

# Doing science with the *Chandra* Source Catalog 2.0

F. Civano (CfA/CXC)

On behalf of the *Chandra* Source Catalog team

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<sup>1</sup>Smithsonian Astrophysical Observatory

<sup>2</sup>Formerly Smithsonian Astrophysical Observatory

<sup>3</sup>Northrop Grumman Mission Systems

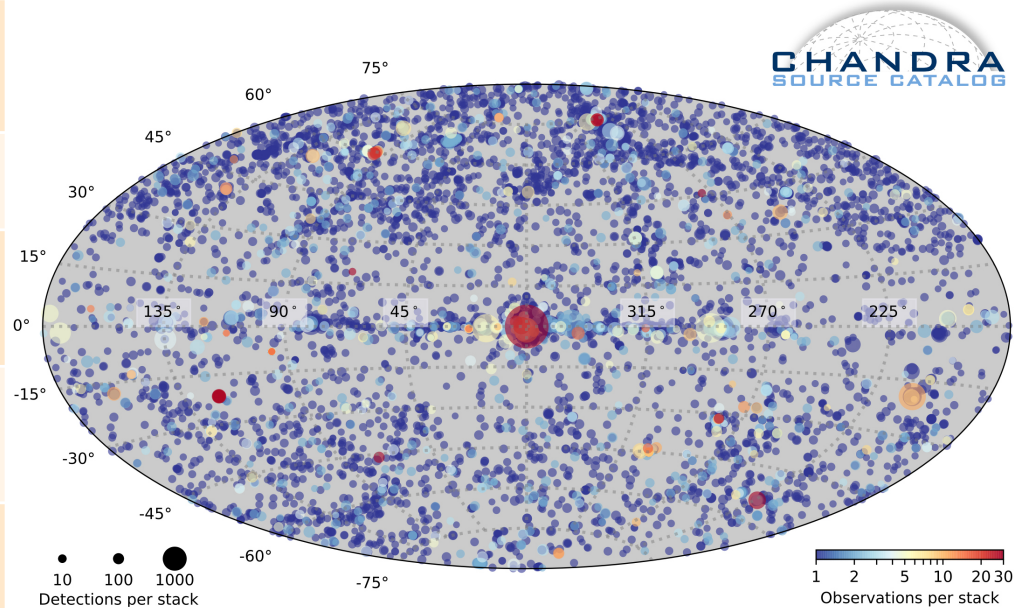
<sup>4</sup>MIT Kavli Institute for Astrophysics and Space Research

100 1000  
sources per stack

1 2 5 :  
Observations per source

# CSC 2.0 in numbers

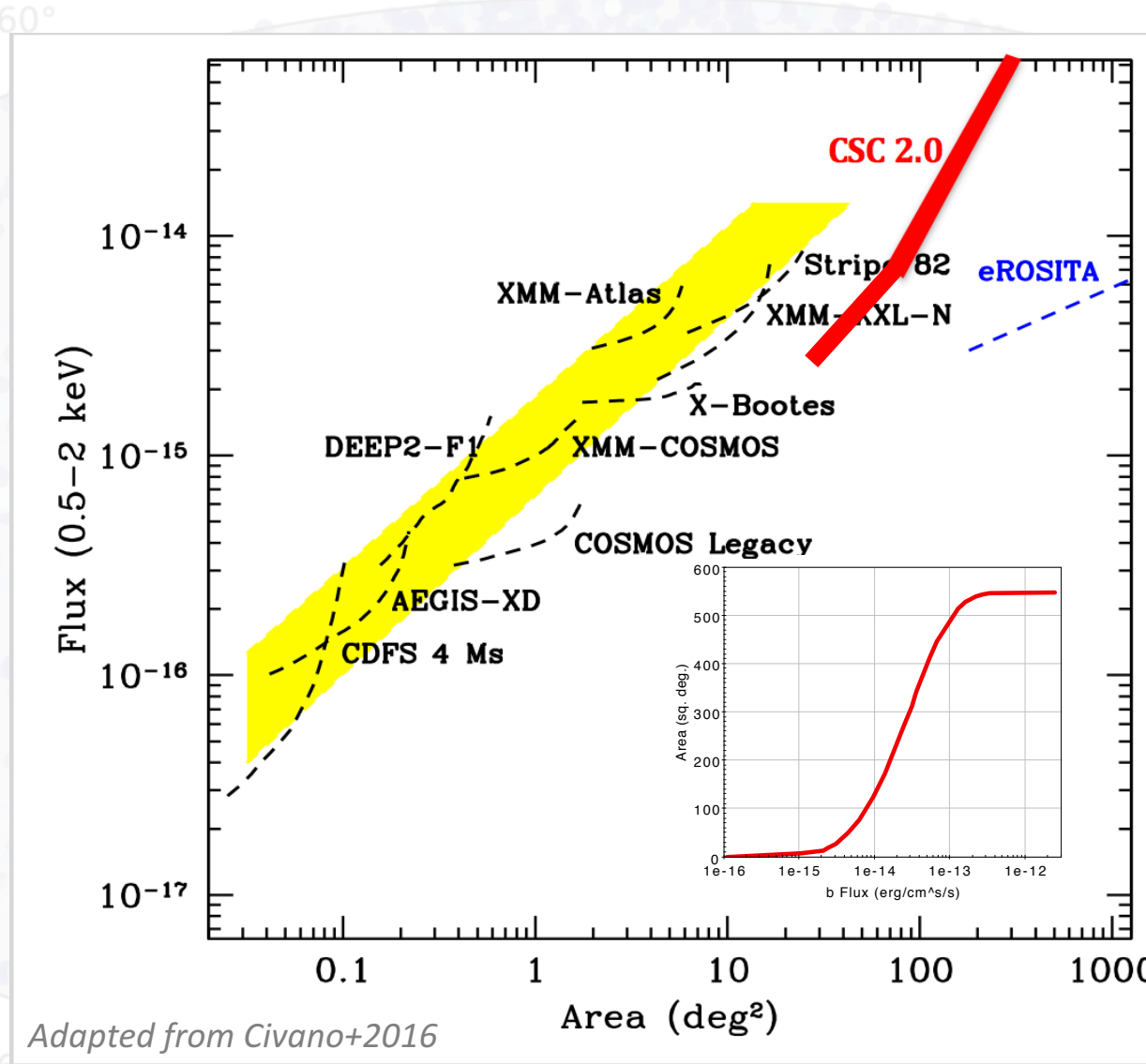
	CSC 1	CSC 2
Individual obsids	5110	10,382
Obsid years	1999-2009	1999-2014
Total exposure		245.8 Ms
longest exposure	190 ks	5.8 Ms
Counts on-axis	~10	~5
Number of sources	106,586	315,875
Number of detections	158,071	374,349



100 1000  
ons per stack

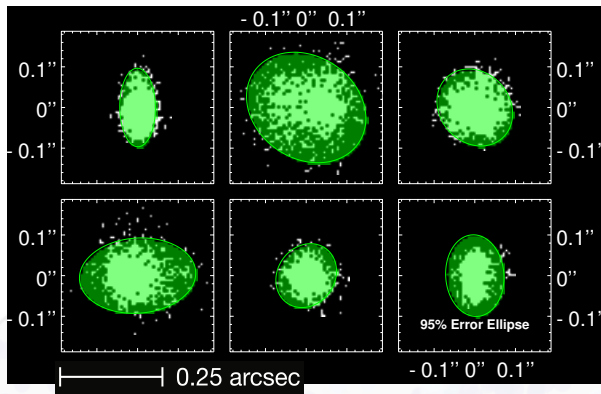
1 2 5 :  
Observations p

# Sky coverage

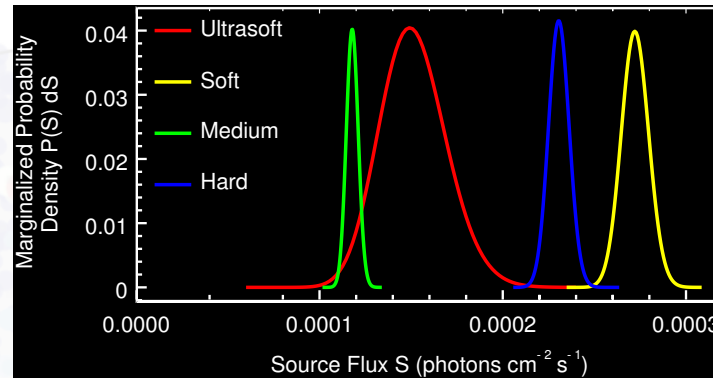


~550 deg<sup>2</sup>  
Area covered

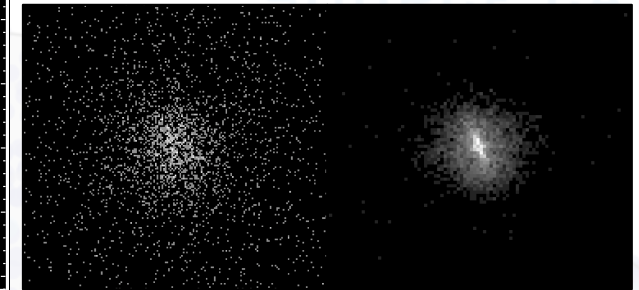
# CSC 2.0 main features



Position error ellipses with position confidence MCMC draws

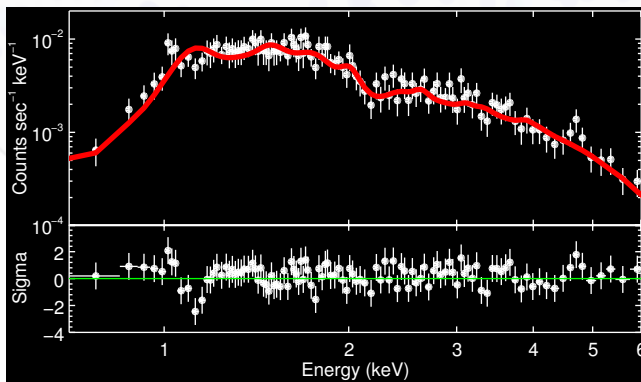


Multi-band aperture photometry with Bayesian probability density functions;  
0.2-0.5 keV , 0.5-1.2 keV, 1.2-2 keV, 2-7 keV

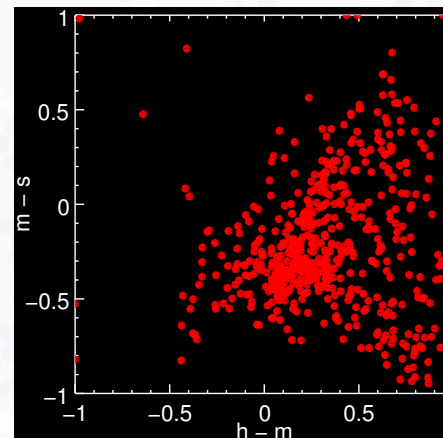


Source extent and local PSF models for every source and energy band

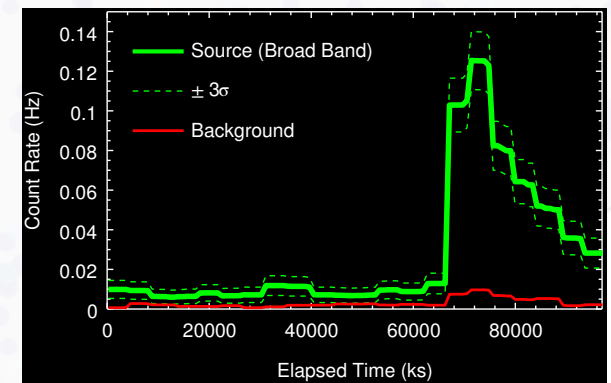
Spectral model fits and fluxes determined using multiple models



Hardness ratios (HM-HS-MS)



Intra- and inter-observation variability measures and light curves



# CSC 2.0 new features

CHAND  
SOURCE CAT

- **Source detection on stacked observations**

New source detection approach

- Wavelet detection with “permissive” parameters *plus* entirely new Voronoi tessellation algorithm for both background determination *and* source detection
- Maximum likelihood estimator grades candidate detection and improves on-axis detection limit  $\sim 15$  net counts for exposures  $< 15$  ks
- MCMC draws provide relative astrometry position error *ellipses*
- Aperture photometry PDFs computed using Bayesian algorithms
- Multiple observations grouped by multi-band Bayesian Blocks algorithm to improve S/N even for variable sources (properties archived for each block)
- Integrated multi-band limiting sensitivity computed on  $4'' \times 4''$  pixels

100 1000  
ons per stack

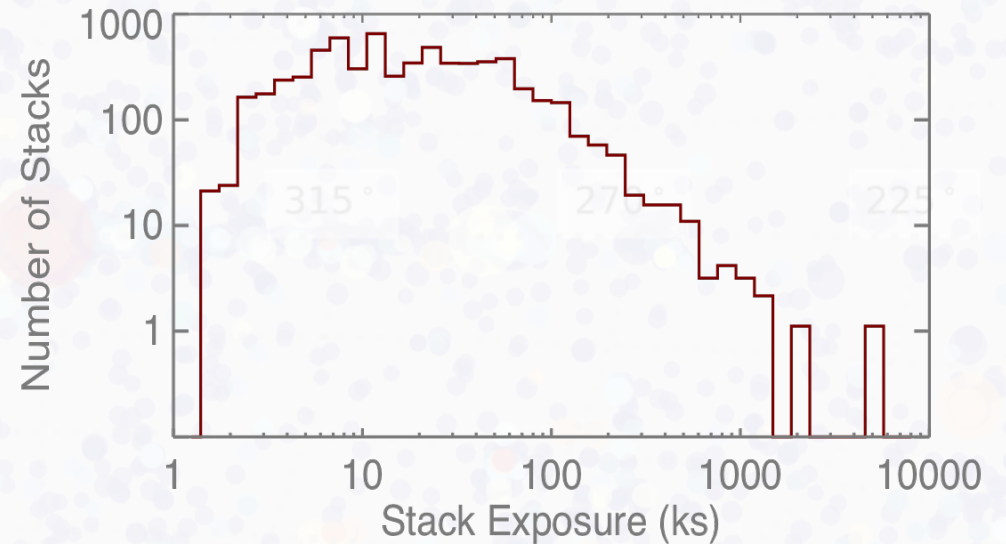
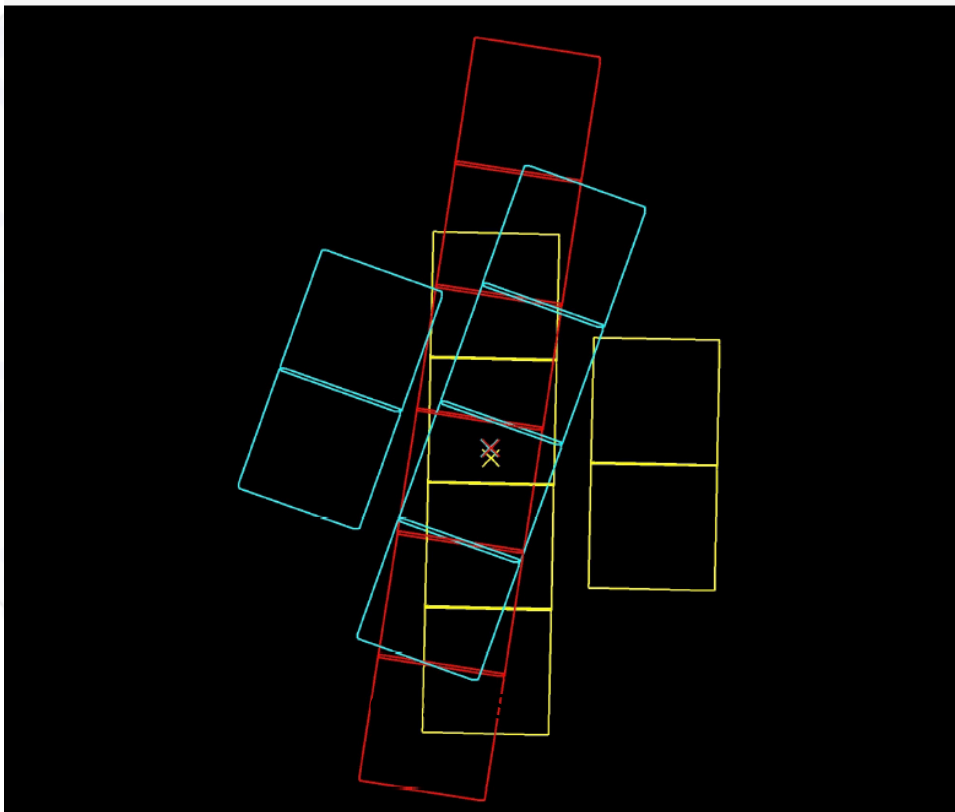
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1 2 5 :  
Observations p

# Stacked observations

STACKS: sum of obsids with aim-point within 1 arcmin

## Example Stack



100 1000  
ons per stack

-60°

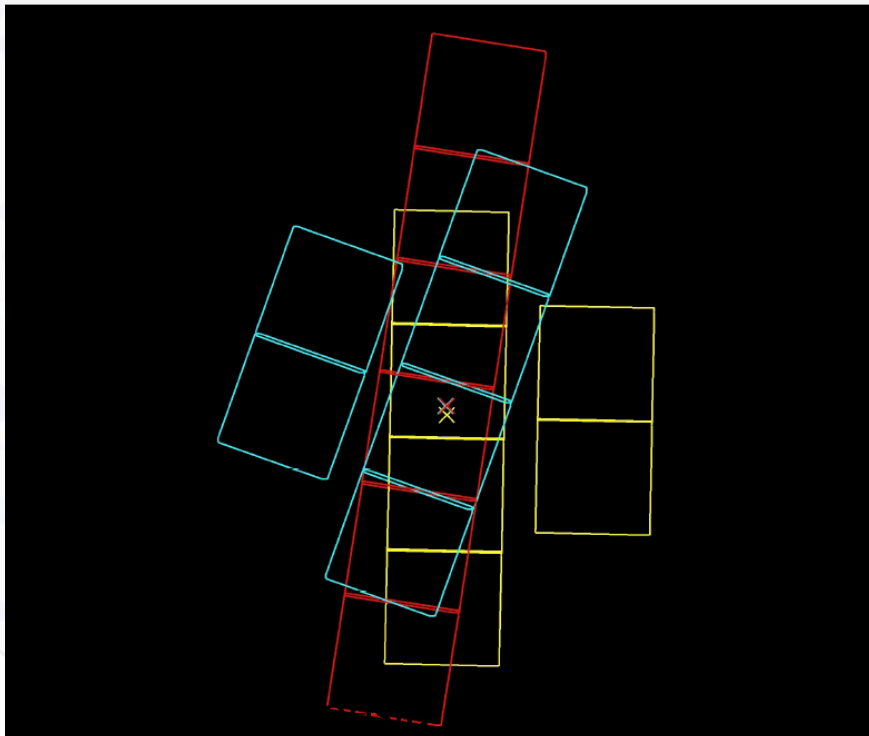
-75°

1 2 5 :  
Observations p

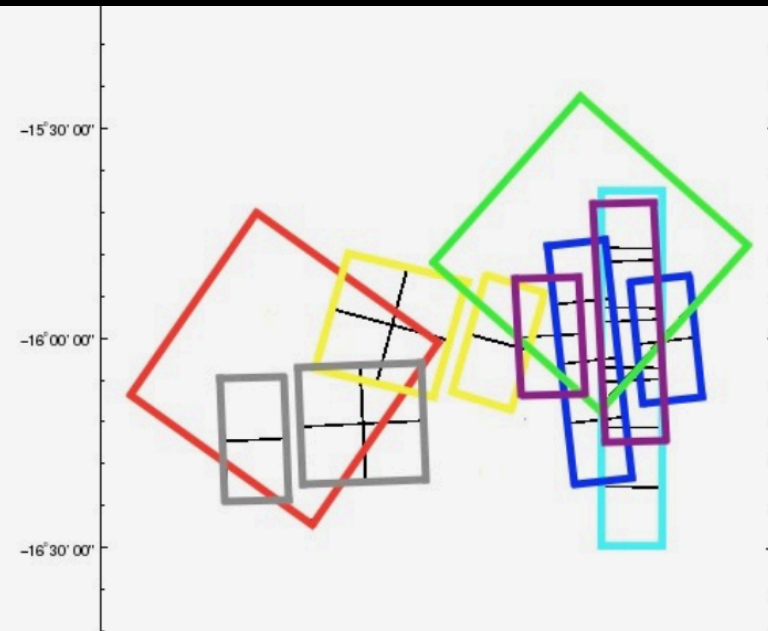
# Stacked observations

STACKS: sum of obsids with pointings within 1 arcmin

## Example Stack



## ENSEMBLES: contiguously overlapping stacks

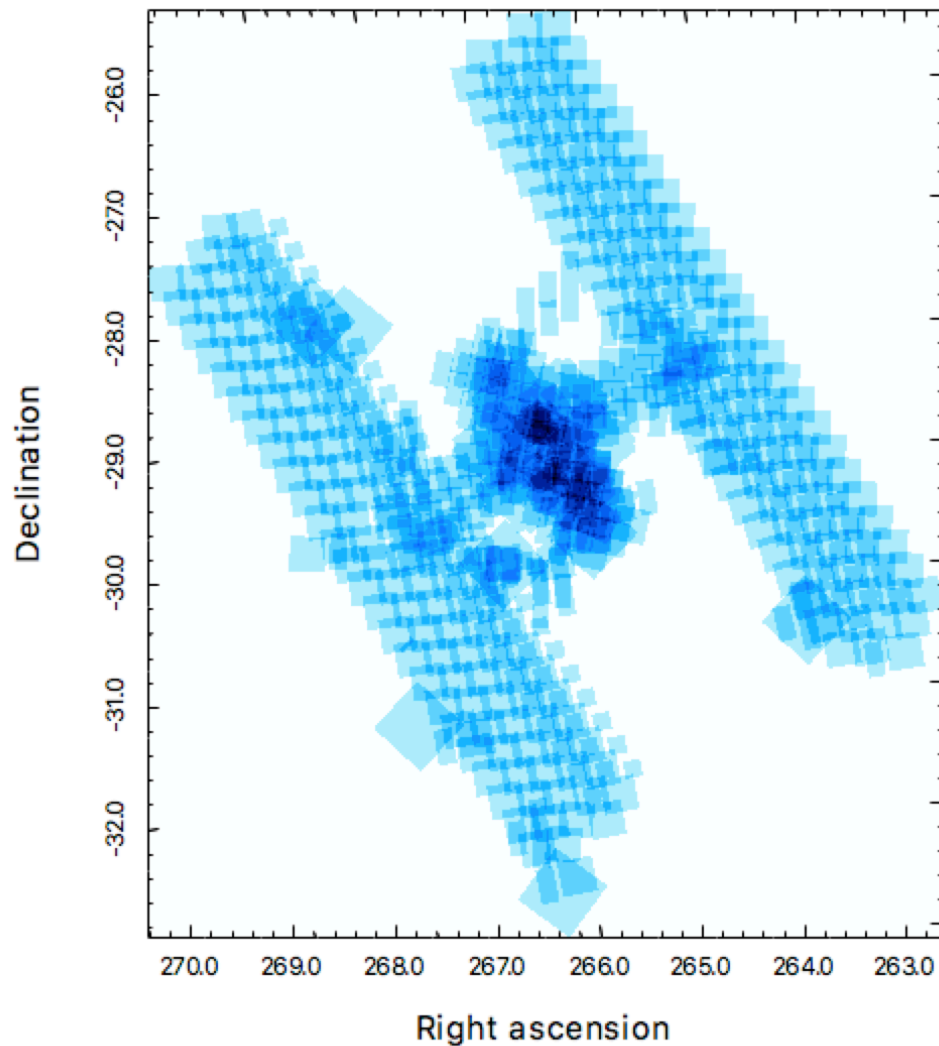


FOVs of 7 Stacks (1 obsid in each)

100 1000  
ons per stack

1 2 5  
Observations p

# Example: Galactic Center Area

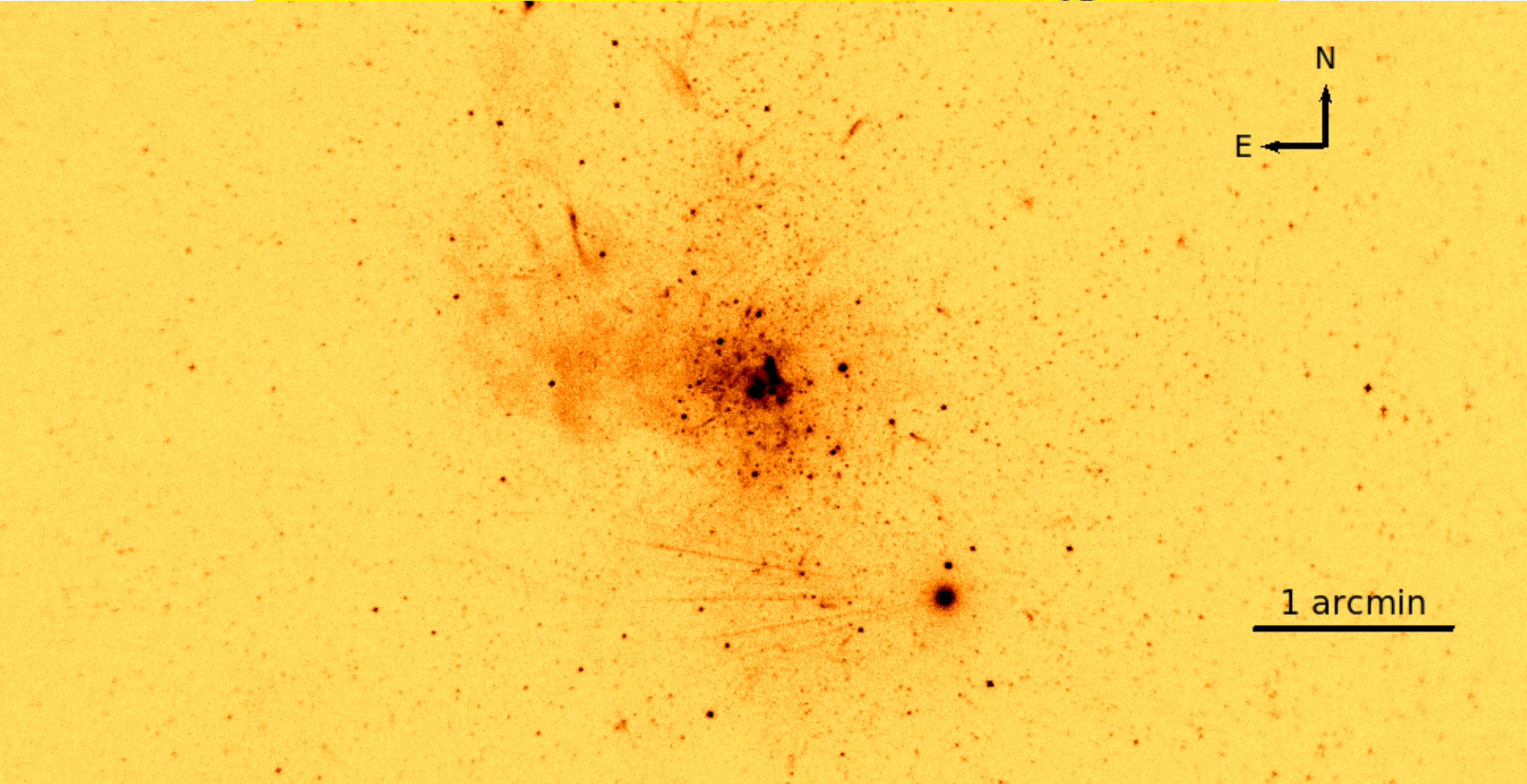


- 1 ensemble
- 379 stacks (36 HRC and 343 ACIS)
- 534 single *Chandra* observations
- Total area covered  $\sim 19 \text{ deg}^2$
- Total exposure time  $\sim 9 \text{ Ms}$



# Example: Galactic Center Area

Sgr A\* - central stack of 71 observations



100 1000  
ons per stack

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1 2 5 :  
Observations p

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- Aperture photometry PDFs computed using Bayesian algorithms
- Multiple observations grouped by multi-band Bayesian Blocks algorithm to improve S/N even for variable sources (properties archived for each block)
- Integrated multi-band limiting sensitivity computed on 4" x 4" pixels

● ●  
100 1000  
counts per stack

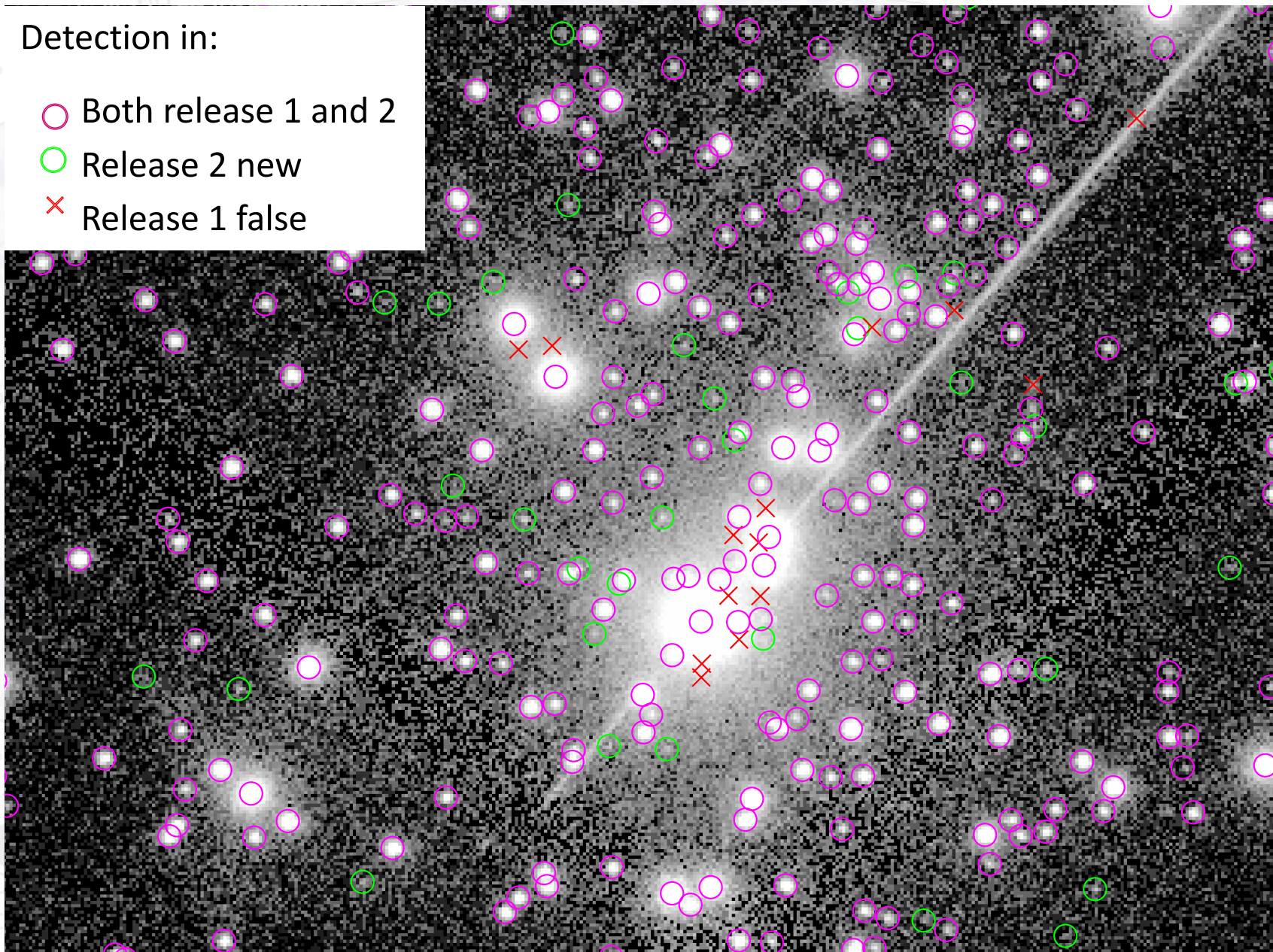
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1 2 5 :  
Observations per pixel

# CSC 1 vs CSC 2

Detection in:

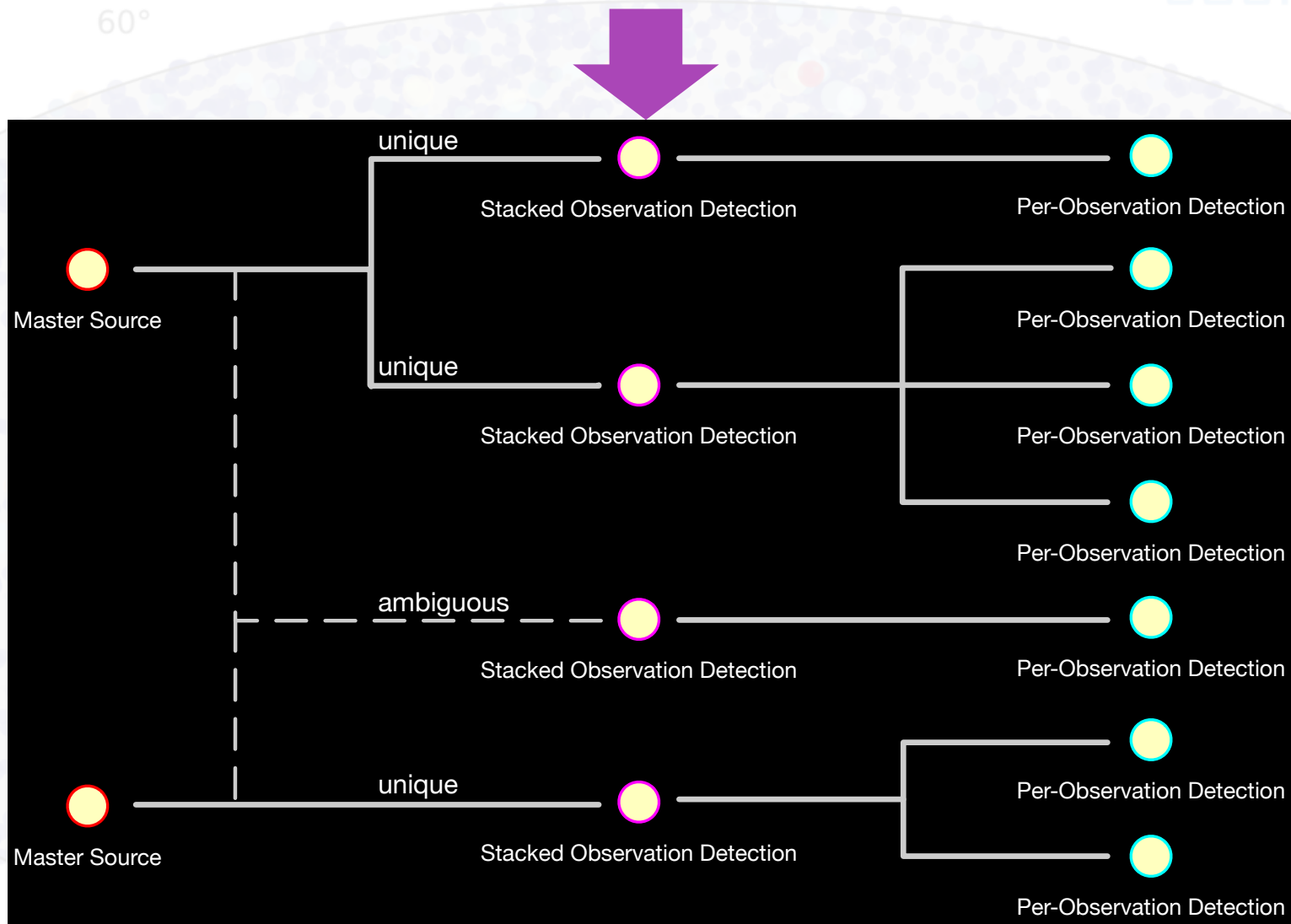
- Both release 1 and 2
- Release 2 new
- × Release 1 false



100 10  
ons per st

5  
tions p

# Source detection hierarchy

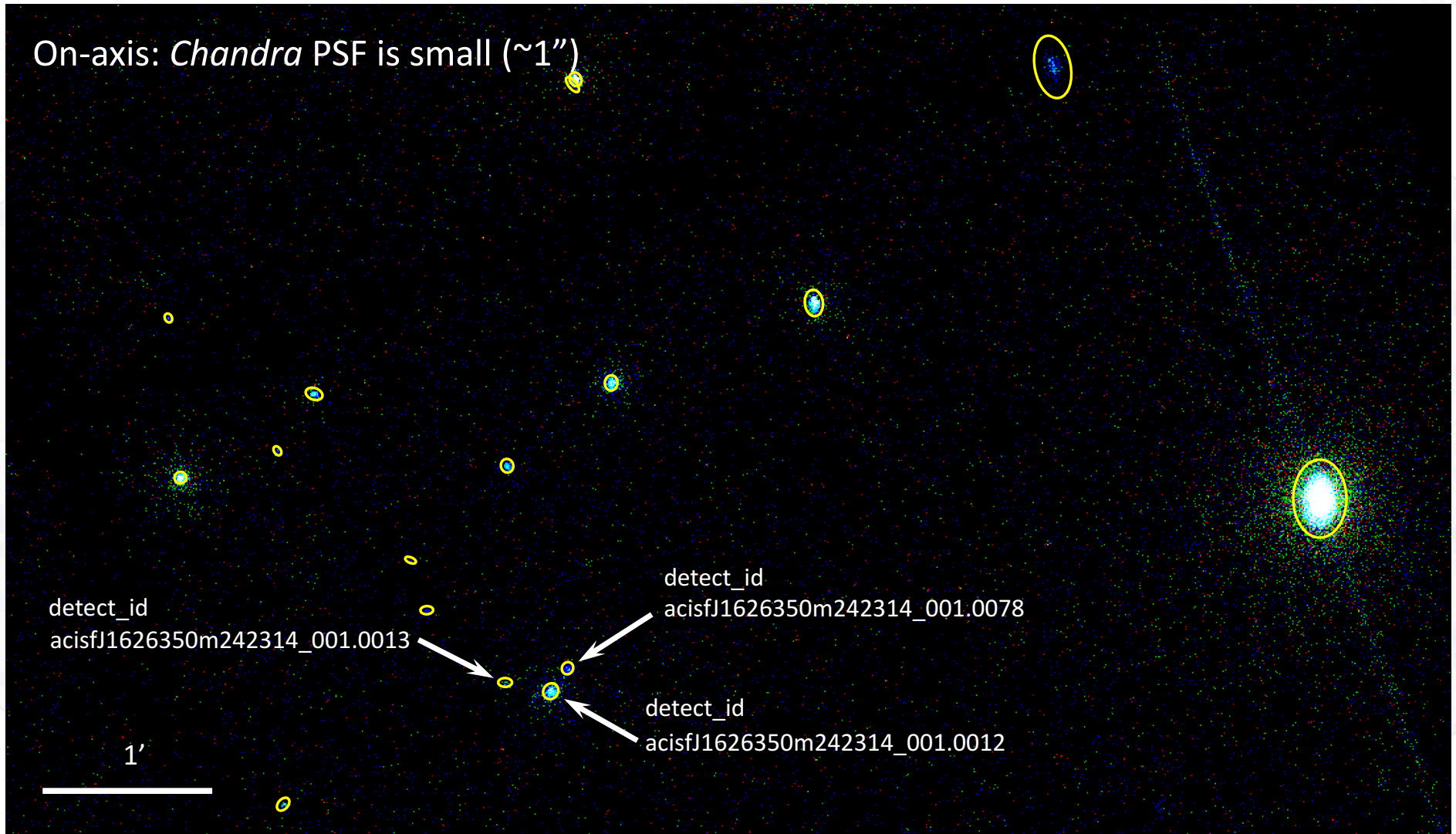


100 1000  
ons per stack

-75°  
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1 2 5 :  
Observations p

# Detections and sources



100 1000  
counts per stack

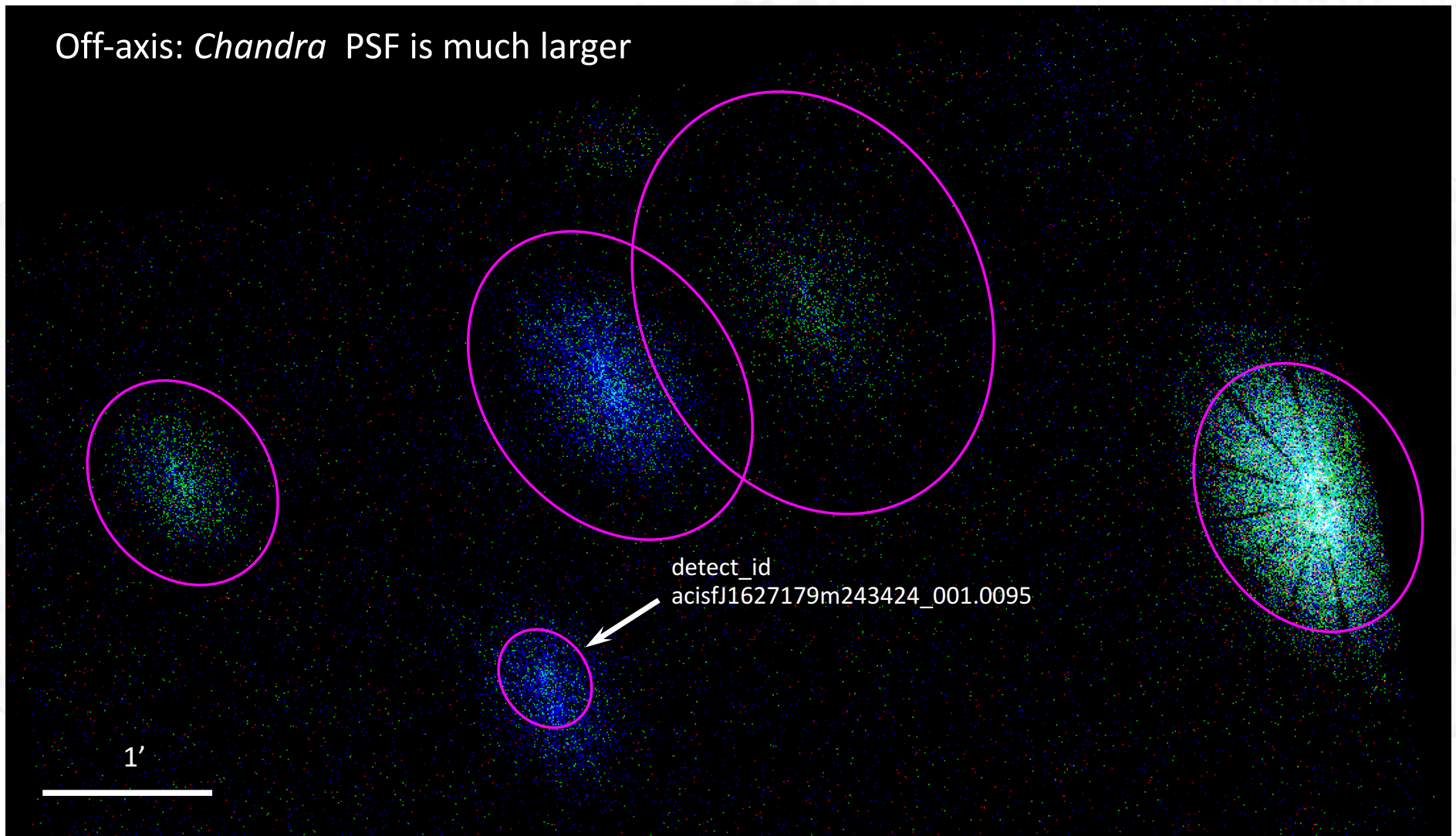
$-60^\circ$

$-75^\circ$

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1 2 5  
Observations p

# Detections and sources



100 1000  
counts per stack

-60°

-75°

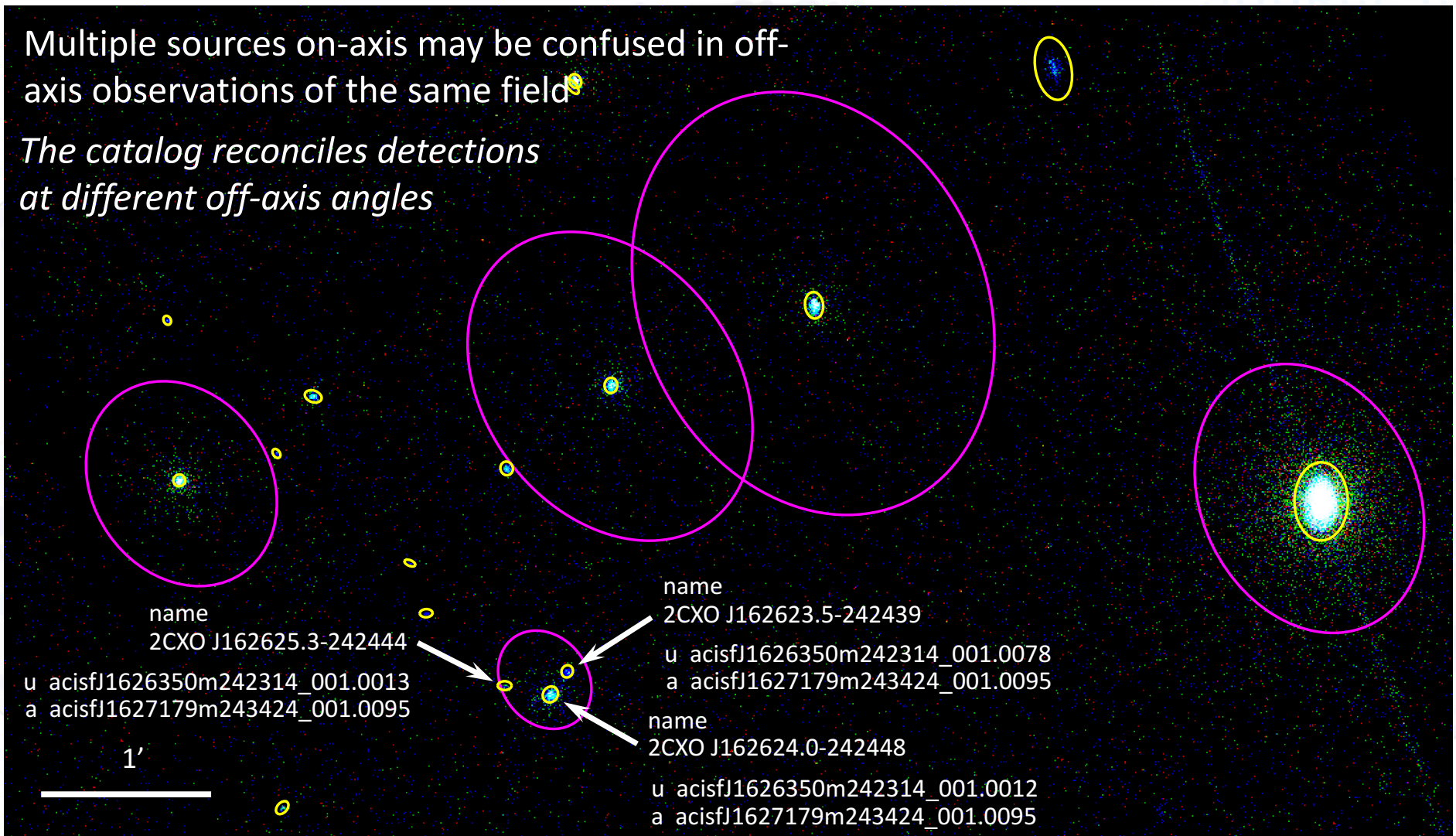
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1 2 5  
Observations per

# Detections and sources

Multiple sources on-axis may be confused in off-axis observations of the same field

*The catalog reconciles detections at different off-axis angles*



100 1000  
ons per stack

-60°

-75°

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1 2 5 :  
Observations p

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- Integrated multi-band limiting sensitivity computed on 4" x 4" pixels

100 1000  
counts per stack

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1 2 5 :  
Observations per pixel



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- MCMC draws provide relative astrometry position error *ellipses*
- **Aperture photometry; multi-band Bayesian Blocks algorithm**
- Integrated multi-band limiting sensitivity computed on 4" x 4" pixels

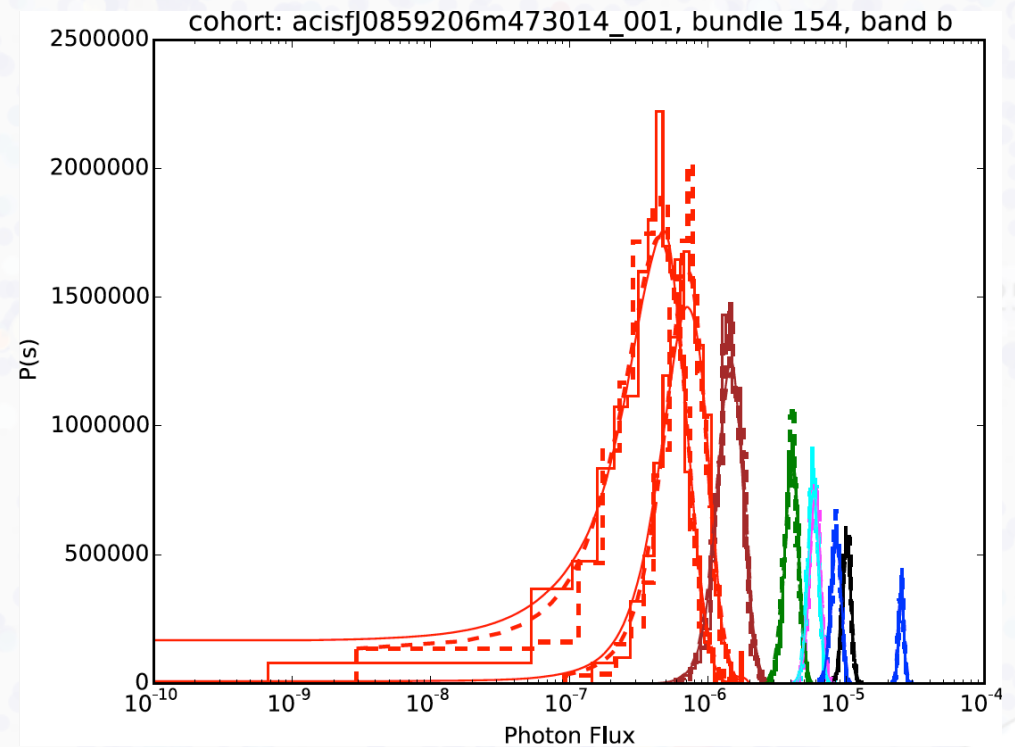
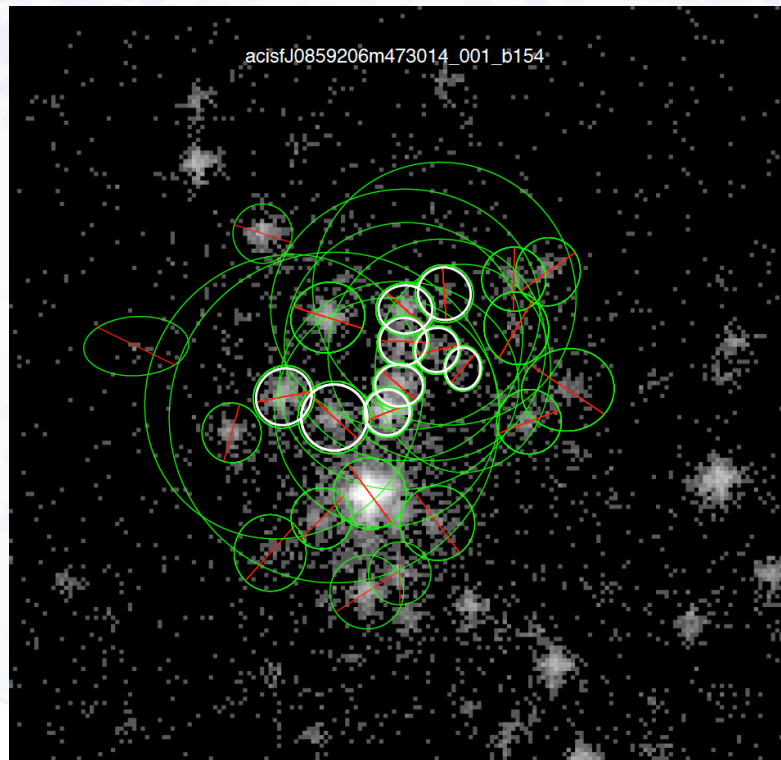
100 1000  
ons per stack

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1 2 5 :  
Observations p

# Source Properties: Aperture Photometry

Bayesian approach for simultaneous aperture photometry estimation in crowded fields  
(Primini, F. A. & Kashyap, V. L. 2014)

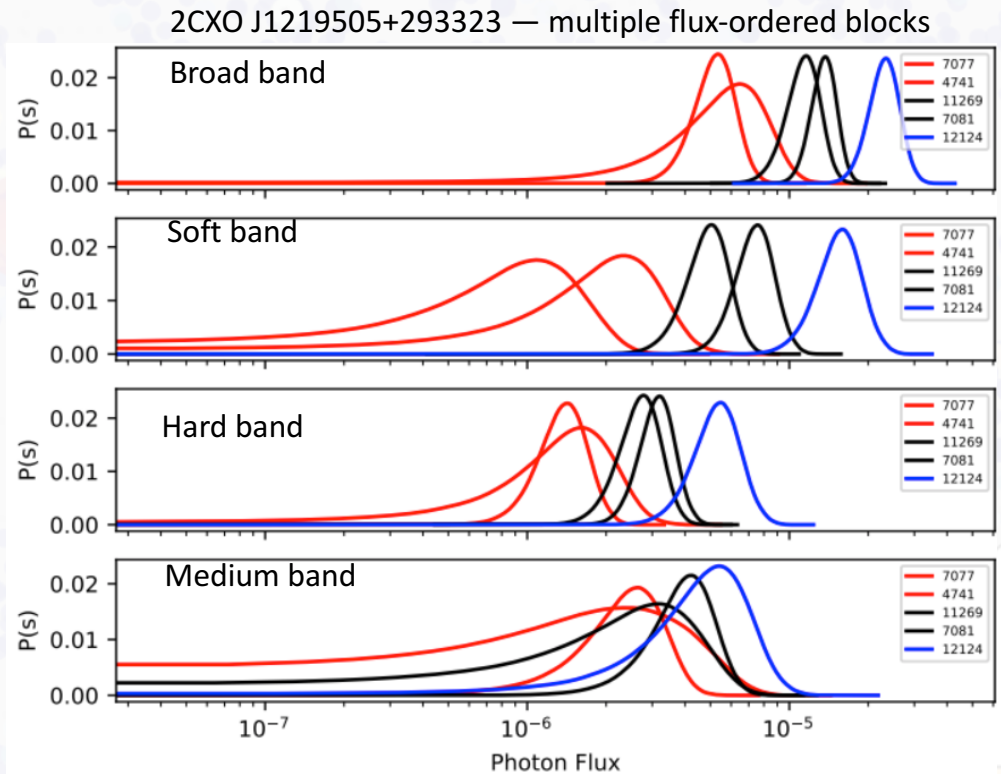
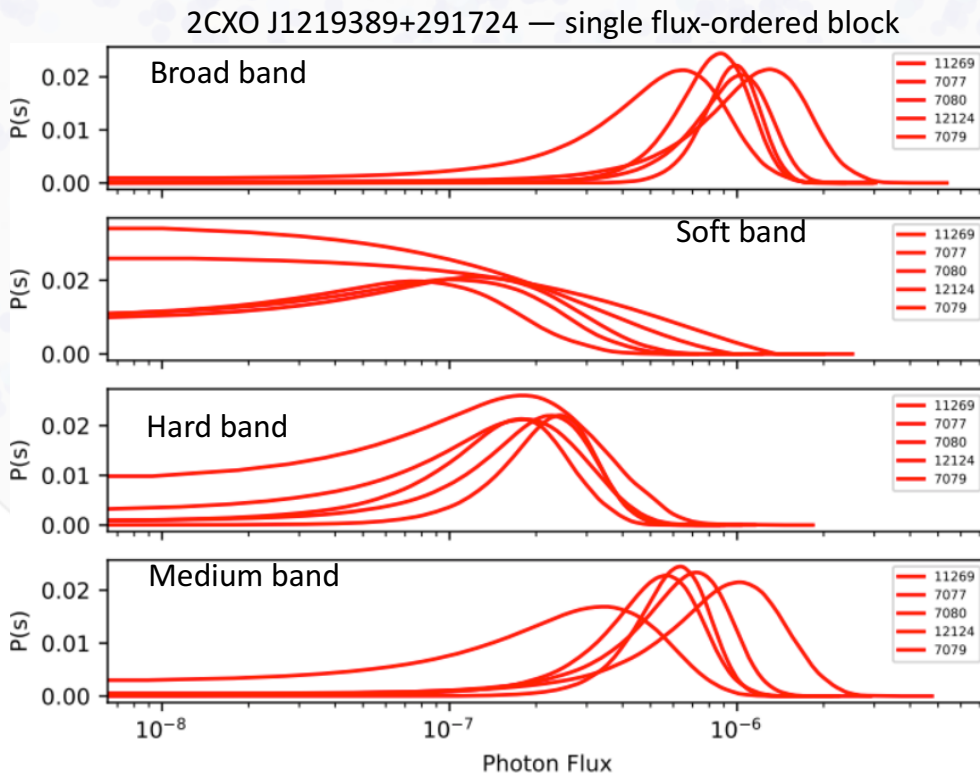


Photometric PDFs are estimated simultaneously for the 9 overlapping detections with the white highlights

The resulting *b* band photon flux PDFs

# Grouping Observations to Improve S/N

- Multi-band Bayesian Blocks analysis (*Scargle+2013*) on detection fluxes to identify observations that can be analyzed/grouped together
- The combined properties for the longest exposure Bayesian Block are databased, but the properties for *all* blocks are recorded in a FITS data product



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- **Multi-band limiting sensitivity computed on 4" x 4" pixels**

100 1000  
ons per stack

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1 2 5 :  
Observations p

# CSC 2.0 new features

CHAND  
SOURCE CAT

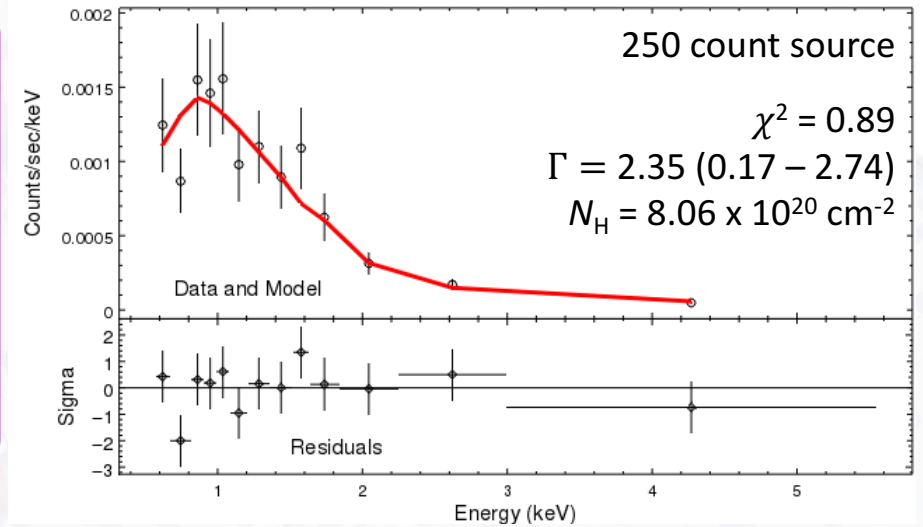
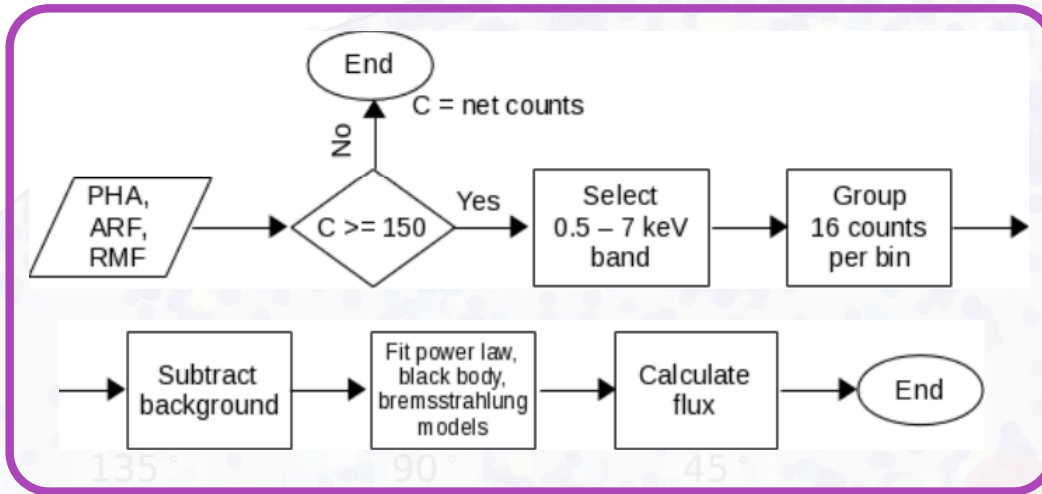
- Source detection on stacked observations
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  - Maximum likelihood estimator to improve on-axis detection (~5 net counts for exposures < 15 ks)
- MCMC draws provide relative astrometry position error *ellipses*
- Aperture photometry; multi-band Bayesian Blocks algorithm
- Multi-band limiting sensitivity computed on 4" x 4" pixels
- **Spectral analysis**

100 1000  
ons per stack

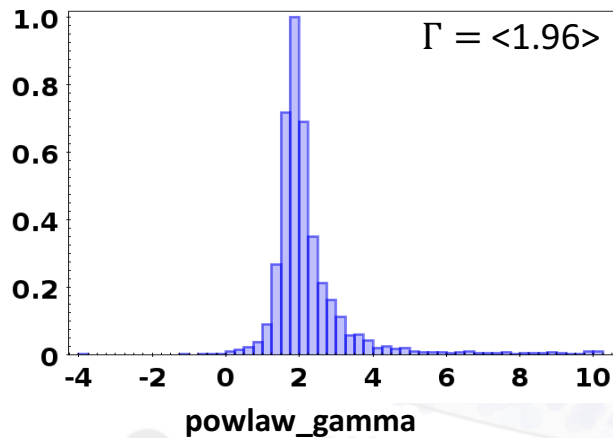
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1 2 5 :  
Observations p

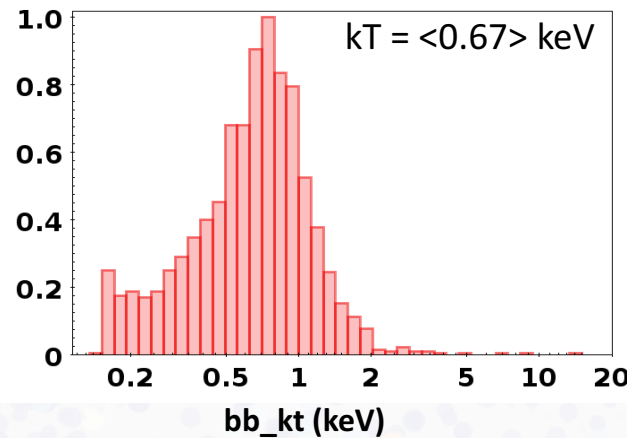
# Spectral Analysis



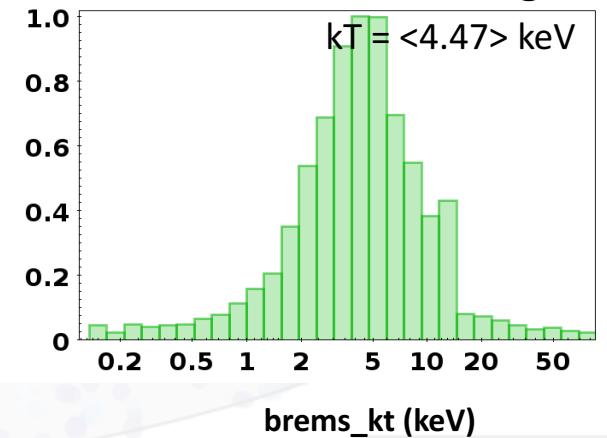
Abs. power law



Abs. black body

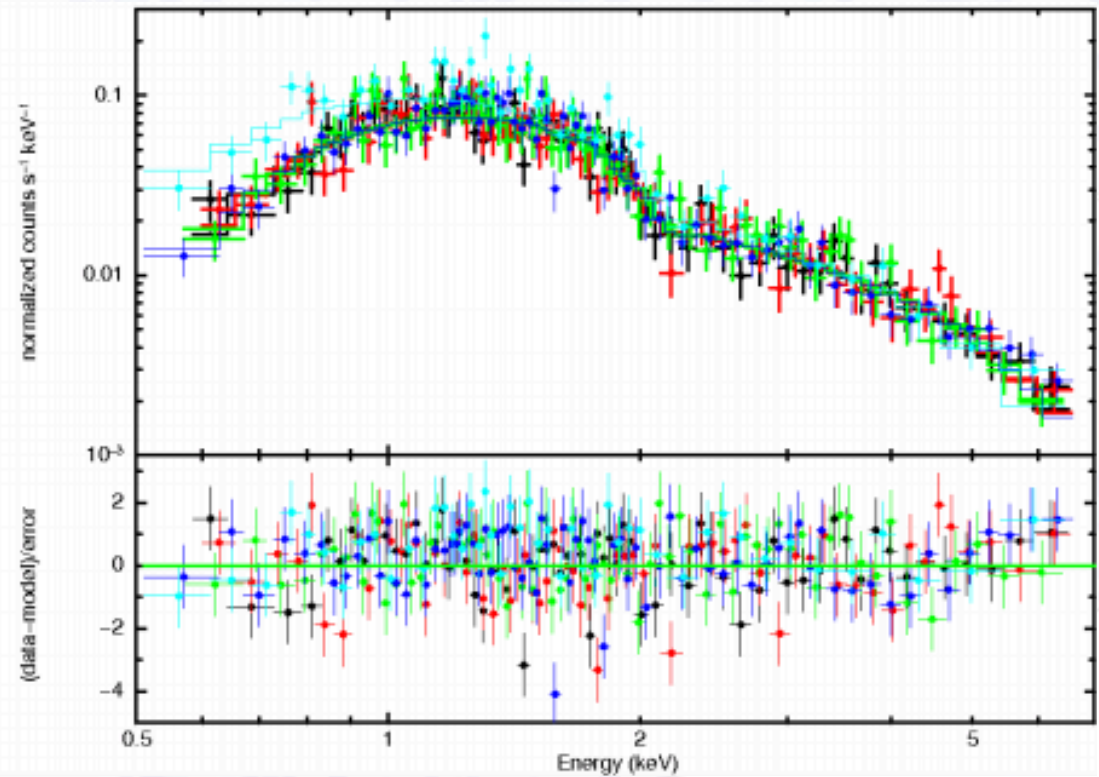
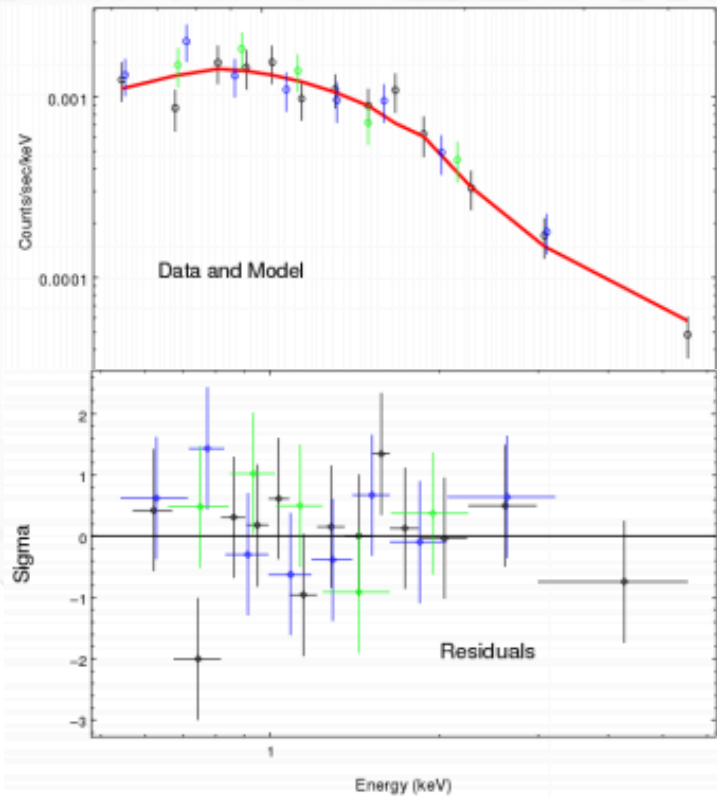


Abs. bremsstrahlung



# Joint Spectral Fits

- Sources that are observed multiple times are grouped by the Bayesian blocks analysis
- All spectra in the block are simultaneously fit



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- Aperture photometry; multi-band Bayesian Blocks algorithm
- Multi-band limiting sensitivity computed on 4" x 4" pixels
- Spectral analysis
- **Extended emission properties**

100 1000  
counts per stack

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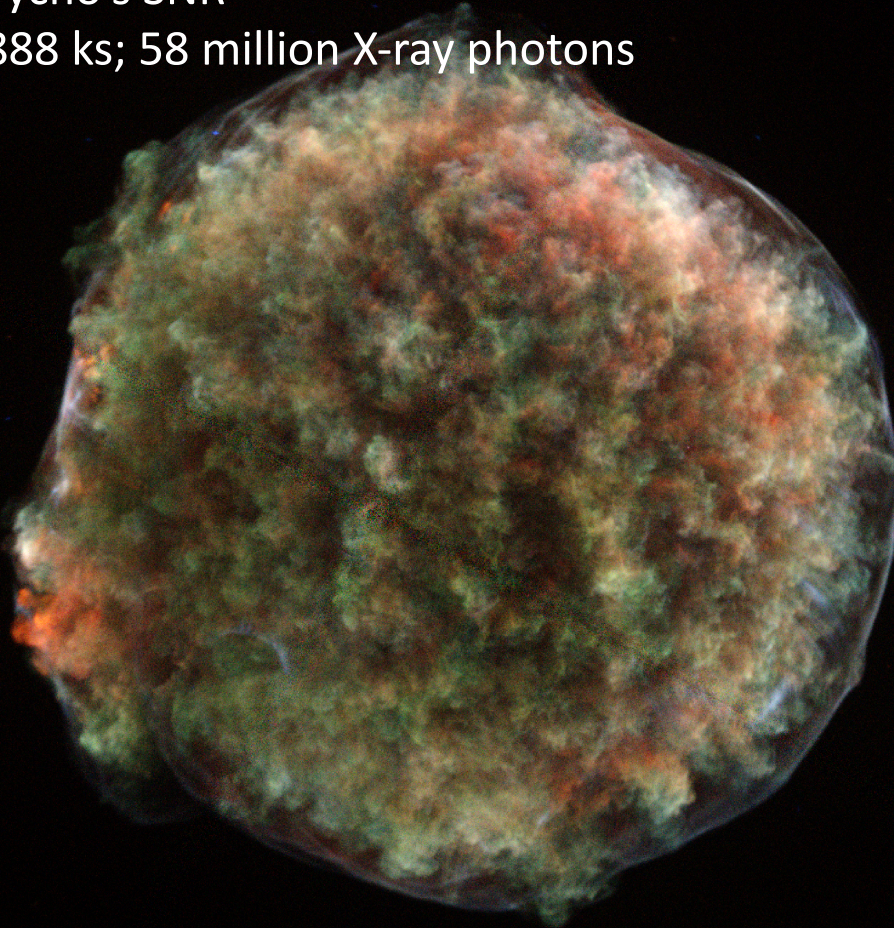
1 2 5 :  
Observations p



# Extended emissions

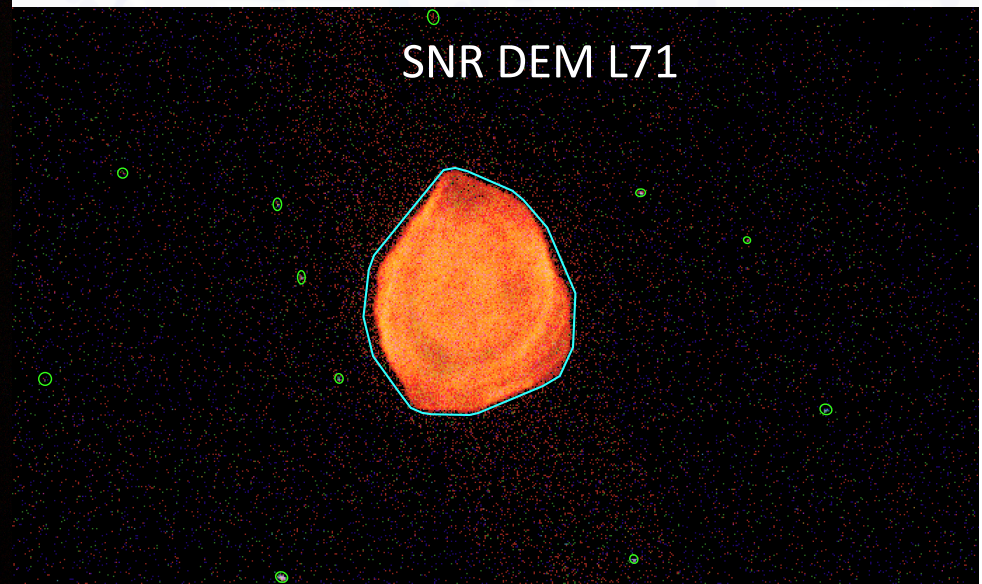
Tycho's SNR

888 ks; 58 million X-ray photons



- SNRs, cluster of galaxies, extended galaxies, jets, etc.
- Photometric properties are integrated over a convex hull bounding region aperture (cyan below).
- Fluxes and regions are going to be provided.

SNR DEM L71



100 1000  
ons per stack

-60°

-75°

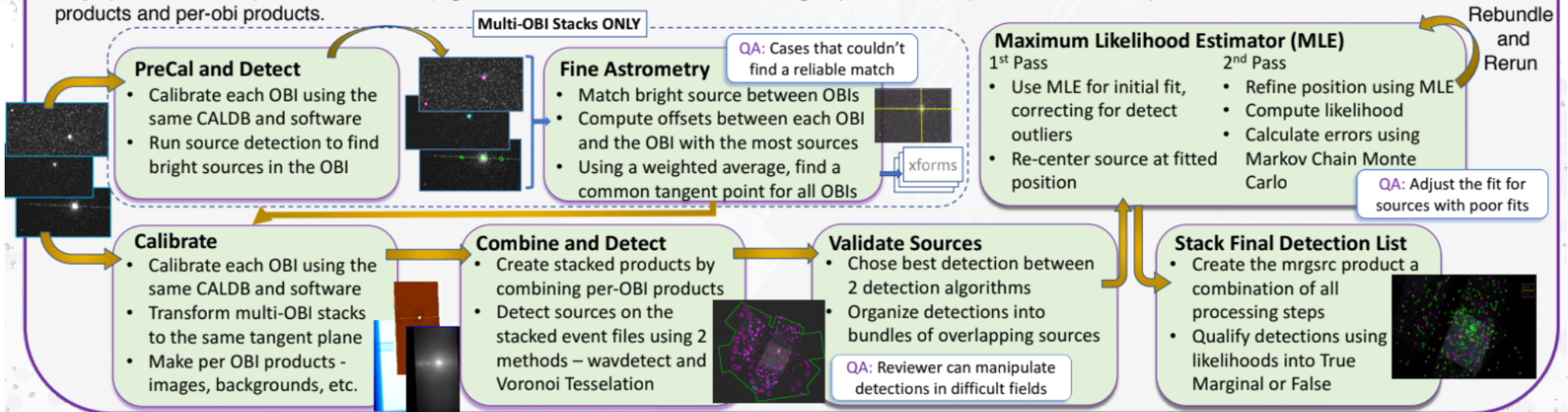
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1 2 5 :  
Observations p

# Pipeline structure

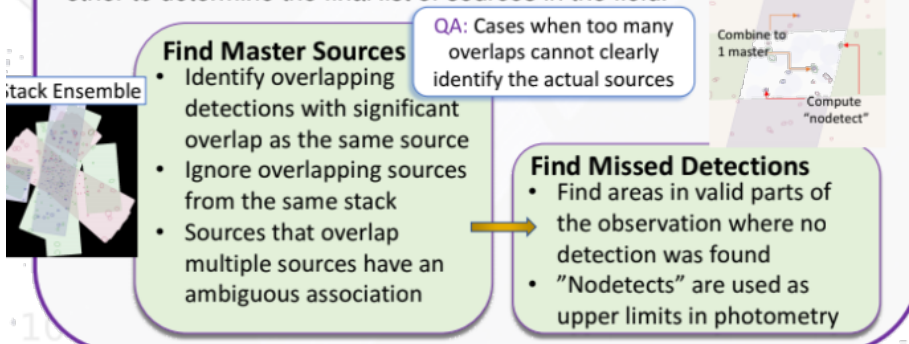
## Detecting Sources

Prior to processing, observations (OBI) within one arcmin of each other, are grouped into stacks. While the collection of pipelines operates on a stack, each pipeline may operate on a component of the stack (e.g an observation in the stack or even a group of detections). The results of this phase include source detections, stacked products and per-obi products.



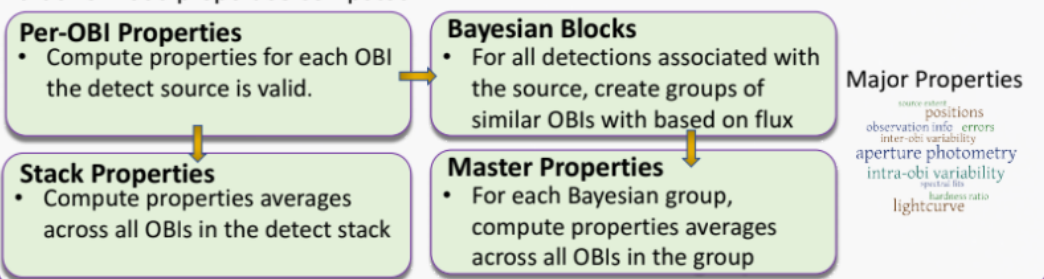
## Master Match

After all detections are found, the true and marginal detections within groups of overlapping stacks (ensembles) are compared against each other to determine the final list of sources in the field.



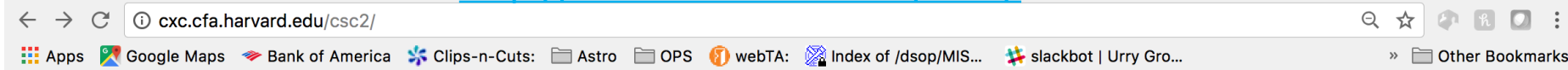
## Source Properties

Once all the sources have been identified, each source is characterized at the OBI, stack and master levels. The catalog identifies on the order of 350 properties for each source. When expanded out for each band and when including errors, there are on the order of 1600 properties computed.



# Data Access

<http://cxc.cfa.harvard.edu/csc2/>



[CSC 2](#) [CSC 1](#)

## CSC Data Access:

[CSCview](#)

[CSCview Help](#)

[Command-line Interface](#)

### CSC Homepage

#### About the Catalog

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- [Catalog Release Views and Database Access Views](#)
- [Catalog Statistical Characterization](#)
- [Caveats and Limitations](#)
- [Version History](#)

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- [Catalog Processing](#)
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- [Chandra Data Archive](#)

#### Using the Catalog

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- [Level-3 Files](#)
- [CSCview GUI](#)

#### Catalog Columns

- Master Sources Table:
  - [alphabetical](#) | [by context](#)
- Stacked Observation Detections Table:
  - [alphabetical](#) | [by context](#)
- Per-Observation Detections Table:
  - [alphabetical](#) | [by context](#)

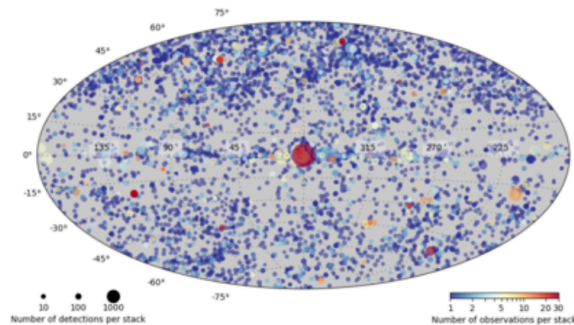
#### Column Descriptions

- [Position and Position Errors](#)

## Chandra Source Catalog Release 2.0 (CSC 2.0) Current Database

[What's New?](#) | [Watch Out](#)

The Chandra Source Catalog (CSC) is ultimately intended to be the definitive catalog of X-ray sources detected by the [Chandra X-ray Observatory](#). To achieve that goal, the catalog will be released to the user community in a series of increments with increasing capability. The second major release of the CSC (release 2.0) includes data for roughly 315,000 X-ray sources on the sky extracted from 10,382 Chandra ACIS and HRC-I imaging observations released publicly through the end of 2014.



[Version: [full-size](#)]

The locations, in Galactic coordinates, of the 362,182 detections in the CSC 2.0 pre1 release. The size of each symbol is proportional to the logarithm of the number of sources detected in the field, while the color encodes the number of closely-located observations.

What is CSC 2.0?

How do I access or download CSC 2.0?

Is my favorite source in CSC 2.0?

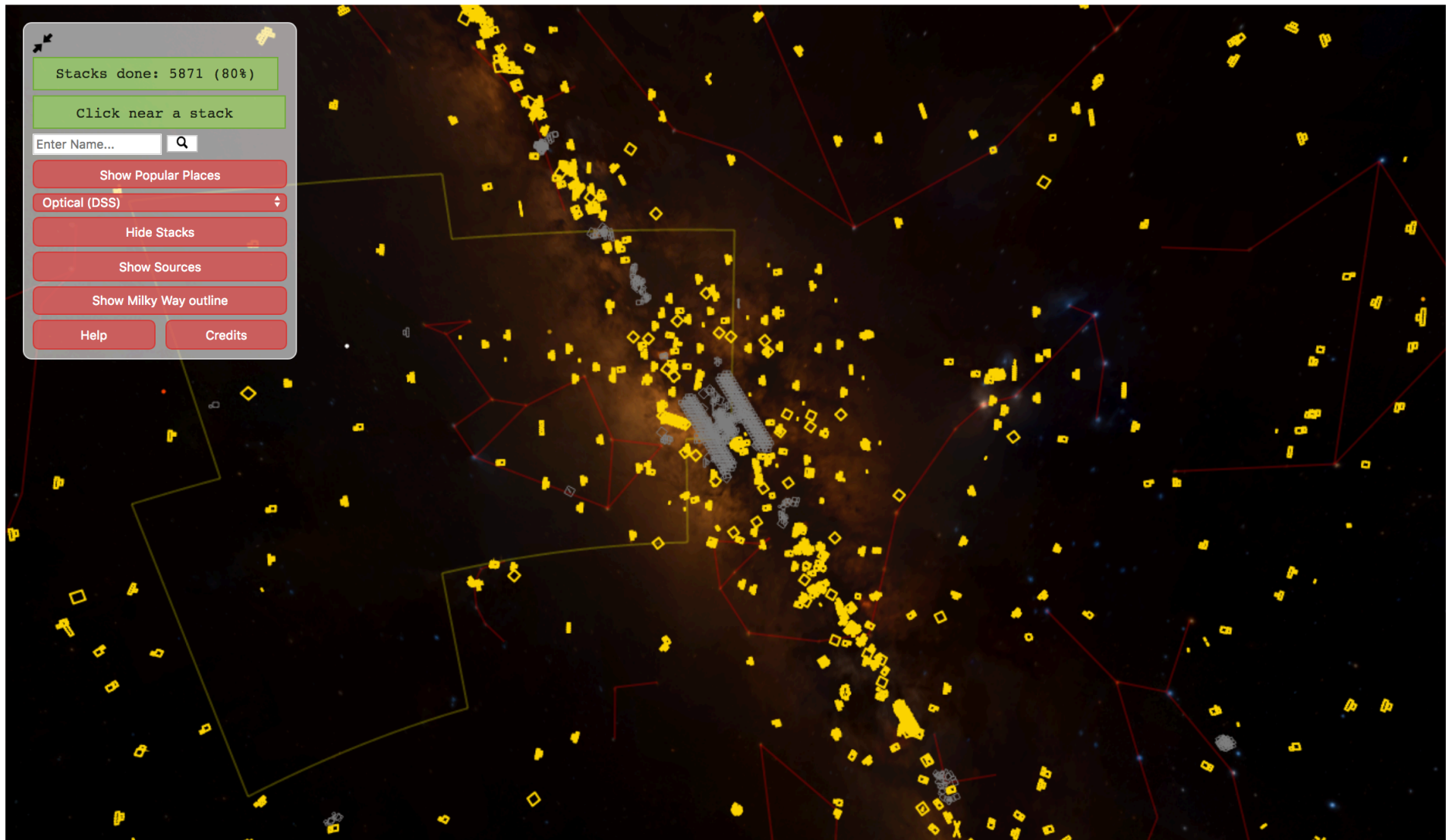
How do I find the flux of a source?

What is the processing status of CSC 2.0?

Use the WWT to view the processing status of CSC 2.0

How do I cite CSC 2.0?

# Current status



100 1000  
ons per stack

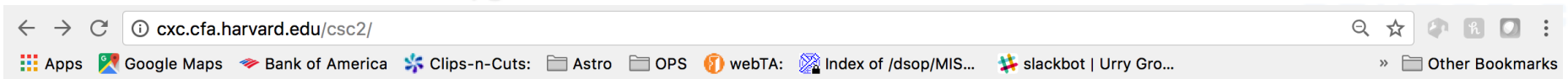
-75°

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1 2 5  
Observations p

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[CSC 2](#) [CSC 1](#)

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[alphabetical](#) | [by context](#)  
Per-Observation Detections Table:  
[alphabetical](#) | [by context](#)

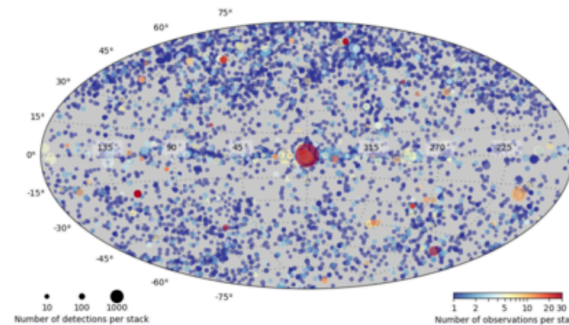
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Use the WWT to view the processing status of CSC 2.0

How do I cite CSC 2.0?

# Data Retrieval: CSCView

The screenshot displays the CSCView interface with several key components and annotations:

- Standard queries:** A red box highlights the 'Standard Queries' list on the left sidebar.
- Properties to be retrieved:** A red box highlights the 'Result Set' table, which lists columns like 'name', 'ra', 'dec', and various error ellipse parameters.
- Criteria to search on: ADQL queries:** A red box highlights the 'Search Criteria' input field containing the query: `( significance >= 5.0 )`.
- List of properties that can be selected:** A red box highlights the 'Source Properties' tree on the left, with 'Position Error Ellipse' expanded.
- Cone search and cross-match:** A red box highlights the 'Position Search' section at the bottom, showing options for 'By Name', 'By Coordinates', and 'Cone' search.

The 'Position Search' section includes the following details:

- Position Search:  None  By Name  By Coordinates
- Cone  Crossmatch
- Name: 4C 23.56A Resolver: Simbad/NED Radius: 30.0 arcmin

The bottom of the interface shows a table with the following columns:

Table	Name	Datatype	Units	Description
Master Sources	err_ellipse_r0	double	arcsec	Major radius of the 95% confidence level position error ellipse
Master Sources	err_ellipse_r1	double	arcsec	Minor radius of the 95% confidence level position error ellipse
Master Sources	err_ellipse_ang	double	deg	Position angle (ref. local true north) of the major axis of the 95% confidence level error ellipse

100 1000  
ons per stack

-60°

-75°

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1 2 5 :  
Observations p

# Data Retrieval: CSCView

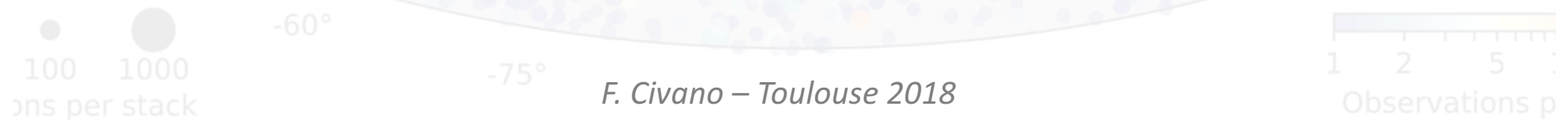
The screenshot displays the CSCView application interface. At the top, there is a menu bar with options: Search, Stop, New, Open, Save, Send, Download, and Script. Below the menu bar, the title bar reads "Chandra Source Catalog: Current Database".

On the left side, there are several filter panels:

- Region:** Includes checkboxes for "Master" (checked), "Bayesian Blocks source properties", "Per-Master source region aperture photometry PDF", "Stack" (with sub-options like "Stack Source Region Event List", "Stack Source Region Image", etc.), and "Observation" (with sub-options like "Event List", "Image", "Point Spread Function", etc.).
- Full Field:** Includes checkboxes for "Stack" (with sub-options like "Stack Event List", "Stack Image", "Stack Background Image").
- Energy Bands:** Includes checkboxes for "broad [ACIS]", "medium [ACIS]", "ultrasoft [ACIS]", "hard [ACIS]", "soft [ACIS]", and "wide [HRC]" (checked).

In the center, a table displays search results. The table has columns: Select, name, ra, dec, err\_ellipse\_r0 (arcsec), err\_ellipse\_r1 (arcsec), err\_ellipse\_ang (deg), conf\_flag, sat\_src\_flag, significance, flux\_aper\_b (erg/s/cm^2), flux\_aper\_lolim\_b (erg/s/cm^2), flux\_aper\_hilim\_b (erg/s/cm^2), and flux\_s (erg/s). Several rows are highlighted in yellow, indicating they are selected. A red box highlights the text "Retrieved tabular properties" above the table, and a red arrow points from this box to the selected rows. Another red box highlights the text "Select FITS data products here" on the left filter panel.

At the bottom, there is a table with columns: Product Type, Product Specifier, Format, and Description. It lists various product types and their corresponding formats and descriptions.



# Databased properties

CHAND  
SOURCE CAT

## 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

100 1000  
ons per stack

-75°

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Observations p



# Science-Ready FITS 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

## 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)

100 1000  
ons per stack

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Observations p

# Multiwavelength crossmatching

- PSF varies significantly over field of view.
  - Bayesian cross-match tool based on *Budavari et al.* uses error ellipses for the derived source positions.
  - Significantly different spatial resolutions are addressed by calculating the Bayes factors
- Systematic Astrometric uncertainty: 0.29"

## CSC2 and SDSS DR13

This cross-match involved 1574 distinct contiguous areas covered by the CSC2, matching with all SDSS "good stars" within the bounding box of each CSC2 area

	CSC2	SDSS DR13
Sample coverage area (sq deg)	197	402
Total number of sources/stars	87,276	2,609,153
Unambiguous matches	17,705	17,705
Ambiguous matches	1,061	14

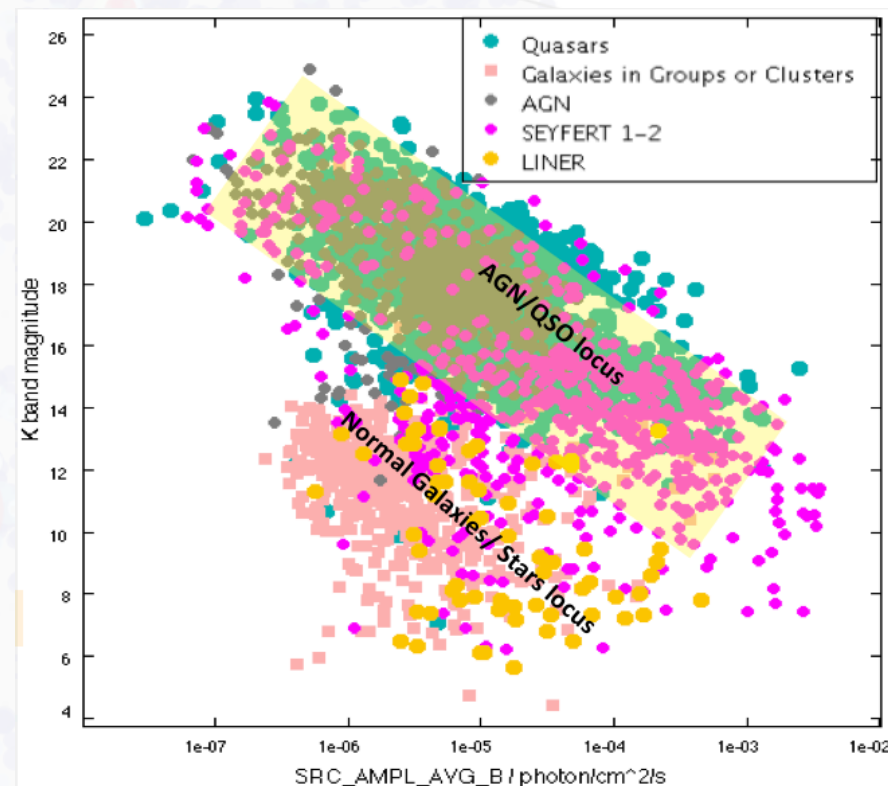
## CSC2 and AllWISE SC

This cross-match involved 4352 distinct contiguous areas covered by the CSC2, matching with all sources from the AllWISE catalog that are within the bounding box of each CSC2 area

	CSC2	WISE
Sample coverage area (sq deg)	568	1147
Total number of sources/stars	330,758	22,633,344
Unambiguous matches	132,519	132,519
Ambiguous matches	5,146	1,863

# Source Classification

- X-ray to Optical/Near-IR flux diagnostic used in extragalactic surveys (contamination can be estimated using already classified sources in the literature).
- Small samples can be used to train algorithms (supervised methods) to find an *X-ray only* classification approach.
- Unsupervised random forest to detect outliers (*“the hidden treasures”*).
- Formulate new approaches more sensitive to rare, unknown X-ray sources.



# SUMMARY

CHANDRA  
SOURCE CAT

→ CSC 2.0 is the largest and most complete catalog of X-ray sources detected by the *Chandra* X-ray Observatory

- Properties for ~375K X-ray detections of ~315K X-ray sources on the sky
- ~1,700 columns of databased information and ~25M science-ready FITS data products

→ The final production phase of release 2.0 of the Chandra Source Catalog is well underway

→ Finalize multiwavelength crossmatching (add also 3XMM-DR8)

→ Classification using standard methods to train a random forest

→ Consolidated 3XMM-CSC catalog of sources



<http://cxc.cfa.harvard.edu/csc2/>

100  
1000  
dots per stack

-75°

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1 2 5 :  
Observations p