A hard X-ray view of the highly obscured AGN population with NuSTAR

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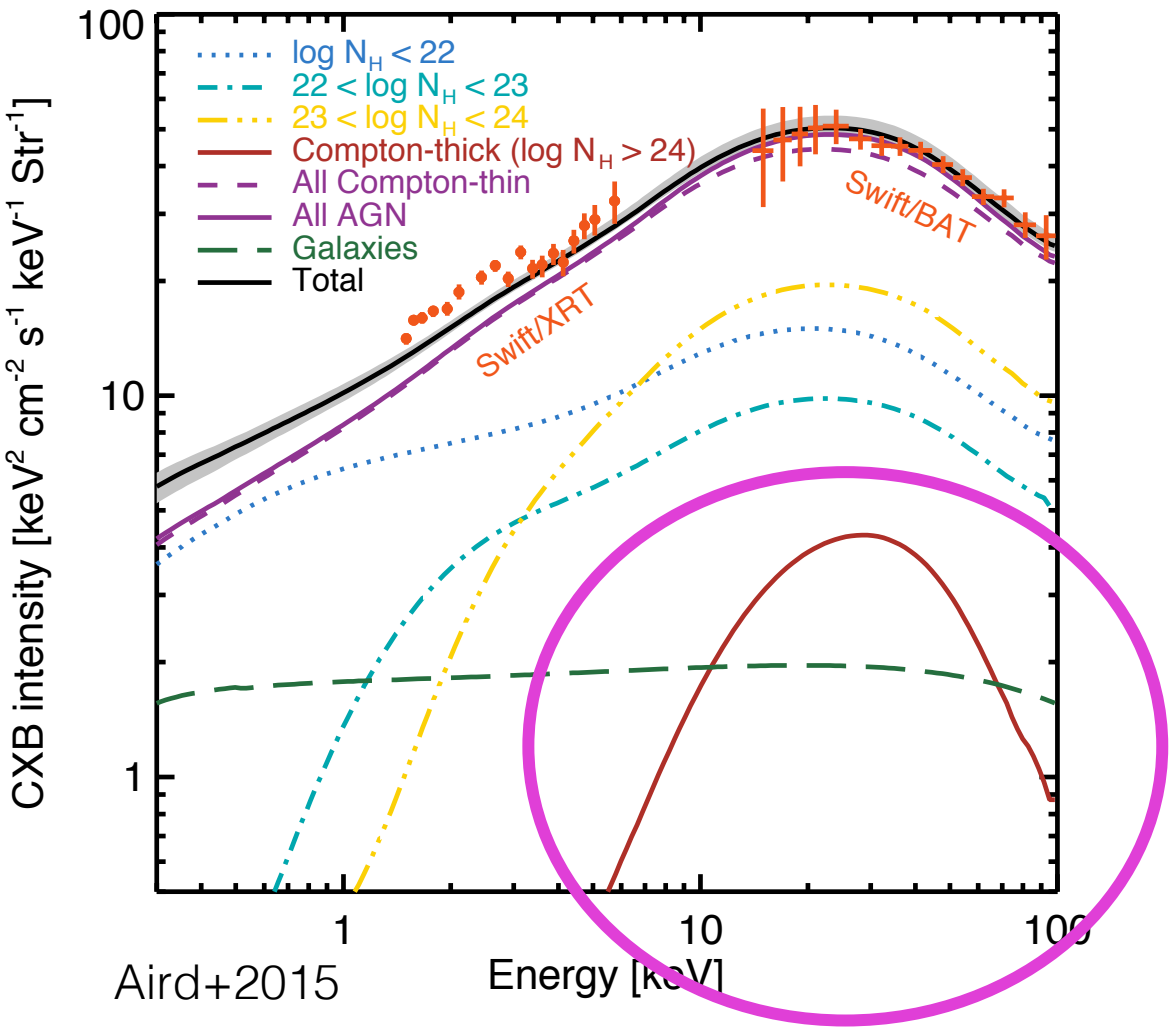
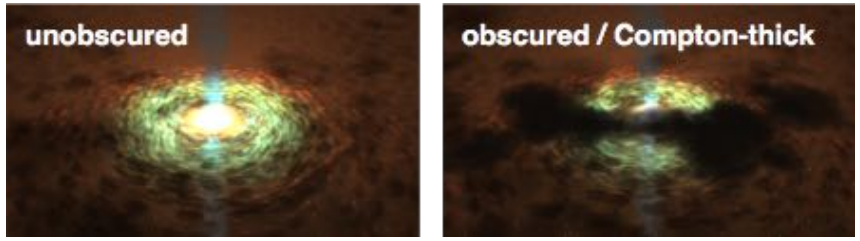
Motivation for an AGN census: The cosmic X-ray background



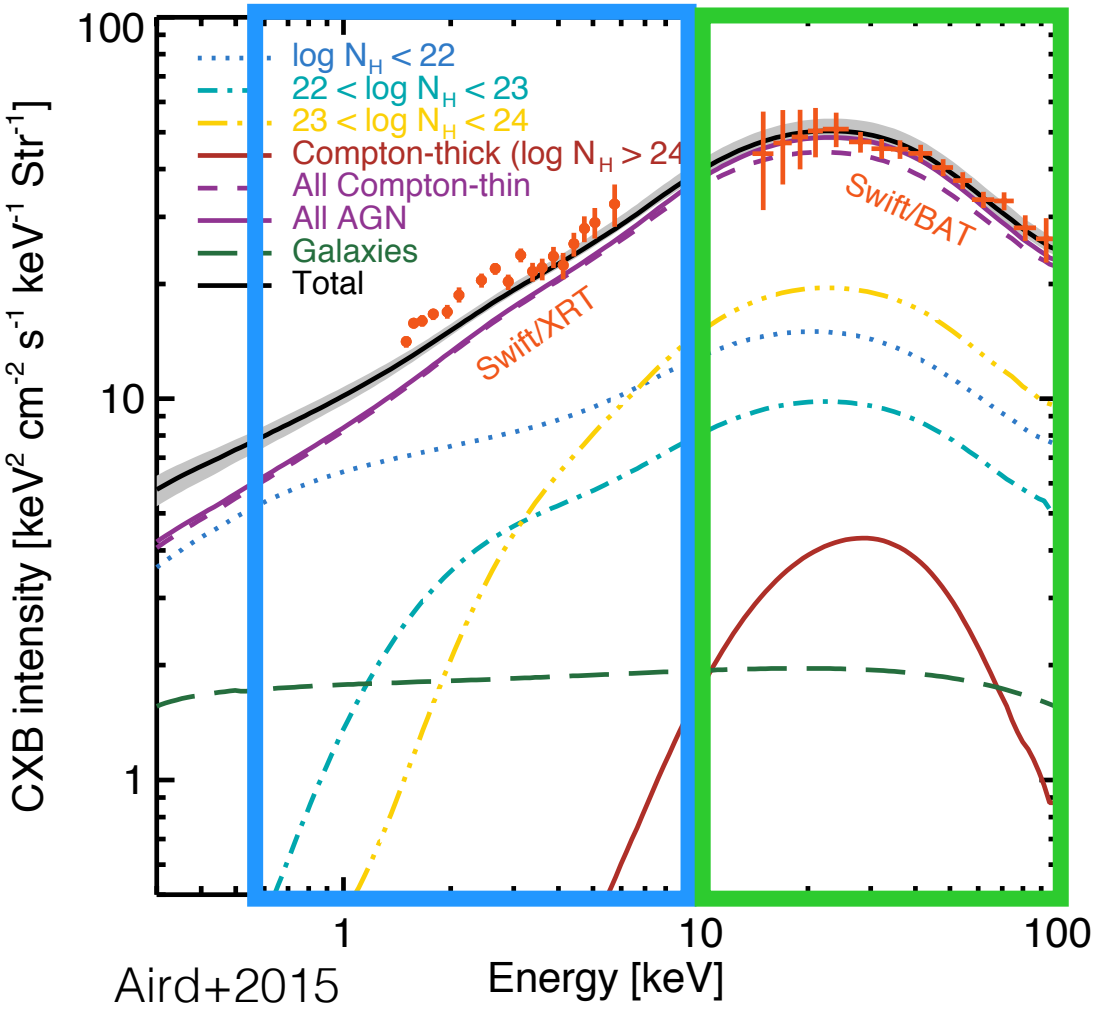
The shape of the cosmic X-ray background (CXB) requires a varied population of AGN (e.g., Setti & Woltjer 1989):

some unobscured ($N_H < 10^{22}$ cm^{-2}),
some obscured ($N_H > 10^{22}$ cm^{-2}),
some **Compton-thick ($N_H \gtrsim 10^{24}$ cm^{-2})**

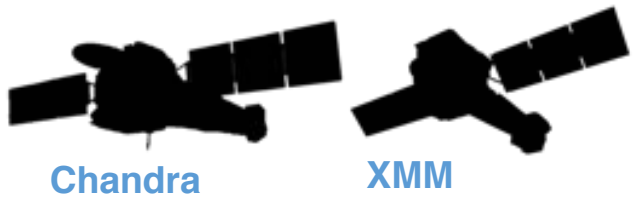


Compton-thick AGN account for a large fraction (~10-60%; e.g., Treister+2009, Buchner+2015) of supermassive black hole growth, but are challenging to observe..

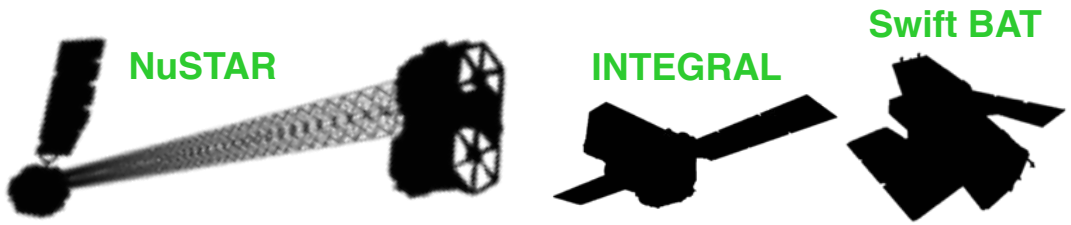
Motivation for an AGN census: The cosmic X-ray background



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



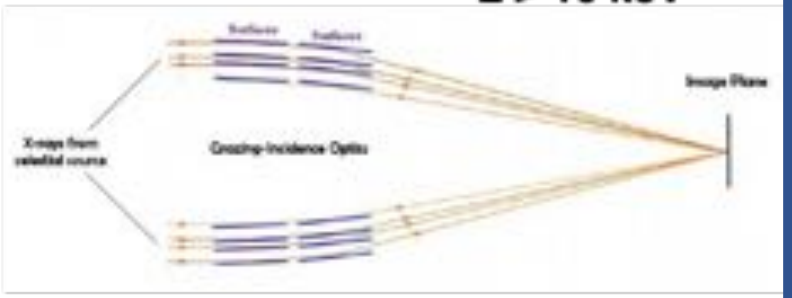
.. but the CXB peaks at **"hard" X-ray energies (>10 keV)** (***NuSTAR*** has resolved ~30% of the CXB peak; Harrison, Aird + 2016)



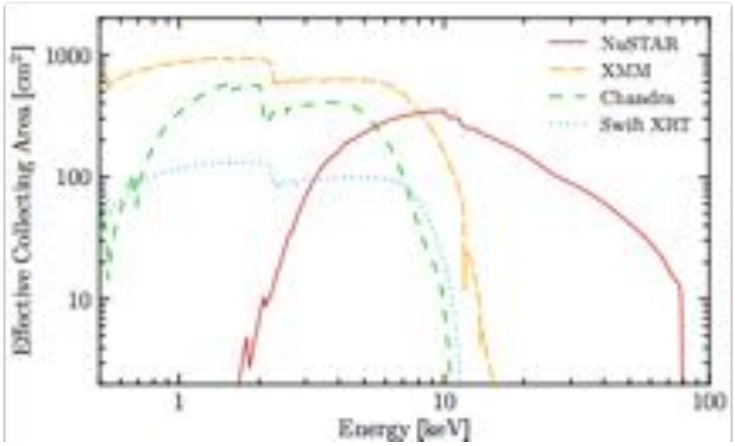
The NuSTAR census of AGN: the extragalactic survey program

NuSTAR quick facts:

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

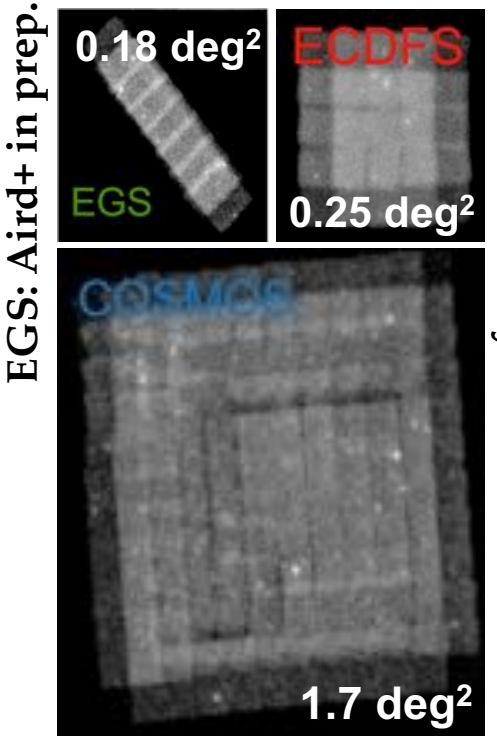


- 12′ × 12′ field-of-view
- Sensitive at $E = 3$–78 keV



NuSTAR extragalactic survey "wedding cake":

(1) Deep surveys in famous blank fields



EGS: Aird+ in prep.

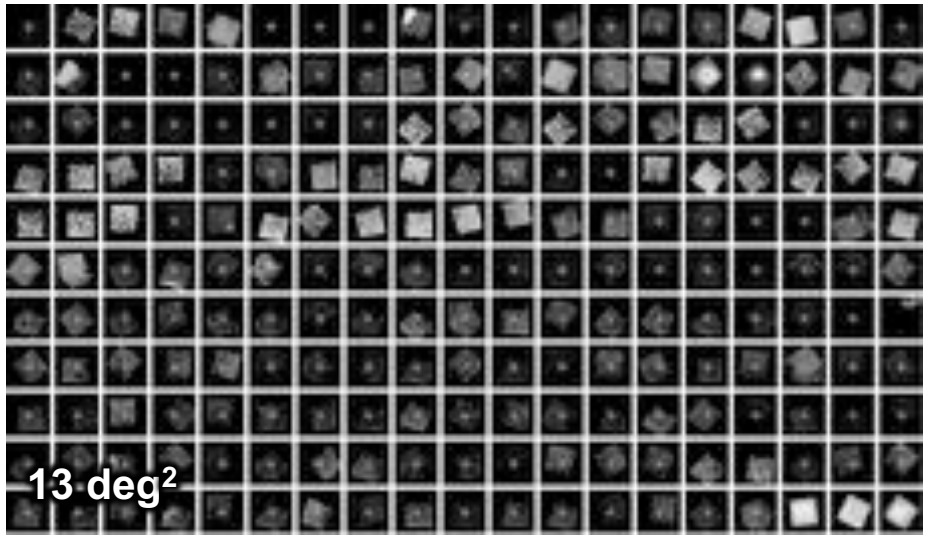
ECDFS: Mullaney+ 2015

COSMOS: Civano+ 2015

GOODS-N: Del Moro+ in prep.

UDS: Masini+ in prep.

(2) The serendipitous ("serendip") survey: wide-area, covering a range of depths

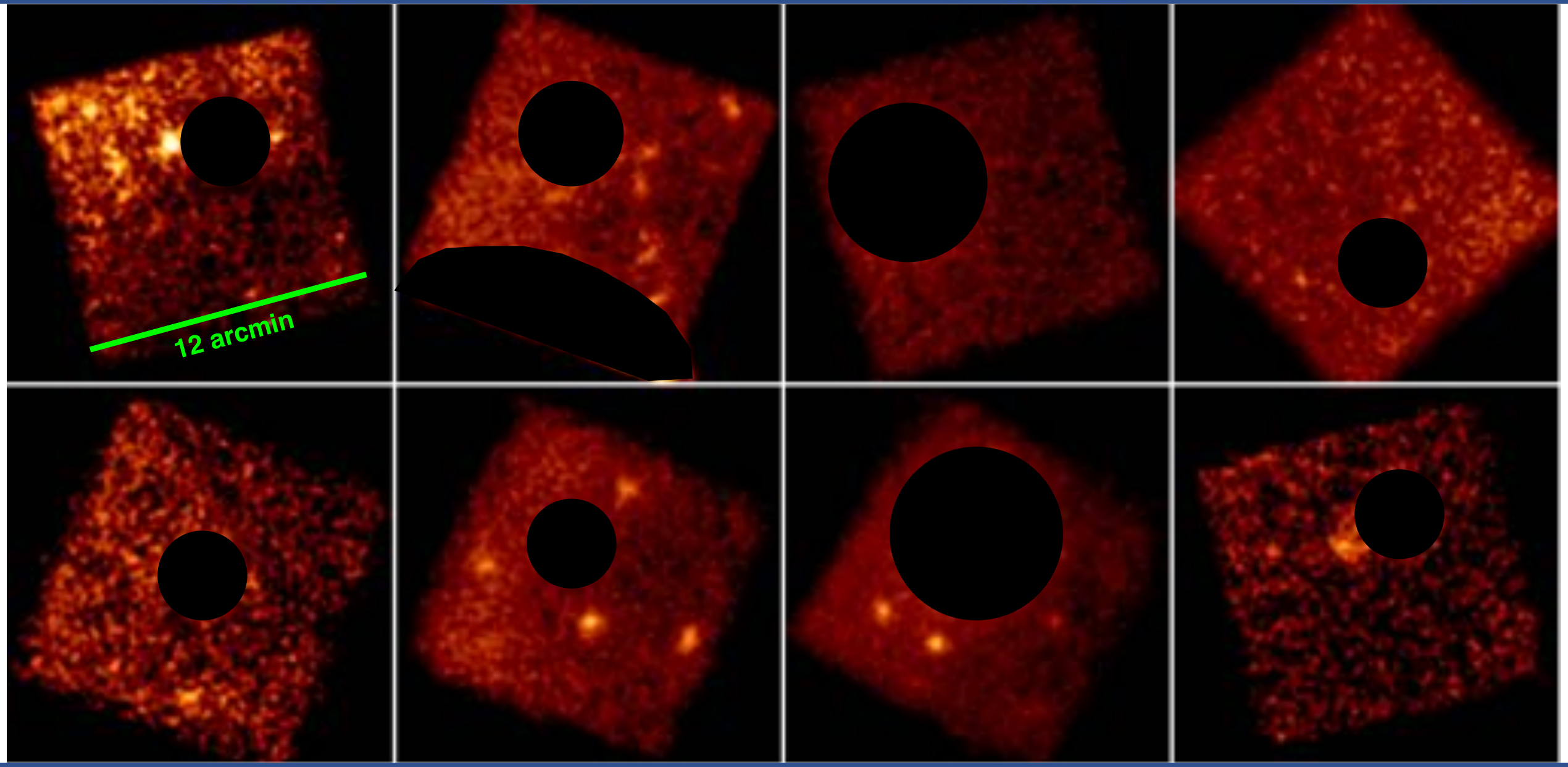


Alexander+ 2013; Lansbury+ 2017

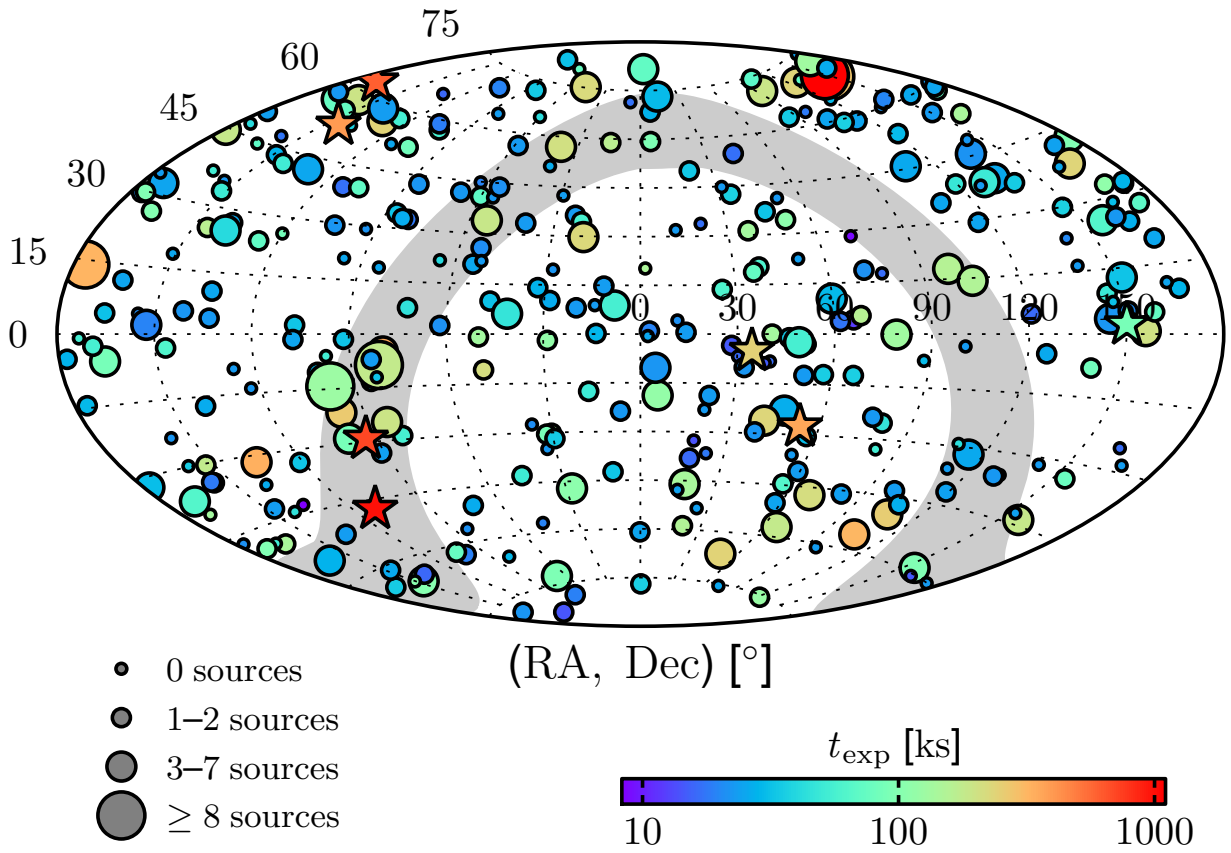
(3) The "snapshot" survey of *Swift* BAT AGN

Baloković+ in prep.

The NuSTAR serendipitous survey: example fields (8 out of 331)



The 40-month NuSTAR serendipitous survey

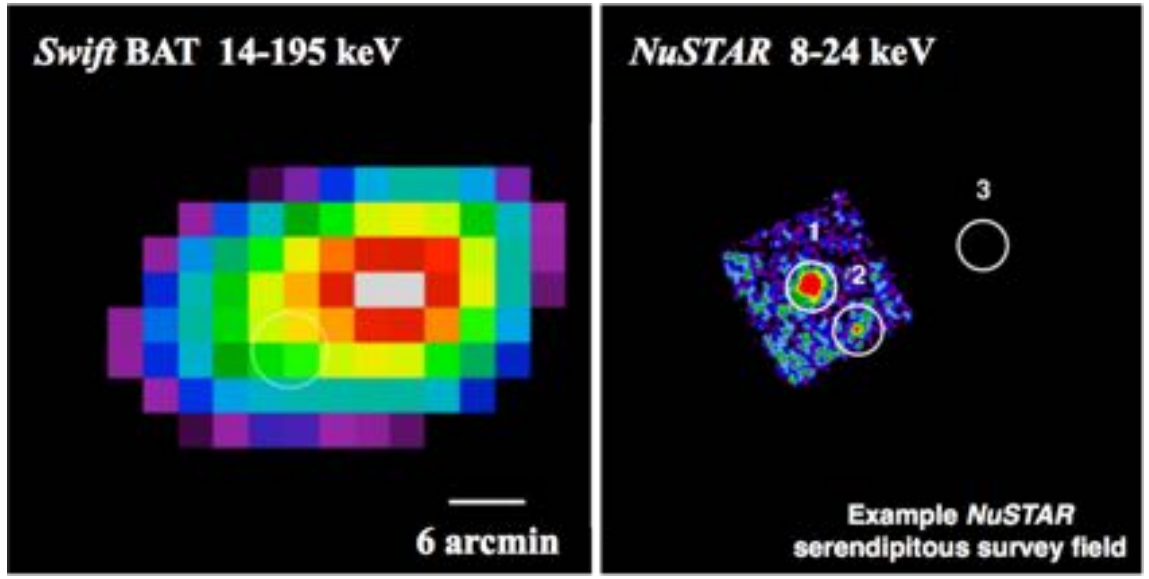


- Performed for **331** NuSTAR fields (510 exposures)
- Cumulative exposure time = **20 Ms**
- Areal coverage ≈ **13 deg^2**
- # detected sources = **497 sources (~300 with spec-z's)**
- Faintest flux (at 8-24 keV) = **1.5 × 10^{-14} erg s^{-1} cm^{-2}**

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

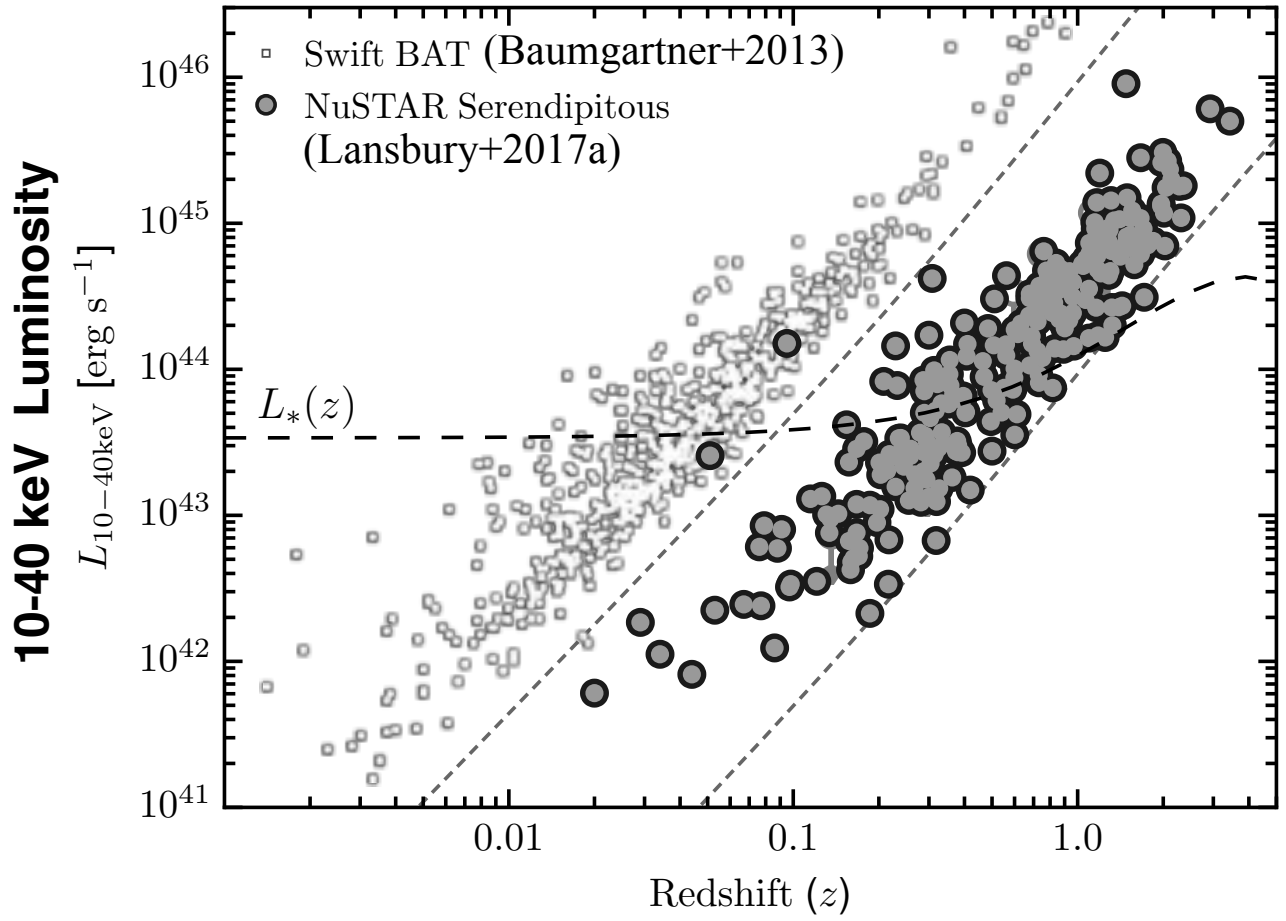
Comparing hard X-ray surveys: Swift BAT survey & NuSTAR serendip survey

Lansbury+2017a, submitted

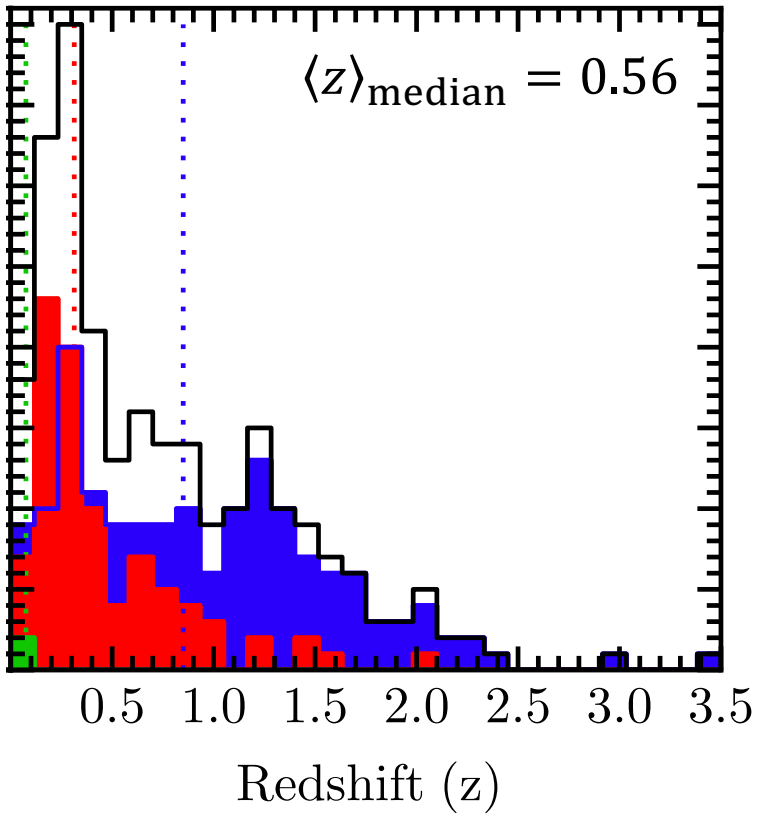


NuSTAR has ≈100 × higher sensitivity
≈10 × higher angular resolution

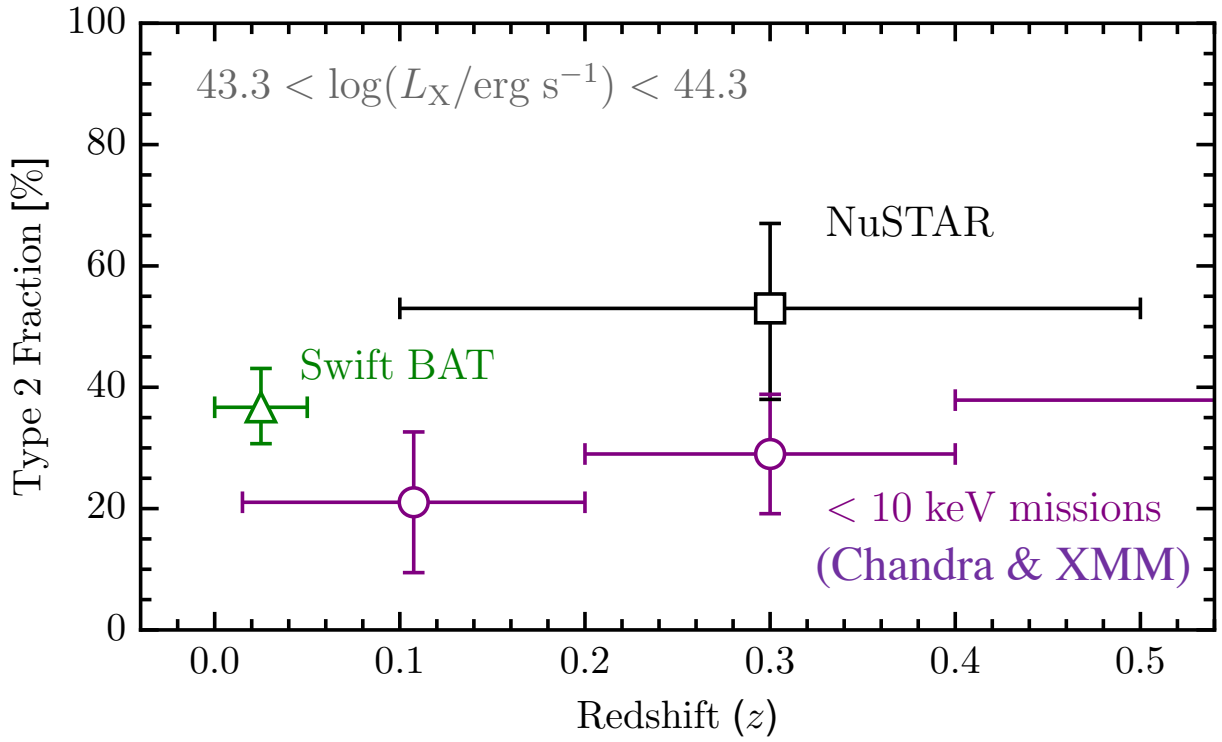
compared to the [all-sky] hard X-ray missions
(*Swift* BAT, *INTEGRAL*)



The 40-month NuSTAR serendipitous survey: optical properties



Type 1 = optically unobscured (broad-line AGN)
Type 2 = optically obscured (narrow-line AGN)

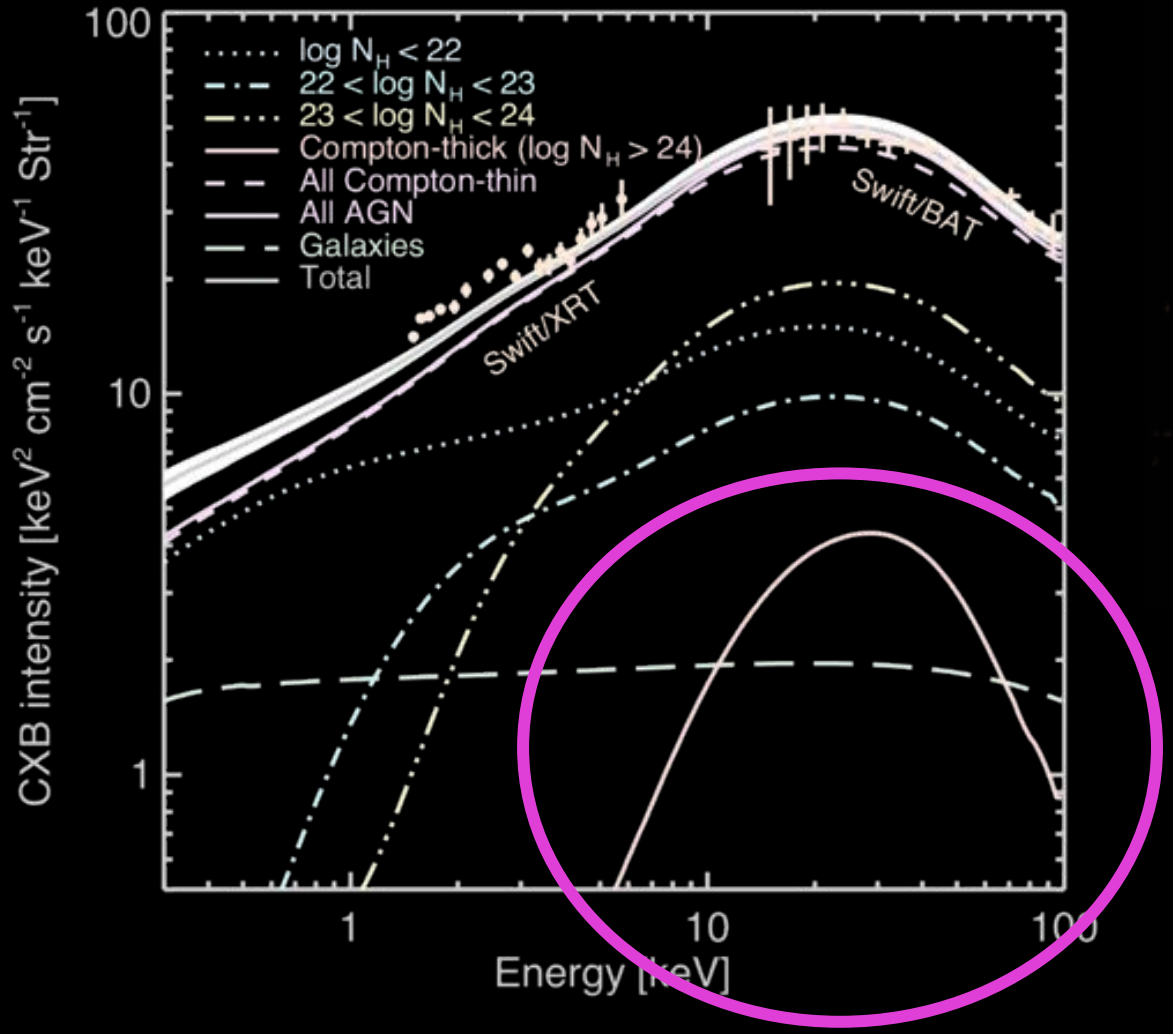


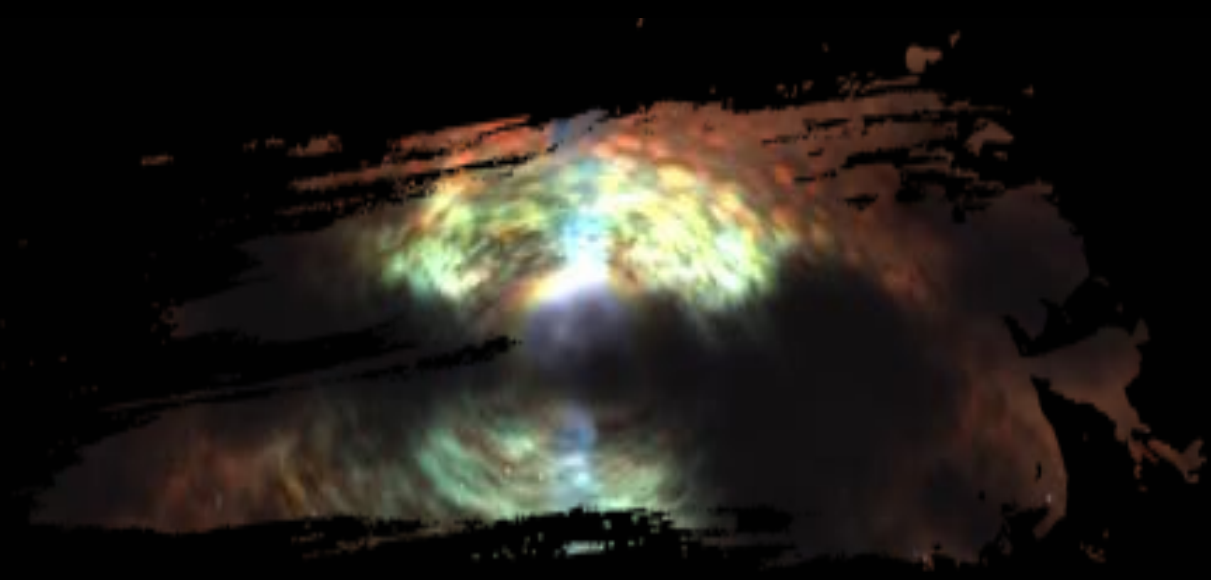
Type 2 fraction for the $0.1 < z < 0.5$ NuSTAR serendipitous survey sample selected at > 8 keV:

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

Lansbury+2017a

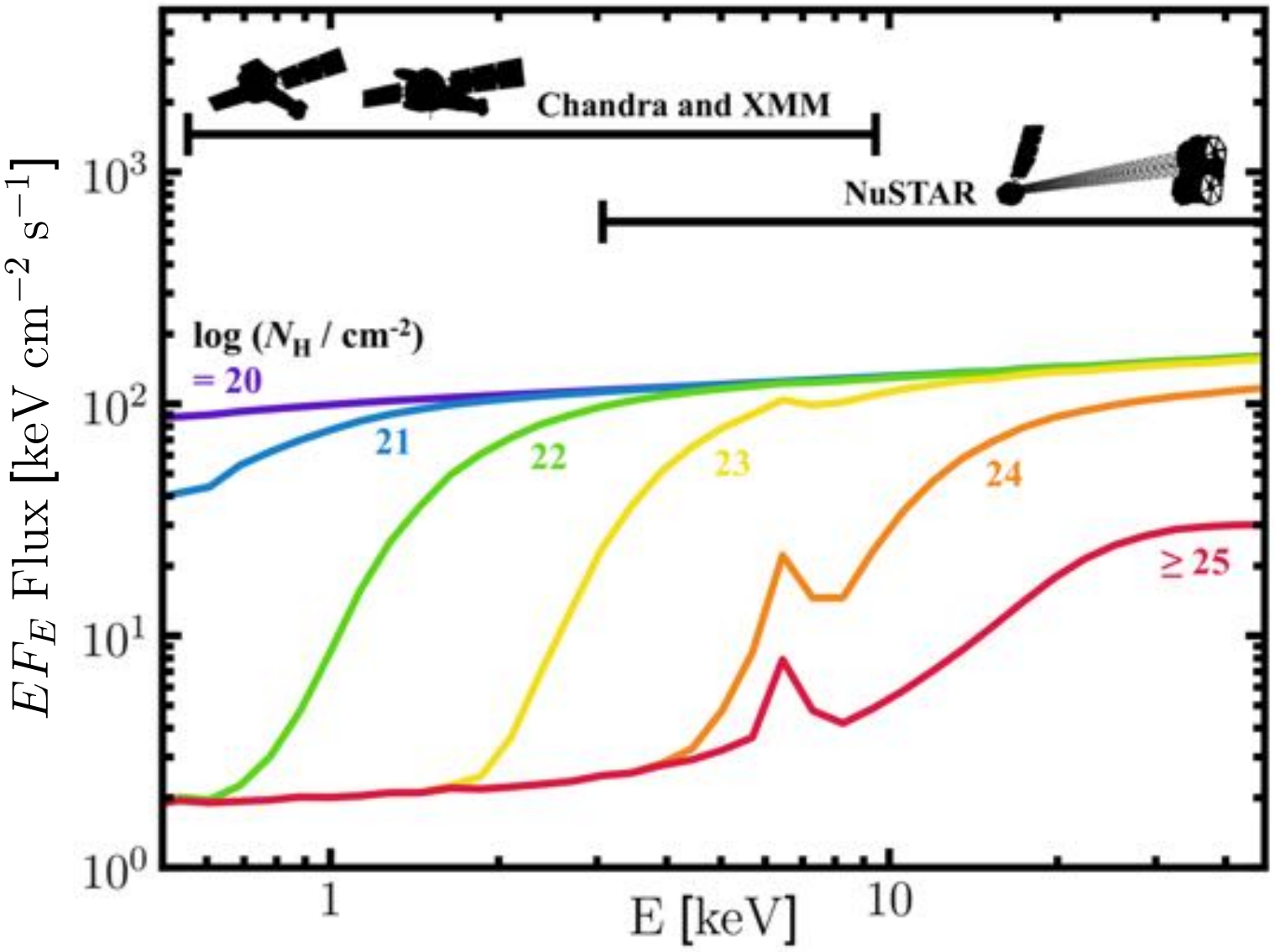
Completing the AGN census: hunting for hidden black hole growth using the NuSTAR serendip survey

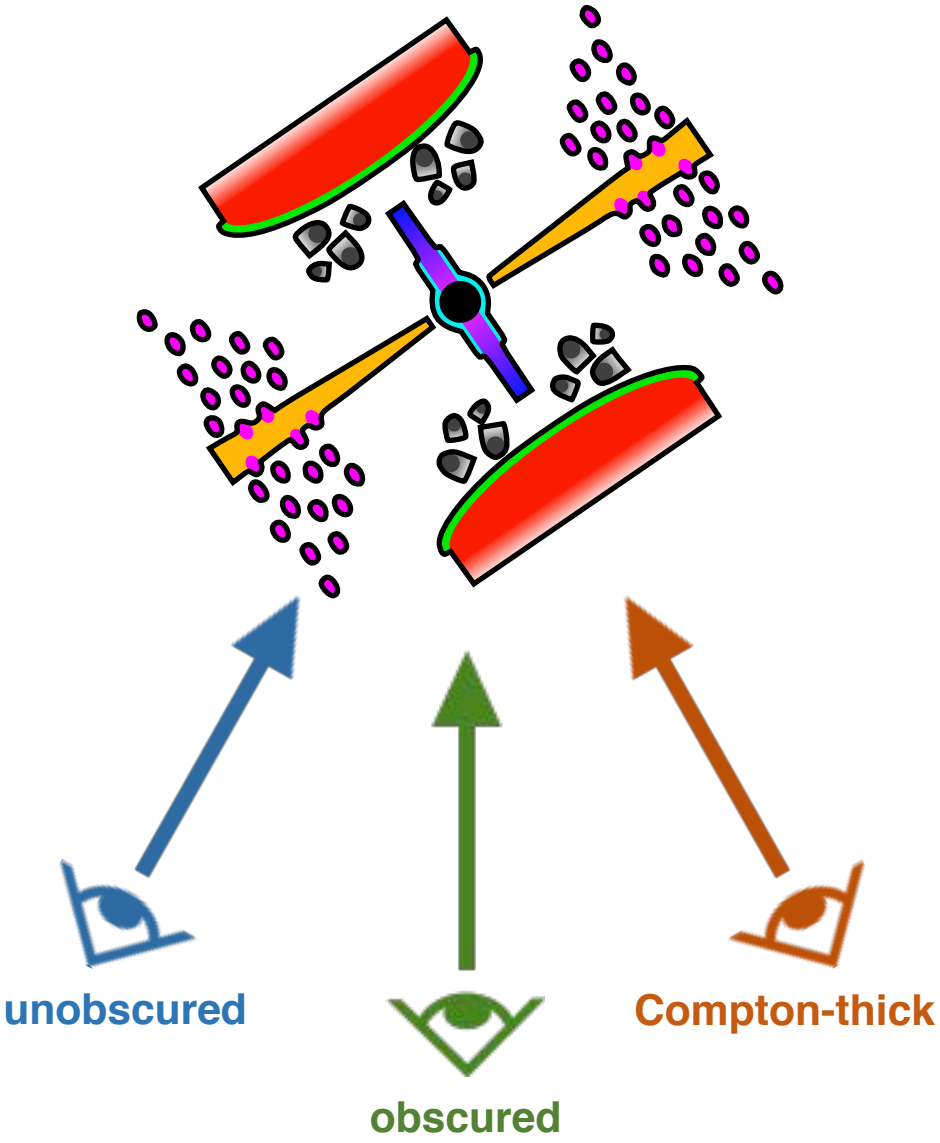




Compton-thick AGN:
$N_H \gtrsim 10^{24}$ cm^{-2}

AGN X-ray spectra: the effect of obscuration

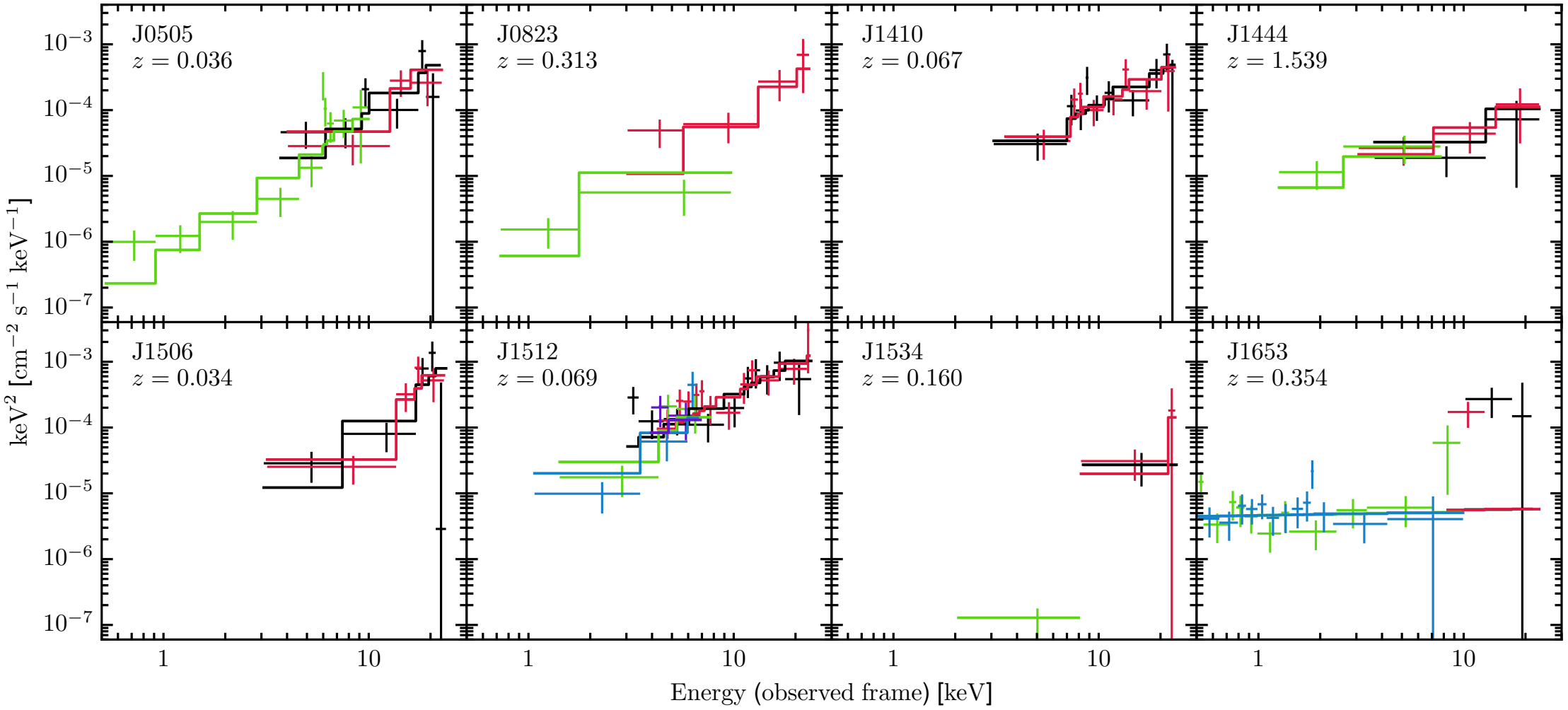




Extremely hard sources in the NuSTAR serendipitous survey

Lansbury+2017b, submitted

NuSTAR + Chandra / XMM / Swift **0.5-24 keV X-ray spectra**
for the hardest *NuSTAR* serendip sources ($\boldsymbol{\Gamma < 0.6}$ at 3-24 keV) :



Extremely hard sources in the NuSTAR serendipitous survey

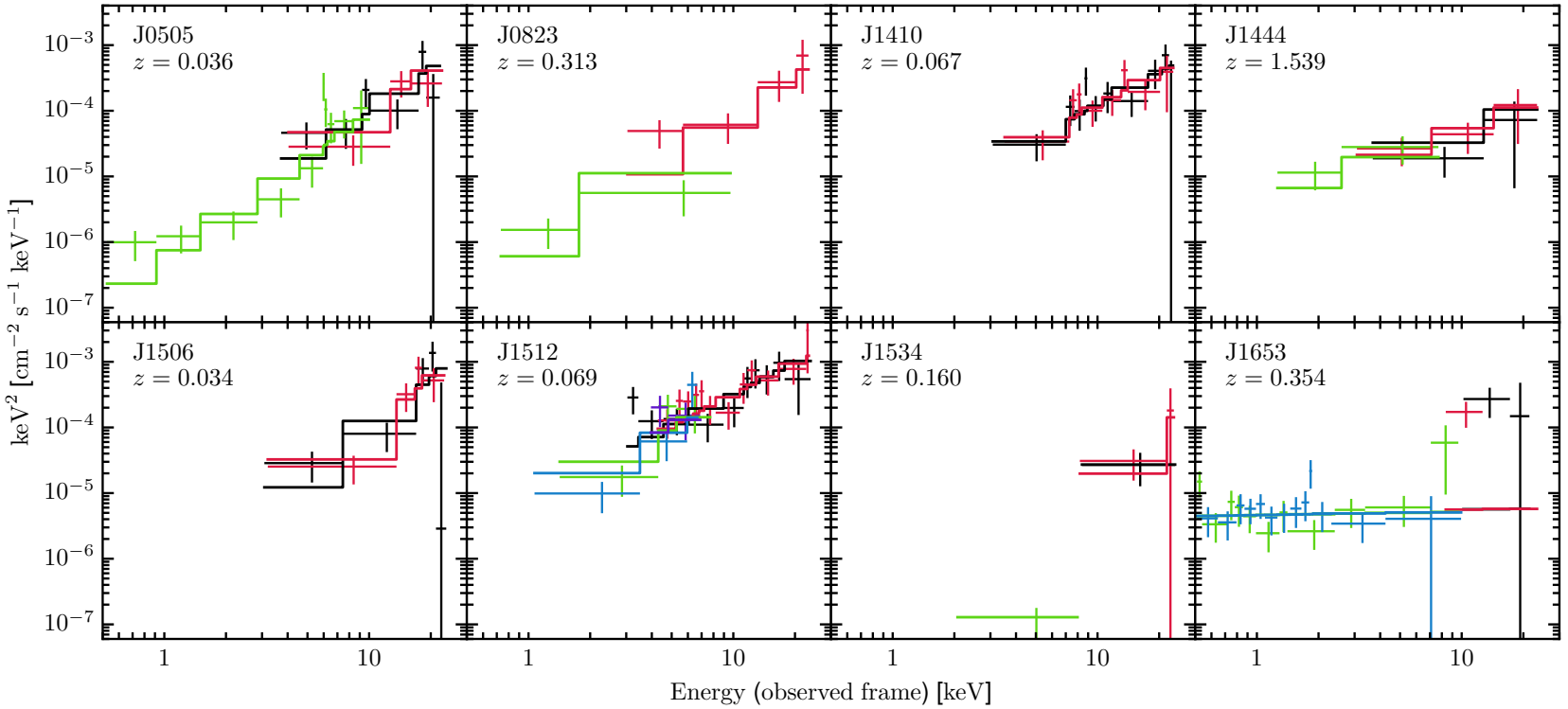
Modelling the X-ray spectra with a range of spectral models:

1. Transmission-dominated model
2. Reflection-dominated model
3. Self-consistent torus model

- **50% are Compton-thick (CT)** ($N_{\rm H} > 1.5 \times 10^{24}$ cm^{-2})
- 50% are likely highly obscured ($N_{\rm H} >$ a few $\times 10^{23}$ cm^{-2})
- Intrinsic X-ray luminosities of $\log L_{\rm X} = 42.5 - 45$

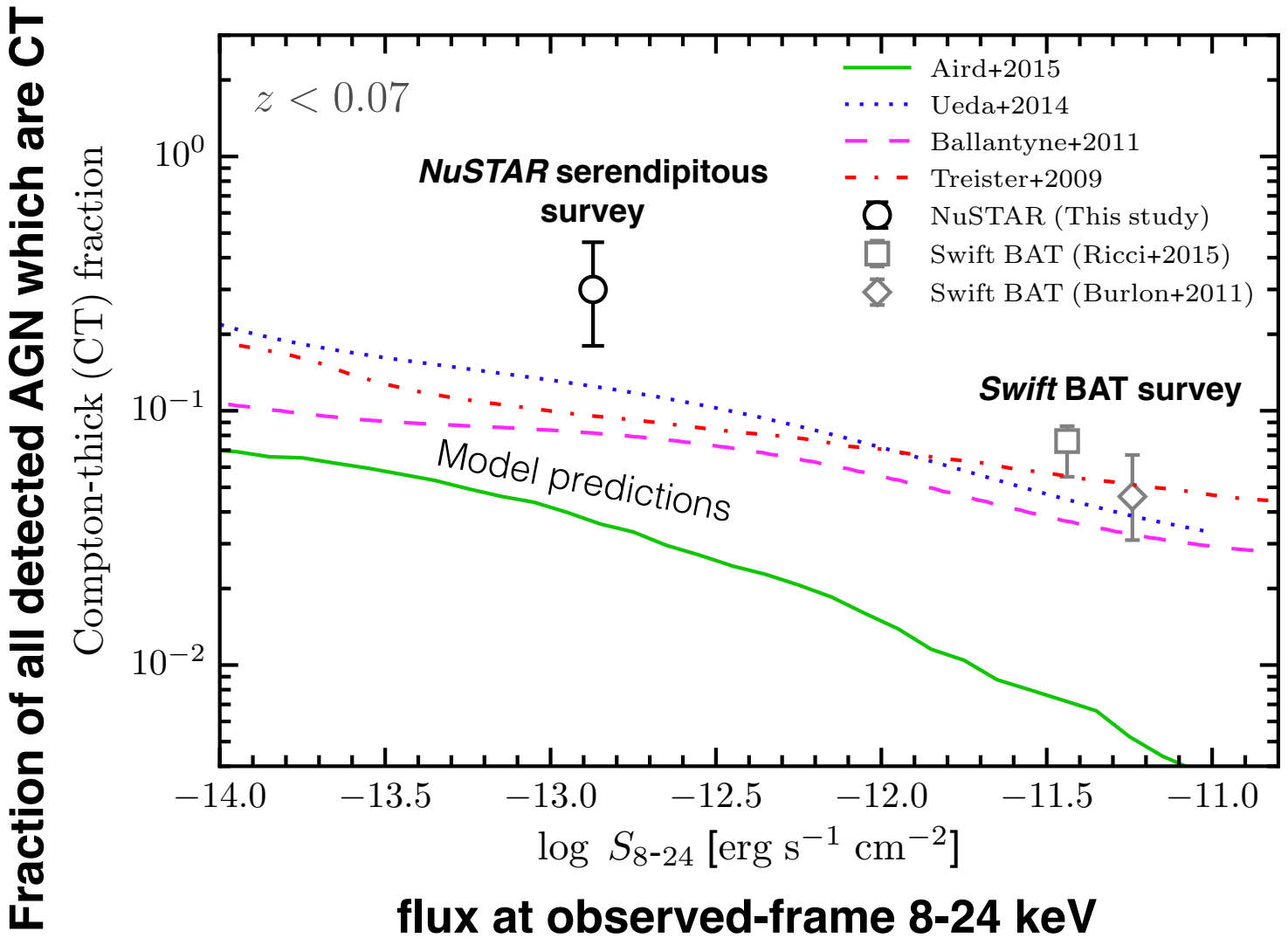
Lansbury+2017b, submitted

see Del Moro+2017, Zappacosta+2017, Civano+2015 for additional CT candidates in the NuSTAR surveys



- Most (≈75%) of the extreme sources **would not be identified as highly obscured based on the <10 keV (e.g., Chandra / XMM-Newton) data alone**
- **Elusive at non-X-ray wavelengths**, e.g.**:**
  - ≥50% not selected as AGN in optical (e.g., BPT)
  - 88% not selected as AGN in infrared (WISE colors)

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



The observed CT fraction at low redshifts, $f_{\mathrm{CT,obs}} \approx 30\%$, is high compared to models.
(The implied intrinsic CT fraction is even higher; $f_{\mathrm{CT,int}} \gtrsim 50\%$)

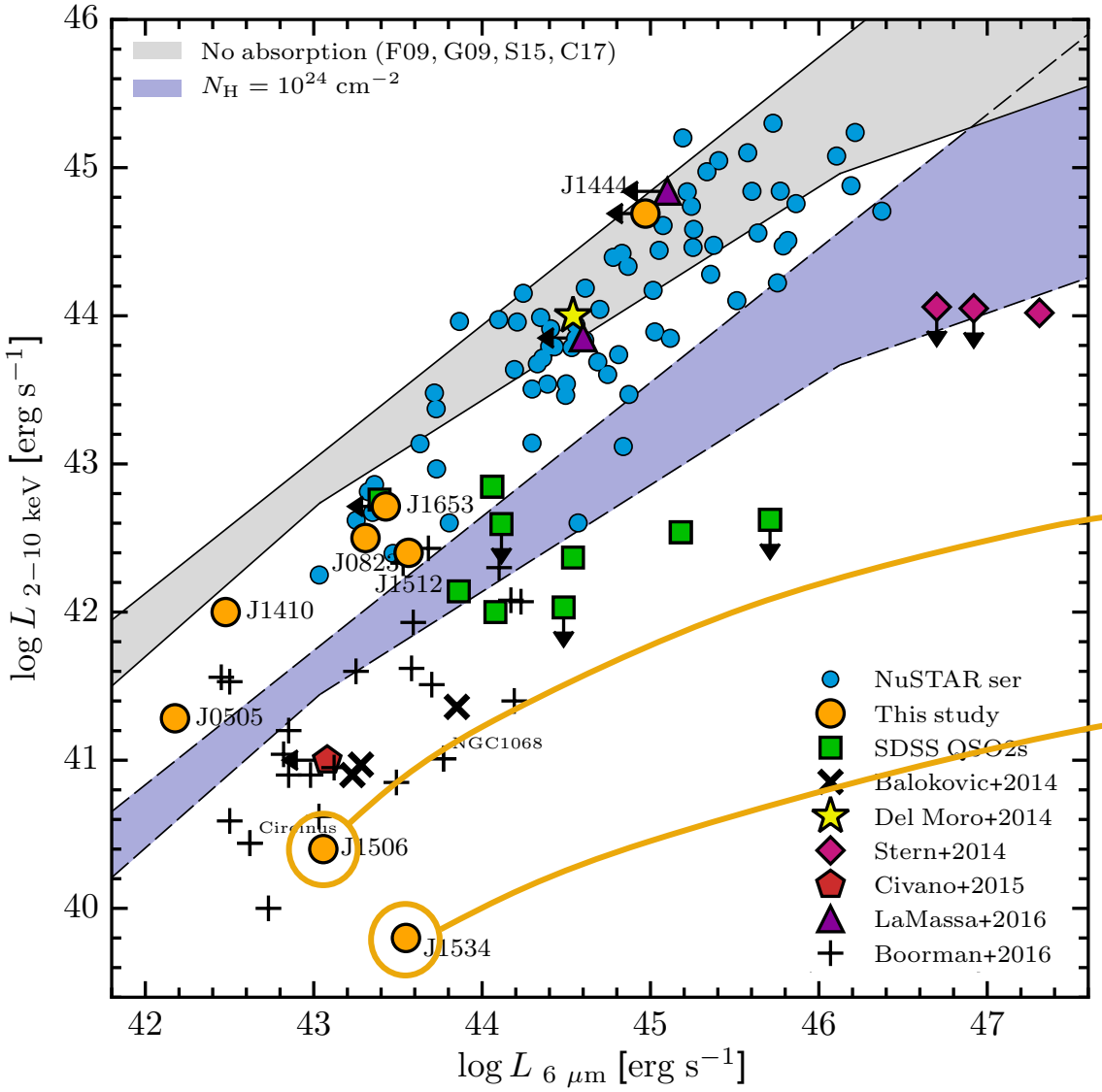
Possible explanations:

1. Current AGN population models underpredict the number of CT AGN – they need updating for the new low-flux/luminosity regime probed by NuSTAR

and/or

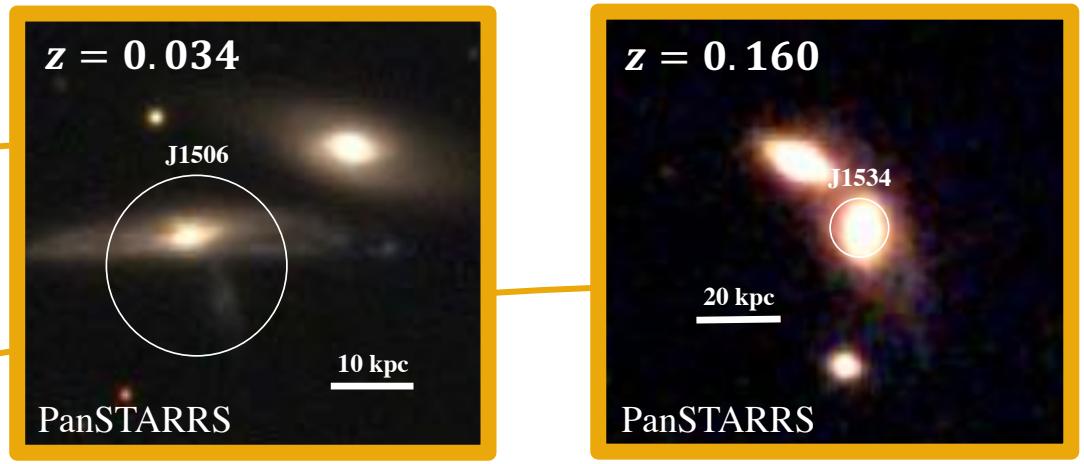
2. There is an intrinsic connection between CT AGN and galaxy-rich environments which is boosting $f_{\mathrm{CT}}(z < 0.07)$ in the NuSTAR serendipitous survey

L_X vs. L_{MIR} : Indirect evidence for extreme absorption



Using the MIR as a proxy for the intrinsic luminosity:

Two CT NuSTAR sources have **X-ray luminosities suppressed by ≈ 2-3 orders of magnitude** (e.g., more extreme than Circinus & NGC1068)



.. and both are hosted by **galaxy major mergers** (typically rare: e.g., <1% of SDSS AGN)

Is there a merger-induced high central gas content, resulting in $N_H \gg 10^{24}$ cm^{-2} obscuration? (relevant to, e.g., Kocevski+2015, Ricci+2017 results)

Lansbury+2017b, submitted

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), $\langle z \rangle = 0.56$
  - Type 2 (i.e., optically obscured) fraction, $f_{\mathrm{Type\ 2}} \approx 53\%$
- 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 $z < 0.07$ ($f_{\mathrm{CT,obs}} \approx 30\%$) is surprisingly high
    → Do AGN population synthesis models need updating for the faint hard X-ray regime?
  - The L_{X}-L_{MIR} plane & host galaxy imaging highlight two particularly extreme CT AGN residing in major mergers