : Event List Binning

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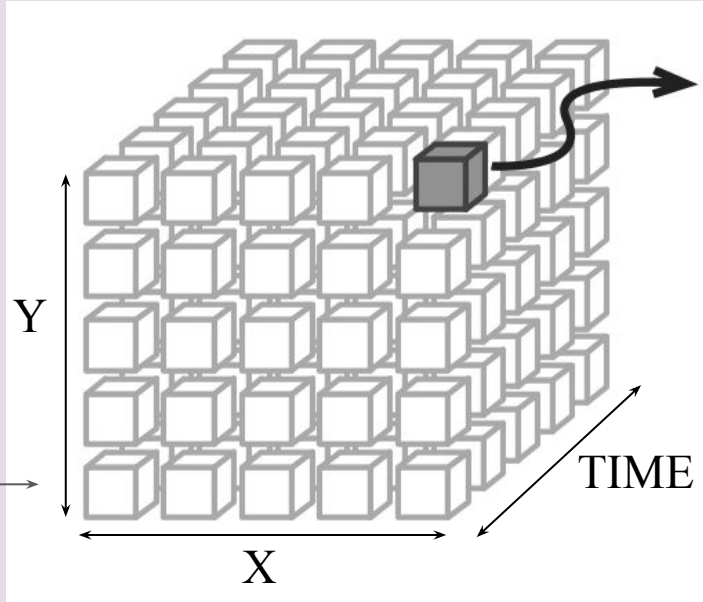
XMM Filtered Event List 0.5-12.0keV:

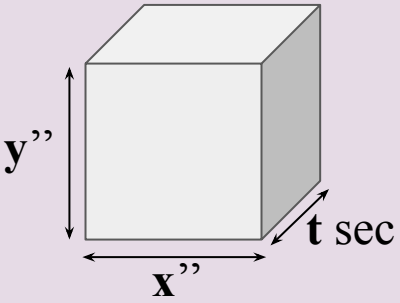
TIME	RAWX	RAWY	DETX	DETY	X	Y	PHA	PI
float64	int16	int16	int16	int16	int32	int32	int16	int16
100529508.04522818	332	107	704	-4263	28955	23995	414	1362
100529506.0787003	350	280	1099	-442	25167	23357	1577	5194
100529505.65984958	317	296	355	-98	24777	24077	331	1096
100529507.25548887	320	302	434	31	24653	23990	445	1491
100529507.88079482	345	318	987	380	24340	23416	245	808

bin counts in (X,Y, TIME)

Event Counts Data Cube :



Data Cell:



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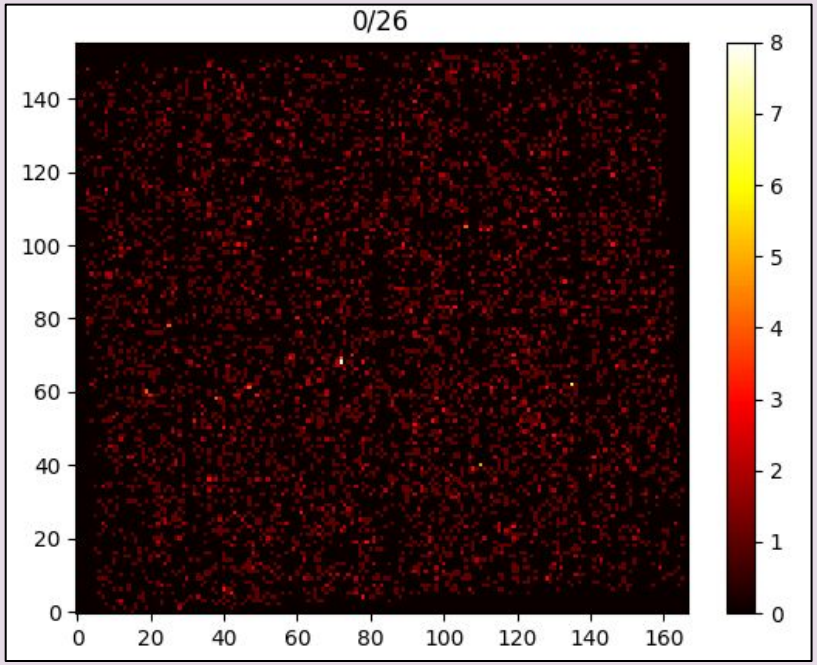
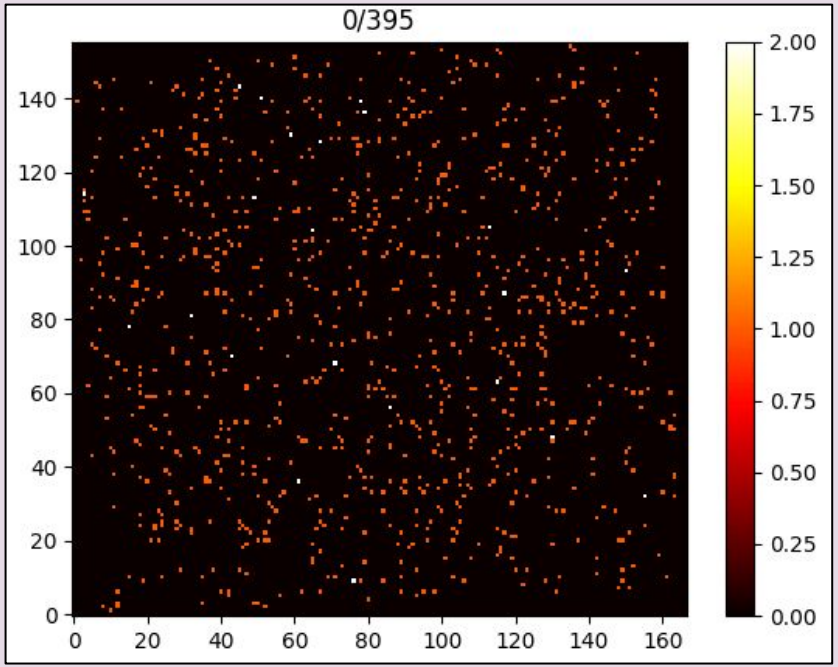
EXOD : Data Cubes



Binning: 10’’, 750s | Data Cells: 677k (5mb)



Binning: 10’’, 50s | Data Cells: 10.2m (78mb)

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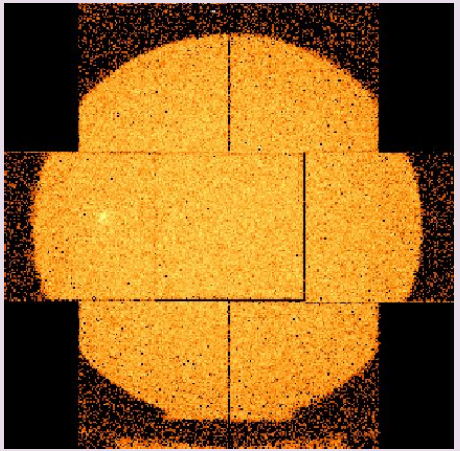
EXOD : Bad Time Intervals (BTIs)

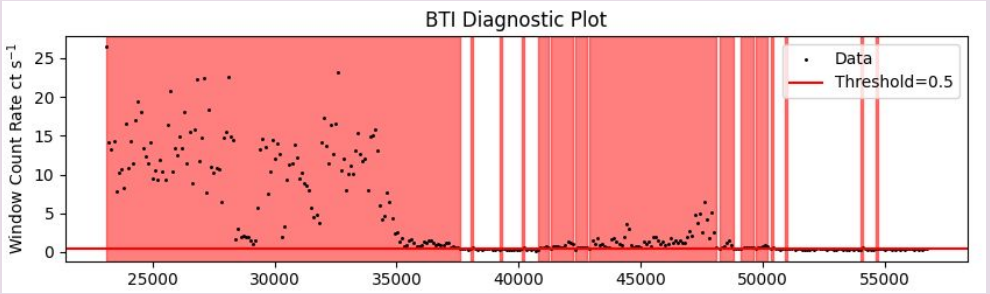
SOHO (2003) λ=195 Å

Periods of flaring background caused by **protons** with E < ~100 keV.

Our current approach is to remove all windows with count rates > 0.5 ct/s at high energies (10-12 keV)

We are working on a way to use these BTIs.





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EXOD : Image Segmentation

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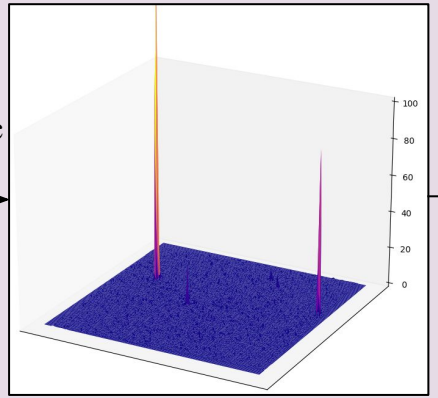
Calculate Variability Metric through time slices



Variability Image

Thresholding

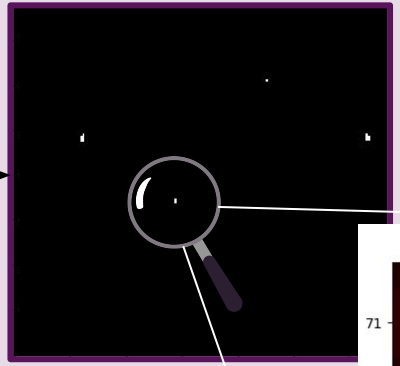
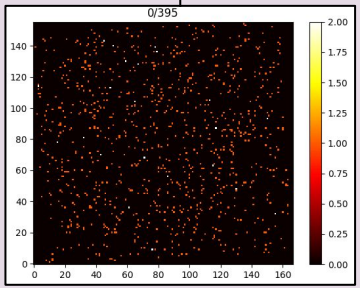


Image Mask (Binary Image)

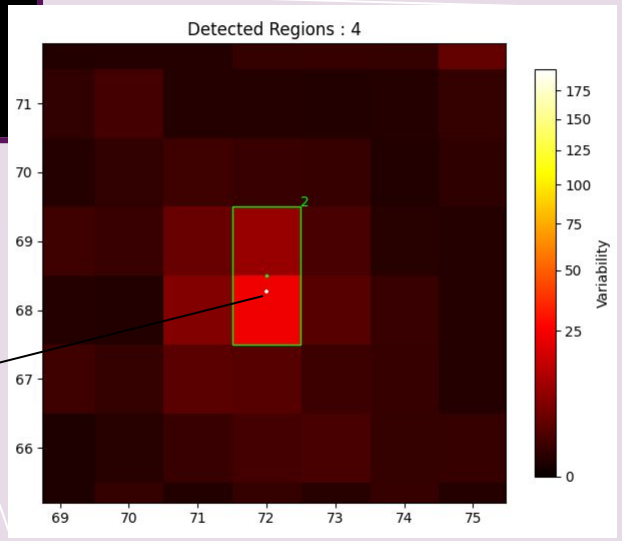
scikit-image



Data Cube

Position : Ra, Dec
Lightcurve: Counts

WCS Conversion



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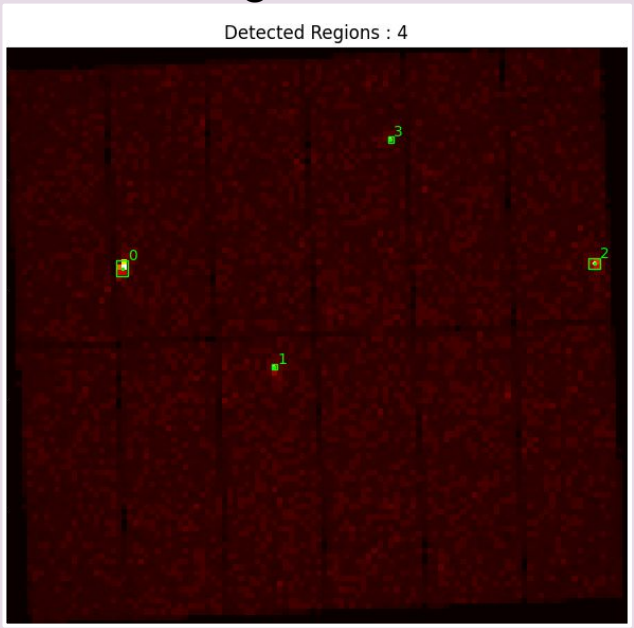
EXOD : Crossmatching and Post-Processing

XMM2ATHENA

Detected Regions



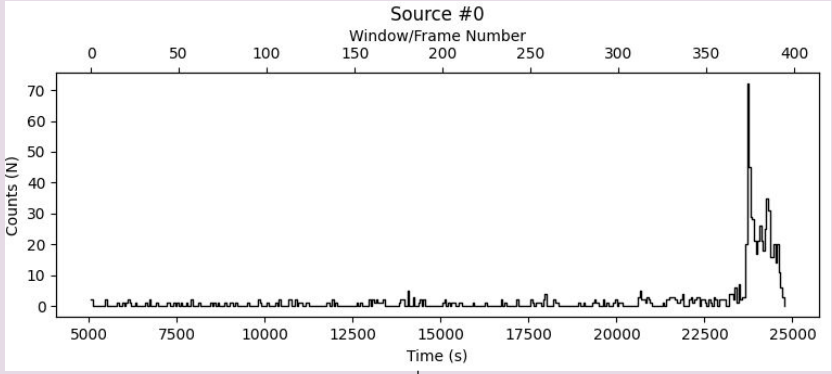
Crossmatching

4XMM-DR13

SIMBAD

esa gaia

Lightcurves



Post-processing

Variability Tests:

- KS
- Gregory-Loredo
- False Alarm Probability

Filtering:

- Feature Extraction
- ML Classification

See: Webbe et al. 2023, (RASTAI 2, 238–255)

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EXOD : Current Status

XMM2ATHENA

- Key Changes from previous version:
  - Bug Fixes: Centroiding, GTI/BTI handling, omitted event lists.
  - Vectorized Calculations → Significant performance improvements.
  - Use of pre-existing libraries: scipy, scikit-image.
  - Use of sky coordinates over detector coordinates (DETX → X)
  - Revised variability formula.
  - Improved Source Extraction Method.
  - Machine learning method for light curve classification.

Status:

✅ : Data Transformations, Variability Calculation, Source Detection, Lightcurve Extraction.

⌛ : Source Cross-matching, Lightcurve classification, Detection and Performance statistics.

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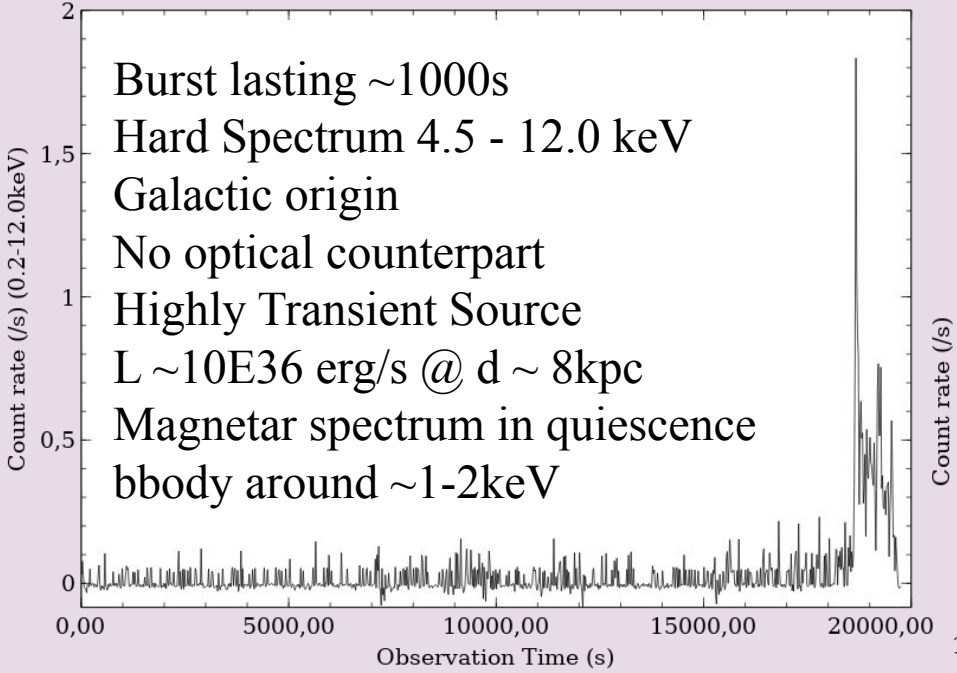
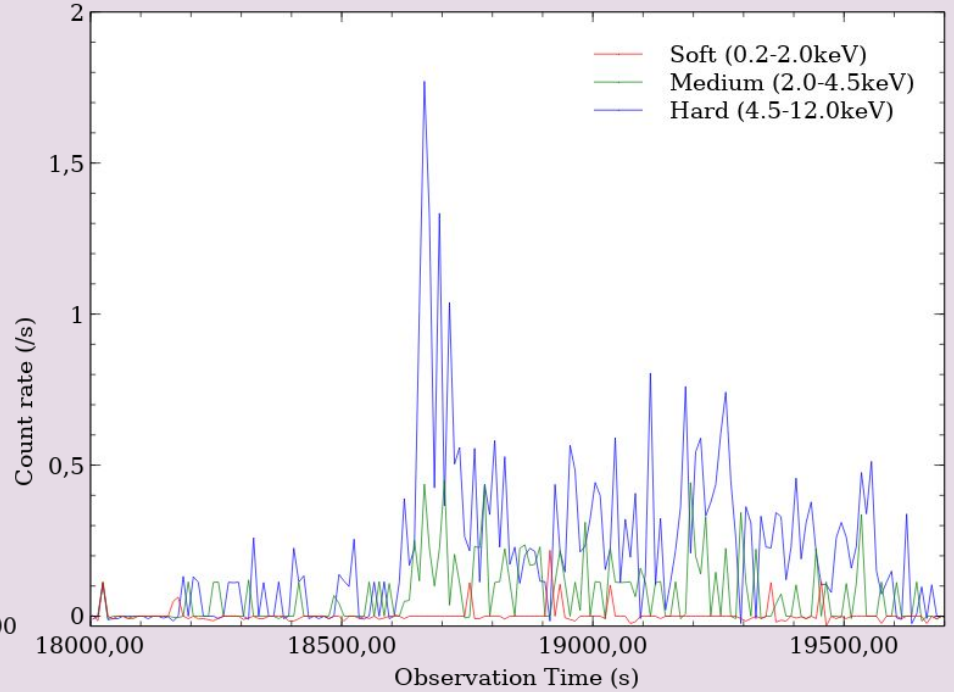
EXOD : Provisional Results





Webbe, Khan et al. (in prep)

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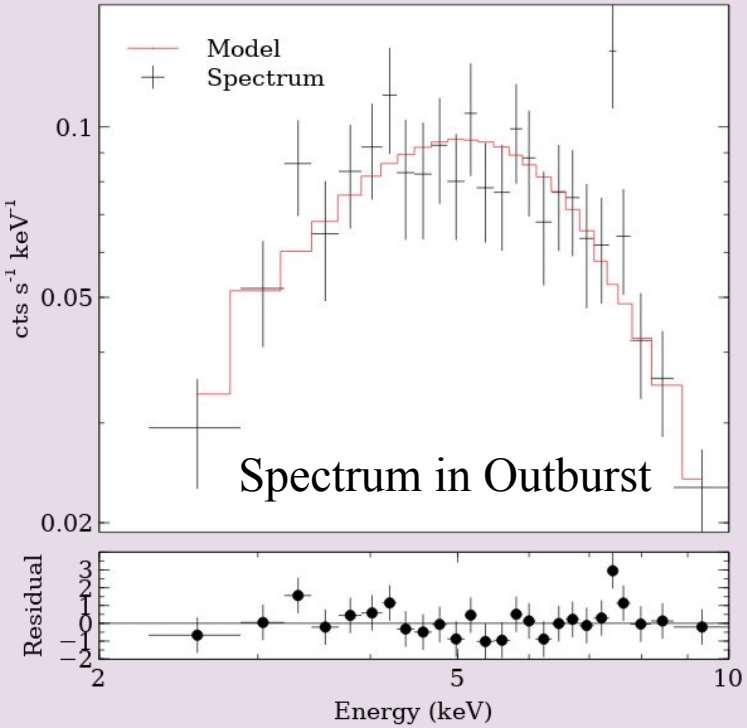

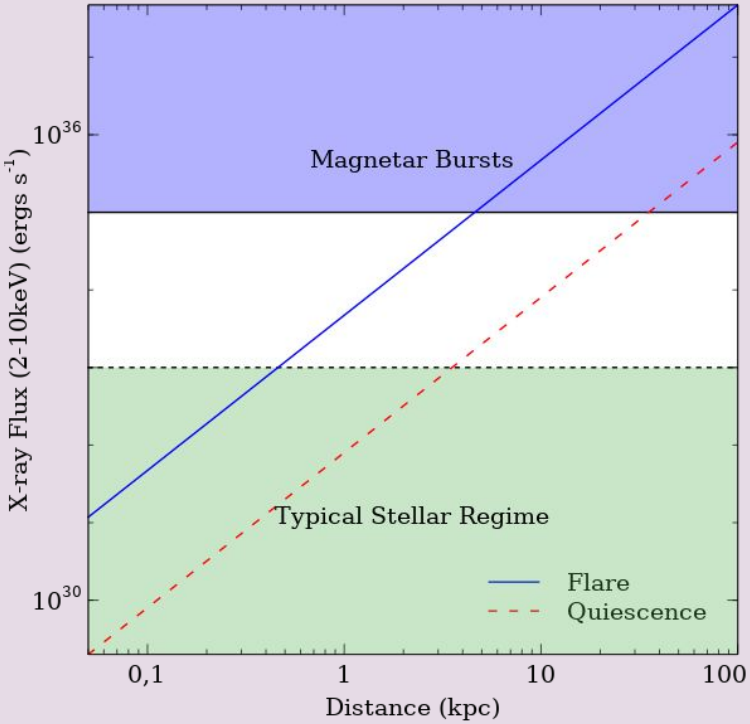

Webbe, Khan et al. (in prep)

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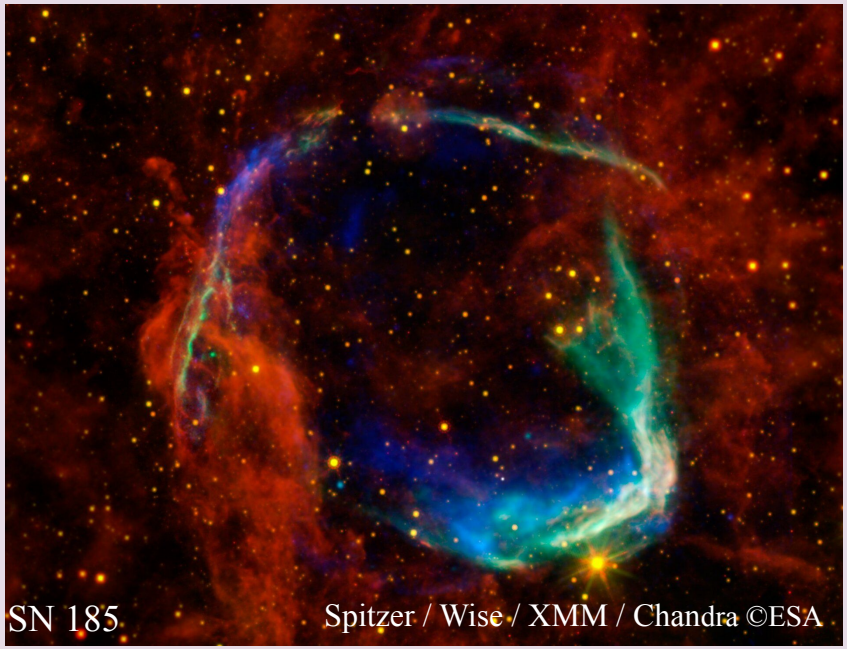
Future Work

1. Calibration Simulations to test detectability limits
2. Merge MOS1 + MOS2 + PN to increase S/N
3. Extract spectral Information
4. Use of the flaring Bad Time Intervals (BTIs)
5. Looking at experimental approach to use
6. Help constrain the rates of specific events.
7. Applicability to Athena data
8. Paper coming soon (Khan et al. in prep)

Thanks for Listening!



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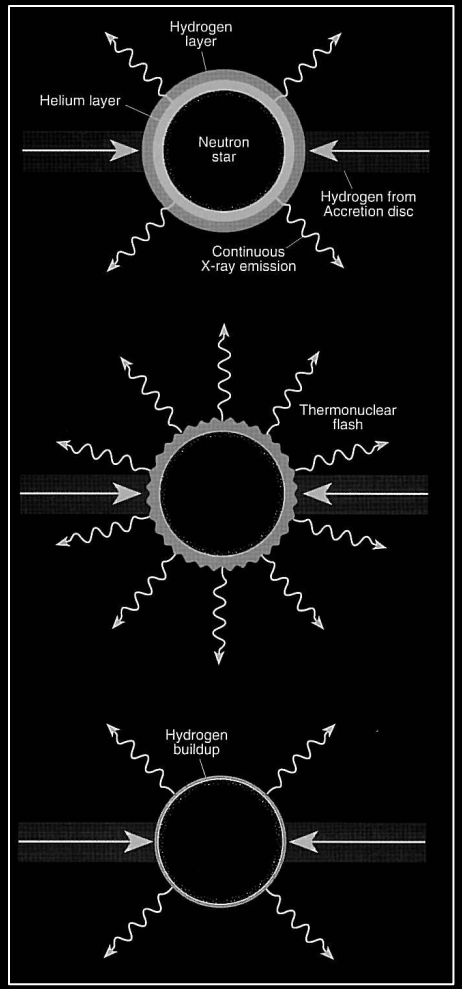
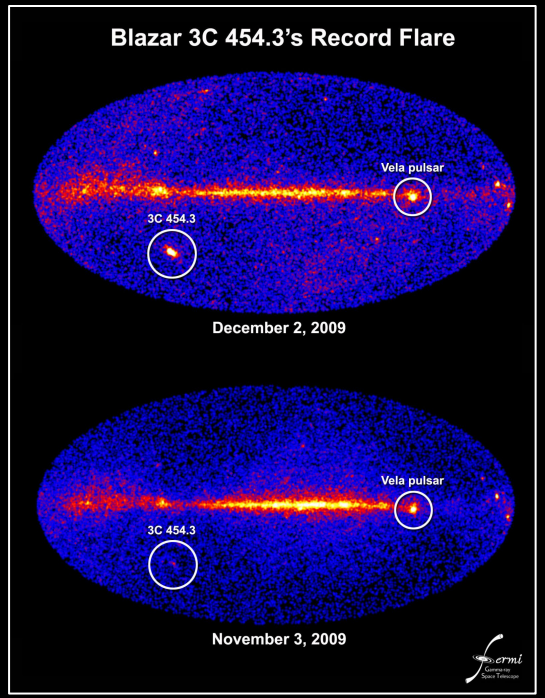
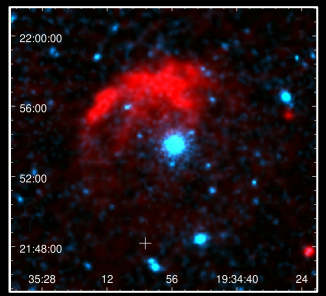


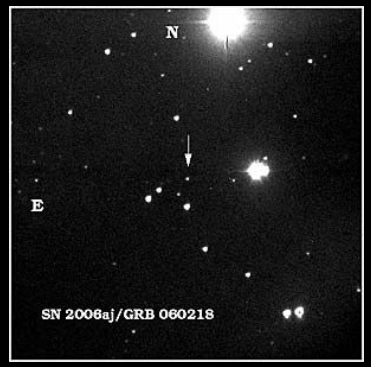
Type I and II X-ray bursts



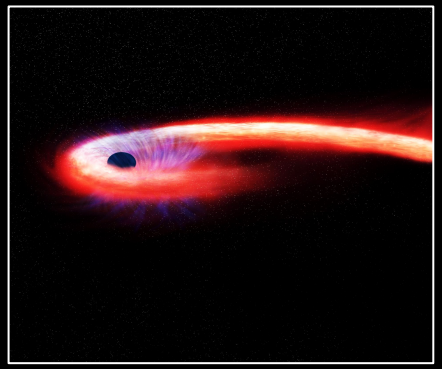
Blazar Flares



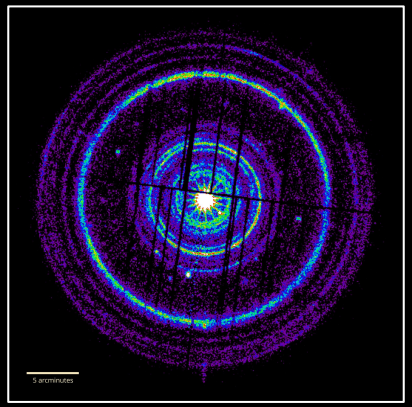
FRBs / SGRs
Magnetar SGR 1935+2154



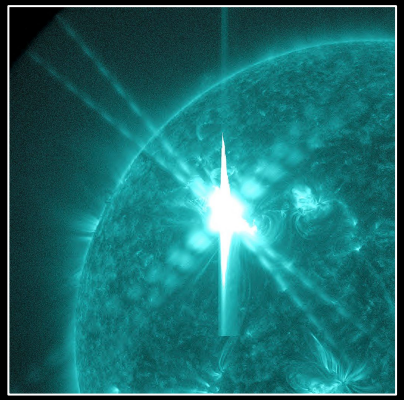
Supernovae X-ray flashes



WD TDEs & QPEs

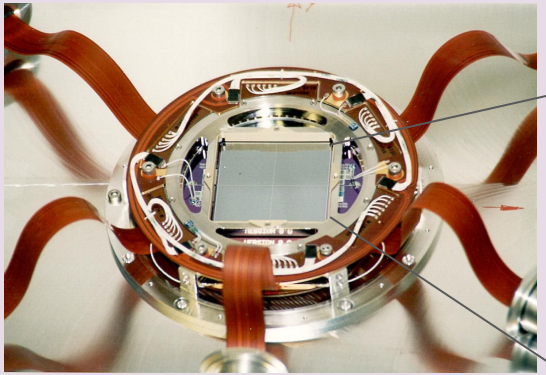


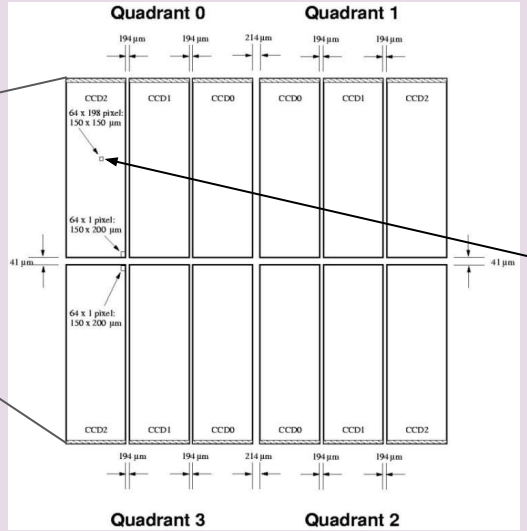
GRBs
GRB 221009A

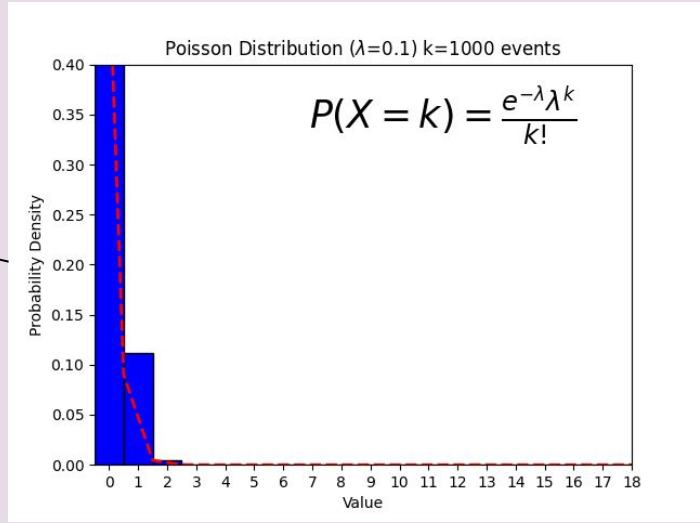


Stellar Flares

EXOD : Source Detection







XMM EPIC-PN

Each CCD : 200 x 64 pixels

Each Pixel : 150 x 150 microns (4.1”)

Time Resolution : 73.4 ms (Full frame)

Source Detection Methods:

- Sliding Cell Detection (SAS: `EMLDETECT`)
- Voronoi Tessellation and Percolation (VTP) (caio: `VTPDETECT`)
- Wavelet Detection (caio: `WAVDETECT`)
- Minimum spanning trees (MSTs)
- Nearest neighbour density (NN)
- And many more…

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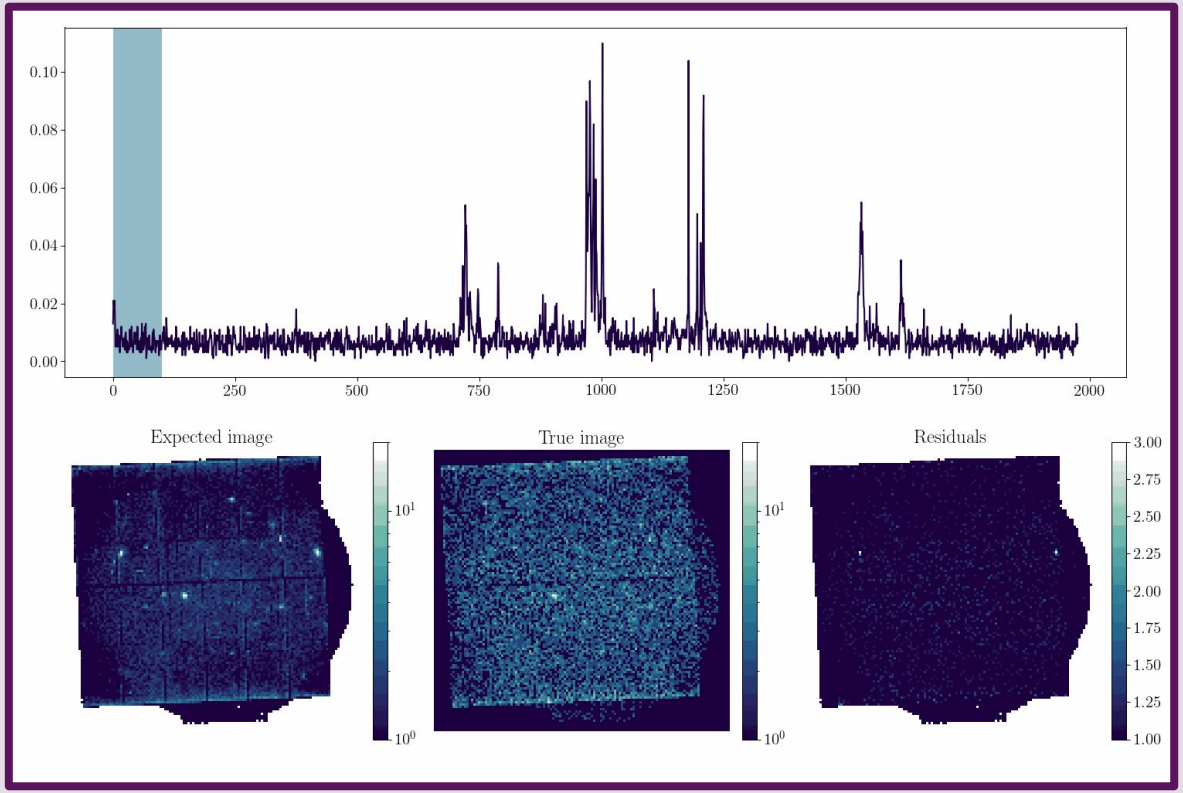
Baseline quantification — Spatial information



Comparison between expected & observed

Residuals $<2\sigma$

Any departure: Peak or eclipse

Direct quantification in sigmas

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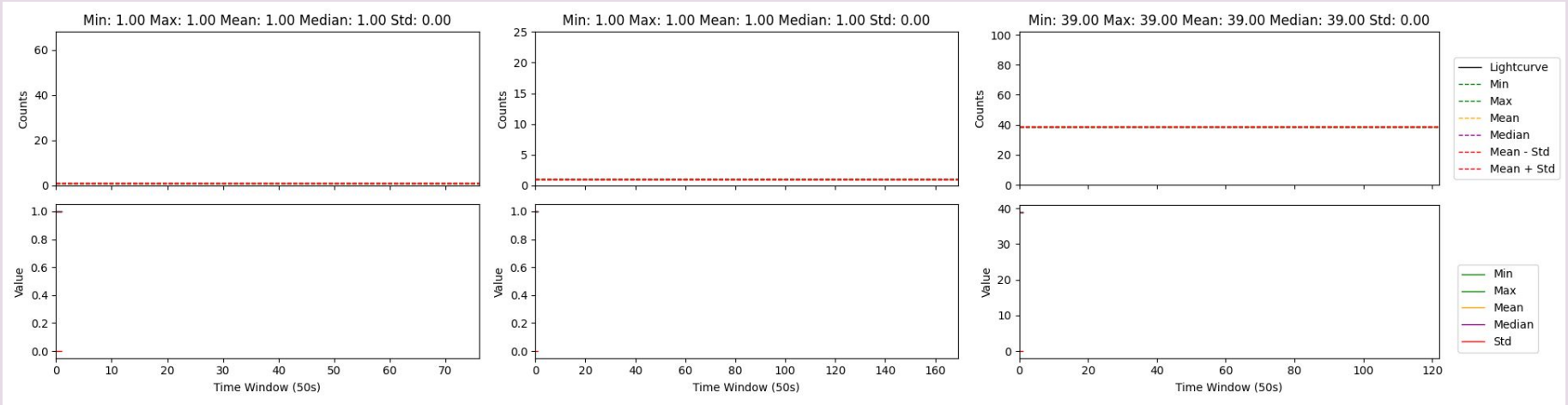
EXOD : Source Detection

Old Variability Calculation:

$$\mathcal{V} = \begin{cases} max(C_{\max} - \tilde{C}, |C_{\min} - \tilde{C}|)/\tilde{C} & \text{if} \tilde{C} \neq 0 \\ C_{\max} & \text{if} \tilde{C} = 0 \end{cases}$$



Long Burst | Short Burst | Burst in a bright source

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What might we Detect?

XMM2ATHENA

Transient	Typical Duration	Origin
Transient X-ray Binaries	~seconds to days	BH, NS, WD
X-ray Bursts (Type I & II)	Rise: 1s-10s | Decay: 10s-100s	NS, Magnetars
Quasi-Periodic Eruptions (QPEs)	~minutes	BH
Gamma Ray Bursts (GRBs)	~ms to hours	?
Tidal Disruption Events from WDs (WD TDEs)	~minutes	WDs
Soft-Gamma Repeaters (SGRs)	~100ms to ~100s	Magnetars
Blazar flares	~minutes to years	SMBHs
Supernova X-ray flashes	90s to 200s	Hypernovae $M > 30M_{\odot}$
Stellar Flares & Superflares	1000s to 10000s	Late-Type Stars (spectral-type F–M)
FRB Precursors	?	Magnetars?
Unknown processes	?	?

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