Ultraluminous X-ray sources: new data

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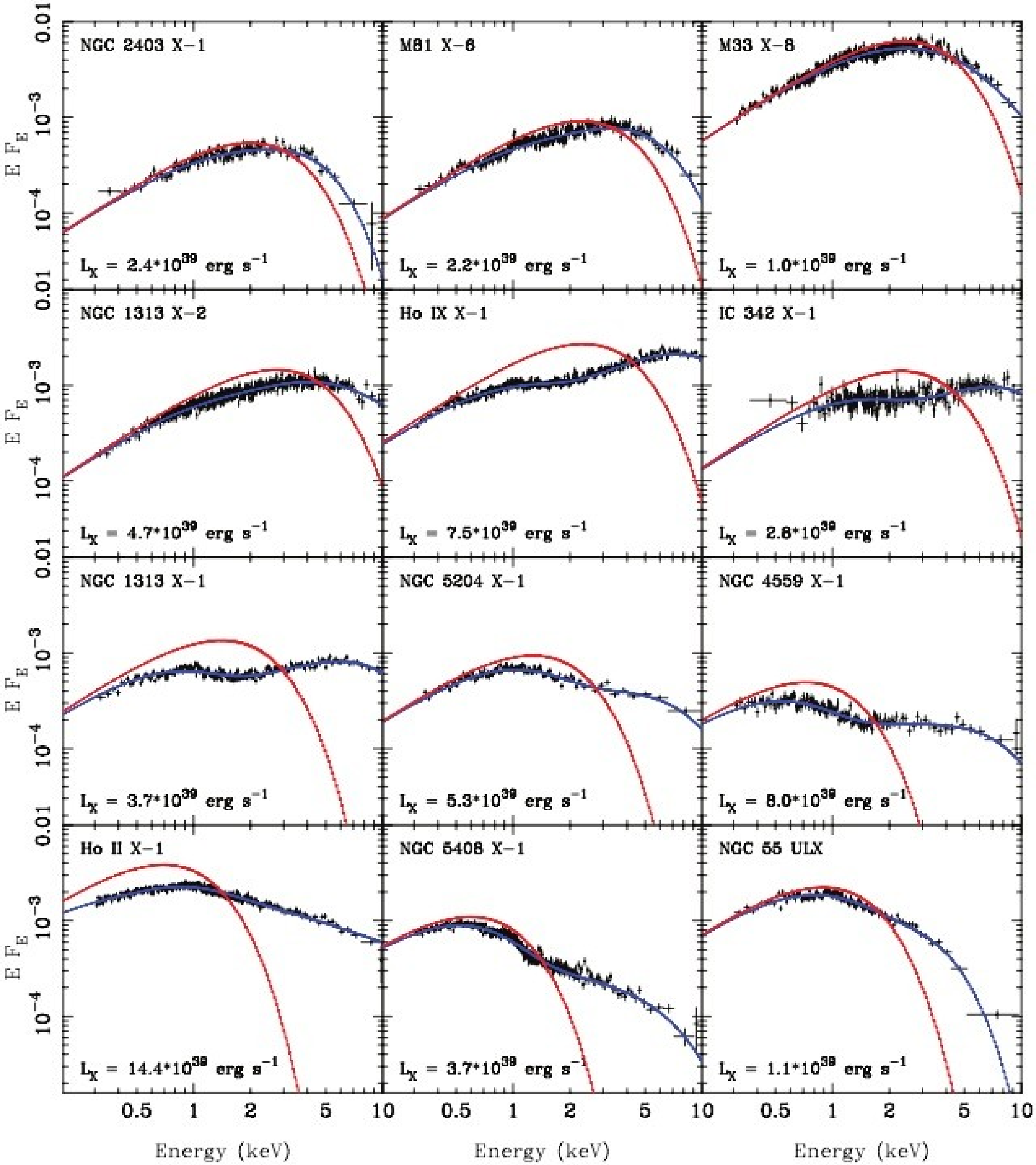
X-ray luminosities of ULXs $L_{0.5\text{-}100\,keV} \sim 10^{39\text{-}42}$ erg/s

The ULXs with $L_x > 10^{41}$ erg/s call hyper-luminous X-ray sources

1. **Supercritical accretion disks in close binaries with a stellar-mass black hole , observed close to the disk axis (≤ 40°). SS433-type. SS433 - Galactic super-Eddington accretor is observed edge-on.**
   Large intrinsic luminosity + geometrical collimation

1a. **Three ULX-pulsars have been discovered (Bachetti+ 2014, Fürst+ 2017, Israel+ 2017). In maximum they may reach $10^{40\text{-}41}$ erg/s**
   One of the best idea is magnetic column with a strong collimation Kawashima+2016)

1. **Intermediate mass black holes (IMBHs) ~ $10^2 – 10^4$ M_o with standard accretion disks. IMBHs must be in close binaries with massive donors.**
   Extension of luminosity range



The best XMM-Newton cases (Gladstone et al., 2009)

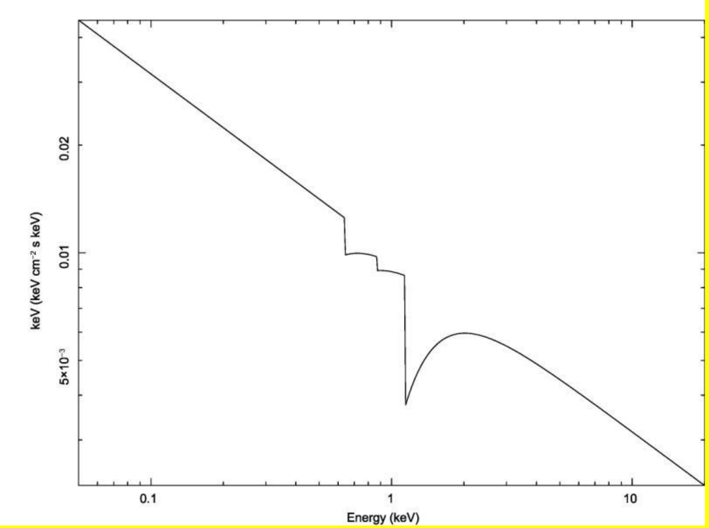
"Ultraluminous state"

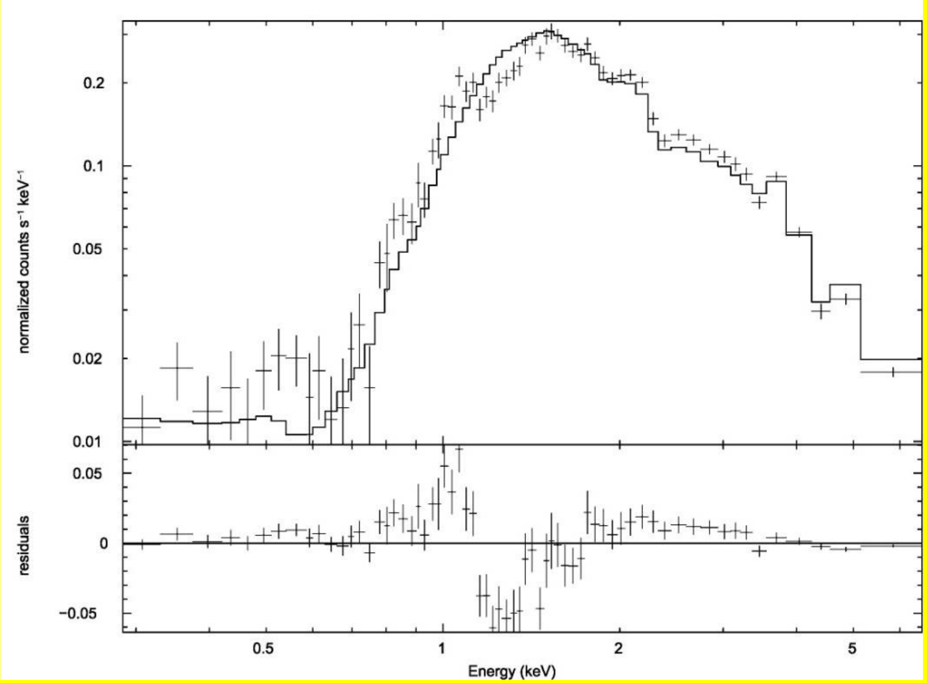
the inner disk is hidden by wind

the wind comptonizes the inner disk photons

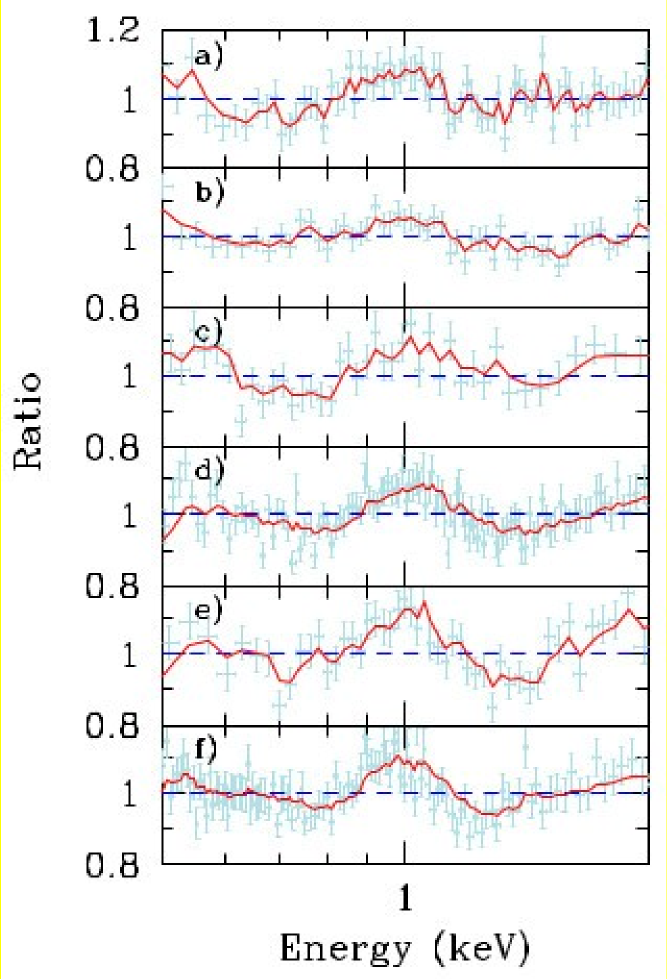
Model spectra:
the outer disk plus the wind
the whole disk

ULX residuals





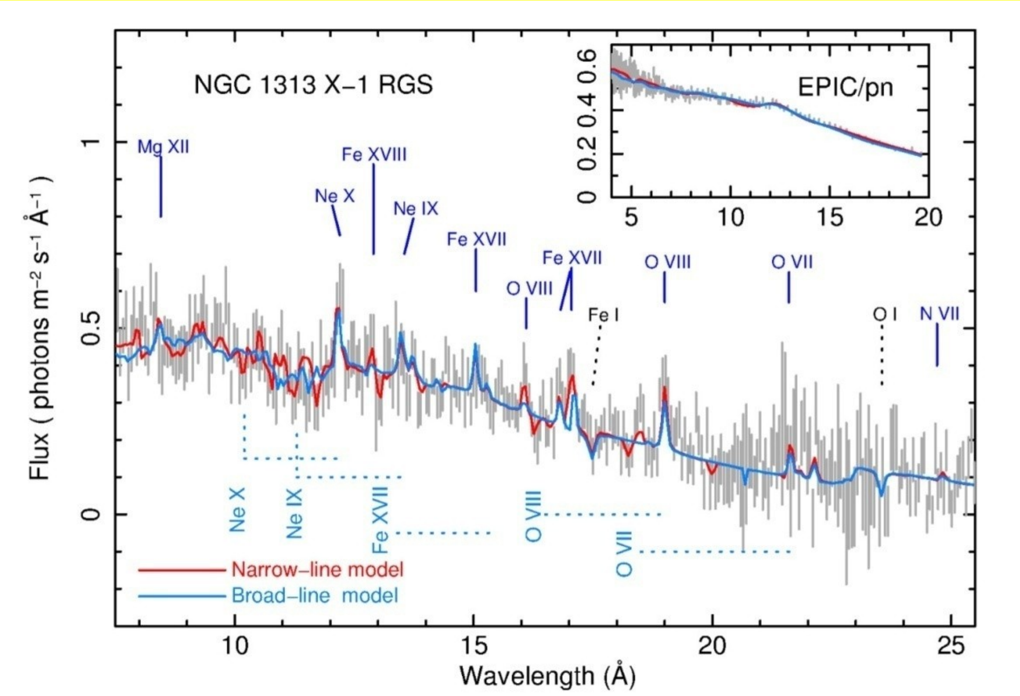
Fabrika+2006, 2008: XMM MOS1 (model spectrum PL+diskbb)
Lc edges CIV, NVII, OVIII. v=0.26c (SS433 type).
"Effective" hydrogen thickness T (Lc) = 20.
Depends on outflow velocity



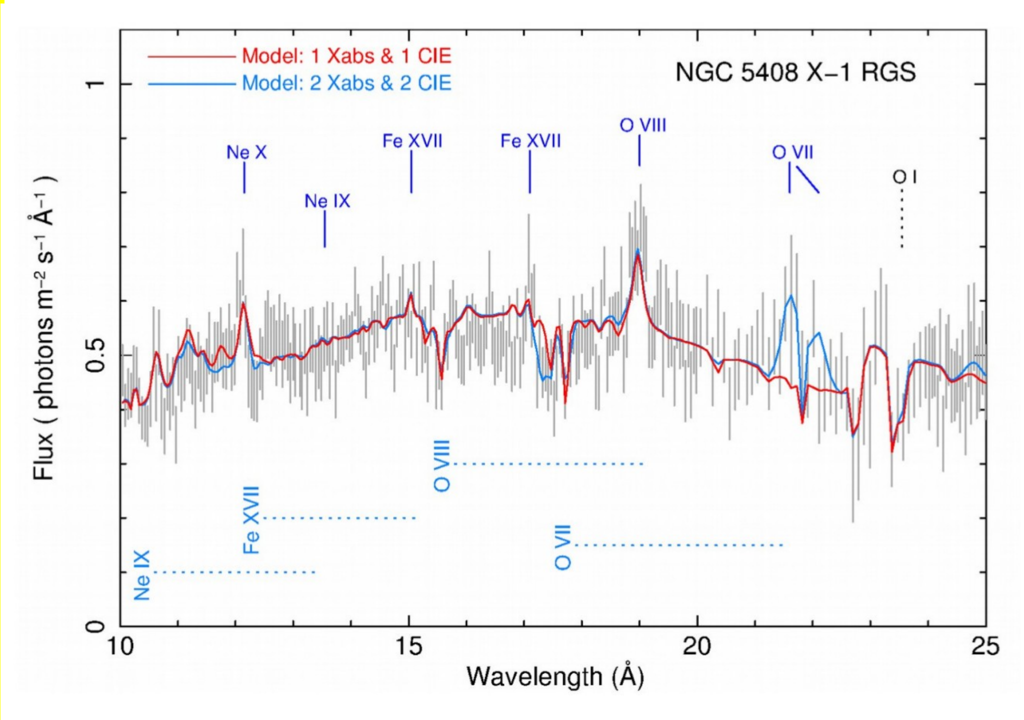
Middleton+2015 (TBAS*diskbb+nthcomp)
From top to bottom: NGC1313 X-1, HoIX X-1, HoII X-1, NGC55 ULX-1, NGC6946 X-1, NGC5408 X-1

Discovery of ultrafast outflows

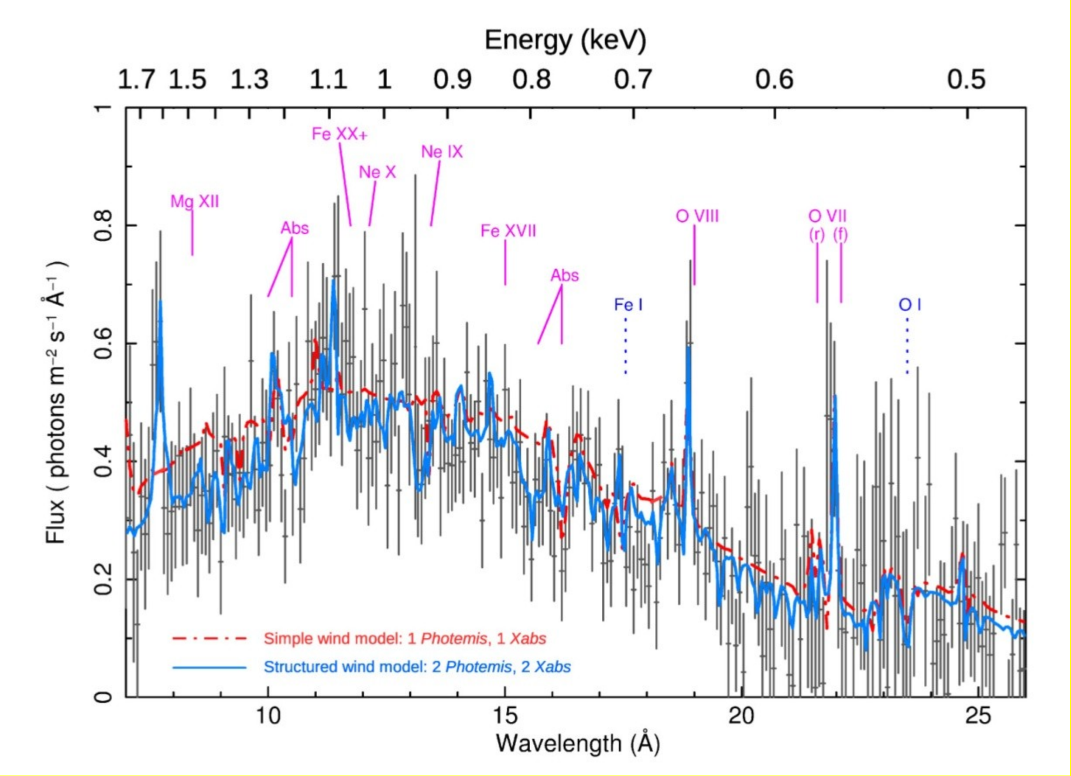
Pinto+2016
XMM Newton RGC and EPIC/pn

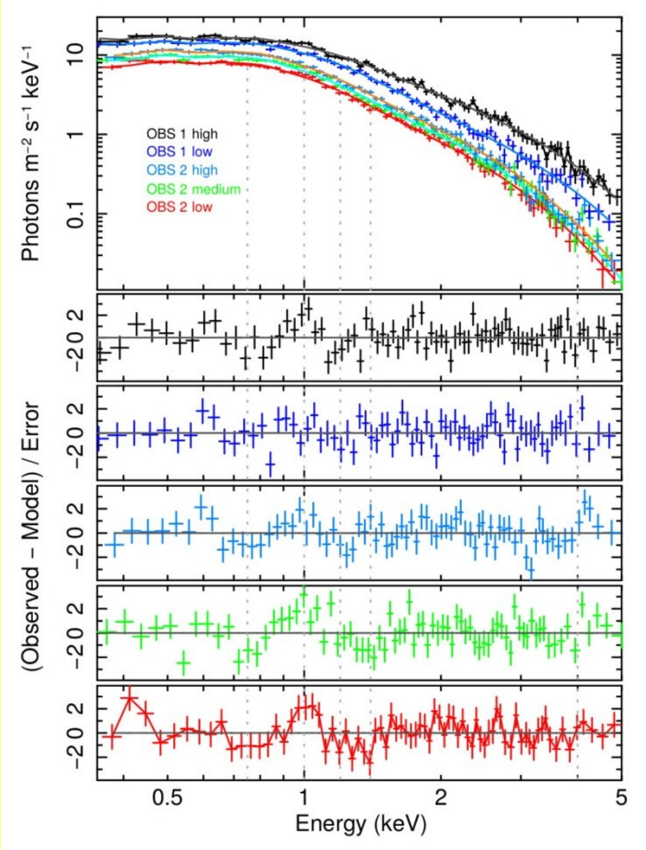


blueshifted lines
red – 0.20c, blue – 0.25c



blueshifted lines
red 0.22c, blue 0.22+0.10c

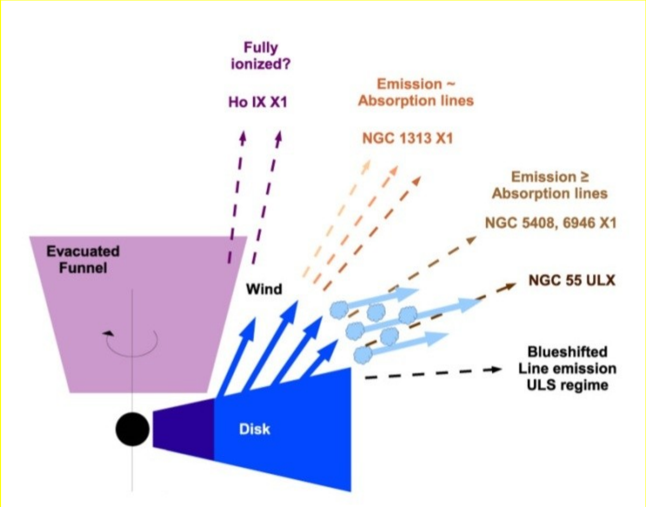




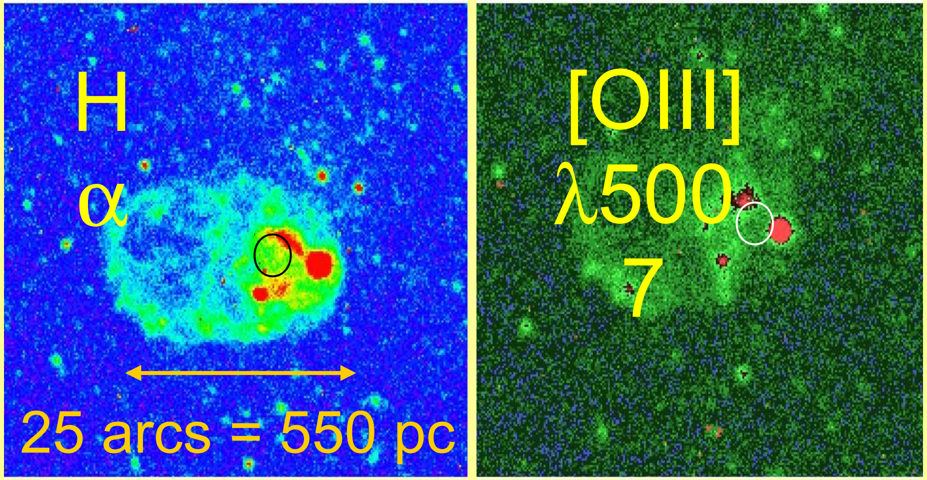
Residuals are shown after model spectra

Pinto+2017 NGC55 ULX-1
XMM Newton RGC + EPIC/pn continuum

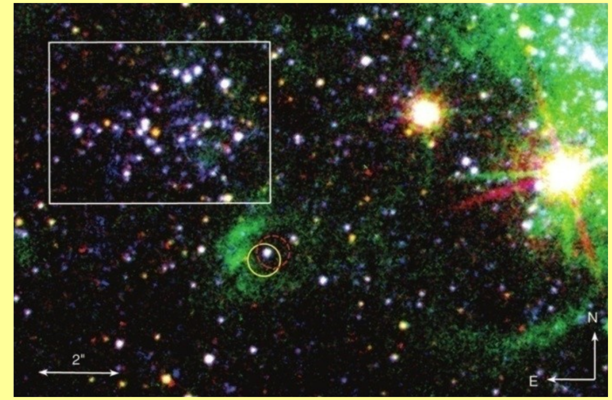
red: emission outflow 0.01c,
blueshifted absorption components 0.16c
blue: absorption components 0.06c and 0.20c



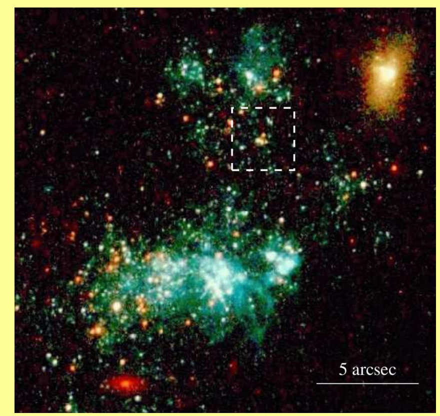
Nebulae associated with ULXs



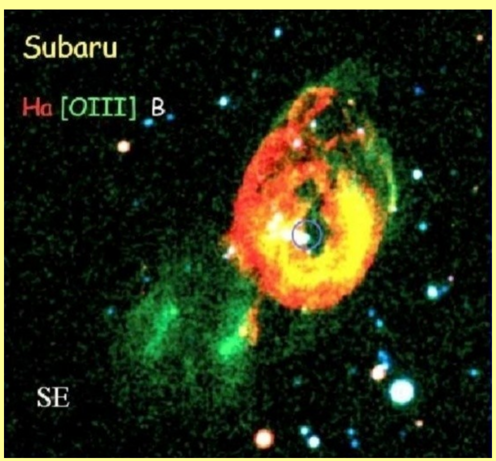
NGC1313 X-2 Pakull, Mirioni, 2002



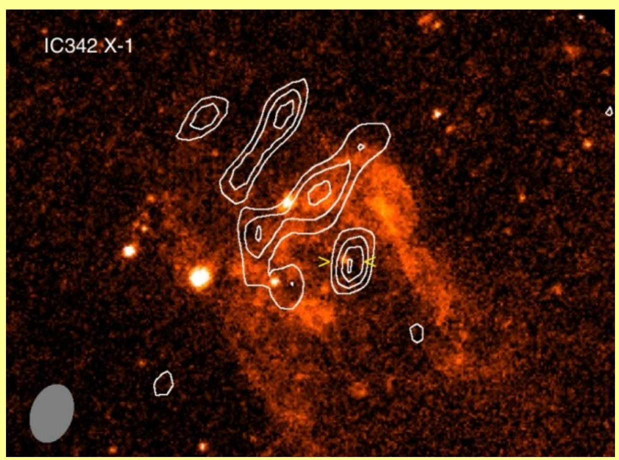
NGC5408 X-1 Grise et al. 2012



NGC4559 X-7   Soria et al. 2005



Holmberg IX X-1 Pakull & Grise, 2008

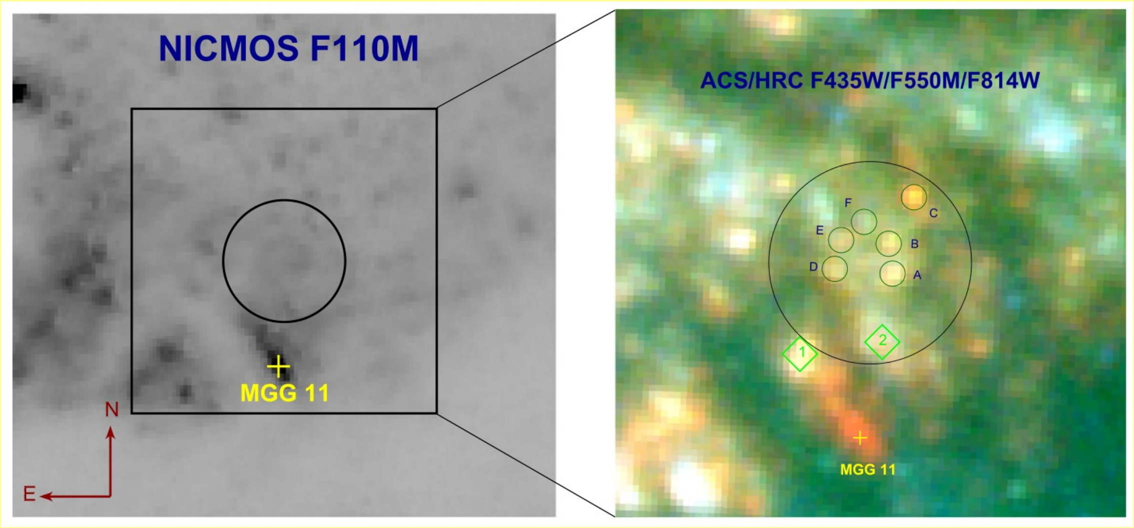


IC342 X-1 Cseh et al. 2012

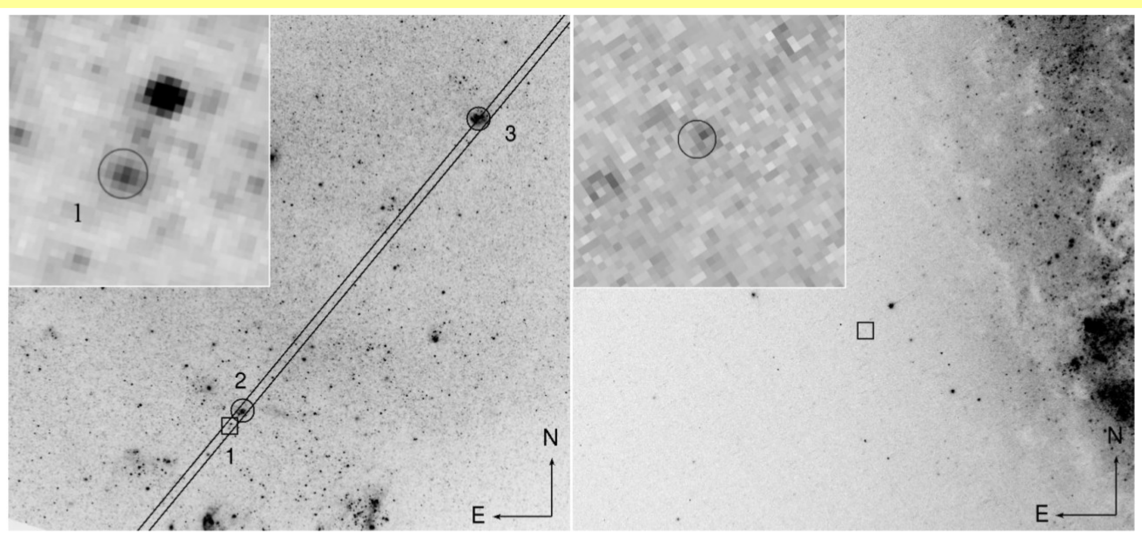
The nebulae have sizes 50-500 pc
They are jet (wind) powered,
their kinetic luminosities ~10^{39} erg/s
with a total energy ~ 10^{51} erg

They are not SNRs

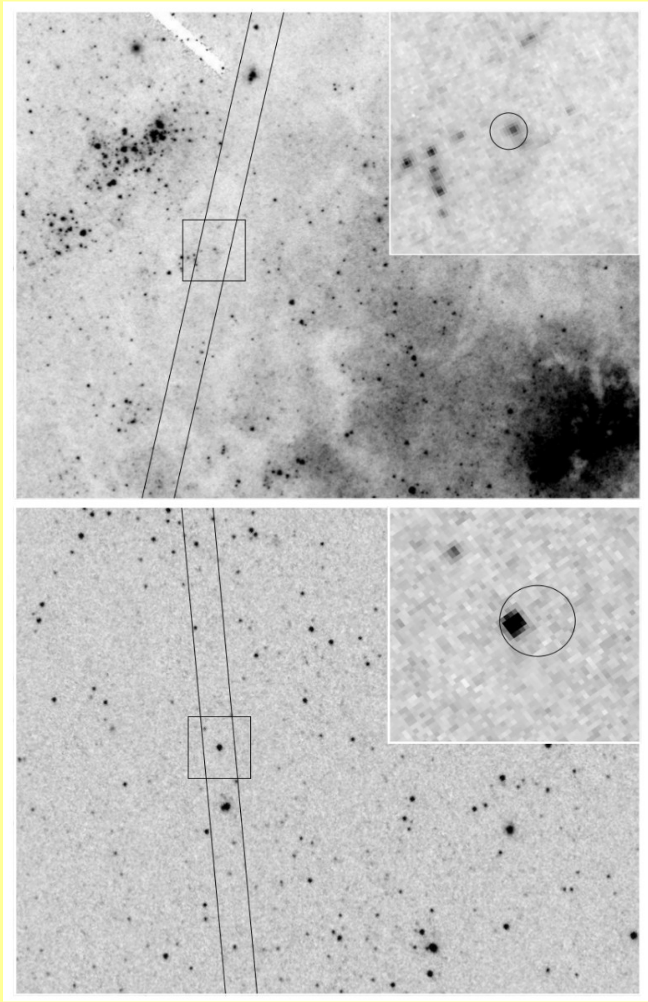
New optical counterparts of ULXs



M82 X-1 Wang et al. 2015



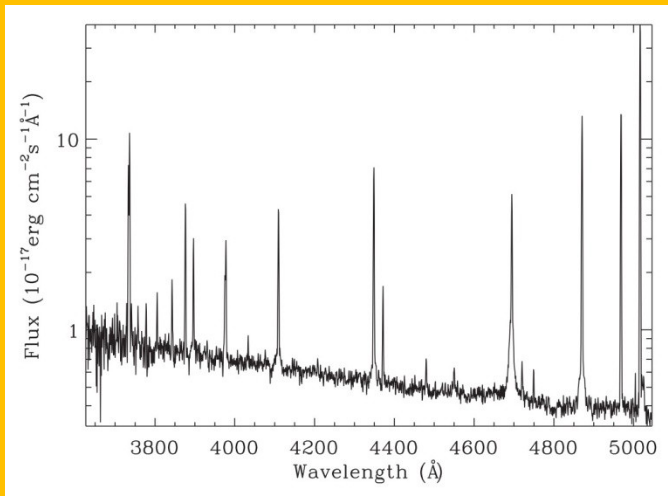
NGC5474 X-1 (left) and M66 X-1 (right) Avdan et al. 2016



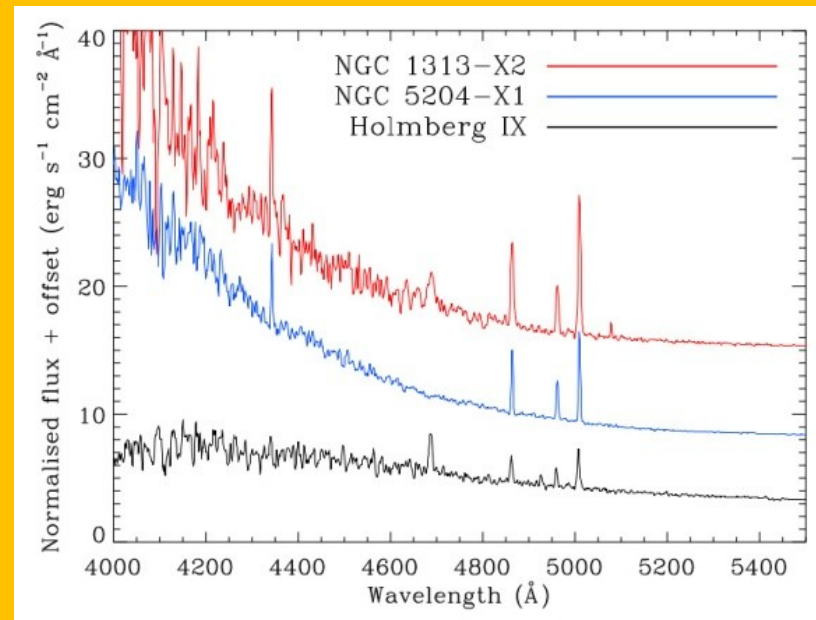
NGC4559 X-10 (top) and NGC4395 ULX-1 (bottom) Vinokurov et al. 2016

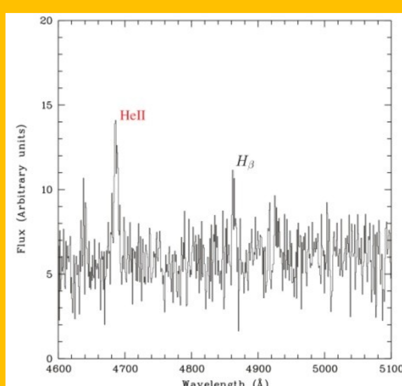
All ULXs identified in the optical range are faint sources with $m_V > 21^m$

Optical spectra of counterparts

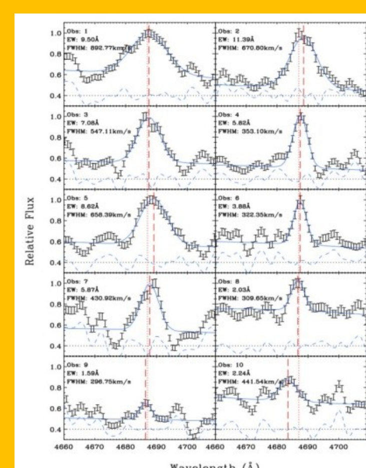


NGC5408 X-1 Cseh et al. 2013



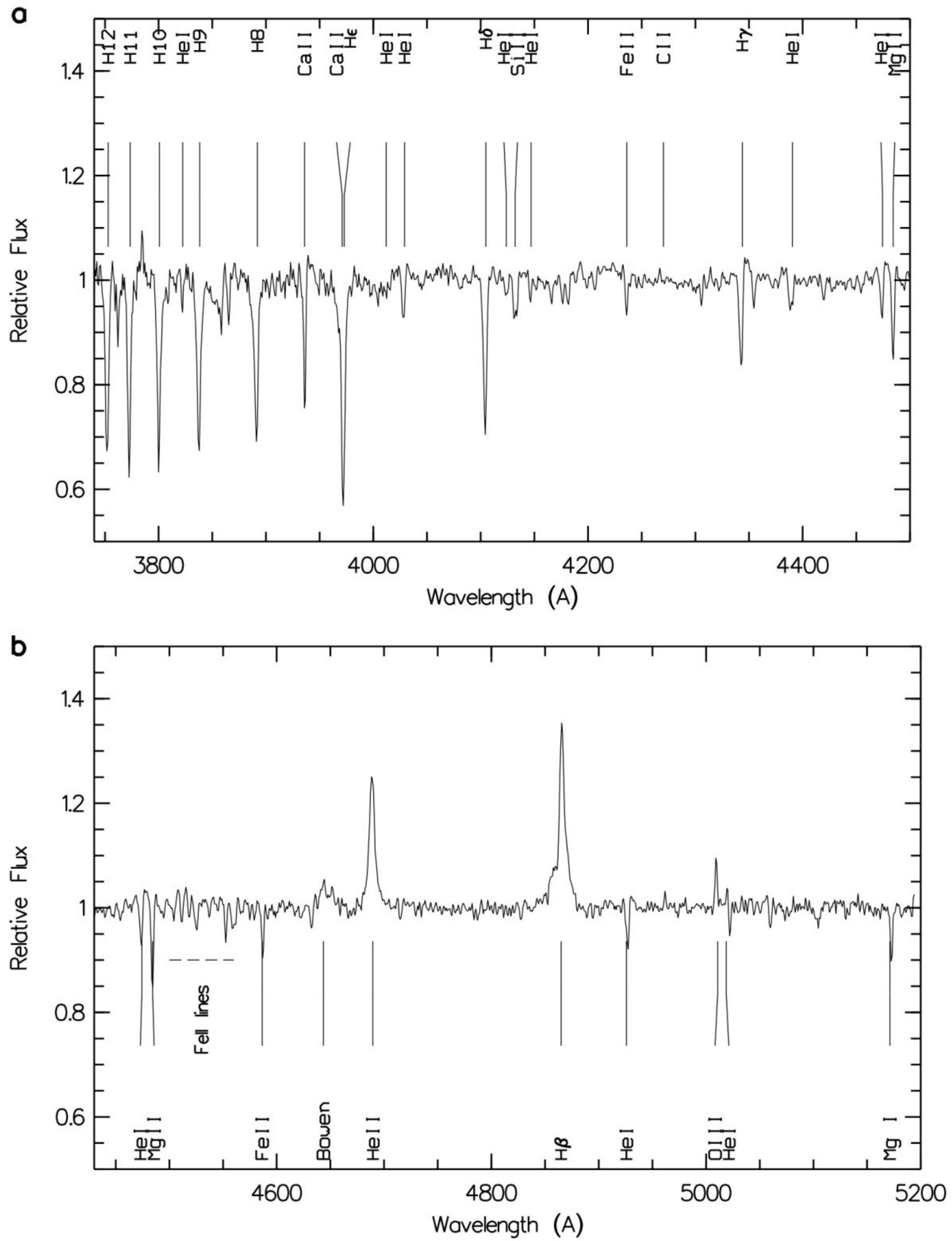


Holmberg IX X-1 Grise et al. 2011



NGC1313 X-2
Roberts et al.
2011

Highly variable
HeII line



P13 in NGC7793

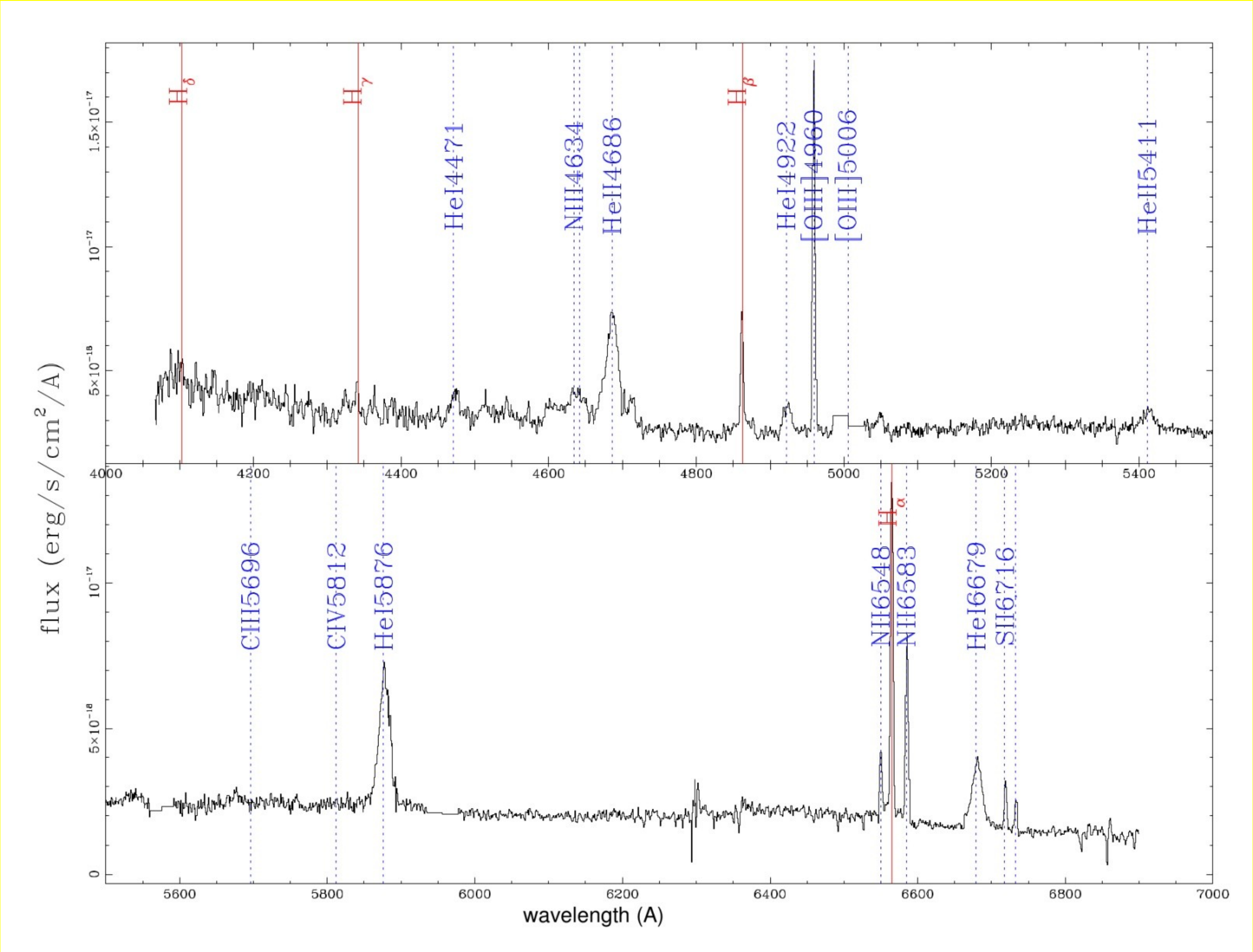
Motch et al. 2014

B9Ia donor star

Black hole mass is restricted to $M_{BH} < 15\ M_{sun}$

Broad emissions are from supercritical disk

Highly variable in X-rays discovered as ULX-pulsar



M101 ULS1

Liu et al. 2013

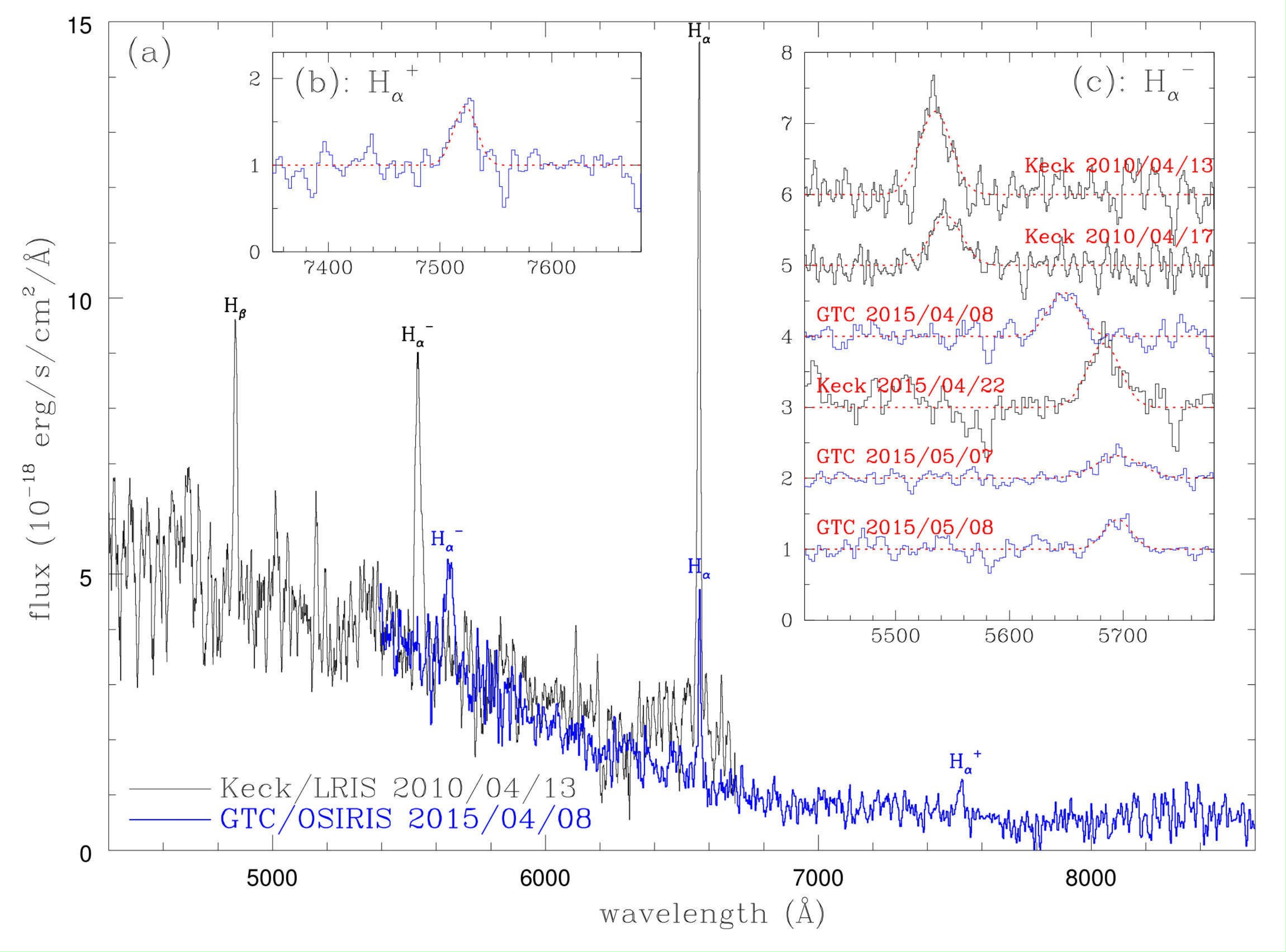
WN8 donor

at 8.2-day orbit

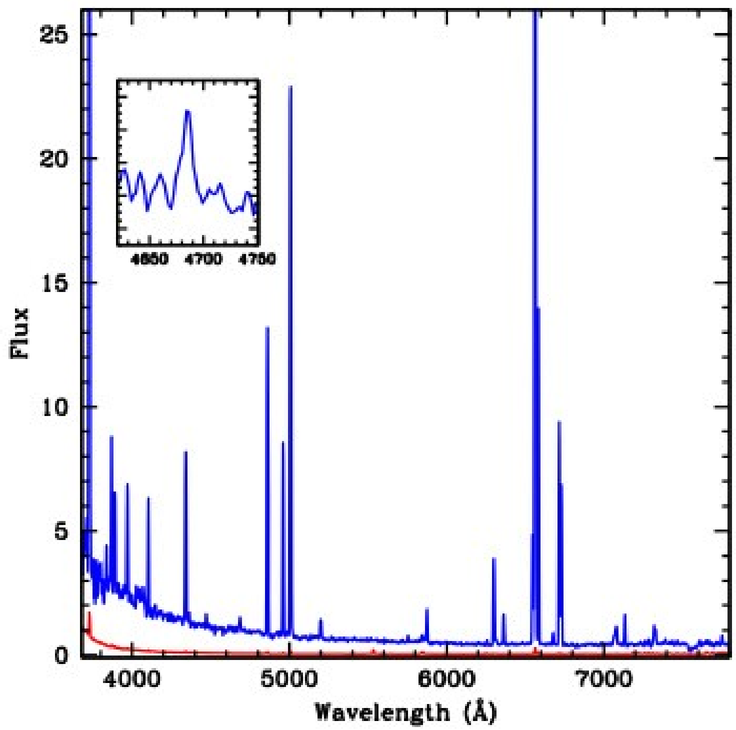
Highly variable in X-rays, short-scale (hours)

M81 ULS1

Liu et al.2015



Barionic jets like that in SS433

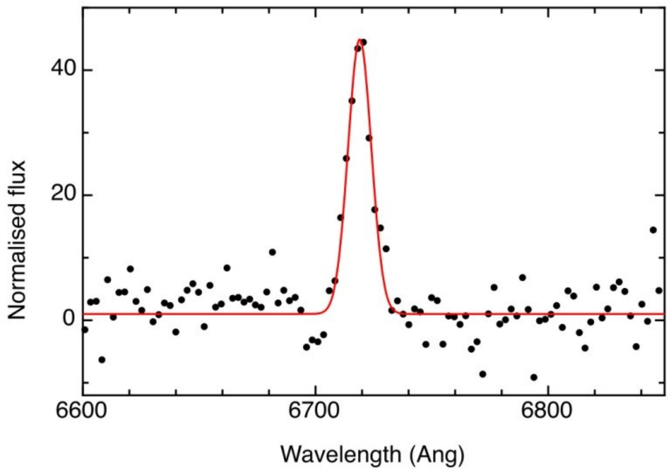


HLX in NGC470
Gutierrez & Moon 2014

Lx > 10^{41} erg/s, L_x/L_{opt} ~ 300

HeII line FWHM ~ 400 km/s

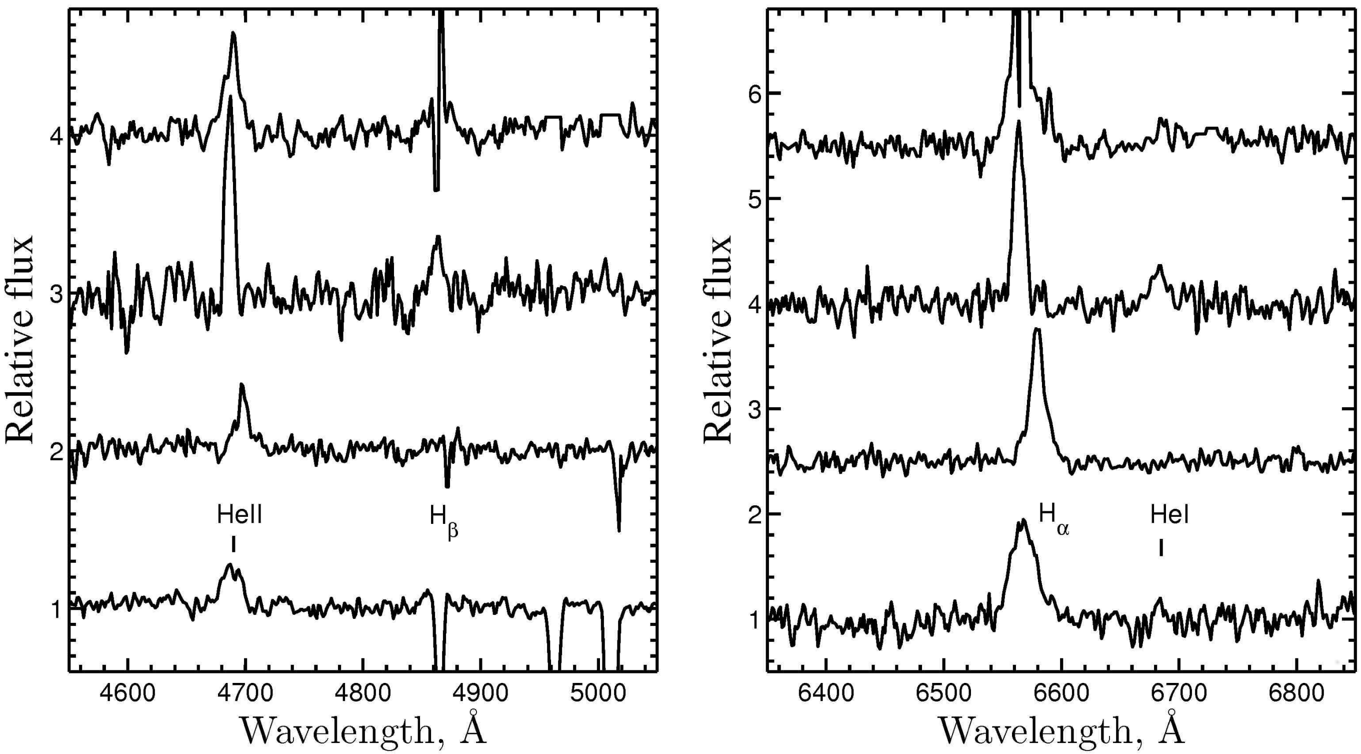
probable blue cluster, M_g ~ -12



HLX-1
Soria et al. 2013

Hα line FWHM ~ 450 km/s

Subaru data



Holmberg II X-1
Holmberg IX X-1
NGC4559 X-7
NGC5204 X-1

Fabrika et al. 2015

IR spectra of ULX counterparts

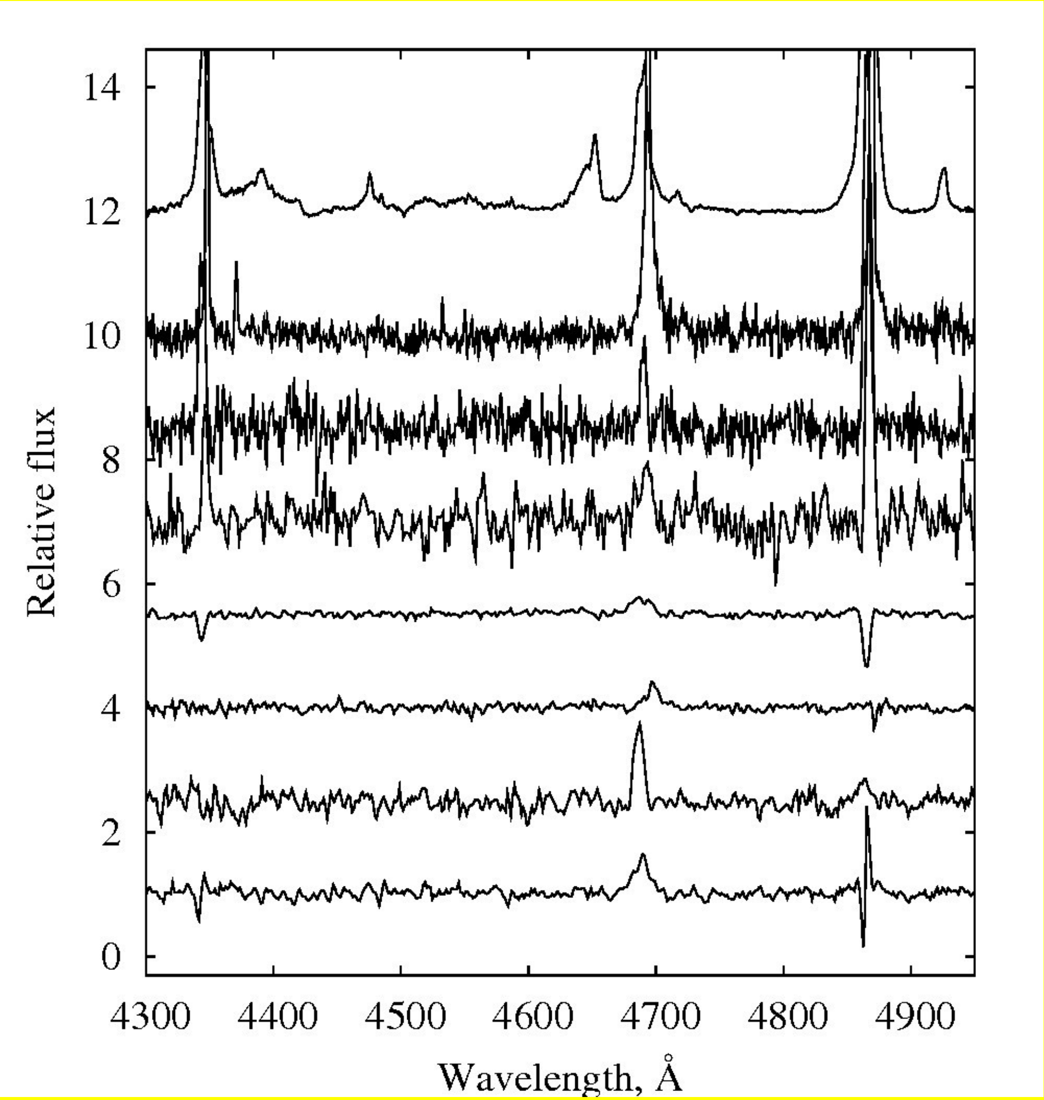
Heida et al, 2014, 2015, 2016
(VLT/X-shooter, Magellan/MMIRS, Keck/MOSFIRE)

11 out of 62 counterparts with luminosities of red supergiants

ULXs in Holmberg II, NGC925, NGC4136, NGC253
all have absorption spectra with nebular emission lines

In visible Holmberg II, NGC925, NGC253 have blue spectra,
probably because of accretion disk

Optical spectra of counterparts



SS433

NGC5408 X-1

NGC4395 X-1

NGC1313 X-2

NGC5204 X-1

NGC4559 X-7

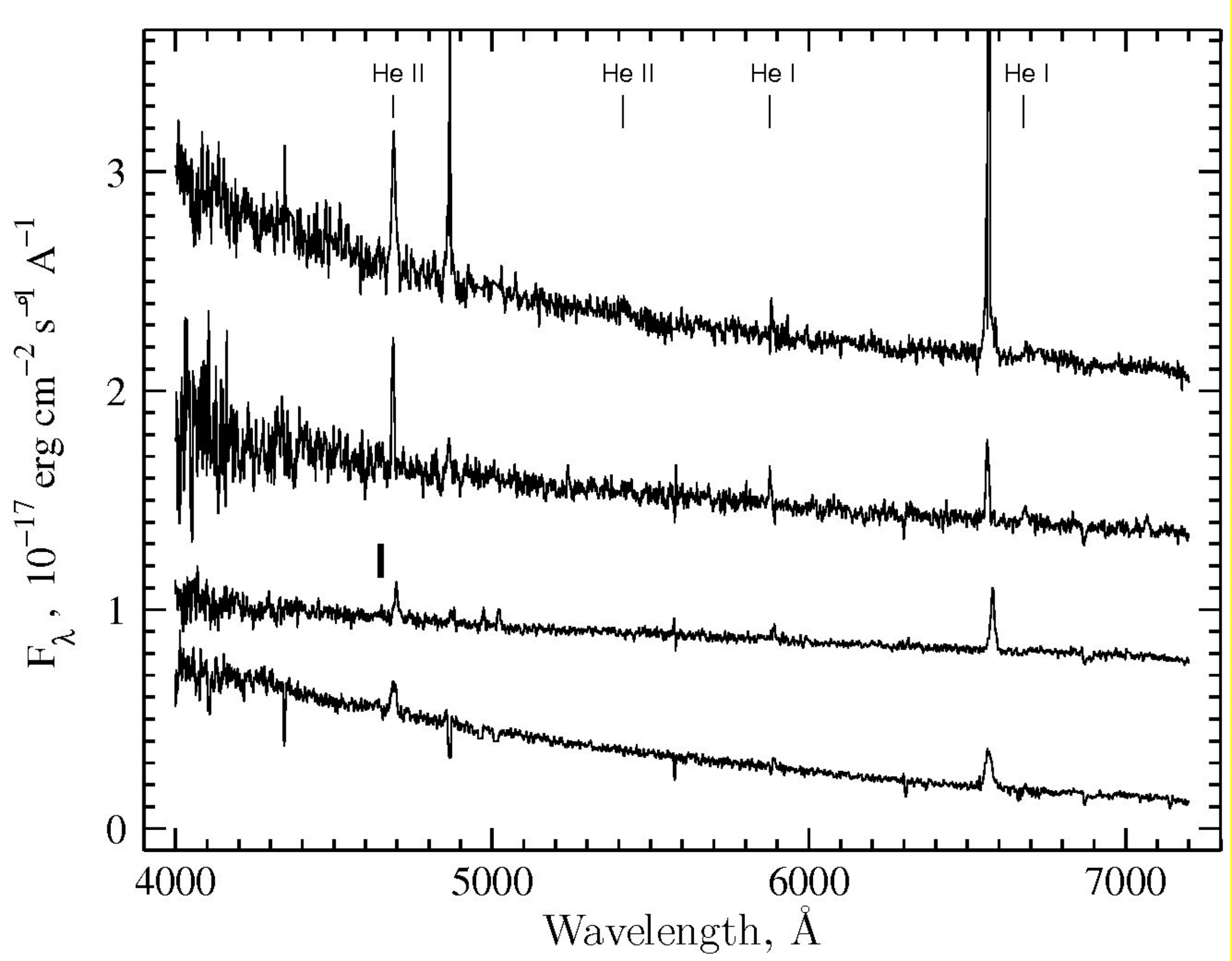
Holmberg IX X-1

Holmberg II X-1

NGC5408, NGC1313

NGC4395 X-1

SS433, NGC5294, NGC4559,
Holm IX, Holm II



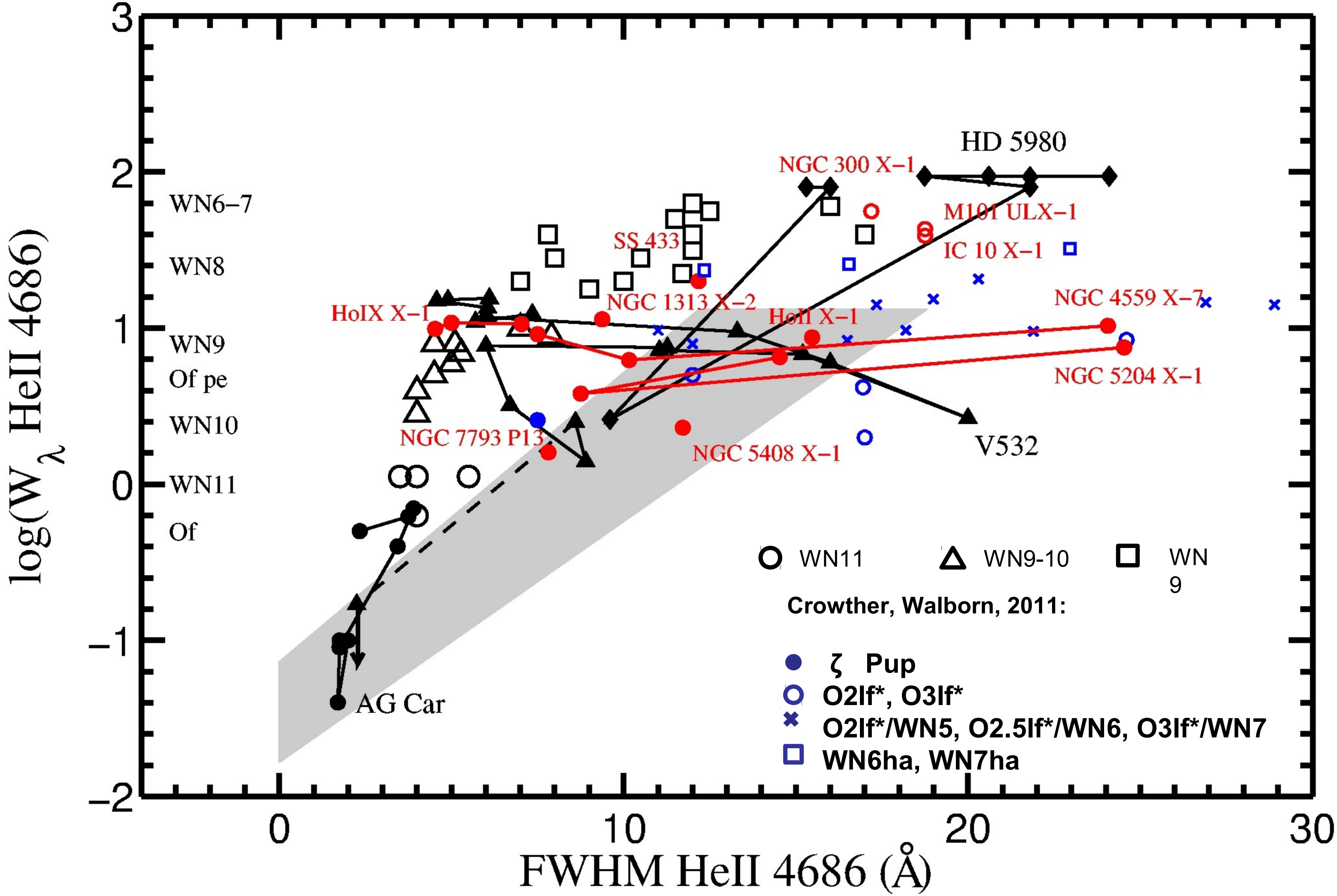
Subaru

All studied ULX have broad HeII 4686 A and Hα.

That is high ionization wind: EW(HeII)/EW(Hβ) ≥ 2

Classification diagram for WNL stars (Crowther & Smith, 1997)

three LBVs - AG Car, V532, HD5980 with known transitions (Sholukhova et al., 2011)



All the nearby persistent ULXs ($L_x > 2\text{-}3\ 10^{39}$ erg/s) ever spectroscopically observed, have the same optical spectra.

(Fabrika et al. 2015)

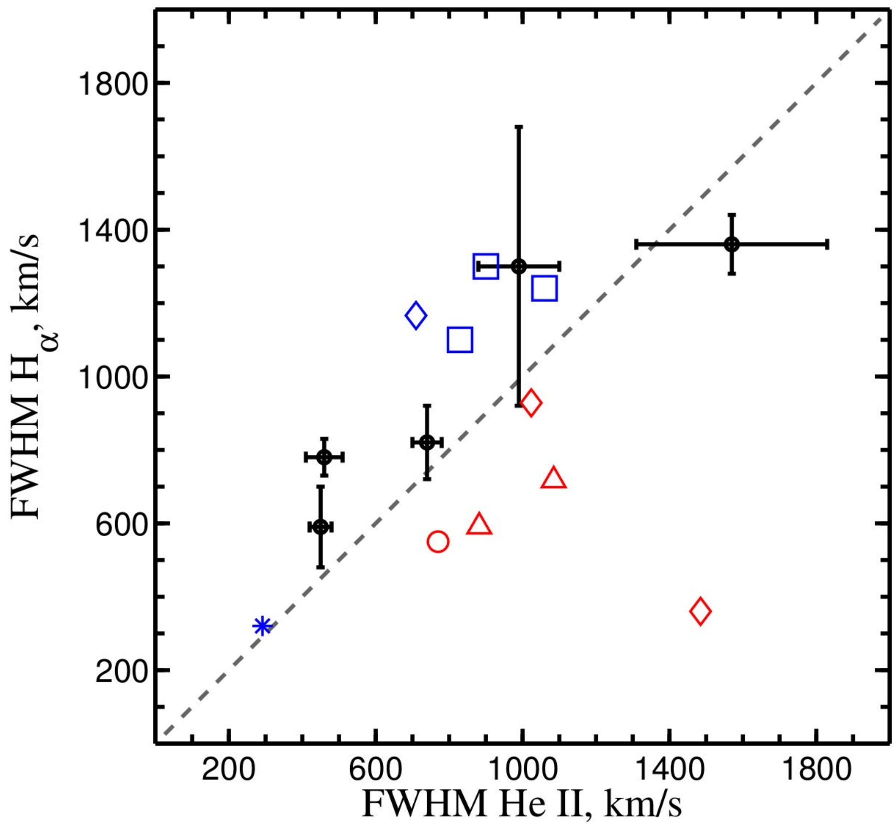
The spectra are similar to:

- SS 433 - Galactic super-accretor with stellar-mass black hole
- or LBVs (luminous blue variables) in their hot states
- or WNLs (late nitrogen Wolf-Rayet stars)

They may constitute a homogeneous class of objects,

which most likely have super-Eddington disks

Super-Eddington or irradiated disk (IMBH)?

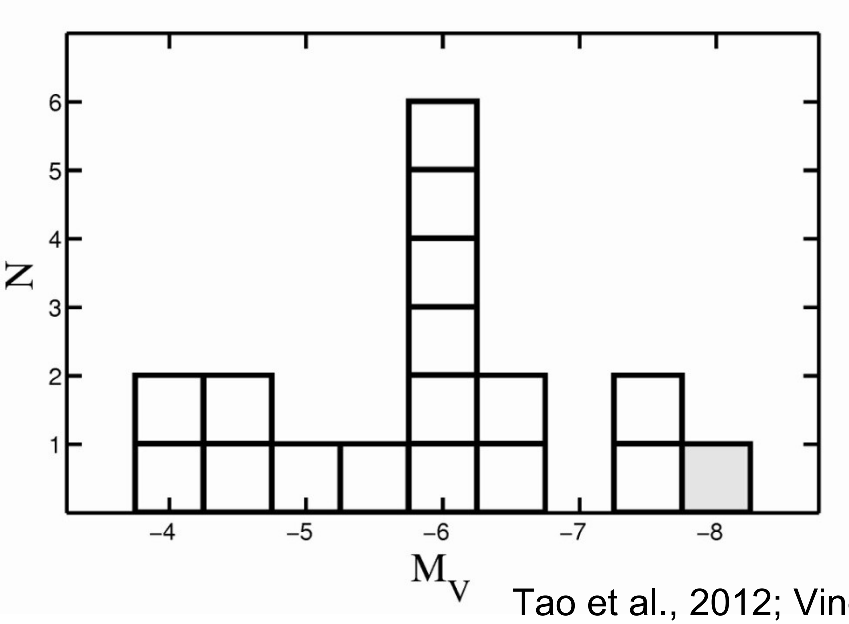


Black with errors from top to bottom:
NGC5204 X-1, Holmberg II X-1,
NGC5408 X-1, NGC4559 X-7,
Holmberg IX X-1
(Fabrika et al. 2015 + archive data)

- SS433
- LBV Romano star (V532) in M33
- WR22 (WN7ha), WR24 (WN6ha), WR25 (WN6ha)
- GX339-4 (Soria et al. 1999; Rahoui et al. 2014)
- V404 Cyg (Casares et al. 1991; Cottehelf et al.1992)
- GRO J1655-40 (Hunstead et al. 1997; Soria et al. 1998)

Dense and optically thick winds in LBVs, WNLs, supergiants, SS433, ULXs
versus
Winds from disks irradiated surface

Optical luminosities of studied ULX and SS433



Tao et al., 2012; Vinokurov et al., 2016

In decreasing luminosity:

SS433, NGC6946 ULX-1, NGC7793 P13, NGC4559 X-7, NGC5408 X-1, NGC5204 X-1, NGC4395 X-1, M81 ULS1, Holmberg II X-1, IC342 X-1, Holmberg IX X-1, NGC4559 X-10, NGC1313 X-2, NGC5474 X-1, NGC1313 X-1, M66 X-1, M81 X-6

In super-Eddington disks X-ray luminosity logarithmically depends on the accretion rate

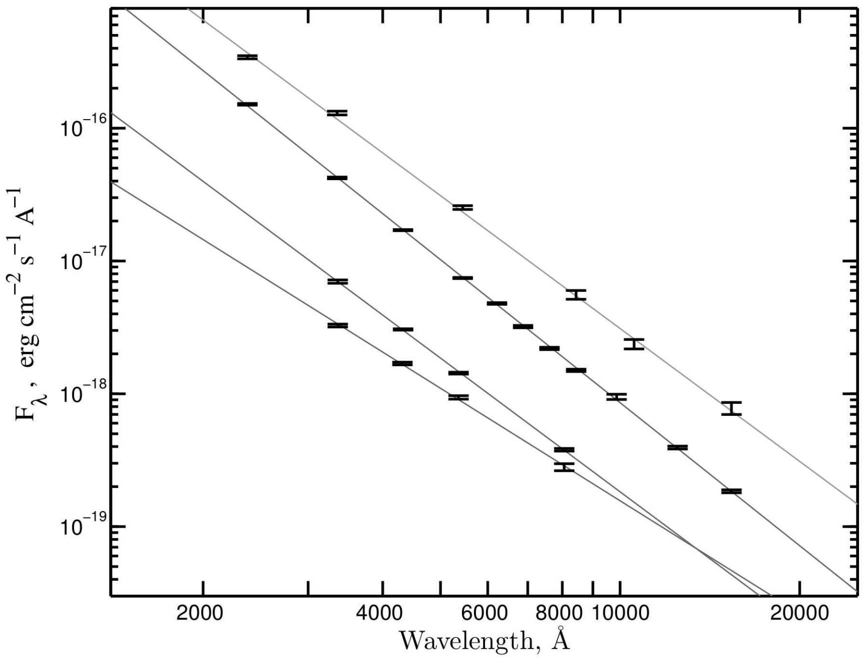
$$L_X \propto L_{Edd}\left(1 + a\ln\left(\dot{M}/\dot{M}_{Edd}\right)\right)$$

L_{Edd} - Eddington luminosity, $\dot{M}_{Edd}$ - Eddington rate

UV/optical luminosity strongly depends on the accretion rate

$$L_V \propto \dot{M}^{9/4} M^{-1/2}, \quad T_{ph} \propto \dot{M}^{-3/4} M^{1/2}$$

Formally, the accretion rate in ULXs 1.5 – 6 times less than in SS433, the wind temperature 1.5 – 4 times higher than in SS 433.



HST data

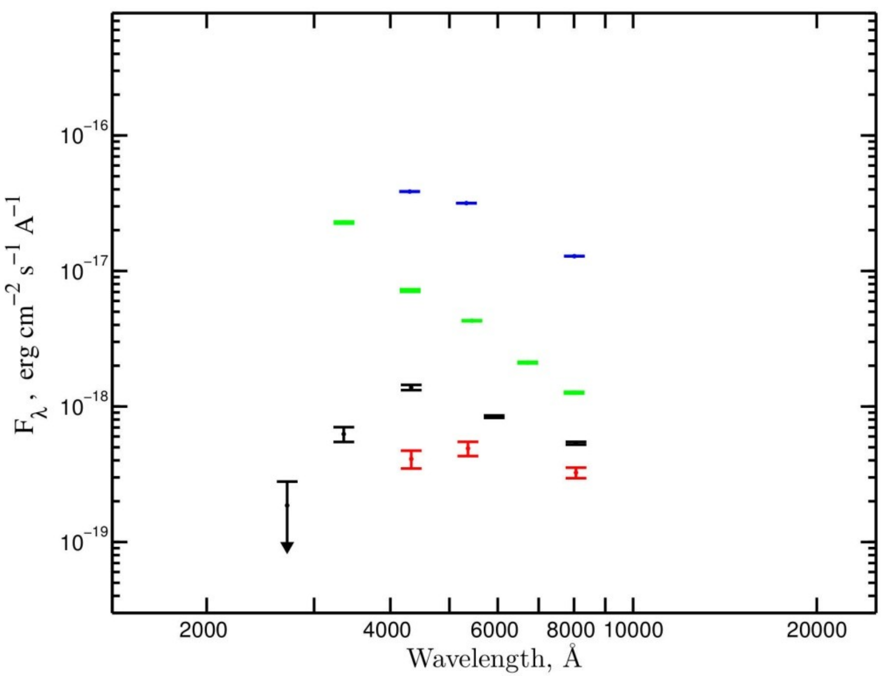
corrected for reddening, for 5 Mpc distance

from top to bottom:

NGC5408 X-1 (x4), α = 3.35
Holmberg IX X-1 (x2), α = 3.58
NGC 1313 X-2 (x1), α = 3.34
NGC1313 X-1 (x1), α = 2.81

F_λ $\lambda^{-\alpha}$

For Raileigh-Jeans BB tail α = 4



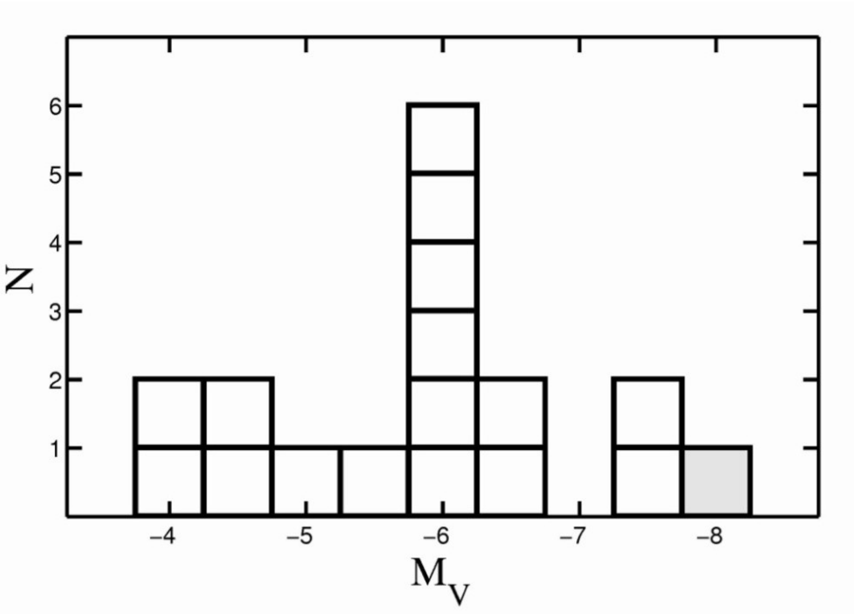
from top to bottom:

F-G-type spectra:

NGC4559 X-1 (x16)
M81 X-6 (x8)
NGC5474 X-1 (x2)
M66 X-1 (x1)

all have $M_V > -5.7$

error bars are real



what about this histogram?

1. Selection effect, objects may be missed in galaxies farther than 10 Mpc

2. With decreasing an accretion rate the optical luminosity does decrease. The donor star becomes dominating. Three of six objects with M_V > -5.3 have F-G type spectra. (Avdan et al. 2016, Vinokurov et al. 2017)

All studied ULXs $L_X / L_{opt} > 200$ (Avdan et al., 2016)

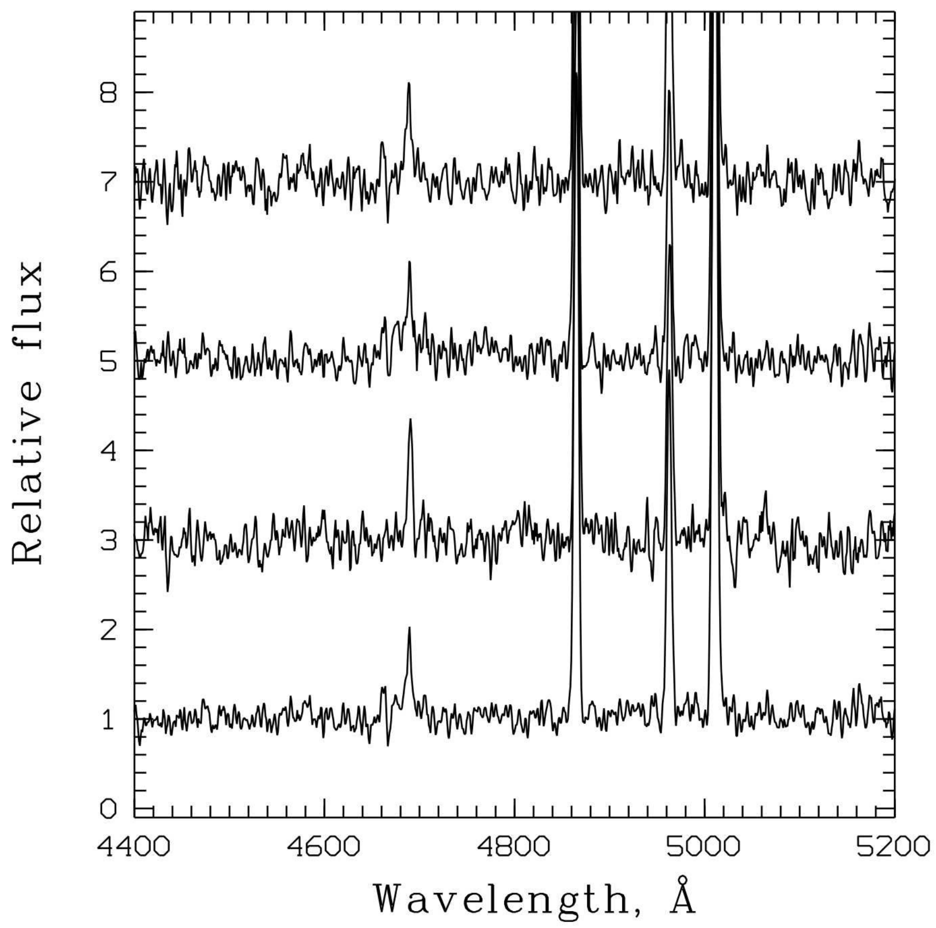
They are super-Eddington accretion disks surrounding stellar-mass black holes ~ 10 solar masses. They produce strong and hot winds from the disks.

Their spectra are very similar to LBV stars in their hot state and SS433 (the only known super-accretor in the Galaxy) .

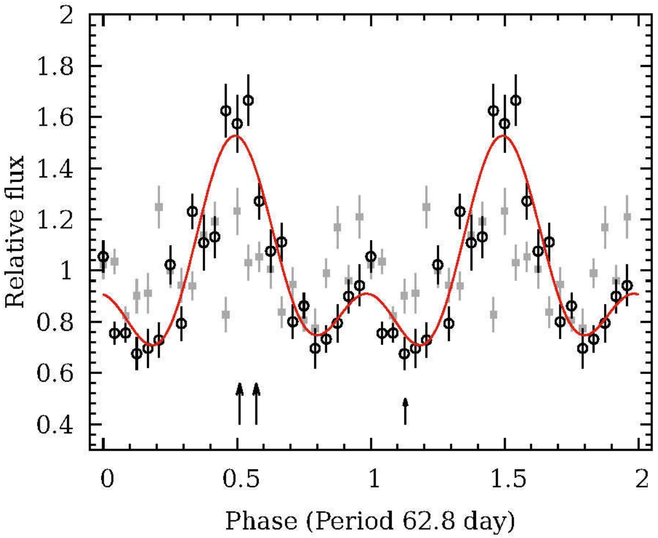
With increasing an accretion rate the supercritical wind dominates.

Thank you

NGC4395 spectra Vinokurov et al. 2017



Variable HeII line



63-day period (Swift data)

Similar to SS433
Cherepashchuk et al. 2005