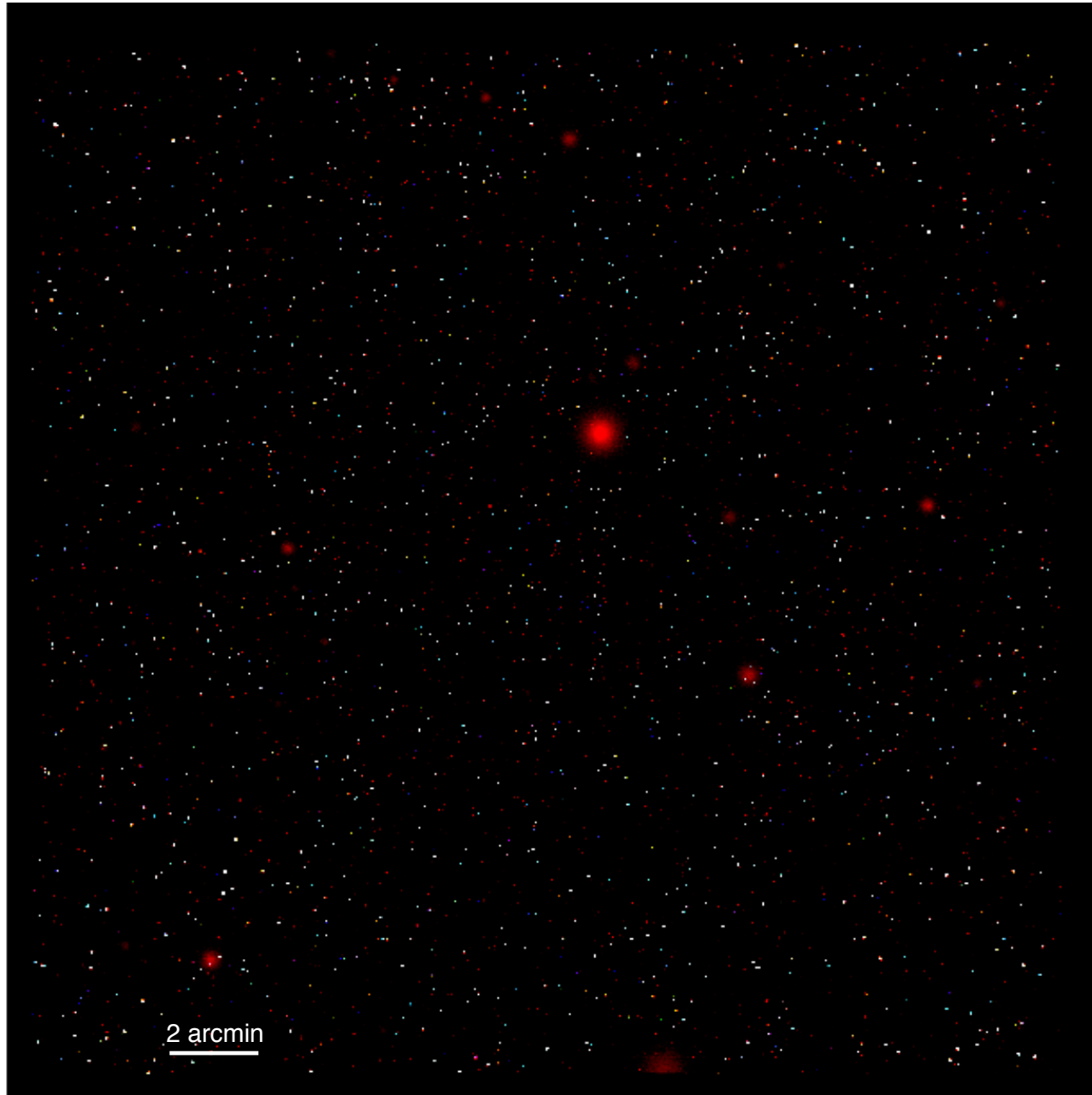
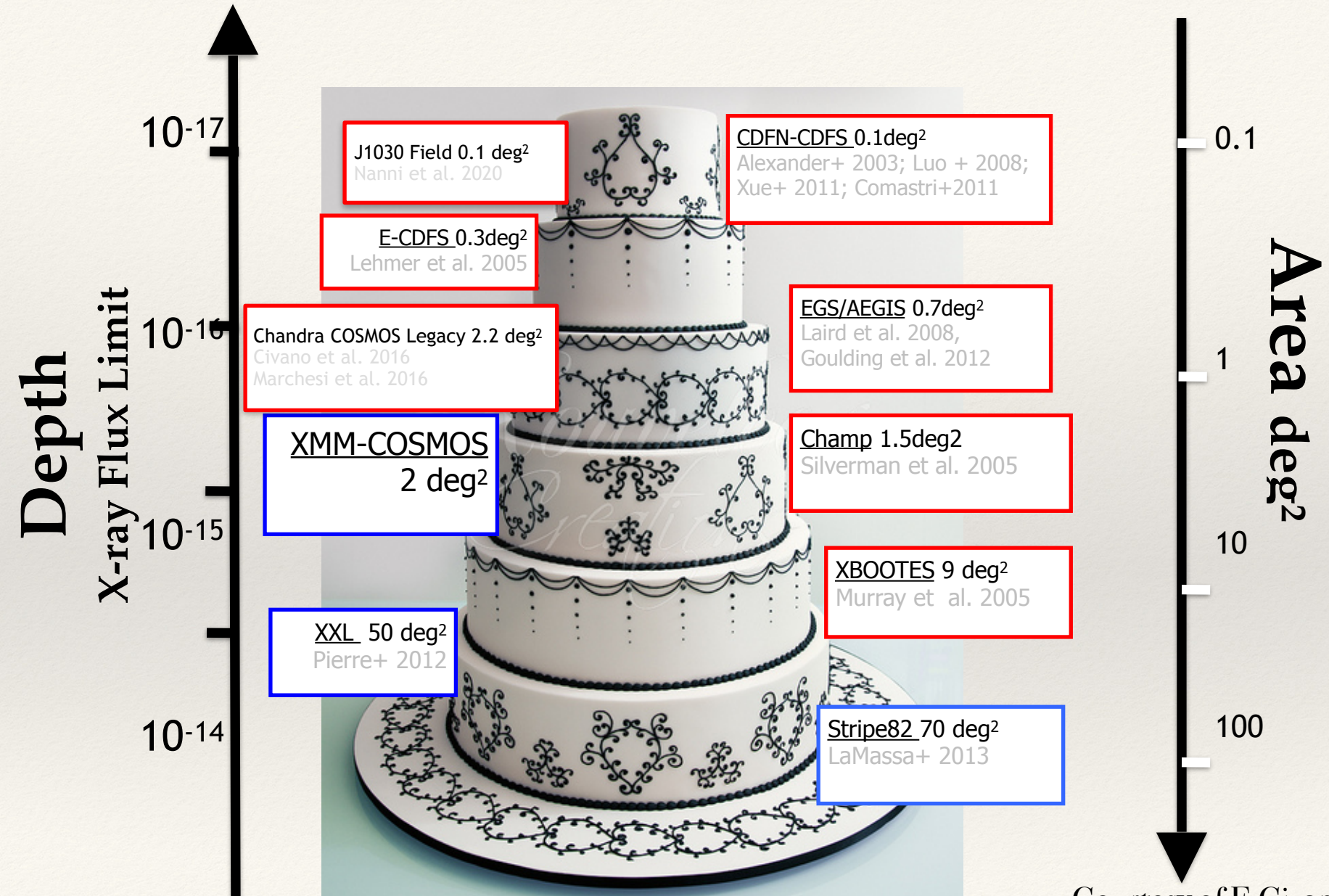


Understanding the AGN population: X-ray surveys

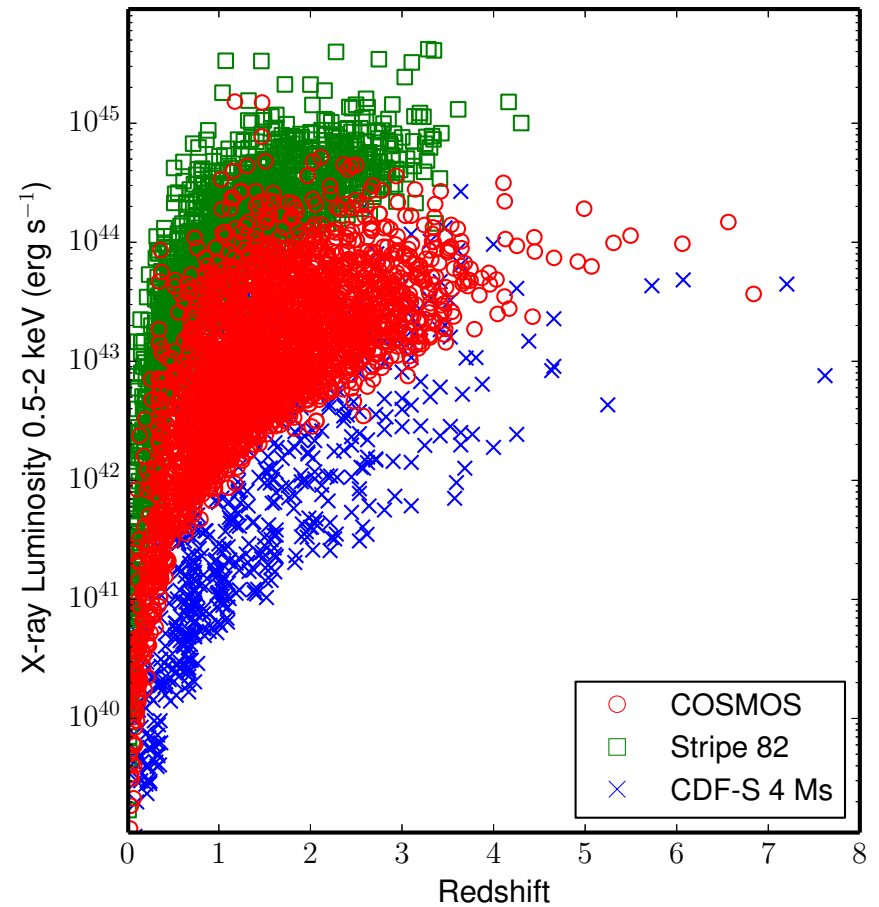
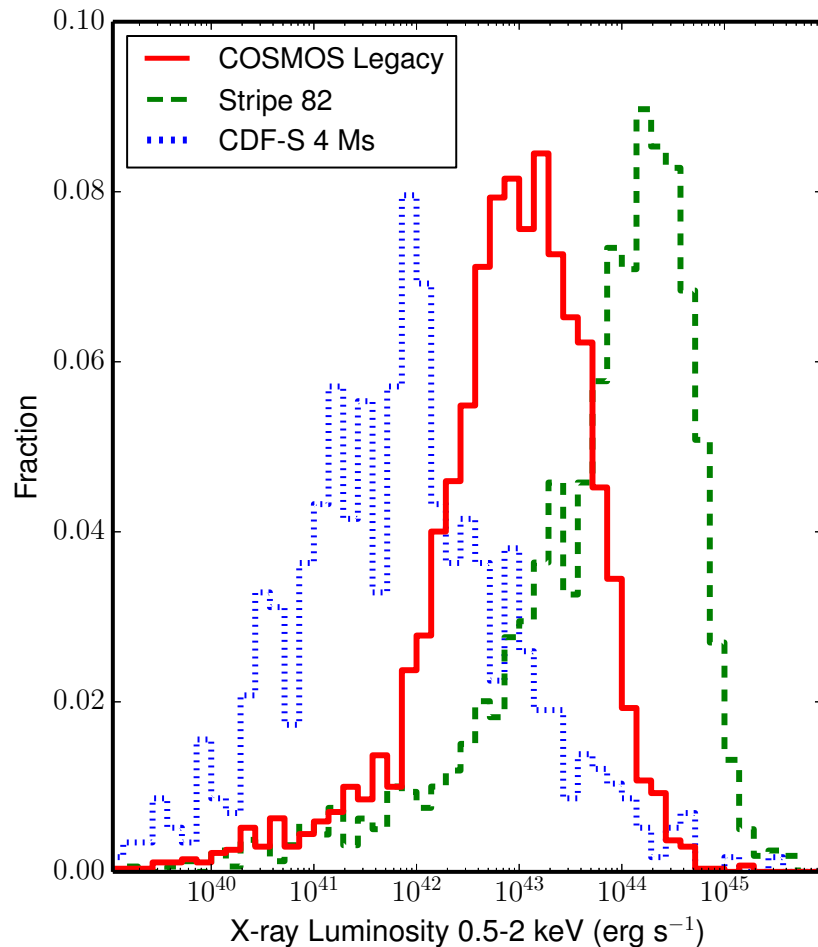


The X-ray surveys wedding-cake strategy



Courtesy of F.Civano

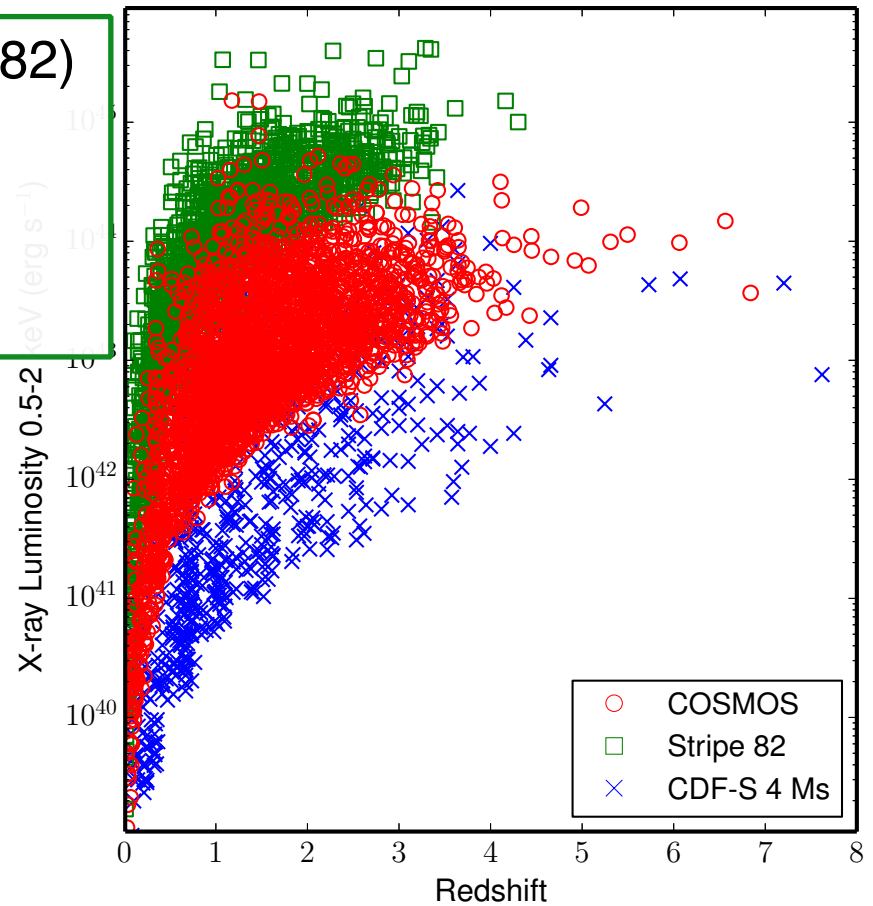
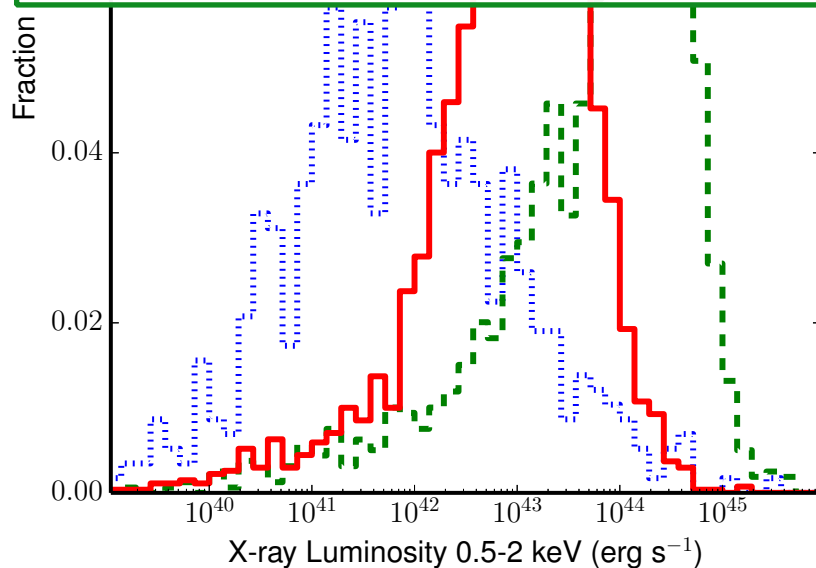
Different surveys for different science



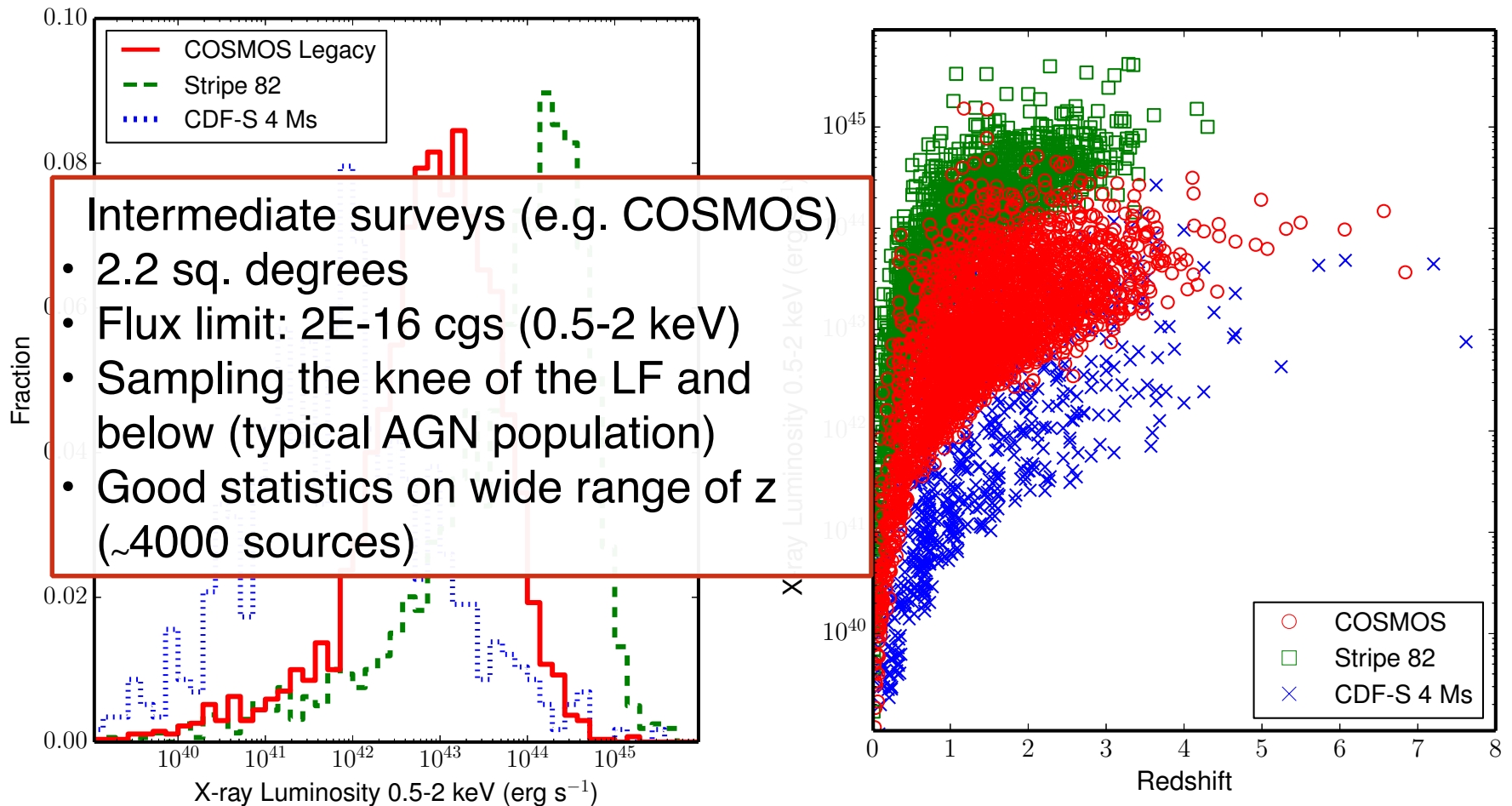
Different surveys for different science

Large area, shallow surveys (e.g., S82)

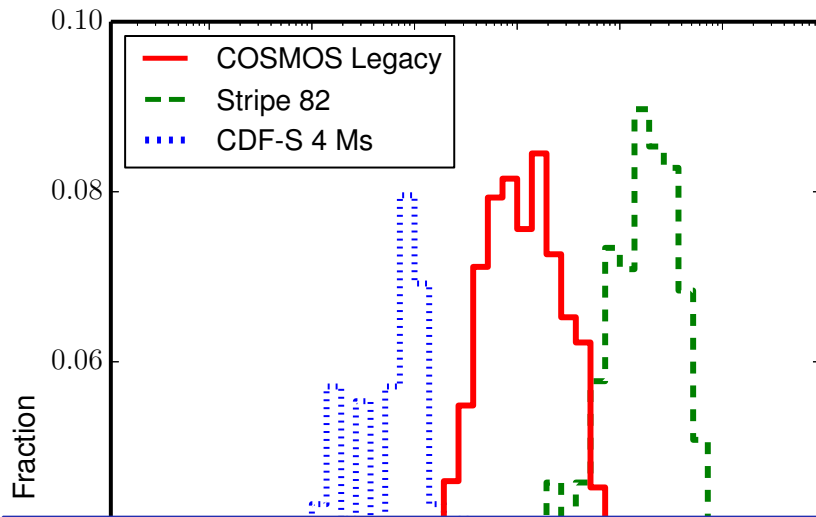
- 70 sq. degrees
- Flux limit: $9E-16$ cgs (0.5-2 keV)
- Looking for rare objects
- Missing low-luminosity objects



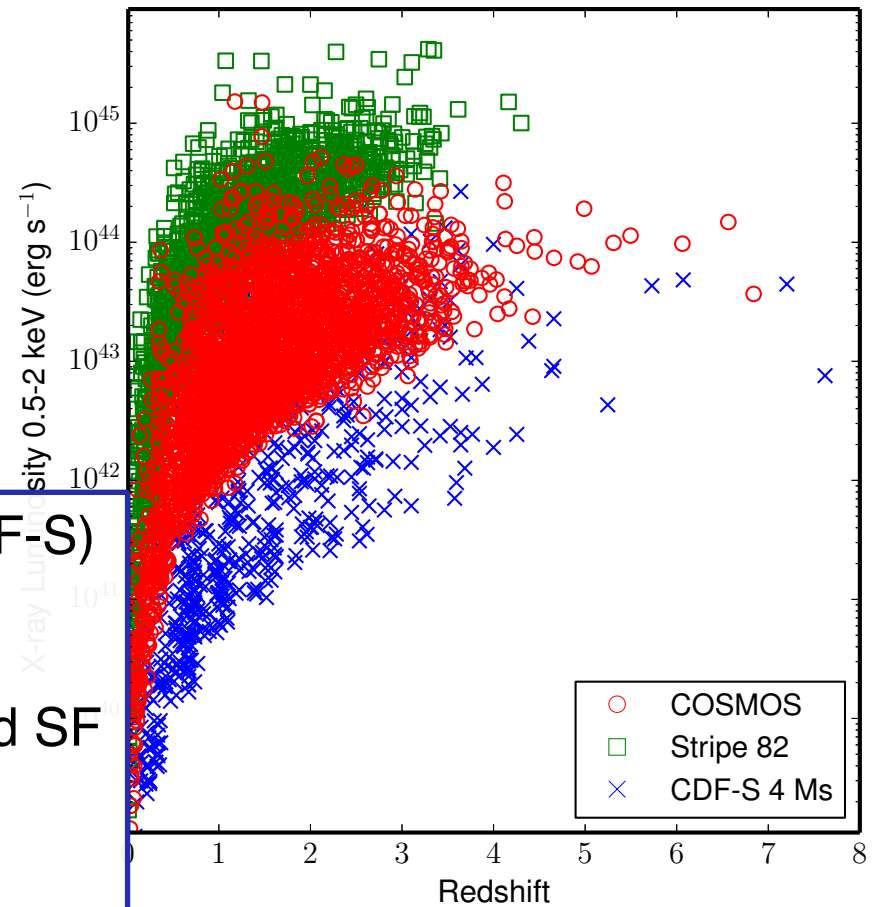
Different surveys for different science



Different surveys for different science



- Deep, pencil beam surveys (e.g. CDF-S)
- 0.1 sq. degrees
 - Flux limit: 6E-18 cgs (0.5-2 keV)
 - Detection of low luminosity AGN and SF galaxies
 - Smaller number of objects (~1000 sources)



Chandra Deep Field-South (CDF-S)

≈ 7 Ms *Chandra* exposure (last obs. at March 2016)

≈ 3 Ms *XMM-Newton* exposure

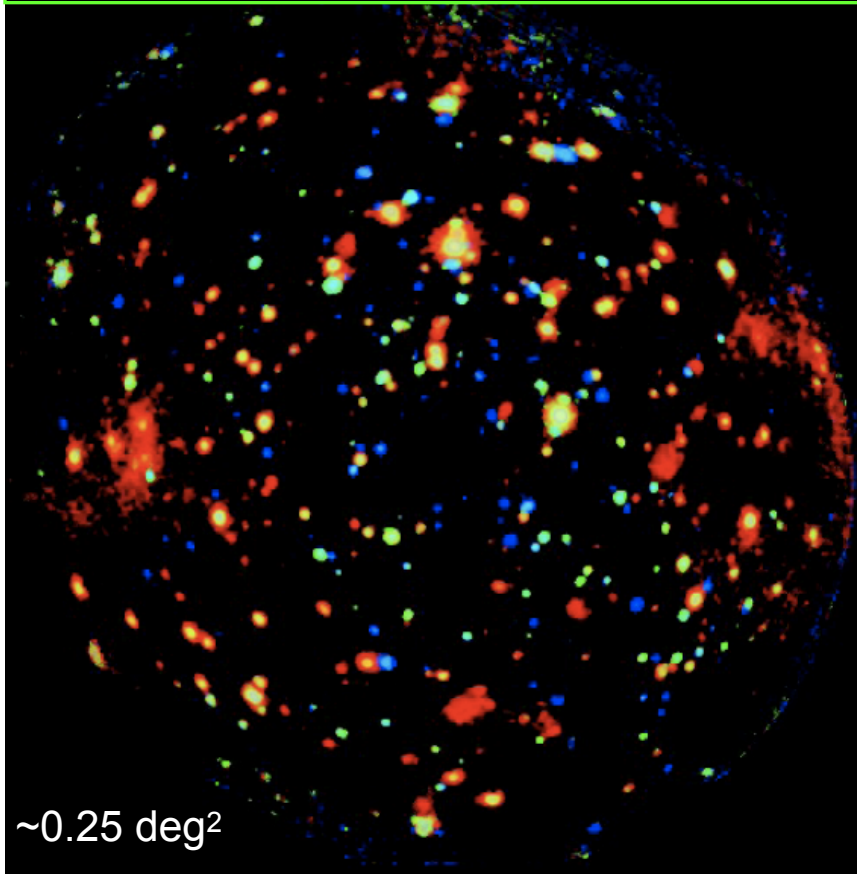
Deep multi-wavelength coverage

One of the legacy fields (no deeper field for the next 20 yrs)

Chandra: good on-axis PSF (i.e., excellent angular resolution) and low background
→ Sensitive to faint and distant AGN

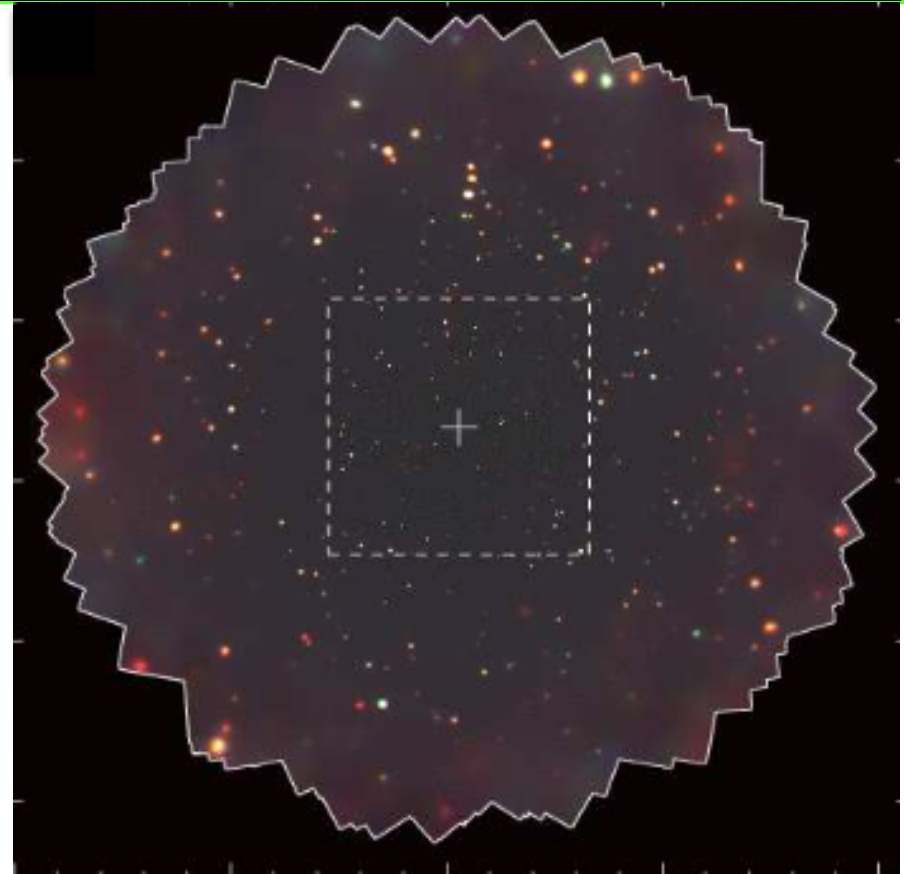
XMM-Newton: larger effective area (hence photon statistics), but much worse angular resolution and higher background
→ Better for X-ray spectroscopy of relatively bright AGN

The deepest X-ray field: CDF-S



XMM-CDFS 3 Ms survey
(PI: A. Comastri; Ranalli+13)

$F(2-10\text{keV}) \approx 6.6 \times 10^{-16} \text{ erg/cm}^2/\text{s}$



Chandra-CDFS 7 Ms survey
(PI: R. Giacconi, W.N Brandt; Xue+11, Luo+17)

$F(0.5-2\text{keV}) \approx 6.4 \cdot 10^{-18} \text{ erg/cm}^2/\text{s}$

Capable of probing the high- z Universe with some photon statistics

This Lab Outline

- 1. Build the source catalog:** Produce a mosaic using 4 long CDFS exposures and provide source detections with different setups. Visualize the outputs and cross-match sources with the official 7Ms source catalog.
- 2. Explore the source catalog:** For one of the newly produced catalogs, produce some relevant plots, and compare quantities with those reported in the 7Ms source catalog
- 3. Analyse the data products:** Fit the X-ray spectra of a few, particularly interesting sources.

Lab Outline

1) Build the source catalog

- a. Reprocess with `chandra_repro` four different Chandra observations of the CDF-S. Generate all data products (event files, exposure maps...) that are needed to perform a source detection using the `merge_obs` tool.

Lab Outline

1) Build the source catalog

- a. Reprocess with `chandra_repro` four different Chandra observations of the CDF-S. Generate all data products (event files, exposure maps...) that are needed to perform a source detection using the `merge_obs` tool.

```
punlearn merge_obs
pset merge_obs infiles=@infile.lis
pset merge_obs outroot=CDFS_4obs
pset merge_obs asolfiles=@asol.lis
pset merge_obs badpixfiles=@bpix.lis
pset merge_obs maskfiles=@mask.lis
pset merge_obs parallel=yes
pset merge_obs nproc=4
pset merge_obs units=time
pset merge_obs bands=broad
pset merge_obs xygrid=0.5:8192.5:1,0.5:8192.5:1
pset merge_obs psfecf=0.9
pset merge_obs psfmerge=exptime
merge_obs
```

Lab Outline

1) Build the source catalog

- a. Download and combine four different Chandra observations of the CDF-S. Generate all data products (event files, exposure maps...) that are needed to perform a source detection using the `merge_obs` tool.

Lab Outline

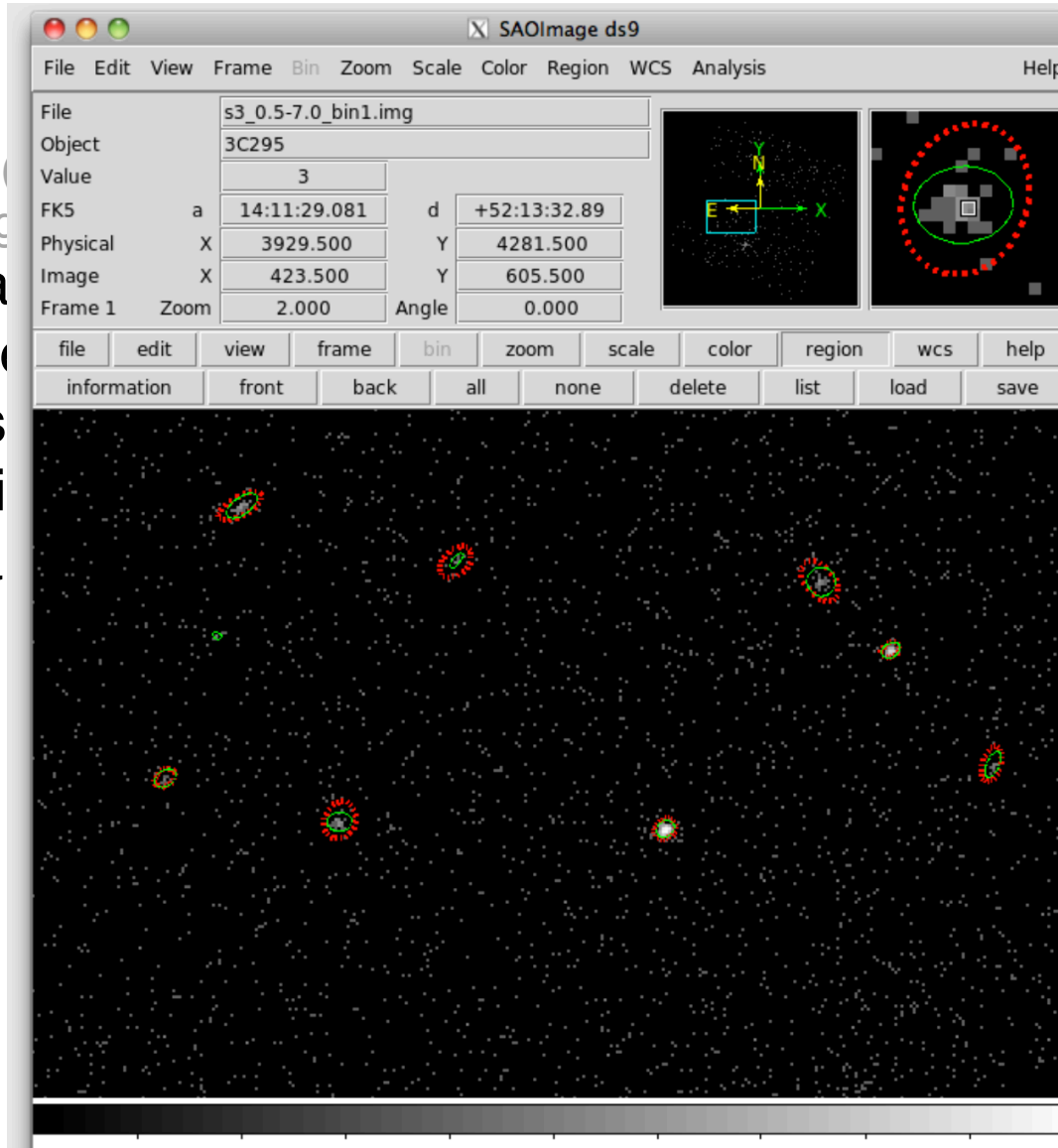
1) Build the source catalog

- a. Download and combine four different Chandra observations of the CDF-S. Generate all data products (event files, exposure maps...) that are needed to perform a source detection using the `merge_obs` tool.
- b. Run the `wavdetect` tool to search sources in your observations, using different significance thresholds (i.e., your detections can be more or less reliable) and different maximum wavelet scales (important if there are extended sources and for objects in the external part of the field).

Lab Outline

1) Build the source catalog

- Download and process data products (e.g., FITS files) using software like DS9.
- Run the wavelet transform (WT) using different scales (more or less important in the external part of the image).



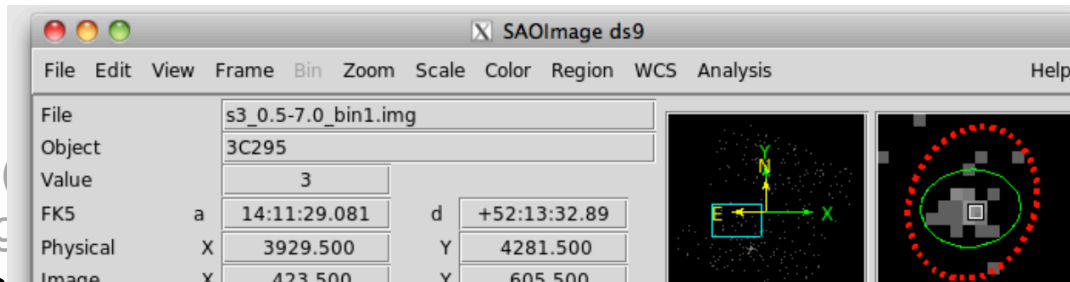
DF-S. Generate all
form a source

ervations,
ctions can be
scales
cts in the

Lab Outline

1) Build the source catalog

a. Download and
data products (e.g.,
detection using

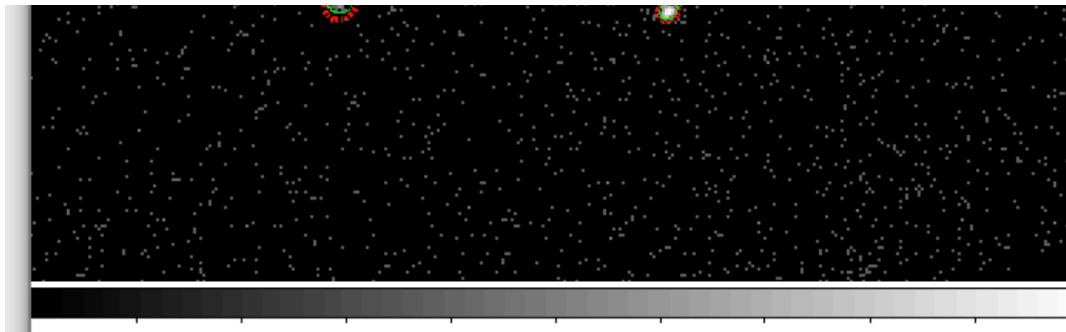


DF-S. Generate all
form a source

b. Run the wavelet

```

unlearn wavdetect
pset wavdetect infile=CDFS_4obs_merged_057keV_bin1.fits
pset wavdetect outfile=CDFS_4obs_merged_057keV_wavdet_1em6_src.fits
pset wavdetect scellfile=CDFS_4obs_merged_057keV_wavdet_1em6_cellimage.fits
pset wavdetect imagefile=CDFS_4obs_merged_057keV_wavdet_1em6_reconstructed.fits
pset wavdetect defnbkgfile=CDFS_4obs_merged_057keV_wavdet_1em6_normbkg.fits
pset wavdetect regfile=CDFS_4obs_merged_057keV_wavdet_1em6.reg
pset wavdetect ellsigma=3.0
pset wavdetect sigthresh=1e-6
pset wavdetect scales="1 1.4 2 2.8 4 5.6 8 11"
pset wavdetect expfile=CDFS_4obs_merged_broad_thresh.expmap
pset wavdetect psffile=CDFS_4obs_merged_broad_thresh.psfmap
wavdetect clobber+ verbose=3
    
```



Lab Outline

1) Build the source catalog

- a. Download and combine four different Chandra observations of the CDF-S. Generate all data products (event files, exposure maps...) that are needed to perform a source detection using the `merge_obs` tool.
- b. Run the `wavdetect` tool to search sources in your observations, using different significance thresholds (i.e., your detections can be more or less reliable) and different maximum wavelet scales (important if there are extended sources and for objects in the external part of the field)
- c. Cross-correlate the source lists generated in the previous steps with the official 7 Ms Chandra source catalog in the CDF-S (Luo et al. 2017), using various cross-matching radii.
 - Compute the fraction of 7Ms sources found in the 4-observation mosaic using different thresholds ($1\text{E-}6/1\text{E-}5/1\text{E-}4$)/scales (5.6/8/11)/matching radii (1/2/3").
 - For your source list which has the largest number matches within 2" with the 7 Ms CDF-S catalog, compute the number of sources detected in the 4-observation mosaic and not in the 7Ms catalog, and visualize them: what are the possible explanations for their detection in the your shorter-exposure mosaic?

Lab Outline

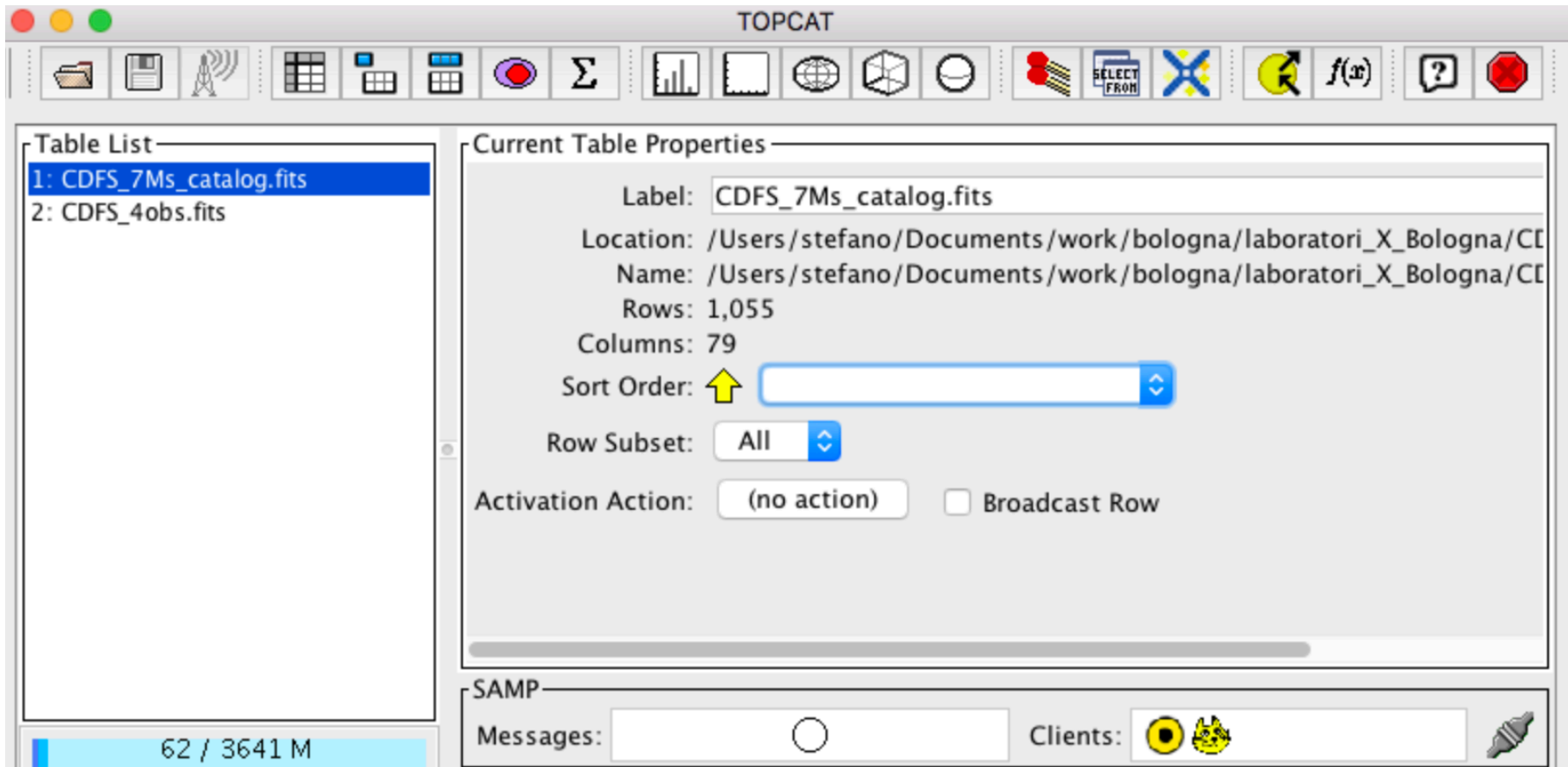
1) Build the source catalog

Cross-correlate the source lists generated in the previous steps with the official 7 Ms Chandra source catalog in the CDF-S (Luo et al. 2017), using various cross-matching radii (e.g., 1,2,3 arcsec)

Lab Outline

1) Build the source catalog

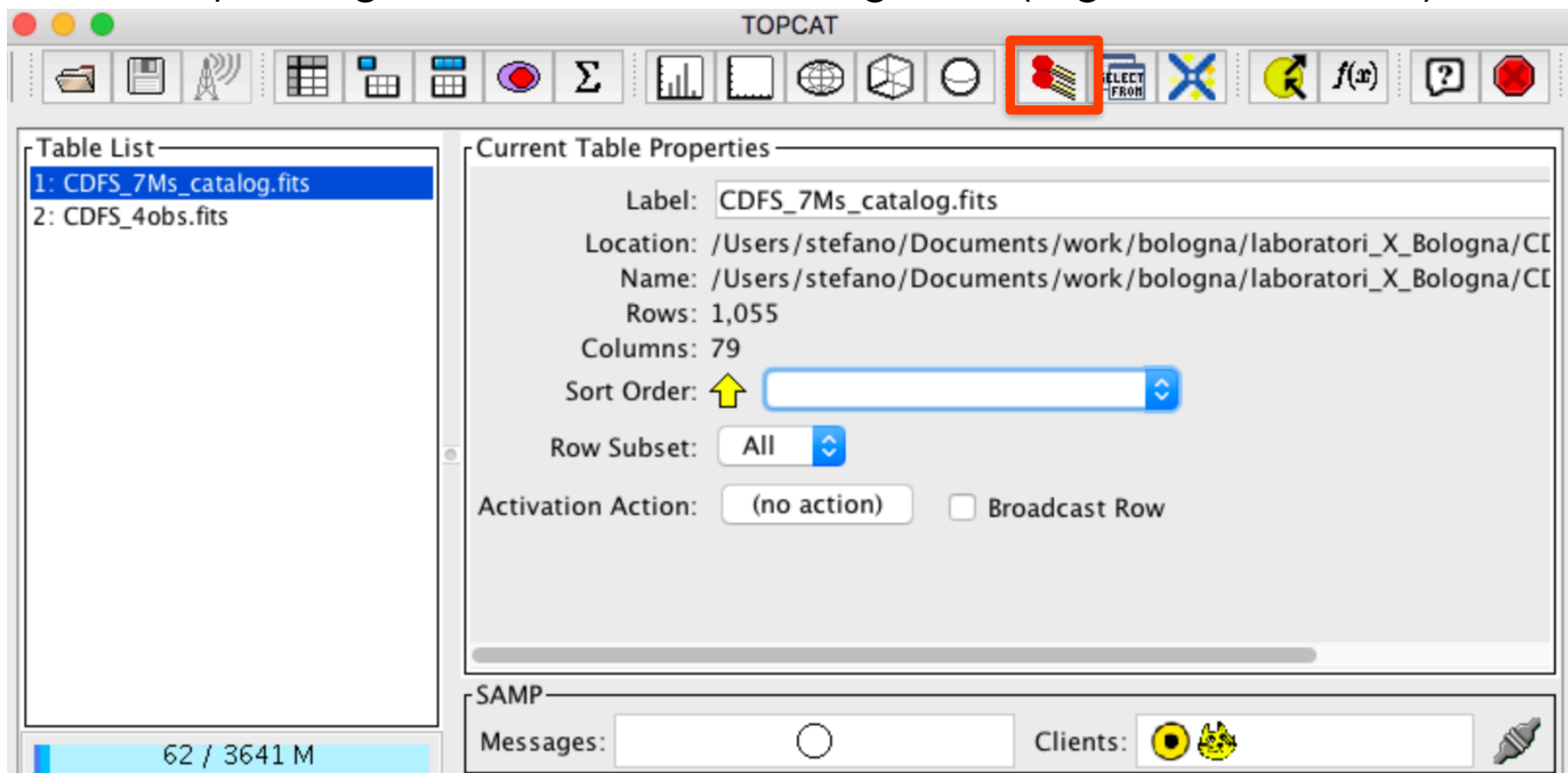
Cross-correlate the source lists generated in the previous steps with the official 7 Ms Chandra source catalog in the CDF-S (Luo et al. 2017), using various cross-matching radii (e.g., 1,2,3 arcsec)



Lab Outline

1) Build the source catalog

Cross-correlate the source lists generated in the previous steps with the official 7 Ms Chandra source catalog in the CDF-S (Luo et al. 2017), using various cross-matching radii (e.g., 1,2,3 arcsec)



1) B

Cross-correlate the
with the official 7
al. 2017), using v

alog

previous steps
e CDF-S (Luo et
,2,3 arcsec)

The screenshot displays the 'Match Tables' application window. On the left, a 'Table List' pane shows two files: '1: CDFS_7Ms_catalog.fits' (selected) and '2: CDFS_4obs.fits'. The main area is divided into sections for 'Match Criteria', 'Table 1', 'Table 2', and 'Output Rows'. The 'Match Criteria' section has 'Algorithm' set to 'Sky' and 'Max Error' set to '2.0' in 'arcsec'. The 'Table 1' section has 'Table' set to '1: CDFS_7Ms_catalog.fits', 'RA column' set to 'RA' in 'degrees', and 'Dec column' set to 'DEC' in 'degrees'. The 'Table 2' section has 'Table' set to '2: CDFS_4obs.fits', 'RA column' set to 'RA' in 'degrees', and 'Dec column' set to 'DEC' in 'degrees'. The 'Output Rows' section has 'Match Selection' set to 'Best match, symmetric' and 'Join Type' set to '1 and 2'. At the bottom, there are 'Go' and 'Stop' buttons, a 'Messages' pane, and a 'Clients' pane showing two active connections. A status bar at the very bottom indicates '62 / 3641 M'.

Match Tables

Match Criteria

Algorithm: Sky

Max Error: 2.0 arcsec

Table List

1: CDFS_7Ms_catalog.fits

2: CDFS_4obs.fits

Table 1

Table: 1: CDFS_7Ms_catalog.fits

RA column: RA degrees

Dec column: DEC degrees

Table 2

Table: 2: CDFS_4obs.fits

RA column: RA degrees

Dec column: DEC degrees

Output Rows

Match Selection: Best match, symmetric

Join Type: 1 and 2

Go Stop

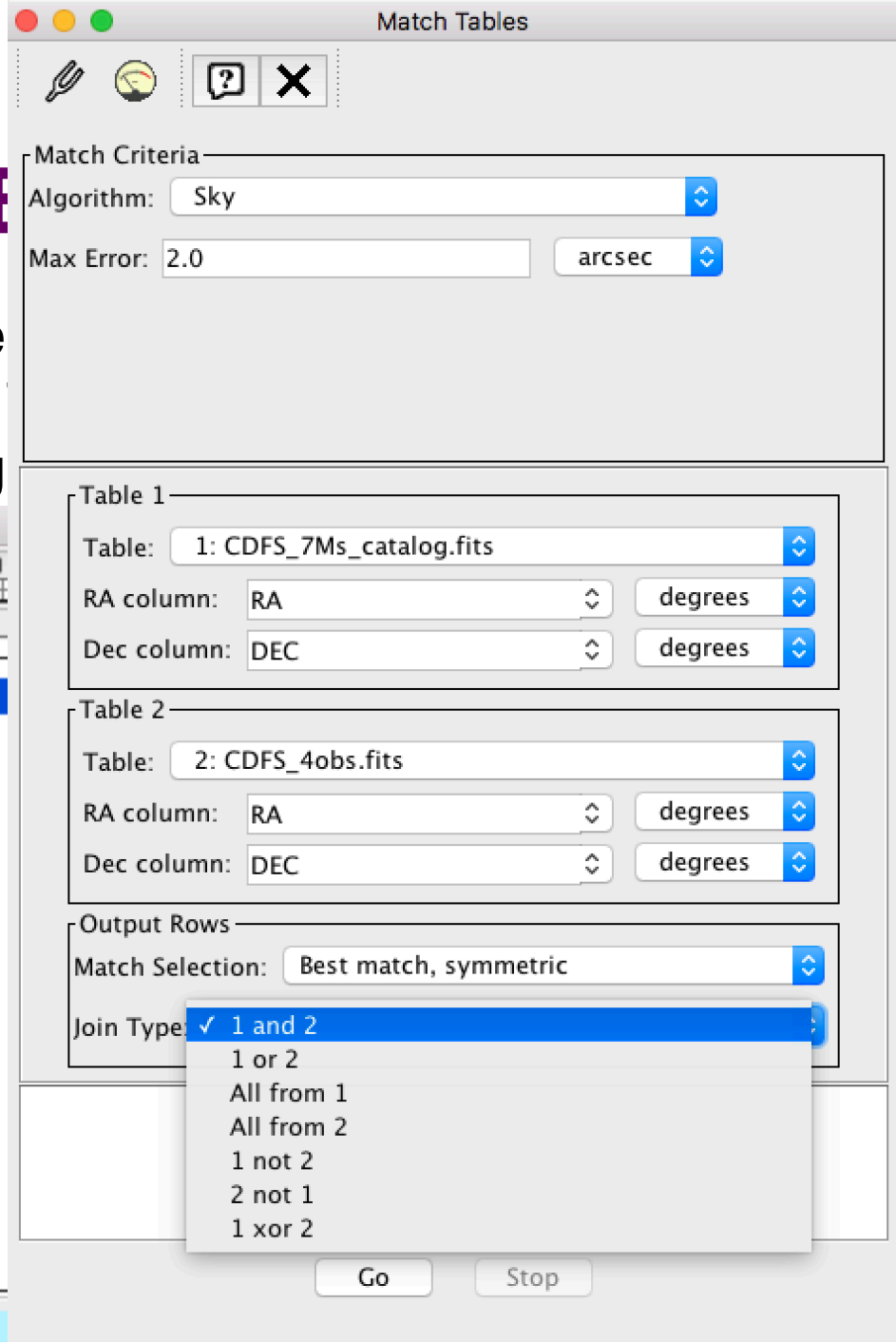
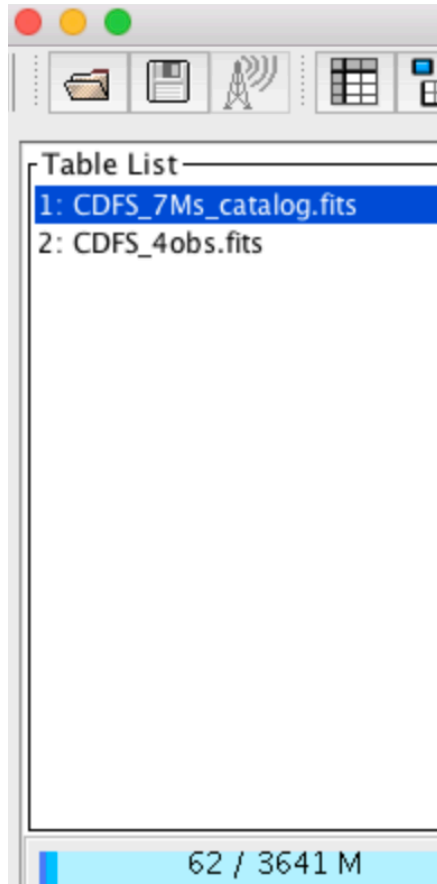
Messages:

Clients:

62 / 3641 M

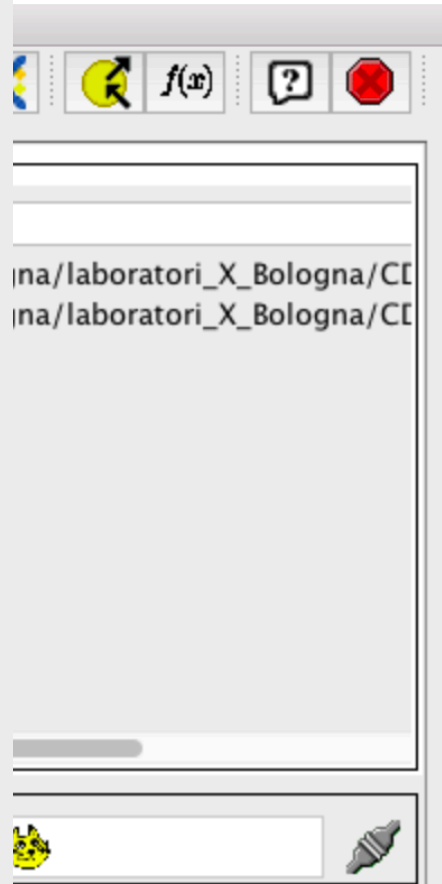
1) E

Cross-correlate
with the official
al. 2017), using



log

vious steps
CDF-S (Luo et
2,3 arcsec)



Lab Outline

2) Explore the source catalog

Lab Outline

2) Explore the source catalog

- a. Choose one of the catalogs you built (e.g., the one with largest number of matches with the CDF-S 7 Ms one) and produce some plots (number of counts vs. source significance, vs. exposure time, vs. positional uncertainty, etc.)

Lab Outline

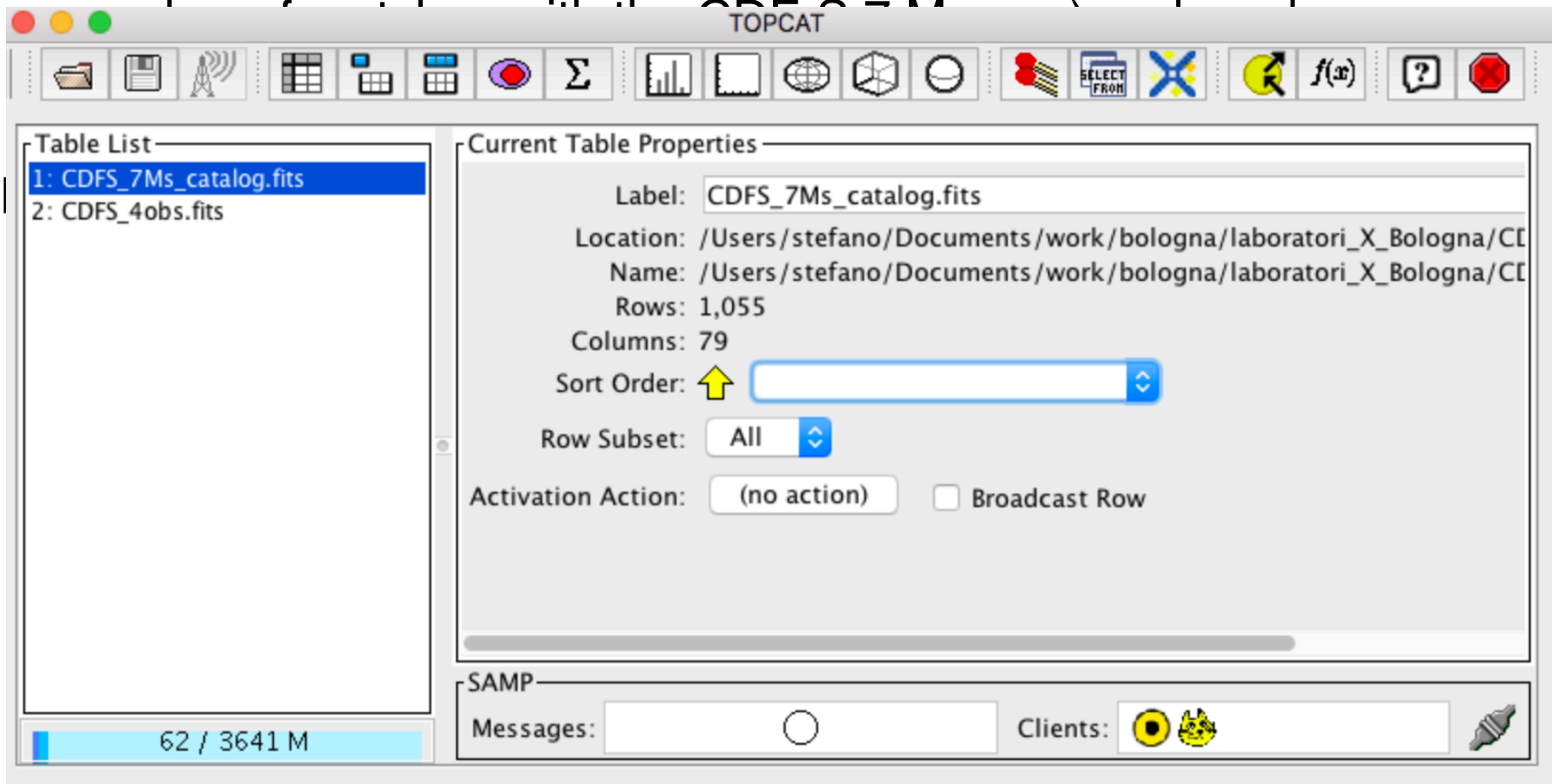
2) Explore the source catalog

- a. Choose one of the catalogs you built (e.g., the one with largest number of matches with the CDF-S 7 Ms one) and produce some plots (number of counts vs. source significance, vs. exposure time, vs. positional uncertainty, etc.)
- b. For the sources associated with the 7Ms source catalog, produce the redshift distribution histogram, L_x vs. z plot, etc.

Lab Outline

2) Explore the source catalog

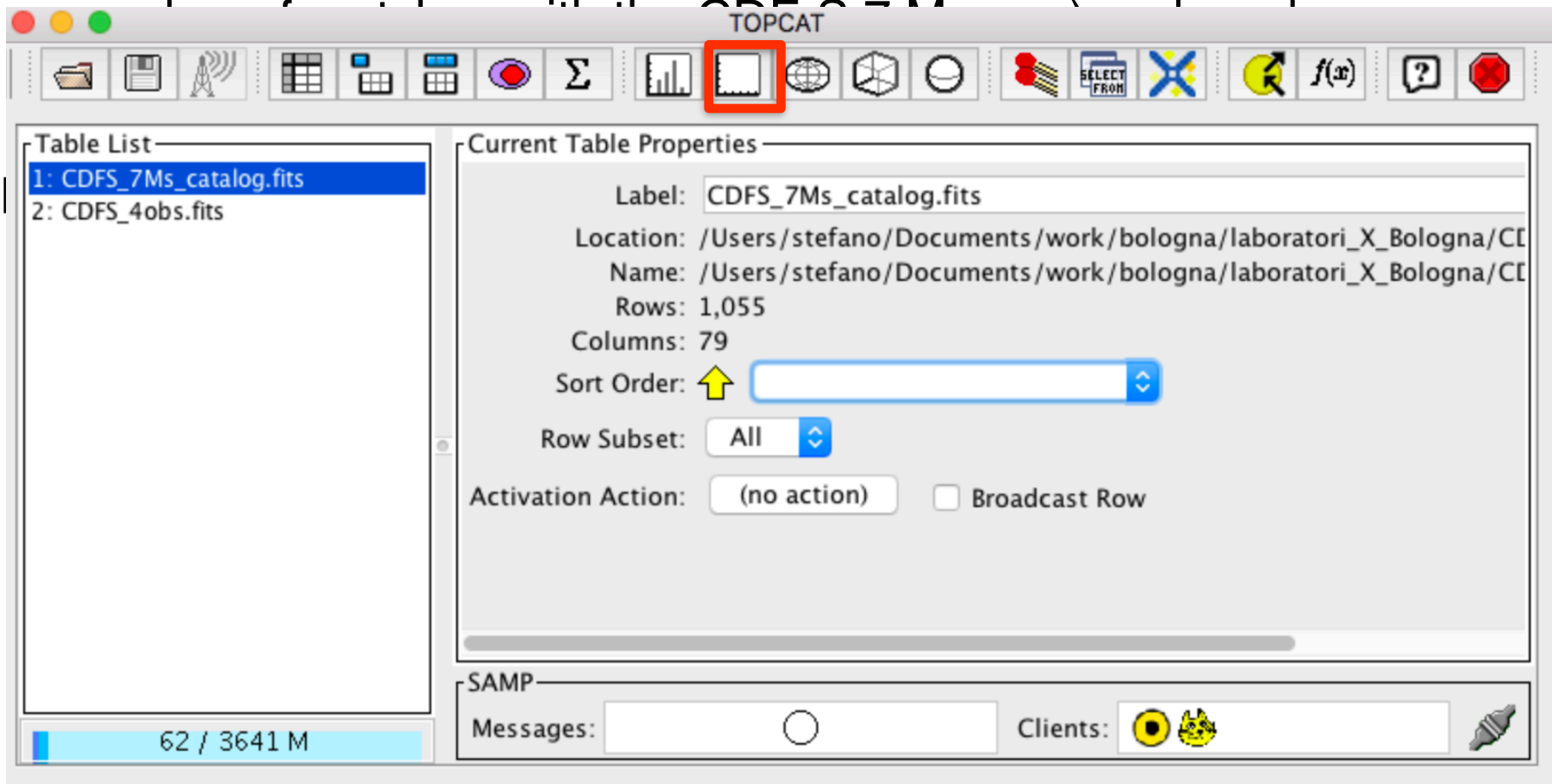
a. Choose one of the catalogs you built (e.g., the one with largest



Lab Outline

2) Explore the source catalog

a. Choose one of the catalogs you built (e.g., the one with largest



2)

log

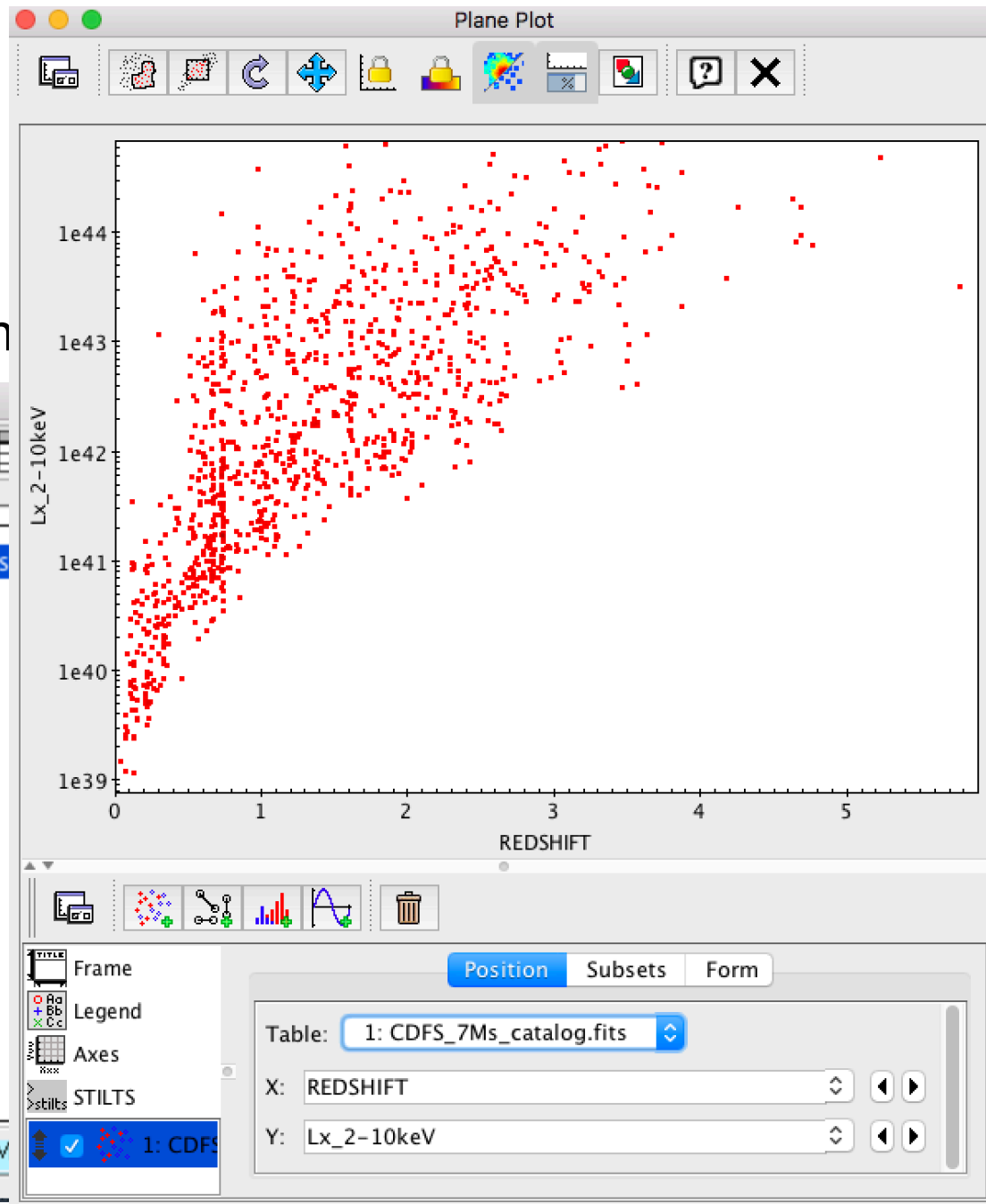
a. Choose on

th largest

Table List

- 1: CDFS_7Ms_catalog.fits
- 2: CDFS_4obs.fits

62 / 3641 M



$f(x)$

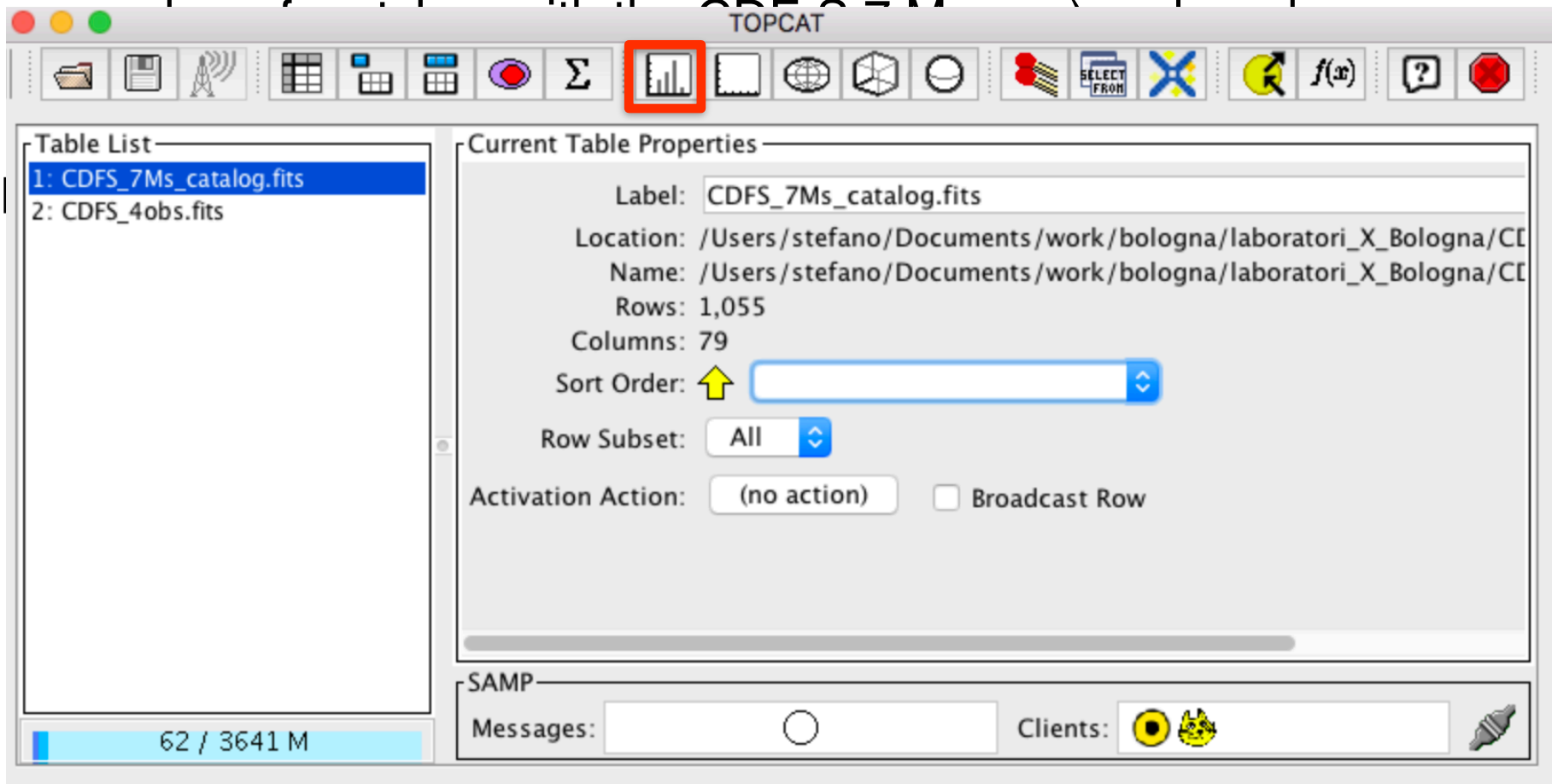
boratori_X_Bologna/CF

boratori_X_Bologna/CF

Lab Outline

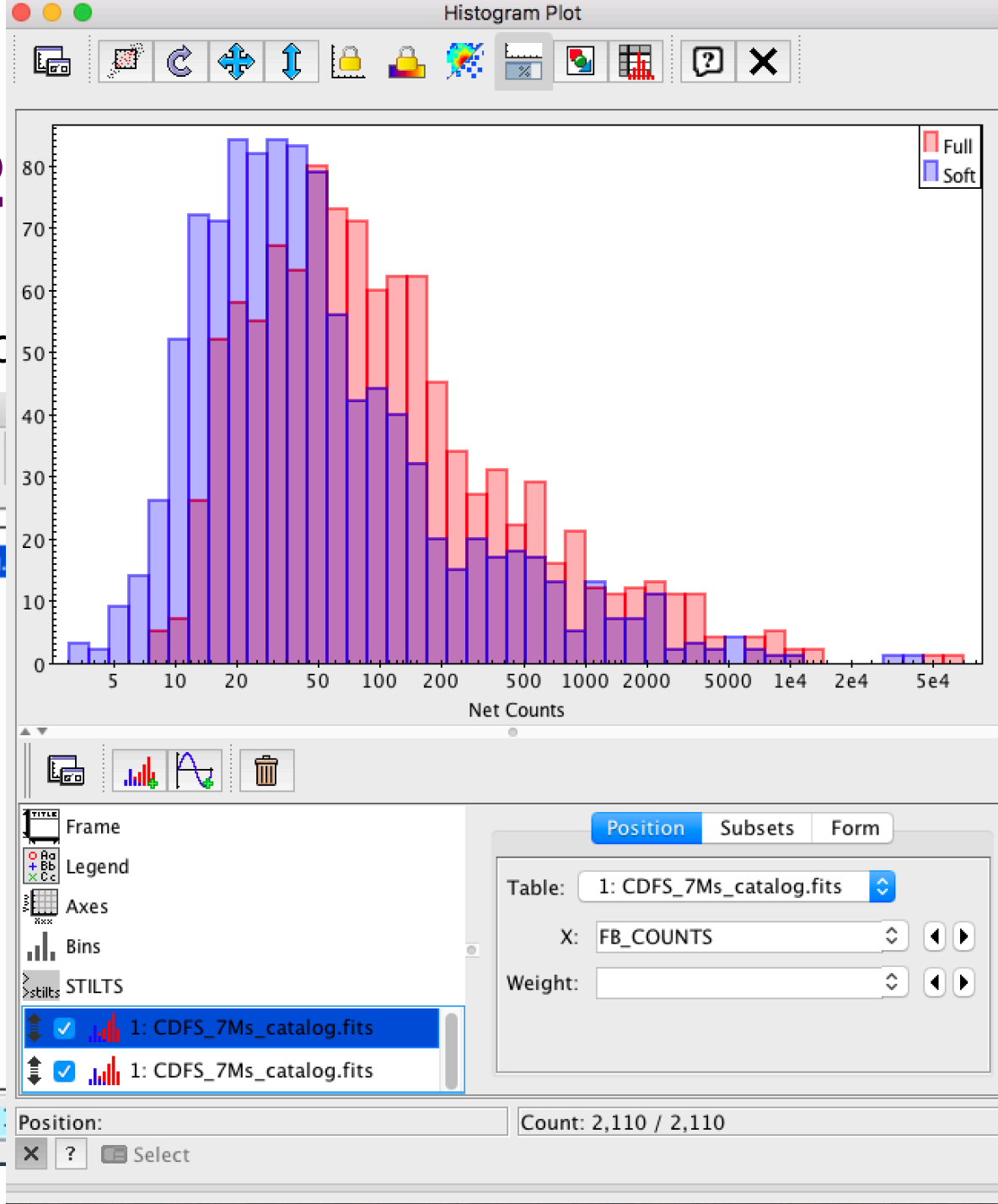
2) Explore the source catalog

a. Choose one of the catalogs you built (e.g., the one with largest



2

a. Choose c



og

largest



Lab Outline

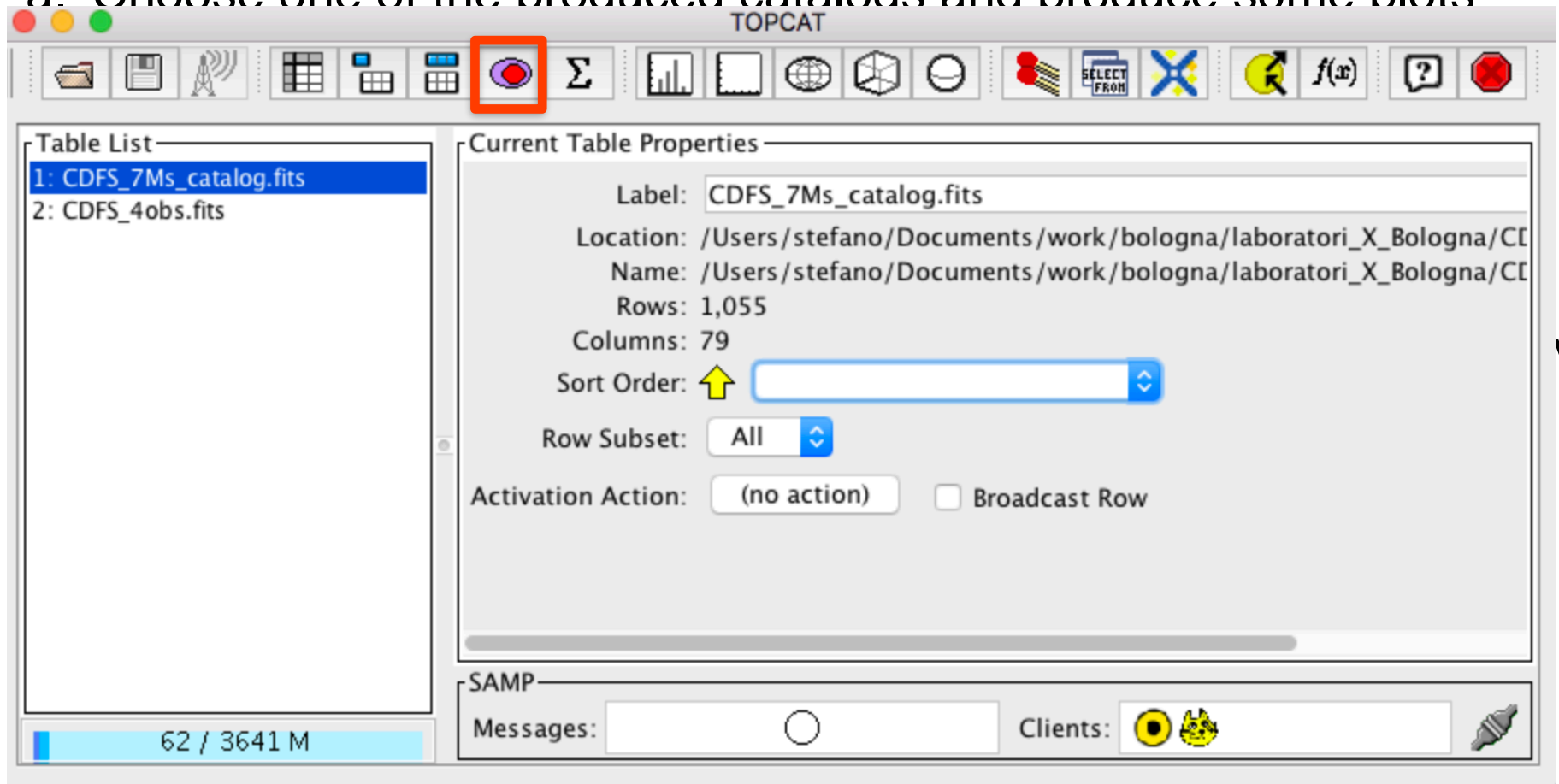
2) Explore the source catalog

- a. Choose one of the produced catalogs and produce some plots (number of counts vs. source significance, vs. exposure time, vs. positional uncertainty, etc.)
- b. For the sources associated with the 7 Ms source catalog, produce the redshift distribution histogram, L_x vs. z plot, etc.
- c. Repeat the operation done in b. after creating subsamples of sources from the 7 Ms source catalog (e.g., spec- z vs phot- z ; low vs high band-ratio...). Are there any noticeable trends?

Lab Outline

2) Explore the source catalog

a. Choose one of the produced catalogs and produce some plots



The screenshot shows the TOPCAT software interface. The title bar reads 'TOPCAT'. The toolbar contains various icons for file operations, data manipulation, and visualization. A red box highlights the 'Plot' icon (a circle with a dot). The 'Table List' panel on the left shows two tables: '1: CDFS_7Ms_catalog.fits' (selected) and '2: CDFS_4obs.fits'. The 'Current Table Properties' panel on the right displays details for the selected table: Label: CDFS_7Ms_catalog.fits, Location: /Users/stefano/Documents/work/bologna/laboratori_X_Bologna/CF, Name: /Users/stefano/Documents/work/bologna/laboratori_X_Bologna/CF, Rows: 1,055, Columns: 79, Sort Order: (indicated by a yellow arrow icon), Row Subset: All, and Activation Action: (no action). The 'SAMP' panel at the bottom shows 'Messages:' and 'Clients:' with icons for network status.

Table List

- 1: CDFS_7Ms_catalog.fits
- 2: CDFS_4obs.fits

Current Table Properties


Label: CDFS_7Ms_catalog.fits

Location: /Users/stefano/Documents/work/bologna/laboratori_X_Bologna/CF

Name: /Users/stefano/Documents/work/bologna/laboratori_X_Bologna/CF

Rows: 1,055


Columns: 79



Sort Order: 

Row Subset: All

Activation Action: (no action) ☐ Broadcast Row

SAMP

Messages: 

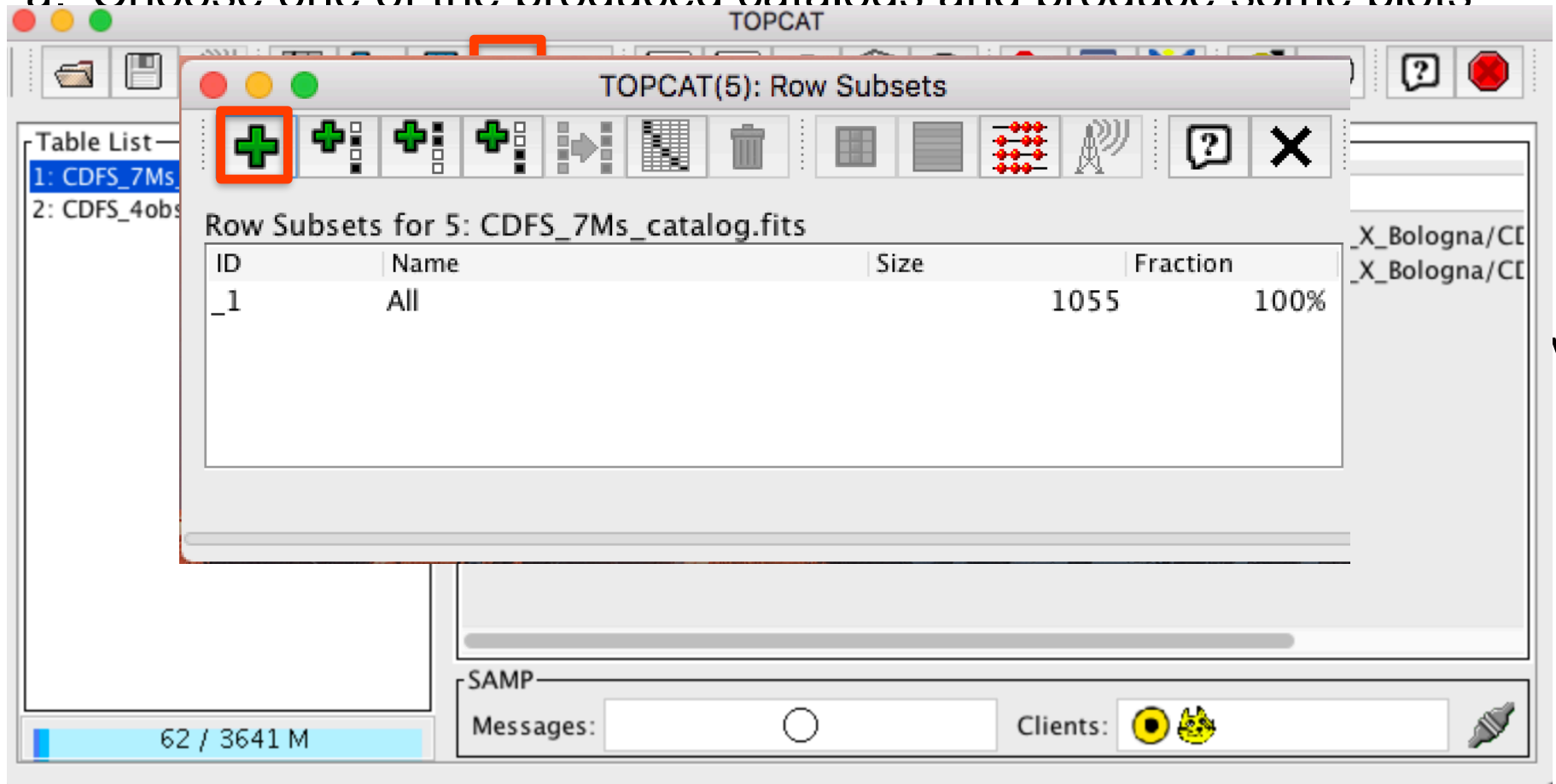
Clients:  

VS

Lab Outline

2) Explore the source catalog

a. Choose one of the produced catalogs and produce some plots



The screenshot shows the TOPCAT software interface. A 'Table List' on the left contains two entries: '1: CDFS_7Ms' and '2: CDFS_4obs'. The 'TOPCAT(5): Row Subsets' dialog box is open, displaying a table of row subsets for the file 'CDFS_7Ms_catalog.fits'. The table has four columns: 'ID', 'Name', 'Size', and 'Fraction'. It shows one subset with ID '_1', Name 'All', Size 1055, and Fraction 100%. The dialog box has a toolbar with various icons, including a green plus sign (highlighted with a red box) for adding new subsets. The main window shows a 'Table List' on the left and a 'SAMP' section at the bottom with 'Messages' and 'Clients' fields. The status bar at the bottom indicates '62 / 3641 M'.

ID	Name	Size	Fraction
_1	All	1055	100%

VS

Lab Outline

2) Explore the source catalog

a. Choose a subset of rows

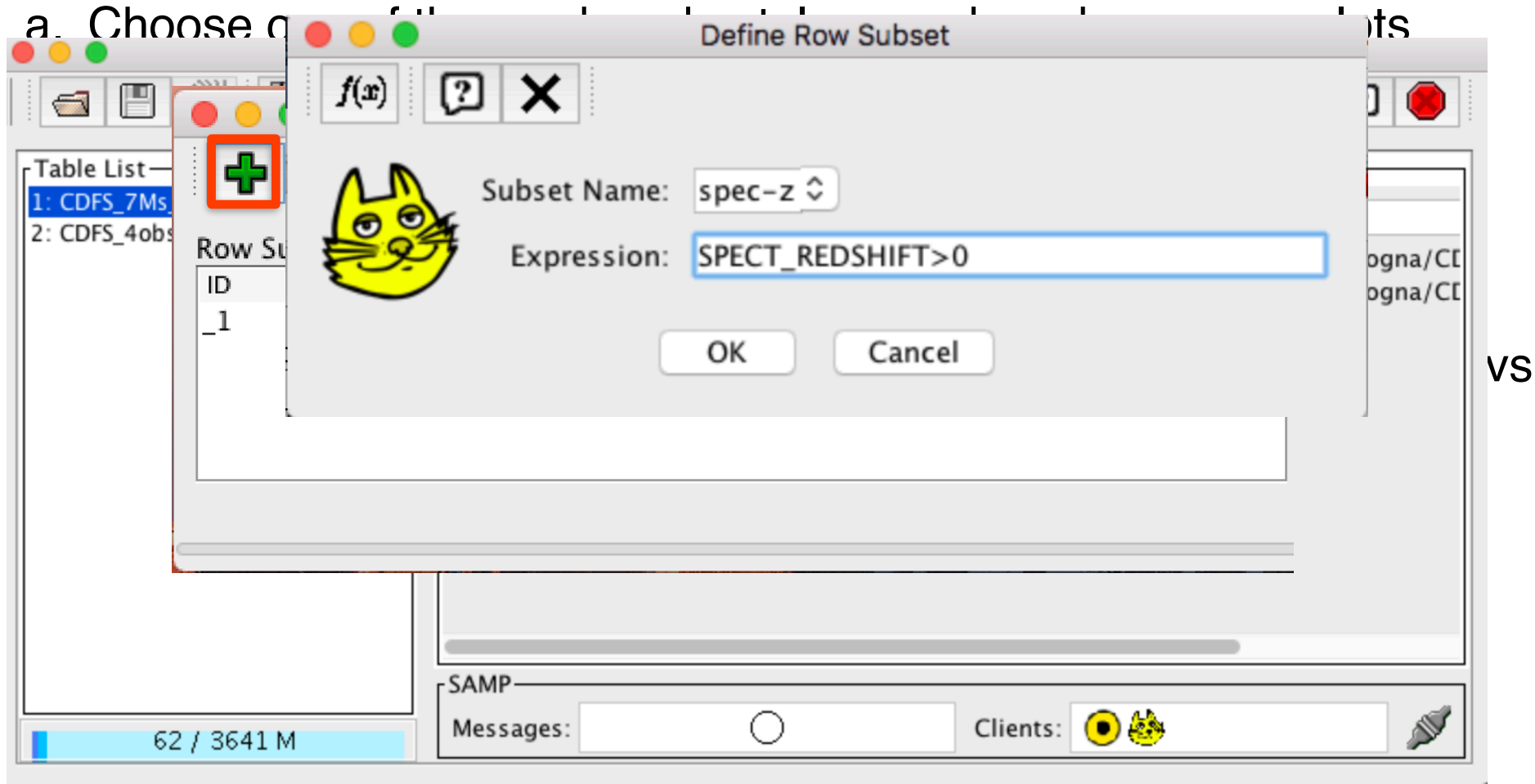


Table List

- 1: CDFS_7Ms
- 2: CDFS_4obs

Row Subset

ID

_1

Define Row Subset

Subset Name: spec-z

Expression: SPECT_REDSHIFT>0

OK Cancel

62 / 3641 M

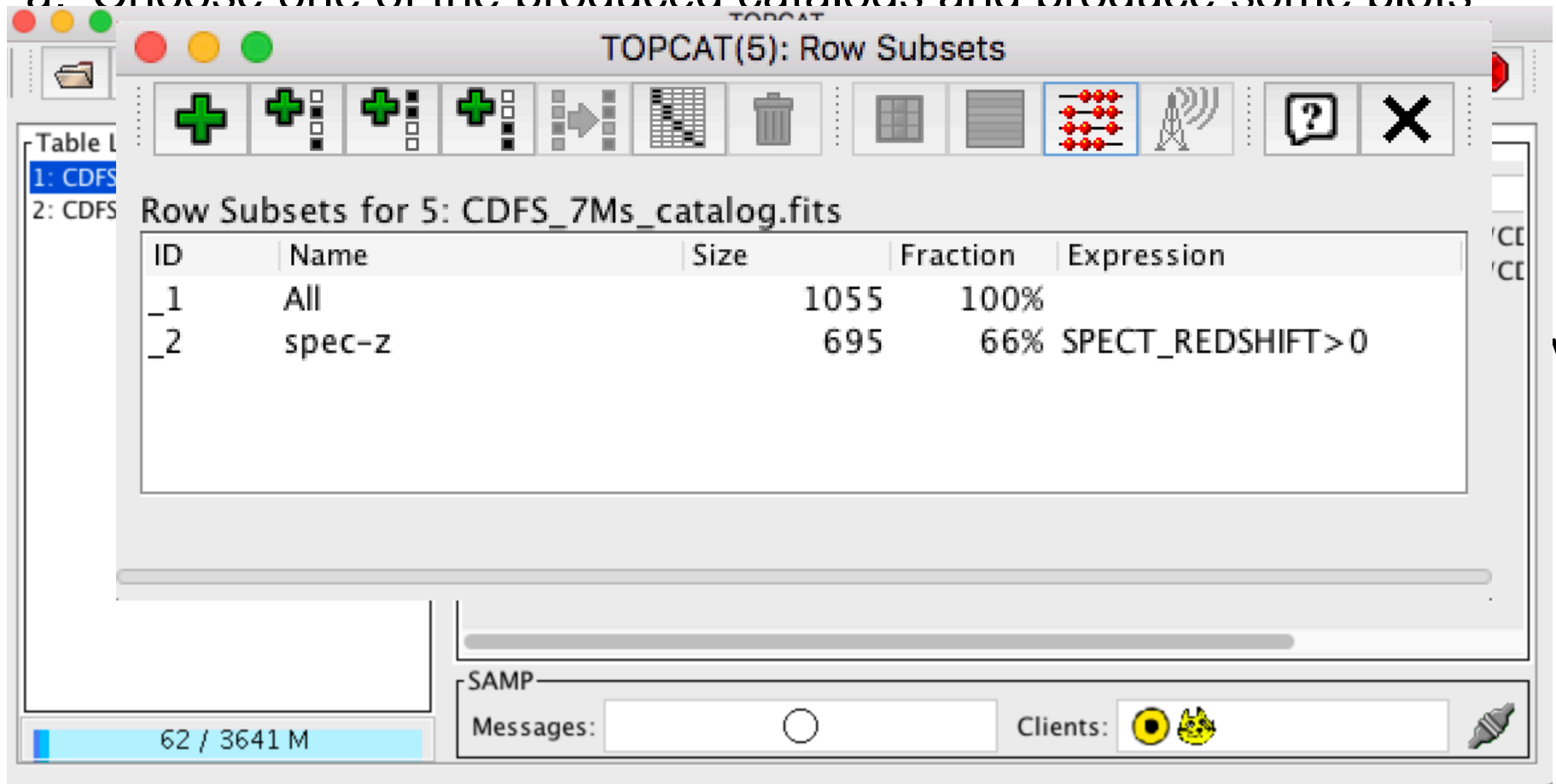
SAMP Messages: Clients: [eye icon] [cat icon]

VS

Lab Outline

2) Explore the source catalog

a. Choose one of the produced catalogs and produce some plots





TOPCAT(5): Row Subsets

Row Subsets for 5: CDFS_7Ms_catalog.fits

ID	Name	Size	Fraction	Expression
_1	All	1055	100%	
_2	spec-z	695	66%	SPECT_REDSHIFT>0

62 / 3641 M

SAMP

Messages: Clients:  

VS

Lab Outline

2) Explore the source catalog

a. Choose

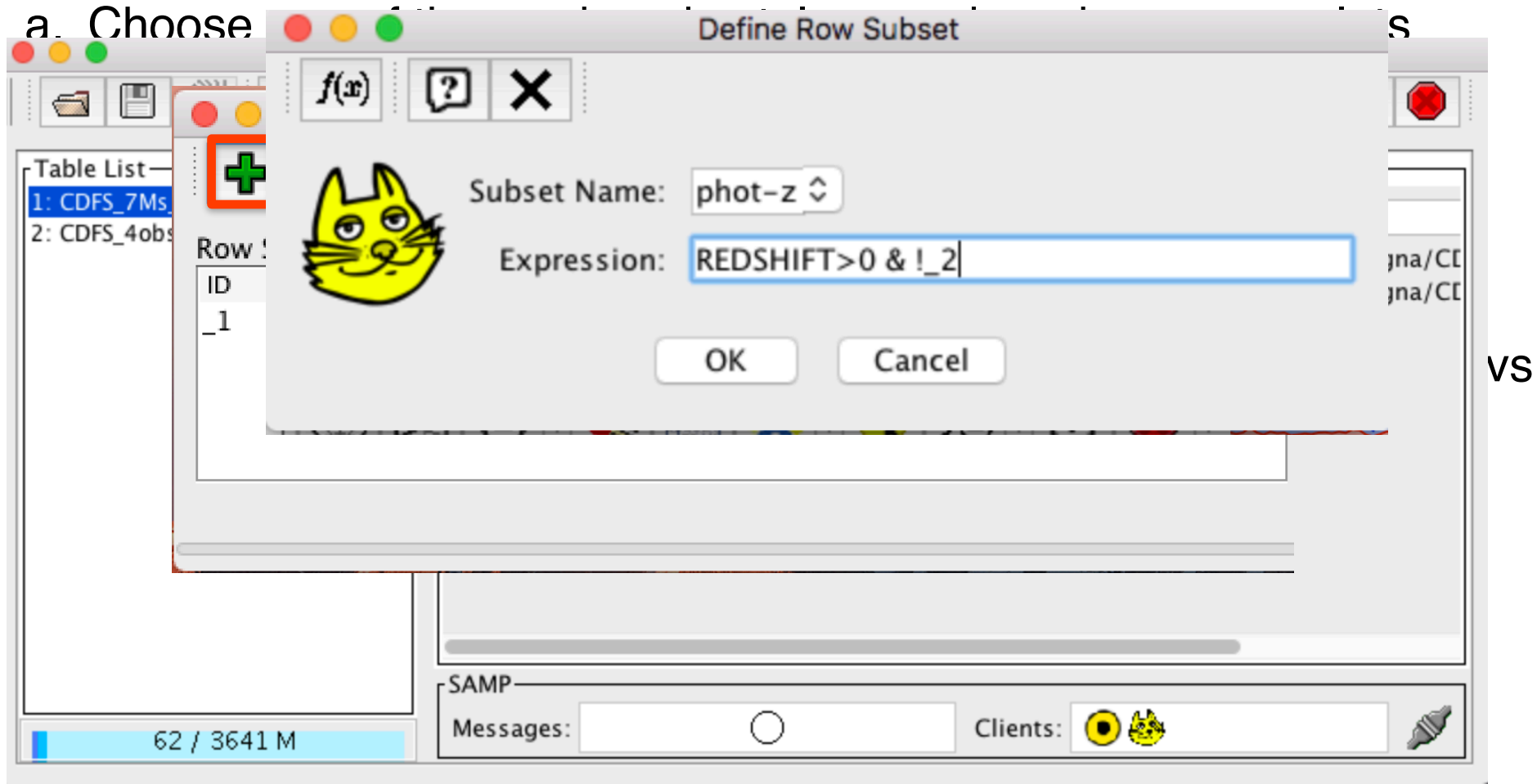


Table List—
1: CDFS_7Ms
2: CDFS_4obs

Row :
ID
_1



Define Row Subset

Subset Name: phot-z

Expression: REDSHIFT>0 & !_2

OK Cancel

62 / 3641 M

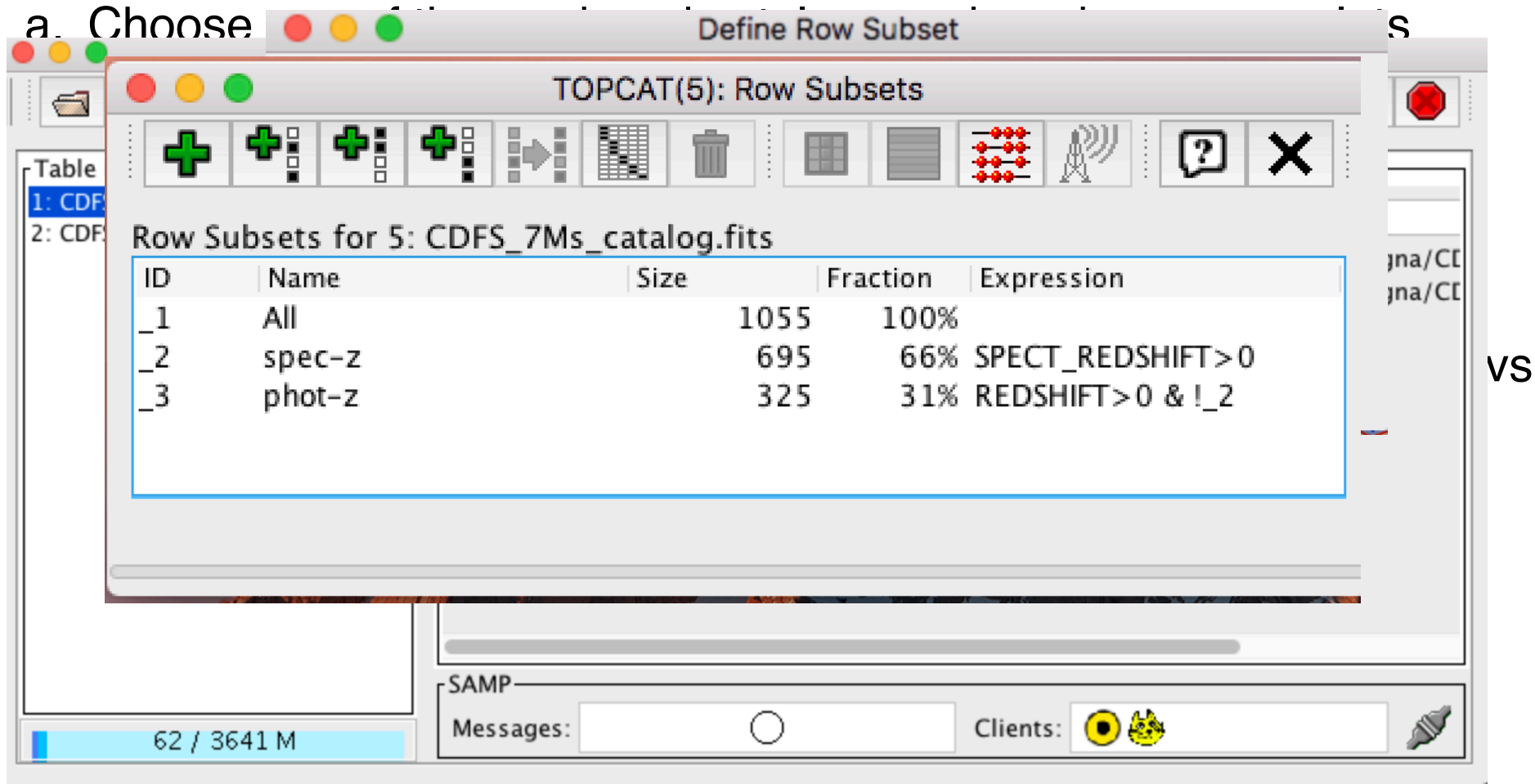
SAMP
Messages: Clients:  

VS

Lab Outline

2) Explore the source catalog

a. Choose





Define Row Subset

TOPCAT(5): Row Subsets

Row Subsets for 5: CDFS_7Ms_catalog.fits

ID	Name	Size	Fraction	Expression
_1	All	1055	100%	
_2	spec-z	695	66%	SPECT_REDSHIFT>0
_3	phot-z	325	31%	REDSHIFT>0 & !_2

SAMP

Messages: Clients:  

62 / 3641 M

VS

Lab Outline

2) Explore the source catalog

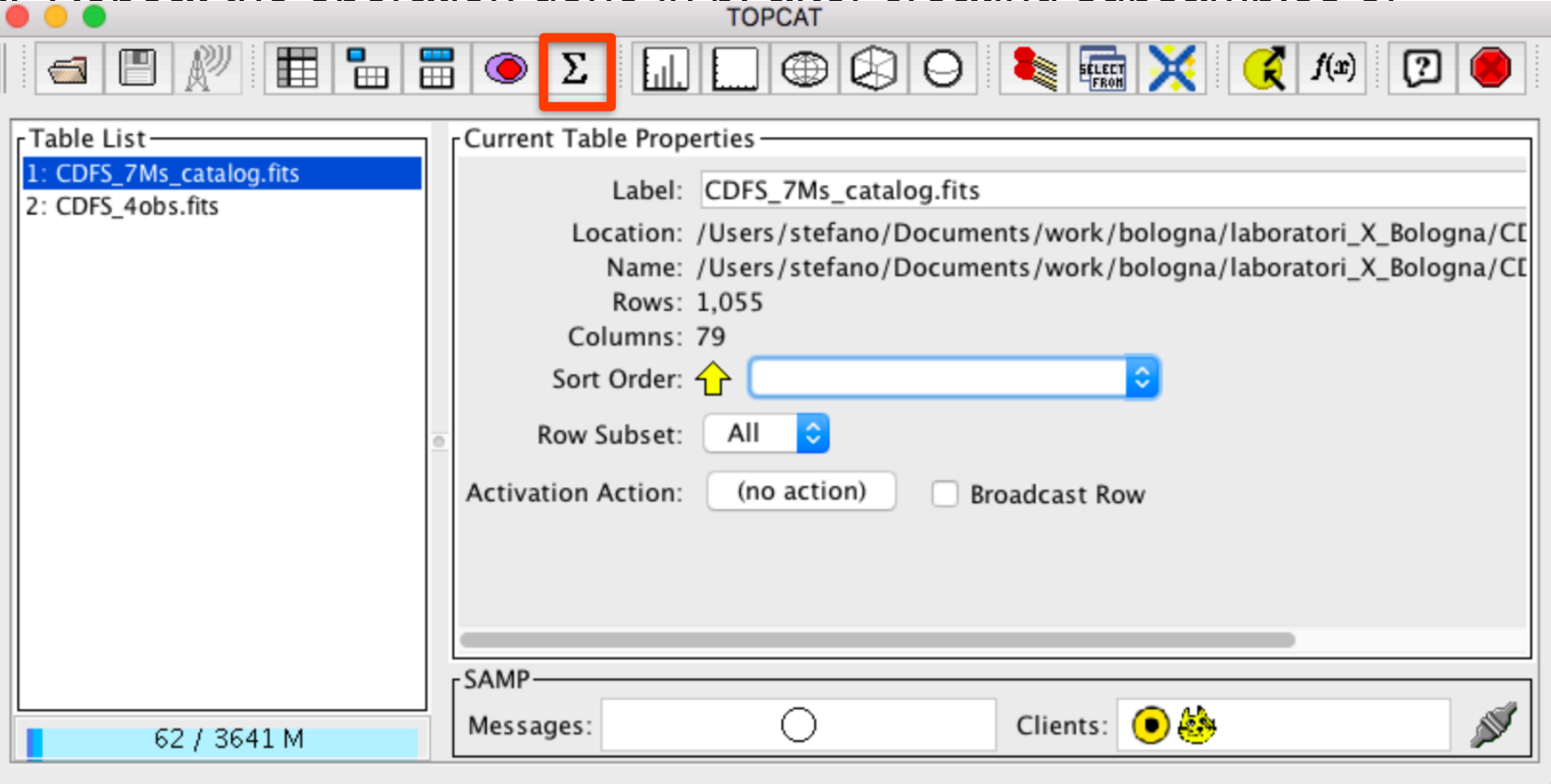
- a. Repeat the operation done in b. after creating subsamples of sources from the 7 Ms source catalog (e.g., spec-z vs phot-z; low vs high band-ratio...). Are there any noticeable trends?
- b. The trends can also be quantified using the Topcat statistics tool.

Lab Outline



2) Explore the source catalog

a. Repeat the operation done in b. after creating subsamples of

b.



The screenshot shows the TOPCAT software interface. The title bar reads "TOPCAT". The toolbar contains various icons, with the summation symbol (Σ) highlighted by a red square. The "Table List" panel on the left shows two tables: "1: CDFS_7Ms_catalog.fits" (selected) and "2: CDFS_4obs.fits". The "Current Table Properties" panel on the right displays the following information for the selected table:

- Label: CDFS_7Ms_catalog.fits
- Location: /Users/stefano/Documents/work/bologna/laboratori_X_Bologna/CF
- Name: /Users/stefano/Documents/work/bologna/laboratori_X_Bologna/CF
- Rows: 1,055
- Columns: 79
- Sort Order: 
- Row Subset: All 
- Activation Action: (no action) ☐ Broadcast Row

The bottom status bar shows "62 / 3641 M" on the left and "SAMP" on the right. The "SAMP" section includes "Messages:" with a circular progress indicator and "Clients:" with two icons (a yellow circle and a yellow cat head) and a plug icon.

Lab Outline

2) Explore the source catalog

a

b

TOPCAT(5): Row Statistics

Row Statistics for 5: CDFS_7Ms_catalog.fits

Name	Mean	SD	Minimum	Max
VLA_DEC	-5.7216	11.2414	-27.9885	
VLA_20_CM_MAG	3.84106	7.57468	0.	
SPECT_REDSHIFT	1.0809	0.784943	0.034	
SPECT_REDSHIFT_FLAG			INSECURE	
REF_SPECT_REDSHIFT	10.6576	6.54157		2
PHOT_REDSHIFT_L10	0.542863	0.848864	0.	
PHOT_REDSHIFT_R11	1.03203	0.749643	0.	
PHOT_REDSHIFT_H14	1.07511	0.787236	0.	
PHOT_REDSHIFT_S14	0.82387	0.80083	0.	
PHOT_REDSHIFT_S15	0.809108	0.814808	0.	
PHOT_REDSHIFT_S16	0.936187	0.826658	0.	
REDSHIFT	1.08991	0.776239	0.038	
REF_REDSHIFT				H14
REDSHIFT_NEG_ERR	0.002921	0.02576	0.	
REDSHIFT_POS_ERR	0.00354	0.026326	0.	

Subset for calculations:

- All
- spec-z
- phot-z

Lab Outline

2) Explore the source catalog

- a. Choose one of the produced catalogs and produce some plots (number of counts vs. source significance, vs. exposure time, vs. positional uncertainty, etc.)
- b. For the sources associated with the 7Ms source catalog, produce the redshift distribution histogram, L_x vs. z plot, etc.
- c. Use the PIMMS Online tool (<https://cxc.harvard.edu/toolkit/pimms.jsp>) to compute the count rate-to-flux correction factor, using the photon index available in the catalog.

Lab Outline

2) Explore the source catalog

PIMMS v4.11a: with ACIS Pile up and Background Count Estimation

Input	
<input checked="" type="radio"/> Count Rate	<input type="radio"/> Flux <input type="radio"/> Flux Density
Mission: CHANDRA-Cycle 11 ▼	Detector/Grating/Filter: ACIS-I/None/None ▼
Input Energy: 0.5 to 2 keV	

Output
<input type="radio"/> Count Rate <input checked="" type="radio"/> Flux <input type="radio"/> Flux Density
Flux: Absorbed ▼
Output Energy: 0.5 to 2

Model: Power Law ▼	Galactic NH: 7E19 cm**2	Redshift(z): 0	Redshifted NH: 0 cm**2	Photon Index: 1.7 N=AE**-a	Count Rate: 1E-2 cts/s
---------------------------------------	---	-----------------------------------	--	--	--

CALCULATE CLEAR HELP

[PIMMS Prediction:](#)

6.383E-14
erg/cm**2/s absorbed flux

Lab Outline

2) Explore the source catalog

PIMMS v4.11a: with ACIS Pile up and Background Count Estimation

Input		Output	
<input checked="" type="radio"/> Count Rate	<input type="radio"/> Flux	<input type="radio"/> Count Rate	<input checked="" type="radio"/> Flux
Mission: CHANDRA-Cycle 11 ▼		Flux:	
Input Energy: 0.5 to 2 keV		Output Energy: 0.5 to 2	

Detector/Crating/Filter:

What happens changing the mission Cycle?

Model:	Galactic NH:	Redshift(z):	Redshifted NH:	Photon Index:	Count Rate:
Power Law ▼	7E19 cm**2	0	0 cm**2	1.7 N=AE**-a	1E-2 cts/s

CALCULATE CLEAR HELP

PIMMS Prediction:

6.383E-14

erg/cm**2/s absorbed flux

3. Analyse the data products: spectral fitting

Fit *Chandra* spectra for sources whose properties suggest potential interesting outcome (e.g, high-z, high obscuration based on hardness ratio...).

XID	Luo17	Source coordinates	z	Opt. Class + Info
551		03:32:29.85 -27:51:05.71	3.700	NL (Comastri+11)
746		03:32:39.66 -27:48:50.64	3.064	NL (Vito+13)
730		03:32:38.91 -27:57:00.48	0.298	NL
242		03:32:13.24 -27:42:40.96	0.605	NL

IDs reported in the spectral files we provide

All spectra and response matrices are provided

3. Analyse the data products: spectral fitting

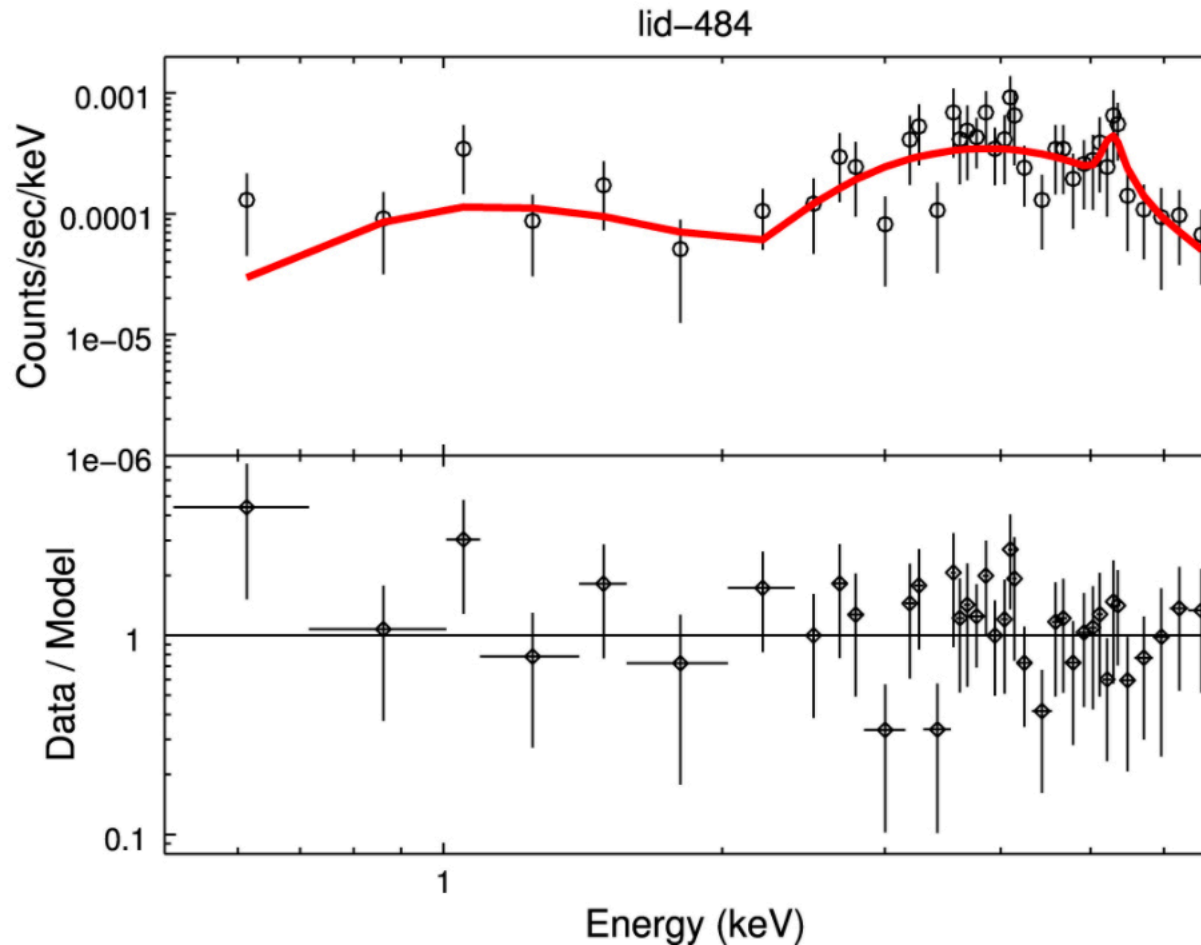
Spectral analysis pipeline

1. Choose one of the four sources
2. Group the spectra (*grppha*) accordingly to the quality of the data
3. Load spectra in XSPEC
4. Define a spectral model and fit it to the data
5. Once a physically justified model is obtained, save the X-ray spectral parameters (including errors) and produce confidence contours
6. Check for further components (to lower the data/model residuals) – Return to point 3

PLAN (III)

OPTIONAL

- a. Re-run the procedure for a second source, better if at a different redshift range.



Main publications

- Xue Y.Q. et al. 2011, ApJS, 195, 10 **4 Ms Chandra source catalog.**
- Vito F. et al. 2013, MNRAS, 428, 354 **High-redshift AGN population in the CDF-S.**
- Luo B. et al. 2017, ApJ Suppl., 228, 2 **The Chandra Deep Field-South Survey: 7 Ms Source Catalogs.**

Command list: merge_obs

```
punlearn merge_obs
pset merge_obs infile=@infile.lis
pset merge_obs outroot=CDFS_4obs
pset merge_obs asolfiles=@asol.lis
pset merge_obs badpixfiles=@bpix.lis
pset merge_obs maskfiles=@mask.lis
pset merge_obs parallel=yes
pset merge_obs nproc=4
pset merge_obs units=time
pset merge_obs bands=broad
pset merge_obs xygrid=0.5:8192.5:1,0.5:8192.5:1
pset merge_obs psfecf=0.9
pset merge_obs psfmerge=exptime
merge_obs
```

Command list: wavdetect

```
punlearn wavdetect
pset wavdetect infile=CDFS_4obs_merged_057keV_bin1.fits
pset wavdetect outfile=CDFS_4obs_merged_057keV_wavdet_1em6_src.fits
pset wavdetect scellfile=CDFS_4obs_merged_057keV_wavdet_1em6_cellimage.fits
pset wavdetect
imagefile=CDFS_4obs_merged_057keV_wavdet_1em6_reconstructed.fits
pset wavdetect defnbkgfile=CDFS_4obs_merged_057keV_wavdet_1em6_normbakg.fits
pset wavdetect regfile=CDFS_4obs_merged_057keV_wavdet_1em6.reg
pset wavdetect ellsigma=3.0
pset wavdetect sigthresh=1e-6
pset wavdetect scales="1 1.4 2 2.8 4 5.6 8 11"
pset wavdetect expfile=CDFS_4obs_merged_broad_thresh.expmap
pset wavdetect psffile=CDFS_4obs_merged_broad_thresh.psfmap
wavdetect clobber+ verbose=3
```