**Title:** The circumgalactic medium in emission and absorption, from dwarf galaxies to massive quasar hosts

**Speakers:** Sean Johnson

**Collection/Series:** Cosmic Ecosystems

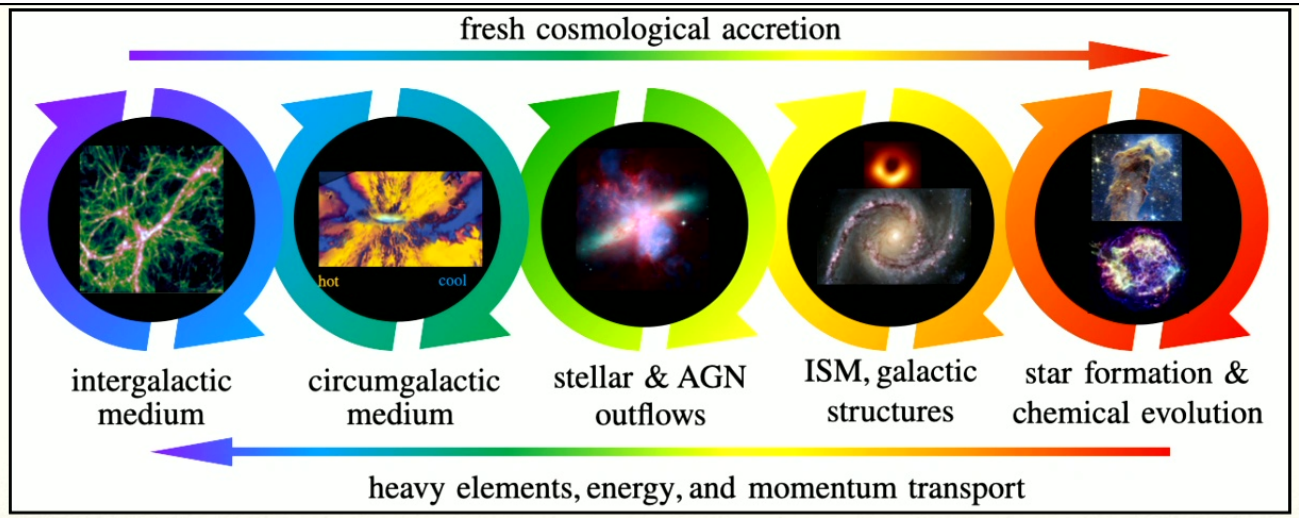
**Subject:** Cosmology

**Date:** July 30, 2025 - 11:15 AM

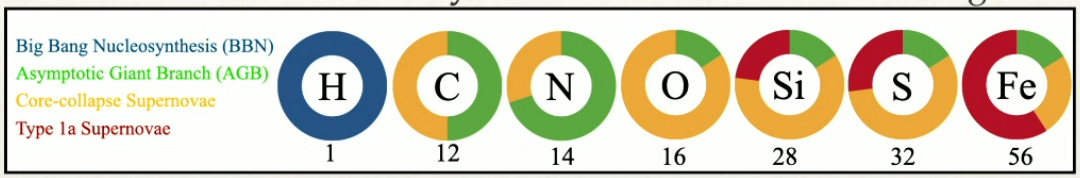
**URL:** https://pirsa.org/25070042

**Abstract:**

The circum-galactic medium (CGM) is at the nexus of the gas inflows and outflows that regulate galaxy evolution. Consequently, the CGM provides an ideal laboratory for studying galaxy fueling, feedback, and interactions.
In the last decade, the simultaneous availability of UV spectra from the Cosmic Origins Spectrograph, deep integral field spectrographs, and wide galaxy redshift surveys have revolutionized our ability to characterize the CGM empirically. I will review recent progress enabled by the Cosmic Ultraviolet Baryon Survey (CUBS) and MUSE Quasar Blind Emitter Survey (MUSEQuBES), which combine these data for 31 intermediate redshift quasar fields. These surveys simultaneously provide for the first studies of physical conditions and abundances of the CGM and IGM around low-mass dwarf galaxies that constrain the physical conditions and abundances of the gas while also enabling the discovery of giant rest-frame optical emission nebulae around quasar hosts. I will highlight enlightening case studies, including filamentary accretion from 100 kpc scales into the ISM of a massive quasar host confirmed by down-the-barrel inflows observed in the UV and the first studies of relative abundances in the CGM/IGM around isolated dwarf galaxies that reveal surprisingly high metallicity and low [C/O] and [N/O] ratios, suggestive of core-collapse supernova outflows with modest mass loading.




CGM/IGM **chemistry** times galactic outflows relative to star formation and **kinematics** + **thermodynamics** constrain feedback energetics

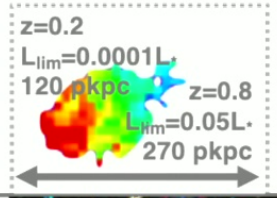
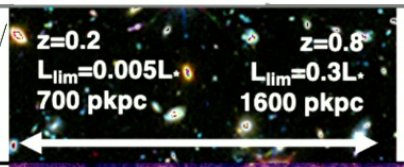
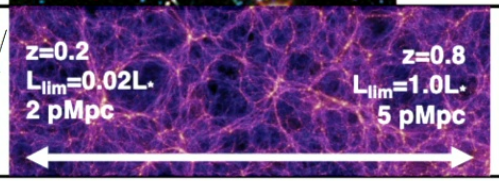


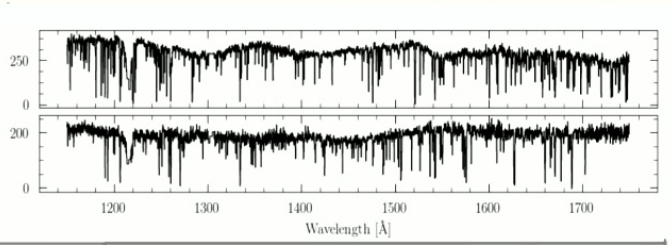

# The circumgalactic medium in emission and absorption, from dwarf galaxies to massive quasar hosts with the Cosmic Ultraviolet Baryon Survey

Sean D. Johnson
Department of Astronomy
National Center for Institutional Diversity
University of Michigan

# Cosmic Ultraviolet Baryon Survey (CUBS): fills a $\approx$ 5 billion year gap in our understanding of the relationship between galaxies and surrounding CGM/ IGM between better constrained epochs at $z = 0$ and Cosmic Noon ($z \approx 2 - 3$)

300 orbits of HST UV IGM absorption spectra of 15 QSOs in Cycle 25 & 31 (PI Chen, co-PI: SDJ, Rudie) + galaxy follow-up

| | | |
|---|---|---|
| Ultra-deep MUSE survey 1 arcmin $r$ or $i$<26 |   | Inner CGM Dwarf galaxies Dynamics |
| Deep Magellan/ LDSS3 survey 7 arcmin $r$ or $i$<24 |   | CGM/IGM interface Group environment |
| Wide Magellan/ IMACS survey 20 arcmin $r$ or $i$ < 22.5 |   | Environment Clustering IGM |




Deep multi-band imaging
*g, r, i, z, H*

galaxy selection
stellar mass estimates
stellar population synthesis

CUBS

MIKE (3 nights)

FourStar (3 nights)

IMACS (~20 nights)

LDSS3 (~20 nights

Bonus: VLT+MUSE (4 nights)

# The Cosmic Ultraviolet Baryon Survey Team


**Hsiao-Wen Chen** (UChicago)


**Sean Johnson** (UMichigan)


**Gwen Rudie** (Carnegie)


**Zhijie Qu** (Tsinghua)


**Fakhri Zahedy** (UNT)


**Nishant Mishra** (UMichigan)


**Suyash Kumar** (UChicago)


**Mandy Chen** (Carnegie/ Caltech)


**Will Liu** (UMichigan)


**David DePalma** (MIT)


**Jennifer Li** (NCSA, Illinois)


**Erin Boettcher** (GSFC)


**Tom Cooper** (Composable Analytics, Inc)


**Greg Walth** (IPAC)


**Rob Simcoe** (MIT)


**John Mulchaey** (Carnegie)


**Michael Rauch** (Carnegie)


**Sebastiano Cantalupo** (Milan)


**Kathy Cooksey** (UH Hilo)


**Claude-Andre Faucher-Giguere** (Northwestern)


**Jenny Greene** (Princeton)


**Sebastian Lopez** (U de Chile)


**Steven Penton** (Colorado)


**Patrick Petitjean** (IAP)


**Mary Putman** (Columbia)


**Marc Rafelski** (STScI)


**Joop Schaye** (Leiden)

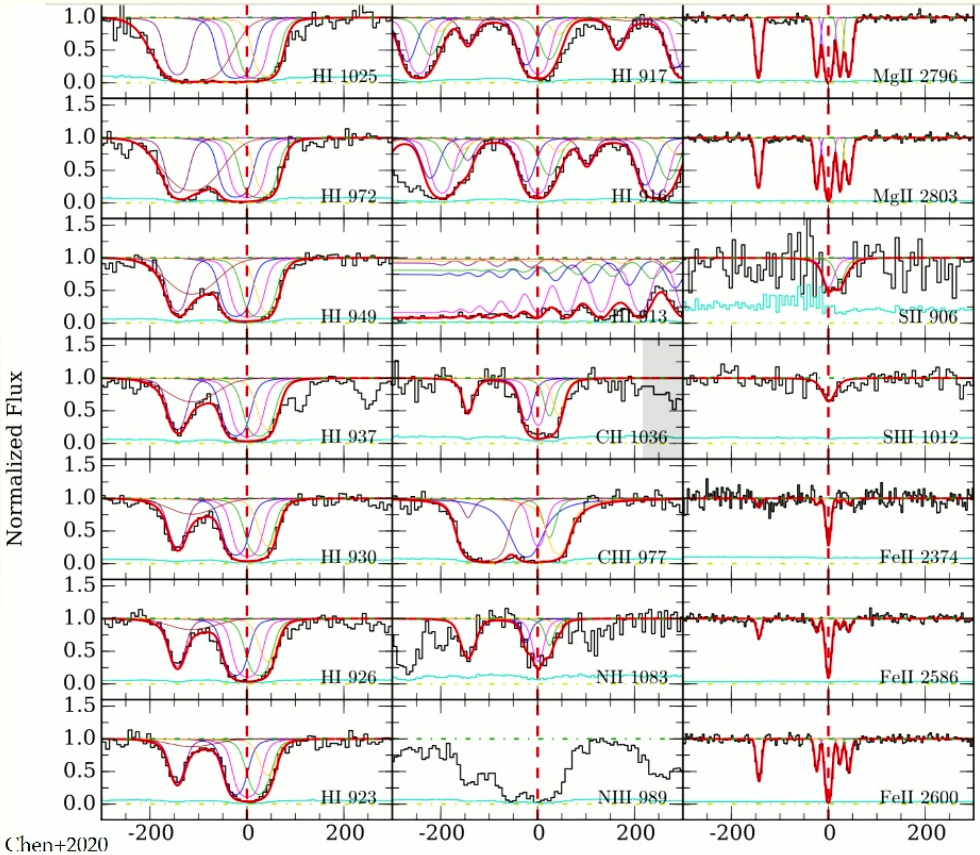

**Ben Weiner** (Steward)

red = at this conference or on the SOC!

# COS+STIS+MIKE constrain kinematics, thermodynamics, and chemistry of the ionized CGM/IGM: see Suyash's talk Thursday!

## For similar kinematic/thermodynamic study at Cosmic Noon: Rudie+2019

Suyash Kumar (UChicago)




redshift → kinamatics

$|v_{CGM} - v_{gal}|/v_{esc}$

line width → thermodynamics

$$b = \sqrt{b_{thermal}^2 + b_{turbulent}^2}$$

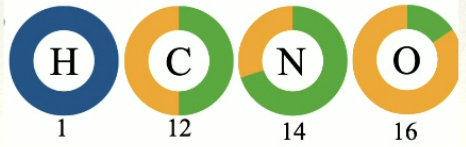
$$b_{thermal} = 0.129\sqrt{\frac{T/10^4\,K}{atomic\ weight}}\ km\,s^{-1}$$

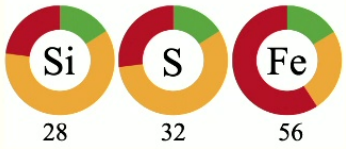
Big Bang Nucleosynthesis (BBN)

Asymptotic Giant Branch (AGB)

Core-collapse Supernovae

Type 1a Supernovae



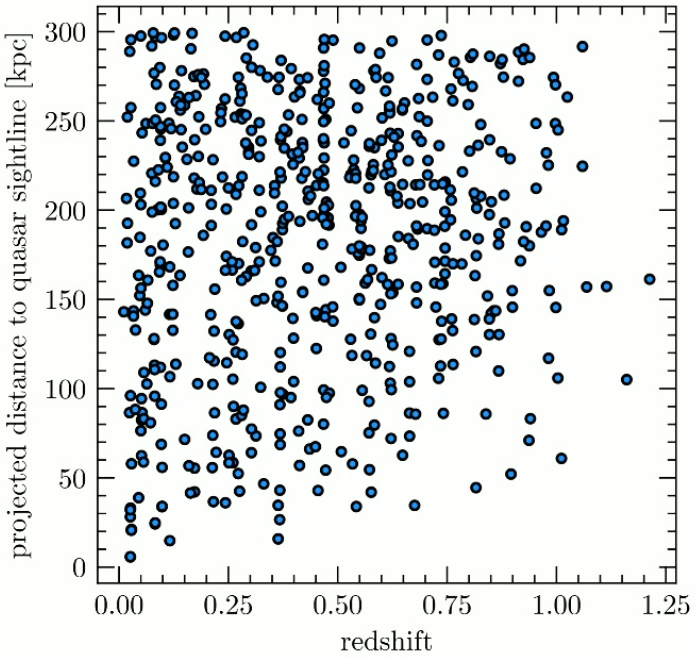



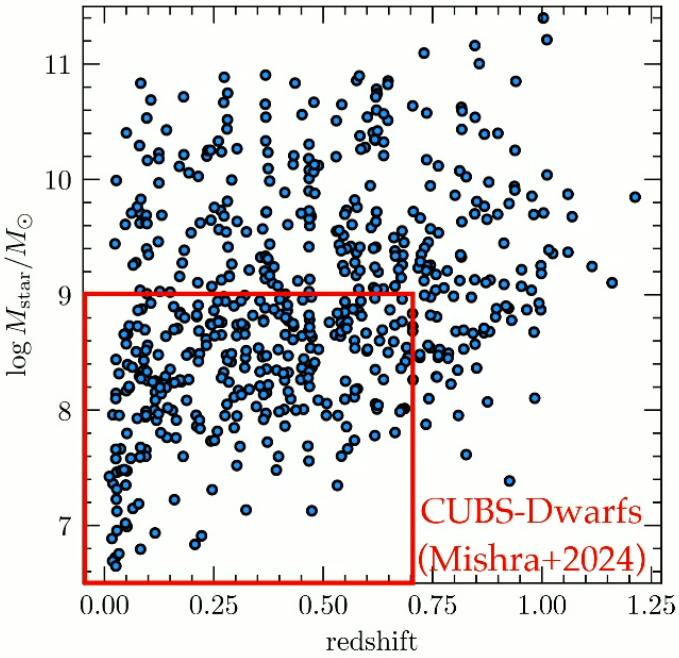

4

# CUBS wedding cake galaxy survey strategy: CGM/IGM over four orders-of-magnitude in stellar mass + environment: isolated dwarf galaxy CGM! See Nishant's talk later today

Nishant Mishra (UMichigan)

~ 10 × increase over the literature

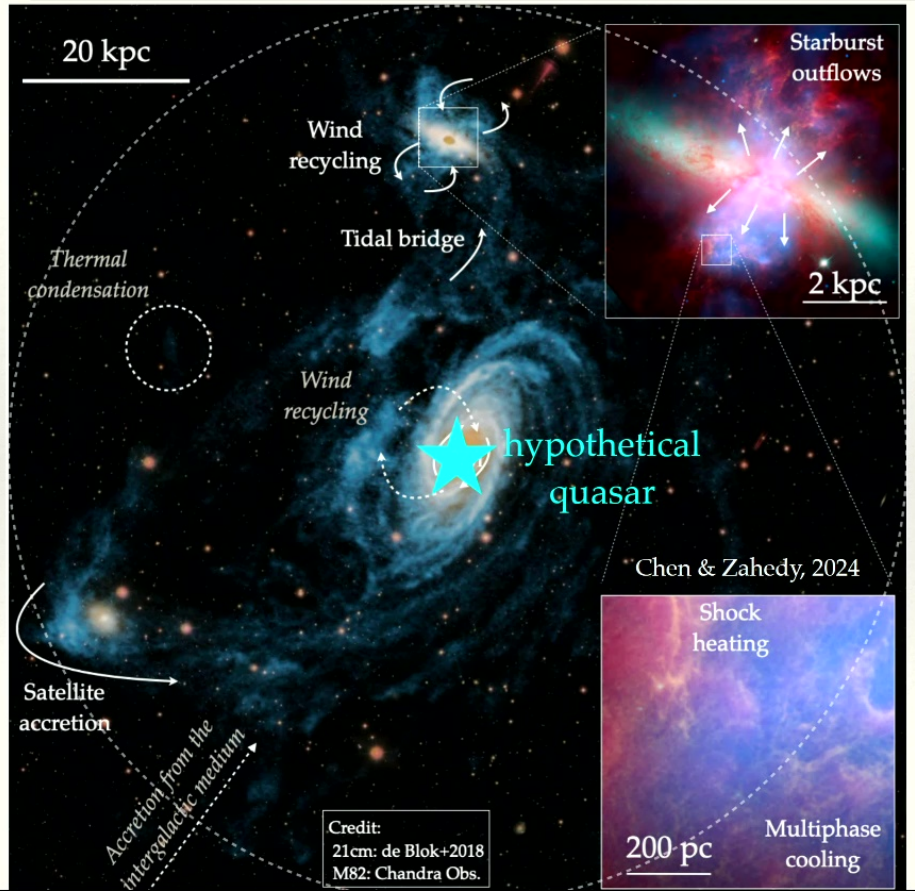



4 decades in stellar mass

## Switching gears: studies of giant ionized nebulae around quasars serendipitously enabled by CUBS & MUSEQuBES (GTO survey; PI Schaye, see Muzahid+2021, Dutta+2024)

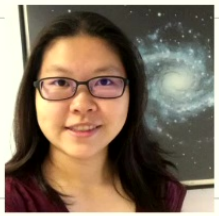

## Gas observable in 21-cm at low-$z$ can be ionized by a central quasar and becomes readily observable in non-resonant, rest-frame optical lines such as [O II], H$\beta$, and [O III] at intermediate redshift.



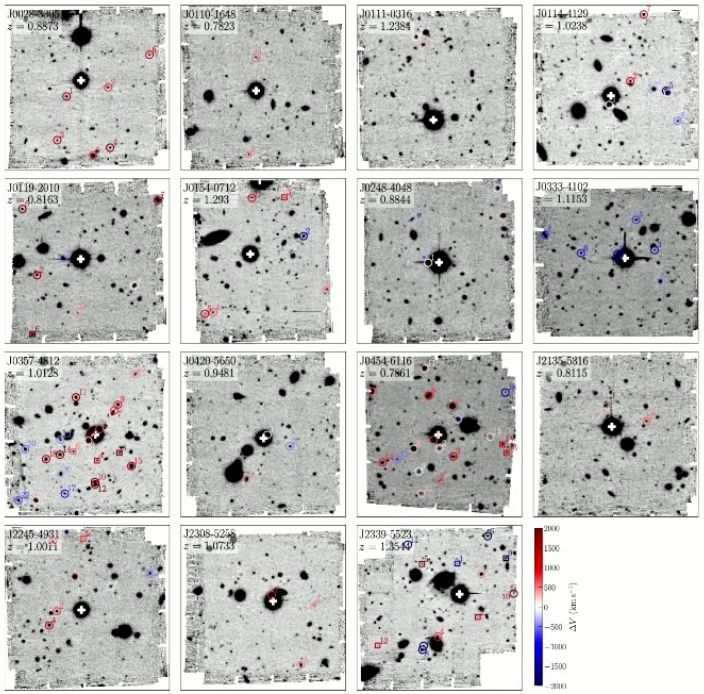

Similar in spirit to Lya nebulae around quasars at Cosmic Noon

Cantalupo+2014
Borisova+2016
Cai+2019
O'Sullivan+2020
Fosatti+2021
Mackenzie+2021
+more

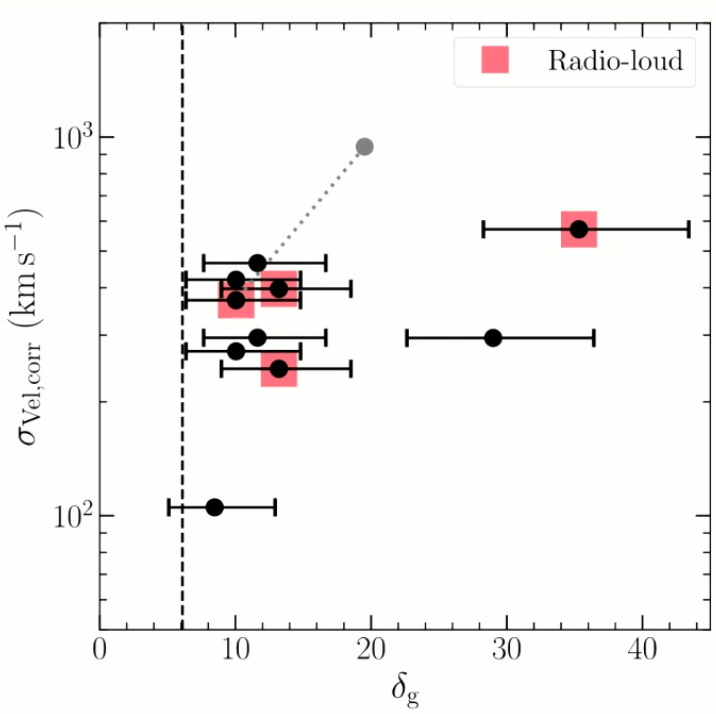
# Two-thirds of UV luminous quasars at $z \approx 1$ are in massive groups of $\gtrsim 10^{13}\ M_\odot$, with lots of scatter.



Jennifer Li
Schmidt AI in Science Fellow
U. Michigan
—> NCSA/UIUC



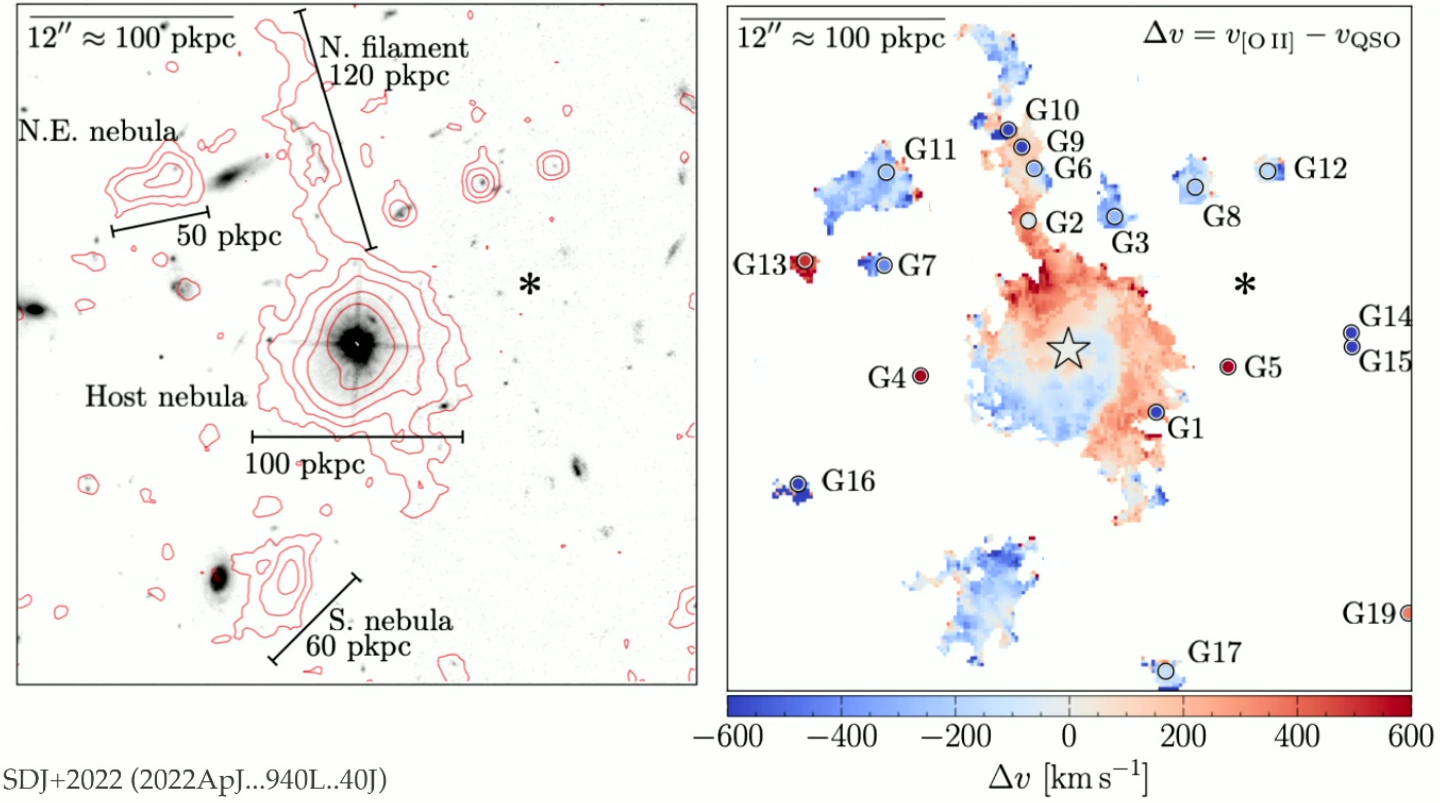
group velocity dispersion




over-density from galaxy counts

Li, SDJ+, 2024 (2024ApJ...965..143L)

# Discovery of filamentary accretion over > 100 kpc from the halo into the ISM of a luminous quasar at $z \approx 1$



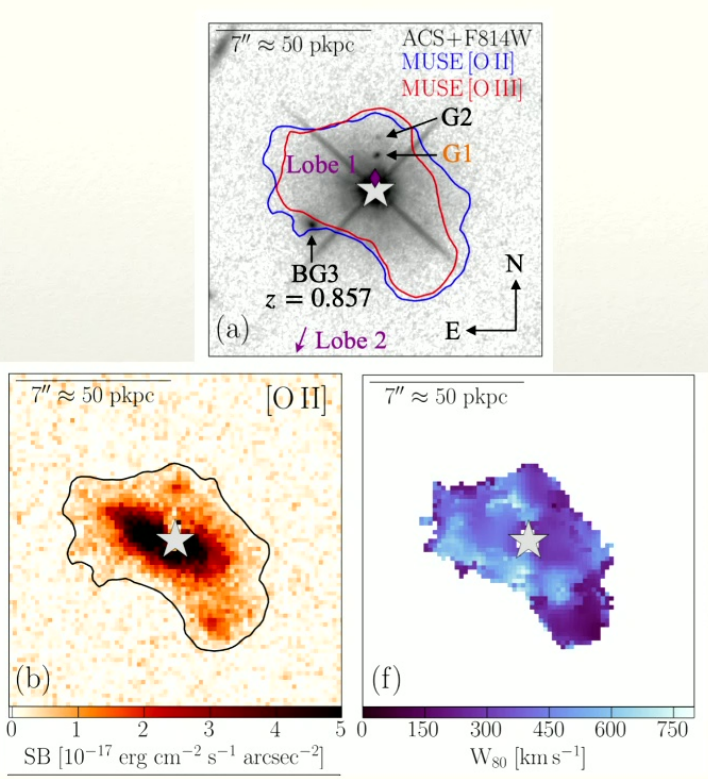

SDJ+2022 (2022ApJ...940L..40J)

$z_{\mathrm{em,[O\,II]}} = 1.1317$ $\log L_{\mathrm{bol}}/\mathrm{erg\,s^{-1}} \approx 47.2$ $\log M_{\mathrm{BH}}/\mathrm{M_\odot} \approx 9.6$ $\sigma_{\mathrm{group}} = 550\ \mathrm{km\,s^{-1}}$ $\log M_{\mathrm{h}}/\mathrm{M_\odot} \approx 13.7$

# Some signatures of feedback, though we had to look harder than expected

Will Liu
NASA FINESST Fellow
U. of Michigan

Giant nebulae around 3C 57

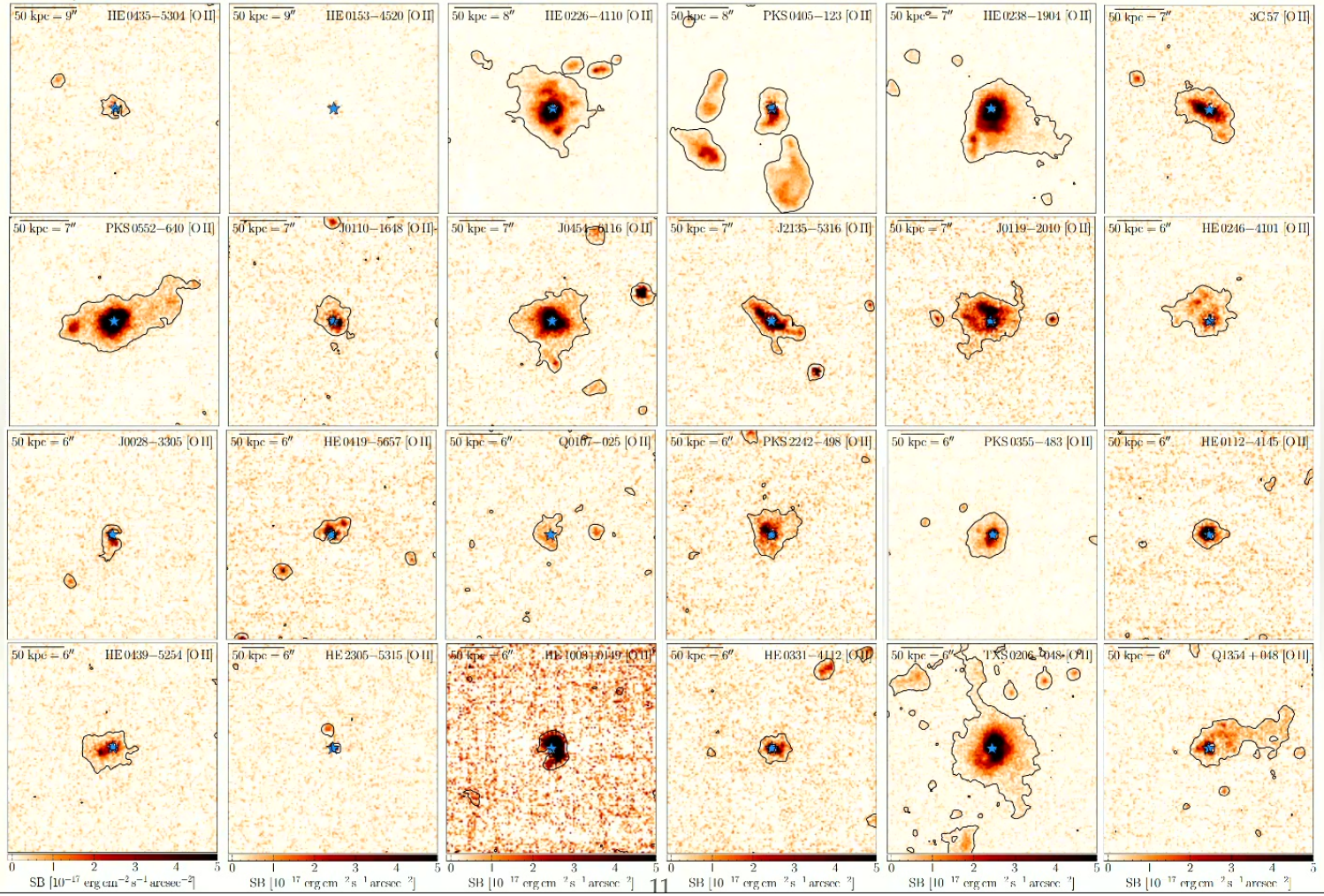



Liu, SDJ+2025 (2025ApJ.984.140L)

# Half of UV luminous quasars have >60 kpc [O II] nebulae!... but not ubiquitous

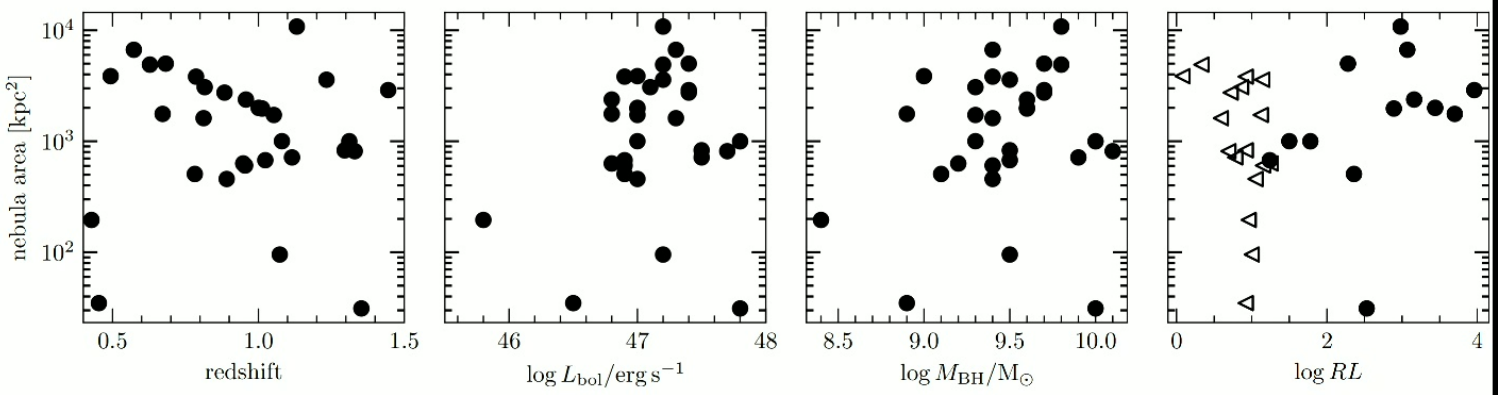
SDJ, Liu + 2024 (ApJ...966..218J)

Liu, SDJ + 2024 (MNRAS.527.5429L)



# Is the presence of nebulae correlated with quasar properties? not really

redshift? luminosity? black hole mass? radio-loudness?




SDJ, Liu+2024 (ApJ...966..218J)

At least not within the CUBS and MUSEQuBES samples—note limited dynamic range in luminosity and BH mass

# CUBS: 11 main survey papers + 6 on quasar nebulae

**The Cosmic Ultraviolet Baryon Survey (CUBS) – I. Overview and the diverse environments of Lyman limit systems at $z < 1$**
2020MNRAS.497..498C
Hsiao-Wen Chen,[1]★ Fakhri S. Zahedy,[2] Erin Boettcher,[1] Thomas M. Cooper,[2] Sean D. Johnson,[2,3]† Gwen C. Rudie,[2] Mandy C. Chen,[1] Gregory L. Walth,[2] Sebastiano Cantalupo,[4] Kathy L. Cooksey,[5] Claude-André Faucher-Giguère,[6] Jenny E. Greene,[3] Sebastian Lopez,[7] John S. Mulchaey,[2] Steven V. Penton,[8] Patrick Petitjean,[9] Mary E. Putman,[10] Marc Rafelski,[11,12] Michael Rauch,[2] Joop Schaye,[13] Robert A. Simcoe[14] and Benjamin J. Weiner[15]

**The Cosmic Ultraviolet Baryon Survey (CUBS) – III. Physical properties and elemental abundances of Lyman-limit systems at $z < 1$**
2021MNRAS.506..877Z
Fakhri S. Zahedy,[1]★ Hsiao-Wen Chen,[2] Thomas M. Cooper,[1] Erin Boettcher,[2] Sean D. Johnson,[3] Gwen C. Rudie,[1] Mandy C. Chen,[2] Sebastiano Cantalupo,[4,5] Kathy L. Cooksey,[6] Claude-André Faucher-Giguère,[7] Jenny E. Greene,[8] Sebastian Lopez,[9] John S. Mulchaey,[1] Steven V. Penton,[10] Patrick Petitjean,[11] Mary E. Putman,[12] Marc Rafelski,[13,14] Michael Rauch,[1] Joop Schaye,[15] Robert A. Simcoe[16] and Gregory L. Walth[1]

**The Cosmic Ultraviolet Baryon Survey (CUBS). II. Discovery of an $H_2$-bearing DLA in the Vicinity of an Early-type Galaxy at $z = 0.576$***
2021ApJ...913..158B
Erin Boettcher[1], Hsiao-Wen Chen[1], Fakhri S. Zahedy[2], Thomas J. Cooper[2], Sean D. Johnson[3], Gwen C. Rudie[2], Mandy C. Chen[1], Patrick Petitjean[4], Sebastiano Cantalupo[5], Kathy L. Cooksey[6], Claude-André Faucher-Giguère[7], Jenny E. Greene[8], Sebastian Lopez[9], John S. Mulchaey[2], Steven V. Penton[10], Mary E. Putman[11], Marc Rafelski[12,13], Michael Rauch[2], Joop Schaye[14], Robert A. Simcoe[15], and Gregory L. Walth[2]

**The Cosmic Ultraviolet Baryon Survey (CUBS) – IV. The complex multiphase circumgalactic medium as revealed by partial Lyman limit systems**
2021MNRAS.508.4359C
Thomas J. Cooper,[1]★ Gwen C. Rudie,[1] Hsiao-Wen Chen,[2] Sean D. Johnson,[3] Fakhri S. Zahedy,[1] Mandy C. Chen,[2] Erin Boettcher,[2] Gregory L. Walth,[3] Sebastiano Cantalupo,[4,5] Kathy L. Cooksey,[6] Claude-André Faucher-Giguère,[7] Jenny E. Greene,[8] Sebastian Lopez,[9] John S. Mulchaey,[1] Steven V. Penton,[10] Patrick Petitjean,[11] Mary E. Putman,[12] Marc Rafelski,[13,14] Michael Rauch,[1] Joop Schaye,[15] and Robert A. Simcoe[16]

**The Cosmic Ultraviolet Baryon Survey (CUBS) V: On the Thermodynamic Properties of the Cool Circumgalactic Medium at $z \lesssim 1$**
2022MNRAS.516.4882Q
Zhijie Qu[1]*, Hsiao-Wen Chen[1], Gwen C. Rudie[2], Fakhri S. Zahedy[2], Sean D. Johnson[3], Erin Boettcher[4,5,6], Sebastiano Cantalupo[7], Mandy C. Chen[1], Kathy L. Cooksey[8], David DePalma[9], Claude-André Faucher-Giguère[10], Michael Rauch[2], Joop Schaye[11], and Robert A. Simcoe[9]

**The Cosmic Ultraviolet Baryon Survey (CUBS) VI: Connecting Physical Properties of the Cool Circumgalactic Medium to Galaxies at $z \approx 1$**
arXiv:2306.11274
Zhijie Qu[1],* Hsiao-Wen Chen[1], Gwen C. Rudie[2], Sean D. Johnson[3], Fakhri S. Zahedy[2], David DePalma[4], Erin Boettcher[5,6,7], Sebastiano Cantalupo[8], Mandy C. Chen[1], Kathy L. Cooksey[9], Claude-André Faucher-Giguère[10], Jennifer I-Hsiu Li[3], Sebastian Lopez[11], Joop Schaye[12], and Robert A. Simcoe[4]

**Discovery of a Damped Ly$\alpha$ Absorber Originating in a Spectacular Interacting Dwarf Galaxy Pair at $z = 0.026$**
2022ApJ...926L..33B
Erin Boettcher[1,2,3], Neeraj Gupta[4], Hsiao-Wen Chen[3], Mandy C. Chen[3], Gyula I. G. Józsa[5,6,7], Gwen C. R[illegible], Sebastiano Cantalupo[9], Sean D. Johnson[10], S. A. Balashev[11,12], Françoise Combes[13], Kathy L. Cooksey[1], Claude-André Faucher-Giguère[15], Jens-Kristian Krogager[16], Sebastian Lopez[17], Emmanuel Momjian[18], Pasquier Noterdaeme[19,20], Patrick Petitjean[19], Marc Rafelski[21,22], Raghunathan Srianand[4], Gregory L. Walth[8], Fakhri S. Zahedy[8]

**The Cosmic Ultraviolet Baryon Survey (CUBS) VII: on the warm-hot circumgalactic medium probed by O VI and Ne VIII at $0.4 \lesssim z \lesssim 0.7$**
2024ApJ...968....8Q
Zhijie Qu,[1] Hsiao-Wen Chen,[1] Sean D. Johnson,[2] Gwen C. Rudie,[3] Fakhri S. Zahedy,[3] David DePalma,[4,5] Joop Schaye,[6] Erin T. Boettcher,[7,8,9] Sebastiano Cantalupo,[10] Mandy C. Chen,[1] Claude-André Faucher-Giguère,[11] Jennifer I-Hsiu Li,[2,12] John S. Mulchaey,[3] Patrick Petitjean,[13] and Marc Rafelski[14,15]

**The Cosmic Ultraviolet Baryon Survey (CUBS). VIII. Group Environment of the Most Luminous Quasars at $z \approx 1$**
2024ApJ...965..143L
Jennifer I-Hsiu Li[1,2], Sean D. Johnson[1], Erin Boettcher[3,4,5], Sebastiano Cantalupo[6], Hsiao-Wen Chen[7], Mandy C. Chen[7], David R. DePalma[8], Zhuoqi (Will) Liu[1], Nishant Mishra[1], Patrick Petitjean[9], Zhijie Qu[7], Gwen C. Rudie[10], Joop Schaye[11], and Fakhri S. Zahedy[12,10]

**The Cosmic Ultraviolet Baryon Survey: Empirical Characterization of Turbulence in the Cool Circumgalactic Medium**
2023MNRAS.524..512Q
Hsiao-Wen Chen[1], Zhijie Qu[1], Michael Rauch[2], Mandy C. Chen[1], Fakhri S. Zahedy[2], Sean D. Johnson[3], Joop Schaye[4], Gwen C. Rudie[2], Erin Boettcher[5,6,7], Sebastiano Cantalupo[8], Claude-André Faucher-Giguère[9], Jenny E. Greene[10], Sebastian Lopez[11], and Robert A. Simcoe[12]

**The Cosmic Ultraviolet Baryon Survey (CUBS). IX. The Enriched Circumgalactic and Intergalactic Medium Around Star-forming Field Dwarf Galaxies Traced by O VI Absorption**
2024ApJ...976..149M
Nishant Mishra[1], Sean D. Johnson[1], Gwen C. Rudie[2], Hsiao-Wen Chen[3], Joop Schaye[4], Zhijie Qu[3], Fakhri S. Zahedy[2,5], Erin T. Boettcher[6,7,8], Sebastiano Cantalupo[9], Mandy C. Chen[3], Claude-André Faucher-Giguère[10], Jenny E. Greene[11], Jennifer I-Hsiu Li[1,12], Zhuoqi (Will) Liu[1], Sebastian Lopez[13], and Patrick Petitjean[14]

Quasar nebulae papers:
SDJ+2024, Chen, M. 2023, 2024, Liu et al., 2024, 2025