Haro 11:
The Resolved Lyman Continuum Source and Cosmological Implications

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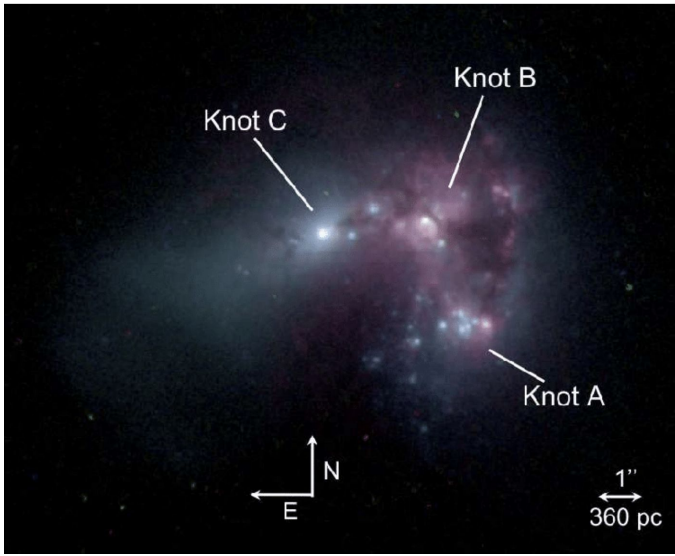
Haro 11

- **Closest, first confirmed LyC emitter** (88 Mpc)
  - $f_{esc} \sim 3$ % (Leitet+ 2011, Bergvall+ 2006)
  - Initial detection aperture covers entire galaxy

- **Knots C** and **B** host ultra-luminous X-ray sources (ULXs)
- **Knot C** is strongest Lyα emitter
- **Knot A** is Green Pea analog, showing low optical depth

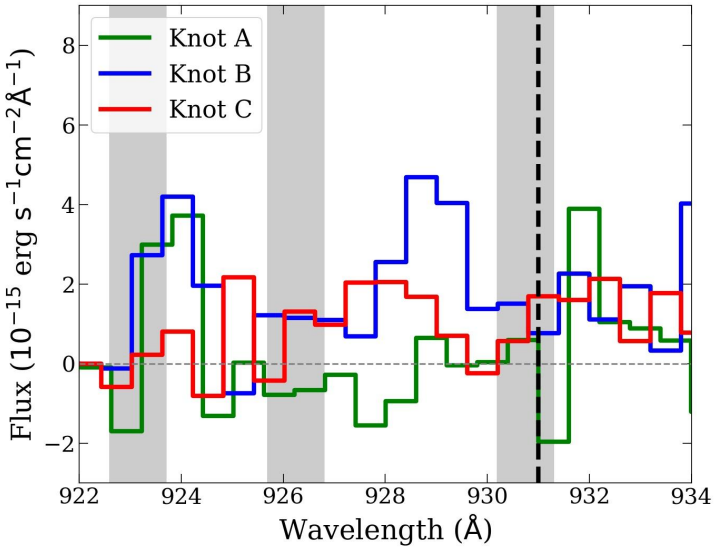
- Our new HST/COS data reveals LyC-leaking knot



RGB Hα,F550,F435. Cormier+ 2012

Identifying LyC-leaking Knot(s)

- HST/COS spectra 900 - 1200 Å, R = 18 000
  - G130M, 2.5'' aperture, 5000 s/knot x 3 visits
  - Reduction in CalCOS/boxcar, custom background



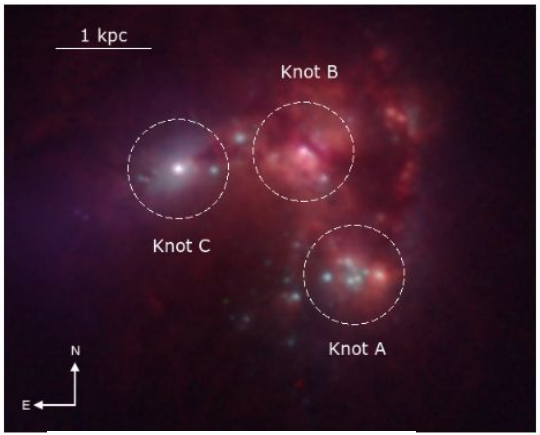
LyC flux density in 10^{-15} erg s^{-1} cm^{-2} Å^{-1}

Knot A: 0.2 ± 1.7 (non-detection)

Knot B: 2.3 ± 1.8

Knot C: 1.2 ± 0.9

➜ Consistent with Leitet+2011 (4 ± 0.9) x 10^{-15} erg s^{-1} cm^{-2} Å^{-1}



HST RGB: Hα, [O II], [O III]

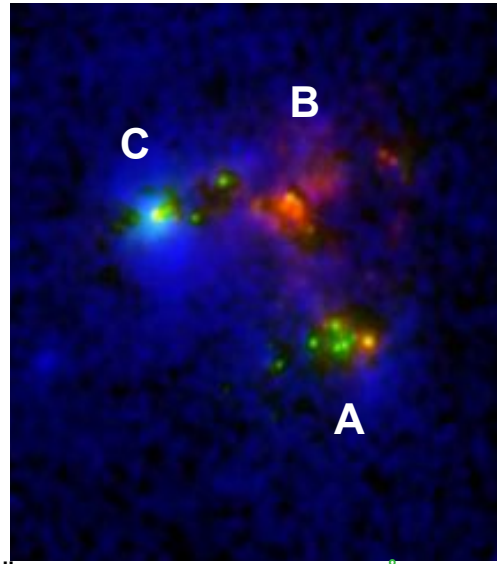
Komarova 2023, in prep

Knot C: An Expected Detection

- Expected based on highest Lyα escape, ~6% (Hayes+2007, Östlin+ 2021)

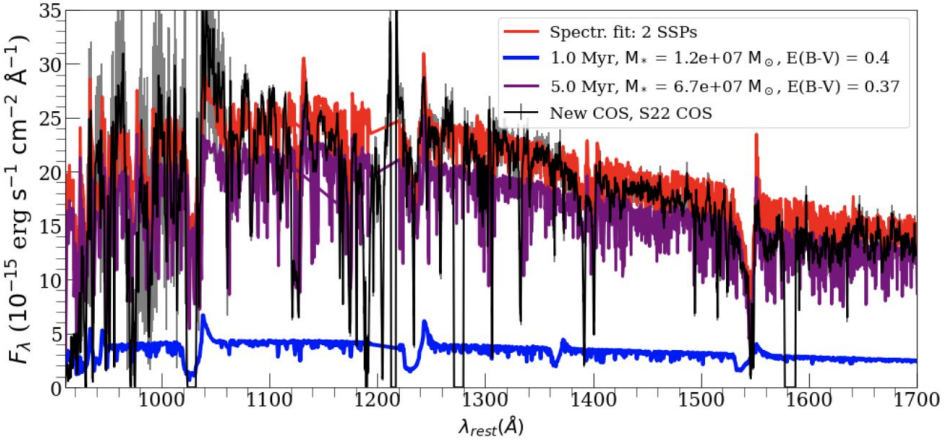
- Likely nuclear cluster

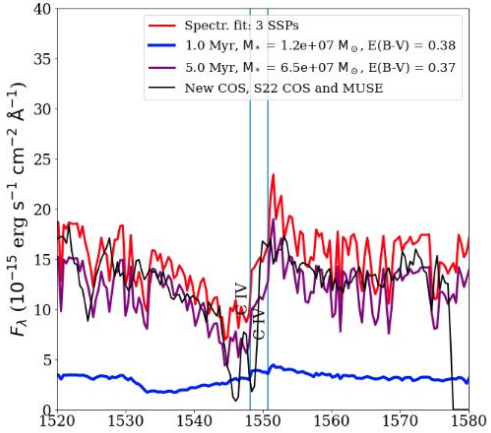
- Longest, strongest stellar feedback (Sirressi+ 2022)
- Lowest M_{H2} and HI covering fraction ~ 0.8 (Gao+2022, Östlin+ 2021)
- Remaining gas is clumpy (Rivera-Thorsen+ 2017)

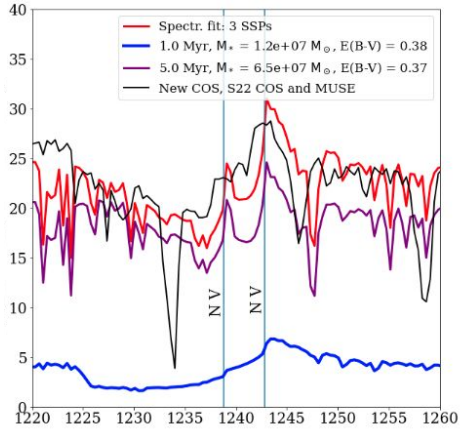


Östlin+ 2021. Lyα, Hα, 1500Å cont

Stellar Population in Knot C and Its LyC Output







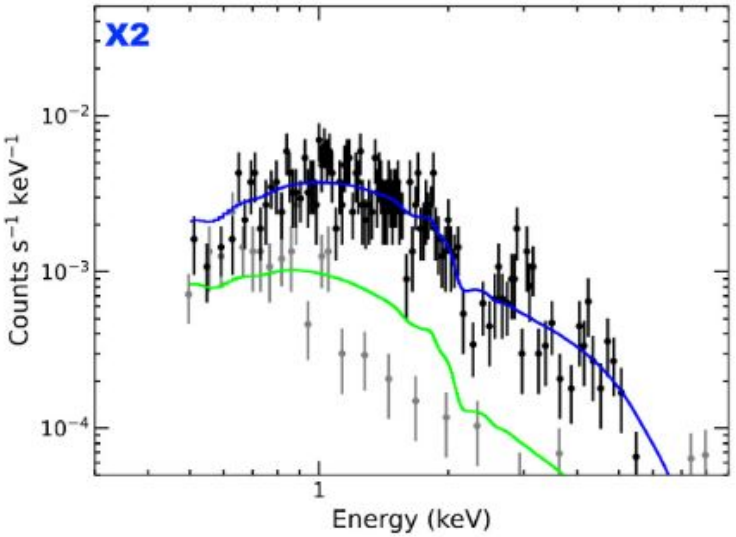
$$f_{esc} = L_{900,obs}/L_{900,int}$$

- What is the intrinsic stellar LyC of Knot C?
- Combine new COS with Sirressi+2022 COS 1060 - 1800 Å
- Find 5 Myr, 7 x 10^6 $M_{\odot,}$ E(B-V) = 0.4 pop to dominate FUV
  - P Cygni point to 1 Myr component
  - $L_{900,int}$ = 5 x 10^{41} erg/s

→ **f_{esc} ~ 0.02** *(Preliminary)*

Knot C: Could the ULX Contribute LyC?

- Knot C hosts a bright, soft ULX Haro 11-X2
    - L_X(0.3-8 keV) = 4 x 10^{40} erg/s
    - Spectral slope Γ = 1.8 (Gross+ 2021)
- Likely super-Eddington accretor ($M_\bullet > 20\ M_\odot$) (Gross+2021)



X2 (ULX in C) Chandra spectrum (Gross+2021), absorbed power law fit

Knot C: Could the ULX Contribute LyC?

Observe ULX in X-ray only; what is its SED in LyC?

Observed

L_x	4×10^{40} erg/s
L_{900}	0.9×10^{40} erg/s

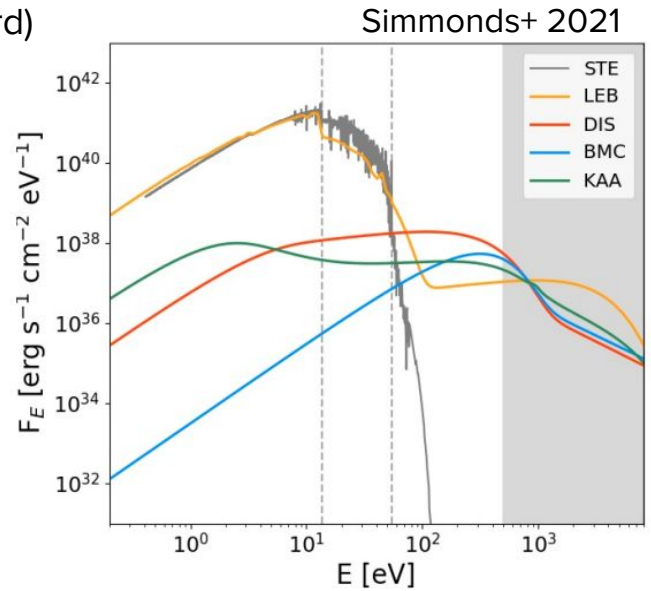
Modelled

$L_{900,star}$	5×10^{41} erg/s
$L_{900,ULX}$	$< 2 \times 10^{40}$ erg/s

DIS - irradiated disk (low-hard)
BMC - bulk motion (generic)
KAA - super-Eddington

Model ULX SEDs

Simmonds+ 2021



- Model SEDs vary by orders of magnitude
- $L_{LyC} \leq L_X$ for most
- **Possible for ULX to contribute LyC**

Knot B: Strongest detection

- Highest SFR, youngest age 1-3 Myr (this work)

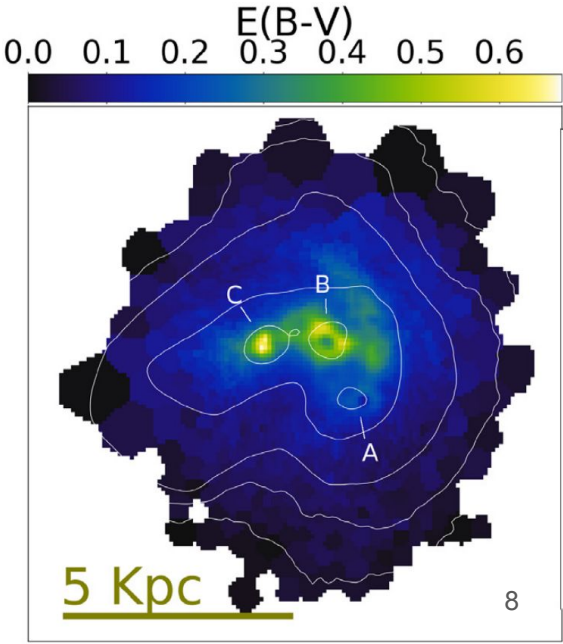
BUT

- Still enshrouded, with highest N_{HI} and M_{H2}, high extinction

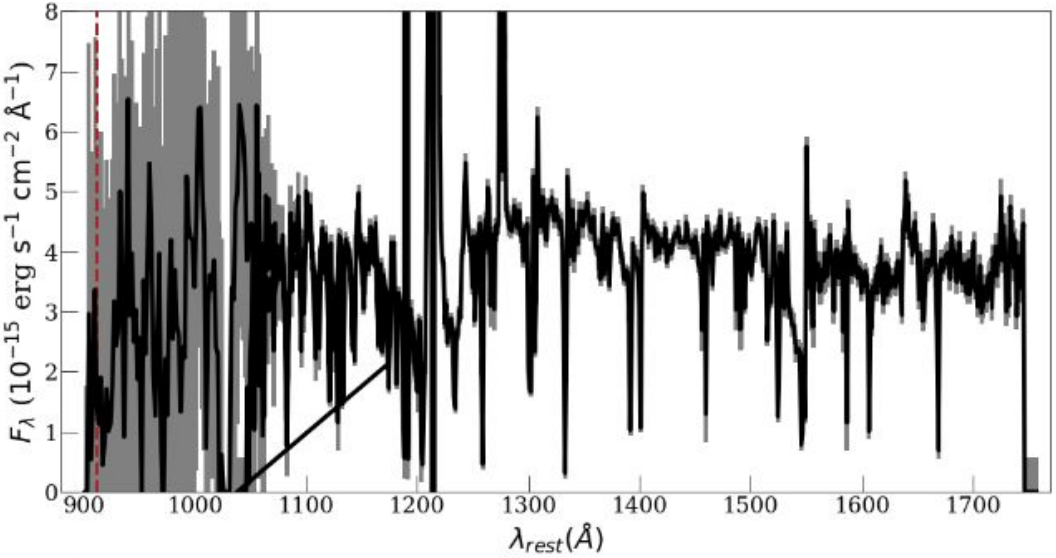
- Neutral covering fraction f_c = 0.96 in S II (Östlin+ 2021)

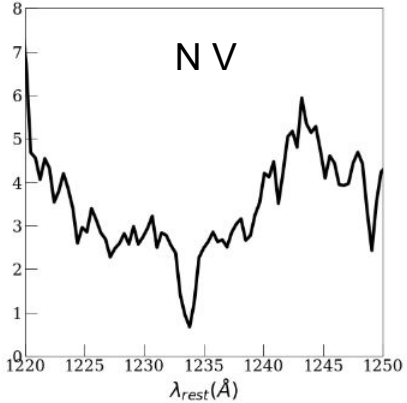
- Ionization-bounded (Keenan+ 2017)

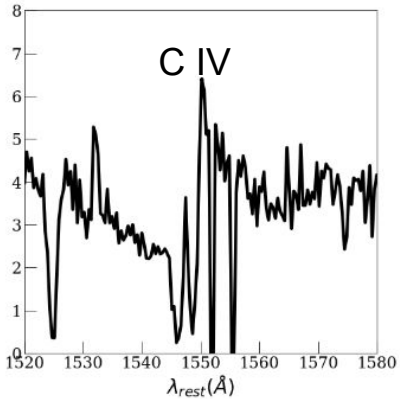
Menacho+ 2021



Stellar Population in Knot B and Its LyC







- P Cygni point to 1 Myr component
- Spectroscopic fit in progress
  - Discrepancy with cluster photometry (Sirressi+2022)
- Based on Sirressi+2022 clusters,

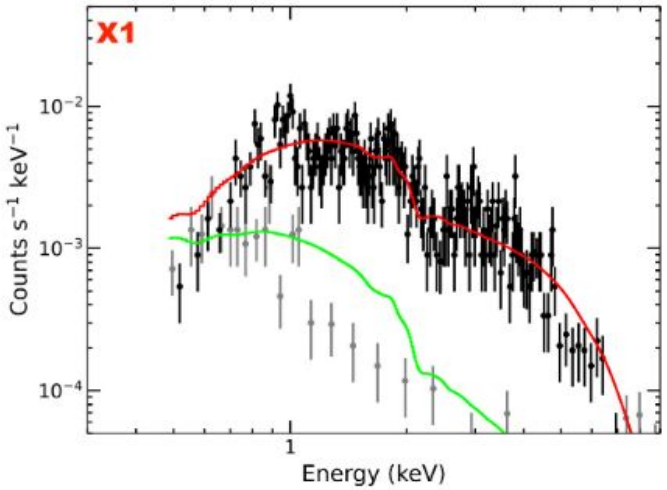
$$L_{900,\mathrm{int}} = 6 \times 10^{41} \text{ erg/s}$$

→ $\boldsymbol{f_{esc} = 0.03 \pm 0.02}$

(Preliminary)

Knot B: Could the ULX Contribute LyC?

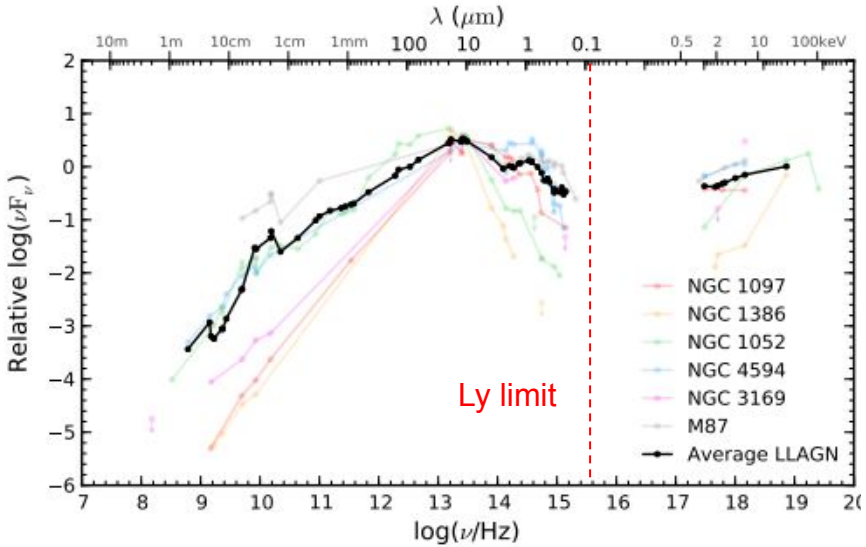
- Knot B hosts a hard ULX Haro 11-X1
  - L_X(0.3-8 keV) ~10^{41} erg/s
  - Spectral slope Γ = 1.5 (Gross+2021)
- Could be LLAGN or low, hard XRB (Gross+2021)



X1 (ULX in B) Chandra spectrum (Gross+2021), absorbed power law fit

Knot B: Could the ULX contribute LyC?

Fernández-Ontiveros+2012 LLAGN SEDs



Observed

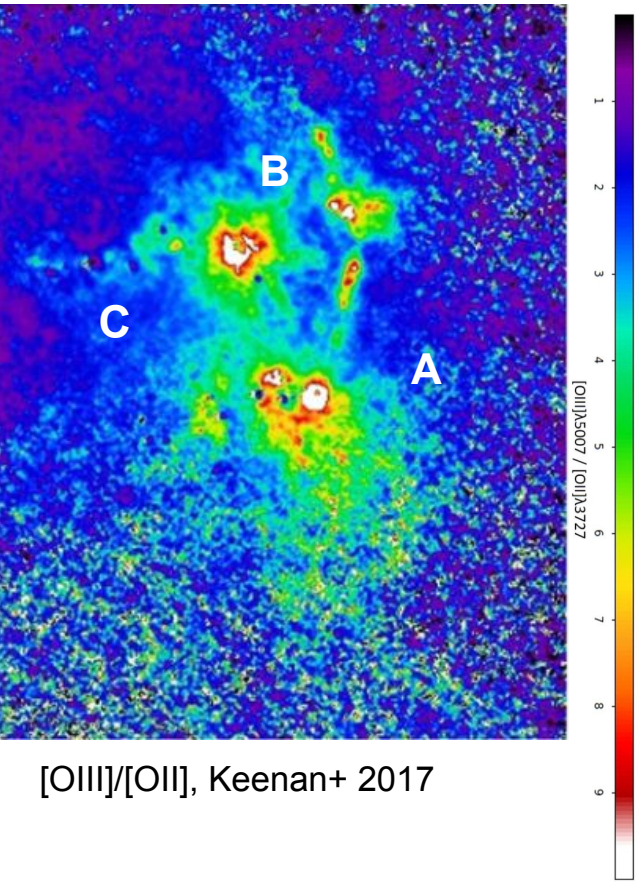
L_x	9.5 x 10^{40} erg/s
L_{900}	1.7 x 10^{40} erg/s

Modelled

$L_{900,star}$	6 x 10^{41} erg/s
$L_{900,\ ULX}$	< 6 x 10^{39} erg/s

- Model SEDs vary by orders of magnitude, $L_{LyC} \leq L_X$ for most
- **ULX is unlikely to contribute LyC**

Knot A: Non-Detection



[OIII]/[OII], Keenan+ 2017

- Drives Green Pea analogy of Haro 11

- Knot with highest ionization, $O_{32} \sim 9$ (Keenan+ 2017)
  - Unconfined morphology ➜ optically thin in sky plane

➜ **If LyC escapes in other LOS, it is highly anisotropic**

➜ **Green Pea nature ≠ LyC escape**

Summary

Komarova 2023, in prep

- Observe Knots B and C in Haro 11 to leak LyC; no leakage in Green Pea Knot A

Knot C: $f_{esc,LyC}$ ~ 2% (*Preliminary*)

- Nuclear region with little HI; $f_{c,\,HI} = 50\%$, $f_{esc,\,Ly\alpha} = 6\%$
- Super-Eddington ULX is a possible contribution?

Knot B: $f_{esc,LyC}$ ~ 3 % (*Preliminary*)

- High SFR in enshrouded, covered region; $f_{c,\,HI} = 100\%$, $f_{esc,\,Ly\alpha} = 1\%$
- LLAGN/XRB feedback may punch pinhole but can't provide required LyC

Cosmological Implications

1) LyC escapes even in high optical depth systems, if stellar FUV is strong
    - High Lyman luminosities may accompany low escape fractions

2) LyC escape in Green Peas may be highly anisotropic

3) Need to clarify importance of accretors in LyC budget
    - LCE candidates show excess of X-ray sources (e.g., Bluem+2019, Dittenber+2020)