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

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master asep

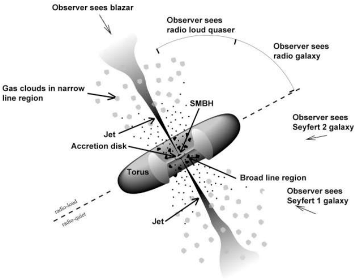
Contents

Introduction

SMBHs

Characteristics

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



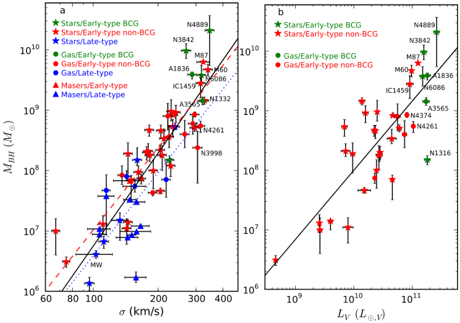
Unified model of AGNs Credit: Fermi & NASA

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



Correlations of SMBH masses and bulk properties of host galaxies McConnell et al. 2011

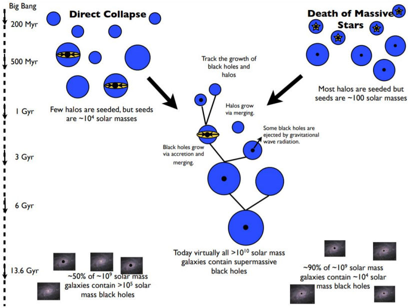
How to grow an SMBH?

Observations

- $8 \times 10^8\ M_\odot$ 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

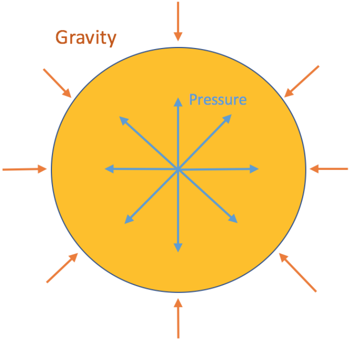
- Hierarchical growth by successive intermediate-mass BH mergers Farouki et al 1983
  $100\ M_\odot \lesssim M_{IMBH} \lesssim 10^5\ M_\odot$ Miller & Colbert 2004
- Sustained accretion episodes at high accretion rates



Greene 2012

Eddington limit

- Gravitational attraction on protons: $F_{grav} = \frac{m_p GM}{r^2}$
- Radiation pressure on the electrons (Thomson scattering): $F_{rad} = \frac{\sigma_T}{c} \frac{L}{4\pi r^2}$
- Eddington luminosity Eddington 1921: $L_{Edd} = \frac{4\pi\ c\ G\ M\ m_p}{\sigma_T} \simeq 1.3 \times 10^{38} \left(\frac{M}{M_\odot}\right) \mathrm{erg} \cdot \mathrm{s}^{-1}$
- 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

Eddington limit

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Consequences

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

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?

ULXs & HLXs

Definition Feng et al 2011

- Extragalactic off-nuclear X-ray source powered by accretion of matter
- ULX: Isotropic equivalent $L_X \geq 10^{39}$ erg · s^{-1} (0.3 – 10 keV)
- HLX: Isotropic equivalent $L_X \geq 10^{41}$ erg · s^{-1} (0.3 – 10 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 ($\sim 1.4 - 1.5\ M_\odot$) with strongly super-Eddington accretion ($L_X \gg 10^{38}$ erg · s^{-1})

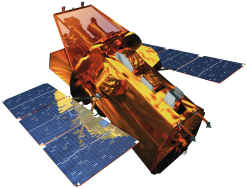
HLXs: accreting IMBHs?

- 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

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

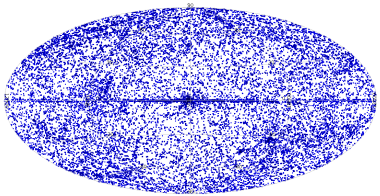
The 2SXPS catalog Evans et al 2020

Characteristics

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

Assets

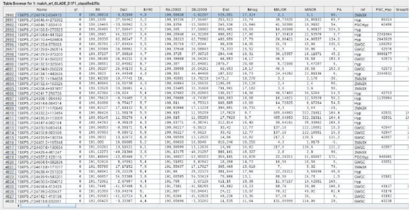
- High number of unknown sources ($\sim$ 90 % not observed by *XMM-Newton*)
- Large sky coverage
- Simultaneous UVOT observations
- Short- and long-term monitoring of sources (from $\sim$ 1 s to $\sim$ 10 years)
- Online tools available



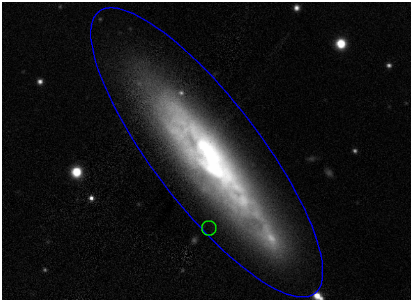
Positions of the sources of 2SXPS in the Galactic coordinates

ULX/HLX candidates selection

Producing a ULX/HLX sample



2SXPS

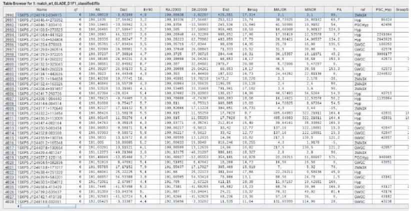


GLADE Dayla et al 2018

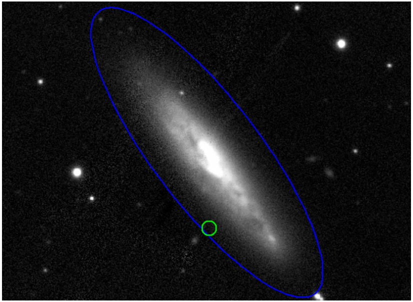
Additional information to the 2SXPS catalog

- 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 $\rightarrow L_X$

Producing a ULX/HLX sample



2SXPS

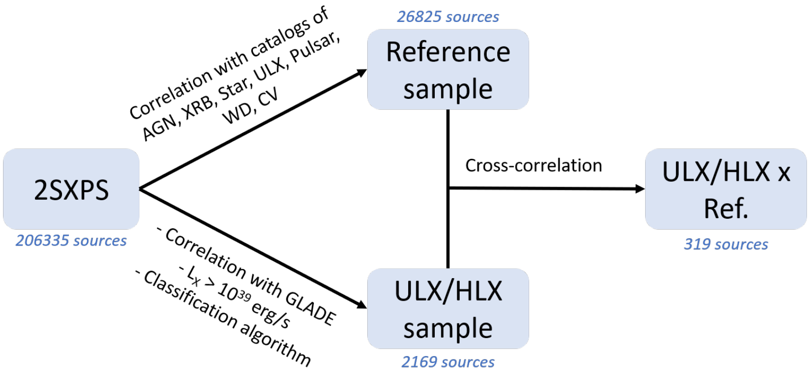


GLADE Dayla et al 2018

The ULX/HLX sample

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

Finding reference sources



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

Classification analysis

Analysis of the classes distribution:

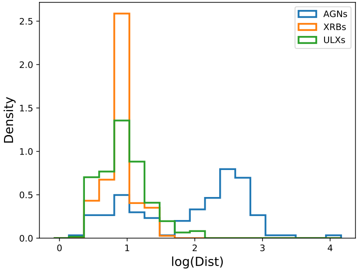
	Reference		ULX/HLX x Ref.		ULX/HLX (prediction)	
Class	**Count**	**%**	**Count**	**%**	**Count**	**%**
AGN	20799	77	134	42	943	43
Star	5181	19	19	6	74	3
XRB	475	2	165	52	1138	52
CV	370	1	1	0	14	1

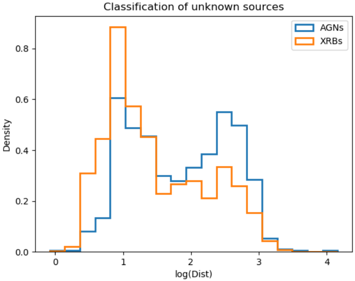
Comparison of statistics on the classes of sources

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

Classification analysis





Comparison of statistics on the classes of sources

Conclusions

- ULX/HLX definition non-physical, but many XRBs retrieved in the ULX/HLX sample
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Classification analysis

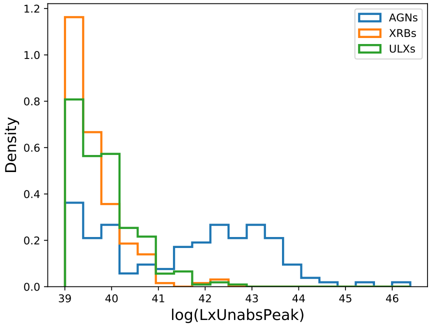
How to select the best ULX/HLX candidates among the 2169 sources?

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

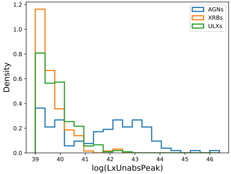
Focusing only on the sources classified as XRBs?

Identification of new selection parameters

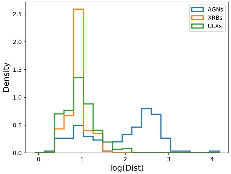


Distribution of the unabsorbed X-ray peak luminosity for the sources of the cross-correlated sample. In blue, sources whose known class is AGN, in yellow, those that are XRBs, in green, sources found in catalogs of ULXs

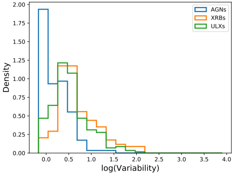
Identification of new selection parameters



Unabsorbed X-ray peak luminosity



Distance



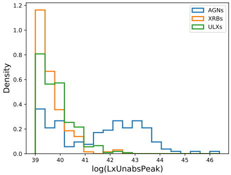
Variability

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

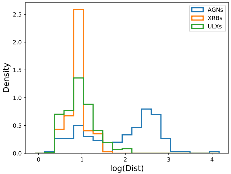
Classification parameters

master asep

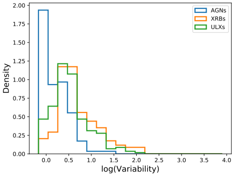
Identification of new selection parameters



Unabsorbed X-ray peak luminosity



Distance



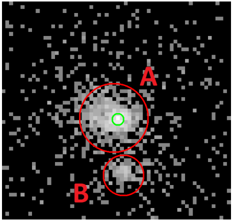
Variability

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

HLX candidate in NGC 5917

2SXPS J152131.9-072242

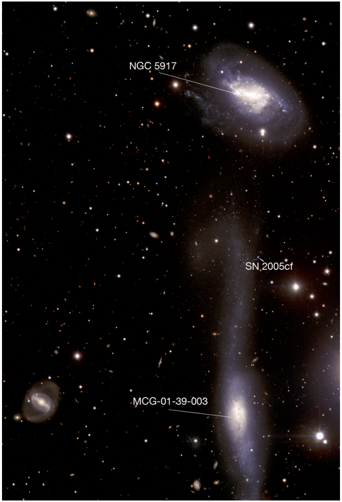


Swift-XRT image of 2SXPS J152131.9-072242

Fact sheet

- RA(J2000): $15^h\ 21^m\ 31.99^s$
- Dec(J2000): $-07^\circ\ 22'\ 42.4''$
- Associated with NGC 5917, interacting spiral galaxy
- $9''$ (1.3 kpc) away from the galactic center
- $d_{NGC5917} = 30.8$ Mpc

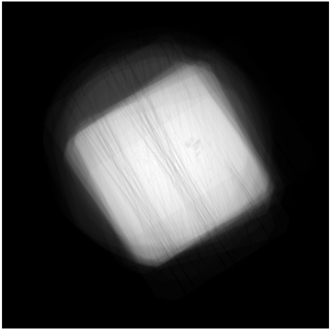
VLT image of NGC 5917 and MCG-01-39-003



Swift-XRT raw data processing

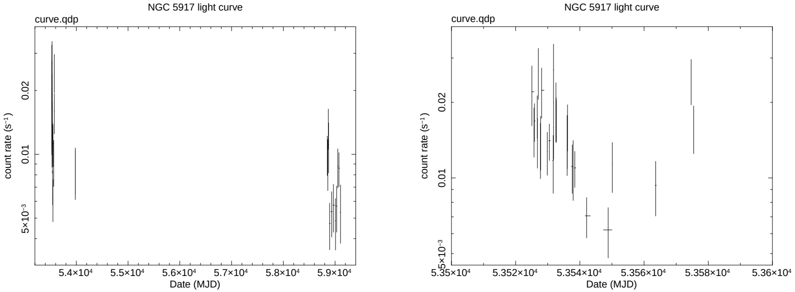
Preprocessing steps, using XSELECT

- 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



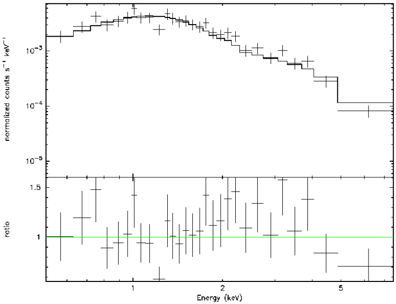
Exposure map for the *Swift*-XRT observations of NGC 5917

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.

X-ray spectral analysis

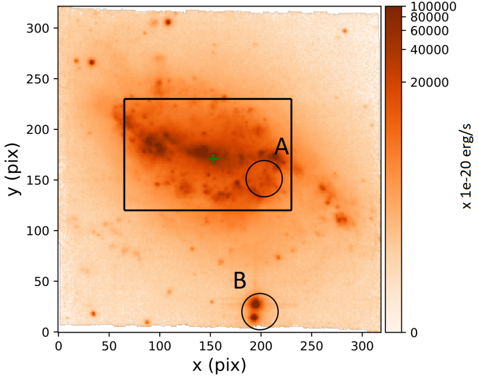


Swift-XRT Photon Counting spectrum of 2SXPS J152131.9-072242 (observations from 2005-06-04 to 2020-04-30). Minimum of 20 counts per bin. Errors at a 1σ confidence level. Solid line corresponds to the best fit using an absorbed power-law model.
Obtained using XSPEC Arnaud 1996

Parameter	**Value $\pm$ error (1σ)**
N_H	$(2.0^{+0.9}_{-0.7}) \times 10^{21}\ cm^{-2}$
Galactic N_H	$6.7 \times 10^{20}\ cm^{-2}$
Γ	2.0 ± 0.2
Unabsorbed L_X (0.3 – 10 keV)	$(3.1 \pm 0.3) \times 10^{40}$ erg $\cdot$ s^{-1}
Peak unabsorbed L_X	8.8×10^{40} erg $\cdot$ s^{-1}
χ^2 / dof	32.82/29

MUSE data analysis

MUSE = Integral field Unit (IFU) taking data cubes (300 × 300 pixels, ∼ 3500-bins visible spectra from 4750 $\AA$ to 9350 $\AA$) Bacon et al 2010



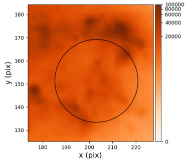
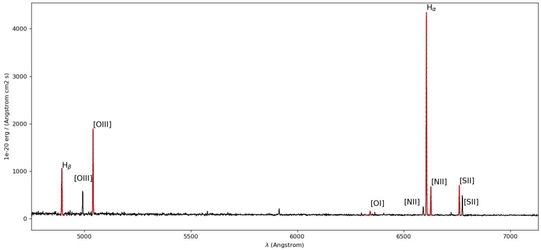


Image of NGC 5917 taken by MUSE on 2016-05-31 in the 6500 $\AA$ − 6624 $\AA$ band (centered on Hα).
Intensity in units of 10^{-20} erg · s^{-1} · cm^{-2}.
Spatial resolution: 0.5″

Spectral fitting

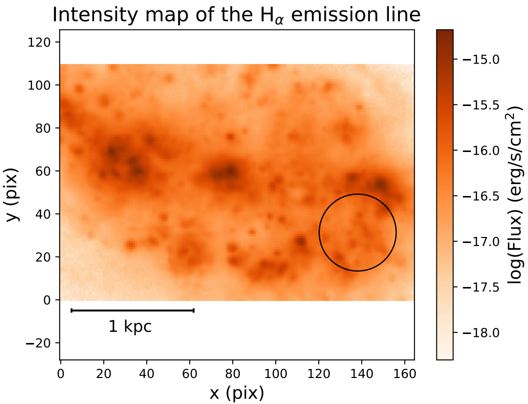
Fitting technique

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



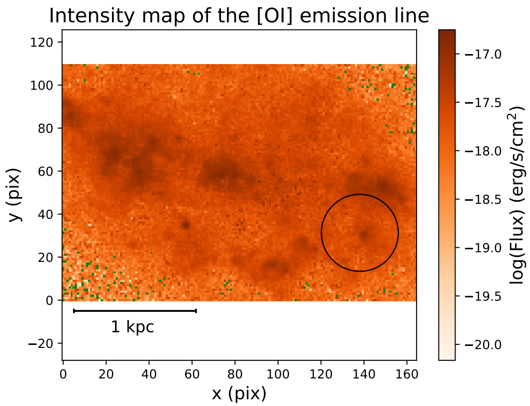
Spectrum of MUSE cube pixel located at the center of the *Swift*-XRT error circle

Spectral ray luminosity maps



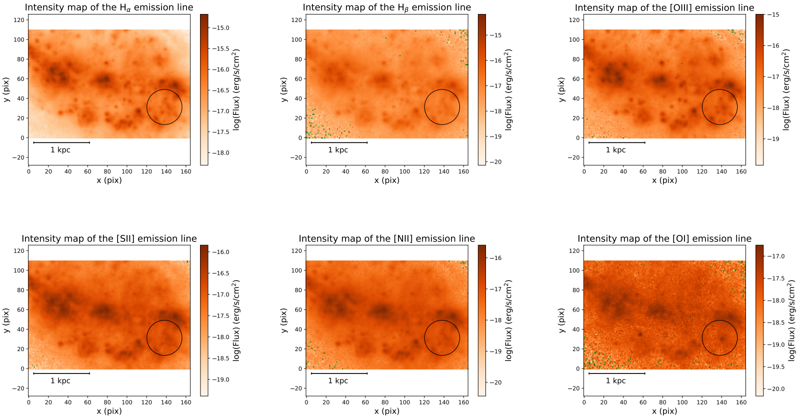
Integrated flux under the fitted gaussian on the $H\alpha$ emission line

Spectral ray luminosity maps



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

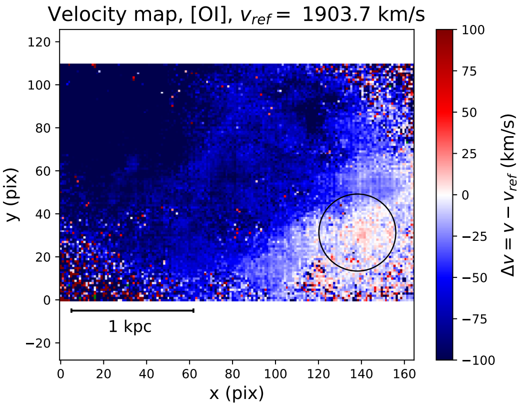
Spectral ray luminosity maps



Top row, left to right: Hα, Hβ, [OIII]. Bottom row: [SII], [NII], [OI].

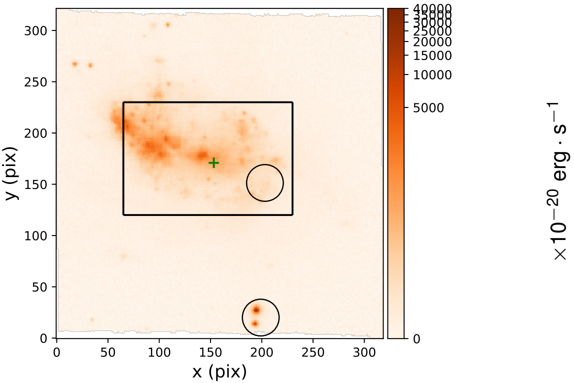
Velocity maps

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



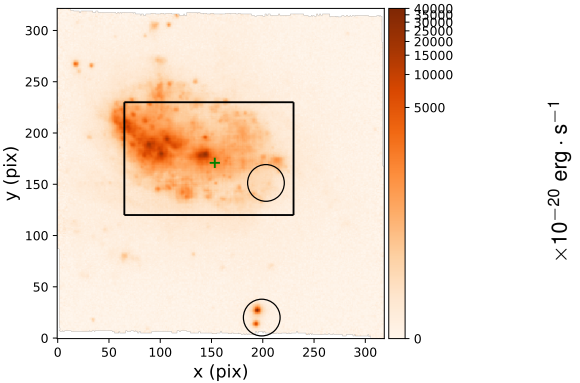
Velocity map of NGC5917 from the [OI] emission line fitting. Each pixel color represents the relative velocity computed from the gaussian fit of the emission line

MUSE Images around Hα



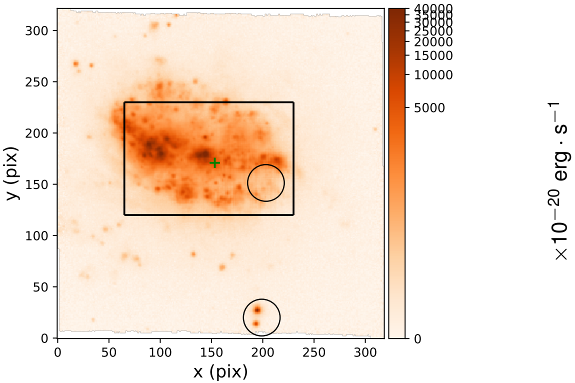
NGC 5917 @6600 Å

MUSE Images around Hα



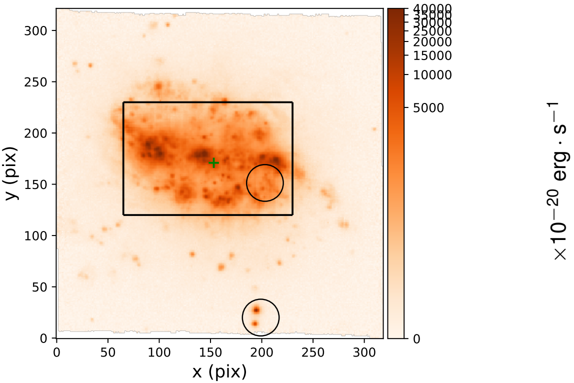
NGC 5917 @6601.25 Å

MUSE Images around Hα



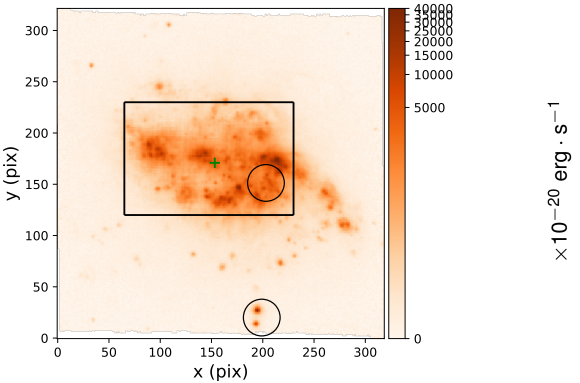
NGC 5917 @6602.5 Å

MUSE Images around Hα



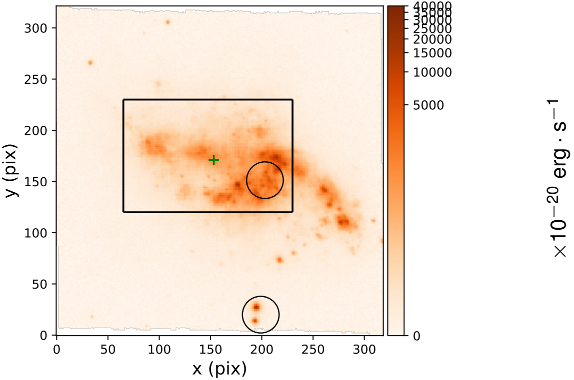
NGC 5917 @6603.75 Å

MUSE Images around Hα



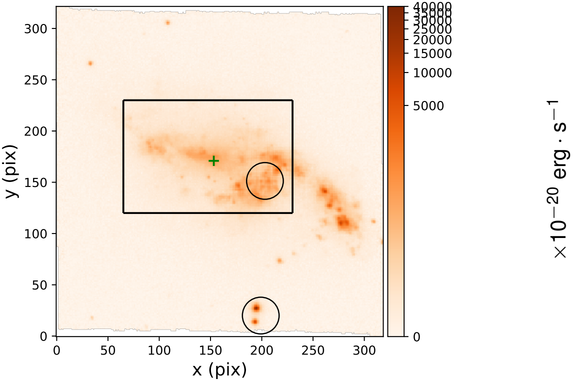
NGC 5917 @6605 Å

MUSE Images around Hα



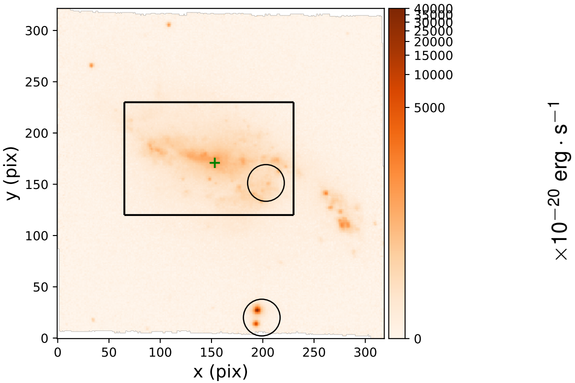
NGC 5917 @6606.25 Å

MUSE Images around Hα



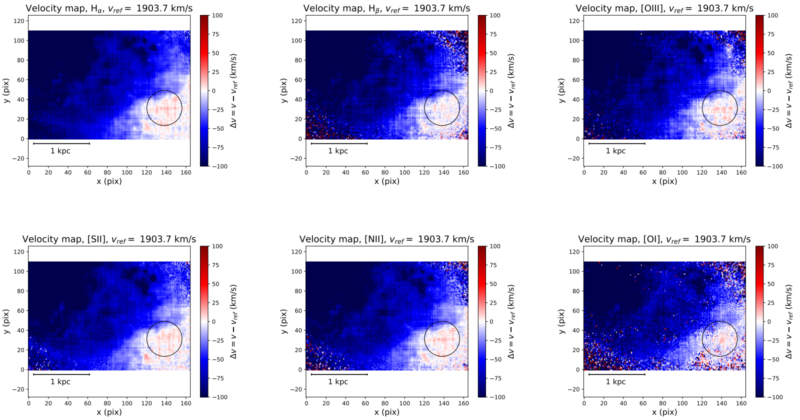
NGC 5917 @6607.5 Å

MUSE Images around Hα



NGC 5917 @6608.75 Å

Velocity maps



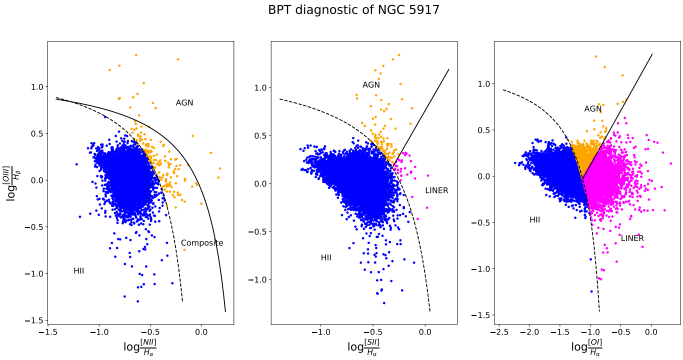
Top row, left to right: $\mathrm{H}\alpha$, $\mathrm{H}\beta$, [OIII]. Bottom row: [SII], [NII], [OI]

BPT Diagnostic

Characteristics

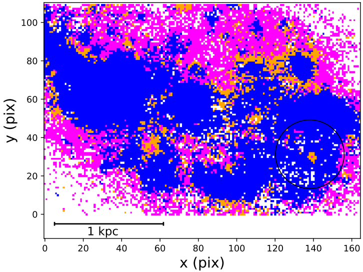
- Introduced by Baldwin, Phillips and Televich Baldwin et al. 1981
- Originally proposed to diagnose AGNs, Low-Ionization Nuclear Emission-line Regions (LINER), and HII ionization regions
- Now also used to probe the local gas ionization mechanism:
  - photo-ionization due to UV photons from young, hot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

BPT Diagnostic

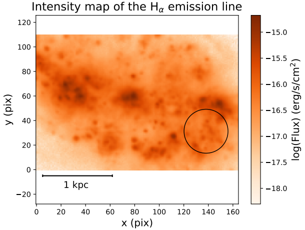


BPT diagnostics for different emission line ratios in NGC 5917

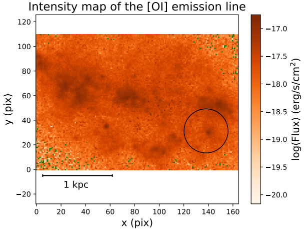
BPT Diagnostic



[OIII]/Hβ versus [OI]/Hα BPT diagnostic map



Hα flux map



[OI] flux map

Conclusion

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

Analysis of the best candidates

In NGC 5917

- *Swift*-XRT X-ray observations:
  - Average unabsorbed luminosity $L_X = (3.1 \pm 0.3) \times 10^{40}$ erg $\cdot$ 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

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

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)

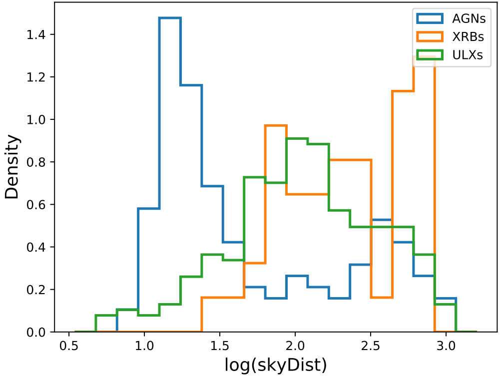
Papers

- 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.

master asep

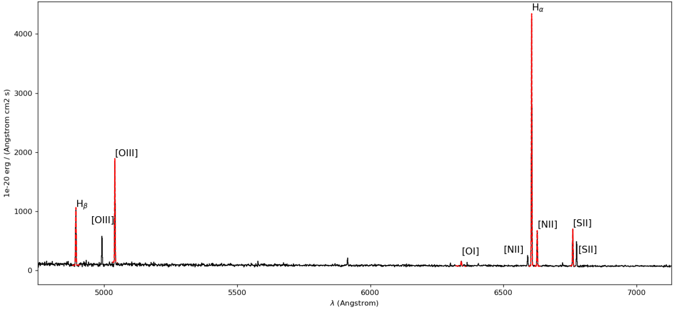
Thanks!

Spectral fitting



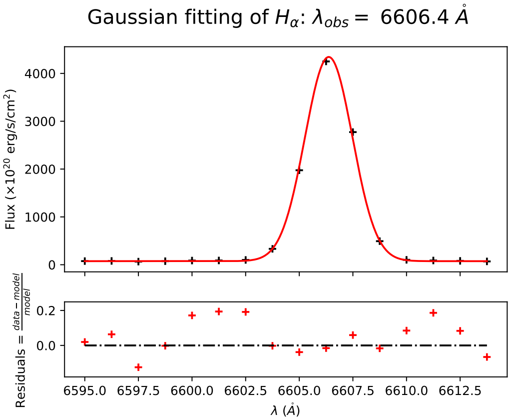
Distribution of the distances to the galactic center (in arcsec)

Spectral fitting



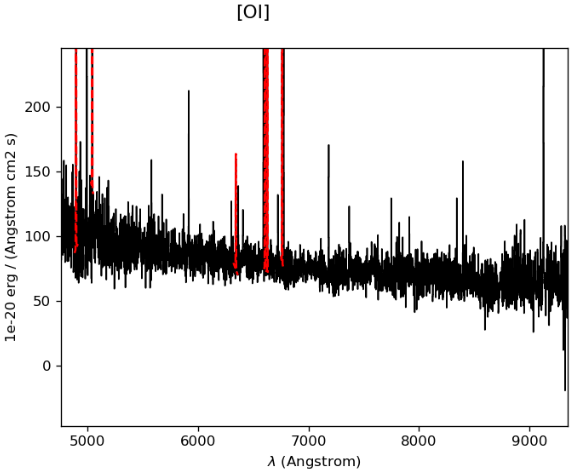
Spectrum of MUSE cube pixel located at the center of the *Swift*-XRT error circle

Spectral fitting



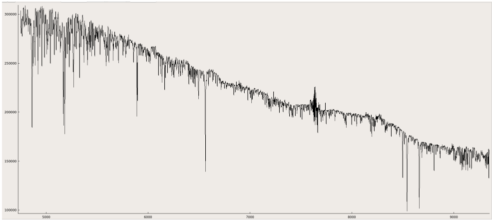
Zoom on the spectral fitting of the Hα emission line

Spectral fitting

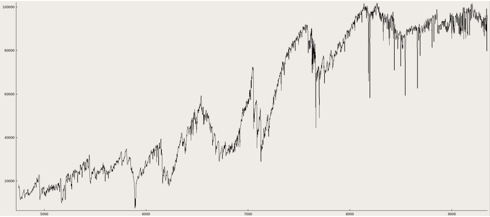


Zoom on the spectral continuum of the MUSE cube pixel located at the center of the *Swift*-XRT error circle

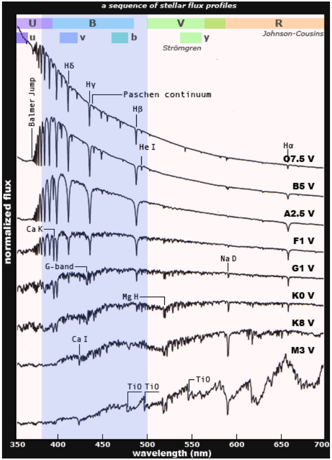
MUSE spectra of the foreground stars



Spectrum of the top, massive star



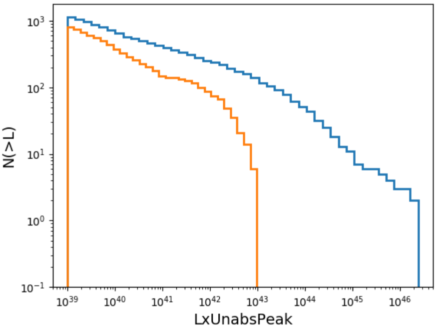
Spectrum of the bottom, low-mass type M star



Reference spectra

https://www.handprint.com/ASTRO/specclass.html

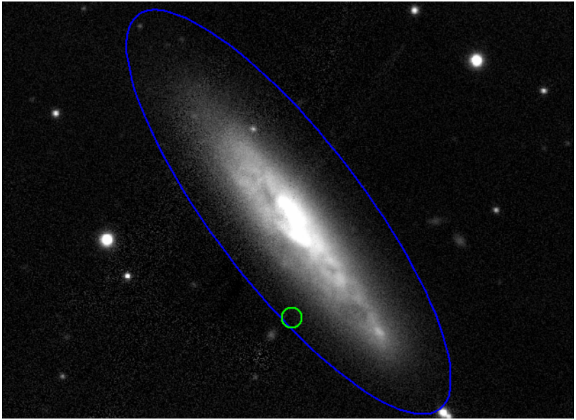
Luminosity Function



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

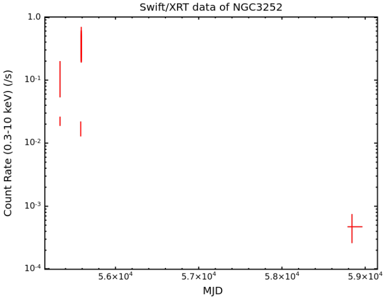
Swartz et al. 2011 showed that the differential ULX luminosity function shows a power law slope $\alpha \propto -1.2 to - 2.0$ with an exponential cutoff at $\sim 2 \times 10^{40}$ erg $\cdot$ s^{-1}

NGC 3252

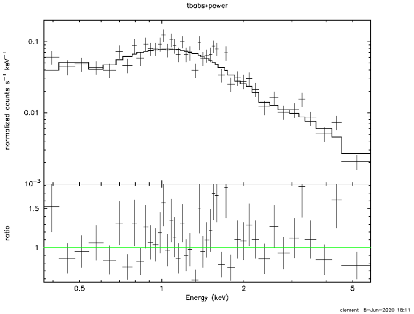


NGC 3252

NGC 3252



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



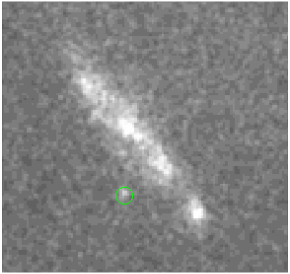
Spectrum of the source using the observations from 2010.

NGC 3252

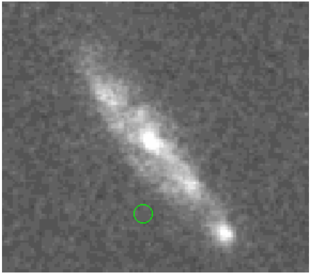
Parameter	**Value $\pm$ error (1σ)**
N_H	$(1.2^{+0.5}_{-0.4}) \times 10^{21}\ cm^{-2}$
Galactic N_H	$4.6 \times 10^{20}\ cm^{-2}$
Γ	$2.23^{+0.18}_{-0.16}$
Unabsorbed L_X (0.3 – 10 keV)	1.8×10^{41} erg $\cdot$ s^{-1}
Peak unabsorbed L_X	7.1×10^{41} erg $\cdot$ s^{-1}
χ^2 / dof	48.5/42

Spectral fit parameters using data from 2010

NGC 3252



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

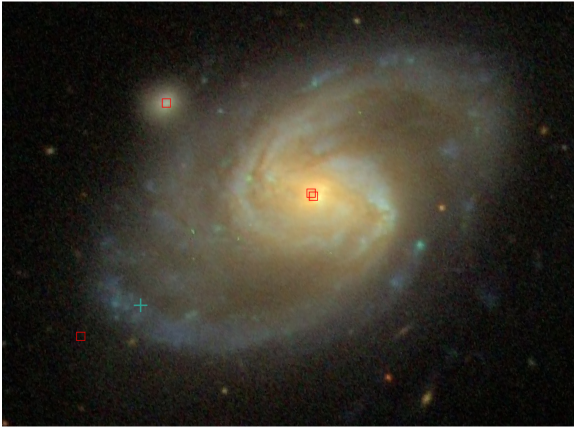


Swift-UVOT observation from 2019 in the UVW2 filter.

Filter λ (A)	**UVW2** 1928	**UVM2** 2246	**UVW1** 2600	**U** 3465	**B** 4392	**V** 5468
2010-2011	21.89 ± 0.29		20.52 ± 0.53	20.72 ± 0.16	19.63 ± 0.30	> 19.51
2019	> 22.58	> 21.70	> 21.52	> 22.91		

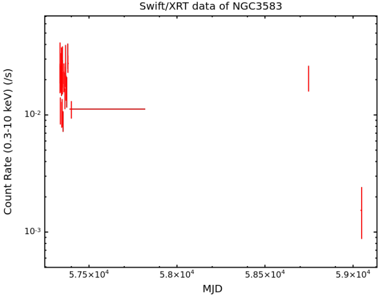
AB magnitudes of the optical counterpart of 2SXPS J103423.1+734519 in different *Swift*-UVOT filters, using stacked observations from NGC 3252. Upper limits are computed at 3σ.

NGC 3583

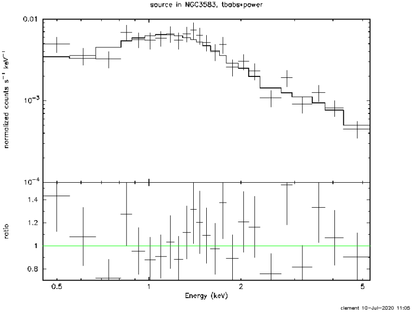


NGC 3583

NGC 3583



Light curve of 2SXPS J111416.1+481833, located in NGC 3583, in the 0.3 – 10 keV band.



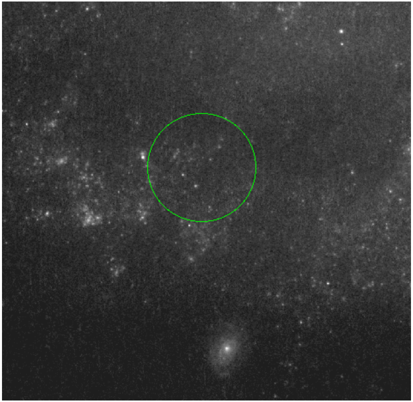
Spectrum of the source using the observations from 2015 and 2020.

NGC 3583

Parameter	Value $\pm$ error (1σ)
N_H	$(1.4^{+0.9}_{-0.8}) \times 10^{21}\ cm^{-2}$
Galactic N_H	$2.4 \times 10^{20}\ cm^{-2}$
Γ	$1.76^{+0.28}_{-0.26}$
Unabsorbed L_X (0.3 – 10 keV)	$(4.4^{+0.5}_{-0.6}) \times 10^{41}$ erg · s^{-1}
Peak unabsorbed L_X	1.7×10^{41} erg · s^{-1}
χ^2 / dof	18.68/24

Spectral fit parameters using data from 2015 and 2020

NGC 3583



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