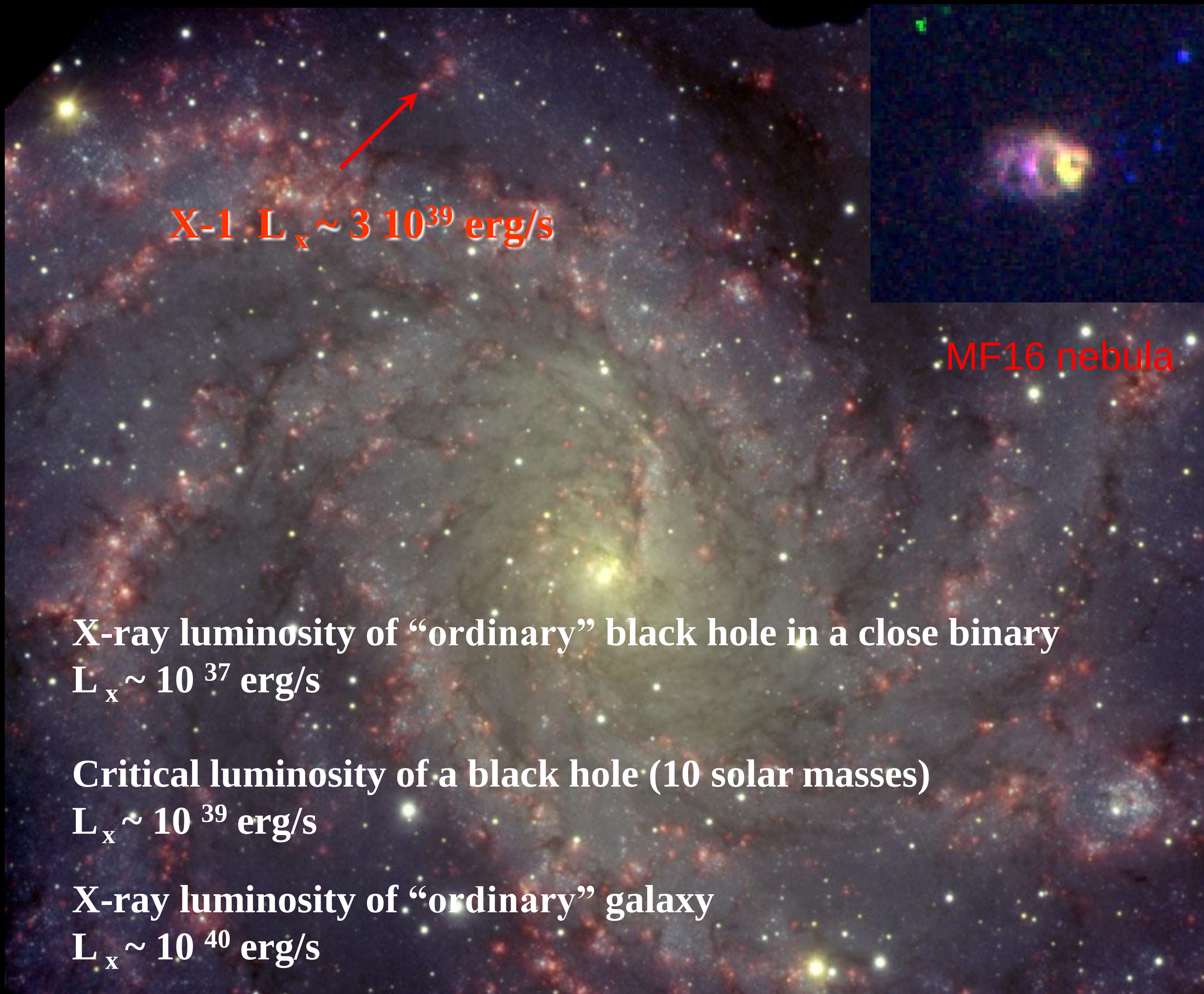
Ultraluminous X-ray sources

S. Fabrika (SAO RAS)

ULX in NGC6946



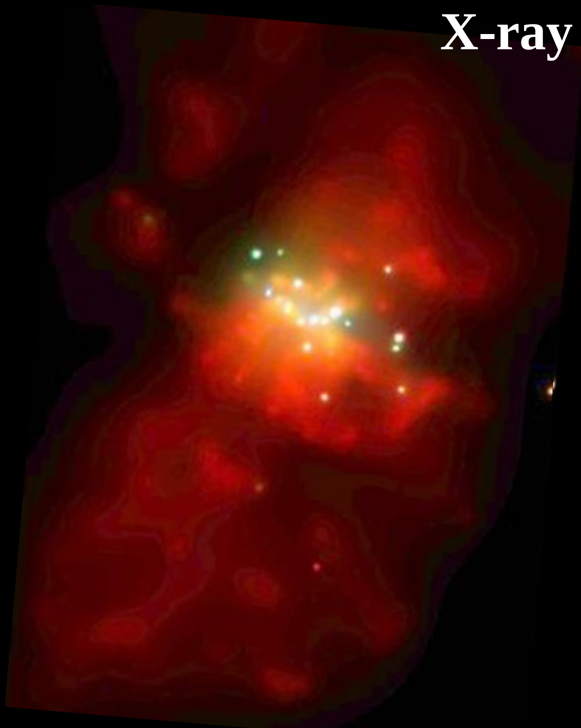
X-ray luminosity of “ordinary” black hole in a close binary
$L_x \sim 10^{37}$ erg/s

Critical luminosity of a black hole (10 solar masses)
$L_x \sim 10^{39}$ erg/s

X-ray luminosity of “ordinary” galaxy
$L_x \sim 10^{40}$ erg/s

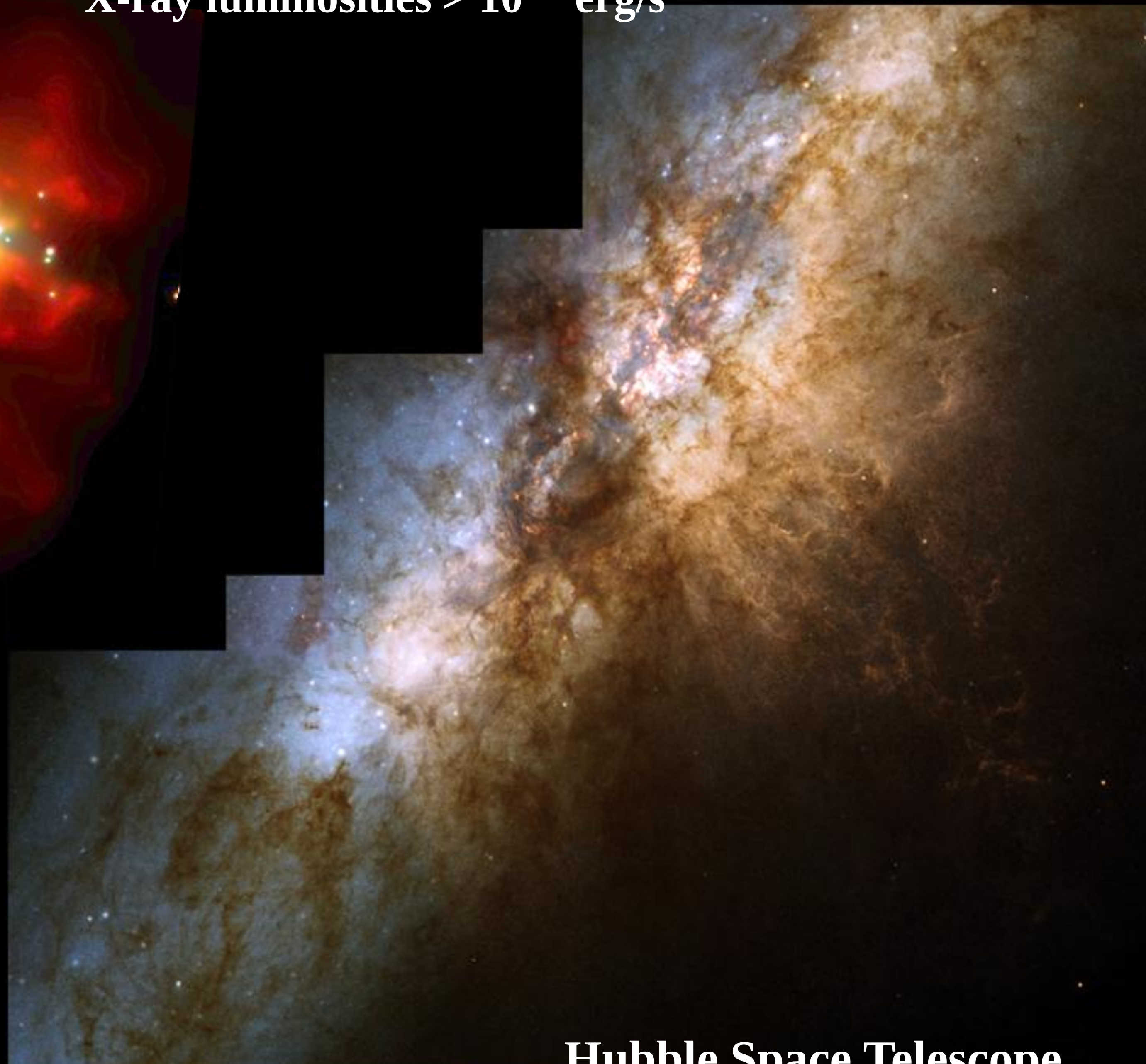
Ultraluminous X-ray sources

X-ray luminosities > 10^{39} erg/s



Chandra

M82



Hubble Space Telescope

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

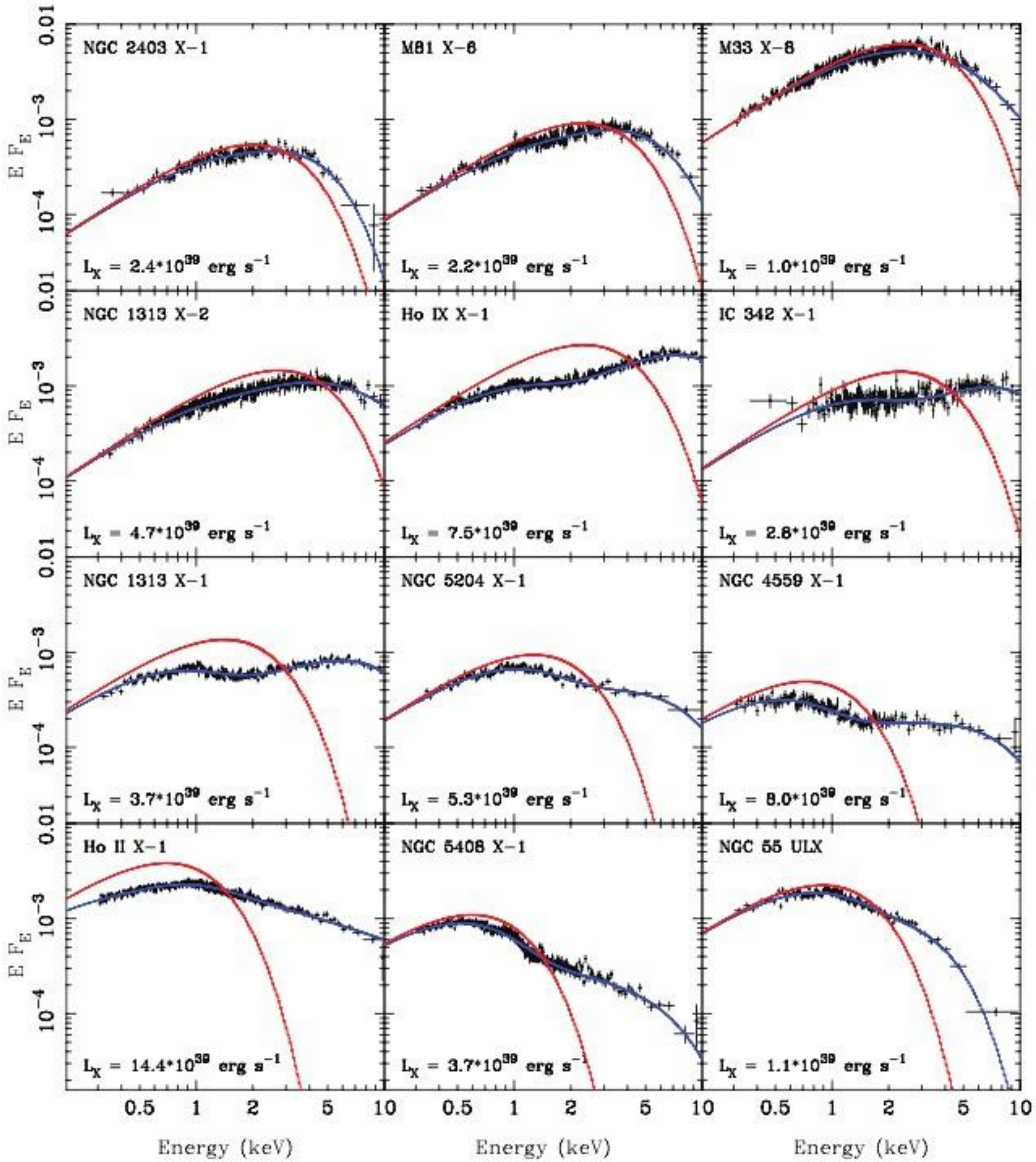
The ULXs with L_x > 10^{41} erg/s call hyper-luminous X-ray sources

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

1a. Three ULX-pulsars have been discovered (Bachetti+ 2014, Fürst+ 2017, Israel+ 2017).
The best idea is magnetic column with a strong collimation Kawashima+2016)

2. **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)



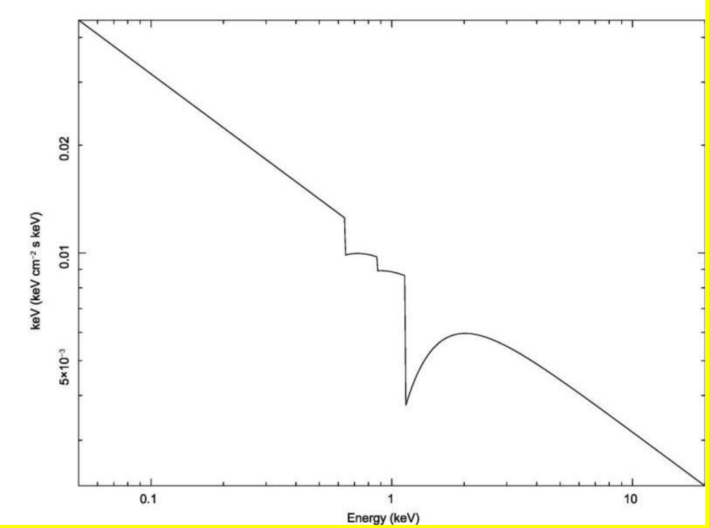
"Ultraluminous state"

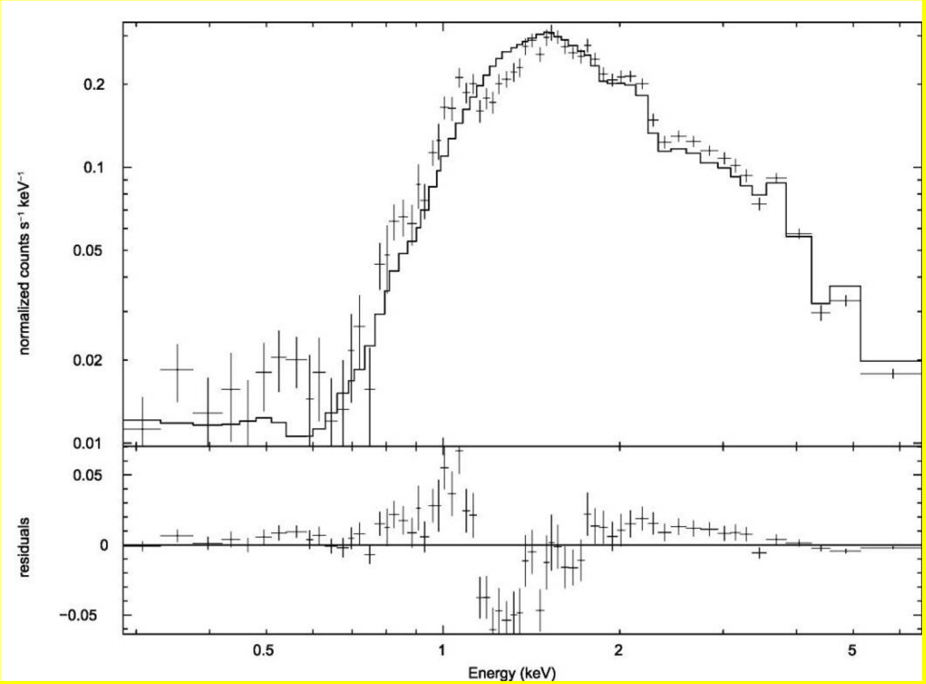
the inner disk is hidden by wind

the wind comptonizes the inner disk photons

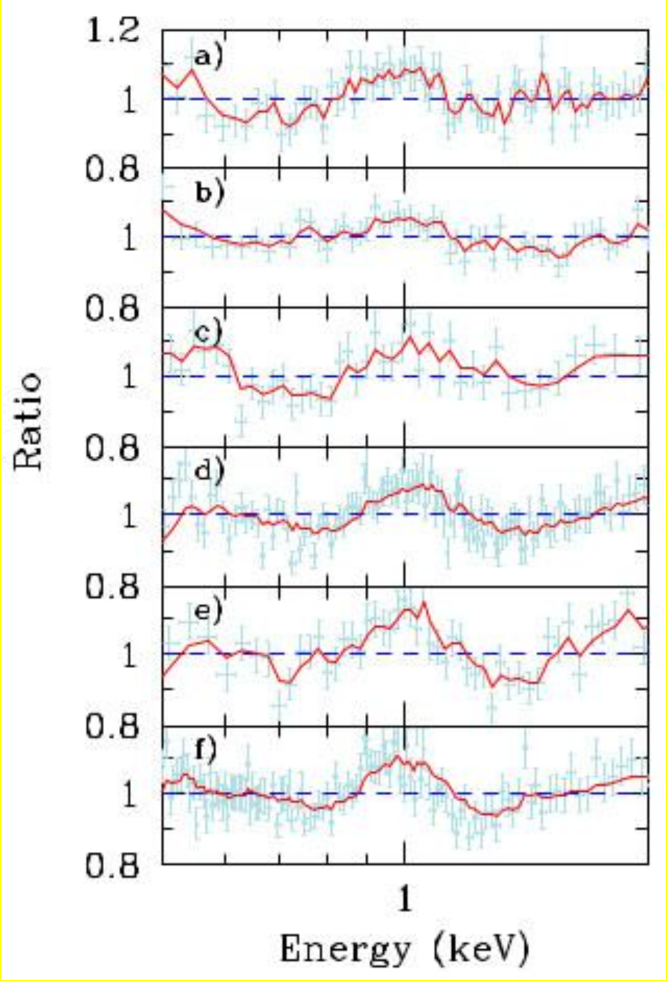
Model spectra:
the outer disk plus the wind
the whole disk

ULX residuals



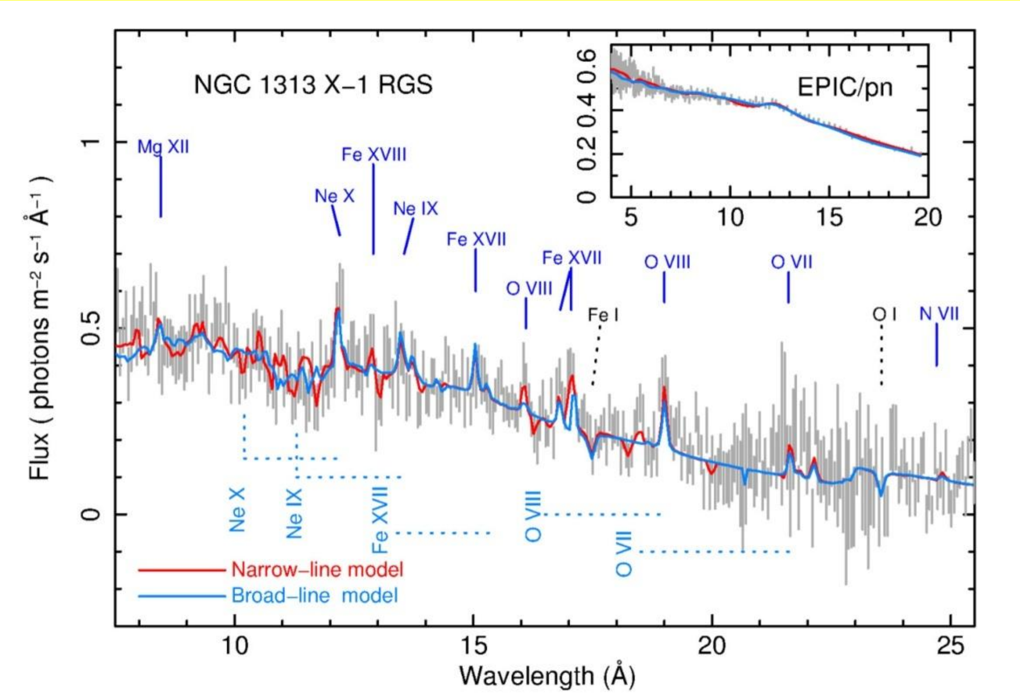


Fabrika+2006: XMM MOS1 (model spectrum PL+diskbb)
Lc edges CIV, NVII, OVIII. 0.26c, SS433 type
T(Lc) hydrogen



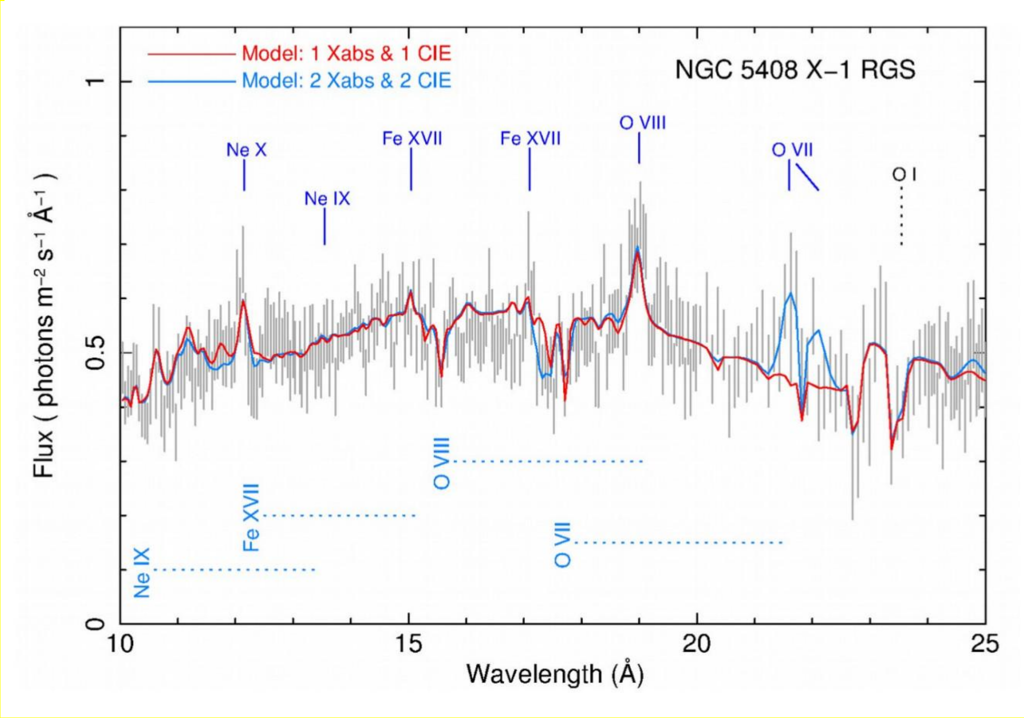
Middleton+2015 (TBAS*diskbb+nthcomp)
From top to bottom: NGC1313 X-1,
HoIX X-1, HoII X-1, NGC55 ULX-1,
NGC6946 X-1, NGC5408 X-1

Discovery of ultrafast outflows

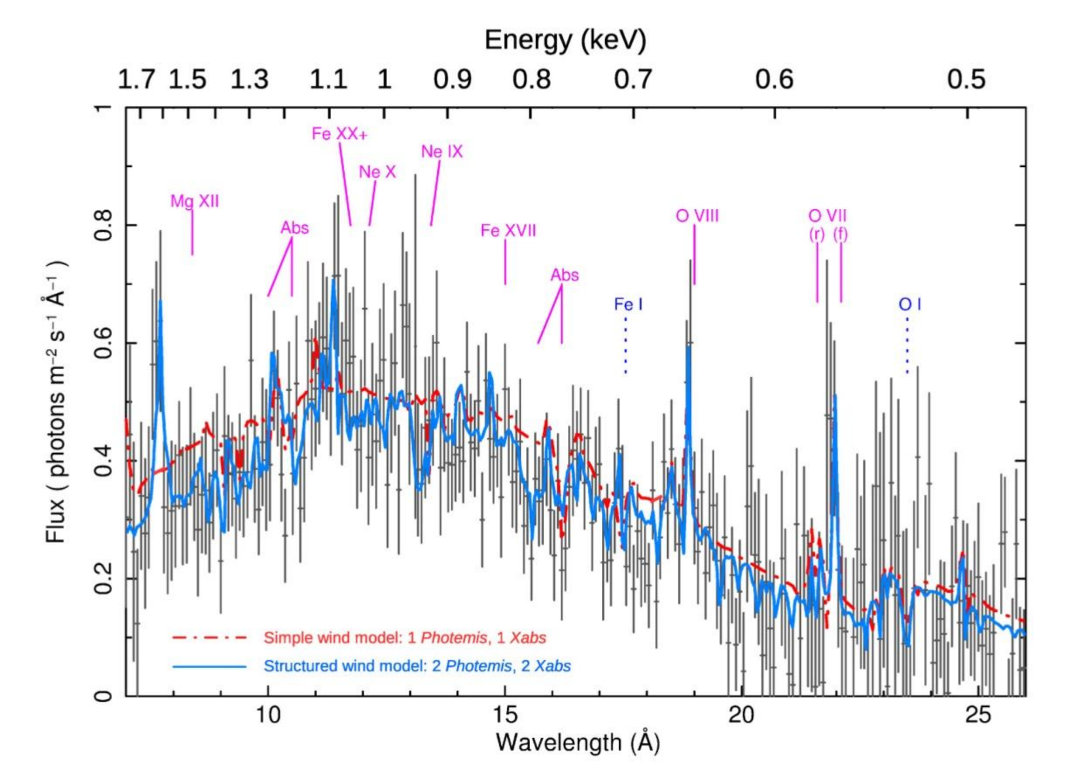


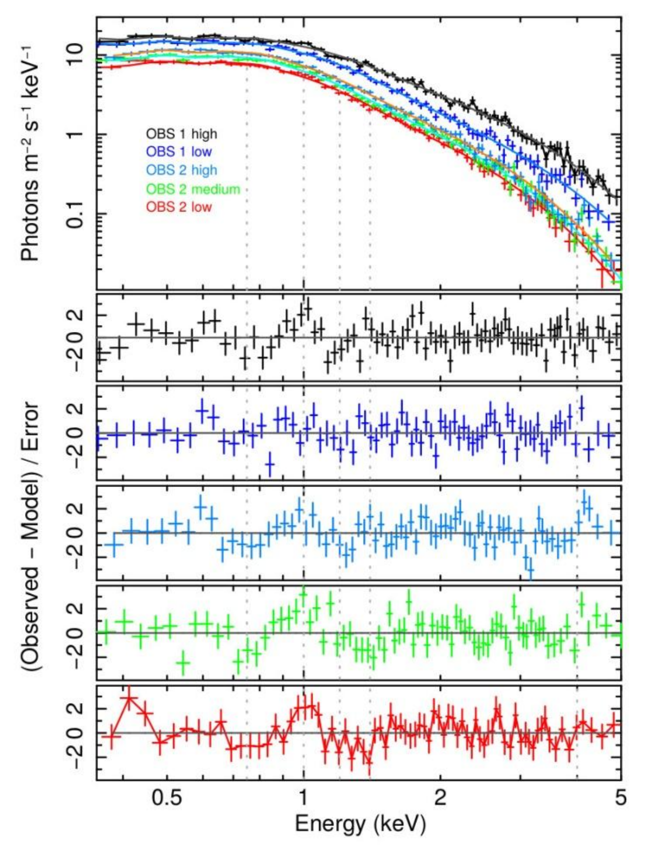
Pinto+2016
XMM Newton RGC and EPIC/pn

blueshifted lines
red – 0.20c, blue – 0.25c



blueshifted lines
red 0.22c, blue 0.22+0.10c

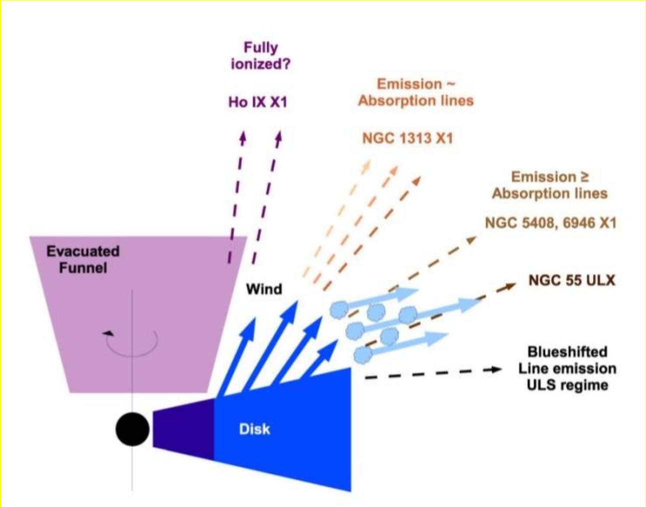




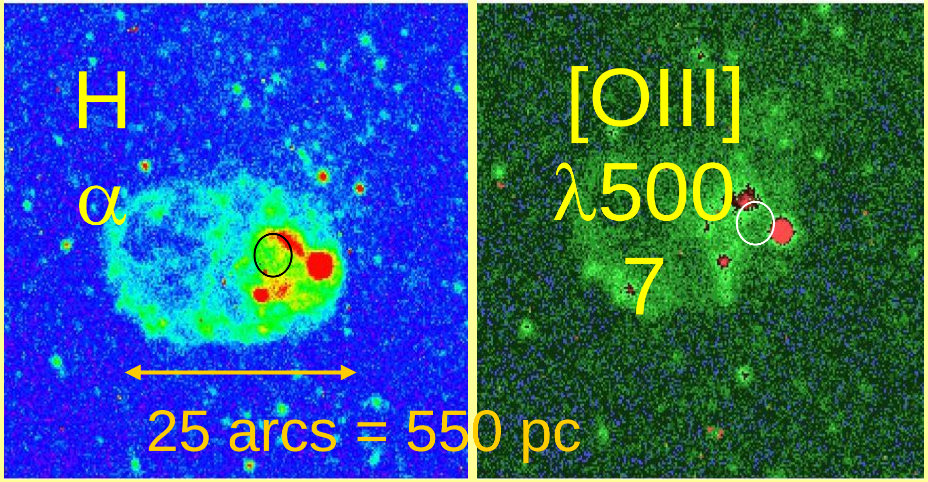
Pinto+2017 NGC55 ULX-1
XMM Newton RGC + EPIC/pn continuum

Residuals are shown after model spectra

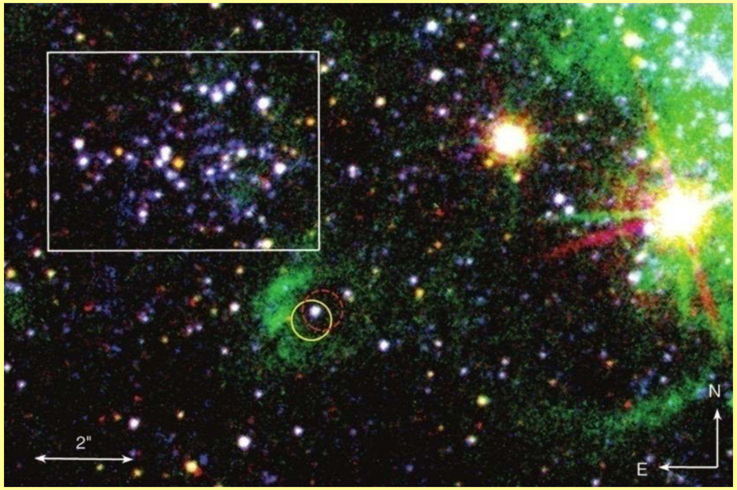
red: emission outflow 0.01c,
blueshifted absorption components 0.16c
blue: absorption components 0.06c and 0.20c



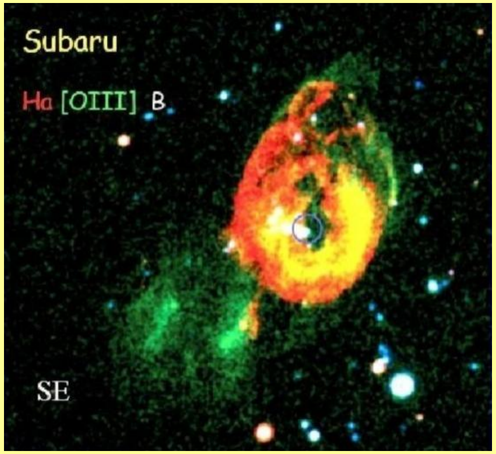
Nebulae associated with ULXs



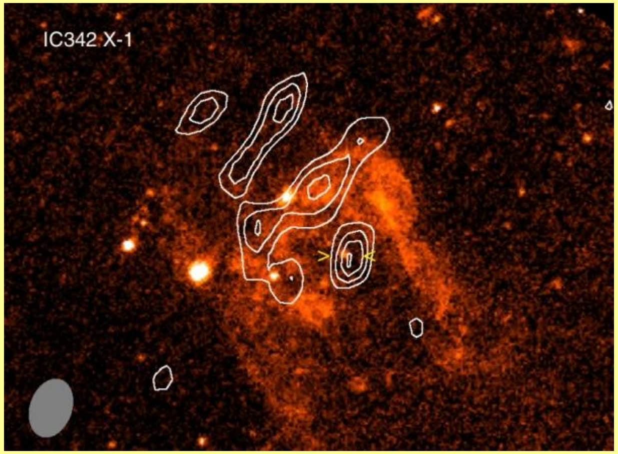
NGC1313 X-2 Pakull, Mirioni, 2002



NGC5408 X-1 Grise et al. 2012



Holmberg IX X-1 Pakull & Grise, 2008



IC342 X-1 Cseh et al. 2012

The nebulae have sizes 50-500 pc

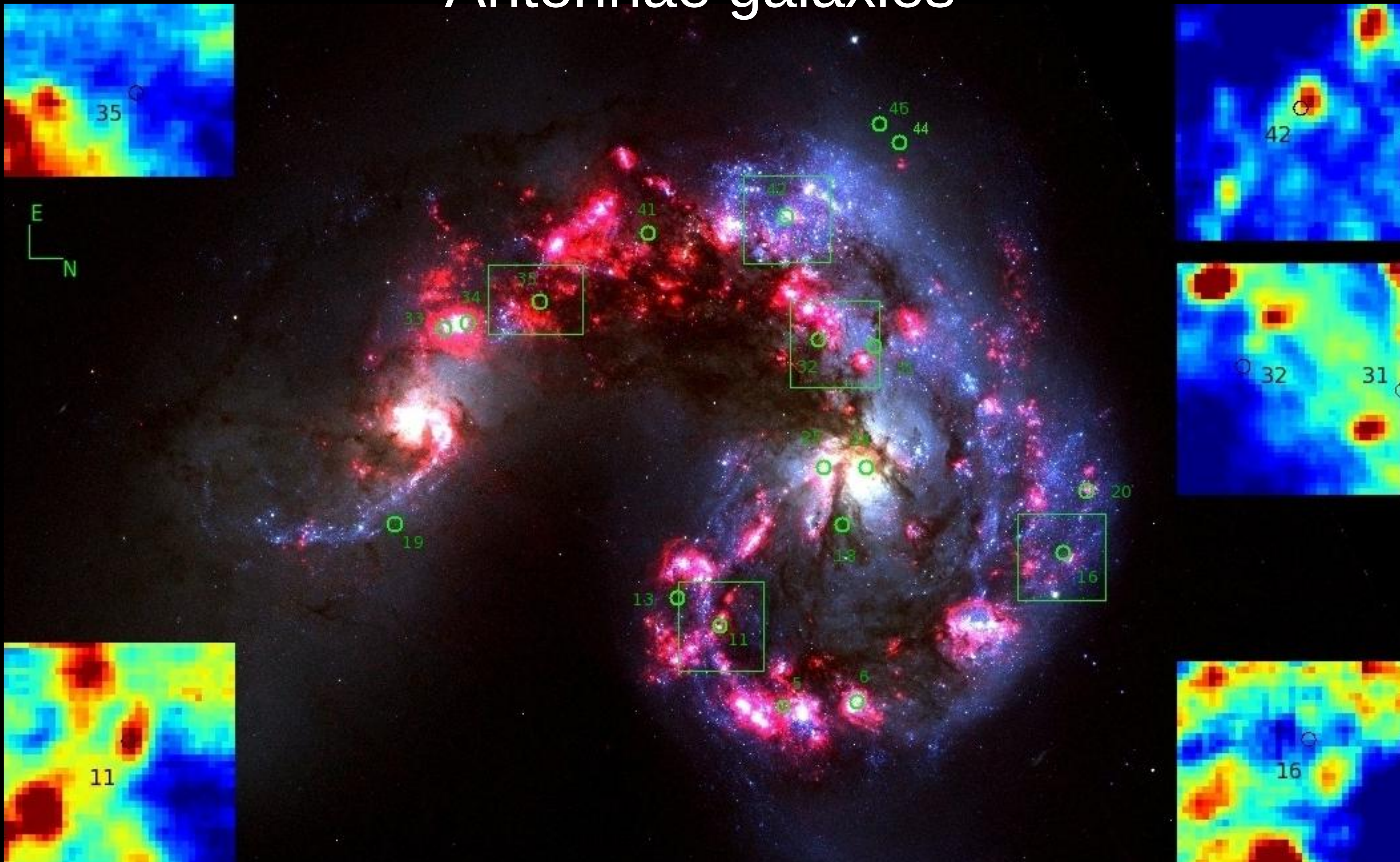
They are jet (wind) powered,
their kinetic luminosities ~10^{39} erg/s
with a total energy ~ 10^{51} erg

They are not SNRs

Poutanen et al. 2013

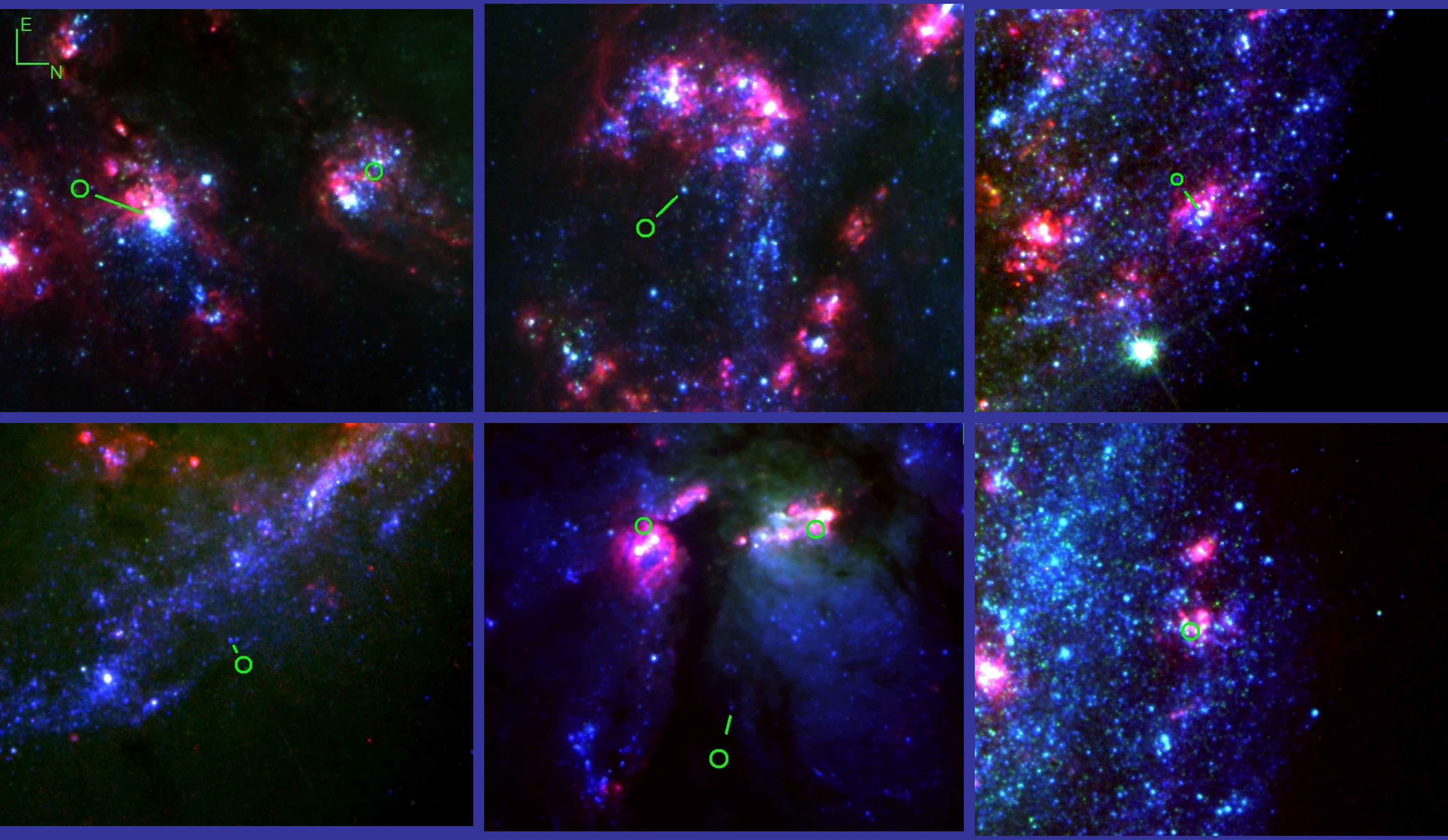
VLT/HST observations of ULX in merging starburst galaxies Antennae and NGC3256

Antennae galaxies

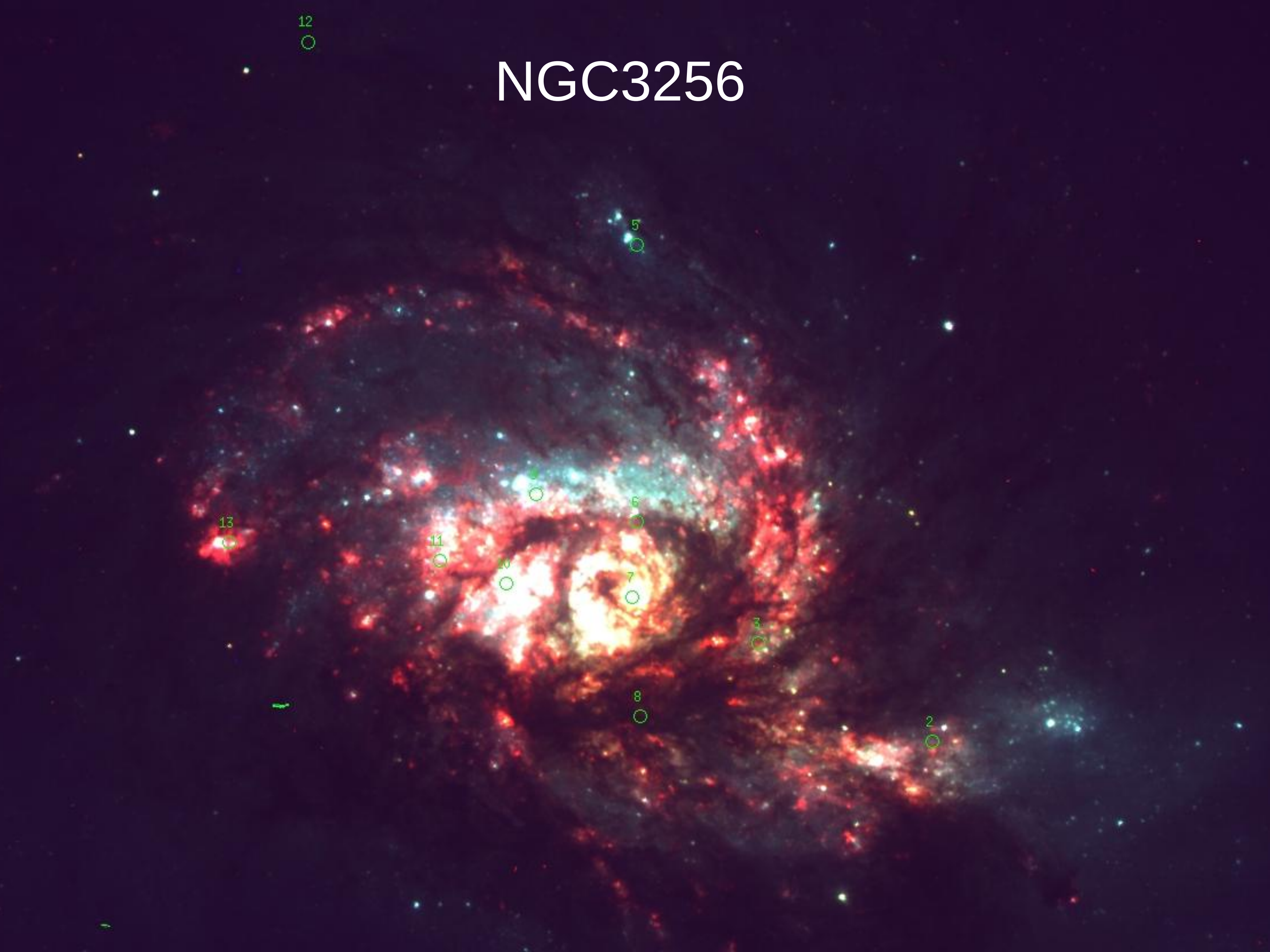


ULXs in Antennae

Sub-ULXs in Antennae
$3\ 10^{38} - 10^{39}$ erg/s

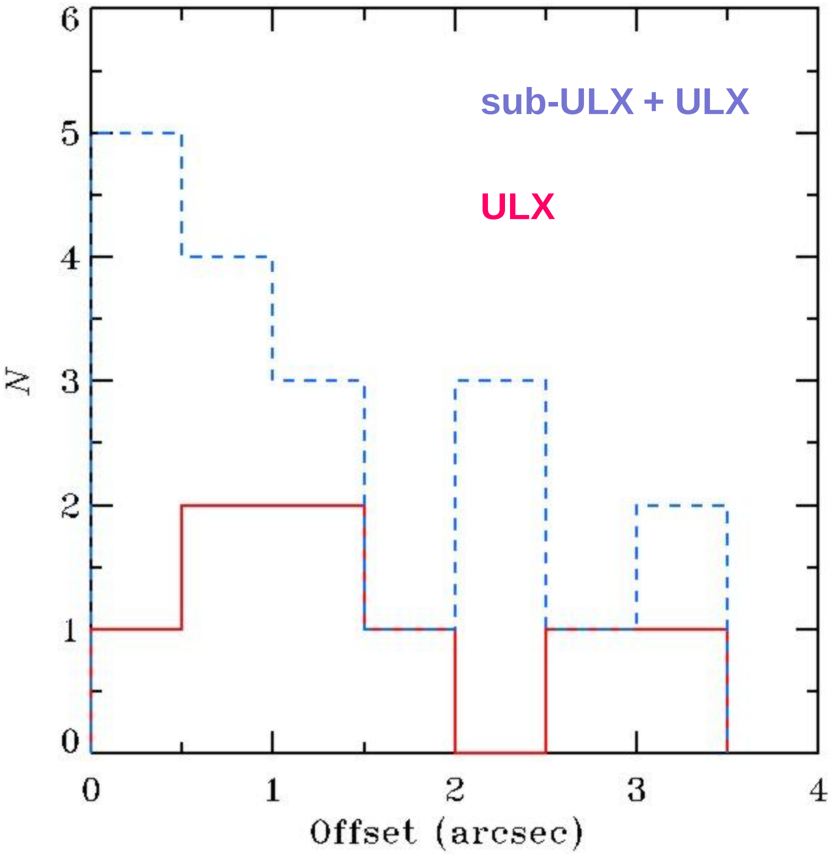


NGC3256

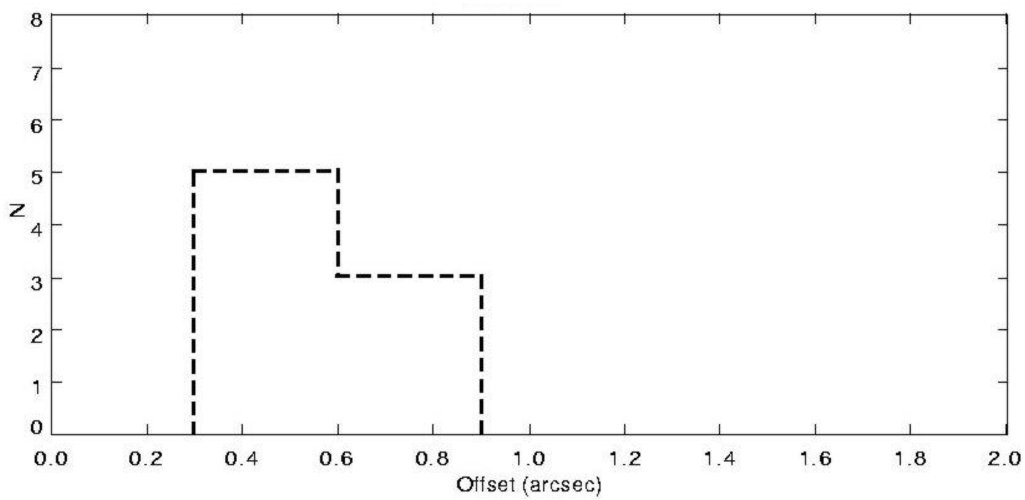


ULX-cluster displacements

in Antennae



in NGC 3256



Association of the ULXs and high-mass X-ray binaries (HMXBs) with extremely young (< 5 Myr) clusters is not occasional, < 0.0000001.

The coordinate displacements, < 200-300 pc, is a common property of the HMXBs and ULXs.

Fainter X-ray sources (LMXB) loose a relation with parent clusters: Kaaret et al. (2004), Rangelov et al. (2011).

Cluster age = Primary evolution + Secondary evolution

The ULX progenitors in Antennae are very massive binary stars, $M_1 \sim M_2 \sim 100$ Mo or $M_1 \sim 2M_2 \sim 100$ Mo

ULXs are stellar-mass black holes with supercritical accretion disks

Why the displacements?
They need ejection velocity ~80 km/s (if only transportation).

Cluster age = Primary evolution + Secondary evolution (+ Transportation time?)

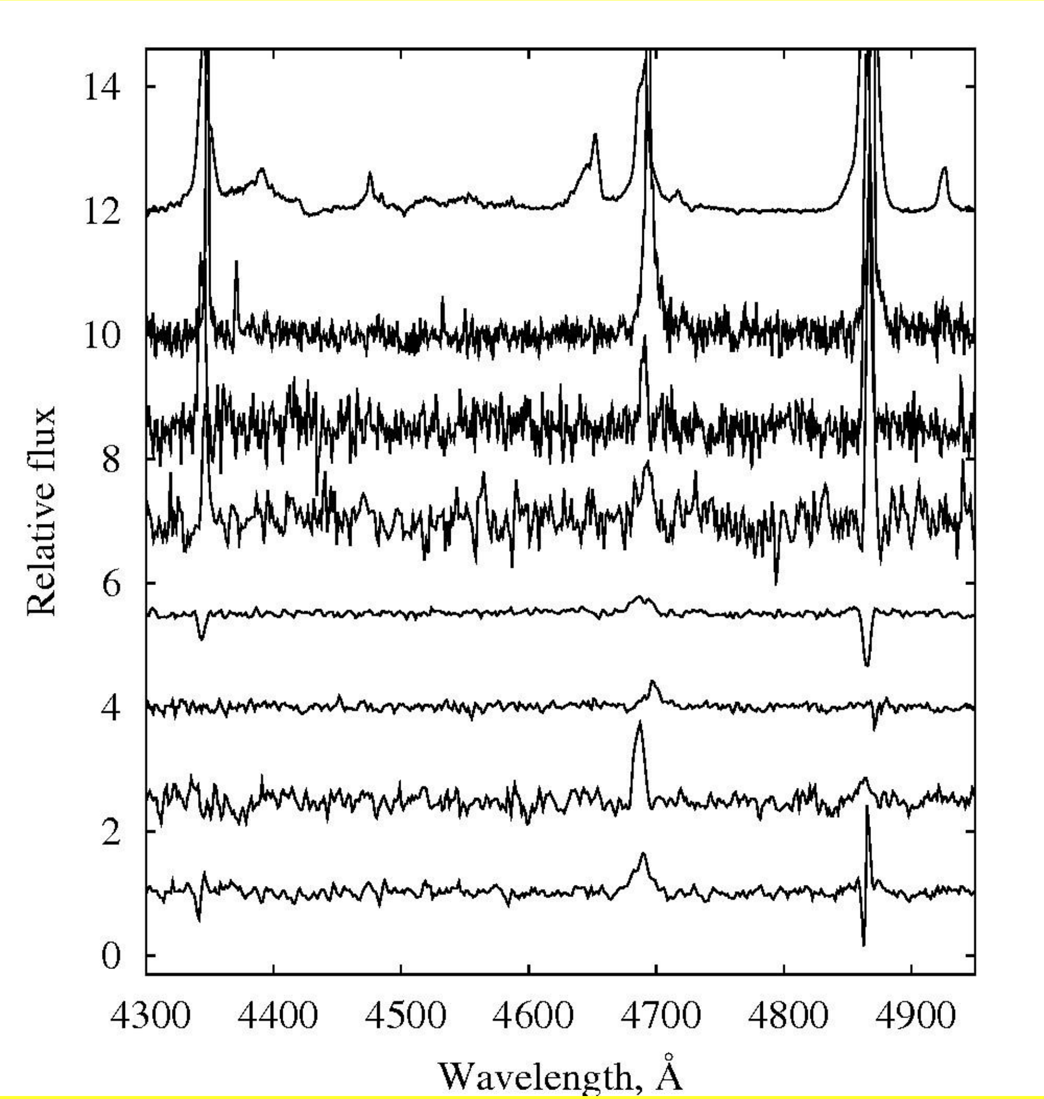
Momentum loss at SN explosion in binary (Zwicky, 1957; Blaauw, 1961; Shklovskii, 1976; van den Heuvel et al., 2000) produces a runaway speed of ~50 km/s (no time for the pre-SN evolution).

Kick velocity from SN (Woosley, 1987; Cordes & Chernoff, 1998) gives ~5 km/s for a black hole. No time, no velocity.
(but magneto-rotational SN-mechanism, Bisnovaty-Kogan, 1970)

Ejection of the binaries from clusters at their beginning stages of formation (Moeckel, Bate, 2010; Pflamm-Altenburg, Kroupa, 2010; +++) due to few-body encounters.

We confirm the current models of the cluster formation

Optical spectra of counterparts



SS433

NGC5408 X-1

NGC4395 X-1

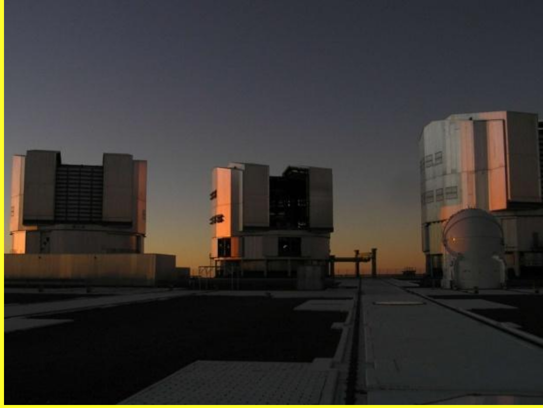
NGC1313 X-2

NGC5204 X-1

NGC4559 X-7

Holmberg IX X-1

Holmberg II X-1



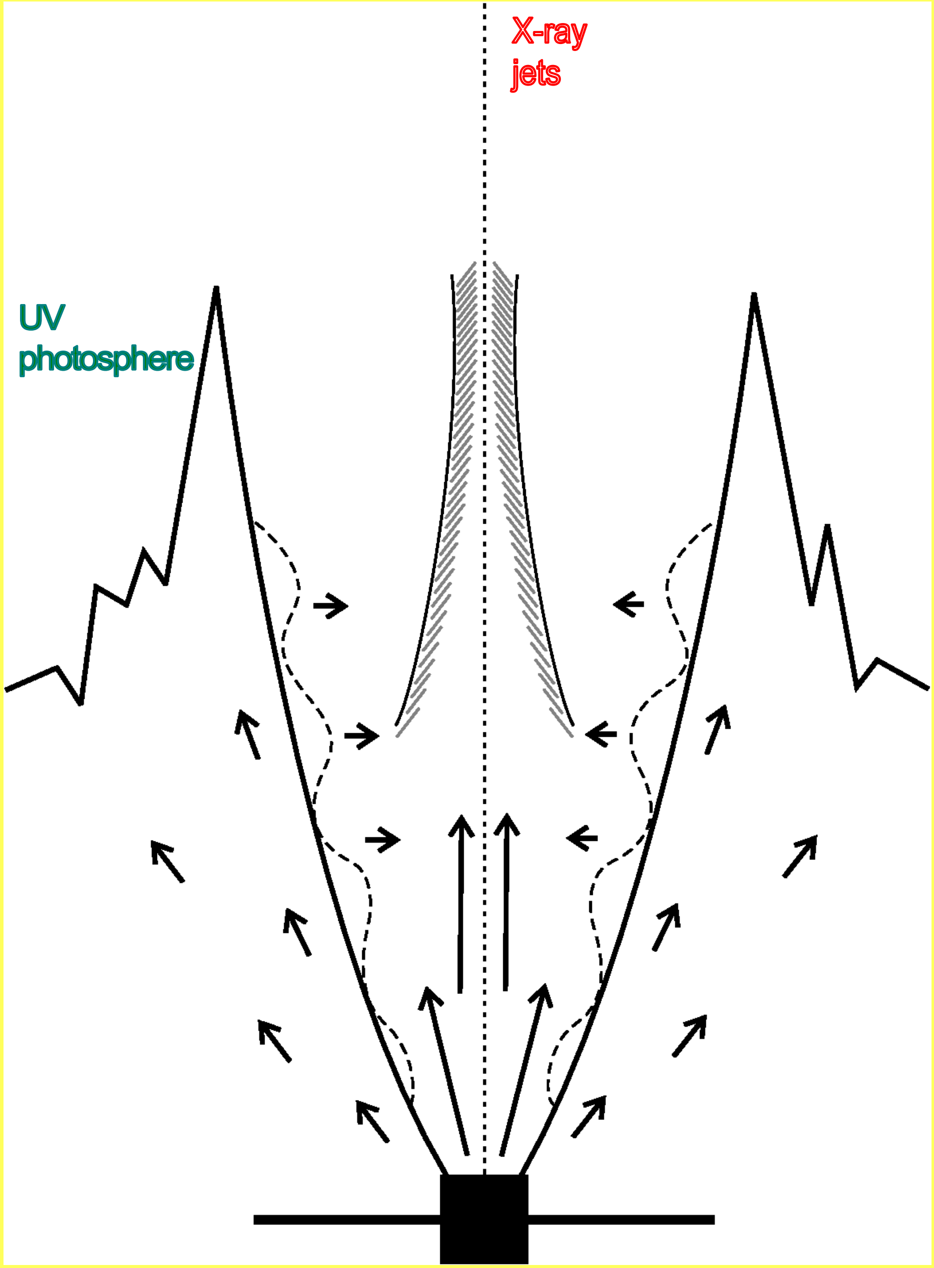
NGC5408, NGC1313

NGC4395 X-1

SS433, NGC5294, NGC4559,
Holm IX, Holm II

All studied ULX have broad HeII 4686 A and Hα.
That is high ionization wind: EW(HeII)/EW(Hβ) ≥ 2

The supercritical disk and its funnel in SS433



$\dot{M}_{wind} \sim 10^{-4}\ M_o$ /y

$T_{wind} \sim (5\text{-}7)\ 10^4$K

$V_{wind} \sim 1500$ km/s

$L_{bol} \sim 10^{40}$ erg/s

$L_X \sim 10^{36}$ erg/s

Jets: $L_k \sim 10^{39}$ erg/s

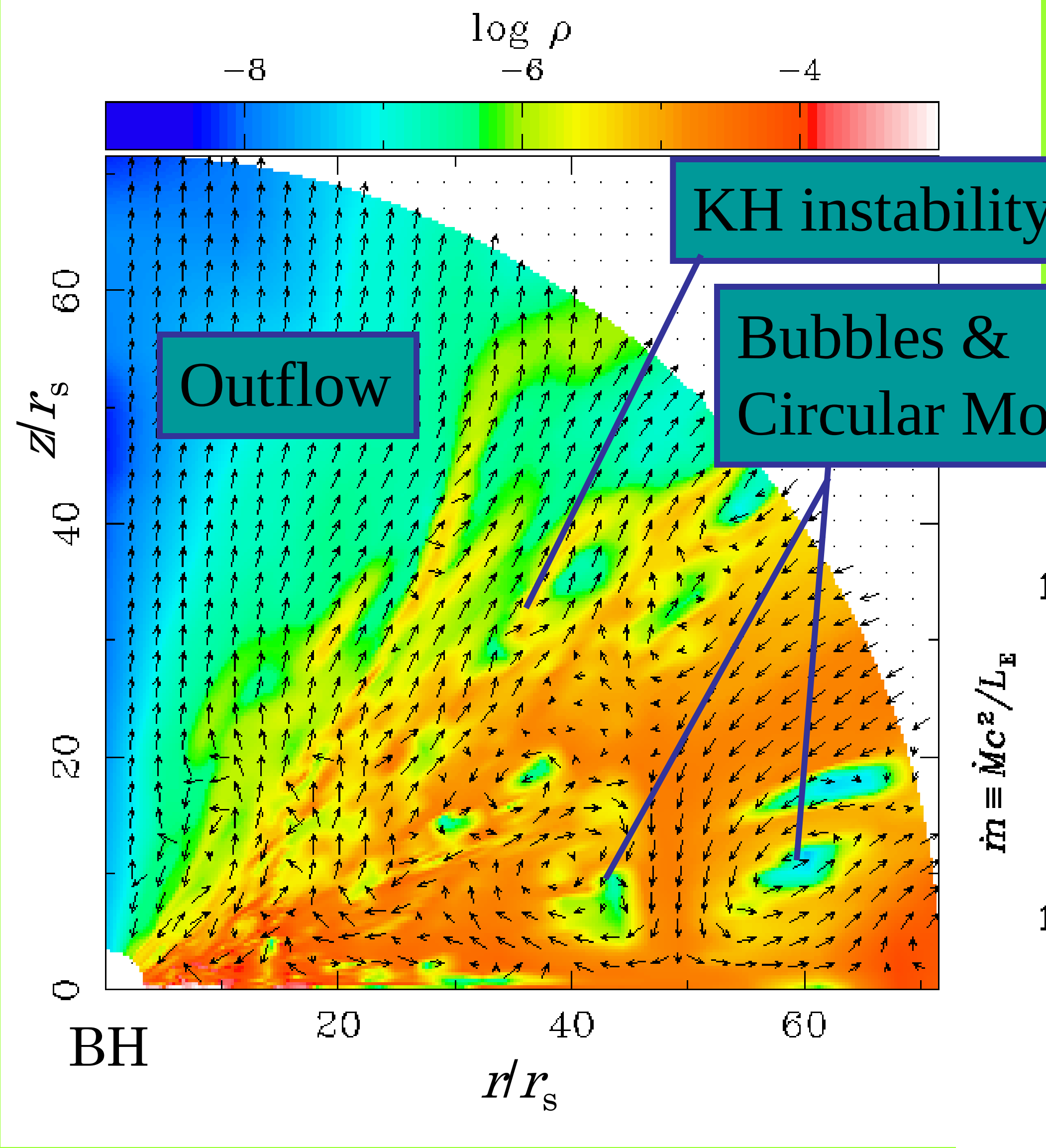
$2\ \theta_j \sim 1.5^o$

Funnel: $2\ \theta_f \sim 50^o$

Intrinsic X-ray budget of 10^{40} erg/s

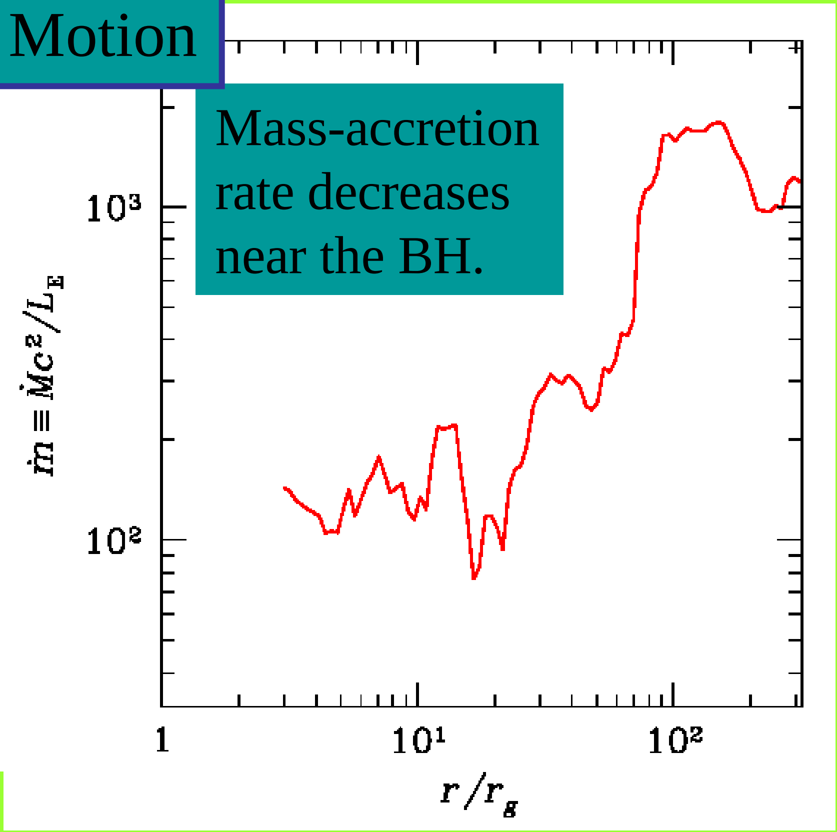
Quasi-steady Structure

Density & Velocity fields



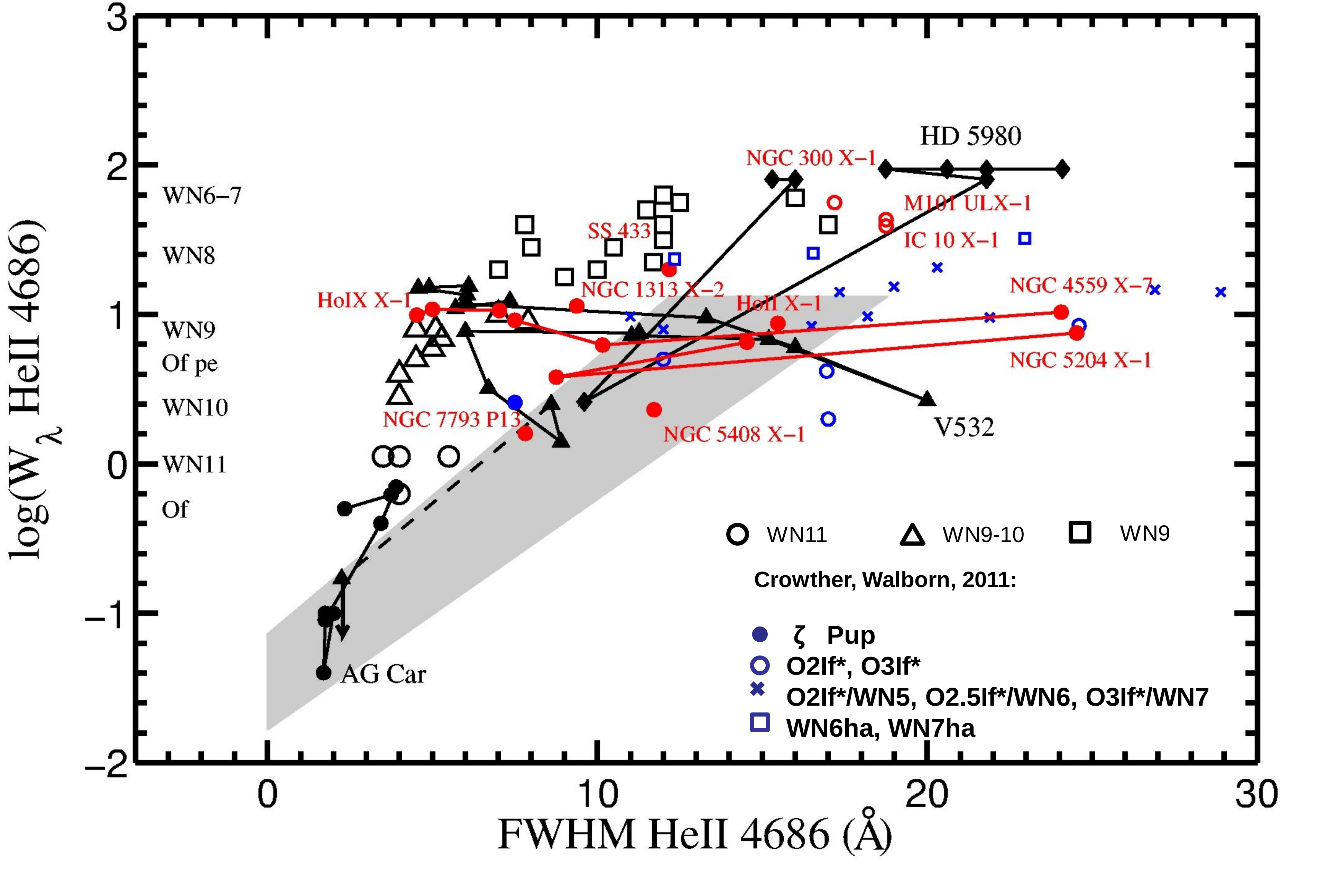
Ohsuga et al. 2005, ApJ, 628, 368

Mass-Accretion Rate



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

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



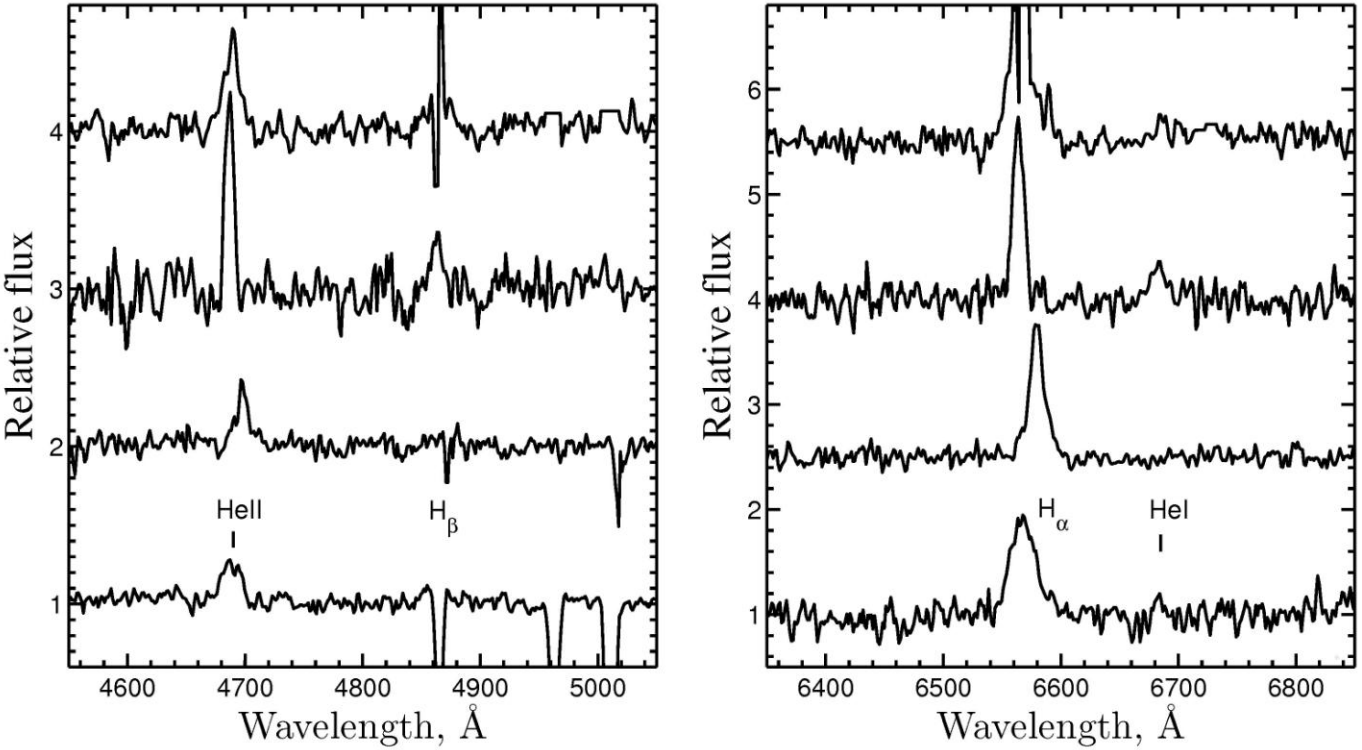
All the nearby persistent ULXs ($L_x > 2\text{-}3\ 10^{39}$ erg/s) ever spectroscopically observed, have the same optical spectra.

(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)

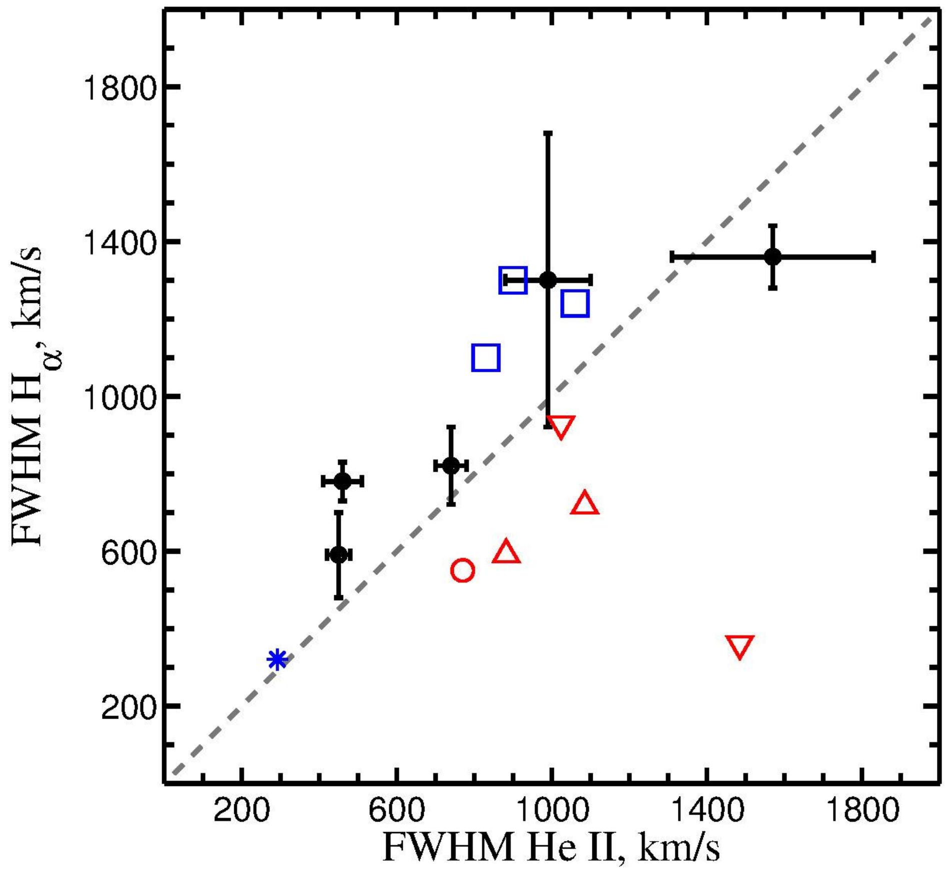
They must constitute a homogeneous class of objects (less that 1% may have another), which most likely have super-Eddington disks



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

Fabrika et al. 2015

Super-Eddington or irradiated disk?



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)

LBV Romano star (V532) in M33

WR22 (WN7ha), WR24 (WN6ha),
WR25 (WN6ha)

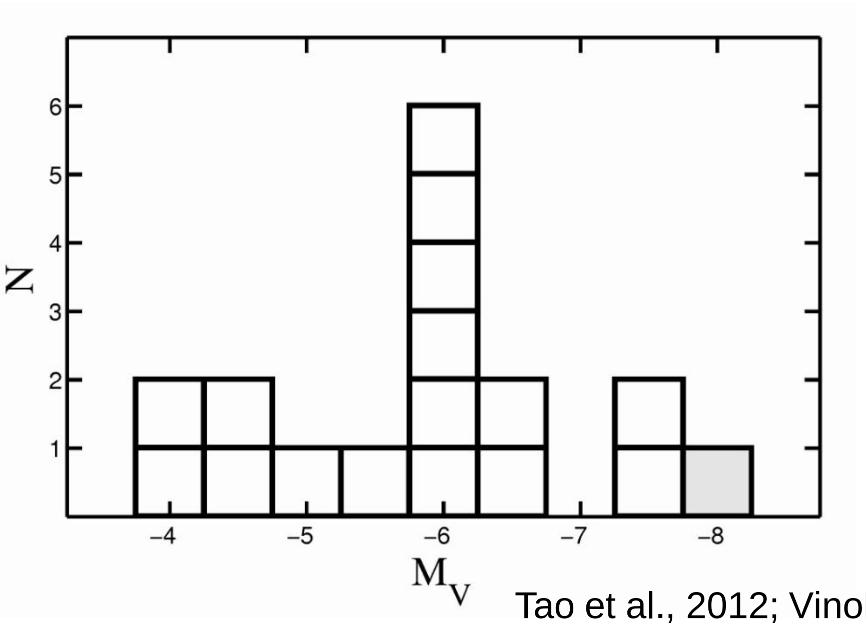
GX339-4 (Soria et al. 1999; Rahoui et al. 2014)

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

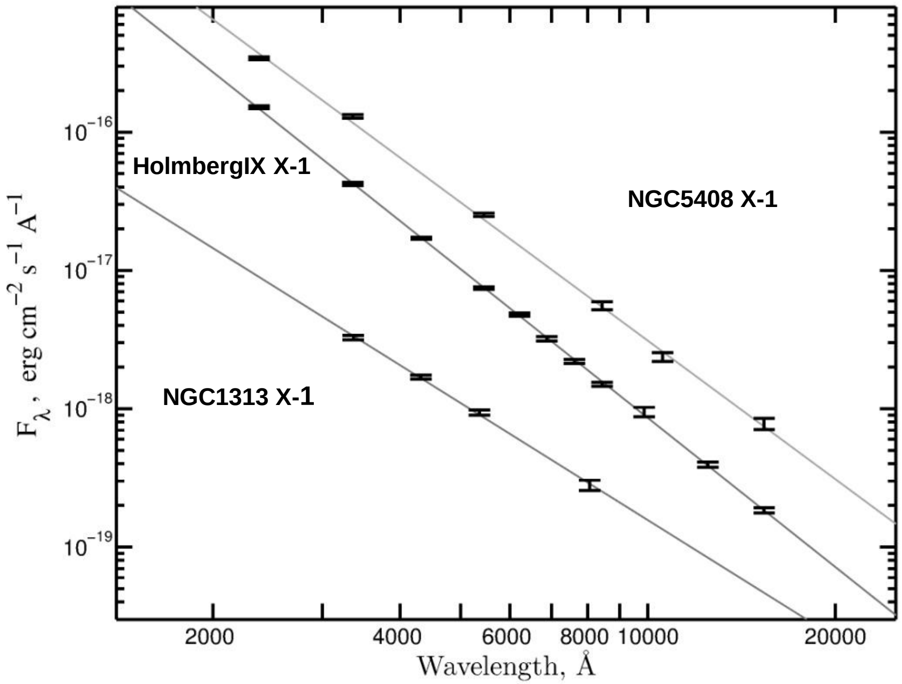
In super-Eddington disks X-ray luminosity logarithmically depends on the accretion rate $$L_X \propto L_{Edd}(1 + a\ln(\dot{M}/\dot{M}_{Edd}))$$

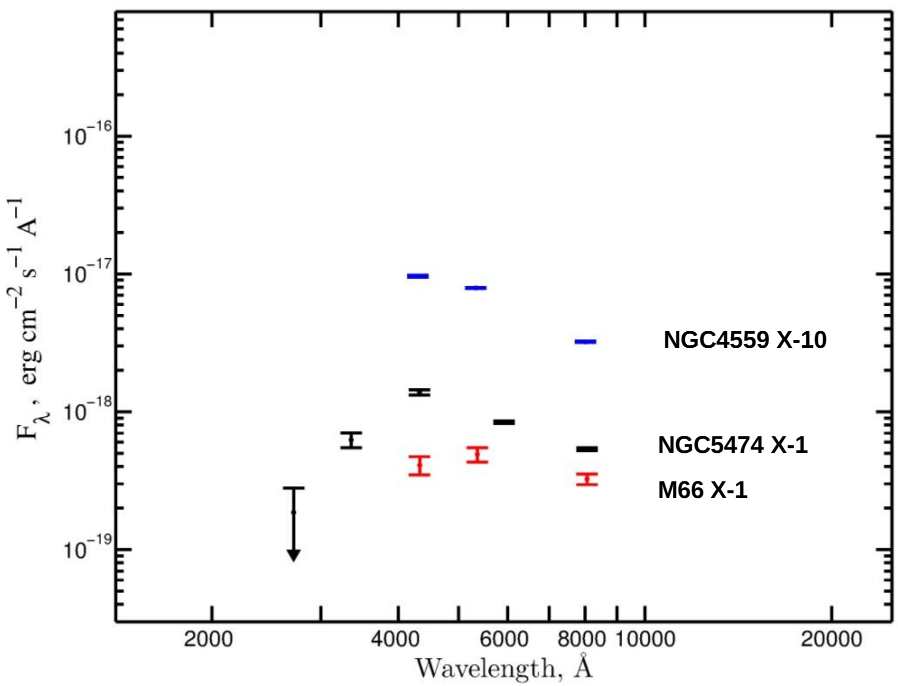
L_{Edd} - Eddington luminosity, $\dot{M}_{Edd}$ - Eddington rate

UV/optical luminosity strongly depends on the accretion rate $$L_V \propto \dot{M}^{9/4} M^{-1/2}, \; T_{ph} \propto \dot{M}^{-3/4} M^{1/2}$$

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.

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





HST data

corrected for reddening, for 5 Mpc distance

NGC5408 X-1 (x4), $\alpha = 3.35$
Holmberg IX X-1 (x2), $\alpha = 3.58$
NGC1313 X-1 (x1), $\alpha = 2.81$

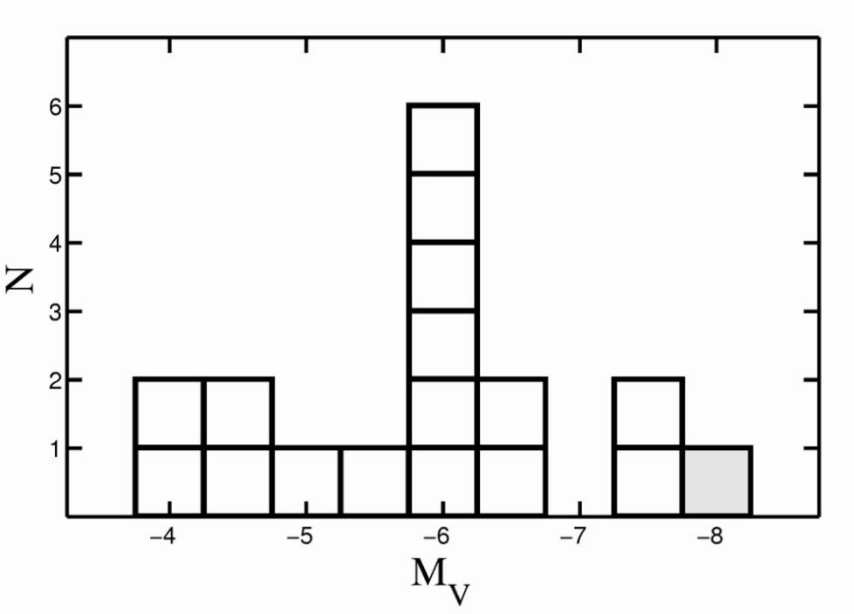
$F_\lambda \propto \lambda^{-\alpha}$

For Raileigh-Jeans BB tail $\alpha = 4$

F-G-type spectra:

NGC4559 X-1 (x4)
NGC5474 X-1 (x2)
M66 X-1 (x1)

all have $M_V > -5.3$



what about this histogram?

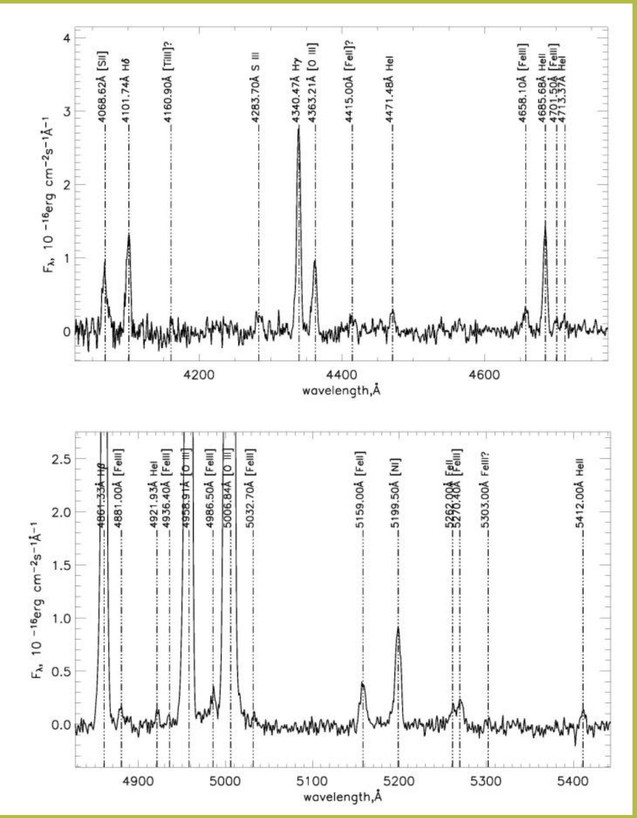
1. Selection effect, objects may be missed in galaxies farther than 10 Mpc

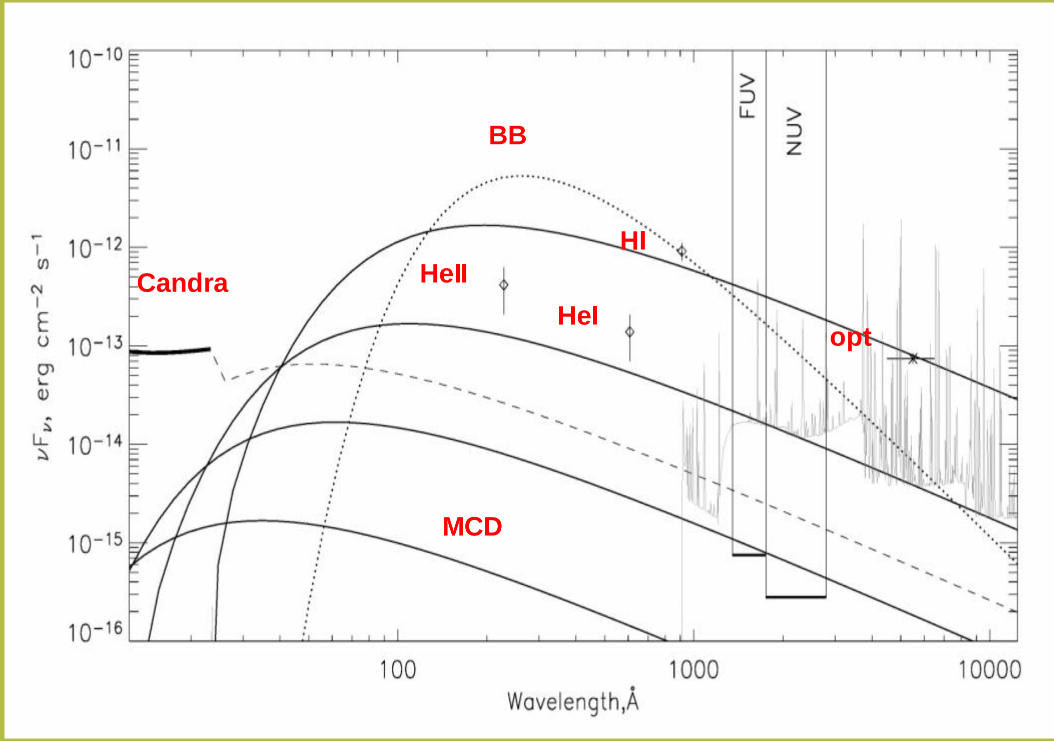
2. With decreasing an accretion rate the optical luminosity does decrease. The donor star becomes dominating. Three of six objects with M_V > -5.3 have F-G type spectra. (Avdan et al. 2016, Vinokurov et al. 2016)

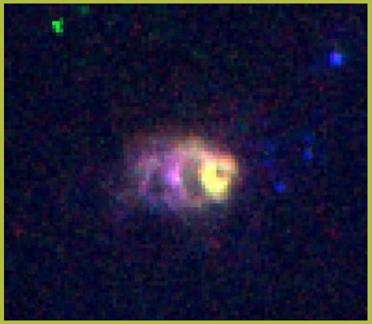
All studied ULXs $L_X / L_{opt} > 200$ (Avdan et al., 2016)

MF16 nebula around NGC6946 ULX-1

Abolmasov et al. 2008

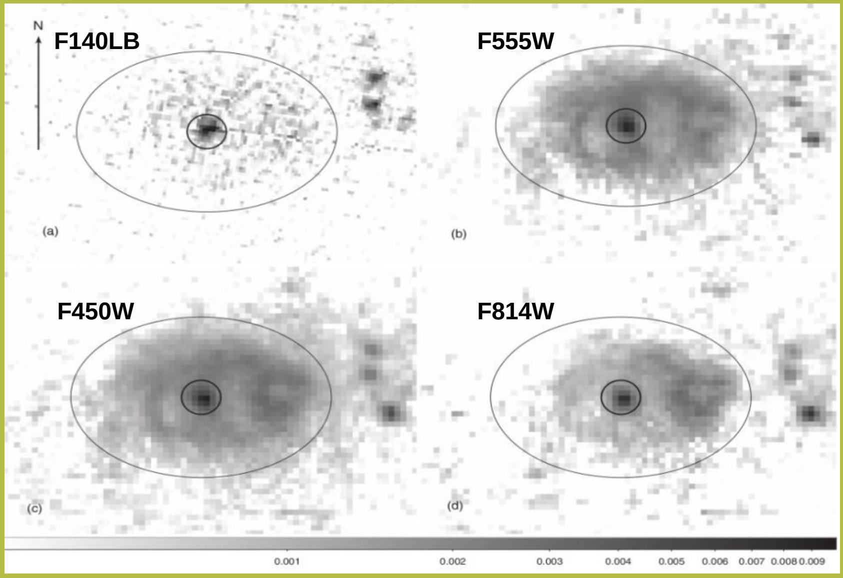




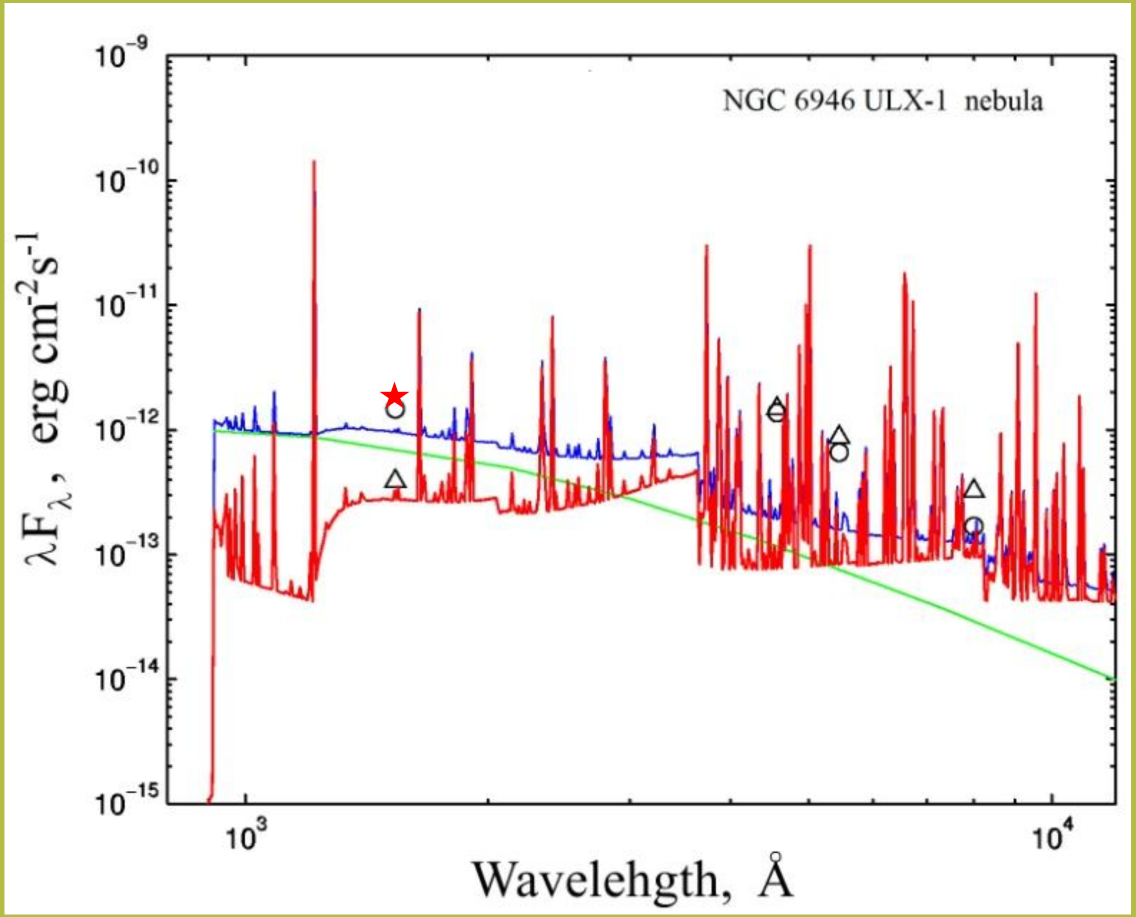


Kaaret et al. 2010:

the nebula 3 times brighter in FUV that the source

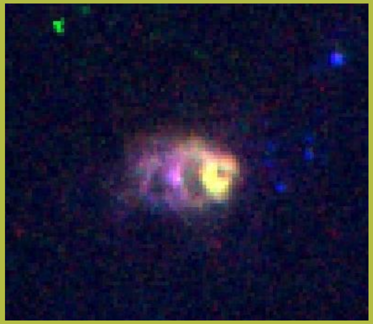


MF16 nebula around NGC6946 ULX-1
Cloudy model by A. Vinokurov



red – Cloudy model
green – SCAD model after passing through the nebula
blue – red + green
circles – HST date (nebula only)
triangles – Cloudy model in the filters

★ **- Kaaret et al. L140LB point**



The MF16 nebula cannot be ionized by X-rays, but FUV radiation

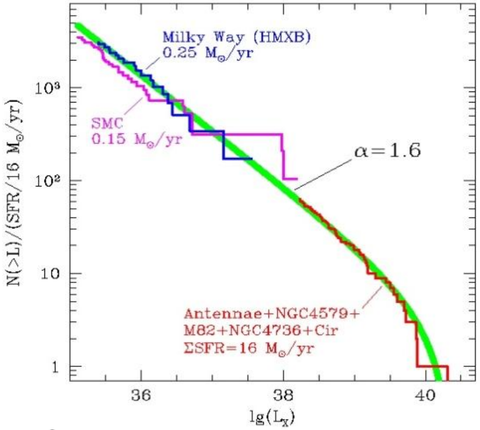
ULXs are close binaries with masses higher than 50 solar masses in each companion.

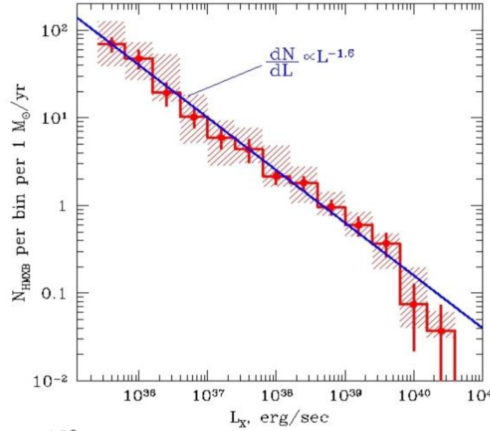
They are super-Eddington accretion disks surrounding stellar-mass black holes ~ 10 solar masses. They produce strong and hot winds from the disks.

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

Thank you

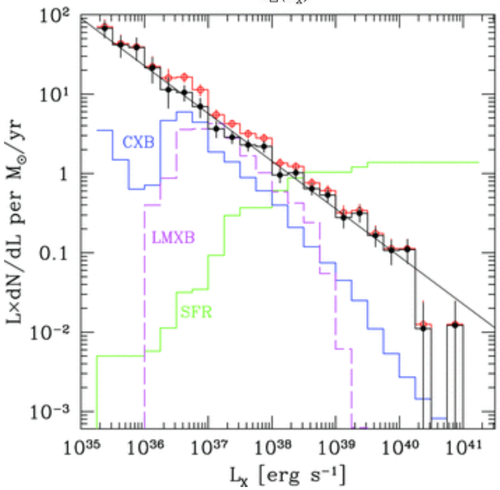
X-ray luminosity functions, XLF

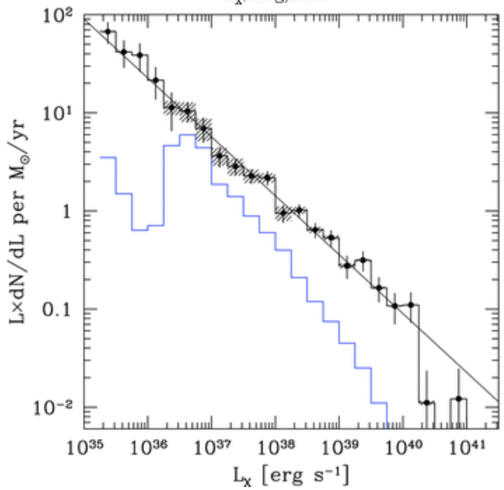




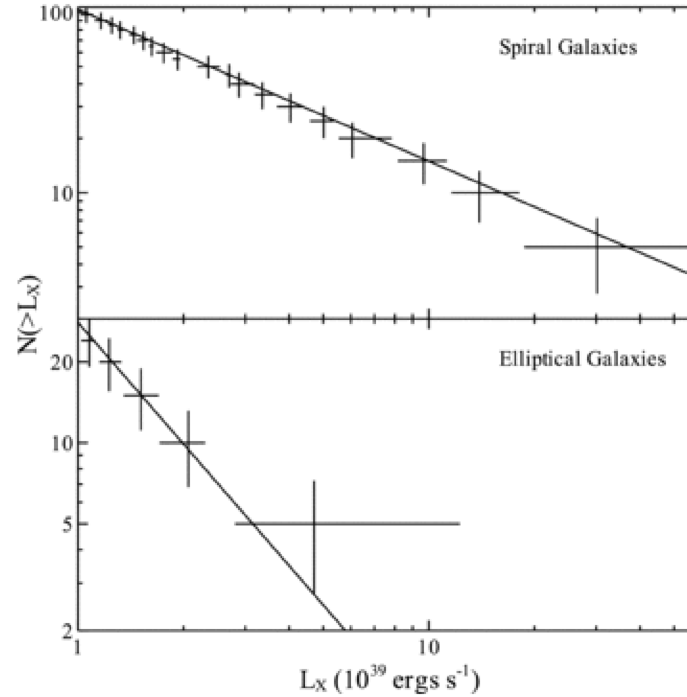
«an universal» LF

(Gilfanov, Grimm, Sunyaev, 2003)

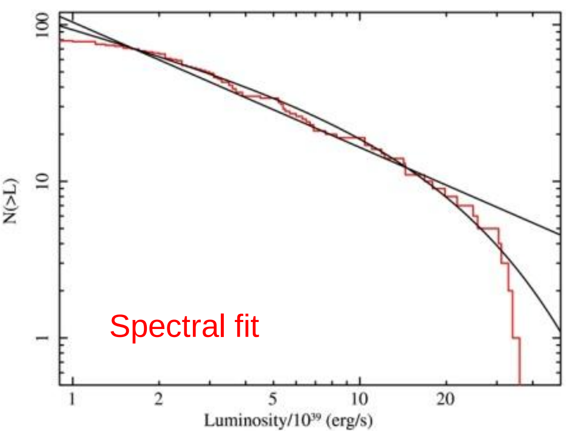


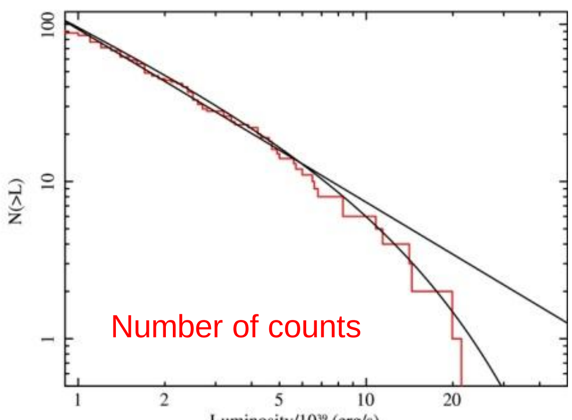


Mineo, Gilfanov, Sunyaev, 2012



However, 2XMM survey: Walton et al 2011





Swartz et al. 2011