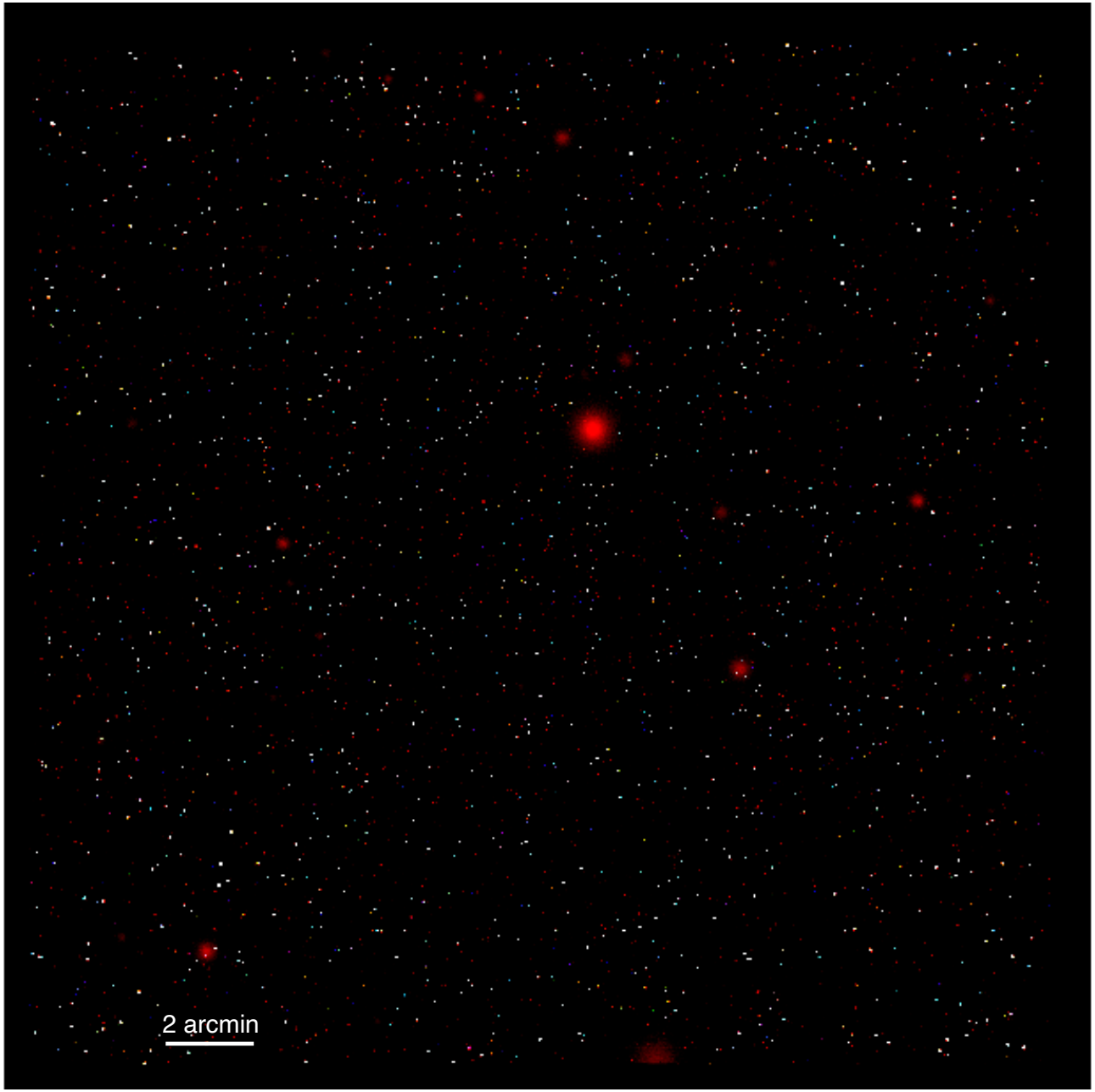
Understanding the AGN population: X-ray surveys



X-rays as a strategic tool in AGN analysis

X-ray emission contributes only to <10% to AGN bolometric luminosity. However, X-ray emission offers an unique point of view in the AGN analysis. In fact, X-ray offer the…

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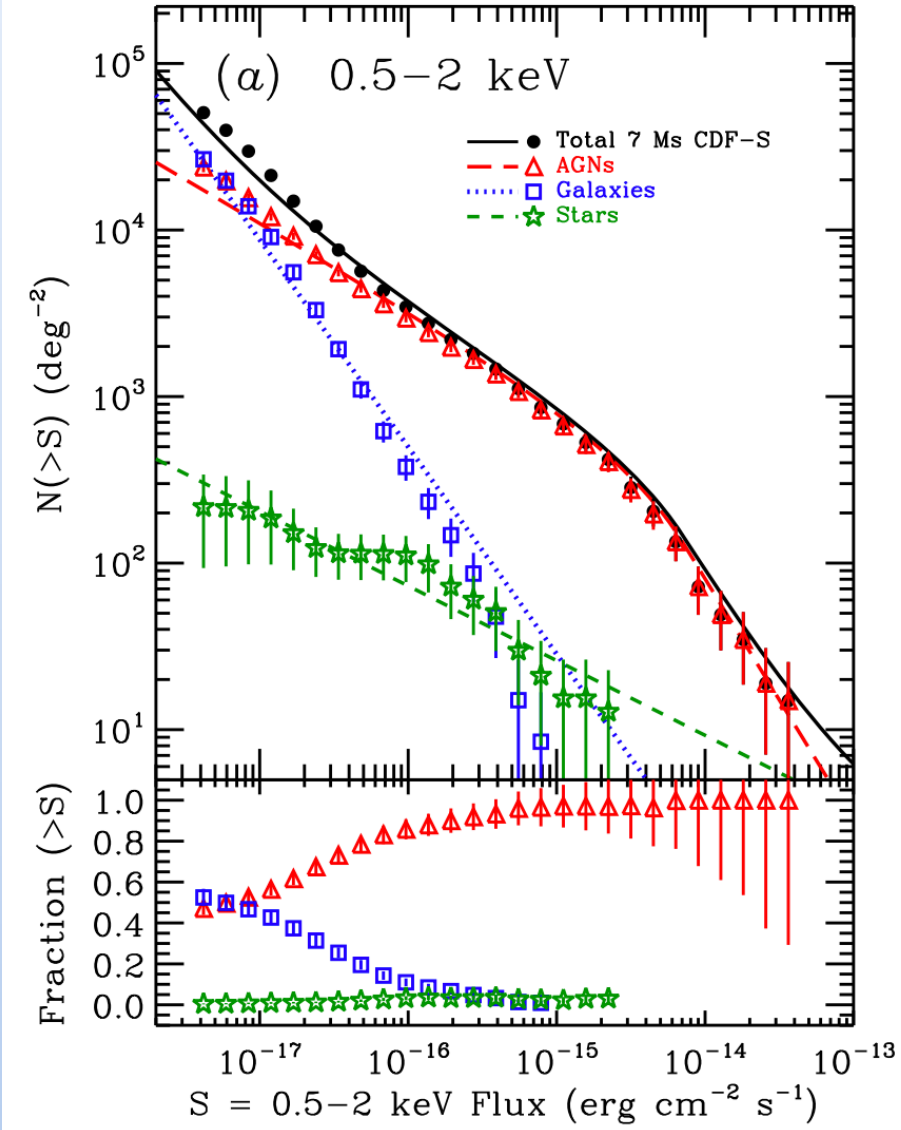

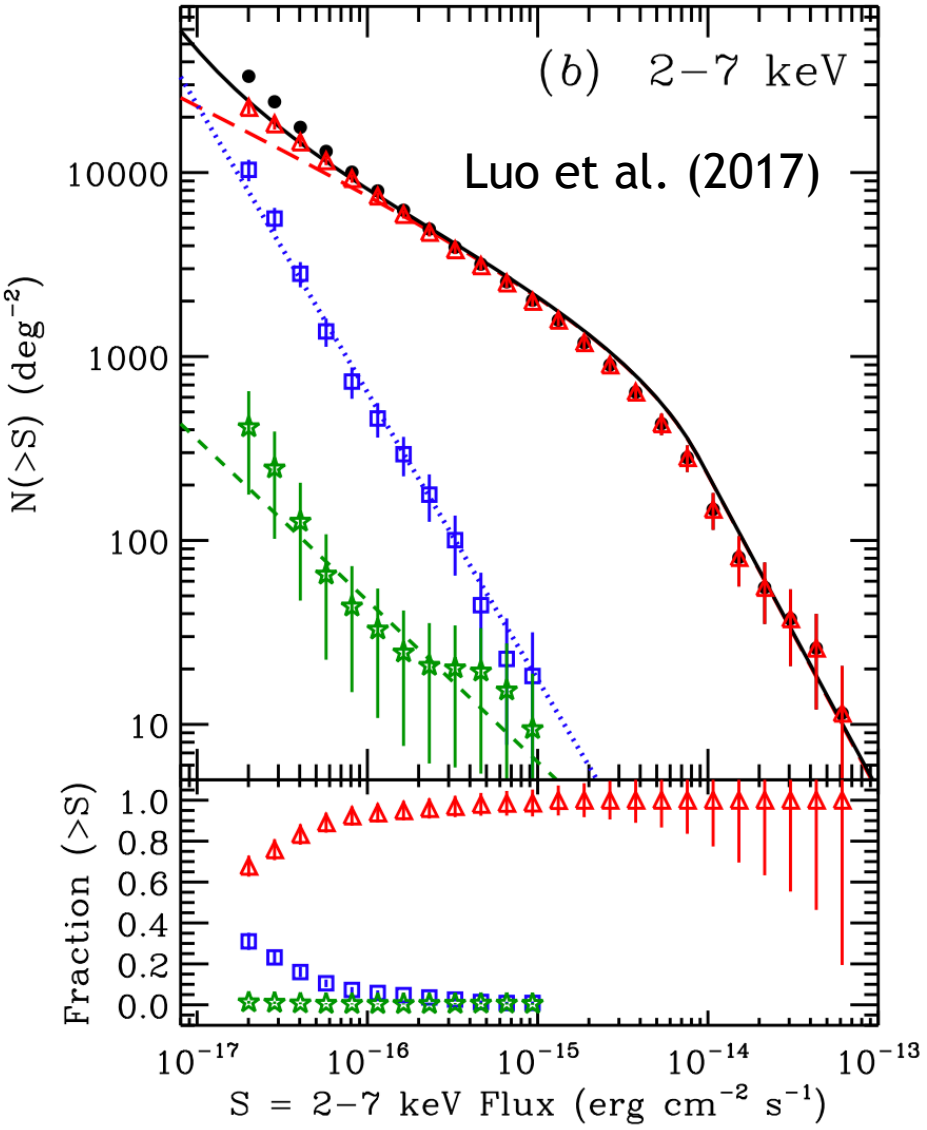

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X-rays as a strategic tool in AGN analysis

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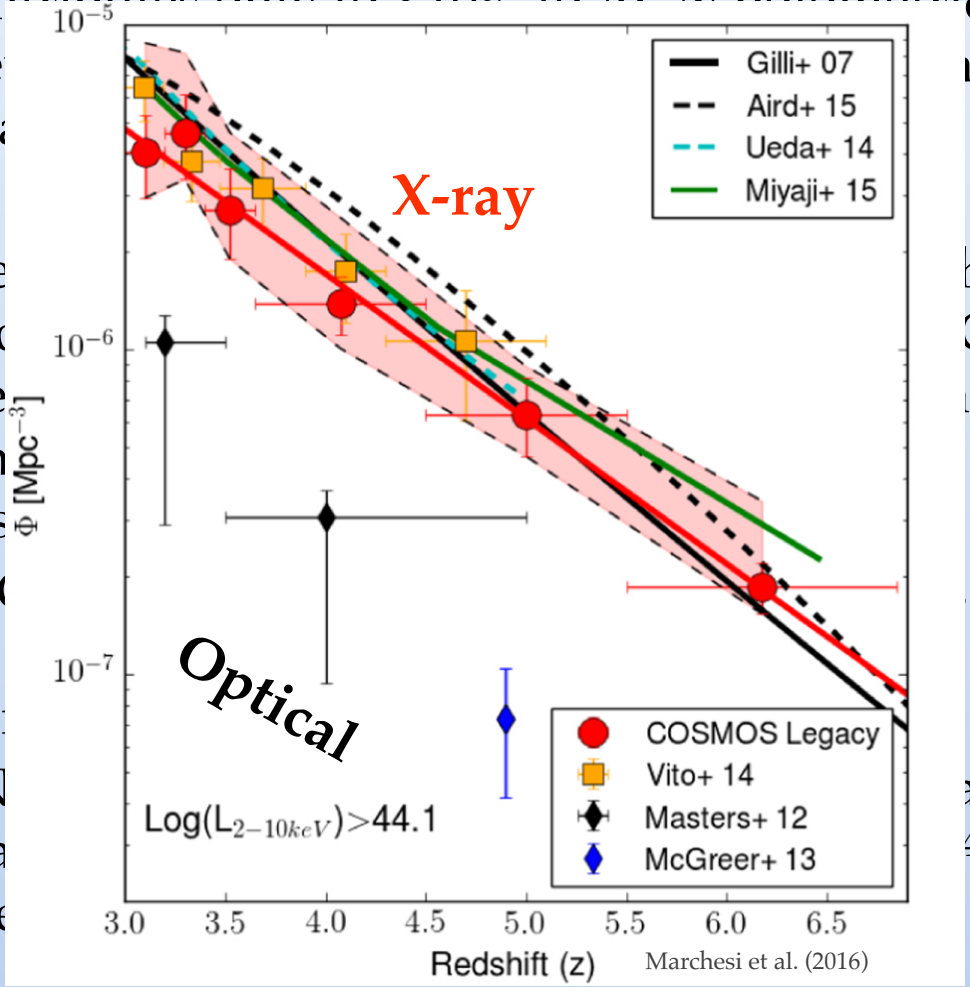

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The X-ray surveys wedding-cake strategy

Depth

X-ray Flux Limit

10^{-14}

10^{-15}

10^{-16}

10^{-17}

J1030 Field 0.1 deg²
Nanni et al. 2020

CDFN-CDFS 0.1deg²
Alexander+ 2003; Luo + 2008;
Xue+ 2011; Comastri+2011

E-CDFS 0.3deg²
Lehmer et al. 2005

Chandra COSMOS Legacy 2.2 deg²
Civano et al. 2016
Marchesi et al. 2016

EGS/AEGIS 0.7deg²
Laird et al. 2008,
Goulding et al. 2012

XMM-COSMOS
2 deg²

Champ 1.5deg2
Silverman et al. 2005

XBOOTES 9 deg²
Murray et al. 2005

XXL 50 deg²
Pierre+ 2012

Stripe82 70 deg²
LaMassa+ 2013

Area deg²

0.1

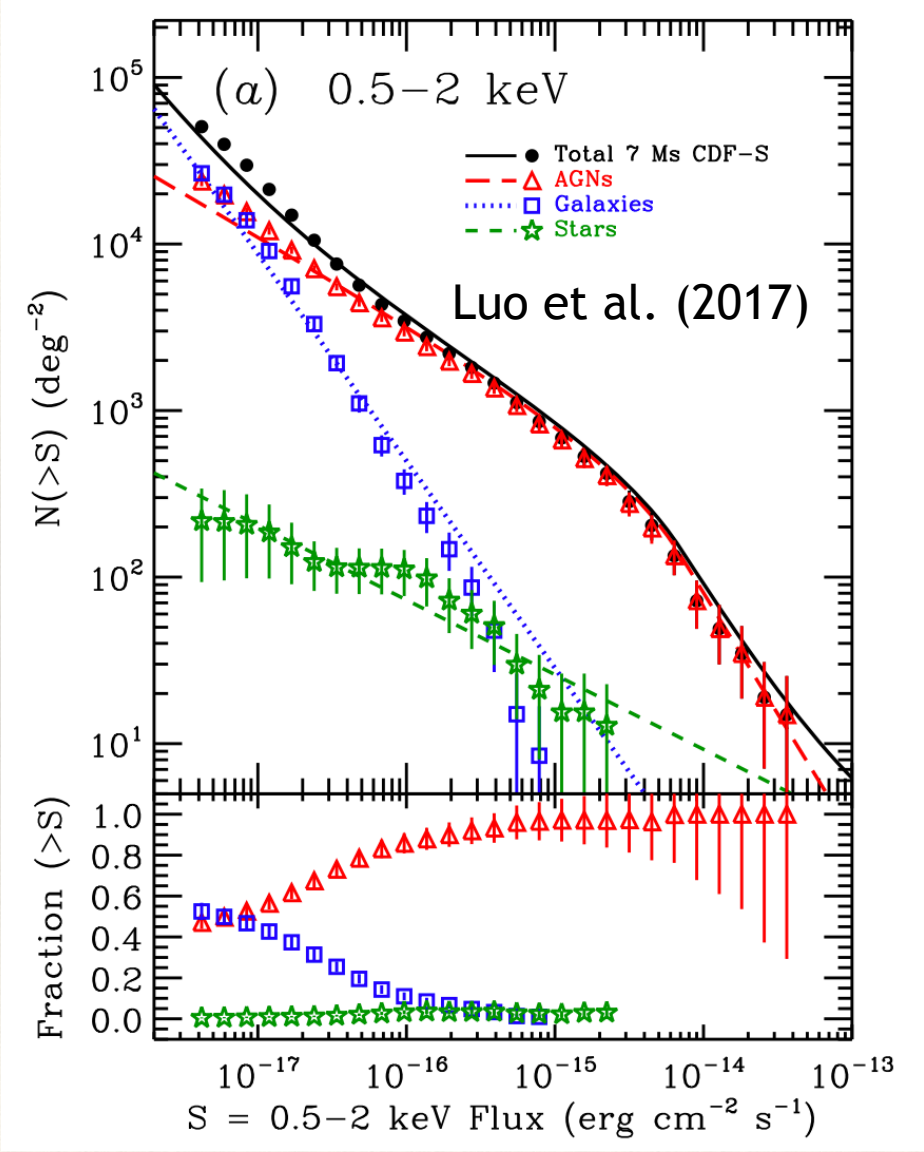
1

10

100

Courtesy of F.Civano

Different surveys for different science



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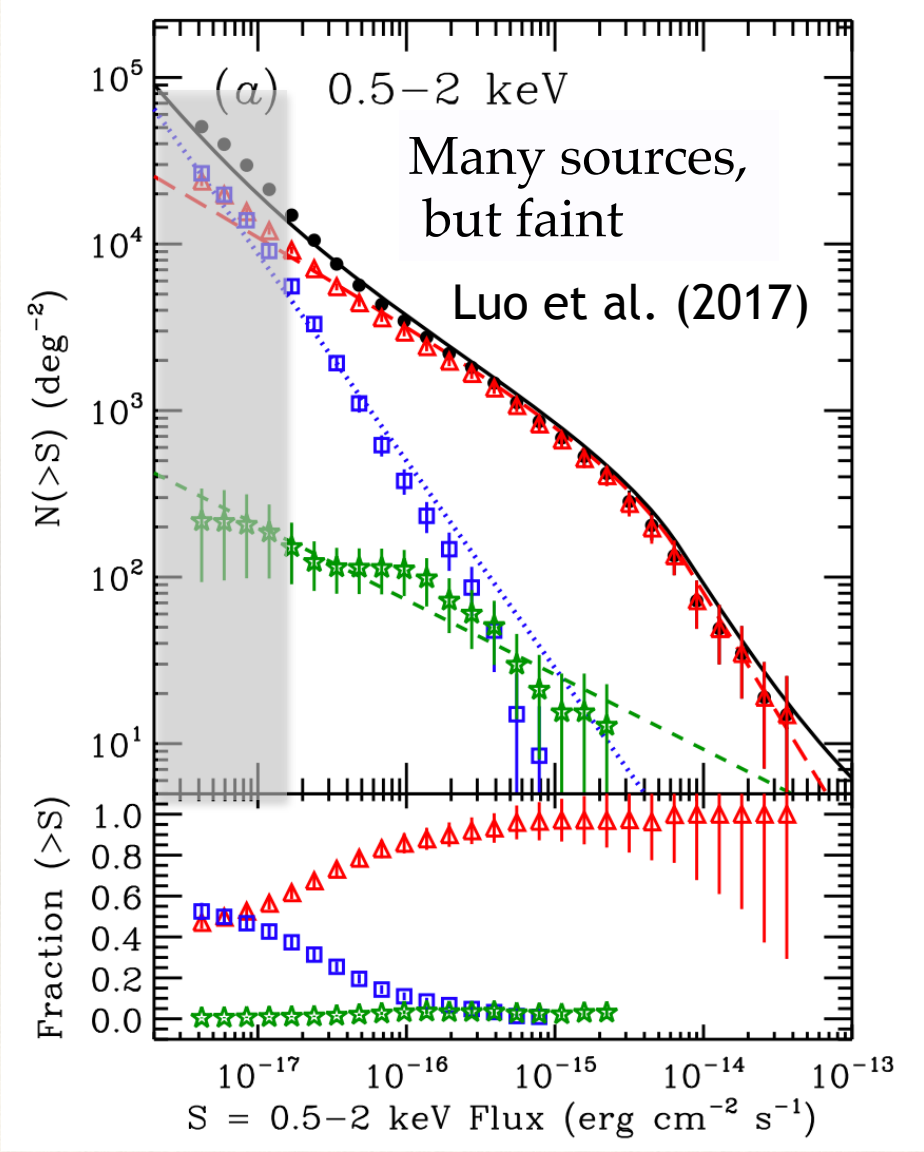

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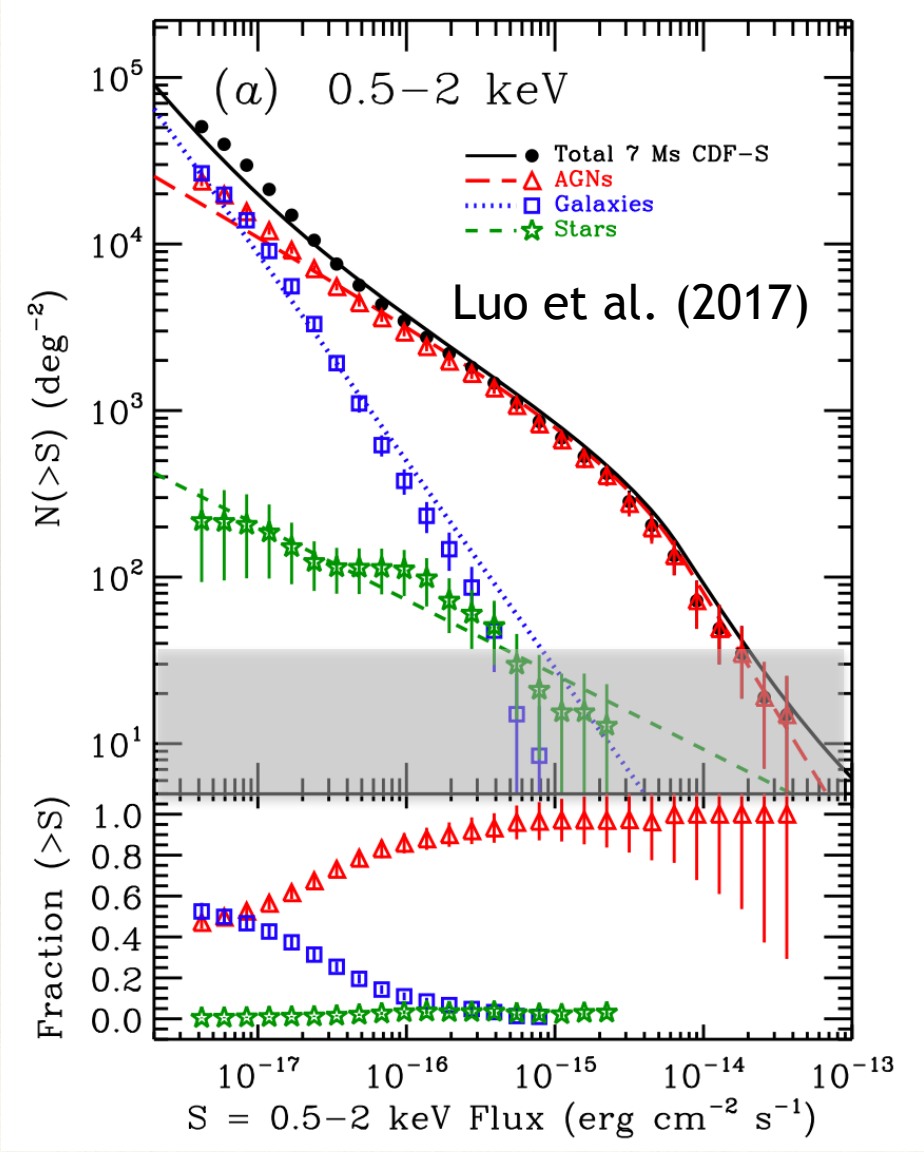
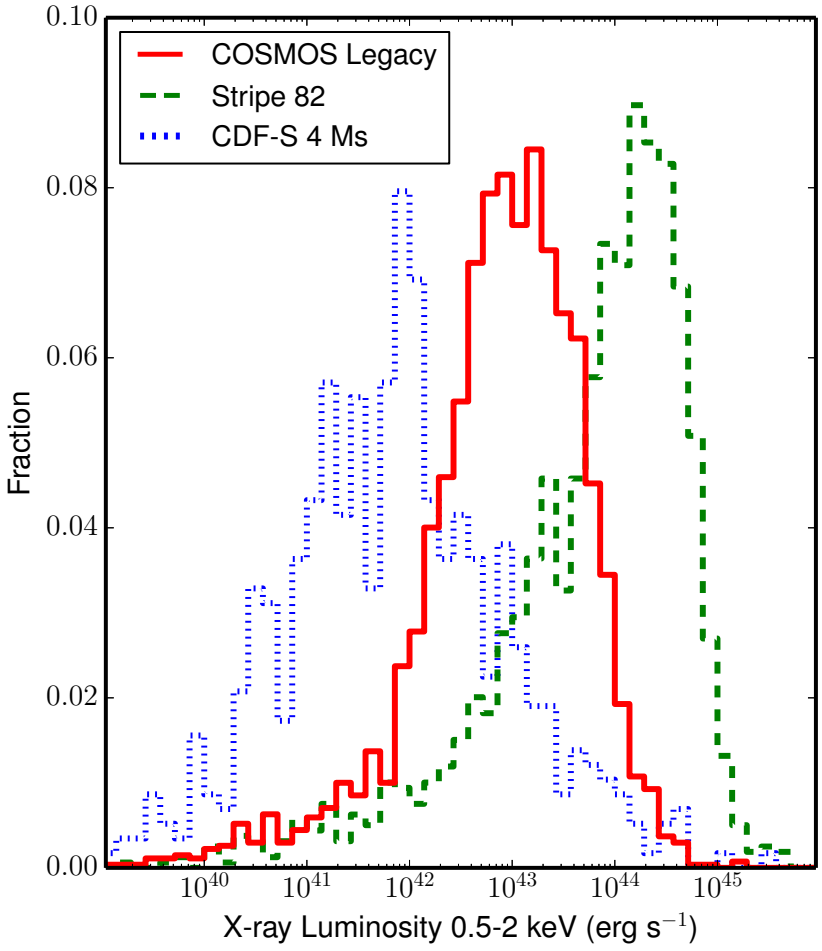
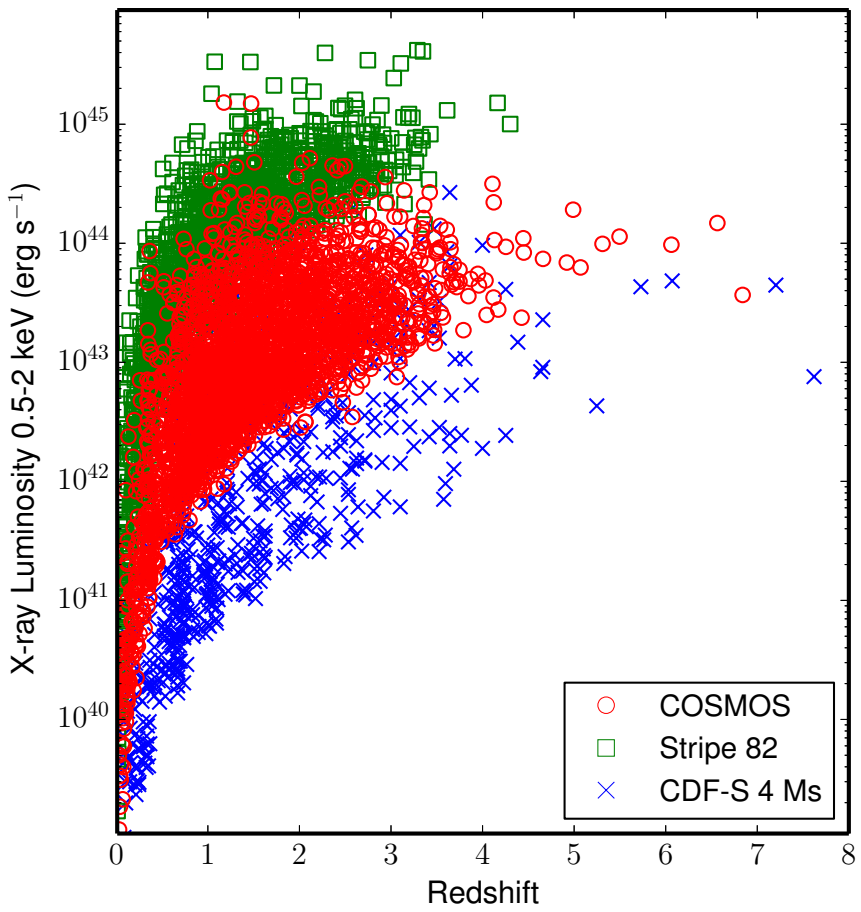


Extremely bright, but rare

Different surveys for different science



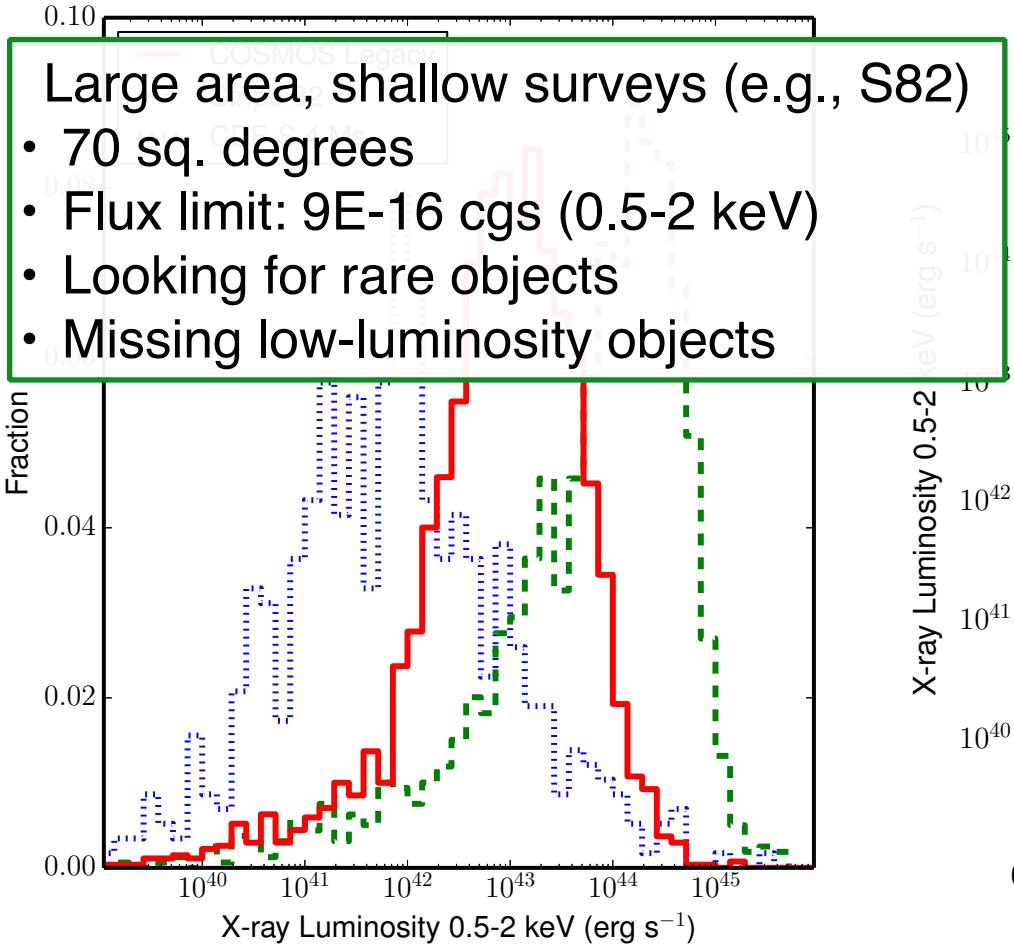


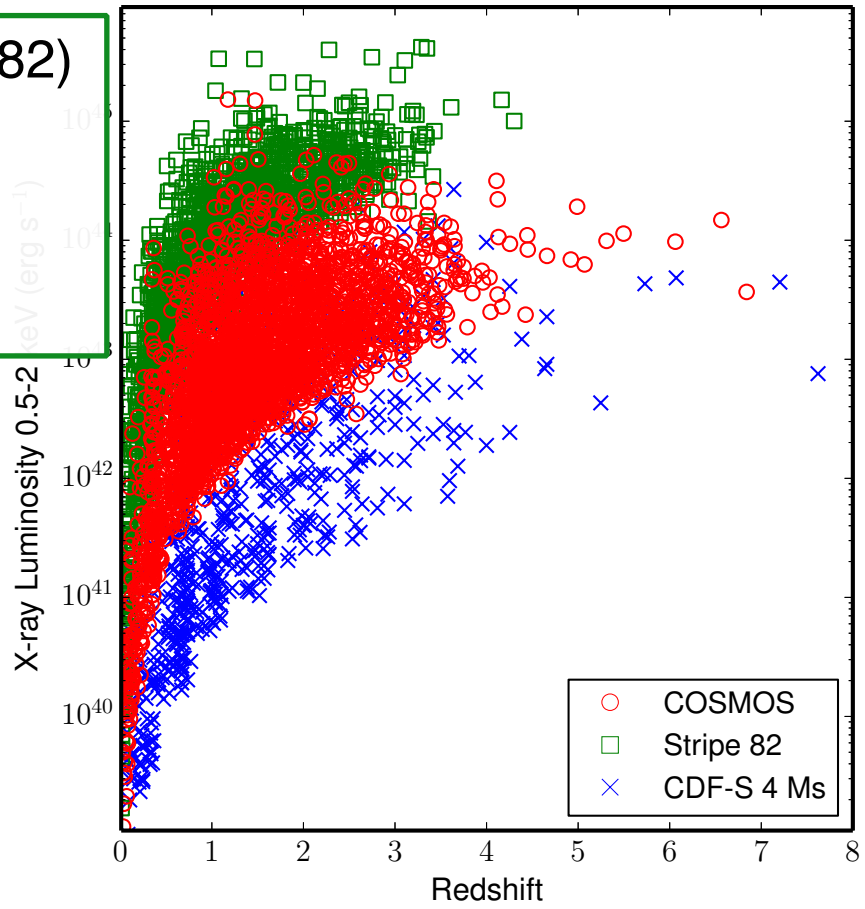
Marchesi et al. 2016

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





Marchesi et al. 2016

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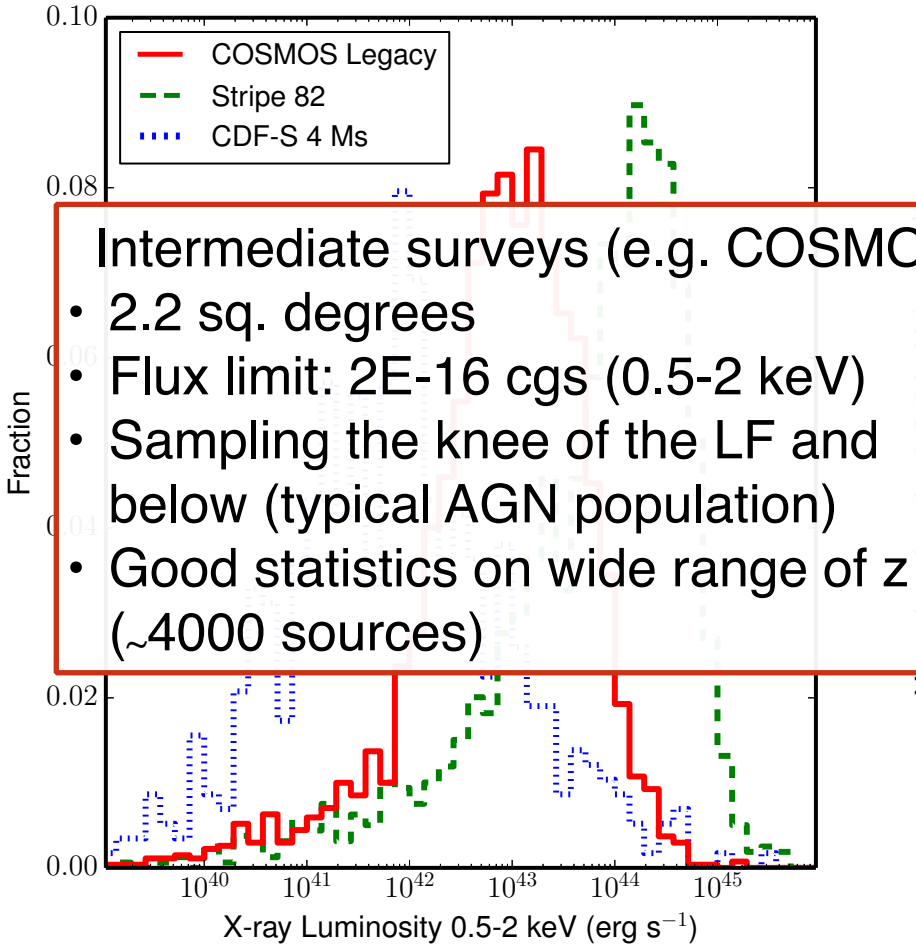
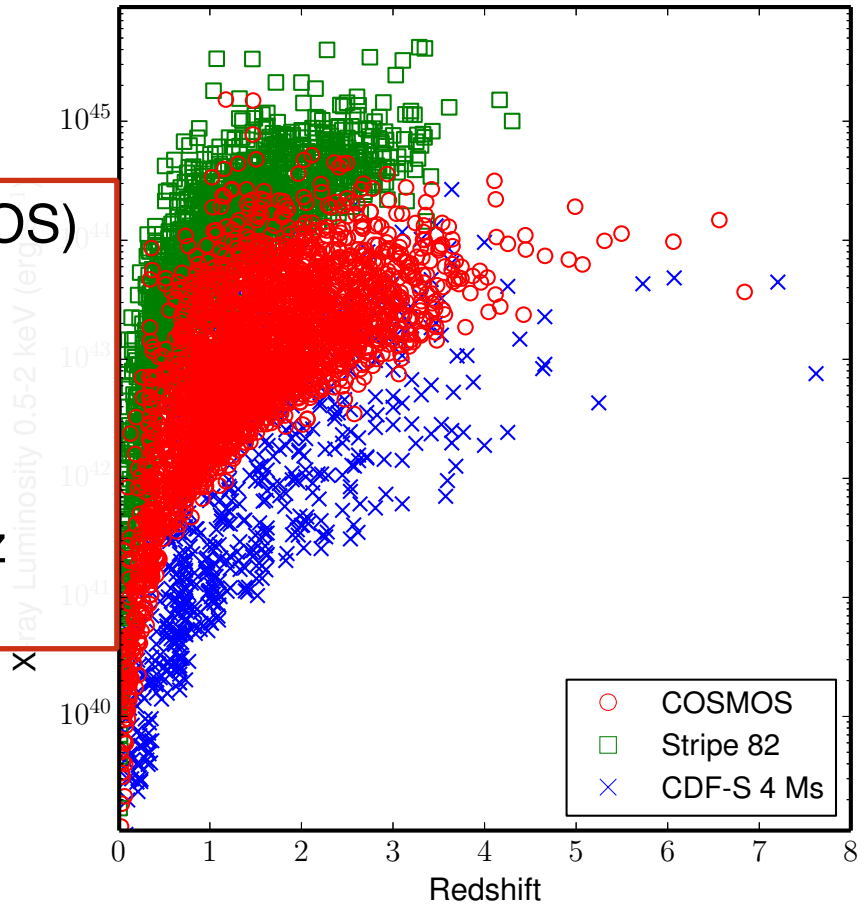


Intermediate surveys (e.g. COSMOS)

- 2.2 sq. degrees
- Flux limit: 2E-16 cgs (0.5-2 keV)
- Sampling the knee of the LF and below (typical AGN population)
- Good statistics on wide range of z (~4000 sources)



Marchesi et al. 2016

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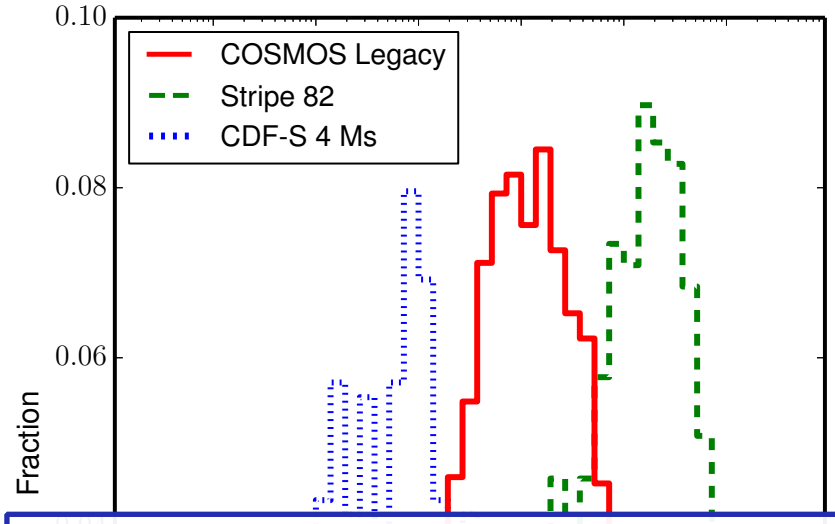
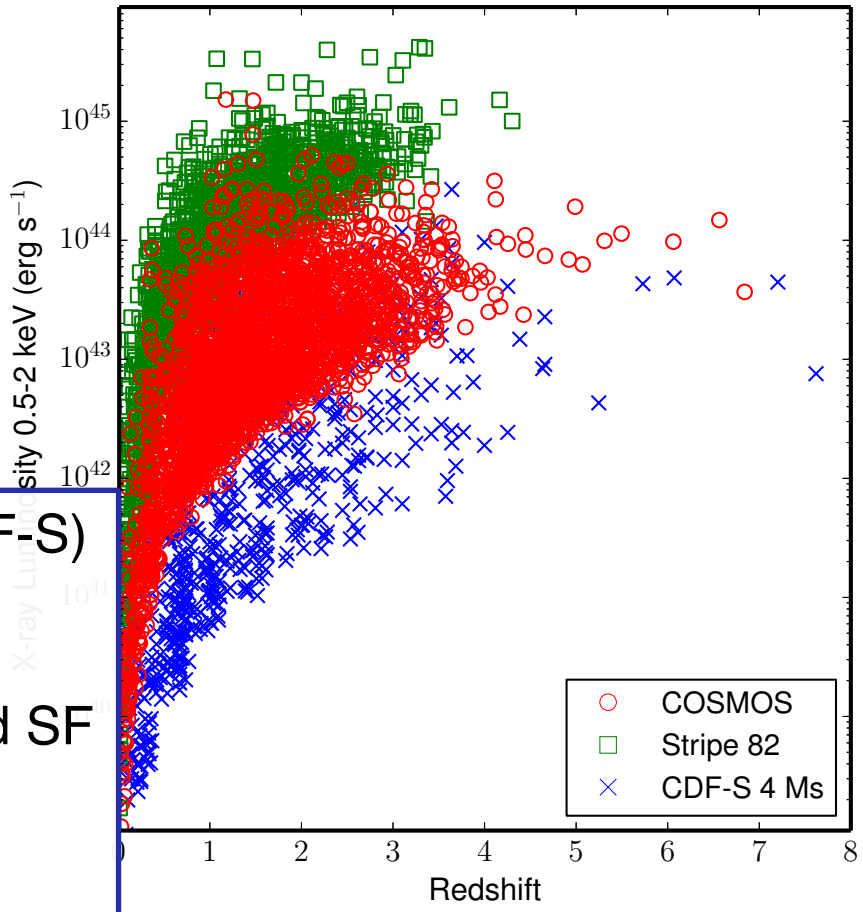




Deep, pencil beam surveys (e.g. CDF-S)

- 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)

Marchesi et al. 2016

Chandra Deep Field-South (CDF-S)

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

≈3Ms XMM-*Newton* exposure

Deep multi-wavelength coverage

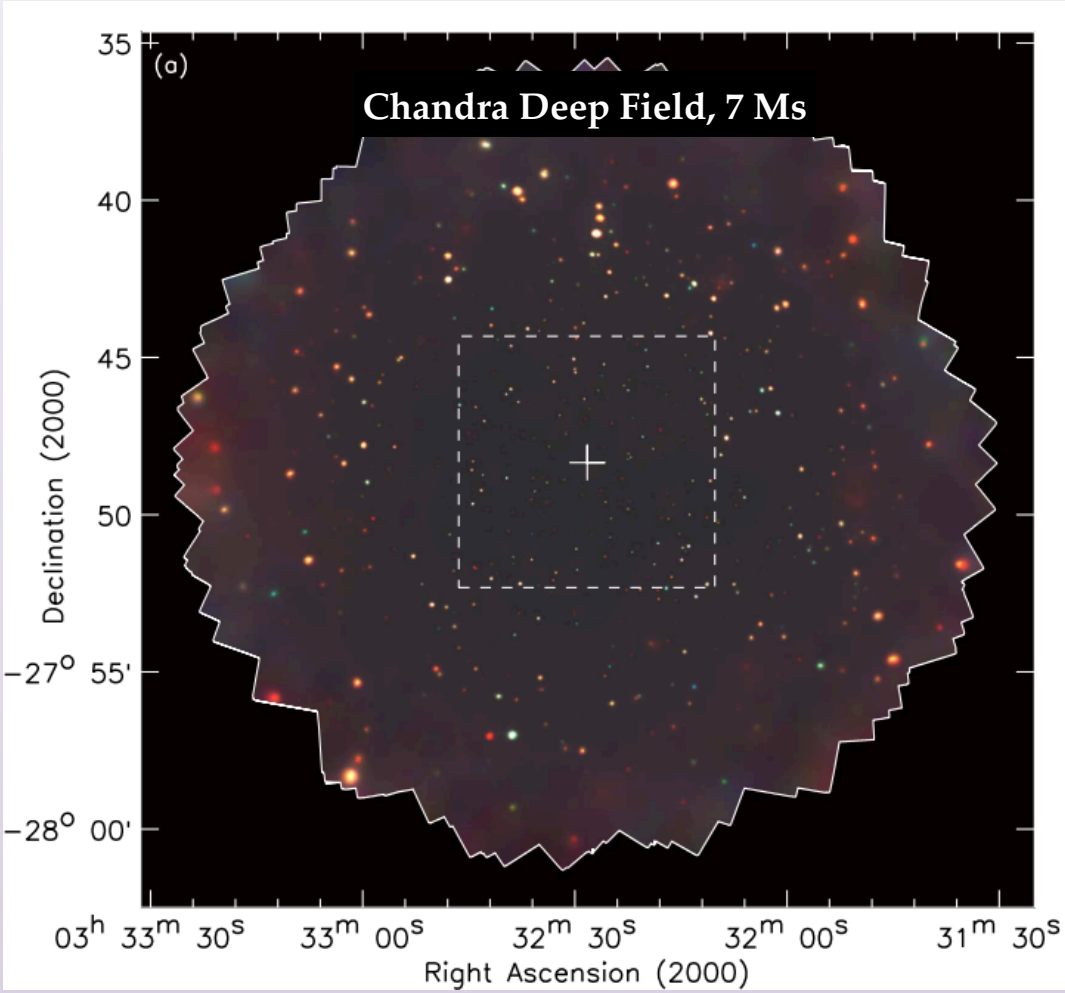
One of the legacy fields (no deeper field for the next 20 yrs)

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 need for new X-ray facilities

- Optical/NIR surveys are biased against obscured AGN at high-z.
- A complete census of accreting supermassive black holes (including obscured and/or intrinsically faint) requires X-ray facilities, and deep surveys.



Luo et al. (2017)

The need for new X-ray facilities

- Optical/NIR surveys are biased against obscured AGN at high-z.
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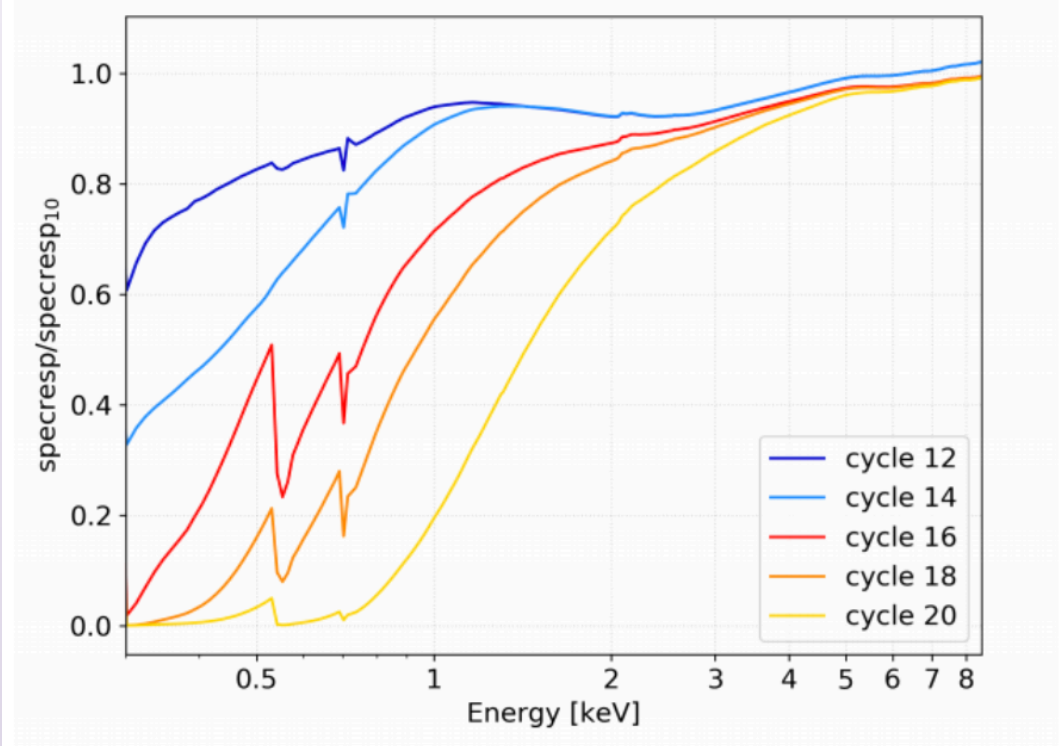

Figure 15. ACIS-I effective area degradation through years. We show the ARF ratios between cycles 12 (blue), 14 (light blue), 16 (red), 18 (orange), 20 (yellow) and the cycle 10.

Peca et al. (2021)

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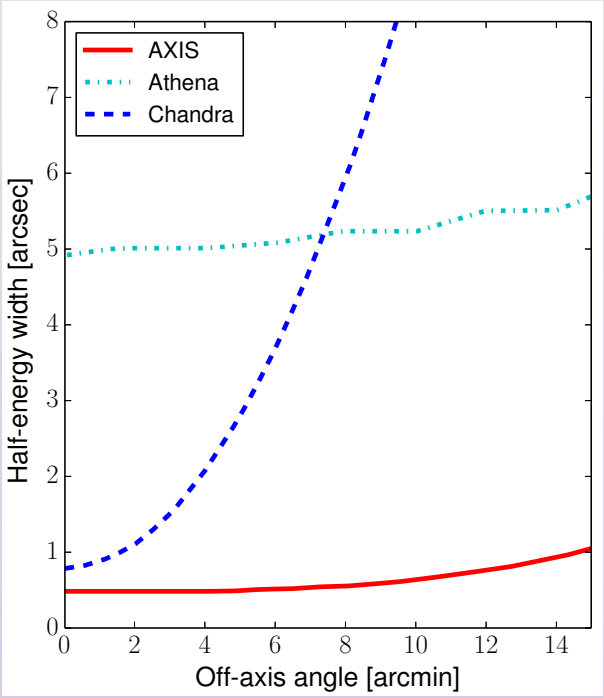
- In particular *Chandra* (only sub-arcsecond X-ray instrument) has seen a significant worsening in effective area below 1 keV, which strongly limits its efficiency as a survey instrument.
- An "XMM-*Newton* 2.0" is being developed (*Athena*), but no X-ray instrument with *Chandra*-like spatial resolution has been cleared for development.

AXIS and *Athena*: a possible bright X-ray future

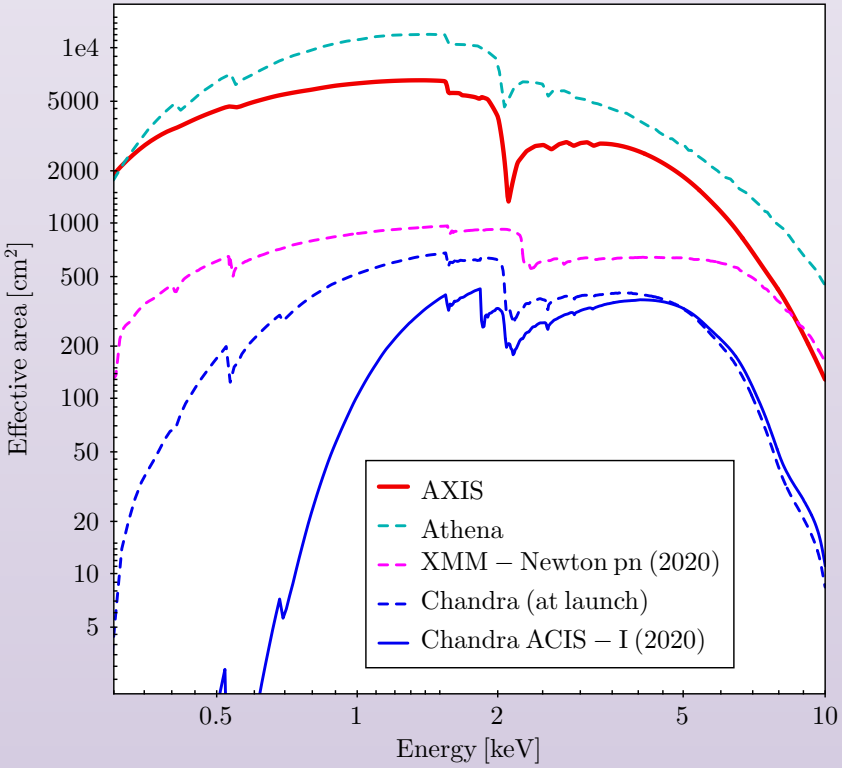
AXIS

- Probe mission (cost <1 B$)
- Feasibility study funded by NASA.
- White paper (https://ui.adsabs.harvard.edu/abs/2019BAAS...51g.107M/abstract) submitted to NASA 2020 Decadal Survey.
- Subarcsecond resolution over wide (24′x24′) field of view.
- Large effective area.



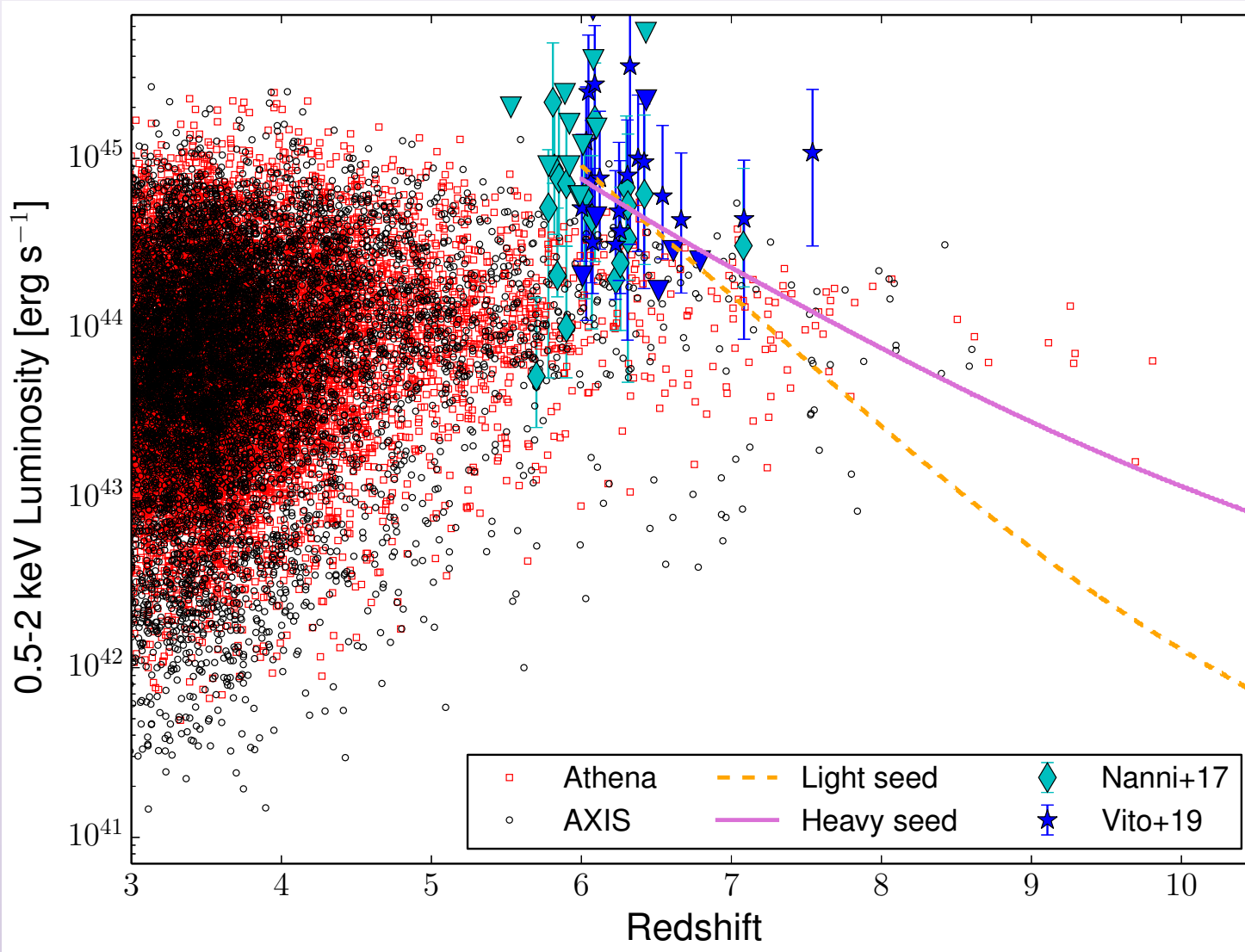
Athena

- *Athena*: next ESA X-ray observatory.
- Expected launch: early 2030s.
- Survey instrument: Wide Field Imager
- Excellent effective area and field of view (40′ radius): ideal for surveys.
- Good PSF (5-10″), stable even at large off-axis angles.



Science with AXIS and *Athena*: the high-*z* Universe

- Up to 20,000 z>3 AGN (<500 in current X-ray surveys combined!)



Marchesi et al. (2020)

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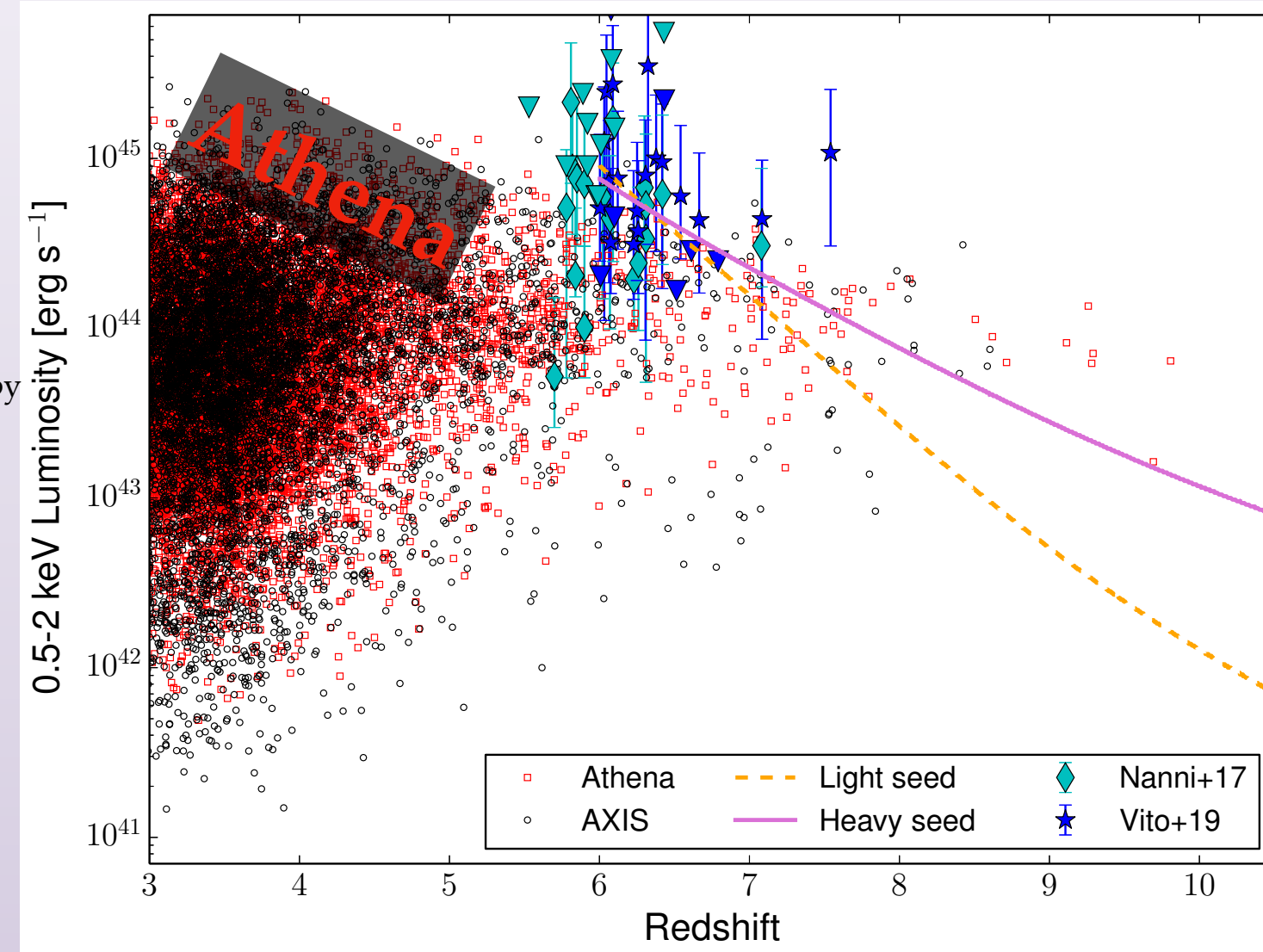

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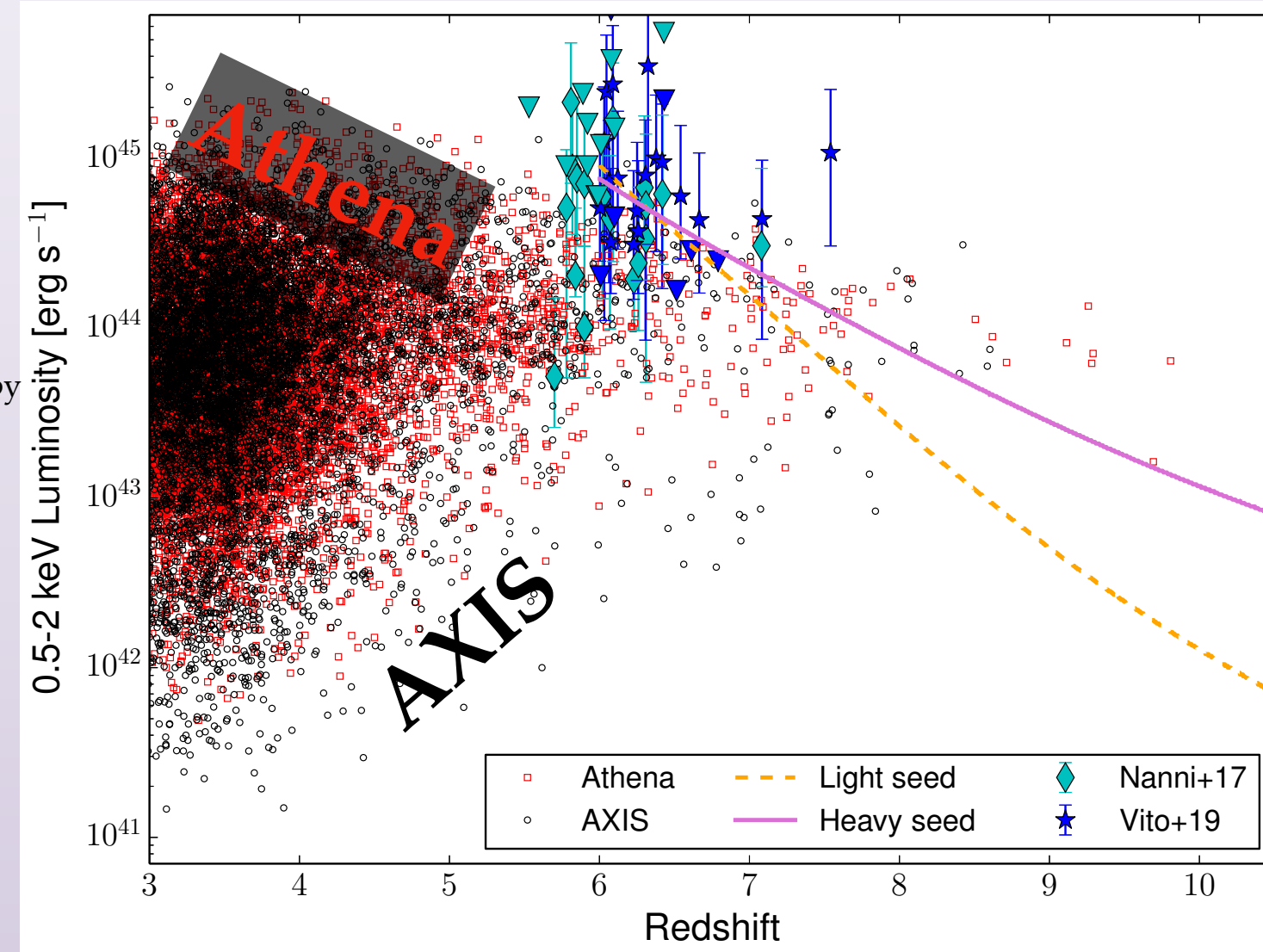

Marchesi et al. (2020)

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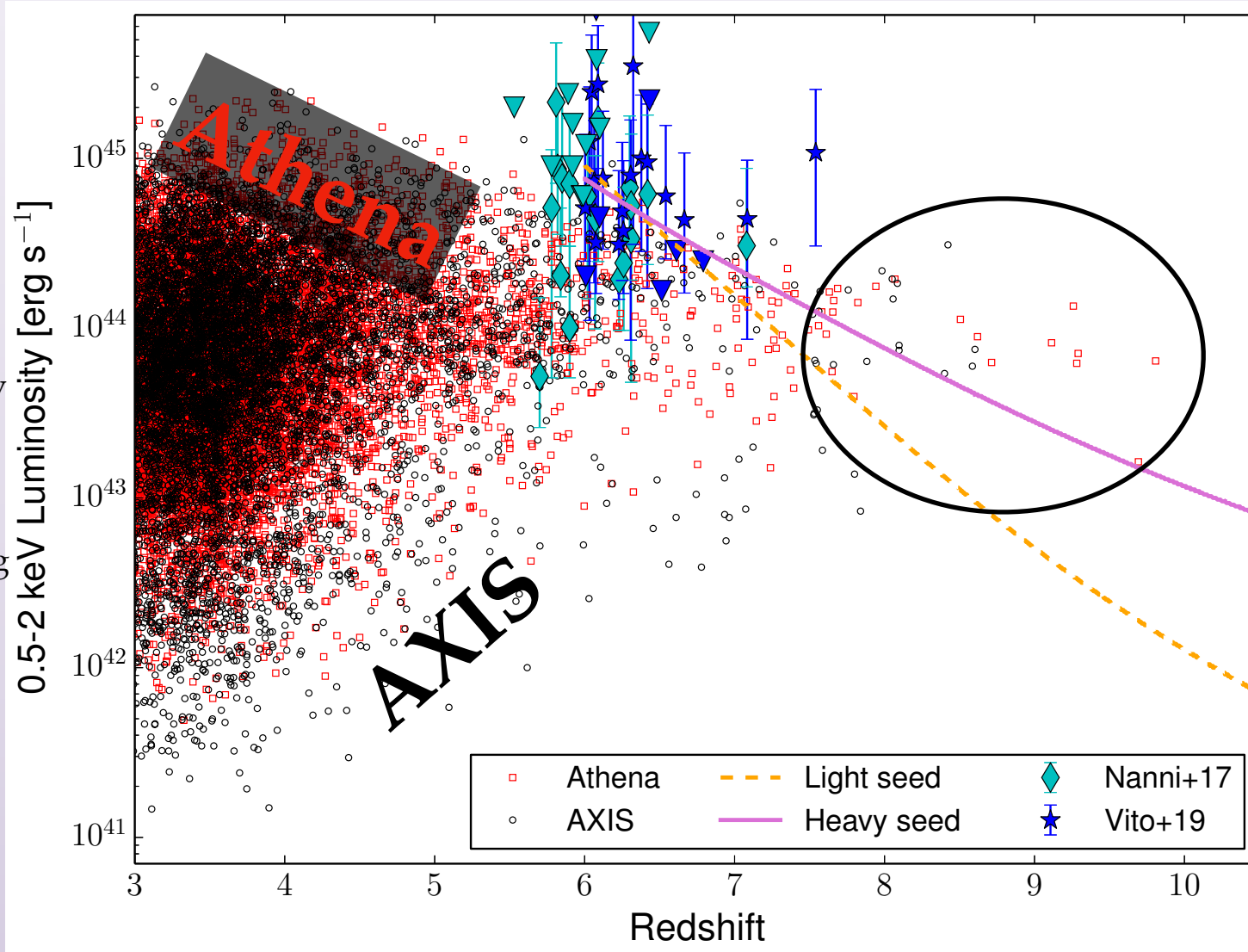
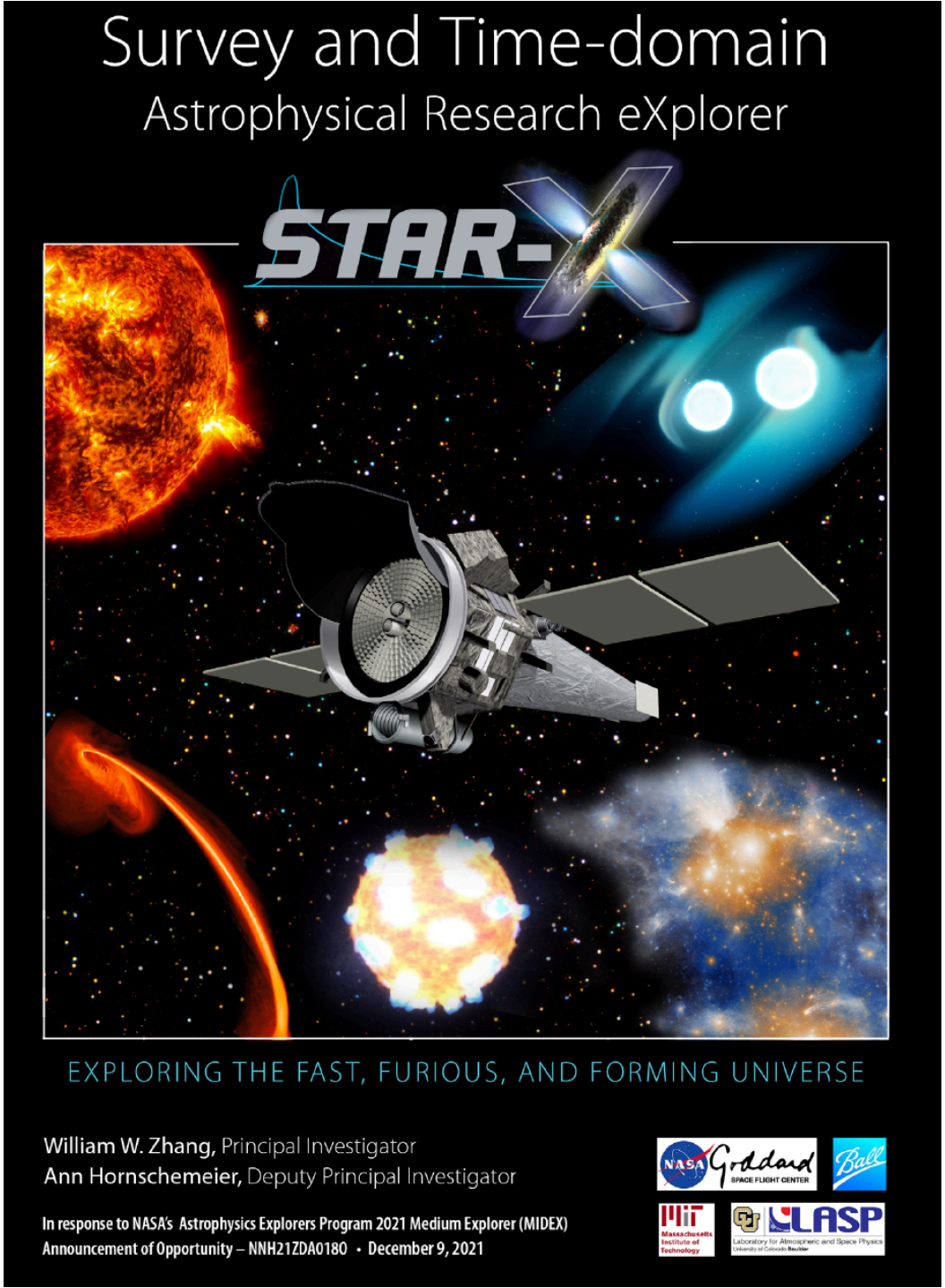
- Excellent complementarity: more sources (and generally more counts) detected by Athena
- Less luminous objects detected by AXIS.
- Tracking of first accreting BH seeds up to z~8-9: a whole new science.

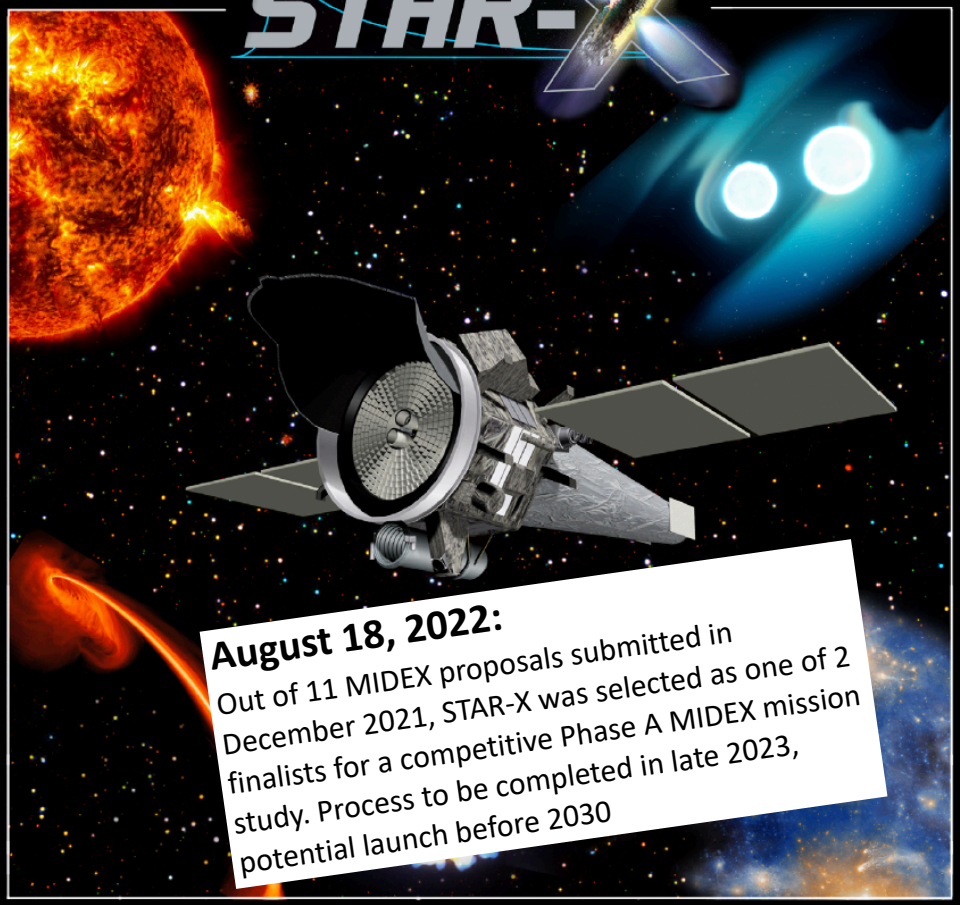


Marchesi et al. (2020)



Courtesy A. Hornschemeier

Survey and Time-domain Astrophysical Research eXplorer



EXPLORING THE FAST, FURIOUS, AND FORMING UNIVERSE

William W. Zhang, Principal Investigator
Ann Hornschemeier, Deputy Principal Investigator

In response to NASA's Astrophysics Explorers Program 2021 Medium Explorer (MIDEX) Announcement of Opportunity – NNH21ZDA018O • December 9, 2021

Courtesy A. Hornschemeier

STAR-X

Survey and Time-domain Astrophysical Research eXplorer

Exploring the Fast, Furious, and Forming Universe

The STAR-X Science Story

The FAST: Locally rare, brief events have an outsized impact on the Universe.

Supernova Explosion

The heavy elements needed for life are synthesized in and dispersed by supernovae and neutron star mergers. Similarly, a single stellar superflare can evaporate an ocean or catalyze prebiotic pathways. The STAR-X wide field UV/X-ray design and fast and flexible operations captures these events.

The FURIOUS: Black holes grow extremely rapidly at early times in the Universe and are critical to galaxy evolution.

Tidal Disruption Event (TDE)

STAR-X will uniquely probe the physics of rapid accretion that allowed massive black holes to grow so quickly in the early Universe. STAR-X will catch transient, extreme black hole feeding events, such as TDEs, where entire stars are disrupted.

The FORMING: Distant galaxy clusters provide maximal leverage in evolutionary studies of structure formation and chemical enrichment.

Clusters of Galaxies

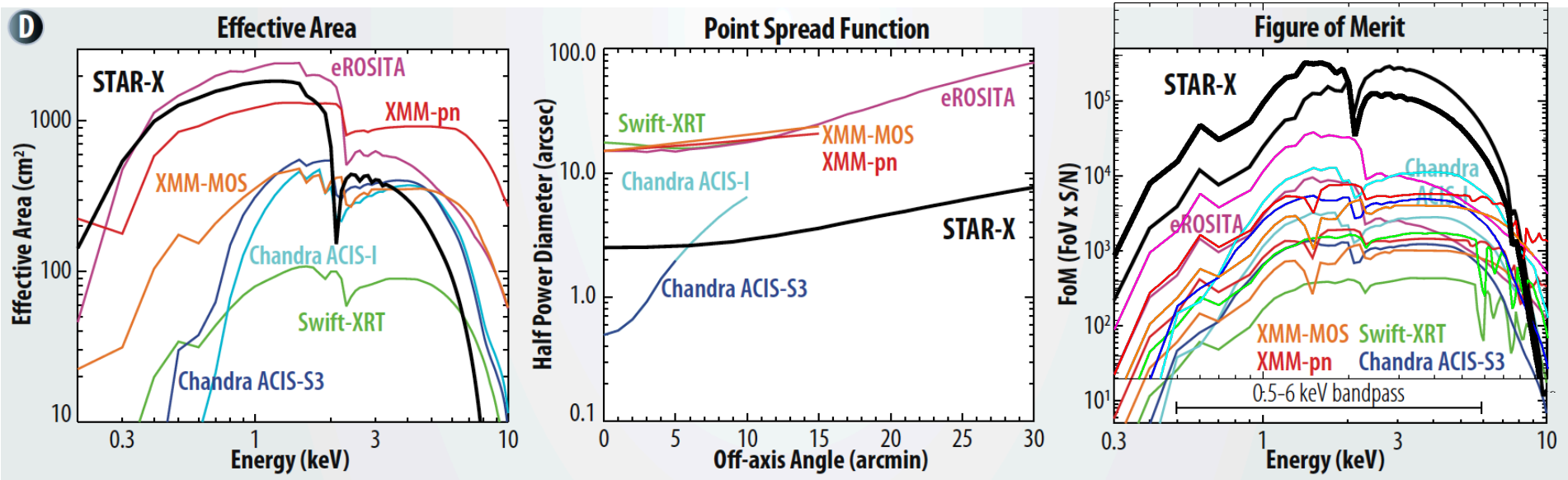
STAR-X will conduct deep surveys and discover the elusive diffuse emission from the largest bound objects in the Universe (clusters of galaxies), shortly after their birth. STAR-X's combination of excellent imaging and low particle background (due to orbit choice) makes this possible in a way that no other mission can.

Ann Hornschemeier NASA Goddard Space Flight Center

Courtesy A. Hornschemeier

Key Features of the X-ray Telescope

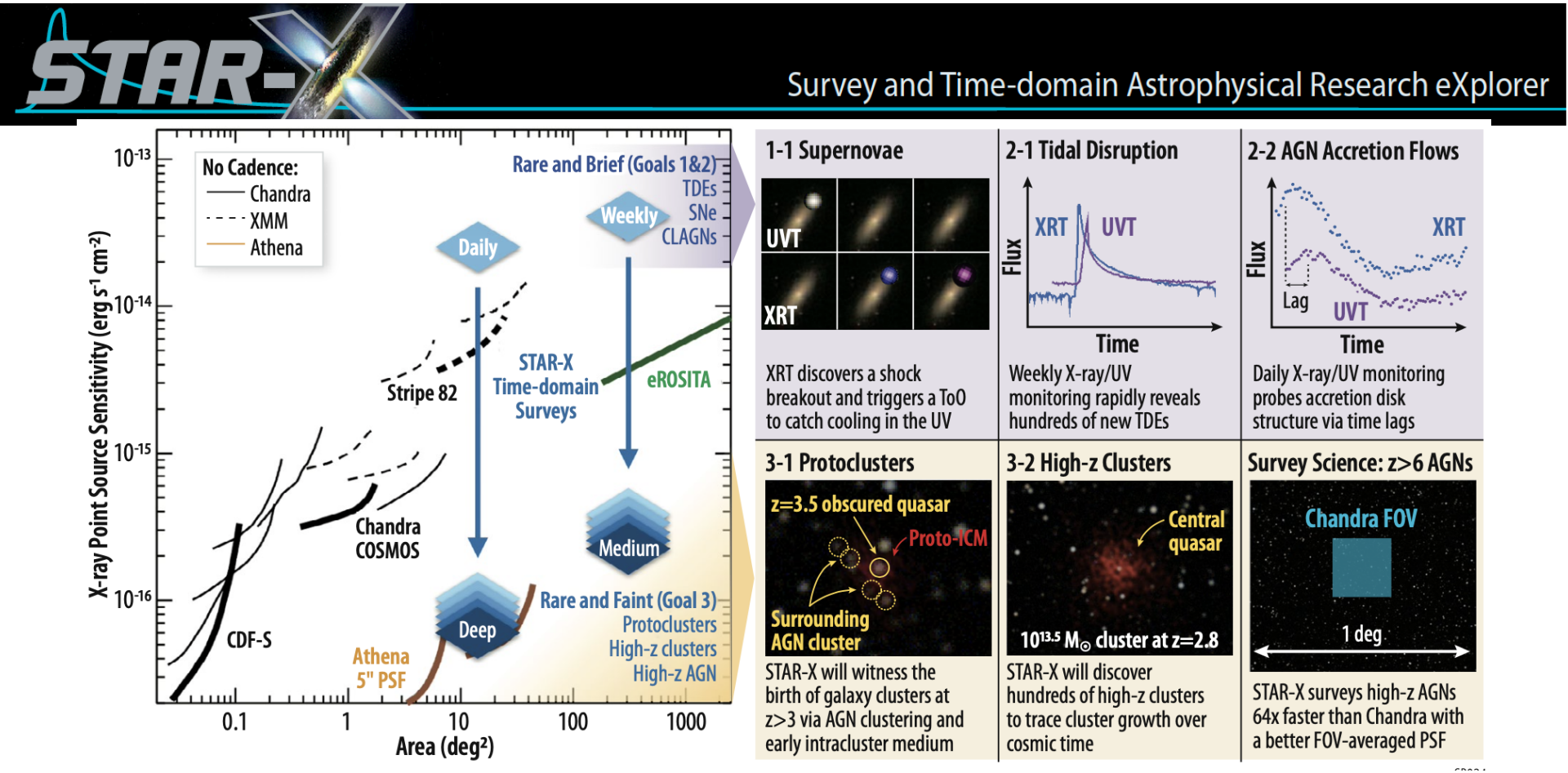
- Excellent PSF: 2.5” on-axis, 8” 0.5-deg off-axis.
- Large FOV: 1 deg^2.
- Large effective area: >1,800 cm^2 at 1 keV.
- Low particle background.



Ann Hornschemeier NASA Goddard Space Flight Center

Courtesy A. Hornschemeier

Survey Strategy



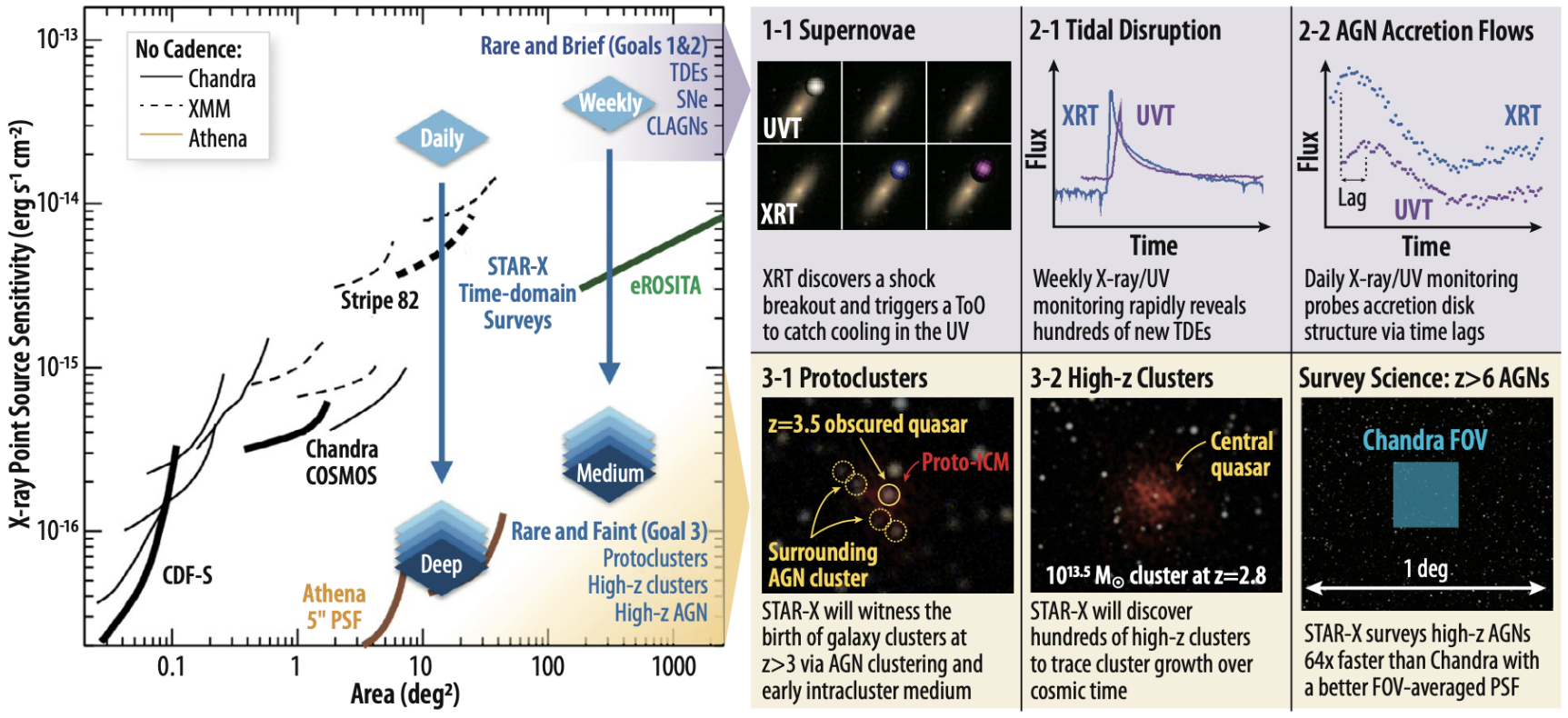
STAR-X finds rare and brief events and rare and faint high-z objects

Courtesy A. Hornschemeier

Survey Strategy

STAR-X

Survey and Time-domain Astrophysical Research eXplorer



STAR-X finds rare and brief events and rare and faint high-z objects

Final depths: MEDIUM: 3×10^{-16} cgs over 300 deg^2 (~100 Chandra COSMOS fields)
DEEP: 7×10^{-17} cgs over 12 deg^2

Courtesy A. Hornschemeier

This Lab Outline

1. **Understand the parameters affecting the source catalog**: We will provide to you a series of catalogs performed using different detection parameter setups. Visualise 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) Explore different source catalogs

Lab Outline
1) Explore different source catalogs

a. We ran for you the wavdetect tool to search sources in a set of observations, using different significance thresholds (i.e., your detections can be more or less reliable; test 1E-6; 1E-5; 1E-4) and different maximum wavelet scales (stop at 5.6 and at 11; important if there are extended sources and for objects in the external part of the field).

Lab Outline
1) Explore different source catalogs

a. We ran for
observation
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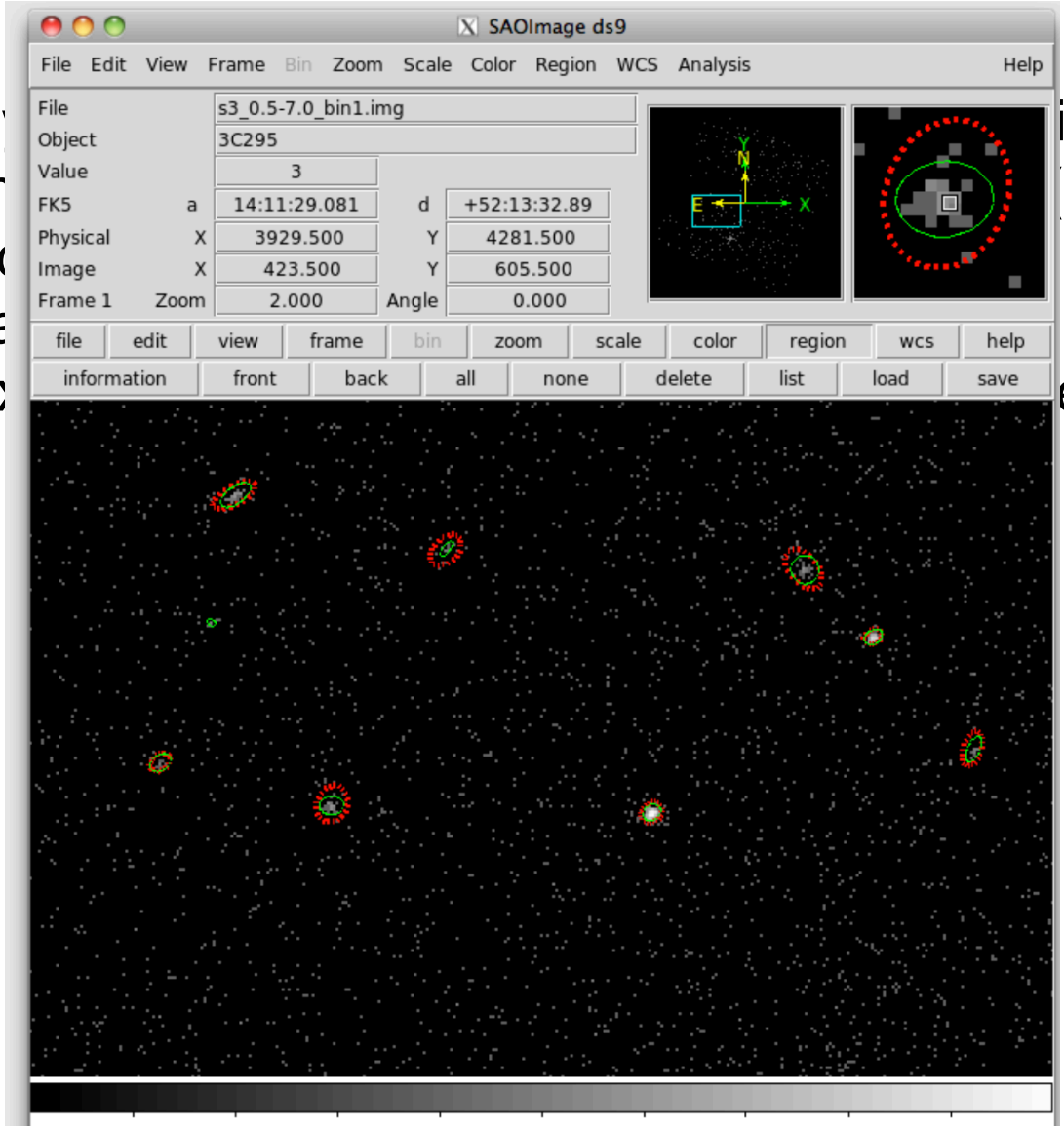

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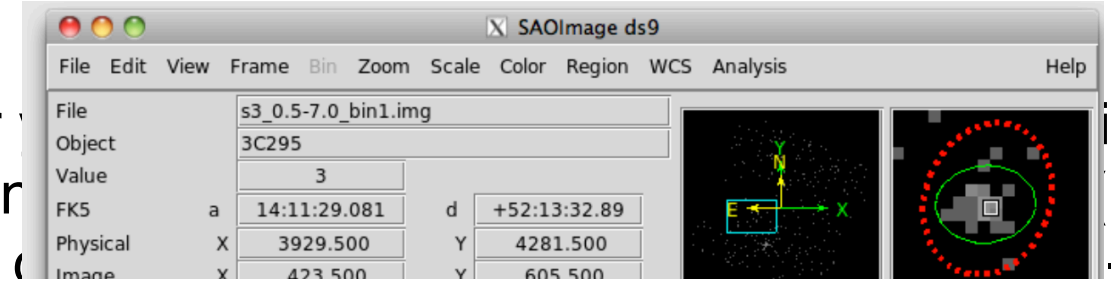


```
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pset wavdetect outfile=CDFS_4obs_merged_057keV_wavdet_1em6_src.fits
pset wavdetect scellfile=CDFS_4obs_merged_057keV_wavdet_1em6_cellimage.fits
pset wavdetect imagefile=CDFS_4obs_merged_057keV_wavdet_1em6_reconstructed.fits
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pset 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
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wavdetect clobber+ verbose=3
```

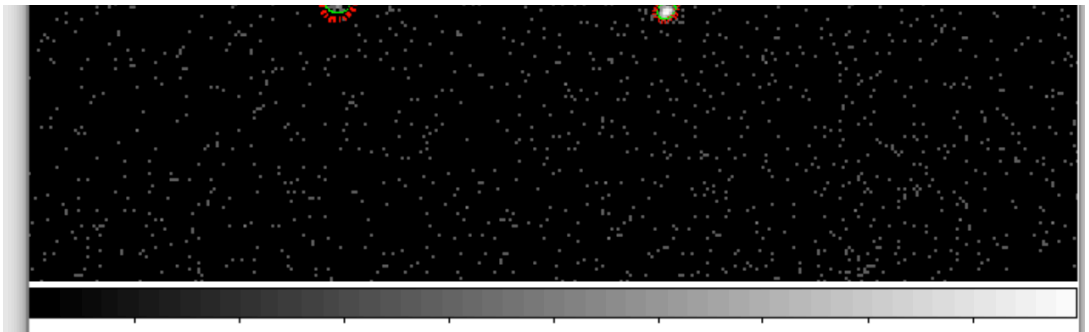

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1) Build the source catalog

a. 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)

b. Cross-correlate the source lists 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 the different catalogs and different 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 study their properties (e.g., number of counts, source significance, position in the field of view…) and their visual appearance: 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)

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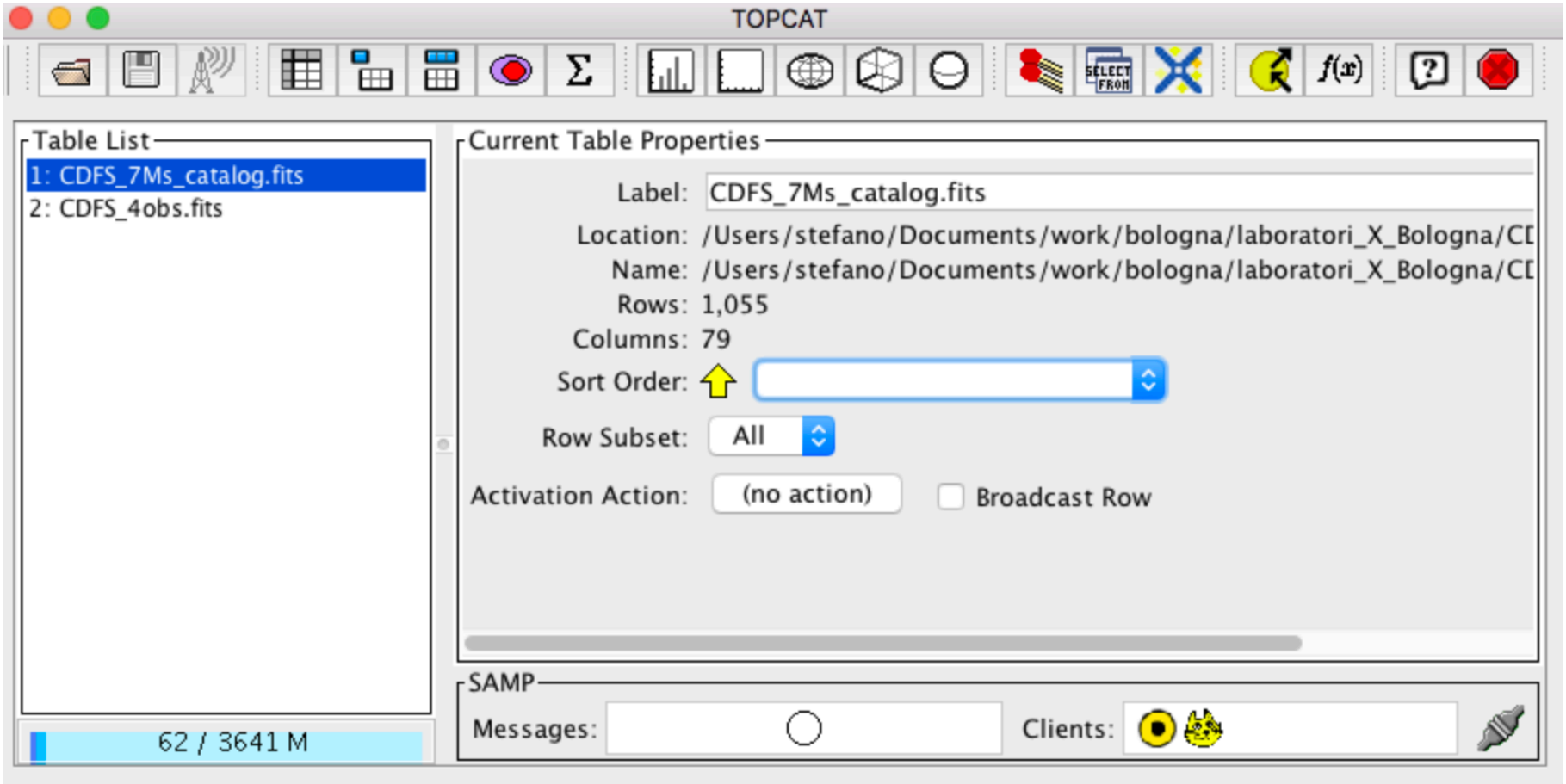

Lab Outline
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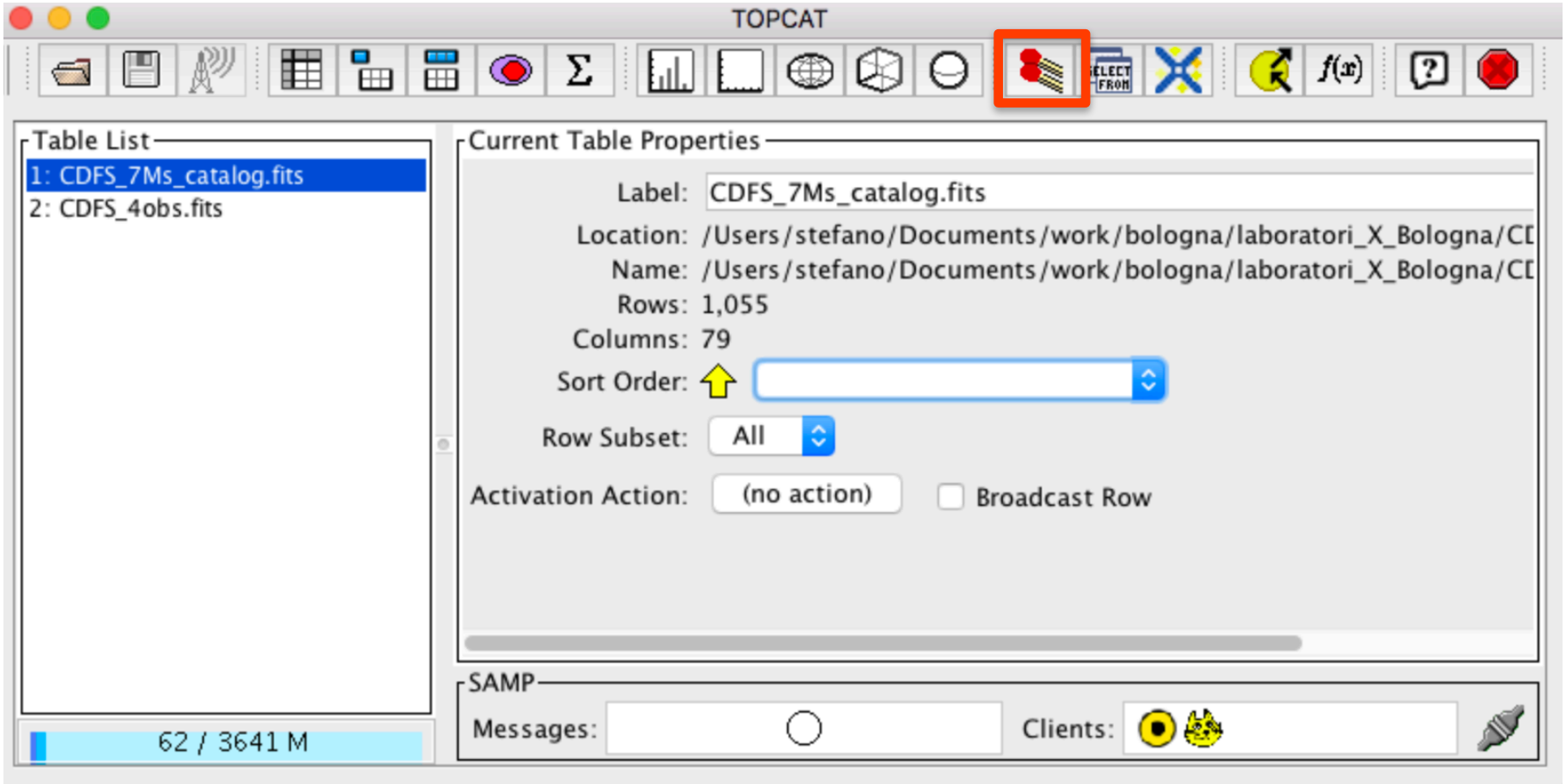
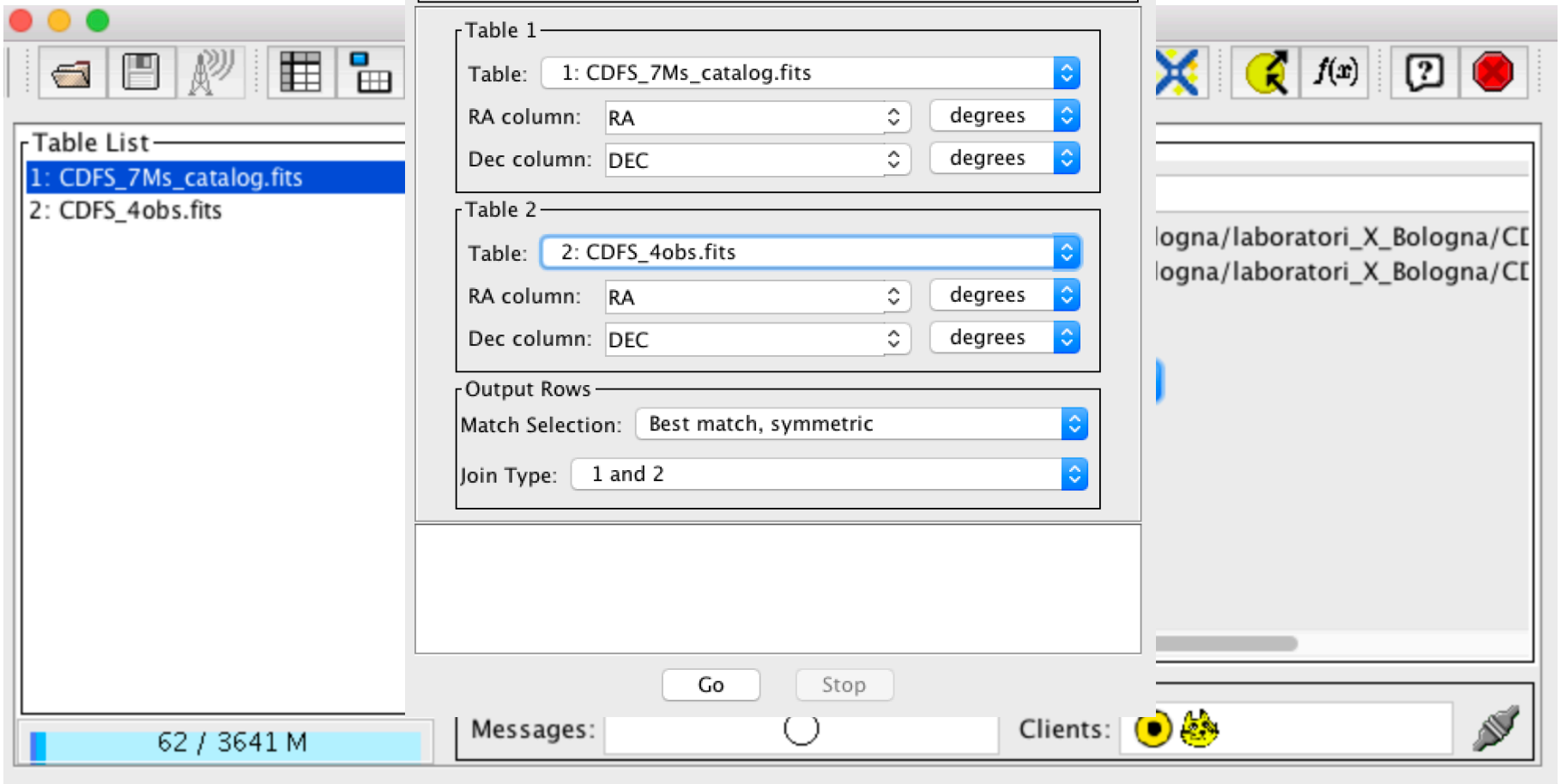


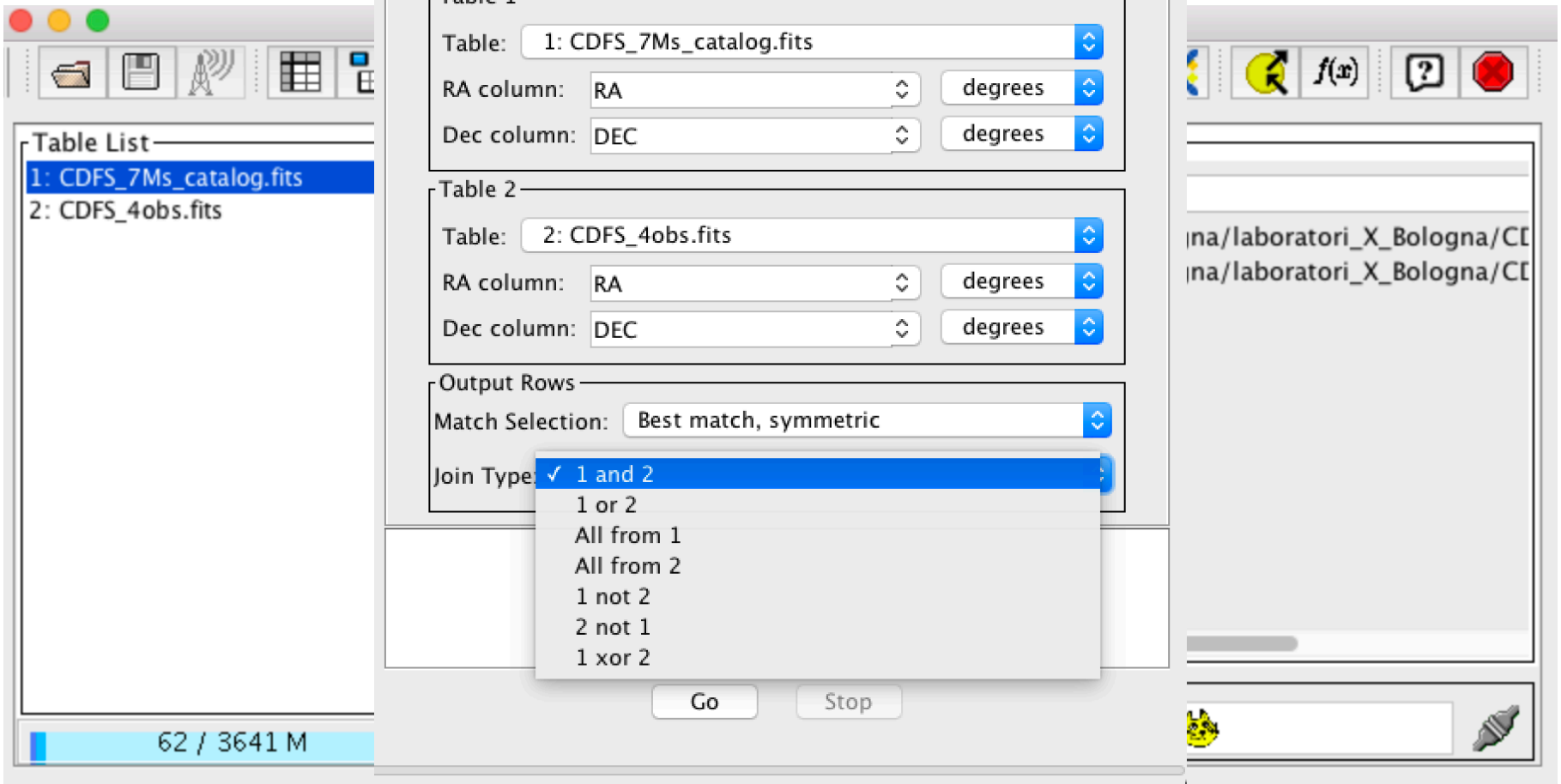
1) B alog

Cross-correlate t evious steps with the official 7 e CDF-S (Luo et al. 2017), using v 1,2,3 arcsec)



1) E log

Cross-correlate vious steps with the official CDF-S (Luo et al. 2017), using ,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.)

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b. For the sources associated with the 7Ms source catalog, produce the redshift distribution histogram, Lx vs. z plot, etc.

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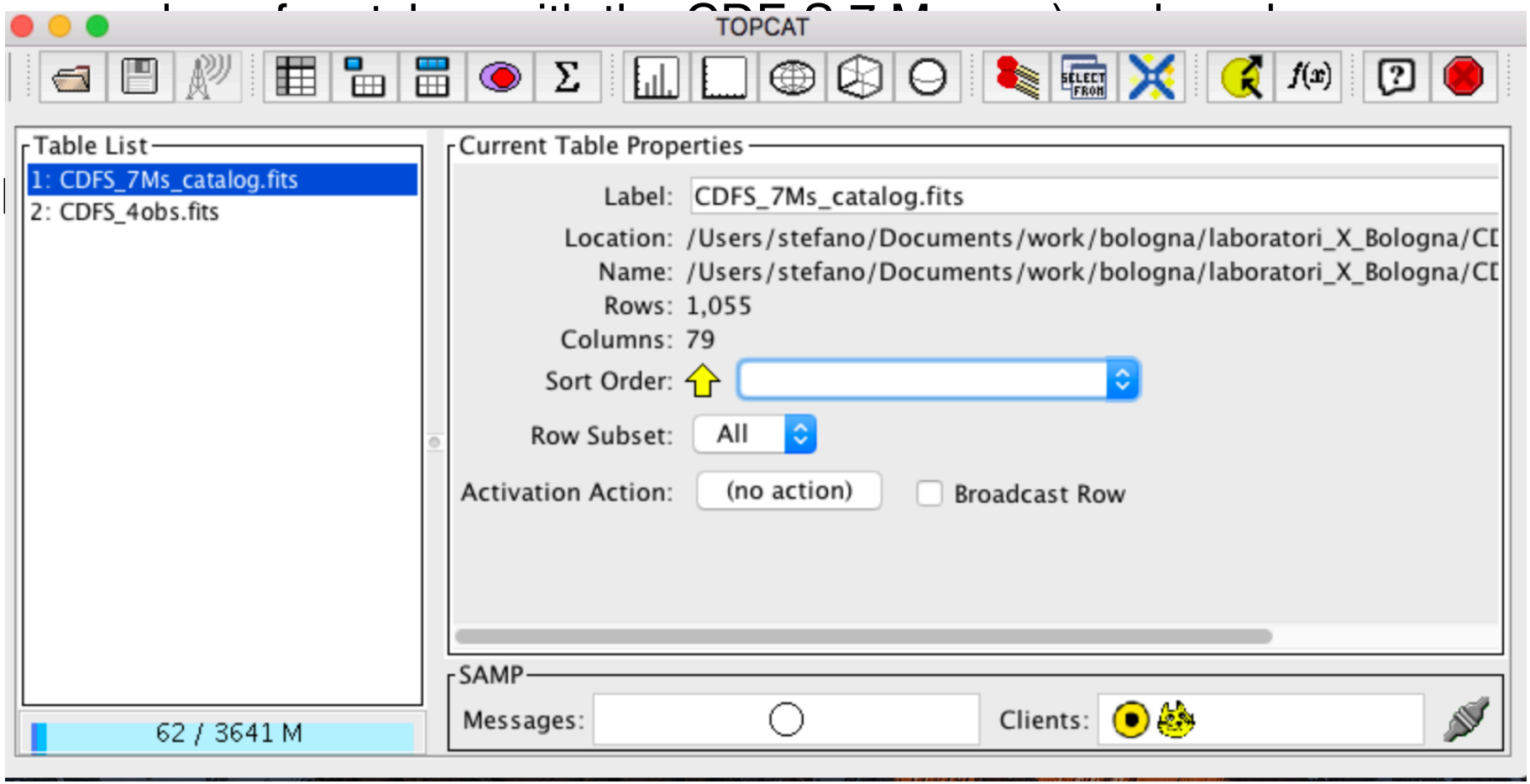

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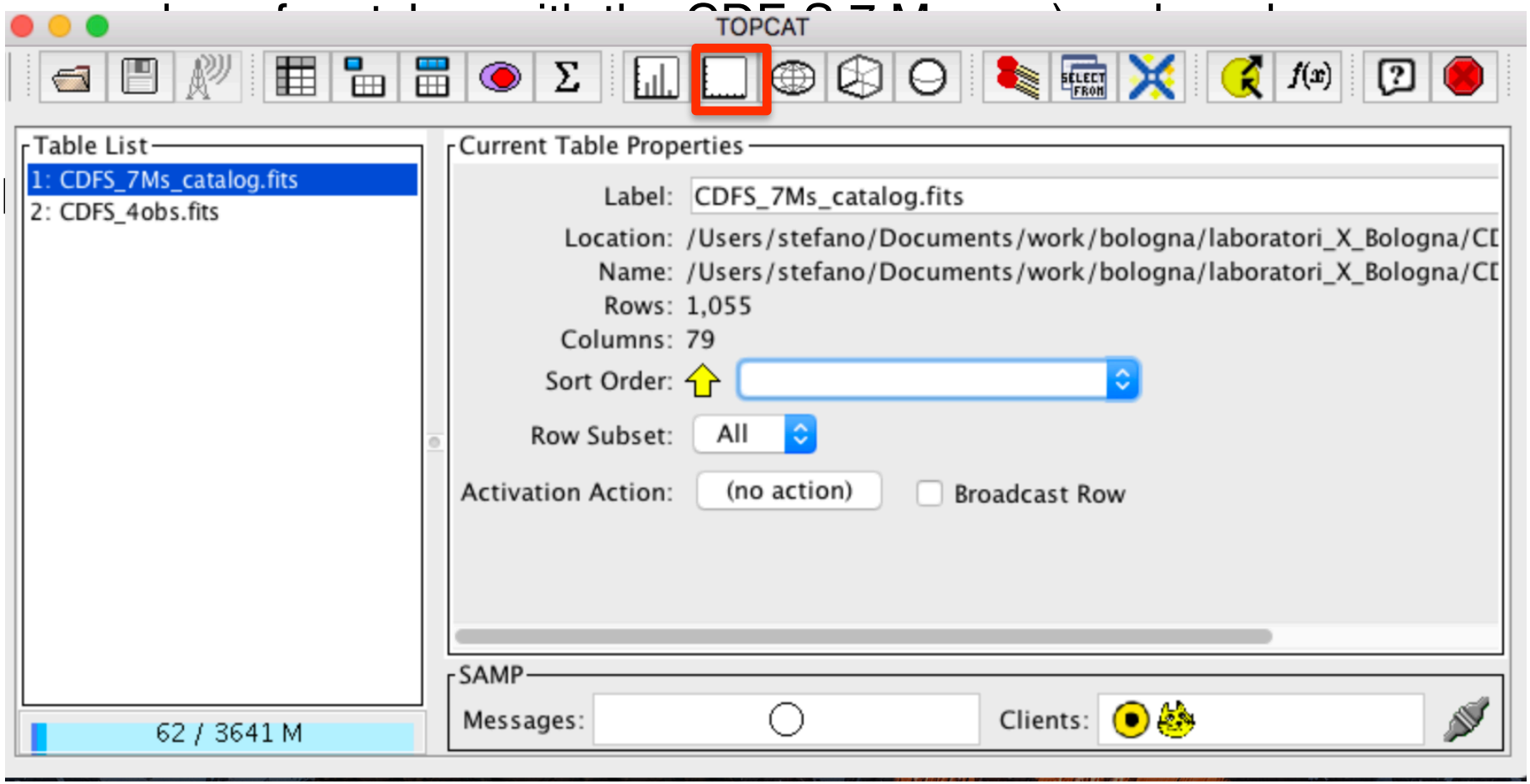
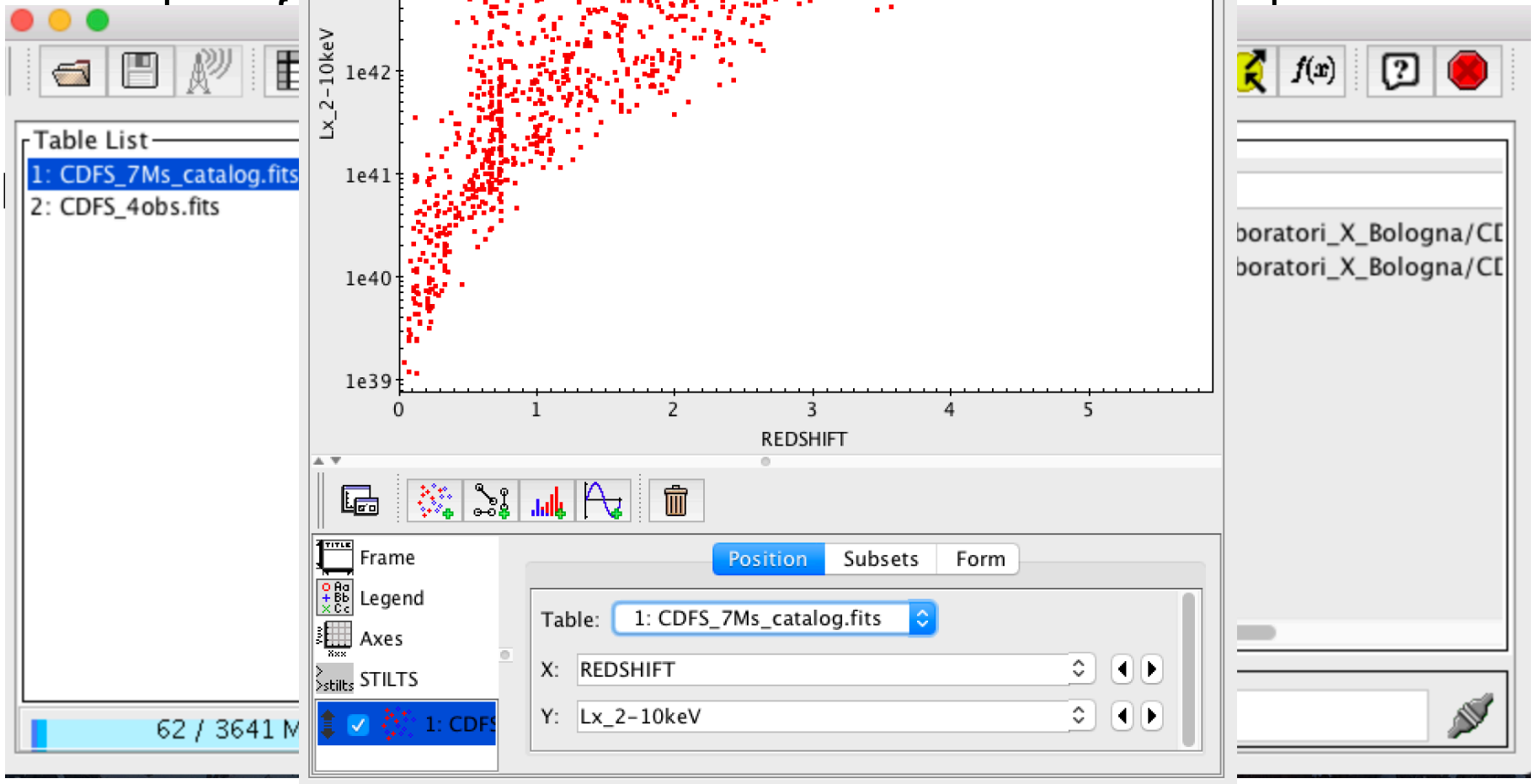


2) log

a. Choose on th largest



Lab Outline
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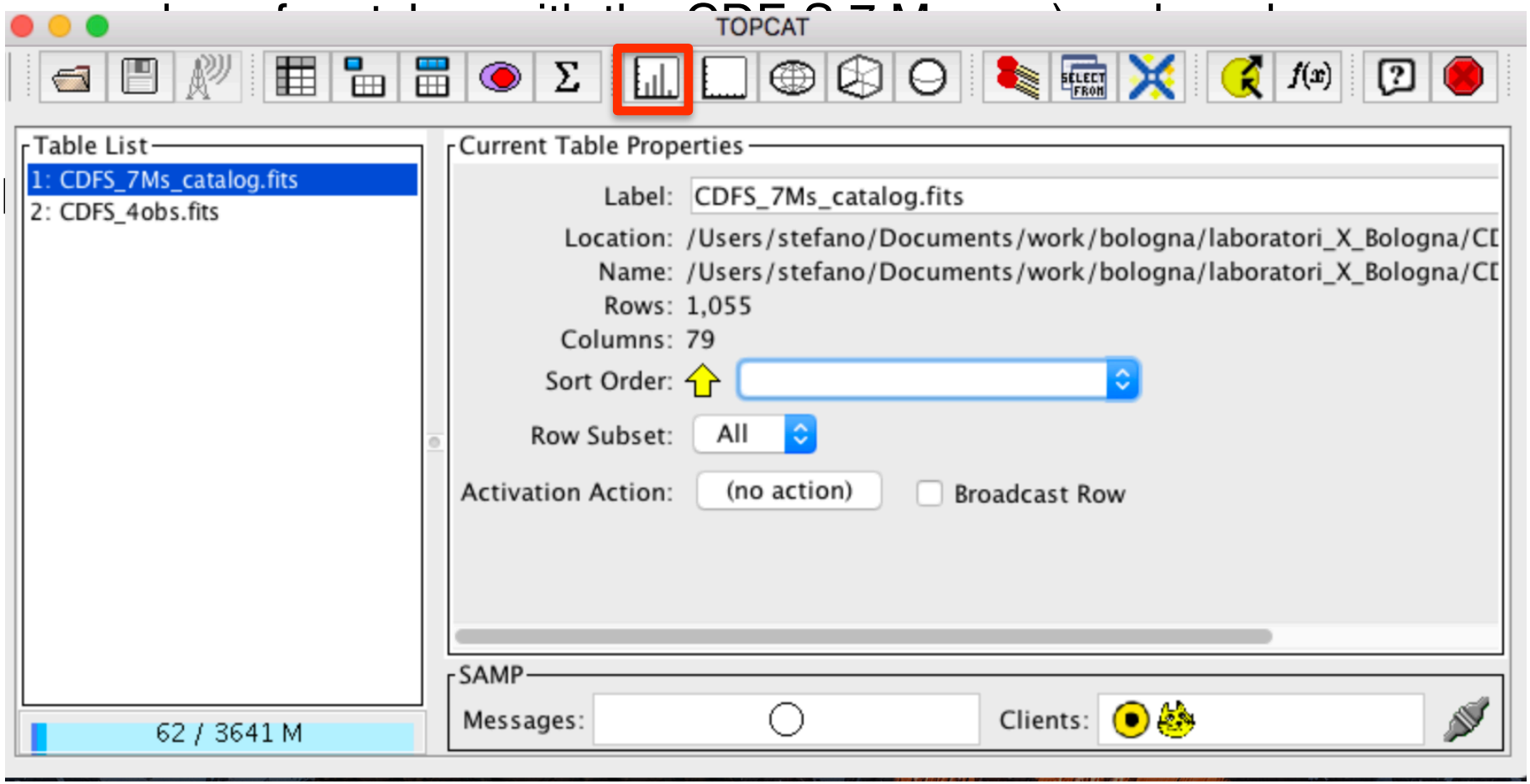
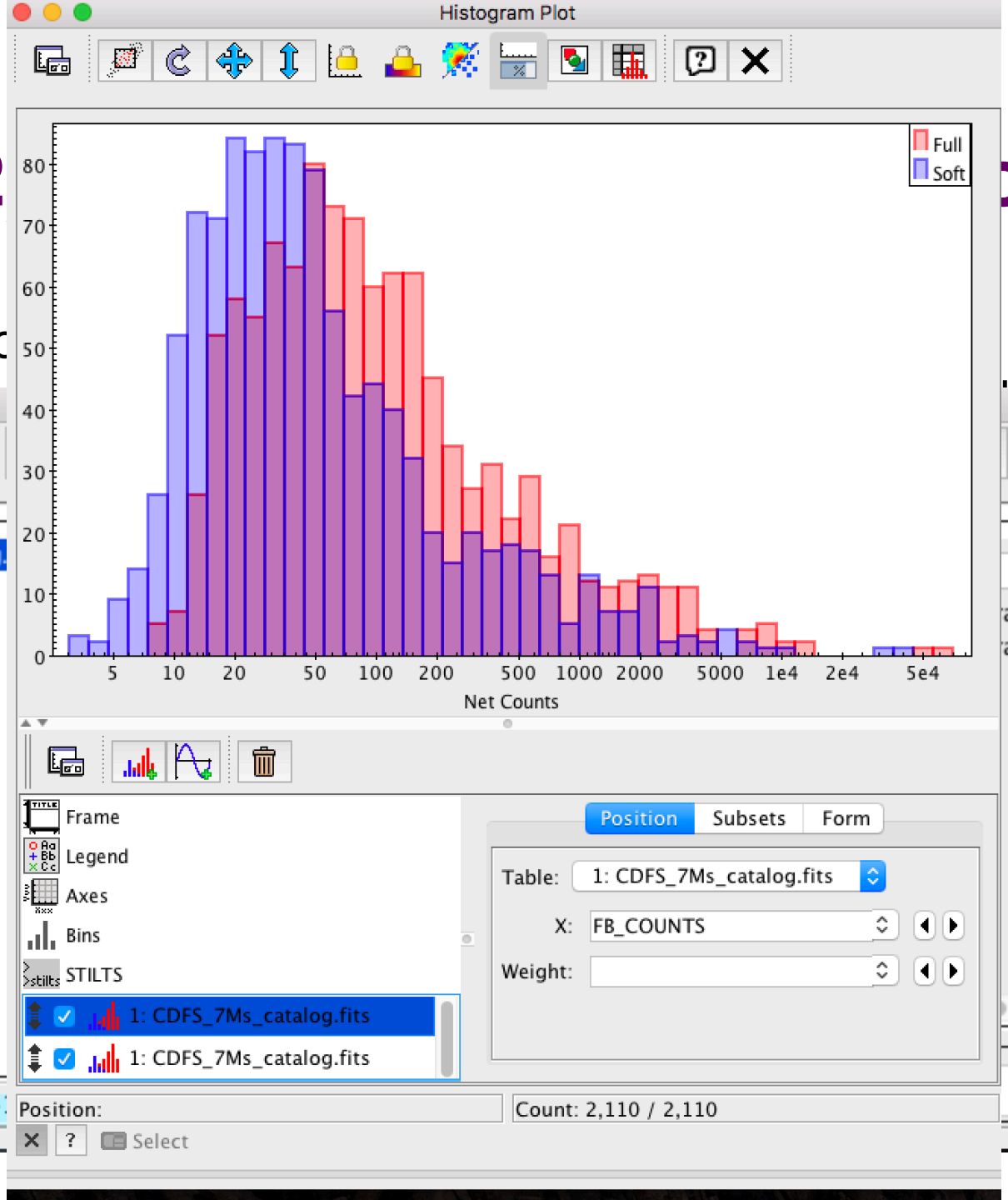


2 og

a. Choose c largest

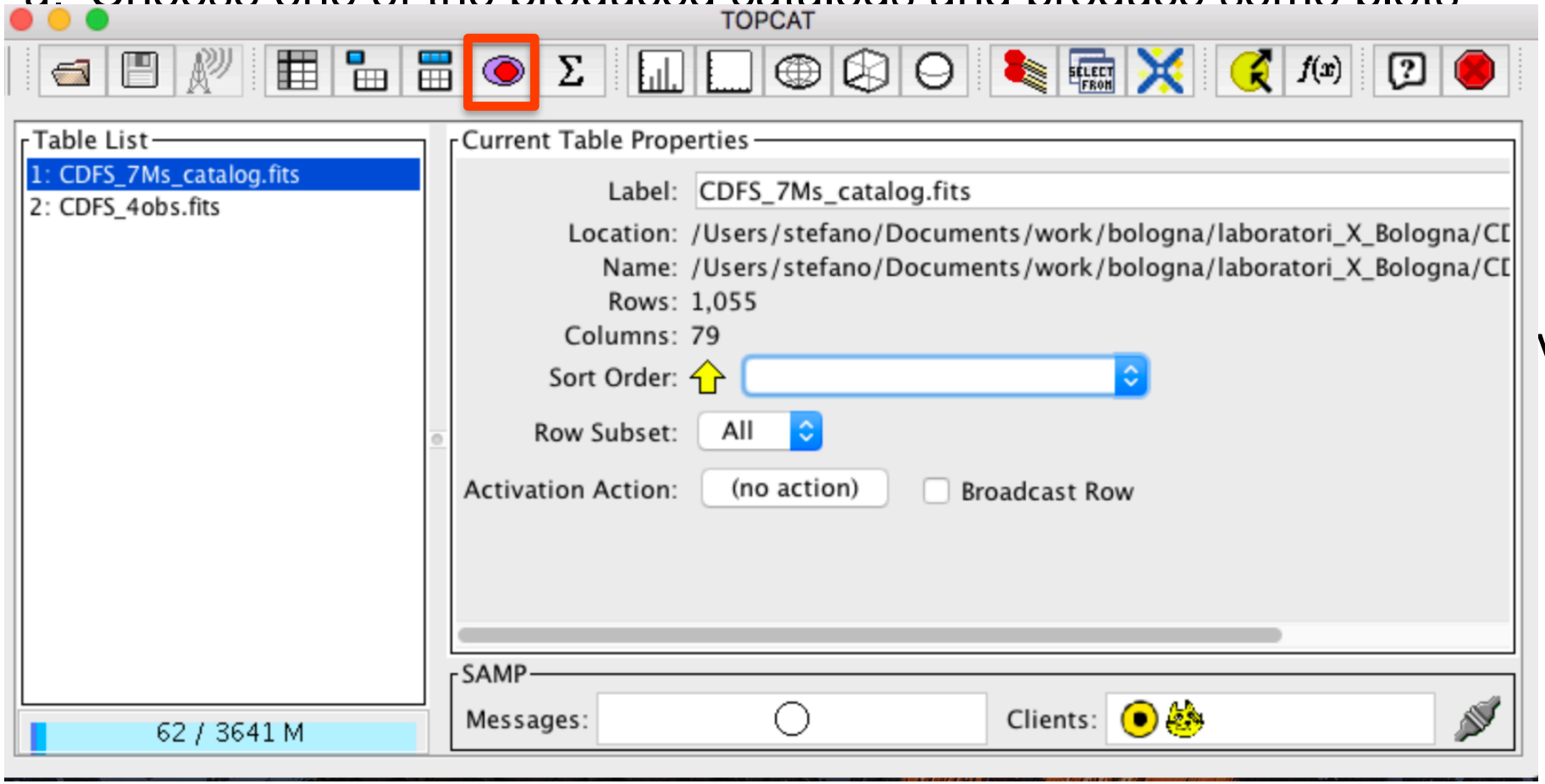


Lab Outline
2) Explore the source catalog

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, Lx 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

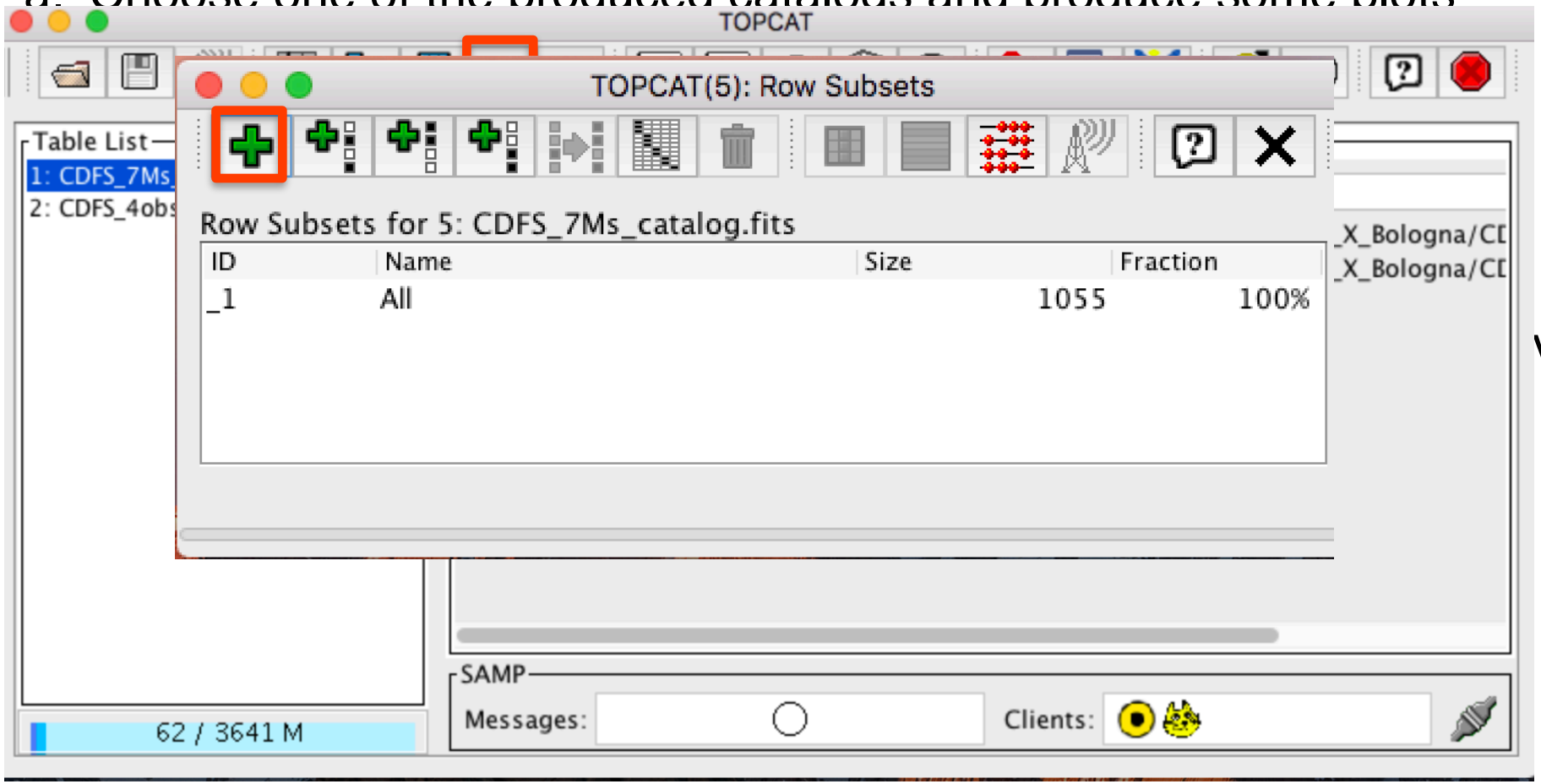
a. Choose one of the produced catalogs and produce some plots



vs

Lab Outline
2) Explore the source catalog

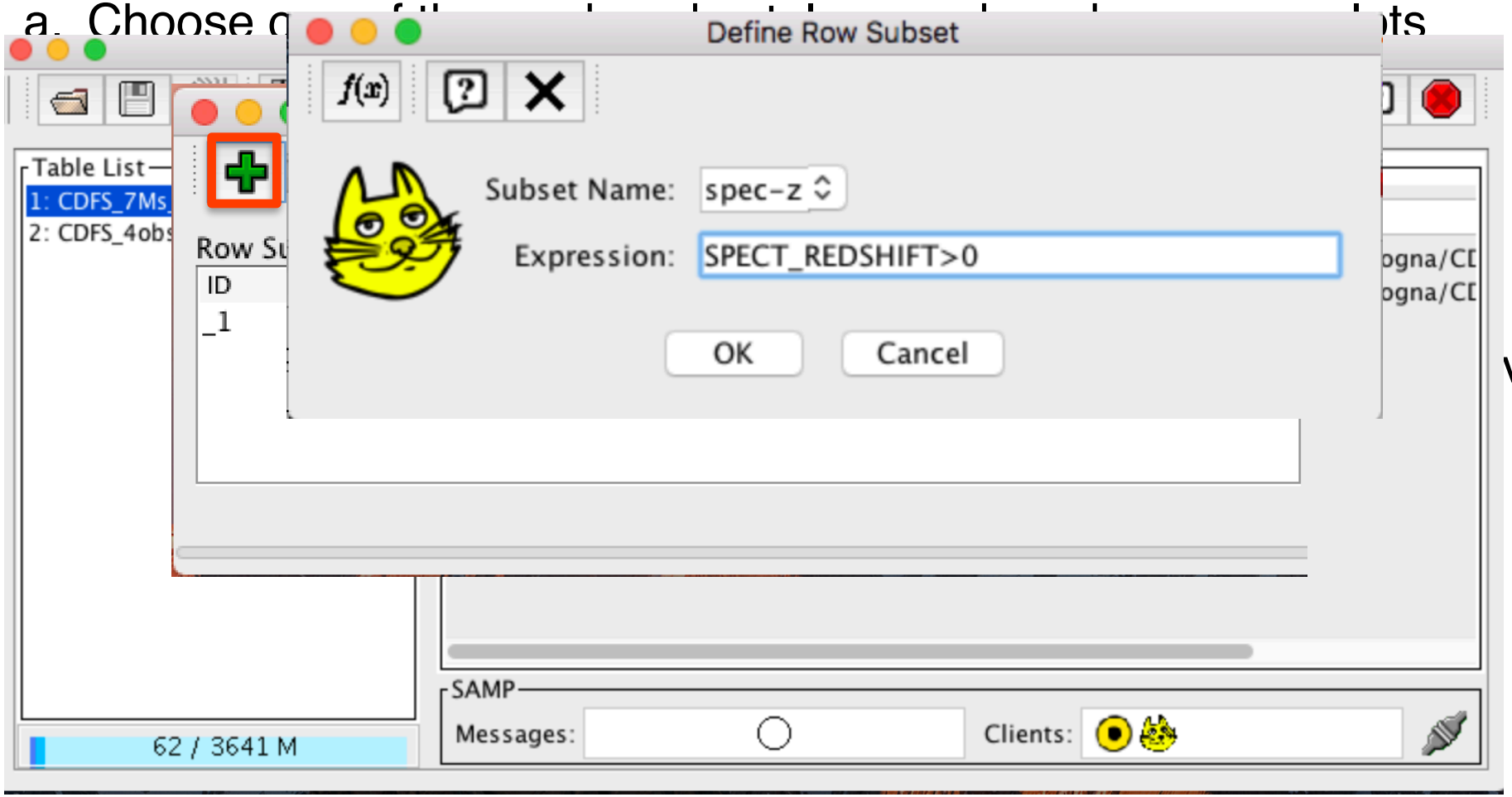
a. Choose one of the produced catalogs and produce some plots



vs

Lab Outline
2) Explore the source catalog

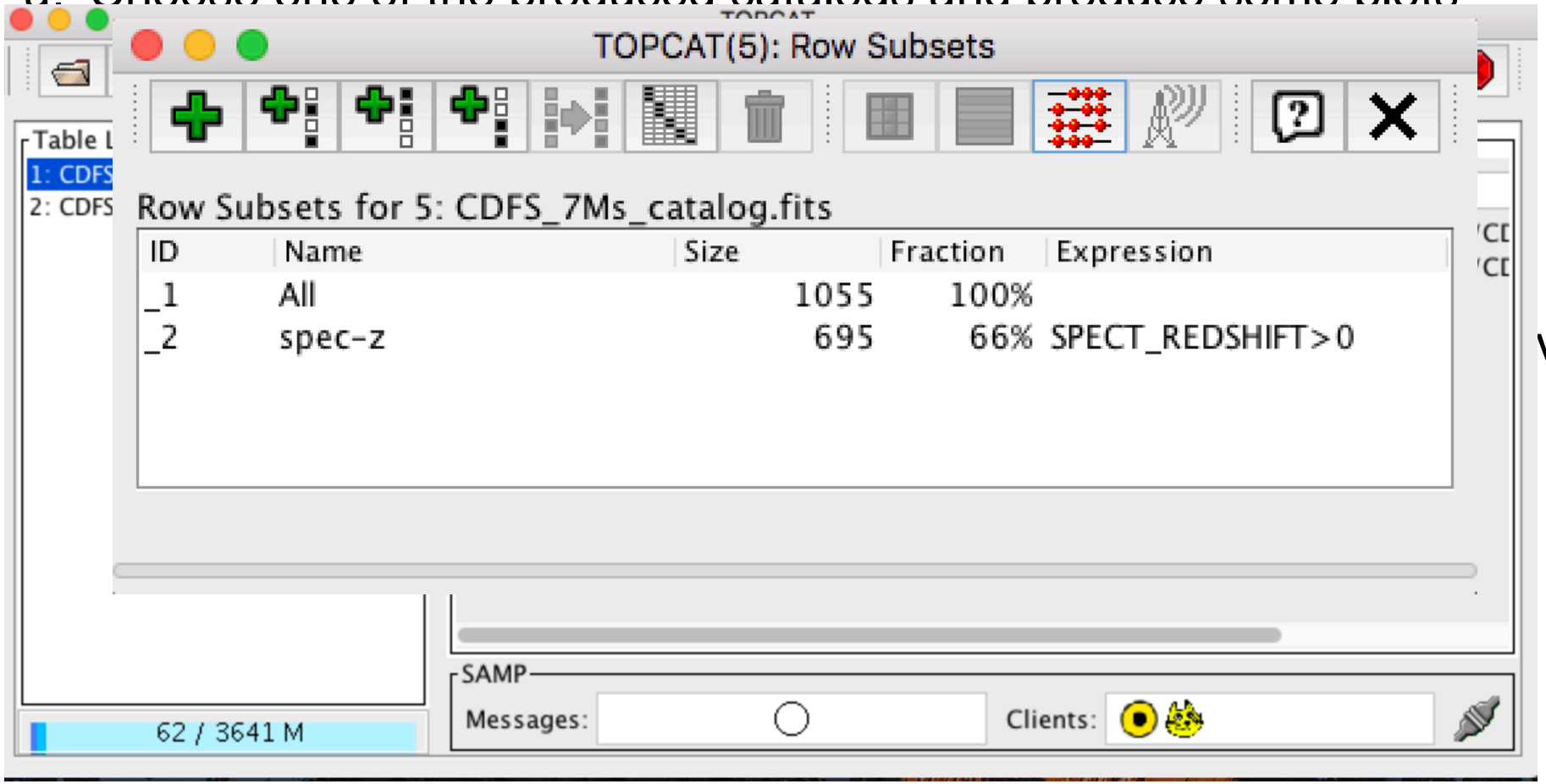
a. Choose o



vs

Lab Outline
2) Explore the source catalog

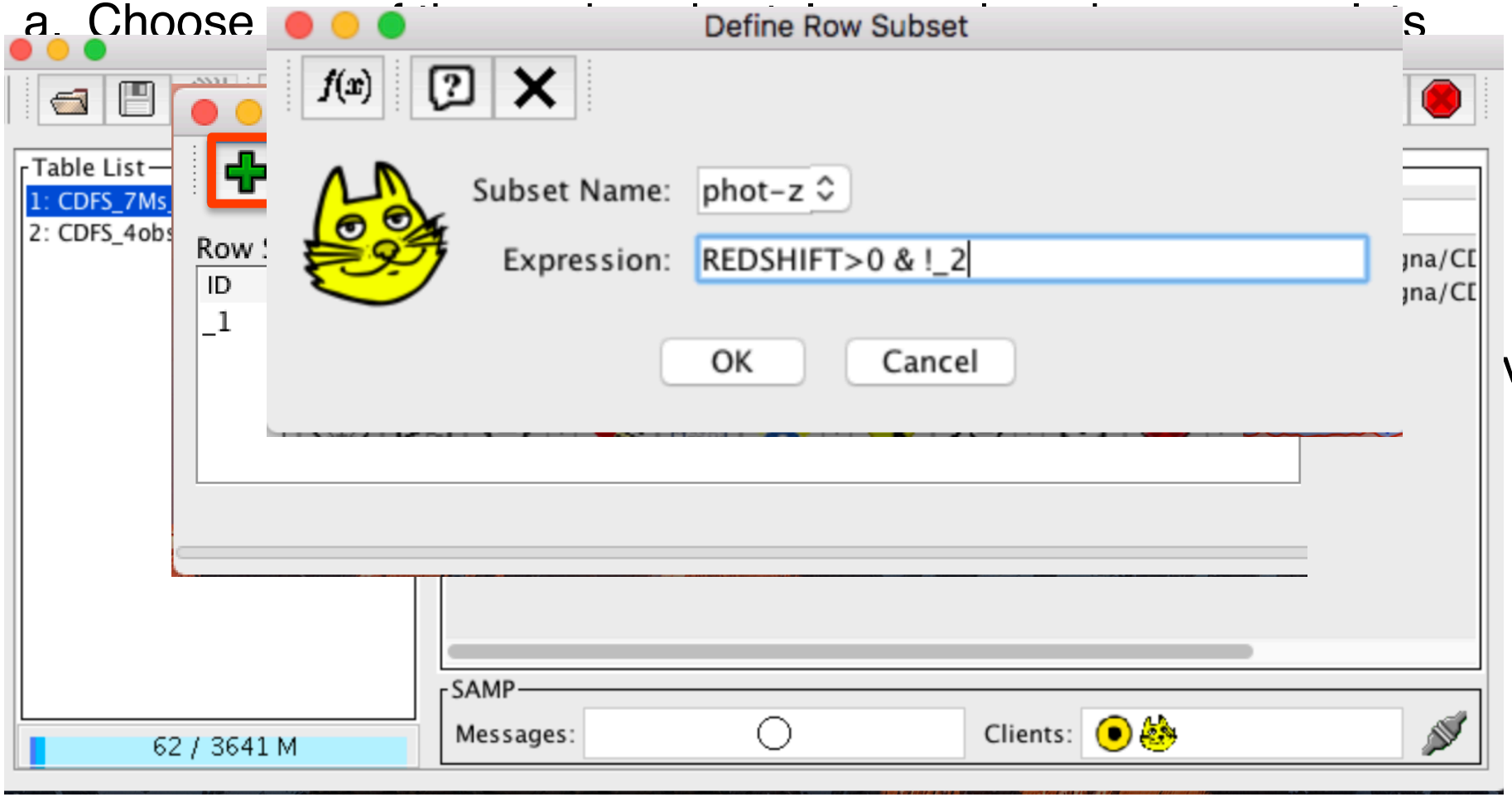
a. Choose one of the produced catalogs and produce some plots



vs

Lab Outline
2) Explore the source catalog

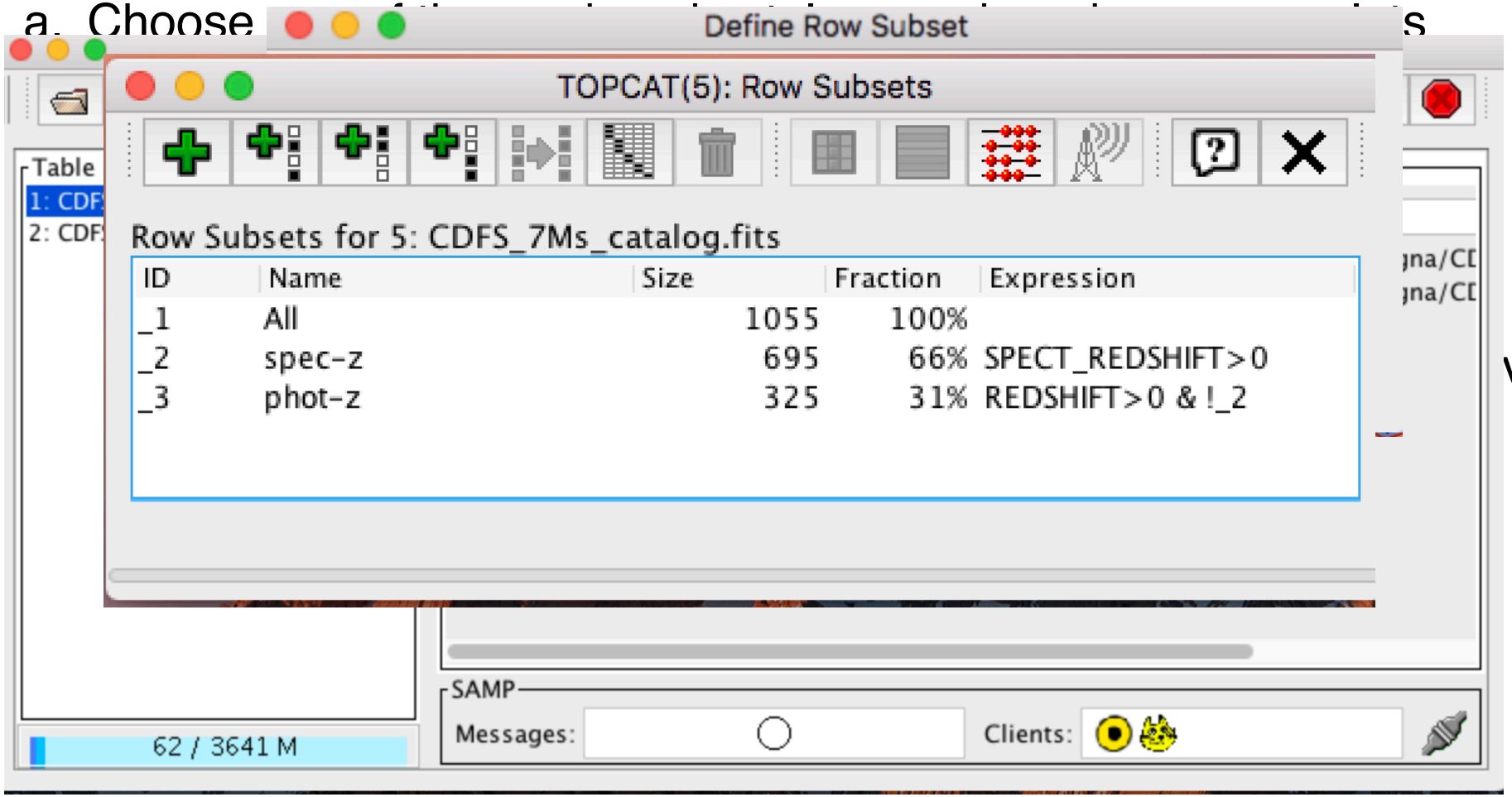
a. Choose s



vs

Lab Outline
2) Explore the source catalog

a. Choose



s

vs

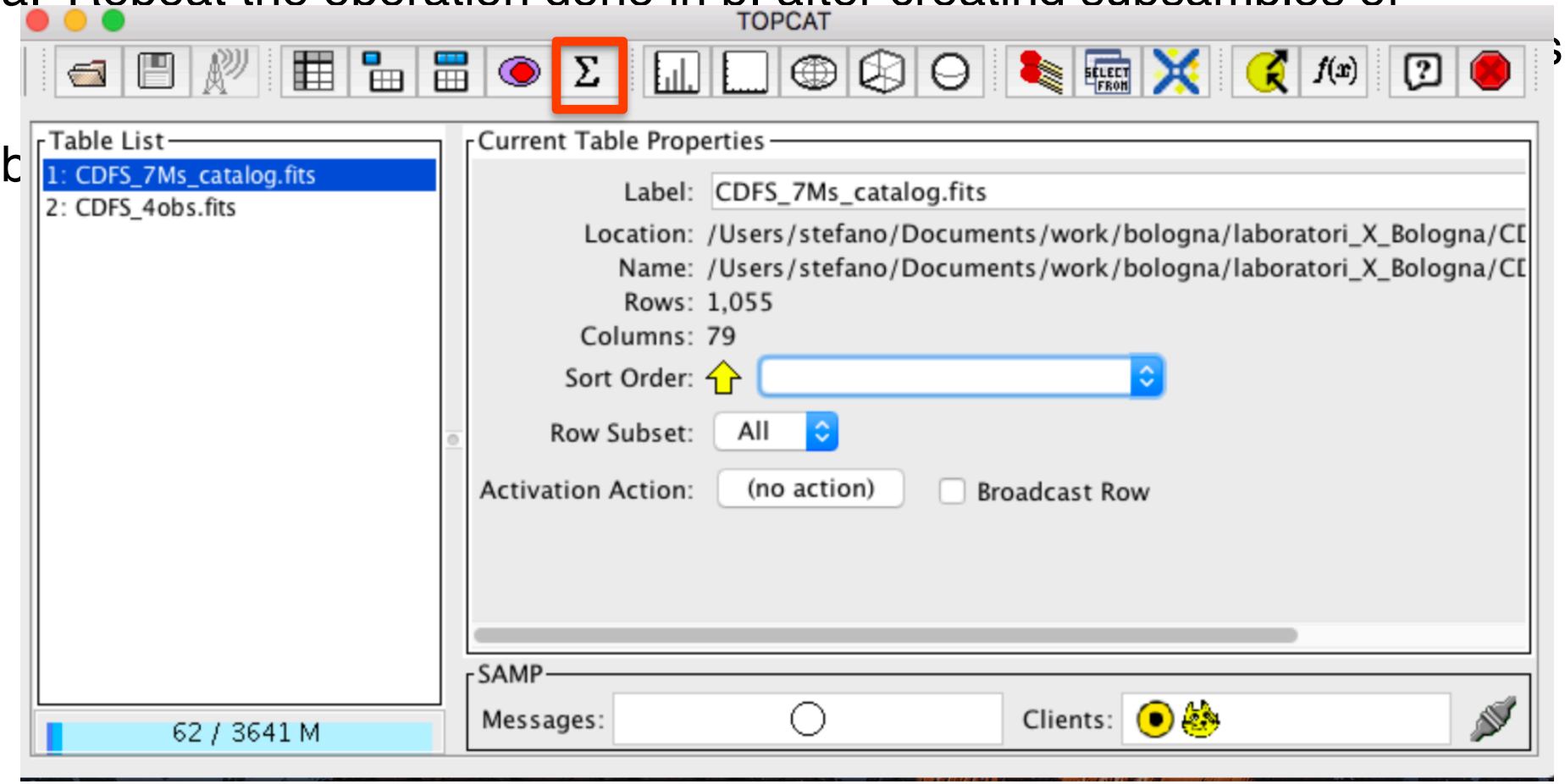
Lab Outline
2) Explore the source catalog

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



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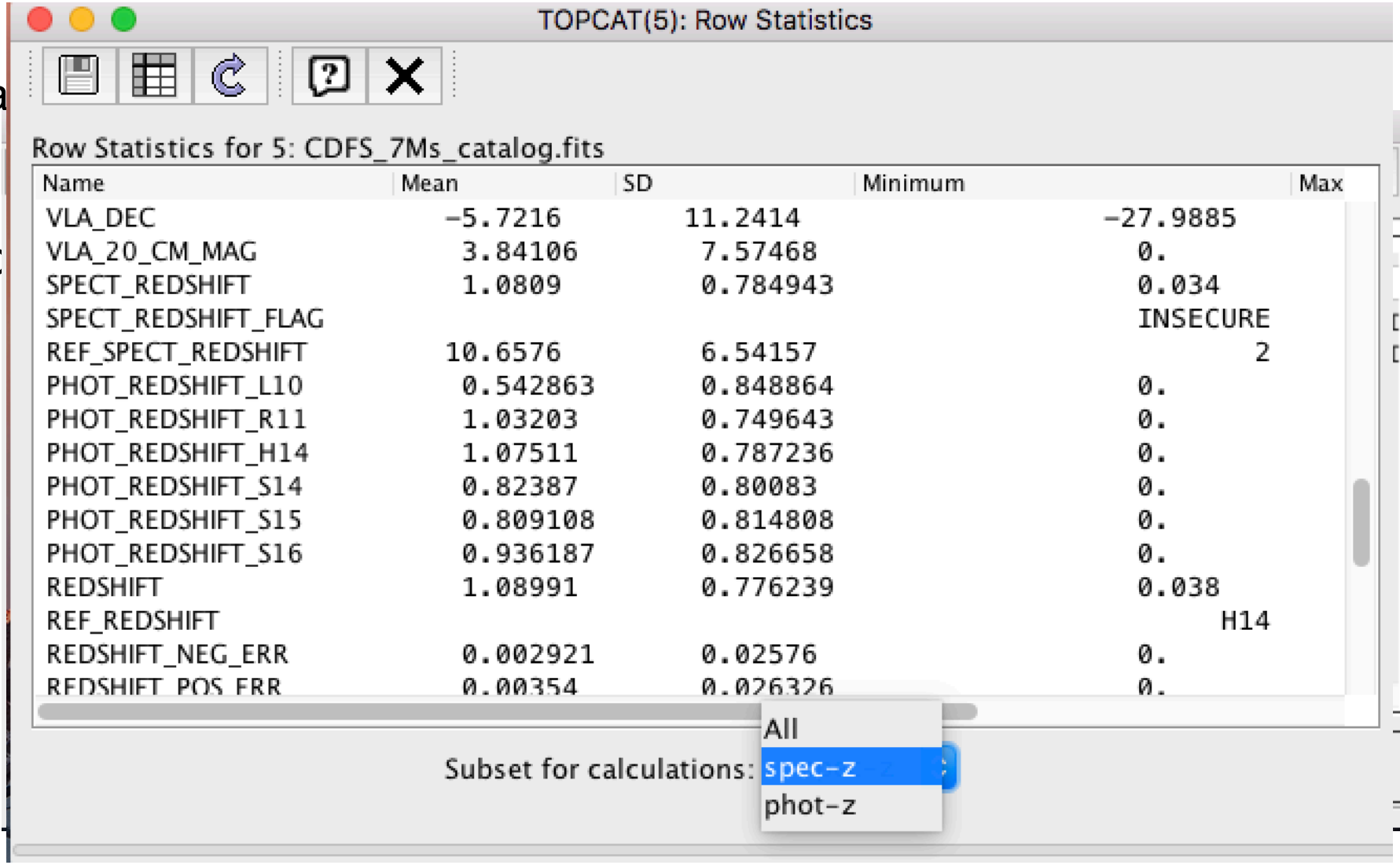

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b. For the sources associated with the 7Ms source catalog, produce the redshift distribution histogram, Lx vs. z plot, etc.
c. OPTIONAL: Select a few sources, then use the PIMMS Online tool (https://cxc.harvard.edu/toolkit/pimms.jsp) to compute the count rate-to-flux correction factor, using the photon index available in the catalog. Does it match the one used in the catalog?

Lab Outline

2) Explore the source catalog

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

Input			Output		
(•) Count Rate	( ) Flux	( ) Flux Density	( ) Count Rate	(•) Flux	( ) Flux Density

Mission: CHANDRA-Cycle 11 — **Detector/Grating/Filter:** ACIS-I/None/None

Flux: Absorbed

Input Energy: 0.5 to 2 keV — **Output Energy:** 0.5 to 2

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

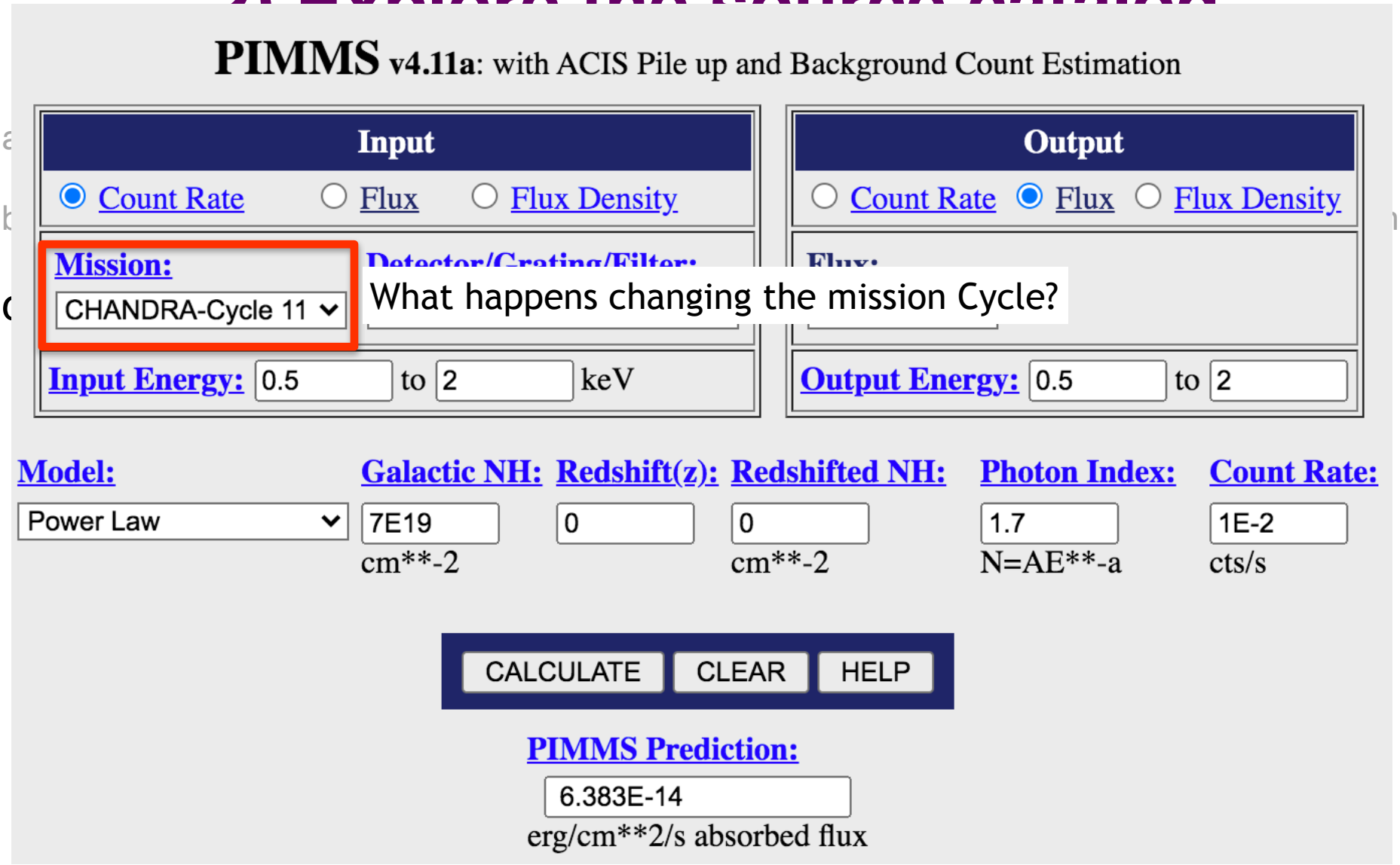
CALCULATE | CLEAR | HELP

PIMMS Prediction:

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

Lab Outline

2) Explore the source catalog



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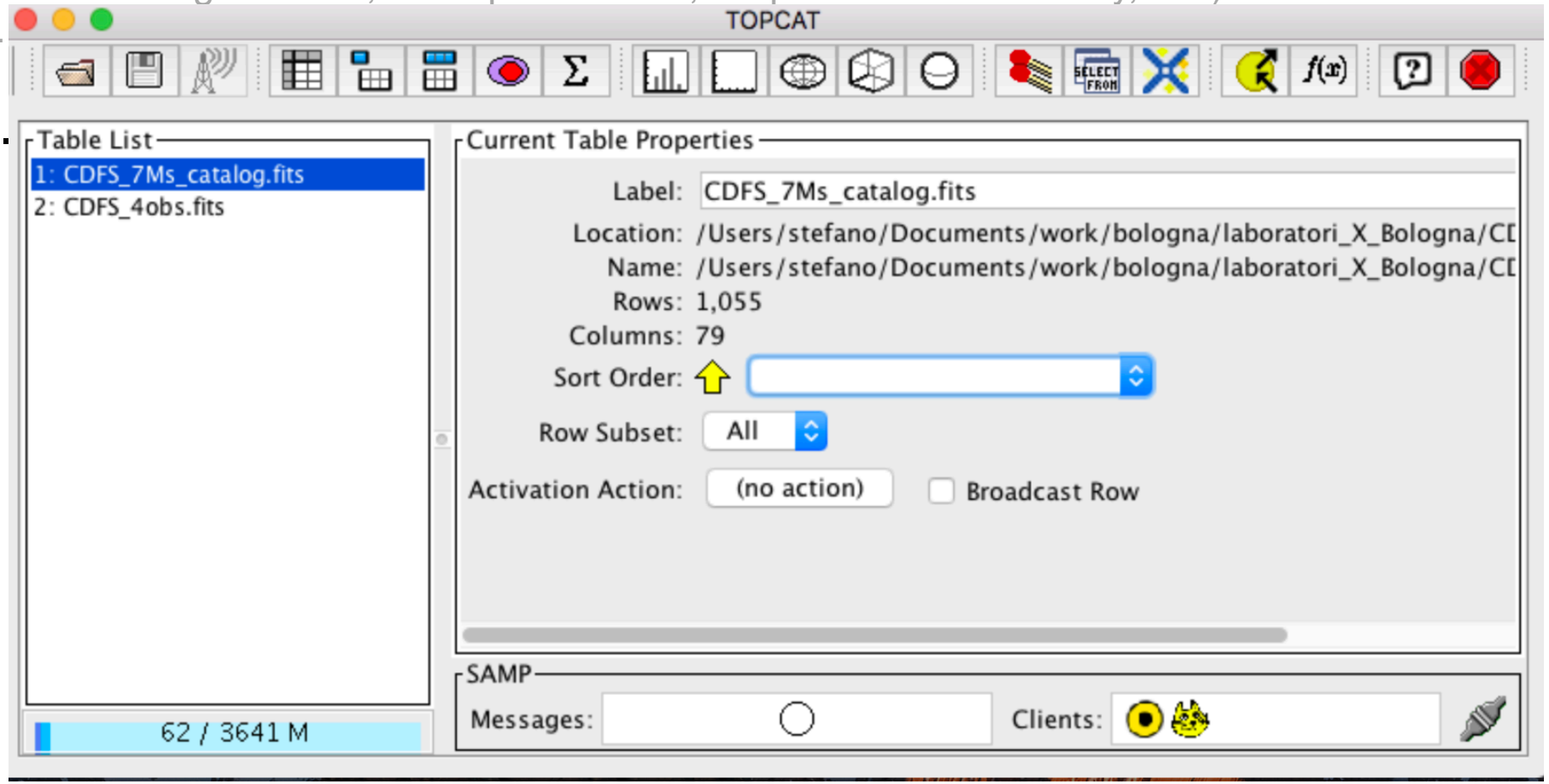
c.



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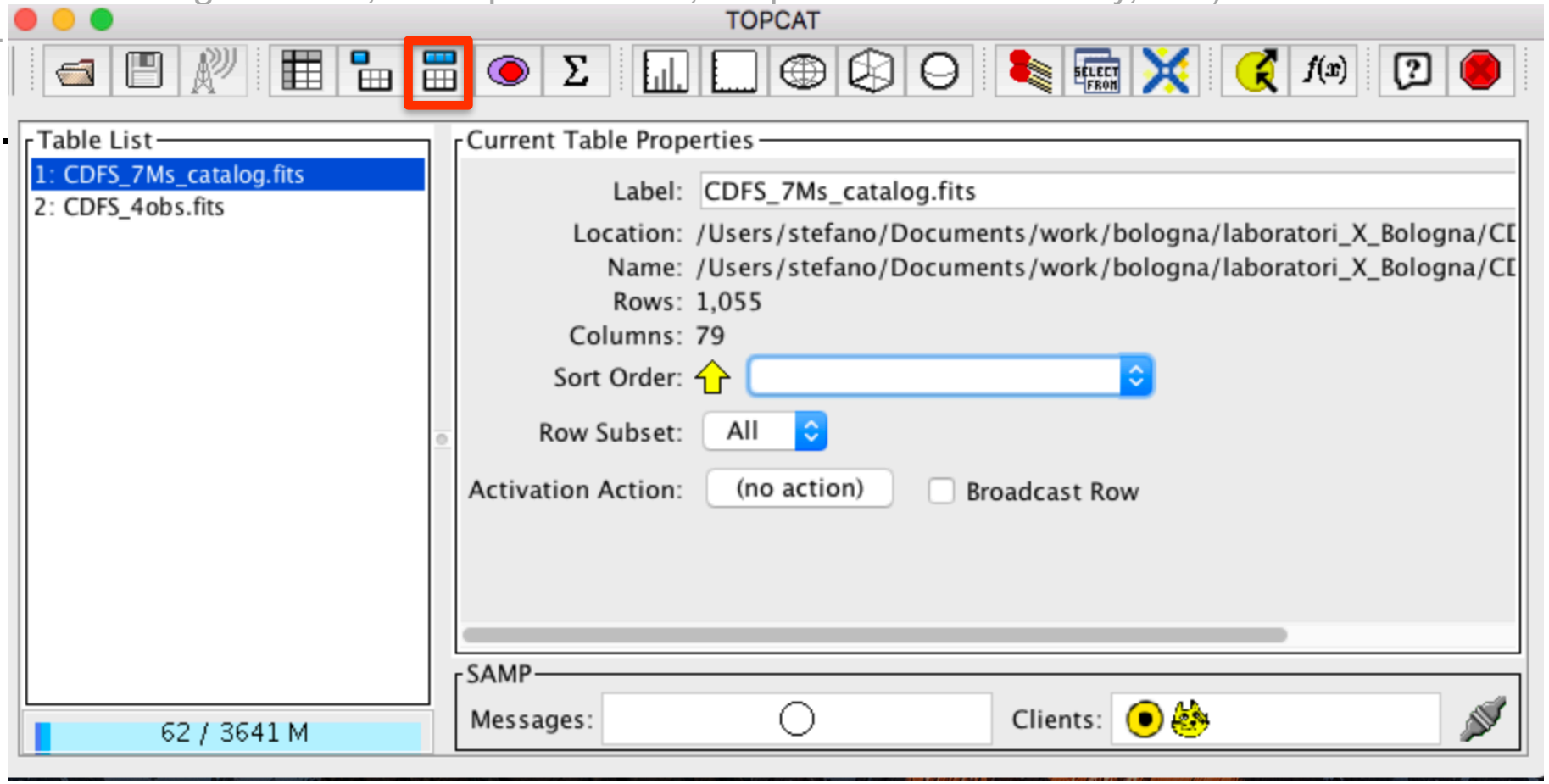
c.

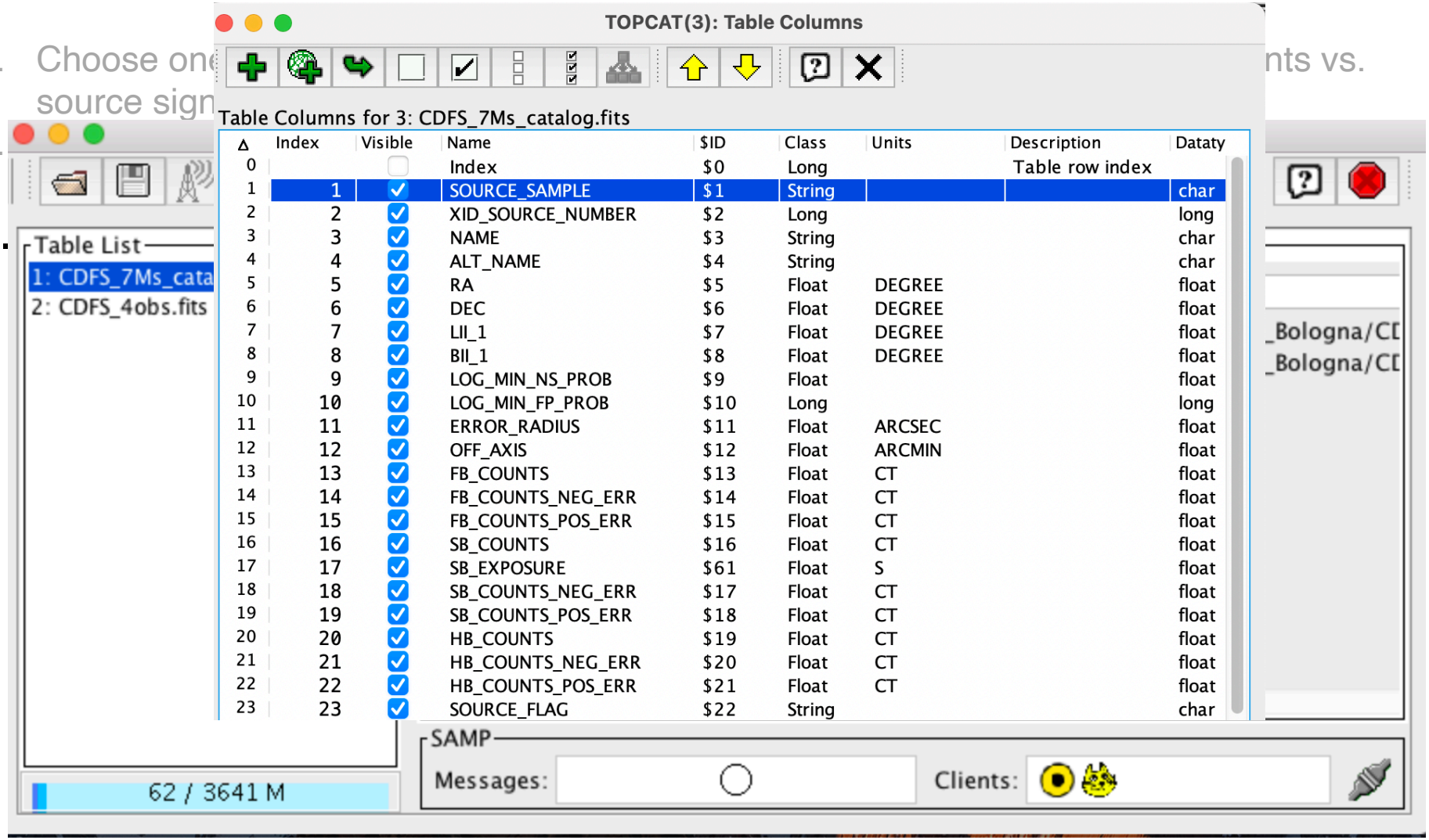


Lab Outline
2) Explore the source catalog

a. Choose one
nts vs.
source sign

b.

c.



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2	✓	XID_SOURCE_NUMBER	$2	Long			long
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4	✓	ALT_NAME	$4	String			char
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6	✓	DEC	$6	Float	DEGREE		float
7	✓	LII_1	$7	Float	DEGREE		float
8	✓	BII_1	$8	Float	DEGREE		float
9	✓	LOG_MIN_NS_PROB	$9	Float			float
10	✓	LOG_MIN_FP_PROB	$10	Long			long
11	✓	ERROR_RADIUS	$11	Float	ARCSEC		float
12	✓	OFF_AXIS	$12	Float	ARCMIN		float
13	✓	FB_COUNTS	$13	Float	CT		float
14	✓	FB_COUNTS_NEG_ERR	$14	Float	CT		float
15	✓	FB_COUNTS_POS_ERR	$15	Float	CT		float
16	✓	SB_COUNTS	$16	Float	CT		float
17	✓	SB_EXPOSURE	$61	Float	S		float
18	✓	SB_COUNTS_NEG_ERR	$17	Float	CT		float
19	✓	SB_COUNTS_POS_ERR	$18	Float	CT		float
20	✓	HB_COUNTS	$19	Float	CT		float
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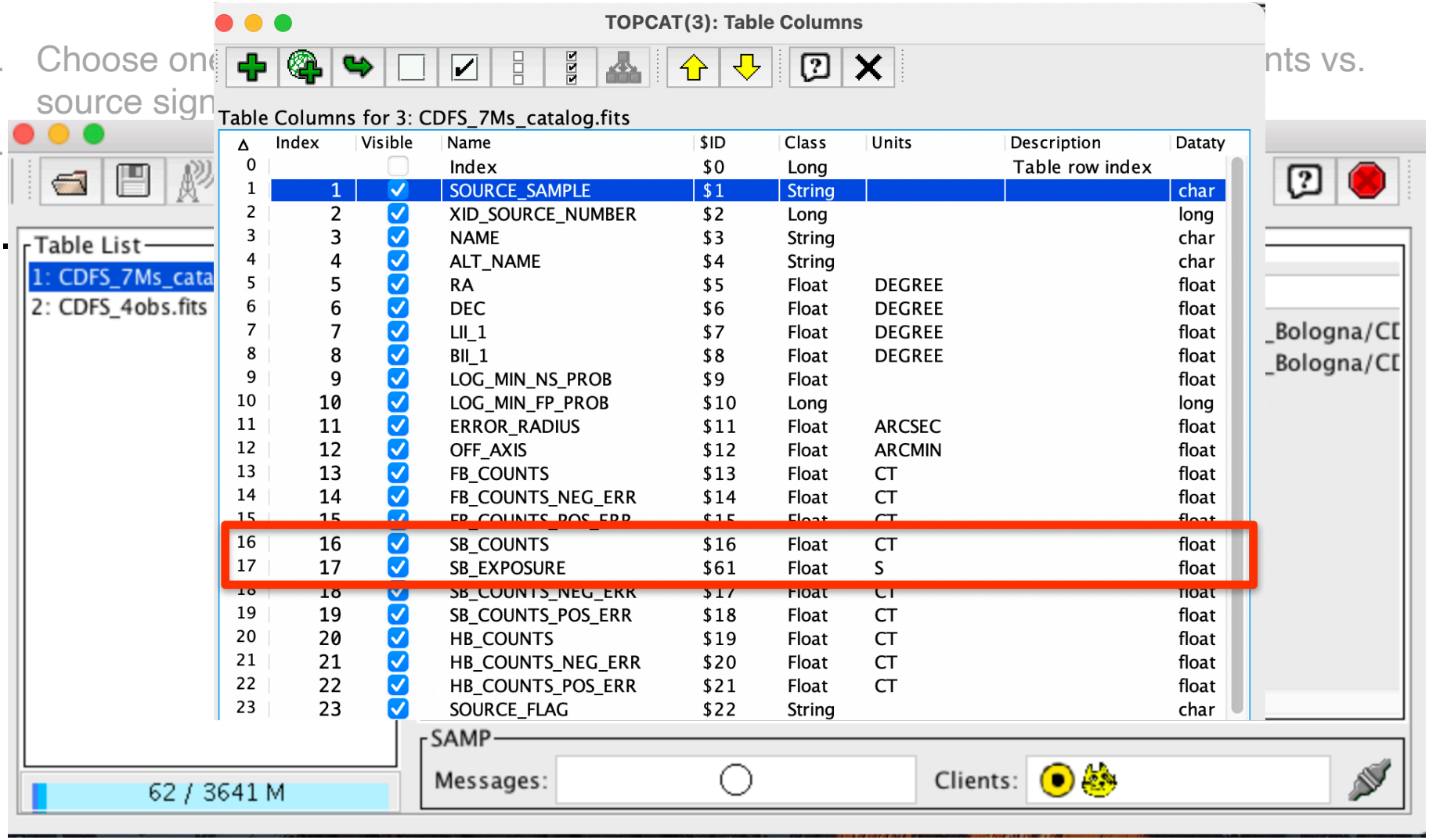
Lab Outline
2) Explore the source catalog

a. Choose one
source sign
nts vs.

b.

c.



Δ	Index	Visible	Name	$ID	Class	Units	Description	Dataty
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4	4	☑	ALT_NAME	$4	String			char
5	5	☑	RA	$5	Float	DEGREE		float
6	6	☑	DEC	$6	Float	DEGREE		float
7	7	☑	LII_1	$7	Float	DEGREE		float
8	8	☑	BII_1	$8	Float	DEGREE		float
9	9	☑	LOG_MIN_NS_PROB	$9	Float			float
10	10	☑	LOG_MIN_FP_PROB	$10	Long			long
11	11	☑	ERROR_RADIUS	$11	Float	ARCSEC		float
12	12	☑	OFF_AXIS	$12	Float	ARCMIN		float
13	13	☑	FB_COUNTS	$13	Float	CT		float
14	14	☑	FB_COUNTS_NEG_ERR	$14	Float	CT		float
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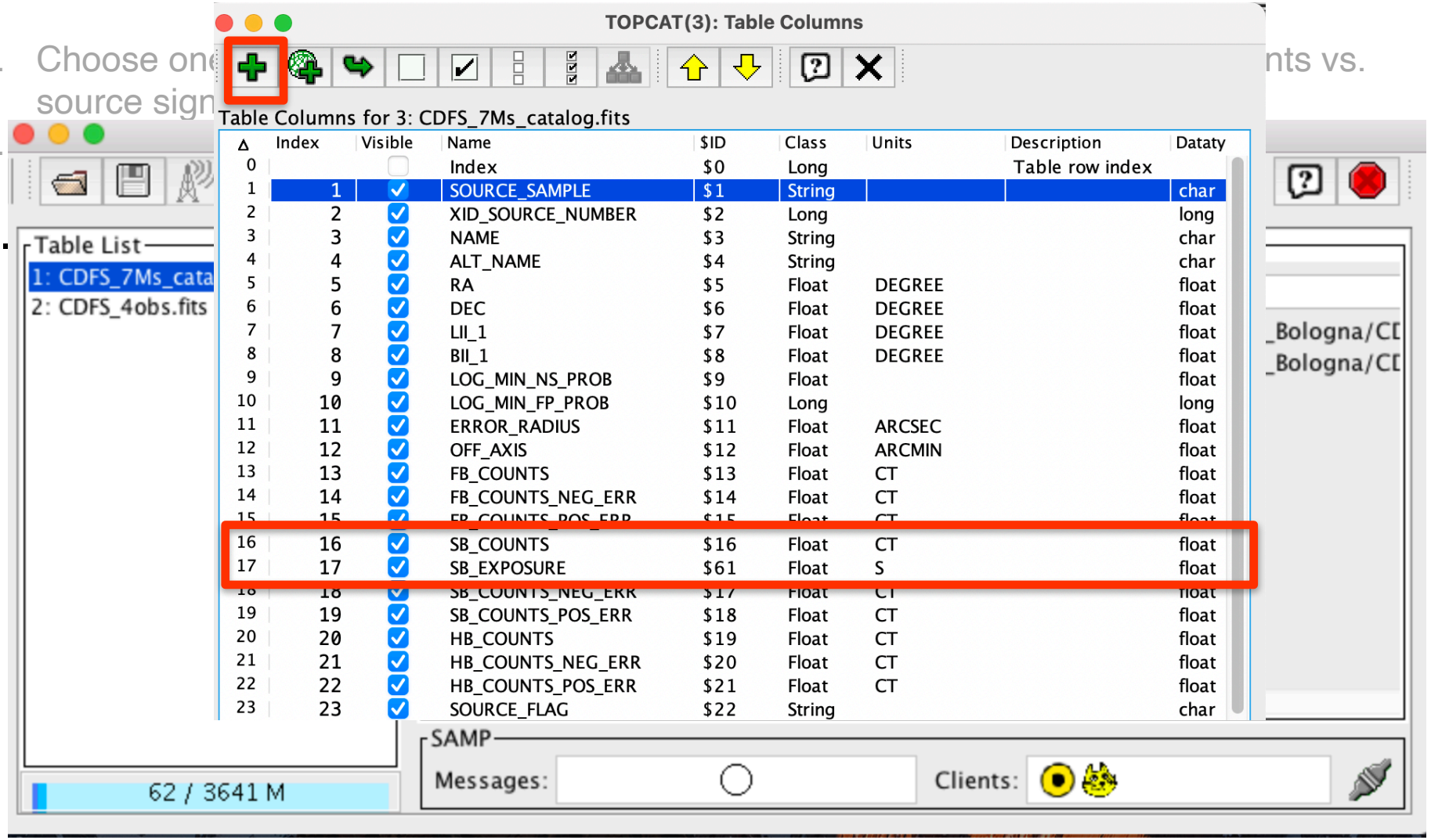
18	18	☑	SB_COUNTS_NEG_ERR	$17	Float	CT		float
19	19	☑	SB_COUNTS_POS_ERR	$18	Float	CT		float
20	20	☑	HB_COUNTS	$19	Float	CT		float
21	21	☑	HB_COUNTS_NEG_ERR	$20	Float	CT		float
22	22	☑	HB_COUNTS_POS_ERR	$21	Float	CT		float
23	23	☑	SOURCE_FLAG	$22	String			char

Lab Outline
2) Explore the source catalog

a. Choose one
source sign
nts vs.

b.

c.



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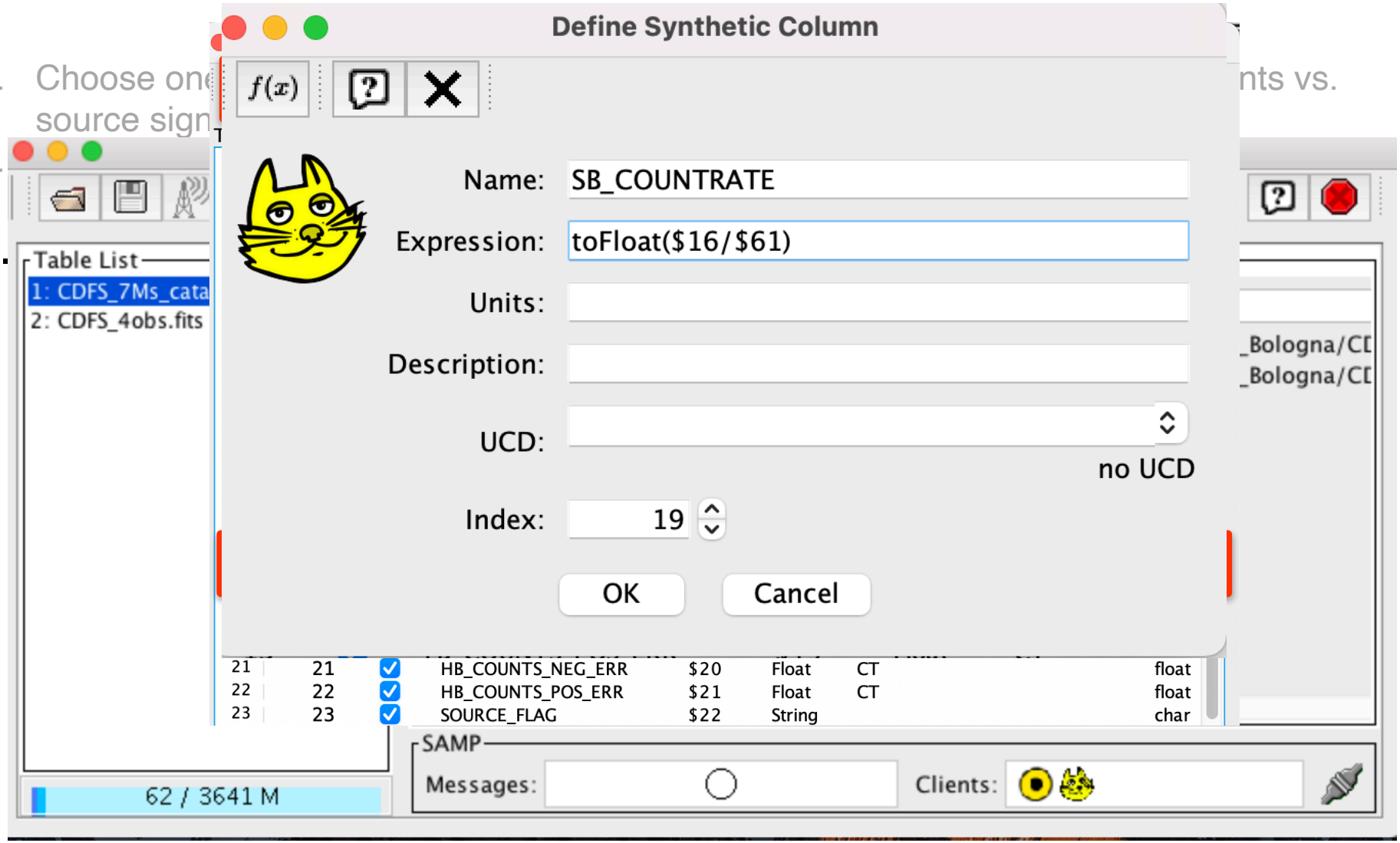
3	3	☑	NAME	$3	String			char
4	4	☑	ALT_NAME	$4	String			char
5	5	☑	RA	$5	Float	DEGREE		float
6	6	☑	DEC	$6	Float	DEGREE		float
7	7	☑	LII_1	$7	Float	DEGREE		float
8	8	☑	BII_1	$8	Float	DEGREE		float
9	9	☑	LOG_MIN_NS_PROB	$9	Float			float
10	10	☑	LOG_MIN_FP_PROB	$10	Long			long
11	11	☑	ERROR_RADIUS	$11	Float	ARCSEC		float
12	12	☑	OFF_AXIS	$12	Float	ARCMIN		float
13	13	☑	FB_COUNTS	$13	Float	CT		float
14	14	☑	FB_COUNTS_NEG_ERR	$14	Float	CT		float
15	15	☑	FB_COUNTS_POS_ERR	$15	Float	CT		float
16	16	☑	SB_COUNTS	$16	Float	CT		float
17	17	☑	SB_EXPOSURE	$61	Float	S		float
18	18	☑	SB_COUNTS_NEG_ERR	$17	Float	CT		float
19	19	☑	SB_COUNTS_POS_ERR	$18	Float	CT		float
20	20	☑	HB_COUNTS	$19	Float	CT		float
21	21	☑	HB_COUNTS_NEG_ERR	$20	Float	CT		float
22	22	☑	HB_COUNTS_POS_ERR	$21	Float	CT		float
23	23	☑	SOURCE_FLAG	$22	String			char

Lab Outline
2) Explore the source catalog

a. Choose one … nts vs. source sign…

b. …

c.



3. Analyse the data products: spectral fitting

Fit *Chandra* spectra for at least one souce 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

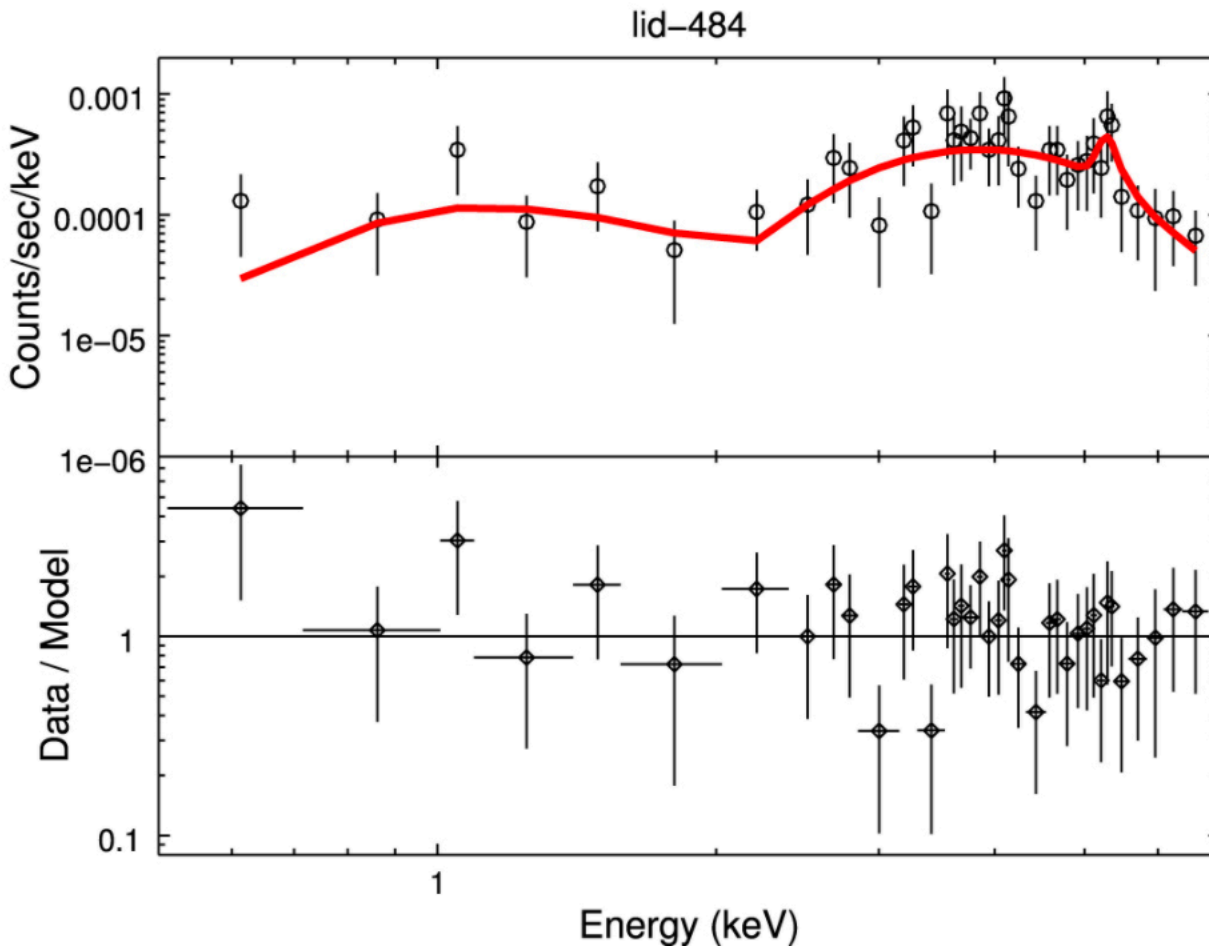
Spectral analysis pipeline

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. Step by step approach: starting with an absorbed power law, then adding additional components (e.g., secondary power law to account for scattered emission, Gaussian to model Iron line at 6.4 keV…)
5. Once a physically justified model is obtained, save the X-ray spectral parameters (including errors) and produce confidence contours

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.**