

How do ULXs couple to their environment?

A JWST view of Holmberg II X-1 and its nebula

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PID 5846: “The enigma of Ultra-Luminous X-ray sources and its Achilles Heel in the Foot Nebula”

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NewAthena Rising: SWG4

June 3rd, 2026



Ultraluminous X-ray sources (ULXs)

→ Off-nuclear extragalactic X-ray sources with $L_x > 10^{39}$ erg/s

→ Preferentially found in star-forming, often low-metallicity environments

Weaker stellar winds → more massive/tighter binaries → high mass transfer rates

Why are they so luminous?

→ Super-Eddington accretion onto neutron stars or black holes

→ Anisotropic emission / geometric beaming

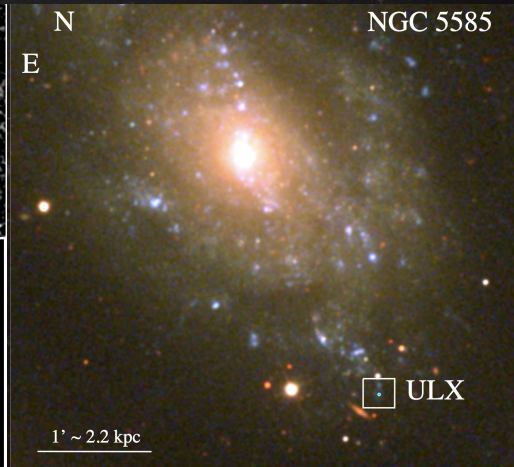
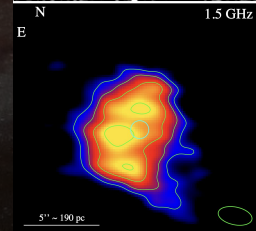
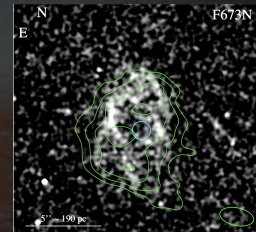
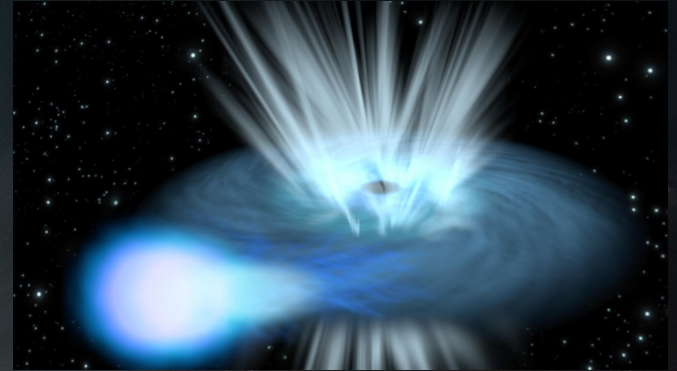
→ Higher compact-object masses in some systems

Why do their nebulae matter?

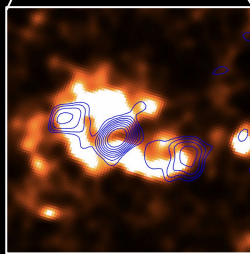
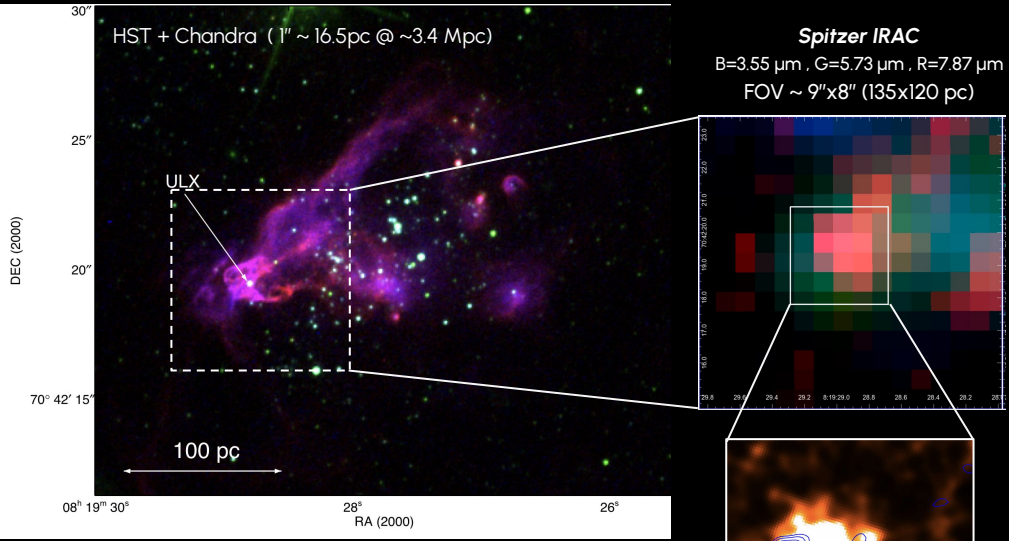
→ ULXs inject energy into the ISM through radiation, winds, and jets

→ ULX nebulae record the time-integrated escaped power of the central engine

→ Optical/IR/radio diagnostics can separate radiative and mechanical feedback



Holmberg II X-1 is in the 'heel' of the Foot nebula



Radio VLT + HST
 (He II $\lambda 4686$)
 FOV ~ 3"x4" (45x60 pc)

→ Nearby ULX in a low-Z dwarf galaxy
 D ~ 3.4 Mpc Z ~ 0.1 Z_{\odot} 1" ~ 16.5 pc $L_x \sim 10^{40}$ erg/s

→ *Multi-wavelength modelling* is consistent with a close HMXB scenario: BH mass ~ 66 M_{\odot} + ~22 M_{\odot} B-supergiant donor (~25 kK)
 - No strong beaming or UV/optical disc-wind signatures required

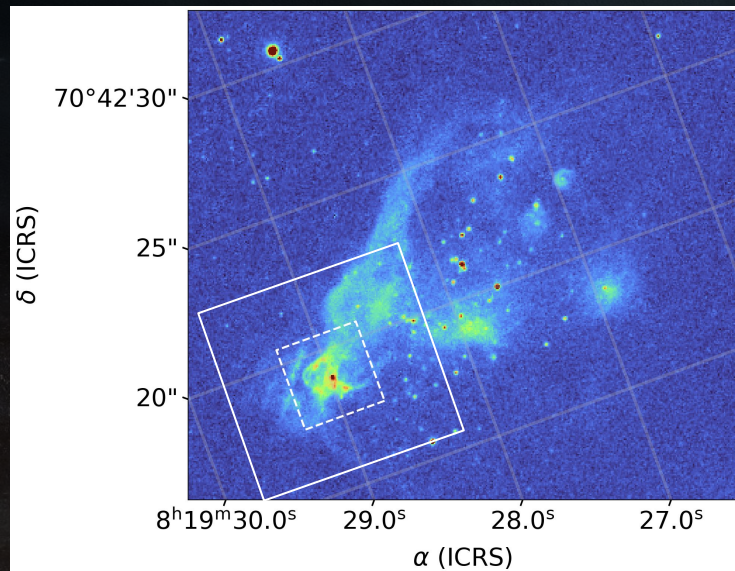
→ *Embedded in the "Heel" of the Foot nebula*
 - Compact He II / He++ region requiring photons above 54.4 eV

→ *Previous clues from observational studies.*
 - Optical: photoionized nebula; no clear dominant shock signatures
 - Spitzer/IRS: [O IV] and [Ne V], but spatially unresolved
 - Radio: Radio: fading optically thin ejecta; jet-lobe structure

JWST objectives (Part 1)

Probe the *morphology and kinematics* of
 Holmberg II X-1 nebula using NIRSpec + MIRI MRS.

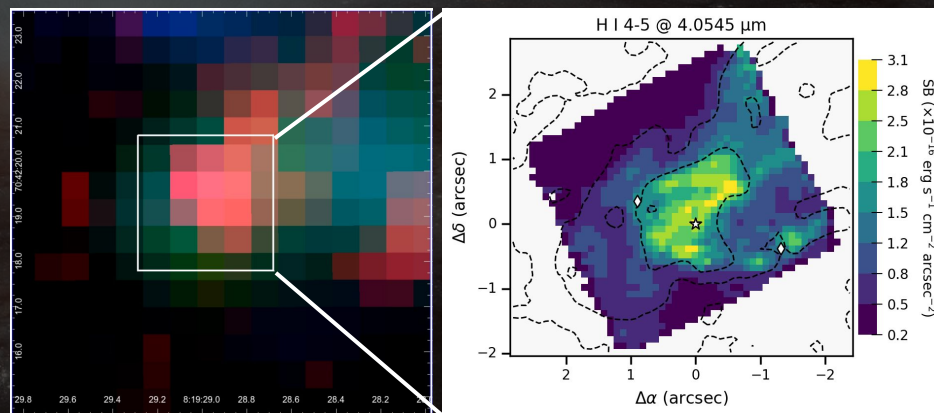
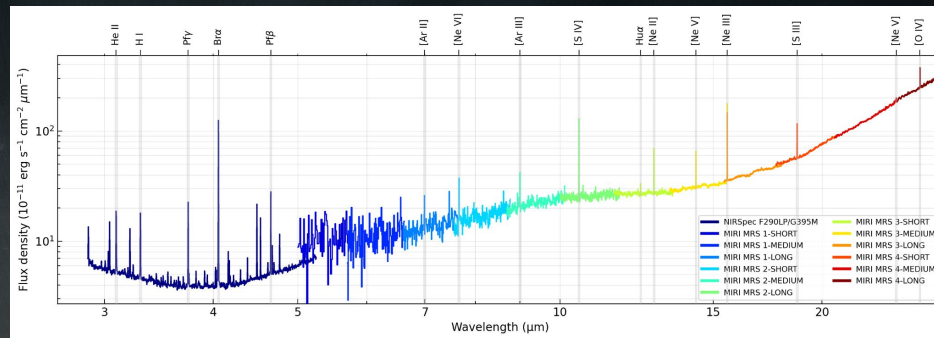
A JWST overview of Holmberg II X-1 nebula



HST/ACS @ 5022 Å (1'' ~ 16.5pc @ 3.4 Mpc)

JWST provides spatially resolved maps of recombination and forbidden lines, spanning a broad range of ionization potentials.

NIRSpec F290LP / G395M IFU + MIRI MRS IFU



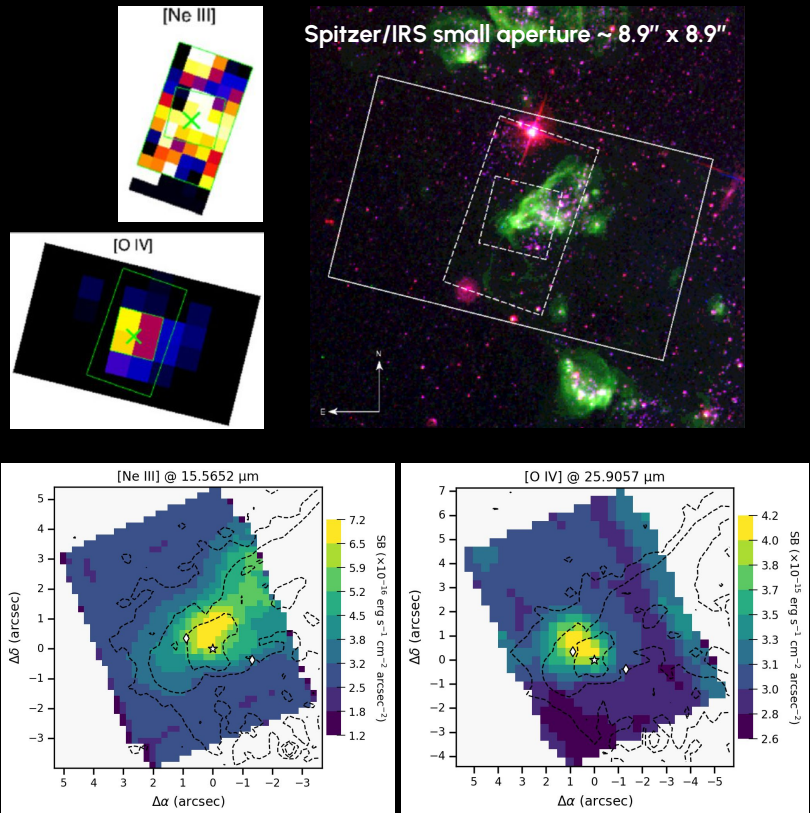
Spitzer IRAC

B = 3.55 μm, G = 5.73 μm, R = 7.87 μm
Resolution ~ 1.22'' / pixel

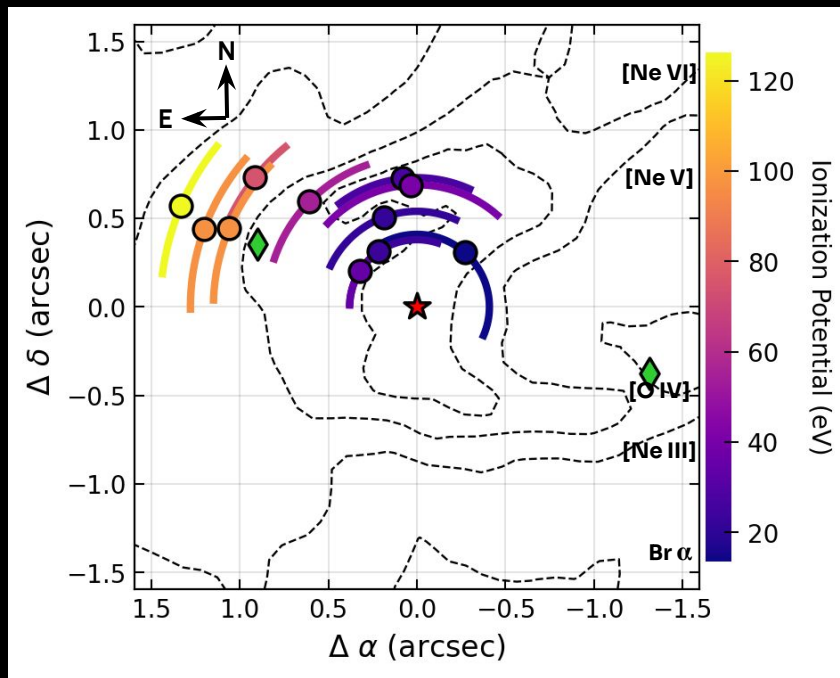
JWST NIRSpec

Br α @ 4.0545 μm
Resolution ~ 0.1'' / pixel

Morphology of Holmberg II X-1 nebula

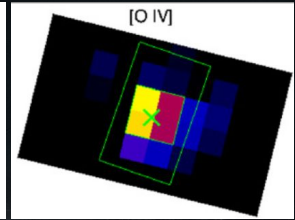
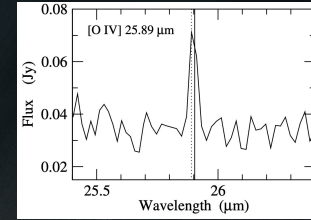
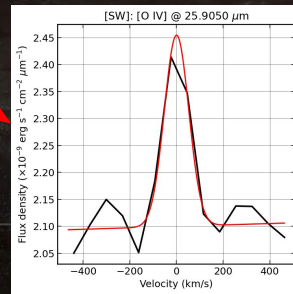
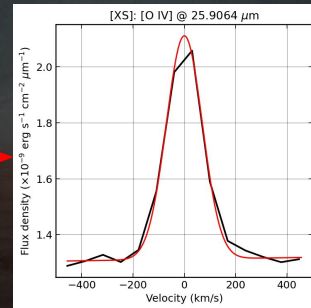
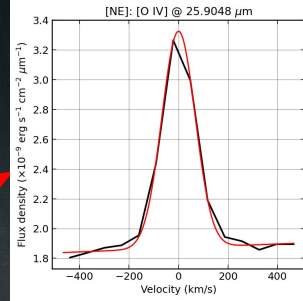
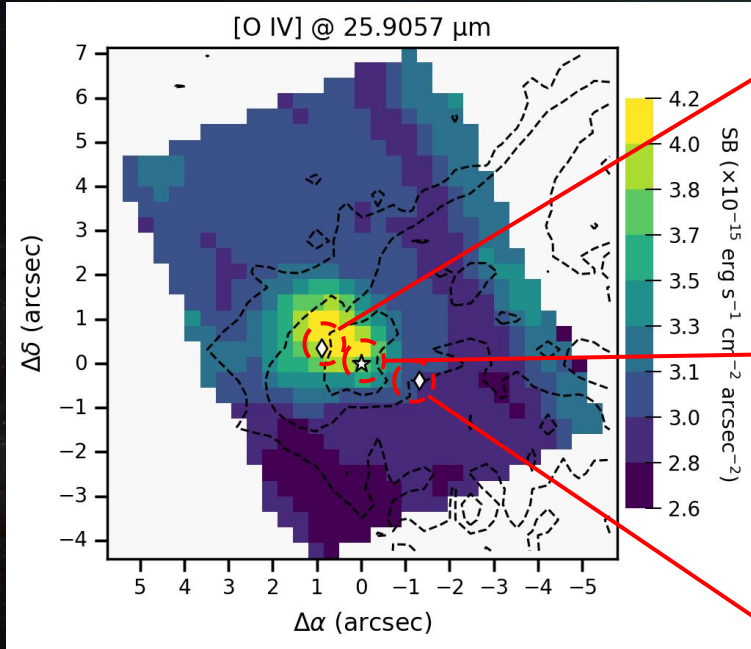


Directional escape of hard radiation



Br α : 4.055 μm (IP \sim 13.6 eV) \rightarrow PA: -45° & OA: 135°
 [Ne VI] : 7.652 μm (IP \sim 126.2 eV) \rightarrow PA: $+70^\circ$ & OA: 35°
 OA: opening angle PA: position angle

Kinematics of Holmberg II X-1 nebula



Spitzer/IRS small aperture $\sim 8.9'' \times 8.9''$

$R_\lambda \sim 600$ (IRS) $\rightarrow < 500 \text{ km/s}$

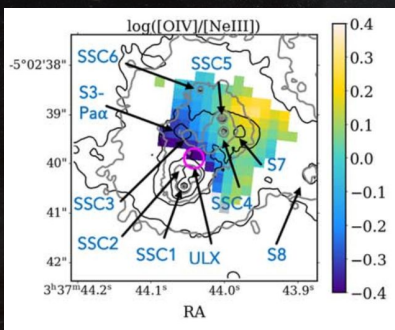
$R_\lambda \sim 1550$ (MRS Ch4) $\rightarrow < 150 \text{ km/s}$

The high-ionization gas is kinematically quiet

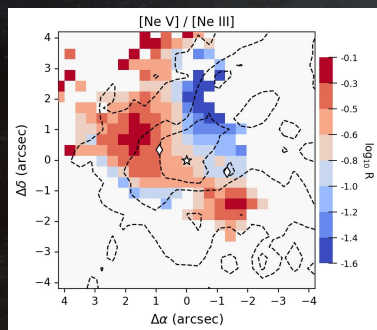
- \rightarrow Narrow line profiles (unresolved $< 150 \text{ km/s}$)
- \rightarrow No significant velocity shifts ($\Delta v \approx 0 \text{ km/s}$)
- \rightarrow No evidence for multiple kinematic components
- \rightarrow No apparent velocity change along radio axis
- \rightarrow **Consistent with XUV-photoionized gas**

Holmberg II X-1 in the context of low-Z galaxies

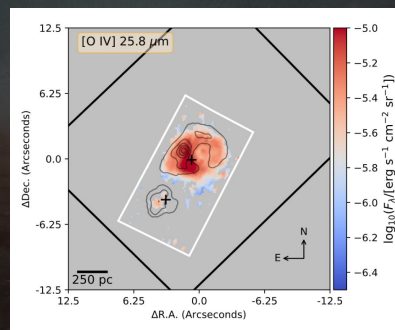
Galaxy	Distance (Mpc)	"/pc	Z (Z _o)	SFR (M _o / yr)	log L [O IV] (cgs)	Aper. [O IV] (pc)	Log L [Ne V] (cgs)	Aper. [Ne V] (pc)
Holmberg II	3.4	17	0.07	0.03	40.4	15.3	39.3	10.2
I Zw 18	18.2	88	0.03	0.2 - 1	36.8	57.2	35.1	57.2
SBS 0335-052E	57.9	280	0.05	0.7 - 1.3	40.8	39.1	168	



SBS 0335-052E
Mingozzi et al. 2025



Holmberg II X-1
(this work)



I Zw 18
Hunt et al. 2025

Emission Scales

→ In SBS0335 and I Zw 18, [Ne V] and [O IV] are measured over much larger, galaxy-integrated apertures

→ In Holmberg II, the emission is localized in a compact ULX nebula (~10-15 pc)

Output luminosities

→ Ho II shows enhanced [O IV] and [Ne V] per unit SFR → Accretion-powered emission dominates over stellar radiation locally

→ A single ULX can dominate the local hard-ionizing budget within its host galaxy

Conclusions

The hard ionizing continuum is accretion-powered

- [Ne V] and [Ne VI] require photons far beyond the B-supergiant donor
- The ULX is the natural source of the XUV/EUV radiation field

Photoionization dominates the observed optical/IR diagnostics

- Narrow line profiles, no strong velocity shifts, no multiple components
- No evidence that fast shocks dominate the high-ionization IR lines

JWST resolves the feedback scale

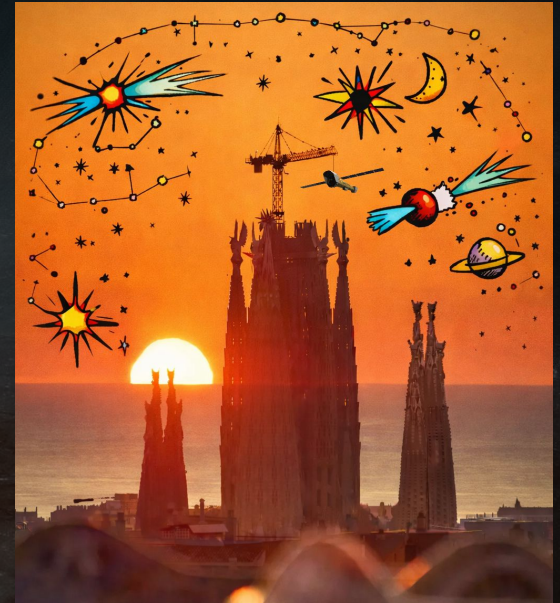
- High-ionization emission is confined to ~10-15 pc
- Lower-ionization gas is more extended
- Hard radiation may escape through low-density channels, funnels, or jet-carved paths

ULXs as hard-ionizing sources

- In Ho II, a single ULX dominates the local hard-ionizing budget
- Similar systems may contribute to hard ionization in low-Z galaxies

Future prospects → JWST + NewAthena

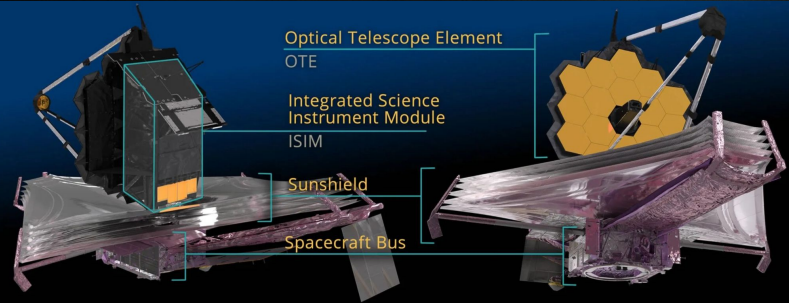
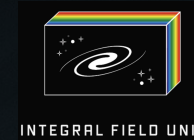
- JWST maps the escaped ionizing radiation
- NewAthena can probe the engine-feedback connection:
X-ray SED, ionized winds, shocked plasma, and variability behind the JWST nebular imprint



Thank you very much!

Appendix

A brief overview of JWST

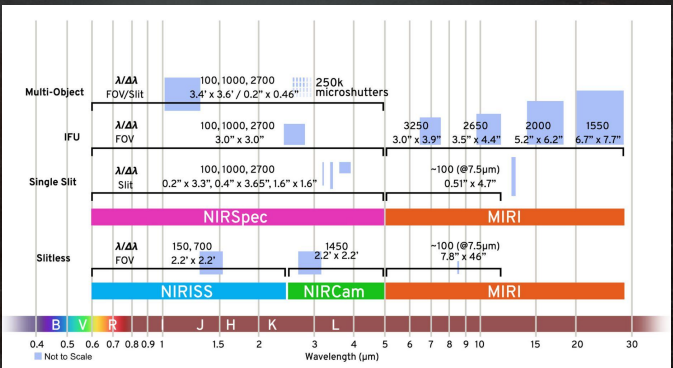
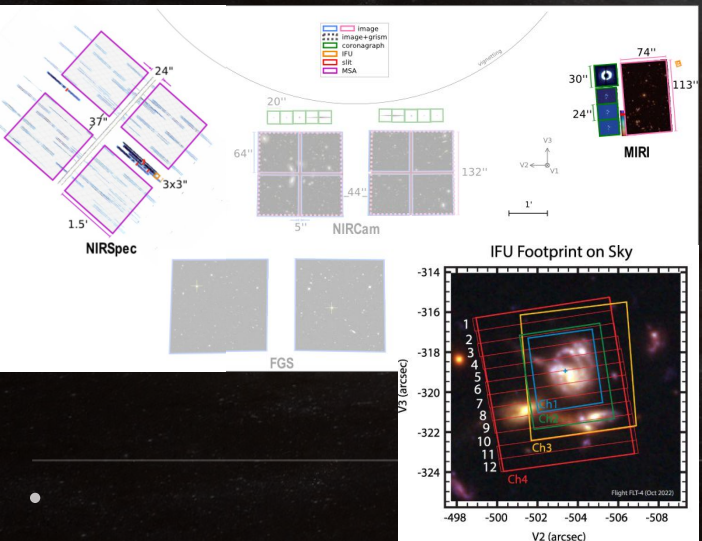


NIRSpec IFU (JWST)

- Configuration: G395M + F290LP
- Wavelength coverage: ~2.9 – 5.2 μm
- Spectral resolving power: $R \sim 1000$ (M)
- Field of view: $\sim 3'' \times 3''$ (0.1'' / px)

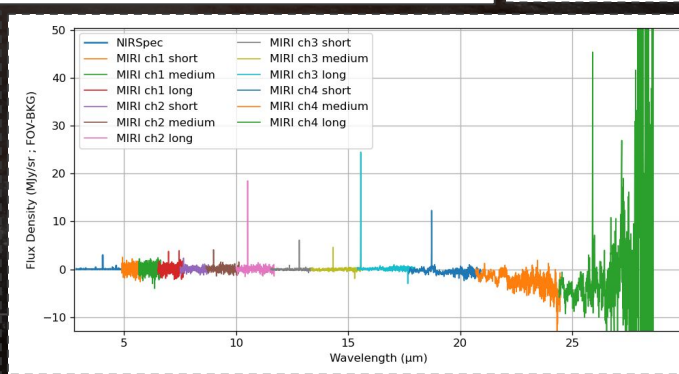
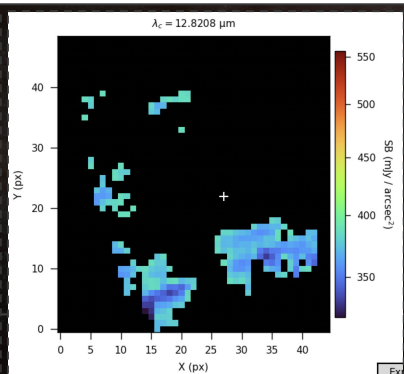
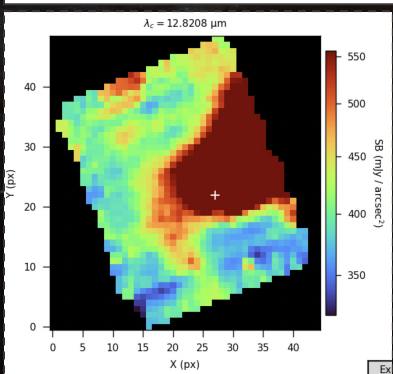
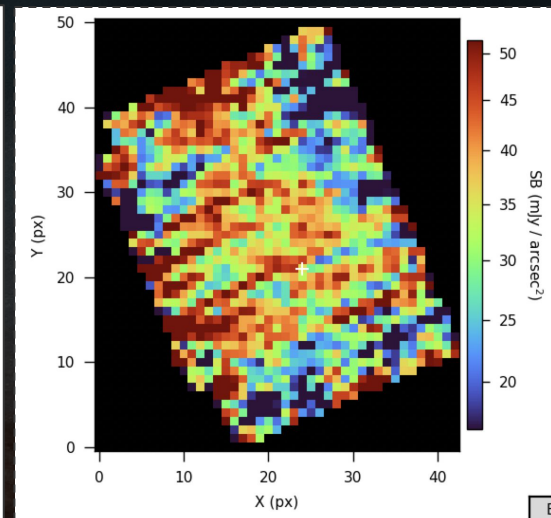
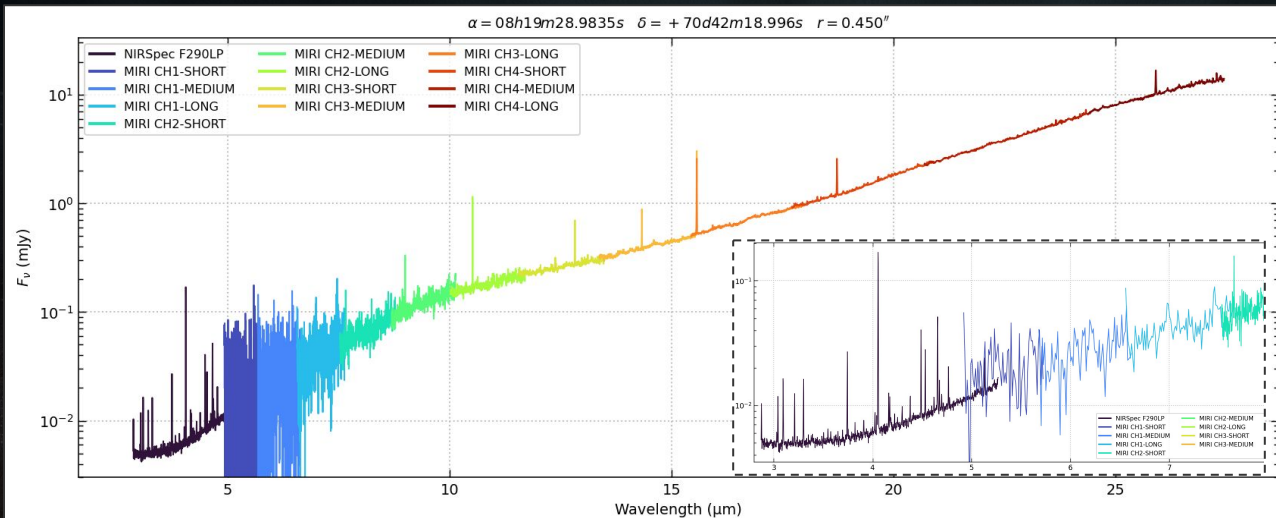
MIRI MRS (JWST)

- 4 integral field units (IFUs, Channel 1-4)
- Wavelength coverage: 4.9 – 27.9 μm
- Pixel sizes from 0.15'' to 0.35''
- PSF sizes from 0.3'' to 0.9''
- Resolving power from 1500 to 3500
- FOV from 3''x3.9'' to 6.7''x7.7''



→ Simultaneous **MIRI IMAGER** exposures can be used to align the WCS.

Appendix: straylight contamination in MIRI MRS channels 1 and 2



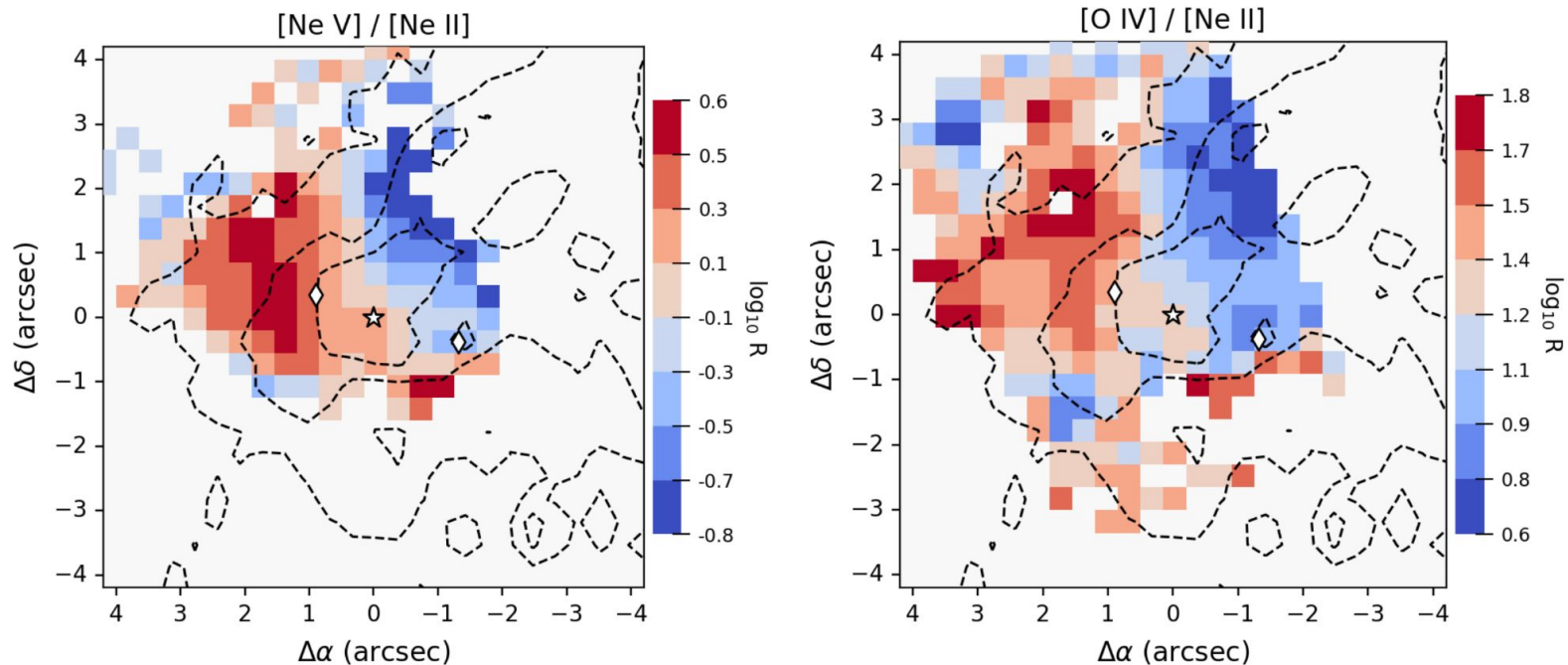


Figure 5. Line-ratio maps between different Ne, O and S transitions used to trace hardness and ionization gradients. The colorbar indicates relative surface brightness in logarithmic units. Only spaxels with $\text{SNR} > 3$ in the resulting ratio map are shown. The ULX position is marked by a white asterisk symbol, while the diamond markers show the compact radio cores (NE and SW). Black dashed contours show *HST*/WFC F502N emission of Ho II X-1. Each map is PSF matched to the highest MIRI MRS channel involved.

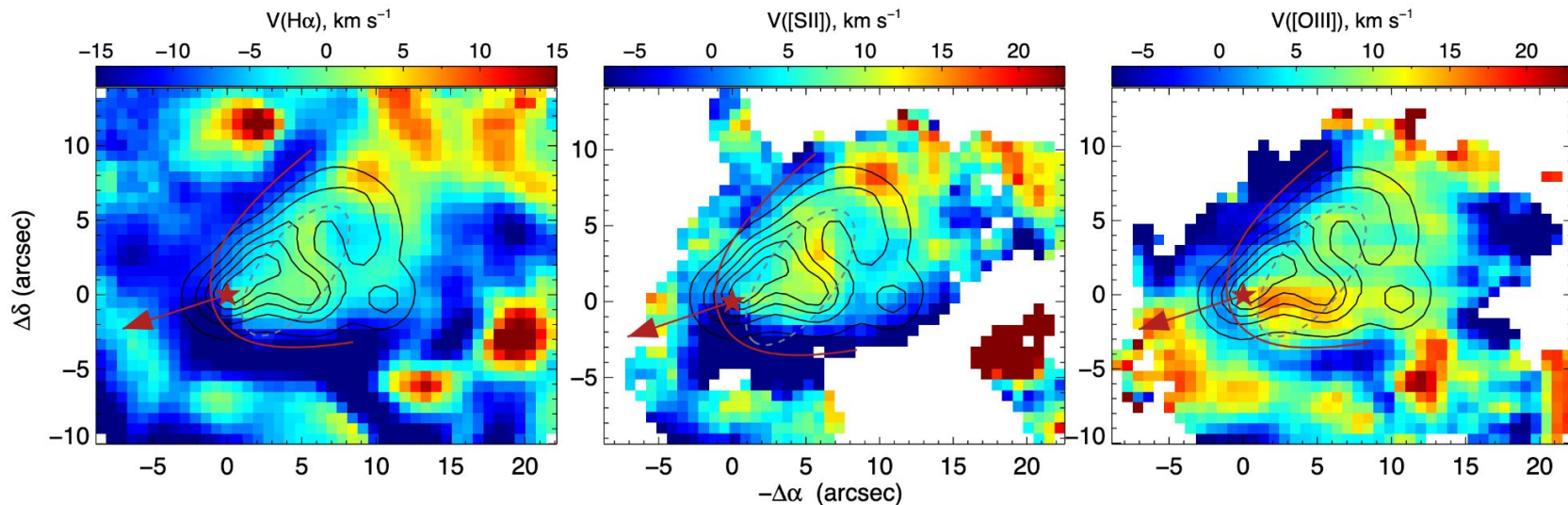
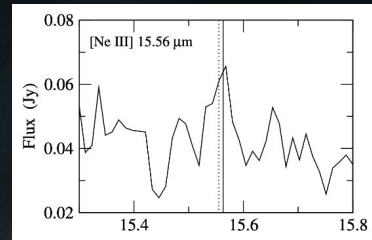
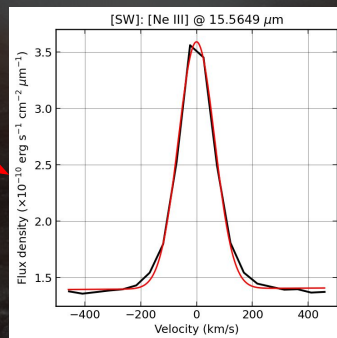
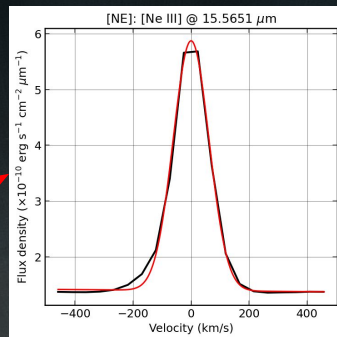
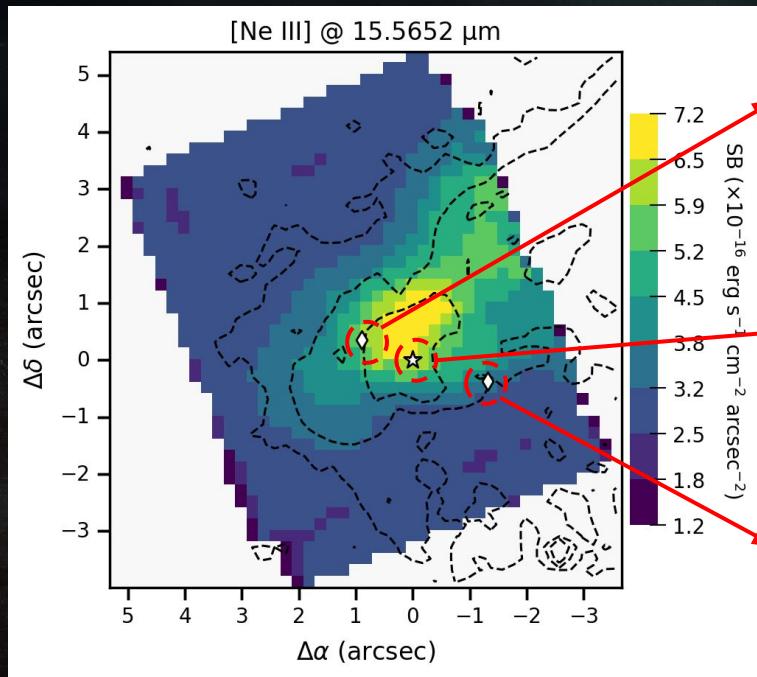
L4 *Egorov et al.*

Figure 3. ‘Foot nebula’ HSK 70 and its surroundings: line-of-sight velocity fields in the H α (left), [S II] (middle), and [O III] (right) emission lines. Pixels with signal-to-noise ratio less than 5 were masked. A red star denotes the HoII X-1 position, black contours are H α isophotes from the previous figure, a grey dashed ellipse shows the borders of a young cluster. A red curve shows the modelled shape of a bow shock that might be induced by the ULX motion in the direction shown with an arrow (see text).

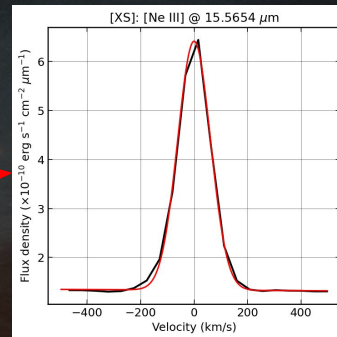
What about kinematics?



IRS small aperture $\sim 8.9'' \times 8.9''$

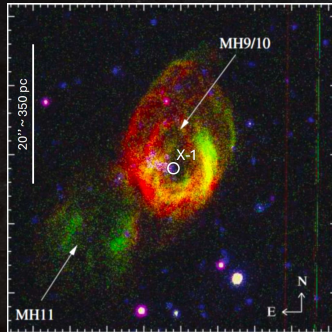
$R_\lambda \sim 600$ (IRS) $\rightarrow < 500 \text{ km/s}$

$R_\lambda \sim 2000$ (MRS Ch3) $\rightarrow < 150 \text{ km/s}$

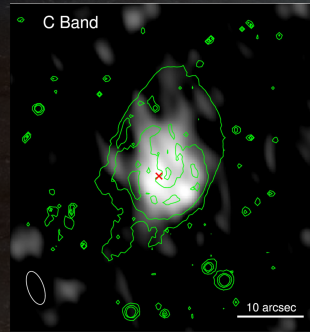


- \rightarrow Narrow line profiles (unresolved $< 150 \text{ km/s}$)
- \rightarrow No significant velocity shifts ($\Delta v \approx 0 \text{ km/s}$)
- \rightarrow No evidence for multiple kinematic components
- \rightarrow No apparent changes in jet-line direction

How do ULXs interact with the ISM?



Subaru
H α (red) + [O III] (green) +
V-band stellar continuum (blue).



VLA C-band + H α contours.
D ~ 3.6 Mpc \rightarrow 10'' ~ 175 pc.

Holmberg IX X-1 (MH9/10/11)

- \rightarrow ULX in low-Z dwarf galaxy ($Z \sim 0.3 Z_{\text{sun}}$, D ~ 3.6 Mpc)
- \rightarrow Persistent source with $L_X \sim 10^{40} \text{ erg s}^{-1}$

Structure

- \rightarrow Giant ionized bubble ($\sim 400 \times 300 \text{ pc}$)
- \rightarrow Asymmetric morphology (MH9/10/11 regions)

Energy injection

- \rightarrow Combination of mechanical outflows and radiative output

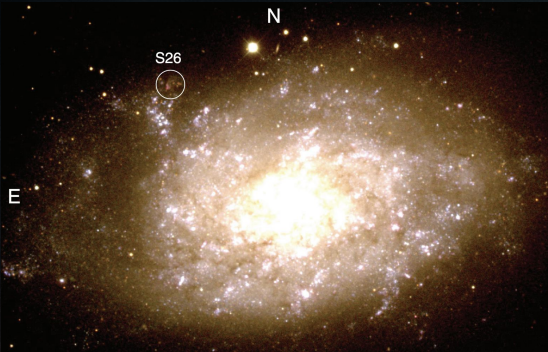
Observational signatures

- \rightarrow Shocks: expanding shell ($\sim 200 \text{ km s}^{-1}$)
- \rightarrow Photoionization: He II $\lambda 4686$ (hard photons required, $>54 \text{ eV}$)
- \rightarrow Strong [O III] emission in localized regions (MH11)
- \rightarrow Off-axis high-ionization gas \rightarrow anisotropic radiation escape

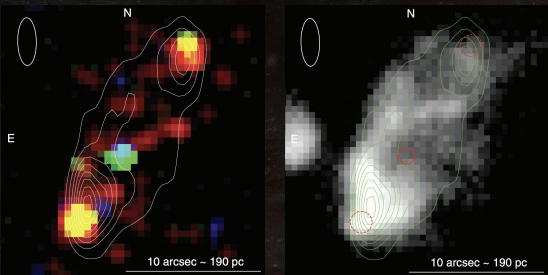
Bubbles are not unique to ULXs



SS433/W50: Our local analogue
 D ~ 5.5 kpc Size ~ 100 x 45 pc



BVR image of NGC 7793 (CTIO) 2' ~ 2.3 kpc



Chandra/ACIS +
 ATCA 5.48-GHz
 contours.

1" ~ 19 pc

H α (CTIO) +
 ATCA 5.48-GHz
 contours.

1" ~ 19 pc

S26 (NGC 7793) — mechanical (shock-dominated) feedback

- Microquasar (D ~ 3.9 Mpc, L_x ~ 10³⁷ erg/s)
- Not X-ray ultraluminous, but ULX-like power released mechanically

Structure

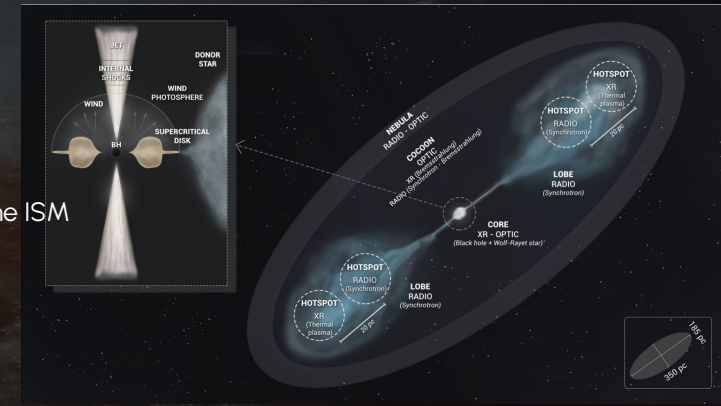
- Elongated bipolar cocoon (~250–300 pc)
- Aligned with jet axis

Energy injection

- Collimated jets deposit mechanical energy into the ISM
- Jet kinetic power ~10⁴⁰ erg s⁻¹

Observational signatures

- Optical: shock-ionized gas (high [S III]/H α)
- Kinematics: expansion velocities up to ~300 km s⁻¹
- X-rays: thermal plasma in shocks (hotspots, bow shock)
- Radio: synchrotron emission from jet lobes



The remarkable microquasar S26: A super-Eddington PeVatron
 L. Abaroa et al. 2024