CHANDRA
X-RAY OBSERVATORY

CIAO Analysis

and Documentation

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“ahelp” — *AXAF* Help in CIAO

- CIAO, Sherpa, and ChIPS comes with the command-line “`ahelp`” system.
- `ahelp` has corresponding online counterpart, which is updated between software releases.
  - `cxc.harvard.edu/ciao/ahelp`
  - `cxc.harvard.edu/sherpa/ahelp`
  - `cxc.harvard.edu/chips/ahelp`
- Python-environments also supports document strings, which Sherpa has migrated to as its primary documentation system for CIAO 4.11.
- Every component of CIAO has a help text: tools, packages (Sherpa and ChIPS), scripts and Python modules, and concepts (regions, coords, datamodel, etc.).

```
unix% ahelp <toolname>
unix% ahelp <context>
unix% ahelp -c
```

- In Sherpa and ChIPS, the string must be in quotes:

```
sherpa> ahelp “toolname”
sherpa> ahelp(“toolname”)
sherpa> help(“docstring”)
```

Tip: if you run a tool in the default interactive mode, when prompted for a parameter, entering ‘?’ opens the tool’s ahelp file.

```
unix% dmextract
Input event file  (): ?
```

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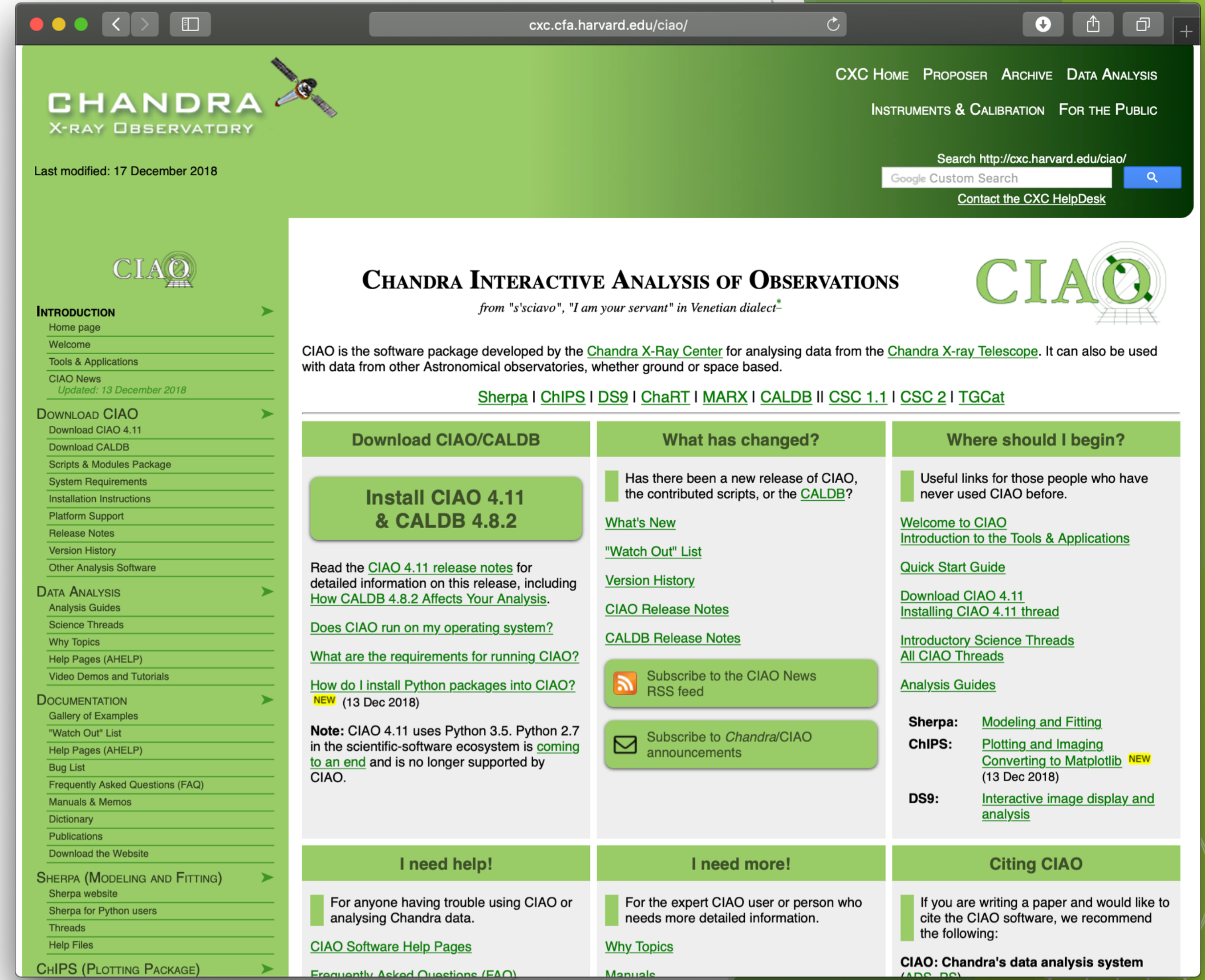
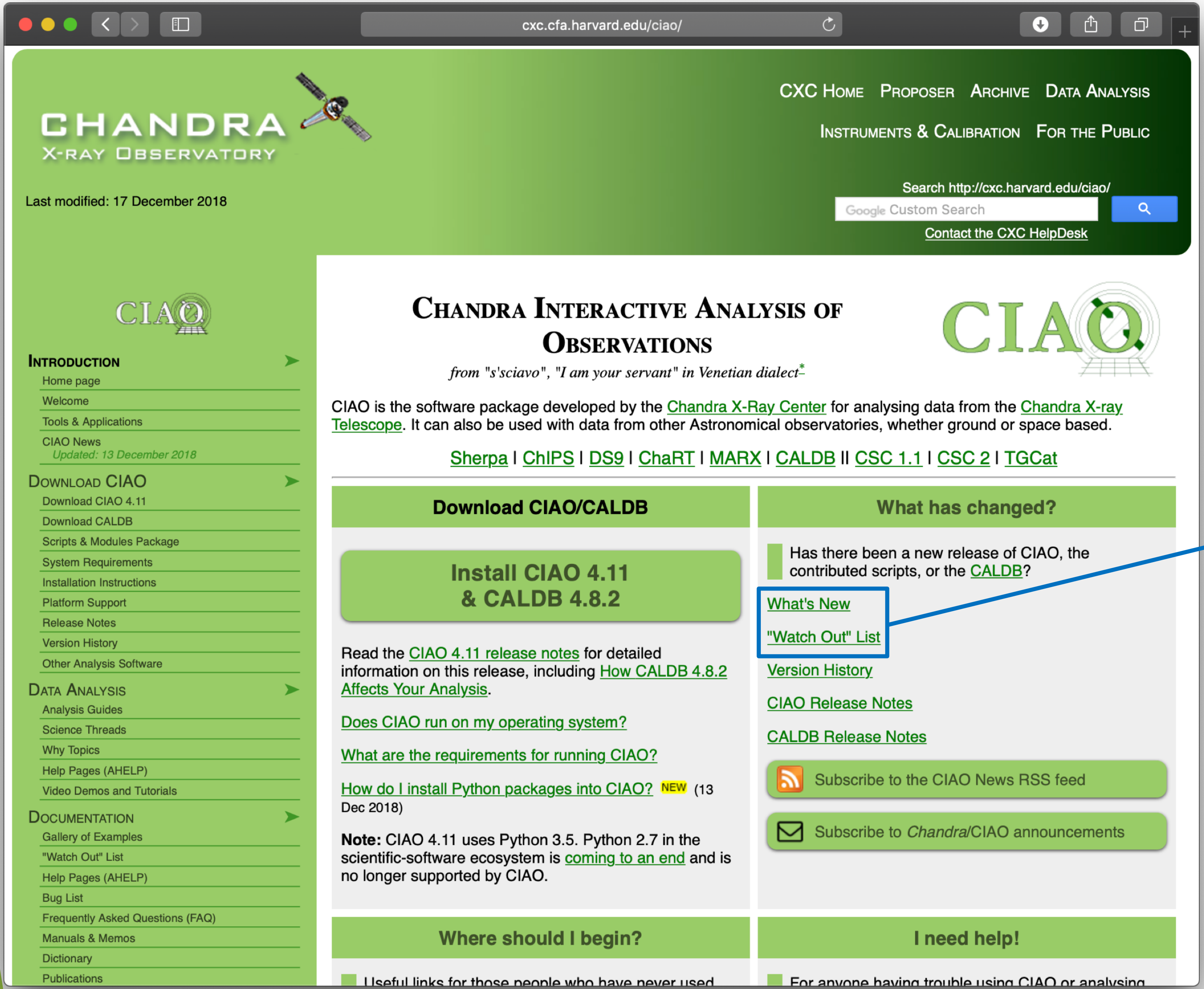
It all starts here: cxc.harvard.edu/ciao

- forwards to the most recent release version of CIAO
- version-specific website can be found at:
  `cxc.harvard.edu/ciaoX.Y`
- similar address structure for Sherpa and ChIPS pages:
  - `cxc.harvard.edu/sherpa`
    `cxc.harvard.edu/sherpaX.Y`
  - `cxc.harvard.edu/chips`
    `cxc.harvard.edu/chipsX.Y`





latest news about the software, contributed scripts, CalDB, and issues

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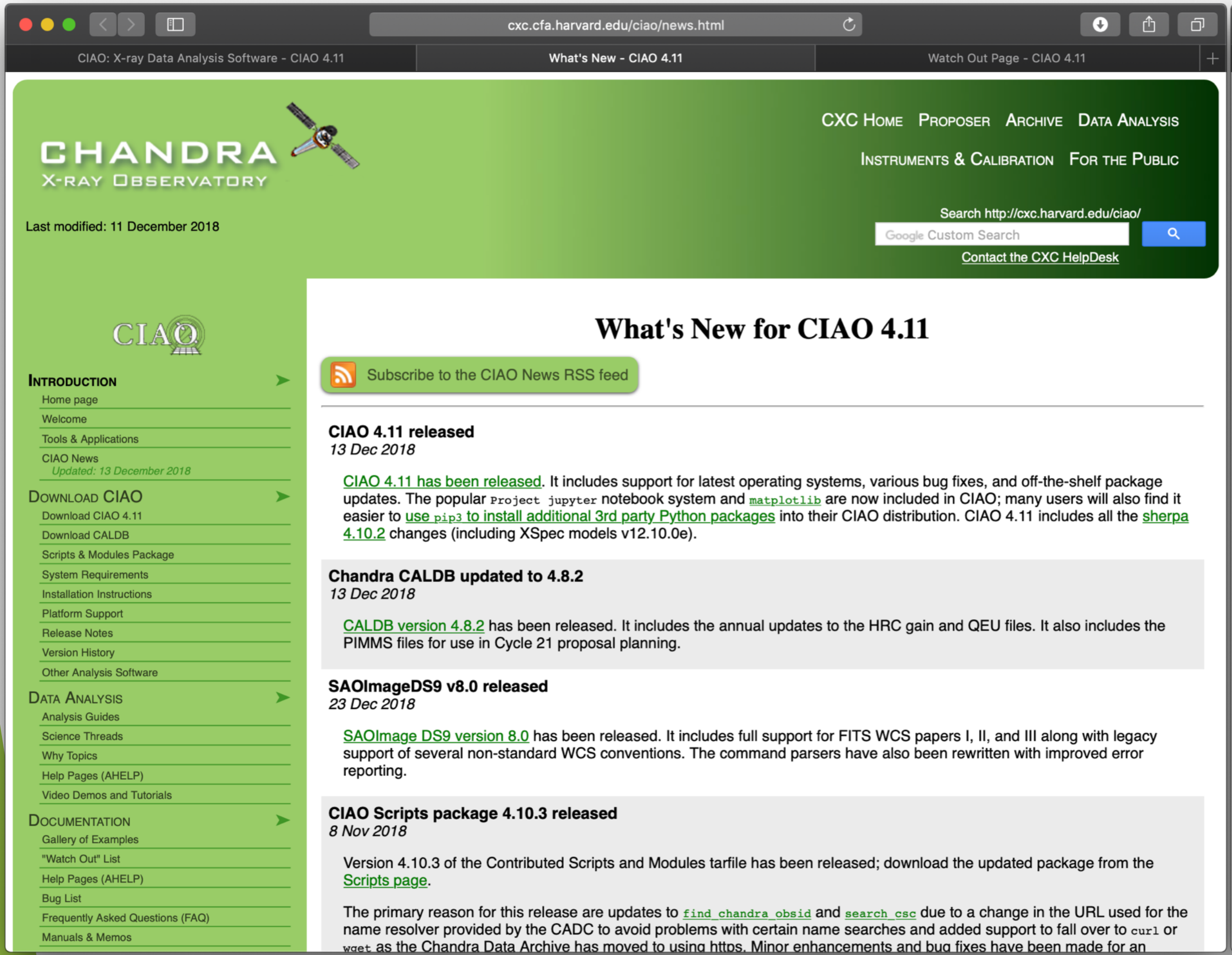
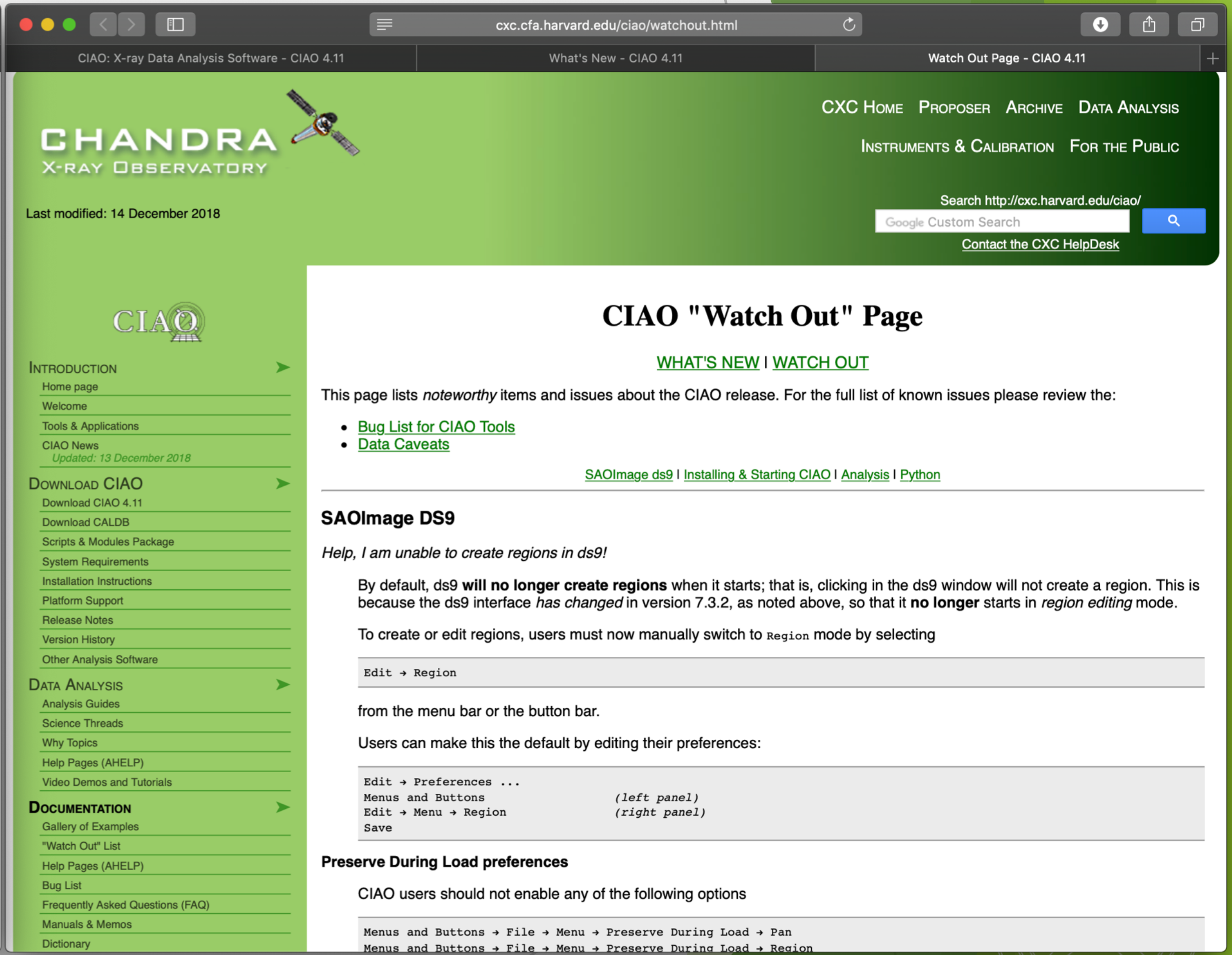
The “What’s New” and “Watch Out” Pages





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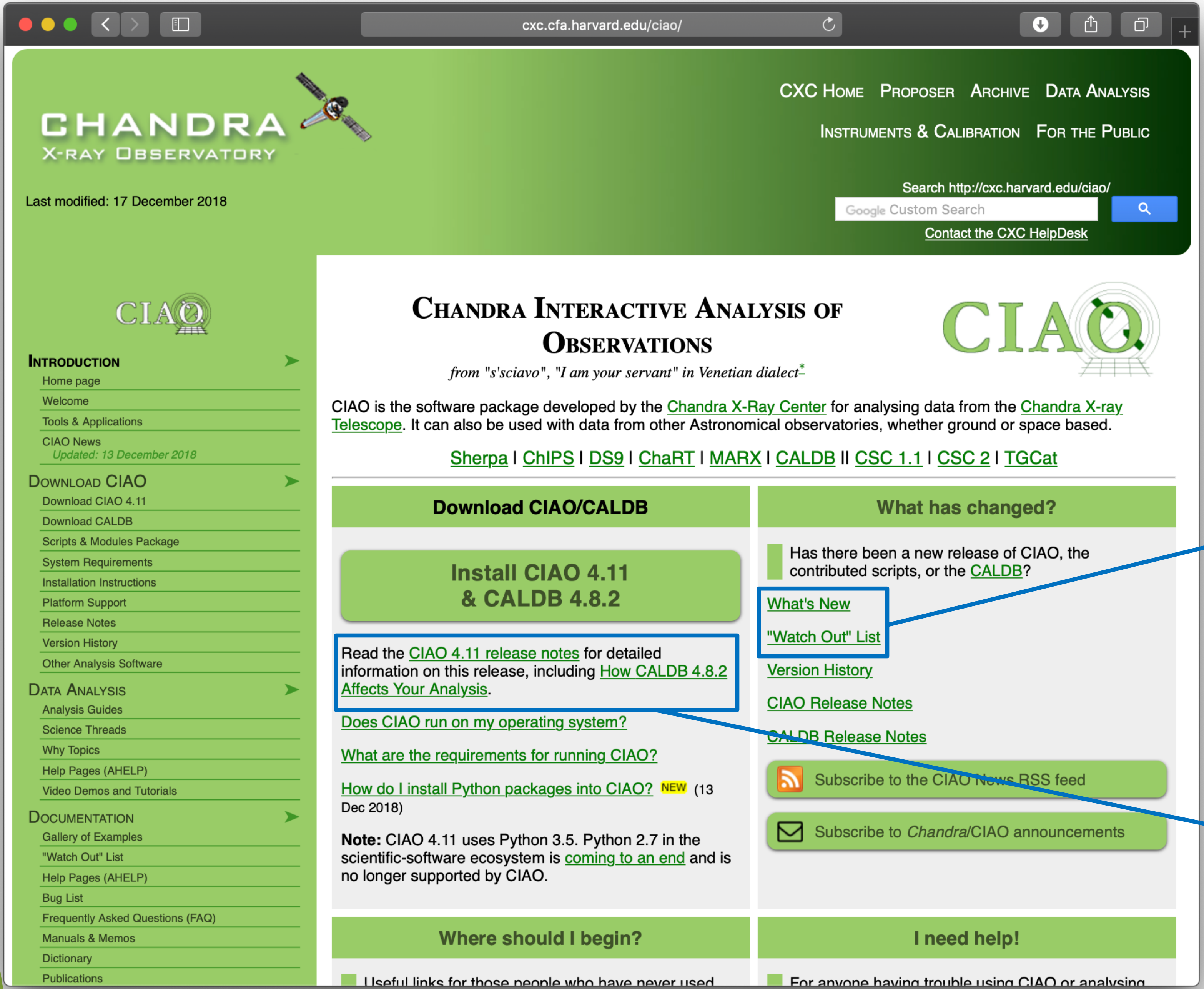

latest news about the software, contributed scripts, CalDB, and issues

important and detailed list of tool changes and the effects of CalDB updates on data analysis

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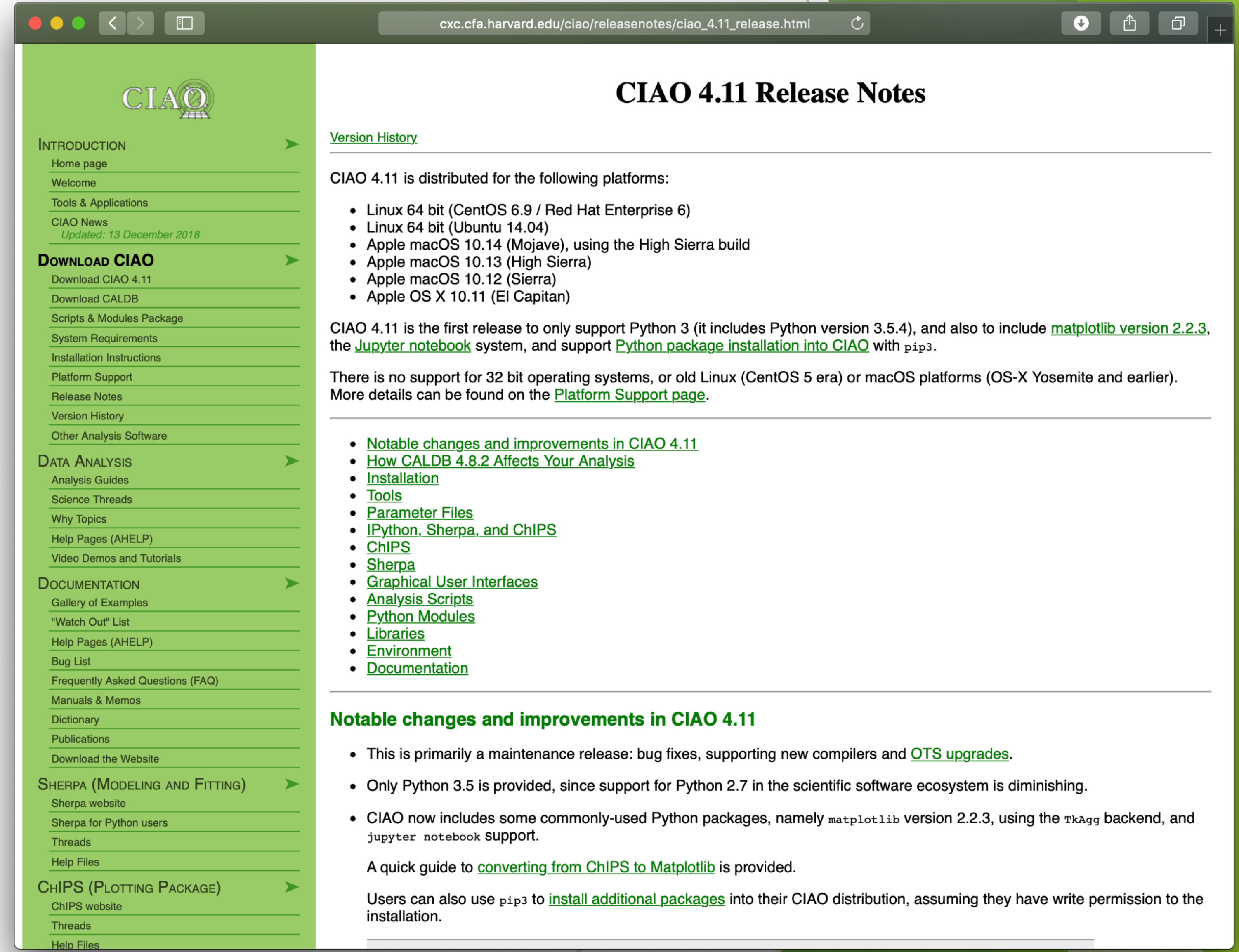
CIAO Release Notes

- CIAO release notes are revised whenever a new version or patch of a package is updated.
- CalDB components are updated periodically, but will vary from one release to the next.
  - categorized by detector and instrument configuration
  - describes files changed and affects on tools, analysis type, and threads
  - since calibrations evolve with time, note the dates calibration files go into effect for the observation
  - more details on the CalDB can be found at: `cxc.harvard.edu/caldb`
- Details of changes to contributed scripts can be seen at: `cxc.harvard.edu/ciao/download/scripts/history.html`



cxc.cfa.harvard.edu/ciao/releasenotes/ciao_4.11_release.html

CIAO

INTRODUCTION
- Home page
- Welcome
- Tools & Applications
- CIAO News
  Updated: 13 December 2018

DOWNLOAD CIAO
- Download CIAO 4.11
- Download CALDB
- Scripts & Modules Package
- System Requirements
- Installation Instructions
- Platform Support
- Release Notes
- Version History
- Other Analysis Software

DATA ANALYSIS
- Analysis Guides
- Science Threads
- Why Topics
- Help Pages (AHELP)
- Video Demos and Tutorials

DOCUMENTATION
- Gallery of Examples
- "Watch Out" List
- Help Pages (AHELP)
- Bug List
- Frequently Asked Questions (FAQ)
- Manuals & Memos
- Dictionary
- Publications
- Download the Website

SHERPA (MODELING AND FITTING)
- Sherpa website
- Sherpa for Python users
- Threads
- Help Files

CHIPS (PLOTTING PACKAGE)
- ChIPS website
- Threads
- Help Files

CIAO 4.11 Release Notes

Version History

CIAO 4.11 is distributed for the following platforms:

- Linux 64 bit (CentOS 6.9 / Red Hat Enterprise 6)
- Linux 64 bit (Ubuntu 14.04)
- Apple macOS 10.14 (Mojave), using the High Sierra build
- Apple macOS 10.13 (High Sierra)
- Apple macOS 10.12 (Sierra)
- Apple OS X 10.11 (El Capitan)

CIAO 4.11 is the first release to only support Python 3 (it includes Python version 3.5.4), and also to include matplotlib version 2.2.3, the Jupyter notebook system, and support Python package installation into CIAO with `pip3`.

There is no support for 32 bit operating systems, or old Linux (CentOS 5 era) or macOS platforms (OS-X Yosemite and earlier). More details can be found on the Platform Support page.

- Notable changes and improvements in CIAO 4.11
- How CALDB 4.8.2 Affects Your Analysis
- Installation
- Tools
- Parameter Files
- IPython, Sherpa, and ChIPS
- ChIPS
- Sherpa
- Graphical User Interfaces
- Analysis Scripts
- Python Modules
- Libraries
- Environment
- Documentation

Notable changes and improvements in CIAO 4.11

- This is primarily a maintenance release: bug fixes, supporting new compilers and OTS upgrades.
- Only Python 3.5 is provided, since support for Python 2.7 in the scientific software ecosystem is diminishing.
- CIAO now includes some commonly-used Python packages, namely `matplotlib` version 2.2.3, using the `TkAgg` backend, and `jupyter notebook` support.

  A quick guide to converting from ChIPS to Matplotlib is provided.

  Users can also use `pip3` to install additional packages into their CIAO distribution, assuming they have write permission to the installation.

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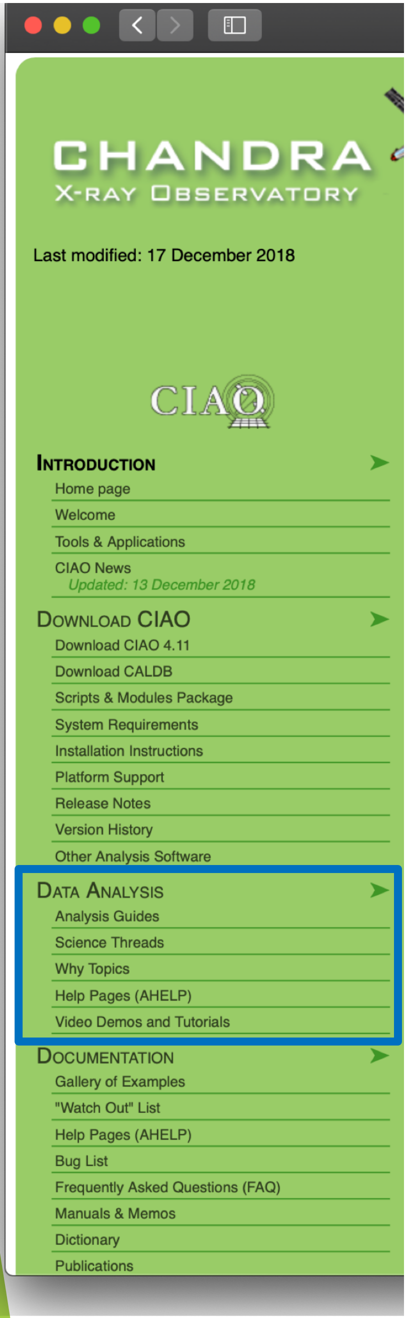
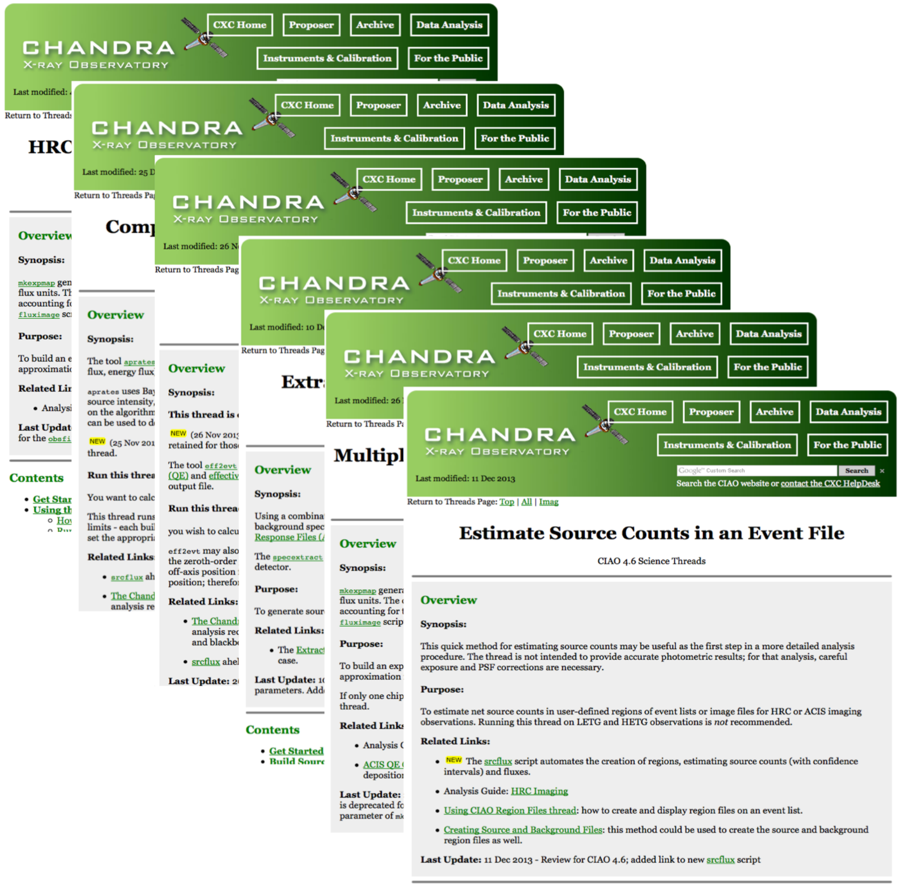


“Guides”, “Threads”, and “Why” Pages

- Analysis Guides are a roadmap to broad categories of analyses; organized based on detector and instrument configuration or source morphology, providing links to more detailed documents, such as science threads.
- Science Threads are the most important document type. Primarily organized based on science analysis categories.
  - over 150 CIAO and Sherpa threads, designed to teach users the approach and concerns that go along with analysis
  - all threads begin with a “quick overview” to provide a synopsis, purpose, and ‘when to use’ the thread
  - updated and added to as needed; look for “new” and “updated” icon tags
- Why Topics supplement threads with more detailed information.
  - some topics highlight common pitfalls and nuances in the software
  - others topics discuss aspects of *Chandra* and the data obtained with it
  - some of these topics will also discuss why certain science decisions are made, enabling the user to tailor the analysis to a particular dataset

More on Science Analysis Threads

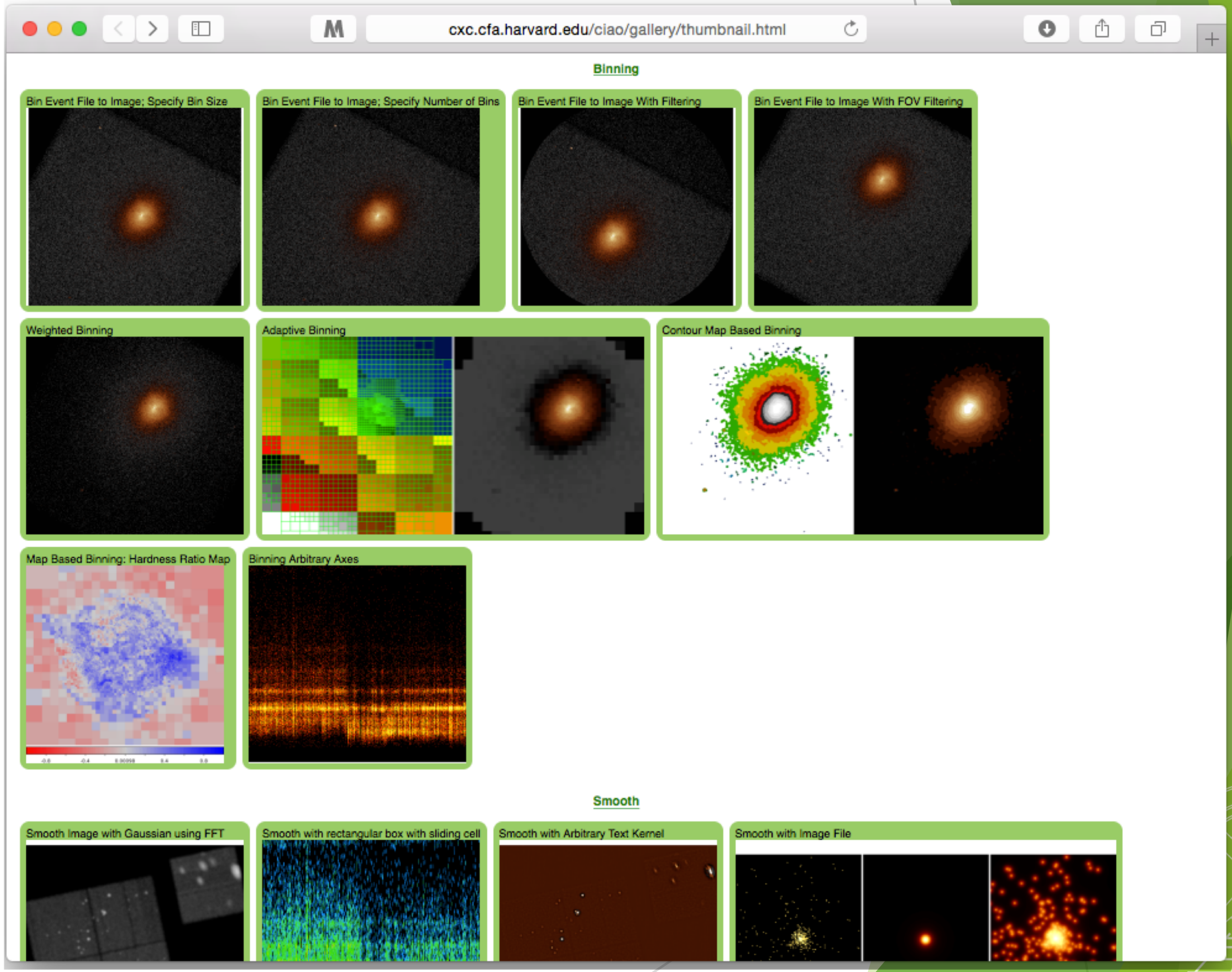


- Threads are just an example on approaching a problem. Don't blindly follow the examples verbatim, the threads are not strict recipes.
- Threads answer more detailed issues that may affect science; ahelps give the details behind the tool itself.
- An effort in the last few years is to wrap laborious thread analysis steps with a single command-line script.

`srcflux` script

The CIAO Gallery of Examples

- Categorized based on type of manipulation to imaging data.
- A description of each type of specific manipulation technique.
- Image included of what the resulting image manipulation returns.



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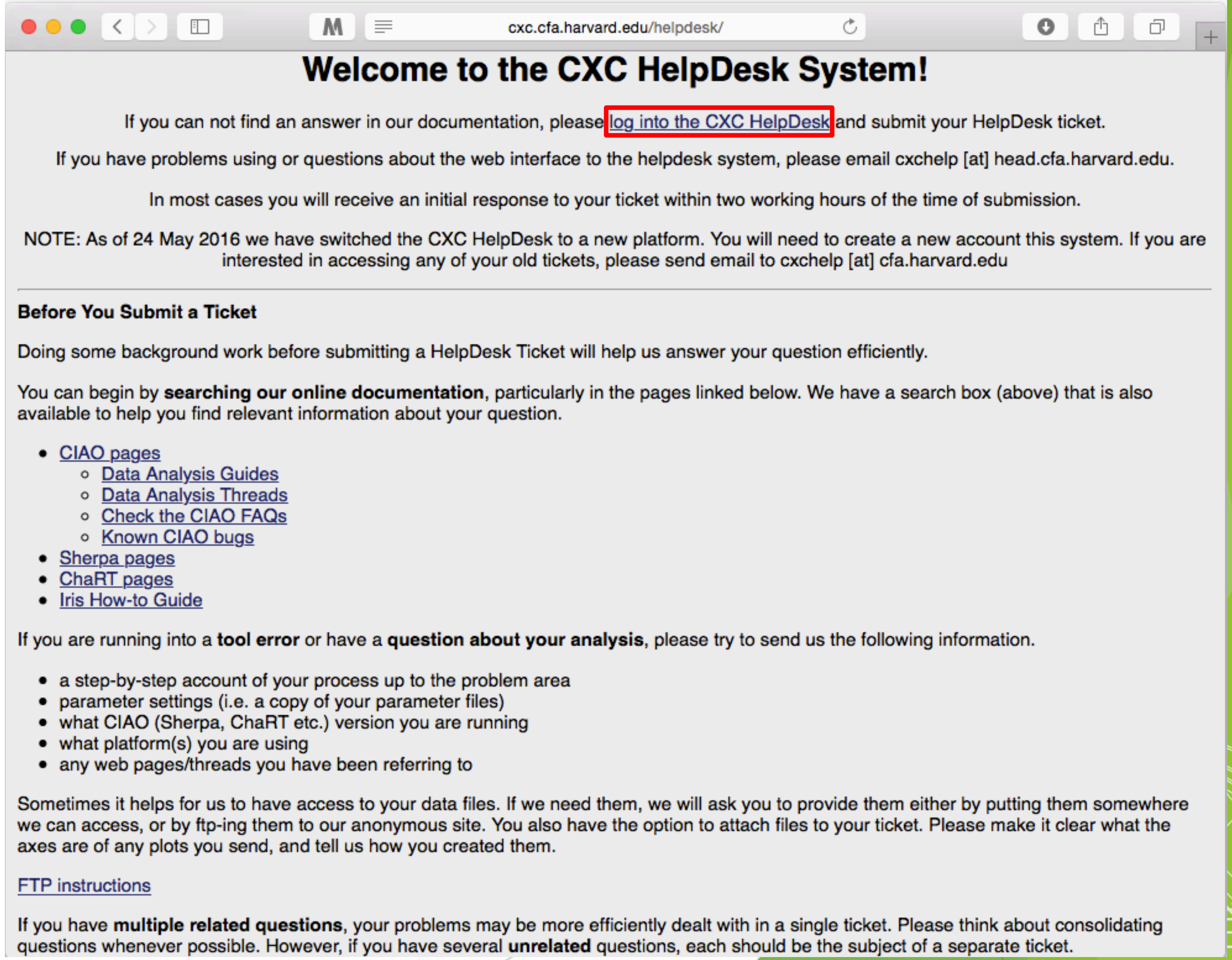
The *Chandra* Helpdesk

cxc.harvard.edu/helpdesk

Provides support for:

- proposals
- proposal planning
- observation scheduling and issues
- proprietary data
- data archive
- data analysis and DS9
    - help with data processing steps and to understand why they are applied
    - help highlight and understand the kinds of mistakes that are made during analysis



cxc.cfa.harvard.edu/helpdesk/

Welcome to the CXC HelpDesk System!

If you can not find an answer in our documentation, please log into the CXC HelpDesk and submit your HelpDesk ticket.

If you have problems using or questions about the web interface to the helpdesk system, please email cxchelp [at] head.cfa.harvard.edu.

In most cases you will receive an initial response to your ticket within two working hours of the time of submission.

NOTE: As of 24 May 2016 we have switched the CXC HelpDesk to a new platform. You will need to create a new account this system. If you are interested in accessing any of your old tickets, please send email to cxchelp [at] cfa.harvard.edu

Before You Submit a Ticket

Doing some background work before submitting a HelpDesk Ticket will help us answer your question efficiently.

You can begin by **searching our online documentation**, particularly in the pages linked below. We have a search box (above) that is also available to help you find relevant information about your question.

- CIAO pages
    - Data Analysis Guides
    - Data Analysis Threads
    - Check the CIAO FAQs
    - Known CIAO bugs
- Sherpa pages
- ChaRT pages
- Iris How-to Guide

If you are running into a **tool error** or have a **question about your analysis**, please try to send us the following information.

- a step-by-step account of your process up to the problem area
- parameter settings (i.e. a copy of your parameter files)
- what CIAO (Sherpa, ChaRT etc.) version you are running
- what platform(s) you are using
- any web pages/threads you have been referring to

Sometimes it helps for us to have access to your data files. If we need them, we will ask you to provide them either by putting them somewhere we can access, or by ftp-ing them to our anonymous site. You also have the option to attach files to your ticket. Please make it clear what the axes are of any plots you send, and tell us how you created them.

FTP instructions

If you have **multiple related questions**, your problems may be more efficiently dealt with in a single ticket. Please think about consolidating questions whenever possible. However, if you have several **unrelated** questions, each should be the subject of a separate ticket.

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Contents of a Ticket

- software information
  - CIAO version
  - CalDB version
  - Sherpa—stand alone or CIAO distribution
- platform and operating system
- question
  - what is the problem or concern encountered?
  - contextualize the question: what are you trying to do, what is your goal?
    - if referencing a document, include citation beyond just the authors (journal, volume, page)
- what did you do?
  - describe what you've done and the steps taken
  - provide commands used
    - copy-and-paste text or provide a log file; no screenshots please
  - include any messages returned by tool, including warning and error messages
  - provide supporting data files

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The *Chandra* Data Archive

cxc.harvard.edu/cda

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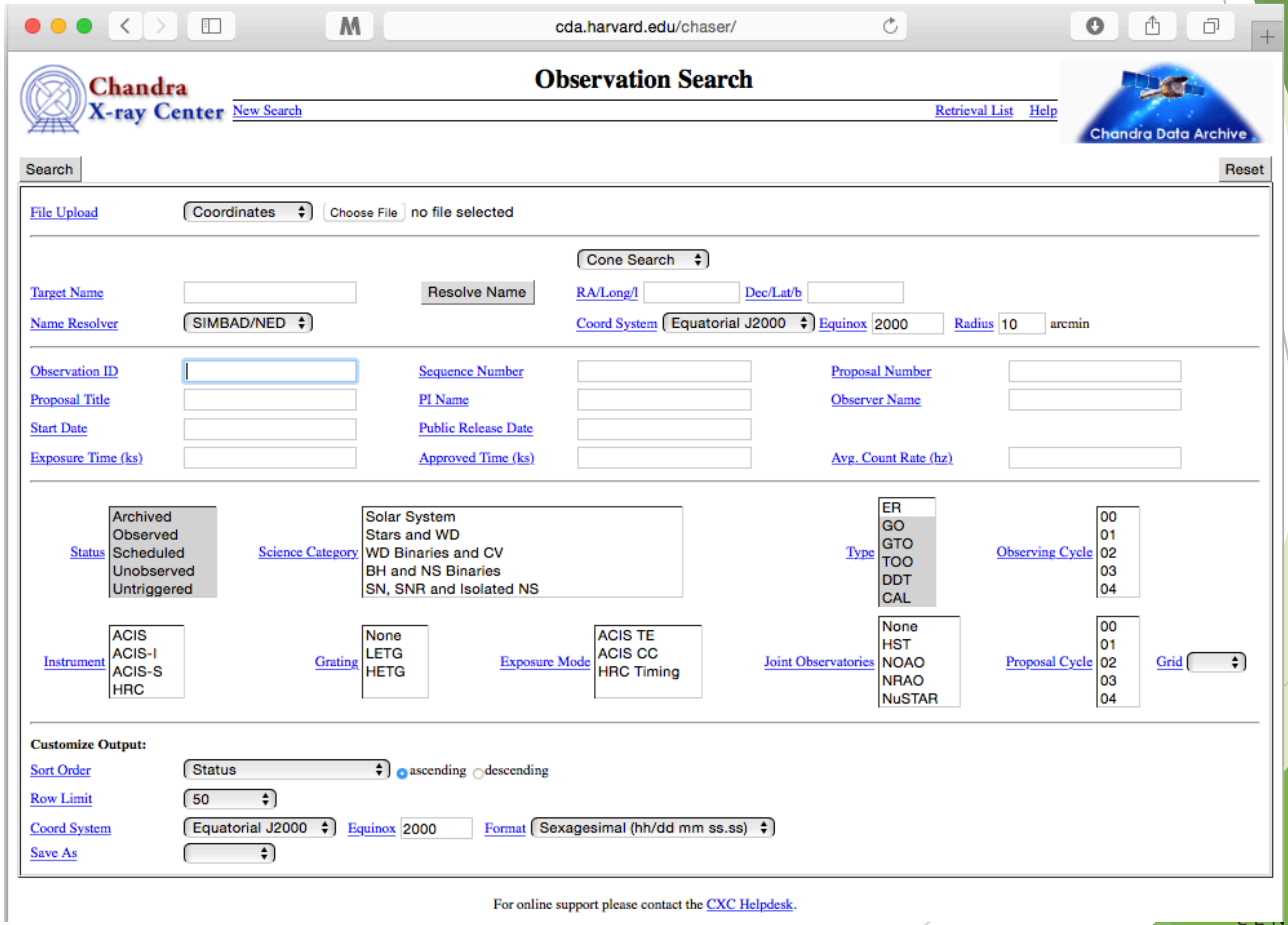
ChaSeR: *Chandra* Search and Retrieval System

cda.harvard.edu/chaser



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ChaSeR: *Chandra* Search and Retrieval System

cda.harvard.edu/chaser

- browse the observation catalog with a variety of search criteria
- search fields are self-explanatory, links lead to description of usage and input format
- cone search or range of coordinates around a celestial position or target name
  - target name can be be resolved to a position with SIMBAD and NED
  - a list of up to 5000 positions can also be supplied to query the catalog
- syntax for a range of dates: T_1/T_2, $T_1/$, $/T_2$
  - T_n format: `YYYY-MM-DD`
  - between T_1 and T_2, after T_1, before T_2

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ChaSeR (continued)

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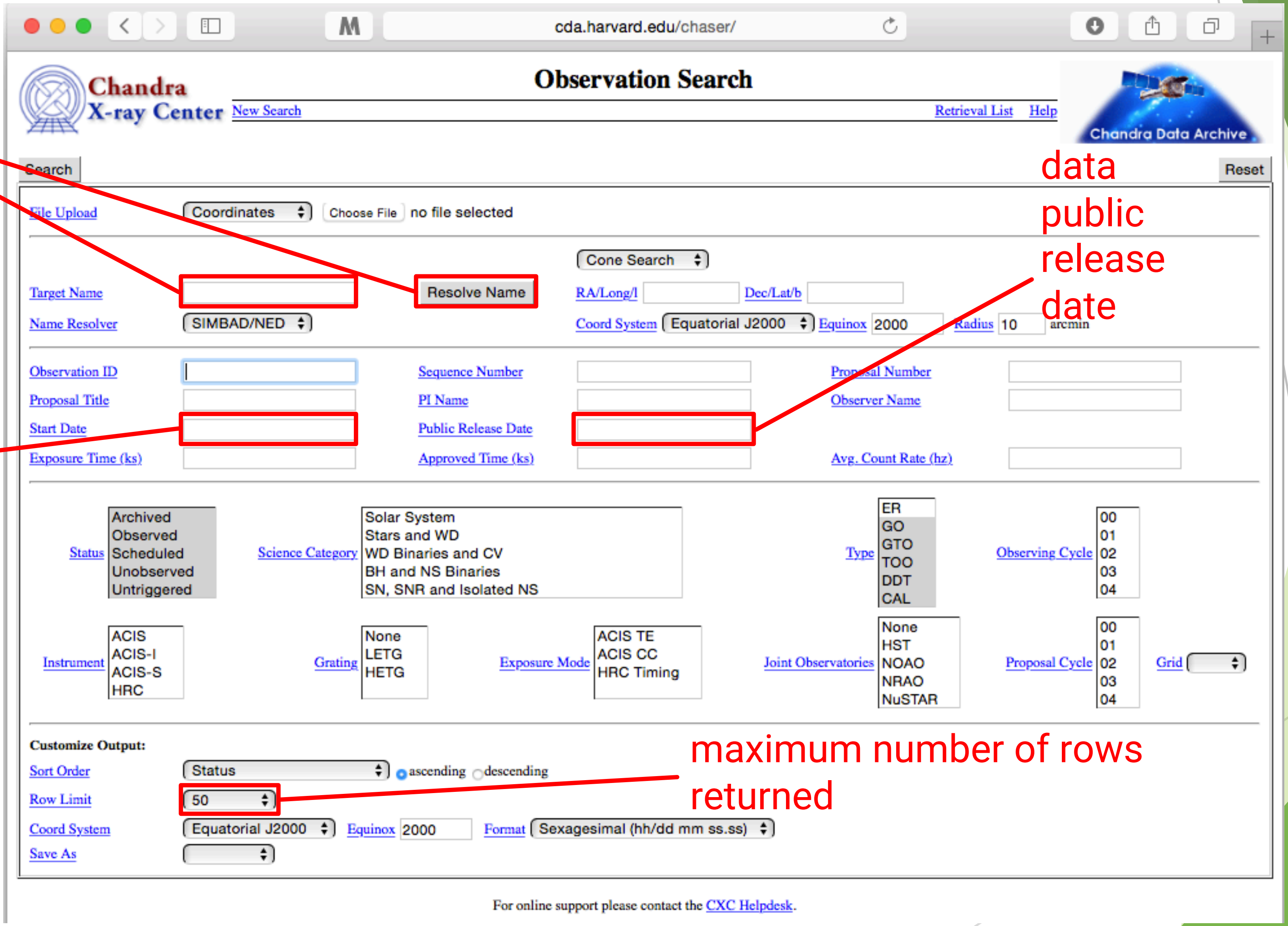
source name and name resolver

data public release date

observation start date

maximum number of rows returned



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ChaSeR (continued)

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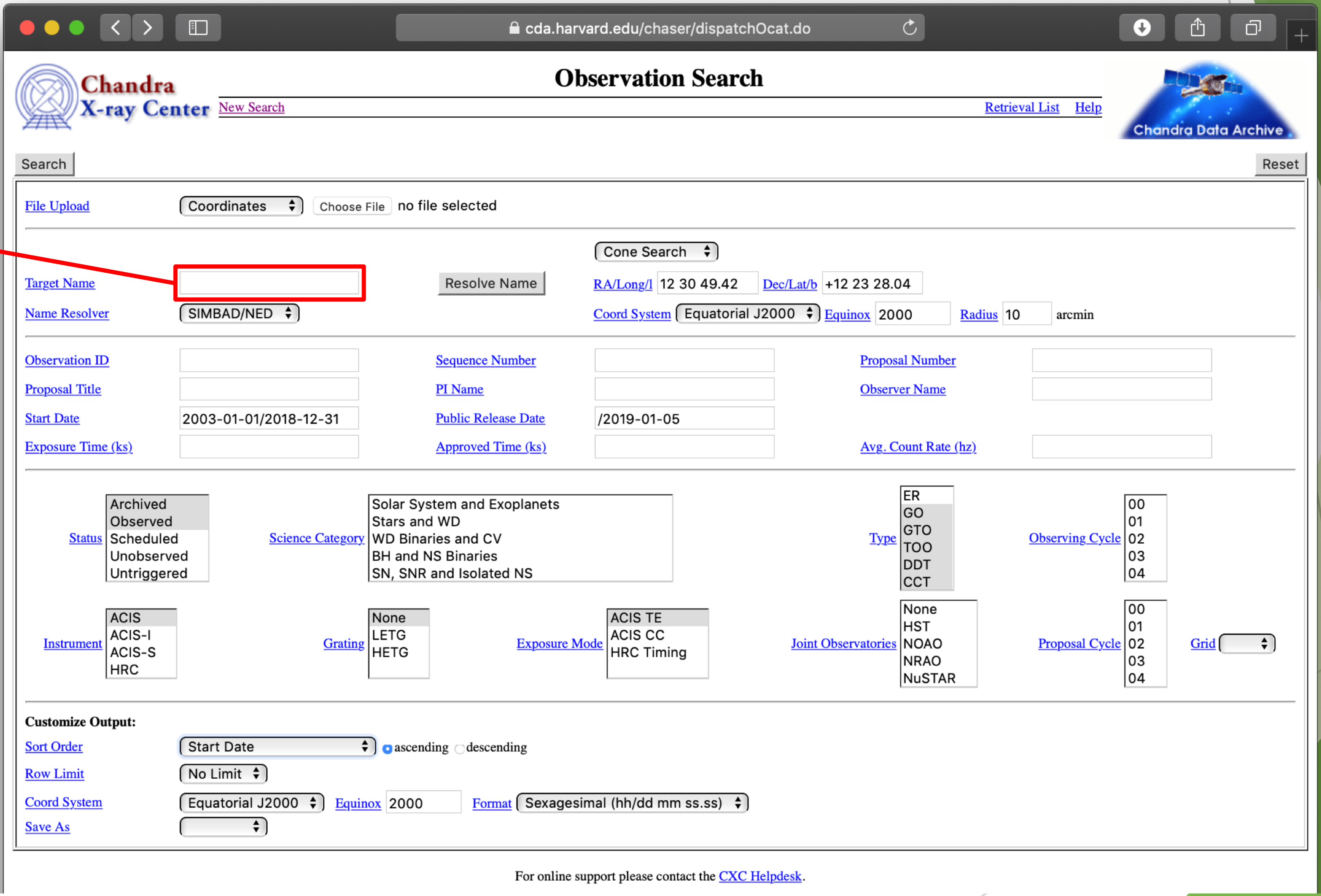
M87



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ChaSeR Query Results

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cda.harvard.edu/chaser/dispatchOcat.do

Chandra X-ray Center

Search Results

New Search | Search Results | Retrieval List | Help

Chandra Data Archive

View Observation Information

Add Products to Retrieval List

- [x] Primary package
- [x] Secondary package
- [ ] Custom selection

Select all | Unselect all

Select	Row	Seq Num	Obs ID	Instrument	Grating	Appr Exp	Exposure	Target Name	PI Name	RA	Dec	Status	Data Mode	Exp Mode	Avg
☐	1	700656	3977	ACIS-S	NONE	5.0	5.28	M87	Harris	12 30 49.00	+12 23 30.00	archived	FAINT	TE	
☐	2	700657	3978	ACIS-S	NONE	5.0	4.85	M87	Harris	12 30 49.00	+12 23 30.00	archived	FAINT	TE	
☐	3	700658	3979	ACIS-S	NONE	5.0	4.49	M87	Harris	12 30 49.00	+12 23 30.00	archived	FAINT	TE	
☐	4	700659	3980	ACIS-S	NONE	5.0	4.79	M87	Harris	12 30 49.00	+12 23 30.00	archived	FAINT	TE	
☐	5	700660	3981	ACIS-S	NONE	5.0	4.68	M87	Harris	12 30 49.00	+12 23 30.00	archived	FAINT	TE	
☐	6	700661	3982	ACIS-S	NONE	5.0	4.84	M87	Harris	12 30 49.00	+12 23 30.00	archived	FAINT	TE	
☑	7	700998	4917	ACIS-S	NONE	5.0	5.03	M87	Biretta	12 30 49.00	+12 23 30.00	archived	FAINT	TE	
☐	8	700686	4007	ACIS-S	NONE	40.0	36.18	NGC 4486B	Fabbiano	12 30 31.80	+12 29 26.00	archived	VFAINT	TE	
☐	9	700999	4918	ACIS-S	NONE	5.0	4.68	M87	Biretta	12 30 49.00	+12 23 30.00	archived	FAINT	TE	
☐	10	701000	4919	ACIS-S	NONE	5.0	4.7	M87	Biretta	12 30 49.00	+12 23 30.00	archived	FAINT	TE	
☐	11	701002	4921	ACIS-S	NONE	5.0	5.25	M87	Biretta	12 30 49.00	+12 23 30.00	archived	FAINT	TE	

108 observations found
Position=cone of radius 10 arcmin around RA: 12 30 49.42, Dec: +12 23 28.04 (frame=j2000 equinox=2000)
Start Date=2003-01-01/2018-12-31
Public Release Date=/2019-01-05
Status=archived; observed
Instrument=ACIS
Grating=NONE
Type=GO; GTO; TOO; DDT; CCT; CAL
Exposure Mode=TE
Sort Order=Start Date ascending

For online support please contact the CXC Helpdesk.

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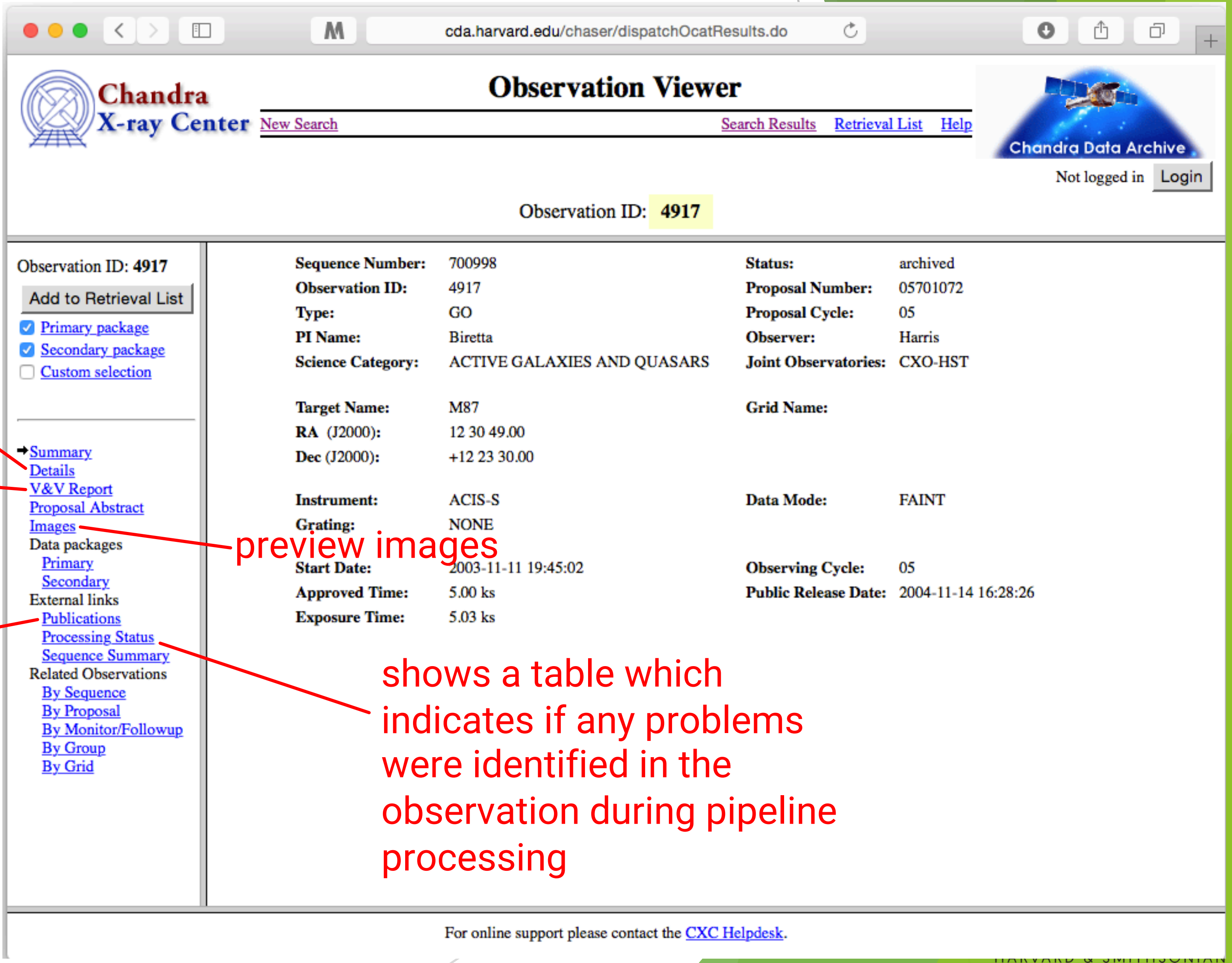
ChaSeR ObsID Entry

details of the instrument configuration for the observation

V&V—Verification and Validation—report includes a summary of any anomalies during the observation, usually noted in the Comments section

list of ADS links to publications that have made use of the observation data

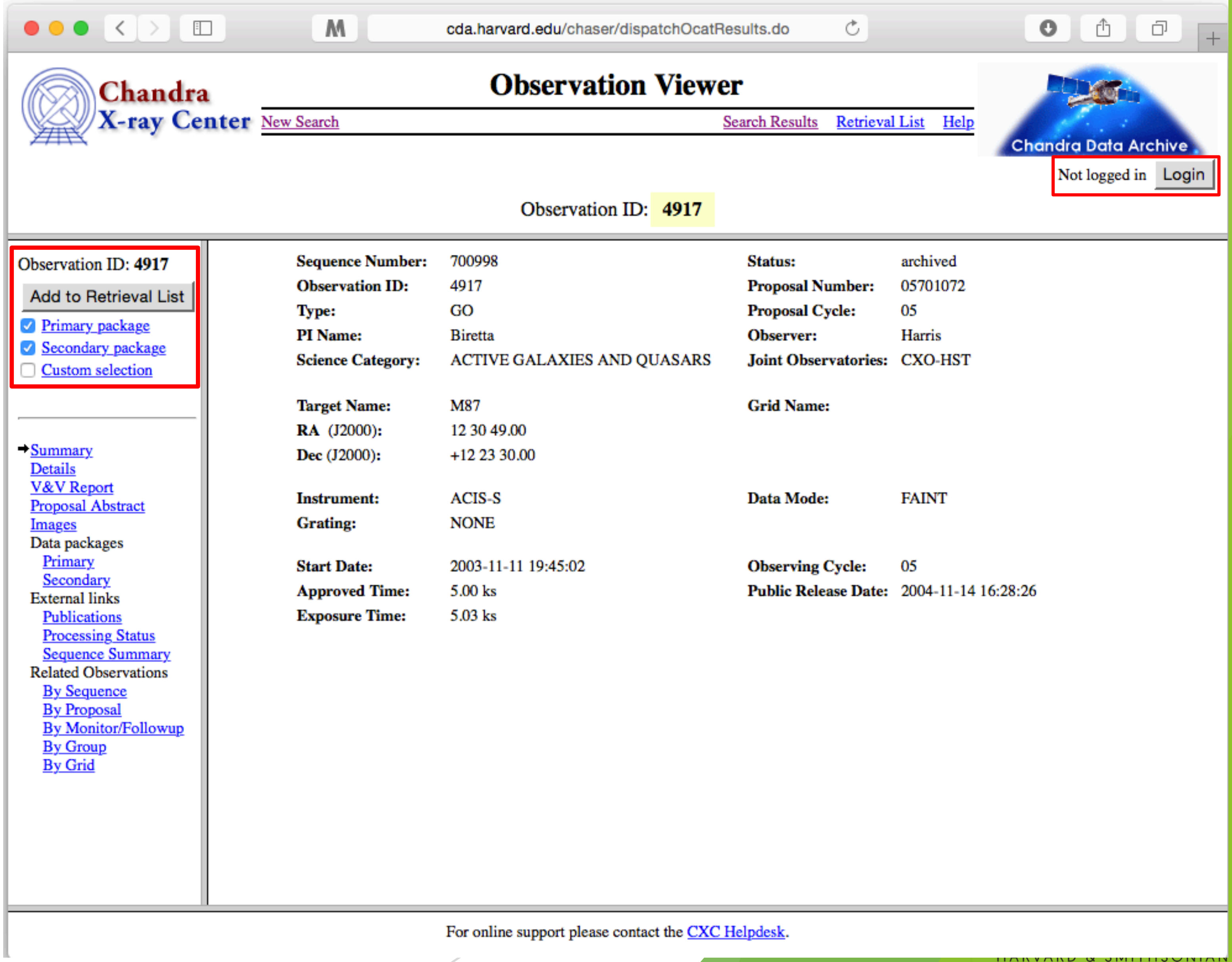


preview images

shows a table which indicates if any problems were identified in the observation during pipeline processing

ChaSeR ObsID Entry

- for non-proprietary data:
  - option to stage primary, secondary, or customized set of data products for retrieval
  - for typical analysis, once you have the ObsID of interest, just use `download_chandra_obsid`
- ChaSeR is required to obtain proprietary data.
- If the existing archive interfaces do not meet your needs, the archive team may consider a special request: cxc.harvard.edu/cgi-gen/cda/specreq



Beyond ChaSeR:
find_chandra_obsid

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```
unix% find_chandra_obsid 4C19.44
# obsid   sepn   inst grat   time    obsdate   piname   target
2140       0.0 ACIS-S NONE    9.1 2001-01-08 Sambruna 1354+195
6903       0.1 ACIS-S NONE   43.7 2006-04-01   Harris  4C19.44
6904       0.1 ACIS-S NONE   34.8 2006-03-20   Harris  4C19.44
7302       0.1 ACIS-S NONE   68.9 2006-03-28   Harris  4C19.44
7303       0.1 ACIS-S NONE   41.5 2006-03-30   Harris  4C19.44
```

```
Parameters for ${HOME}/cxcds_param4/find_chandra_obsid.par

           arg =                       RA, ObsId, or name of source
           dec =                       Dec of source if arg is not the ObsId/name
       (radius = 1.0)                  Radius for search overlap in arcmin
     (download = none)                 What ObsIDs should be downloaded?
   (instrument = all)                  Choice of instrument
      (grating = all)                  Choice of grating
       (detail = basic)                Columns to display
       (mirror = )                     Use this instead of the CDA FTP site
      (verbose = 1)                    Verbose level
         (mode = h)
```

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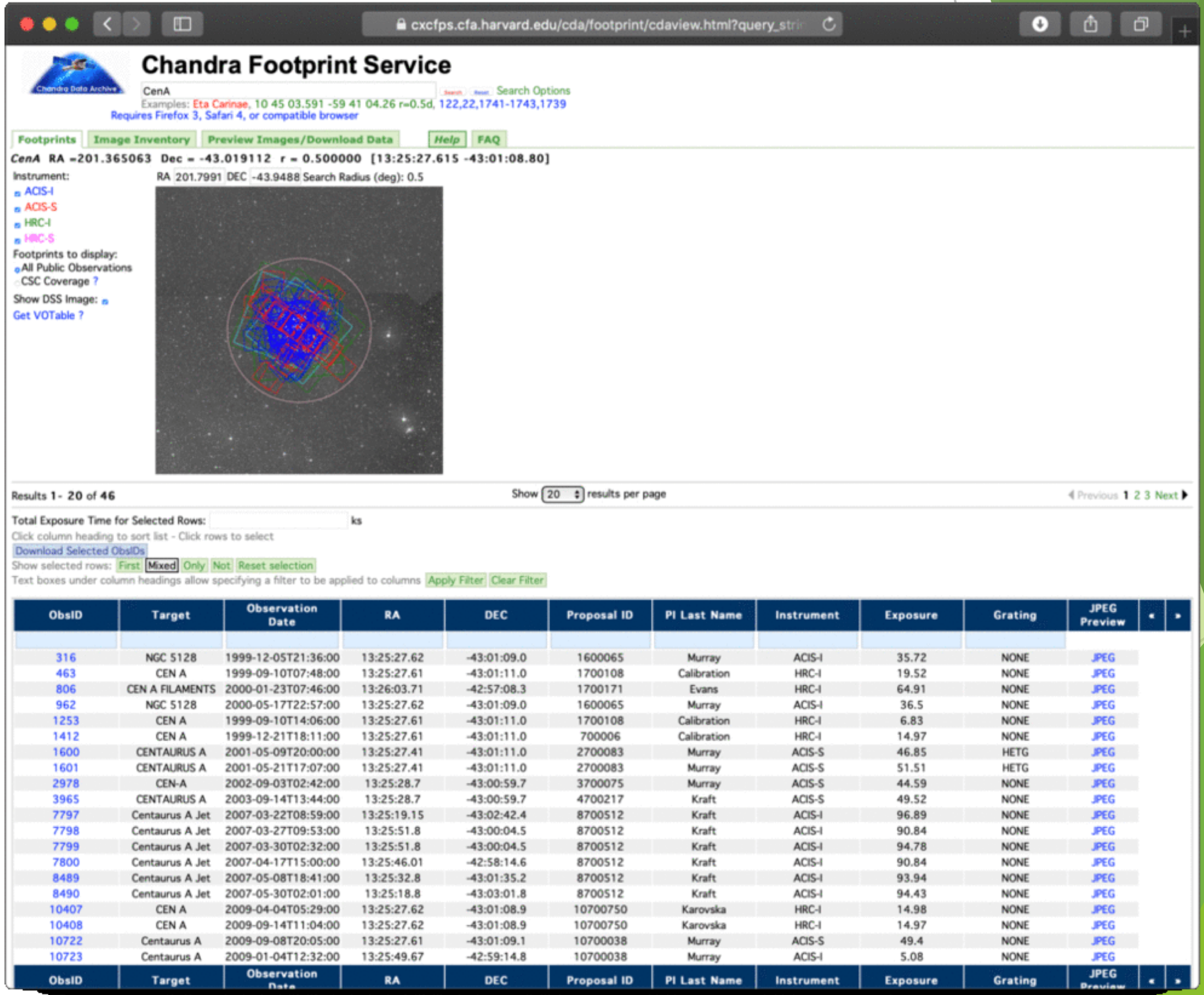
Beyond ChaSeR:
Chandra Footprint Service

cxcfps.cfa.harvard.edu/cda/footprint/cdaview.html

- A search by position or object name overlays the footprints of *Chandra* Observations on Digital Sky Survey images, allowing further selection and retrieval of observations.



ObsID	Target	Observation Date	RA	DEC	Proposal ID	PI Last Name	Instrument	Exposure	Grating	JPEG Preview
316	NGC 5128	1999-12-05T21:36:00	13:25:27.62	-43:01:09.0	1600065	Murray	ACIS-I	35.72	NONE	JPEG
463	CEN A	1999-09-10T07:48:00	13:25:27.61	-43:01:11.0	1700108	Calibration	HRC-I	19.52	NONE	JPEG
806	CEN A FILAMENTS	2000-01-23T07:46:00	13:26:03.71	-42:57:08.3	1700171	Evans	HRC-I	64.91	NONE	JPEG
962	NGC 5128	2000-05-17T22:57:00	13:25:27.62	-43:01:09.0	1600065	Murray	ACIS-I	36.5	NONE	JPEG
1253	CEN A	1999-09-10T14:06:00	13:25:27.61	-43:01:11.0	1700108	Calibration	HRC-I	6.83	NONE	JPEG
1412	CEN A	1999-12-21T18:11:00	13:25:27.61	-43:01:11.0	700006	Calibration	HRC-I	14.97	NONE	JPEG
1600	CENTAURUS A	2001-05-09T20:00:00	13:25:27.41	-43:01:11.0	2700083	Murray	ACIS-S	46.85	HETG	JPEG
1601	CENTAURUS A	2001-05-21T17:07:00	13:25:27.41	-43:01:11.0	2700083	Murray	ACIS-S	51.51	HETG	JPEG
2978	CEN-A	2002-09-03T02:42:00	13:25:28.7	-43:00:59.7	3700075	Murray	ACIS-S	44.59	NONE	JPEG
3965	CENTAURUS A	2003-09-14T13:44:00	13:25:28.7	-43:00:59.7	4700217	Kraft	ACIS-S	49.52	NONE	JPEG
7797	Centaurus A Jet	2007-03-22T08:59:00	13:25:19.15	-43:02:42.4	8700512	Kraft	ACIS-I	96.89	NONE	JPEG
7798	Centaurus A Jet	2007-03-27T09:53:00	13:25:51.8	-43:00:04.5	8700512	Kraft	ACIS-I	90.84	NONE	JPEG
7799	Centaurus A Jet	2007-03-30T02:32:00	13:25:51.8	-43:00:04.5	8700512	Kraft	ACIS-I	94.78	NONE	JPEG
7800	Centaurus A Jet	2007-04-17T15:00:00	13:25:46.01	-42:58:14.6	8700512	Kraft	ACIS-I	90.84	NONE	JPEG
8489	Centaurus A Jet	2007-05-08T18:41:00	13:25:32.8	-43:01:35.2	8700512	Kraft	ACIS-I	93.94	NONE	JPEG
8490	Centaurus A Jet	2007-05-30T02:01:00	13:25:18.8	-43:03:01.8	8700512	Kraft	ACIS-I	94.43	NONE	JPEG
10407	CEN A	2009-04-04T05:29:00	13:25:27.62	-43:01:08.9	10700750	Karovska	HRC-I	14.98	NONE	JPEG
10408	CEN A	2009-09-14T11:04:00	13:25:27.62	-43:01:08.9	10700750	Karovska	HRC-I	14.97	NONE	JPEG
10722	Centaurus A	2009-09-08T20:05:00	13:25:27.61	-43:01:09.1	10700038	Murray	ACIS-S	49.4	NONE	JPEG
10723	Centaurus A	2009-01-04T12:32:00	13:25:49.67	-42:59:14.8	10700038	Murray	ACIS-I	5.08	NONE	JPEG

Beyond ChaSeR:
Chandra Source Catalog-Worldwide Telescope

cxc.harvard.edu/csc2/wwt.html

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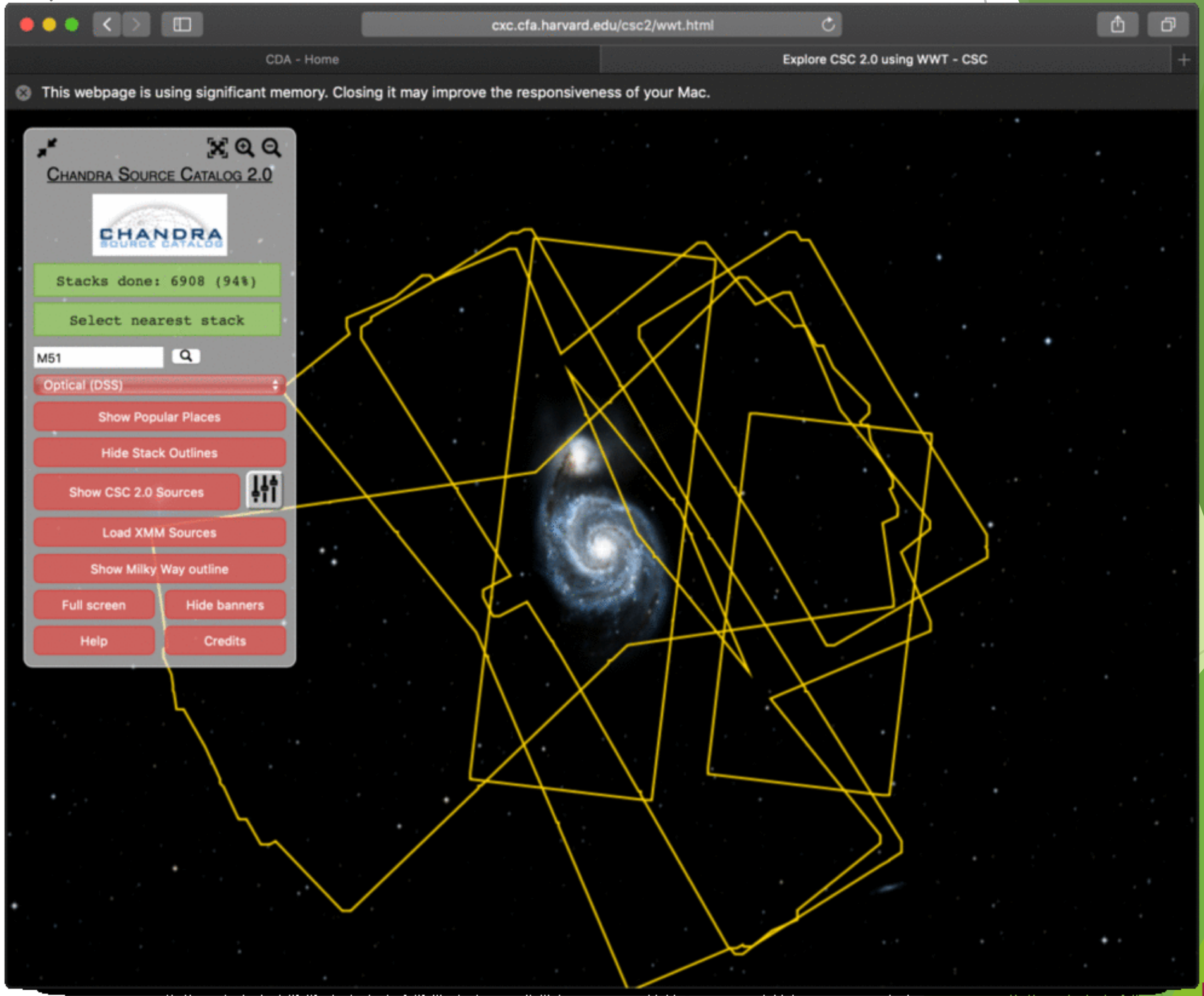
- Uses the AAS's WWT interface to explore the sky coverage and source properties of CSC 2.0.
- Provides links for ObsIDs to ChaSeR.
- Provides info to access catalog data products via CSCView.



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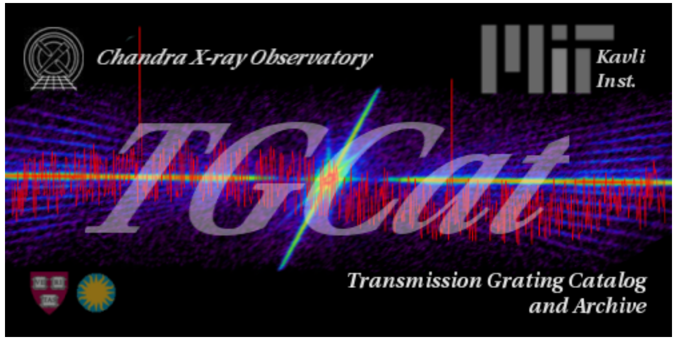
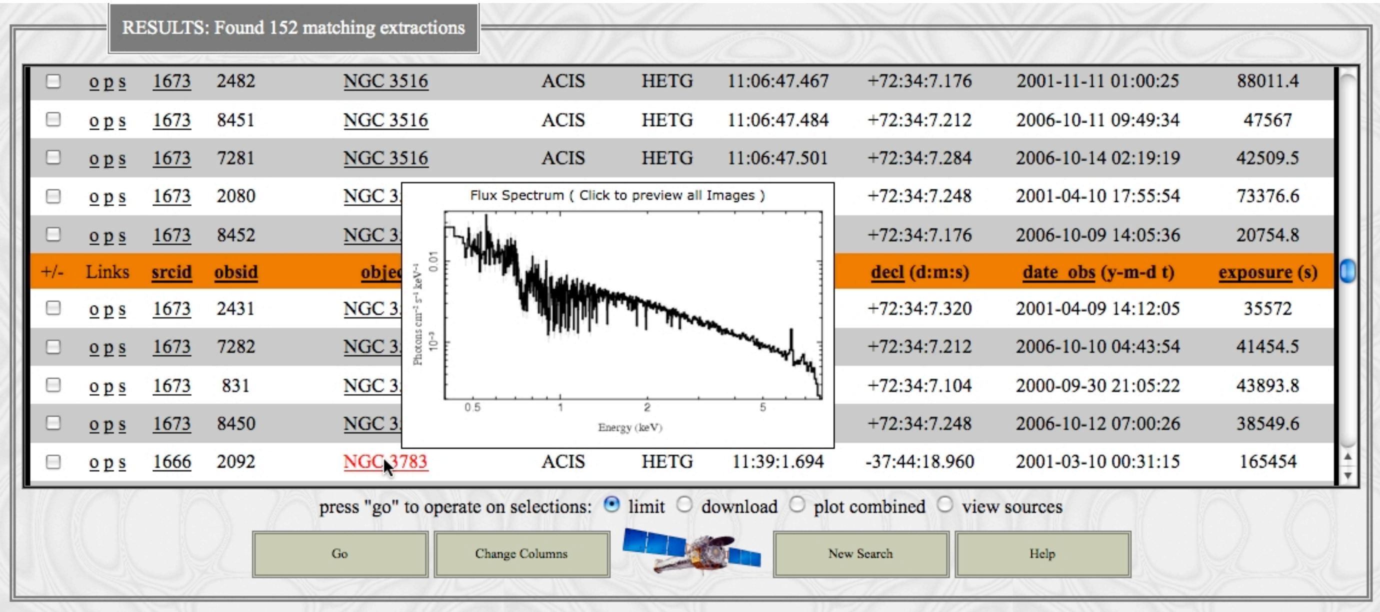
Beyond ChaSeR:
TGCat

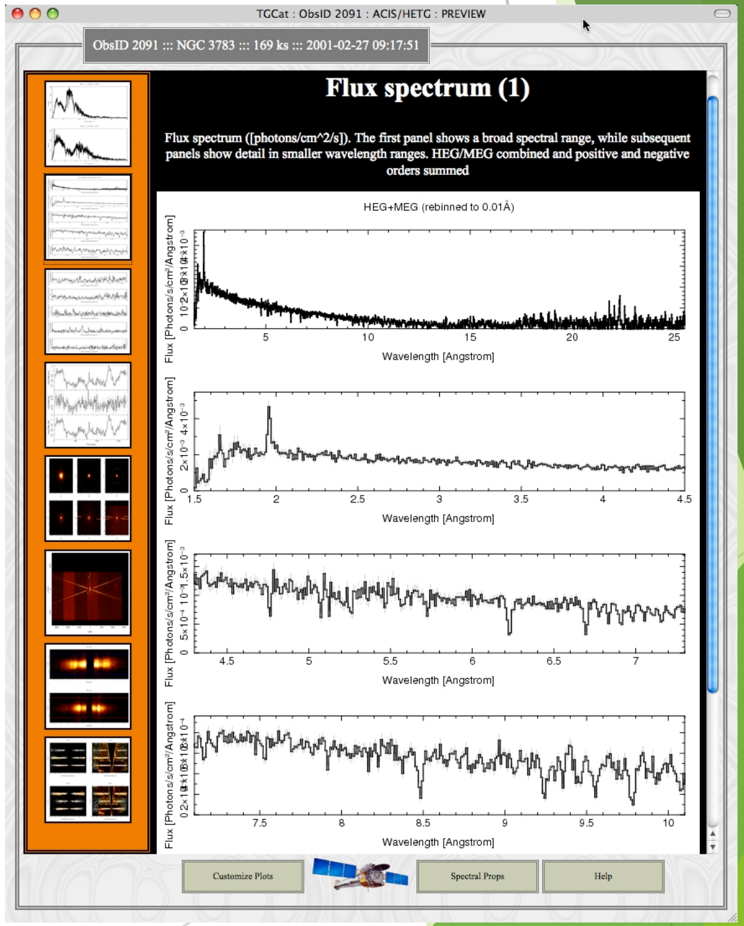
tgcat.mit.edu



- Includes all publicly available gratings observations.
- Provides calibrated spectra and responses.
- Provides quick-look visualization and summary products.



+/-	Links	srcid	obsid	object				decl (d:m:s)	date_obs (y-m-d t)	exposure (s)
	o p s	1673	2482	NGC 3516	ACIS	HETG	11:06:47.467	+72:34:7.176	2001-11-11 01:00:25	88011.4
	o p s	1673	8451	NGC 3516	ACIS	HETG	11:06:47.484	+72:34:7.212	2006-10-11 09:49:34	47567
	o p s	1673	7281	NGC 3516	ACIS	HETG	11:06:47.501	+72:34:7.284	2006-10-14 02:19:19	42509.5
	o p s	1673	2080	NGC 3				+72:34:7.248	2001-04-10 17:55:54	73376.6
	o p s	1673	8452	NGC 3				+72:34:7.176	2006-10-09 14:05:36	20754.8
	o p s	1673	2431	NGC 3				+72:34:7.320	2001-04-09 14:12:05	35572
	o p s	1673	7282	NGC 3				+72:34:7.212	2006-10-10 04:43:54	41454.5
	o p s	1673	831	NGC 3				+72:34:7.104	2000-09-30 21:05:22	43893.8
	o p s	1673	8450	NGC 3				+72:34:7.248	2006-10-12 07:00:26	38549.6
	o p s	1666	2092	NGC 3783	ACIS	HETG	11:39:1.694	-37:44:18.960	2001-03-10 00:31:15	165454



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NASA's HEASARC Archive

(High-Energy Astrophysics Science Archive Research Center)

`heasarc.gsfc.nasa.gov/docs/archive.html`

- Primary portal to all data from EUV/X-ray/γ-ray missions (past and present) with NASA involvement and supported with public funds.
  - also provides access to data archives of other space agencies

- NASA's primary repository of the observations of relic CMB radiation from space missions, balloons, and ground-based facilities in the sub-mm, mm and cm bands.

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Threads of Analyses

cxc.harvard.edu/ciao/threads

cxc.harvard.edu/sherpa/threads

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Analyses:

- The data contained in the events list informs us of the types of data products we can generate.
  - Image—bin on spatial-axes, lose energy and temporal information
  - Spectra—bin on spectral-axis, lose spatial and temporal information
  - Lightcurves—bin on time-axis, lose spatial and energy information
  - Source Lists—identify regions in spatial, energy, and time coordinates corresponding to sources
- Available data products determine possible types of analysis.

```
unix% dmlist evt.fits cols
```

- Extract and Fit a spectrum
  - download data
  - exclude serendipitous field sources and find periods of flaring background
  - define extraction regions
  - extract spectra and generate response files
  - spectral fitting and source flux

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Download and Reprocess (single ObsID)

always: reprocess, reprocess, reprocess

```
unix% download_chandra_obsid 7302

. . . SCREEN OUTPUT (DOWNLOAD PROGRESS). . .

unix% dmkeypar primary/acisf07302N002_evt2.fits.gz DATAMODE echo+
FAINT

unix% chandra_repro indir=7302 outdir=7302/repro check_vf_pha=no
Processing input directory '${HOME}/Work/CIAO-AAS233/Example/7302'

. . . MORE SCREEN OUTPUT . . .

The data have been reprocessed.
Start your analysis with the new products in
${HOME}/Work/CIAO-AAS233/Example/7302/repro
```

- Latest version of time-dependent gain applied.
- Latest temperature-dependent CTI correction applied.
- Ensures common set of calibration files used.

Tip: boolean arguments can also be recognized as for example:
echo=yes/echo+ and
echo=no/echo-

- Can download multiple datasets using a comma-separated string of ObsIDs and specify file types.
- `check_vf_pha` controls whether `acis_process_events` flags potential events near the event island as cosmic rays that are filtered out by the tool.

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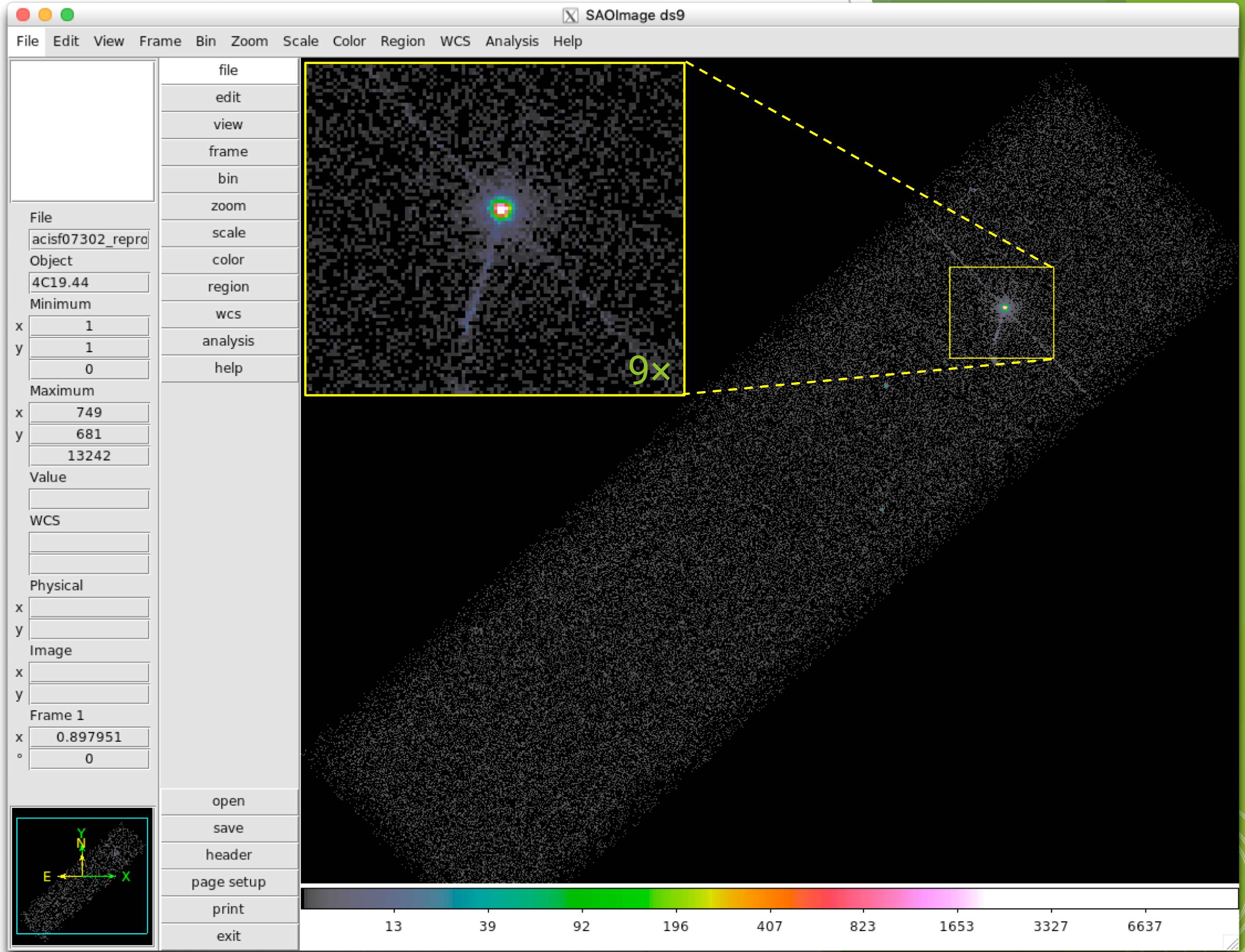
Quick Glance:

- quasar 4C+19.44/PKS 1354+195
  - ~69 ks observation of a ~190 ks joint *CXO* program with *HST* and VLA
- ACIS-S3, sub-array
  - other special cases: multi-ObI, Interleaved (aka "alternating exposure") mode, and spatial window
  - ACIS CC-mode and HRC-S Timing mode
- readout streak
  - events detected during frame readout have correct column, random row
  - source bright enough to have readout streak will have some degree of pile up
  - extract streak spectrum
  - `acisreadcorr` used to remove readout streak for cosmetic or source detection purposes, but has issues with sub-array mode



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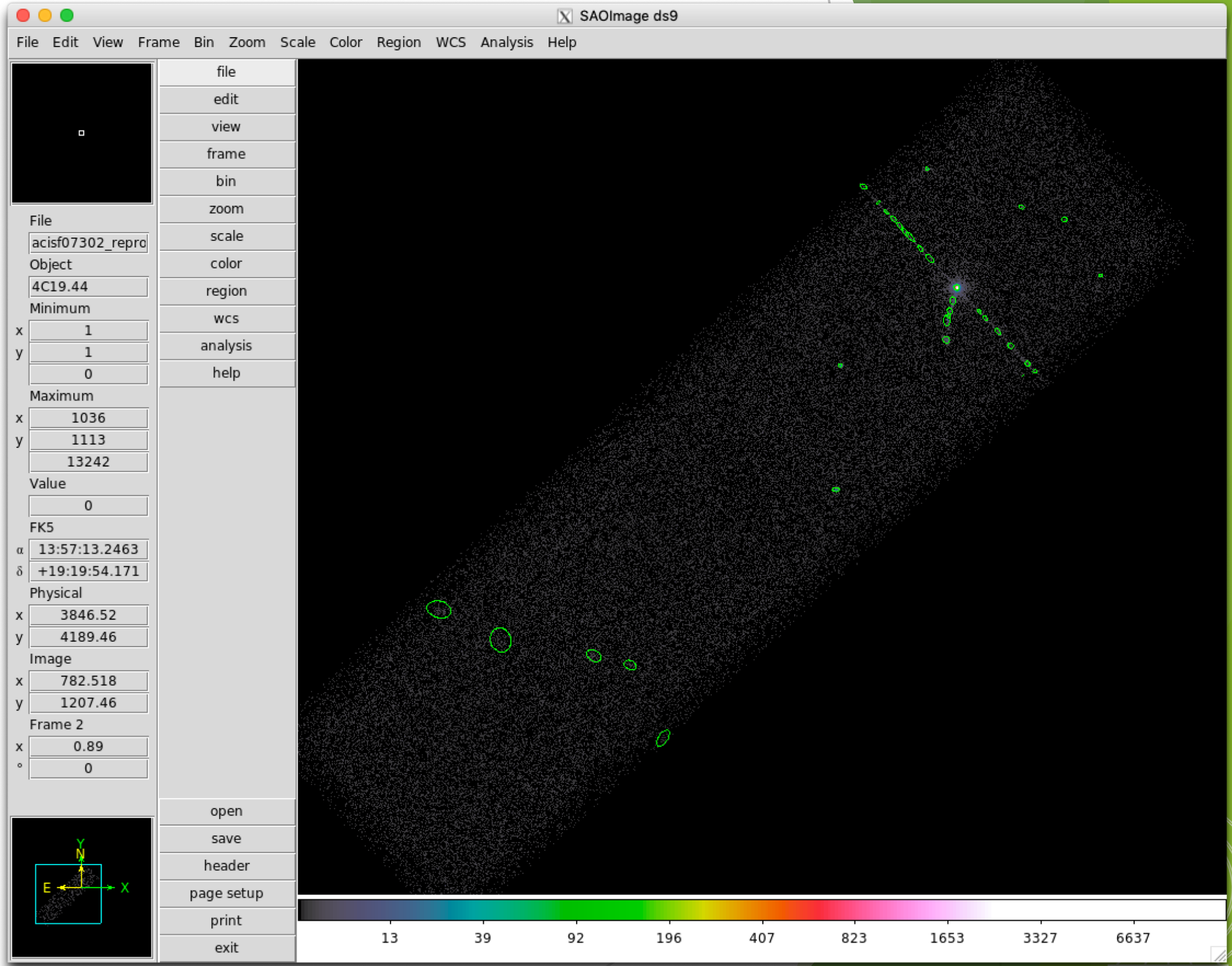
Background Flares and Source Detection

- Create lightcurve of the background events.
  - exclude sources in the field
  - exclude readout streak
- X-ray source detection
  - Identify statistically significant brightness enhancements, over local background, deriving from both unresolved & resolved and point & extended X-ray sources.
  - Other source properties, like intensity and size, may also be reported, but may be more reliably evaluated separately.



Note: source properties derived from source detection aren't intended for photometric usage!

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Background Flares and Source Detection

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- CIAO source detection algorithms
  - `wavdetect` — wavelet correlation

Pros
- works well in crowded fields
- works well with point sources embedded in diffuse emission
- only requires an approximate PSF shape
- not strongly affected by detector edge effects

Cons:
- slow, especially if many wavelets are used
- memory intensive
- no recursive blocking built-in, so running on entire image may require multiple, binned images. Source lists must then be combined.

  - `celldetect` — sliding cell

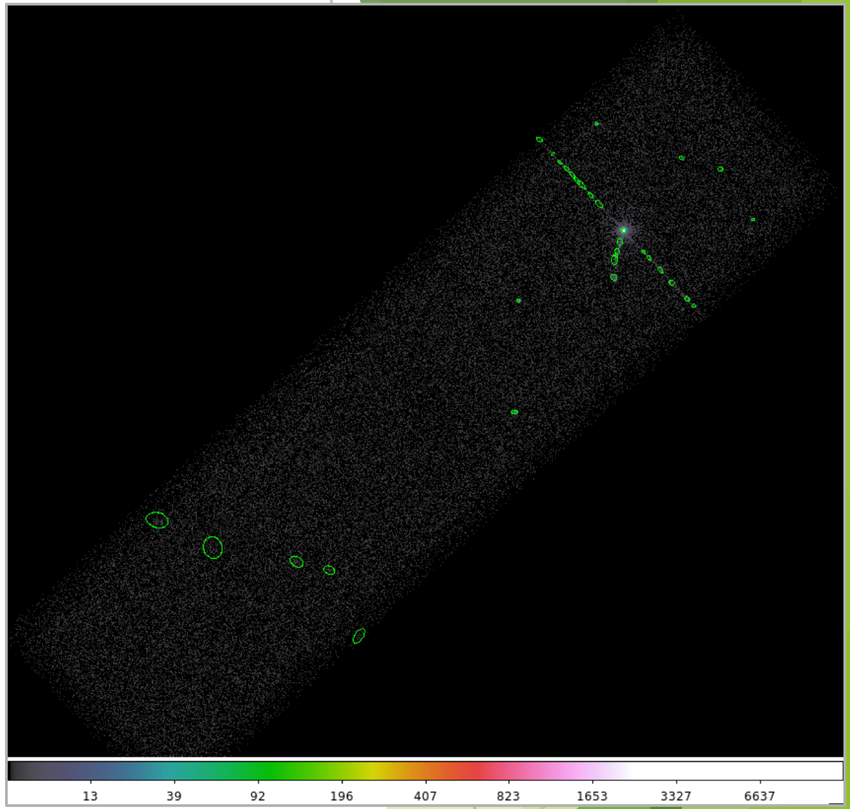
Pros
- fast and robust
- works well for point sources
- only requires an approximate PSF shape
- can handle very large images easily

Cons
- extended sources are difficult without careful cell size selection
- can get confused in crowded fields
- exposure maps needed to reduce edge effects
- not very sensitive unless background maps are used, which may be difficult to construct

  - `vtpdetect` — Voronoi tesselation and percolation

Pros
- works well for extended sources and irregularly shaped sources
- works on large areas at full resolution
- works well on low surface brightness extended sources

Cons
- can get confused in crowded fields
- slow, especially if there is a large number of photons and the contrast between background and sources is low



Reality is X-ray source detection is often a difficult—or at least challenging—task. A reliable source list may require running more than one tool, or one tool multiple times.

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Source Detection (cont.)

- Reducing spurious source detections.
  - All CIAO detection tools can use an optional exposure map
  - PSF maps can be used by `celldetect` and `wavdetect`
- `fluximage` provides an easy interface to generate these data products.

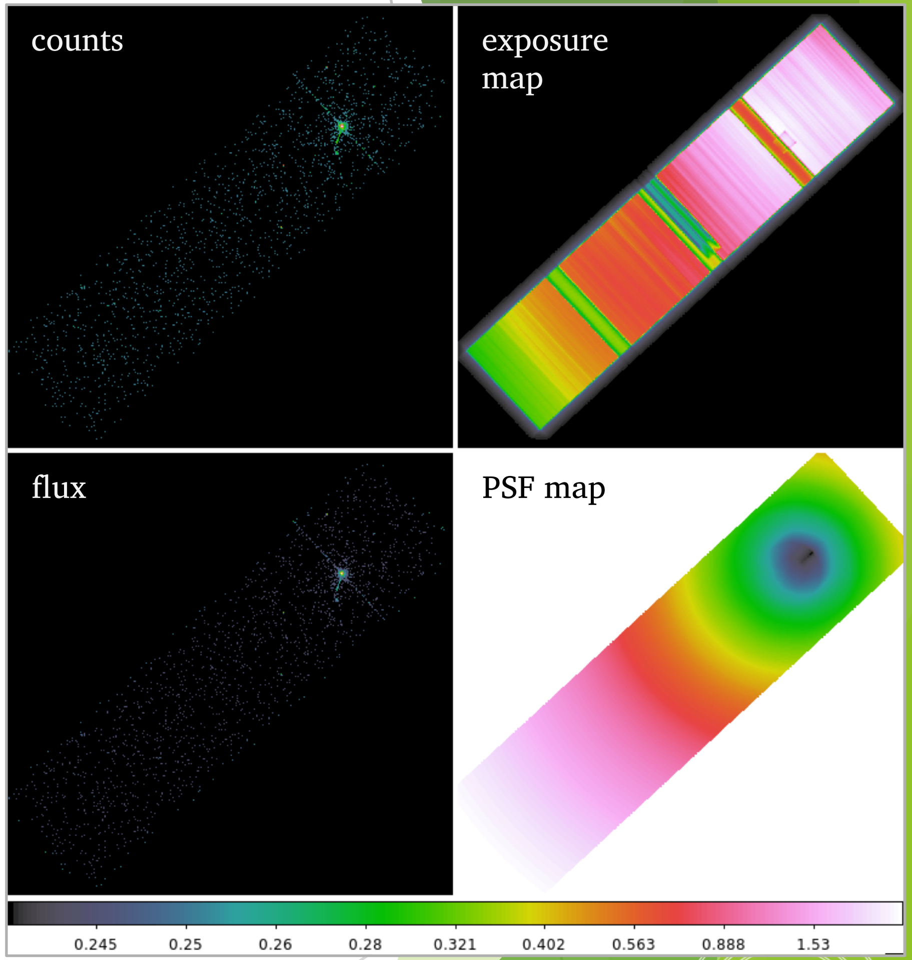
reduces false source detections from detector effects

PSF info allows for more reliable characterization of source; does not affect detection

```
unix% fluximage acisf07302_repro_evt2.fits \
? outroot=flux/7302 binsize=1 bands=broad psfecf=0.393

. . . SCREEN OUTPUT . . .

The following files were created:

 The clipped counts image is:
     flux/7302_broad_thresh.img

 The clipped exposure map is:
     flux/7302_broad_thresh.expmap

 The PSF map is:
     flux/7302_broad_thresh.psfmap

 The exposure-corrected image is:
     flux/7302_broad_flux.img
```

Note: prior to CIAO 4.11, the separate mkpsfmap tool needs to be run to generate the PSF map.

ECF=0.393 corresponds to the 1σ integrated volume of a 2D Gaussian




```
unix% mkpsfmap infile=7302_broad_thresh.img \
? outfile=7302_broad_thresh.psfmap \
? energy=2.3 ecf=0.393
```

Effective area used for exposure map (2.3 keV for CSC broad band)

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`fluximage` Data Products

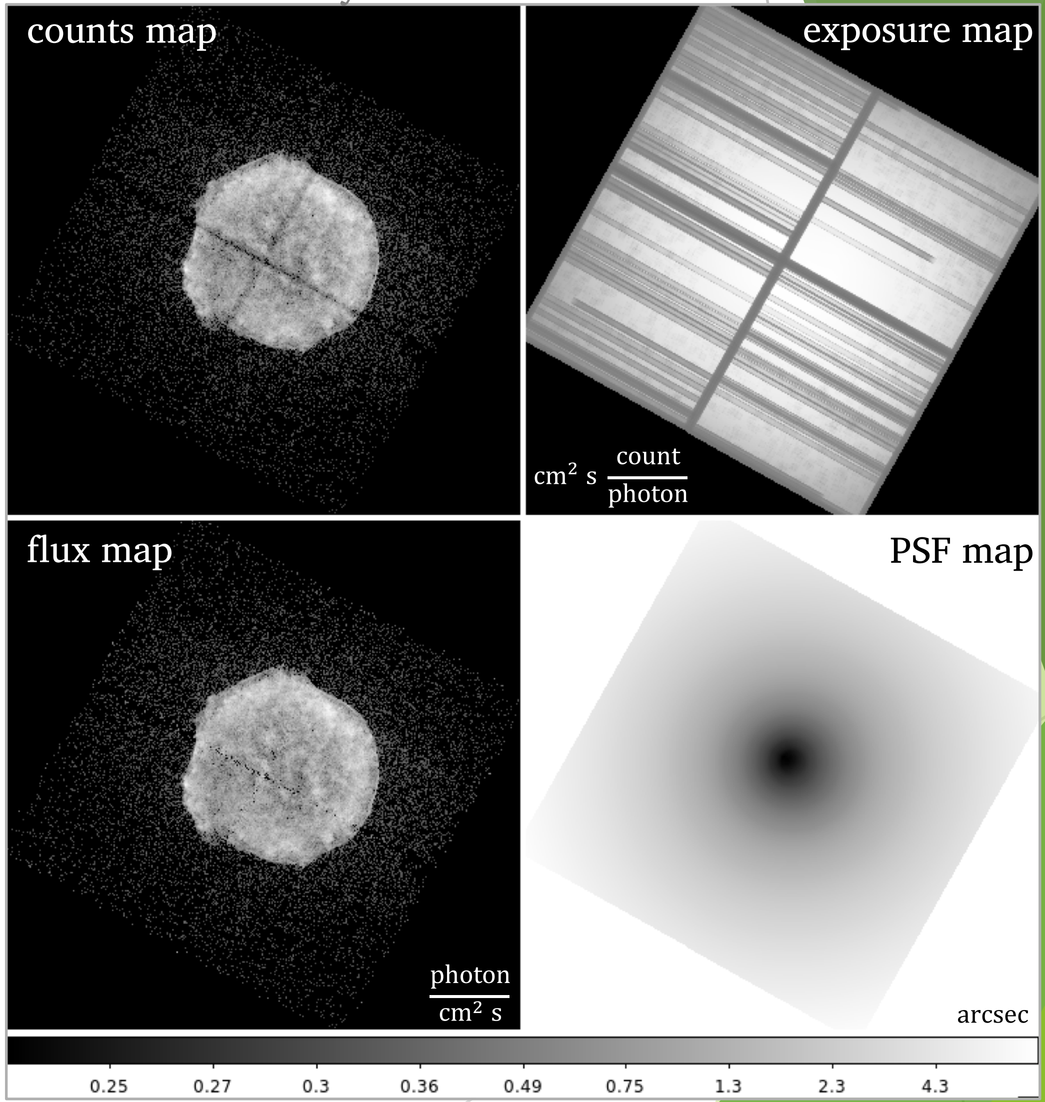
- Binned counts map with clipping.

- Exposure maps are observation-specific maps of the instrument sensitivity, incorporating mirror area and detector QE, convolved with the telescope's aspect solution.
  - units of $cm^2 \cdot s \cdot \frac{count}{photon}$ or $cm^2 \cdot \frac{count}{photon}$
  - analogous to optical/IR flat field image

- Exposure-corrected image (flux map): $\frac{counts\ map}{exposure\ map}$

- PSF map provides the PSF size at each pixel of an image.
  - the `mkpsfmap` size is the radius of a circular region enclosing a given fraction of the counts from a point source (the "ECF" or "encircled counts fraction")
  - sizes are for a PSF of a given monochromatic energy or photon distribution

ObsID 10095: Tycho's SNR



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Source Detection

by way of `wavdetect`

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```
unix% punlearn ardlib
unix% acis_set_ardlib 7302/repro/acisf07302_repro_bpix1.fits

unix% pset wavdetect infile=7302_broad_thresh.img
unix% pset wavdetect psffile=7302_broad_thresh.psfmap
unix% pset wavdetect expfile=7302_broad_thresh.expmap
unix% pset wavdetect outfile=detect/.
unix% pset wavdetect scellfile=detect/.
unix% pset wavdetect imagefile=detect/.
unix% pset wavdetect defnbkgfile=detect/.
unix% pset wavdetect regfile=detect/.
unix% pset wavdetect scales="1.0 2.0 4.0 8.0 16.0 32.0"
unix% pset wavdetect sigthresh=1e-6
unix% wavdetect clobber+ verbose=1 mode=h

. . . SCREEN OUTPUT . . .

Output background image: detect/7302_broad_nbkg.img
Output source image: detect/7302_broad_image.img
Output source cell image: detect/7302_broad_scell.img
Output source list file: detect/7302_broad_src.fits
Output source regions file: detect/7302_broad_src.reg
```

set bad pixel file for the tool to use in the terminal

Note: `infile` requires Z-valued pixels for valid results

`fluximage` results

output files, the "." in the arguments automatically names output files for `wavdetect` based on `infile` string

set of wavelet scales

`regfile` is the ASCII region file and `outfile` is the source list

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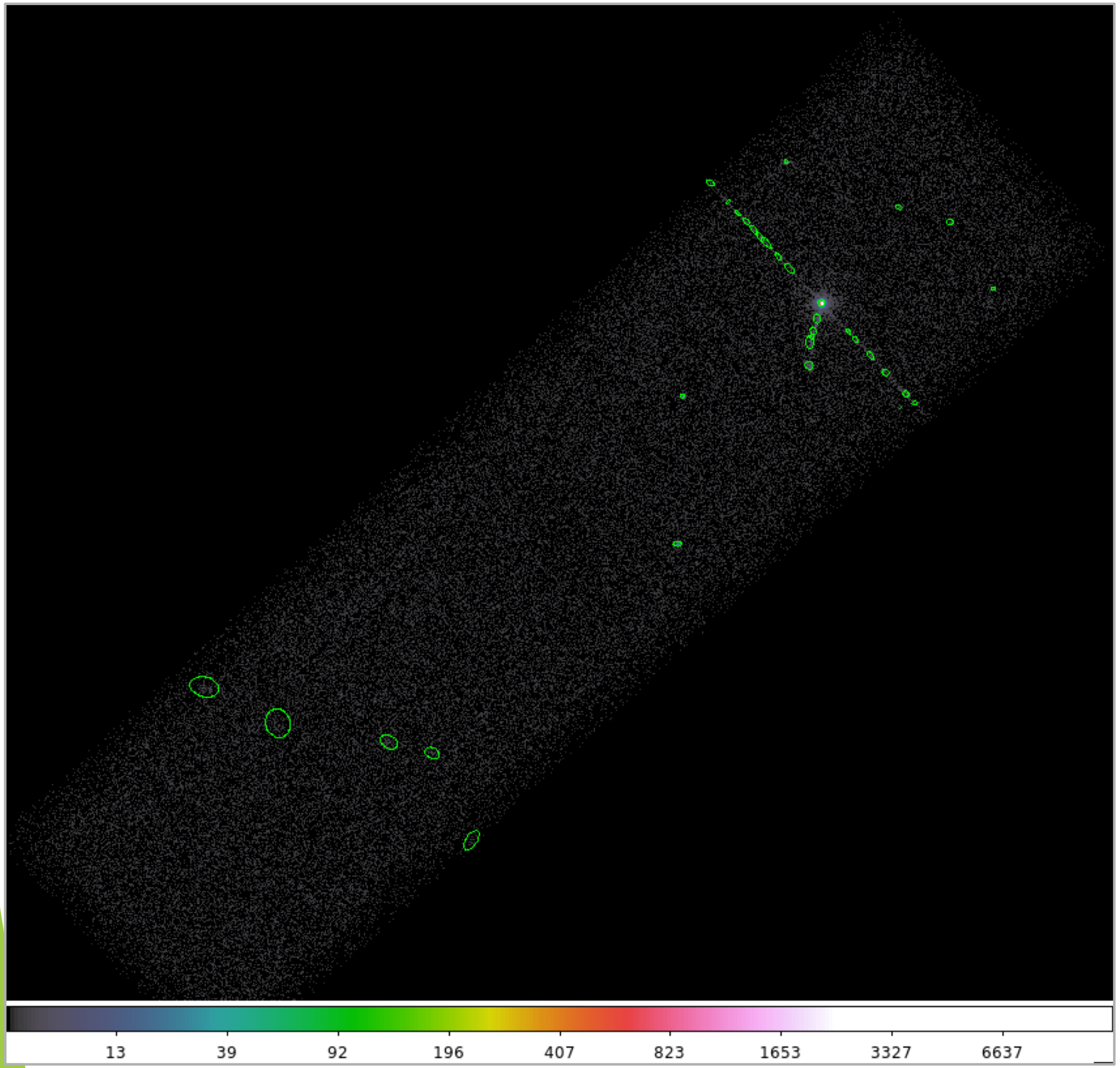
wavdetect Results



- Explore the source list with DS9 and `dmlist`.

```
unix% dmlist detect/7302_broad_src.fits blocks

--------------------------------------------------------------------------------
Dataset: detect/7302_broad_src.fits
--------------------------------------------------------------------------------

     Block Name                          Type         Dimensions
--------------------------------------------------------------------------------
Block     1: PRIMARY                       Null
Block     2: SRCLIST                       Table        26 cols x 33   rows
```

```
unix% dmlist 7302_src.fits cols

--------------------------------------------------------------------------------
Columns for Table Block SRCLIST
--------------------------------------------------------------------------------

ColNo  Name                  Unit        Type             Range
   1   RA                    deg          Real8          0:       360.0        Source Right Ascension
   2   DEC                   deg          Real8          -90.0:       90.0     Source Declination
   3   RA_ERR                deg          Real8          -Inf:+Inf             Source Right Ascension Err
   4   DEC_ERR               deg          Real8          -Inf:+Inf             Source Declination Error
   5   POS(X,Y)              pixel        Real8          3386.50:     4354.50  Physical coordinates
   6   X_ERR                 pixel        Real8          -Inf:+Inf             Source X position error
   7   Y_ERR                 pixel        Real8          -Inf:+Inf             Source Y position error
   8   NPIXSOU               pixel        Int4           -                     pixels in source region
   9   NET_COUNTS            count        Real4          -Inf:+Inf             Net source counts
  10   NET_COUNTS_ERR        count        Real4          -Inf:+Inf             Error in net source counts
  11   BKG_COUNTS            count        Real4          -Inf:+Inf             Background counts
  12   BKG_COUNTS_ERR        count        Real4          -Inf:+Inf             Error in BKG_COUNTS

. . . MORE INFO . . .
```

Source Detection (cont.)

by way of `wavdetect`

- Wavelets are correlated with data image at each scale size.
  - scales are the radii of the Ricker (aka "Mexican Hat") wavelet function
  - scales in units of image pixels
  - minimum and maximum scales chosen w.r.t. instrumental PSF sizes
    - smaller scales tend to detect small features and larger scales, large features
    - very large scales may be needed to characterize extended sources
  - scales typically separated by factor of 2 or $\sqrt{2}$
- `sigthresh` parameter is the threshold that a pixel belongs to a source.
  - $sigthresh \approx \frac{1}{number\ of\ image\ pixels}$
- `ellsigma` parameter affects region size in `regfile` for visualization purposes.
  - scales the major- and minor-axes of the ellipses for each detection
  - does not affect source detection or source properties

```
unix% dmlist flux/7302_broad_thresh.img blocks

--------------------------------------------------------------------
Dataset: flux/7302_broad_thresh.img
--------------------------------------------------------------------

     Block Name                          Type         Dimensions
--------------------------------------------------------------------
Block     1: EVENTS_IMAGE                  Image        Int4(968x926)

unix% python -c 'print(1/(968*926))'
1.1156132302804205e-06
```

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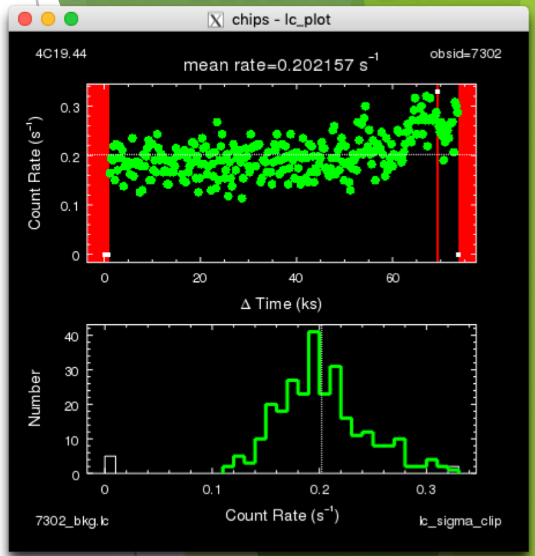
Finding background flares



- The `deflare` script is a command-line interface to the `lightcurves` Python module to apply the `lc_clean` and `lc_sigma_clip` algorithms.
  - requires an input lightcurve of the background
  - returns a GTI file that can be used to filter FITS tables
  - done on a per CCD basis
- Extract lightcurve for each CCD, excluding the field sources.

```
unix% dmcopy acisf07302_repro_evt2.fits"[energy=500:7000,ccd_id=7]" 7302_0.5-7.0keV.evt

unix% dmextract "7302_0.5-7.0keV.evt[exclude sky=region(detect/7302_broad_src.fits)][bin time=::259.28]” \
? 7302_bkg.lc opt=ltc1
```

- run `deflare`

```
unix% deflare infile=7302_bkg.lc outfile=7302.gti\
? method=sigma plot=yes

. . . SCREEN OUTPUT . . .

Creating GTI file
Created: 7302.gti
Light curve cleaned using the lc_sigma_clip routine.
```

Optional: Applying GTI to events file

```
unix% dmcopy "acisf07302_repro_evt2.fits[@7302.gti]” \
? 7302_clean_evt.fits

unix% dmkeypar acisf07302_repro_evt2.fits EXPOSURE echo+
68937.080789336
unix% dmkeypar 7302_clean_evt.fits EXPOSURE echo+
68443.824820477
```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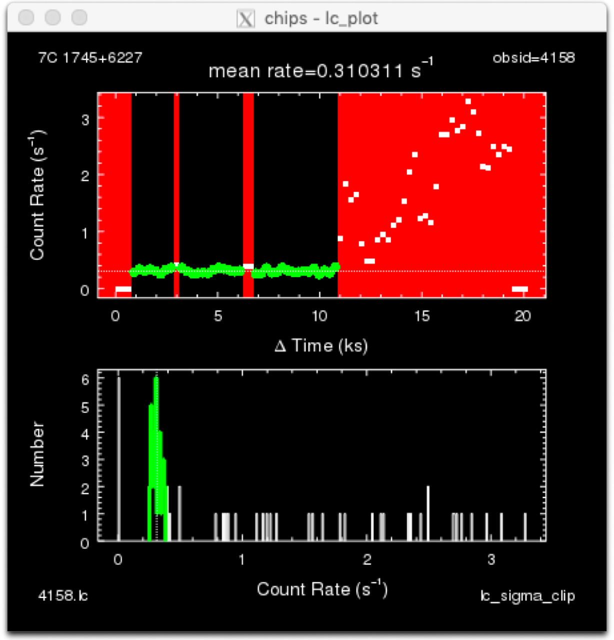
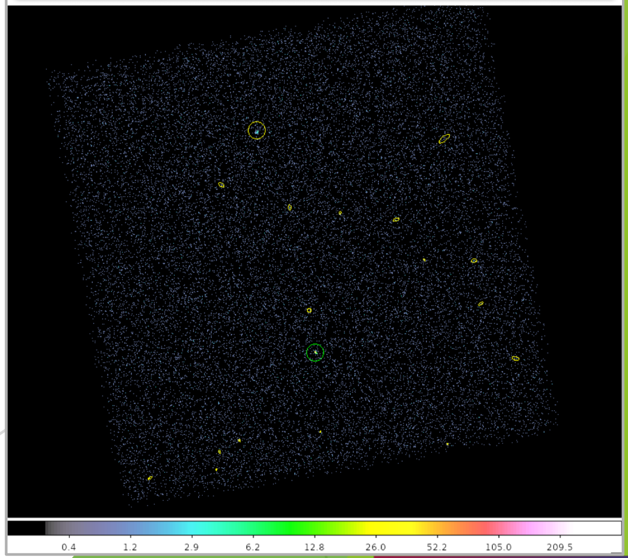
Should deflaring always be applied?

Generally: IF we have variable background, AND if it would be significant for the source region, THEN we exclude the affected times.

- Need to weigh the pros and cons.
  - reduced exposure time ⇒ less source counts
  - longer exposure time ⇒ higher uncertainty from background
- Point source
  - how much of the observed background will coincide with the point source?
  - how much brighter is the apparent surface brightness of the source over the background?
- Extended source
  - accounting for background more important than in point source analysis
  - complex spatial structure in source may dominate over background effects
  - does effects in embedded structure spillover to ambient background?
  - how much source free background available in observation?





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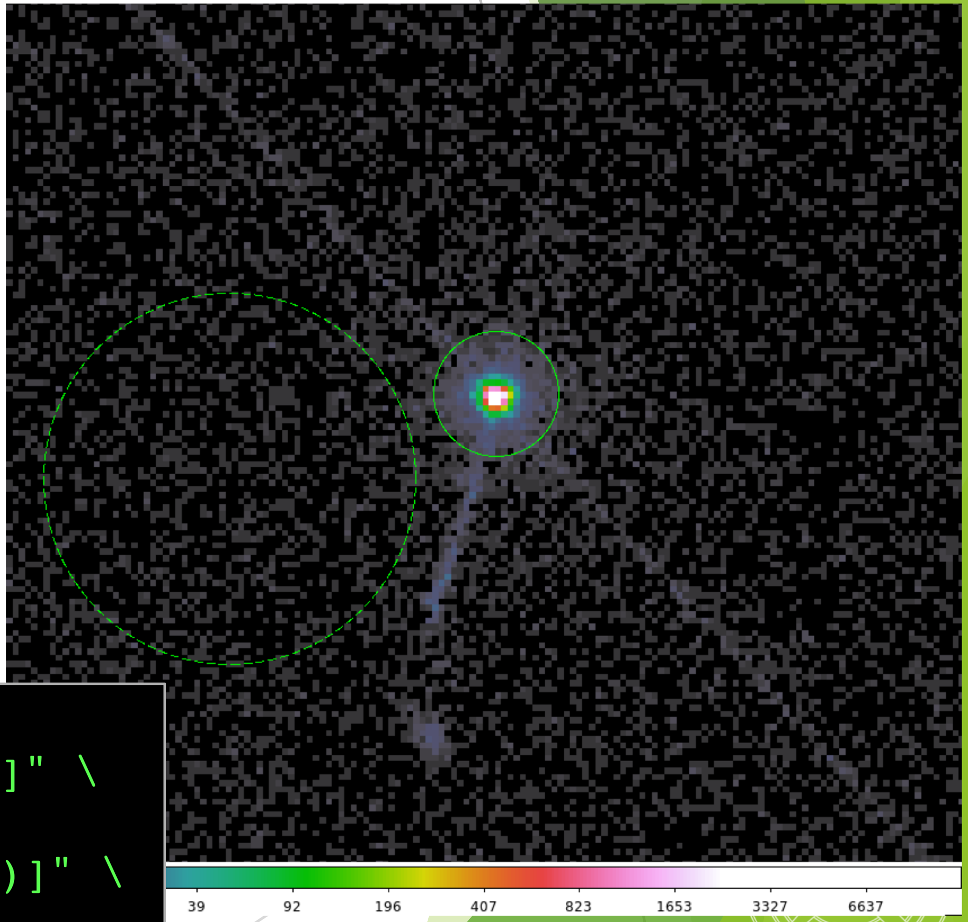
Extracting Spectrum
from an Imaging Spectroscopy Observation

- `specextract` extracts spectrum and calculates corresponding responses
  - background products optional
- extract background or not
  - point source: how much brighter is the source than the local background?
  - extended source and crowded fields: can be critical, but also non-trivial to extract
  - if planning on fitting background spectrum, create background responses




```
unix% specextract
infile="acisf07302_repro_evt2.fits[sky=region(src.reg)]" \
outroot=spec/7302_core \
bkgfile="acisf07302_repro_evt2.fits[sky=region(bkg.reg)]" \
bkgresp=yes weight=no correctpsf=yes grouptype=NONE \
mode=h clobber=yes
```

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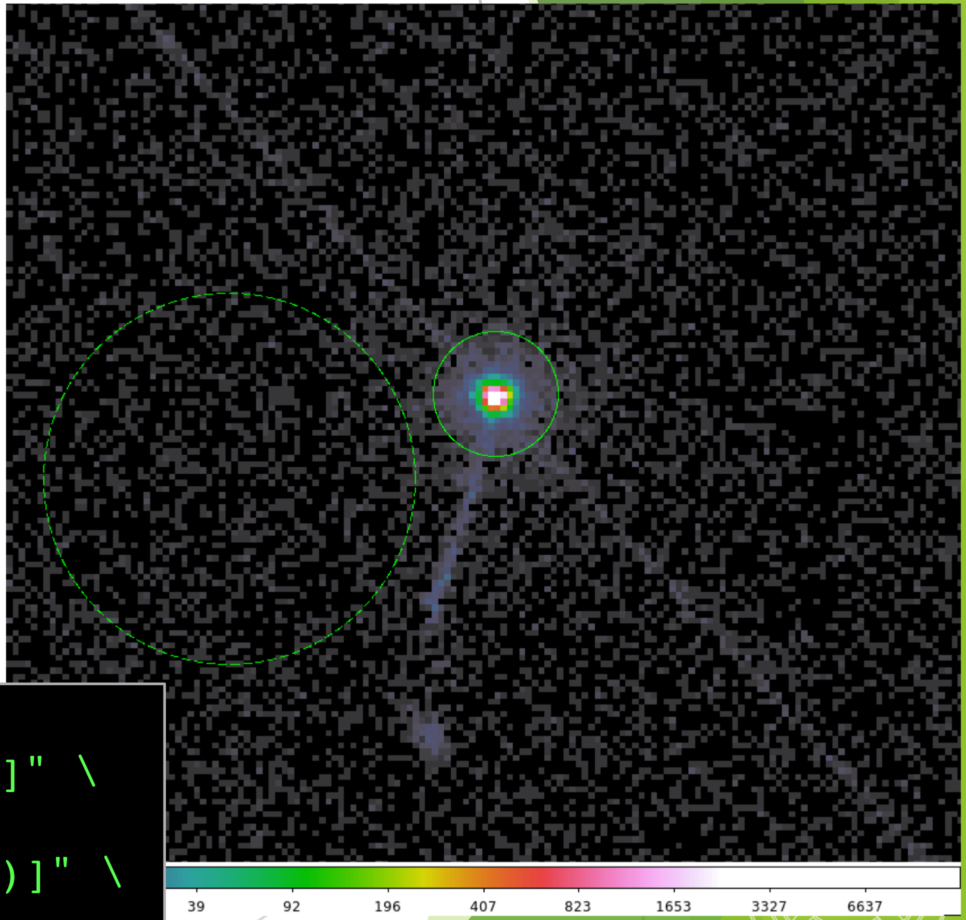
Extracting Spectrum (cont.)
from an Imaging Spectroscopy Observation

- unweighted vs weighted responses
  - on-axis point sources, unweighted responses
    - correct ARF for events that fall outside the the aperture
  - extended and far off-axis point sources, weighted responses
    - weighted ARFs are needed if interested in the spatial variation of the effective area
    - weighted RMFs are computationally expensive, scaling with the number of pixels in the extraction region, but the probability variation with spatial position is small
  - point sources near chip gaps should use weighted responses, since it accounts for affects of source dithering off detector




```
unix% specextract
infile="acisf07302_repro_evt2.fits[sky=region(src.reg)]" \
outroot=spec/7302_core \
bkgfile="acisf07302_repro_evt2.fits[sky=region(bkg.reg)]" \
bkgresp=yes weight=no correctpsf=yes grouptype=NONE \
mode=h clobber=yes
```

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X-ray Spectral Fitting Packages

- *Sherpa* is the spectral fitting package native to CIAO.
  - **XSpec** is the gold standard in X-ray astronomy for 1D fitting
  - **Sherpa** designed to fit *n*-dimensional data sets and can be used beyond X-ray spectra and 2D image fitting; built on Python
  - **ISIS** (*Interactive Spectral Interpretation System*) is optimized for gratings analysis
  - **SPEX** has many unique (but closed source) non-equilibrium, collisional ionization and plasma models
- All packages designed to solve:

$$C(h) = t \int_0^\infty R(E,h)A(E)S(E)dE + B(h)$$

and in practice, discretized as:

$$C(h) = t \sum_i R_{i,h} A_i S(E_i) \Delta E_i + B(h)$$

where $C(h)$ is the observed counts in a spectrum at detector channel h; t is the exposure time, $R(E,h)$ is the probability of observing a photon of energy E at channel h represented by the dimensionless RMF, $A(E)$ is the effective area and QE encapsulated in the ARF, $S(E)$ is the source model, and $B(h)$ is the observed background counts at channel h.

- Models are fit by the iterative technique of *forward folding*.
  - directly inverting the integral in $C(h)$ is not mathematically possible due to the non-diagonality of RMFs, so there is no *unique* inversion

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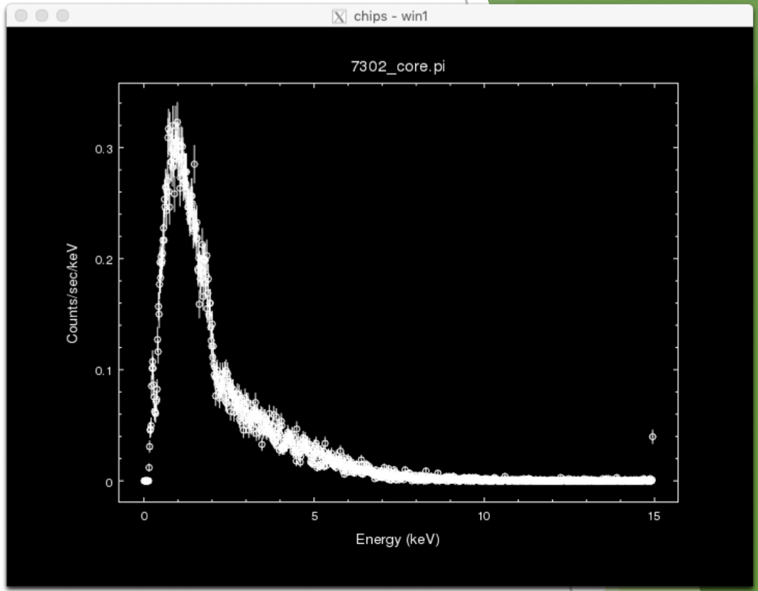
Sherpa: Load and Filter Data

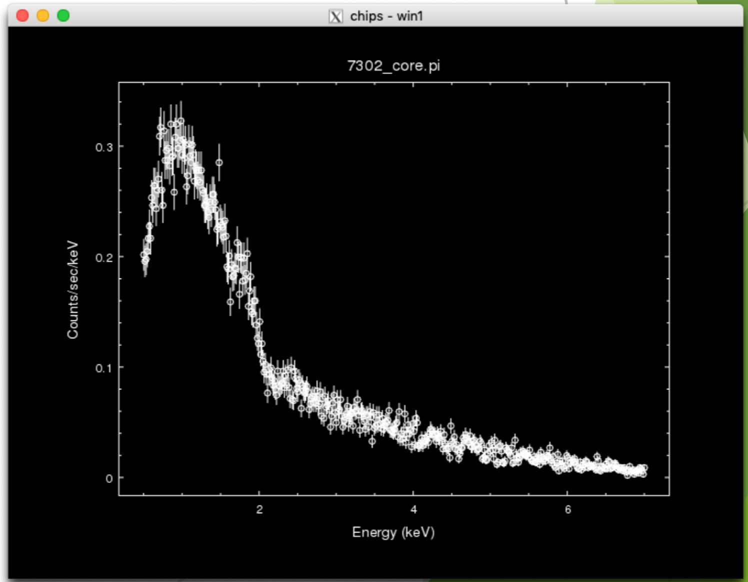
```
sherpa> load_data("7302_core.pi")
```

ARF, RMF, background, and background responses automatically loaded if defined in header keywords and can be found.

```
sherpa> plot_data()

sherpa> show_filter()
Data Set Filter: 1
0.0110-14.9431 Energy (keV)

sherpa> notice(0.5,7.0)
sherpa> show_filter()
Data Set Filter: 1
0.5037-7.0007 Energy (keV)

sherpa> plot_data()
```

The filter ranges are ultimately determined by the bin edges of the grid that were used to create the response files.





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Sherpa: “source” vs. “model”

- “source” is the $S(E)$ in the equation solved by software; it is the physical model describing the source.
- “model” refers to the source convolved with the responses and scaled by various terms, including exposure time.

```
sherpa> set_model(xsphabs.abs1*powlaw1d.p1)

sherpa> show_source()
Model: 1
(xsphabs.abs1 * powlaw1d.p1)
   Param        Type          Value          Min          Max      Units
   -----        ----          -----          ---          ---      -----
   abs1.nH      thawed            1            0       100000 10^22 atoms / cm^2
   p1.gamma     thawed            1          -10           10
   p1.ref       frozen            1 -3.40282e+38  3.40282e+38
   p1.ampl      thawed            1            0  3.40282e+38

sherpa> show_model()
Model: 1
apply_rmf(apply_arf((68937.080789336 * (xsphabs.abs1 * powlaw1d.p1))))
   Param        Type          Value          Min          Max      Units
   -----        ----          -----          ---          ---      -----
   abs1.nH      thawed            1            0       100000 10^22 atoms / cm^2
   p1.gamma     thawed            1          -10           10
   p1.ref       frozen            1 -3.40282e+38  3.40282e+38
   p1.ampl      thawed            1            0  3.40282e+38
```


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Model Component Parameters

- model components are represented with the model objects **`abs1`** and **`p1`**.
- `freeze` and `thaw` entire model component or specific component parameters.
- provide reasonable initial parameter values or use `guess`.

```
sherpa> !dmkeypar 7302_core.pi BELL_NH echo+
0.0221
sherpa> !dmkeypar 7302_core.pi NRAO_NH echo+
0.0223

sherpa> abs1.nh=0.0223

sherpa> freeze(abs1) # or freeze(abs1.nh)
```

header keywords written by `specextract`

```
sherpa> show_source()
Model: 1
(xsphabs.abs1 * powlaw1d.p1)
   Param        Type          Value          Min          Max      Units
   -----        ----          -----          ---          ---      -----
   abs1.nH      frozen       0.0223            0       100000  10^22 atoms / cm^2
   p1.gamma     thawed            1          -10           10
   p1.ref       frozen            1 -3.40282e+38  3.40282e+38
   p1.ampl      thawed            1            0  3.40282e+38
```


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Statistics and Optimization Methods

`cxc.harvard.edu/sherpa/methods/` and `cxc.harvard.edu/sherpa/statistics/`

- χ^2 and [Poissonian] maximum likelihood statistics
- Optimization Methods
  - Levenberg-Marquardt — quick but very sensitive to initial parameters and easily trapped in local extrema; works well for simple models, but fails to converge on complex models.
  - Nelder-Mead = Simplex — robust exploration of parameter-space, converges with complex models.
  - Monte Carlo — global search of parameter-space and converges on complex models, very slow.
  - `gridsearch` used for template models

```
sherpa> list_stats()
['cash’, 'chi2', 'chi2constvar’, 'chi2datavar’, 'chi2gehrels',
 'chi2modvar', 'chi2xspecvar', 'cstat', 'leastsq', 'userstat’, 'wstat’]

sherpa> list_methods()
['gridsearch', 'levmar', 'moncar', 'neldermead', 'simplex']

sherpa> set_stat("wstat")
sherpa> set_method("neldermead")
```

Statistics Choice for Forward Folding

the Conventional Approaches

For the observed net counts in bin h, $C(h)$, then $C(h) = N(h) - B(h)$ where $N(h)$ is the observed total counts and $B(h)$ is the observed background counts in bin h. The convolved source model, $M(h)$, is then iteratively compared with $C(h)$ until the difference is minimized (or alternatively maximizing the probability/likelihood).

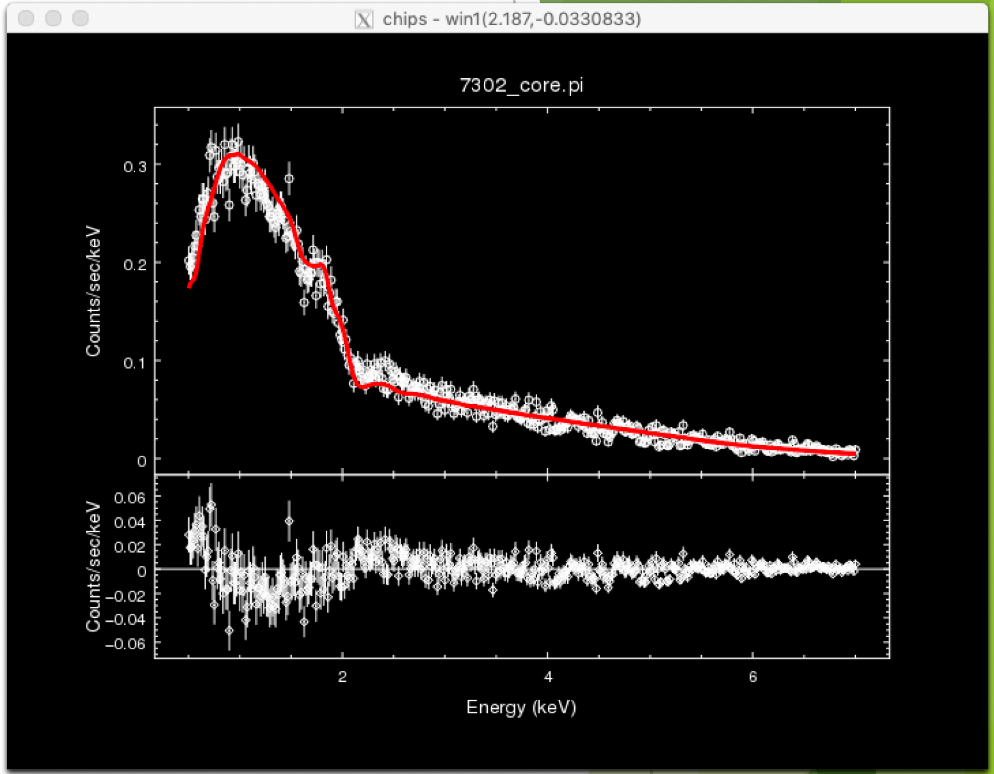
- use χ^2 statistics
  - bin the observed spectrum so there are ~10–20 counts per bin (`group_counts`) so that Gaussian statistics apply (i.e., uncertainty in spectral bin h is the standard deviation $\sigma(h) \longrightarrow \frac{1}{\sqrt{N(h)}}$)
  - directly subtract background
- use Poisson statistics
  - unbinned spectrum
  - ignore or model background
- hybrid of the above two
  - include observed background, but as part of the model, $M(h)$
  - assume Poisson statistics

Fitting and Residuals

- $\texttt{resid} = data - model$
- $\texttt{delchi} = \delta\chi = \sigma = \frac{data-model}{error}$
  - only available with χ^2 statistics

```
sherpa> fit()
Dataset               = 1
Method                = neldermead
Statistic             = wstat
Initial fit statistic = 1.32374e+08
Final fit statistic   = 646.322 at function evaluation 329
Data points           = 446
Degrees of freedom    = 444
Probability [Q-value] = 1.05436e-09
Reduced statistic     = 1.45568
Change in statistic   = 1.32374e+08
   p1.gamma        1.32409
   p1.ampl         0.000684984

sherpa> plot_fit_resid()
```



reduced statistic $\longrightarrow$ 1, good fit
reduced statistic < 1, unexpectedly good fit
reduced statistic $\gg$ 1, insufficient data points to believe fit

Uncertainties on Model Free Parameters and Source Model Fluxes

CHANDRA X-RAY OBSERVATORY

- Uncertainties on free parameters
  - confidence
  - projection
  - covar
  - reg_proj and reg_unc
- unconvolved model fluxes
  - calc_energy_flux(ID,[lo,hi])
    - $\frac{ergs}{cm^2 \cdot s}$
    - $\frac{ergs}{cm^2 \cdot s \cdot keV}$ or $\frac{ergs}{cm^2 \cdot s \cdot Å}$
  - calc_photon_flux(ID,[lo,hi])
    - $\frac{photons}{cm^2 \cdot s}$
    - $\frac{photons}{cm^2 \cdot s \cdot keV}$ or $\frac{photons}{cm^2 \cdot s \cdot Å}$

```
sherpa> set_conf_opt("sigma",1.6)
sherpa> conf()
p1.gamma lower bound:   -0.0133297
p1.ampl lower bound:    -7.2076e-06
p1.gamma upper bound:   0.0133297
p1.ampl upper bound:    7.25513e-06
Dataset               = 1
Confidence Method     = confidence
Iterative Fit Method  = None
Fitting Method        = neldermead
Statistic             = wstat
confidence 1.6-sigma (89.0401%) bounds:
   Param            Best-Fit  Lower Bound  Upper Bound
   -----            --------  -----------  -----------
   p1.gamma          1.32409   -0.0133297    0.0133297
   p1.ampl       0.000684984  -7.2076e-06  7.25513e-06
```

1.645σ ≃ 90% C.I.

```
sherpa> calc_energy_flux(lo=0.5,hi=7.0)
4.939230677499014le-12

sherpa> calc_photon_flux(lo=0.5,hi=7.0)
0.0014449101021993681
```

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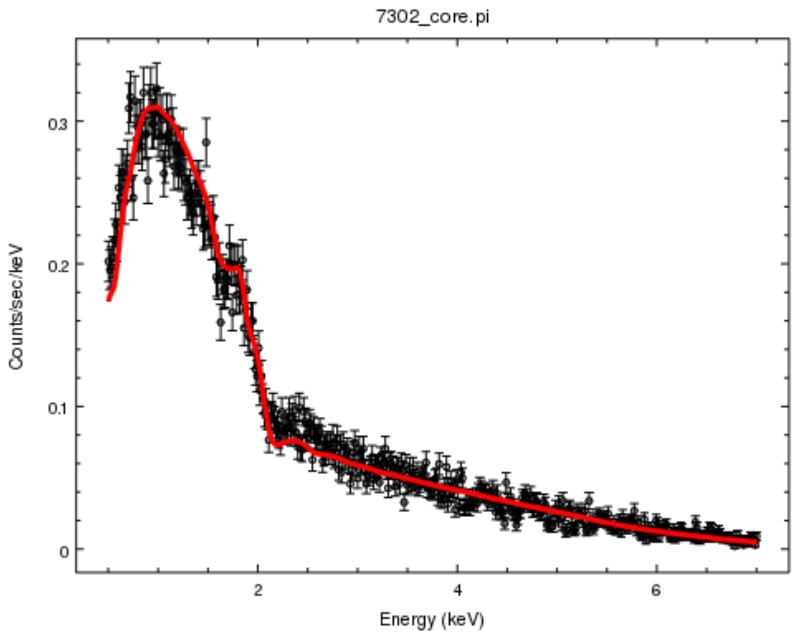
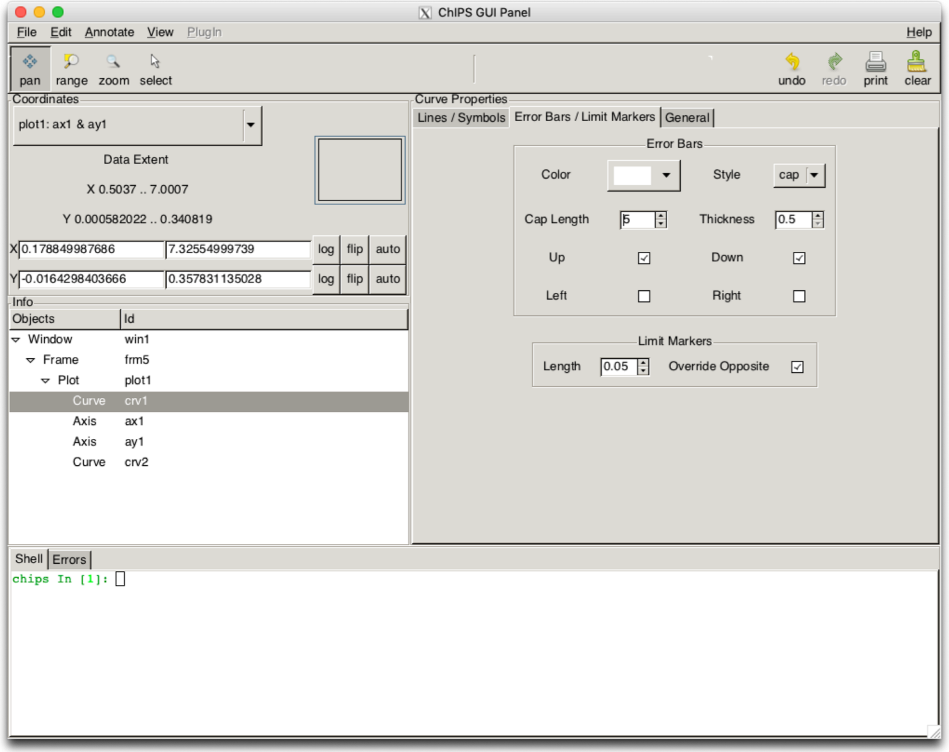
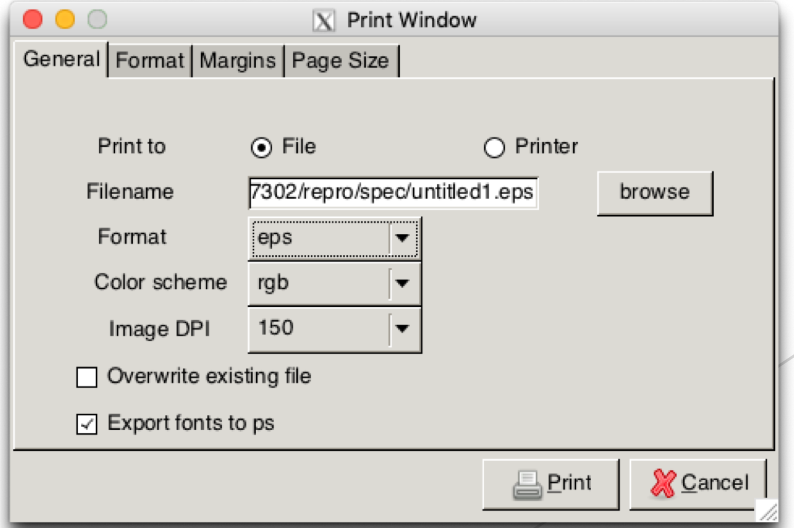
Modifying Plots

- `show_gui()`
- LaTeX symbols support available.
  - prepend quoted string with `r` (e.g. `r"\Gamma"`)
- printing to file inverts black and white seen in X-window.





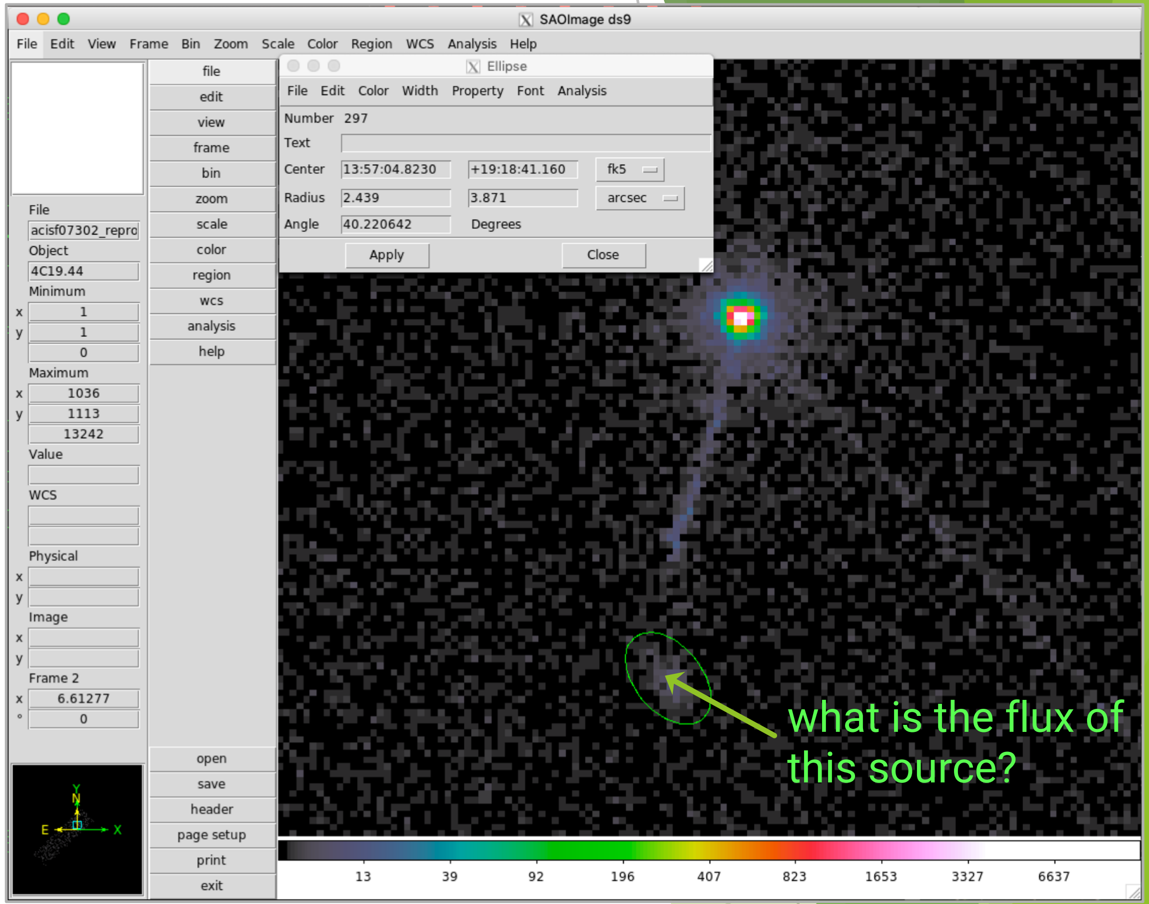


CHANDRA X-RAY OBSERVATORY

Source Properties

by way of `srcflux`

- Encodes the logic described in six different CIAO threads. Returns count rates, fluxes, and errors with all appropriate corrections.
- `srcflux` capabilities:
  - automatically determines PSF-appropriate extraction region size for source and background, or user-defined
  - uses one of four methods to apply aperture correction
  - runs on multiple energy bands
  - accepts one position or a list
  - calculates count rates using `aprates` method
  - calculates fluxes two different ways (specified spectral model and `eff2evt` method; however, no spectral fit is performed)
  - generates spectral responses for downstream analysis



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Source Properties (cont.)

by way of `srcflux`

```
unix% srcflux infile=acisf07302_repro_evt2.fits pos="13:57:04.823 +19:18:41.16" \
? outroot=srcflux/lobe mode=h

. . . SCREEN OUTPUT . . .

Summary of source fluxes
      Position                            0.5 - 7.0 keV
                                          Value           90% Conf Interval
#0001|13 57 4.82 +19 18 41.1  Rate        0.000657 c/s (0.000499,0.00084)
                              Flux        6.44E-15 erg/cm2/s (4.9E-15,8.23E-15)
                              Mod.Flux    4.24E-15 erg/cm2/s (3.22E-15,5.42E-15)
                              Unabs Mod.Flux 4.41E-15 erg/cm2/s (3.35E-15,5.64E-15)
```

- `srcflux` has options for PSF corrections, energy bands, confidence intervals (including upper-limits), spectral models, and user supplied regions.
- lower and upper bounds of confidence interval in parentheses.

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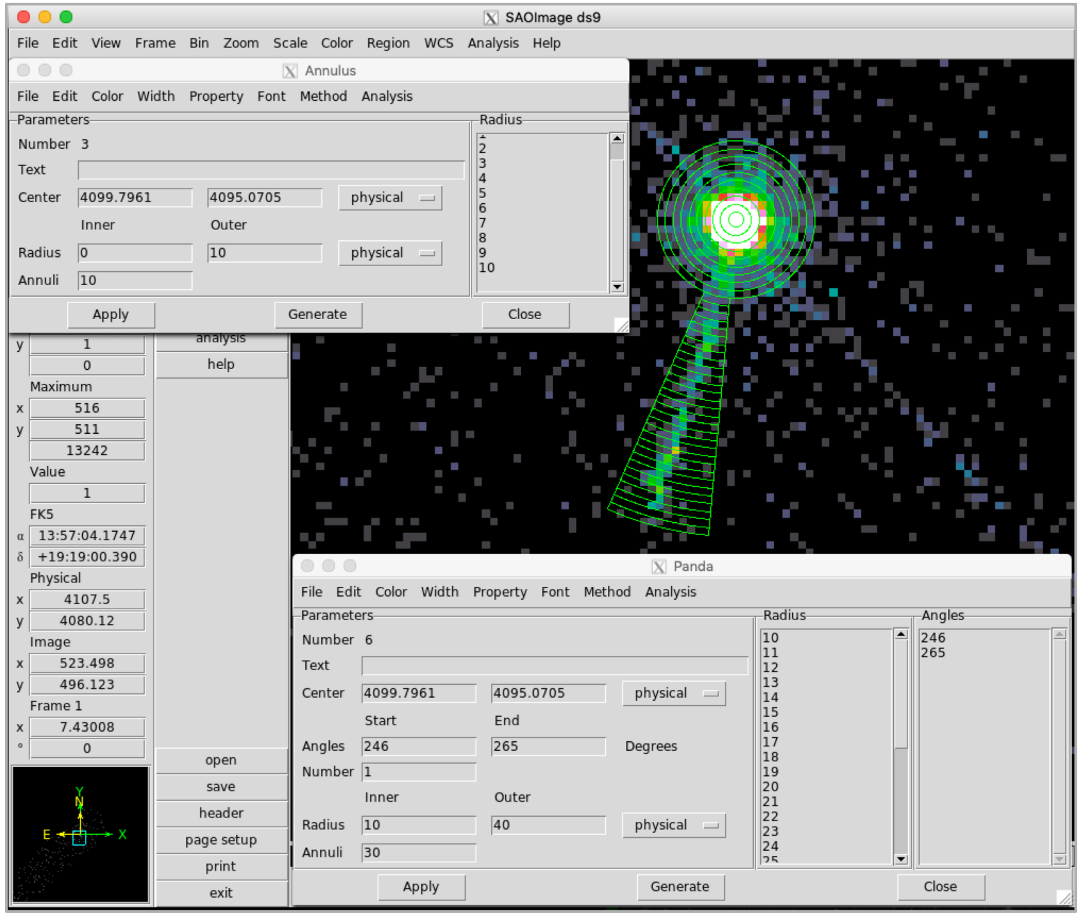
Radial Profiles

- Extract from annular regions with `dmextract`.
  - set `opt=generic`
  - in this example, the background region is the same as the one used for spectral extraction




```
unix% cat src.reg
annulus(4099.7961,4095.0705,0,1)
annulus(4099.7961,4095.0705,1,2)
annulus(4099.7961,4095.0705,2,3)
annulus(4099.7961,4095.0705,3,4)
annulus(4099.7961,4095.0705,4,5)
annulus(4099.7961,4095.0705,5,6)
annulus(4099.7961,4095.0705,6,7)
annulus(4099.7961,4095.0705,7,8)
annulus(4099.7961,4095.0705,8,9)
annulus(4099.7961,4095.0705,9,10)
pie(4099.7961,4095.0705,10,11,246,265)
pie(4099.7961,4095.0705,11,12,246,265)
pie(4099.7961,4095.0705,12,13,246,265)
pie(4099.7961,4095.0705,13,14,246,265)
pie(4099.7961,4095.0705,14,15,246,265)
pie(4099.7961,4095.0705,15,16,246,265)
pie(4099.7961,4095.0705,16,17,246,265)
pie(4099.7961,4095.0705,17,18,246,265)
pie(4099.7961,4095.0705,18,19,246,265)
pie(4099.7961,4095.0705,19,20,246,265)
pie(4099.7961,4095.0705,20,21,246,265)
pie(4099.7961,4095.0705,21,22,246,265)
pie(4099.7961,4095.0705,22,23,246,265)
pie(4099.7961,4095.0705,23,24,246,265)
pie(4099.7961,4095.0705,24,25,246,265)
pie(4099.7961,4095.0705,25,26,246,265)
pie(4099.7961,4095.0705,26,27,246,265)
pie(4099.7961,4095.0705,27,28,246,265)
pie(4099.7961,4095.0705,28,29,246,265)
pie(4099.7961,4095.0705,29,30,246,265)
pie(4099.7961,4095.0705,30,31,246,265)
pie(4099.7961,4095.0705,31,32,246,265)
pie(4099.7961,4095.0705,32,33,246,265)
pie(4099.7961,4095.0705,33,34,246,265)
pie(4099.7961,4095.0705,34,35,246,265)
pie(4099.7961,4095.0705,35,36,246,265)
pie(4099.7961,4095.0705,36,37,246,265)
pie(4099.7961,4095.0705,37,38,246,265)
pie(4099.7961,4095.0705,38,39,246,265)
pie(4099.7961,4095.0705,39,40,246,265)

unix% cat radprof_bkg.reg
circle(4057.2756,4081.423,29.742616)
```

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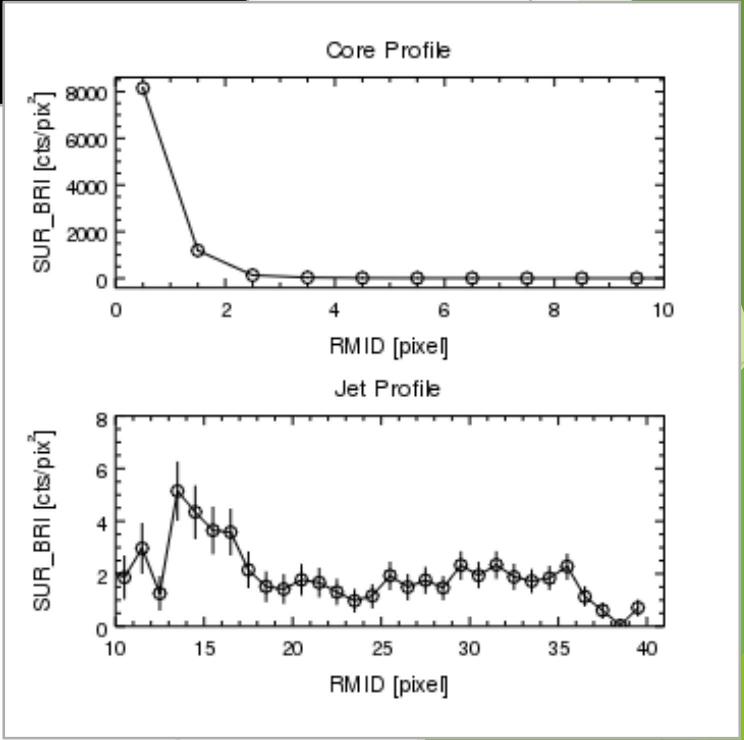
Radial Profiles (cont.)

```
unix% punlearn dmextract

unix% dmextract \
? infile="acisf07302_repro_evt2.fits[bin sky=@radprof.reg]" \
? outfile=7302_corejet.rprof \
? bkg="acisf07302_repro_evt2.fits[bin sky=@radprof_bkg.reg]" \
? opt=generic \
? mode=h clobber=yes
```

- source and background region files read in as stacks
- prior to CIAO 4.11, would need to calculate `RMID` column with `dmtcalc` which defines the midpoint of the annular regions:

```
unix% punlearn dmtcalc
unix% pset dmtcalc infile=1838_rprofile.fits
unix% pset dmtcalc outfile=1838_rprofile_rmid.fits
unix% pset dmtcalc expression="rmid=0.5*(R[0]+R[1])"
unix% dmtcalc
```



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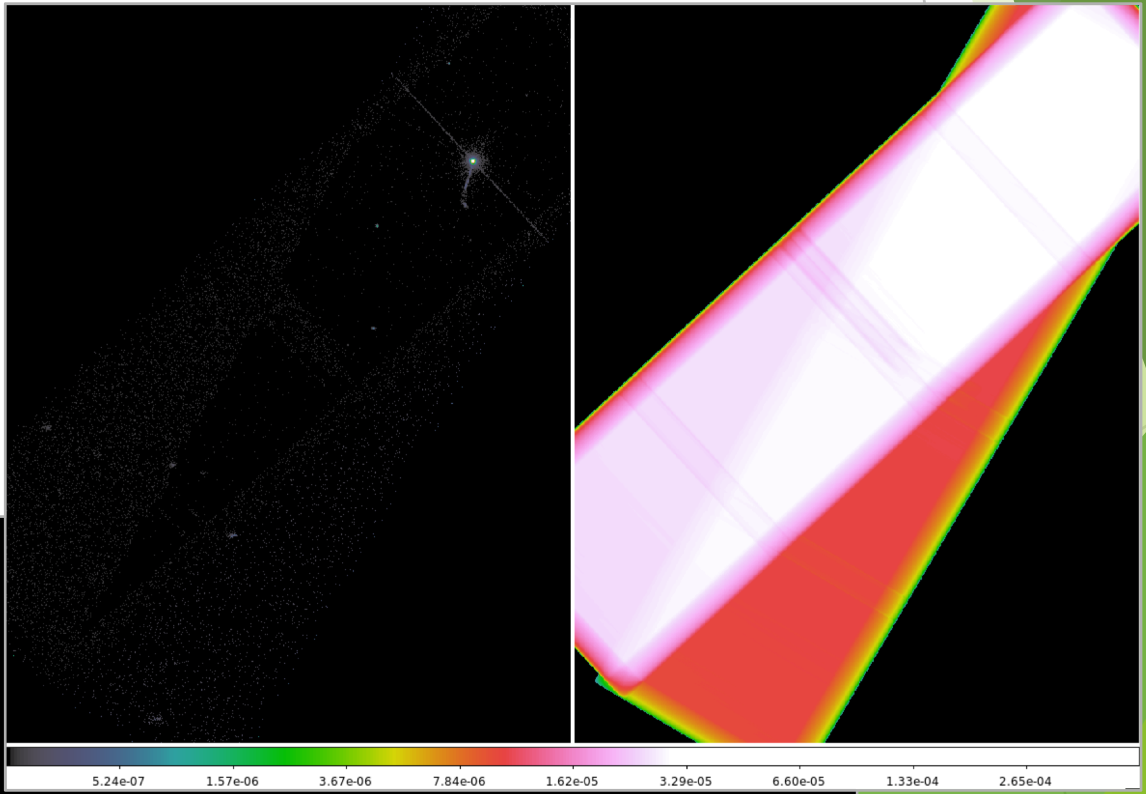
Reprojecting and Co-adding Imaging Data

- Combining observations for spatial analysis facilitated by the `merge_obs` script (wrapper around `reproject_obs` and `flux_obs`) using events files.
- Do not use combined events file for spectral extraction.
  - responses vary with time, no calibration products available covering large time spans
  - if observations occur over short period, using the response from a single observation maybe reasonable.
- `dmmerge` used to combine FITS tables.
- `dmimgcalc` used to perform array arithmetic.




```
unix% cat evt2.lis
6903/repro/acisf06903_repro_evt2.fits
6904/repro/acisf06904_repro_evt2.fits
7302/repro/acisf07302_repro_evt2.fits
7303/repro/acisf07303_repro_evt2.fits

unix% merge_obs infiles=@evt2.lis outroot=merged/4C+19.44 bands=broad binsize=1
```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Reprojecting and Co-adding Imaging Data

CHANDRA X-RAY OBSERVATORY

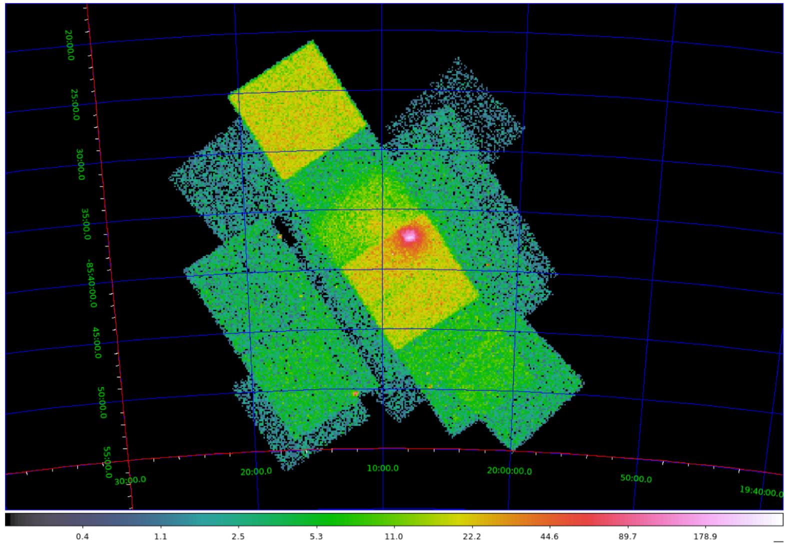
- reprojecting events can be critical to get correct field location
  - match set of observations to a common tangent point
  - often neglected if observations have similar pointings
- `reproject_image` and `reproject_image_grid` match image pixels between images.

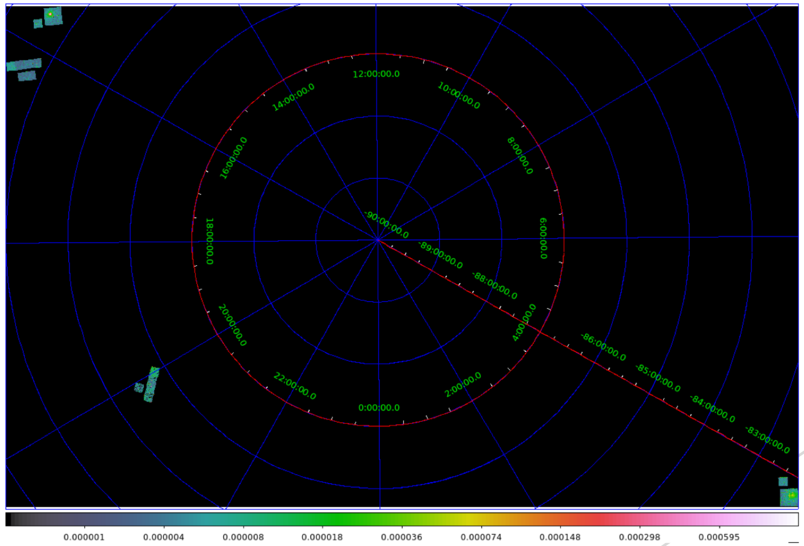
Select	Row	Seq Num	Obs ID	Instrument	Grating	Appr Exp	Exposure	Target Name	PI Name	RA	Dec	Status	Data Mode	Exp Mode	Avg
☐	1	500294	3477	ACIS-S	NONE	20.0	19.8	GRB020321	Fox	16 11 02.40	-83 42 00.00	archived	FAINT	TE	
☐	2	501070	10143	ACIS-S	NONE	2.0	2.01	1RXSJ200924.1-853911	Fox	20 09 13.00	-85 38 46.80	archived	VFAINT	TE	
☐	3	800661	8266	ACIS-I	NONE	8.0	7.99	RXJ1539.5-8335	Murray	15 39 25.20	-83 35 34.00	archived	VFAINT	TE	
☐	4	800667	8272	ACIS-I	NONE	8.0	7.94	S0405	Murray	03 51 28.00	-82 14 11.00	archived	VFAINT	TE	

```
unix% cat evt2.lis
10143/primary/acisf10143N002_evt2.fits.gz
3477/primary/acisf03477N002_evt2.fits.gz
8266/primary/acisf08266N002_evt2.fits.gz
8272/primary/acisf08272N003_evt2.fits.gz

unix% dmmerge infile=@evt.lis outfile=lowlat_bad.fits

unix% merge_obs infiles=@evt2.lis outroot=lowlat_good bands=broad binsize=64
```





- `reproject_aspect` (wrapper around `wcs_match` and `wcs_update`) used to match source lists and update WCS of images, tables, and asols

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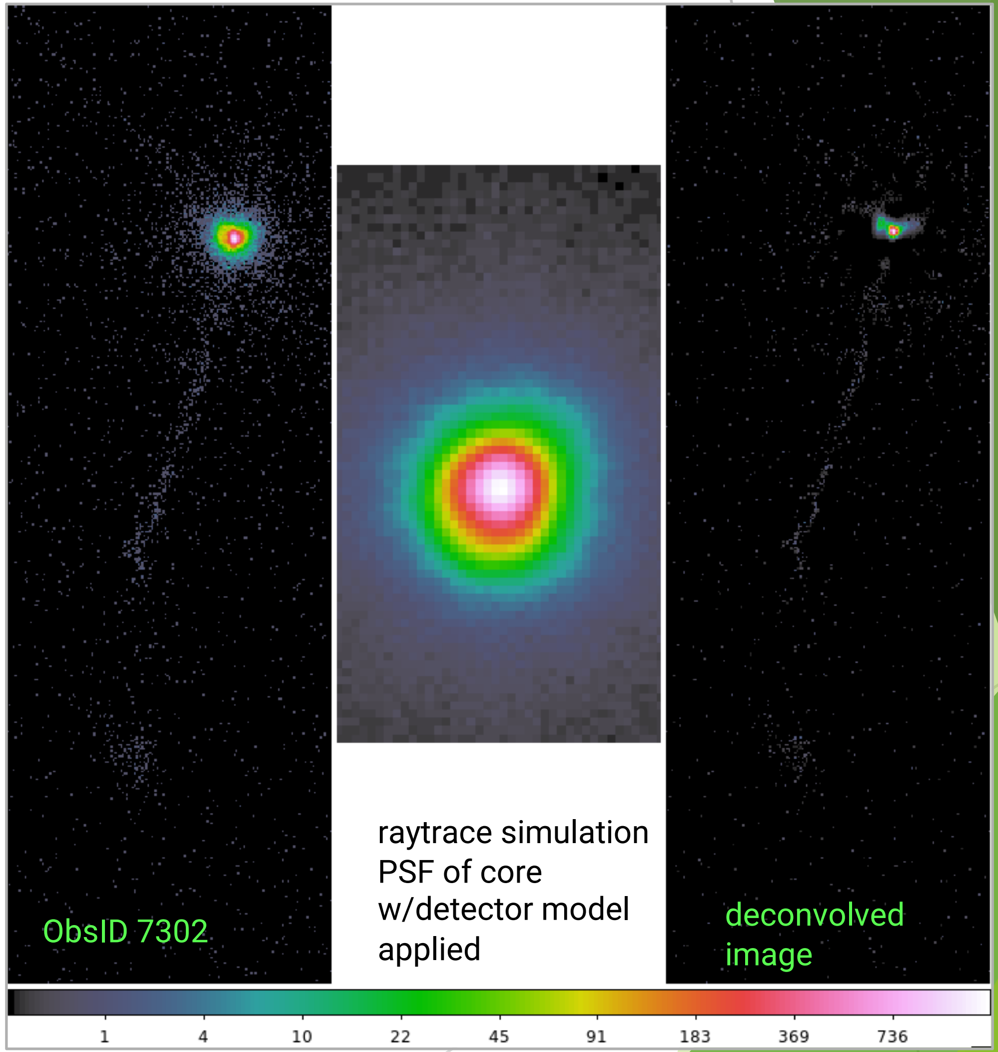
Image Smoothing and PSF Deconvolution

- PSF deconvolution
  - Obtain background-subtracted spectrum in ASCII format of the core
  - Use ChaRT/SAOTrace or MARX to simulate PSF
  - Use MARX/`simulate_psf` to project simulated rays on to detector-plane
  - Use `arestore` to deconvolve PSF from observation
- Image smoothing
  - `aconvolve` smooths image with user-defined kernel
  - `csmooth` adaptive image smoothing technique



all figures binned to 1/5 an ACIS pixel

Timing Analysis

- light curves
  - `dmextract` with `opt=ltc1` or `opt=ltc2` properly accounts for GTI
  - remember that dither periods are typically 707.1 s and 1000 s for ACIS, 768.6 s and 1087 s for HRC, so beware of variability on those time scales.
- barycentric correction
  - `axbary` corrects all time to a common location, the barycenter
- variability
  - `glvary` is a Bayesian technique based on Gregory-Loredo algorithm that returns an estimate of the most probable light curve from the source, as opposed to what is observed by the telescope and instruments
  - `apowerspectrum` finds $|\mathcal{FFT}|^2$ of a light curve to find the periodicity (or aperiodicity) of variable source by looking for peaks in the power spectrum.