CHANDRA SOURCE CATALOG

# The *Chandra* Source Catalog

## Release 2.1: The Twenty-Two Year Catalog

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On behalf of the *Chandra* Source Catalog team

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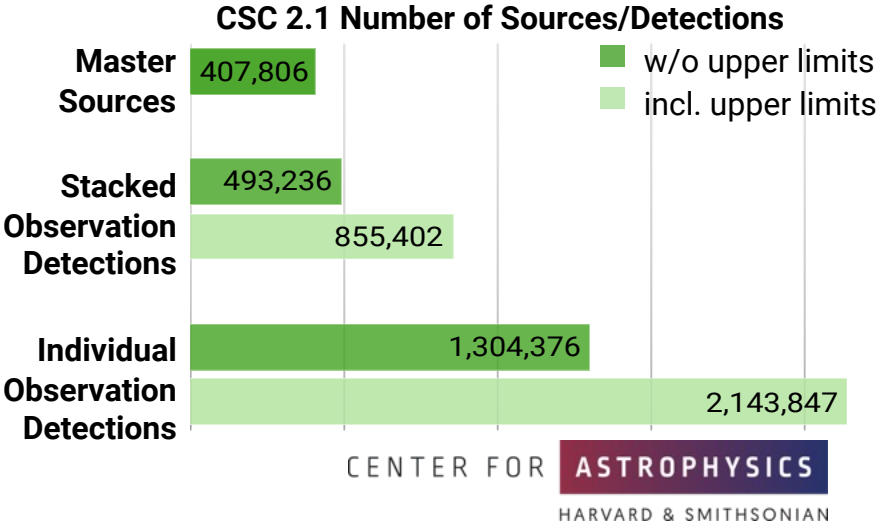
# *Chandra* Source Catalog Release 2.1

- **Uniformly calibrated observations**
  - Uniform calibrations and processing using state-of-the-art Bayesian algorithms
- **Extensive set of tabulated properties**
  - Position, extent, photometry, variability, hardness ratio, spectral parameters in multiple energy bands
- **Science-ready FITS data products**
  - Per source / detection / field / stacked field event files, images, backgrounds, calibrations, regions, local PSFs, spectra, light curves, photometry probability density functions, sensitivity, extended source polygons
- **Current catalog release**
  - Version 2.1, minor version 2.1.1, released 2024 October 18

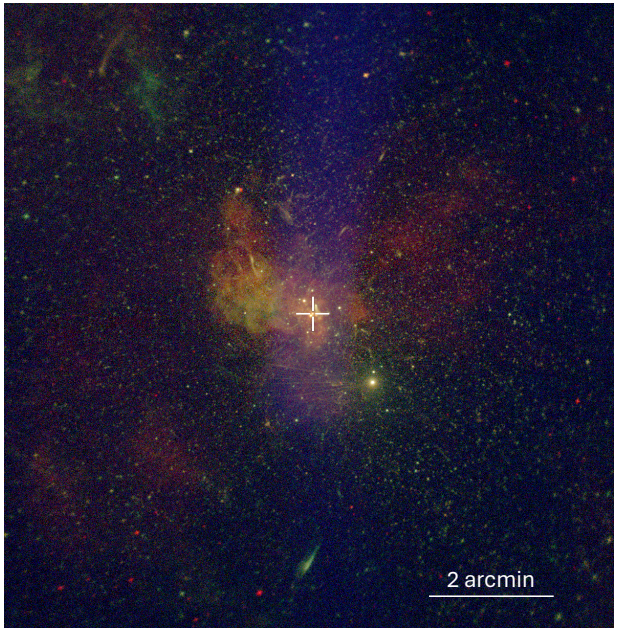
- **Stacked imaging observations**
  - Co-added exposure times up to ~6.7 Ms
- **Catalog limiting sensitivity**
  - Estimated source flux required to detect a point source (on a 3.22 × 3.22 arcsec HEALPIX grid)
- **Total sky coverage**
  - 730 $deg^2$ (681 $deg^2$ ACIS; 67 $deg^2$ HRC-I)

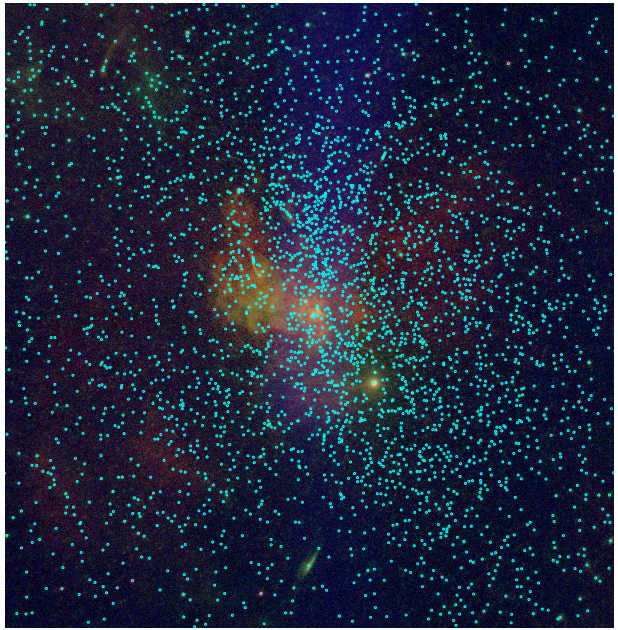


# Source Detection Threshold

- **Outstanding sensitivity in heavily crowded fields** due to *Chandra*'s arcsecond spatial resolution on-axis combined with very low instrumental backgrounds

  ⟹ **CSC point source detection limit is ~4–5 X-ray photons over much of the field and for most exposure times**

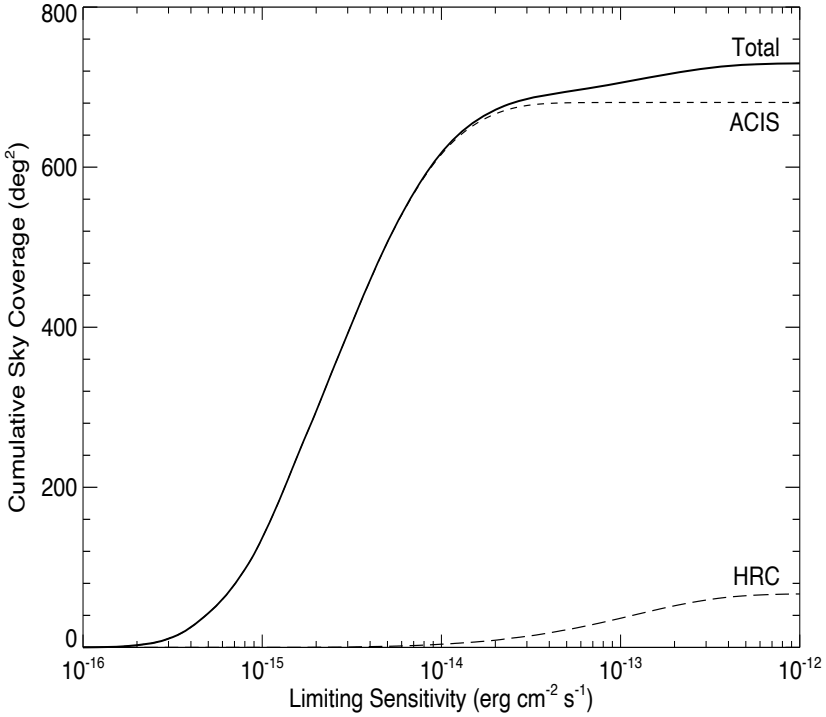


*Far Left:* Cutout of ~3 Ms observation stack (a co-add of 86 observations) from CSC 2.1, centered on Sgr A*

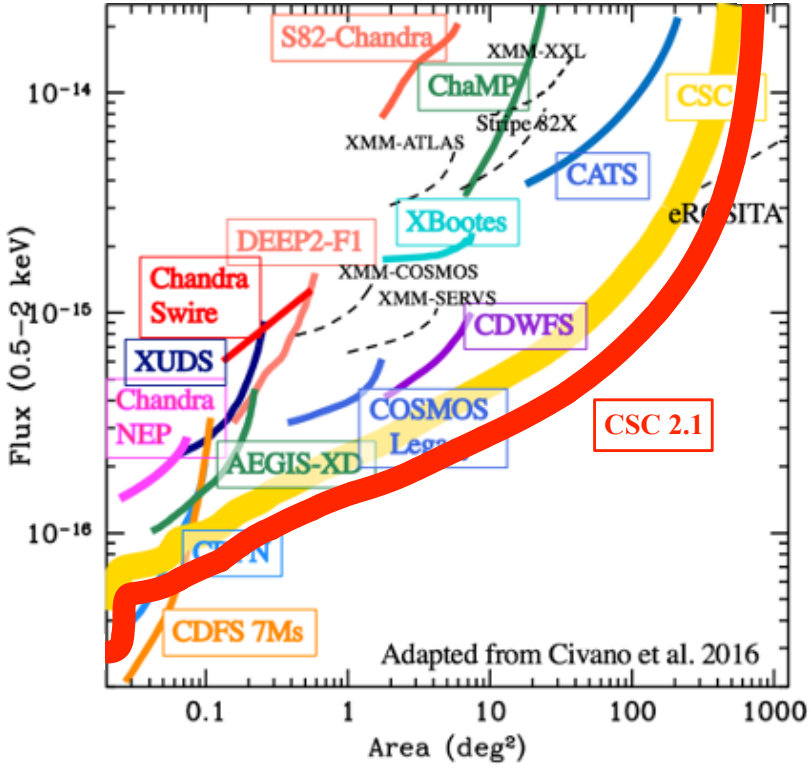
*Left:* CSC 2.1 identifies ~3,300 compact X-ray sources in this region *roughly a dozen times more X-ray sources than have been detected by any other mission*

# Sky Coverage and Compact Detection Sensitivity



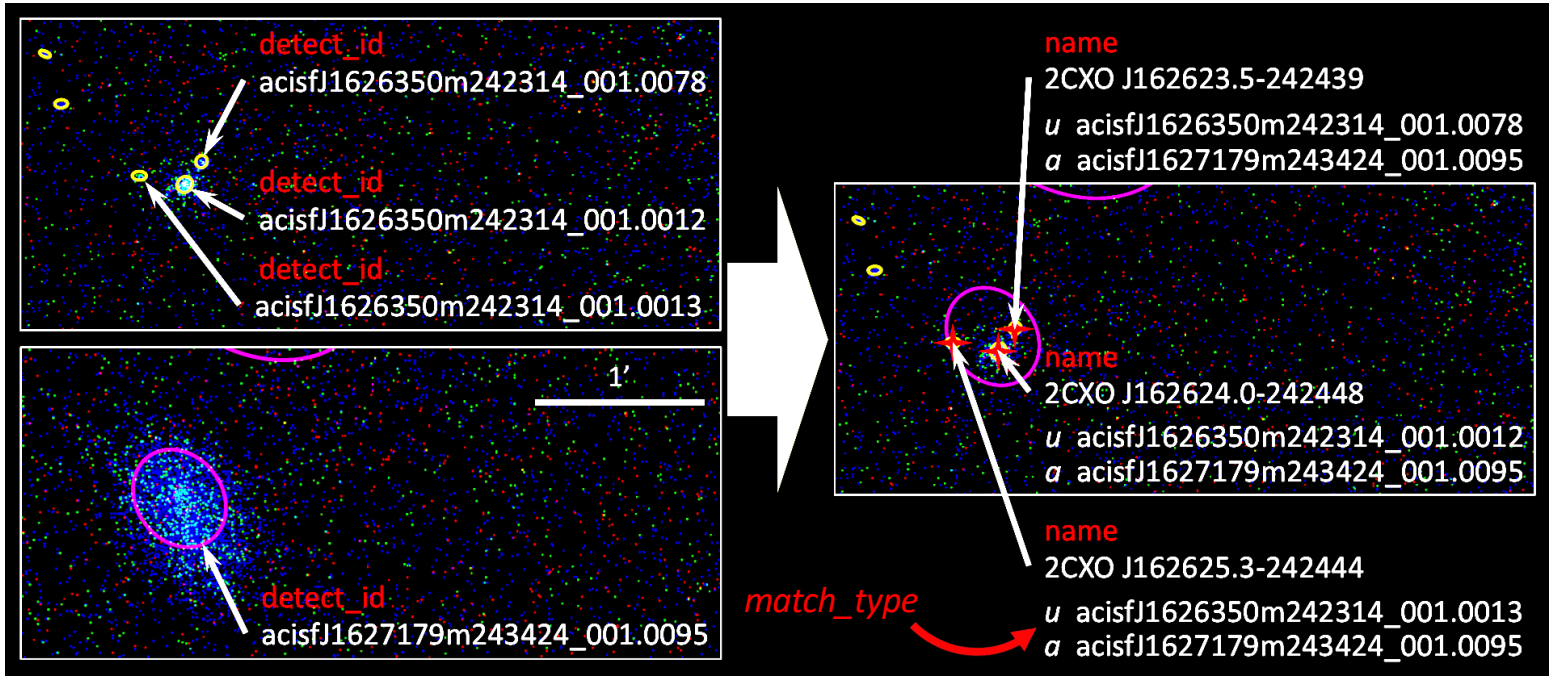

CSC 2.1 cumulative sky coverage vs. limiting sensitivity

More Sensitive




Larger Area

# Detections vs. Sources




- ***Detections are photon blobs on the detector; sources are best estimates of X-ray emitters on the sky***
- **Source ⟺ detection linkages are managed automatically by the catalog**
- Matching detections to identify sources is a many-to-many problem
- *match_type* identifies type of linkage between detections and sources

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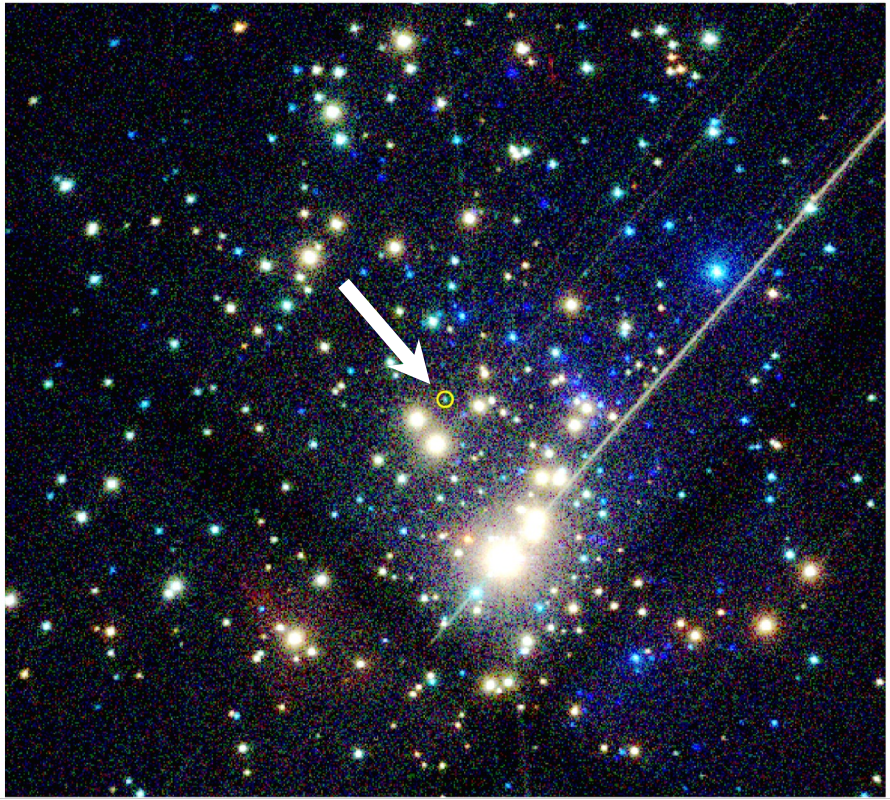
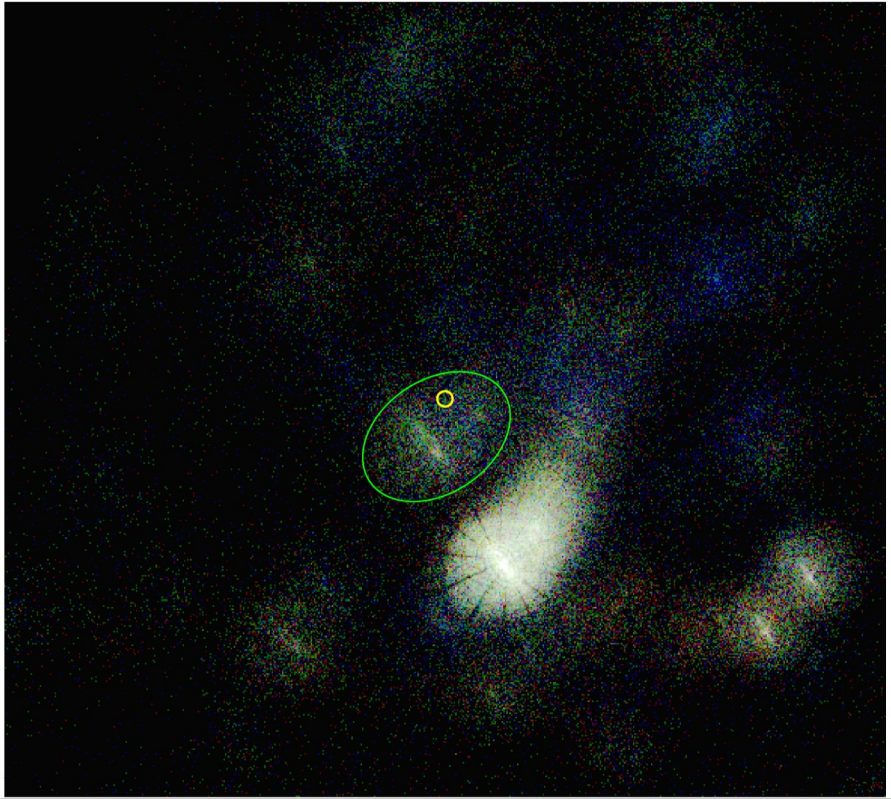
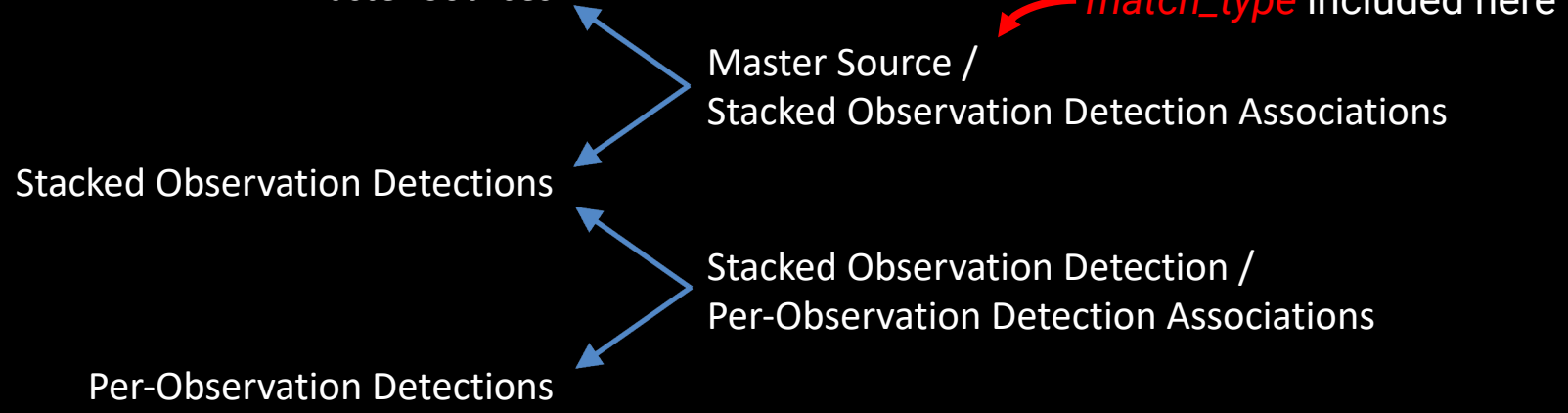
# Detections vs. Sources





**Confusing sources and detections is the most common issue seen in helpdesk questions**

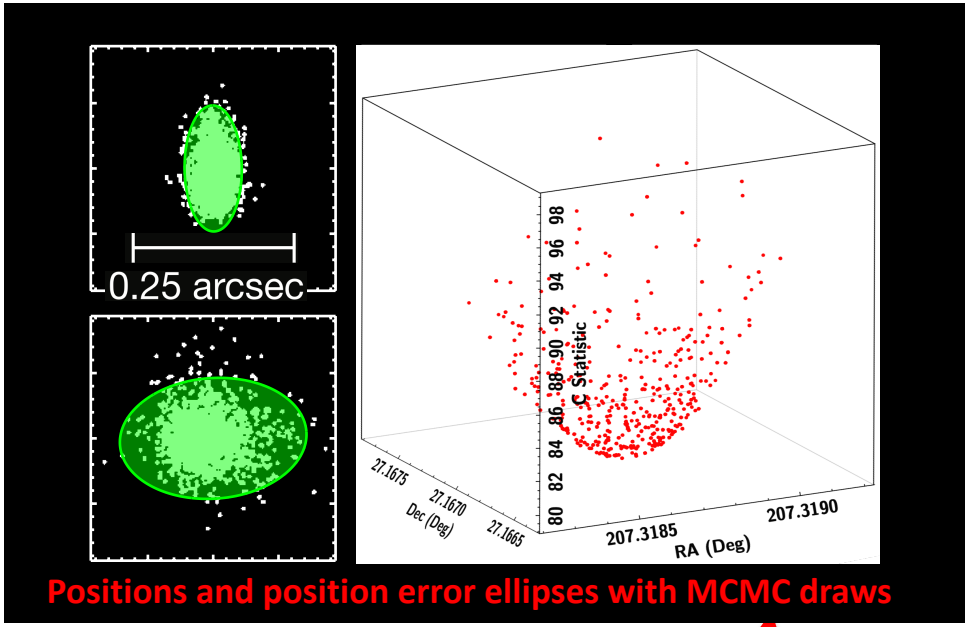
# *Chandra* Source Catalog Tables




## Ancillary Tables

| | |
|---|---|
| Detect Stack | Maps stacks to observations |
| Valid Stack | Identifies observations in a stack where the detection is valid |
| Likely Stack | Identifies observation-set in a stack that maximizes detection likelihood |
| Limiting Sensitivity | Estimated detection-threshold point source flux (3.22×3.22 arcsec HEALPIX grid) |

# Catalog Properties




Positions and position error ellipses with MCMC draws

`draws3` FITS data product

- Properties are measured/derived for individual- and stacked-observation detections as well as for master sources by *simultaneously analyzing* individual-observation detections
- Numeric properties have associated *independent* lower and upper confidence intervals
- Most properties are computed in 6 energy bands:

| | | |
|---|---|---|
| ACIS: | ultrasoft | 0.2–0.5 keV |
| | soft | 0.5–1.2 keV |
| | medium | 1.2–2.0 keV |
| | hard | 2.0–7.0 keV |
| | broad | 0.5–7.0 keV |
| HRC: | wide | ~0.1–10.0 keV |

# Catalog Properties

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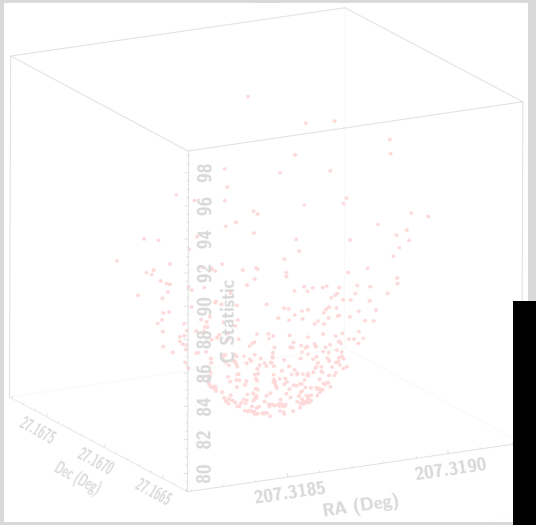
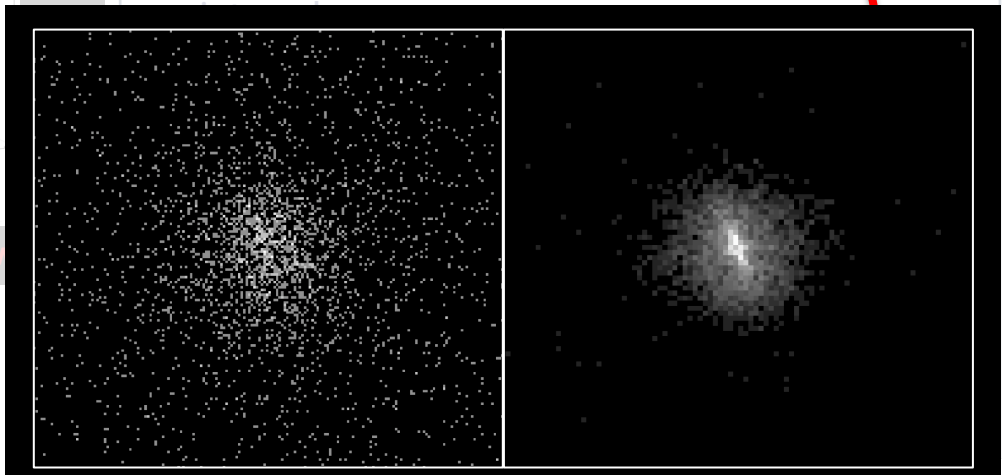



Positions and position error ellipses with MCMC draw

`draws3` FITS data product

`psf3` FITS data product



Detection and local PSF extents and deconvolved source extent

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# Catalog Properties

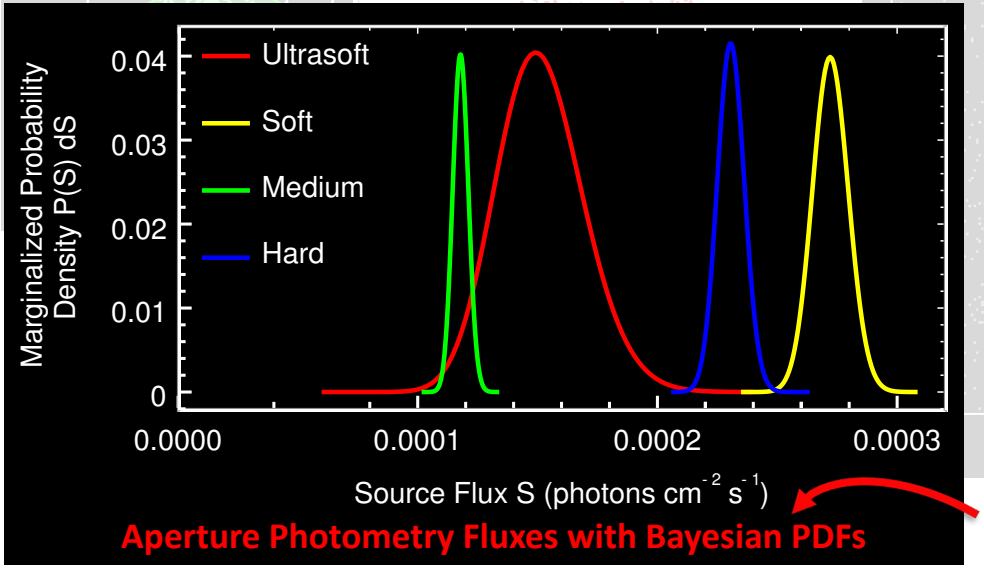
- Properties are measured/derived for individual- and stacked-observation detections as well as for master sources by *simultaneously analyzing* individual-observation detections
- Numeric properties have associated *independent* lower and upper confidence

psf3 FITS data product



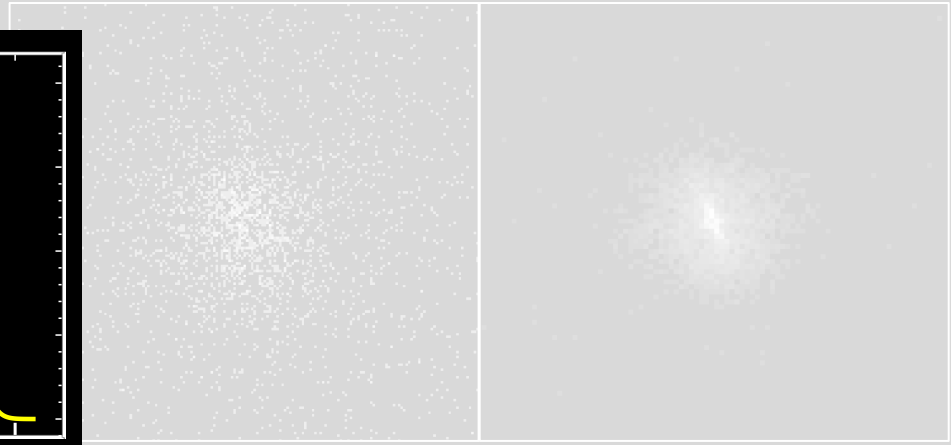







Aperture Photometry Fluxes with Bayesian PDFs

phot3 FITS data product



# Catalog Properties

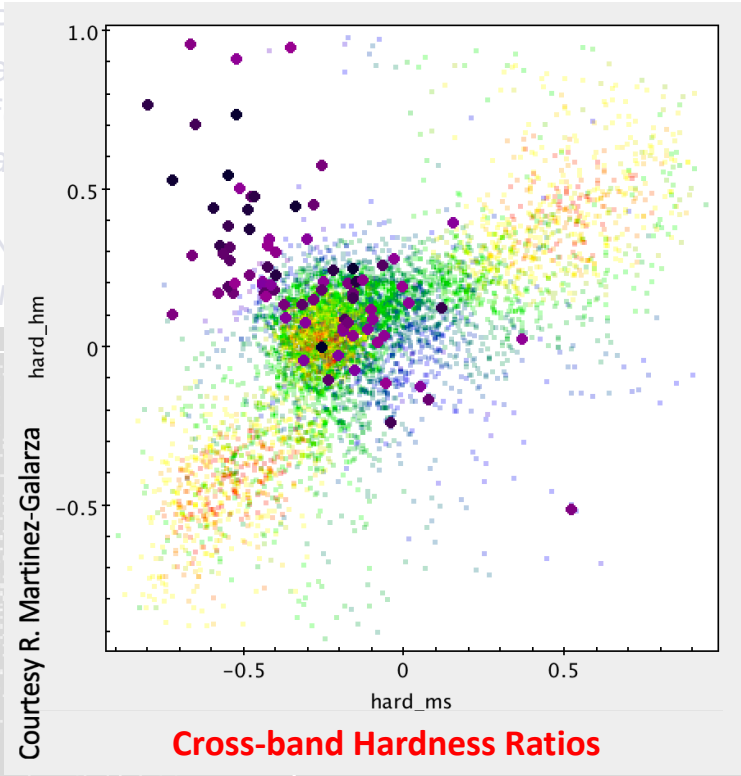









Aperture Photometry Fluxes with Bayesian PDFs




Cross-band Hardness Ratios

tion and local PSF extents and deconvolved source extent

phot3 FITS data product

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# Catalog Properties





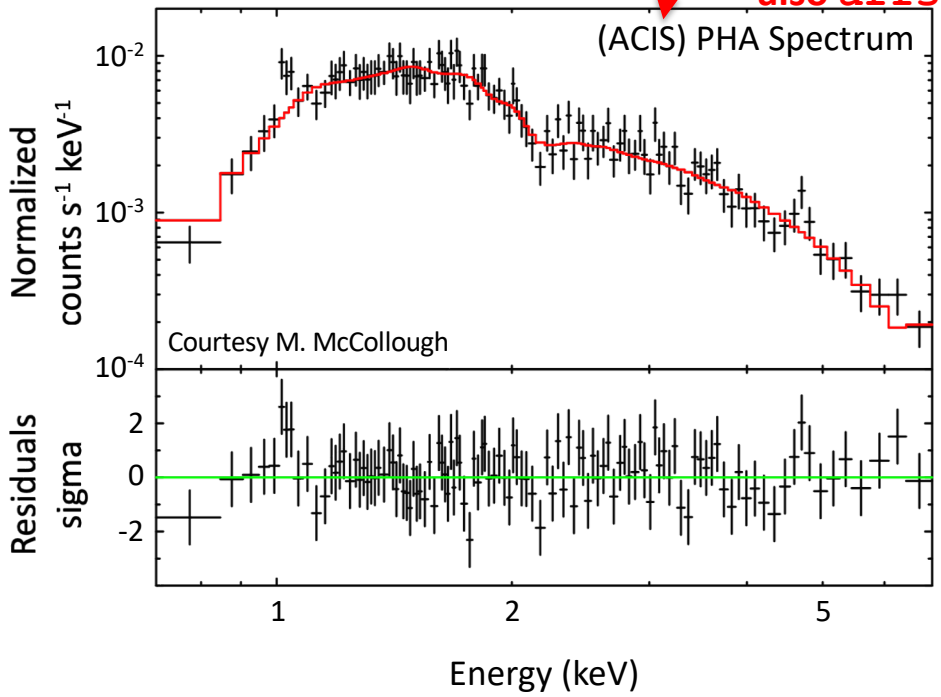





Aperture Photometry Fluxes with Bayesian PDFs

**pha3 FITS data product**

**also arf3, rmf3 etc.**




Joint Spectral Fits (Multiple Models)

FITS data product

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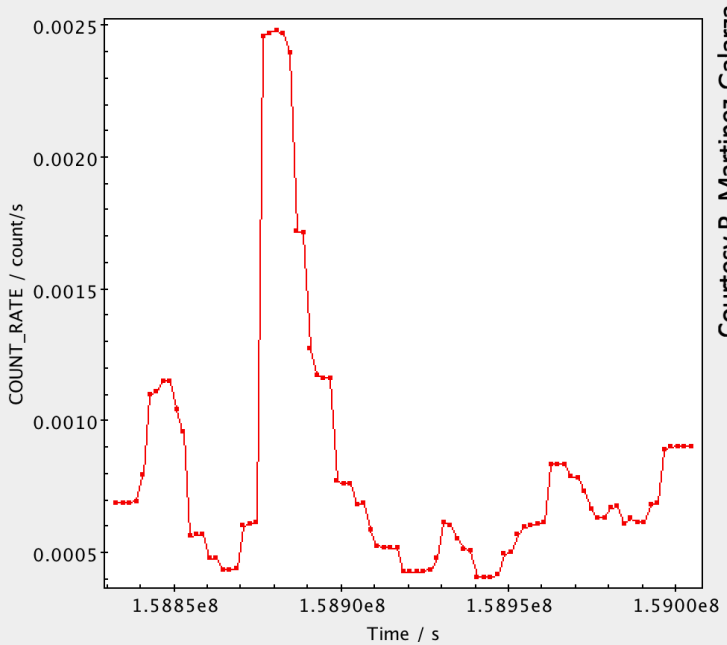
# Catalog Properties




Courtesy R. Martinez-Galarza

**Intra- and Inter-Observation Variability**

**Intra-Observation Optimally Binned Light Curves**

pha3 FITS data product

also arf3, rmf3 etc.




lc3 FITS data product

Joint Spectral Fits (Multiple Models)

Marginalized Probability

0.0000

0.0001

Source Flux S (photons cm$^{-2}$ s$^{-1}$)

Aperture Photometry Fluxes with Bayesian PDFs

FITS data product

source extent

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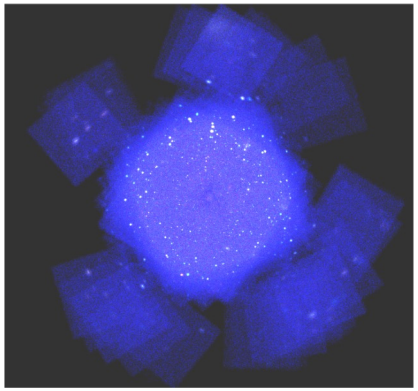
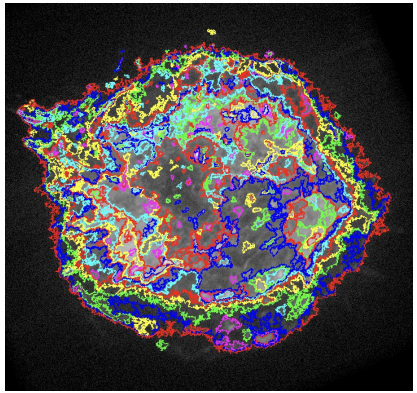
# Source Detection

- **Observations using the same instrument that have pointings within 60 arcsec are stacked prior to source detection**
  - X-ray to x-ray detection matching to align individual observations
- **Candidate compact source detection combines wavelet and Voronoi algorithms with MLE fitting**
  - Candidate compact detections are merged and then graded by MLE
  - MLE fits detections with local per-band PSF model and PSF model convolved with rotated elliptical Gaussian
  - All detection and MLE fit information available in **`mrgsrc3`** data product
- **Detections graded by highest MLE fit likelihood**
  - **`TRUE`** threshold ⟹ false source rate ~0.1 per field
  - **`MARGINAL`** threshold ⟹ false source rate ~1 per field
  - **`FALSE`** not included in catalog (available in **`mrgsrc3`** data product)
- **Highly extended source detection uses Voronoi algorithm**
  - Simplified convex hull representation in catalog
  - Polygons at various contour levels available in **`poly3`** data product



Observation stack
acisfJ0332281m274818_002
100 observations, 6.69 Ms



Extended source polygons
ACIS ObsId 14482 – Cas A

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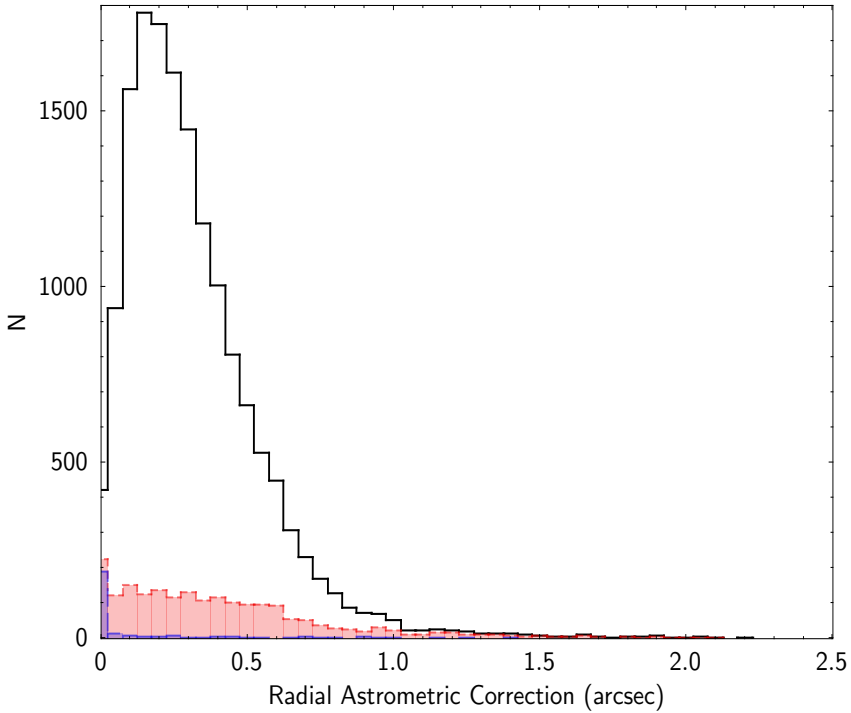
# CSC 2.1 Astrometry

- **CSC 2.1 astrometry is tied to Gaia-CRF3**
  - Observation stacks are matched to Gaia directly or via AllWISE (X-ray to optical matches)
  - Extensive automatic and manual QA to ensure robust solutions
  - All data products have updated astrometry
  - 95% confidence systemic error 0.29 arcsec per axis
  - Individual source position error estimates have MLE fit position error added in quadrature

*Above Right:* Magnitudes of individual observation astrometric corrections required to tie observation stacks to Gaia-CRF3

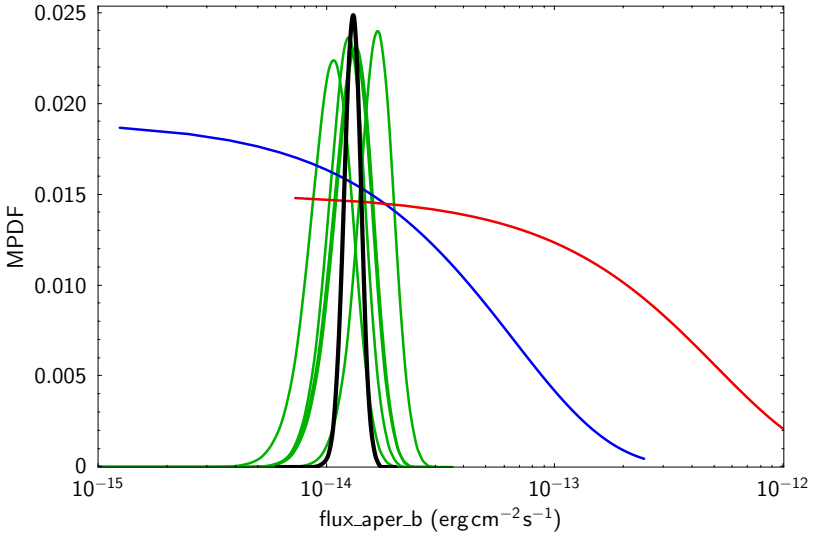
*Red:* observations for which manual QA was required (either at individual observation or stacked observation level)

*Blue:* observations for which absolute astrometric correction could not be determined due to insufficient matches



# Bayesian Blocks

- **Detections of the same source *with consistent multi-band aperture photometry* are analyzed together to increase S/N**
  - Grouping is based on a multi-band Bayesian Blocks analysis
- **Source aperture photometry and derived properties (*e.g.*, hardness ratios, spectral fits) are populated from the longest duration Bayesian Block**
  - Properties for **all** blocks are available in the `blocks3` data product
- **Source temporal variability properties are computed using all observations**



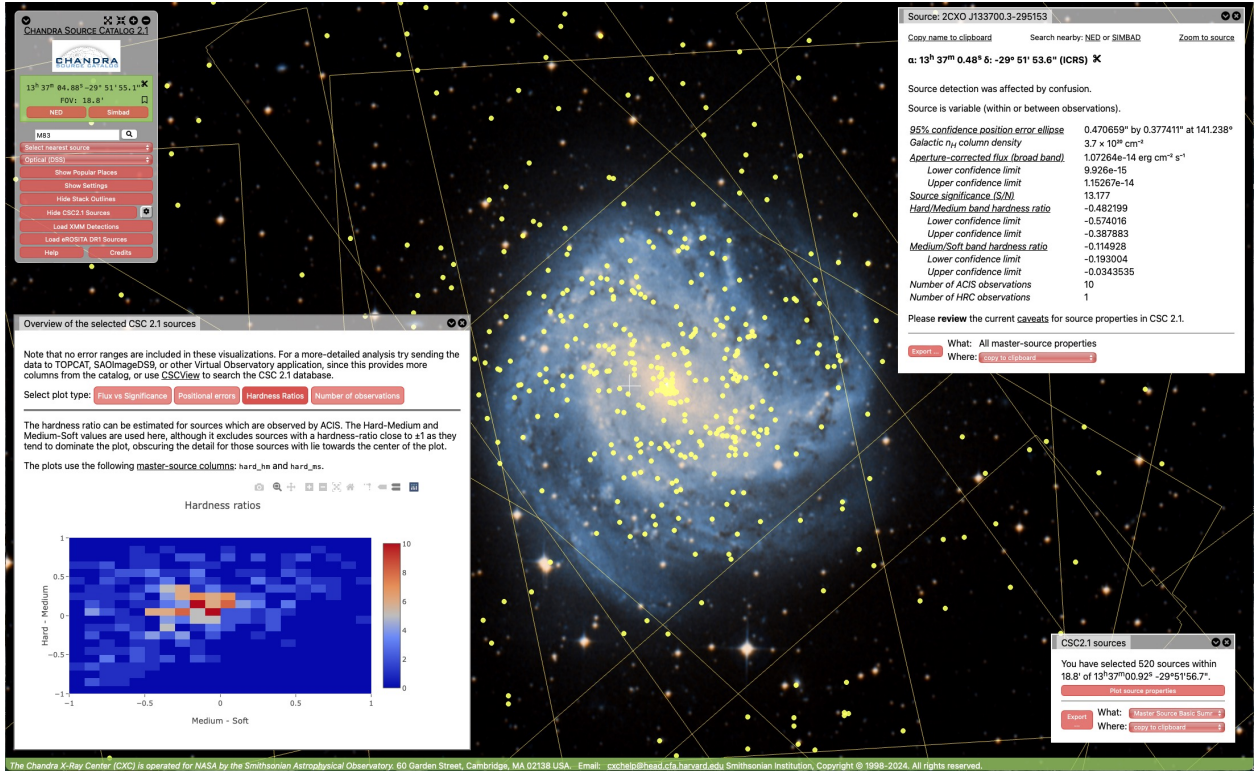

*Above:* Marginalized probability density functions (MPDFs) for ACIS broad band energy flux in 7 observations contributing to master source 2CXO J004152.6−092213

Green, blue, red indicate different Bayesian Blocks (longest block is green in this example)

The black curve is the master source "best-estimate" MPDF, which combines data from all observations included in that block

# Catalog User Interfaces

- *CSC WWT visualizer*
- *CSCview data-mining interface*
- *IVOA standard interfaces (TAP, SCS, SIAP) provide access to Jupyter notebooks using PyVO*
- *Simple web form*
- *Web command line*
- *CIAO scripting & ds9*




WWT provides a visual interface to CSC 2.1 data
See https://cxc.cfa.harvard.edu/csc/wwt.html

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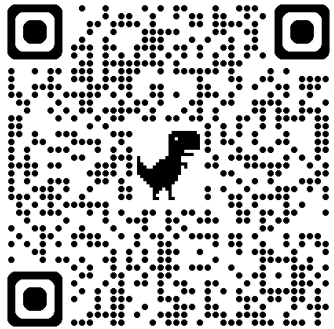
# Summary

- ***CSC 2.1 released April 2024 and includes public data from 2000–2021 inclusive***
  - Minor update 2.1.1 released October 2024 corrected some source names and populated missing (incorrectly null) properties
- ***Multiple interfaces available, including WWT, simple web form, CSCview, scripting, IVOA compliant (e.g., for use with PyVO)***
- ***CSC 2.1 cross-matches with other catalogs will be available soon***

For more information see the catalog website https://cxc.cfa.harvard.edu/csc/

Please respond to the *Chandra* Source Catalog Workshop Questionnaire



The *Chandra* Source Catalog is developed and made available to the community by the Smithsonian Astrophysical Observatory's *Chandra* X-ray Center, which operates the *Chandra* X-ray Observatory for and on behalf of the National Aeronautics and Space Administration (NASA)

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# *Backup Slides*

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# Tabulated Properties

## Master Source Properties

- Source name, position and position errors, significance, source flags, multi-band deconvolved extent, multi-band aperture photometry (photon and energy fluxes, spectral model fluxes [multiple spectral models]), hardness ratios, spectral model fits [multiple spectral models], multi-band intra- and inter-observation temporal variability

## Stacked-Observation Detection Properties

- Position and position errors, multi-band significance, detection flags and codes, multi-band deconvolved extent, multi-band aperture photometry (net counts and count rates, photon and energy fluxes), aperture parameters, hardness ratios, multi-band intra- and inter-observation temporal variability

## Per-Observation Detection Properties

- Detector position, multi-band significance, detection flags and codes, multi-band raw, PSF, and deconvolved extent, multi-band aperture photometry (total counts, net counts and count rates, photon and energy fluxes, spectral model fluxes [multiple spectral models]), masked aperture parameters, spectral model fits [multiple spectral models], multi-band intra-observation temporal variability

# Data Products

## Observation Data Products

- Observation event list, aspect solution and histogram, bad pixel map, FoV, pixel mask
- Multi-band images, background images, exposure maps, surface brightness contours

## Stacked-Observation Data Products

- Stack event list, FoV, merged detection list
- Multi-band images, background images, exposure maps, limiting sensitivity

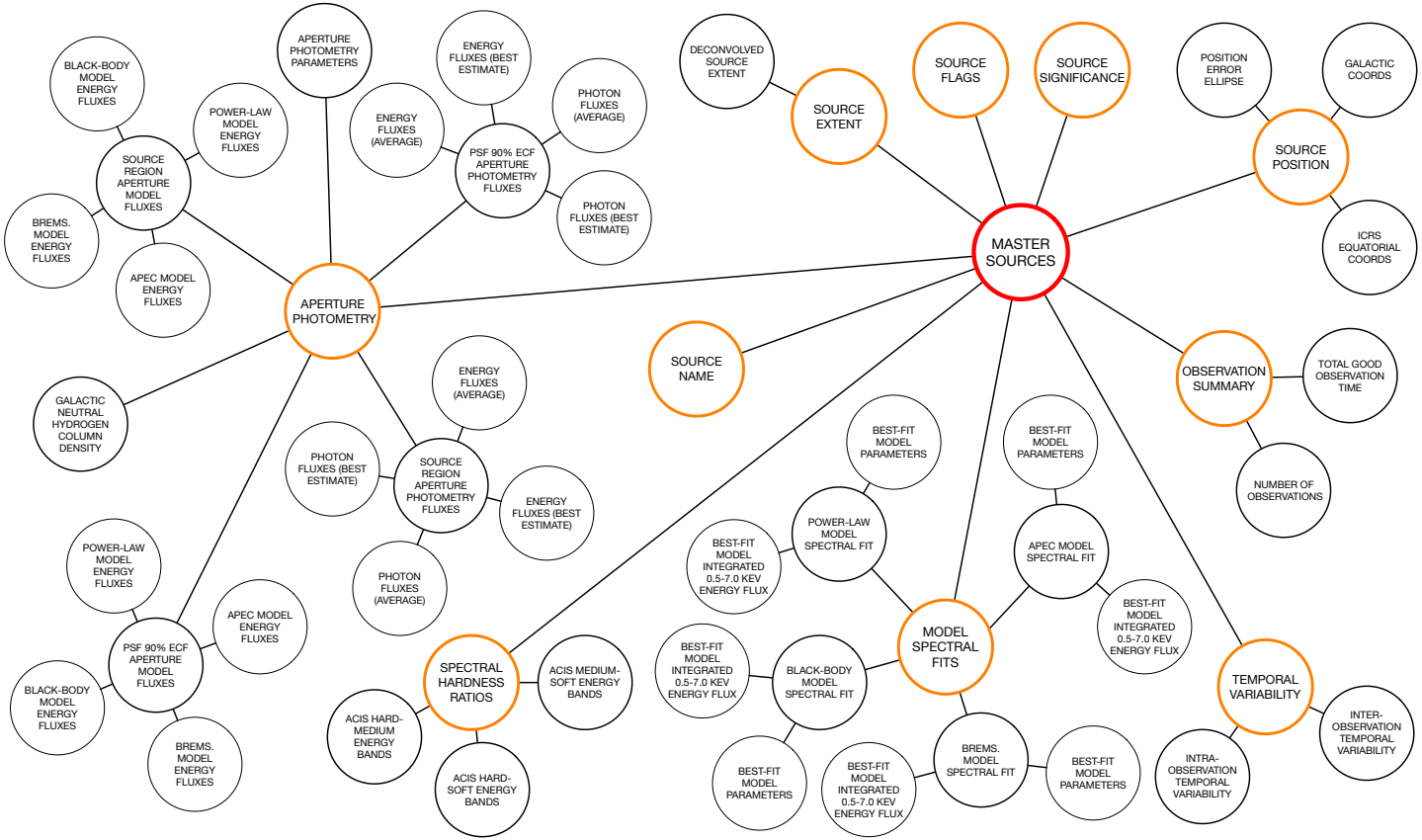
## Detection Region Data Products

- Detection region stack and observation region definitions, event lists
- Multi-band per-stack and per-observation images, exposure maps, position error MCMC draws, aperture photometry PDFs
- Multi-band per-observation PSFs, light curves
- Per-observation PHA spectrum, RMF, ARF

## Source Level Data Products

- Aperture photometry PDFs, per-Bayesian block properties (aperture photometry fluxes, model energy fluxes, spectral fits, hardness ratios), extended source convex hull polygons

# Master Sources Databased Properties

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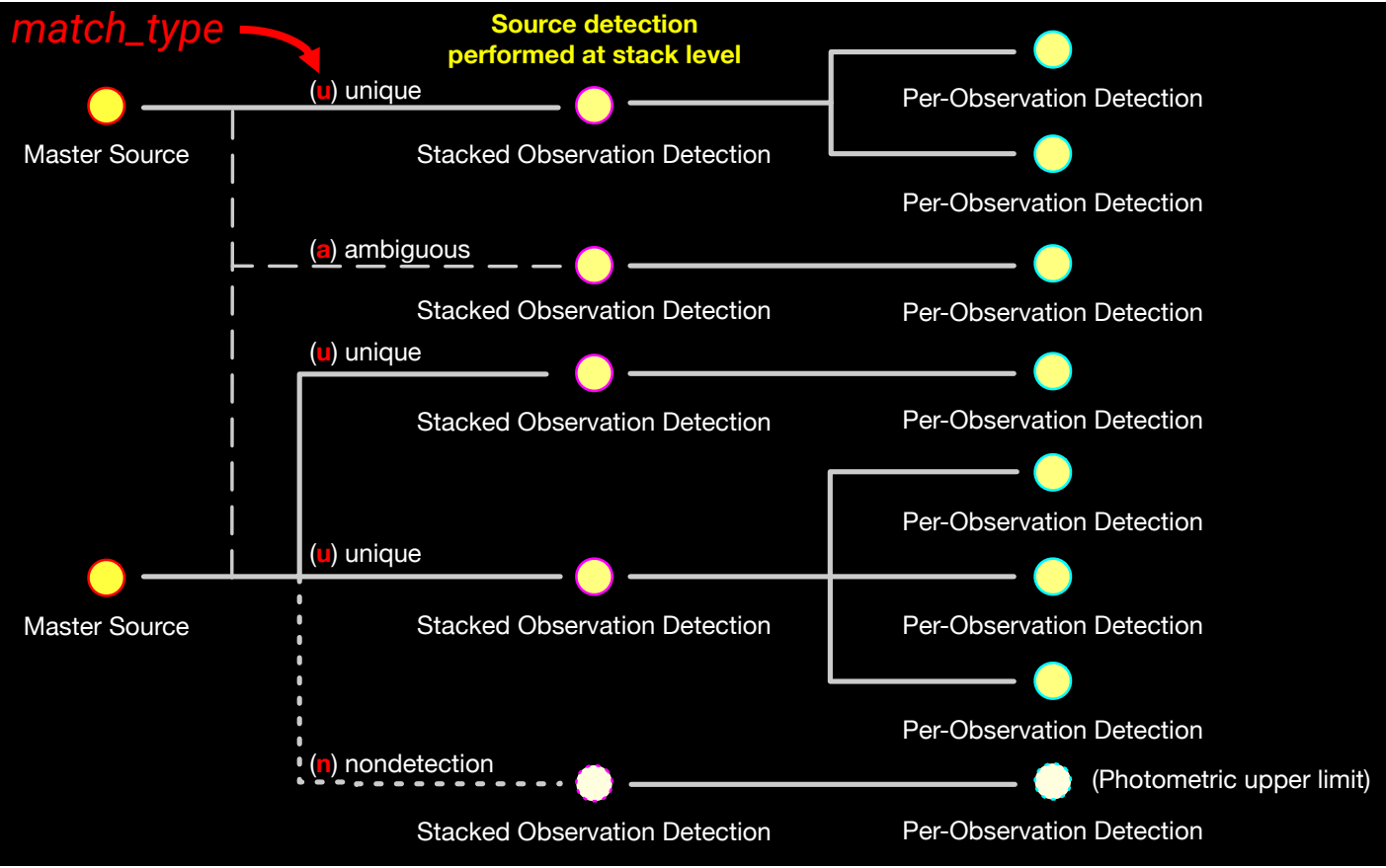
# Source/Detection Hierarchy



# Aperture Photometry

- Aperture photometry PDFs determined using Bayesian model from Primini & Kashyap 2014 ApJ 796, 24
- Photometry for multiple detections with overlapping apertures, nearby source apertures, and background region, are solved for simultaneously
- Joint posterior for source fluxes and background flux (for a single observation):

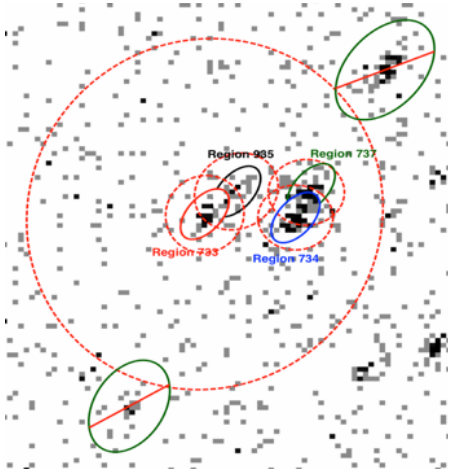
$$P(s_1 \ldots s_n, b | C_1 \ldots C_n, B) = K \times P(b) P_{Pois}(B | \phi) \prod P(s_i) P_{Pois}(C_i | \theta_i)$$

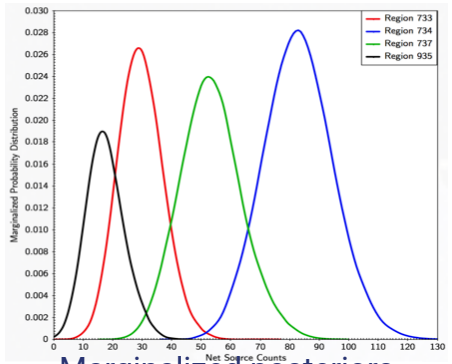
$$\theta_i = E_i \times \left[ \sum_{j=1}^{n} f_{ij} s_j + \Omega_i b \right] ; \phi = E_b \times \left[ \sum_{i=1}^{n} g_i s_i + \Omega_b b \right]$$

- Counts in overlapping regions are assigned to the brightest source
- Master source flux for source $s_k$ in an *n*-source bundle is determined from the Bayesian block with the largest exposure:

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

- Posteriors are optimized and sampled using MCMC in *Sherpa*




Marginalized posteriors

Figures courtesy F. Primini