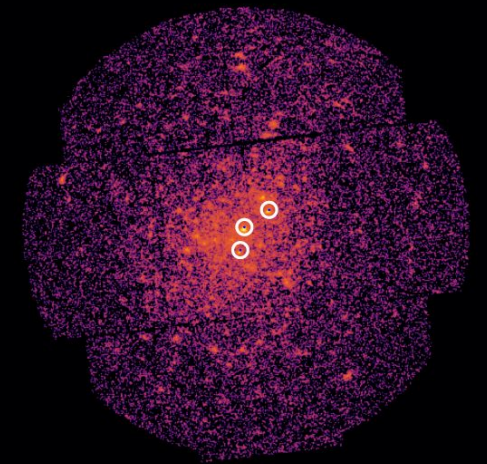


Studying X-ray variability and identifying low mass AGN with the EPIC XMM Outburst Detector Ultimate System (EXODUS)



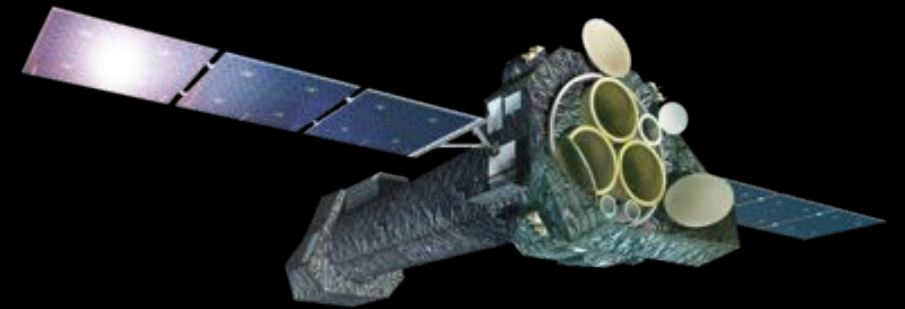
Maitrayee Gupta

Collaborators : Natalie Webb,
Swayamtrupta Panda, Vincent Foustoul,
Iris Traulsen, Axel Schwobe,
Erwan Quintin, Matheen Musaddiq



The EPIC XMM Outburst Detector Ultimate System (EXODUS)

- XMM-Newton's pipeline extracts time series
- Provides variability for detections with EPIC counts > 100
- Faint & short variable source
 - Time series not generated,
 - Timescales shorter than bin size,
 - Drowned out by the background noise



The EPIC XMM Outburst Detector Ultimate System (EXODUS)

- Computes variability of whole FOV without a priori source detection, timescales ~ 3 s to detect rapid faint transients missed by pipeline.
- Prior to EXODUS, variability analysis not run on 2/3 of catalogue.
- Light curve generation: computationally expensive.
- Might fail to detect all sources in FOV.
- EXODUS is built upon EXOD (*Pastor-Marazuela et al. 2020*). Code available for use on [GitHub](#), paper submitted *Gupta et al.*

EXODUS algorithm pipeline

List of OBSIDs

```
0005210101 0008220201 0014150401 0022340201 0033540901 0082540401 008  
1 0123100201 0123940201 0142680701 0143150101 0143653901 0149880101  
0101 0301651101 0305600501 0305640201 0306680101 0311791601 040208080  
4620301 0510011301 0556212801 0556215201 0603500701 0610980101 065353  
0725300134 0728960632 0742830150 0743090201 0743420601 0744220301 074
```

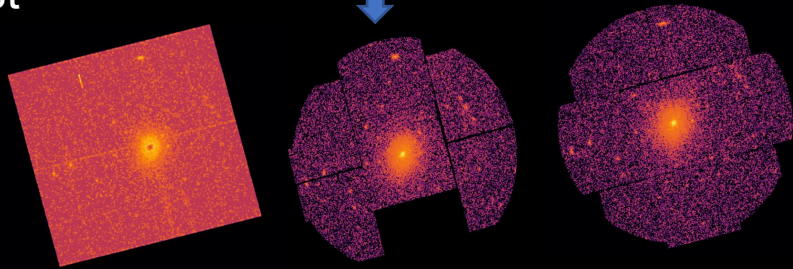


EXODUS algorithm pipeline

List of OBSIDs

```
0005210101 0008220201 0014150401 0022340201 0033540901 0082540401 008  
1 0123100201 0123940201 0142680701 0143150101 0143653901 0149880101  
0101 0301651101 0305600501 0305640201 0306680101 0311791601 040208080  
4620301 0510011301 0556212801 0556215201 0603500701 0610980101 065353  
0725300134 0728960632 0742830150 0743090201 0743420601 0744220301 074
```

Filter event list

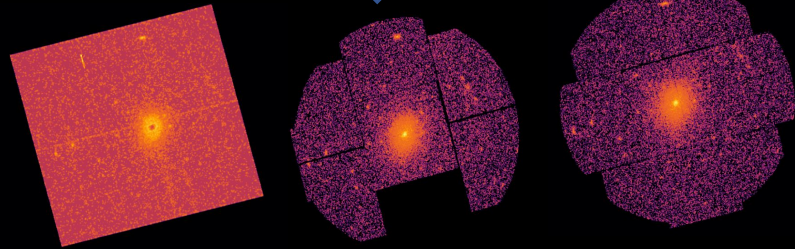


EXODUS algorithm pipeline

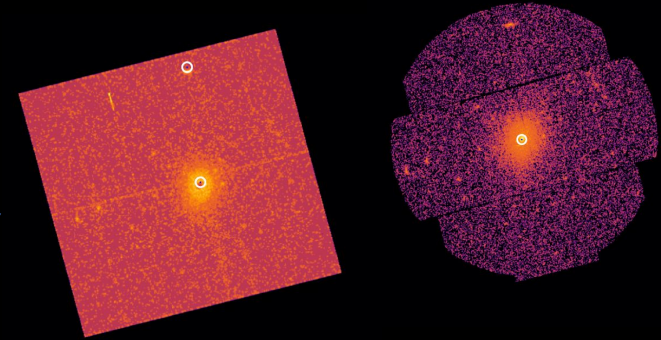
List of OBSIDs

```
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4620301 0510011301 0556212801 0556215201 0603500701 0610980101 065353  
0725300134 0728960632 0742830150 0743090201 0743420601 0744220301 074
```

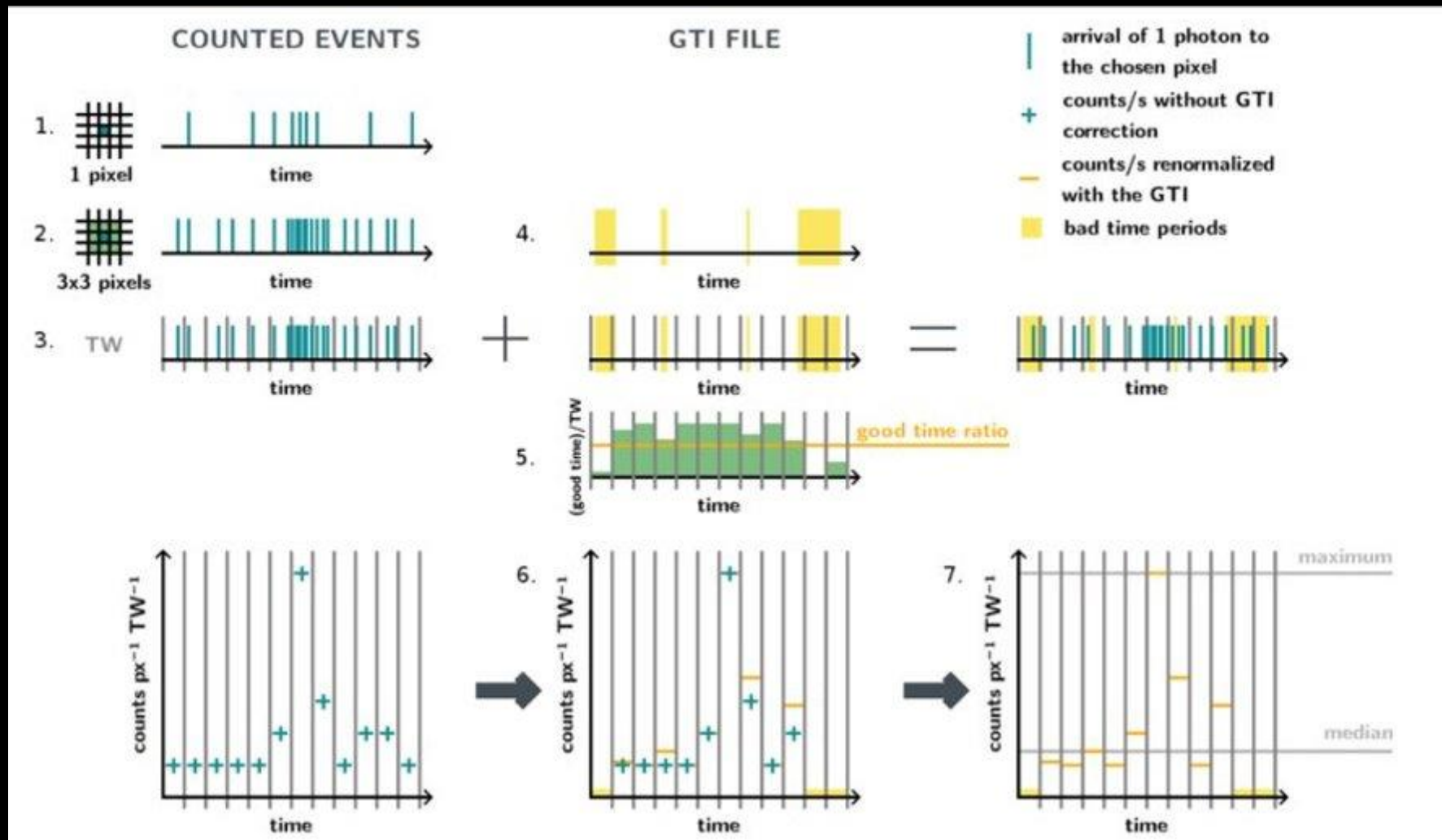
Filter event list



Variable source detection



Variability Computation



Source detection

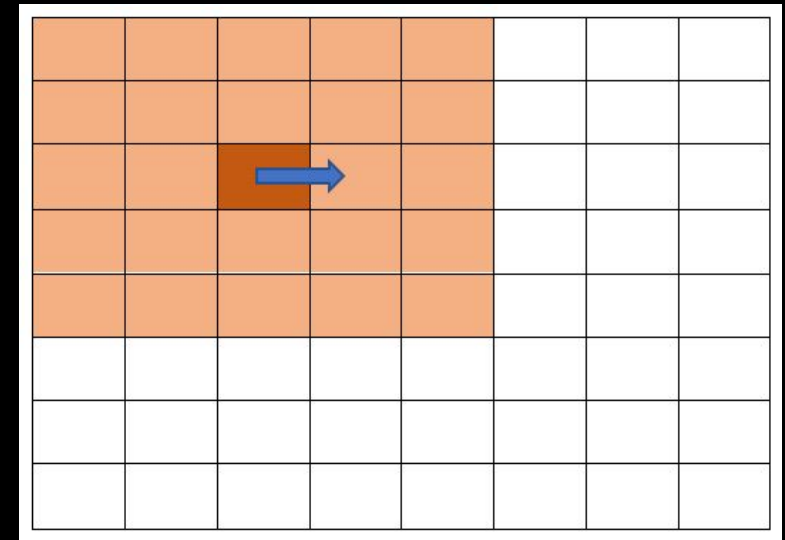
- Ability to choose time bins → Long observations → short bins
- Time binned pixel by pixel count estimation.

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

- $C_{\max} - \tilde{C}$ targets outbursts
- $|C_{\min} - \tilde{C}|$ sources with a period of lower flux.

- Sliding box technique to determine variable areas.

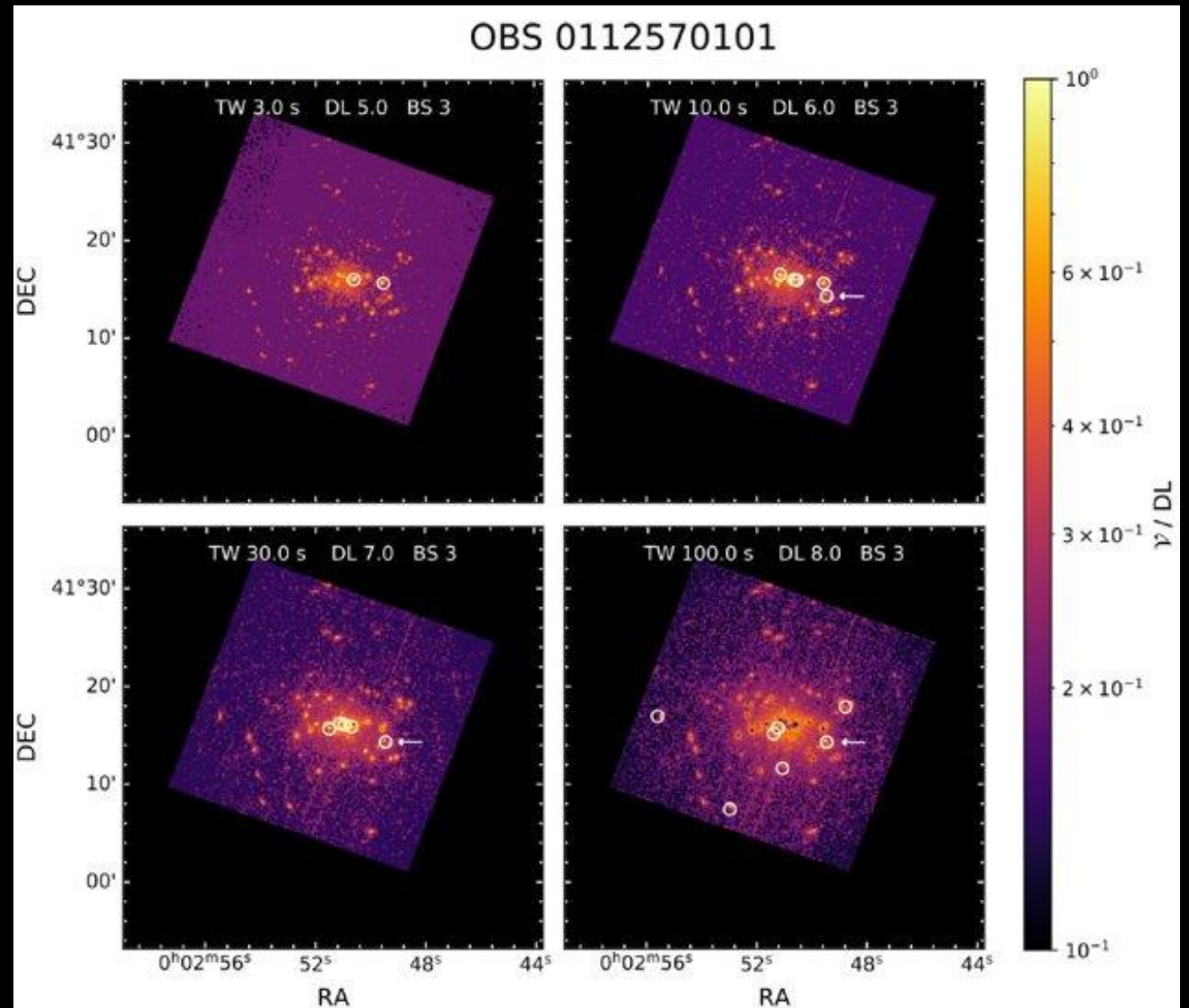
- Variable if above cut off $\mathcal{V}_{\text{box}} > DL \times |b|^2 \times \tilde{\mathcal{V}}$



Source detection

Optimal parameters for Detection Limit and Time Window

- Maximizing variable sources.
- Minimizing spurious detections.

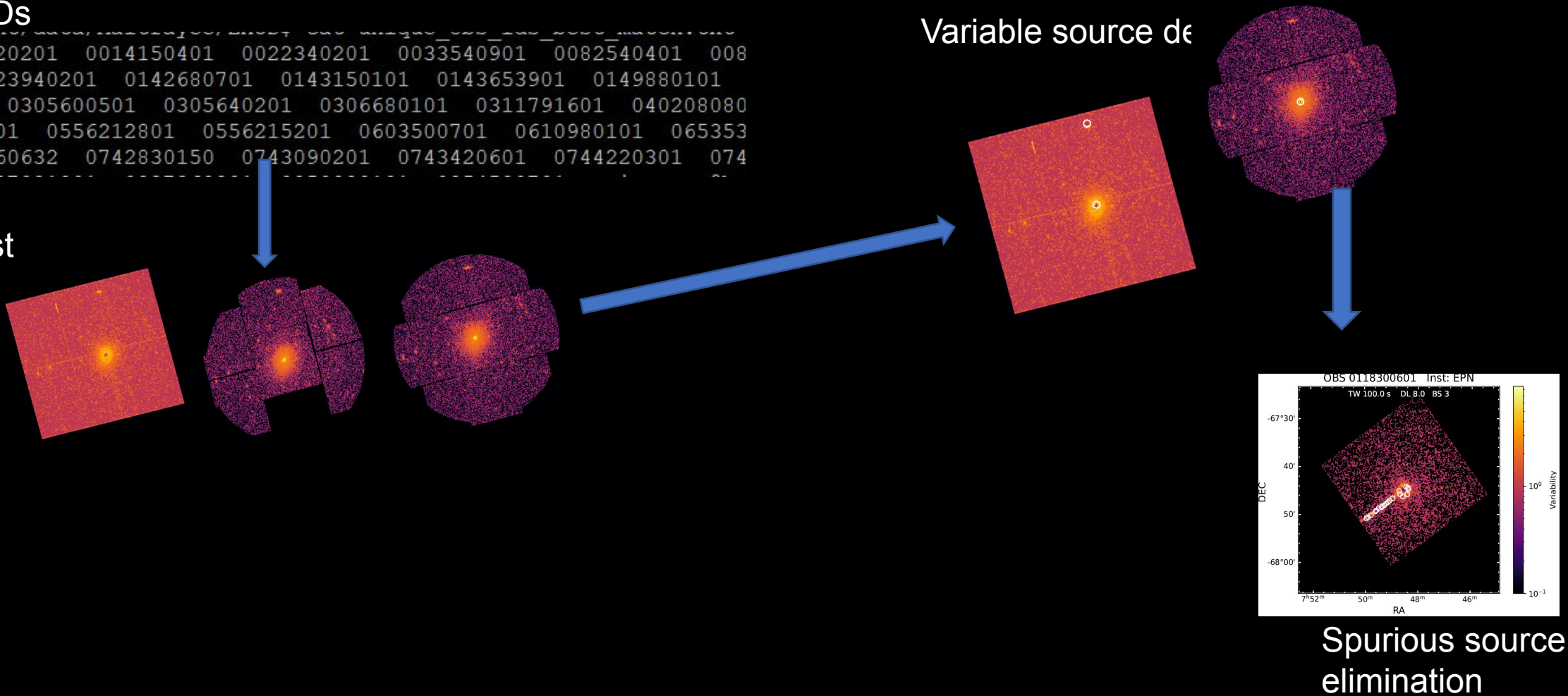


EXODUS algorithm pipeline

List of OBSIDs

```
0005210101 0008220201 0014150401 0022340201 0033540901 0082540401 008  
1 0123100201 0123940201 0142680701 0143150101 0143653901 0149880101  
0101 0301651101 0305600501 0305640201 0306680101 0311791601 040208080  
4620301 0510011301 0556212801 0556215201 0603500701 0610980101 065353  
0725300134 0728960632 0742830150 0743090201 0743420601 0744220301 074
```

Filter event list

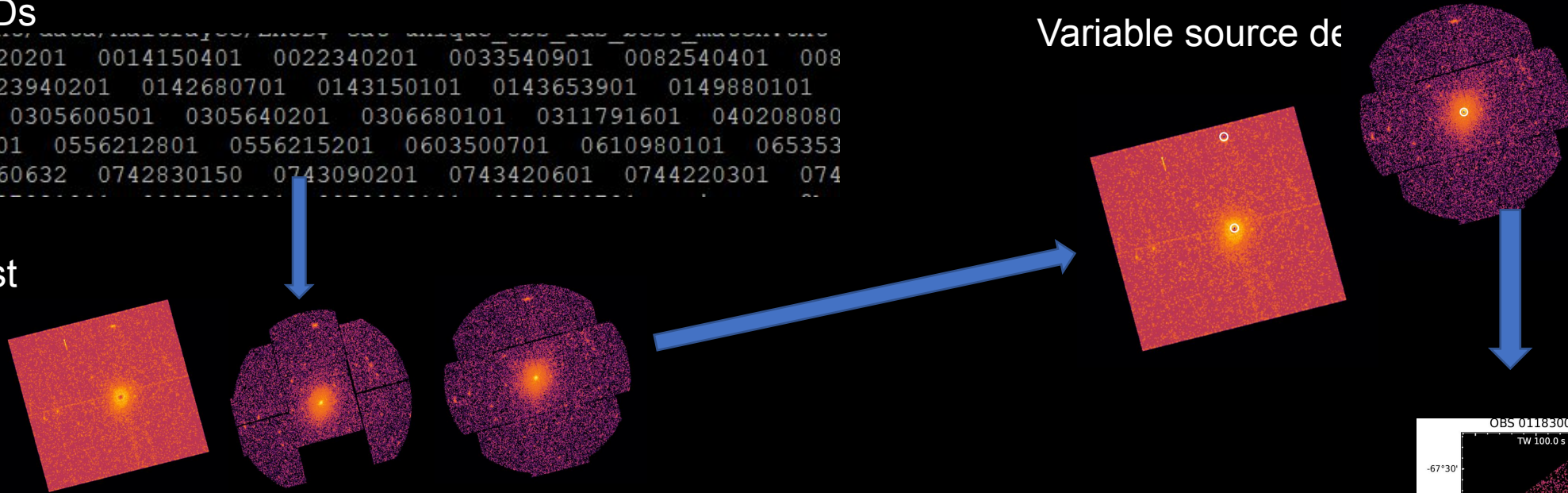


EXODUS algorithm pipeline

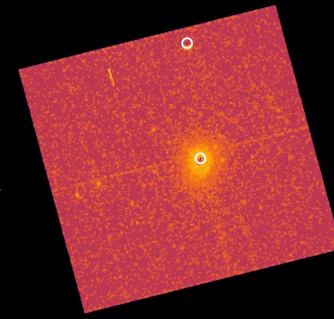
List of OBSIDs

```
0005210101 0008220201 0014150401 0022340201 0033540901 0082540401 008  
1 0123100201 0123940201 0142680701 0143150101 0143653901 0149880101  
0101 0301651101 0305600501 0305640201 0306680101 0311791601 040208080  
4620301 0510011301 0556212801 0556215201 0603500701 0610980101 065353  
0725300134 0728960632 0742830150 0743090201 0743420601 0744220301 074
```

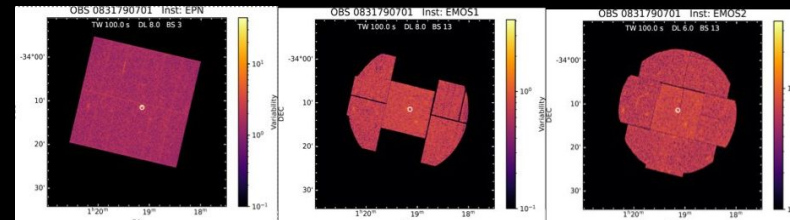
Filter event list



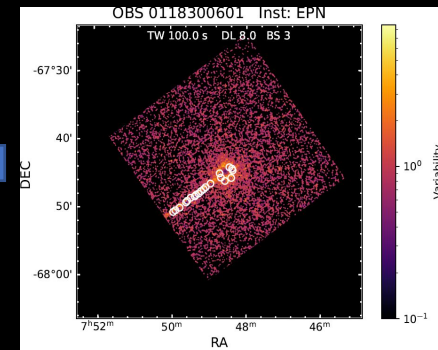
Variable source de



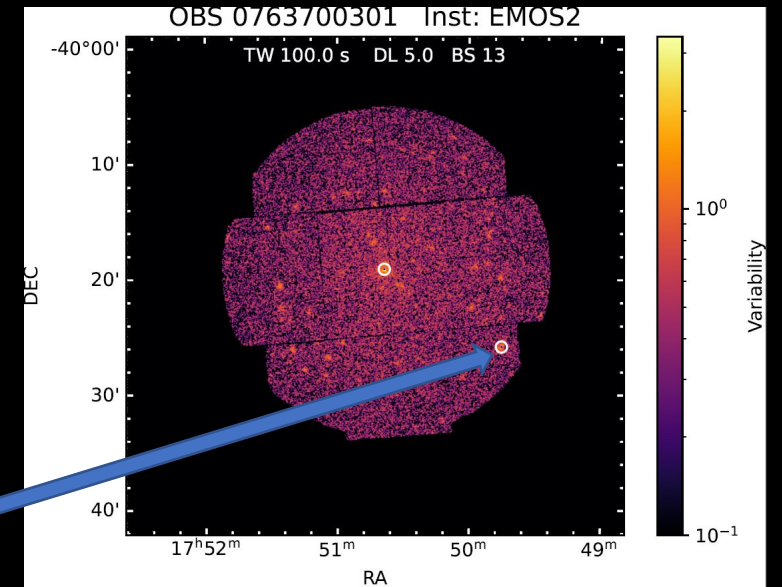
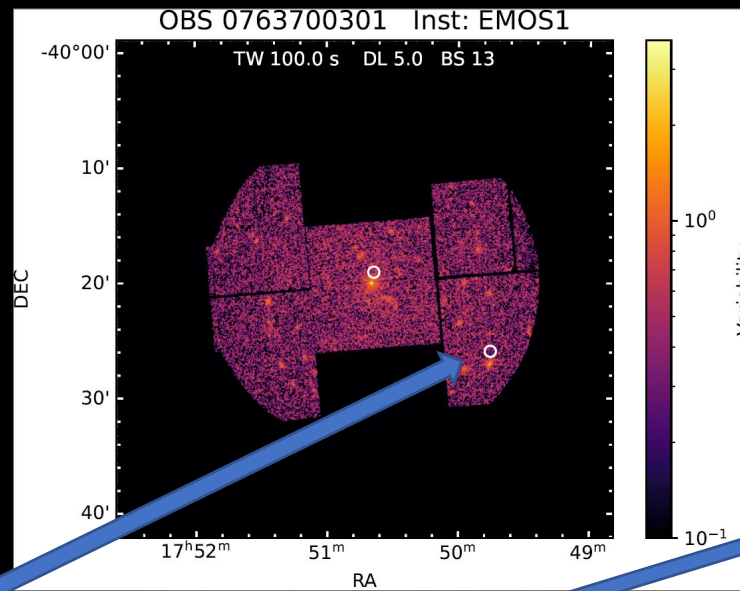
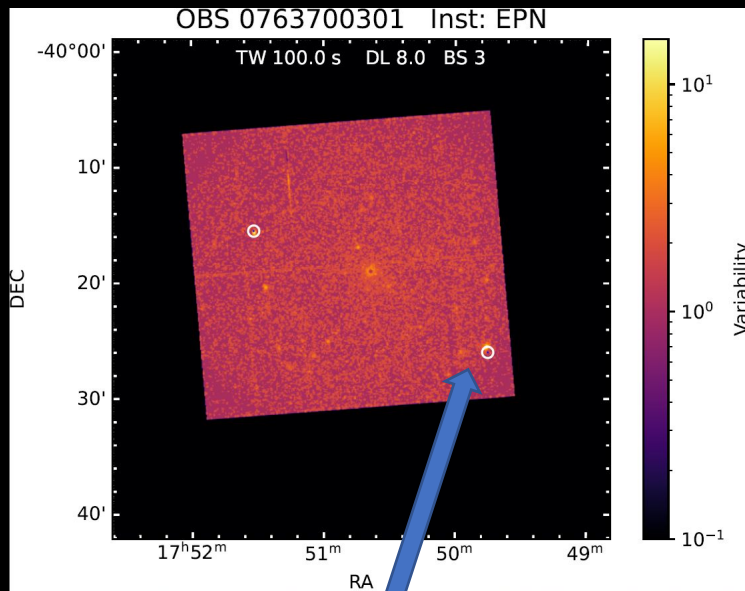
Cross correlation



Spurious source elimination



Correlation Between PN/MOS1/MOS2



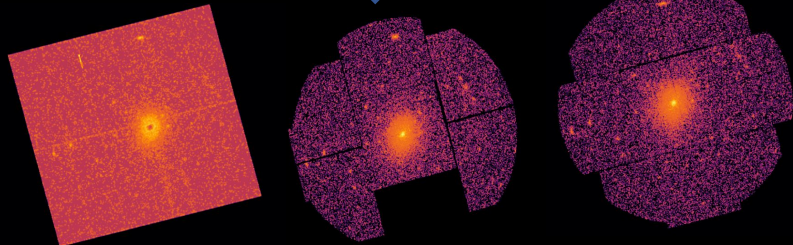
Cross-correlation - helpful to validate the robustness of the algorithm and a detection.

EXODUS algorithm pipeline

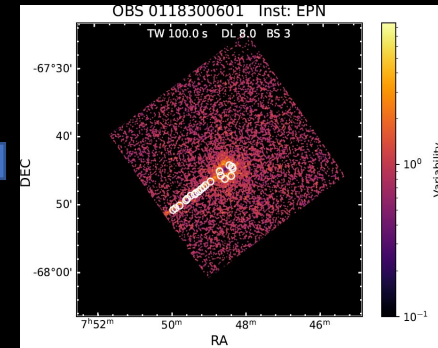
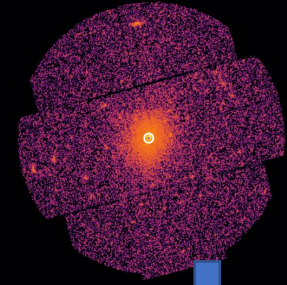
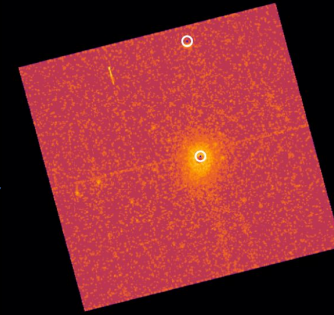
List of OBSIDs

```
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1 0123100201 0123940201 0142680701 0143150101 0143653901 0149880101
0101 0301651101 0305600501 0305640201 0306680101 0311791601 040208080
4620301 0510011301 0556212801 0556215201 0603500701 0610980101 065353
0725300134 0728960632 0742830150 0743090201 0743420601 0744220301 074
```

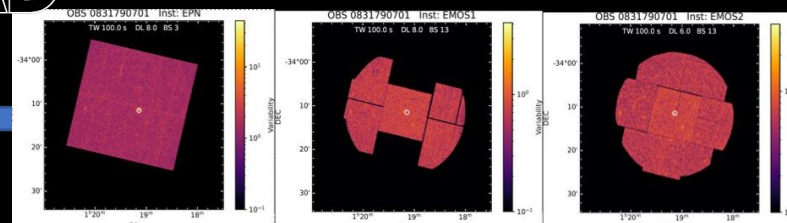
Filter event list



Variable source de



Cross correlation

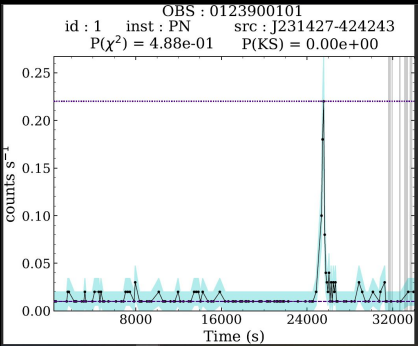


Spurious source elimination

Collated results



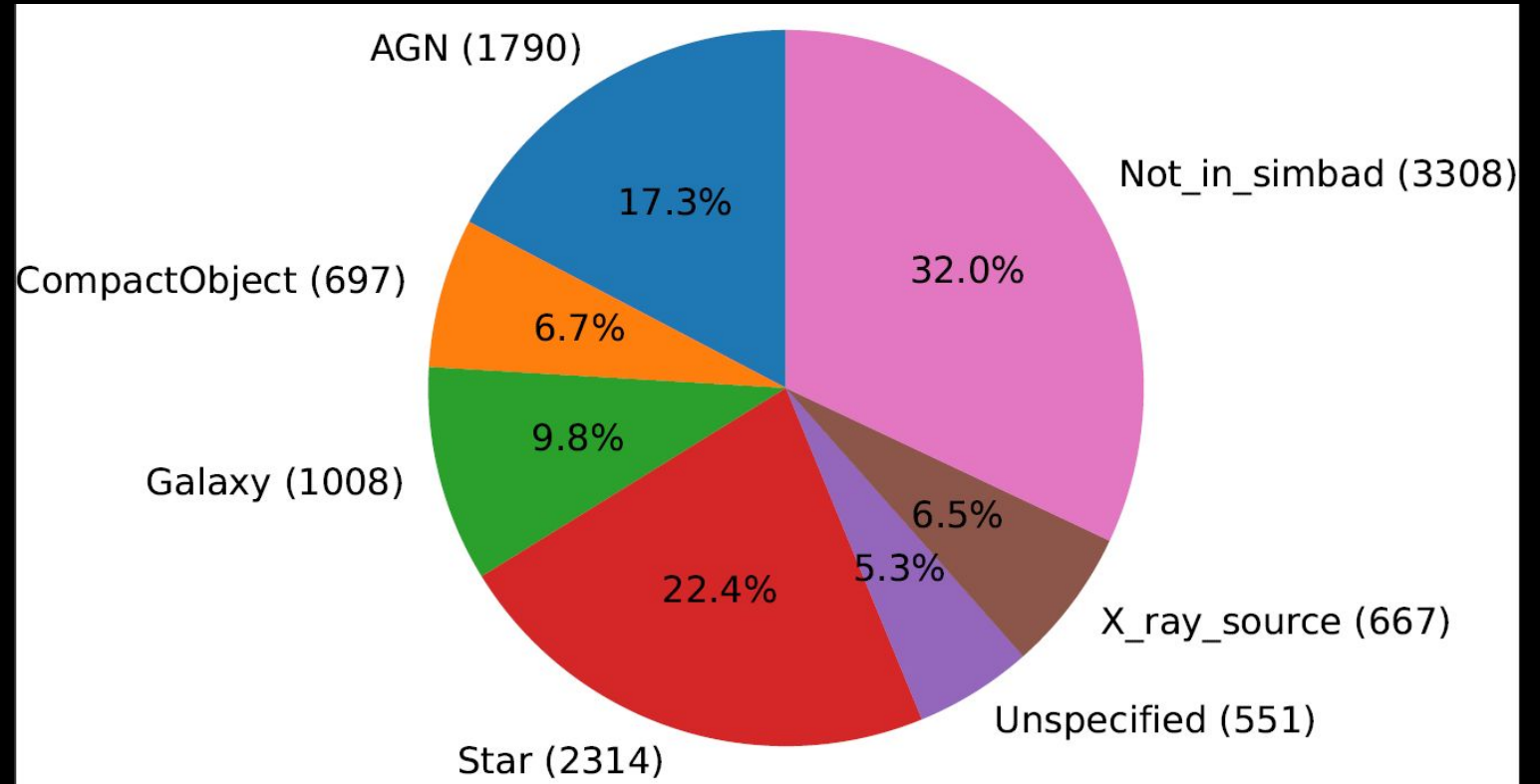
ObsID	RA	DEC	FWHM	SNR	...
0005210101	1.704861	55.4567	1.704861	55.4567	...
0008220201	2.181376	27.8985	1.813765	27.9055	...
0014150401	9.181384	27.8985	1.813765	27.9055	...
0022340201	1.085163	27.9011	1.085163	27.9011	...
0033540901	1.239216	81.4810	1.239216	81.4810	...
0082540401	1.216897	26.5432	1.116897	26.5432	...
0123100201	1.115180	78.5672	1.115180	78.5672	...
0123940201	1.128729	55.5792	1.128729	55.5792	...
0142680701	1.183024	78.426	1.183024	78.426	...
0143150101	1.181376	27.9055	1.181376	27.9055	...



Light curve extraction for interesting sources

Cross-match with SIMBAD

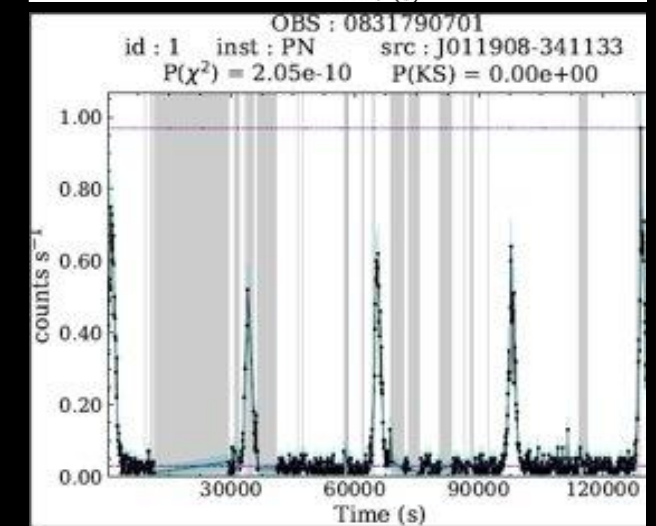
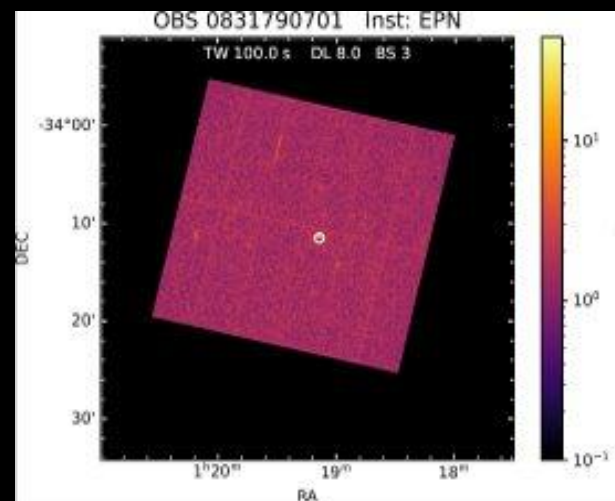
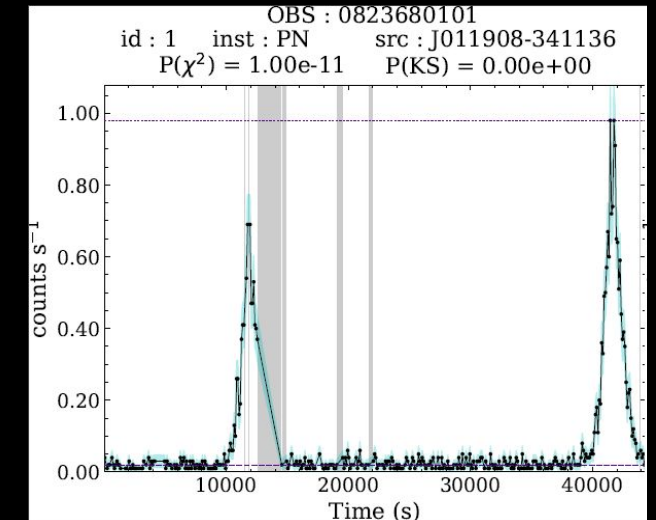
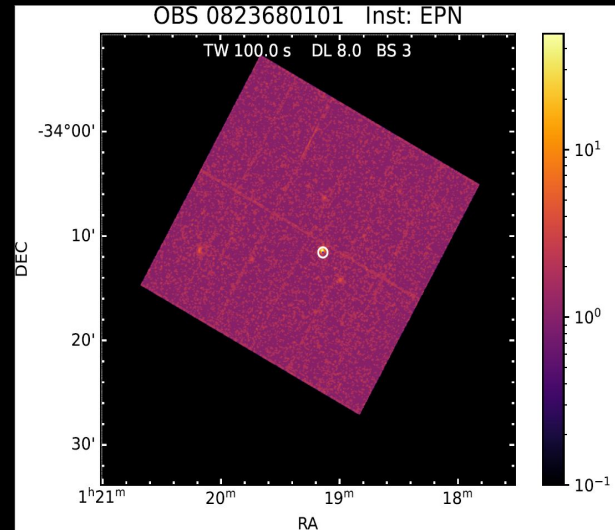
Placed into one of 6 bins.



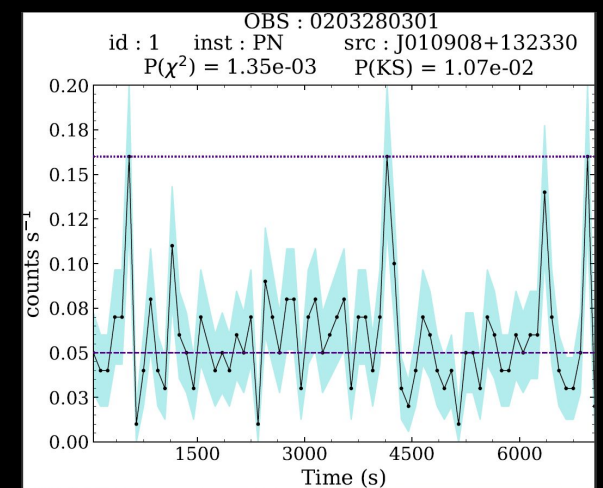
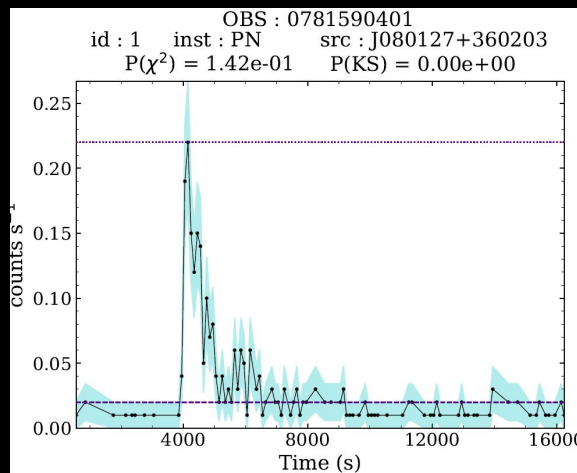
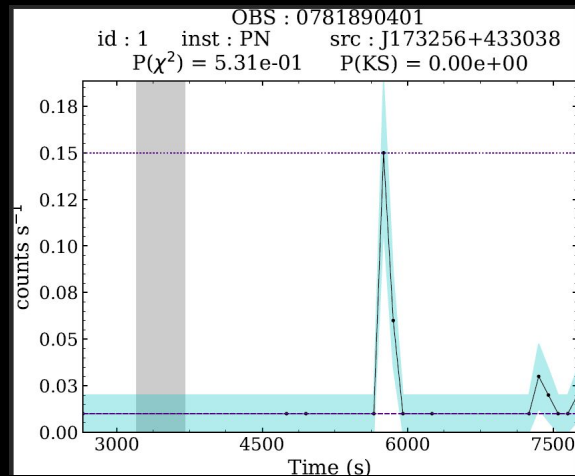
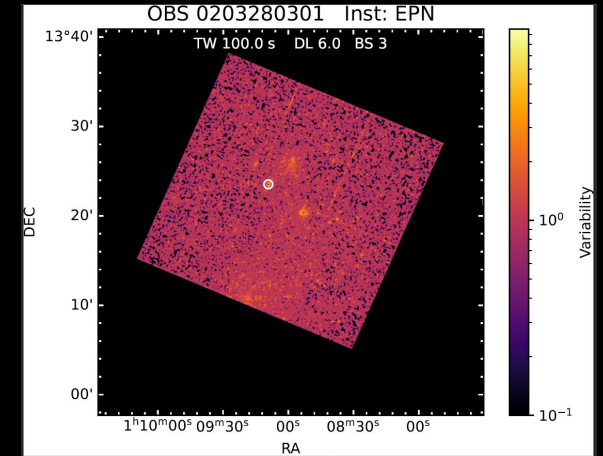
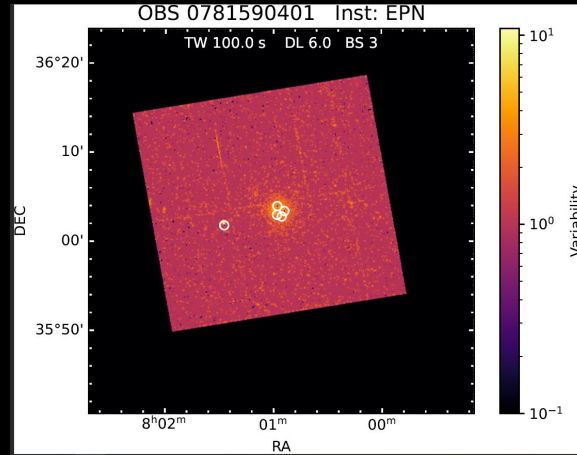
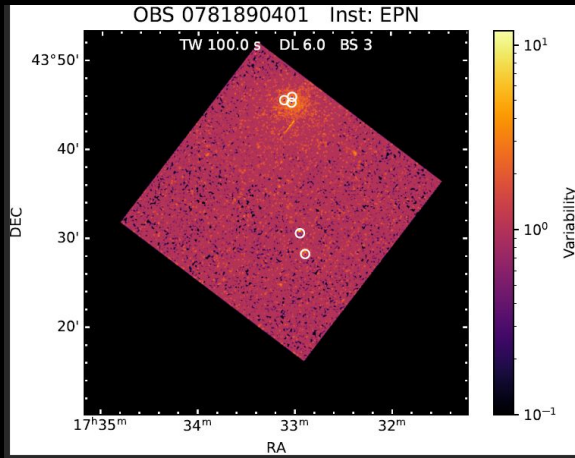
Results

Quasi-Periodic Objects

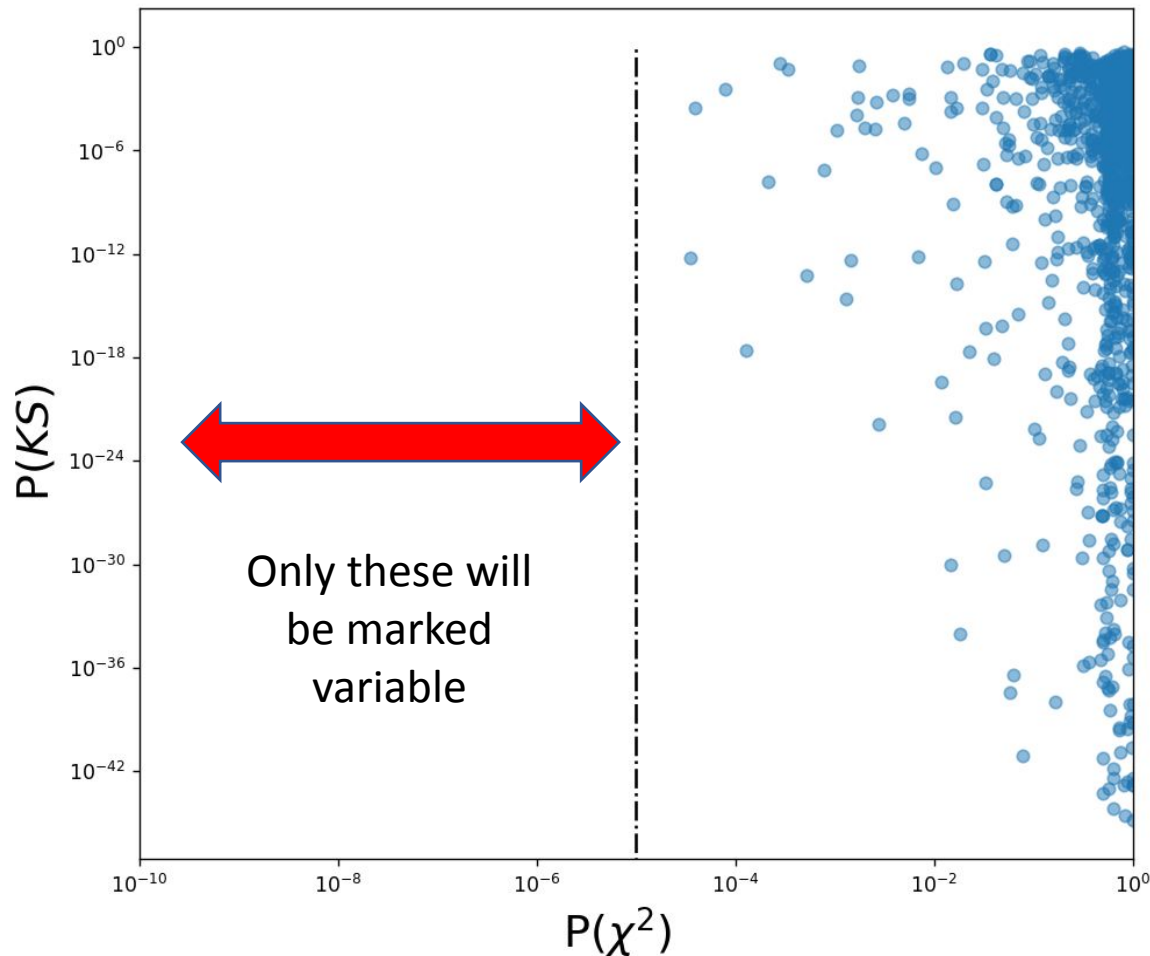
Identified previously
studied QPEs



Sources not identified as variable by the XMM pipeline



Sources not identified as variable by XMM pipeline



- The XMM pipeline classifies a source as variable using the simple χ^2 test where the time series are tested against a constant model.
- If the probability of constancy, $P(\chi^2) < 1E-5$ (Watson et al. 2009) the source is flagged as variable.
- The Kolmogorov-Smirnov test is a much better metric (Massey Jr. 1951).

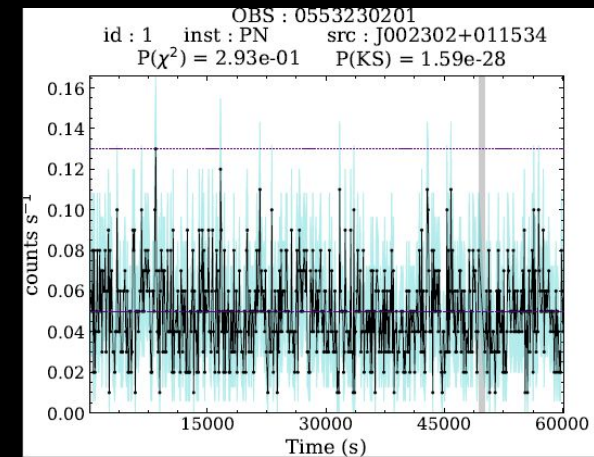
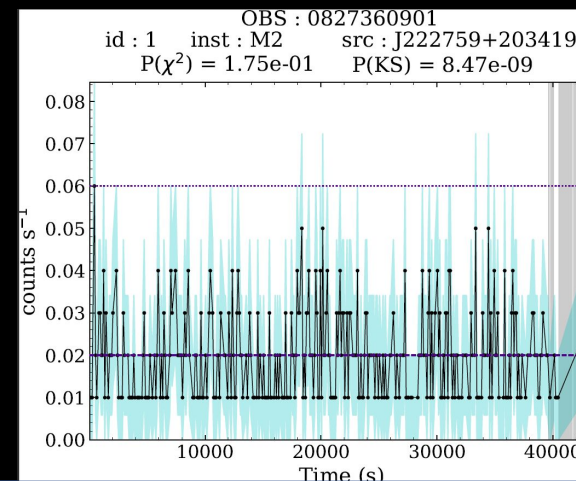
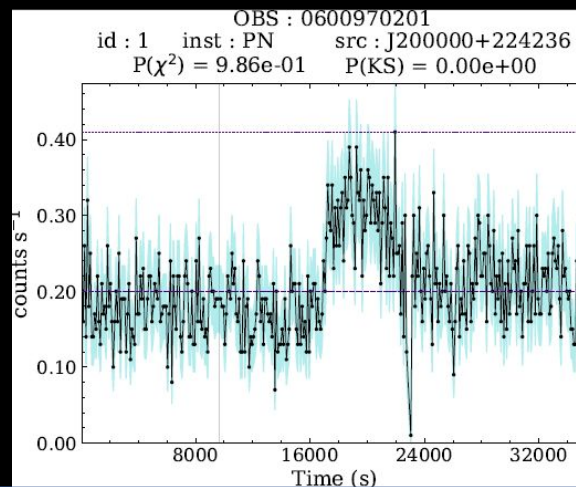
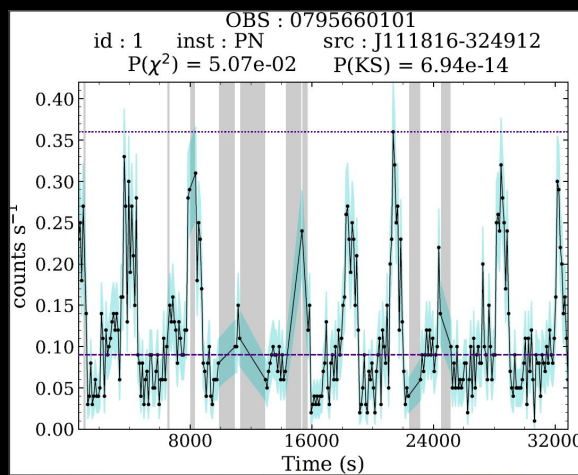
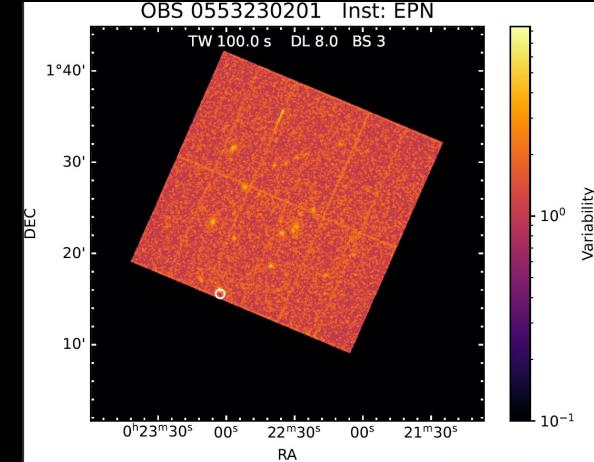
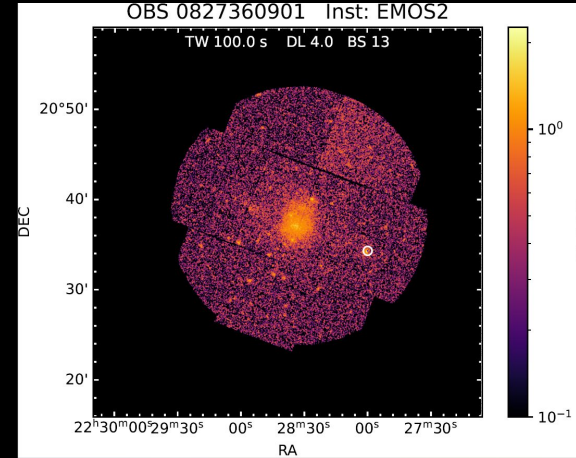
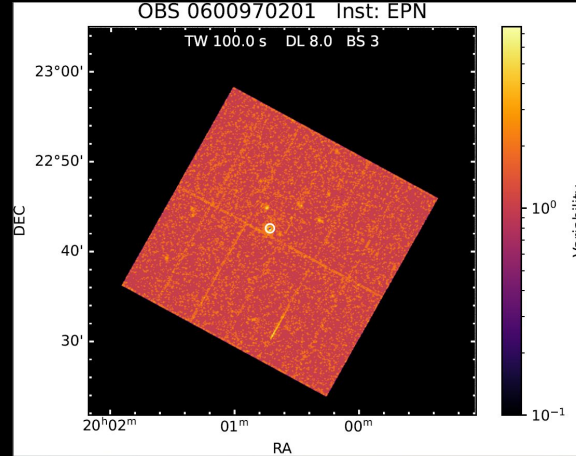
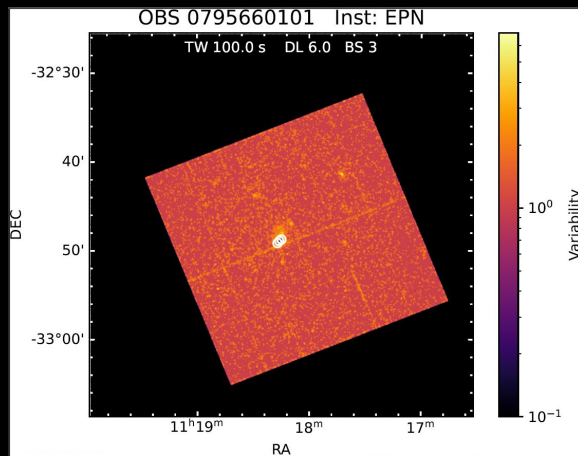
Wide variety of objects

ULX

Eclipsing binary with WD

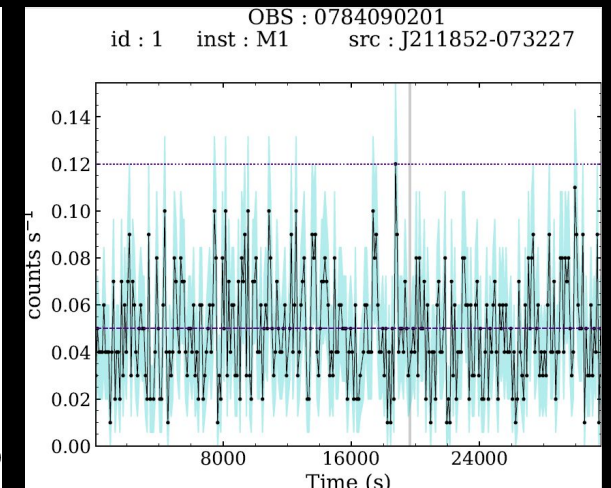
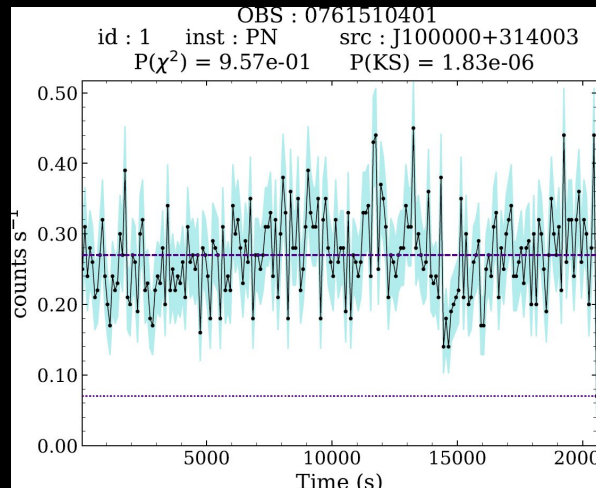
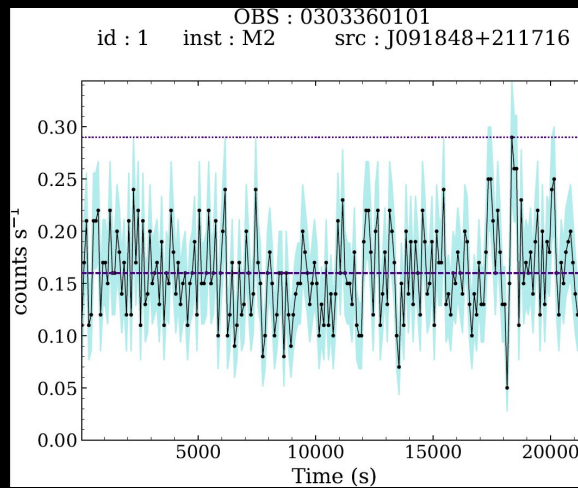
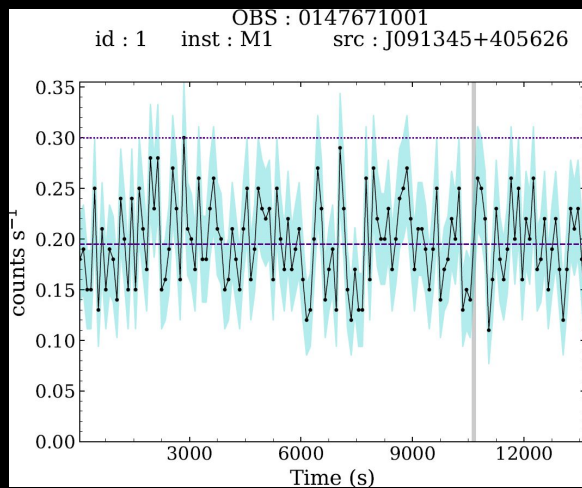
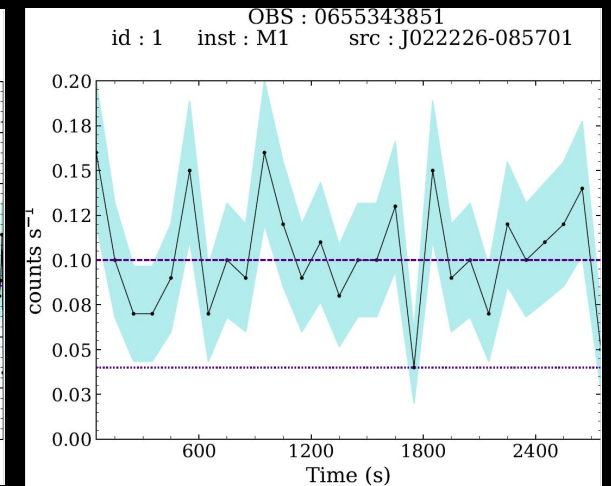
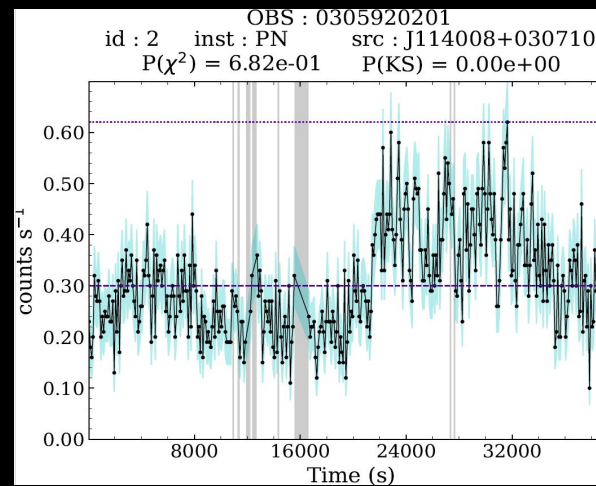
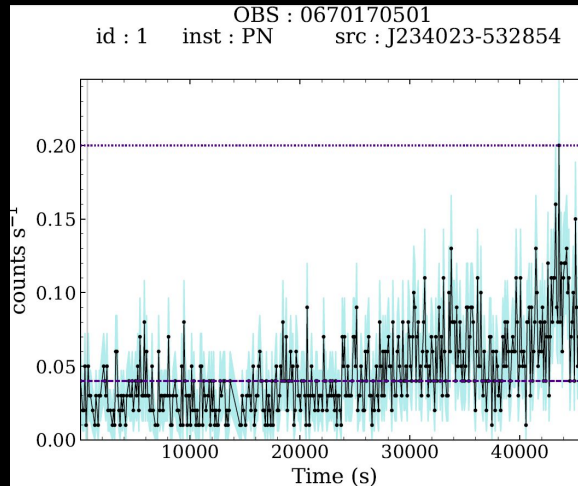
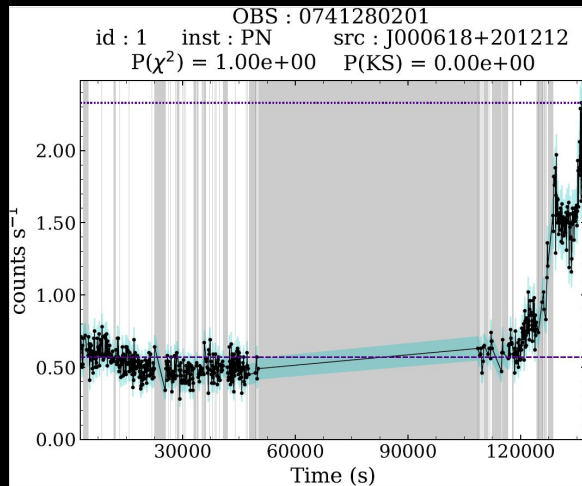
X-ray binary

quasar

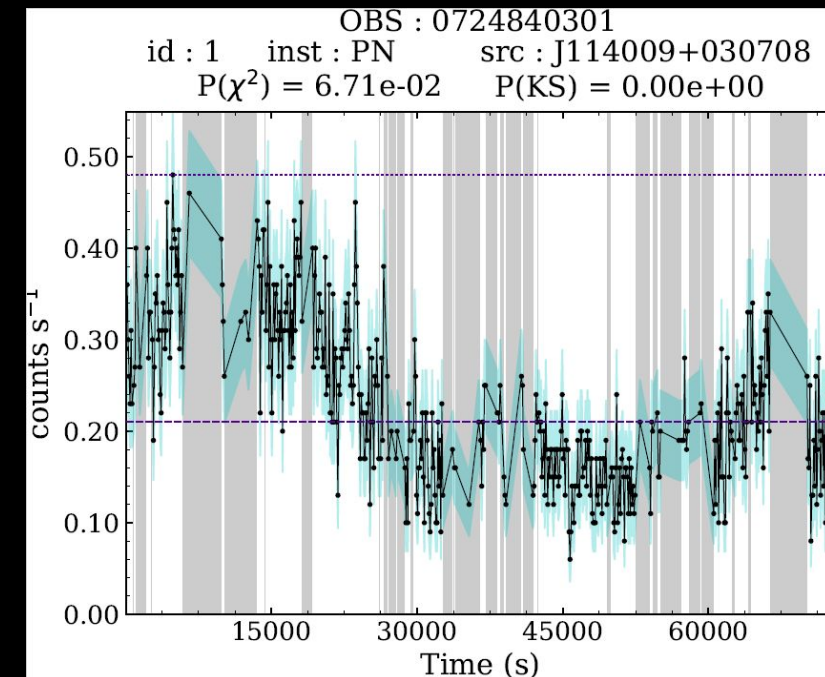
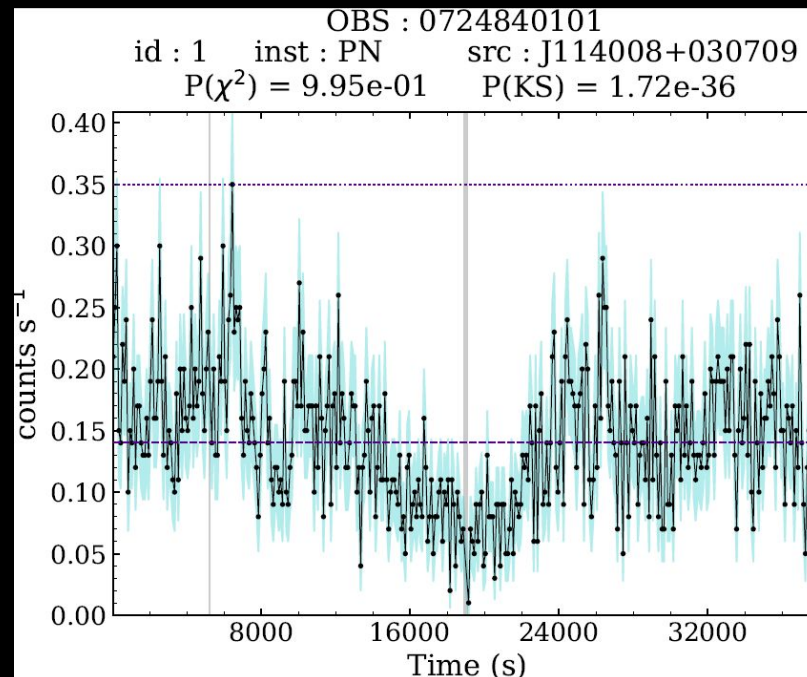
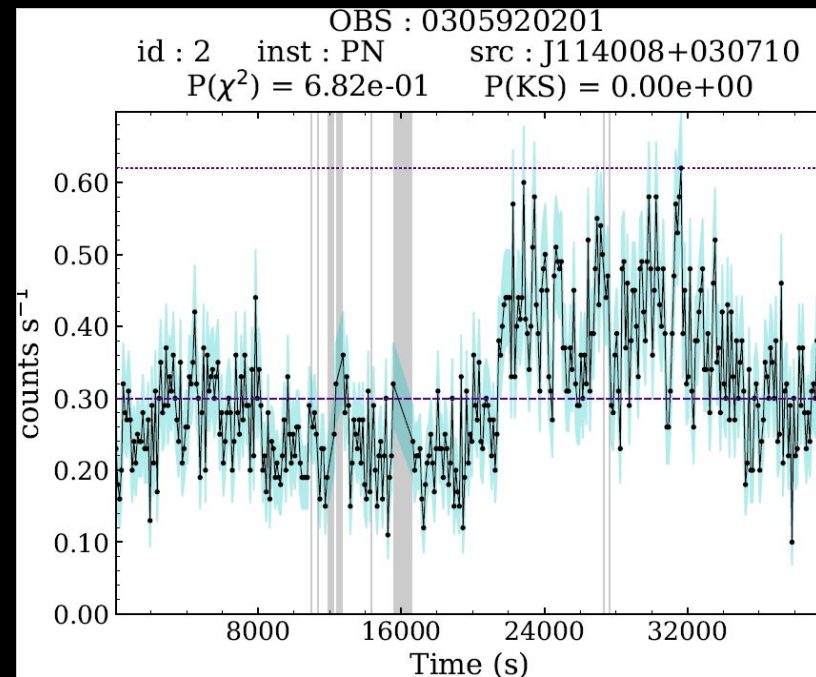


AGN Subsample

Selected subsample for closer analysis



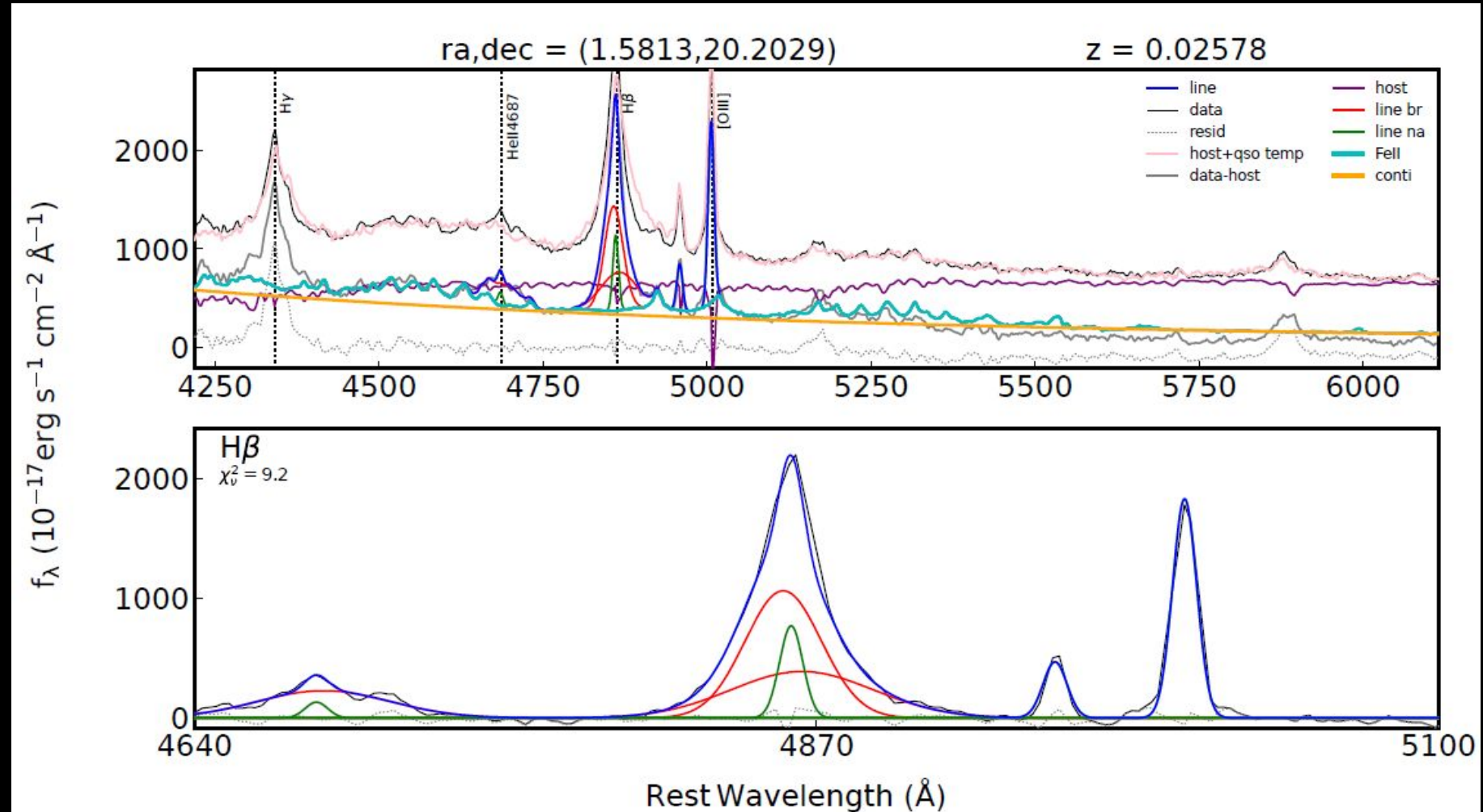
Selected subsample for closer analysis



- Selected sources with multiple observations.
- Crossmatched with SDSS and other catalogues (6dF, [Reines et al. 2013](#)) for optical spectral data.

Optical spectrum decomposition Mrk 335

- Optical spectrum primarily focussing on H β region
- Fit using PyQSOFit ([Guo et al. 2018](#)) with BIC.
- Includes AGN power-law continuum, host galaxy template through galaxy eigenspectra, and FeII (iron) pseudo-continuum.
- Broad lines fitted with Gaussian profiles.



BH Mass and Eddington ratio estimates

Estimated masses and accretion rates from fits and compared results with an identical approach in SDSS QSO catalogues.

$$M_{\text{BH}} = 10^{6.91} \left(\frac{\text{FWHM}(\text{H}\beta)}{1000 \text{ km s}^{-1}} \right)^2 \left(\frac{L_{5100}}{10^{44} \text{ erg s}^{-1}} \right)^{0.5} M_{\odot}$$

Vestergaard and Peterson (2006)

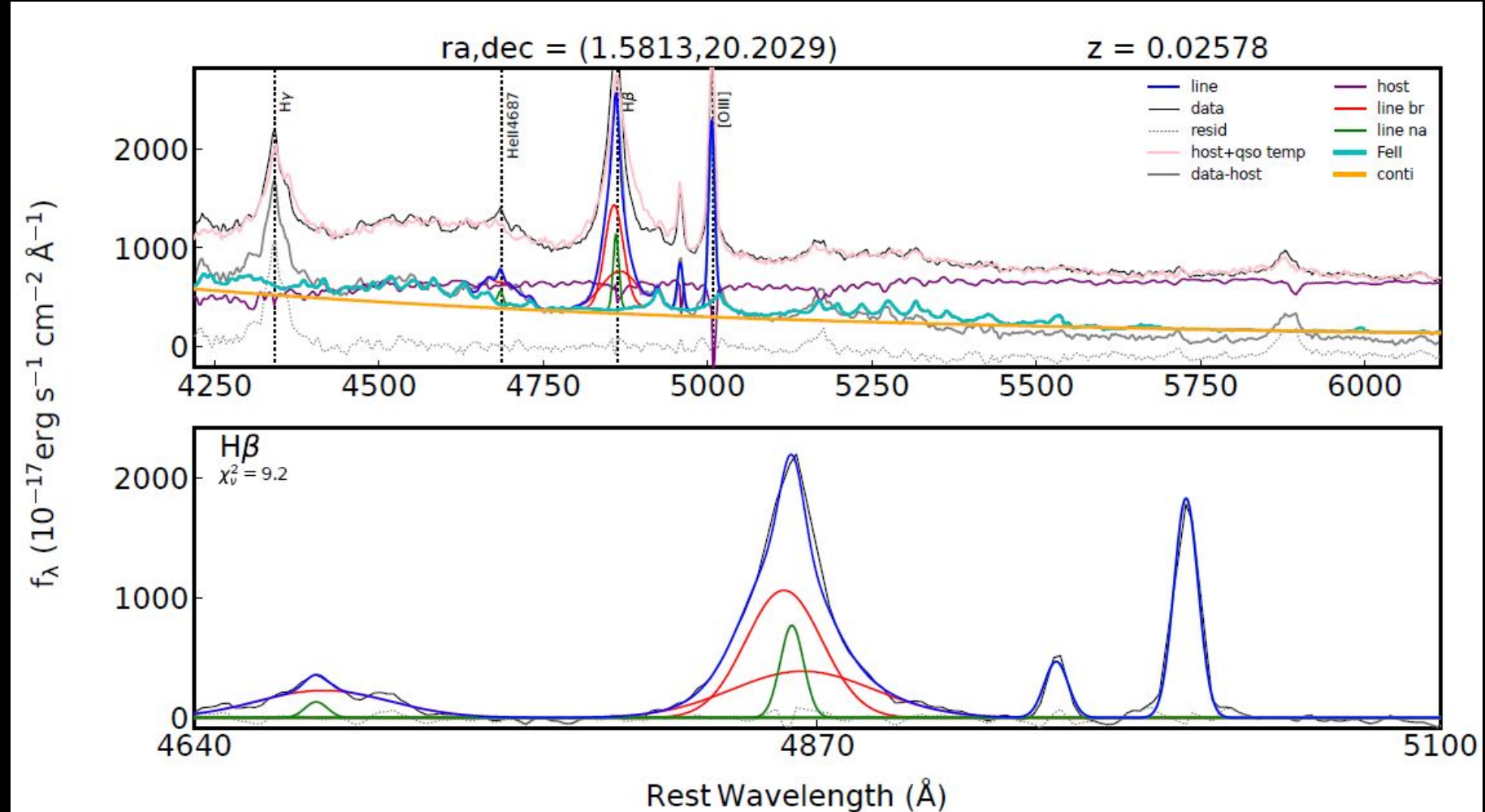
$$L_{\text{bol}} = 9.26 \times L_{5100}$$

Richards et al. (2006)

$$L_{\text{Edd}} = 1.38 \times 10^{38} \left(\frac{M_{\text{BH}}}{M_{\odot}} \right)$$

Optical spectrum decomposition Mrk 335

- $\text{FWHM}(\text{H}\beta) = 2360.30 \pm 259.9$
- $\text{Log } L_{5100} = 43.47 \pm 0.03$
- $\text{Log } L_{\text{bol}} = 44.44 \pm 0.03$
- $\text{Log } M_{\text{BH}} = 7.39 \pm 0.05$
- $\text{Log } \lambda_{\text{Edd}} = -1.09 \pm 0.06$

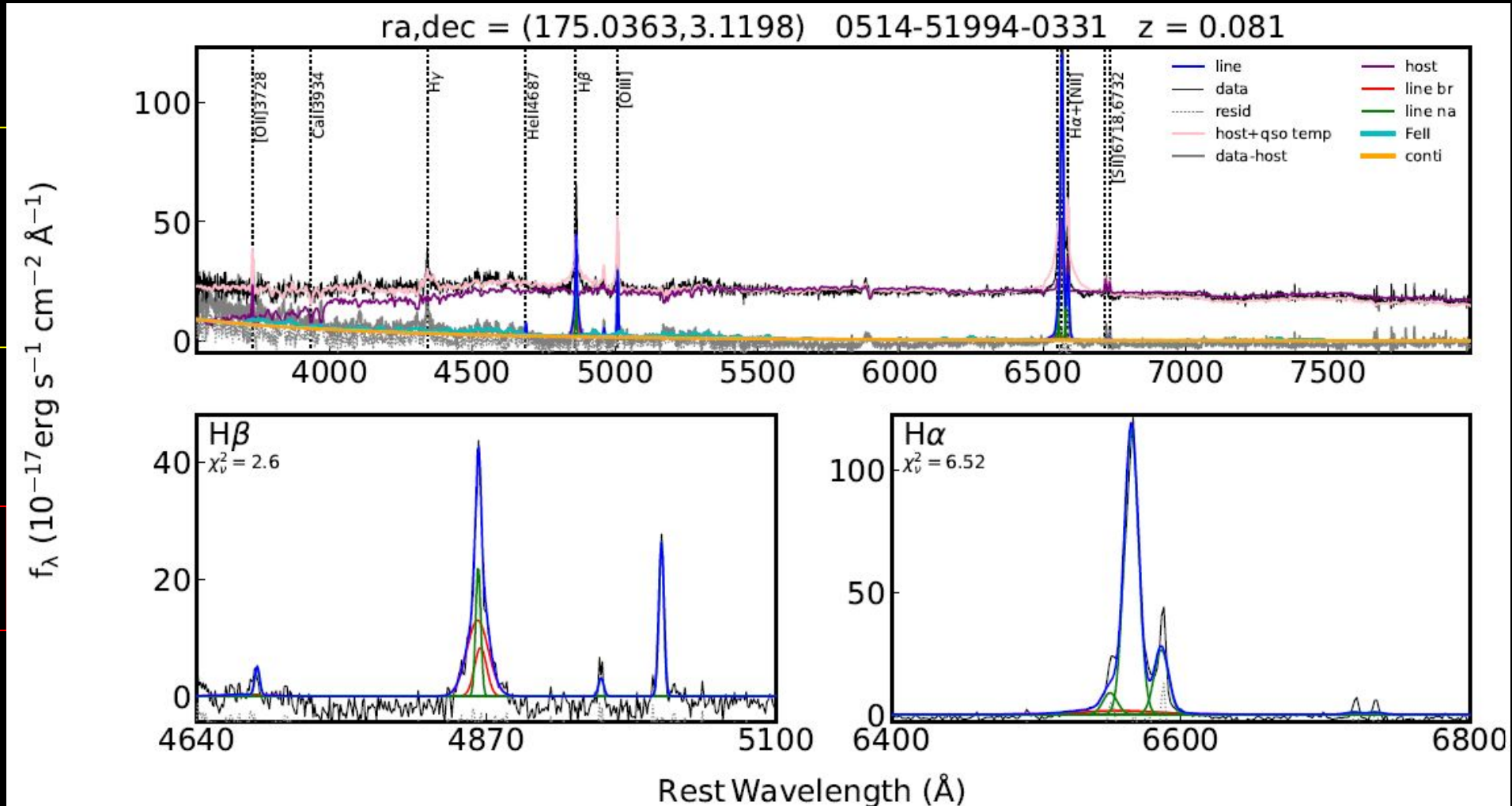


Optical spectrum decomposition

SDSS J122342.82+581446.4

- $\text{FWHM}(\text{H}\beta) = 1651.33 \pm 132.4$
- $\text{Log } L_{5100} = 42.20 \pm 0.01$
- $\text{Log } L_{\text{bol}} = 43.17 \pm 0.01$
- $\text{Log } \text{MBH} = 6.45 \pm 0.03$
- $\text{Log } \lambda \text{Edd} = -1.42 \pm 0.03$

Process repeated for other objects in the sample.

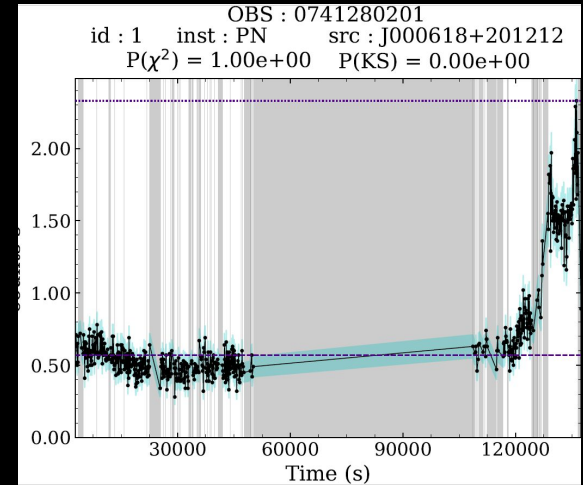
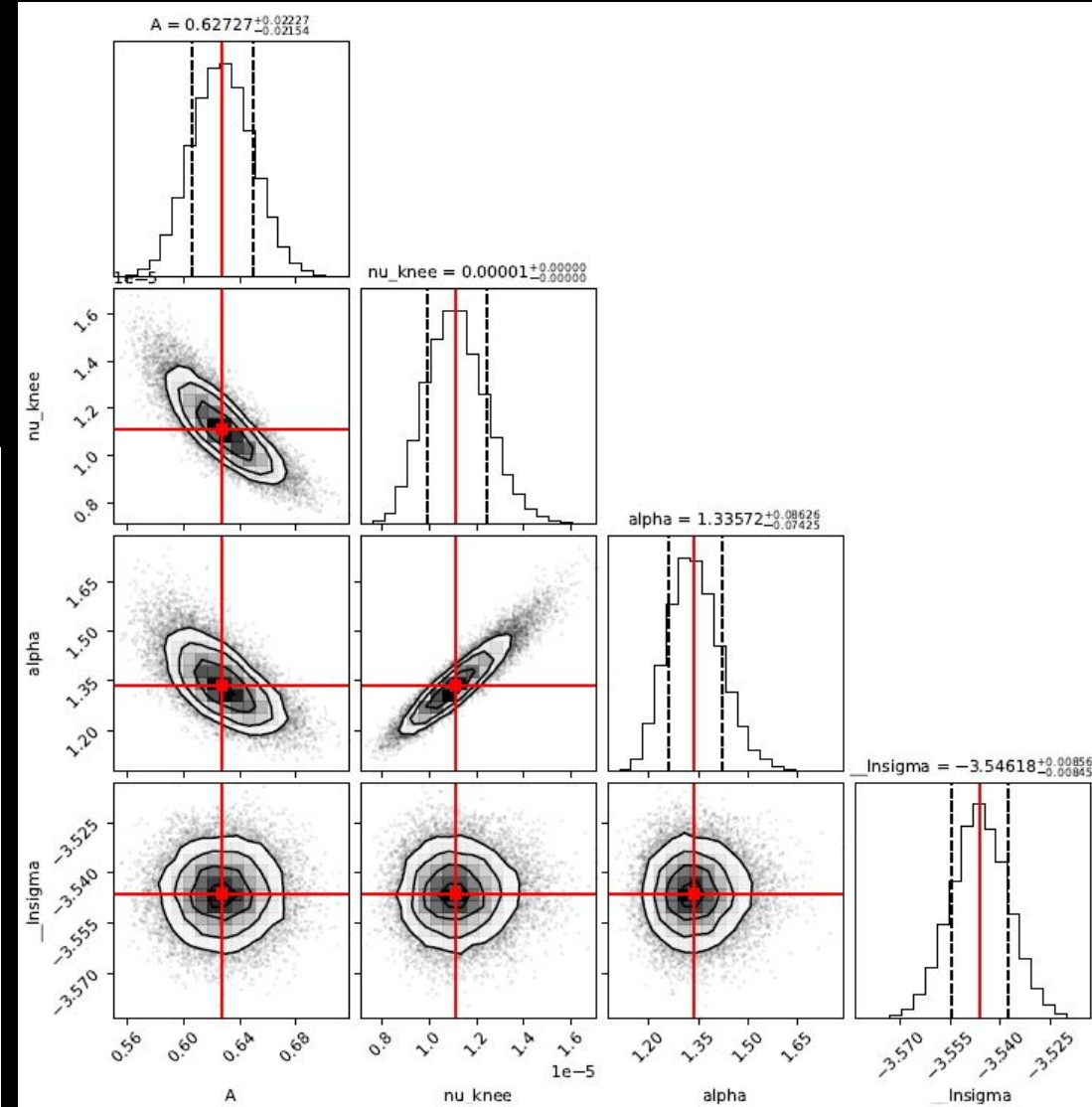
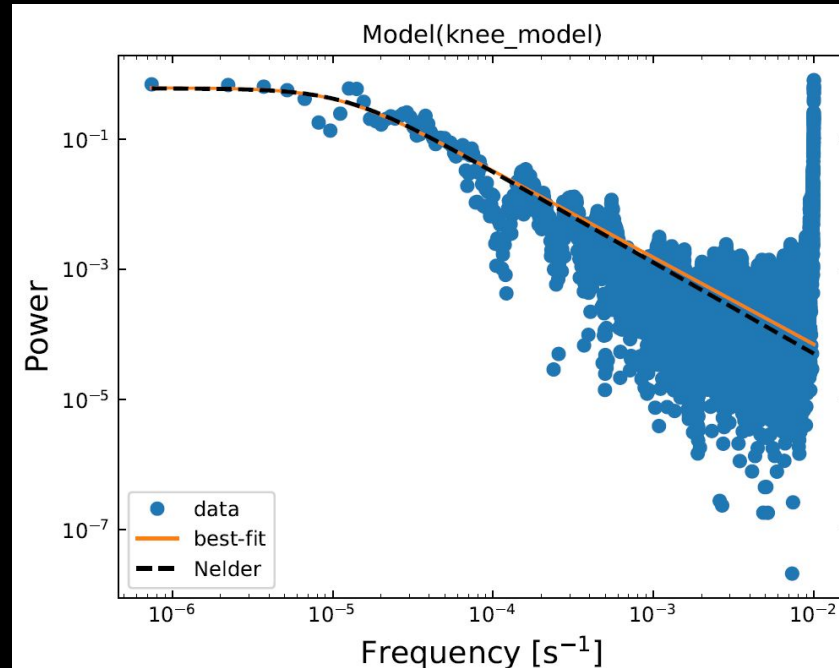


Knee model fit to the X-ray power spectrum for Mrk 335



$$P(\nu) = \frac{A}{\left[1 + \left(\frac{\nu}{\nu_{\text{knee}}}\right)^2\right]^{\alpha/2}}$$

Uttley et al. (2002)



Take-Home Results

- ❖ Computes variability of whole FOV without a priori source detection, timescales ~ 3 s to find faint rapid transients.
- ❖ Prior to EXODUS, variability analysis not run on 2/3 of catalogue.
- ❖ Able to detect a wide variety of variable sources not identified by the XMM pipeline, doubling the number of variable sources.
- ❖ Identified new faint sources.
- ❖ Code available online, paper submitted *Gupta et al.*
- ❖ Studying low mass AGN with EXODUS (paper in prep).

Thank you!

