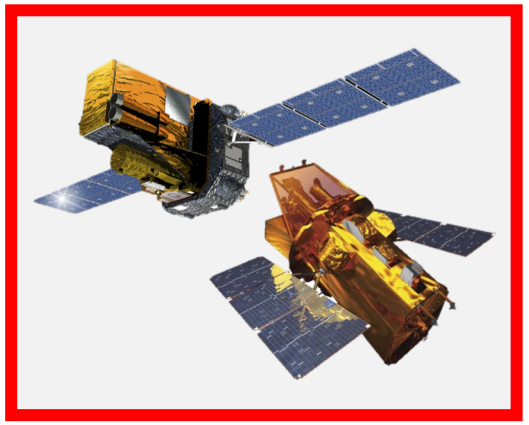
A sensitive hard X-ray census of the AGN population with NuSTAR

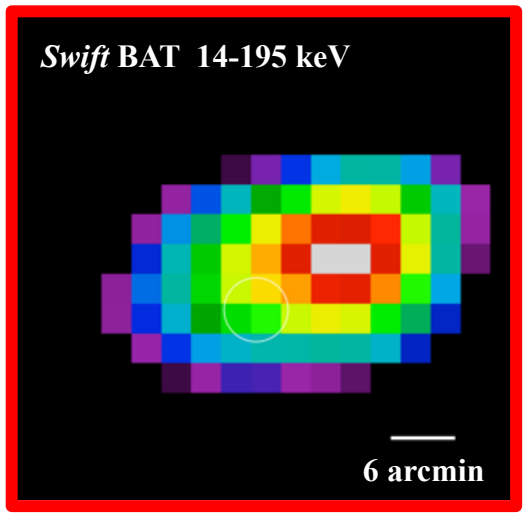
George Lansbury
(IoA Cambridge, Herchel Smith fellowship)

With:
David Alexander (Durham), James Aird (IoA),
Poshak Gandhi (Southampton), Daniel Stern (JPL),
Mike Koss (Eureka), Agnese Del Moro (MPE),
Ezequiel Treister (PUC), Fiona Harrison (Caltech), Roberto Assef (UDP),
and many others including The NuSTAR Extragalactic Surveys group

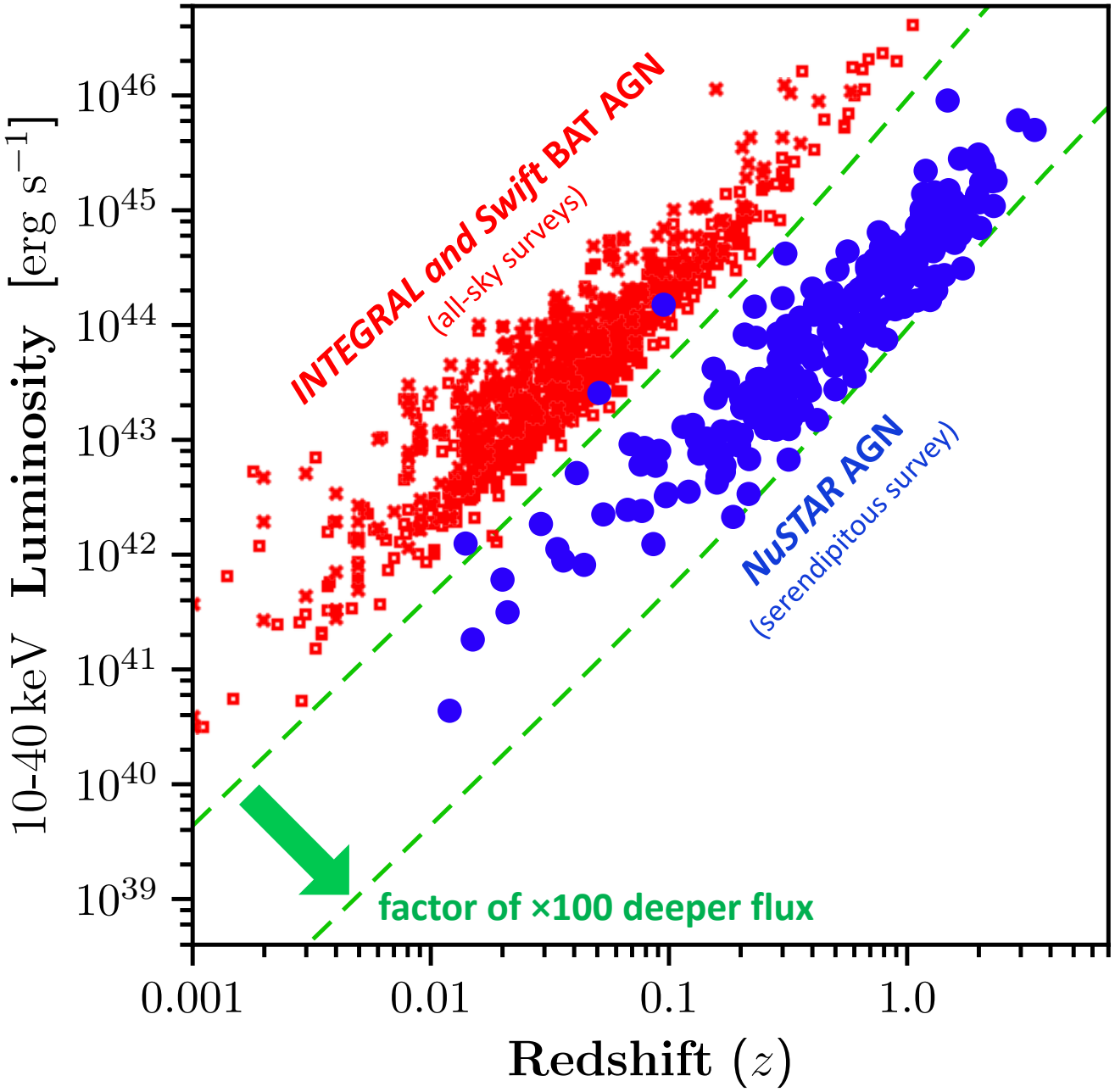
UNIVERSITY OF CAMBRIDGE
Herchel Smith Fund

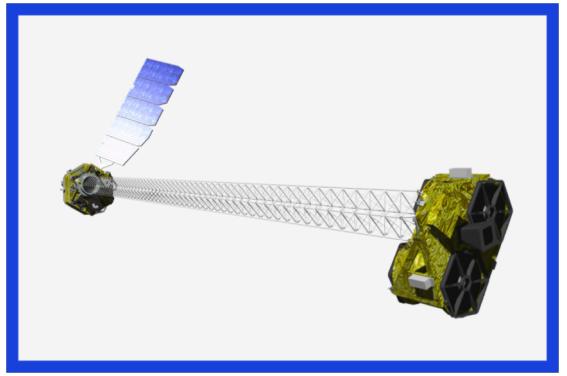
Current hard (> 10 keV) X-ray census:

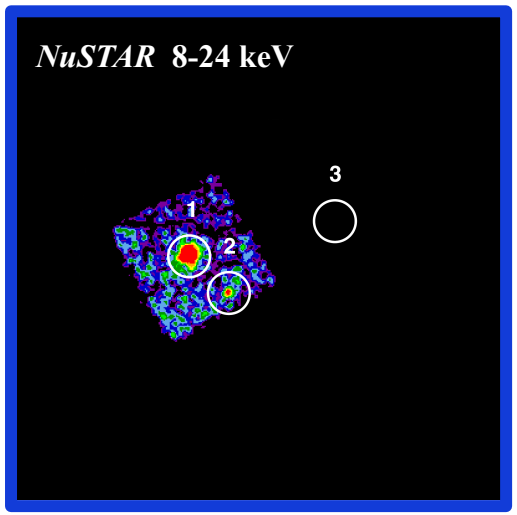




J150645+0346.2
viewed with BAT





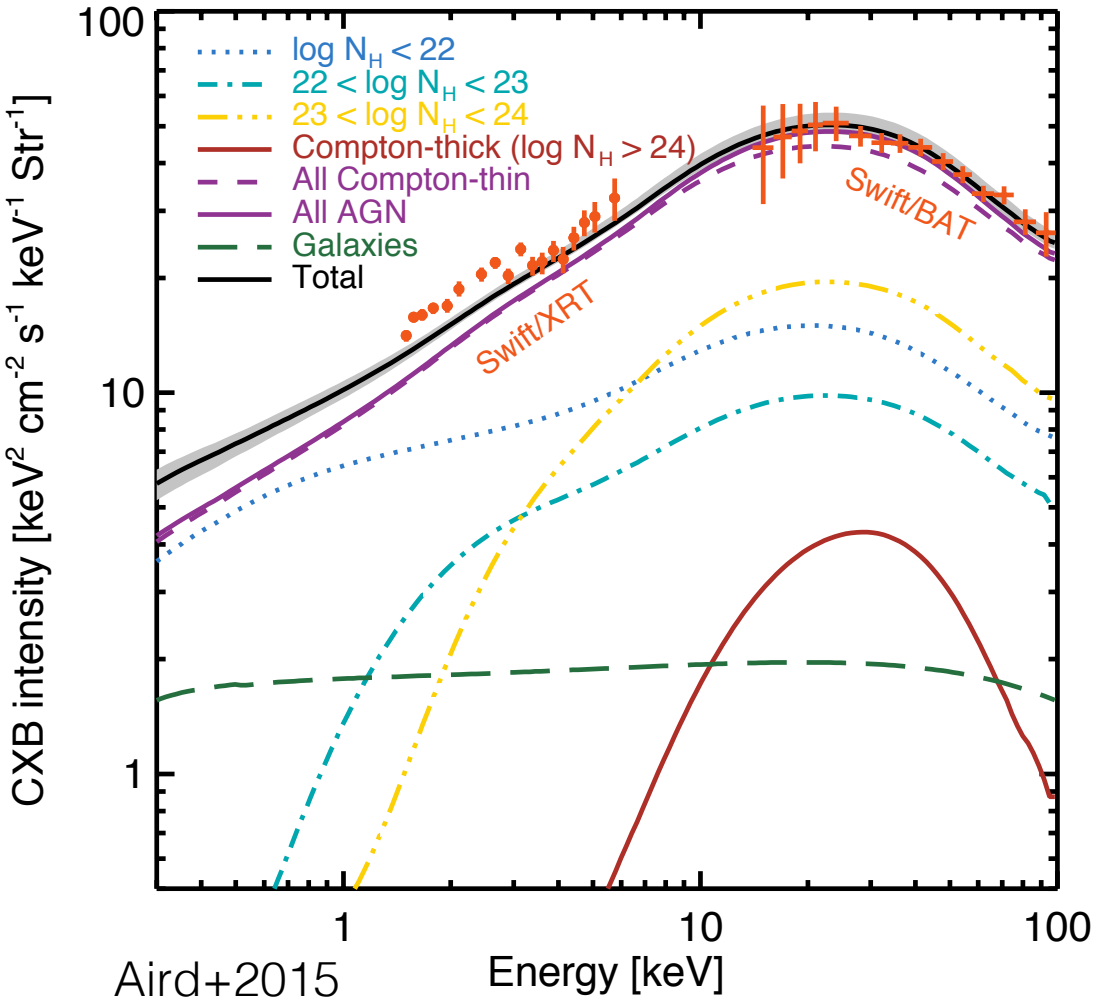


J150645+0346.2
viewed with NuSTAR

Outline

- Motivations
- *NuSTAR* surveys: the serendipitous survey catalogue
  - The sample
  - Synergy with Chandra/XMM/Swift
  - Multiwavelength result highlights
- Hidden treasure: Hunting for highly obscured black hole growth
  - Extremely hard *NuSTAR* sources in the survey
  - The Compton-thick fraction of AGN

Motivation for hard X-ray census of AGN: The cosmic X-ray background (CXB)



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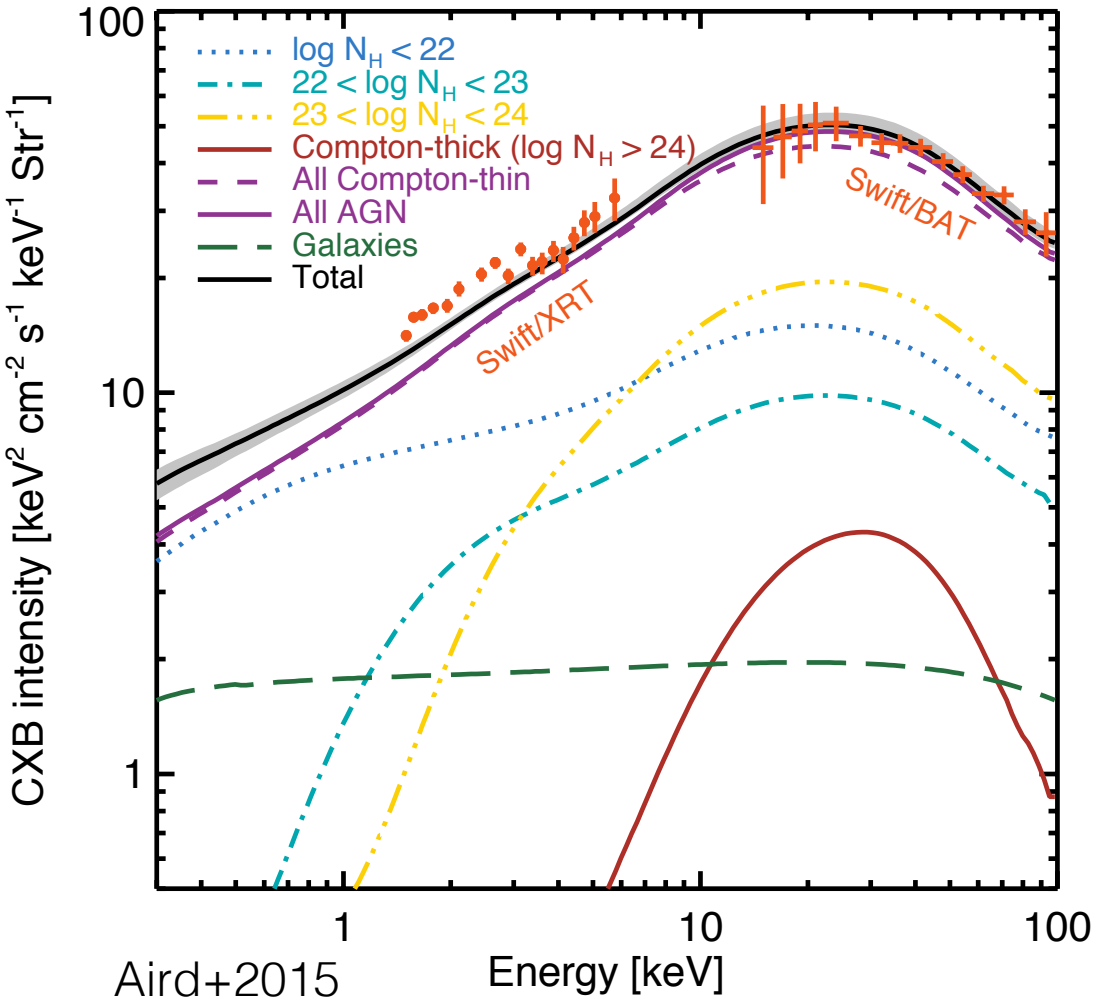

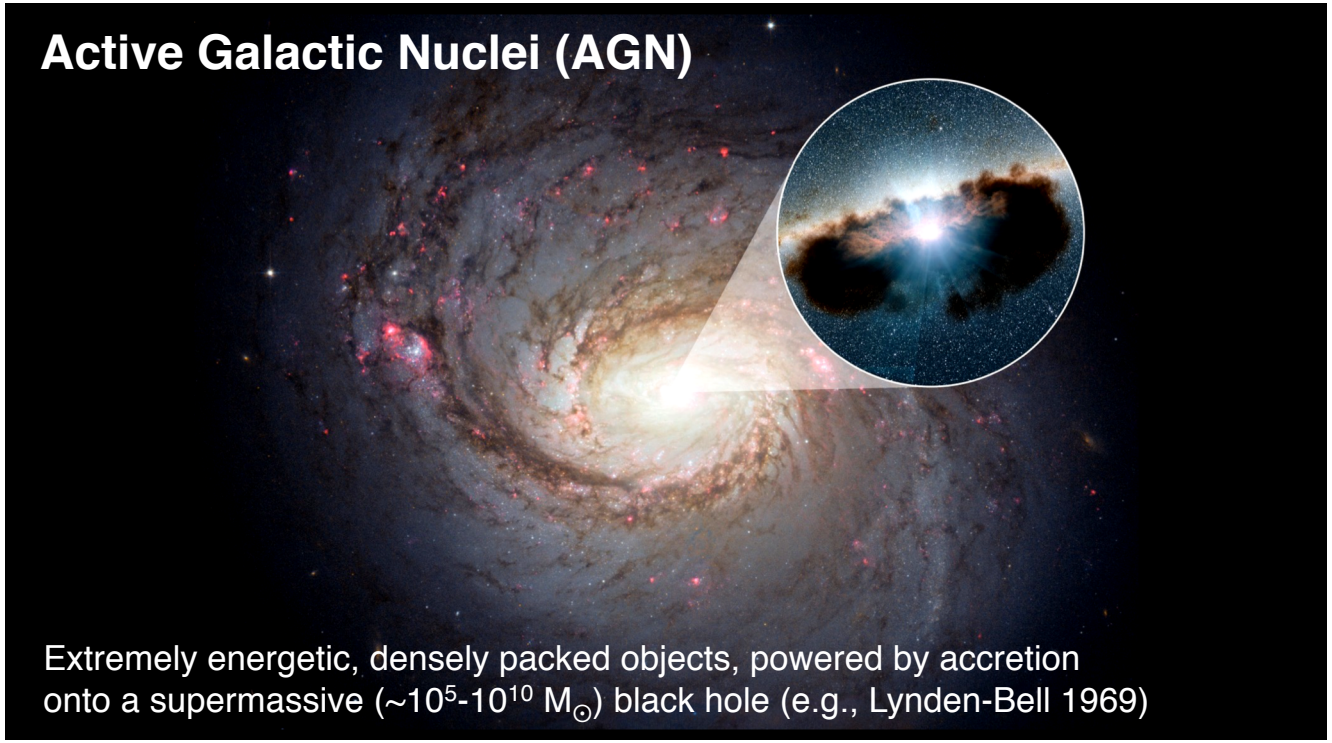

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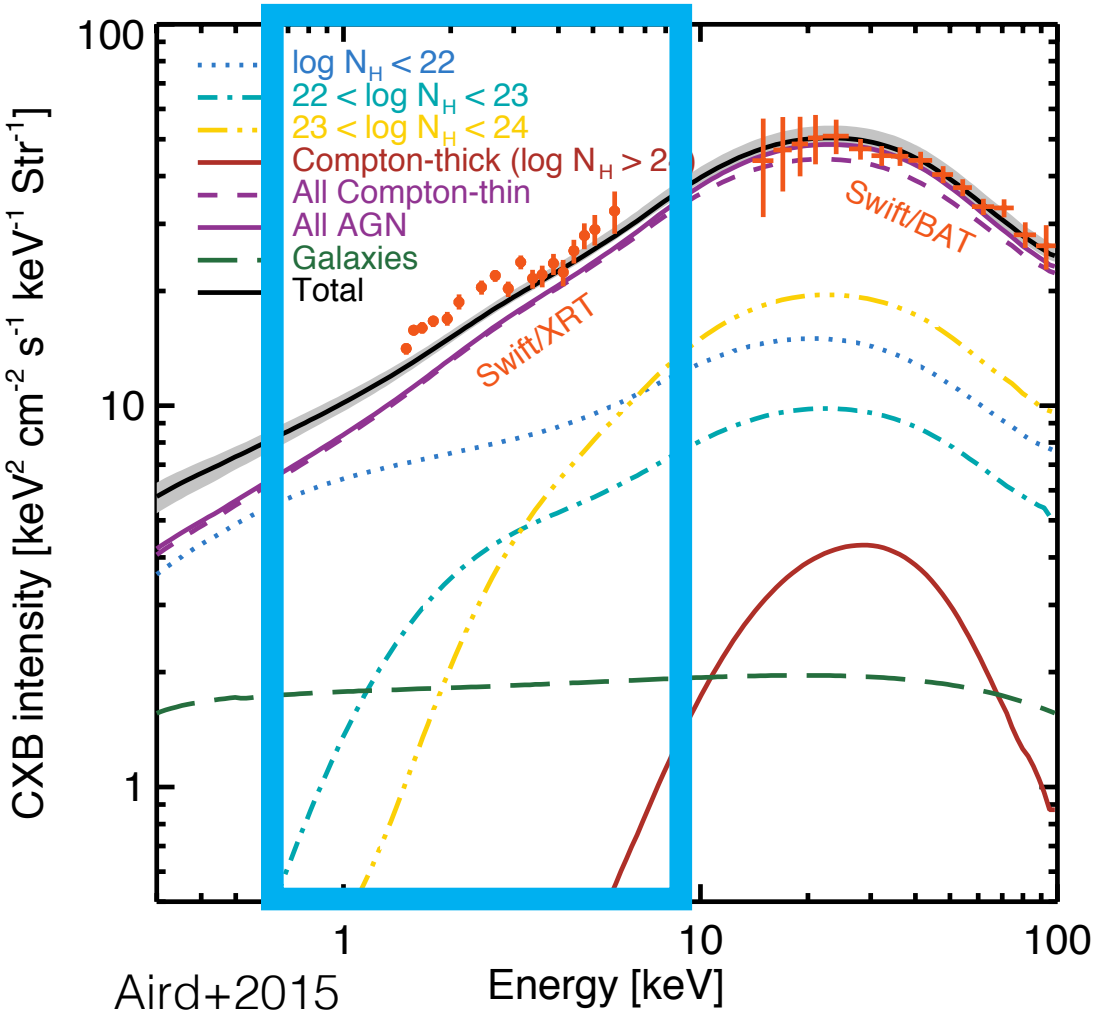
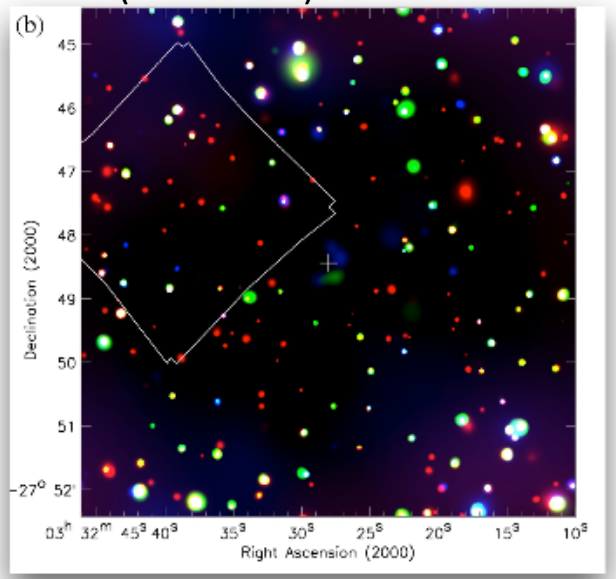


Aird+2015

At **lower energies (<10 keV)** Chandra and XMM surveys have resolved 70-90% of the CXB into individual AGN (e.g., Worsley+2006)

CDFS (Xue+2011)



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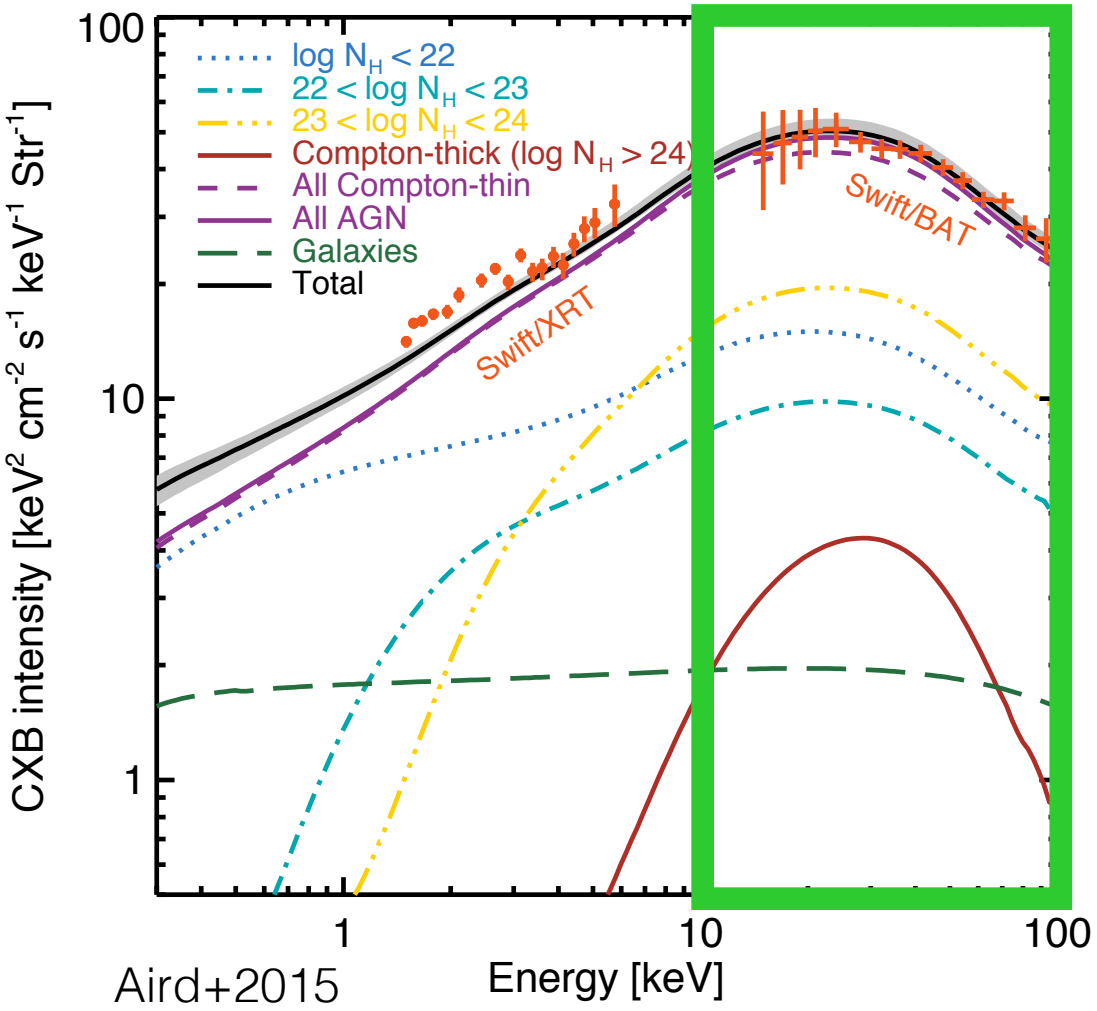
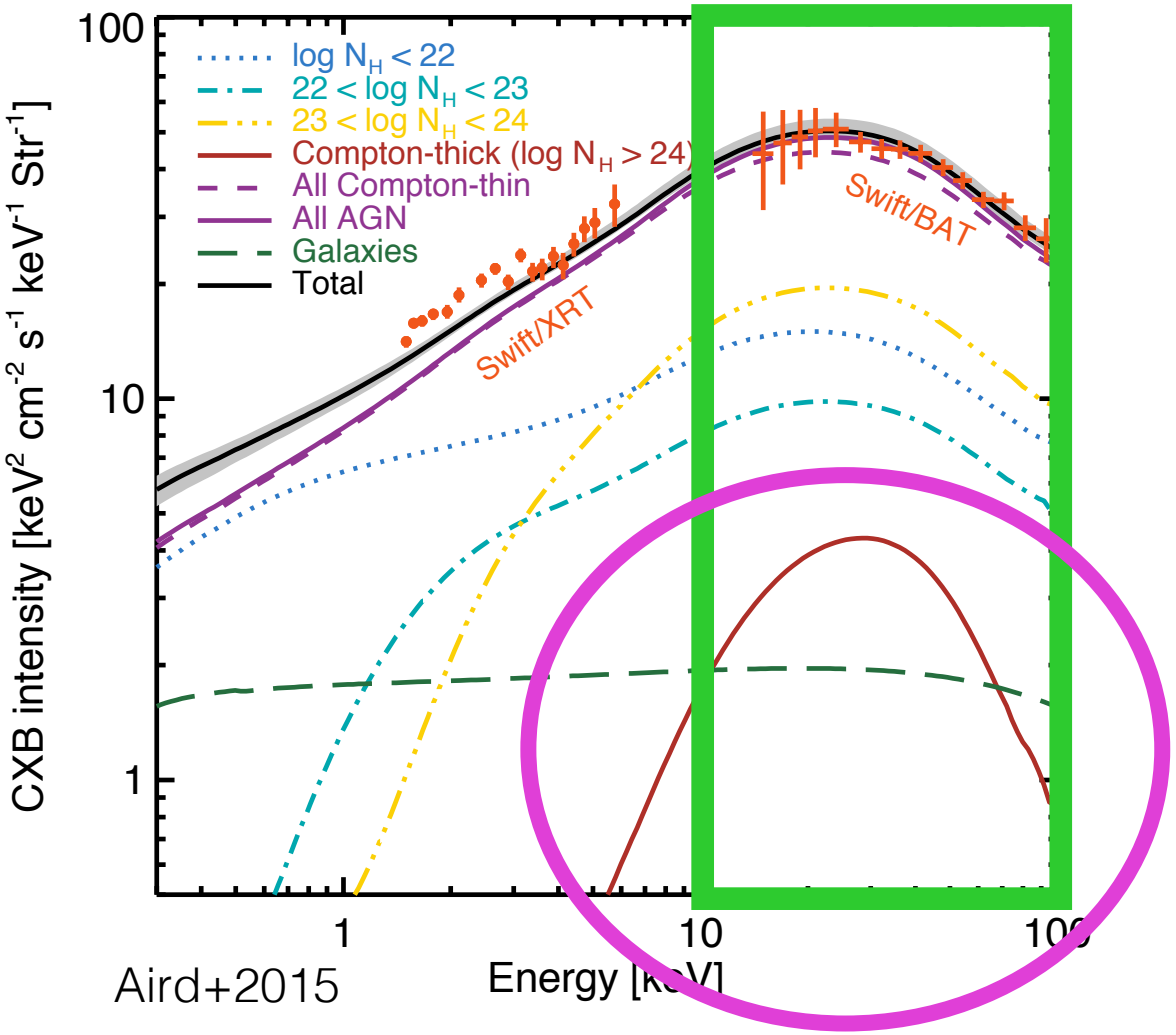


The **CXB peak** is at **"hard" X-ray energies (>10 keV)**

NuSTAR surveys resolve ~30% of the CXB peak
(Harrison, Aird + 2016)

Motivation for hard X-ray census of AGN: The cosmic X-ray background (CXB)

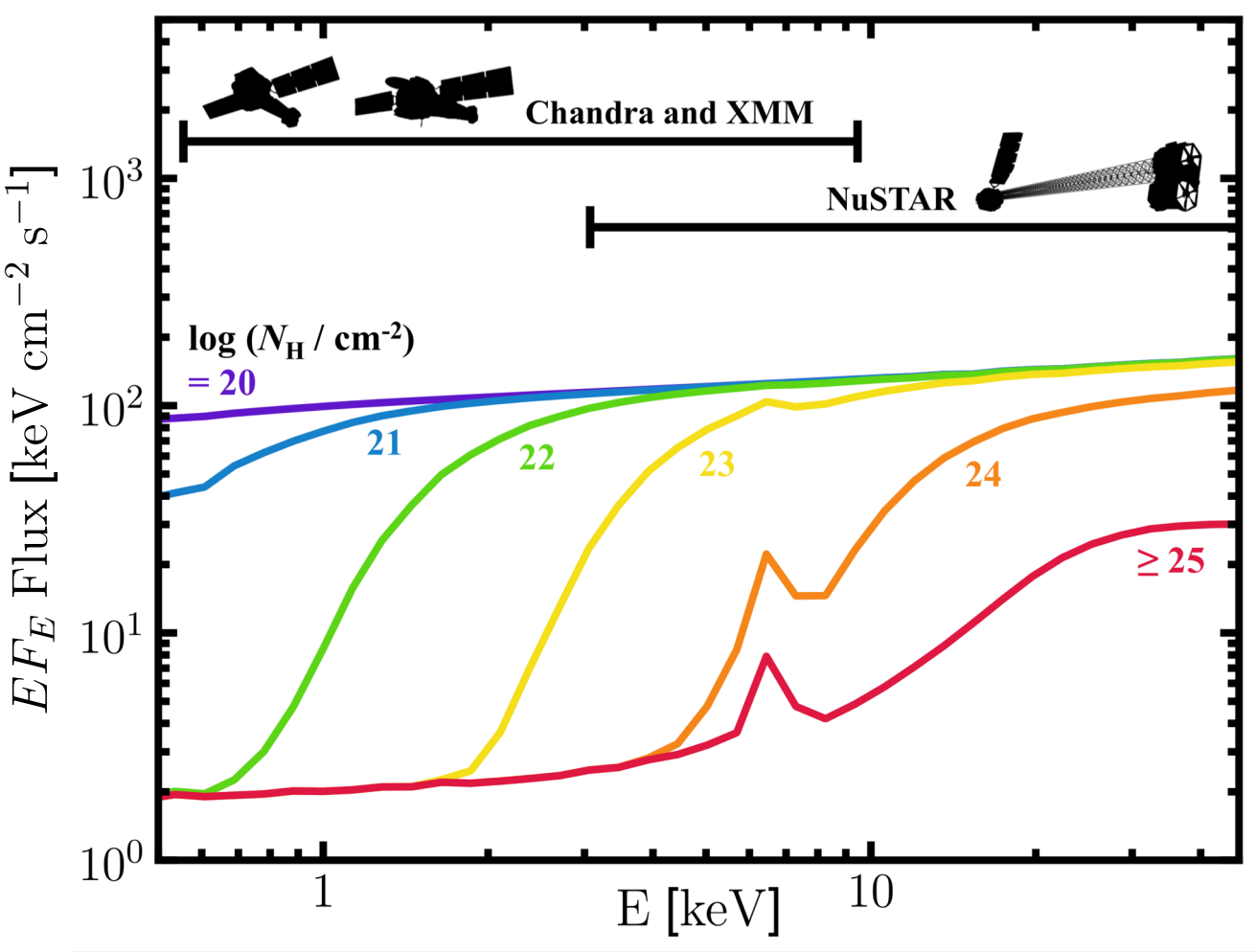


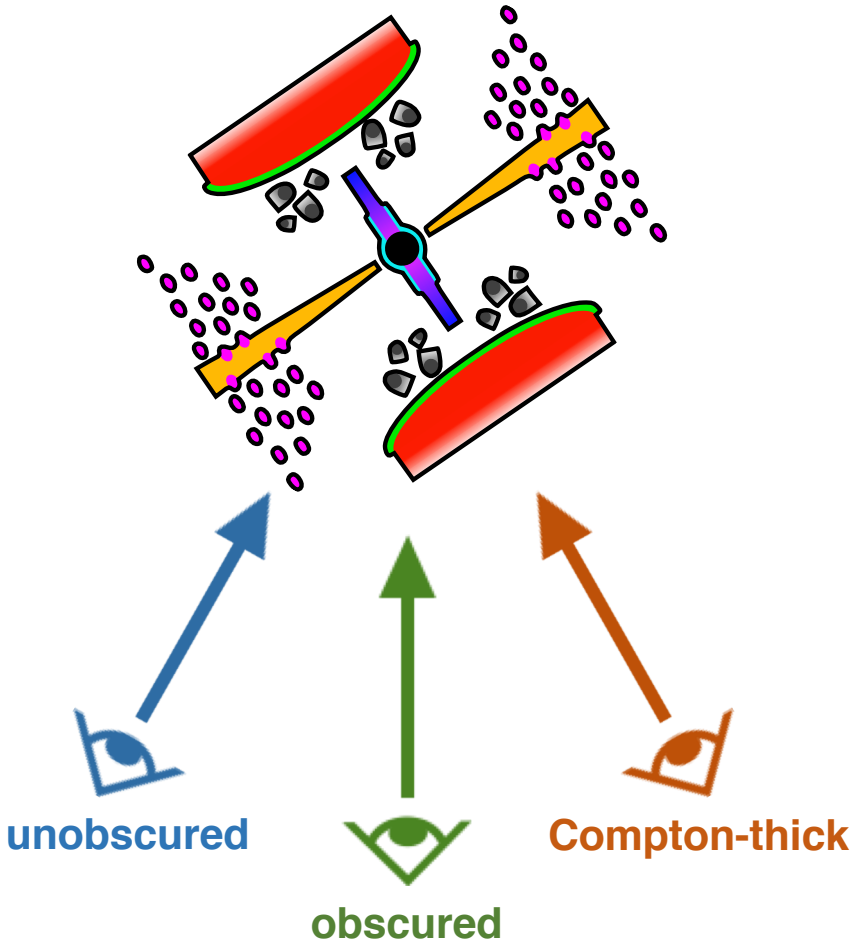
The **CXB peak** is at **"hard" X-ray energies (>10 keV)**

The **CXB shape** predicts:

- unobscured ($N_H < 10^{22}$ cm^{-2}) AGN
- obscured ($N_H > 10^{22}$ cm^{-2}) AGN
- **Compton-thick ($N_H \gtrsim 10^{24}$ cm^{-2})** AGN, which **account for a large fraction of supermassive black hole growth** (**~10-60%**; e.g., Treister+2009, Buchner+2015), but are **difficult to identify**.

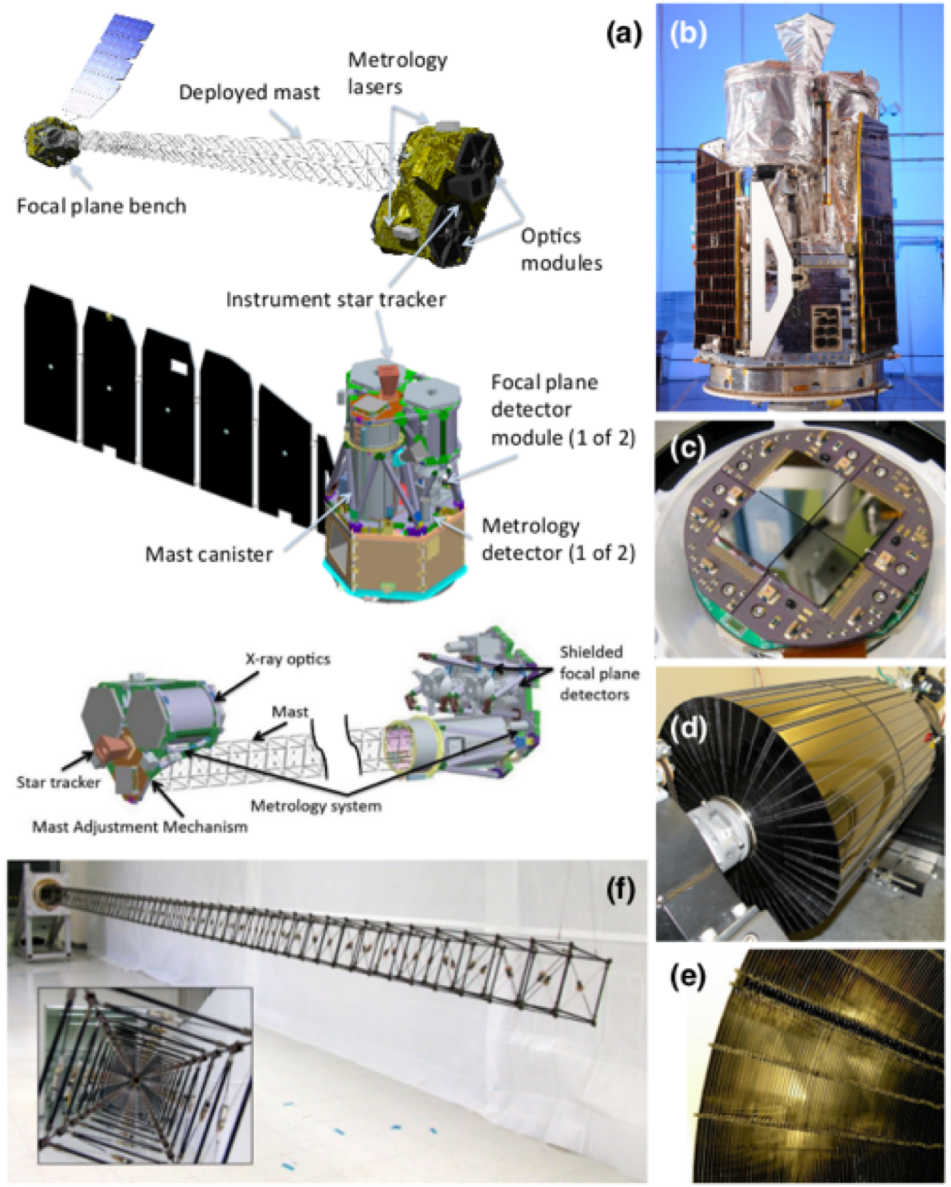
Motivation for hard X-ray census of AGN: identifying highly obscured AGN



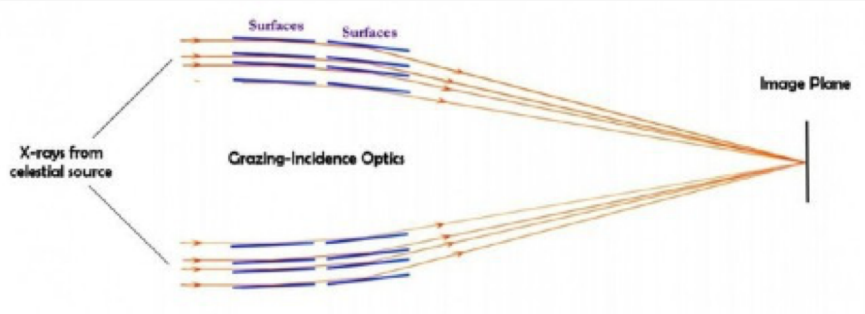


Hard X-ray surveys have a relatively clean AGN selection function

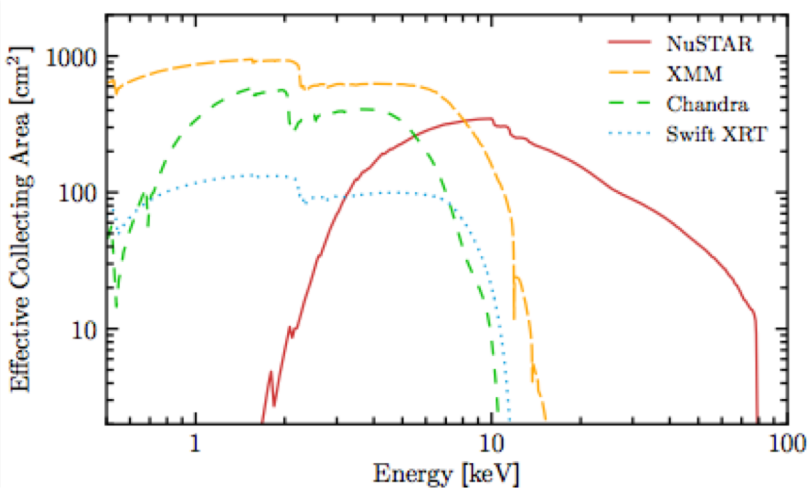
The Nuclear Spectroscopic Telescope Array (NuSTAR)



- **NASA Small Explorer (SMEX)**
- **Launched in June 2012**
- **The first focusing mission at $E > 10$ keV**



- **12′ × 12′ field-of-view**
- **Sensitive at E = 3–78 keV**



NuSTAR extragalactic surveys overview

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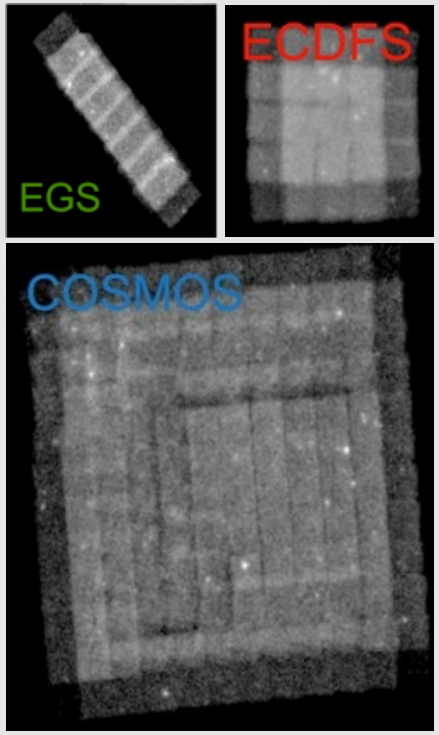
(1) Surveys in famous blank fields



COSMOS: Civano+ 2015
ECDFS: Mullaney+ 2015
UDS: Masini+ 2018
EGS: Aird+ in prep.
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Total area = **2.8 deg^2**

Total # sources = **272**

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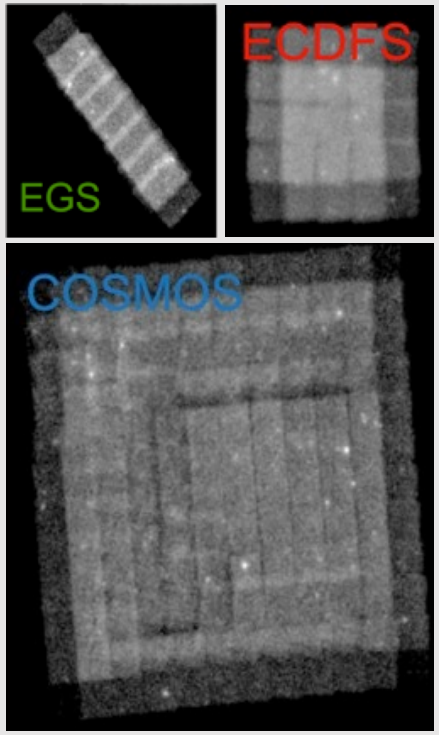

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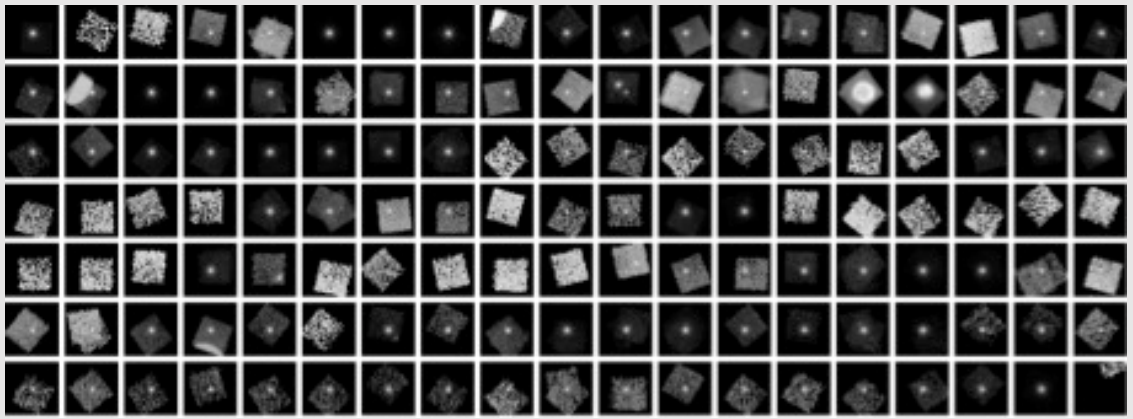
Wide-area survey, covering a range of depths



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Alexander+ 2013; Lansbury+ 2017a

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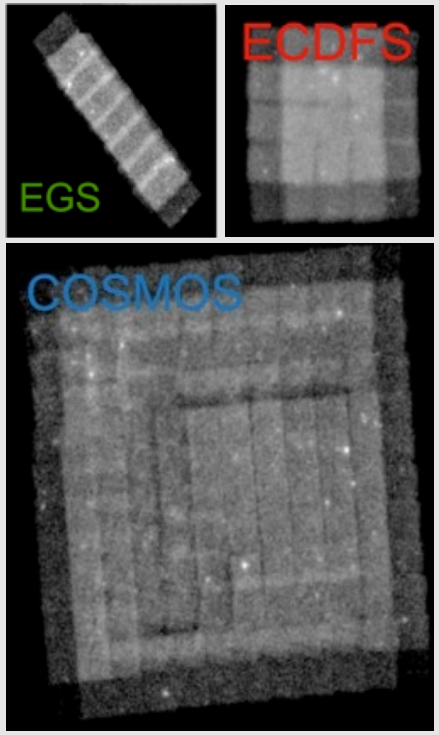

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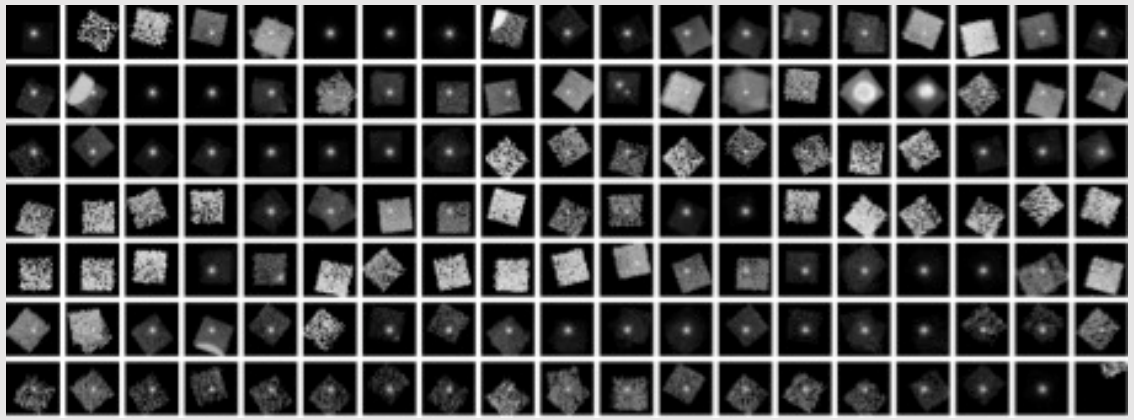

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Snapshot survey of Swift BAT AGN: Baloković+ 2014, Baloković+ in prep.

Legacy survey of bright AGN from XMMLSS, XBootes, and SDSS stripe 82: Kamraj+ in prep.

Legacy survey of IRAS AGN (NuLANDS): Boorman+ in prep.

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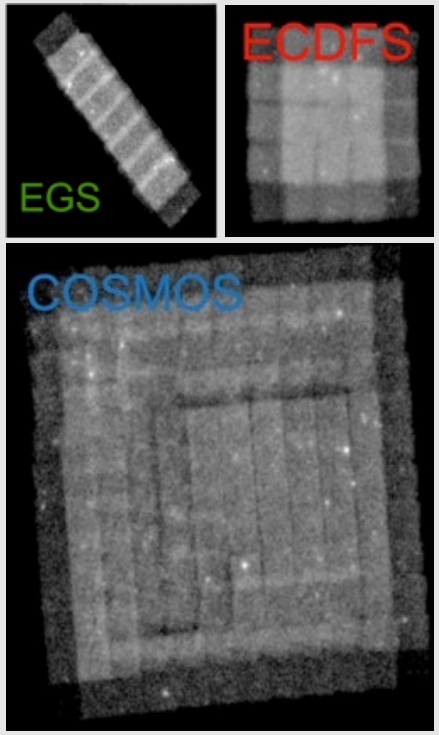

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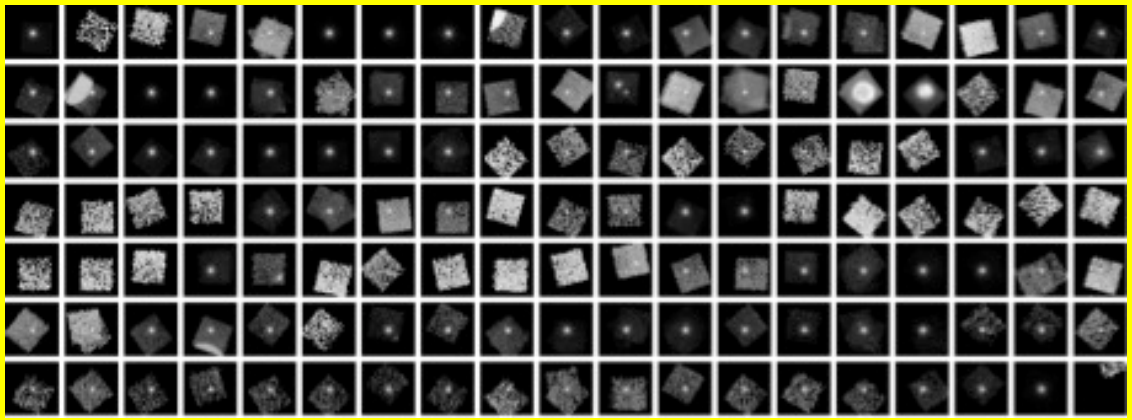

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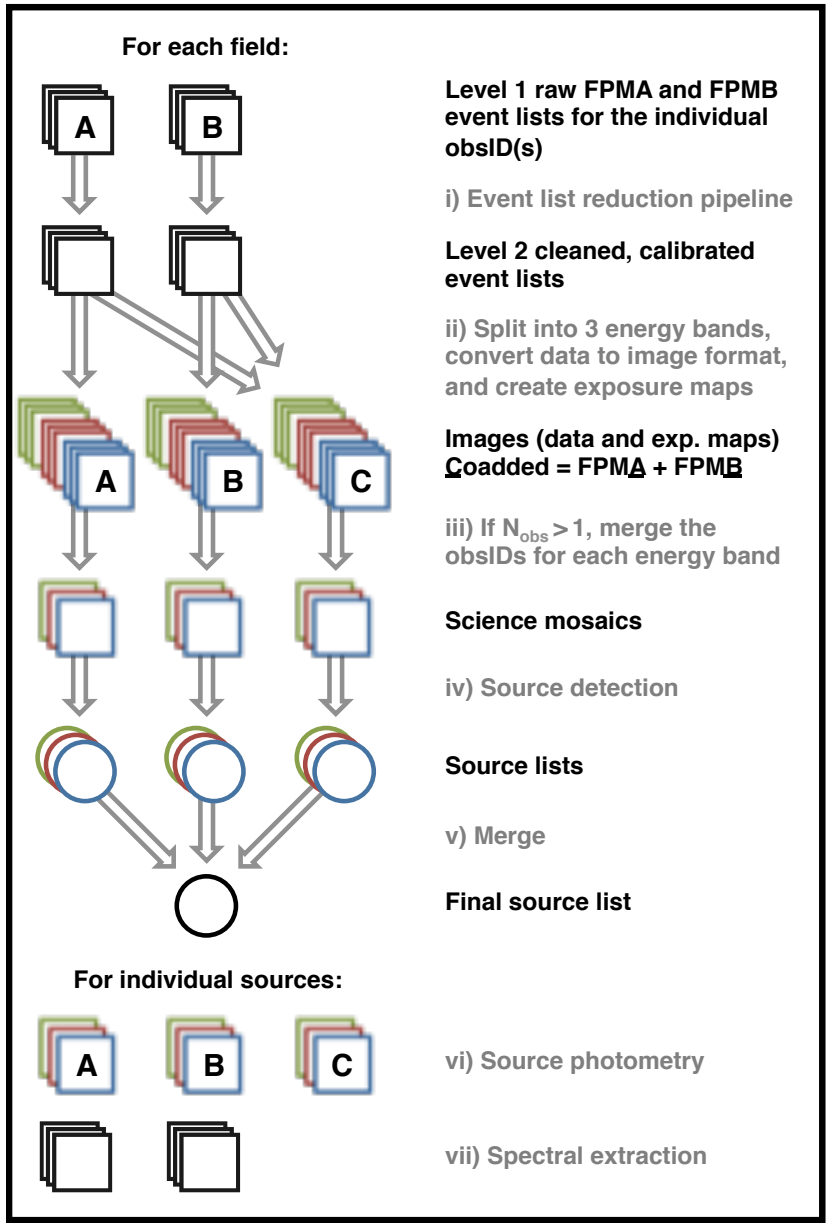
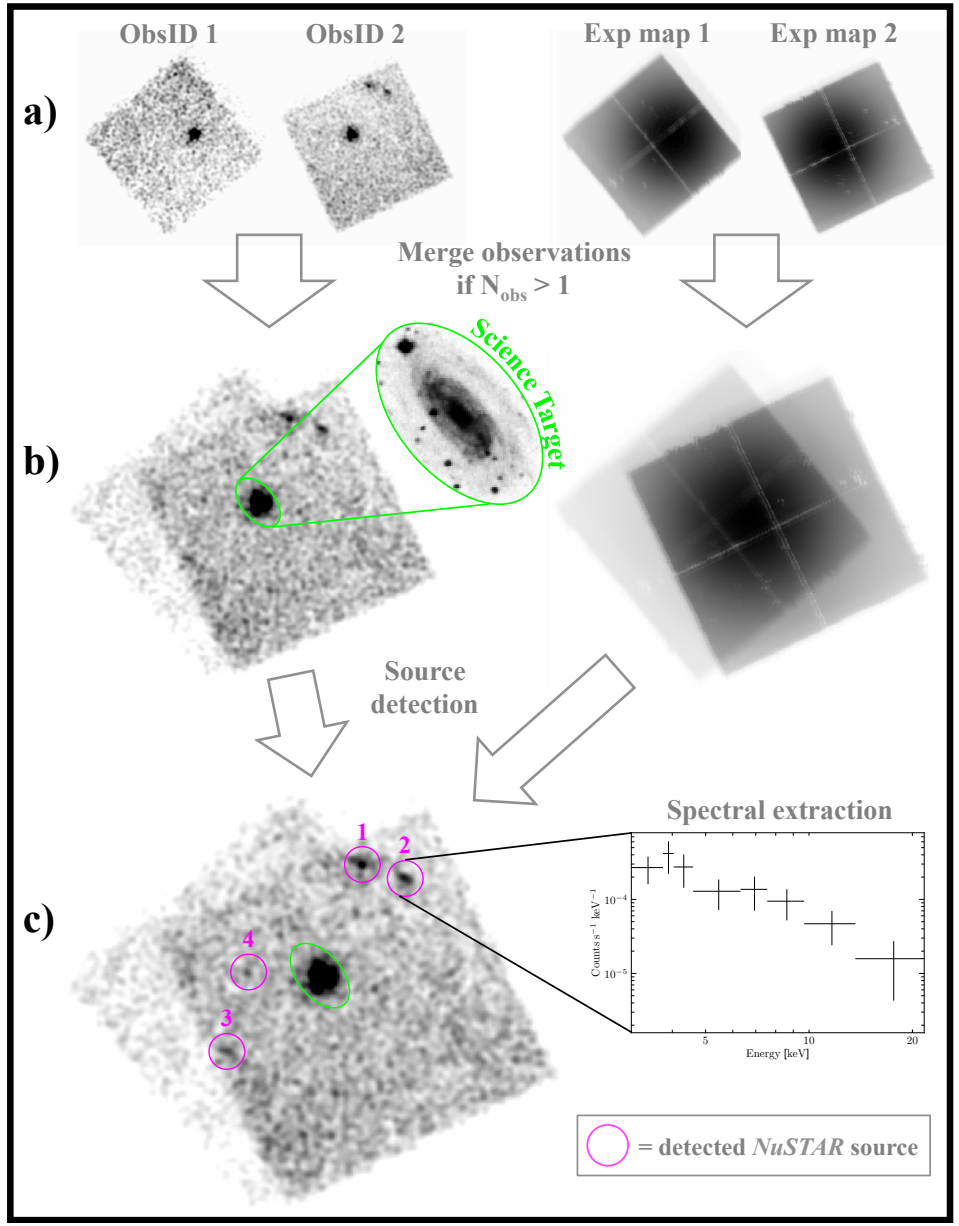
The NuSTAR serendipitous survey: data flow

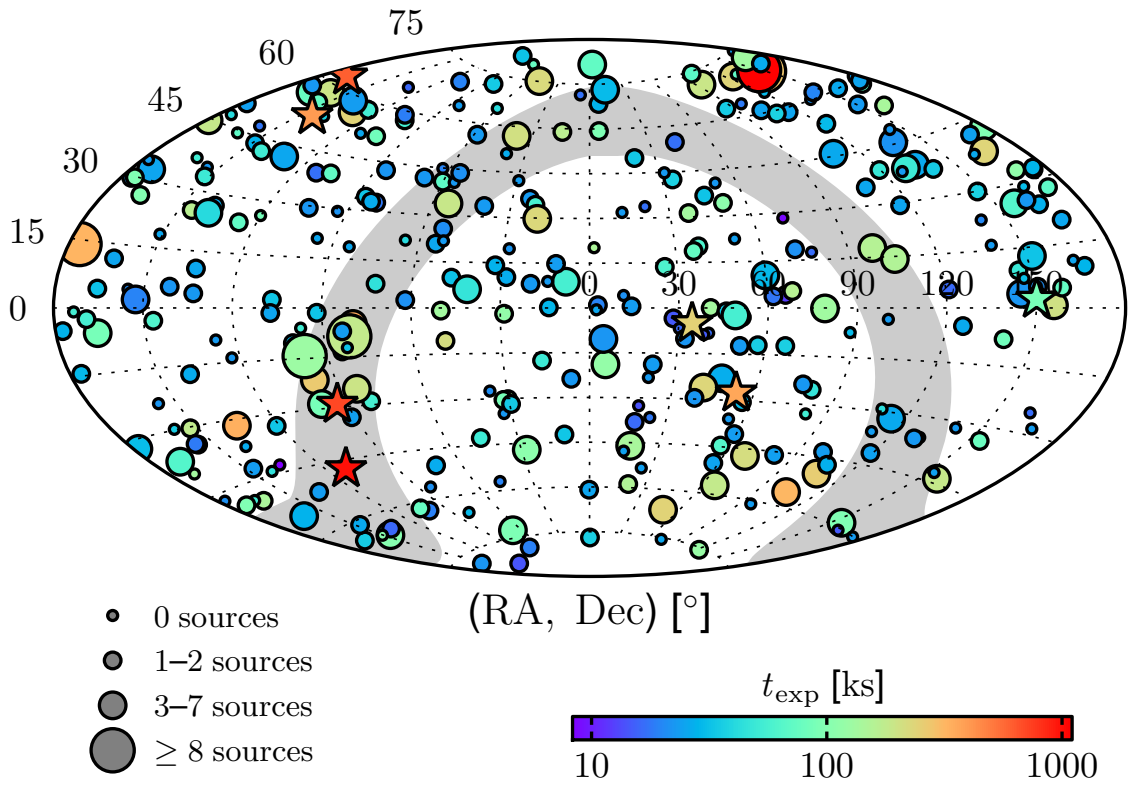




Perform for full >20Ms of NuSTAR science data

Lansbury+2017a

NuSTAR serendipitous survey: overview of the 40-month catalog



Lansbury+ 2017a ApJ 836 99L
see electronic article for
machine-readable catalog tables,
optical spectra, etc.

Area covered	13 deg^2
Sources detected	497
AGN with spec-*z's*	300
Galactic sources with spec-ID's	20
Faintest hard-band flux (8-24 keV)	1.5×10^{-14} erg s^{-1} cm^{-2}
Max. effective exposure	1 Ms
Median effective exposure	28 ks

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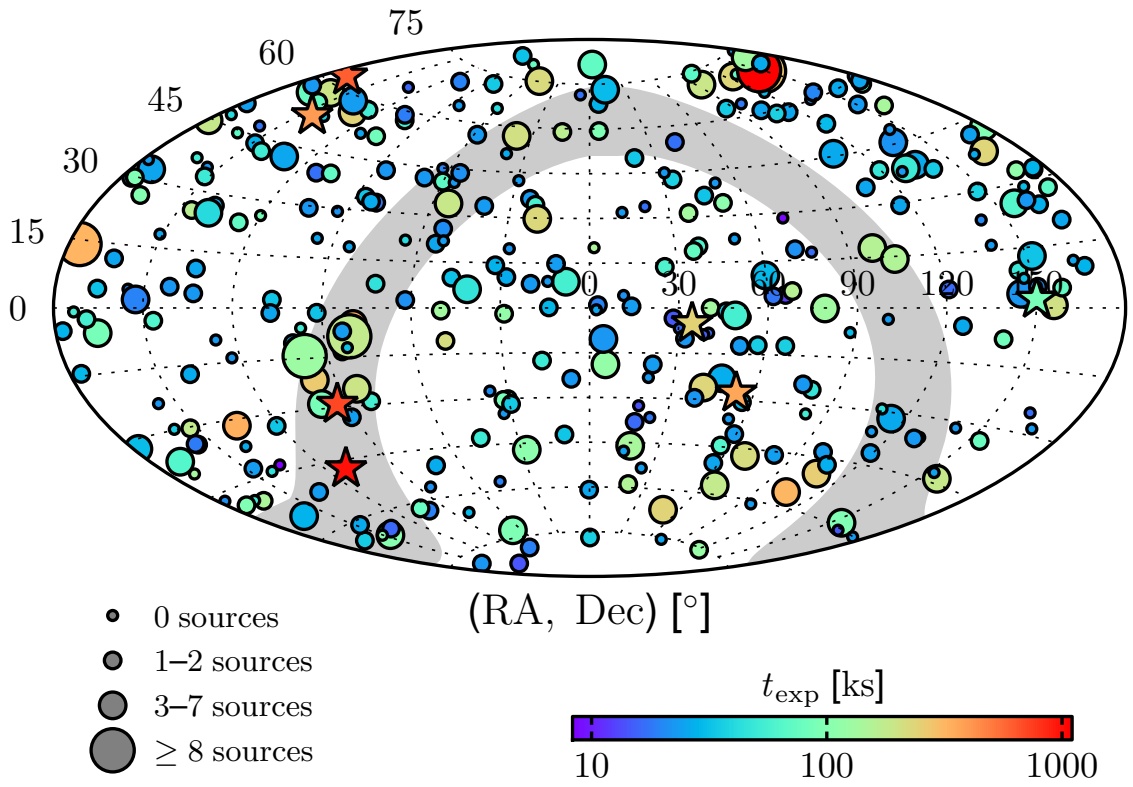

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→ **763**

→ **388**

~60 month statistics, from **Lizelke Klindt**, Durham

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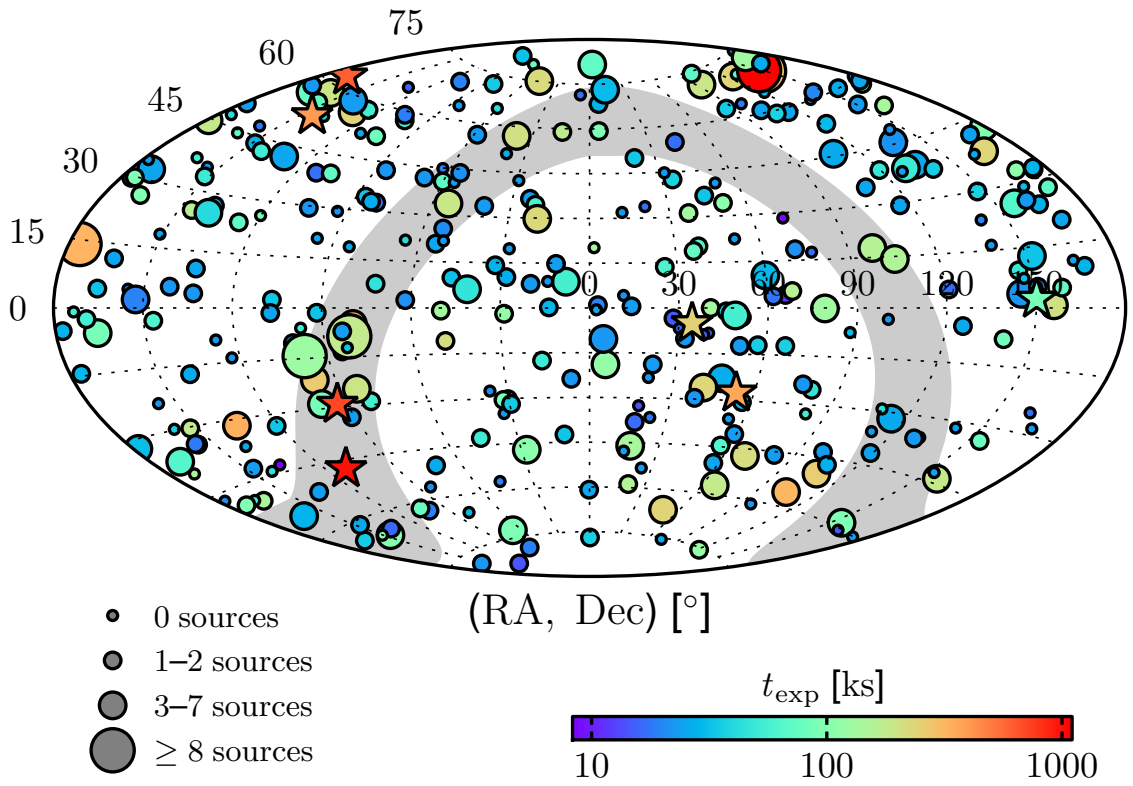

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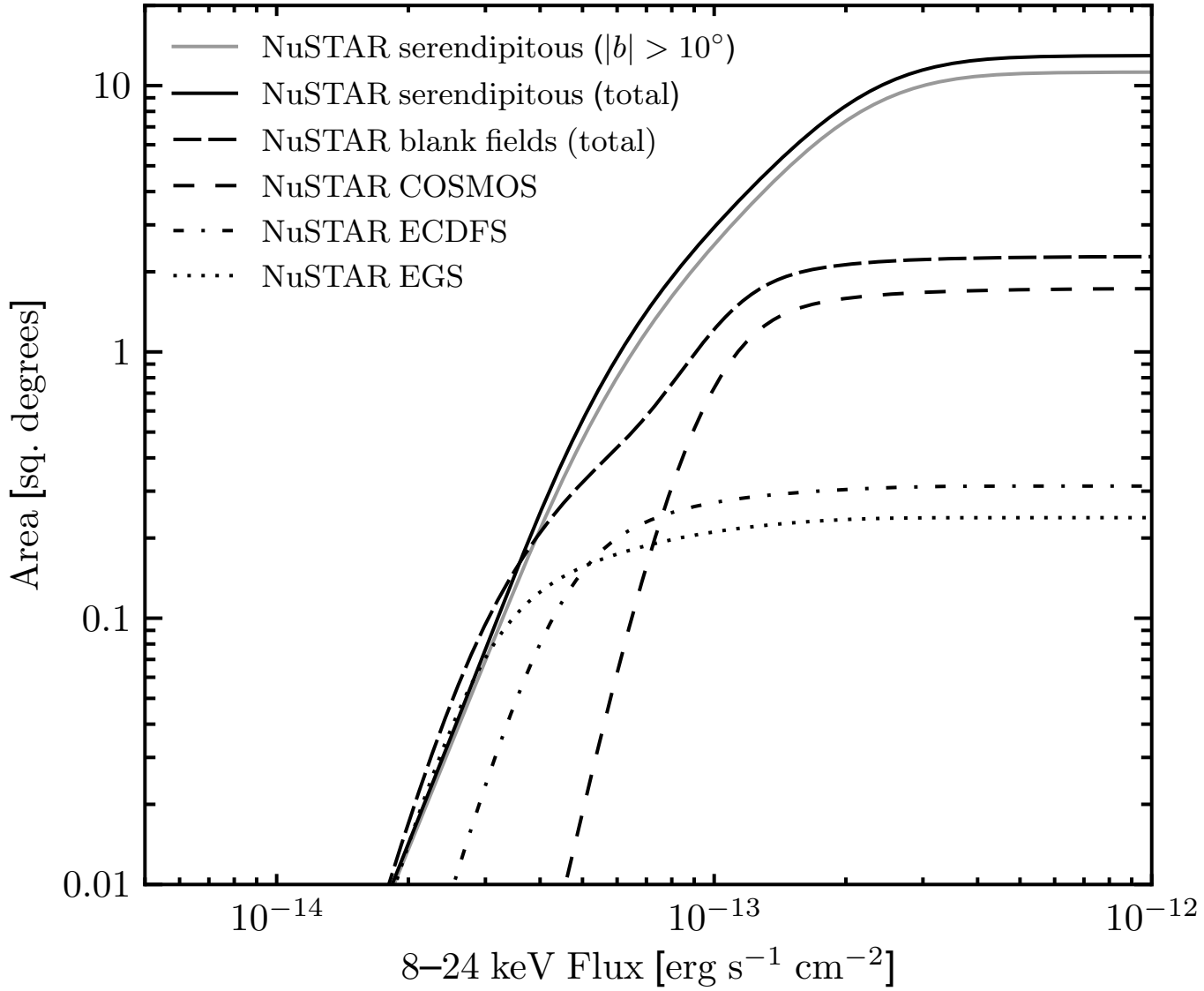
Catalog contents
(106 columns in total) include:

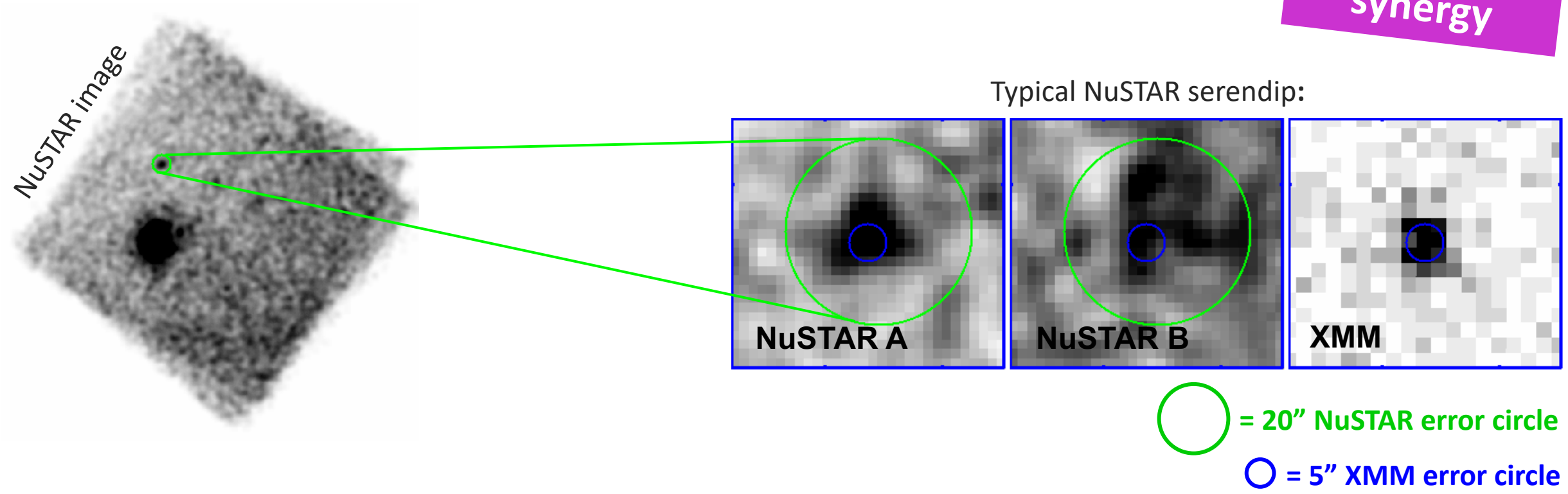
- Positions
- Three-band photometry
- Band ratios
- Effective photon indices
- Chandra/XMM/XRT counterparts
- WISE and optical counterparts
- Redshifts
- Luminosities
- Optical classifications
- Optical spectra

NuSTAR serendipitous survey: overview of the 40-month catalog



NuSTAR serendipitous survey: counterpart identification

Multi-mission synergy



- **The NuSTAR source positional accuracy ranges from ≈10” to ≈20”** (Lansbury+ 2017a)
- **79% (395/497) of NuSTAR serendips have soft X-ray counterparts in archival XMM / Chandra / Swift XRT data**
  - 284/395 of these counterparts are in the **3XMM** (Rosen+ 2016) and **CSC** catalogs (Evans+ 2010)
  - 111/395 of these counterparts are newly identified in the XMM / Chandra / XRT archival data

→ XMM/Chandra/XRT essential for refining the X-ray positional accuracy & matching to optical–IR

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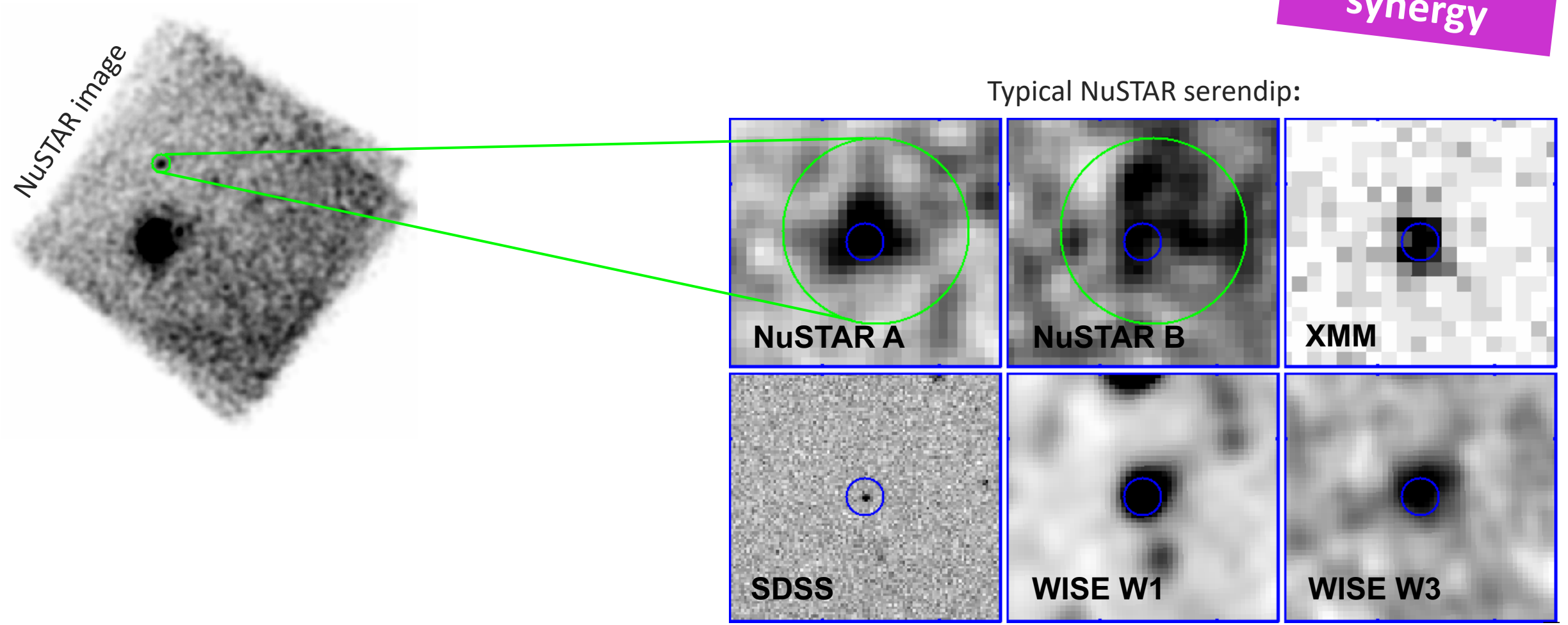

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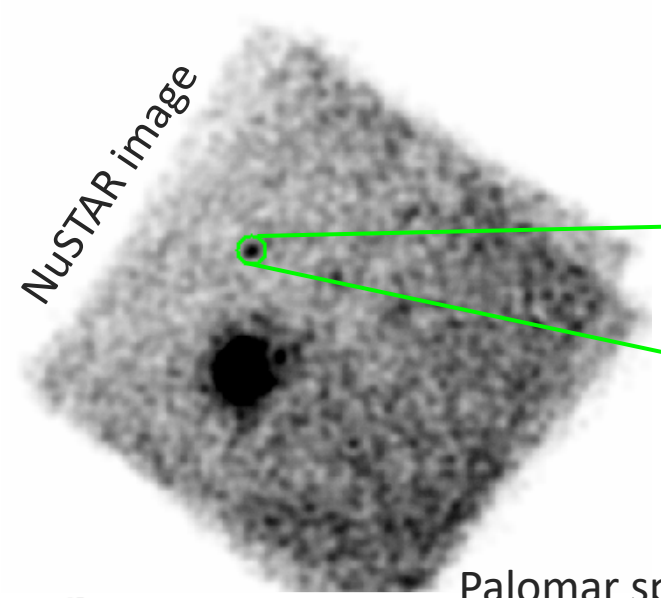
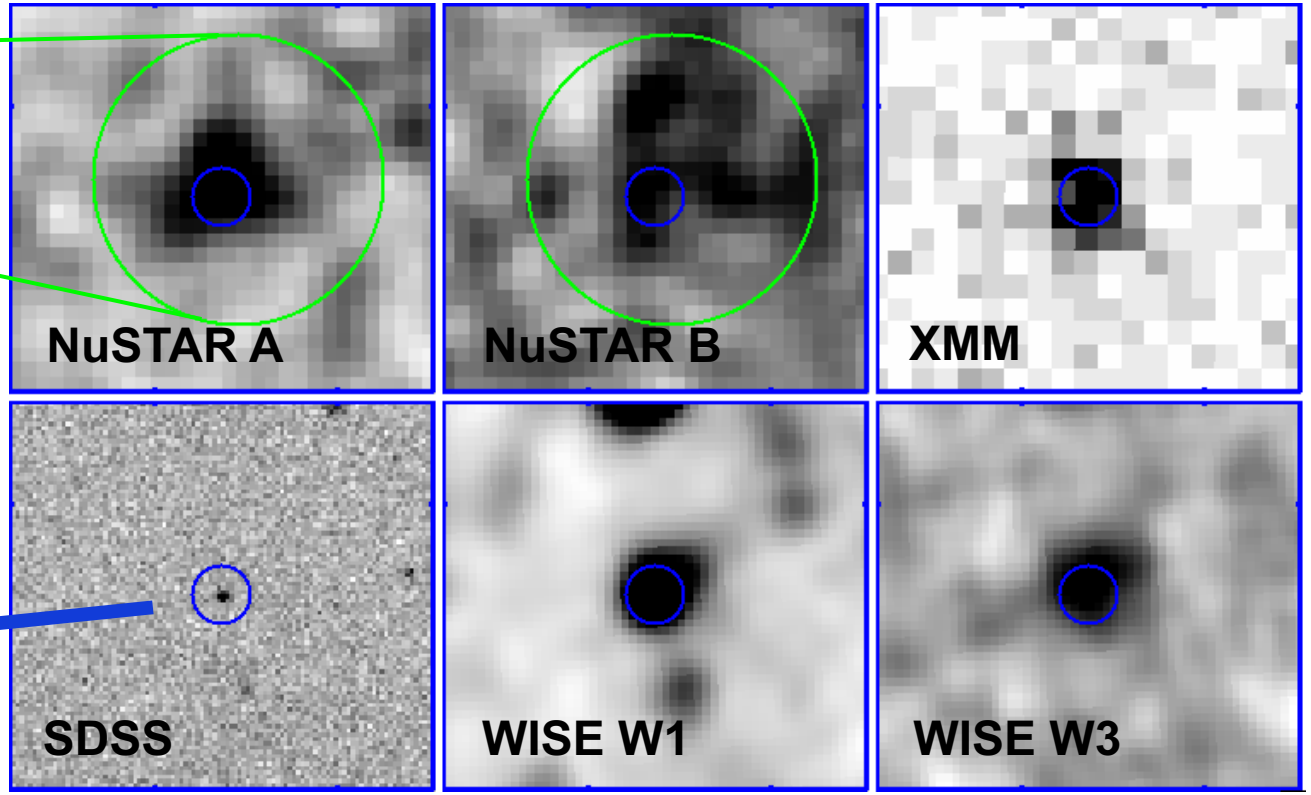
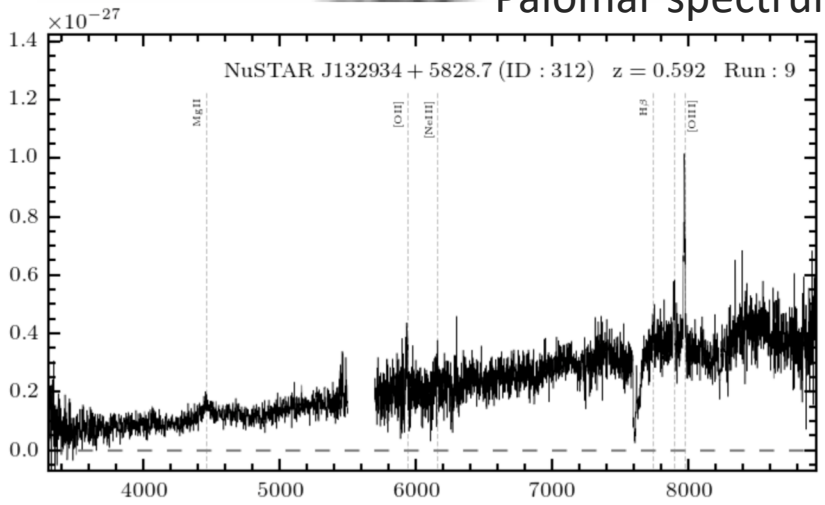


Typical NuSTAR serendip:



Palomar spectrum



optical spectroscopic followup

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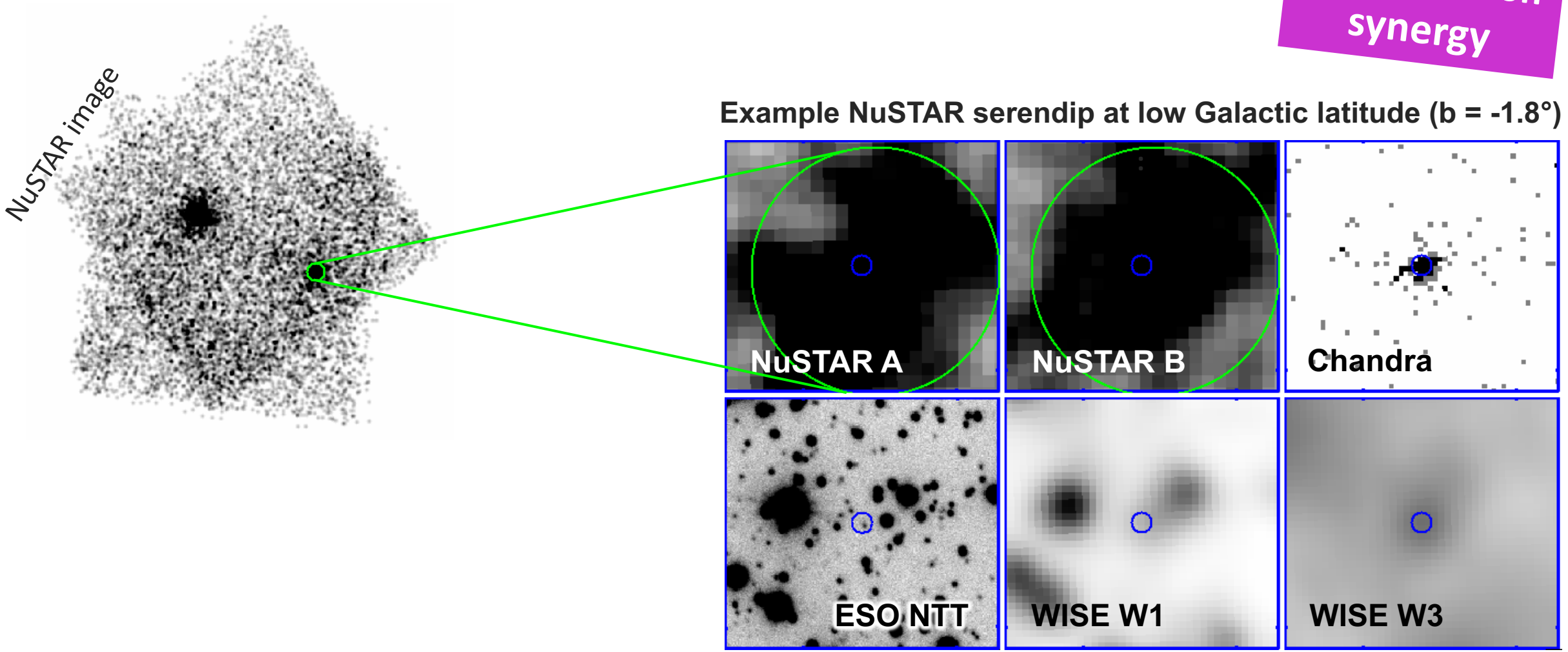

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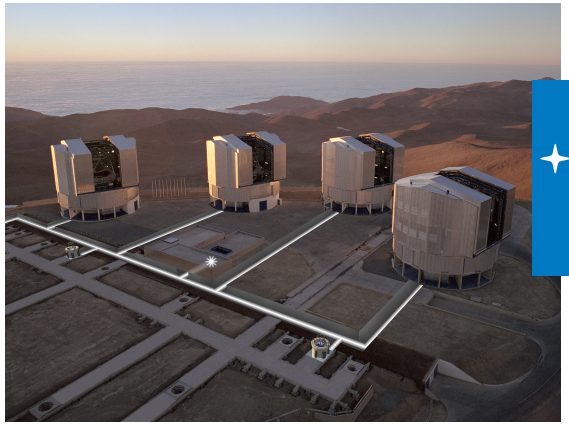
Multiwavelength properties: Optical followup



90% of the NuSTAR serendipitous survey sources do not have existing optical/IR spectroscopic coverage –
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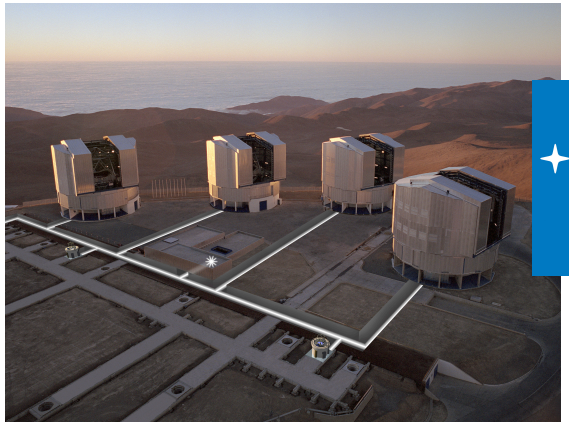
Multiwavelength properties: Optical followup

(NuSTAR Photometric And Spectroscopic Survey)



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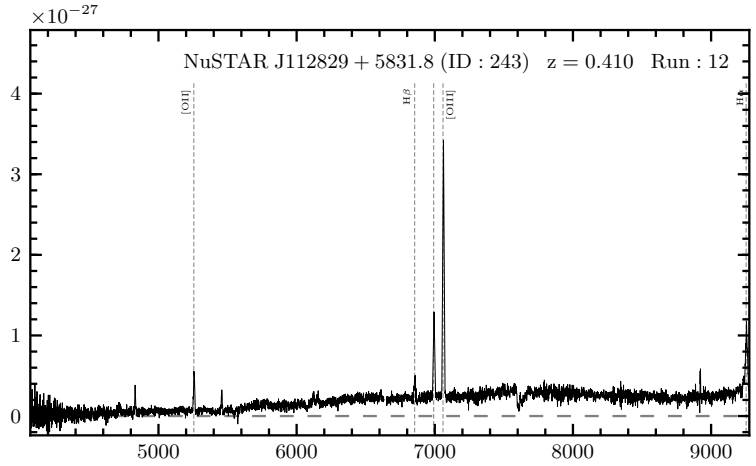
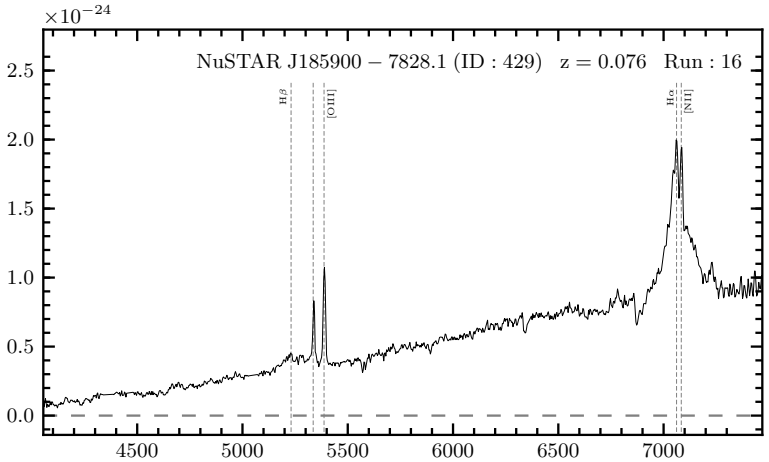
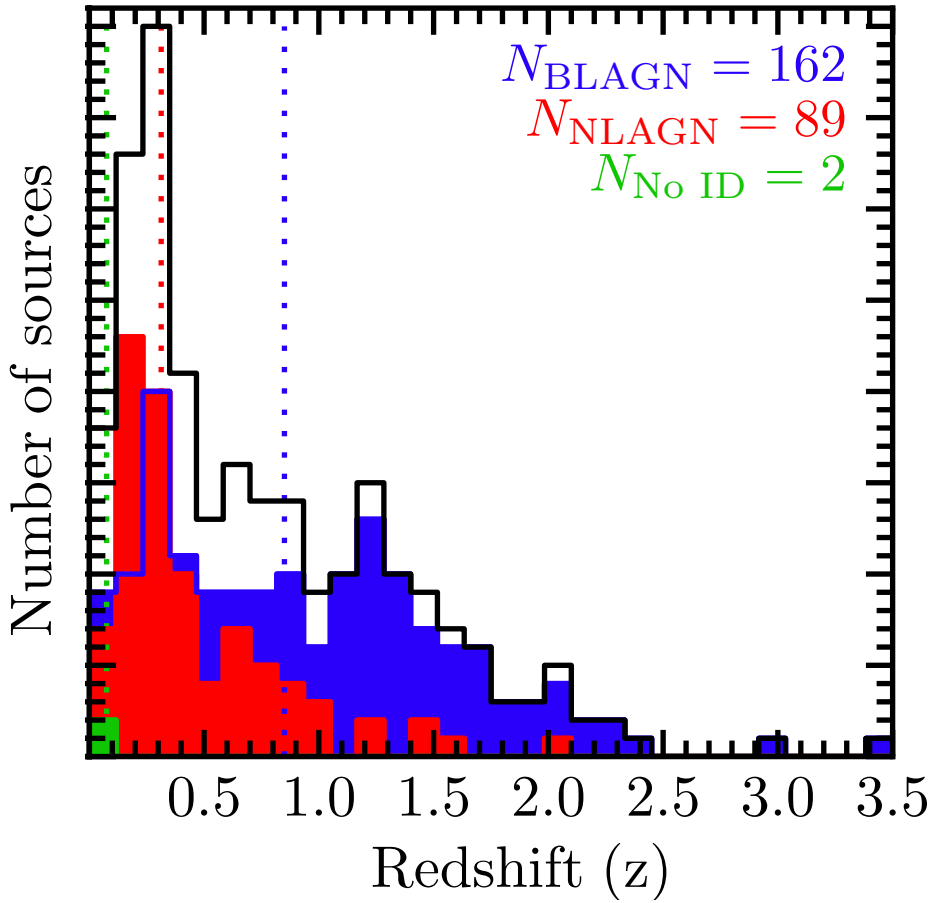
Multiwavelength properties: Optical followup (NuPASS)



Type 2 = optically obscured (narrow-line AGN)



Type 1 = optically unobscured (broad-line AGN)



Lansbury+2017a

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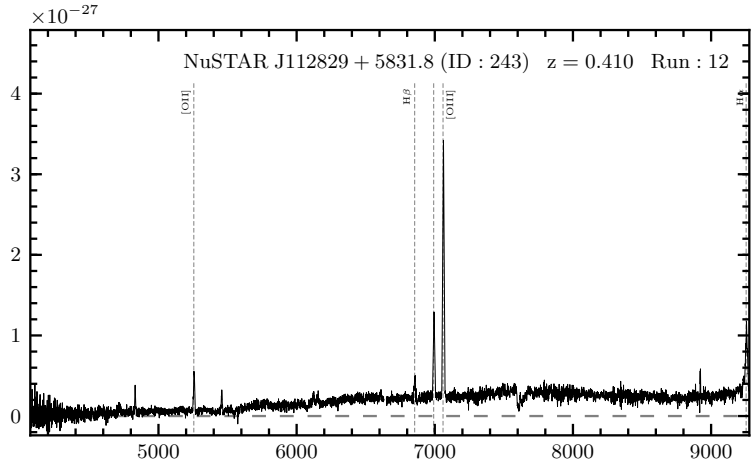

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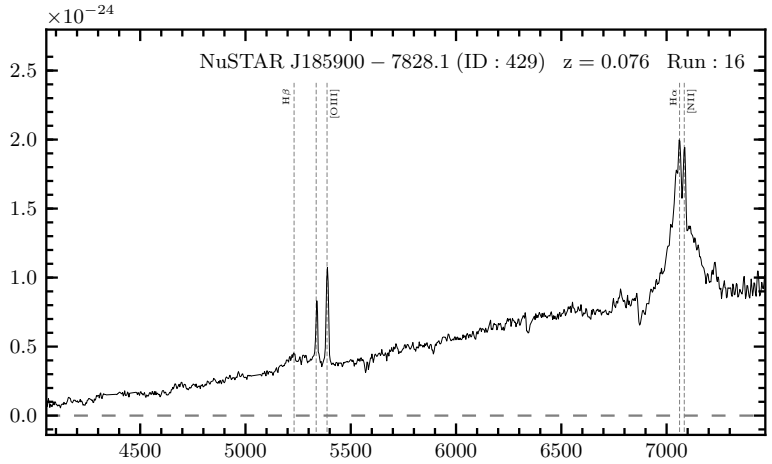
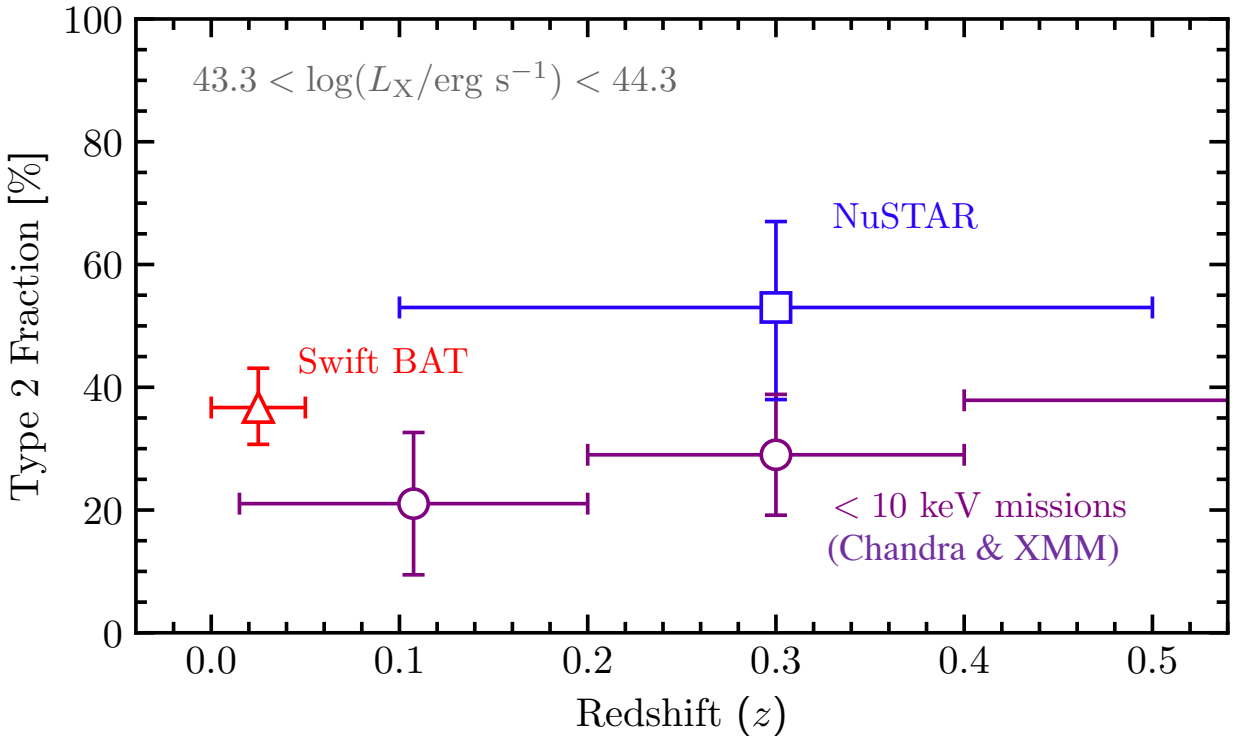


Type 1 = optically unobscured (broad-line AGN)

Lansbury+2017a



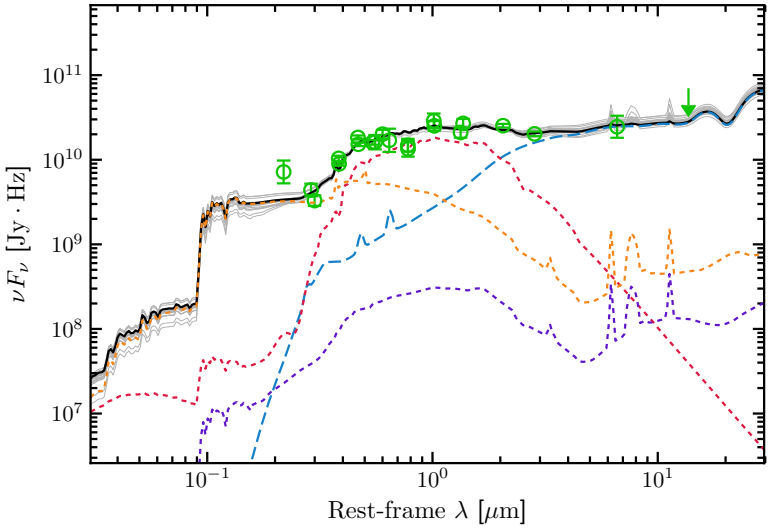
Type 2 fraction for the $0.1 < z < 0.5$ NuSTAR serendipitous survey sample selected at > 8 keV:

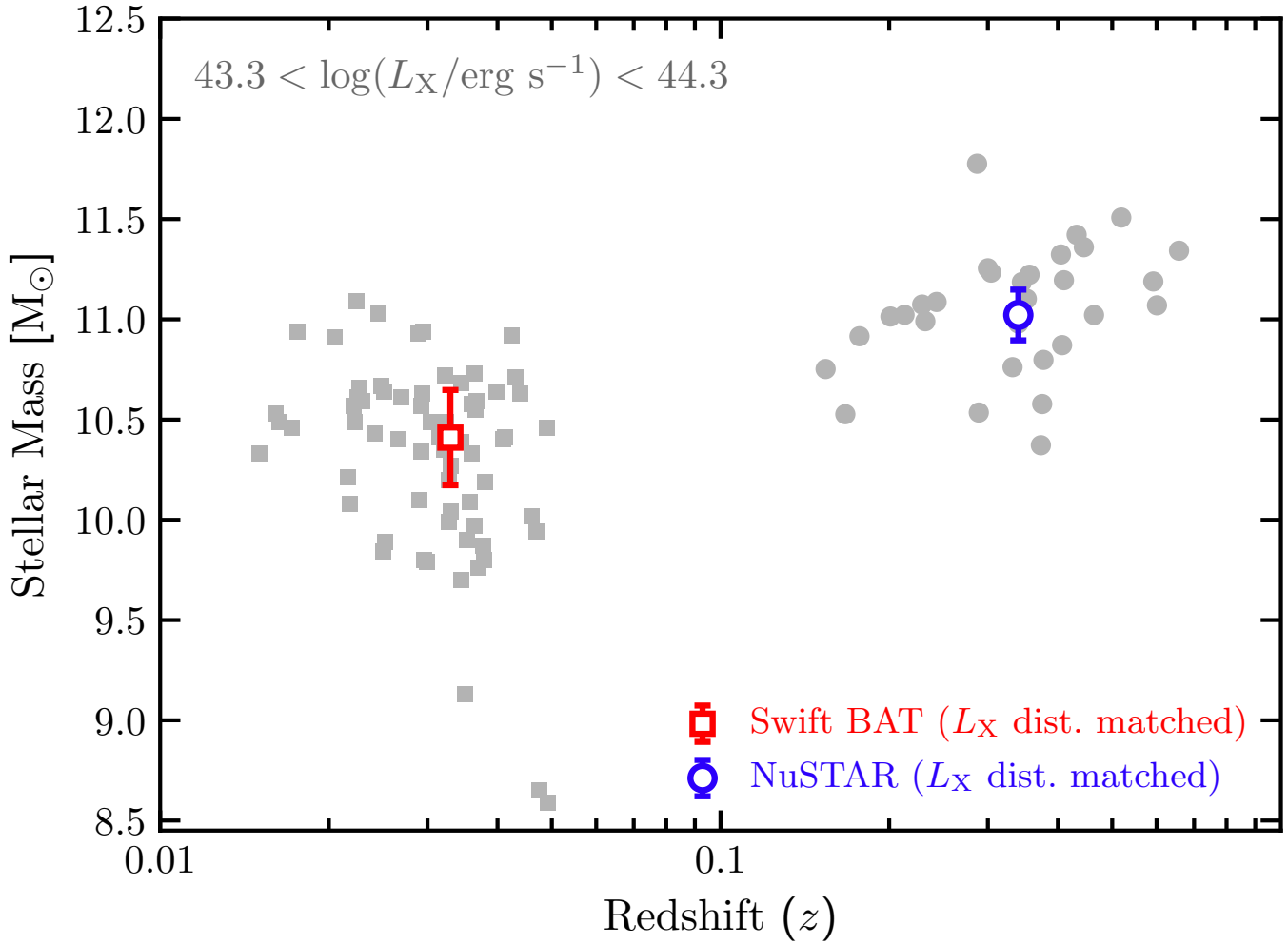
$$f_{\text{Type 2}} = 53^{+14}_{-15}\%$$

.. in agreement with torus covering factors inferred from infrared studies (Mateos+2017)

Multiwavelength properties: host galaxies

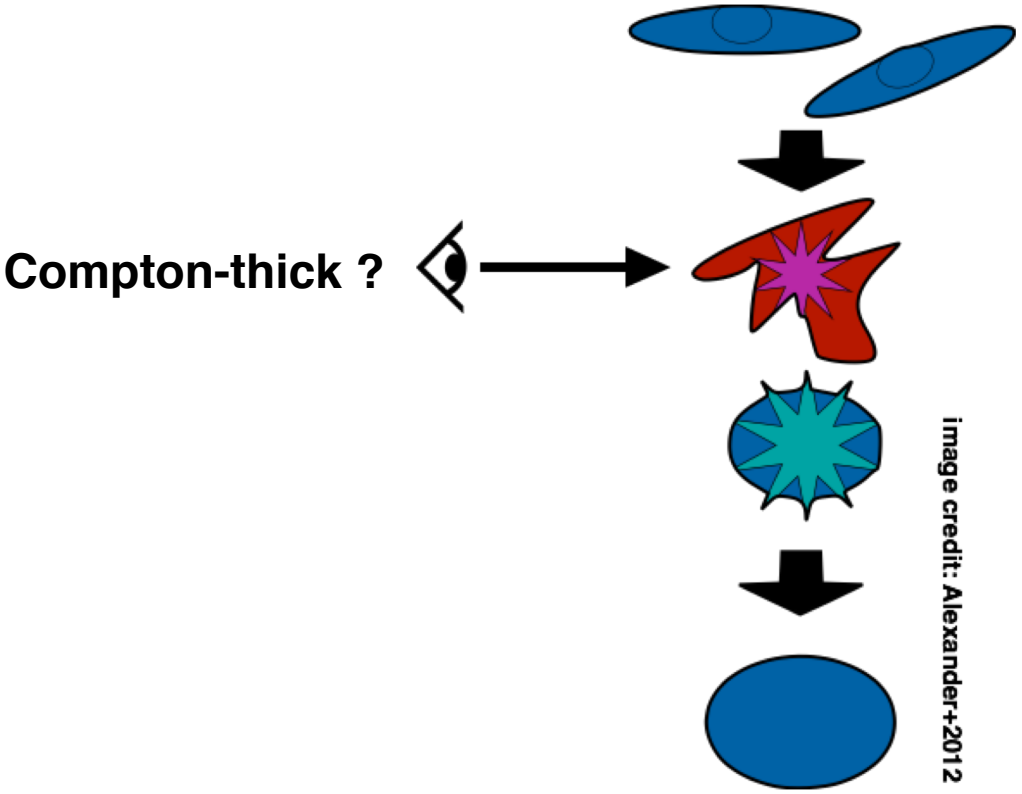
Example UV—MIR SED for NuSTARJ204020-0056.1

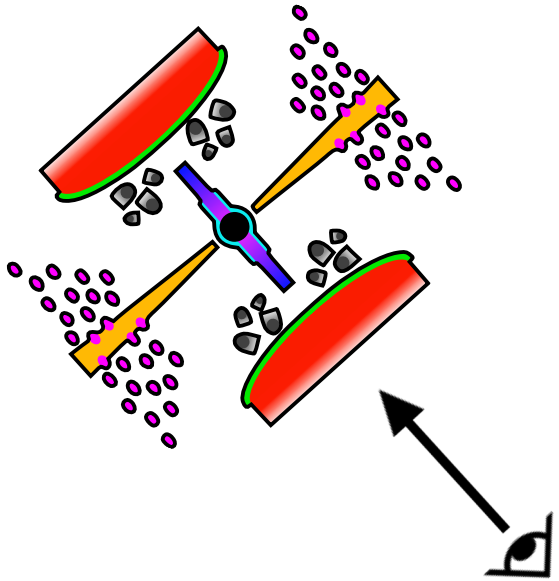




- SED modelling being performed for full NuSTAR extragalactic survey sample
- **Stellar mass of NuSTAR serendip host galaxies: $\langle M_\star \rangle \approx 10^{11}\,M_\odot$**

Hunting for hidden treasures: highly obscured growing black holes in the NuSTAR serendipitous survey

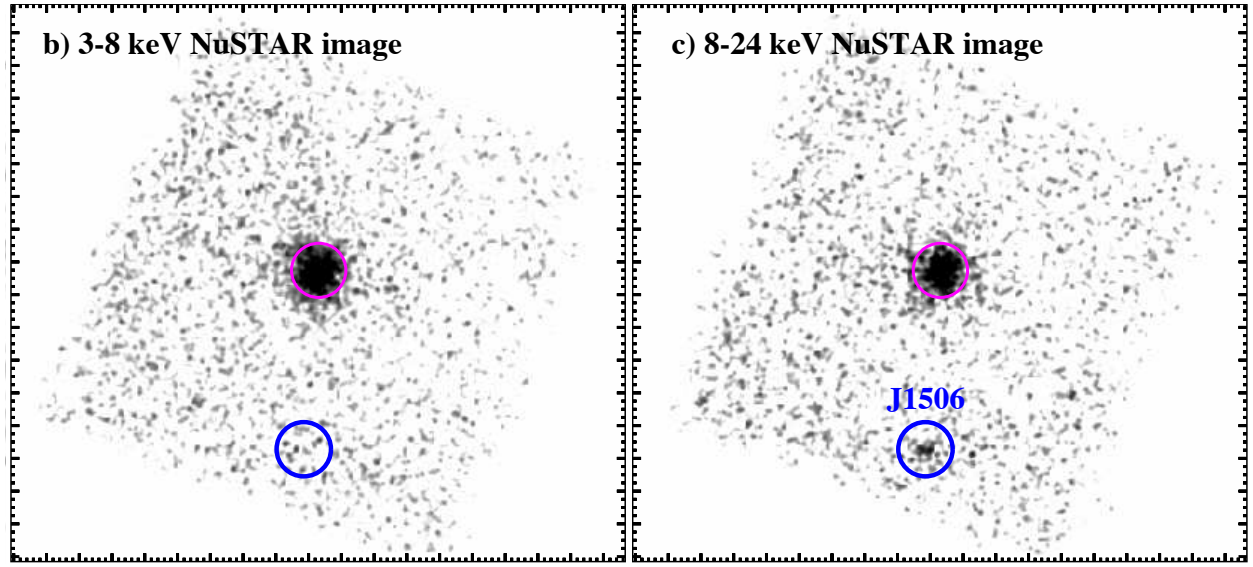




Compton-thick

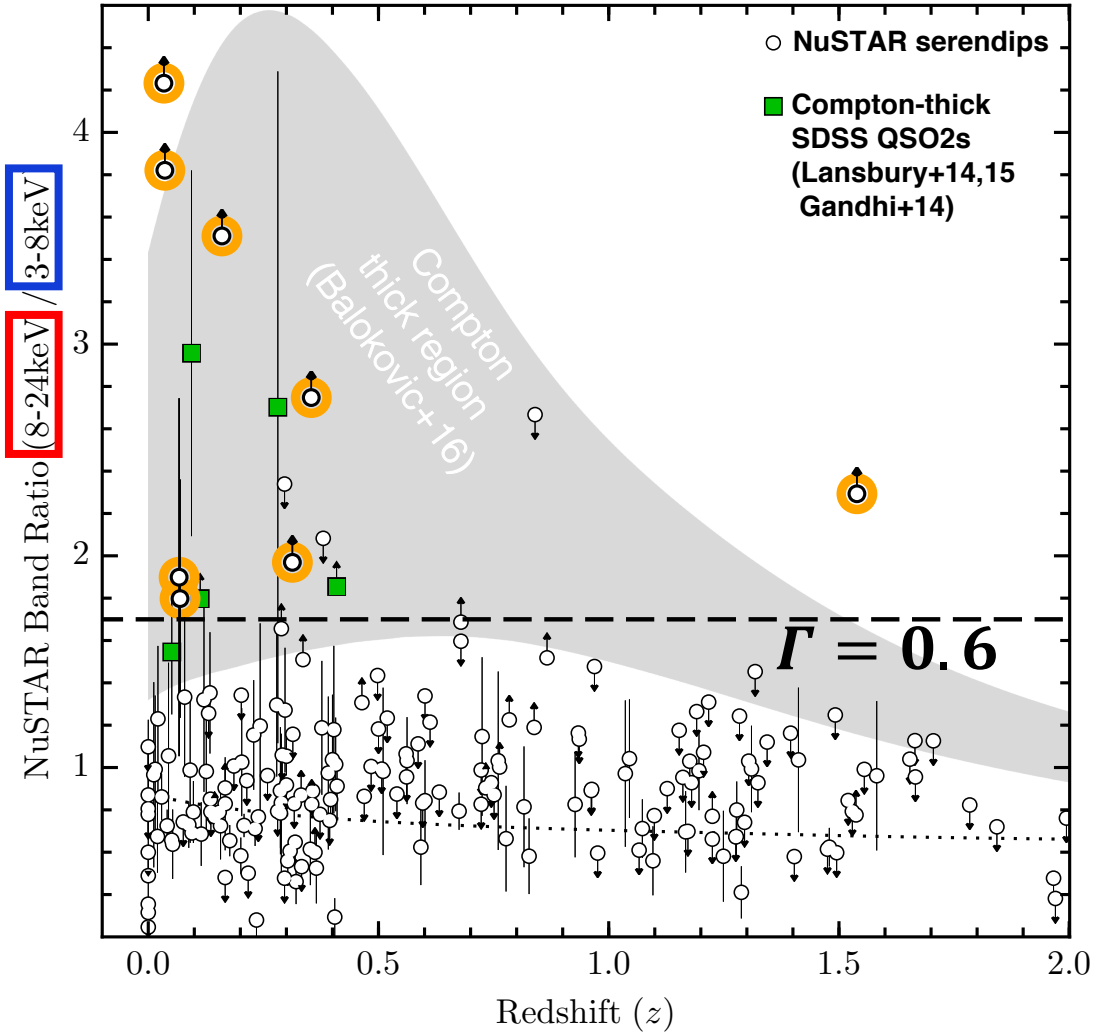
$N_H > 10^{24}$ cm^{-2}

Extremely hard sources in the NuSTAR serendipitous survey



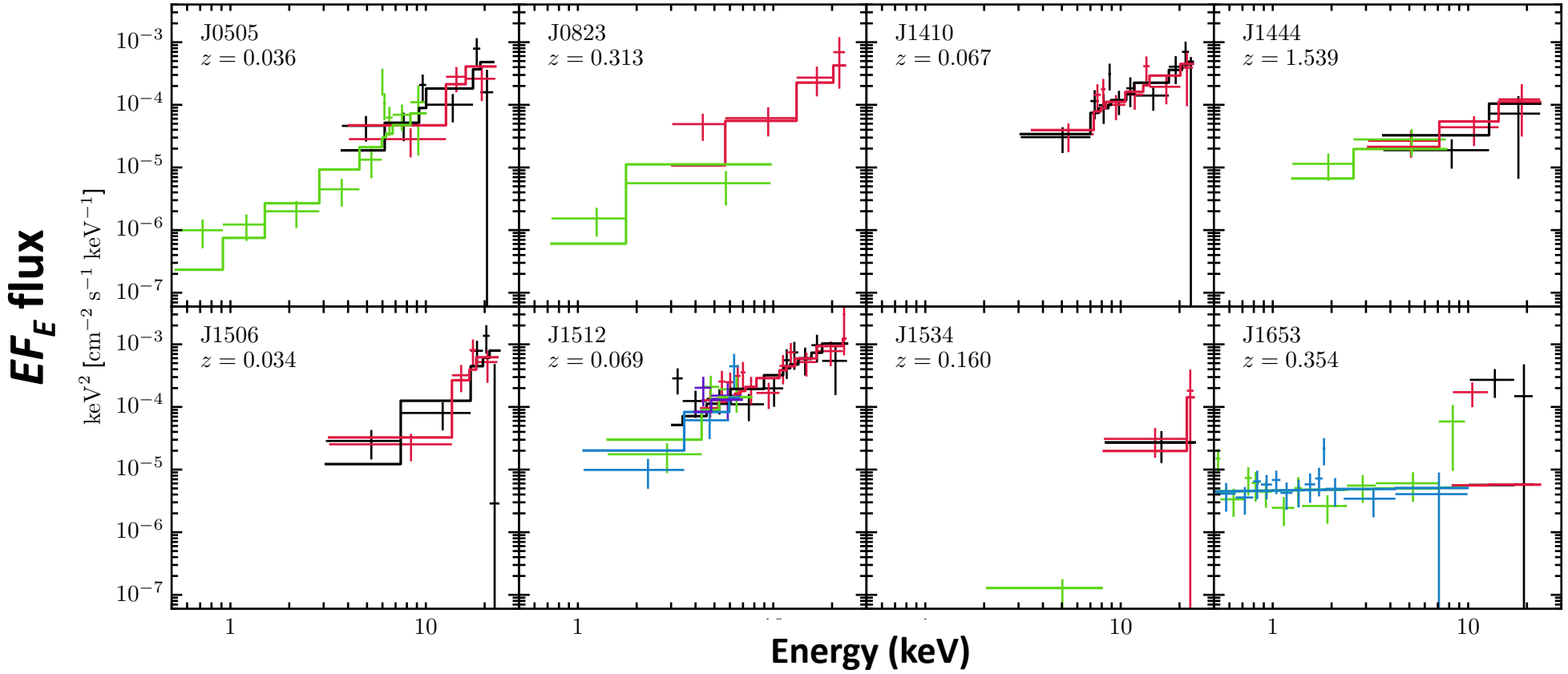
3-8 keV
("soft" band)

8-24 keV
("hard" band)



Extremely hard sources in the NuSTAR serendipitous survey

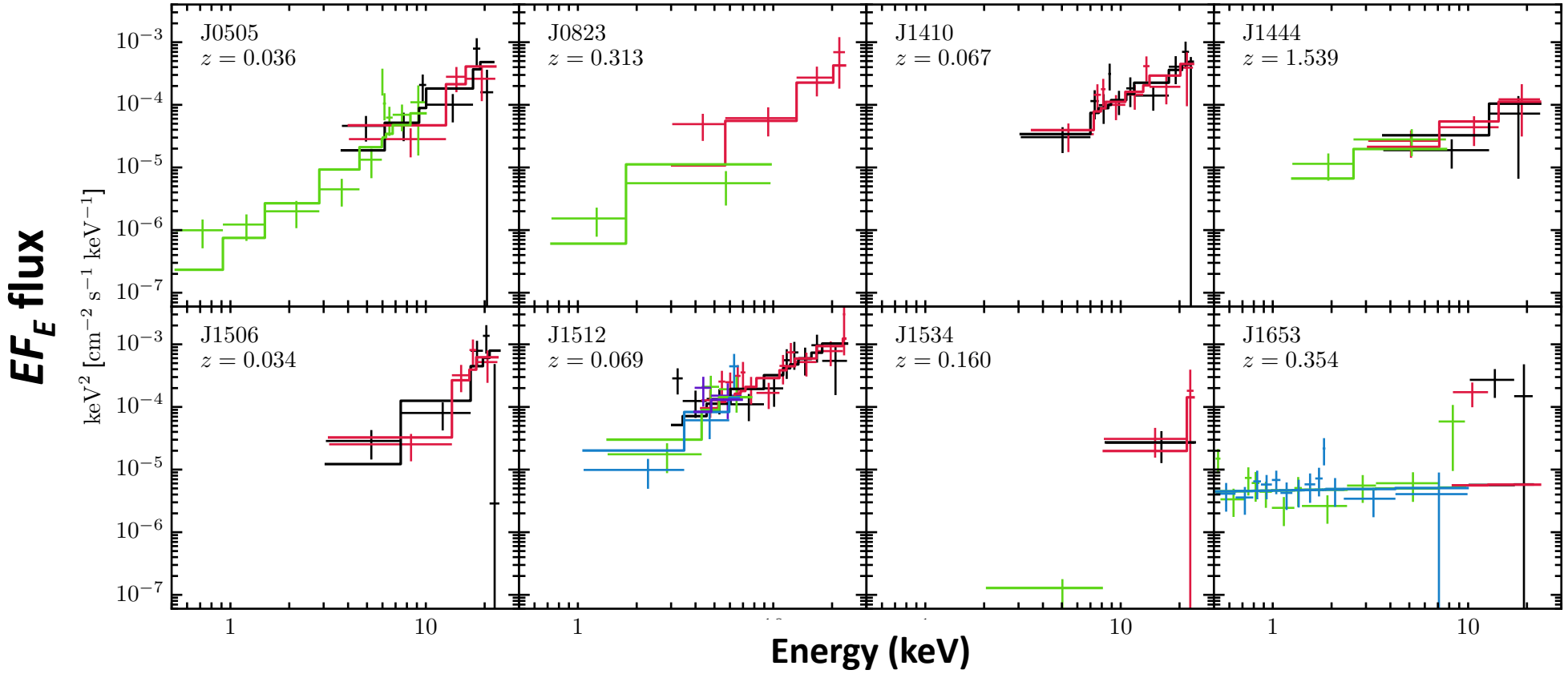
NuSTAR (+ *Chandra*/*XMM*/*Swift*) spectra for the 8 hardest sources (out of total ≈300) :



Lansbury+2017b

Extremely hard sources in the NuSTAR serendipitous survey

NuSTAR (+ *Chandra*/*XMM*/*Swift*) spectra for the 8 hardest sources (out of total ≈300) :



- **≥ half are Compton-thick (CT) ($N_H > 1.5 \times 10^{24}$ cm^{-2})**
- **Elusive at non-X-ray wavelengths, e.g.: Only 1 source (out of 8) selected as an AGN with WISE**

Lansbury+2017b

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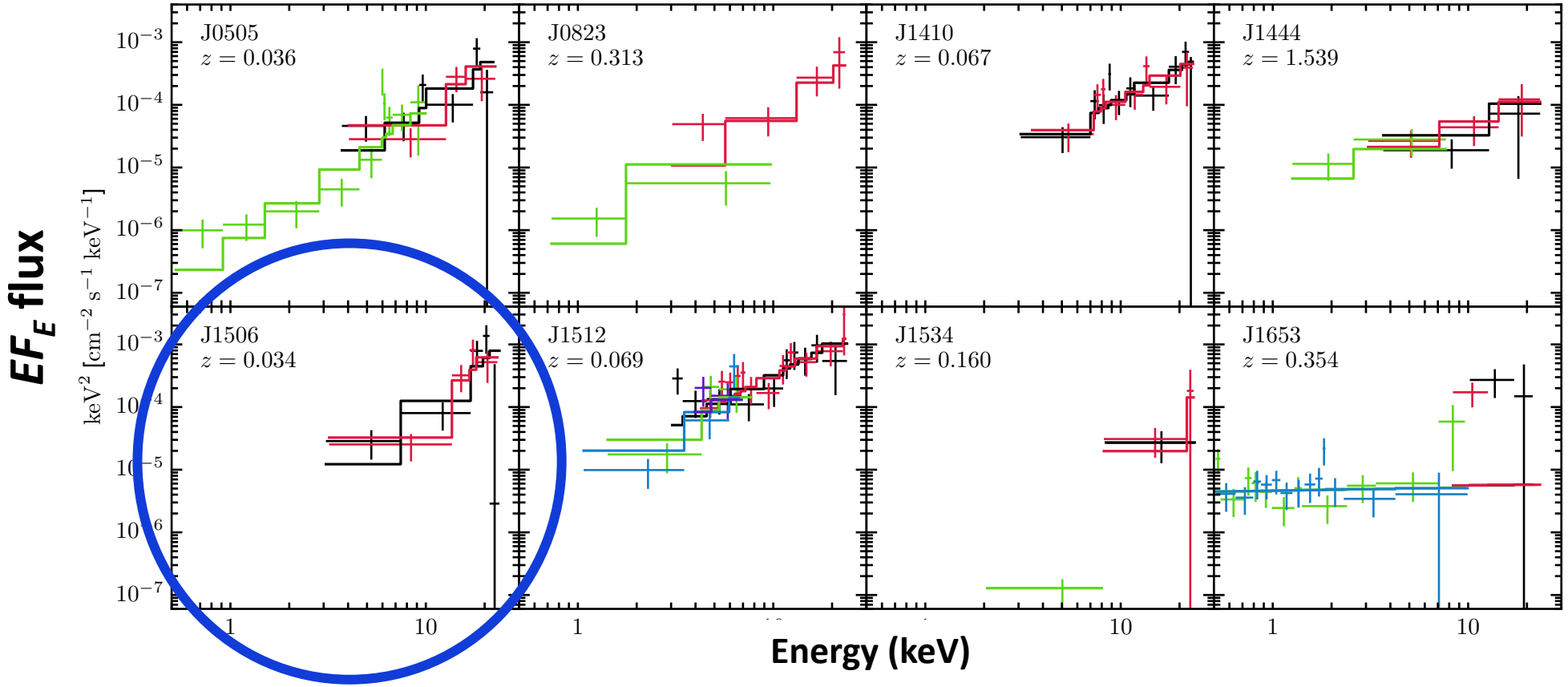

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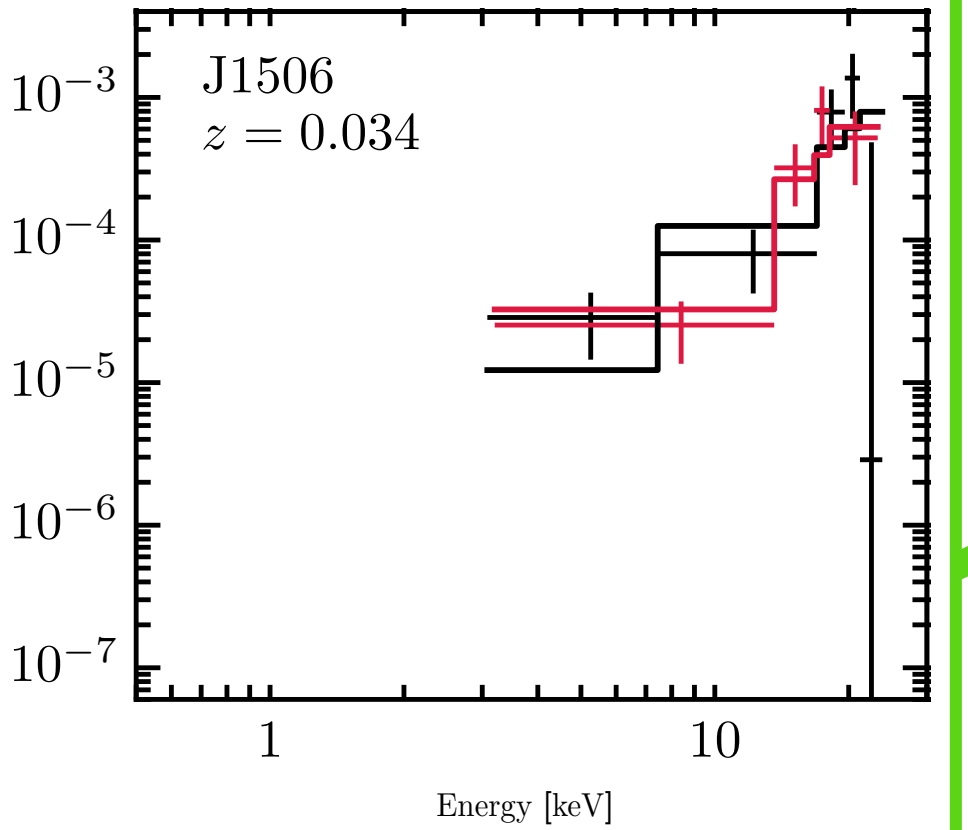
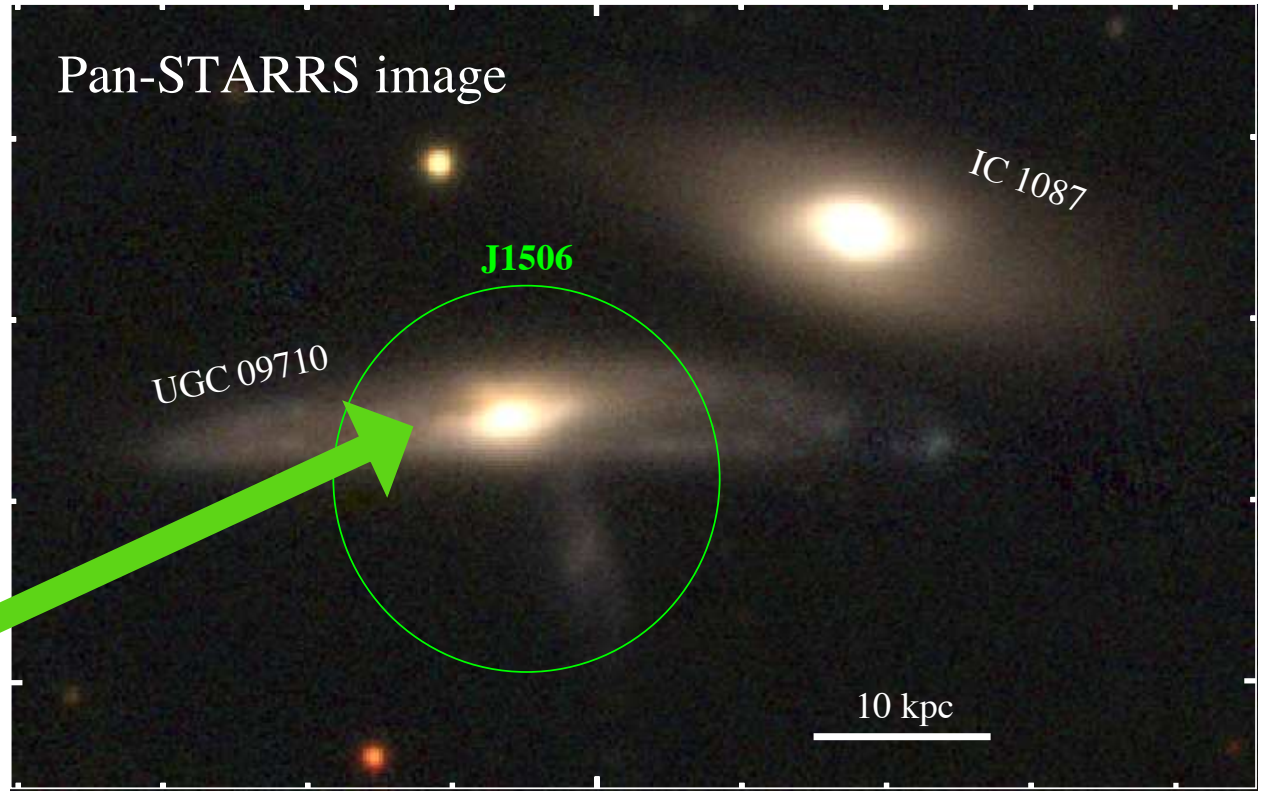
Lansbury+2017b

NuSTAR J1506 (z = 0.034)

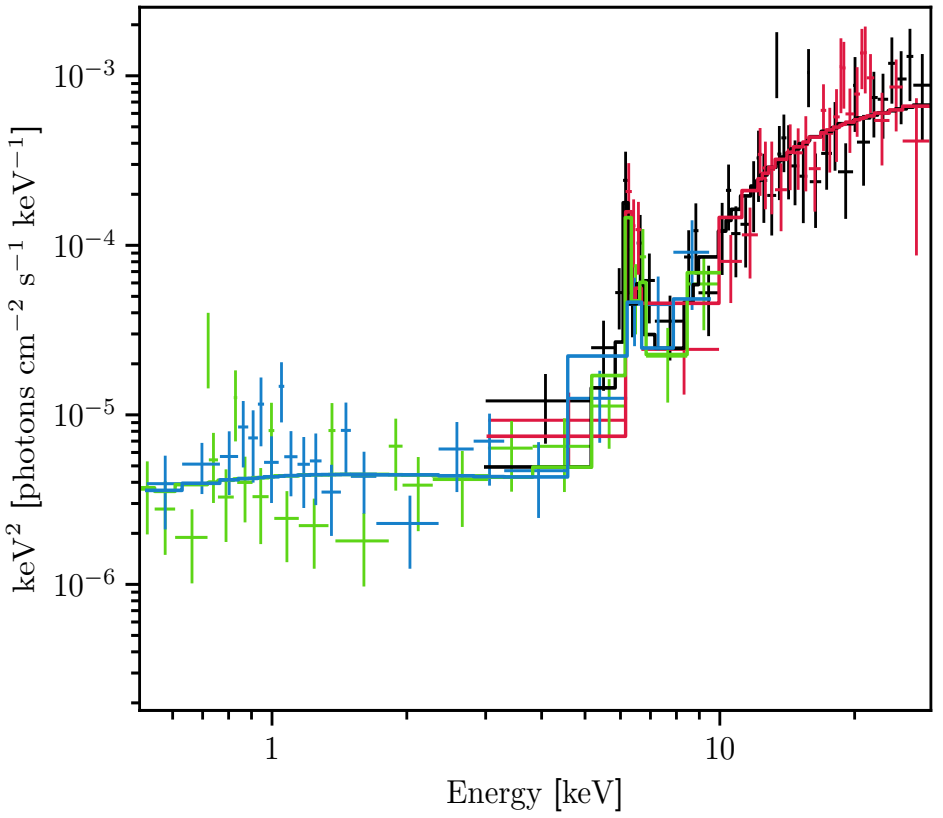


Original NuSTAR spectrum

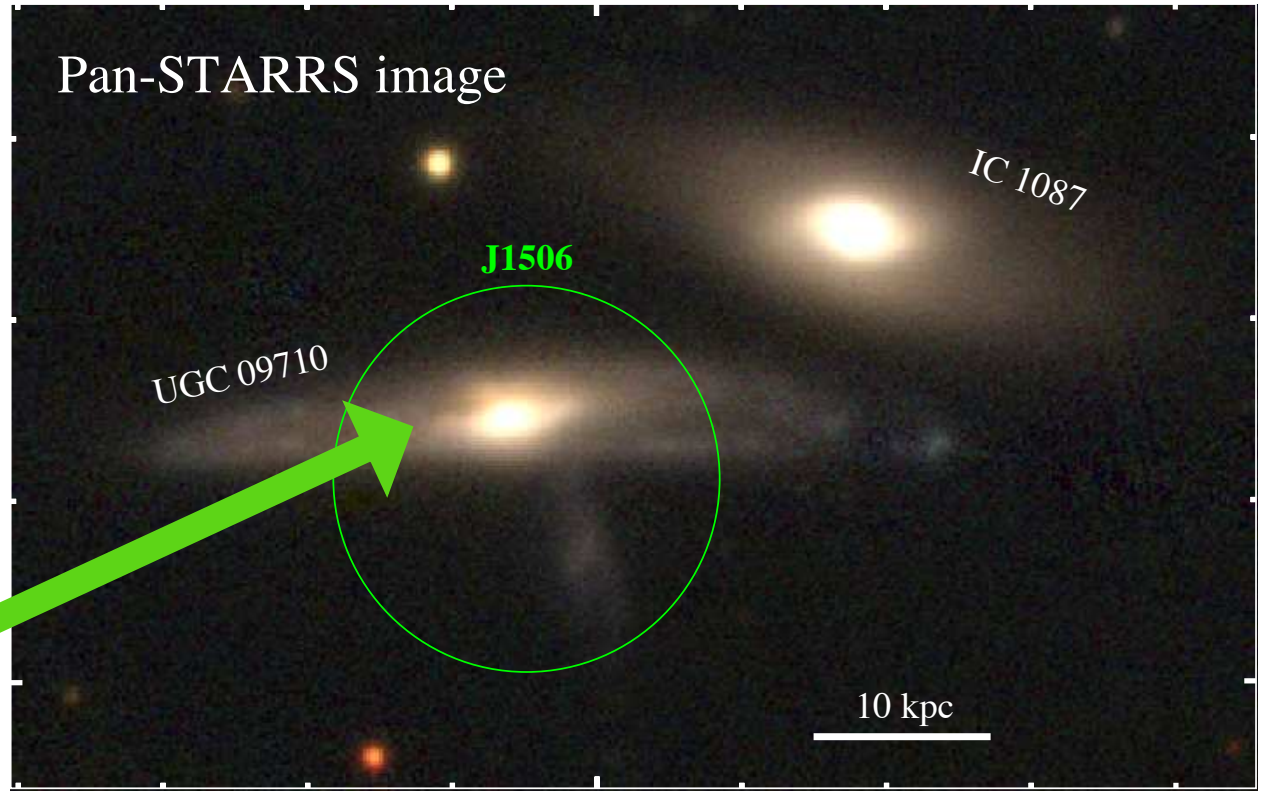


- Host galaxy in an early-stage major merger

NuSTAR J1506 (z = 0.034)

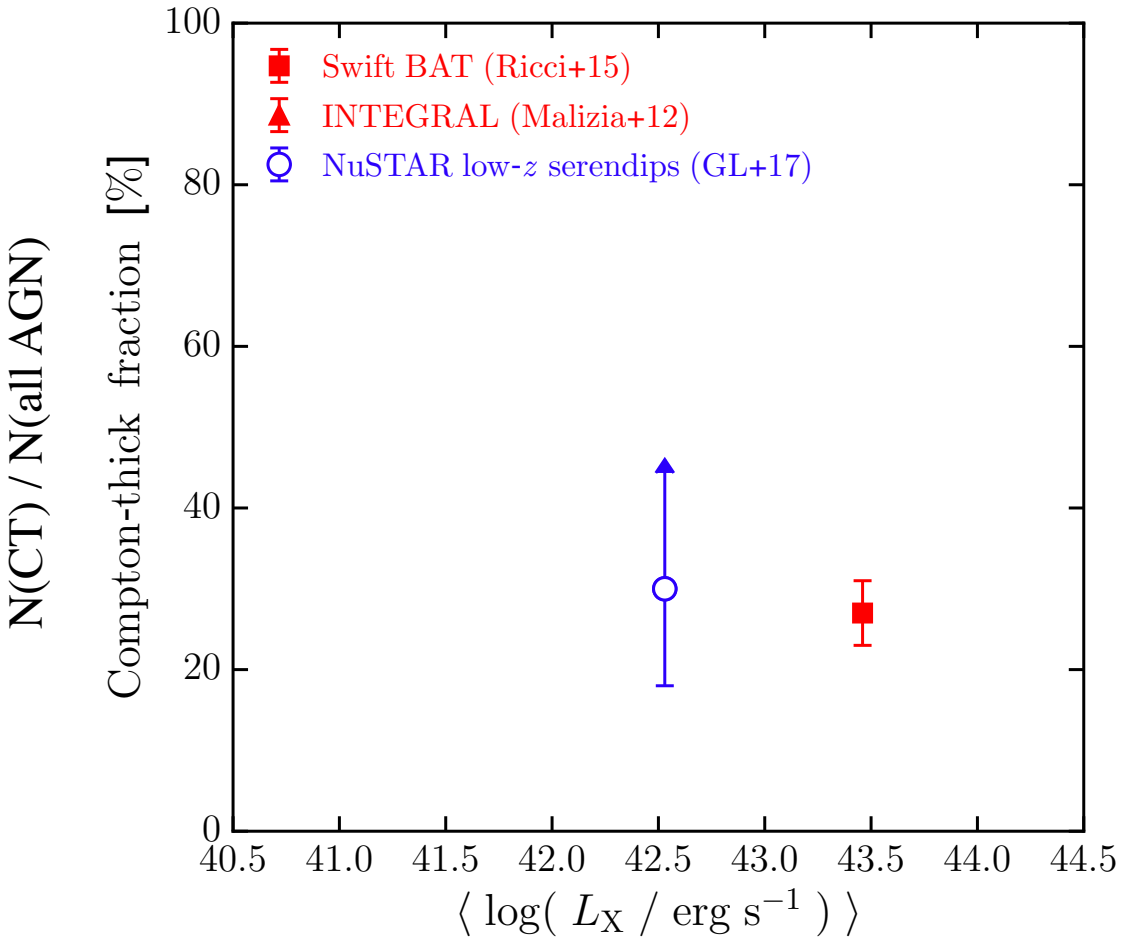


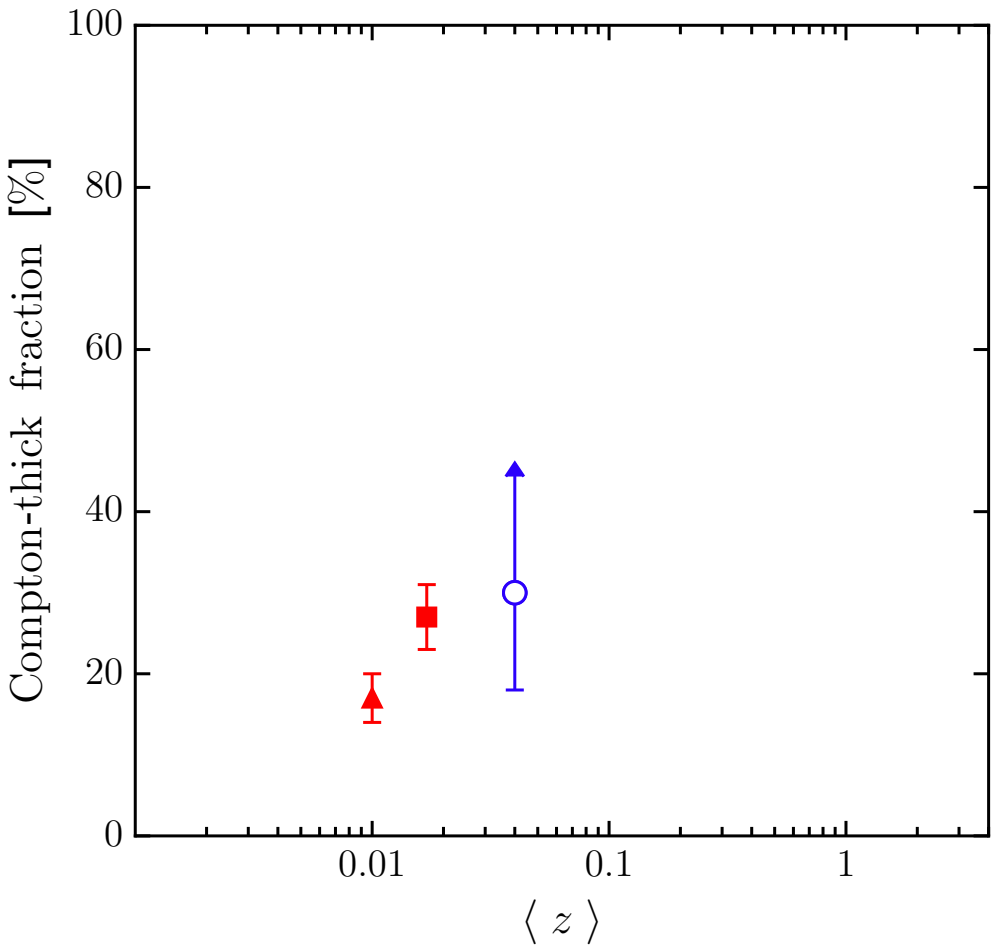
Deeper *NuSTAR*(60ks)+*XMM*(30ks) data from 2018 cycle 3 follow-up obs



- Host galaxy in an early-stage major merger
- New **local *bona-fide* CT AGN with log L_X > 43** (of which there are ≈handful)

Hard X-ray Compton-thick (CT) AGN census versus L_X and z



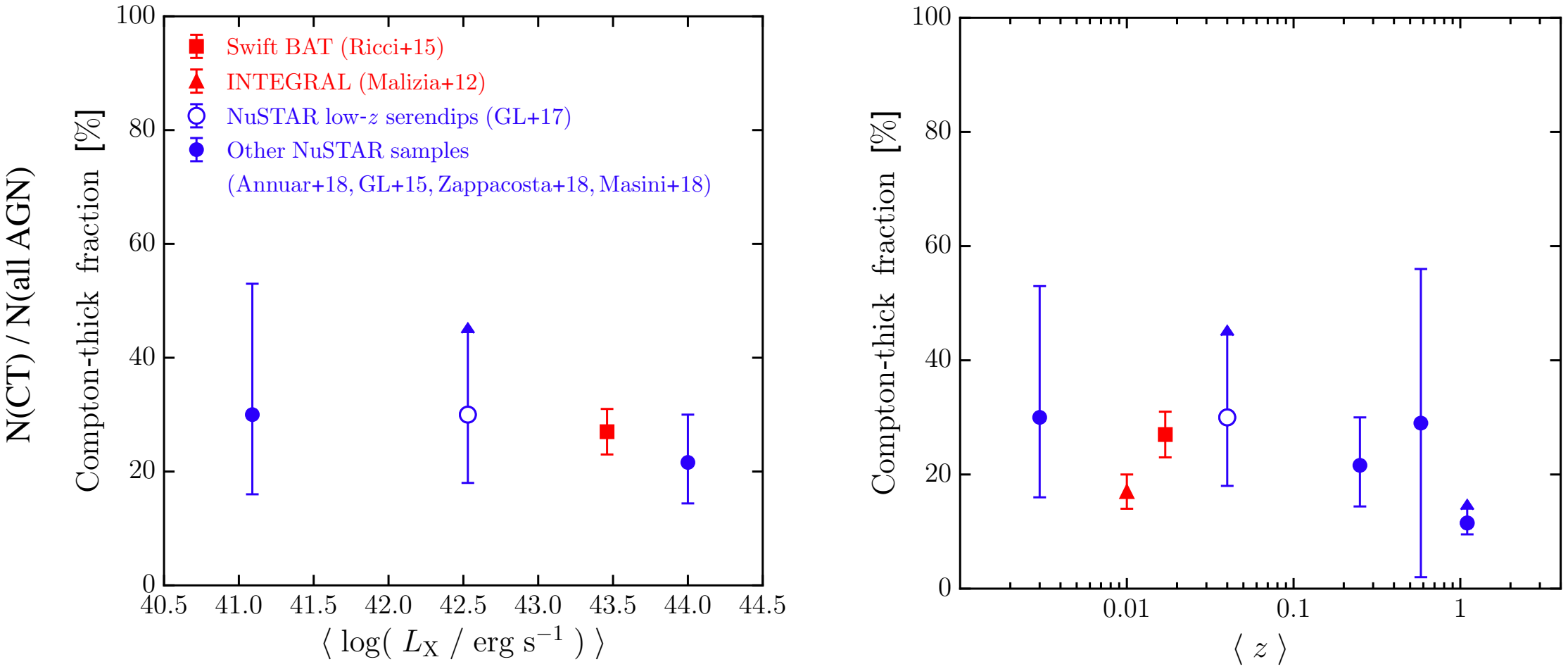


NuSTAR $z < 0.07$ serendips: $f_{\mathrm{CT,observed}} \approx 30\%$

Swift BAT: $f_{\mathrm{CT,intrinsic}} \approx 27\%$

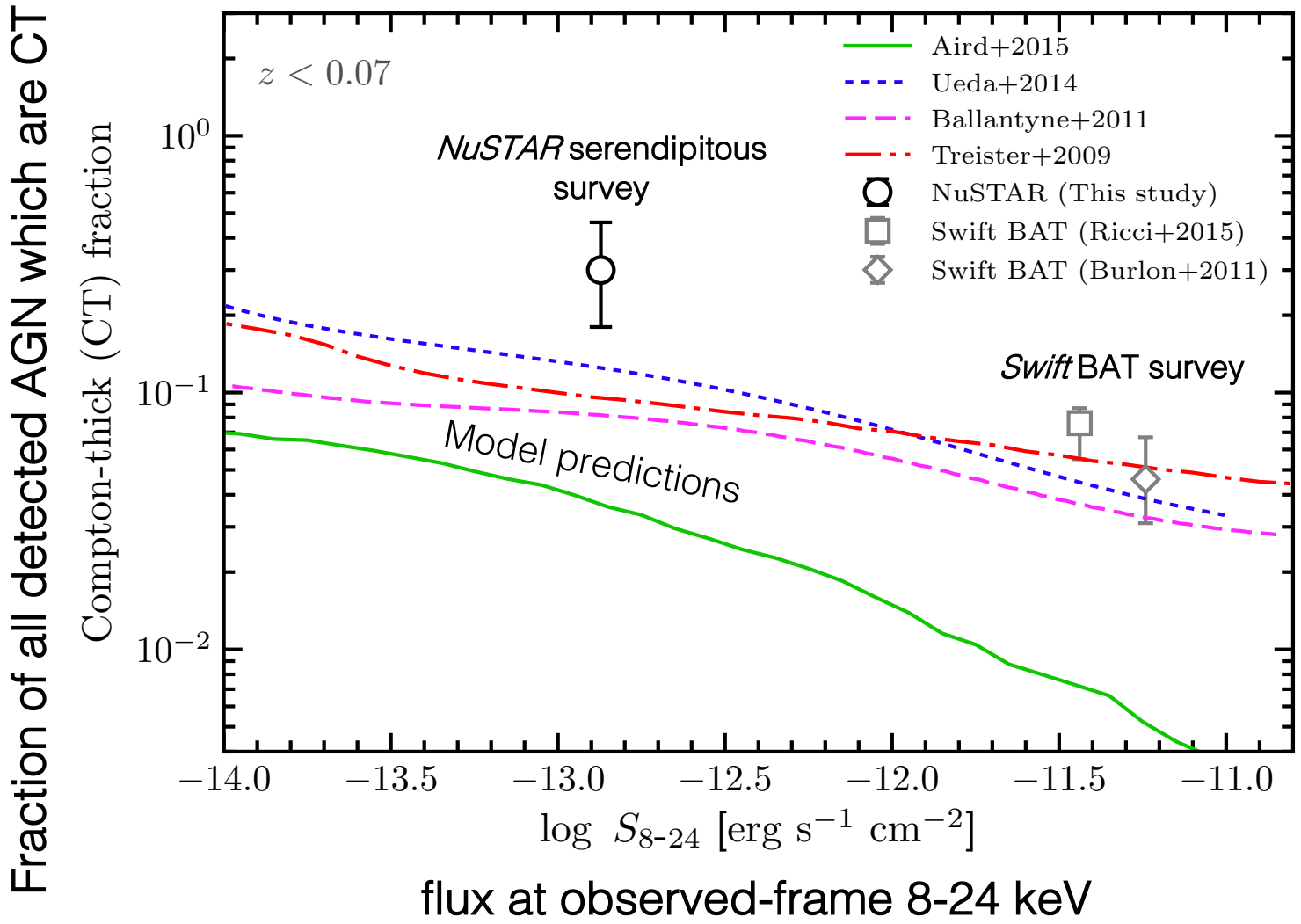
INTEGRAL: $f_{\mathrm{CT,intrinsic}} \approx 17\%$

Hard X-ray Compton-thick (CT) AGN census versus L_X and z



Broad agreement between different NuSTAR hard X-ray samples over range of L_X and z

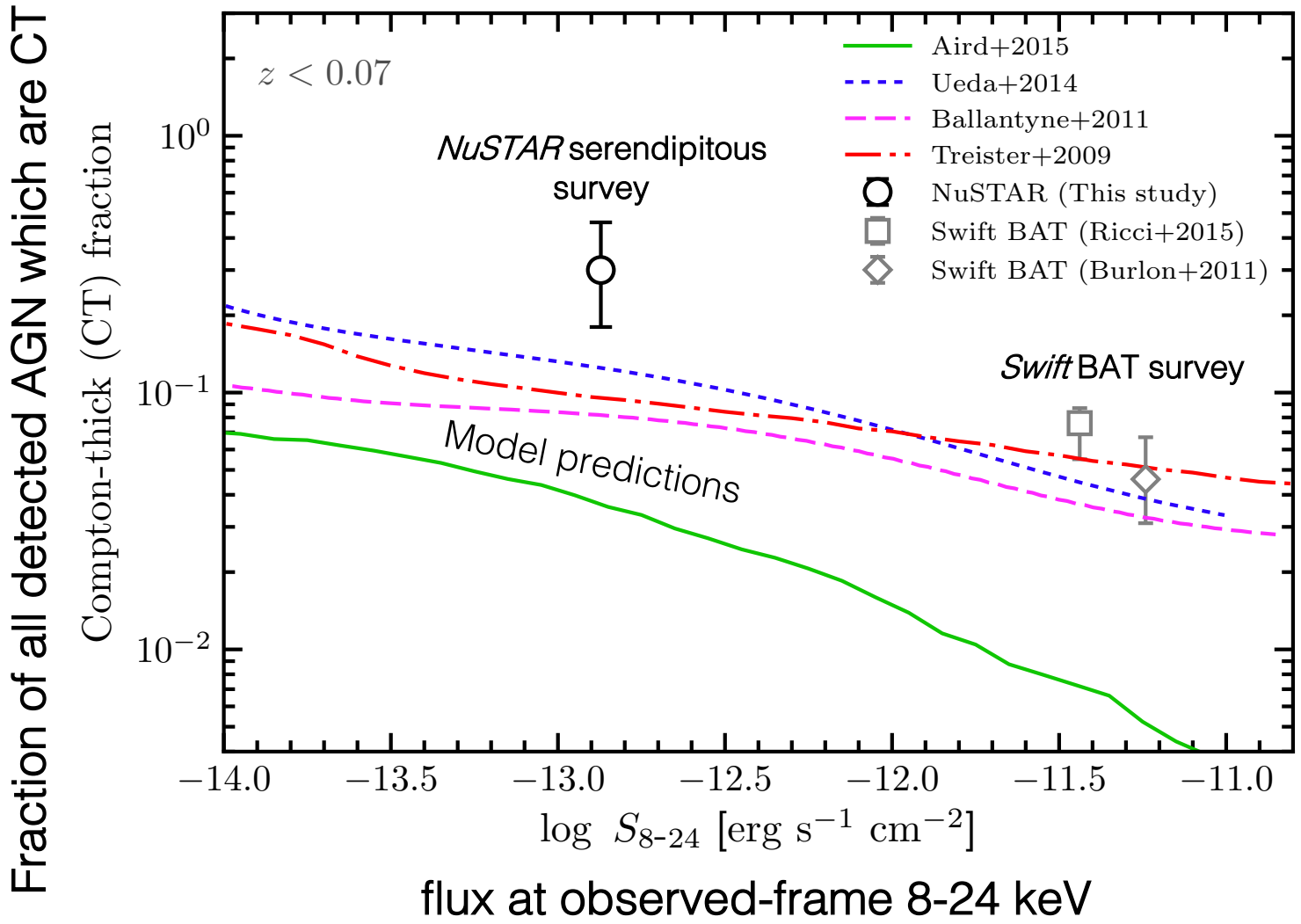
The low redshift Compton-thick (CT) fraction: data versus models



The *NuSTAR* low-*z* CT fraction is high compared to models.

Lansbury+2017b

The low redshift Compton-thick (CT) fraction: data versus models



Lansbury+2017b

The *NuSTAR* low-*z* CT fraction is high compared to models.

Possible causes:

The models – need updating?

and/or

The data – low-*z* CT fraction boosted due to environments sampled?

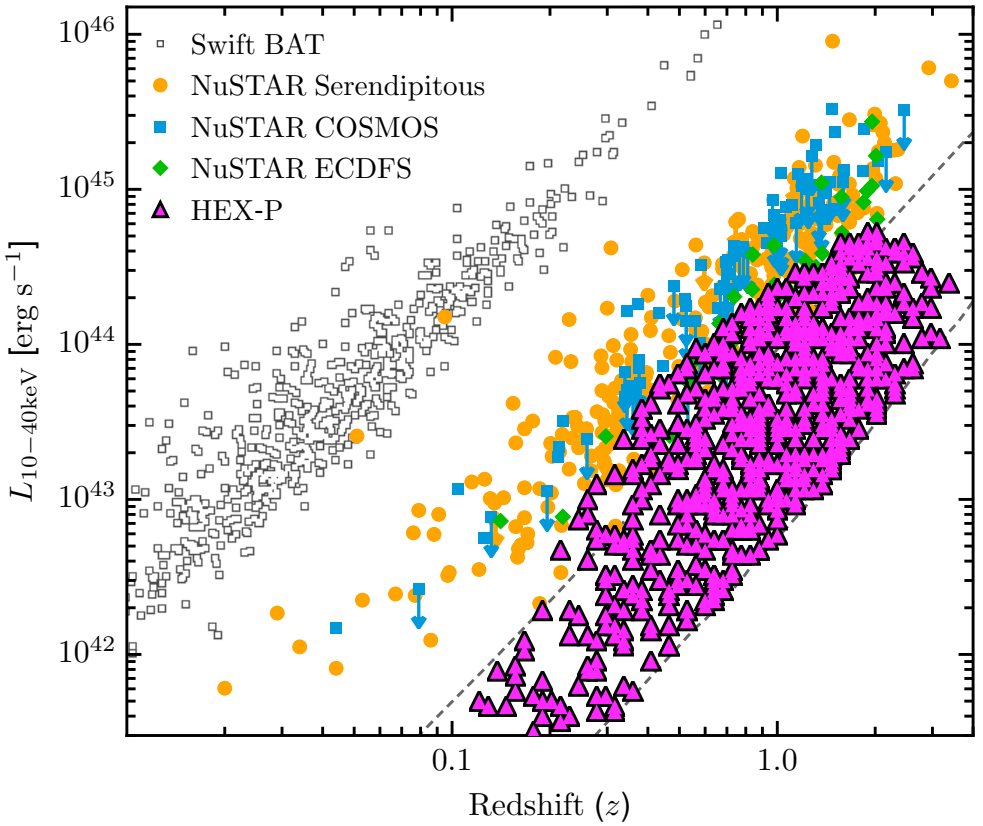
Future of the sensitive hard X-ray census

- Near future:
  The *NuSTAR* serendipitous survey continues to grow with time, at ≈constant rate,
  as long as *NuSTAR* continues operation.
  Expect to reach sample size of >1000.

Future of the sensitive hard X-ray census

- Near future:
  The *NuSTAR* serendipitous survey continues to grow with time, at ≈constant rate, as long as *NuSTAR* continues operation.
  Expect to reach sample size of >1000.

- More distant future:
  Higher sensitivity hard X-ray mission concept
  High-Energy X-ray Probe (***HEX-P***)
  (see Harrison+2016 white paper)



Summary

- The NuSTAR serendipitous survey:
  - 40-month catalog: resources available online
  - The survey provides a large hard X-ray census of (relatively) distant AGN:
    497 sources (276 spec-ID'd), $\langle z \rangle = \mathbf{0.56}$
  - Synergy with Chandra / XMM / XRT catalogs - matching to multiwavelength counterparts
  - Type 2 (i.e., optically obscured) fraction, $f_{\mathbf{Type\ 2}} \approx \mathbf{53\%}$
  - Typical stellar mass of NuSTAR sources: $\langle \boldsymbol{M_\star} \rangle \approx \mathbf{10^{11}\ M_\odot}$

- Completing the AGN census by hunting for Compton-thick (CT) AGN:
  - Identified extremely hard sources in the NuSTAR serendipitous survey.
    Modelling the X-ray spectra → new highly obscured & CT AGN
  - The *observed* CT fraction at $z < 0.07$ ($f_{\mathbf{CT,obs}} \approx \mathbf{30\%}$) is surprisingly high
    → Do AGN population models need updating for the faint hard X-ray regime?

END