How to find variable sources in low count rate X-ray all-sky surveys: The case of eROSITA

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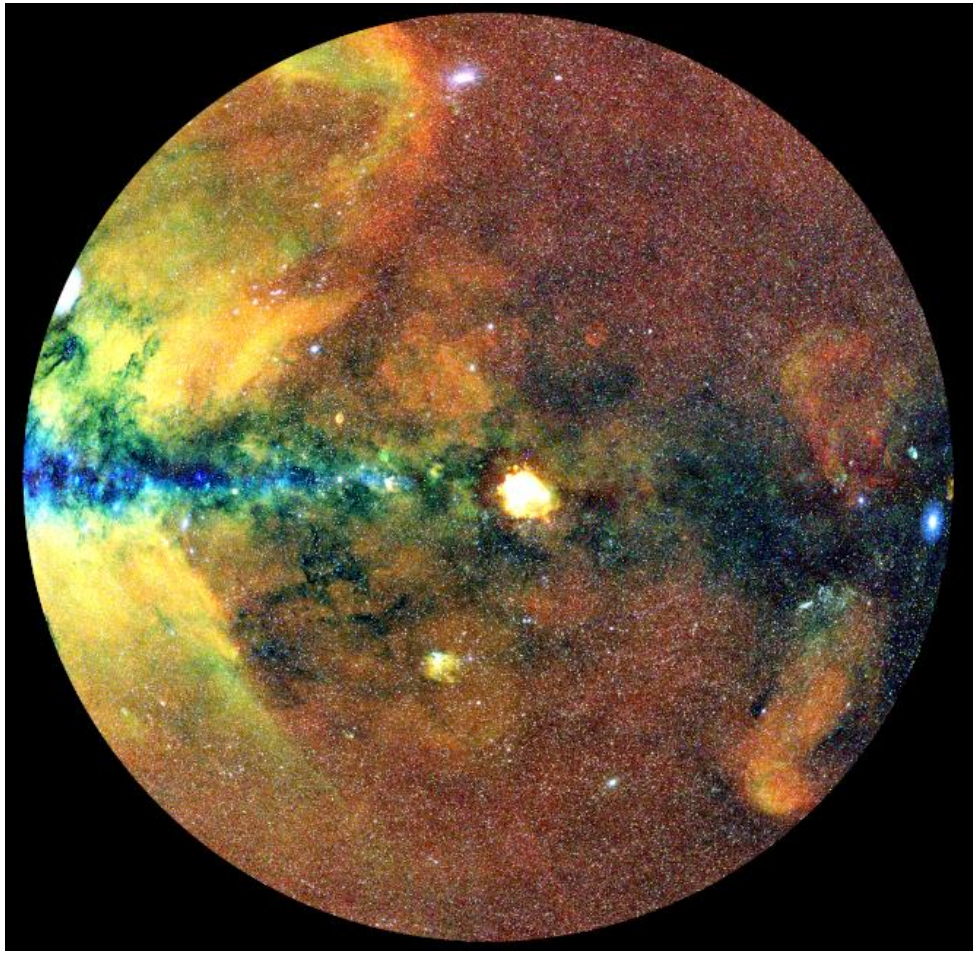


X-ray Variability in Astrophysics

X-ray variability serves as a powerful diagnostic tool in astrophysics.

It enables the identification of **compact objects**, probes extreme physics near Galactic and supermassive black holes, supports the study of accretion processes, and helps us to understand explosive events throughout the universe.

The timescales of X-ray changes can reveal processes such as turbulence and magnetic reconnections in **stellar objects**.

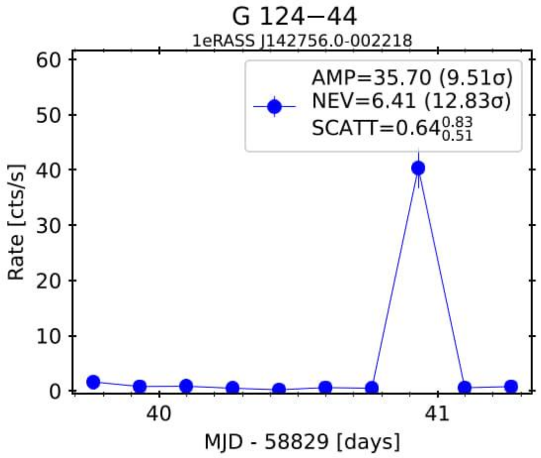
Studies of X-ray variability provide insights into the most energetic phenomena in the universe.

Variability is found in Stars, Galactic Binaries, and AGN

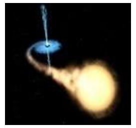
Stars

X-ray variability is primarily driven by magnetic activity. These stars have strong, dynamic magnetic fields that can produce energetic flares similar to those seen on the Sun, but on a much larger scale.

X-ray flares result from the reconnection of magnetic field lines, releasing enormous energy and causing sudden increases in X-ray emission.



X-ray binaries



X-ray binaries are stellar systems where a compact object, either a **neutron star or a black hole, accretes matter from a companion star.**

X-ray binaries often display rapid variability, including **quasi-periodic oscillations** (QPOs) that occur on timescales of milliseconds to seconds.

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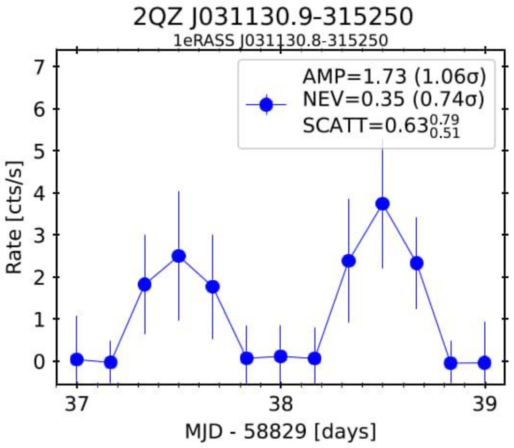
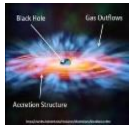
In some X-ray binaries, variability is caused by the **orbital motion of the companion star,** leading to periodic eclipses or dips in the X-ray light curve.



AGN

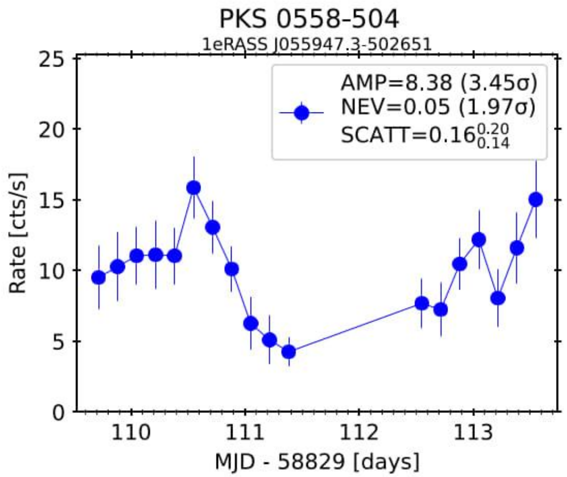


Various models for AGN variability have been proposed:

The light-bending model, in which a compact power-law emitting source moves close to the black hole, with photons being lost depending on their distance from the black hole.

The hot spot model, temperature inhomogeneities in the accretion disc

The Bardeen-Petterson effect, involving a precessing accretion disc.



Methods for assessing and characterizing variability

Maximum Amplitude Variability (AMP)

$$AMP = (X_{\max} - \sigma_{\max}) - (X_{\min} + \sigma_{\min})$$

$$AMP_e = \sqrt{\sigma_{\max}^2 + \sigma_{\min}^2}$$

The maximum amplitude variability is quantified as the range between the most extreme values of the count rate. (Boller 2016)

Normalized Excess Variability (NEV)

$$NEV = \frac{< (X_i - \mu)^2 > - < \sigma_i^2 >}{\mu^2}$$

$$NEV_e = \sqrt{\frac{2}{N}\left(\frac{< \sigma_i^2 >}{\mu^2}\right)^2 + \frac{< \sigma_i^2 >}{N}\left(\frac{2F_{var}}{\mu}\right)^2}$$

The normalized excess variance is determined by calculating the difference between the expected variance derived from the error bars and the observed variance.

(Nandra 1997)

Bayesian Excess variance (bexvar)

$$P(D|\bar{R}_S, \sigma_{\text{bexvar}}) \propto$$

$$\prod_{i=1}^{N} \sum_{j=1}^{M} P_{i,j} \times \text{Normal}(\log R_j | \log \bar{R}_S, \sigma_{\text{bexvar}}))$$

The assumption of Gaussianity in calculating AMP and NEV becomes unreliable in low-count-rate regimes. To address this limitation, Buchner (2022) introduced a Bayesian excess variance estimate (bexvar), which applies to event counts that follow a Poisson distribution.

Variability Selection Flowchart for the first eROSITA all-sky survey scan (DR1)

Sample selection

128,669 DR1 sources

ML_CTS_1 >= 10 ∧ DET_LIKE_0 >= 7 ⊄ SEP

Light Curve Methodology

Maximum Amplitude Variability (AMP)

$$AMP = (X_{\max} - \sigma_{\max}) - (X_{\min} + \sigma_{\min})$$

$$AMP_e = \sqrt{\sigma^2_{\max} + \sigma^2_{\min}}$$

Normalized Excess Variability (NEV)

$$NEV = \frac{< (X_i - \mu)^2 > - < \sigma_i^2 >}{\mu^2}$$

$$NEV_e = \sqrt{\frac{2}{N}\left(\frac{< \sigma_i^2 >}{\mu^2}\right)^2 + \frac{< \sigma_i^2 >}{N}\left(\frac{2F_{var}}{\mu}\right)^2}$$

Bayesian Excess variance (bexvar)

$$P(D|\bar{R}_S, \sigma_{\mathrm{bexvar}}) \propto \prod_{i=1}^{N} \sum_{j=1}^{M} P_{i,j} \times \mathrm{Normal}(\log R_j | \log \bar{R}_S, \sigma_{\mathrm{bexvar}})).$$

DR1 variable content

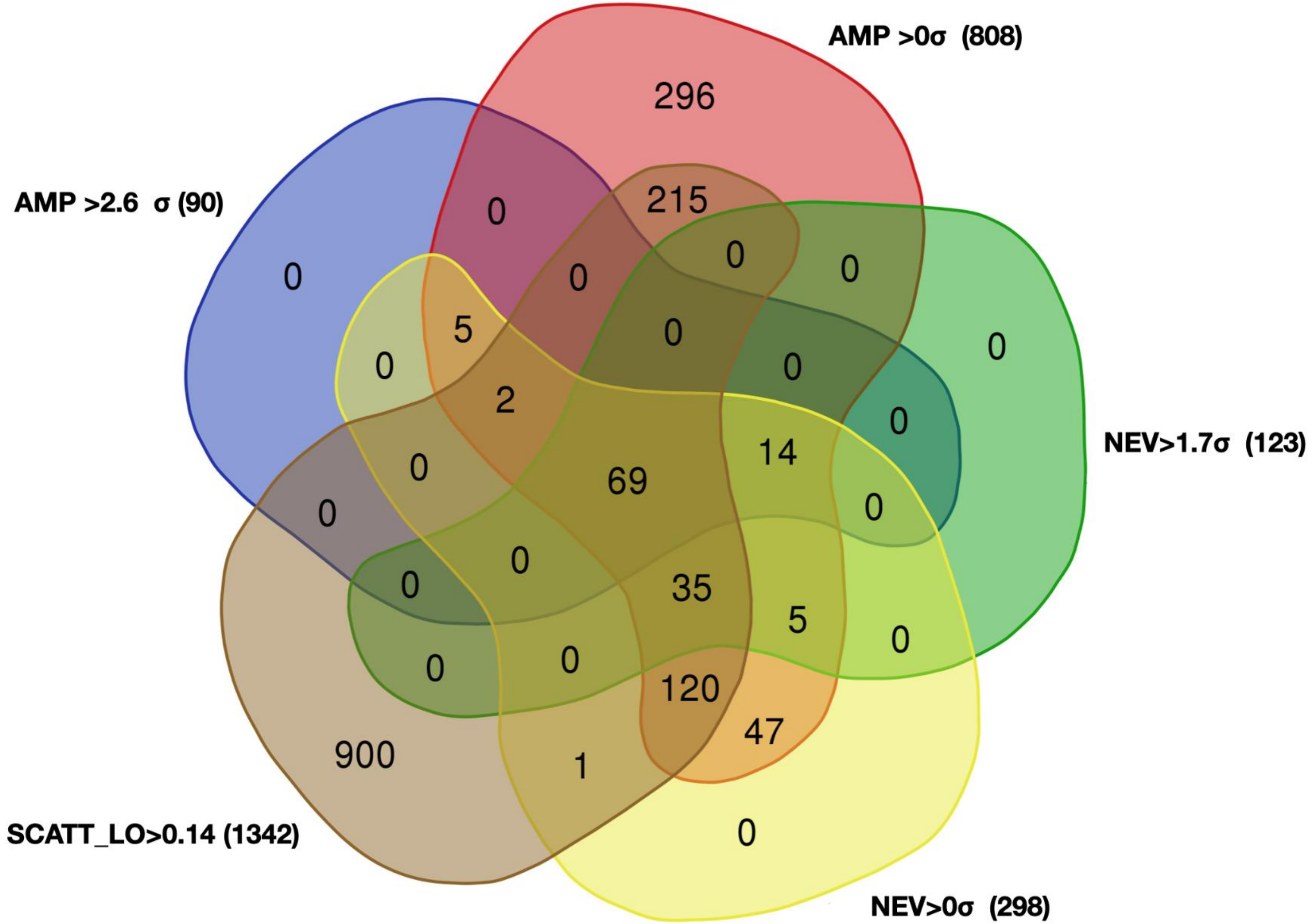
808 (90 > 2.6 σ)

298 (123 > 1.7 σ)

1,342 (scatt_lo > 0.14)

1709 DR1 variable sources

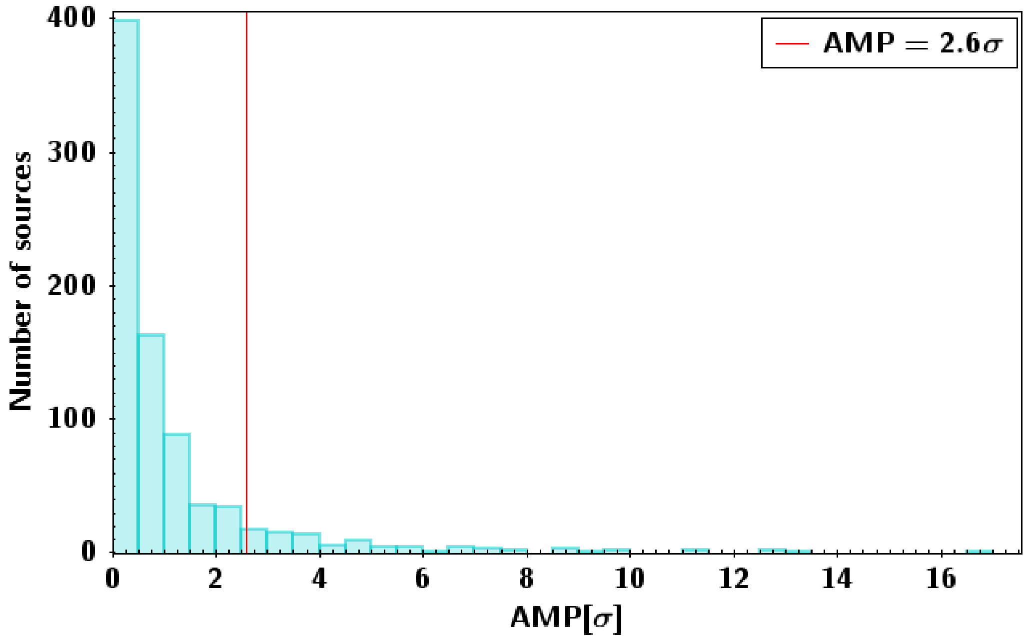
Variability selection results from standard and Bayesian tests

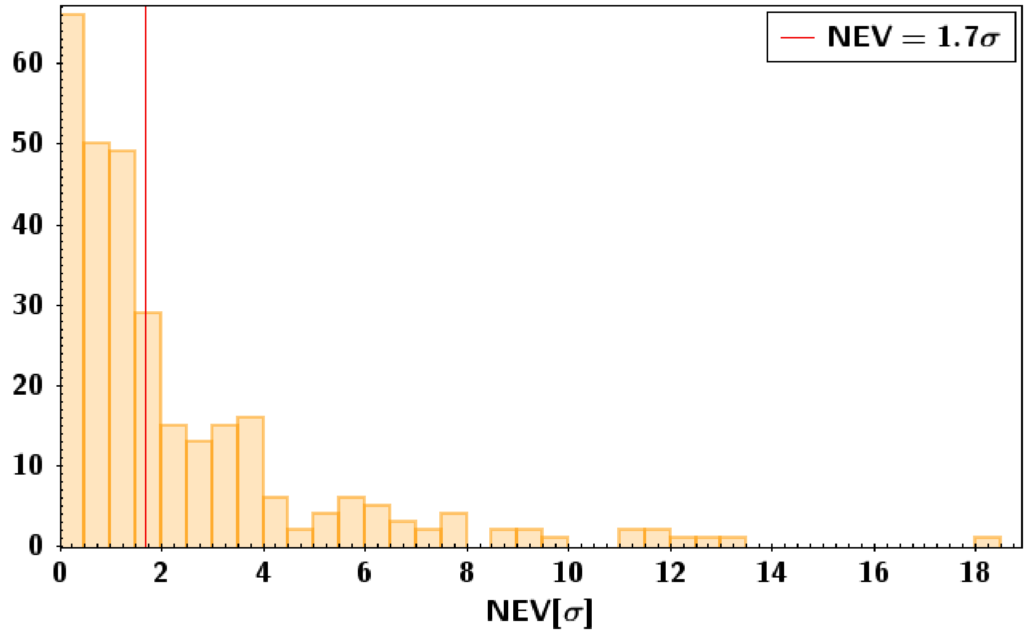


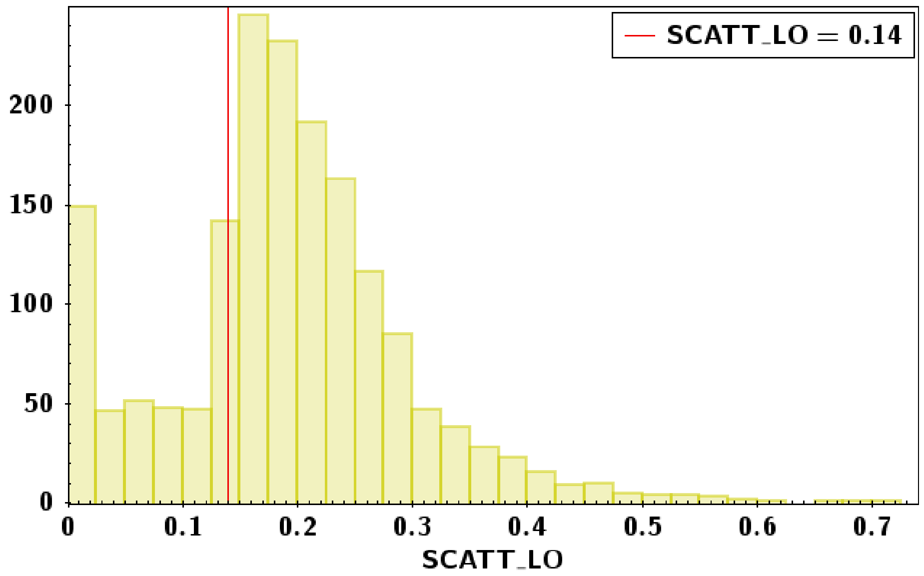
The total number of unique sources is **1709.**

69 of the 1709 sources are considered variable by the three criteria **simultaneously.**

Histograms of variable sources for standard and Bayesian tests

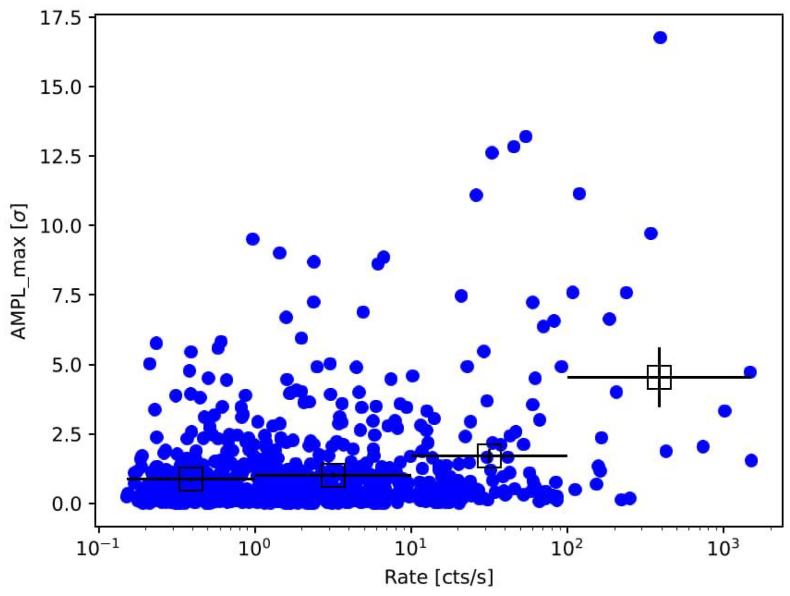




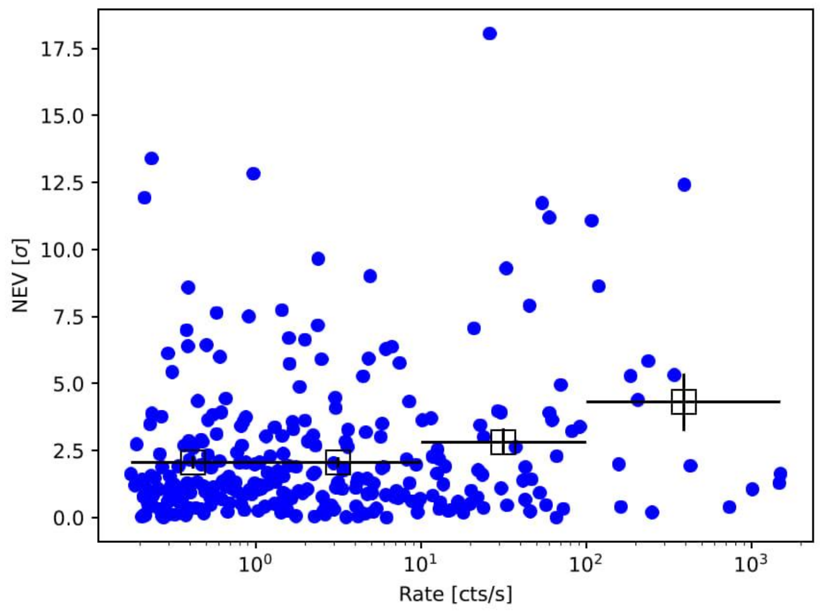


Dependence of Source Count Rates on Variability Significance

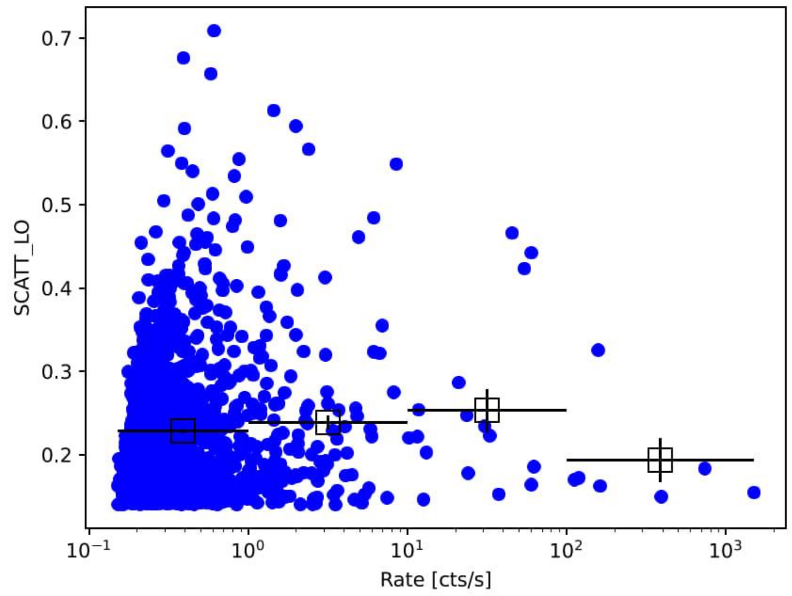
Maximum Amplitude Variability (AMP)



Normalized Excess Variability (NEV)



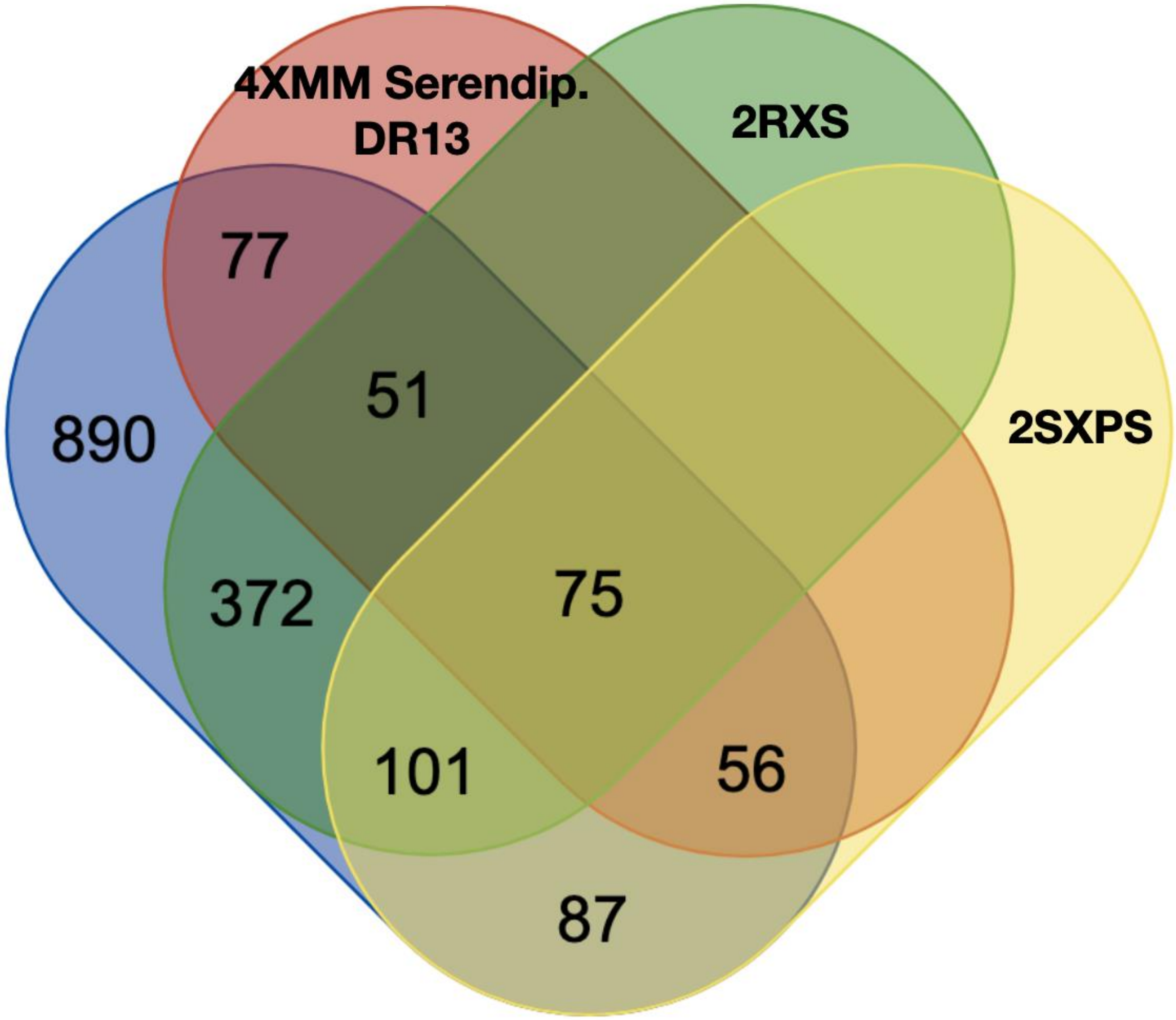
Bayesian Excess variance (bexvar)



According to an ANOVA test comparing the means across all count rate groups (indicated by black error bars), both **AMP (p-value < 0.001) and NEV (p = 0.008) show a positive trend.**

SCATT_LO does not show a positive trend according to the ANOVA test. This is because AMP and NEV are most sensitive when the error bars are smallest at high count rates, whereas **SCATT_LO performs well even in the Poisson regime.**

Cross matches of the variable eROSITA sources with existing catalogs



Venn Diagram representing the **eROSITA variable sources distributed among the 4XMM DR13, 2RXS and 2SXPS catalogues.**

890 (52 per cent) of the sources are new detections by eROSITA.

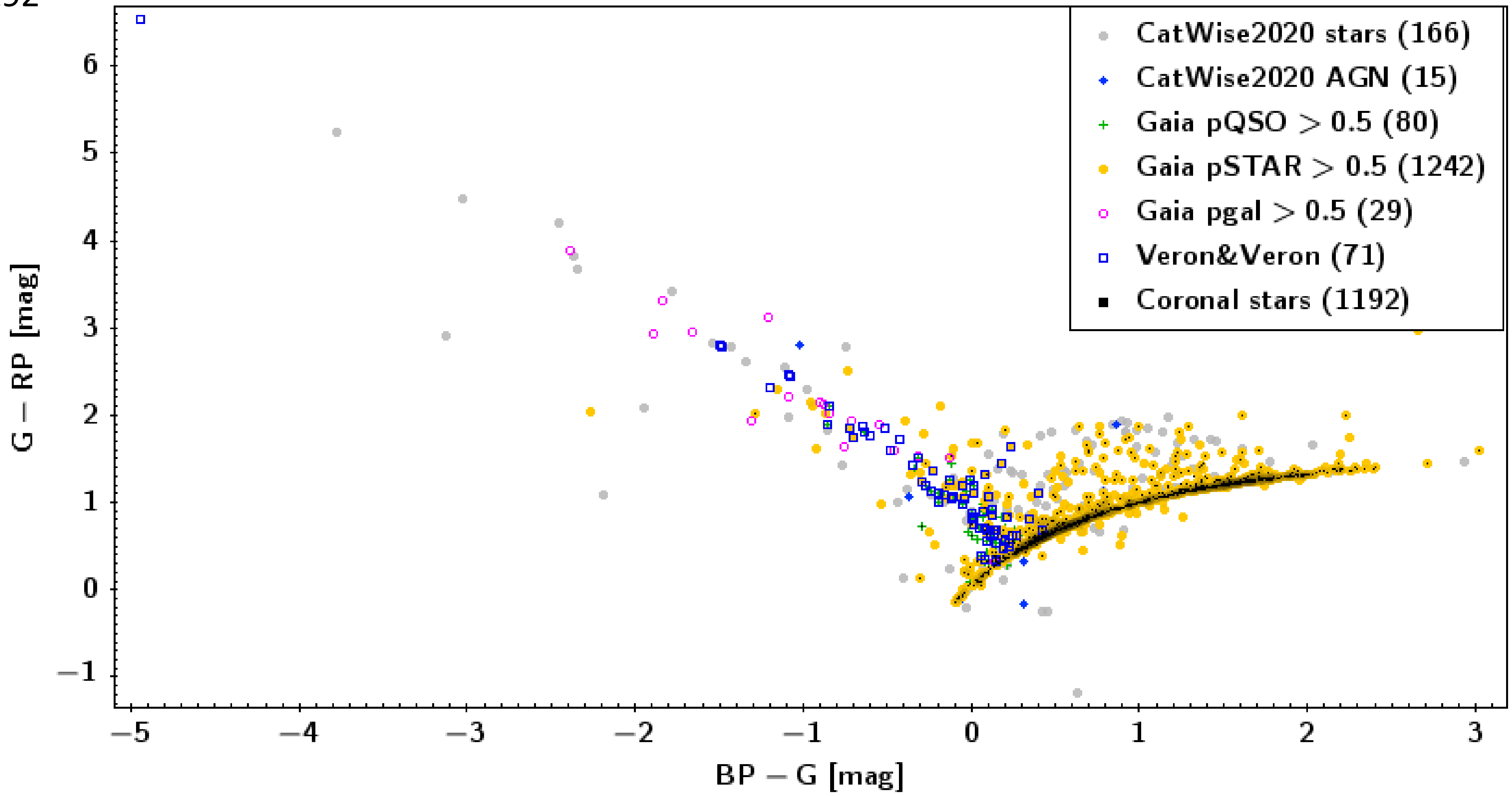
The DR1 variability catalogue is an excellent database for detailed follow-up observations with other X-ray telescopes.

Source class characterisation

coronal stars: 1192
Bright stars: 14

QSO: 71
Galaxies: 29

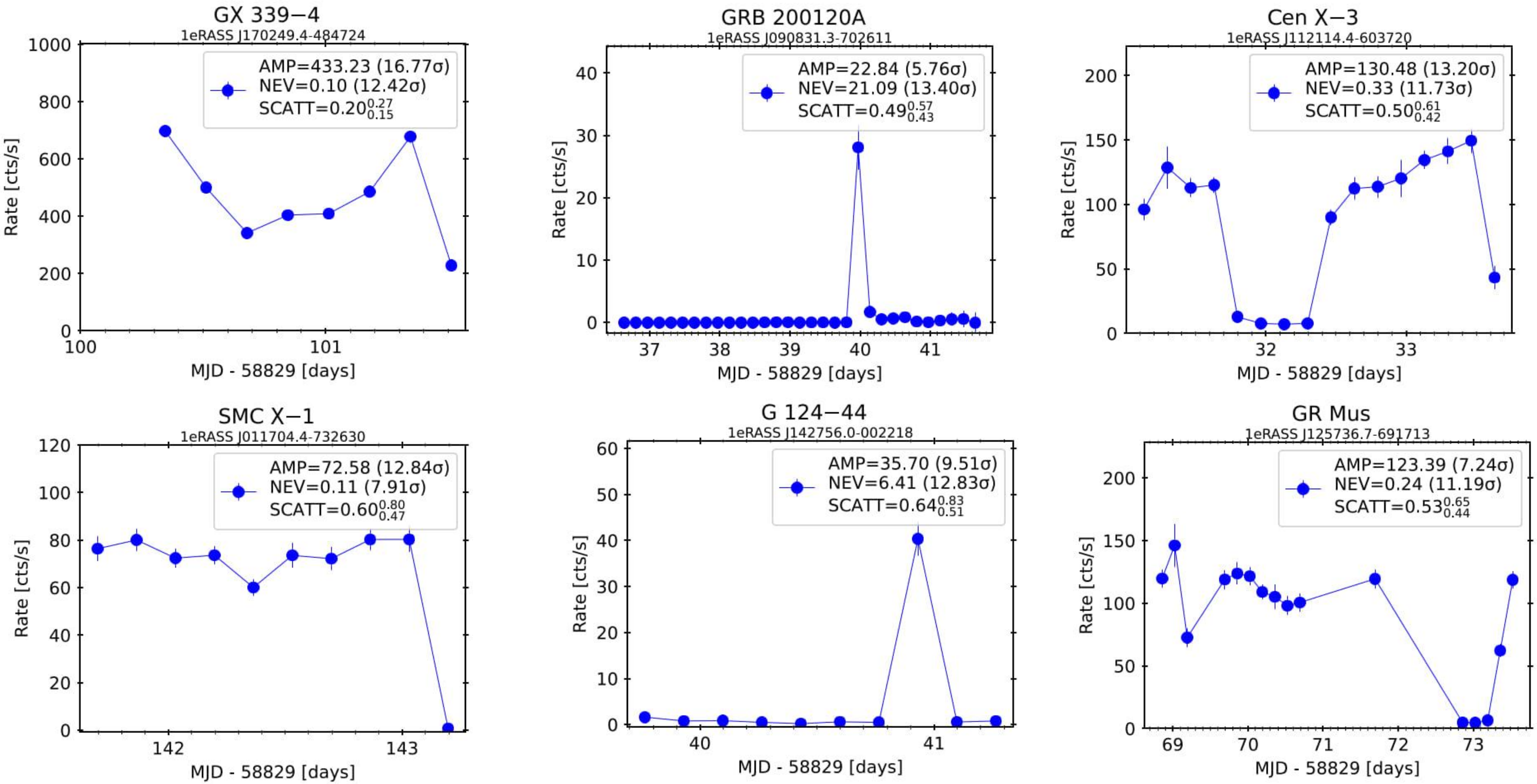
LMXB: 18
HMXB: 11



The majority of sources 1192 (69.7 per cent) are classified as coronal stars.

Only 188 of the 1708 (11 per cent) sources forming our catalogue are associated with extragalactic sources.

The most variable eRASS1 sources



The eROSITA DR1 variability catalogue

Th. Boller, M. Freyberg, J. Buchner, F. Haberl, C. Maitra, A. Schwope, J. Robrade, A. Rau, I. Grotova, S. Waddell, Q. Ni, M. Salvato, M. Krumpe, A. Georgakakis, A. Merloni, and K. Nandra