KOOLS-IFUによるブラックホール形成環境の解明

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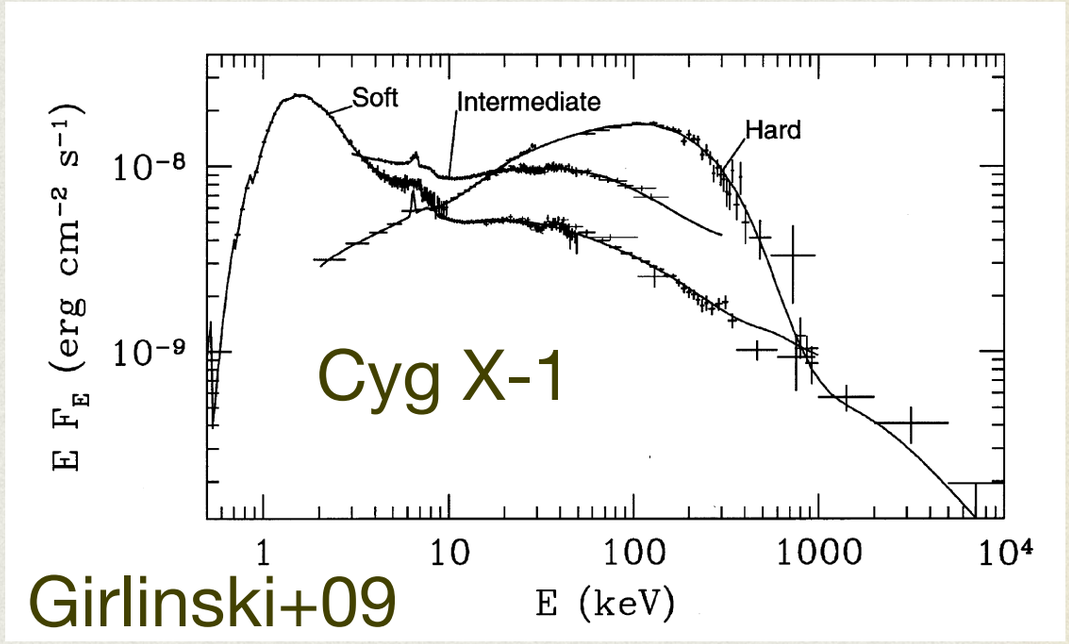
Ultra-luminous X-ray sources (ULXs)

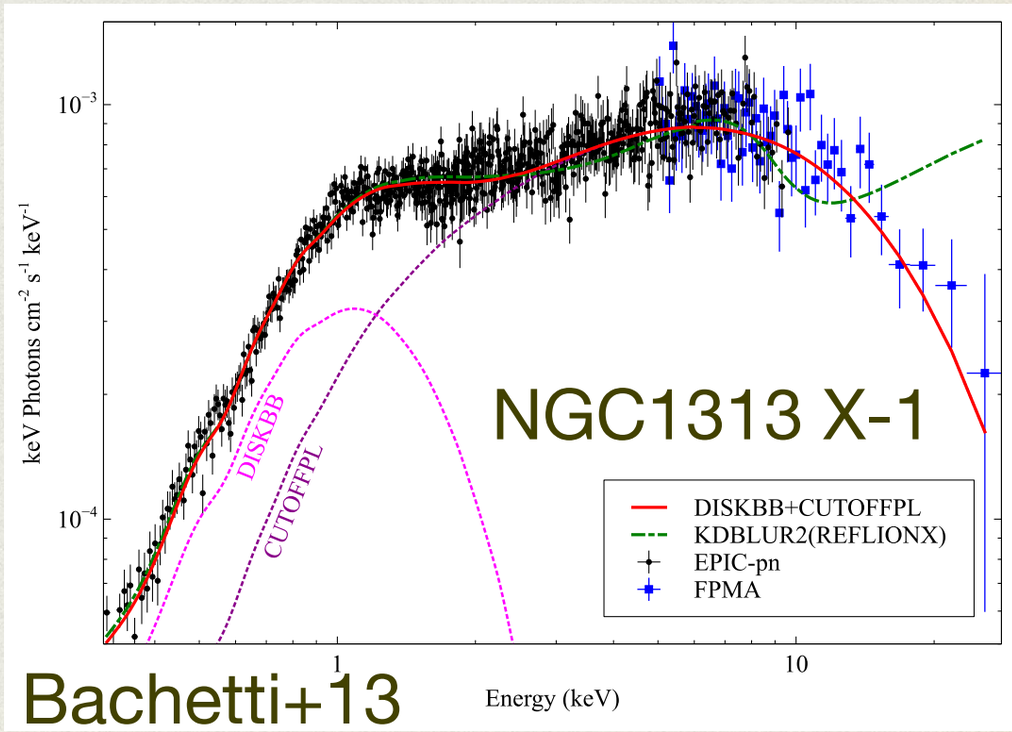
- ULXs are extra-galactic X-ray binary (XRB) systems with $L_X > 10^{39}$ erg/s at off-nucleus position

- A large variety of X-ray spectral shapes (Gladstone+09)
  - Different from Galactic X-ray binaries
  - Cut-off at 10 keV?

- The origin of ULXs
  - Stellar mass BHs with M_{BH}~10 M_{sun}? (e.g. Gladstone+09)
  - Intermediate mass BHs with M_{BH}>>10 M_{sun}? (e.g, Makishima+00)
  - Neutron stars? (e.g., Bachetti+13)
  - or combination of these scenarios?



Girlinski+09

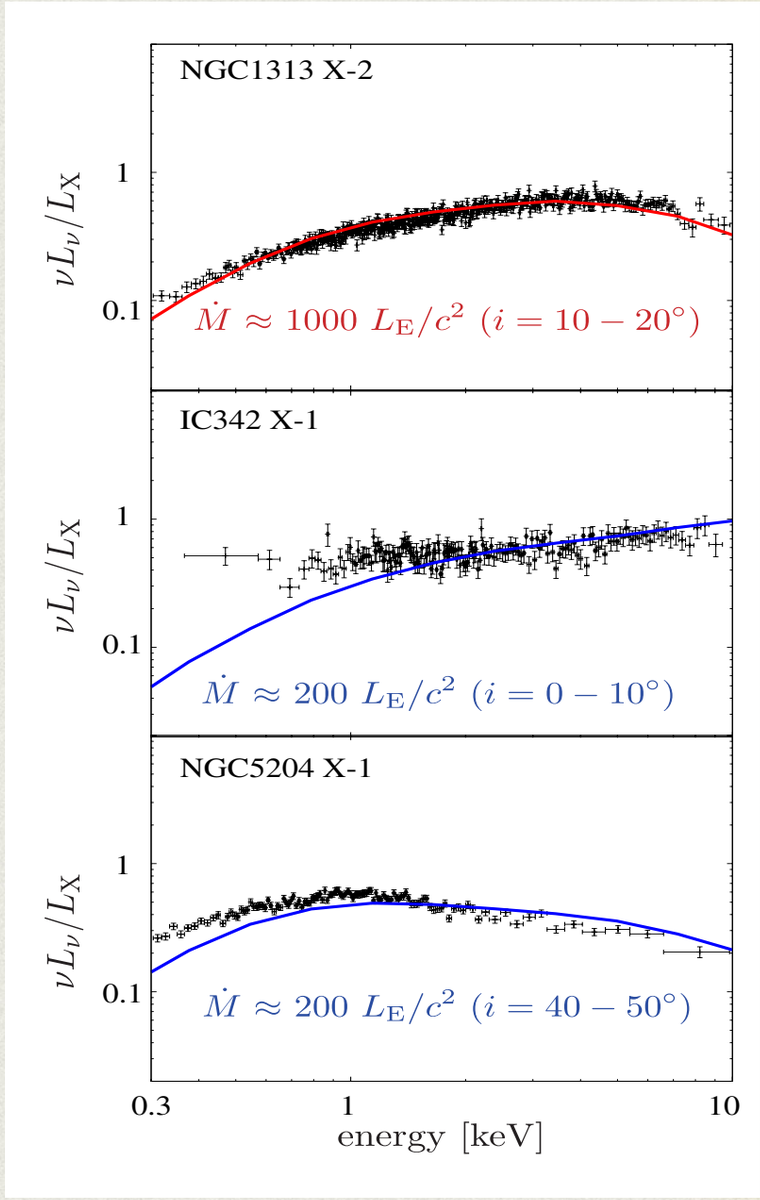


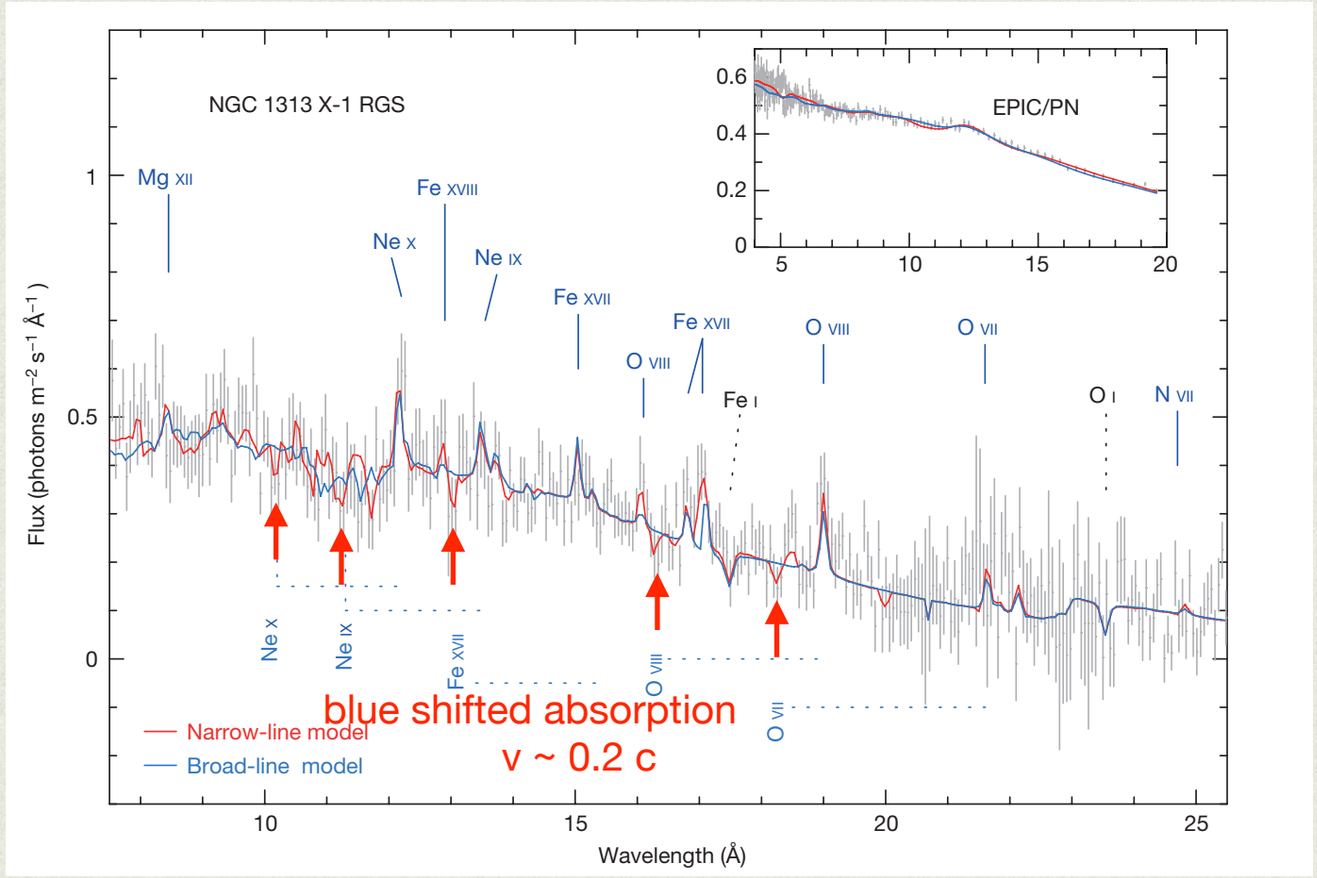
Bachetti+13

Stellar mass black hole scenario

- Supercritical Accretion (e.g., Ohsuga+09)
  - dM/dt >> dM_{Edd}/dt
  - v~0.3 c outflow is predicted
- Observed X-ray spectra of ULXs can be explained by this scenario (e.g., Kawashima+12)
- A possible evidence of the associated outflow has been reported (Pinto+16)

Kawashima+12

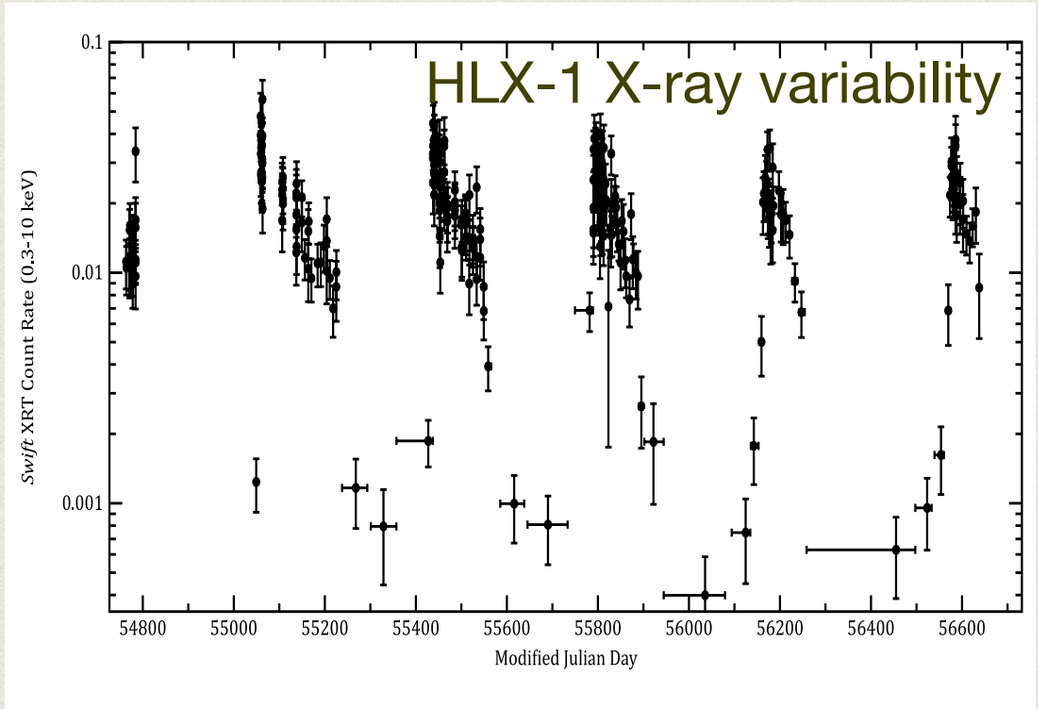




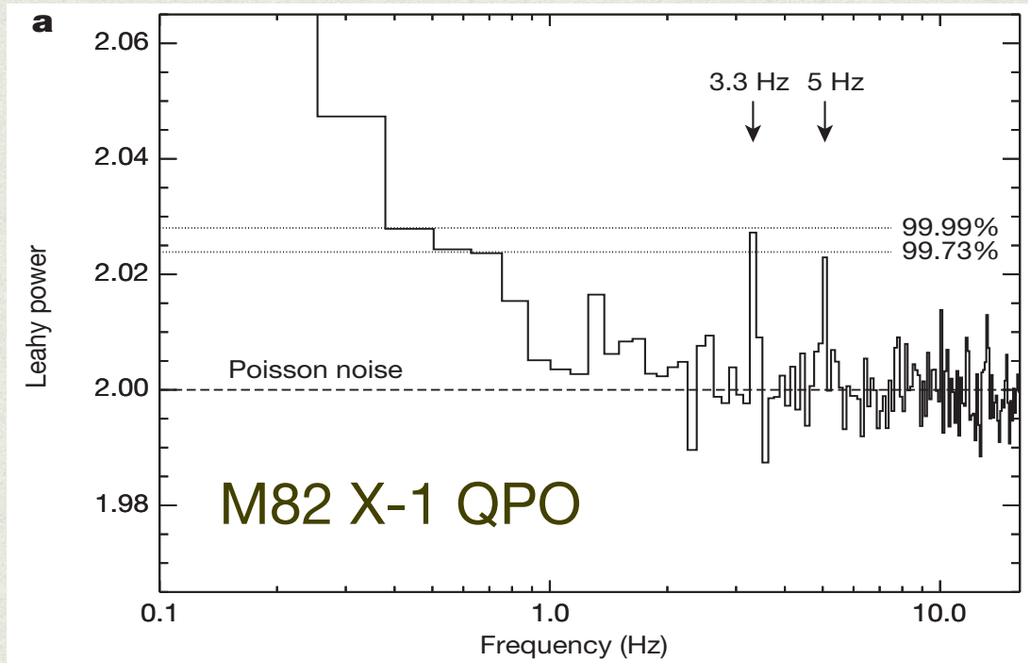
Pinto+16

Intermediate mass black hole scenario

- HLX-1
  - L_X ~ 10^{42} erg/s
  - State transition (Farrell+09)
  - Radio flares observed (Webb+12)
  - M_{BH} ~ 10^4 M_{sun}?
- M82 X-1
  - L_X ~ 10^{41} erg/s
  - Quasi-periodic oscillations (QPOs) with 3:2 frequency are detected (Pasham+14)
  - M_{BH} ~ 500 M_{sun}?
- Some evidences for NGC 2276 X-1 and others ...

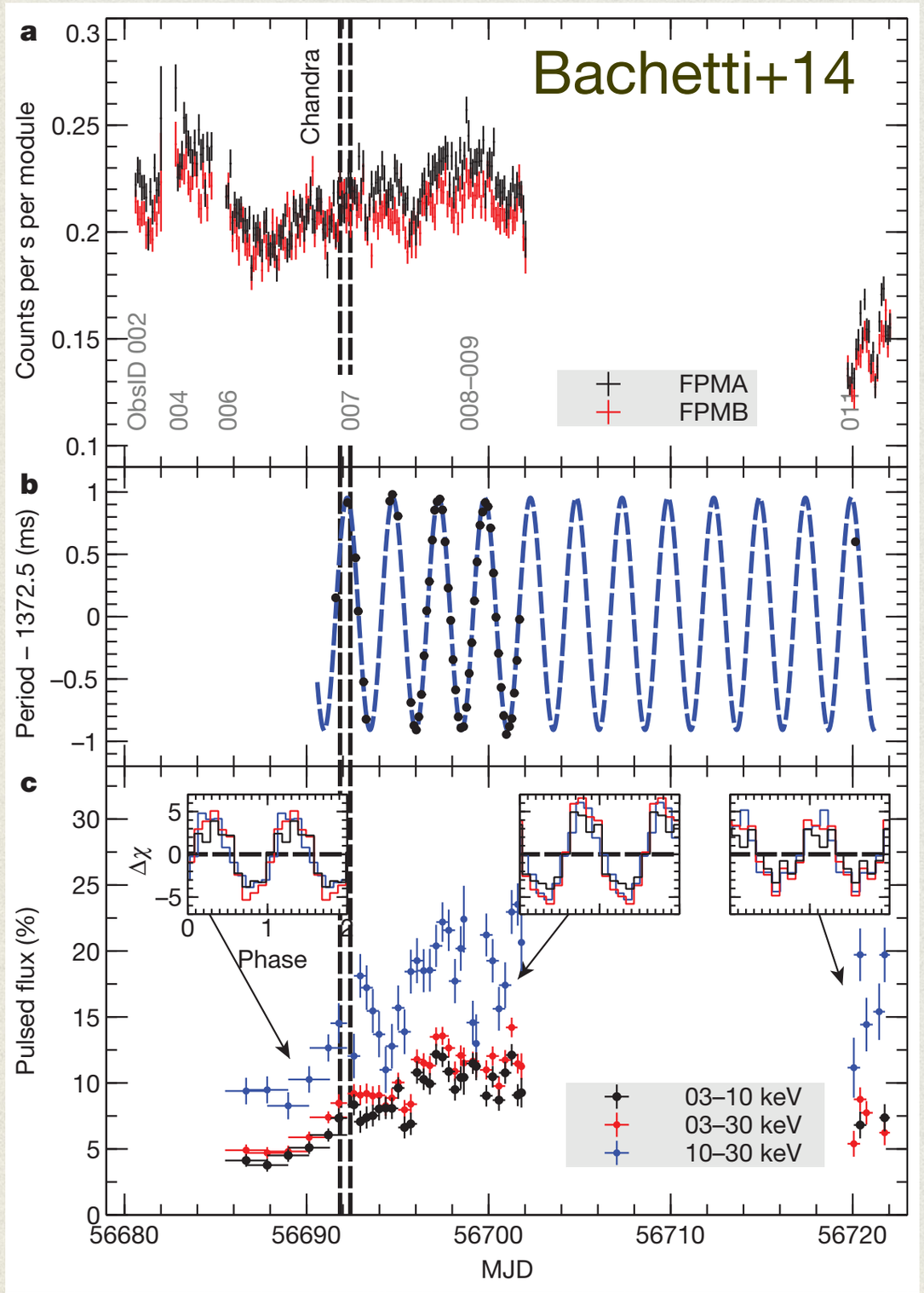


Webb+14

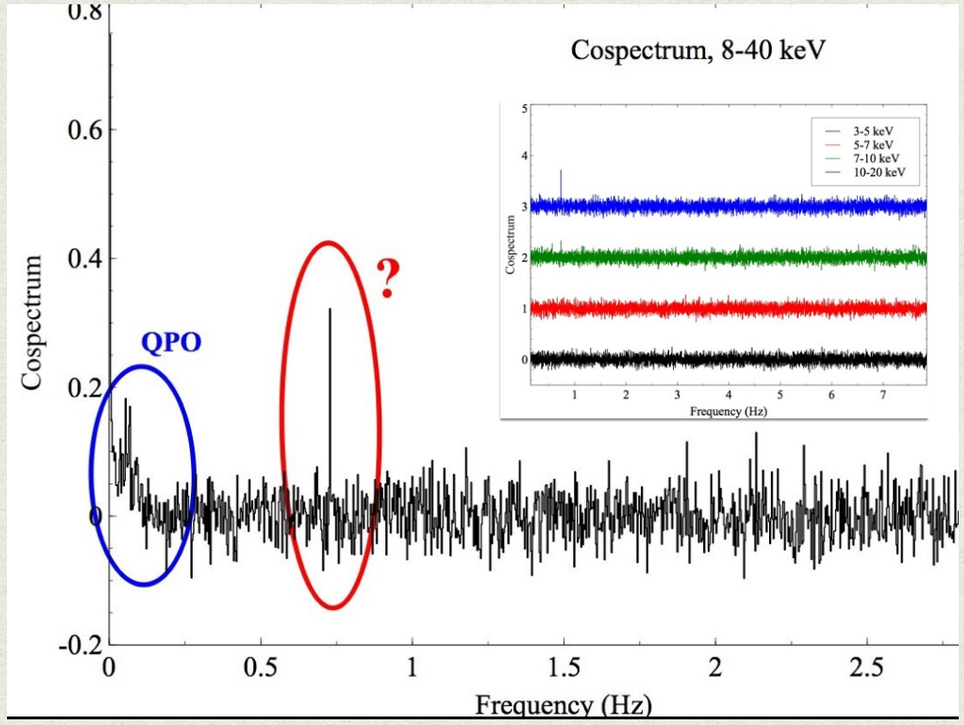


Pasham+14

Neutron star scenario



- M82 X-2 (L_X ~ 10^{40} erg/s)
  - QPO of 3-4 mHz (Feng+10)
  - Intermediate mass BH?
- A pulse feature is discovered with NuSTAR (Bachetti+14)
  - Pulsars can host ULXs
  - Only 3 known ULX pulsars

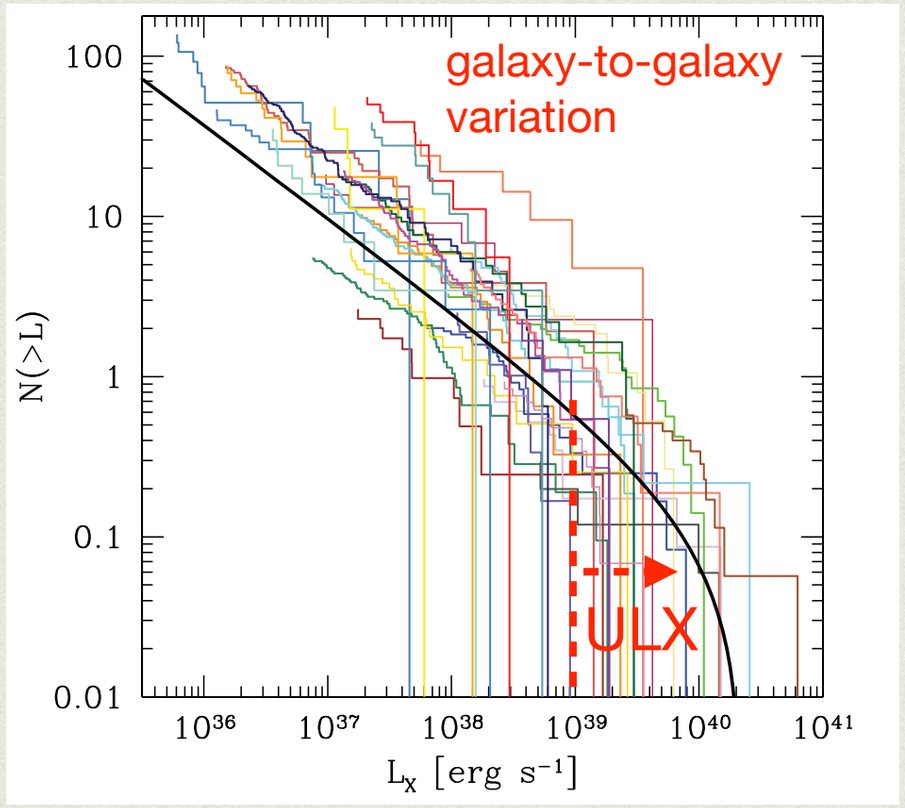


Bachetti+15

Luminosity function (LF) of ULXs

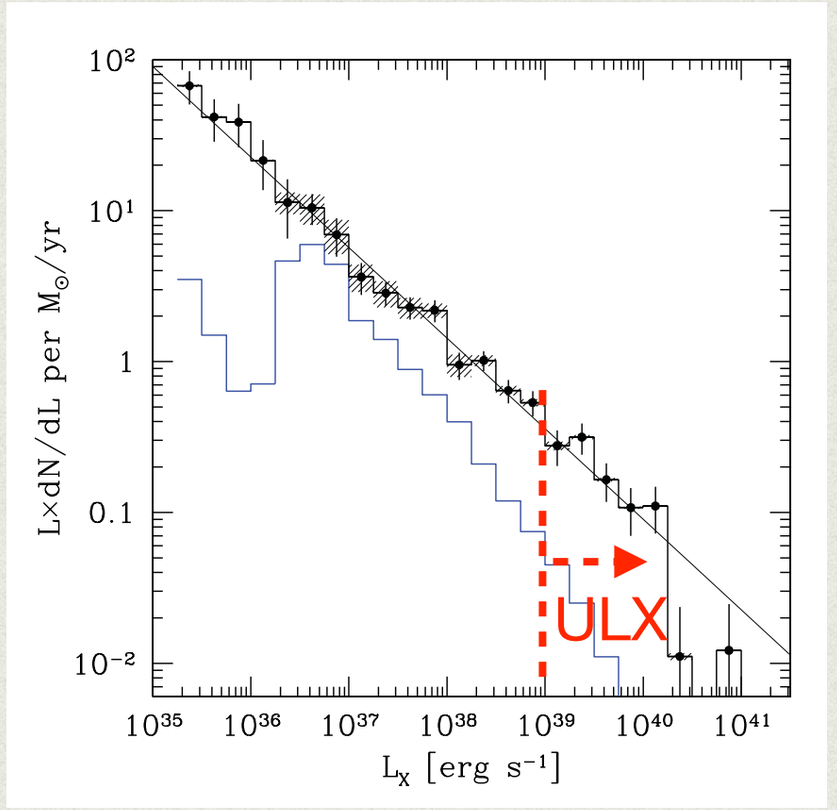
- XRB luminosity function is known to be correlated with star formation rate (e.g., Mineo+12)
- A simple power-law (γ~1.6) + cutoff over 10^{40} erg/s (e.g., Grimm+03, Swartz+11, Walton+11, Mineo+12)
- Single or multiple population?

XRB LF in each galaxy



Mineo+12

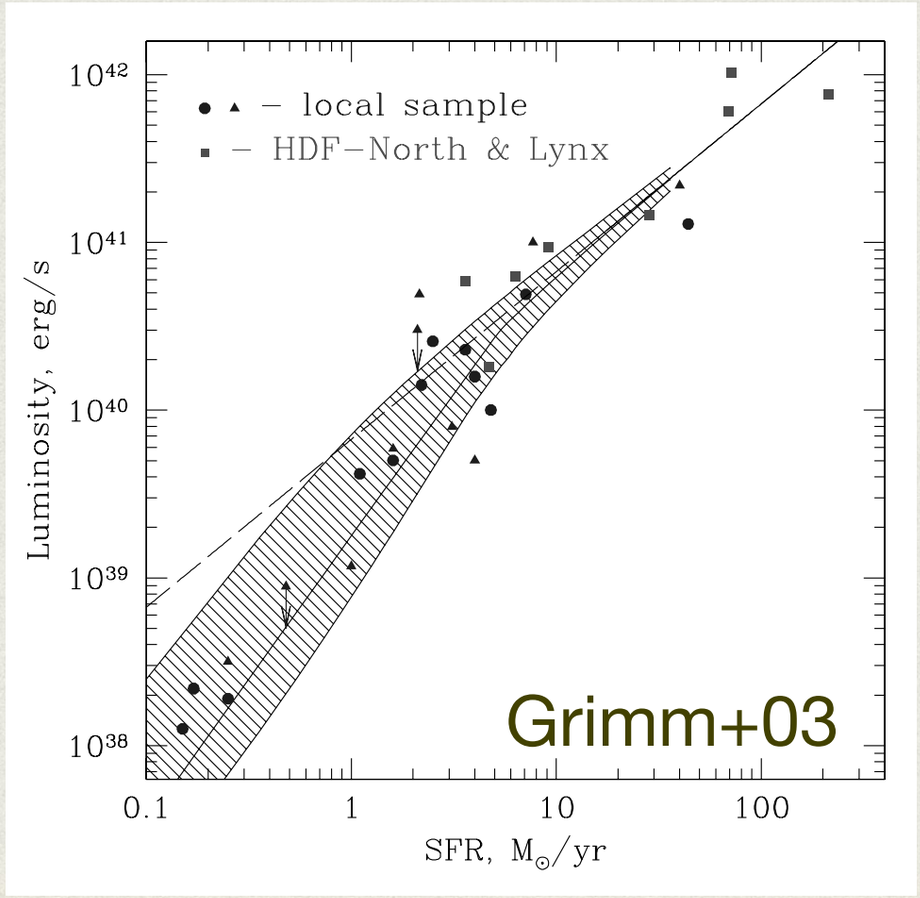
SFR normalized XRB LF

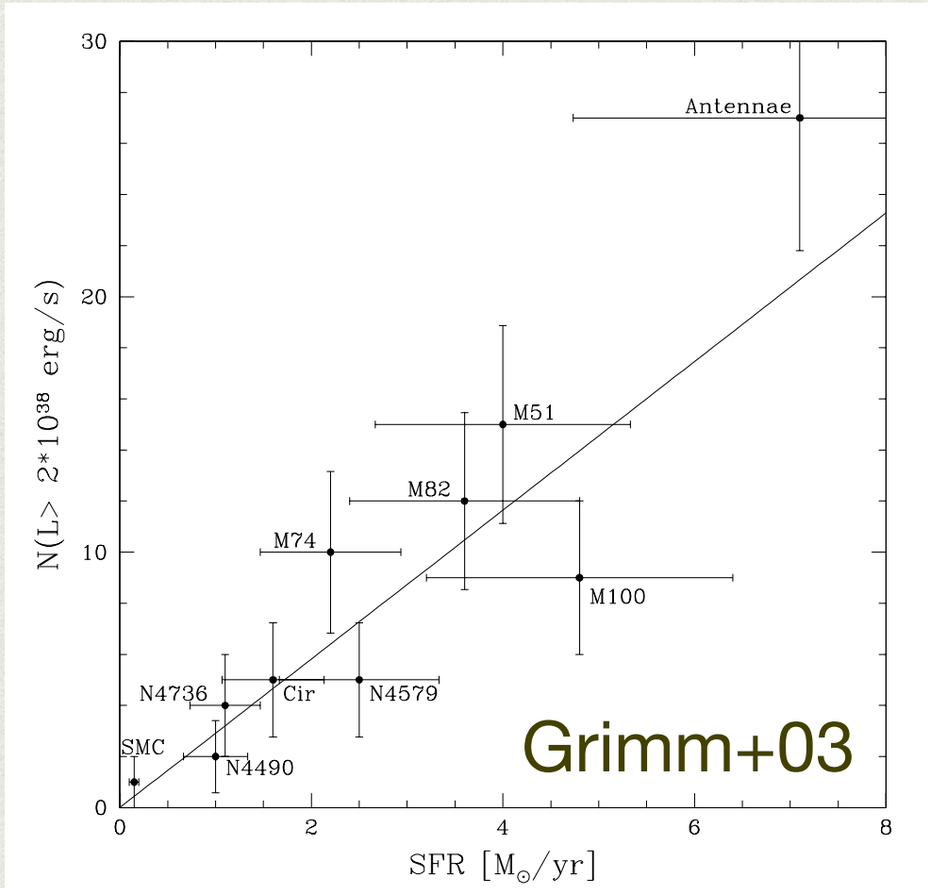


Mineo+12

X-ray binary system as a tracer of galaxy SFR

- These populations are a good tracer of the star-formation rate of the host galaxies (e.g., Grimm+03)
  - The number of HMXBs increases with increasing host SFR
  - $L_X \propto SFR^{\sim 1.7}$



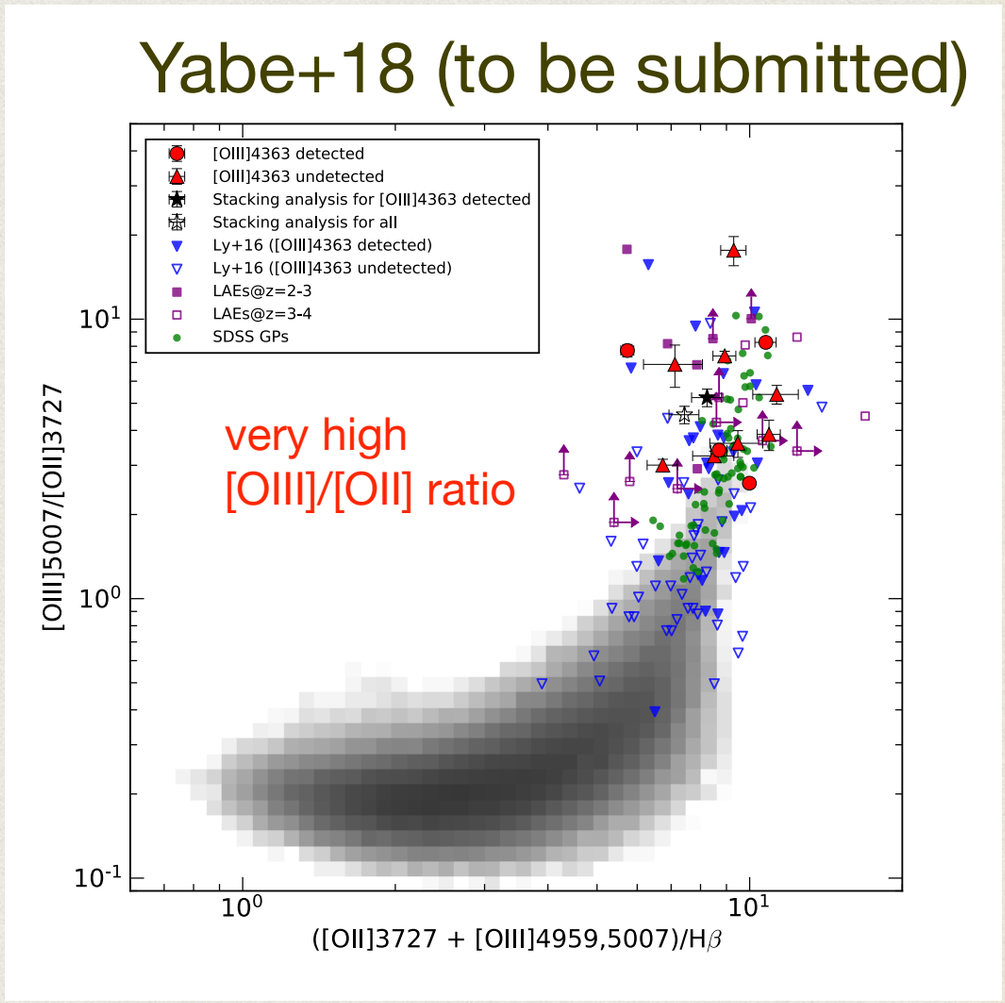


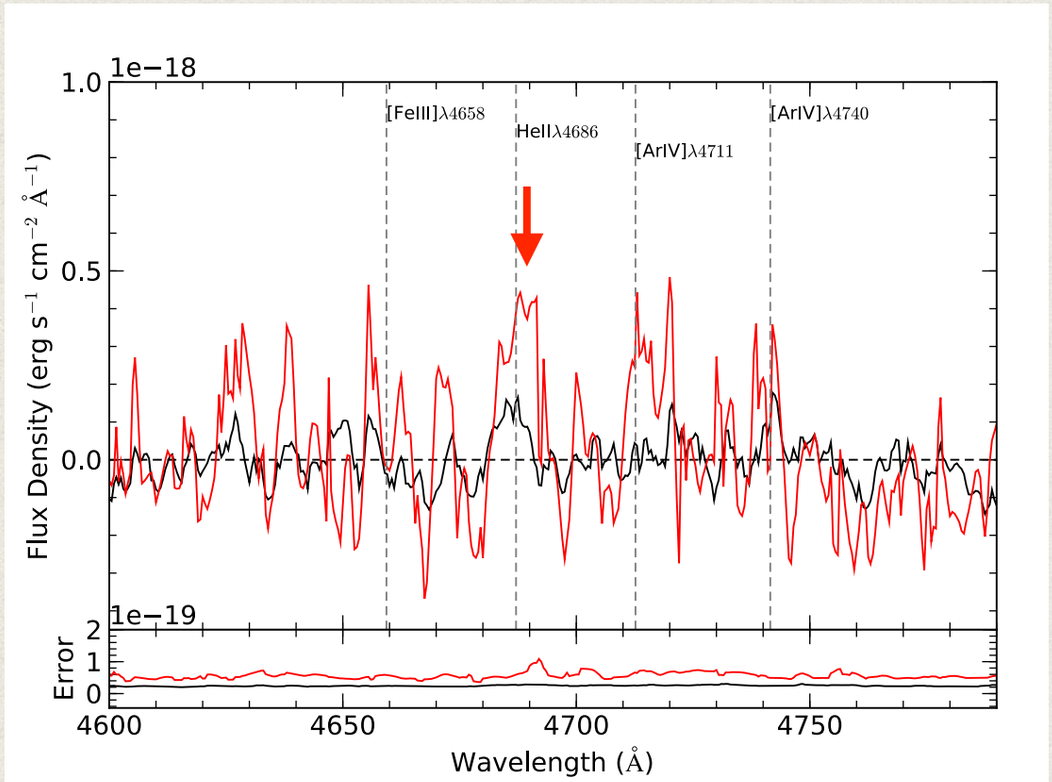
- Good correlations with other SFR indicators such as far-infrared (FIR) and radio (1.4GHz) luminosity (e.g., Ranalli+03)

XRB contribution to spectra of metal poor galaxies?

- Strong emission line galaxies at z=0.4-0.9 discovered by Subaru/HSC
  - Very low-mass ($10^{7\text{-}9}$ M_{sun})
  - High specific SFR (10-1000 x MS)
  - Metal poor ($Z < 0.2\ Z_{sun}$)
  - Extreme [OIII]5007/[OII]3727 ratio
- Similar to those in the early Universe

Yabe+18 (to be submitted)



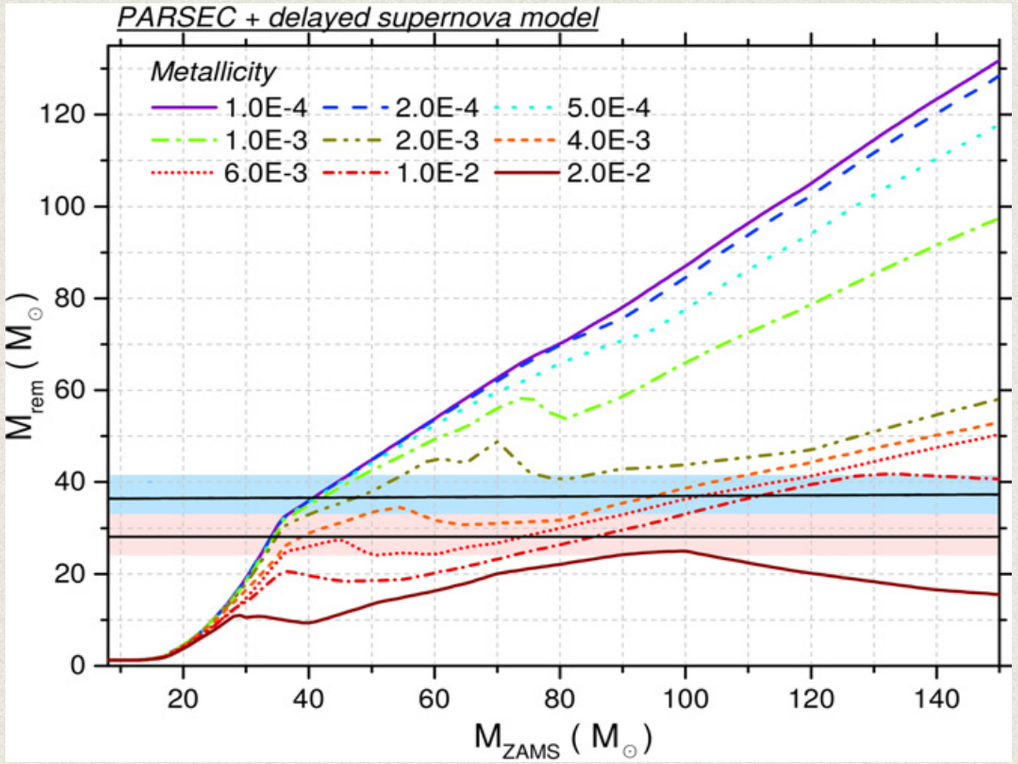


Yabe+18 (to be submitted)

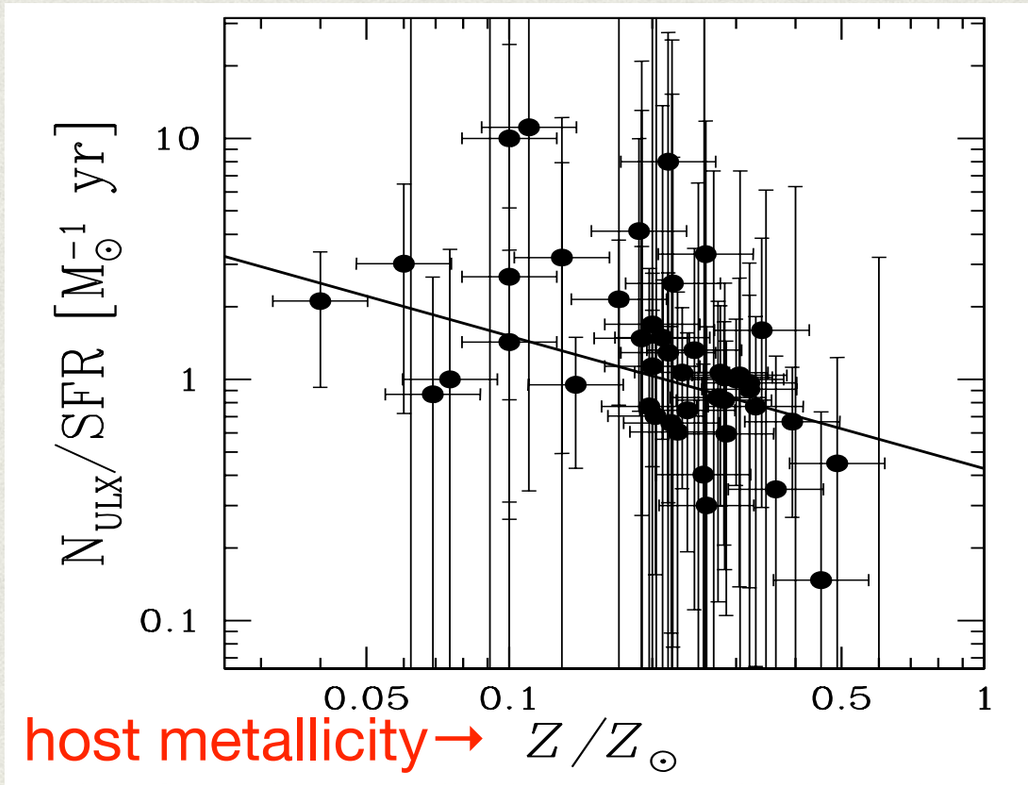
- HeII λ4686 detected
  - WR (or O-stars)? (e.g.,Crowther+06)
    → but no clear WR feature?
  - Shock? (e.g., Dopita+96)
  - HMXB? (e.g., Garnett+91)
  - ...

Motivation of this work

- What kind of environment ULXs/XRBs are in?
  - Are ULXs and XRBs in different environment?
  - Massive BHs are hard to form in metal rich environment (e.g. Spera+15)
  - If ULXs are very massive BHs in origin, they are presumably in low-metal environment
  - ULX host galaxies have $Z < 0.5\ Z_{sun}$ (Mapelli+10)
- The local environment of ULXs/XRBs remains unclear, and detailed examination (especially spectroscopically) is indispensable



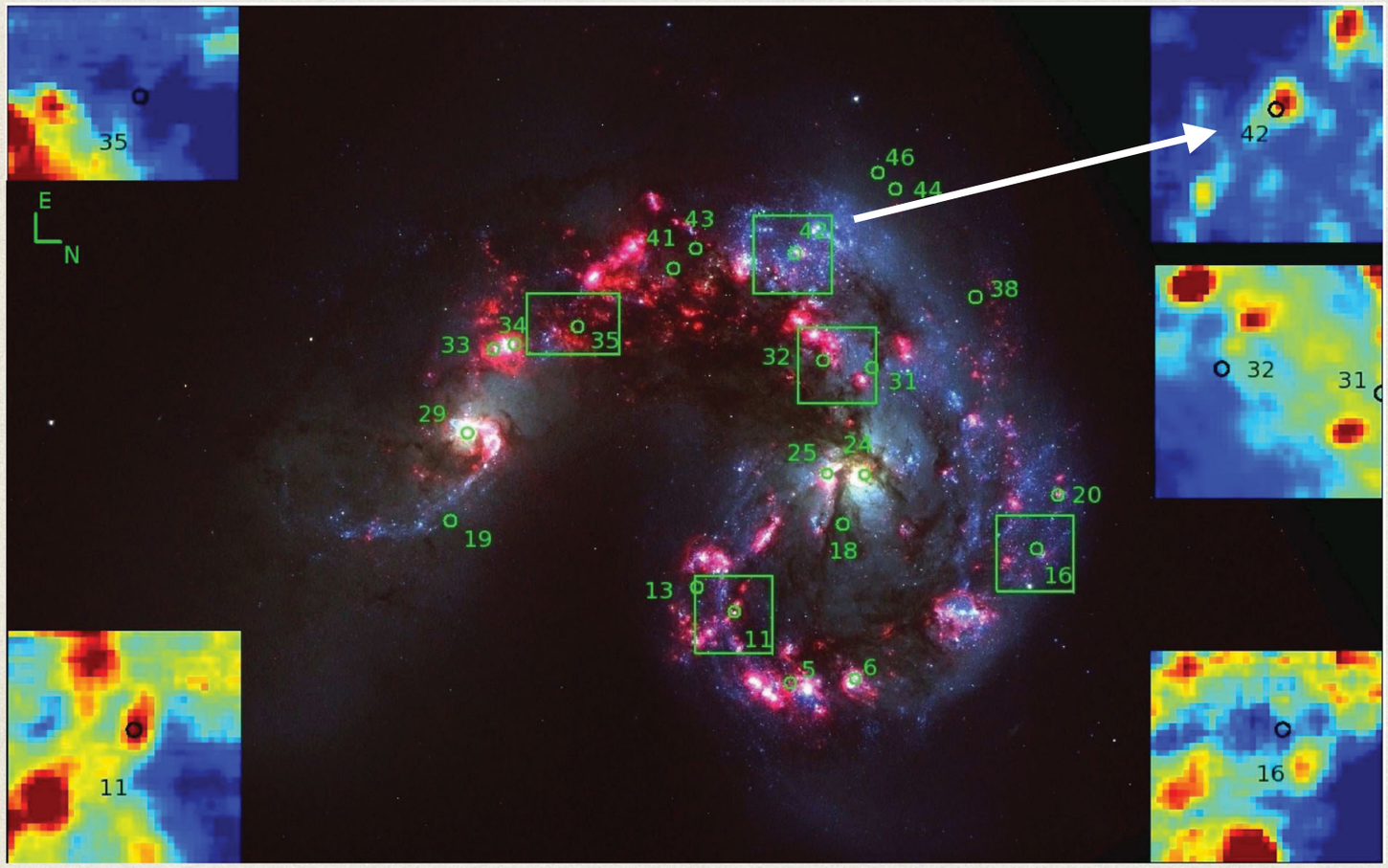
Spera+15



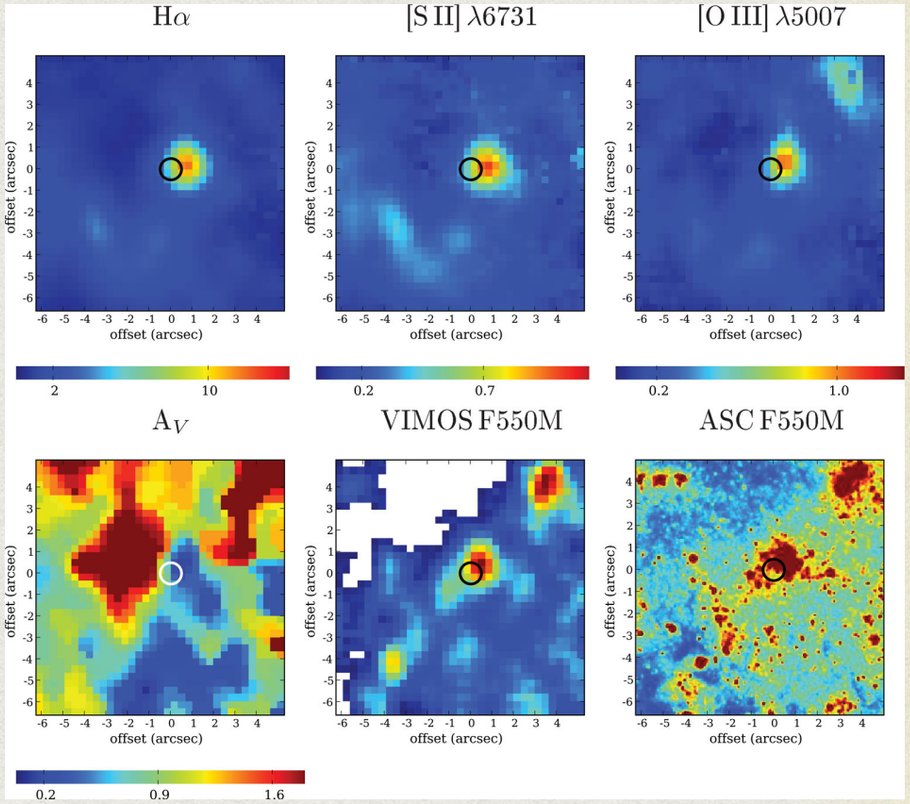
Mapelli+10

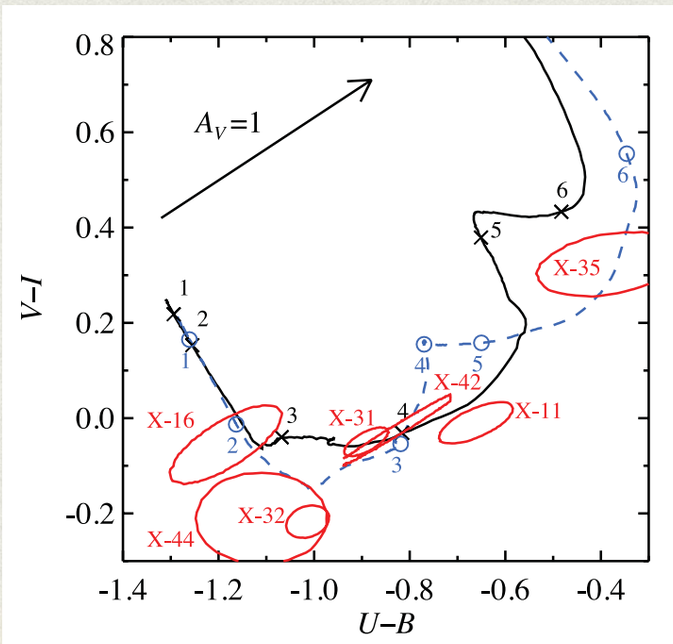
Antennae (NGC 4038/4039)

- Correlation between X-ray source positions and stellar clusters (Kaaret+14)
- Mostly showing strong emission lines
- ULXs are associated with young (<10 Myr) star clusters (Poutanen+13)



Poutanen+13



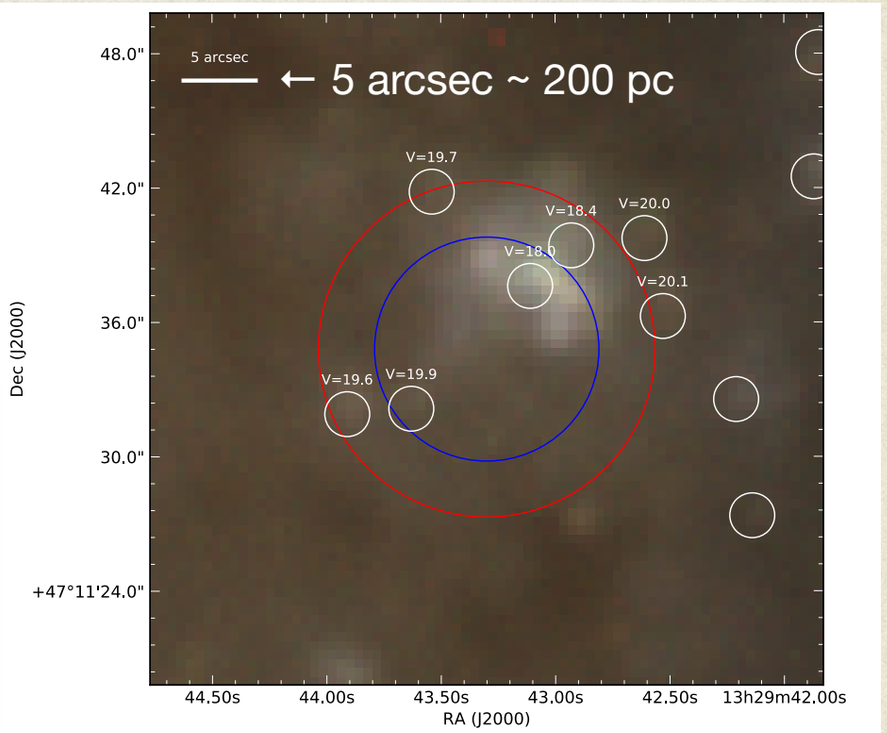


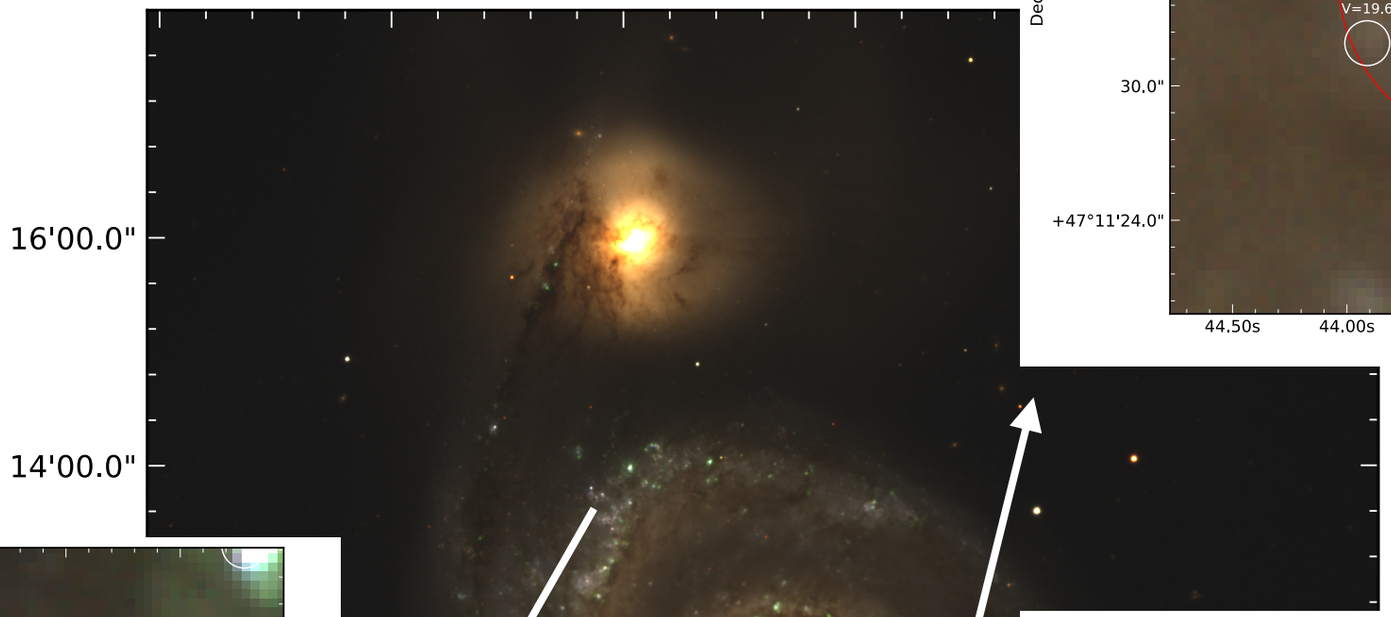
Proposed observation with 3.8m/KOOLS-IFU

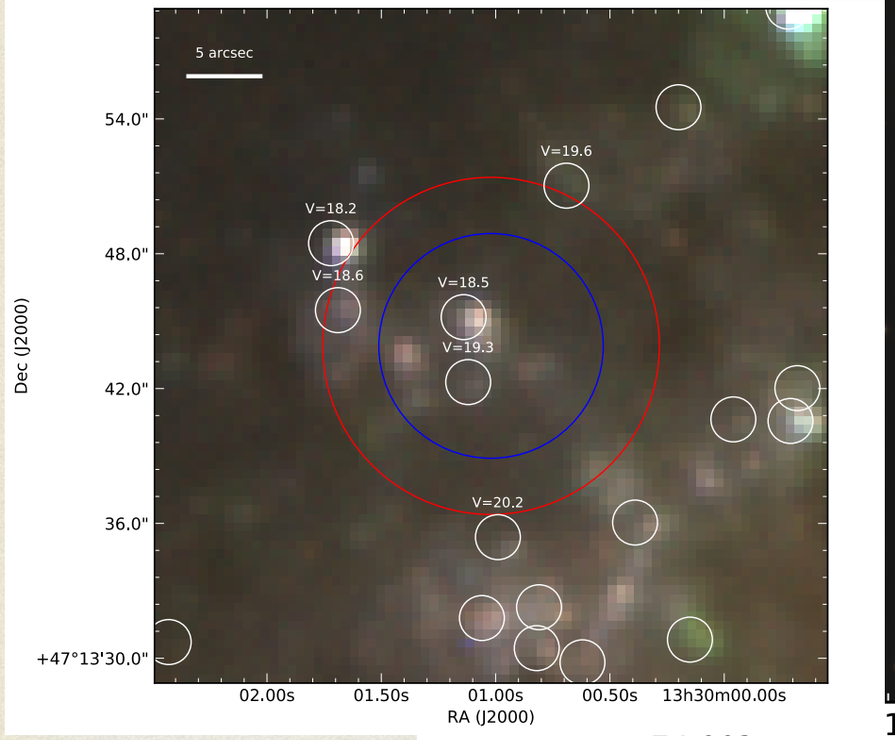
- A systematic spectroscopic observation of ULXs/XRBs with stellar cluster associations in nearby galaxies (<100 Mpc?)
- The main goals:
  - Local metallicity measurement for ULXs/XRBs/others
  - Age estimation of the associated stellar cluster (ULX lifetime)
- Comparison between ULXs/XRBs/others
- IFU would be very useful if there are multiple stellar clusters in possible associations with ULXs/XRBs (see next page)
- 3.8m telescope capability is enough as long as we target relatively bright stellar clusters (see after next page)

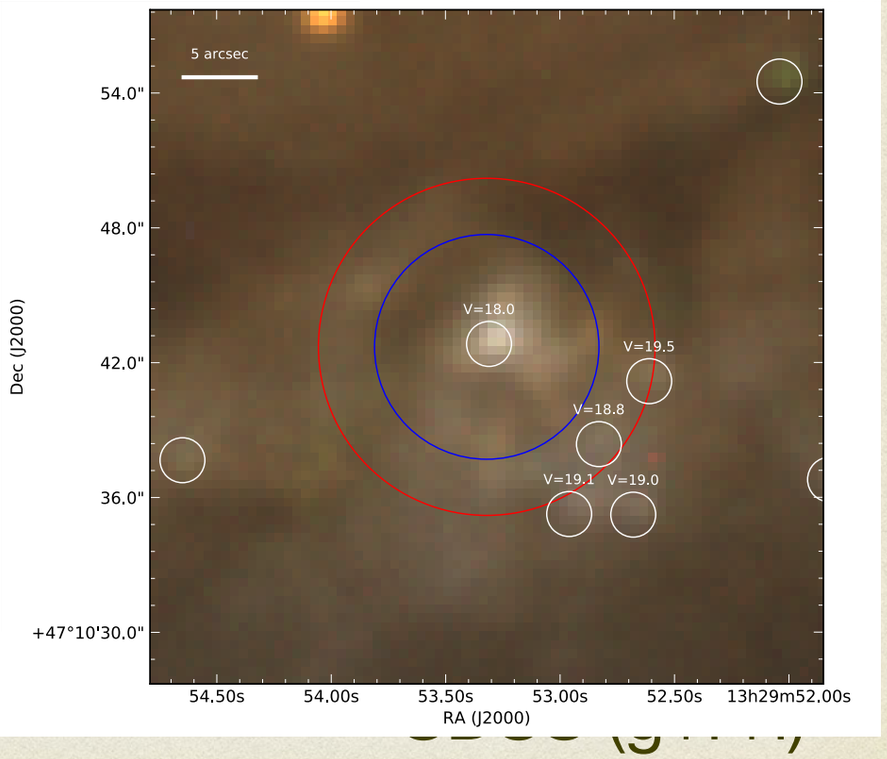
Example: M51 (NGC 5194/5195)

- 3 ULXs associate with star clusters (SCs)
- Offsets from the SC positions (kicked?)



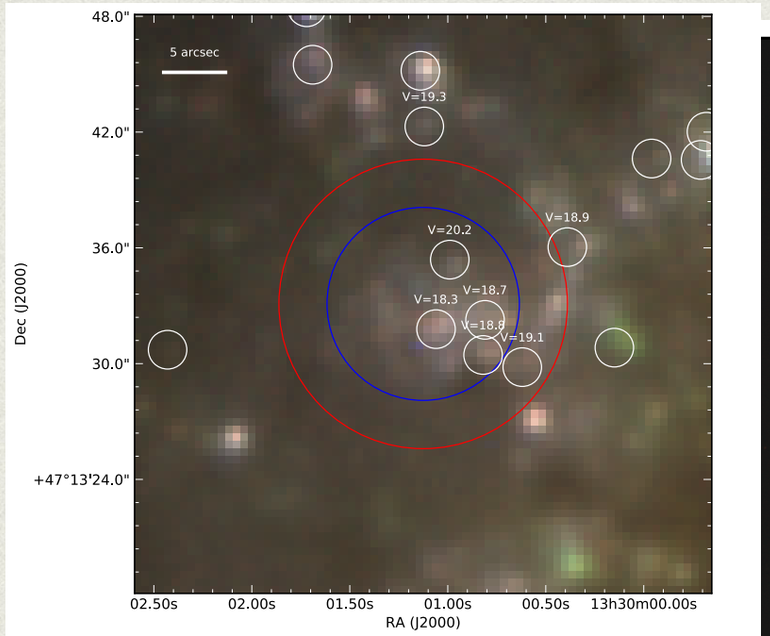


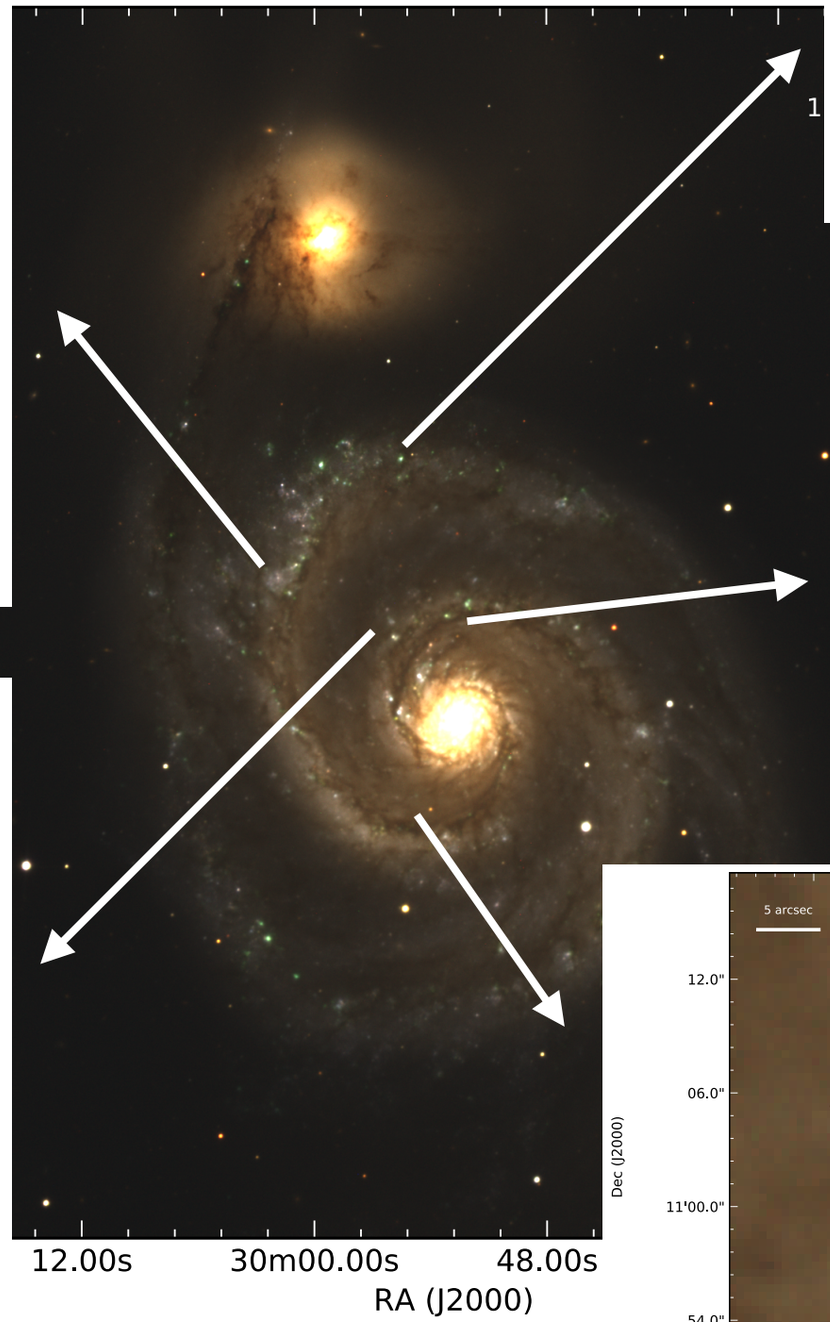


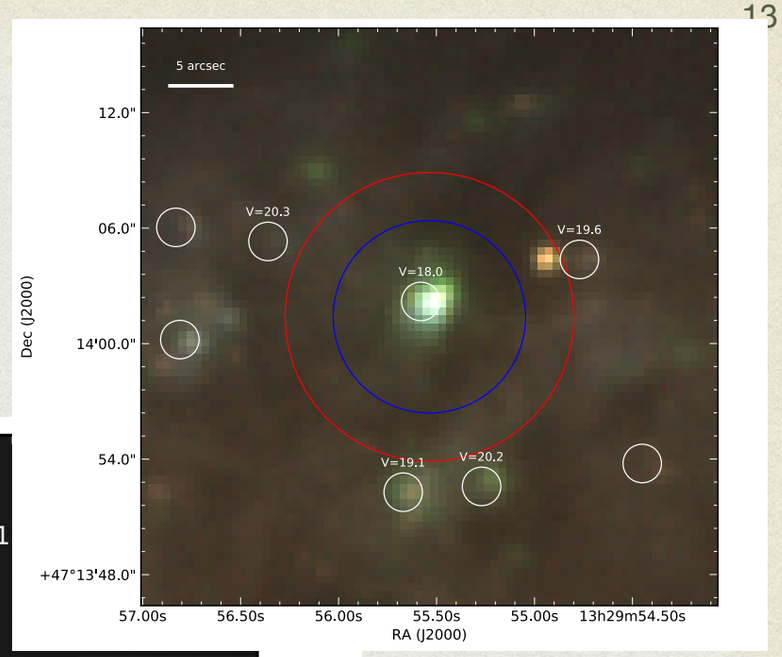


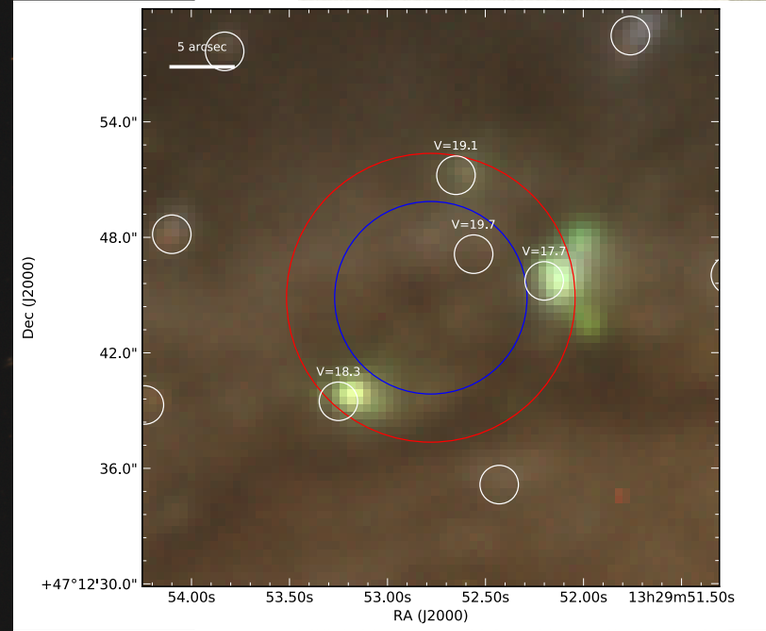
Example: M51 (NGC 5194/5195)

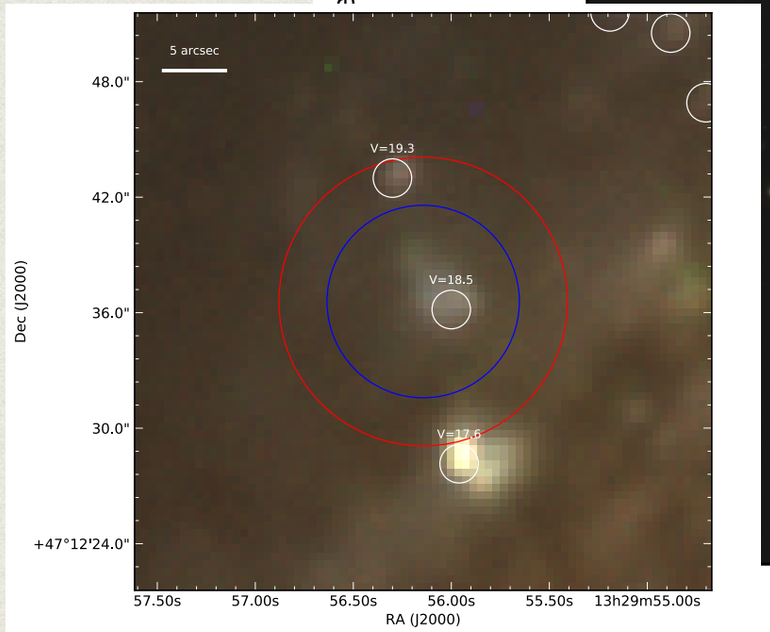
- 5 XRBs associate with star clusters (SCs)
- Offsets from the SC positions (kicked?)

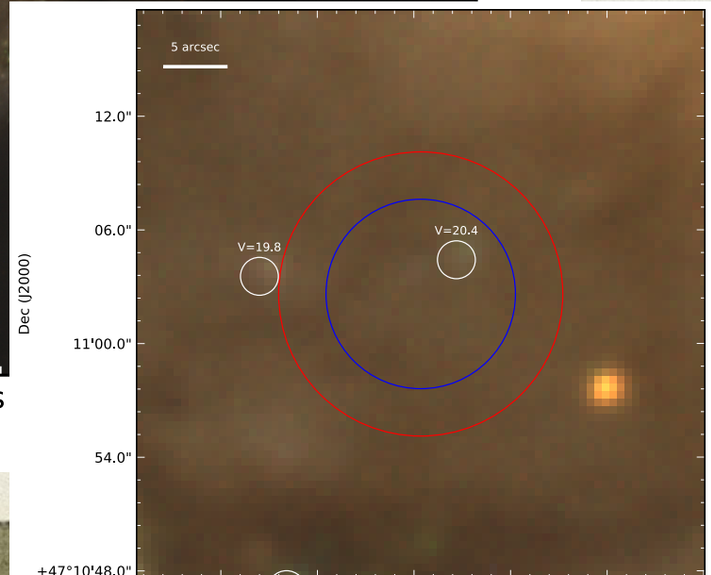












g+r+i)

Observation feasibility

- Typical magnitude of the bright SCs is V=18-19 AB mag
  - There are some faint SCs (<19 AB mag.) around X-ray sources
  - Mostly point sources under the seeing in Okayama (~1.5 arcsec.)
  - The target wavelength range is 3500 - 7000 Å, which covers the major stellar feature and nebular emission lines
- Sensitivity of KOOLS-IFU
  - No.5 grism (4000 - 7000 Å)
  - t_{exp}=3600 sec., S/N=10 → m^{limit}~19.5 mag

3.8m搭載時の (予想) パラメータ

グリズム	No. 5	No. 2	VPH495	VPH683
ファイバー本数	127本			
1ファイバーの視野	0.91'' (直径)			
全ファイバーでの視野	14.8'' (直径)(filling factor~0.58)			
観測可能波長	(4000—7000 Å)	(6000—10000 Å)	4160—6000 Å	6150—7930 Å
波長分解能 (λ/Δλ)	(~600)	(~1000)	N/A	1900—2300
最大スループット	5.3%	8.1%	N/A	8.2%

(※ 1ファイバーに全ての天体光が入った場合)

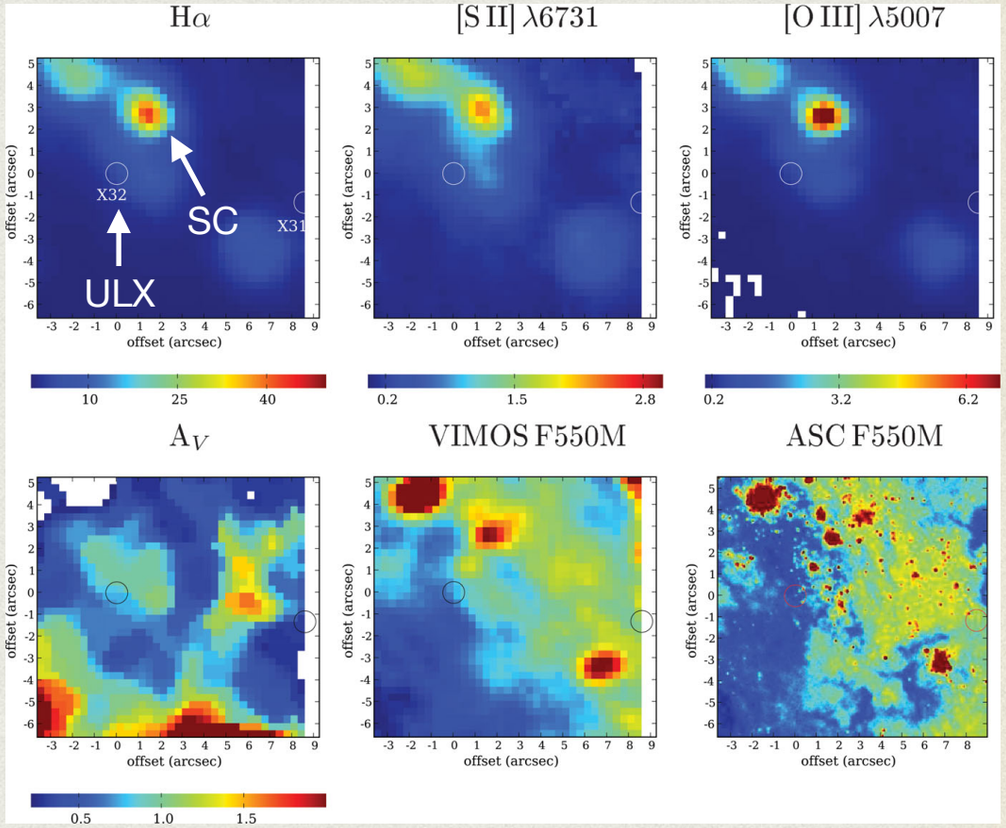
予想限界等級 @3.8 m望遠鏡

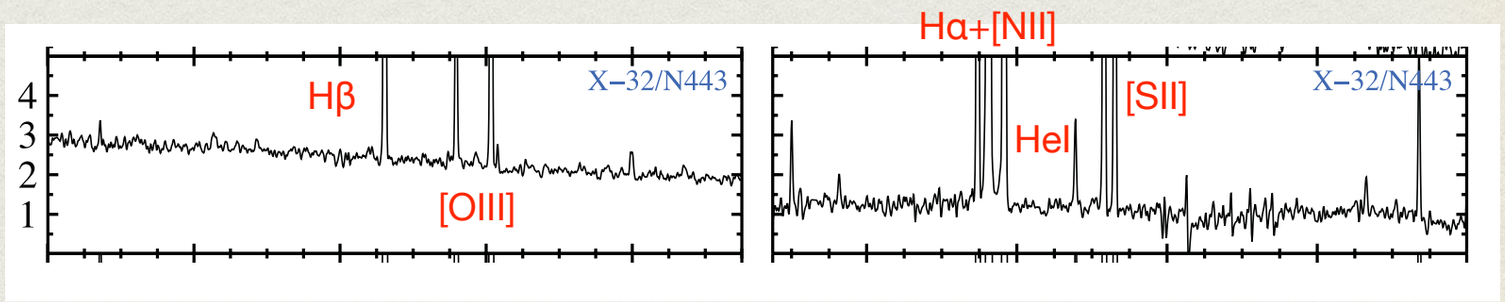
グリズム	No.5 (青)	No.2 (赤)
	19.1 mag	19.0 mag

- Enough capability to target most of our targets
- VPH-blue is better choice?

Observation feasibility

- We also aim to detect emission lines
  - Emission lines would be sufficiently bright compared to the continuum level according to the past observations for ULXs (Poutanen+13)
  - Spectral resolution (R~600) is enough to separate major emission lines (such as Hα and [NII]6584)





V~18.5

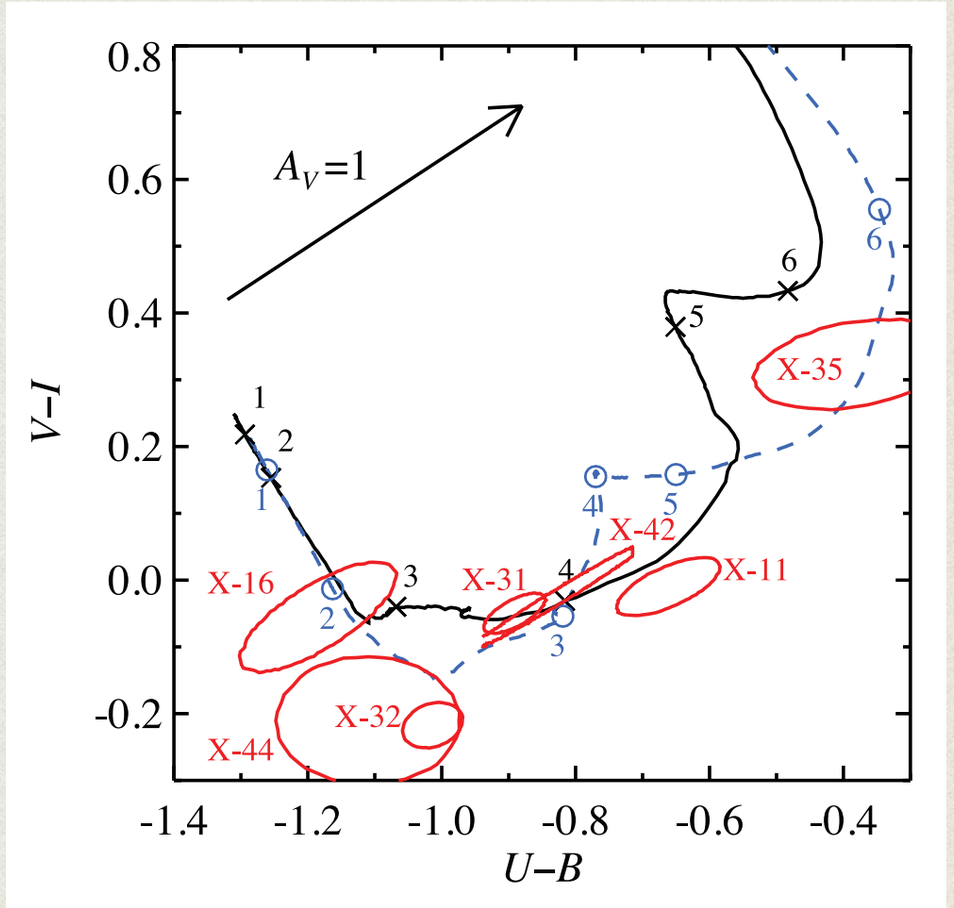
Poutanen+13

The immediate objectives

- Gas metallicity measure from obtained emission lines
  - Various metallicity indicators (e.g., T_e, R23, N2, O3N2)

- Age measurements of the star clusters
  - Color-color diagram?
  - Age-metallicity-extinction degeneracy
  - Upper limits for ULX/XRB lifetime

- Comparison between ULXs and XRBs
- Comparison to SCs without ULX/XRB associations
- If ULXs associate with preferentially low metal SCs, they may be very massive black hole in origin?



Poutanen+13

Summary

- ULXs are extra-galactic X-ray binary (XRB) systems with $L_X > 10^{39}$ erg/s at off-nucleus position
- Different X-ray spectra from Galactic X-ray sources
- Their origin is still unclear
  - Stellar mass black holes?
  - Intermediate mass black holes?
  - Neutron stars?
- The LF of XRBs indicates that they are a single population
- The environment of ULXs/XRBs is still unclear
- KOOLS-IFU spectroscopy for SCs with ULX/XRB association
- The local metallicity measurements from emission lines
- The age of SCs would be a constraint to the ULX/XRB lifetime