**Title:** Investigating Galaxy Ecosystems with Multi-wavelength Observations of Gas and Dust

**Speakers:** Varsha Kulkarni

**Collection/Series:** Cosmic Ecosystems

**Subject:** Cosmology

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**Abstract:**

We report results from observations of the CGM ionized, atomic, molecular, and condensed phases using a combination of integral field spectroscopy (MaNGA, VLT MUSE, JWST MRS), and imaging and spectroscopy from HST, VLT, Magellan. In a study of the warm and cool CGM of galaxies mapped with IFS, and a comparison of the kinematics, ionization, and metallicity of this gas with the ionized gas in star-forming regions in the galaxies, we find consistency with a co-rotation of the cool CGM with galaxy disks and hints of changes in gas ionization, potentially due to the stronger intergalactic radiation field at larger galactocentric distance. Our spatially resolved maps of gas metallicity and ionization around galaxies provide constraints on models of the metal distribution around galaxies. Our results are also consistent with higher metallicity and higher ionization parameter for gas at higher elevation angles, as expected for outflows. Our JWST studies of the composition, structure, and extinction properties of the dust grains in both the diffuse and dense ISM/CGM of galaxies at $0<z<1.5$ indicate that dust grains in distant galaxies differ in physical and chemical properties from grains in local galaxies. Finally, our study of the ISM/CGM at $4<z<6$ shows that high-redshift galaxies show a wide diversity of chemical enrichment histories, including some cases of highly accelerated chemical evolution.

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# Investigating Galaxy Ecosystems with Multi-wavelength Observations of Gas and Dust

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Cosmic Ecosystems 2025

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# Motivations

- How do CGM and stellar properties relate?

- How does gas distribution in galaxies vary with distance from the galaxy centers?

- How are the outer parts of galaxies coupled to their inner parts?

- How does dust in and around galaxies evolve?

Combine absorption and emission studies.

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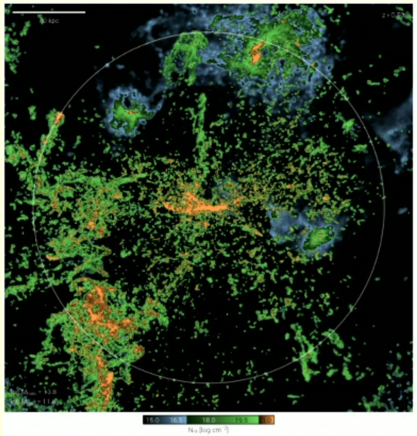
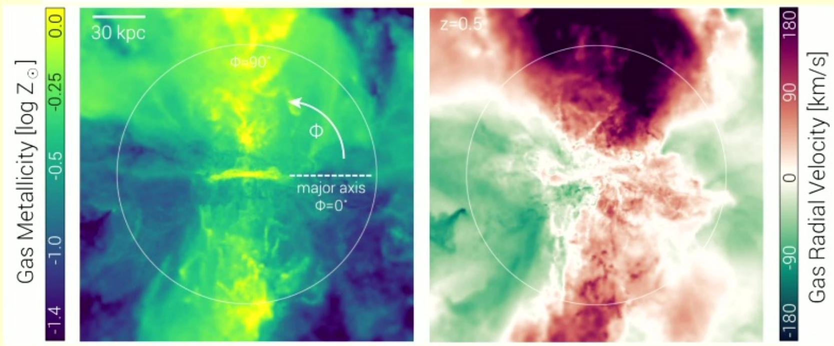
# Some Predictions from Sims: H I, Metals, Kinematics

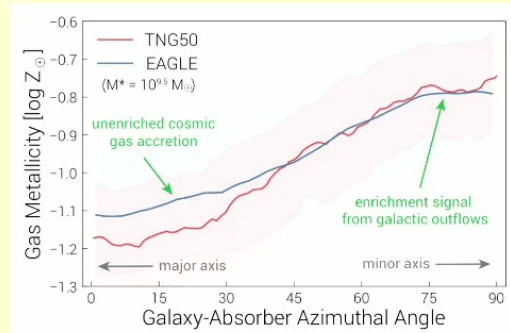


$N_{HI}$ distribution in a TNG50 halo at z=0.5
log M*=11.8

**log $N_{HI} \gtrsim 18$ gas can extend out to >0.25 $R_{vir}$**

Nelson+2020




A TNG50 galaxy at z = 0.5 with $M_* = 10^{10.3}\, M_\odot$, $M_h = 10^{11.8} M_\odot$, rotated edge-on
Péroux+ 2020

**Can test such predictions by combining galaxy integral field spectroscopy and CGM absorption spectroscopy.**

# MUSE-ALMA-Halos

(Péroux+ 2022; Weng+2023; Karki, Kulkarni+ 2023, 2025 submitted)

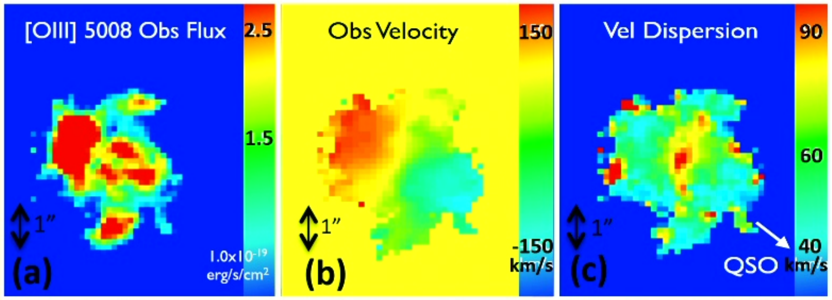
- 19 quasar fields with 32 HI-strong absorbers ($N_{HI} > 10^{18}$) at 0.3<z< 1.4

-VLT MUSE IFS ($H\alpha$, $H\beta$, [O II], [O III]...)

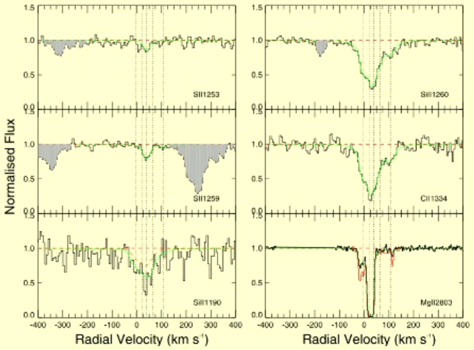
-ALMA CO

-HST WFC3/WFPC2
3 broad-band imaging
3658 objects total,
703 with specz (MUSE),
66 @ absorber redshift

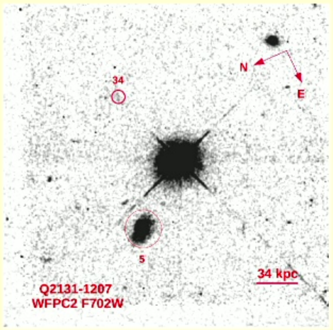
-HST STIS/COS,
Keck HIRES or VLT
UVES/X-shooter (metals)




A rotation-dominated galaxy at z~0.4 (MUSE)




HST COS Metals
Som, Kulkarni+ 2015

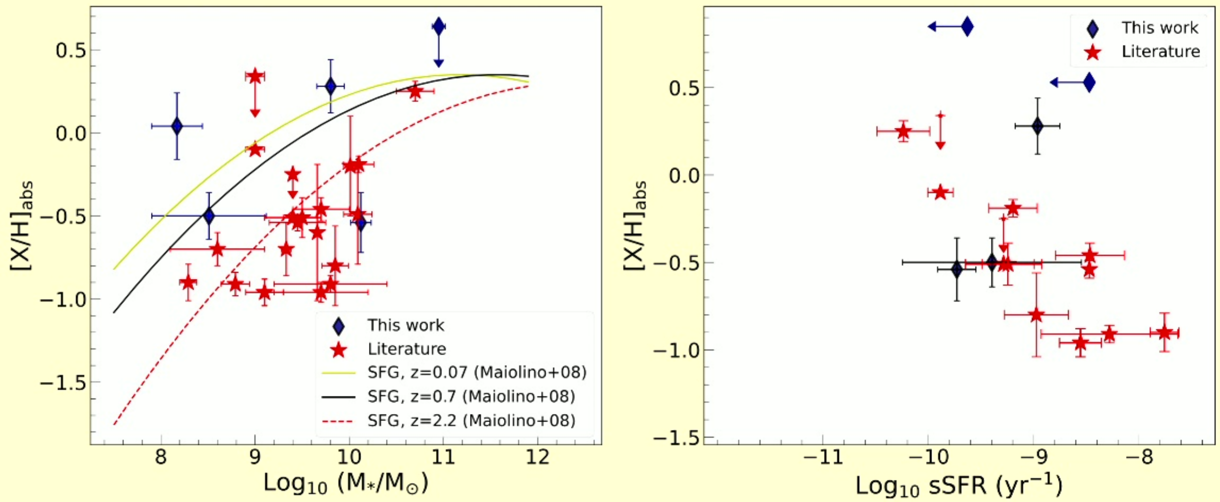



HST WFC3
Karki, Kulkarni+ 2023

# How do CGM and stellar properties relate?

(Karki, Kulkarni+ 2023, MNRAS, 524, 5524;
Augustin+ 2024, MNRAS, 528, 6159; Karki, Kulkarni+ 2025 submitted)

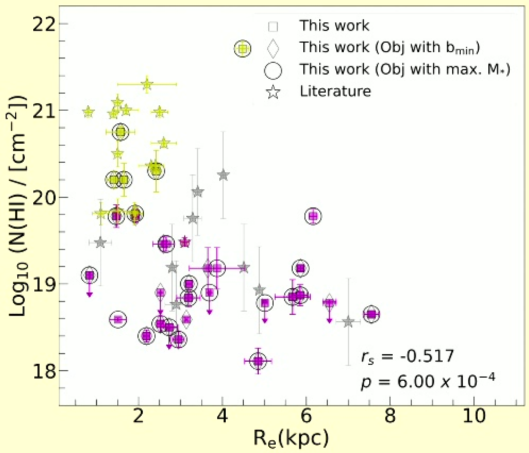
## Metallicity correlated with M* and anticorrelated with sSFR



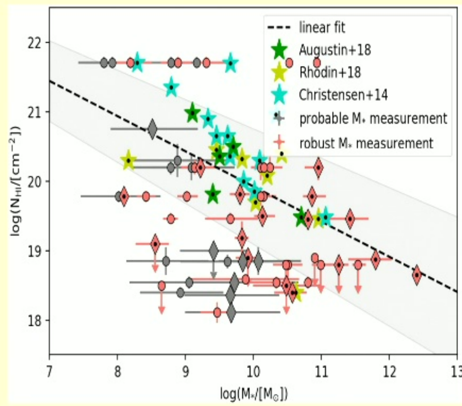

**Low-metallicity absorbers are associated with galaxies with vigorous current star formation but low past star formation.**

# Higher $N_{HI}$ associated with smaller and less massive galaxies

Karki, Kulkarni+ 2023, MNRAS, 524, 5524




Augustin+ 2024 MNRAS, 528, 61




DLA gas (log $N_{HI} \geq 20.3$) associated with $R_e$<3 kpc galaxies.

$N_{HI}$ also anticorrelated with M*

$$\log(N_{\rm H\,I}/[\rm cm^{-2}]) = -0.51(\pm 0.1) \times \log(M_*/[\rm M_\odot]) + 25.0(\pm 1.2)$$

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## How does gas distribution vary with distance? How do inner and outer parts compare?

**(Klimenko, Kulkarni+ 2023, ApJ, 954, 115**
**Klimenko, Kulkarni+ 2025, in prep)**


z < 0.1 galaxies with inner 1-2 effective radii region exquisitely mapped in emission lines (hence in SFR, ionization, ionized-gas metallicity, gas velocity, velocity dispersion etc….)

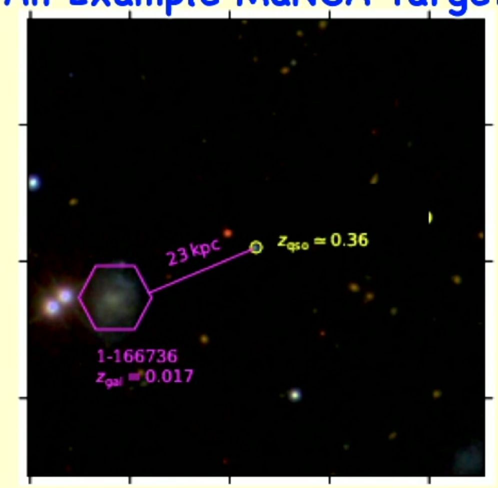
Also well-imaged in continuum light, but outer regions not covered by MaNGA

log $M_*$ ~ 9-11, Re ~ 2-11 kpc

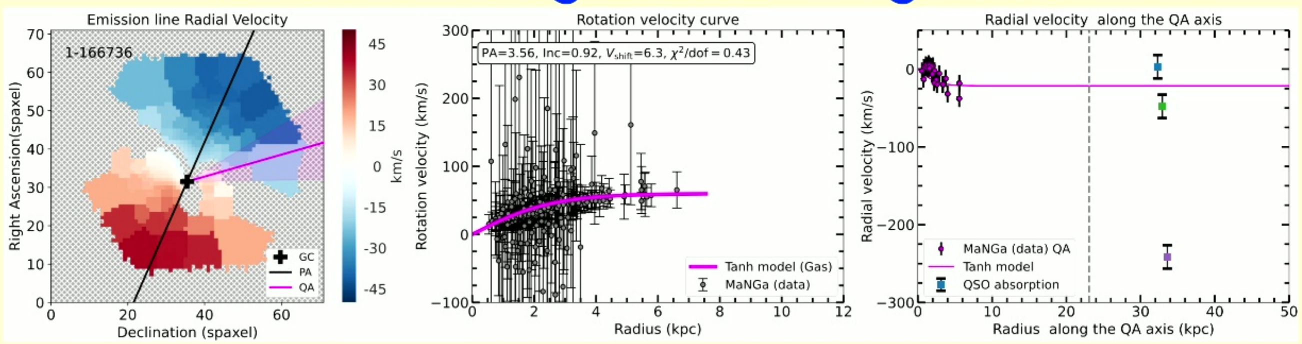
Probe CGM with HST COS spectra of quasars/AGNs at $z \geq z_{gal}$ with impact parameters b < 140 kpc

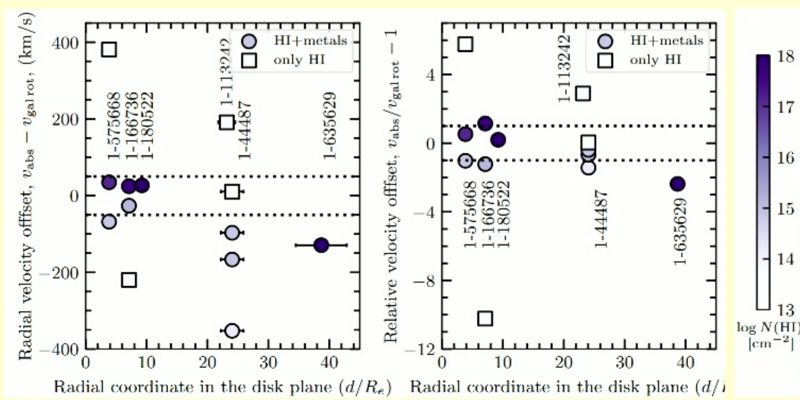
Cy 28, Cy 30

**An Example MaNGA target**



# Gas Kinematics in Inner Parts vs. in CGM along Quasar Sightline

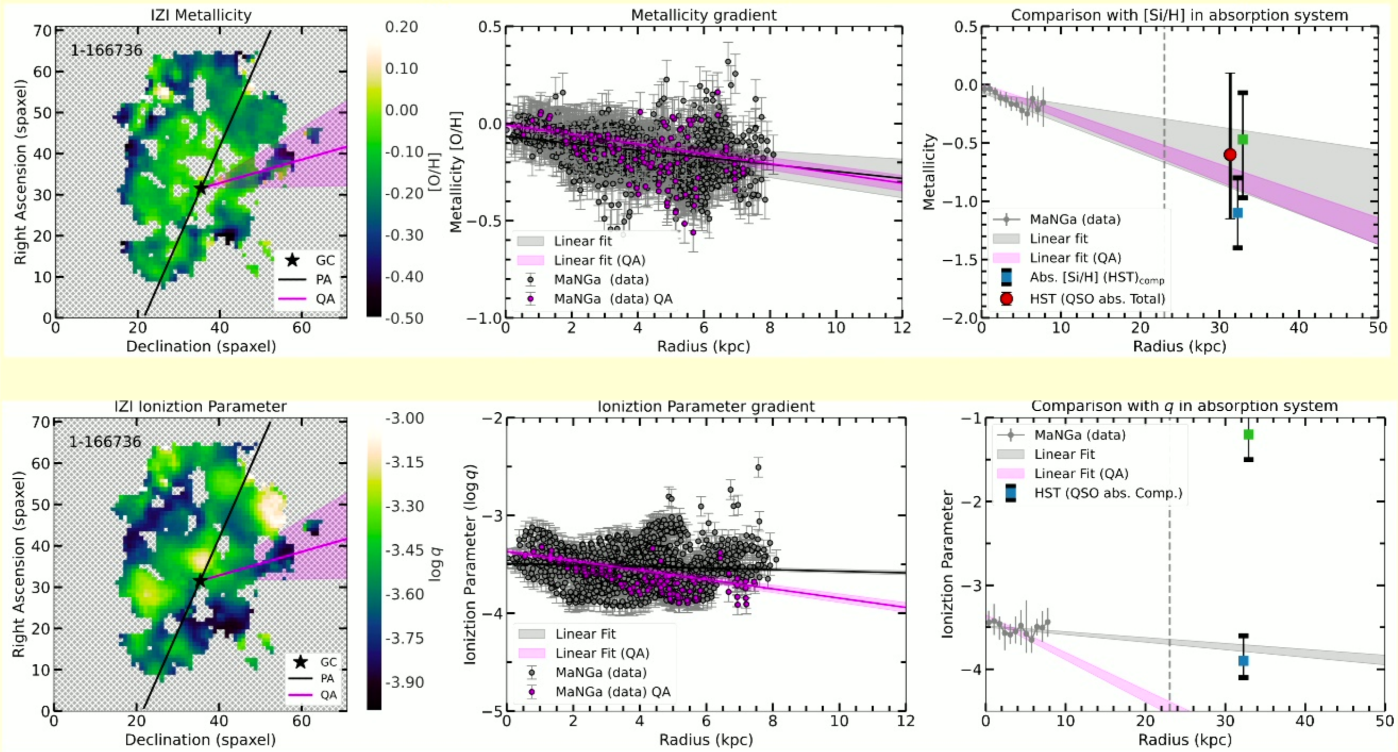



Stronger H I-absorption components consistent with corotation with the disk within $\pm$50 km/s out to ~10 $R_e$.

Klimenko, Kulkarni+ 2023, ApJ, 954, 115

# Metallicity and Ionization in Inner Parts vs. in CGM along Quasar Sightline: An Example




Klimenko, Kulkarni+ 2023, ApJ, 954, 115

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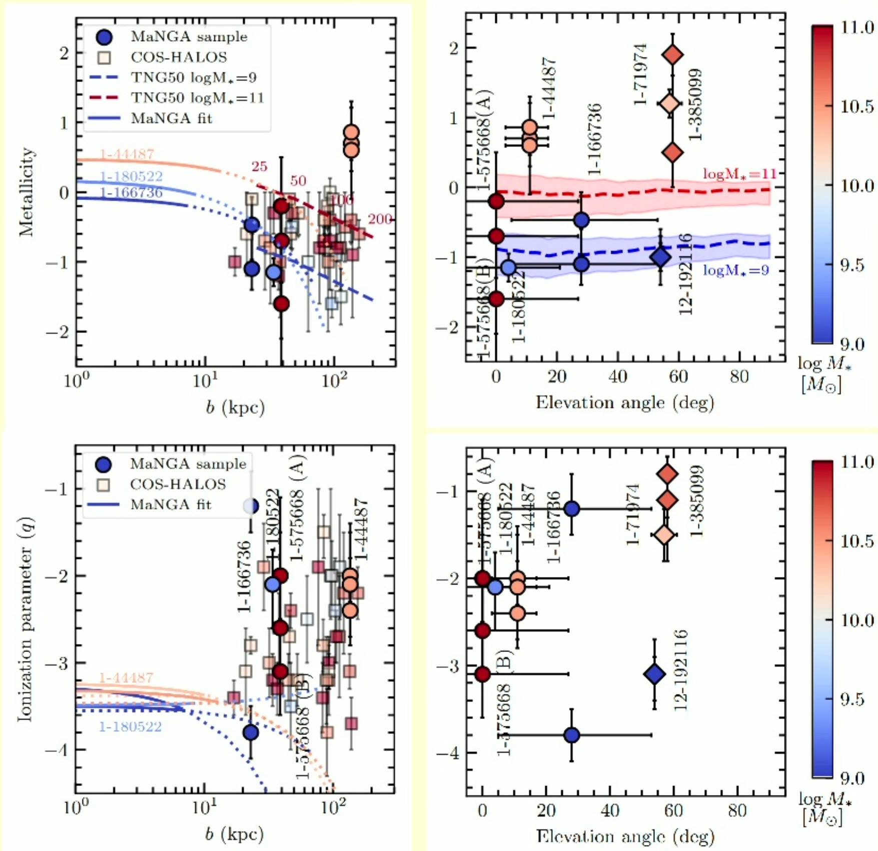
# Radial and Azimuthal Variation in Metallicity and Ionization

Klimenko, Kulkarni +2023, ApJ, 954, 115

Lower ionization and lower metallicity at lower elevation angles

Consistent with inflows

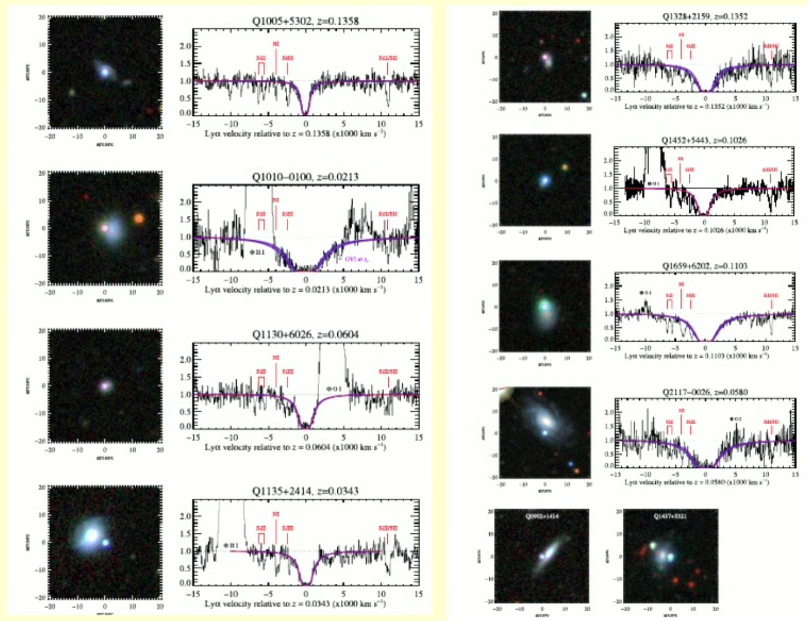


# GOTOQs: $N_{HI}$ at low impact par.

Kulkarni+ 2022, ApJ, 929, 150

"Galaxies on top of quasars"--quasars with foreground star-forming galaxies (log M* ~7-10) at z < 0.15 within impact parameters of 1-7 kpc

HST COS spectra




GOTOQs are essentially always DLAs or sub-DLAs!

(Anchor the low-b end of the $N_{HI}$ vs. b relation.)

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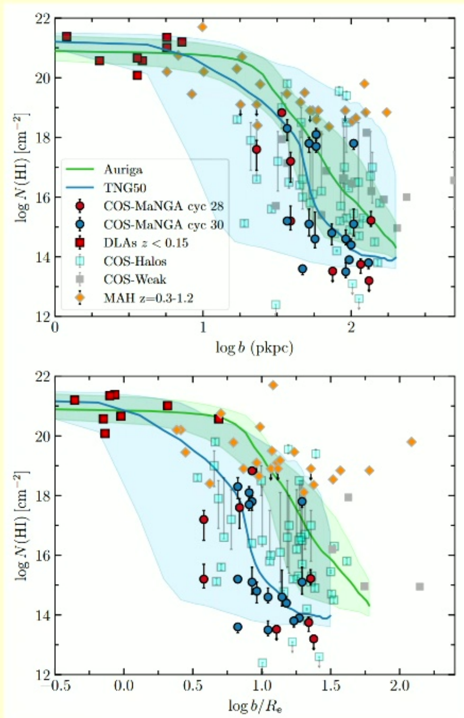
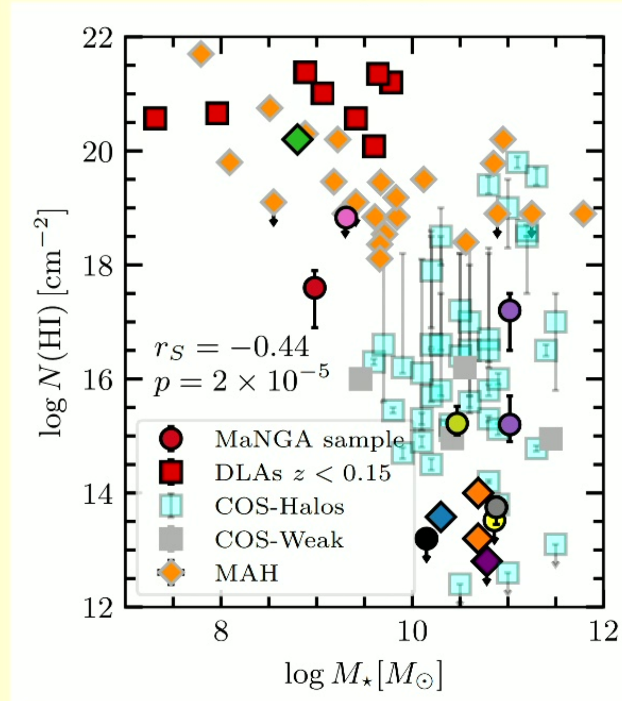
# Radial Profile of H I and Dependence on M*

Klimenko, VK+2023, ApJ, 954, 115; Klimenko, VK+2025 in prep




Combining GOTOQs, MaNGA, MUSE-ALMA-Halos, COS-Halos, COS-Weak




$N_{HI}$ falls off radially.

$N_{HI}$ flattens in inner regions.

$N_{HI}$ anti-correlated with M*

# How does dust evolve?

- Dust impacts ISM Heating, cooling, molecule production, star formation
- Dust attenuates and reddens star light, affects derived galaxy properties—distances, structures etc.
- Dust potentially affects studies of cosmic expansion

- Silicates comprise ~70% mass of the cores of interstellar dust grains, but were not probed in most previous studies of dust in distant galaxies (which searched for the 2175 Å feature).

- We have been studying silicate features in quasar absorbers—earlier with Spitzer (e.g. Kulkarni+2007, 2011; Aller+2012, 2014), now with JWST

--35.3 hrs in Cycle 1, 49.5 hrs in Cycle 3)
--23 gas-rich, dusty galaxies at $0.1 < z < 1.2$
--MIRI MRS covers silicates, ices, molecules.

# JWST obs. of silicates in 2175 Å absorbers

(Klimenko, Kulkarni, & Aller 2025 a,b, ApJ, submitted)

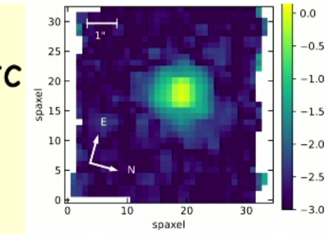
--Strong 2175 Å absorbers at $0.5 < z_{abs} < 1.2$

--Have $W_{Mg\ II\ 2796} > 2$ Å

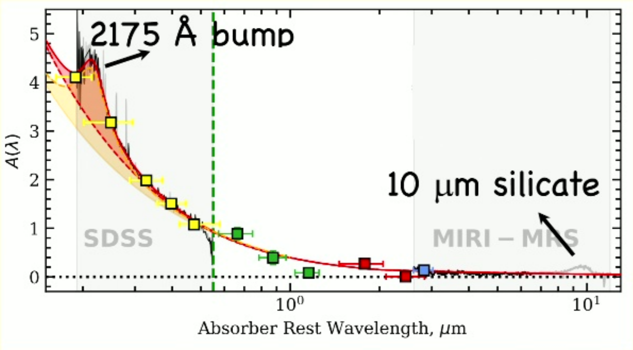
Mid-IR background subtraction, cosmic ray showers etc

Pipeline not enough!

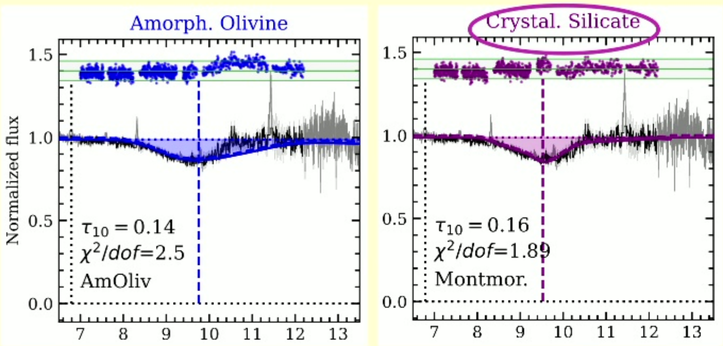
Continuum fit: composite spectrum of similar AGNs




**Extinction Curve Fit including IR data**




**JWST MIRI 10 μm Silicate Absorption**

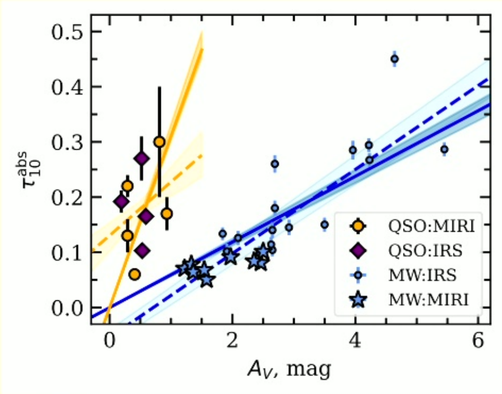


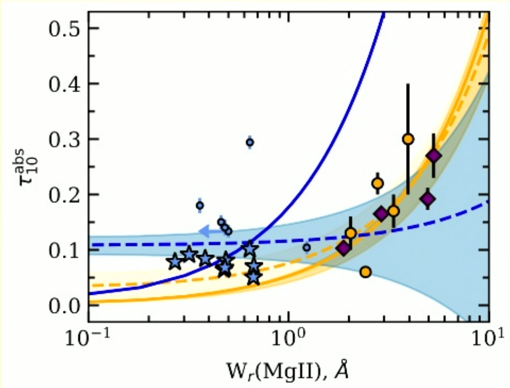
# Trends between Dust, Metal properties

Klimenko, Kulkarni, & Aller 2025a,b, ApJ, submitted

Stronger silicate absorption than expected from extrapolation of MW trend

Stronger silicate content for higher metallicity (or higher M or stronger outflows?)



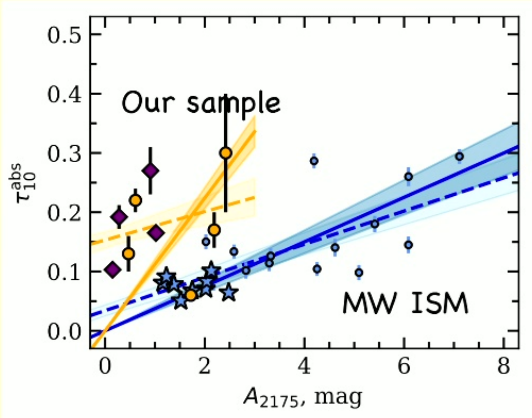



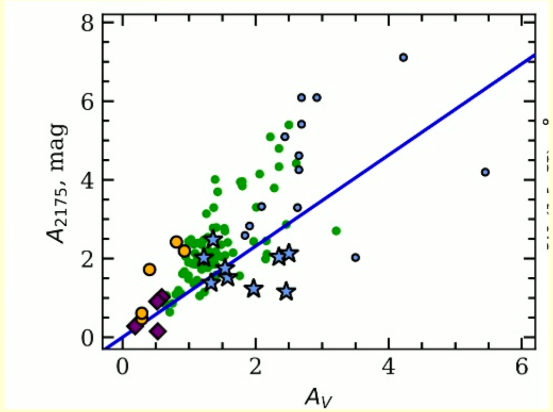

**Dust grain composition and/or sizes different than in ISM!**

**Cycle 3 observations in progress**

--Both diffuse ISM (0.3 < Av < 3.3) and dense ISM (Av > 20)

# Silicate vs. Carbonaceous Dust




Silicate and 2175 Å bump strengths are correlated (but not $\tau_{10}/A_v$ and $A_{2175}/A_v$) for diffuse ISM in Milky Way →independent formation processes)

No correlation for our sample—formation processes for silicate and carbonaceous grains not related in distant galaxies

2175 Å bump strength is indeed correlated with Av for diffuse ISM in Milky Way

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# CONCLUSIONS

- Gas metallicity is correlated positively with M*, negatively with sSFR. Low M* galaxies have low past star formation, vigorous current star formation.

- H I falls off with galaxy size, stellar mass, and with distance.
H I profile flattens in inner regions.

- CGM seems to co-rotate with the galaxy disk out to ~10 Re.

- CGM metallicity consistent with trends from inner galaxy.

- Ionization may be higher in outer parts.

- Silicate dust in distant galaxies differs in composition and/or grain sizes compared to Milky Way ISM.

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