The 80-month *NuSTAR* Serendipitous Survey

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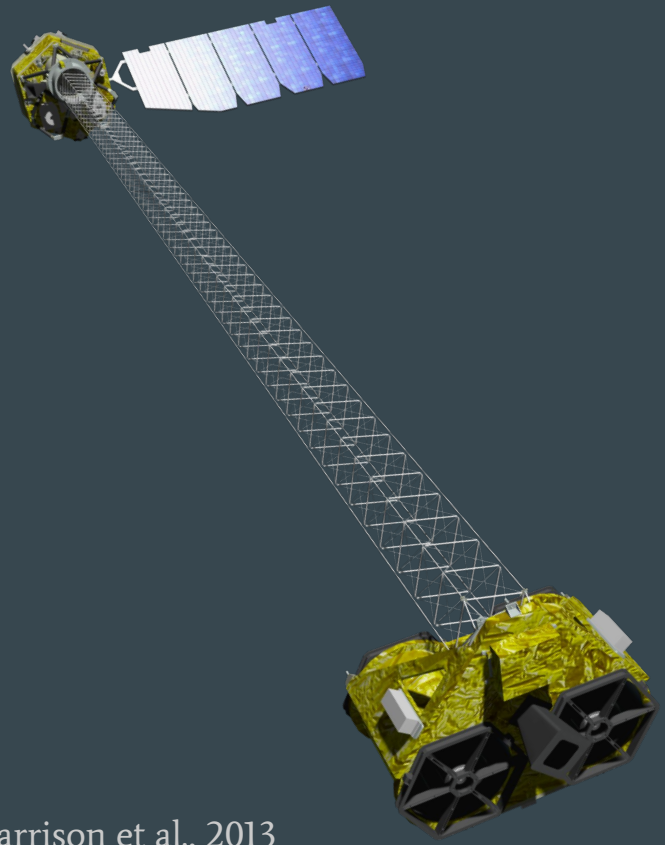
NuSTAR telescope

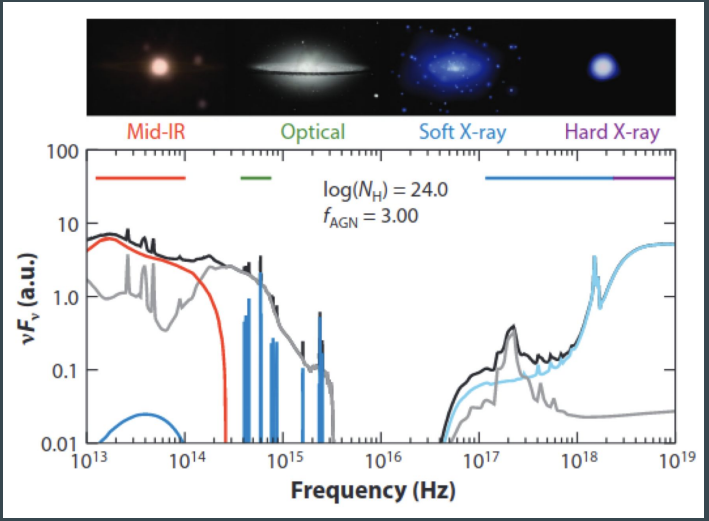
- Launched in 2012
- First orbiting focusing hard X-ray telescope
- Theoretically 3-78 keV
- Best at 3-24 keV
- Two detectors: FPMA and FPMB
- Half power diameter 60-70”
- Positional uncertainty much better than this (~12-16”)



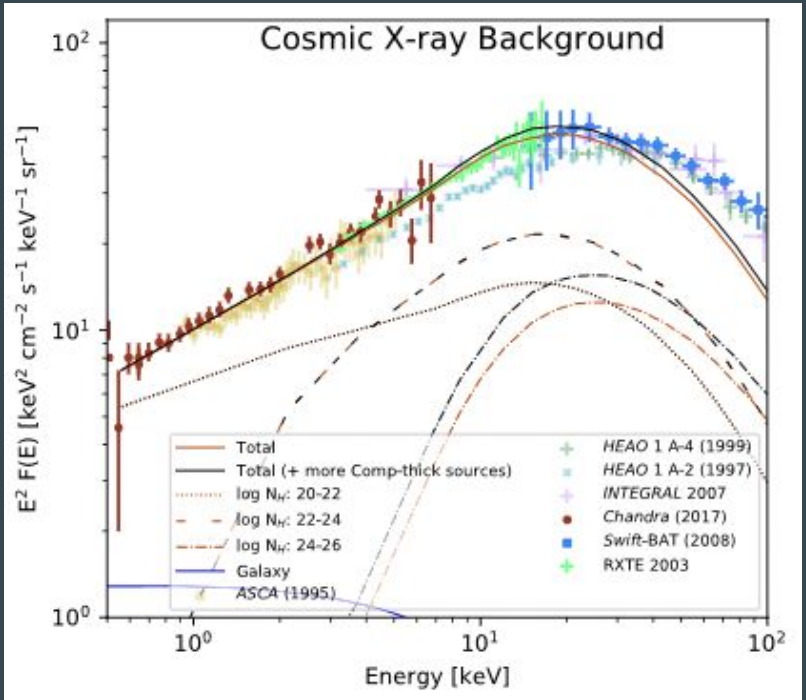
See Harrison et al., 2013

NuSTAR telescope

- Particularly useful for obscured AGN and studies of the **CXB**



Hickox & Alexander, 2018



Ananna et al., 2020

NuSTAR Extragalactic Survey

Two main components:

- Dedicated field surveys (totalling ~3 deg^2) of COSMOS, ECDFS, EGS, GOODS-N, UDS
  - Civano et al., 2015; Mullaney et al., 2015; Aird et al., in prep.; Masini et al., 2018
- Wide-area serendipitous surveys (36 deg^2)
  - Alexander et al., 2013; Lansbury et al., 2017; Greenwell, Klindt et al., 2024, submitted

The serendipitous survey provides 75-80% of all *NuSTAR* detected sources

NuSTAR Extragalactic Survey

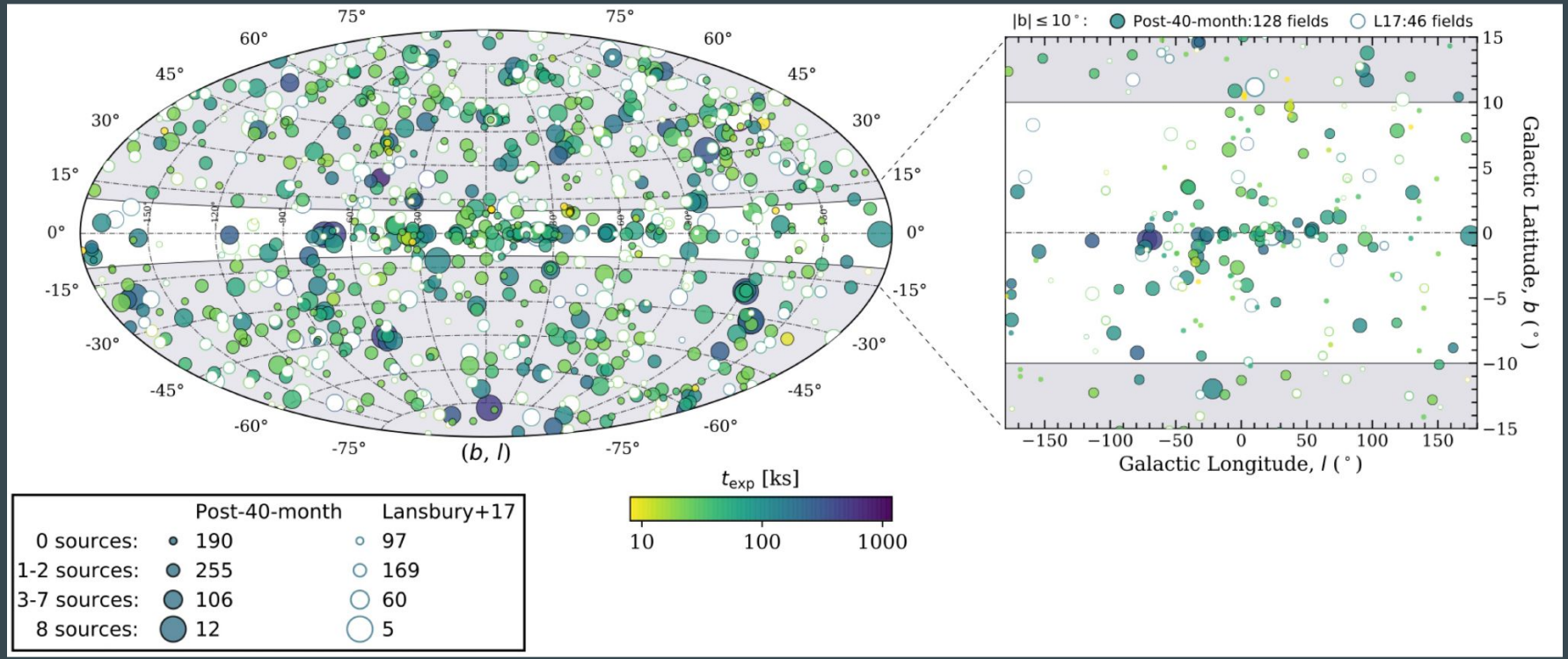
Key contributions:

- Resolved ~35% of the Cosmic X-ray Background at 8-24 keV (Harrison et al., 2016)
- Measured > 10 keV AGN luminosity function at $z > 0.1$ (Aird et al., 2015)
- Identified heavily obscured AGN (Civano et al., 2015; Lansbury et al., 2017; Masini et al., 2018; Greenwell et al., in prep.)

NuSTAR 80-month Serendipitous Survey (NSS80)

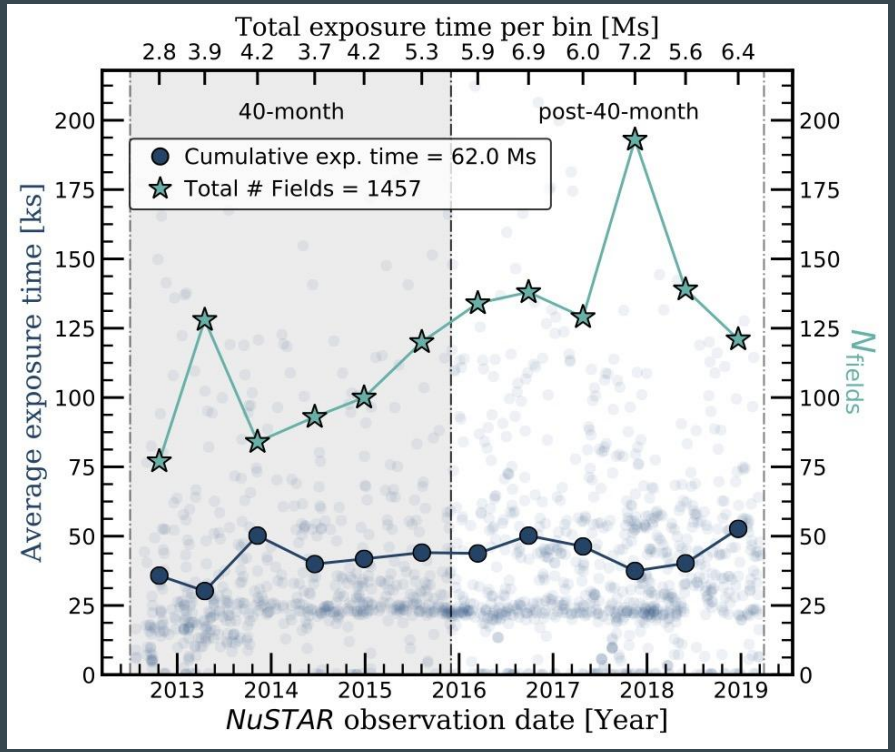
- Observations taken from July 2012 to March 2019
- Searches background regions of targeted observations for sources not associated with the original science target
- ***EXCLUDES*** pointings associated with dedicated survey fields (e.g. extragalactic surveys already mentioned, Galactic surveys: e.g. Mori et al., 2015, Hong et al., 2016)
- ***EXCLUDES*** fields with extremely high counts due to bright science targets, or high background contamination
- ***EXCLUDES*** solar system fields, nebular fields, clusters, very nearby galaxies

NSS80 field locations



Greenwell, Klindt et al., 2024 (submitted)

NSS80 Observations



Greenwell, Klindt et al., 2024 (submitted)

Compared to other X-ray serendipitous surveys

	XMM-Newton	*Chandra*	*Swift*-XRT	*Swift*-BAT	*NuSTAR*
Coverage	1,283 deg^2	~600 deg^2	3,790 deg^2	~40,000 deg^2	36 deg^2
Energy range	0.2-12 keV	0.5-7 keV	0.3-10 keV	14-195 keV	3-78 keV
Number of unique sources	637,347	317,167	206,335	1,632	1,274
Most recent publication	Webb et al., 2020	Evans et al., 2019	Evans et al., 2020	Oh et al., 2018	This work

Large area

Small area

High spatial resolution

Low resolution

High resolution and sensitivity at > 10 keV

Sensitive at < 10 keV

> 10 keV

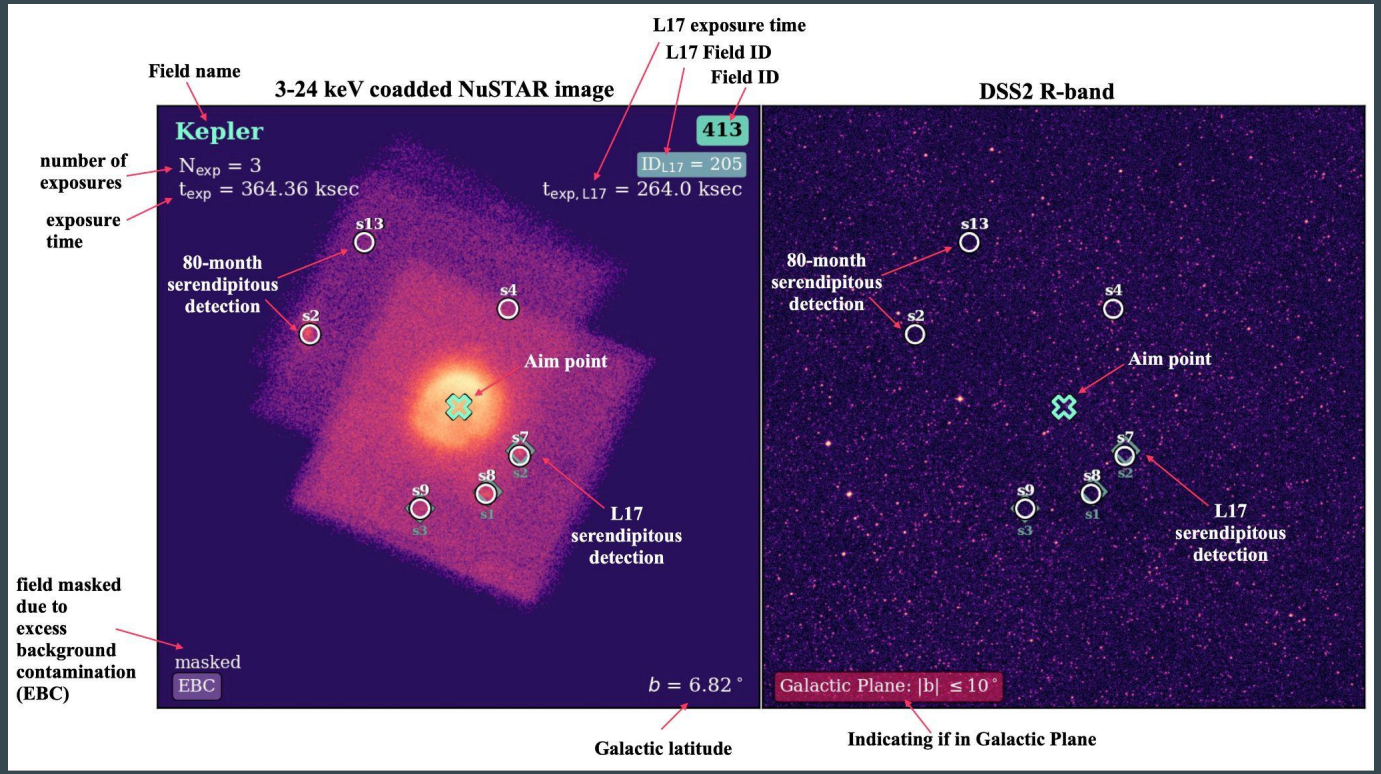
Source Detection Process

1. Raw event files produced for both detectors
2. Cleaned event lists produced for 3 energy bands
    a. Full (3-24 keV), soft (3-8 keV), hard (8-24 keV)
3. Produce merged images for fields with multiple observations, in each band
4. Source detection, as in Lansbury et al., 2017: created source list using “false probability maps” of each band
5. Inspection to mask out excess background contamination
    a. stray light, ghost rays, aperture background, bright targets
    b. if EBC > ⅔ observation, it is discarded

$\Longrightarrow$ final source list: 1274 detected in at least one energy band each

$\Longrightarrow$ 214 sources in extended optical galaxies or clusters are kept in a secondary catalog

NSS80 Field Example



Greenwell, Klindt et al., 2024 (submitted)

Changes from NSS40

- **Previously**: combined exposures of the same science target
- **Now**: coadd all exposures within 12’ of aim point

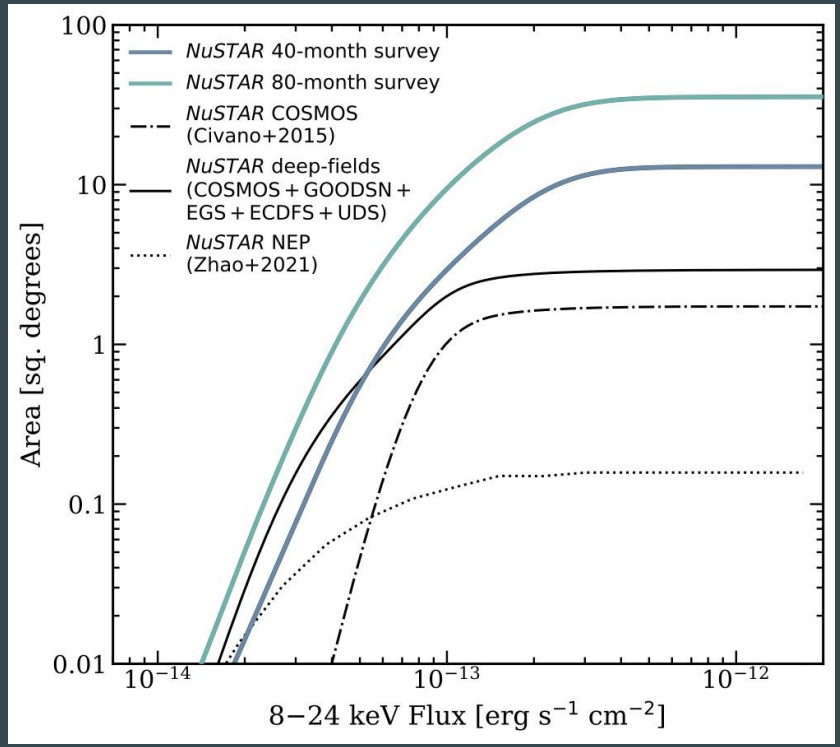
- **Previously**: excluded observations of < 1 ks
- **Now**: all data coadded

- **Previously**: detections associated with extended optical/IR sources were manually removed
- **Now**: these are retained in the secondary catalog

⟹ from 497 NSS40 sources: 452 are in the NSS80 primary catalog, 22 in the secondary catalog

Changes from NSS40

Lansbury et al., 2017	Greenwell et al., 2024 (submitted)
331 fields	894 fields
20.4 Ms	62.0 Ms
13 deg^2	36 deg^2
497 sources	1274 sources

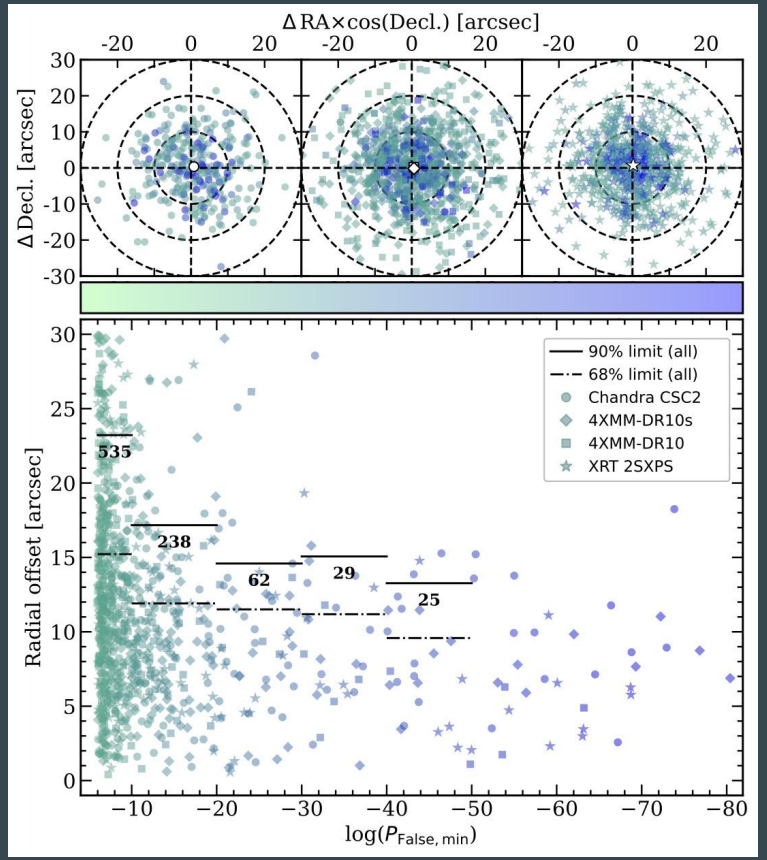


Multi-wavelength Information

- The catalog is selected *independent* of any prior multi-wavelength information
- But to explore the properties, we need further data
  - Soft X-ray
    - If detected by NuSTAR and covered by another catalog, likely to be detected there
    - Improves knowledge of source position, helping further matching
    - Improves X-ray spectral fitting
  - MIR
    - AGN are often bright and distinctive in MIR
  - Optical
    - Spectroscopy of counterparts provides redshift and identification of type
  - We use NWAY to match MIR and optical counterparts

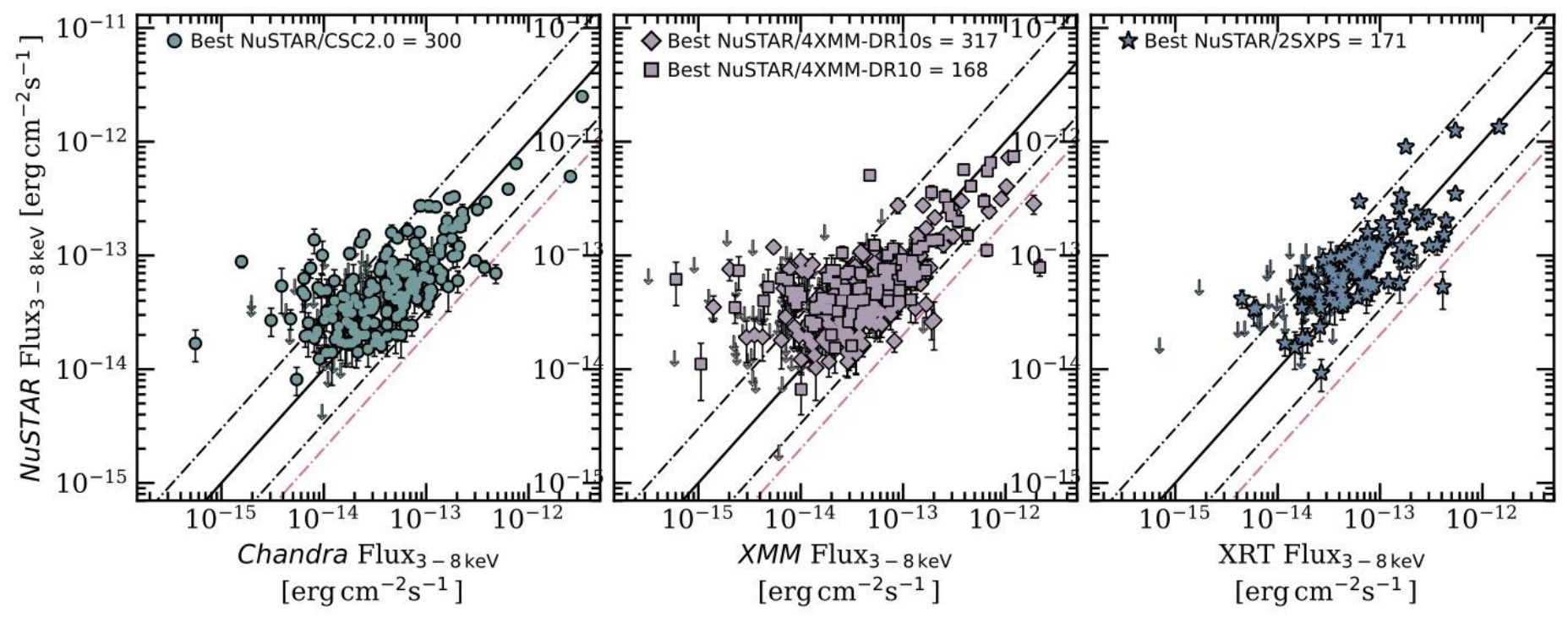
Soft X-ray Cross Matching

- CSC2 (*Chandra*), 4XMM-DR10 & 4XMM-DR10s (*XMM-Newton*), 2SXPS (Swift-*XRT*)
- 76% of catalog have counterparts within 30”
  - 11% have counterparts in more than one catalog
  - Of the rest, 94.5% have coverage, but no counterpart in the corresponding catalog
- 23% have multiple possible counterparts
  - We select the counterpart with the brightest flux



Greenwell, Klindt et al., 2024 (submitted)

Soft X-ray Cross Matching

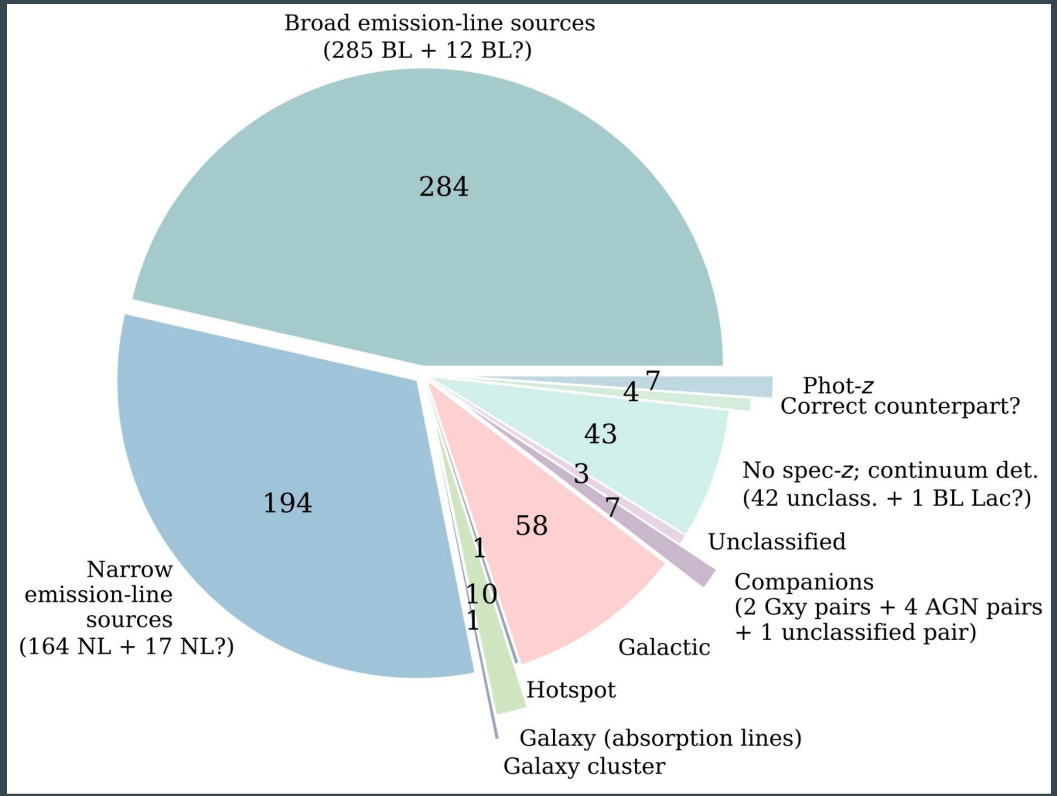


Greenwell, Klindt et al., 2024 (submitted)

Optical Spectra

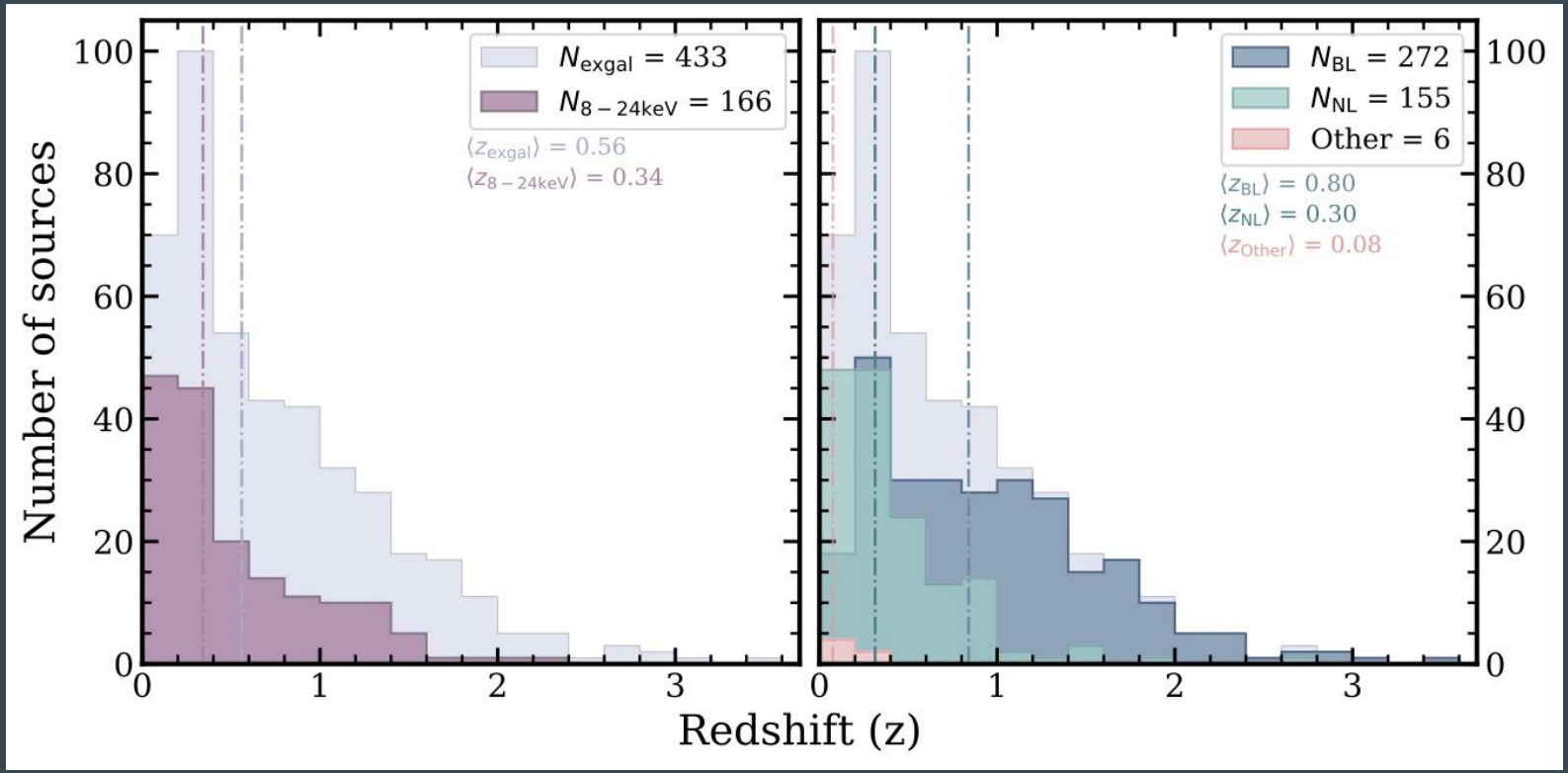
- A mixture of archival and dedicated follow-up spectra
- 550 sources (including NSS40)
  - 427 from dedicated follow-ups, including new for NSS80:
    - 24 nights on Keck & Palomar
    - 4 VLT/FORS2 semesters
    - 4 SALT/RSS semesters
- 547 classified (43% of catalog)
  - Galactic (e.g. cataclysmic variables, X-ray binaries)
  - Extragalactic Broad Line (permitted emission lines broader than forbidden lines, or line width > 1000 km s^{-1})
  - Extragalactic Narrow Line (permitted line widths similar to forbidden lines)
  - Galaxy (absorption lines only)
- Ambiguous sources flagged
- Additional 18 cases with multiple potential counterparts
  - Including 6 sources with companions

Optical Spectra: Classifications



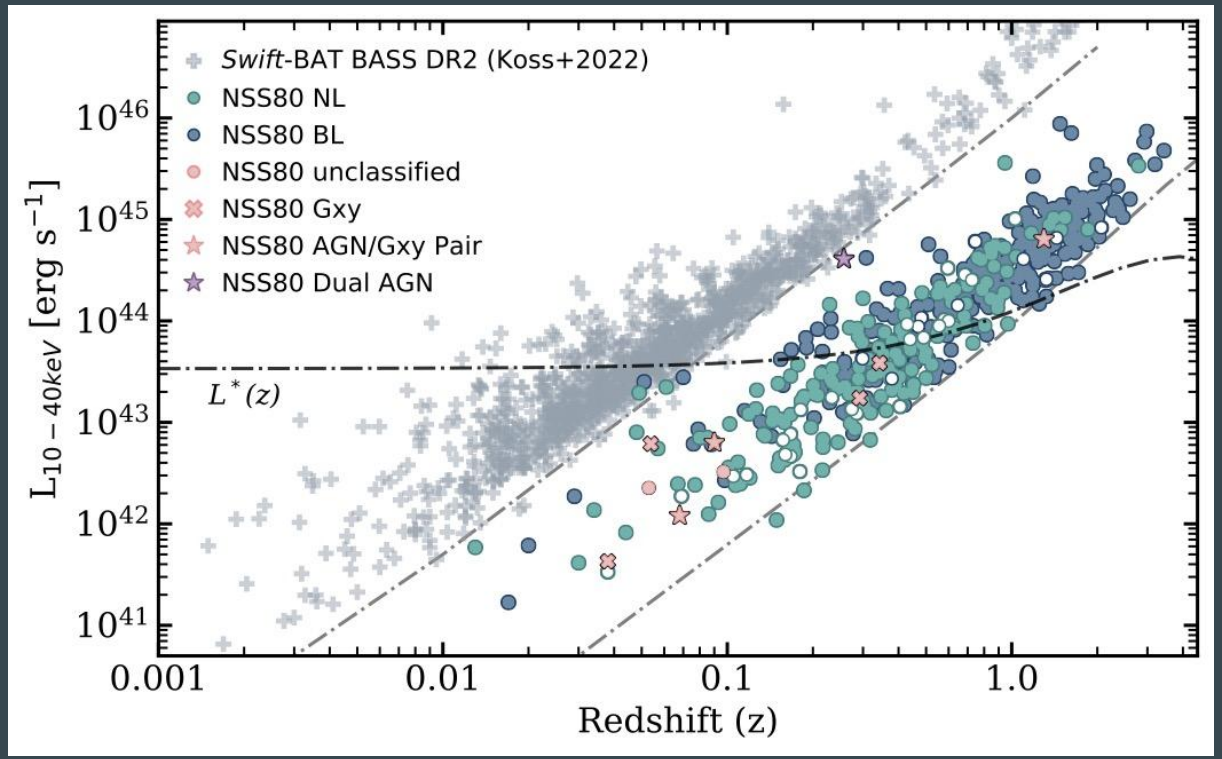
Greenwell, Klindt et al., 2024 (submitted)

Overview of Properties: Redshifts



Greenwell, Klindt et al., 2024 (submitted)

Overview of Properties: L_X-Redshift Plane



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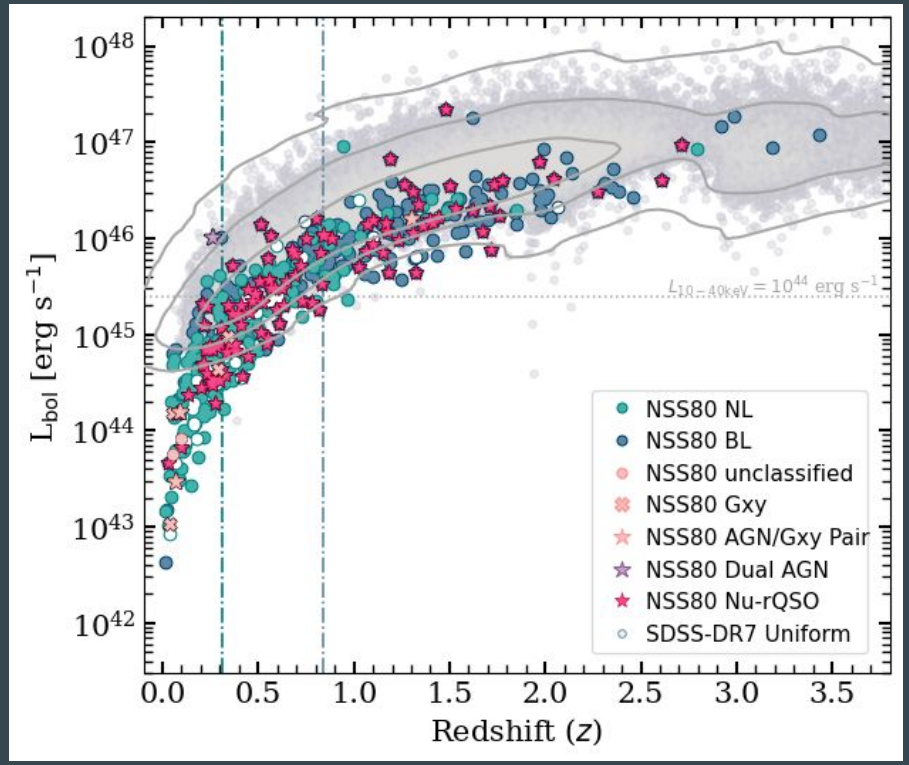
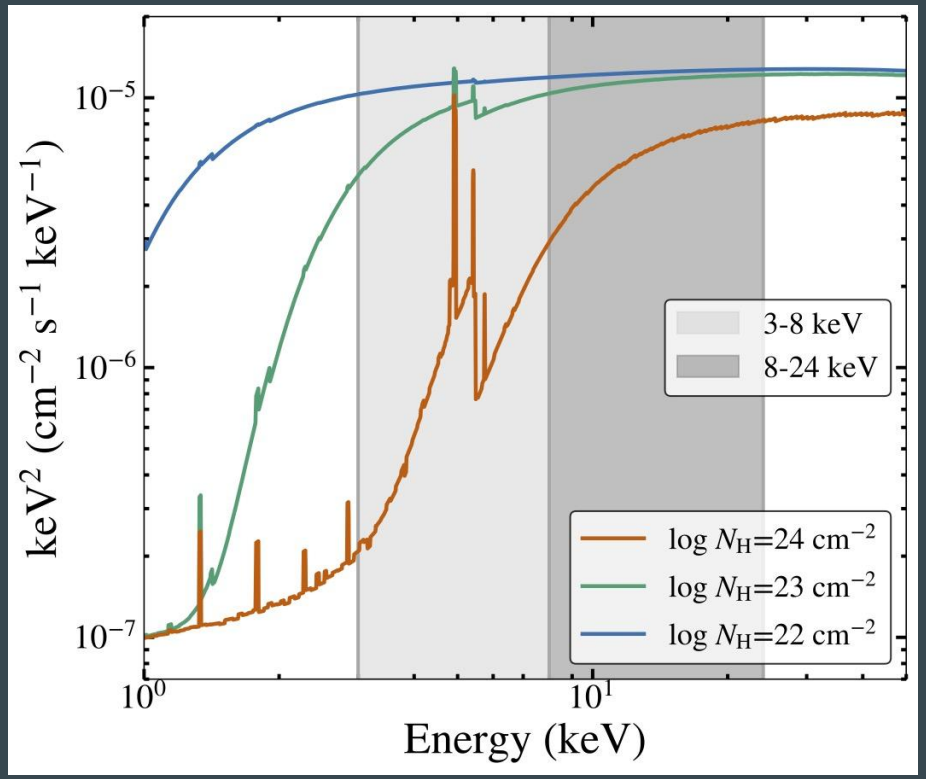
Overview of Properties: L_{bol}-Redshift Plane



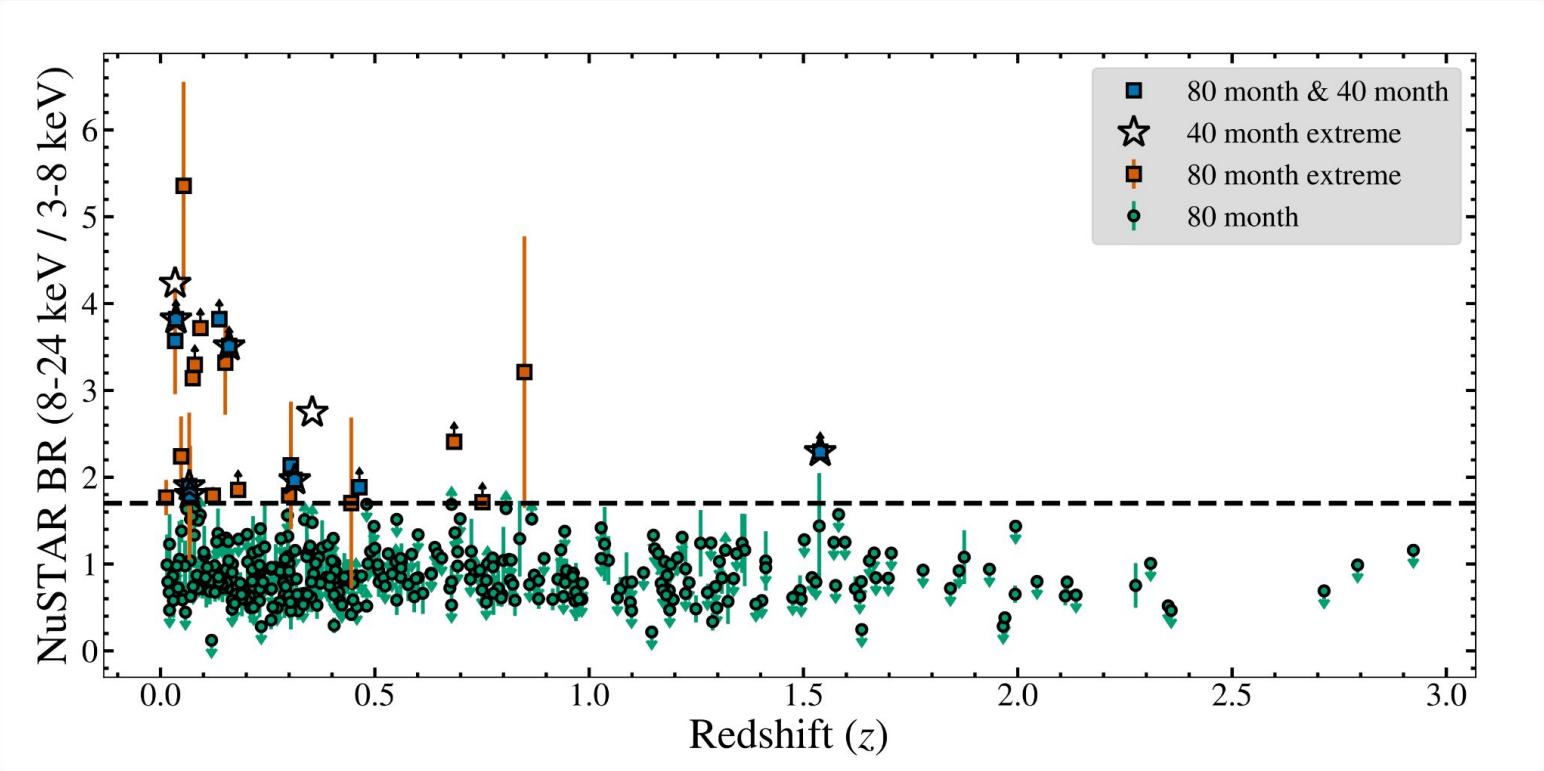
Greenwell, Klindt et al., 2024 (submitted)

Some initial results...

Selection of candidate Compton Thick AGN

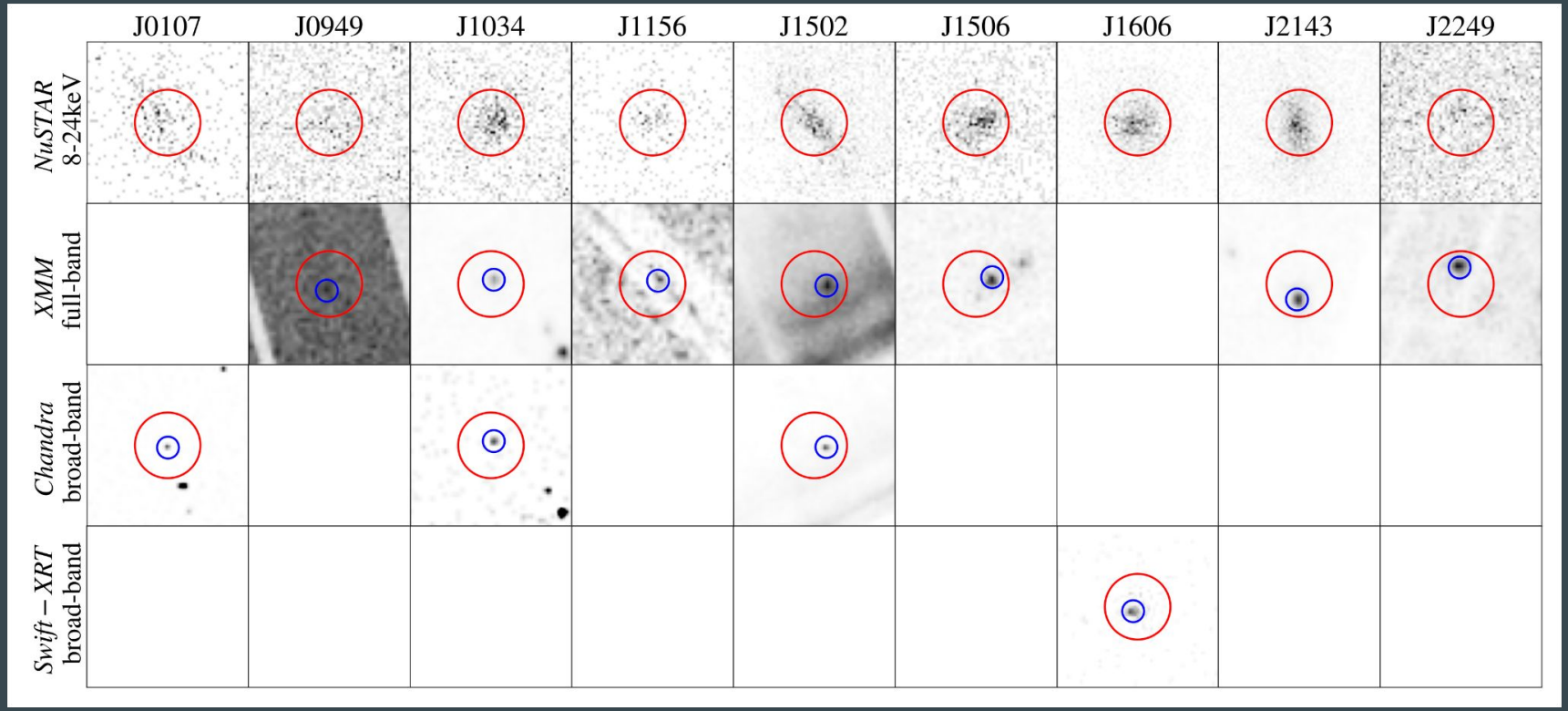


Selection of candidate Compton Thick AGN



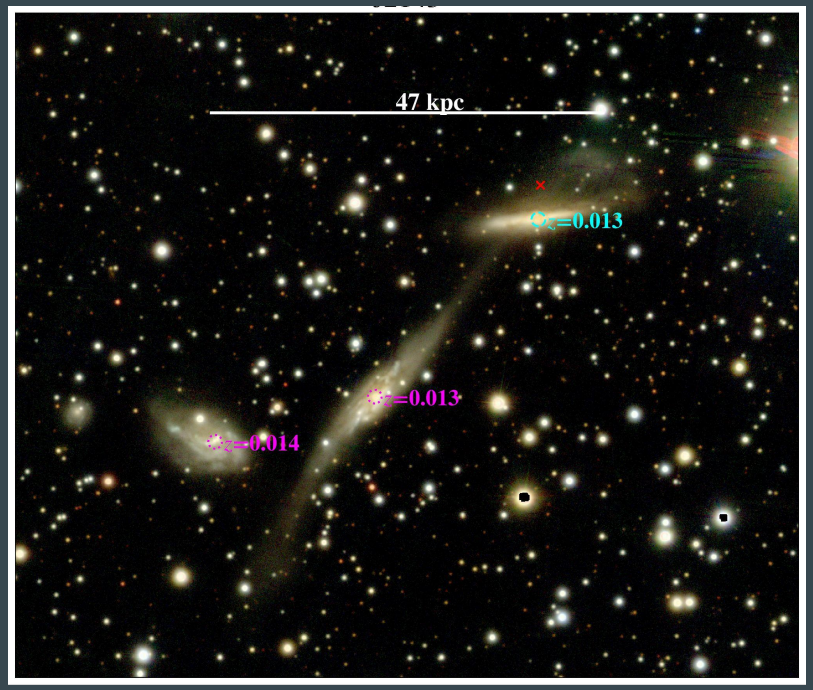
Greenwell et al., (in prep.)

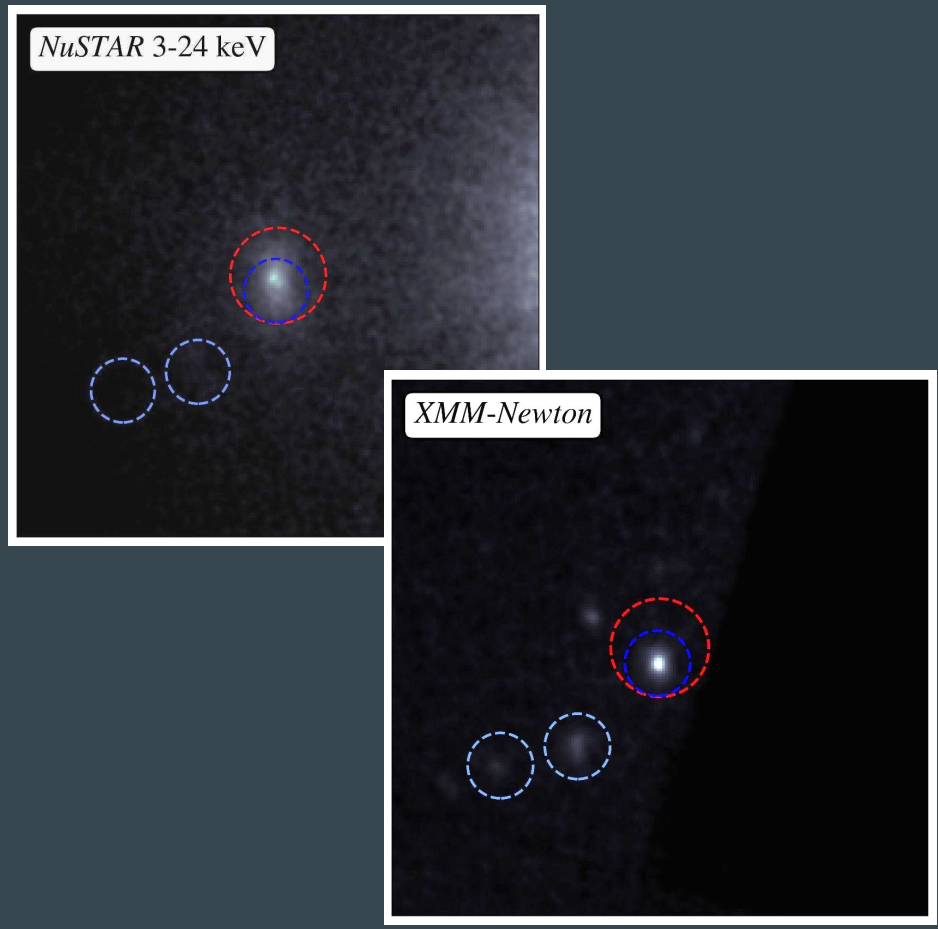
Final sample: new heavily obscured AGN



Greenwell et al., (in prep.)

Example source: J2143+4334

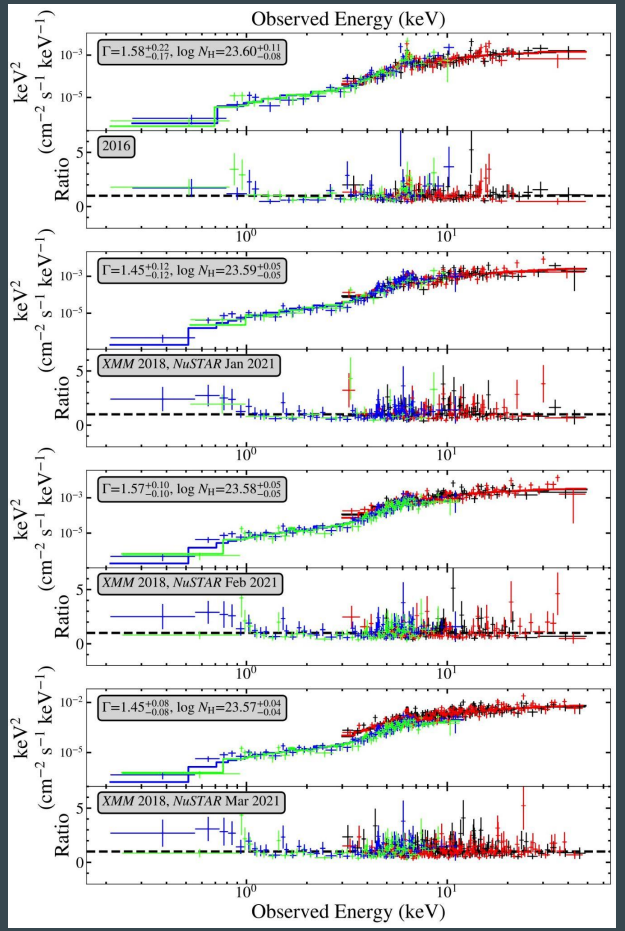




Greenwell et al., (in prep.)

Example source: J2143+4334

- AKA UGC 11797
- Part of a group of galaxies
- Both companions detected by *XMM-Newton* but only one significantly by *NuSTAR*
- Host to SN in 2015, but unlikely to cause contamination
- Heavily obscured but not Compton Thick



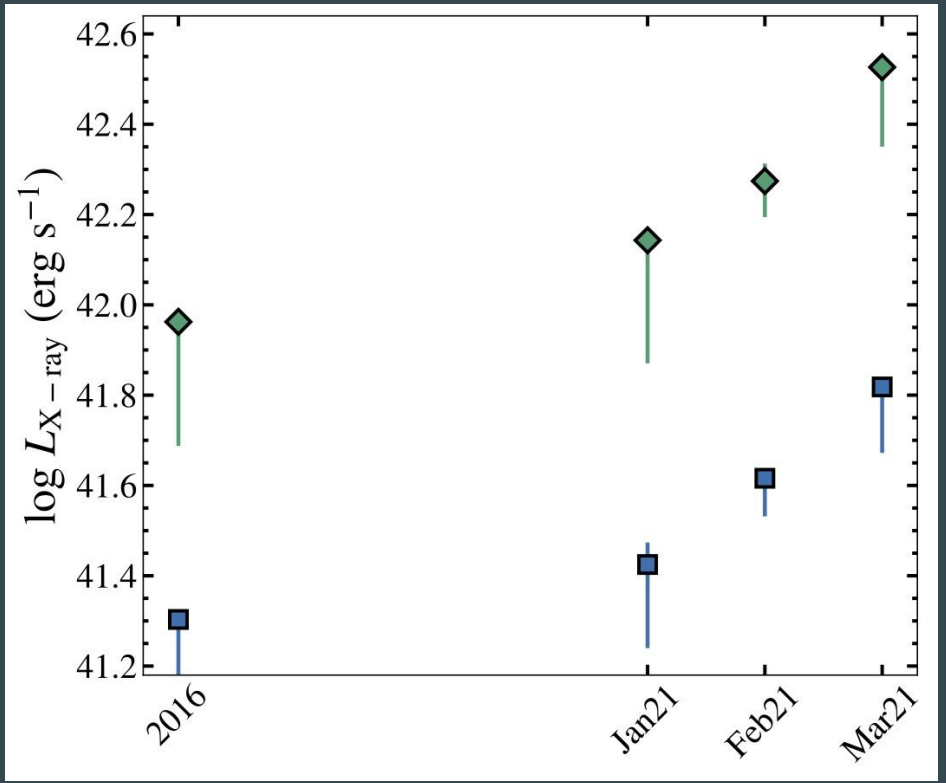
Greenwell et al., (in prep.)

Example source: J2143+4334

- Measured over multiple epochs:
  - 2016 (*XMM* and *NuSTAR*)
  - 2018 (*XMM*)
  - Jan 2021 (*NuSTAR*)
  - Feb 2021 (*NuSTAR*)
  - Mar 2021 (*NuSTAR*)
  - (none targeted at this source)
- Spectral slope and $N_{\rm H}$ remain consistent

$\Longrightarrow$ accretion change?

- Would not have been discovered without NSS!



Greenwell et al., (in prep.)

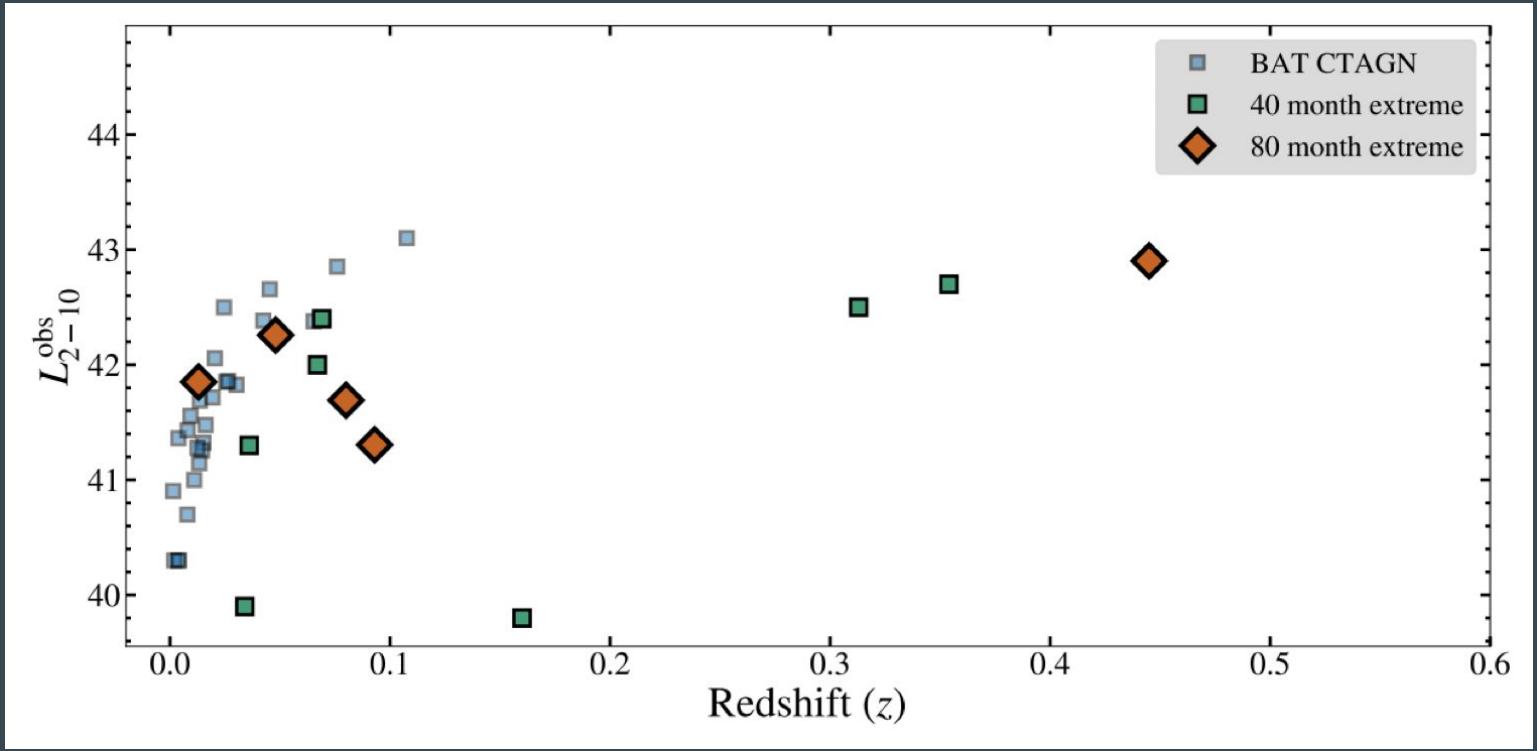
Full heavily obscured AGN sample

- NSS40 heavily obscured sources (Lansbury et al., 2017): 8
  - of which are Compton Thick: 3
- NSS80 heavily obscured sources (Greenwell et al., in prep.): 14
  - Including one from NSS40 with new *NuSTAR* data
  - CT: 4

- CT fraction: $5^{+2}_{-1}\%$
- If we limit to low redshift ($z < 0.1$): $16^{+8}_{-5}\%$
  - Can be considered lower limit, as we expect to miss primarily fainter, more obscured sources

- Merger fraction in CT AGN: $29^{+21}_{-12}\%$

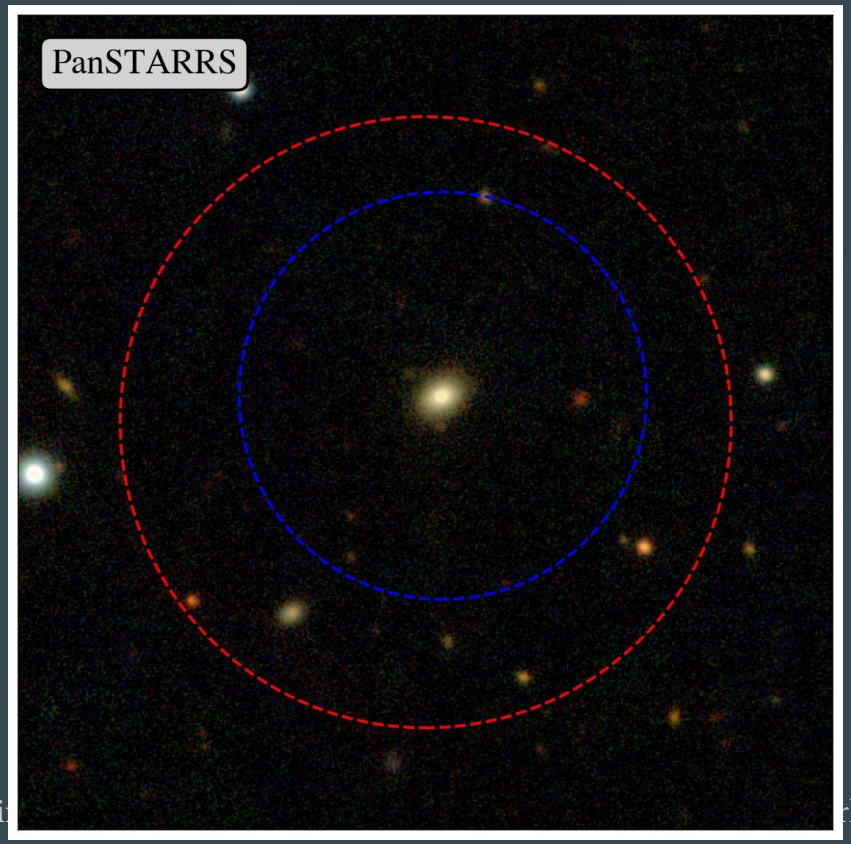
Full heavily obscured AGN sample

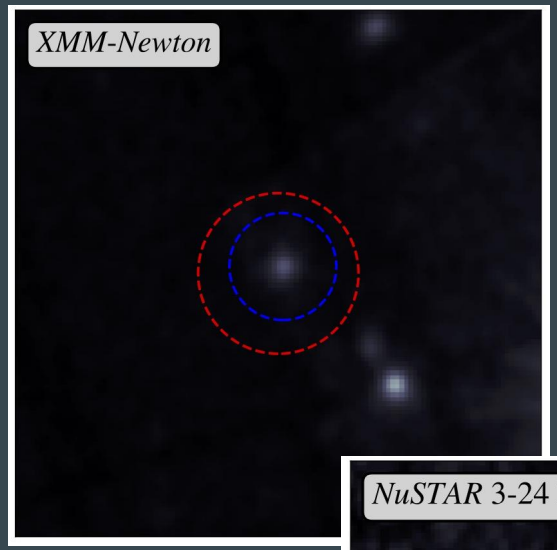


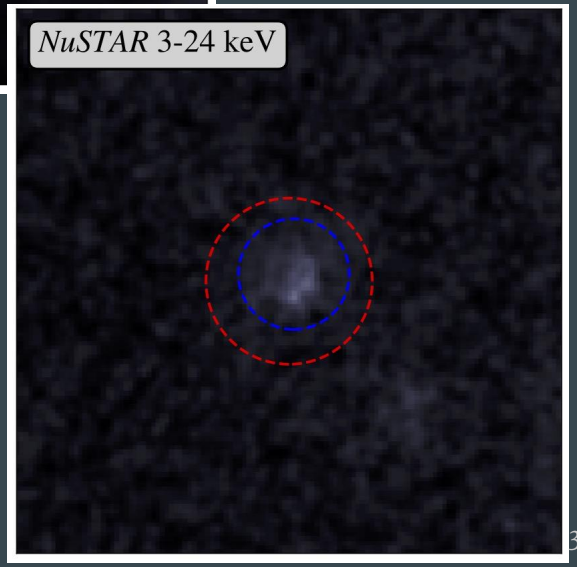
Summary

- 1274 unique primary sources + 214 secondary sources
- 3-24 keV fluxes in range 10^{-14}-10^{-11}, with median of 9.82×10^{-13} erg s^{-1}
- Reaches ~2 orders of magnitude fainter than *Swift*-BAT all sky survey
- Identified soft X-ray counterparts for 76% of the primary catalog
- Identified MIR/optical counterparts using NWAY
- Spectroscopic follow up provided redshifts for 43% of the primary catalog
- With classified spectra, we can look at the properties of subsets (e.g., NL, BL)
- We can select for other interesting subsets, such as heavily obscured AGN, that are hard to discover without *NuSTAR*

Example source: J1034+3939

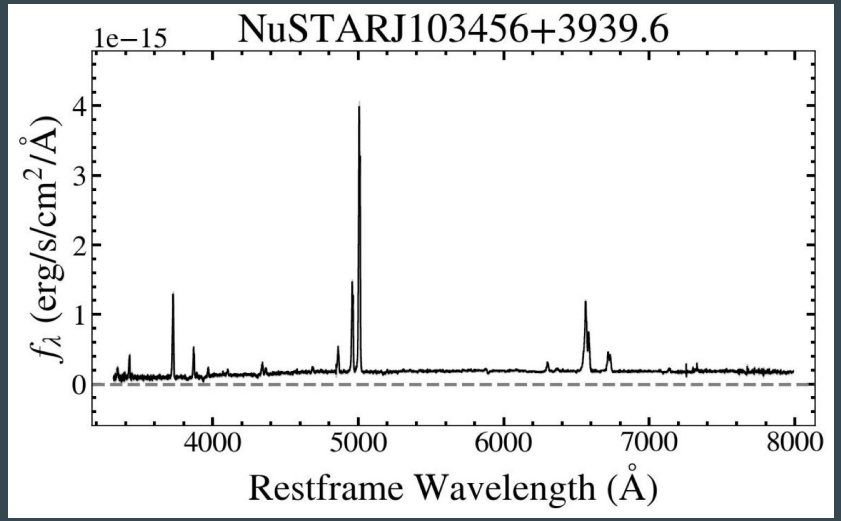






Example source: J1034+3939

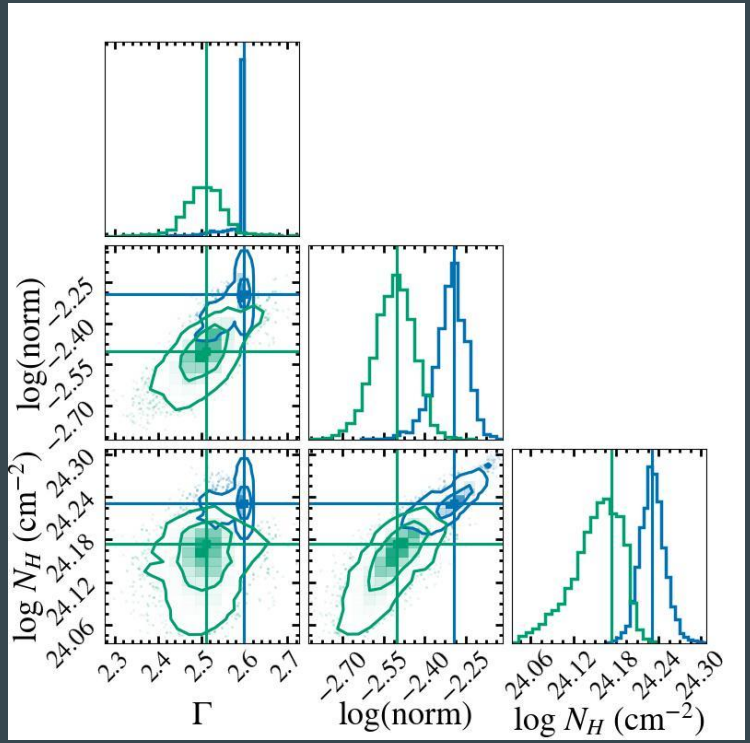
- MIR detections consistent with AGN presence
- BH mass 8.38, Eddington ratio -1.11 (Kong+18)
- Single optical spectrum from SDSS: sometimes identified as a QSO, sometimes Seyfert 2, depending on analysis
- Certainly AGN, *possibly* weak broad component



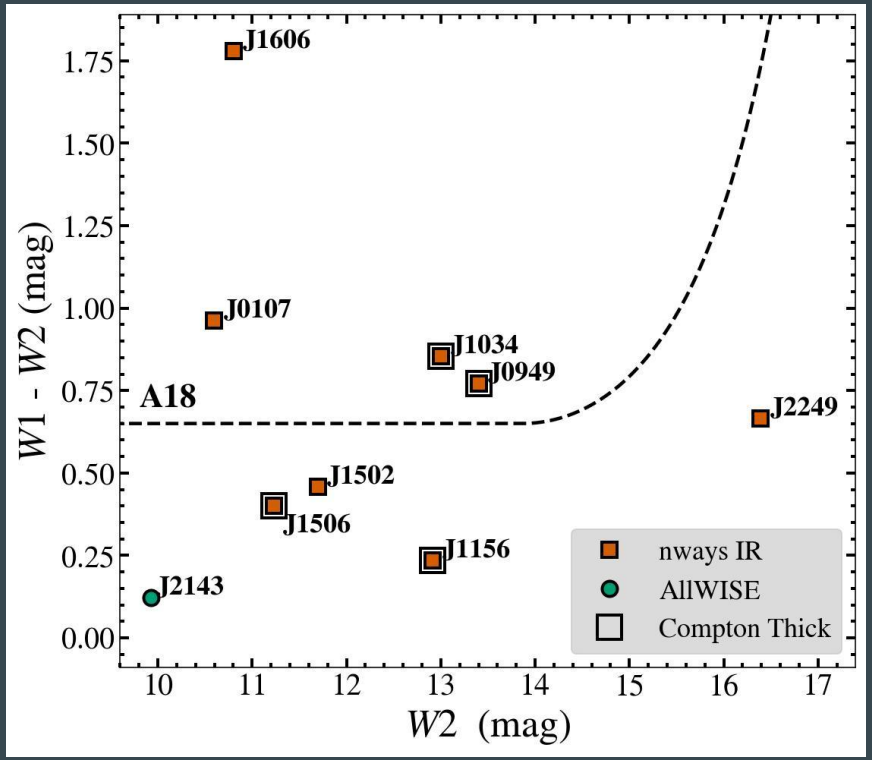
Example source: J1034+3939

- Detected with *NuSTAR* from 3-50 keV
- Previously Compton Thick candidate (Koulouridis+16) and fitted with a spherical obscuration model (log $N_{\rm H}$= 23.72; LaMassa+14)
  - These are with XMM-Newton *only*
- We find that it is Compton Thick, with exact $N_{\rm H}$ depending on model

$\Longrightarrow$ *NuSTAR* has confirmed and better constrained our knowledge of this source

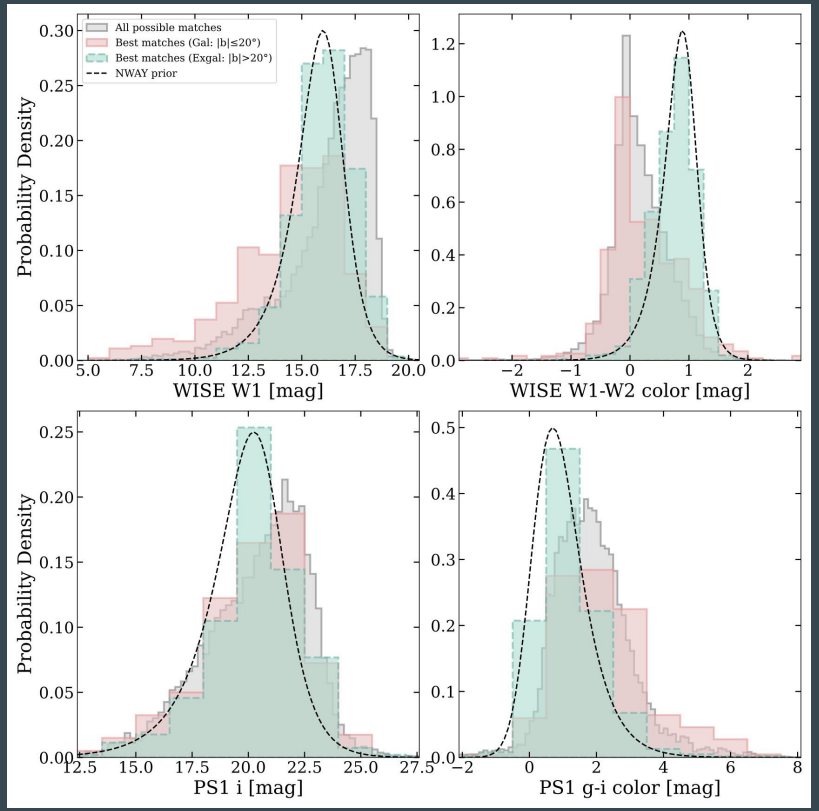


Heavily obscured AGN: MIR



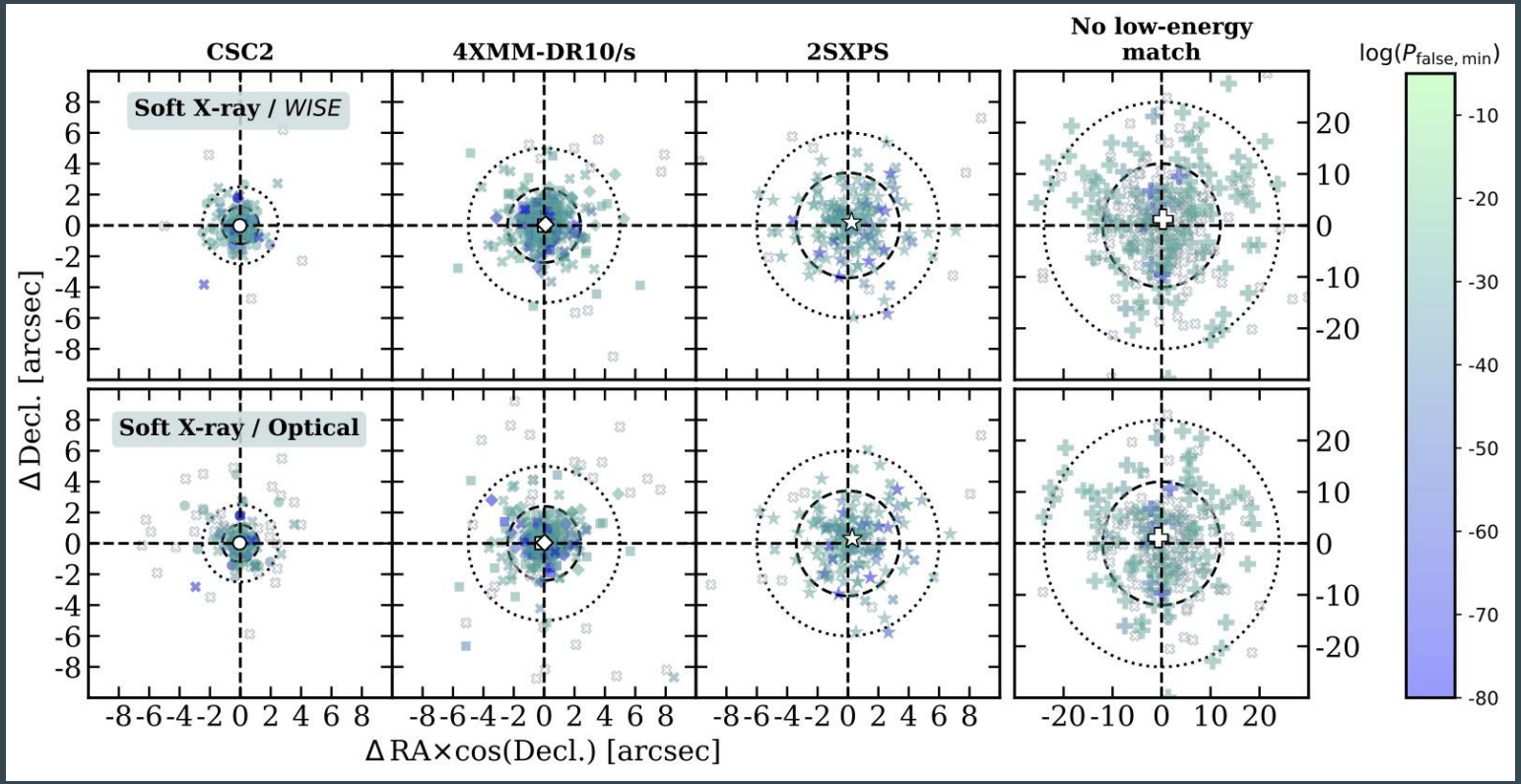
MIR and Optical Cross Matching

- Difficult to distinguish correct options
- So instead of simple positional match we use a statistical method: NWAY
- We can take into account:
  - Positional uncertainty
  - Colour and magnitude priors
- We construct these only for sources outside of the galactic plane



Greenwell, Klindt et al., 2024 (submitted)

MIR and Optical Cross Matching



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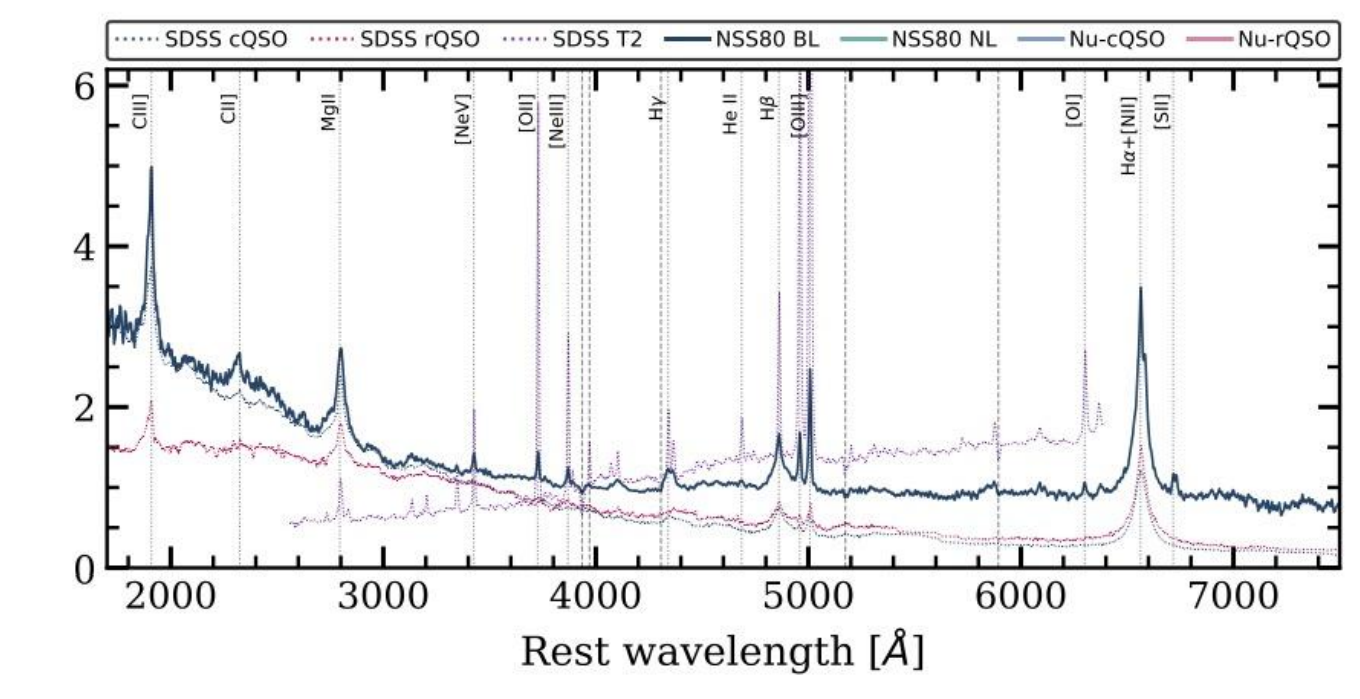
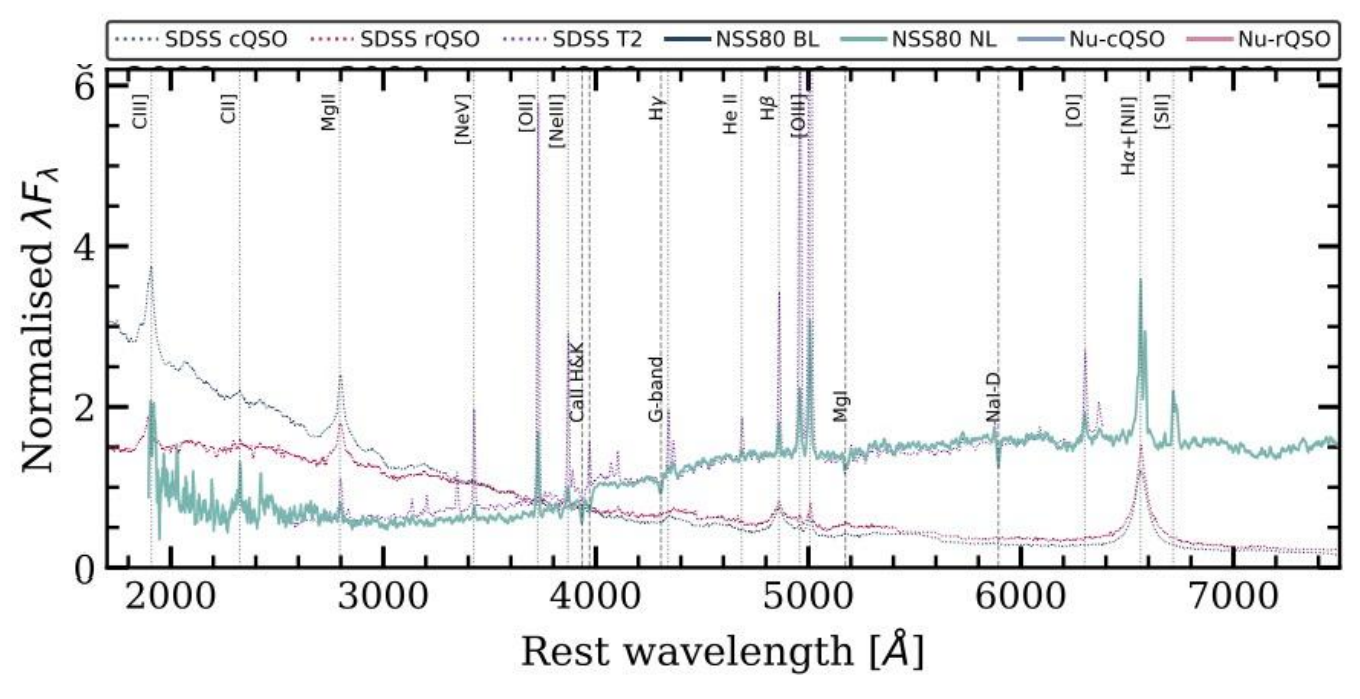
Overview of Properties: BL Composite



Greenwell, Klindt et al., 2024 (submitted)

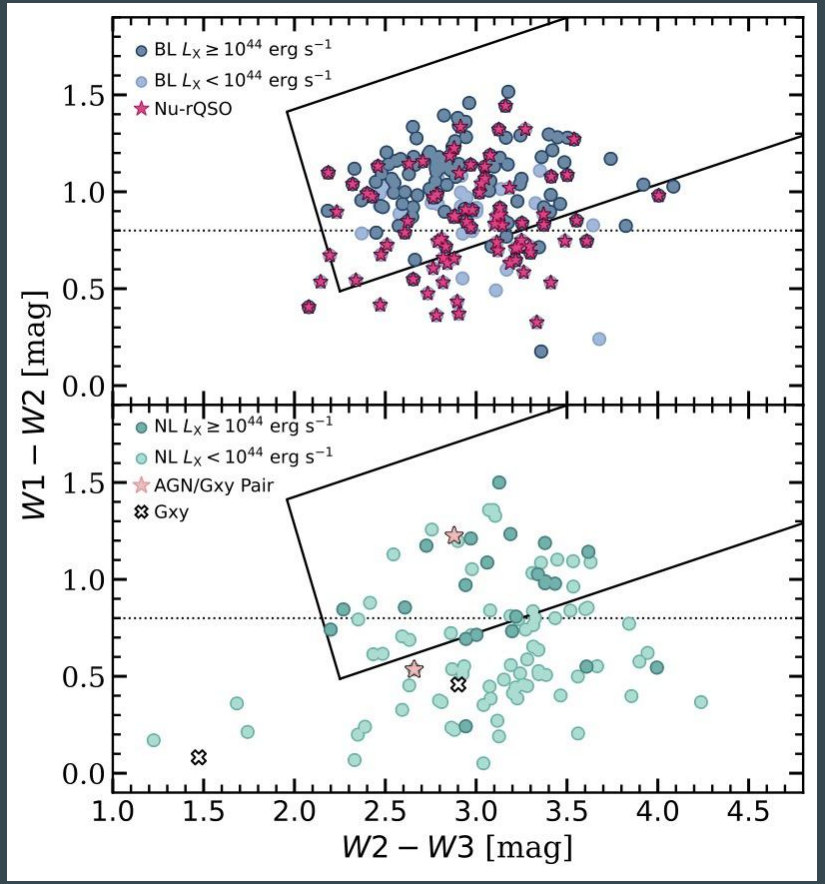
Overview of Properties: NL Composite



Greenwell, Klindt et al., 2024 (submitted)

Overview of Properties: MIR

- MIR colours commonly used to identify AGN
- Wedge from Mateos et al., 2012 selects AGN using 3-band *WISE* colours
- 80% of BL sources selected
- 42% of NL sources selected
- Unselected proportion mostly driven by low luminosity sources



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