The Weirdest Sources in the CSC
A Machine Learning Approach

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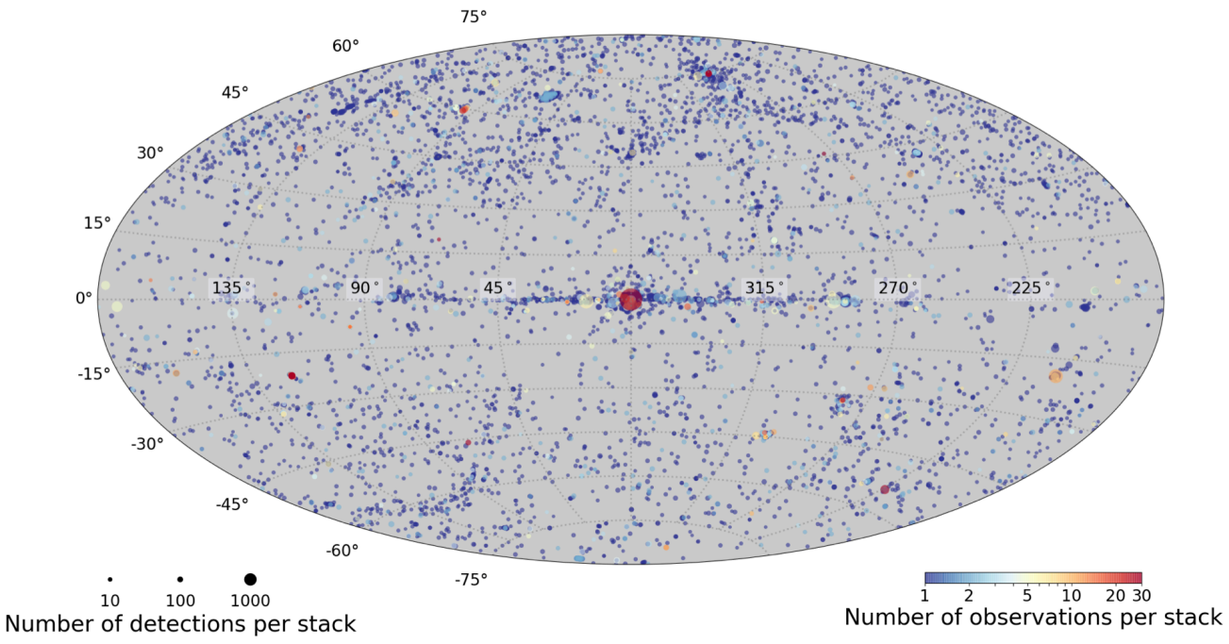
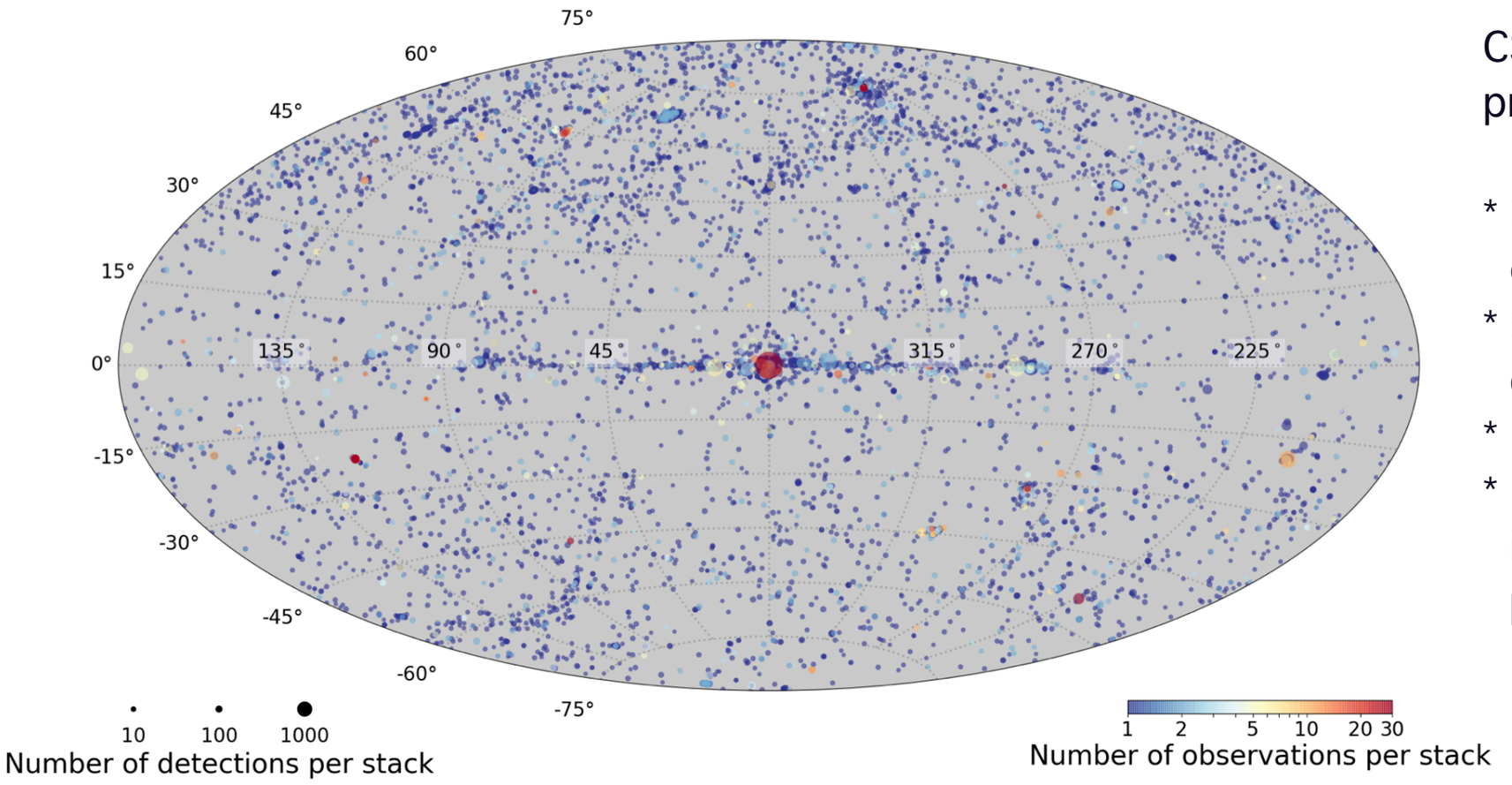


Chandra 20 Symposium - December 6, 2019

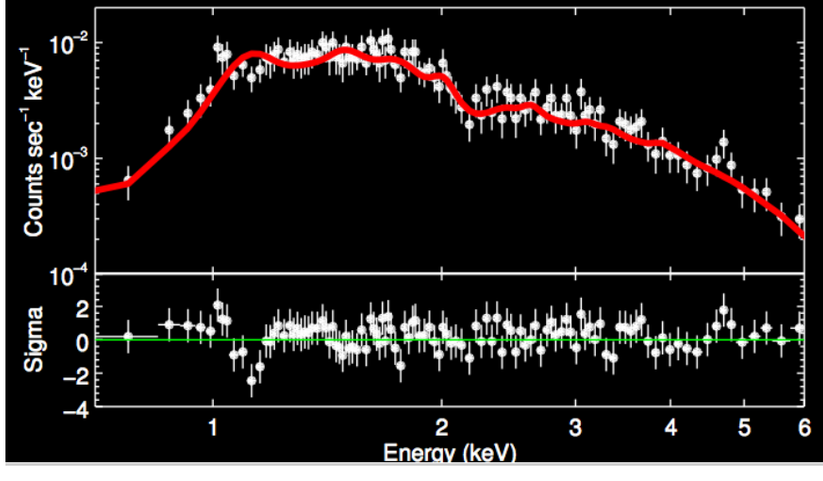
The Chandra Source Catalog 2.0



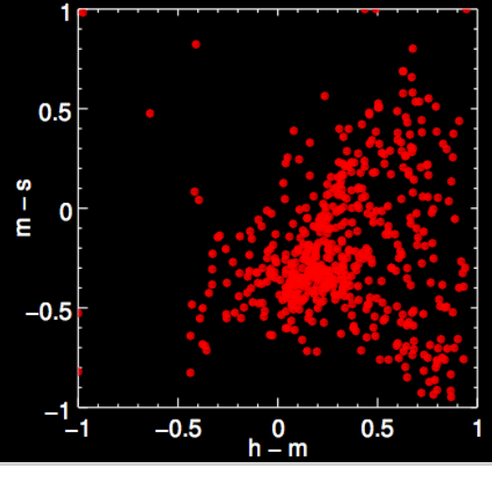
CSC 2.0 includes measured properties for:

* 317,167 unique compact and extended X-ray sources in the sky.
* 928,280 individual observation detections
* 7,287 stacks made from *
* 10,382 Chandra ACIS and HRC-I imaging observations released publicly through the end of 2014.

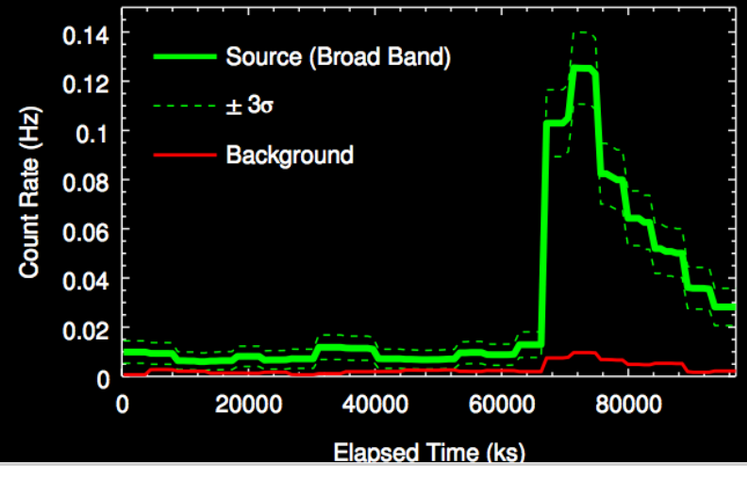
Spectral model fits and fluxes determined using multiple models



Hardness ratios



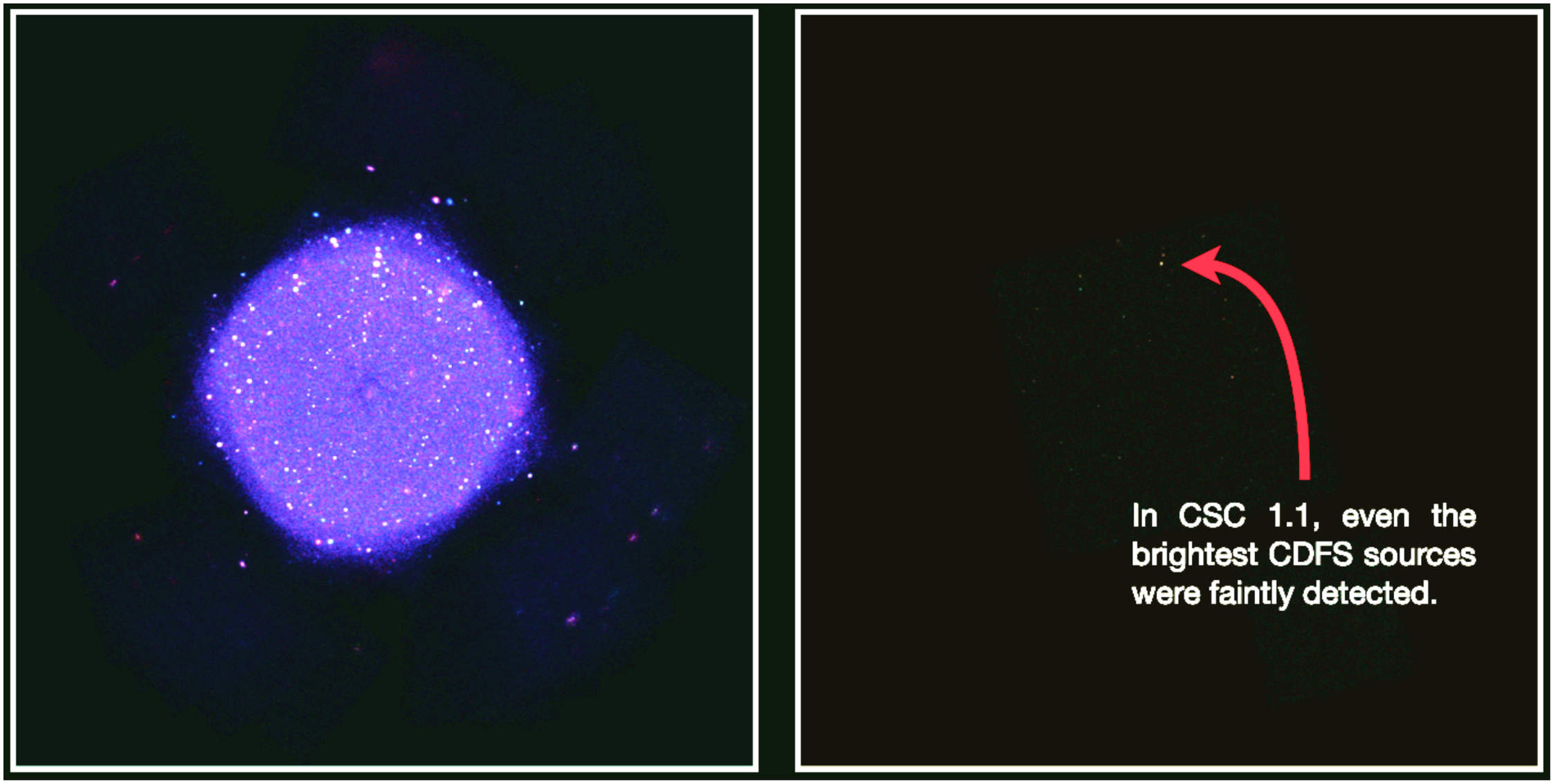
Intra- and inter-observation variability measures and light curves



CSC2: Detecting the faintest high-energy sources

Chandra Deep Field South in CSC 2.0 — stack of 81 observations, 5.8 Ms total exposure

Source detection in CSC 2.0 is performed on *stacked* (co-added) observations to enhance source detectability



Visit: http://cxc.harvard.edu/csc2/

The question-driven approach

Well defined, pre-established research questions, e.g.:

- What is the nature of gravitational wave sources progenitors?
- What is the value of Ω_0 to a precision below 1% percent?
- How common are terrestrial planets around main-sequence stars?

Known unknowns. Based on present knowledge

Design targeted observations/ surveys. Model specific objects.
TAC panels are tuned for this.

Solar System and Exoplanets
Stars and WD
WD Binaries and CV
BH and NS Binaries
SN, SNR and Isolated NS
Gravitational Wave Event
Normal Galaxies: Diffuse Emission
Normal Galaxies: X-ray Populations
Active Galaxies and Quasars
Clusters of Galaxies
Extragalactic Diffuse Emission and Surveys
Galactic Diffuse Emission and Surveys

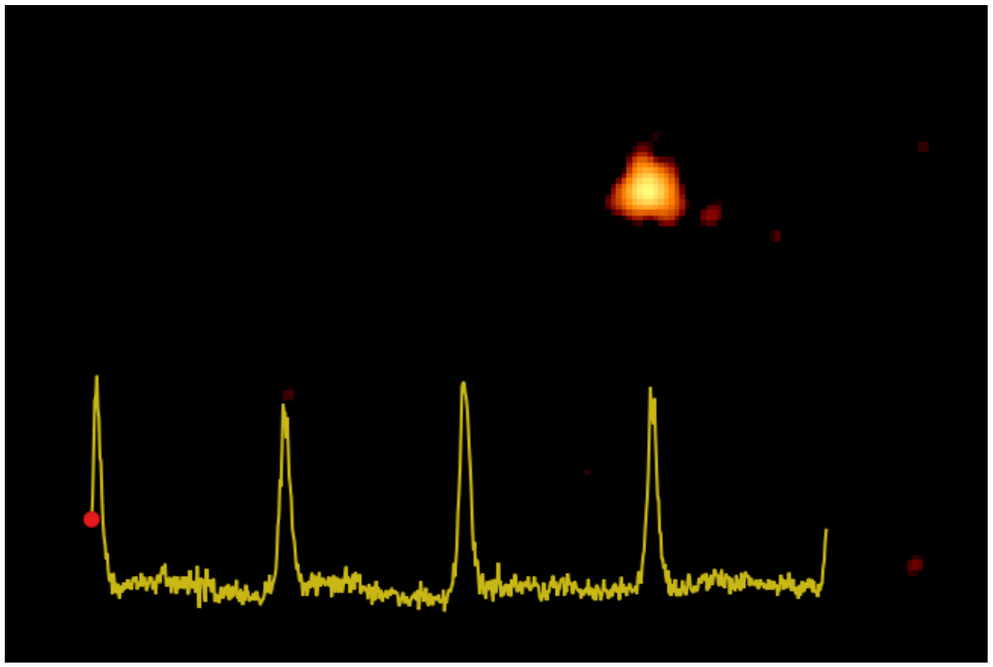
Cool stuff that no one can explain!

The exploration approach

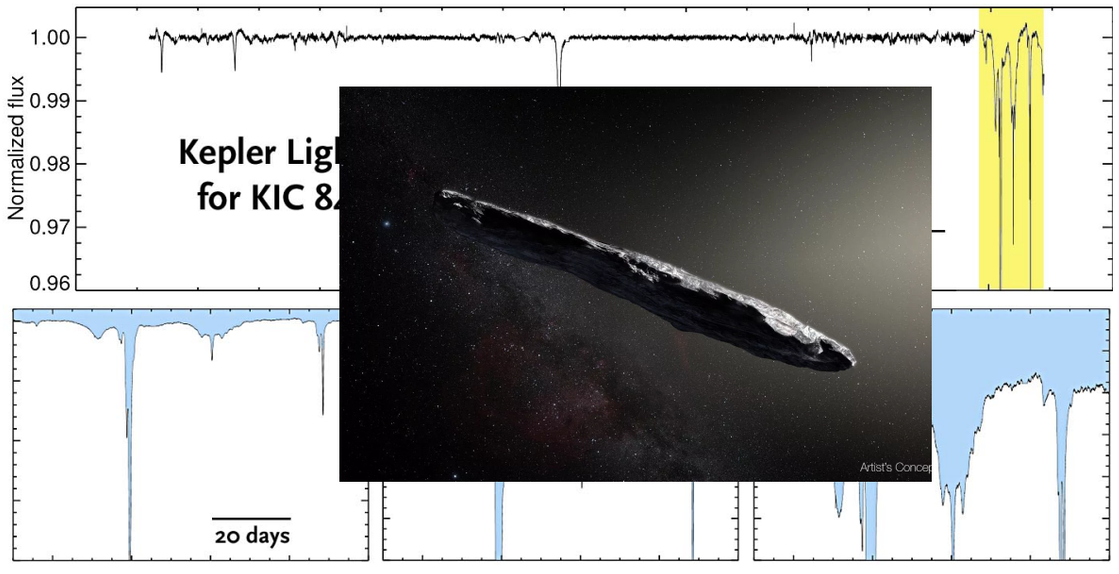
Gain the capability to pose **new** questions, to formulate new hypotheses.

- This is a way to deal with the *unknown unknowns*
- Particularly pressing in astronomy, a science which is mostly exploratory
- We need to expand our discovery space.

The golden age of machine learning in astronomy combined with exquisite datasets like CSC 2.0 provide the perfect opportunity to do so.

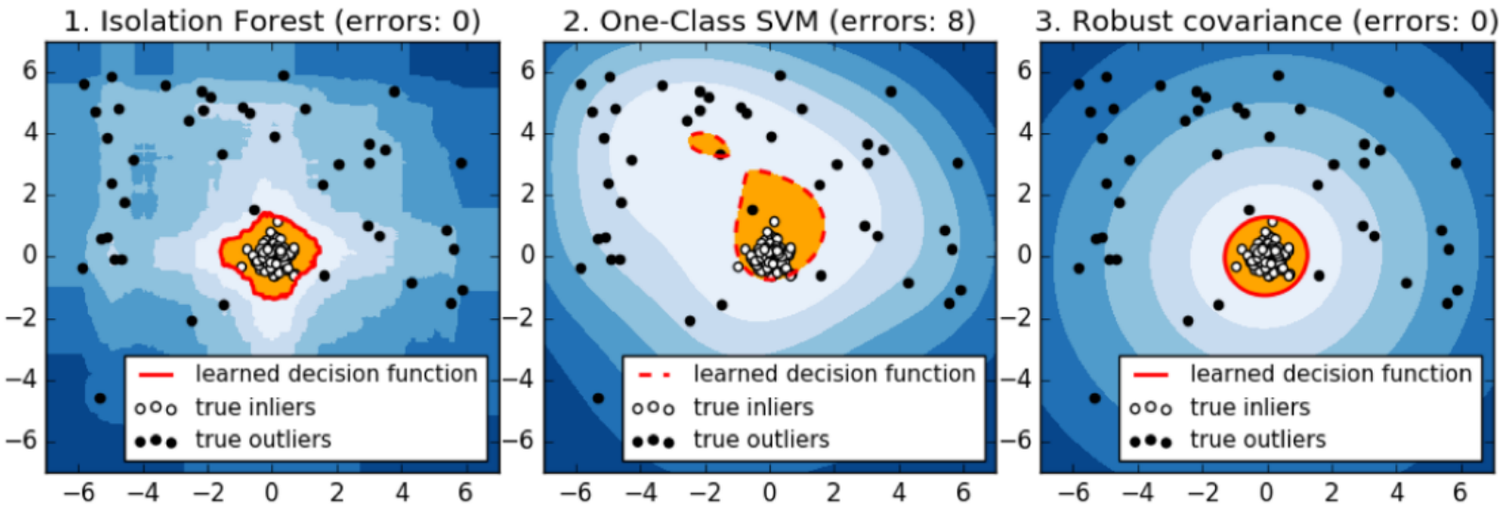


Quasi-periodic oscillations in GSN 069 likely due to a tidal disruption event “in pieces.” (Miniutti et al. 2019, Nature). This was a **serendipitous** discovery



Making serendipitous discovery systematic - Finding anomalies

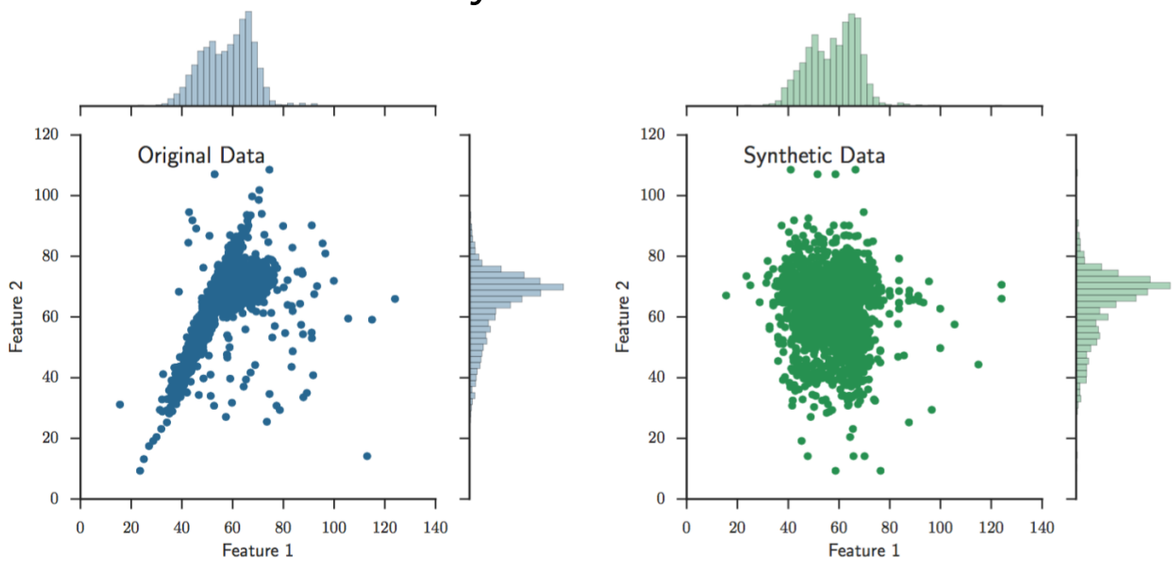
"An anomaly is an observation that differs so much from other observations as to arouse suspicion that it was generated by a different mechanism"
-- Hawkins (1980)



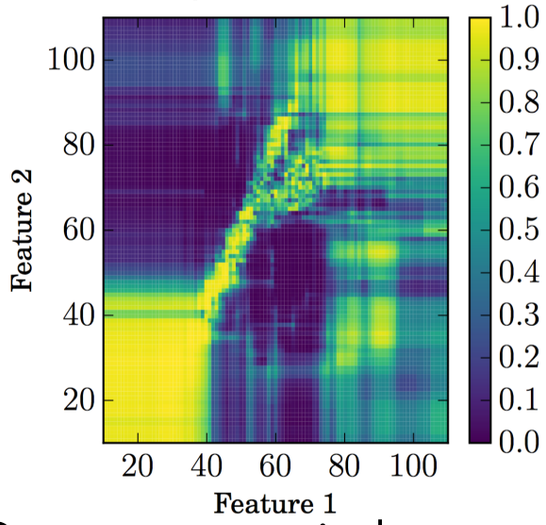
- We need a metric to measure similarity (or dissimilarity) between them. Not so easy in multidimensional parameter spaces.
- We also need a set of features to characterize each example in the dataset. These features can be defined by the scientist, or found through, e.g., deep learning.
- We then rank all objects in our dataset according to their dissimilarity from other objects.
- **Anomalies are scientifically interesting objects: they are often not explained by current models, and could lead to new discoveries.**

Unsupervised Random Forest

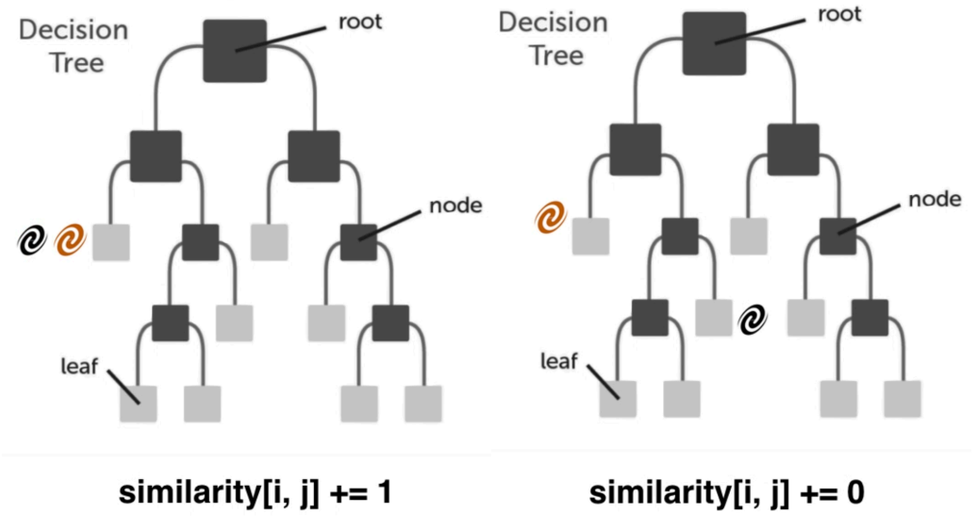
1. Generate synthetic dataset from



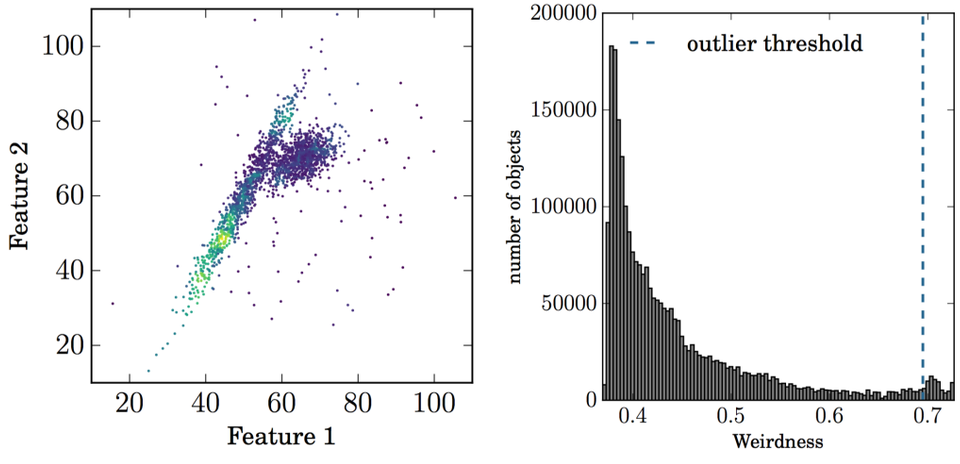
2. Train RF classifier with real+synthetic data



3. Propagate the real data



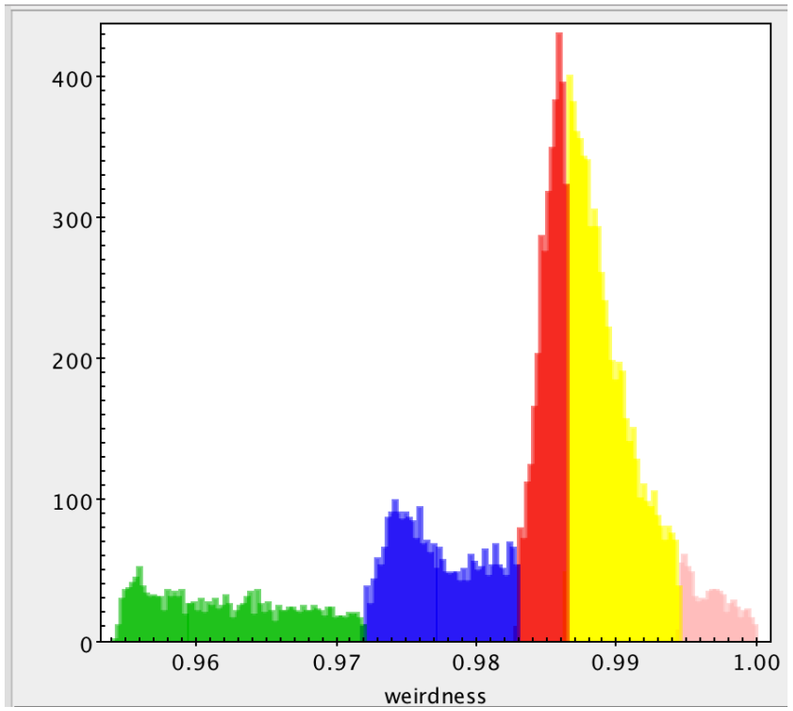
4. Compute weirdness

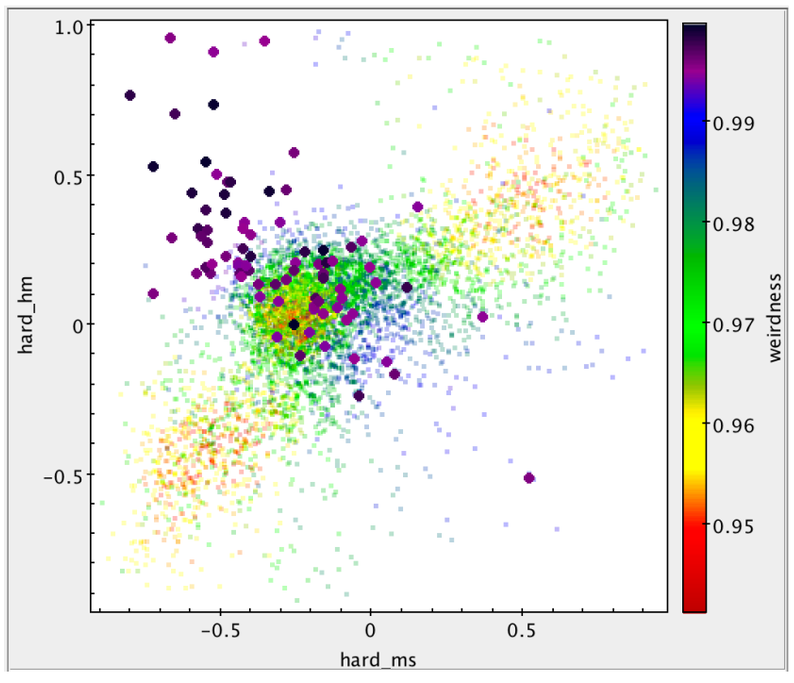


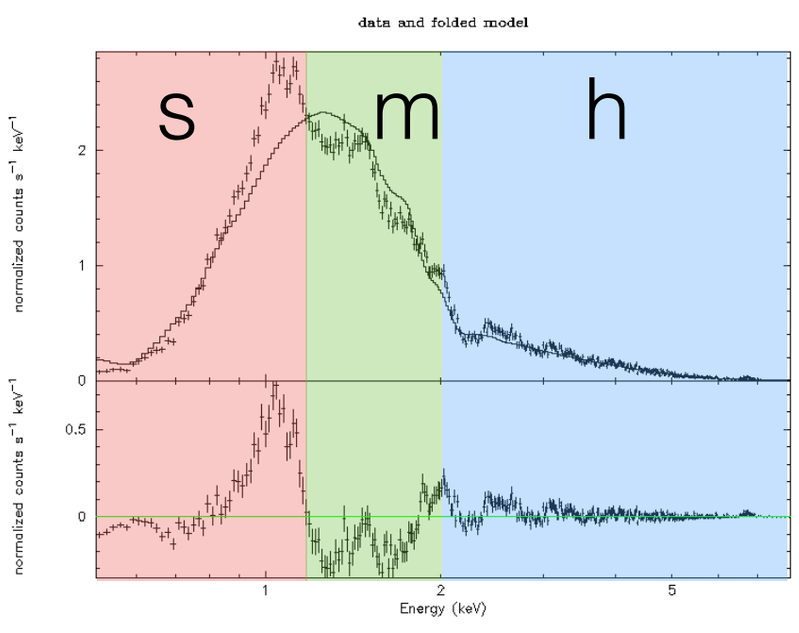
Baron & Poznanski , 2017

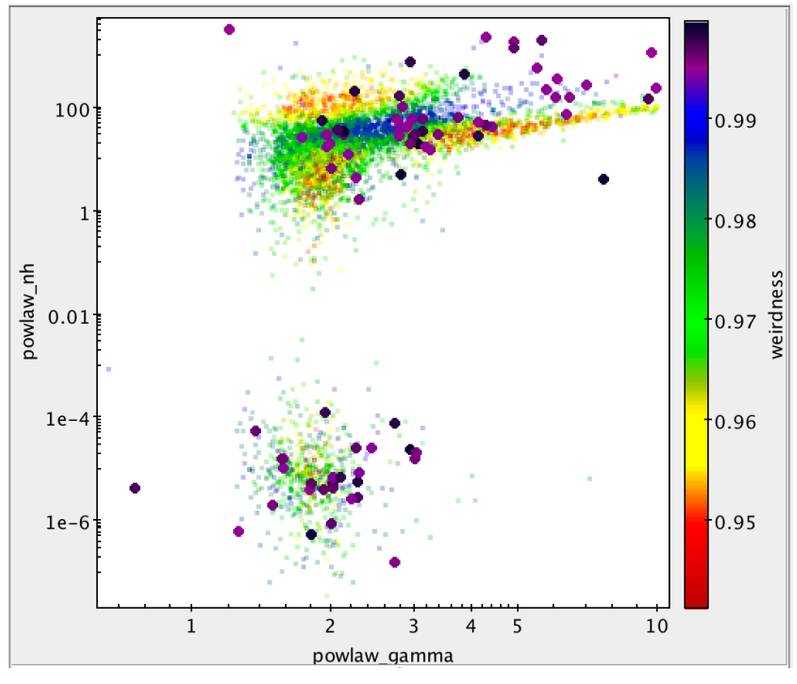
What CSC 2.0 features matter?

- We performed a feature importance analysis using scikit-learn.
- This is based on what features are used the most to split the trees during the training of the model.
- Features that come at the top are:
  - Hardness ratios
  - Spectral fit parameters
  - Spectral variability

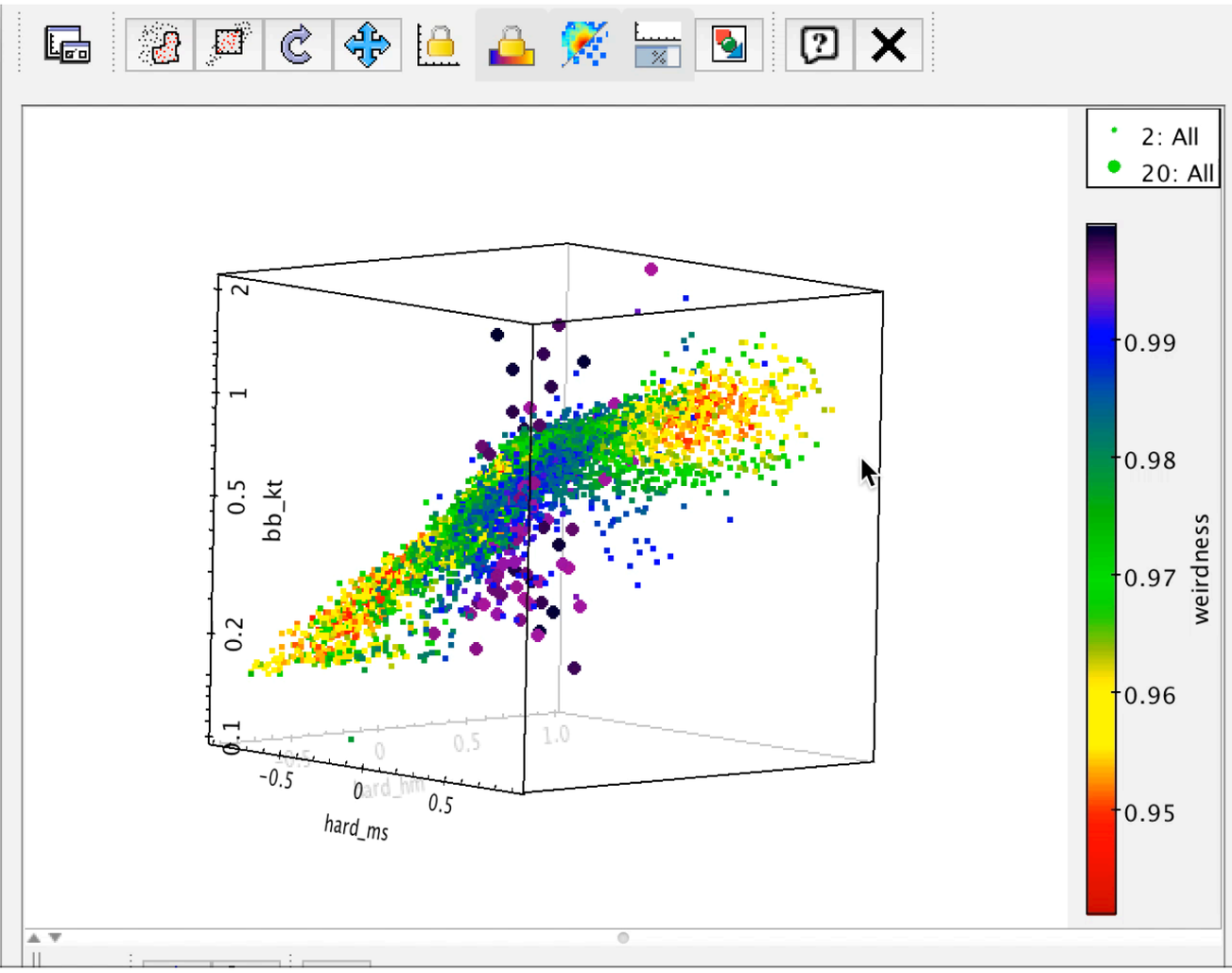


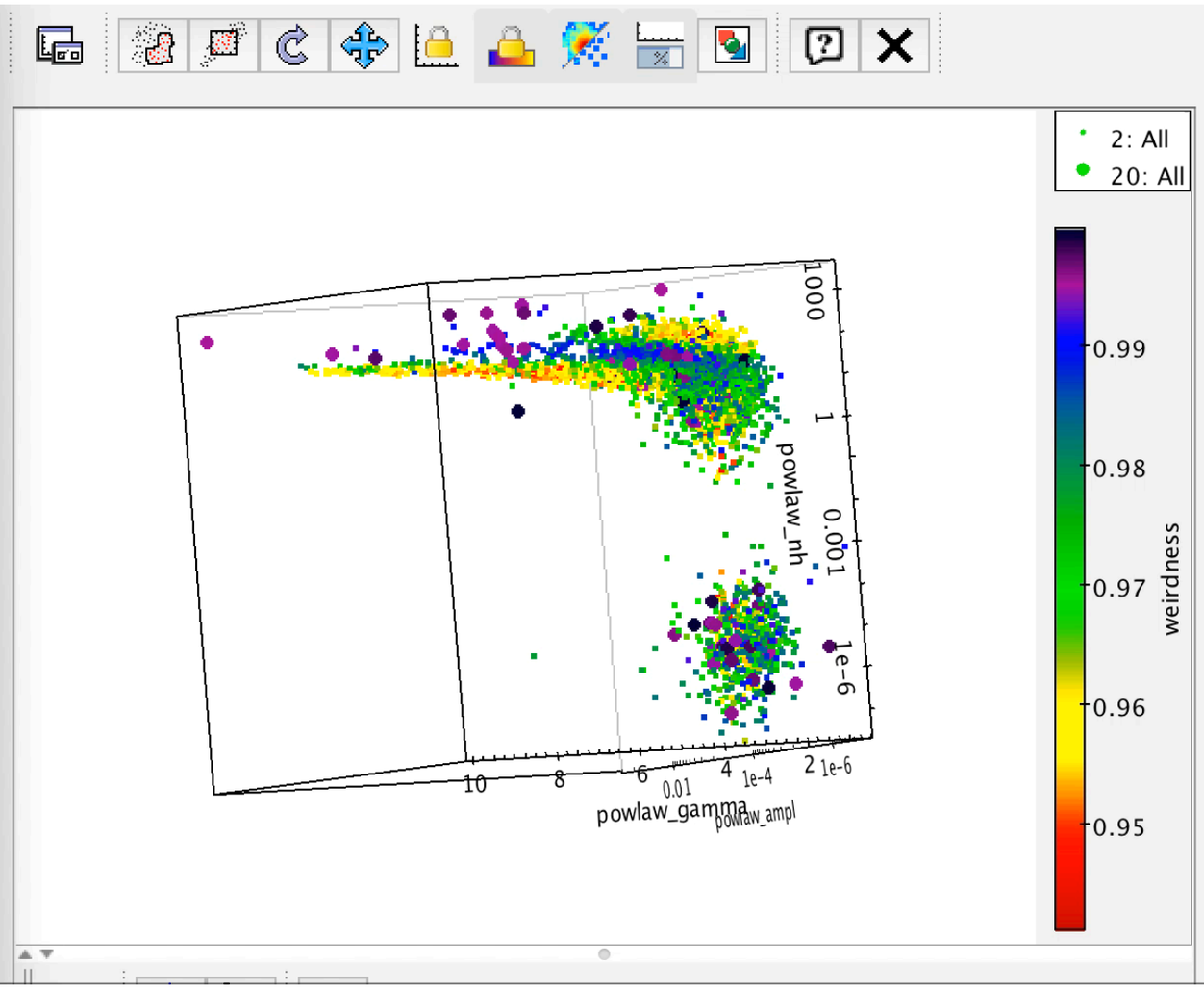






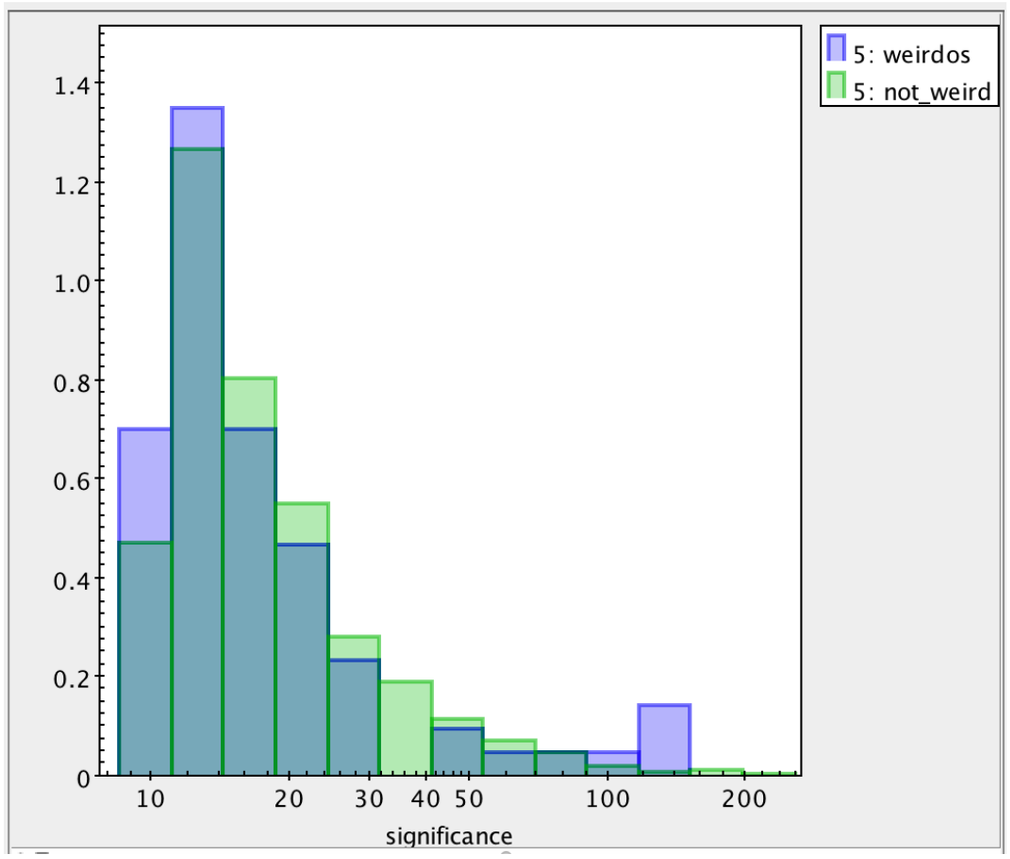
Outliers are sampled from a different distribution



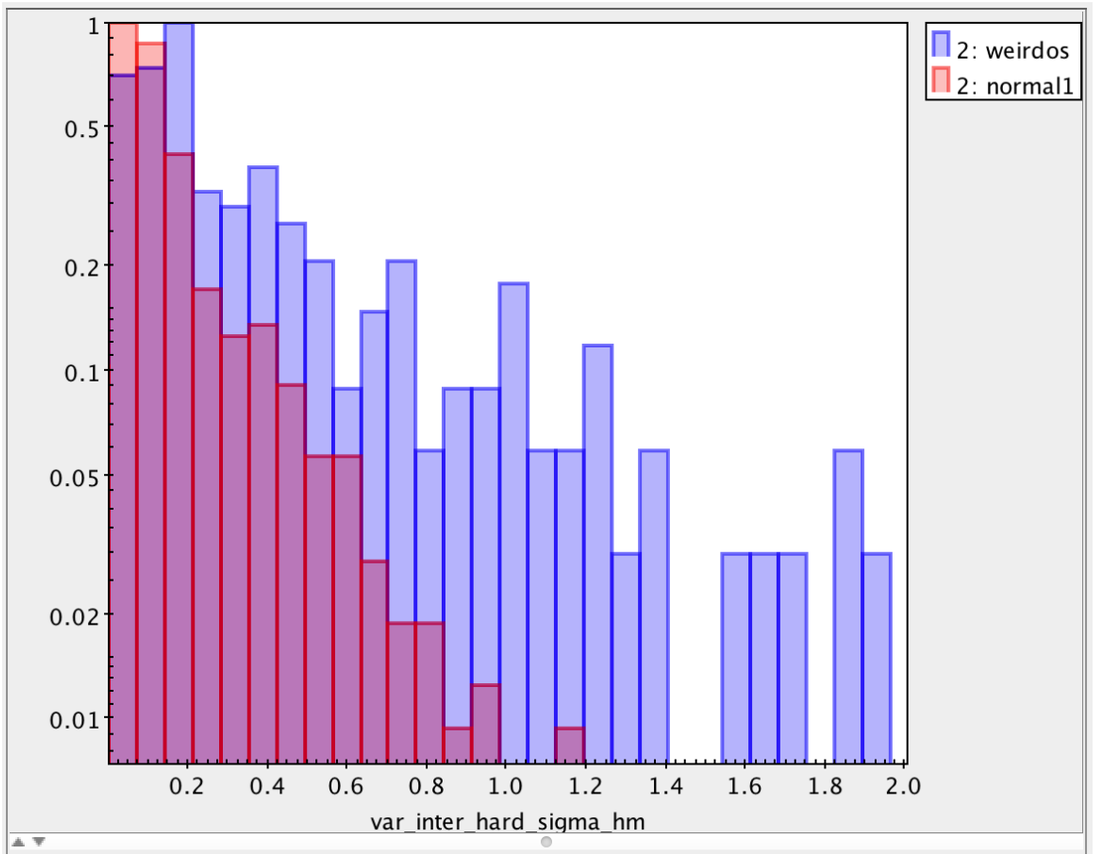


Are we just picking artifacts?

Important: weirdness does not depend on significance



But weirdos are more likely to be spectrally variable



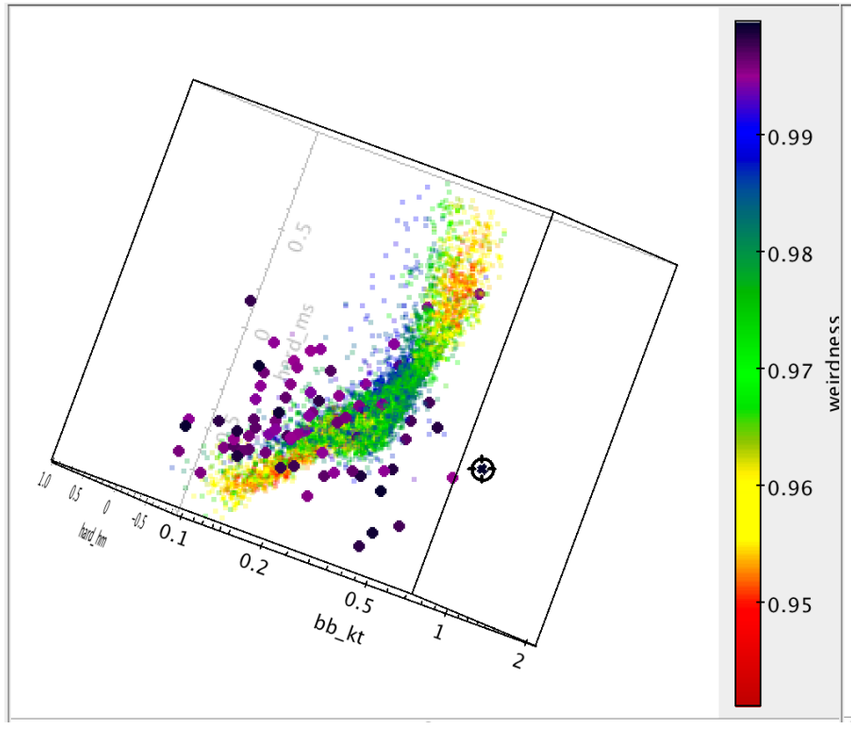
Spectral variability conveniently characterized in CSC2!
Look for var_inter_hard_prob, var_inter_hard_sigma

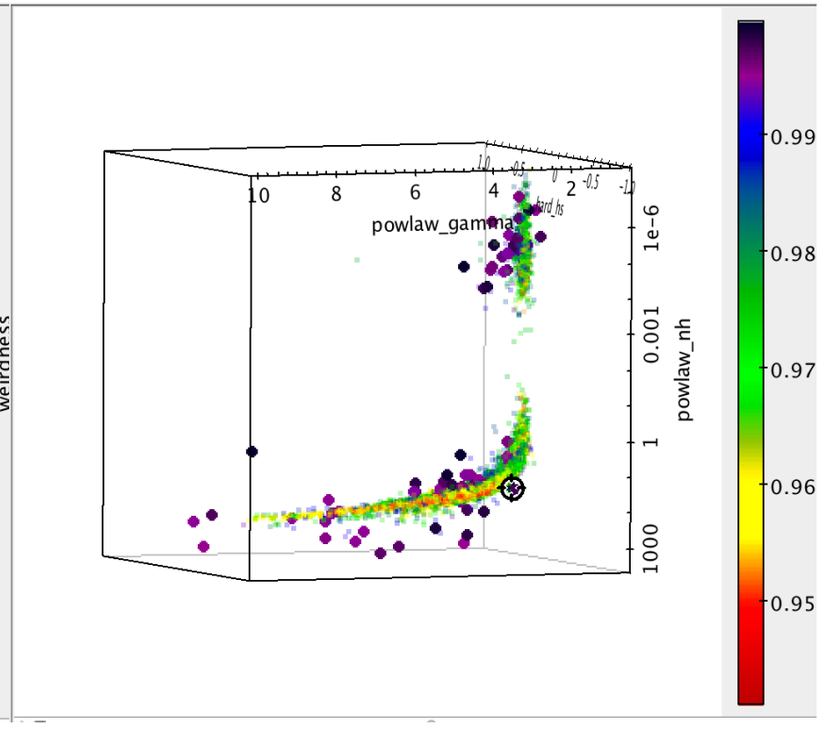
Example of a weird object

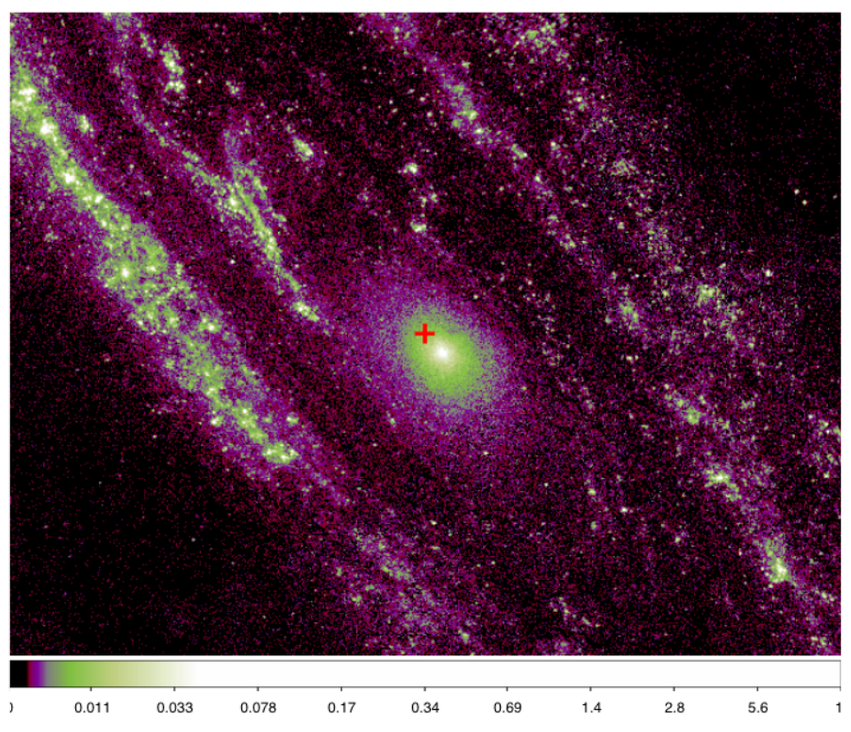
The Astronomer's Telegram

Post | Search | Policies
Credential | Feeds | Email

M 31 in X-rays with Swift - a new transient and an old source gone







Never characterized using Chandra data

Variability and Multi-Wavelength Aspects

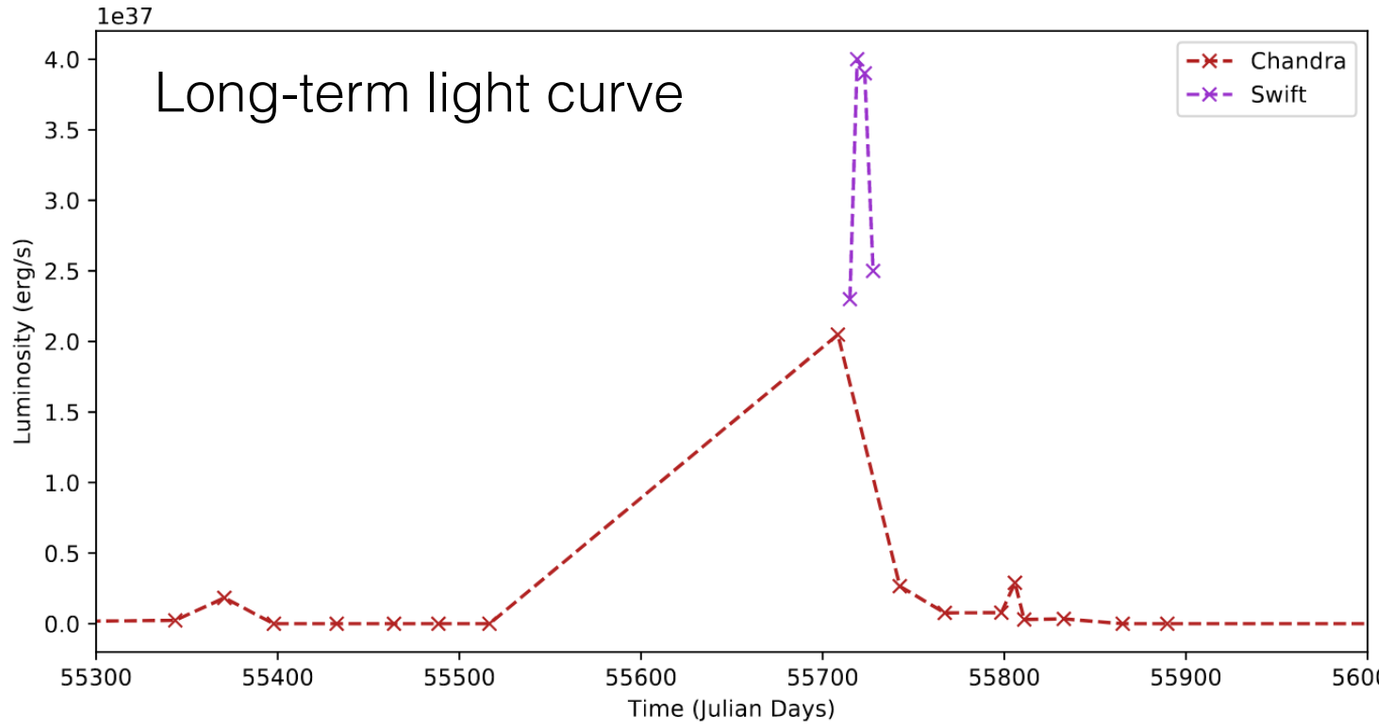
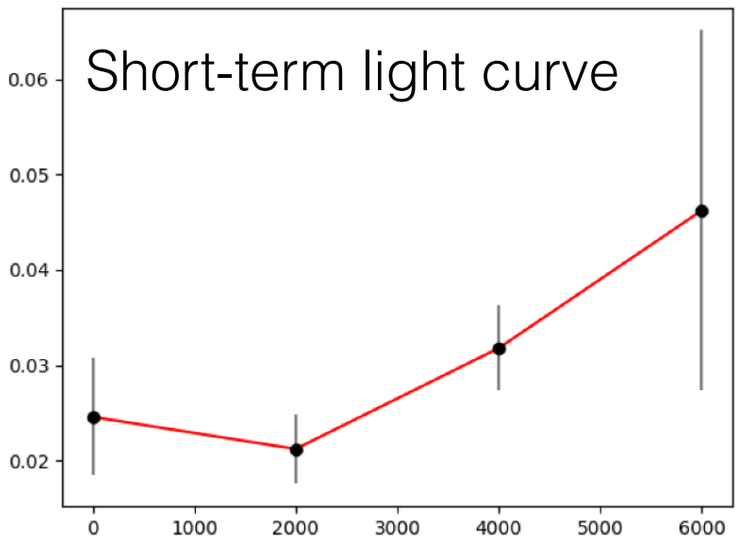
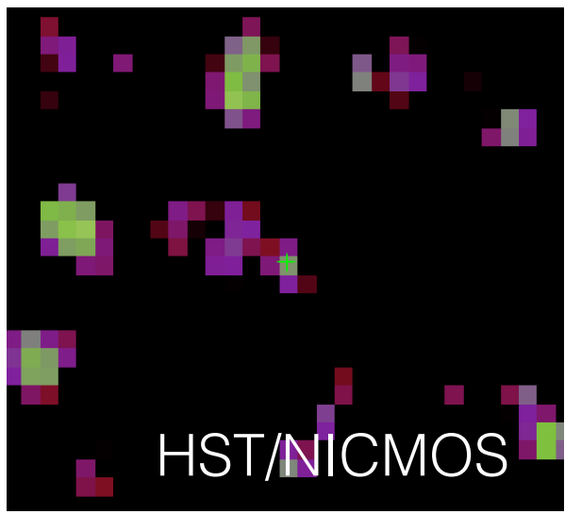
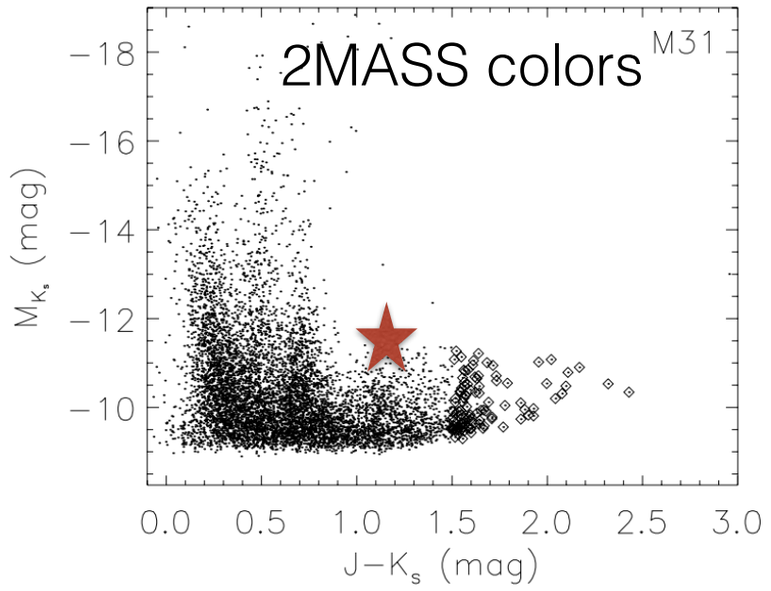


Figure 5. The light curve of the transient between May 2010 and May 2012, using Chandra and SWIFT observations

The transient seems to have undergone a second outburst a couple of months after the main one.







Spectral fits

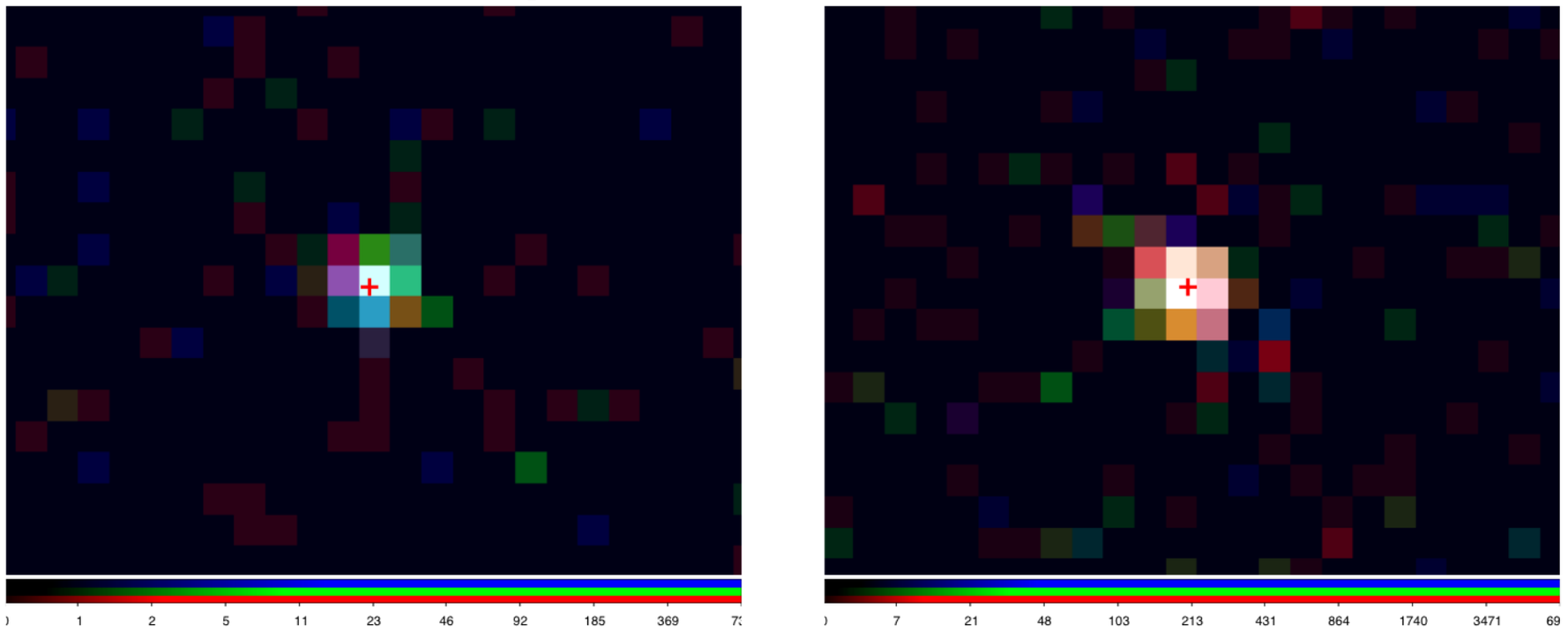


Figure 1. Three color stacked images (red: soft band, green:medium band, blue:hard band) of the transient. The red cross indicates the position of the source as determined in CSC2. The left panel corresponds to the observation made on 2011-05-27, whereas the right panel corresponds to the observation made on 2011-09-01.

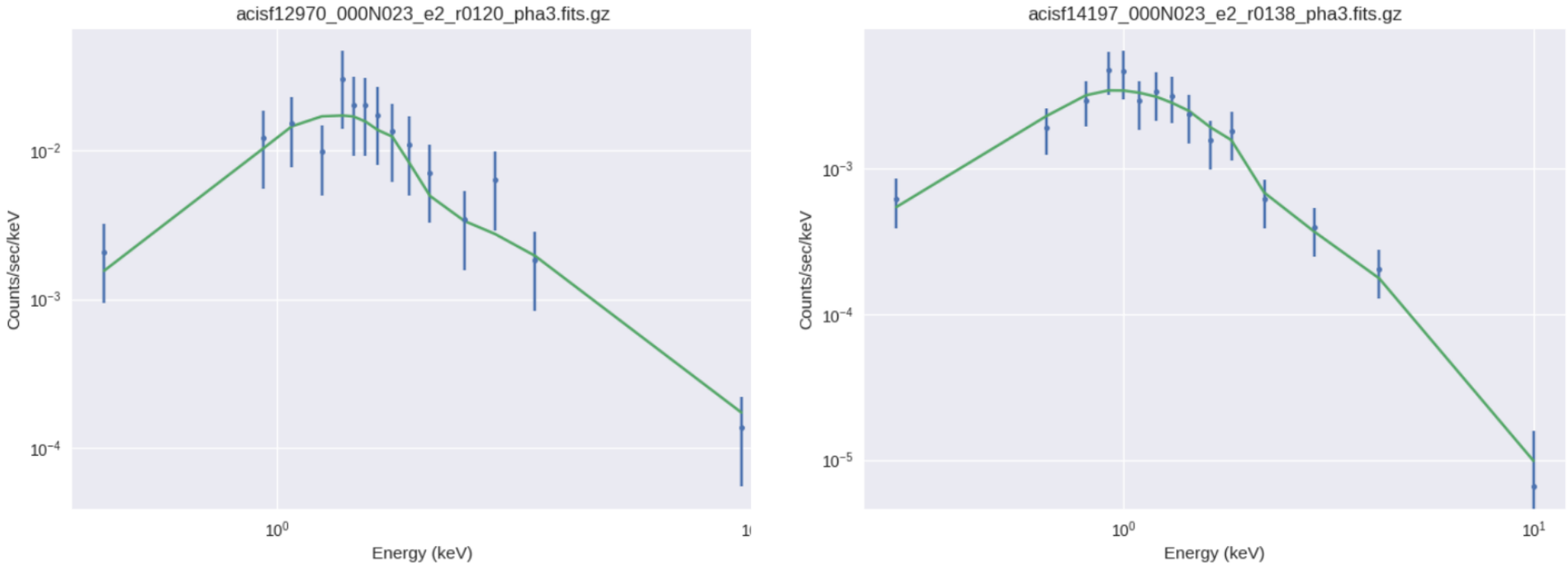


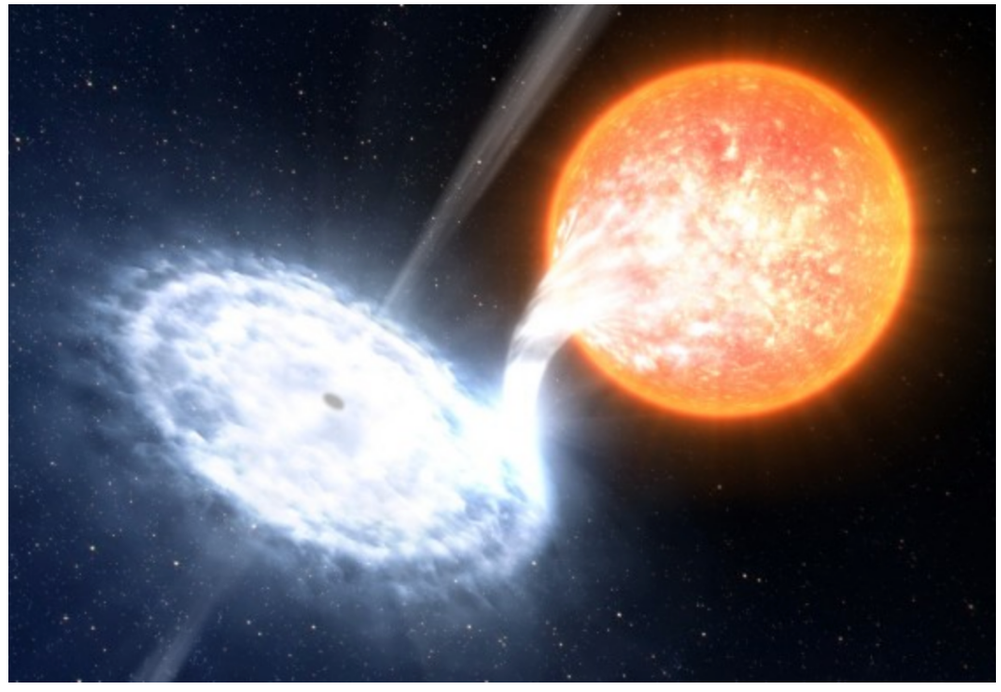
Figure 2. Power-law spectral fits to the two Chandra observations in which the transient is observed. The left panel corresponds to the observation made on 2011-05-27, whereas the right panel corresponds to the observation made on 2011-09-01. Note the significant increase in the total flux of the source.

Spectral fit parameters

obsid	statistic	n_H	$n_H^{\rm err}$	Γ	$\Gamma^{\rm err}$	ampl	ampl$^{\rm err}$
12970	5.27584	0.429982	0.280321	2.54135	0.547819	0.000133904	8.13E-05
14197	2.96245	0.0959689	0.0847944	2.16471	0.3681	9.96E-06	3.04E-06

Table 1. Spectral fit parameters for the transient using a single component power-law model.

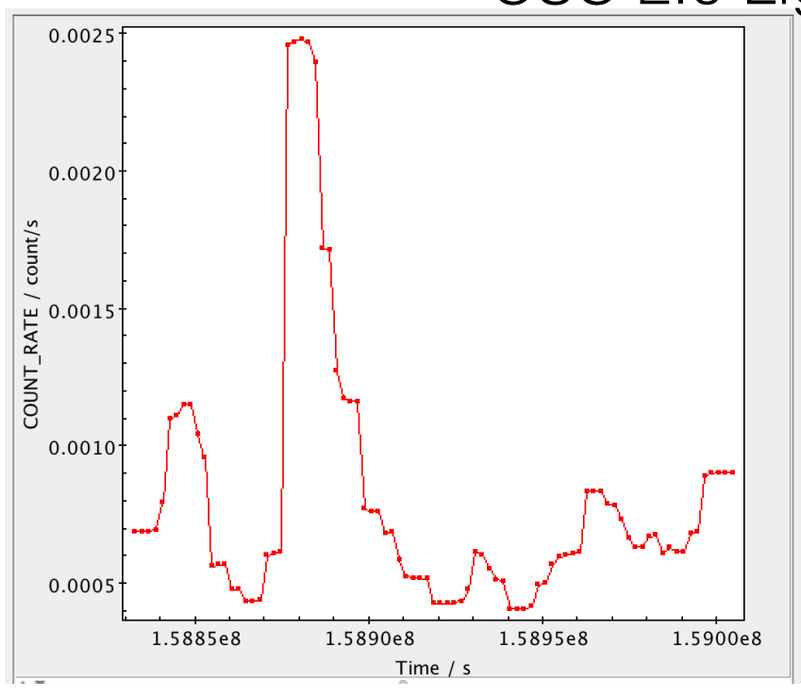
- Chandra peak luminosity: 2E37 erg/s
- Not a lot of star formation expected in the bulge of M31 - High mass binary unlikely.
- This transient is most likely an outburst from a low mass X-ray binary. If so, at the distance to M31 the IR emission might come from the disk.
- If not the disk, then the IR photometry of the source is consistent with the donor being and evolved (AGB?) red star. This is relatively rare.

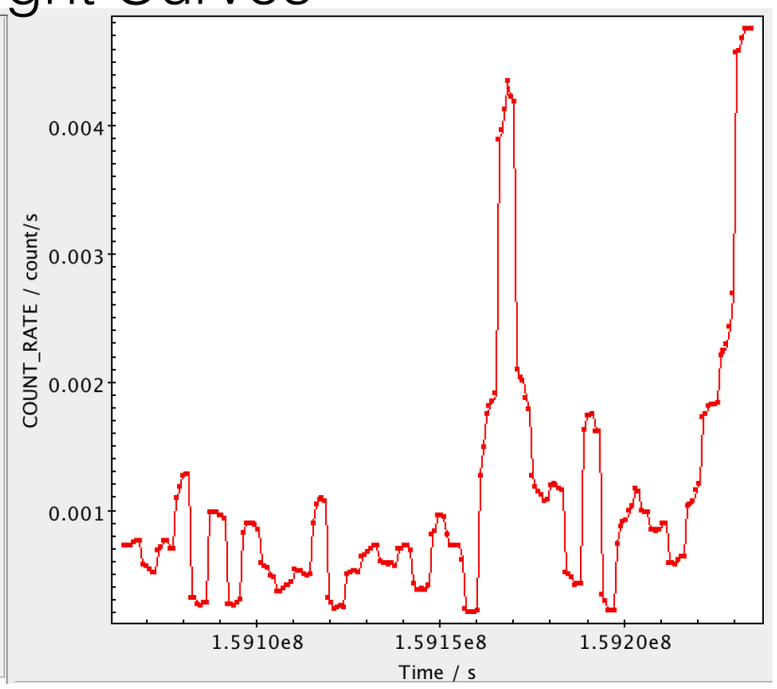


Example: Flaring cool stars

. Flaring events tend to be stronger in non-accreting YSOs. They provide insight about physical processes driving very dynamical events. How do we find them?

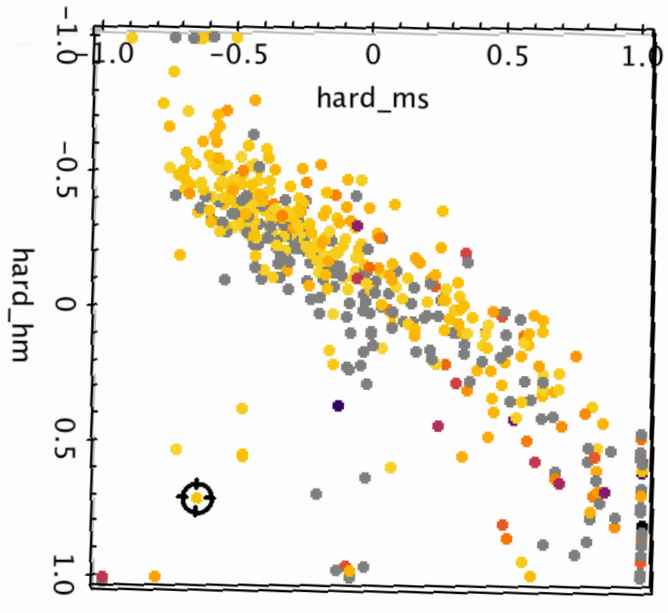
CSC 2.0 Light Curves

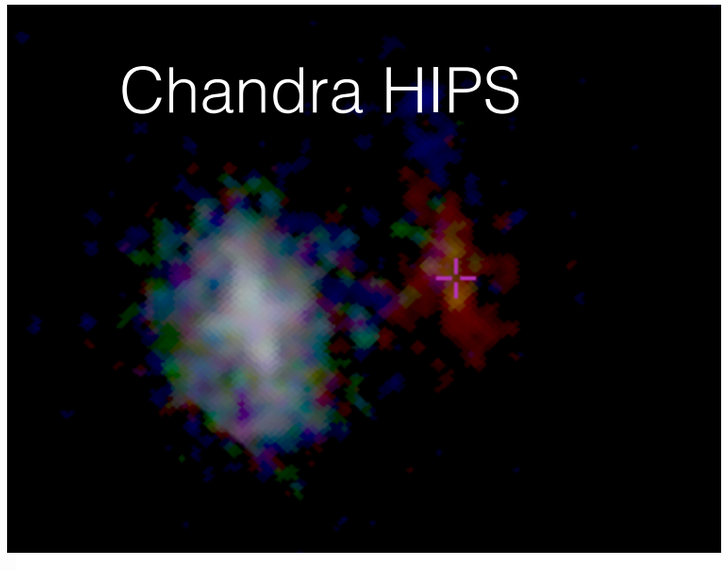


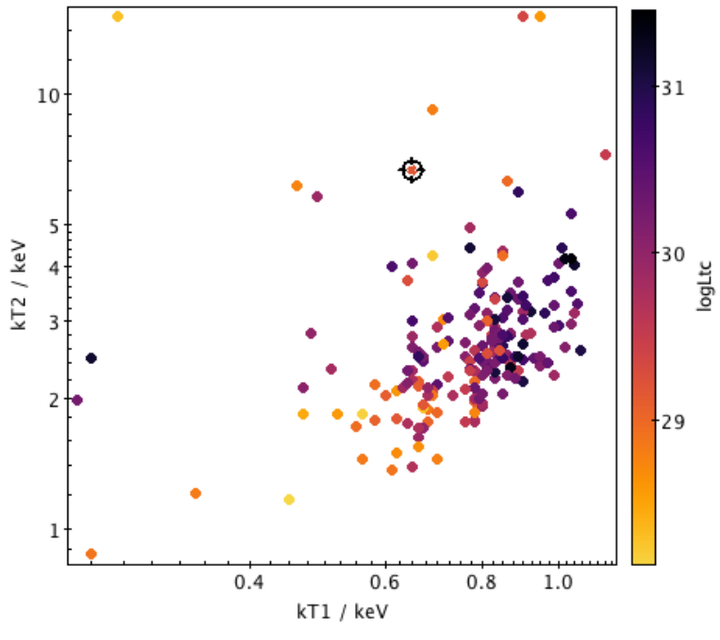


Both plasma temperature and hardness ratios indicate a moderately energetic and peculiar flare.

Other similar flaring young stars have been identified in Orion and other SF fields. Several of them are not characterized.







Got weirdos?

- Candidates for containing a stellar-mass black hole in early-type galaxies.

- Pulsating ULXs. - Georgios Vasilopoulos's told us about these earlier in this meeting.

- Highly obscured quasars and AGNs. Several not reported.

- Young stars with strong Fe line emission at 6.4keV.

- Unknown, rare new types of X-ray sources? Stay tuned!

Take home messages

- Anomaly detection is an excellent way to do “exploration approach” science.

- The Chandra Source Catalog is a fertile ground for discovery. But we are by no means constrained to limit the search to CSC.

- Astronomical outliers (anomalies) represent extreme stages in the evolutionary history of astrophysical objects - they used to be found by chance.

- In the golden age of data mining and machine learning, time allocation committees and funding agencies should be ready to be more welcoming to “exploration approach” proposals.

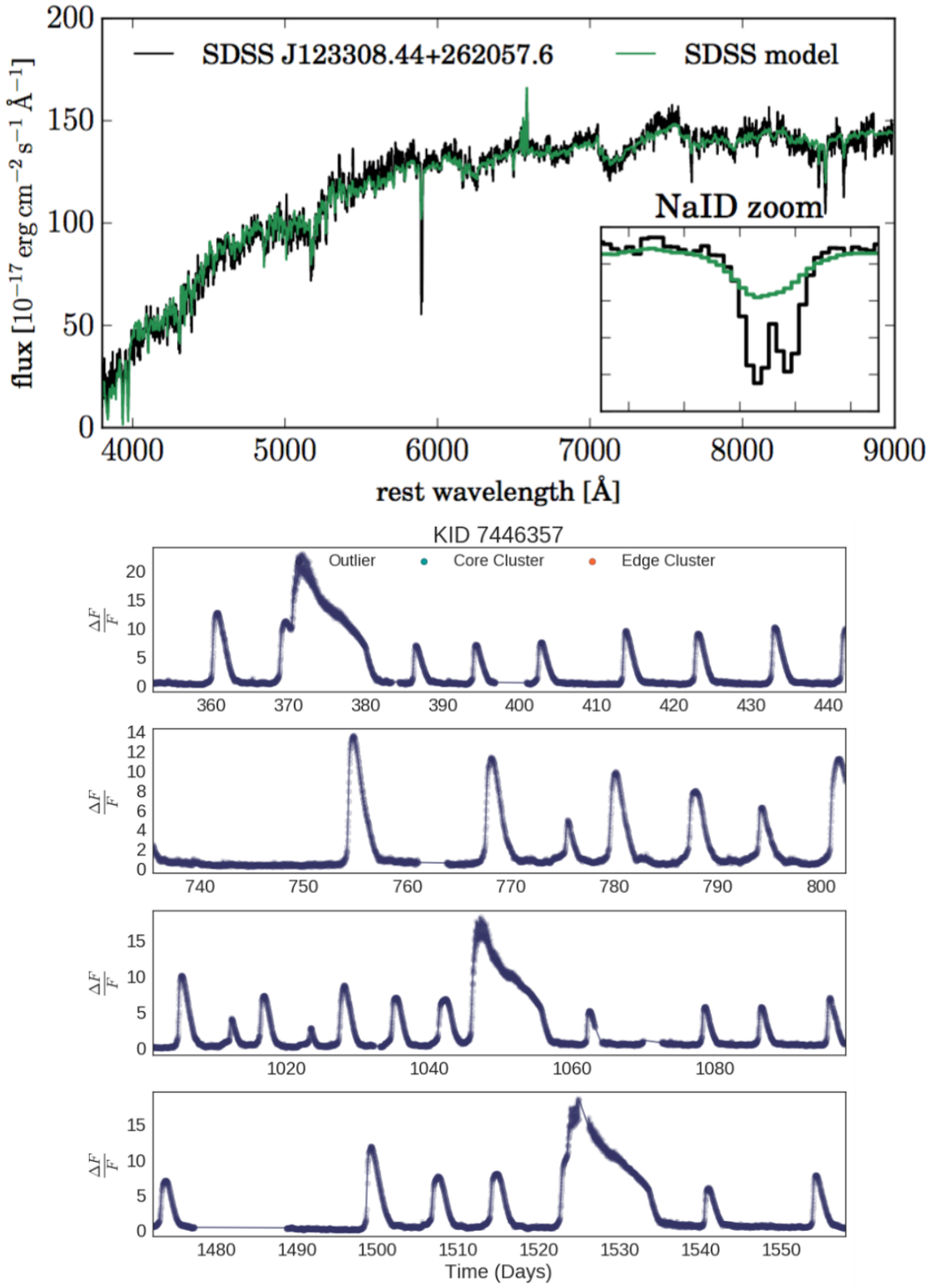
Thanks for a great conference!

Making serendipitous discoveries systematic

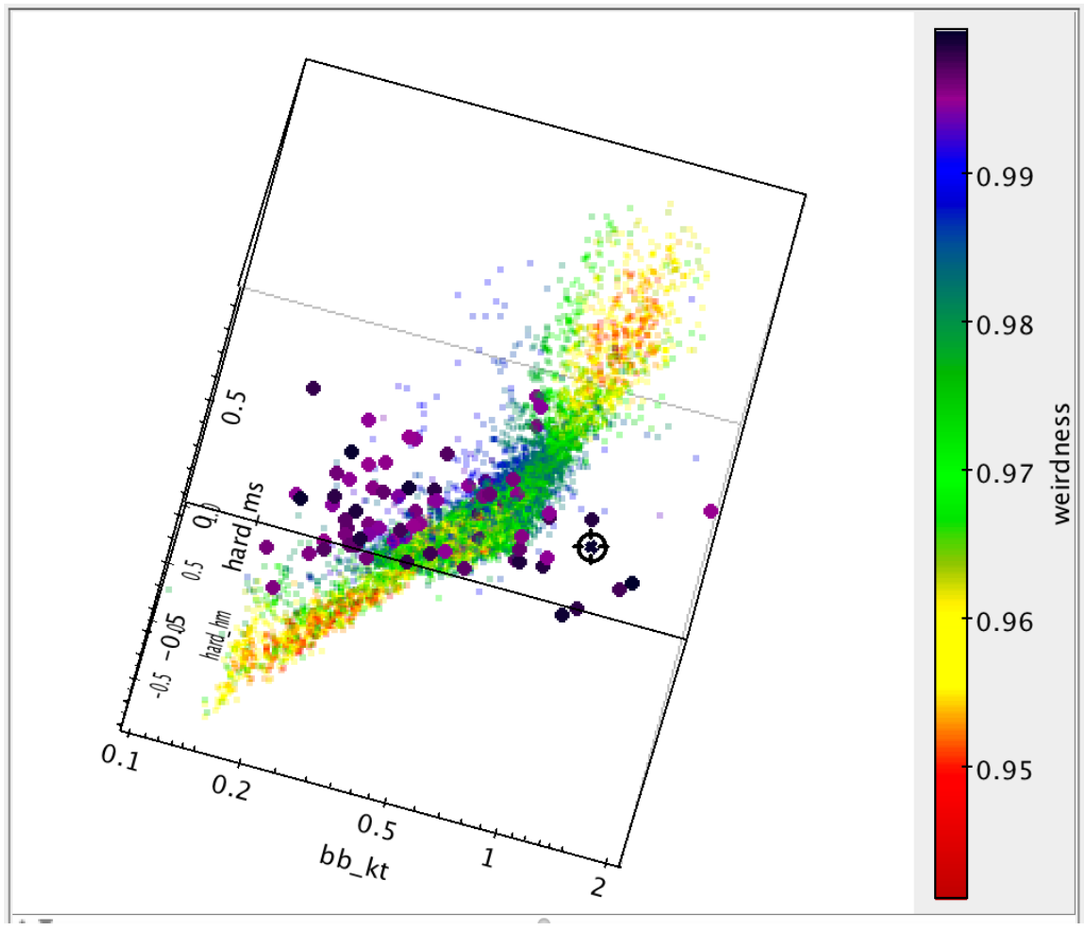
Anomaly detection algorithms offer a natural way to find the weirdest objects in large datasets.

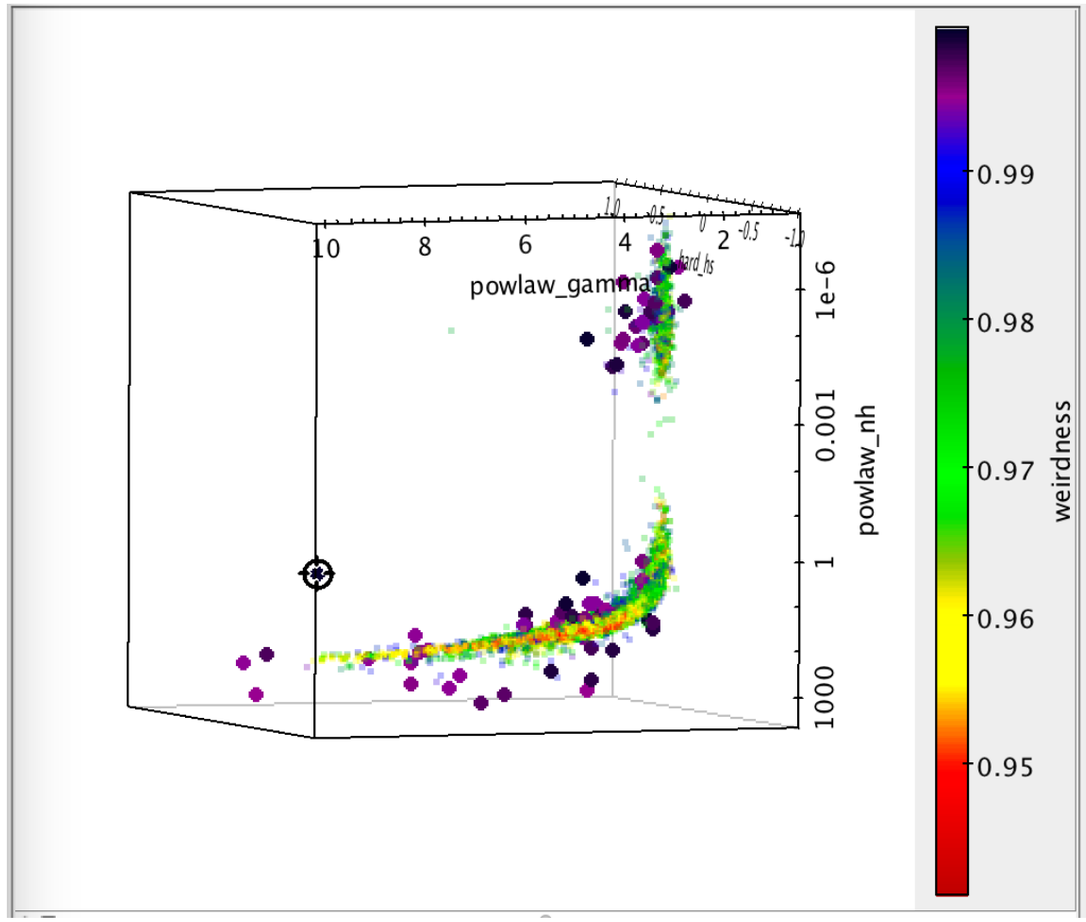
- Unsupervised Random Forest (URF) applied to SDSS spectra: complex velocity structures, extremely strong or rare absorption lines (Baron & Poznanski, 2017).

- Proximity clustering + dimensionality reduction applied to Kepler light curves: cataclysmic variables. (Giles & Walkowicz, 2019).



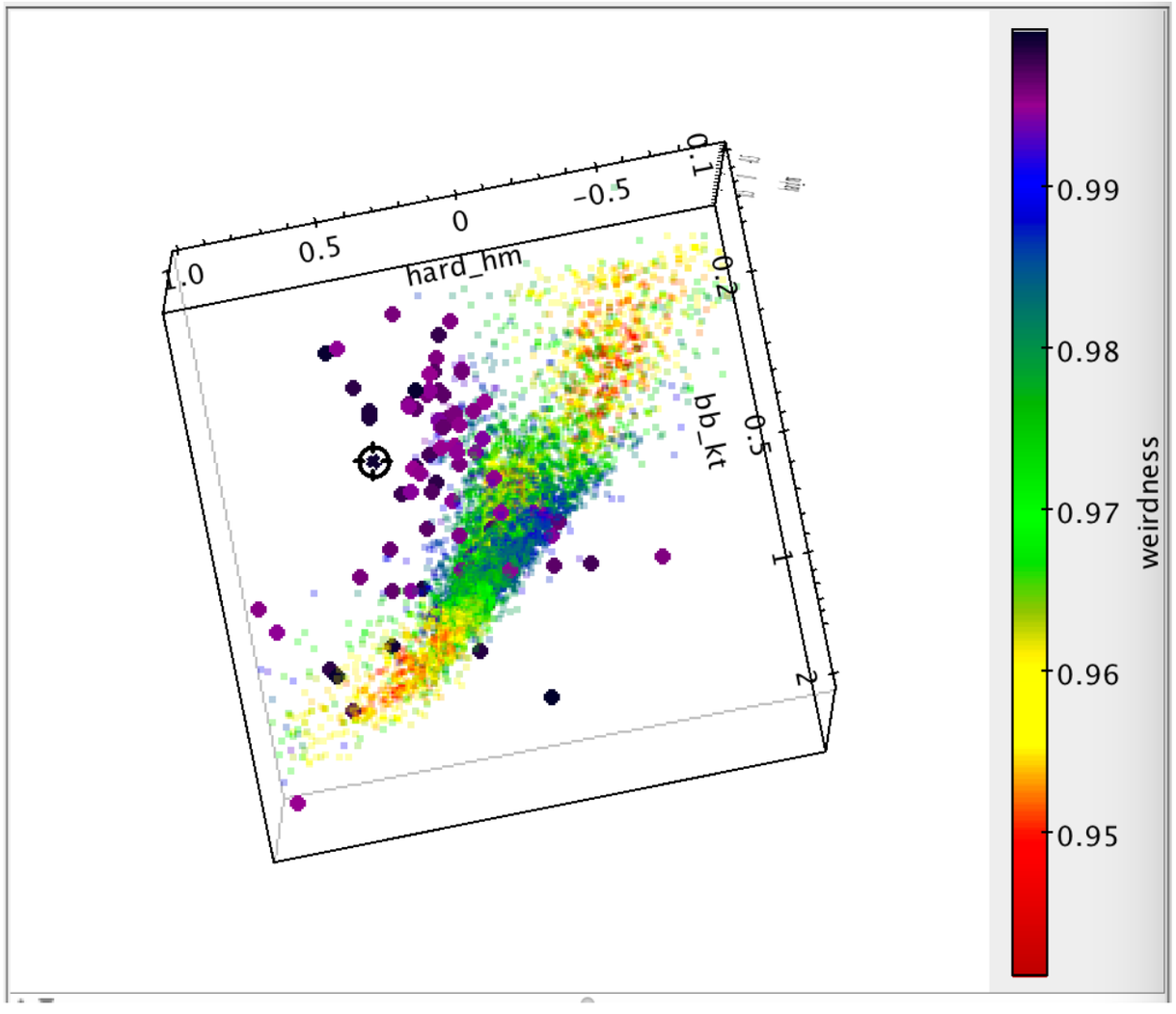
Unreported X-ray source in the outskirts of Abell 2052

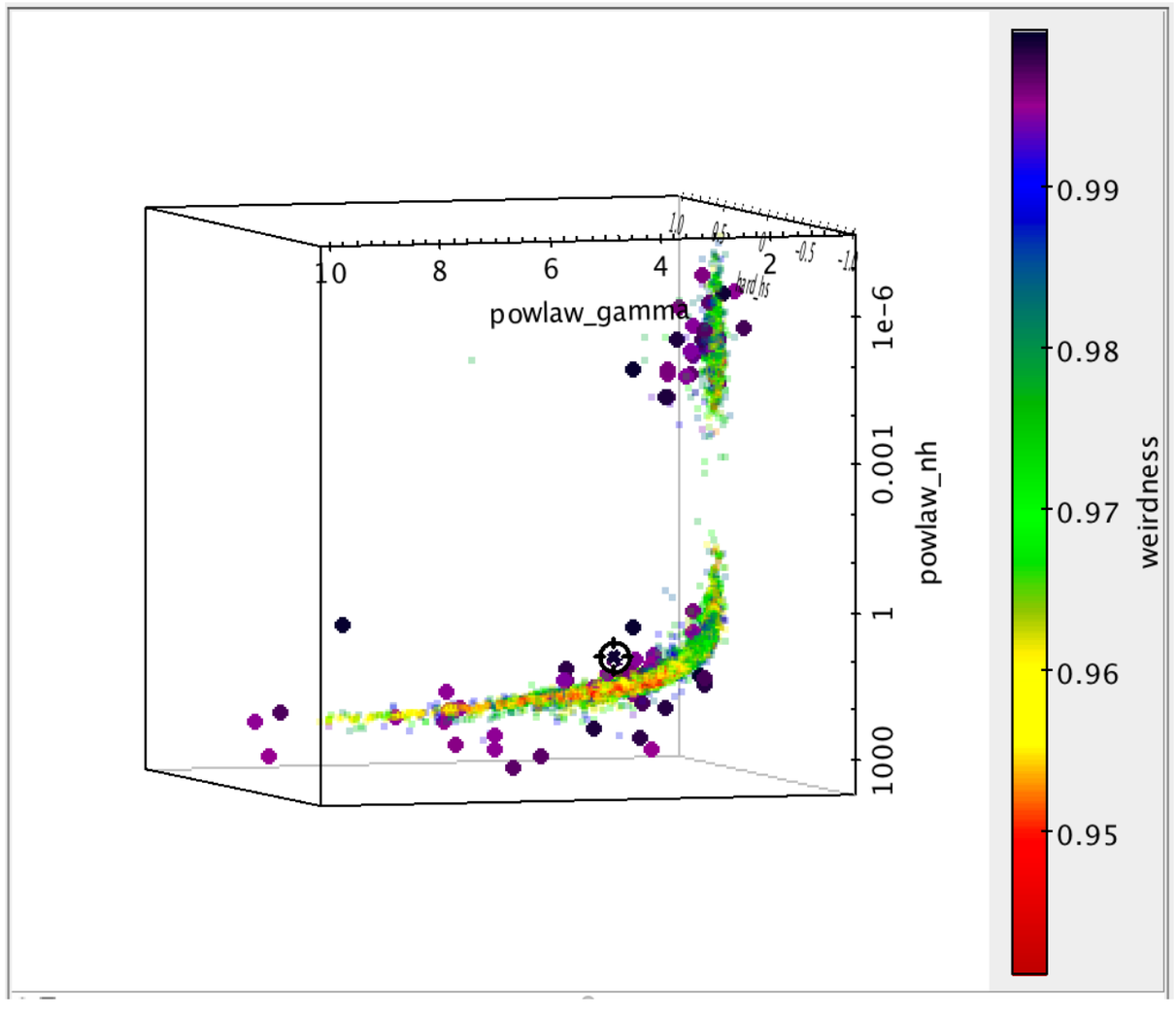




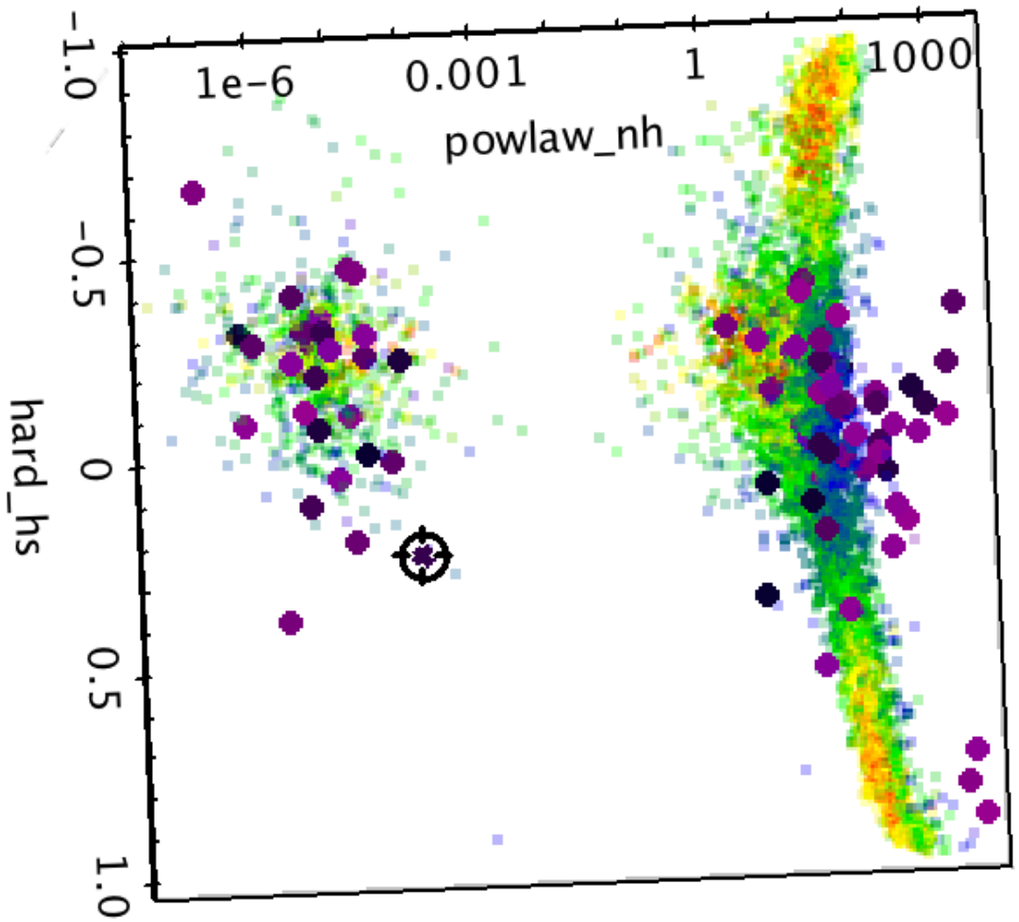
Quasar

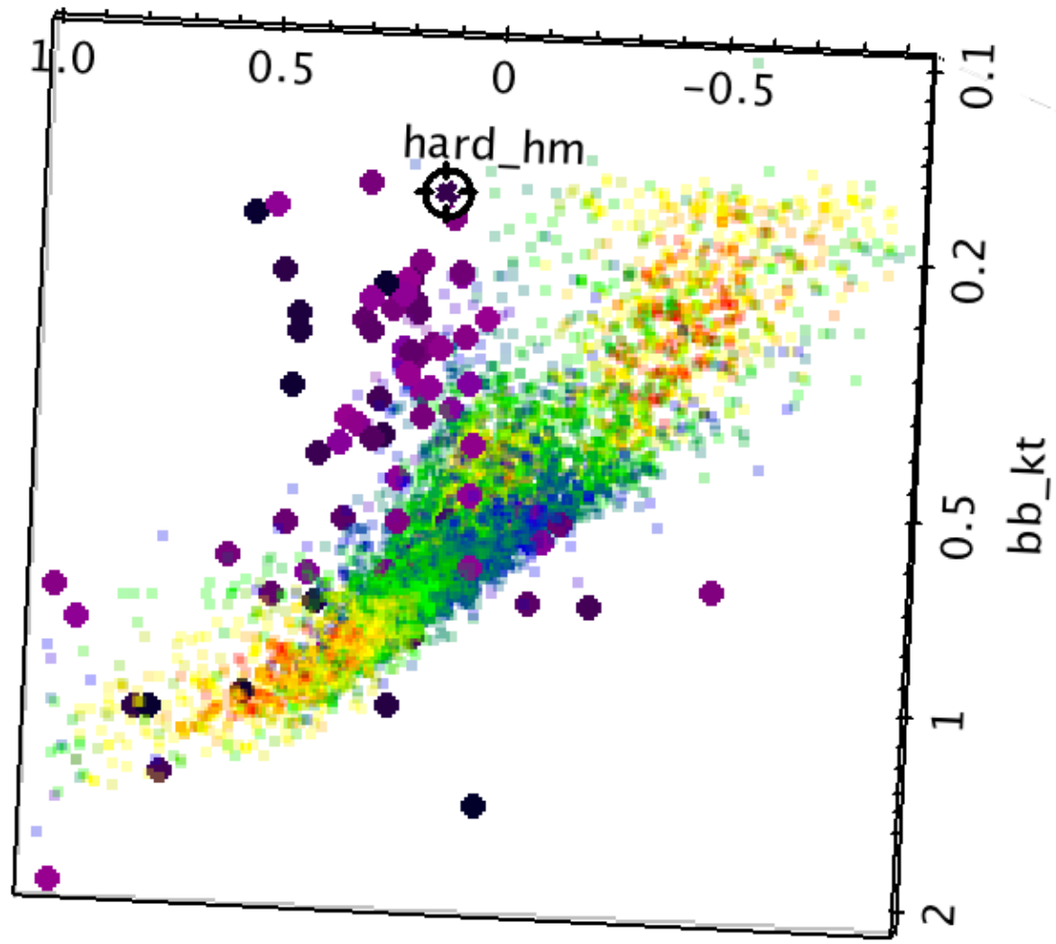
Nothing peculiar published about this object. High excess variance (Vagnetti et al. 2016), funny spectral fits, hard spectrum.



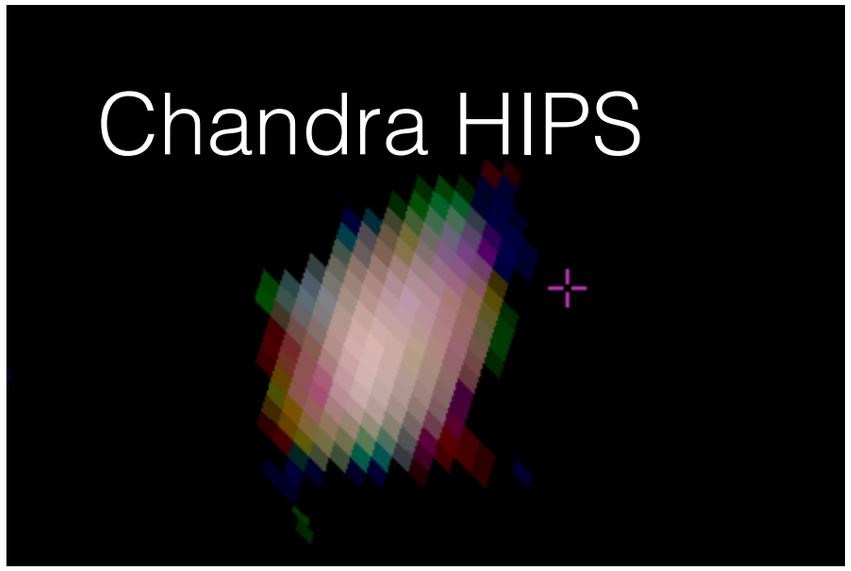


High-mass X-ray binary candidate in the SMC

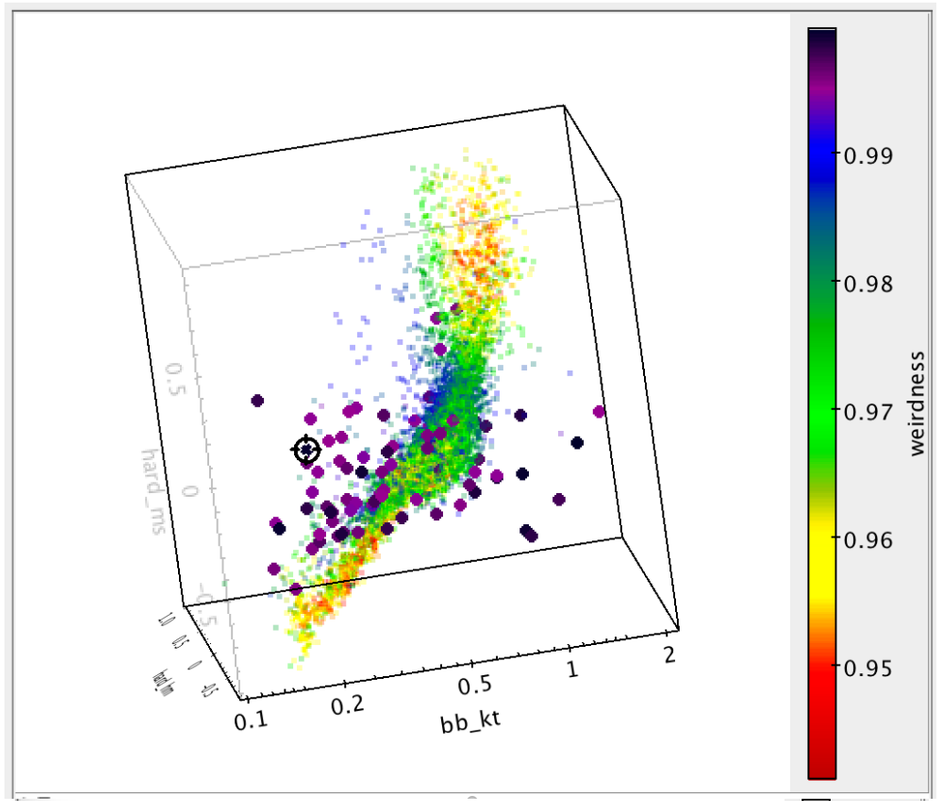


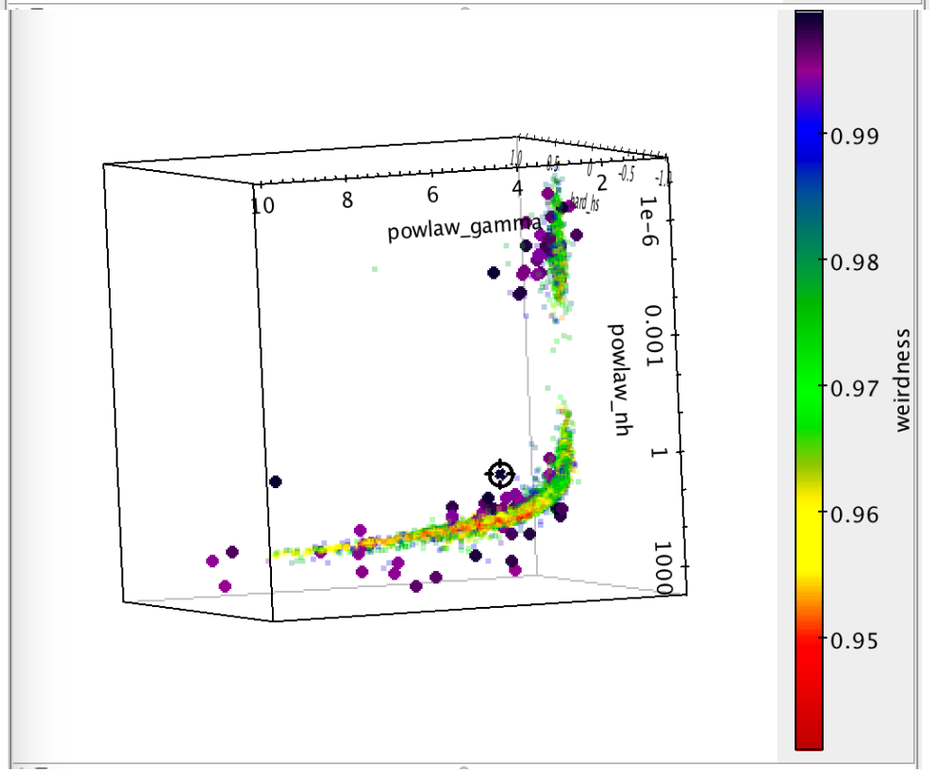


PN in Centaurus A

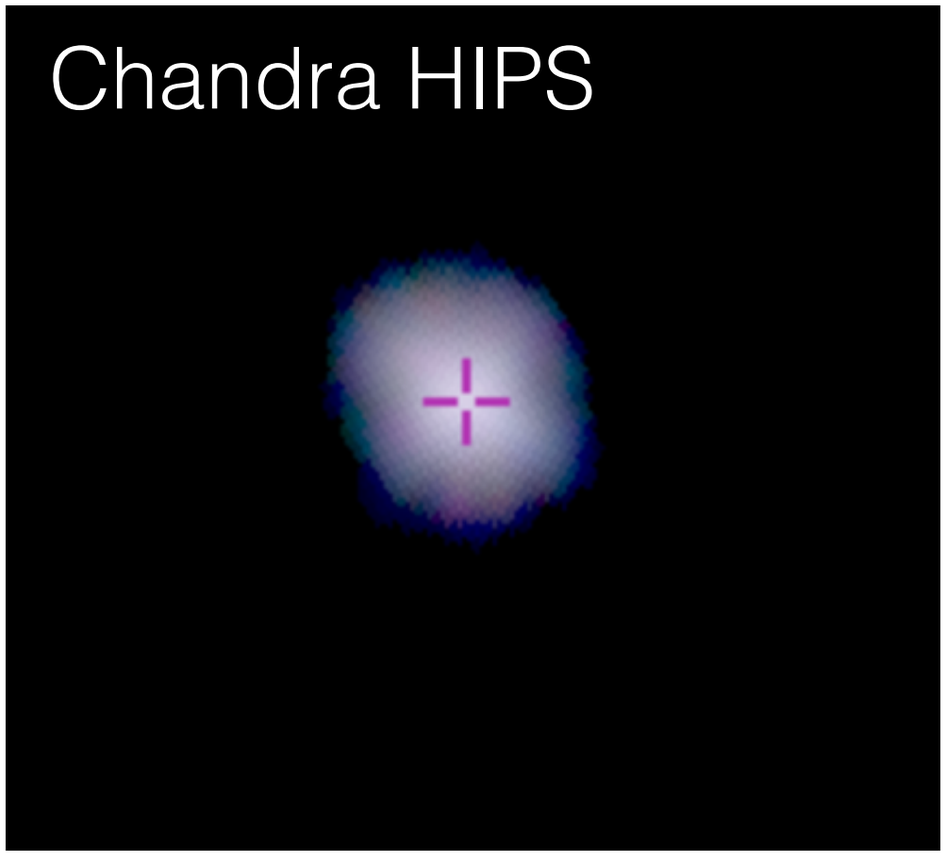


95% confidence position error ellipse	0.71" by 0.71" at 141°
Galactic n_H column density	8.45×10^{20} cm^{-2}
Aperture-corrected flux (broad band)	5.995e-14 erg cm^{-2} s^{-1}
Lower confidence limit	5.745e-14
Upper confidence limit	6.23e-14
Source significance (S/N)	22.51
Hard/Medium band hardness ratio	0.2473
Lower confidence limit	0.2017
Upper confidence limit	0.2929
Medium/Soft band hardness ratio	-0.1611
Lower confidence limit	-0.208
Upper confidence limit	-0.1131
Number of ACIS observations	22
Number of HRC observations	2





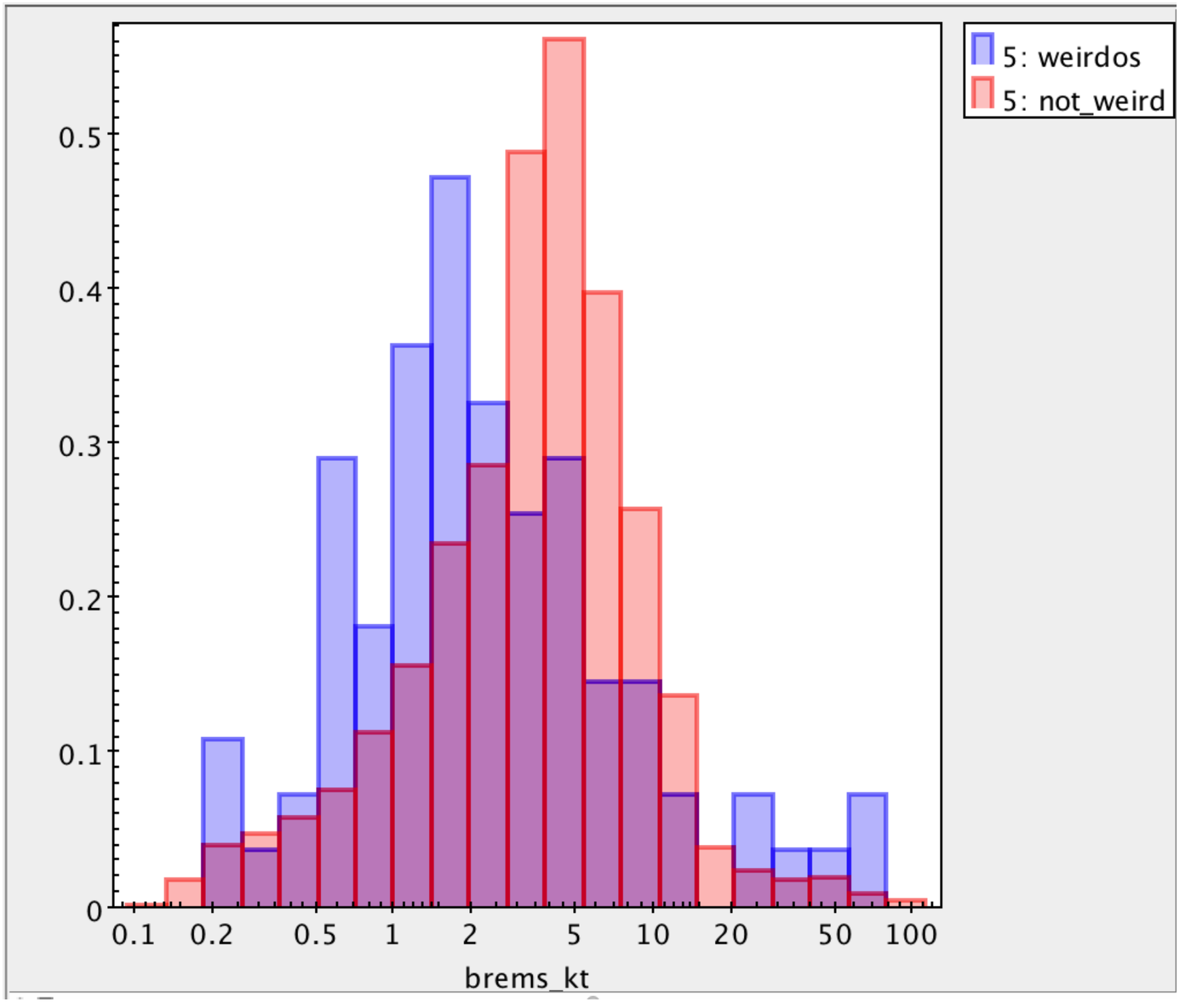
Globular cluster in Andromeda



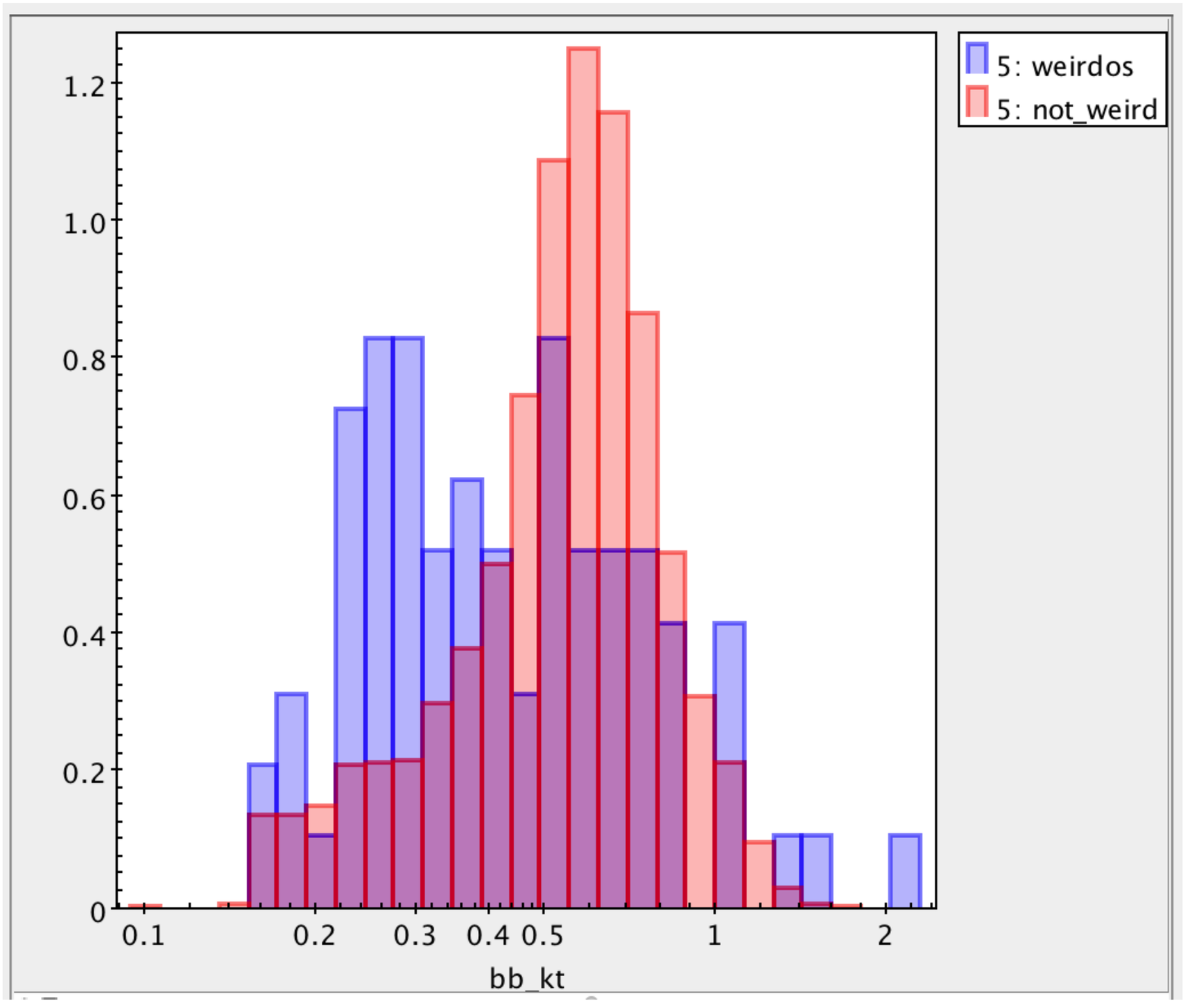
Source is variable (within or between observations).

95% confidence position error ellipse	0.71" by 0.71" at 1°
Galactic n_H column density	6.77 × 10^{20} cm^{-2}
Aperture-corrected flux (broad band)	4.159e-13 erg cm^{-2} s^{-1}
Lower confidence limit	4.122e-13
Upper confidence limit	4.196e-13
Source significance (S/N)	129.66
Hard/Medium band hardness ratio	0.0862
Lower confidence limit	0.0768
Upper confidence limit	0.0956
Medium/Soft band hardness ratio	-0.1012
Lower confidence limit	-0.1118
Upper confidence limit	-0.0906
Number of ACIS observations	103
Number of HRC observations	64

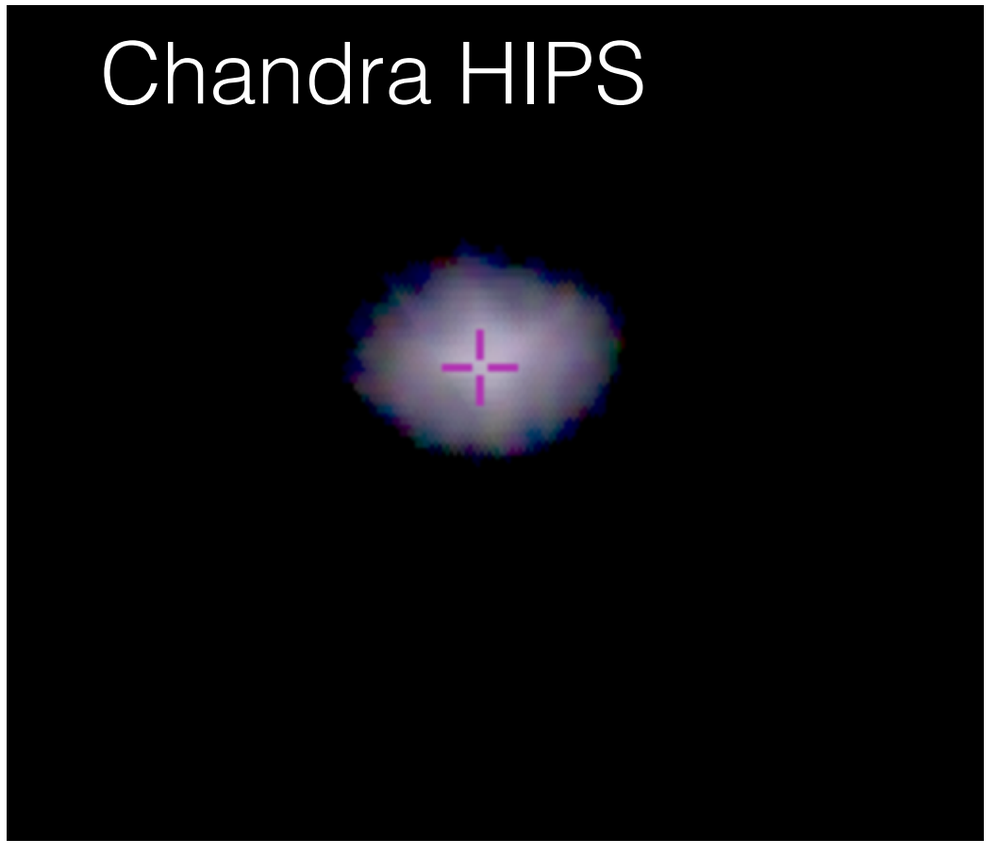
Bremsstrahlung temperature



Blackbody temperature



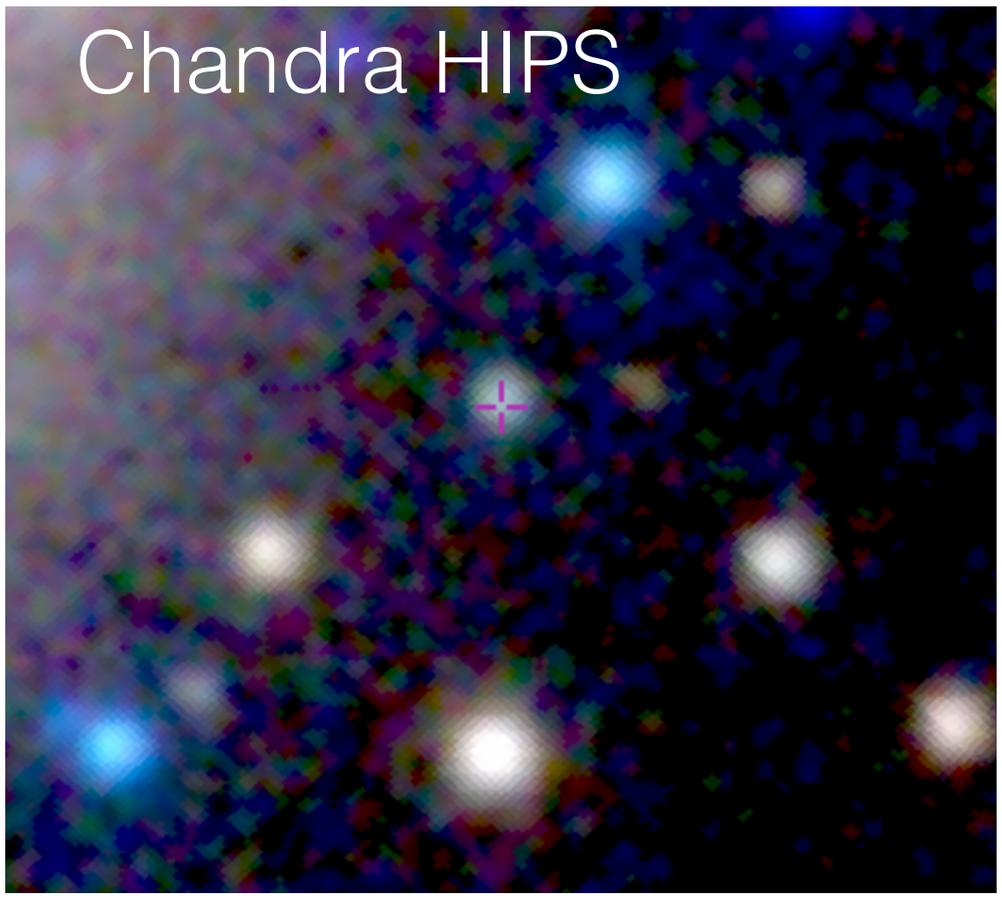
BH candidate in Andromeda



Source is variable (within or between observations).

95% confidence position error ellipse	0.71" by 0.71" at 21.4°
Galactic n_H column density	6.62×10^{20} cm^{-2}
Aperture-corrected flux (broad band)	4.178e-13 erg cm^{-2} s^{-1}
Lower confidence limit	4.147e-13
Upper confidence limit	4.207e-13
Source significance (S/N)	127.21
Hard/Medium band hardness ratio	0.0587
Lower confidence limit	0.0506
Upper confidence limit	0.0668
Medium/Soft band hardness ratio	-0.1137
Lower confidence limit	-0.1218
Upper confidence limit	-0.1056
Number of ACIS observations	105
Number of HRC observations	65

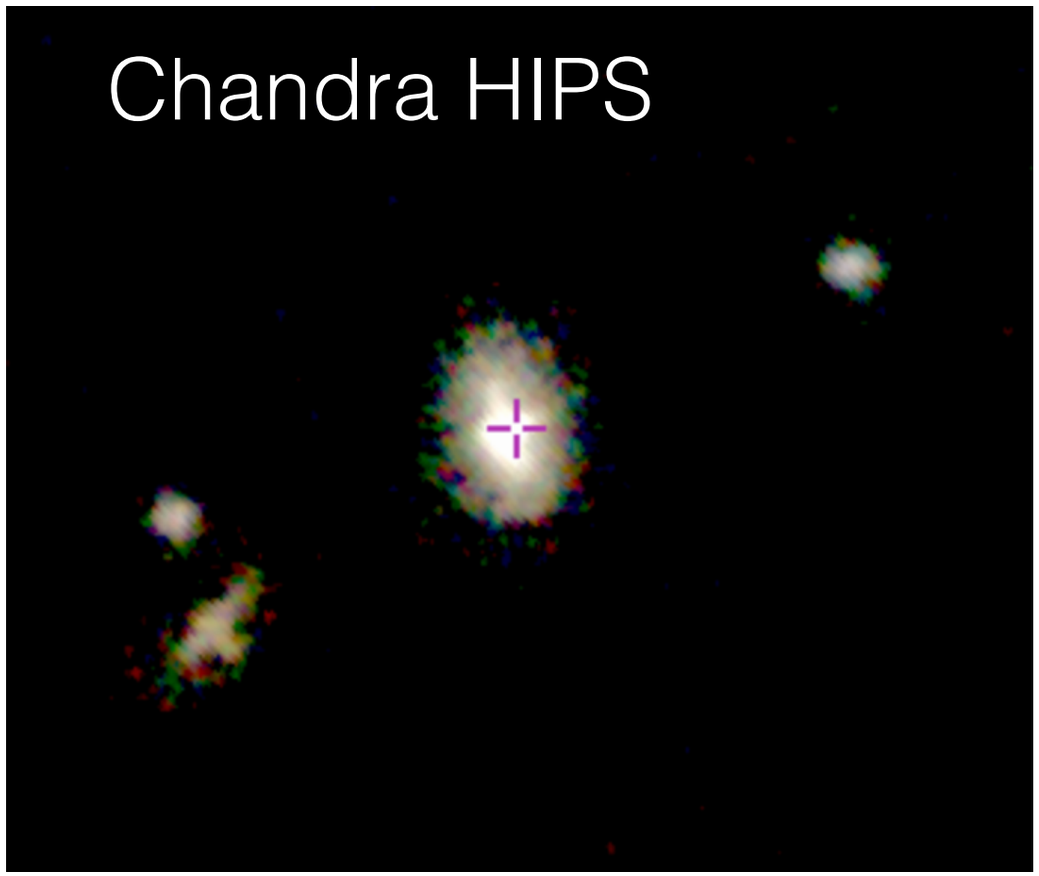
Young star in Orion



Source is variable (within or between observations).

95% confidence position error ellipse	0.71" by 0.71" at 69.3°
Galactic n_H column density	19.31 × 10^{20} cm^{-2}
Aperture-corrected flux (broad band)	3.792e-15 erg cm^{-2} s^{-1}
Lower confidence limit	3.506e-15
Upper confidence limit	4.078e-15
Source significance (S/N)	127.21
Hard/Medium band hardness ratio	0.0287
Lower confidence limit	-0.0606
Upper confidence limit	0.1181
Medium/Soft band hardness ratio	0.3673
Lower confidence limit	0.2255
Upper confidence limit	0.5378
Number of ACIS observations	13
Number of HRC observations	1

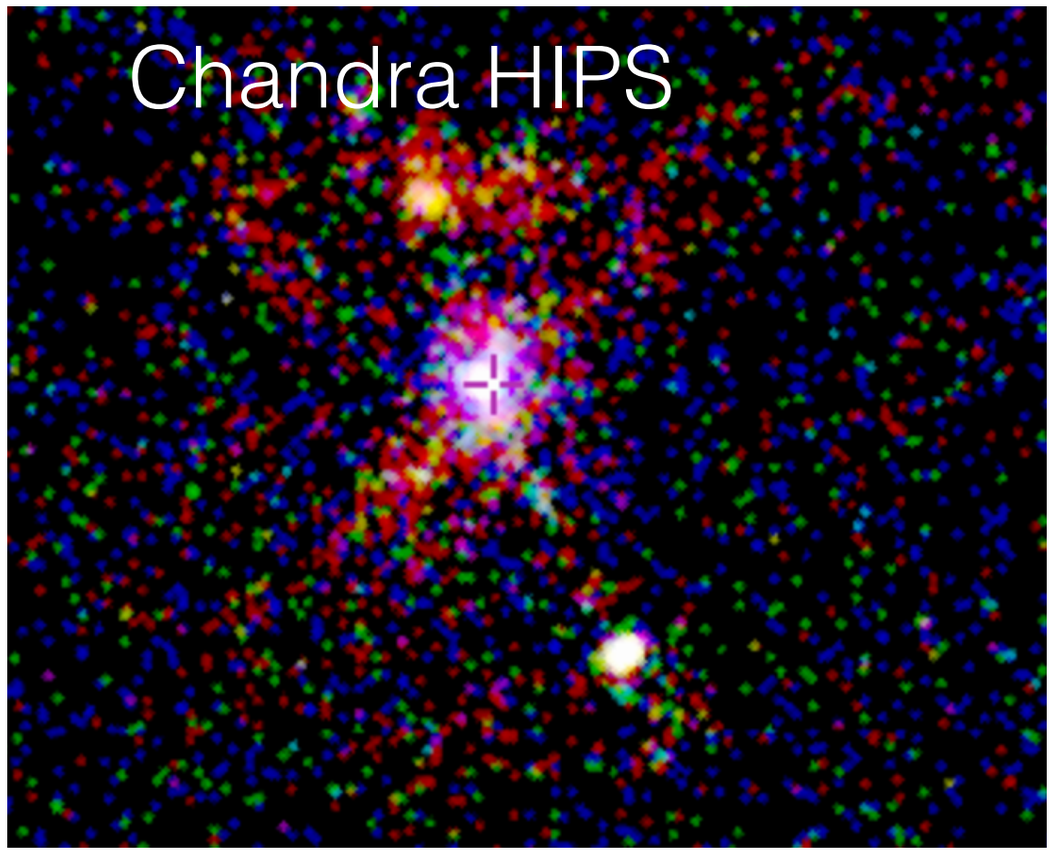
Transient ULX in the vicinity of Centaurus A (similar to M86 tULX-1)



Source is variable (within or between observations).

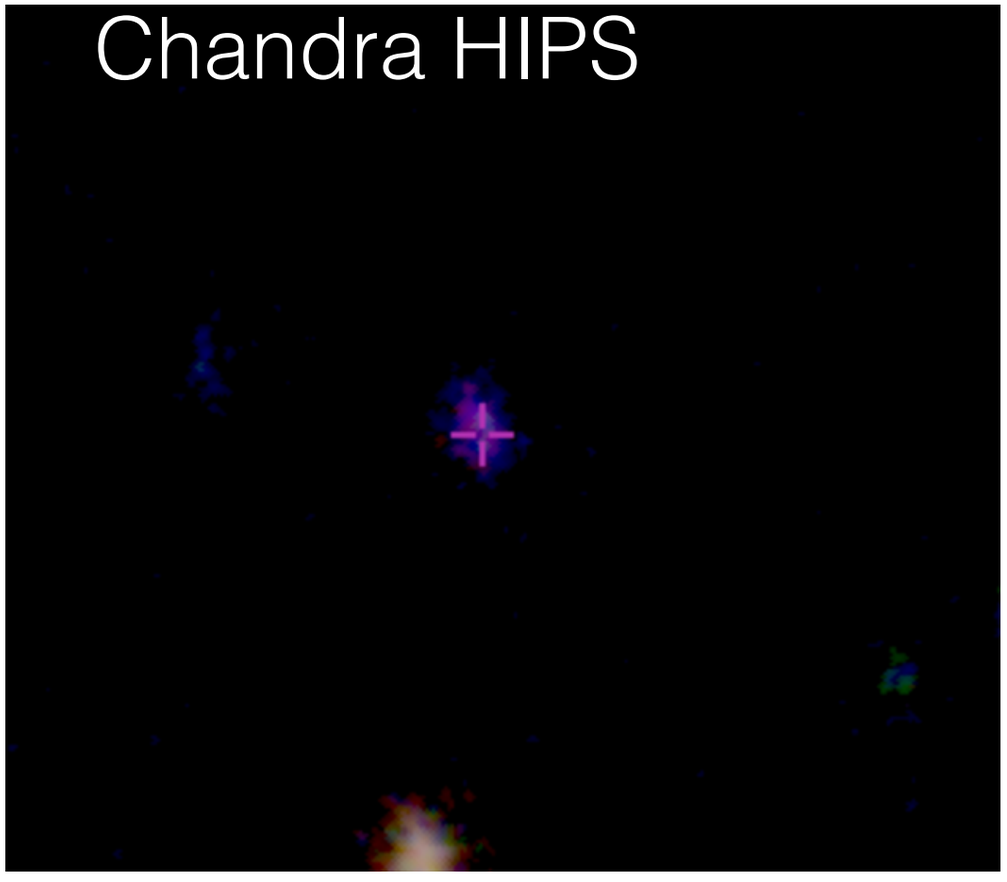
95% confidence position error ellipse	0.71" by 0.71"
Galactic n_H column density	8.4 × 10^{20} cm^{-2}
Aperture-corrected flux (broad band)	6.427e-13 erg cm^{-2} s^{-1}
Lower confidence limit	6.394e-13
Upper confidence limit	6.458e-13
Source significance (S/N)	110.61
Hard/Medium band hardness ratio	0.0175
Lower confidence limit	0.0119
Upper confidence limit	0.0231
Medium/Soft band hardness ratio	-0.0837
Lower confidence limit	-0.0893
Upper confidence limit	-0.0781
Number of ACIS observations	22
Number of HRC observations	2

Seyfert 2 galaxy with hard spectrum and high spectral temperature



95% confidence position error ellipse	0.71" by 0.71" at 178.3°
Galactic n_H column density	3.98×10^{20} cm^{-2}
Aperture-corrected flux (broad band)	6.894e-13 erg cm^{-2} s^{-1}
Lower confidence limit	6.784e-13
Upper confidence limit	6.997e-13
Source significance (S/N)	68.24
Hard/Medium band hardness ratio	0.9494
Lower confidence limit	0.9463
Upper confidence limit	0.9538
Medium/Soft band hardness ratio	-0.3548
Lower confidence limit	-0.4004
Upper confidence limit	-0.3092
Number of ACIS observations	5
Number of HRC observations	0

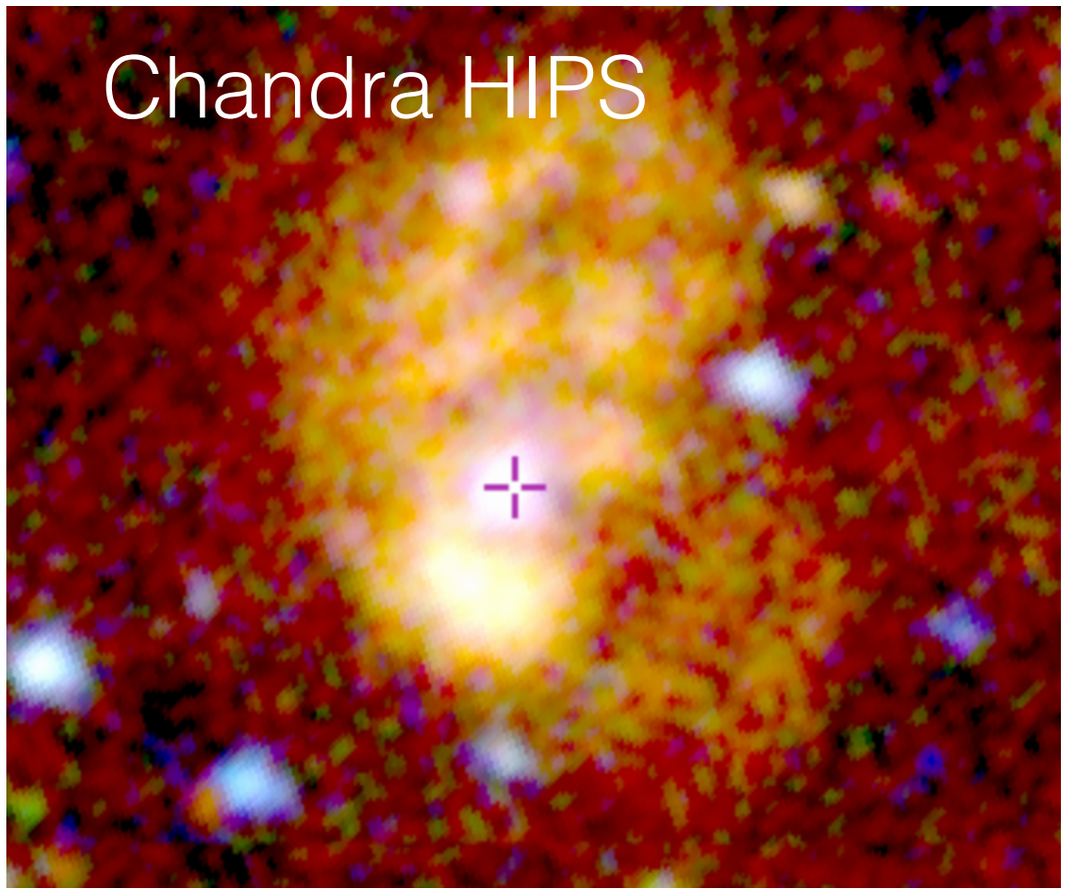
Variable young star in Orion with peculiar HRs and high spectral T



Source is variable (within or between observations).

95% confidence position error ellipse	0.72" by 0.72" at 28.8°
Galactic n_H column density	19.12 × 10^{20} cm^{-2}
Aperture-corrected flux (broad band)	7.224e-15 erg cm^{-2} s^{-1}
Lower confidence limit	6.676e-15
Upper confidence limit	7.737e-15
Source significance (S/N)	20.93
Hard/Medium band hardness ratio	0.7071
Lower confidence limit	0.6502
Upper confidence limit	0.7626
Medium/Soft band hardness ratio	-0.6508
Lower confidence limit	-0.7177
Upper confidence limit	-0.5815
Number of ACIS observations	12
Number of HRC observations	1

X-ray source near the nucleus of M51. Weird spectrum



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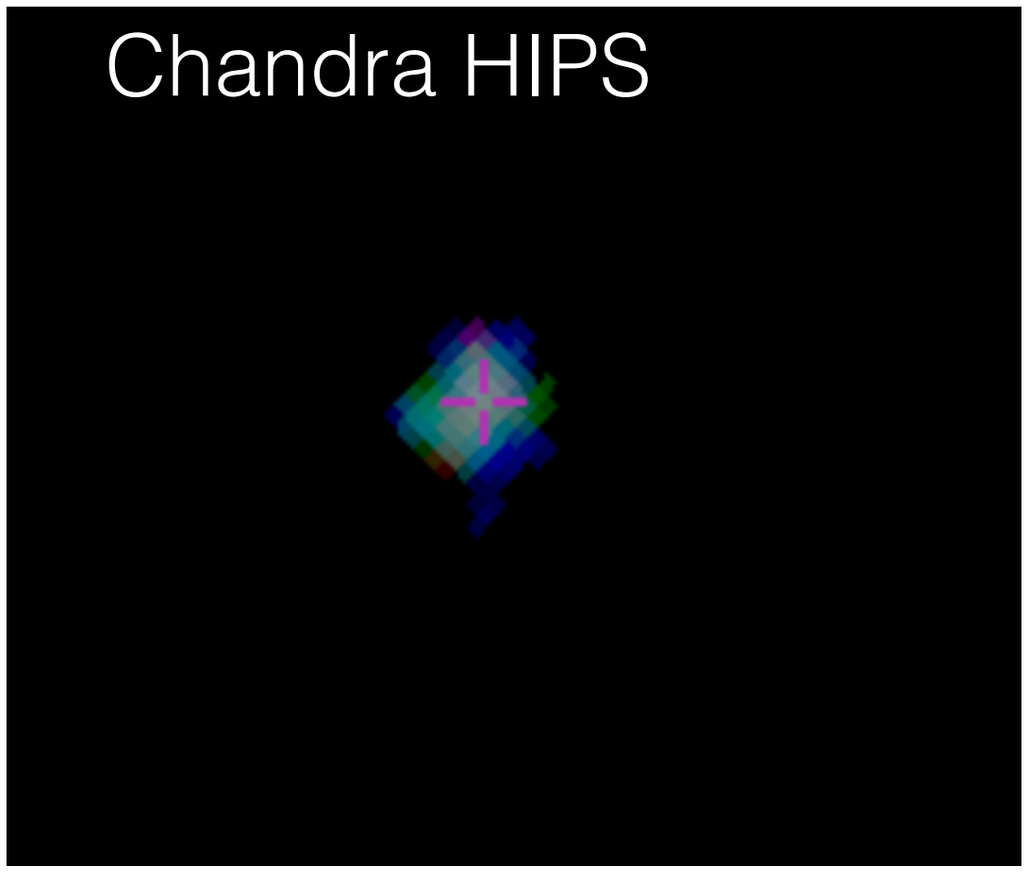
Source significance (S/N)	20.93
Hard/Medium band hardness ratio	0.7071
Lower confidence limit	0.6502
Upper confidence limit	0.7626
Medium/Soft band hardness ratio	-0.6508
Lower confidence limit	-0.7177
Upper confidence limit	-0.5815
Number of ACIS observations	12
Number of HRC observations	1

Galaxy in CDFS. Low spectral T, high photon index



Source is variable (within or between observations).

95% confidence position error ellipse	0.72" by 0.72" at 5.4°
Galactic n_H column density	0.9×10^{20} cm^{-2}
Aperture-corrected flux (broad band)	7.78e-16 erg cm^{-2} s^{-1}
Lower confidence limit	7.057e-16
Upper confidence limit	8.502e-16
Source significance (S/N)	16.1
Hard/Medium band hardness ratio	0.0787
Lower confidence limit	0.0006
Upper confidence limit	0.1555
Medium/Soft band hardness ratio	-0.1786
Lower confidence limit	-0.253
Upper confidence limit	-0.1006
Number of ACIS observations	83
Number of HRC observations	0

Please **review** the current caveats for source properties in CSC 2.0.

Aperture Photometry in CSC2

- **Bayesian Model**

Sources with overlapping apertures, nearby sources, and background simultaneously.
Joint posterior for source fluxes and background flux (for single observation):

$$P(s_1 \ldots s_n, b | C_1 \ldots C_n, B) = K \times P(b) P_{Pois}(B \,|\, \phi) \prod P(s_i) P_{Pois}(C_i \,|\, \theta_i)$$

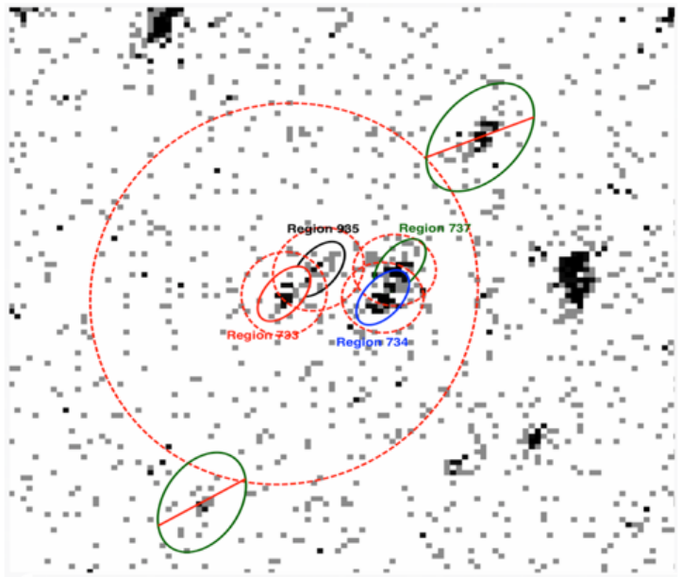
$$\theta_i = E_i \times \left[\sum_{j=1}^{n} f_{ij} s_j \; + \; \Omega_i b \right] ; \; \phi = E_b \times \left[\sum_{i=1}^{n} g_i s_i \; + \; \Omega_b b \right]$$

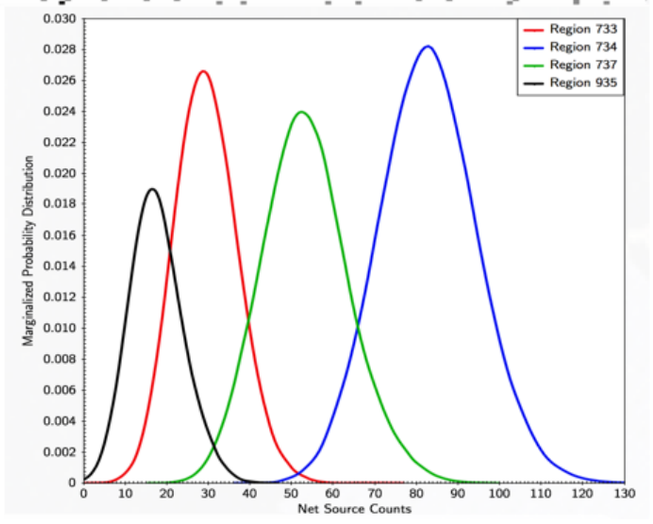
Counts in overlaping regions assigned to brightest source

Master source flux for source s_k in an n-source bundle is determined from the Bayesian block for that source with the largest exposure:

$$P(s_k | \{C_i^j\}, \{B^j\}) \cong P(s_k) \prod_{j=1}^{m} \left[P_{Pois}(B^j \,|\, \hat{\phi}^j) \times P_{Pois}(C_k^j | \hat{\theta}_k^j) \prod_{i=1, i \neq k}^{n} P_{Pois}(C_i^j \,|\, \hat{\theta}_i^j) \right]$$

Bottom plot to the right: marginalized posteriors
Posteriors optimized and sampled using MCMC in Sherpa.





Relevant catalog properties:
Photflux_aper_x, flux_aper_x, flux_bb_aper_x
flux_aper90_x, flux_aper90_x

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Aperture Photometry in CSC2

- **Spectral Model Fits**

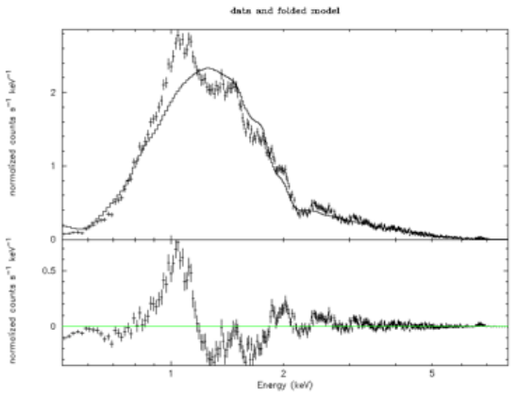
  For sources with more than 150 counts in the energy band 0.5-7 keV, two spectral model fits are done:

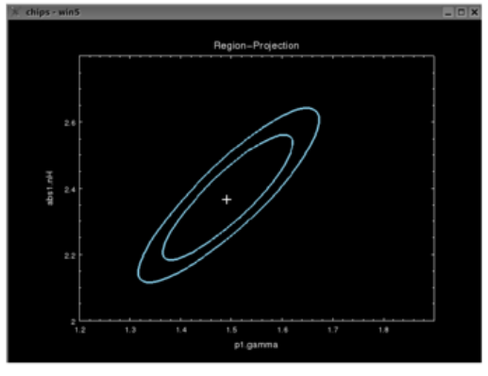
  * Absorbed black body (thermal) $f(E) = \exp^{-N_{\rm H}\bar{\sigma}_E}\ \bar{A}(E^2/(\exp^{E/kT}-1))$

  * Absorbed power law (non-thermal) $f(E) = \exp^{-N_{\rm H}\bar{\sigma}_E}\ A\,E^{-\Gamma}$

  Background-subtracted counts forward fitted using Sherpa (χ^2 stat.), and 1s confidence intervales estimated using Sherpa's projection method.

  Model flux for the energy interval 0.5-7 keV found by integration of the best fit.





Relevant catalog properties: flux_powlaw, flux_bb, flux_brems

Hardness Ratios

- **Single Observation**

For each band pair x,y, the hardness ratio (H_{xy}) is the flux value for the softer band, subtracted from the harder band, relative to their sum (x-y)/(x+y). Just like F_x and F_y are random variables with associated probabilities, so is Hxy:

$$P_{H_{xy}}(H_{xy})\,dH_{xy} \quad = \quad \int_{F_{xy}=0}^{\infty} P_x\left(\frac{(1+H_{xy})F_{xy}}{2}\right) P_y\left(\frac{(1-H_{xy})F_{xy}}{2}\right) \frac{F_{xy}}{2}\, dH_{xy} dF_{xy}$$

Hardness ratios listed in the catalog (hard_ms, hard_hm, hard_hs) are the values of Hxy that maximize the above distribution for the corresponding bands

- **Multiple observations (Combine all PDFs together)**

Stack: all observations in the stack

Master: all observations in Bayesian block

Relevant catalog properties:
hard_ms, hard_hm, hard_hs

Variability

- **Single observation:**

  Gregory-Loredo Test: Hypothesis rejection test (i.e., odds ratio of assuming variability vs not assuming it). The resulting var_prob gives the probability that events detected are not arriving at a uniform rate. Used to estimate intra-obs variability (pick max prob among stack obsids).

- **Multiple observations:**

  Inter-observation variability. Variability test is based on a likelihood ratio between the null hypothesis of no variability, and the assumption of variability, when several observations are considered. Var_inter_prob is a p, value.