Introduction	ULX/HLX candidates selection	HLX candidate in NGC 5917	Conclusion	Backup

# Searching for ultra- and hyper- luminous X-ray sources in the *Swift*-XRT catalog

Supervisor: Dr. Olivier GODET April-September 2020

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#### M2 Internship Presentation IRAP

September 30th, 2020



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## Introduction



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Formation paths of Supermassive Black Holes (SMBHs)											
SMBHs											

#### Characteristics

- $\blacksquare$  10<sup>6</sup>  $M_{\odot} \lesssim M_{SMBH} \lesssim 10^{10} M_{\odot}$  Kormendy et al. 1995
- At the center of most galaxies with  $M_{aal} \gtrsim 10^9 \ M_{\odot}$  Kormendy & Ho 2013
- Can have phases of enhanced activity (10<sup>7</sup> 10<sup>8</sup> years): Active Galactic Nuclei (AGNs) Hong et al. 2015
- During AGN phase, huge release of energy through radiation  $(L_X \sim 10^{38} - 10^{48} \text{ erg} \cdot \text{s}^{-1})$  and kinetic energy (outflows: jets & winds)



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## SMBH and galaxy joint growth

#### Feedback processes

- Enhanced/Quenched star formation
  - Higher gas density
  - Higher velocity dispersion
  - Winds and outflows
- Auto-regulation of accretion rates
- Baryons reprocessing

SMBH, host galaxy growth and galaxy dynamics in a cluster are entangled



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## How to grow an SMBH?

#### Observations

- **8**  $\times$  10<sup>8</sup>  $M_{\odot}$  SMBH at z = 7.5 Banados et al. 2018
- $2 \times 10^9 M_{\odot}$  SMBH in a quasar at z = 7.1 Mortlock et al. 2011
- Masses up to  $6.6 \times 10^{10} M_{\odot}$  shemmer et al. 2004

#### SMBH growth scenarios

Hierarchical growth by successive intermediate-mass BH mergers Farouki et al 1983  $100 \ M_{\odot} \lesssim M_{IMBH} \lesssim 10^5 \ M_{\odot}$  Miller &

 $100 M_{\odot} \gtrsim M_{IMBH} \gtrsim 10^{\circ} M_{\odot}$  Miller & Colbert 2004

 Sustained accretion episodes at high accretion rates



Greene 2012



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## Eddington limit

- Gravitational attraction on protons:  $F_{grav} = \frac{m_p GM}{r^2}$
- Radiation pressure on the electrons (Thomson scattering):  $F_{rad} = \frac{\sigma_T}{c} \frac{L}{4\pi r^2}$
- $\begin{array}{l} \hline \quad \mbox{Eddington luminosity Eddington 1921:}\\ L_{Edd} = \frac{4\pi\ c\ G\ M\ m_p}{\sigma_T} \simeq \\ 1.3 \times 10^{38} \left(\frac{M}{M_\odot}\right) \mbox{erg}\cdot\mbox{s}^{-1} \end{array}$
- Corresponding to an accretion rate limit:  $\dot{m}_{Edd} = \frac{4\pi GMm_p}{\eta c\sigma_T} \propto M$



Gravitational attraction on the protons balances outbound pressure on the electrons



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Gravitational attraction on protons:

$$F_{grav} = \frac{m_p GM}{r^2}$$

- Radiation pressure on the electrons (Thomson scattering):  $F_{rad} = \frac{\sigma_T}{c} \frac{L}{4\pi r^2}$
- Corresponding to an accretion rate limit:  $\dot{m}_{Edd} = \frac{4\pi G M m_p}{\eta c \sigma_T} \propto M$

#### Consequences

- Eddington limit directly proportional to the accretor mass
- If  $L \ge L_{Edd}$ , accretion may stop
- Impossible to grow a SMBH at sub-Eddington rates at high redshifts



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## Looking for super-Eddington accretion and IMBHs

#### Two directions of research

- Potential episodes of super-Eddington accretion
- SMBH growth by IMBH mergers

#### Open questions

- Is super-Eddington accretion possible?
- Are Eddington rates sufficient to grow a SMBH given the outflows?
- How long can accretion last?
- What are the feedback mechanisms?
- What impacts does this feedback induce on the BH environment at different spatial scales?
- How do IMBHs form? How do they grow?
- What are the hosts of IMBHs?

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## ULXs & HLXs

#### Definition Feng et al 2011

- Extragalactic off-nuclear X-ray source powered by accretion of matter
- ULX: Isotropic equivalent  $L_X \ge 10^{39} \text{ erg} \cdot \text{s}^{-1} (0.3 10 \text{ keV})$
- HLX: Isotropic equivalent  $L_X \ge 10^{41} \text{ erg} \cdot \text{s}^{-1} (0.3 10 \text{ keV})$

#### ULXs: super-Eddington accretion?

- bubbles observed around some ULXs (winds/radiation) Pakull & Mirioni 2002
- 6 persisting pulsating ULXs discovered with period spin-up Bachetti et al 2014: NS progenitors (~ 1.4 1.5  $M_{\odot}$ ) with strongly super-Eddington accretion ( $L_X \gg 10^{38} \text{ erg} \cdot \text{s}^{-1}$ )

#### HLXs: accreting IMBHs?

- Very few candidates:
- HLX-1 Farrell et al 2009 has multi-wavelength properties similar to an X-ray binary (XRB), but 1000 times more luminous
- Tidal Disruption Event (TDE) Lin et al 2018

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## The Neil Gehrels Swift observatory

#### Characteristics Gehrels et al. 2004

- Multi-wavelength gamma-ray burst (GRB) observatory
- Carries 3 instruments:
  - BAT (Burst Alert Telescope, Barthelmy et al. 2005): GRB prompt emission detection at 15 - 150 keV
  - XRT (X-ray Telescope, Burrows et al. 2005): sky observation at 0.3 - 10 keV (GRB afterglows, X-ray source monitoring)
  - UVOT (Ultraviolet/Optical Telescope, Roming et al. 2005): 6 filters for a sensitivity at 160 - 600 nm
- Automatic sky localization and repositioning after a GRB detection



The Swift spacecraft model Credit: NASA E/PO



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## The 2SXPS catalog Evans et al 2020

#### Characteristics

- Swift-XRT observations between 2005-01-01 and 2018-08-31
- 206335 X-ray sources
- Sky coverage: 3790 deg<sup>2</sup>
- Up to 230 data columns per source (Position, Exposure, Flags, Count rates, Spectral/Flux information, Cross-correlations)

#### Assets

- High number of unknown sources (~ 90 % not observed by XMM-Newton)
- Large sky coverage
- Simultaneous UVOT observations
- Short- and long-term monitoring of sources (from ~ 1 s to ~ 10 years)
- Online tools available



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Positions of the sources of 2SXPS in the Galactic coordinates

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## ULX/HLX candidates selection

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#### The ULX/HLX sample

## Producing a ULX/HLX sample

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2SXPS



GLADE Dayla et al 2018

#### Additional information to the 2SXPS catalog

- Multi-wavelength information from other catalogs (XMM-Newton Lumb et al 2012, Chandra Garmire et al 2003, USNO-B1 Monet et al 2003, 2MASS Cutri et al 2003)
- Galactic correlation with GLADE using TOPCAT Taylor 2005  $\rightarrow L_X$

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#### The ULX/HLX sample

## Producing a ULX/HLX sample

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2SXPS



GLADE Dayla et al 2018

#### The ULX/HLX sample

- 2169 candidates Godet, Pellouin, Tranin et al, in prep
- Selection process:
  - GLADE association
  - Unabsorbed  $L_X \ge 10^{39} \text{ erg} \cdot \text{s}^{-1} (0.3 10 \text{ keV})$
  - Not located in the galactic center
  - Detection flag: Good

Clément Pellouin

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Finding re	lerence sources			



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The ULX/HLX sample

## Classifying the sources of the ULX/HLX sample

#### Classification algorithm

- Probabilistic classification based on the properties observed in the reference sample
- 2169 sources classified as AGNs (43%), XRBs (52%), Stars (3%), CVs (cataclysmic variables, 1%) Tranin, Pellouin et al, in prep

#### Using the ULX/HLX sample, two main objectives:

- Cleaning the ULX/HLX sample
- Analyzing the best ULX/HLX candidates



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#### Classification analysis

#### Analysis of the classes distribution:

	Refere	nce	ULX/HLX x Ref.		ULX/HLX (prediction)	
Class	Count	%	Count	%	Count	%
AGN	20799	77	134	42	943	43
Star	5181	19	19	6	74	3
XRB	475	2	165	52	1138	52
CV	370	1	1	0	14	1

Comparison of statistics on the classes of sources

#### Conclusions

- ULX/HLX definition non-physical, but many XRBs retrieved in the ULX/HLX sample
- Potentially high level of AGN contamination
- Contaminants are mostly background AGNs instead of foreground stars

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## Classification analysis



#### Conclusions

- ULX/HLX definition non-physical, but many XRBs retrieved in the ULX/HLX sample
- Potentially high level of AGN contamination
- Contaminants are mostly background AGNs instead of foreground stars

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Classification analysis						

#### How to select the best ULX/HLX candidates among the 2169 sources?

Prediction	AGN	Star	XRB	CV
Literature				
AGN	132	1	2	0
Star	2	17	0	0
XRB	42	7	84	2
CV	0	0	1	0

Confusion matrix of the classification source types

Focusing only on the sources classified as XRBs?

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#### Identification of new selection parameters



Distribution of the unabsorbed X-ray peak luminosity for the sources of the cross-correlated sample. In blue, sources whose known class is AGN, in yellow, those that are XRBs, in green, sources found in catalogs of ULXs

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#### Identification of new selection parameters



Parameter	Criterion (ULX)	Sources	%	Criterion (HLX)	Sources	%
LX	$\leq$ 5 $\times$ 10 <sup>41</sup> erg $\cdot \cdot \cdot^{-1}$	1529	70	$\in [10^{41}, 10^{43}] erg \cdots ^{-1}$	626	29
Variability	> 1	1817	84	> 1	1817	84
Distance	$\leq$ 100 Mpc	1438	66	$\leq$ 400 Mpc	1877	87
Combined		1221	56		415	19

**Classification parameters** 

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#### Identification of new selection parameters



#### Objective = Finding interesting sources to study:

- Focus on sources that are in a MUSE cube (400/2169)
- Focus on sources with other multi-wavelength observations
- Focus on sources with XMM-Newton and/or Chandra observations

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## HLX candidate in NGC 5917

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HLX candidate in NGC 5917

Conclusion

## 2SXPS J152131.9-072242



Swift-XRT image of 2SXPS J152131.9-072242

#### Fact sheet

- RA(J2000): 15<sup>h</sup> 21<sup>m</sup> 31.99<sup>s</sup>
- Dec(J2000): -07° 22′ 42.4″
- Associated with NGC 5917, interacting spiral galaxy
- 9" (1.3 kpc) away from the galactic center
- *d<sub>NGC5917</sub>* = 30.8 Mpc

#### VLT image of NGC 5917 and MCG-01-39-003





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X-ray data analysis				

## Swift-XRT raw data processing

#### Preprocessing steps, using XSELECT

- Produce a clean, stacked event list (events = photons detections on the CCD)
- Produce an exposure map (dead pixels & columns, vignetting)
- Take into account the CCD temporal and spectral response to incoming photons
- Filter bad events



Exposure map for the Swift-XRT observations of NGC 5917



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X-ray light	curve			



Left: Light curve showing the 2 series of observations observations of 2SXPS J152131.9-072242 taken between 2005-06-04 and 2020-08-28, in the 0.3 - 10 keV band. Every bin has a 20-count statistic. **Right:** Zoom on the light curve between 2005-06-04 and 2005-07-23.

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X-ray data analysis				

## X-ray spectral analysis



Swift-XRT Photon Counting spectrum of 2SXPS J152131.9-072242 (observations from 2005-06-04 to 2020-04-30). Minimum of 20 counts per bin. Errors at a  $1\sigma$  confidence level. Solid line corresponds to the best fit using an absorbed power-law model.

Obtained using XSPEC Arnaud 1996

Parameter	Value $\pm$ error (1 $\sigma$ )
N <sub>H</sub>	$(2.0^{+0.9}_{-0.7}) imes 10^{21}~cm^{-2}$
Galactic N <sub>H</sub>	$6.7  imes 10^{20} \ cm^{-2}$
Г	$\textbf{2.0}\pm\textbf{0.2}$
Unabsorbed $L_X$ (0.3 – 10 keV)	$(3.1\pm0.3)\times10^{40}~\text{erg}\cdot\text{s}^{-1}$
Peak unabsorbed $L_X$	$8.8 imes10^{40}~erg\cdot s^{-1}$
$\chi^2$ / dof	32.82/29

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MUSE data analysis				
MUSE dat	a analvsis			

 $\begin{array}{l} \textbf{MUSE} = \textbf{Integral field Unit (IFU) taking data cubes (300 \times 300 pixels, \sim 3500\text{-bins} \\ \textbf{visible spectra from 4750 Å to 9350 Å)} \\ \textbf{Bacon et al 2010} \end{array}$ 



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## Spectral fitting

#### Fitting technique

- Based on the Python library mpdaf
- Emission lines fitted by gaussian profiles
- $\chi^2$  minimization
- Output parameters: wavelength of the peak, peak value, FWHM, continuum, integrated flux under the gaussian, 1σ errors on these parameters



Spectrum of MUSE cube pixel located at the center of the Swift-XRT error circle

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#### Spectral ray luminosity maps



Integrated flux under the fitted gaussian on the H $\alpha$  emission line

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#### Spectral ray luminosity maps



Integrated flux under the fitted gaussian on the [OI] emission line

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## Spectral ray luminosity maps



Top row, left to right:  $H\alpha$ ,  $H\beta$ , [OIII]. Bottom row: [SII], [NII], [OI]



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## Velocity maps

Emission line redshift velocity:  $v = c \times \frac{\lambda_{obs} - \lambda_{ref}}{\lambda_{ref}}$ 



Velocity map of NGC5917 from the [OI] emission line fitting. Each pixel color represents the relative velocity computed from the gaussian fit of the emission line

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NGC 5917 @6601.25 Å

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NGC 5917 @6602.5 Å

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NGC 5917 @6603.75 Å

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imes 10<sup>-20</sup> erg  $\cdot$  s

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NGC 5917 @6605 Å

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 $\times 10^{-20}~\text{erg}\cdot\text{s}^-$ 

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NGC 5917 @6606.25 Å

# $\times 10^{-20}~\text{erg}\cdot\text{s}^-$

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NGC 5917 @6607.5 Å

 $\times 10^{-20} \text{ erg} \cdot \text{s}^-$ 

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 $\times 10^{-20}~\text{erg}\cdot\text{s}^-$ 

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NGC 5917 @6608.75 Å

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#### Velocity maps



Top row, left to right:  $H\alpha$ ,  $H\beta$ , [OIII]. Bottom row: [SII], [NII], [OI]

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#### **BPT** Diagnostic

#### Characteristics

- Introduced by Baldwin, Phillips and Telervich Baldwin et al. 1981
- Originally proposed to diagnose AGNs, Low-Ionization Nuclear Emission-line Regions (LINER), and HII ionization regions
- Now also used to probe the local gas ionization mechanism:
  - photo-ionization due to UV photons from young, hot stars;
  - photo-ionization from accretion activity;
  - shock ionization
- Uses 3 different line ratios plots:
  - [OIII]/H $\beta$  versus [NII]/H $\alpha$
  - [OIII]/Hβ versus [SII]/Hα
  - $\blacksquare \text{ [OIII]/H}\beta \text{ versus [OI]/H}\alpha$



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BPT diagnostic of NGC 5917

#### **BPT** Diagnostic



BPT diagnostics for different emission line ratios in NGC 5917

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## **BPT** Diagnostic





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## Conclusion



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#### Conclusion

- Search for IMBHs and super-Eddington accretion
- X-ray catalogs correlated with multi-wavelength catalogs
- ULX/HLX candidates sample (2169 candidates)
- Tools to clean the sample (1221 candidates)
- Focus on sources with MUSE cubes (400/2169)
- 3 good candidates identified
- Multi-wavelength approach to study them



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#### Analysis of the best candidates

#### In NGC 5917

- Swift-XRT X-ray observations:
  - Average unabsorbed luminosity  $L_X = (3.1 \pm 0.3) \times 10^{40} \text{ erg} \cdot \text{s}^{-1}$
  - Flux variation by a factor  $\sim$  4 between 2005 and 2020
- MUSE observations:
  - NGC 5917 rotating as a whole
  - An optical source showed a more intense [OI] line emission
  - BPT diagnostic showed gas ionization due to accretion in this region
- Probable association of the optical counterpart to the X-ray source

#### Other sources studied

- In NGC 3252
  - Source vanished between 2011 and 2020 (more than 40 times fainter)
  - Swift-UVOT counterpart found
- In NGC 3583
  - Source found using my selection method
  - HST observations show structures, likely star-forming, in the region of the source

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ntroduction	ULX/HLX candidates selection	HLX candidate in NGC 5917	Conclusion	Backup
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#### Perspectives and continuations

#### Perspectives

- Study of the X-ray luminosity function
- Systematic study of the host galaxies properties (interacting, dwarf, spiral, star-forming, ...)
- Analysis of the reference sample contamination rates
- Determination of the fraction of background sources using MUSE cubes
- Using HST analyses for more sources



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#### Perspectives and continuations

#### Proposals

- XMM-Newton observation of NGC 3252 at the end of the year
- Possible observation of NGC 5917 and NGC 3583 by Swift in 2021-2022 (proposal submitted) and by XMM-Newton (proposal in prep Pellouin 2020)

#### Papers

- Presentation of the ULX/HLX candidates sample Godet, Pellouin, Tranin et al, in prep
- Classification of X-ray sources: an example with 2SXPS Tranin, ..., Pellouin et al, in prep.
- NGC 5917 HLX candidate discovery Pellouin et al, in prep.
- NGC 3252 analysis following XMM-Newton observations Tranin et al, in prep.
- NGC 3583 HLX candidate discovery Pellouin et al, in prep.

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## Thanks!



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## Spectral fitting



Distribution of the distances to the galactic center (in arcsec)

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## Spectral fitting



Spectrum of MUSE cube pixel located at the center of the Swift-XRT error circle

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Spectral fitting					

Gaussian fitting of  $H_{\alpha}$ :  $\lambda_{obs} = 6606.4 \text{ Å}$ 



Zoom on the spectral fitting of the H $\alpha$  emission line

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## Spectral fitting



Zoom on the spectral continuum of the MUSE cube pixel located at the center of the Swift-XRT error circle

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#### MUSE spectra of the foreground stars



Spectrum of the bottom, low-mass type M star



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#### Luminosity Function



Luminosity function of the sources in the ULX/HLX catalog. Blue: total catalog. Orange: Filtered catalog.

Swartz et al. 2011 showed that the differential ULX luminosity function shows a power law slope  $\alpha \propto -1.2$ to -2.0 with an exponential cutoff at  $\sim 2 \times 10^{40}$  erg  $\cdot$  s<sup>-1</sup> moster OSE

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NGC 3252



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Light curve of 2SXPS J103423.1+734519, located in NGC 3252, in the 0.3 - 10 keV band.



Spectrum of the source using the observations from 2010.



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Parameter	Value $\pm$ error (1 $\sigma$ )
N <sub>H</sub>	$(1.2^{+0.5}_{-0.4})  imes 10^{21} \ cm^{-2}$
Galactic N <sub>H</sub>	$4.6  imes 10^{20} \ cm^{-2}$
Г	$2.23^{+0.18}_{-0.16}$
Unabsorbed $L_X$ (0.3 $-$ 10 keV)	$1.8  imes 10^{41} \text{ erg} \cdot \text{s}^{-1}$
Peak unabsorbed $L_X$	$7.1  imes 10^{41} \text{ erg} \cdot \text{s}^{-1}$
$\chi^2$ / dof	48.5/42

Spectral fit parameters using data from 2010



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Swift-UVOT observation of 2SXPS J103423.1+734519 from 2010-2011 in the UVW2 filter.



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Swift-UVOT observation from 2019 in the UVW2 filter.

Filter	UVW2	UVM2	UVW1	U	В	v
$\lambda$ (A)	1928	2246	2600	3465	4392	5468
2010-2011	21.89 ± 0.29		$20.52 \pm 0.53$	$20.72 \pm 0.16$	$19.63 \pm 0.30$	> 19.51
2019	> 22.58	> 21.70	> 21.52	> 22.91		

AB magnitudes of the optical counterpart of 2SXPS J103423.1+734519 in different swift-UVOT filters, using stacked observations from NGC 3252. Upper limits are computed at  $3\sigma$ .

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NGC 3583



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band.

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Parameter	Value $\pm$ error (1 $\sigma$ )
N <sub>H</sub>	$(1.4^{+0.9}_{-0.8})  imes 10^{21} \ cm^{-2}$
Galactic N <sub>H</sub>	$2.4 imes10^{20}\ cm^{-2}$
Г	$1.76^{+0.28}_{-0.26}$
Unabsorbed $L_X$ (0.3 – 10 keV)	$(4.4^{+0.5}_{-0.6}) imes 10^{41}~\text{erg}\cdot\text{s}^{-1}$
Peak unabsorbed $L_X$	$1.7  imes 10^{41} \text{ erg} \cdot \text{s}^{-1}$
$\chi^2$ / dof	18.68/24

Spectral fit parameters using data from 2015 and 2020

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HST image of NGC 3583, in the F814W filter (IR at 8043 Å), taken on 2018-05-14 (exposure time: 1.8 ks)

