Looking Ahead: Circumgalactic Metals and Gas with HST and LUVOIR

J. Christopher Howk
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The visible **stars** in a galaxy trace only a portion of the baryonic matter important to its evolution.
An extended *corona* of gas may be a remnant of the collapse of the galaxy, perhaps at the virial temperature of the dark matter halo.
Outflows driven by star formation and/or AGN activity circulate **baryons, metals, and energy** into the **corona** (and perhaps beyond the halo).
Inflowing pristine matter from the intergalactic medium may fuel star formation in the disk or be heated, subsumed into the corona.

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Outflows driven by star formation and/or AGN activity circulate baryons, metals, and energy into the corona (and perhaps beyond the halo).

The visible stars in a galaxy trace only a portion of the baryonic matter important to its evolution.
The galaxy itself is embedded in and draws from the cosmic web of gas and galaxies.
The CGM plays a **fundamental role** in and potentially provides **unique constraints** on galaxy evolution.

1. How does the CGM reflect galaxy evolution?

2. What role does the CGM play in shaping galaxies?
I. How does the CGM reflect galaxy evolution?

The baryonic and metal content of the CGM trace matter collected from the assembly of the galaxy & matter expelled from the galaxy.

Recycling?
Satellite stripping?

Hot-mode accretion?
Primordial corona?
1. How does the CGM reflect galaxy evolution?

*The galactic mass-metallicity relationship may be shaped by galactic outflows.
1. How does the CGM reflect galaxy evolution?

*The CGM may host a significant number of “invisible” baryons.
ILLUSTRIS simulations: Vogelsberger+ (2014)
Projected $\text{HI}$ and $\text{OVI}$ column densities (units: atoms cm$^{-2}$)
Color (Wavelength)

Brightness

Quasar

Lehner+ (2013)

$16.0 \leq \log N(\text{HI}) \leq 18.6$

Fox+ (2013)

Inflowing Gas

Outflowing Gas

Shen+ (2013)

$z \sim 2.8$

$\text{H I}$

$\text{O VI}$

2.5% solar

40% solar

Upper limits
COS-Halos survey studied CGM vs. galaxy properties

- COS-Dwarfs
  - $z = 0.02 - 0.10$
  - $\log M^* = 8 - 10$
  - Optimal for CIV

- COS-Halos
  - $z = 0.15 - 0.35$
  - $\log M^* = 10 - 11.5$
  - Optimal for OVI

ALL GALAXIES SELECTED PRIOR TO ABSORPTION

“Map” of QSOs relative to foreground galaxies.

Slide courtesy of J. Tumlinson
The CGM harbors a large fraction of galactic baryons.

Cool+Warm CGM mass budget:

Typical mass of cool gas in CGM:
$$M_{\text{Cool CGM}} \sim 6 \times 10^{10} \, M_\odot$$

Typical mass of warm gas in CGM:
$$M_{\text{Warm CGM}} \sim 2 \times 10^{10} \, M_\odot$$

There is probably not a galactic “missing baryons problem.”

Baryon budget of typical L* galaxy ($\sim 10^{12} \, M_\odot$):

- Stars: 24%
- CGM (Cool): 35%
- CGM (Warm): 15%
- Hot Corona: 10%
- Other: 13%
- ISM: 3%
- HVCs: 0%

Werk+ (2014); also Stocke+ (2013), Lehner+ (2015), Keeney+ (2017)
The CGM harbors a large fraction of galactic baryons

Cool+Warm CGM mass budget:

Typical mass of cool gas in CGM:
$$M_{\text{Cool CGM}} \sim 6 \times 10^{10} M_\odot$$

Typical mass of warm gas in CGM:
$$M_{\text{Warm CGM}} \sim 2 \times 10^{10} M_\odot$$

There is probably not a galactic “missing baryons problem.”
Local galaxies show CGM is a large baryon reservoir.
Gas content of satellites hint at large gaseous halos about local galaxies.

Neutral gas mass

$\log_{10}(\frac{M_{HI}}{M_\odot})$

Distance from MW or M31

$\log_{10}(d_{\text{gal}}/\text{kpc})$

Adapted from Westmeier+ (2015)

See also Grcevich & Putman (2009), Spekkens+ (2014)
Andromeda houses a huge gaseous halo.
M31 compared with angular size of Earth’s moon.

$2R_{\text{vir}} \sim 600 \text{ kpc}$
The CGM of the Andromeda galaxy bears at least $\sim 10\%$ of its stellar mass.

\[ M_{\text{CGM}}(\rho \leq 50 \text{ kpc}) > 3 \times 10^8 \, M_\odot \]

\[ M_{\text{CGM}}(\rho \leq 300 \text{ kpc}) > 10^9 \, M_\odot \]
Project AMIGA: Andromeda’s CGM bears a huge baryonic mass.

**Project AMIGA**

**25 total targets**
- 18 new targets (93 orbits)

- Proposed Targets
- Archival targets with detections
- Archival targets with non-detections
- Archival MW halo star sightlines

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**AMIGA sight lines**

- Data from Lehner+ (2015)
- Models from Ford+ (2014)

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**Figure 2:** Examples of Archival COS G130M/G160M spectra of 2 QSOs piercing the CGM of M31. AMIGA C IV sensitivity is shown with a blue dashed line, while AMIGA Si IV sensitivity is shown with a red dashed line. The horizontal lines indicate our current sensitivity limits. The downward arrows are non-detections of M31 CGM gas, and the horizontal bars show our S/N requirements. The blue circles are archival targets, and the red circles are proposed targets. The gray circles are archival MW halo star sightlines.

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**Distribution of the targets within ~1.5 R_vir**

- All the 18 proposed targets (93 orbits)
- Blue circles are archival targets
- Red circles are proposed targets
- Gray circles are archival MW halo star sightlines

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**Figure 1:** Distribution of the targets within ~1.5 R_vir. The blue circles represent archival targets, the red circles represent proposed targets, and the gray circles represent archival MW halo star sightlines. The tick marks show the proposed targets, filling out the R—φ parameter space in a similar fashion as the AMIGA sample, filling out the R—φ parameter space. Our future zoom-in simulations will explicitly explore the R—φ parameter space in a similar fashion as the AMIGA sample, filling out the R—φ parameter space (see L15 for the entire suite of ions). Open circles with downward arrows are non-detections of M31 CGM gas, mostly beyond 1.1 R_vir. The horizontal lines show our sensitivity limit for these key ions with the proposed S/N=15. The MW halo stars demonstrate that any absorption at v_LSR ≲ 150 km s^-1 is not part of the MW halo. Unlike single sightline studies in distant galaxies, our observations will provide unique constraints at various R—φ parameters and azimuths but different regions of the key azimuthal sectors (projected minor and major axes). Our proposed sample complements the existing one to allow us to probe the M31 CGM uniformly radially in-between.

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**Description of Observation**

- The column densities of Si III, Si IV, C IV of the M31 CGM gas at v_LSR ≲ 150 km s^-1 are shown in Figure 2. The thick dashed lines show models from CoI Ford (Ford et al. 2014). These models appear to be appropriate for CIV, but do not do a good job for SiIV (which behaves like the low ions in these models), possibly because they are only averaged over many impacts. Our models require that the absorption at v_LSR ≲ 150 km s^-1 be suitably constrained at small and large projected distances (4–5; 7–8; 9–12). We use the AMIGA sample, filling out the R—φ parameter space, to improve our current constraints on both sides of M31 along the minor axis, we will be able to gauge the effect of its substructure on the CGM (e.g., 4–5; 7–8; 9–12).

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The CGM harbors as many metals as stars in galaxies.

First pointed out by Molly Peeples.
COS-Halos: warm metals in CGM associated with star formation.

The presence and quantity of “warm” metals is strongly correlated with star formation properties of galaxies.

…but it is not for H I (Thom+ 2012).
2. What role does the CGM play in shaping galaxies?

Flows through the CGM or condensation out of CGM gas provides fuel for star formation in galaxies.
A majority of stars in $z=0$ galaxies may have been formed by “recycled” CGM gas (winds).

2. What role does the CGM play in shaping galaxies?

*Oppenheimer+ (2010)*
Infall of metal-poor IGM gas may be required to fuel multi-Gyr star formation in galaxies.

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*Infall of metal-poor IGM gas may be required to fuel multi-Gyr star formation in galaxies.

Adapted from Daddi+ (2008)
2. What role does the CGM play in shaping galaxies?

*The CGM may keep incoming fuel from reaching the centers of galaxies, and thus in quenching star formation.

Schawinski+ (2014)
A. Dekel

Cold Gas Accretion onto Galaxies

The accretion of IGM gas onto galaxies is a crucial part of their evolution.
The accretion of IGM gas onto galaxies is a crucial part of their evolution.

Much of this matter may come in “cold,” but this is thought to depend on the mass of the central galaxy.
Role of cold accretion is topic of hot debate.

Arepo simulations show lower mix of cold accretion for star formation.

Cold accretion at the virial radius is unaltered.

Fraction of final mass accreted cold

Milky Way

Central Galaxy

Halo Atmosphere

10.0 10.5 11.0 11.5 12.0

log $M_{\text{halo}}$ [log $h^{-1} M_{\odot}$]
We want to dissect the CGM of galaxies, learning about each component.

We’d like to make a map of the CGM and tag the gas by its origins.

The accretion of IGM gas onto galaxies is a crucial part of their evolution.

The expulsion of gas from galaxies is a crucial part of their evolution.

COS-Halos attempts this... but the covering factors of streams are small!
Lyman limit systems probe infall and outflows at low-z.

Metallicity distribution of $z \leq 1.0$ Lyman limit systems

$[16.1 \leq \log N(\text{H I}) \leq 18.5]$ |

2.5% solar metallicity | 40% solar metallicity

Lehner+ (2013): 28 LLS @ $z \leq 1$

>400 orbits of HST UV spectroscopy
Lyman limit systems probe infall and outflows at low-z.

Metallicity distribution of $z \leq 1.0$ Lyman limit systems

$[16.1 \leq \log N(H I) \leq 18.5]$
Surprises still to be found

\[ z < 1 \]

Figure 1: The metallicity distribution of z < 1 strong LLSs from Wotta et al. 2016. The bimodality and very low metallicities (< −1.4) in the metallicity histogram of LLSs show a different distribution from those of the sub-DLAs and DLAs. This suggests that the ionization conditions for the strong LLSs are the same as for the weak LLSs (which are different from both the bimodal weak LLSs and the unimodal (but higher-metallicity) distributions of the sub-DLAs and DLAs). This can be fit with a Gaussian that is consistent with the log \( \mathrm{N}_{\mathrm{HI}} \) histogram of \( \sim –3.1 \), and is centered at log \( \mathrm{N}_{\mathrm{HI}} \) ~ 19.5. The ionization parameter distributions therefore with location in the CGM change with the CGM of galaxies at dense gas flows through the circumgalactic medium (CGM) — the gas within roughly the virial radius, at the interface of a galaxy and the flows to the evolution of the galaxies themselves. To understand the growth of galaxies, therefore, we must study the properties of these cold, \( \mathrm{H} \) I-selected “strong LLSs” with good S/N. We estimate the \( \mathrm{H} \) I column density of the absorbers from the \( \mathrm{H} \) I column densities with those predicted from photoionization modeling (Cloudy) of these highly-ionized LLSs. Using this technique, we are able to compare the observed absorption profiles with theoretical calculations. We make use of our COS-Legacy archive program and find 93 LLSs at \( z < 1 \). We make use of our COS-Legacy archive program and find 93 LLSs at \( z < 1 \). We apply the MCMC technique to these absorbers for consistency (see Wotta et al. 2016). At \( z < 1 \), the strong LLSs have a unimodal metallicity distribution, its peaks are centered at 1.3% and 48% solar metallicity, with half of the absorbers metallicity, at the location of the dip to find the full posterior distribution for the metallicities, allowing us to estimate the uncertainty in the photoionization modeling. Surprises still to be found.
COSMIC METALS in astrophysics include stars, galaxies, and the ISM/CGM. The 2017 STScI Spring Symposium aims to bring together multi-wavelength and multi-discipline communities to understand metal production, transport, evolution, and distribution. We will celebrate the next half century of UV astronomy, which is now seeing the 50th year of productivity, and strategize about the future use of HST, LUVOIR, and JWST to ensure that the next half century of UV astronomy is as exciting as the last.
LUVOIR: \( D_A \sim 15 \, \text{m} \)

**UV spectroscopy:**

\( \lambda_{\text{UV}} \sim 1,000 - 4,000 \, \text{Å} \)

\( R \sim 500; 5,000; 50,000 \ldots 500,000? \)

MOS/IFU over \( \sim 2' \) field.
What cool things can we do with LUVOIR?

What do we need to get ready for and scope the design requirements of LUVOIR?

What legacy do we want to leave for our decade without UV access?
LUVOIR will not be just HST with a bigger aperture

What doesn’t HST do well?

• High-resolution spectroscopy at high sensitivity
• FUV (<1200 Å)
• NUV (>1800 Å)
• Multiplexed spectroscopy
• Simulations (!)
These 2 HST programs represent ~300 HST orbits.
We use EW measurements, harkening back to Strömgren??

Why do we still do this?

We have no choice:
Resolution, wavelength coverage, S/N limit our ability to derive column densities.

The EW does not tell us how much gas is there (necessarily). It is a complex combination of the surface density of gas, the temperature and turbulence within that gas, and the overlap of gaseous structures.
Resolution, S/N matter

The more limitations we have on spectroscopy, the further we get from the physics.
Access to $\lambda \sim 1000$ Å is critical

Courtesy J. Werk [Tumlinson+ 2017]
Ne and dashed, dotted and dashed-dotted lines indicate lines in the Mg II system and related lines. Considering that stronger line and 14.3 km s$^{-1}$, the total significance of the doublets is 5.8 ± 0.32, 2.7 ± 0.30, 97.5 ± 3.5 km s$^{-1}$, and 82.4 ± 1.6 km s$^{-1}$.

For the weaker line.

Table 1

<table>
<thead>
<tr>
<th>Line</th>
<th>Number</th>
<th>Strength</th>
<th>Equivalent Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda$6098 Å</td>
<td>Ne II</td>
<td>14.6</td>
<td>7.0 mÅ</td>
</tr>
<tr>
<td>$\lambda$6249 Å</td>
<td>Mg X</td>
<td>14.9</td>
<td>38.4 mÅ</td>
</tr>
<tr>
<td>$\lambda$6302 Å</td>
<td>Fe II</td>
<td>15.2</td>
<td>13.29 km s$^{-1}$</td>
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</table>

The future: mapping the origins of the CGM gas

We want to map the CGM as a function of ionization state and metallicity.

This means:

- Developing better statistical maps of the CGM with galaxy properties, etc. (ala COS-Halos).

- Directly mapping absorption lines toward many sight lines in individual galaxies, headed toward tomography. (Not even done yet for M31.)

- Observing resolved galaxies at low redshift to connect to HI mapping. (21-cm won’t get <few x 10^{17} cm^{-2}.)

- Emission line imaging.

Critical capabilities:

- Large aperture (sensitivity).
- High resolution (R>20,000).
- FUV capability to ~1000 Å.
- Efficient NUV capabilities to 3000 Å (Lyα).
- …or UV imaging sensitivity, perhaps spectral image slicers or narrowband filters.
The future: mapping the origins of the CGM gas

We want to map the CGM as a function of ionization state and metallicity.

Why do we need more of this if we have samples like this from HST?
The future: mapping the origins of the CGM gas

Why do we need more of this if we have samples like this from HST?

This is actually a very small sample if we want to understand the scaling relations in galaxies.
The AGN Impact on the CGM of Cen A

Figure 1: The multi-scale structure of the AGN jets about Cen A.

Top: The γ-ray (left) and radio (right) emission from the outer lobes of Cen A with locations of our proposed COS sight lines marked (adapted from Sun et al. 2016). The green contours on the top left show the Planck 30 GHz lobe contours.

With targets #1-4, we will directly determine the extent of the influence of AGN feedback and the AGN impact on the geometry of the CGM of a radio galaxy.

With target #5, we will assess the roll-off in CGM surface density as it dovetails with potential gas from the Centaurus Group (25 galaxies, including well-known M83 and NGC5253). NGC5128 is the only massive elliptical in the group. We emphasize that the COS observations of the MW Fermi Bubbles demonstrated the ability of UV absorption lines to probe entrained cool gas in hot gamma-ray emitting plasma and AGN-driven outflows (Fox et al. 2015; Bordoloi et al. 2017).

Bottom: Color composite images of Centaurus A at smaller scales, revealing the inner lobes and jets emanating from the active galaxy's central black hole.

Note the different scales between the top and bottom panels.

Credit: NASA/DOE/Fermi LAT Collaboration, Capella Observatory

Credit: ESO; NASA

Credit: ESO; NASA
The future: mapping the origins of the CGM gas

![Diagram of galaxy and sight lines](image)

**Normalized Impact Parameter $\rho/R_{vir}$**

![Graph of normalized impact parameter vs log (NH)](image)

**Howk+ (2017)**

![Graph of covering factor vs impact parameter](image)
Absorption line tomography of galaxy halos enabled by LUVOIR.
Each HST spectrograph had a factor of 10 improvement over its predecessor.

**GHRS**
- 10x spectral resolution of IUE
- At $R \sim 100,000$, $\Delta \lambda \sim 7 \text{ Å}$!

**STIS**
- ~30x spectral coverage for $R \sim 100,000$

**COS**
- ~10x sensitivity, at lower $R$
- > 10x greater observable sample of objects!
Mapping the origins of stars in galaxies means imaging the CGM.

The presence and quantity of “warm” metals is strongly correlated with star formation properties of galaxies. 

…but it is not for H I (Thom+ 2012).
Mapping the origins of stars in galaxies means imaging
including the radio mode in particular is responsible for prevalent in AMR cause Figure 10. Suresh et al. simulation. Like Hummels et al. feedback in an from the simulations are relevant for upcoming observations. Galaxy is known to be too centrally concentrated at substructure in the halo of the main galaxy. SN feedback in SPH simulations is to give either a constant or prescription, we included prescriptions for SN pressure and that the simulation has difficulty in capturing. Furthermore, the simple as opposed to the wind velocity approach of SPH simulations, lowering the star formation efficiency led to greater agreement. However, new methods are emerging that incorporate additional components of the SN feedback. For example, momentum in addition to a thermal heating model in a series of wind particles. Radial pro.

In this paper, we have examined a single simulation of a galaxy. If these scales — 2' @ z~0.2 detected the presence of eight — 2.5 foreground galaxy. If these scales — 500 pc — 1000 pc, the larger of — 2000 pc, the larger of — 5000 pc, the larger of.

Morphological information – Where are the filaments and winds?

Cooling rates – Do galaxies acquire their gas from the CGM? Do winds lose their energy to radiation?

Physical Scales – What are the relevant length, density scales for halo structures? Pressures, temperatures?

See also van de Voort & Schaye (2013), Bertone & Schaye (2012)
The “cosmic web” in Lyα, lit up by QSOs/AGNs

FABulous Nebula

Courtesy Fabrizio Arrigoni
Low backgrounds, FUV wavelength access, low \((1+z)^4\) make this problem a tempting target for LUVOIR.
Necessity of OVI imaging: We present recent efforts to characterize feedback in low-redshift starbursts via HST observations of the warm, OVI absorption line survey [15,16] of halos, effectively bypassing many of systematic limitations technical limitations make the survey of distribution of metals [see 7]. To date, detection of OVI emission has been limited to spectroscopic UV observations (FUSE;[8]) and restricted to a small aperture. These studies were limited to specific galaxies, with few being confirmed OVI emitters (EWR > 200, α Å, J1156=35 M☉ yr−1, redshift 0.23<z<0.29; and 3) minimal MW extinction (<0.1mag). With SFR =35M☉ yr−1, we can begin to quantify the contribution of this source to the ISM.

Understanding the ISM is critical for confirming this outflow, with velocity, δv ~ 350 km s−1, for the first OVI imaging campaign with HST. In low-redshift galaxies, we identified four galaxies with flat continuum synthesis, FUV spectroscopy. SBC data are used to directly synthesize the stellar continuum per pixel, we determine the ultimate fate of a galactic superwind in a starburst galaxy.

Figure 1: Synthesized OVI Narrowband — Applying a methodology first used to imaging HI Lyα in low-redshift galaxies in the LARS survey [10,11,12], we combine SBC long-pass (above) filters to synthesize a narrowband sensitive to OVI & Lyα. Subtracting the underlying spectrum, we can isolate these lines and image the full spatial profile at the HST spatial resolution.
The future: probing origins of galactic outflows

We want to map the origins of outflows across galaxies, understanding the dynamics of both fountains and winds.

This means:

- Using down-the-barrel experiments to trace outflows at their source against individual star forming regions.
- Leveraging multi-object capabilities.
- Coupled with background QSO galaxy spectroscopy.

Critical capabilities:

- Multi-object capability.
- Moderate resolution (R ~ 5000+).

Imagine 10s of individual UV slits for which we obtain R~5000+ spectra.

*Especially powerful on larger scales against redshifted galaxies for mapping OVI, HI absorption.
An HST *Pathfinder* Mode: Preparing the case for LUVOIR

The case is made easier if the parameters can be constrained ahead of time.

- How weak is the hot gas absorption from the halos of galaxies?
- Can we detect emission from the hot halo of a galaxy?
- …
An HST *Legacy* Mode: Preparing for the Abyss

We will have a decade without traditional access to the UV. What keeps the science progressing during that time?

- G140L survey of a uniform sample of Local Group star forming regions.
- Comprehensive survey of WD metals
- UV irradiance / variability in planet host stars across HR diagram [e.g., K. France MUSCLES survey]
- Variability survey of debris disk absorption
- Uniform spectroscopy of top 10 QSOs at z>1 at high S/N to survey EUV transitions. [H.W. Chen Cycle 25 program]

Done through community working groups and the continued availability of extra large proposal categories.
What cool things can we do with LUVOIR?

Plenty!!
And the STDT is seeking science input now…

What do we need to get ready for and
scope the design requirements of LUVOIR?
Let’s test the more extreme cases to see what can be done

What legacy do we want to leave for
our decade without UV access?
Let’s decide this within our communities, seek a
continued very large opportunity.
Probing the CGM of Luminous Red Galaxies

Figure 1: The CGM traced by LLSs.

Left: Metallicity distribution function of 54 $z \leq 1$ LLSs from the combined samples of Lehner et al. (2013) and Wotta et al. (2016). A unimodal distribution is ruled out at >99.6% significance, and the results are consistent with a bimodal distribution (see Lehner et al. 2013). The Wotta et al. results rely on low-resolution metallicity determinations, described in Fig. 2. The lowest metallicity systems are candidates for infalling material.

Right: Cumulative covering factor of log N(HI) ≥ 16.4 absorption about COS-Halos galaxies (data from Prochaska et al. 2017) versus normalized impact parameter, with error bars representing the [10%, 90%] confidence interval. We show results only for bins that continue to include new sight lines, and the impact parameters are shifted slightly to avoid confusion. We find $f_c(\leq 0.25R_{vir}) = 0.54$ with the [10%, 90%] confidence range [0.36, 0.71] for the COS-Halos quiescent galaxies. Our program will probe much higher stellar masses than probed by the COS-Halos observations.

Figure 2: Low-resolution metallicities.

Comparison of [Mg/H] derived through our "low-resolution metallicities" using only Mg II/H I (Wotta et al. 2016) versus [X/H] from detailed ionization corrections in the same absorbers (Lehner et al. 2013). The top panel shows the residuals as a function of [X/H], which are in agreement with expectations based on our estimated uncertainties. Our low-resolution metallicity determinations can readily distinguish between absorbers in the low- or high-metallicity branches of the LLS MDF. We refer to this method as "low-resolution" both because the results are somewhat less precise than with detailed models and because we can rely on low-resolution UV (H I) and ground-based optical (Mg II) spectroscopy to derive these metallicities. This method is tested and calibrated over the same redshift range as our target galaxies.
Evolution of the CGM probed by Lyman limit systems over cosmic time

- HI-selected pLLSs and LLSs

2.3 < z < 3.3
Lehner+ (2016)

z < 1.0
Wotta+ (2016)
Probing the CGM of Luminous Red Galaxies

Figure 1: The CGM traced by LLSs.

Left: Metallicity distribution function of 54 \( z \leq 1 \) LLSs from the combined samples of Lehner et al. (2013) and Wotta et al. (2016). A unimodal distribution is ruled out at >99.6% significance, and the results are consistent with a bimodal distribution (see Lehner et al. 2013). The Wotta et al. results rely on low-resolution metallicity determinations, described in Fig. 2. The lowest metallicity systems are candidates for infalling material. Most of the low-metallicity absorbers would not be identified in previous Mg II searches given their low metal content (equivalent widths).

Right: Cumulative covering factor of \( \log N(\text{H}I) \geq 16.4 \) absorption about COS-Halos galaxies (data from Prochaska et al. 2017) versus normalized impact parameter, with error bars representing the [10%, 90%] confidence interval. We show results only for bins that continue to include new sight lines, and the impact parameters are shifted slightly to avoid confusion. We find \( f_c(\leq \rho/R_{\text{vir}}) = 0.54 \) with the [10%, 90%] confidence range [0.36, 0.71] for the COS-Halos quiescent galaxies. Our program will probe much higher stellar masses than probed by the COS-Halos observations.

\[ \text{Ribaudo et al. (2017)} \]

\[ \log N(\text{H}I) > 17.5 \quad z \sim 0.6 - 1.2 \]

\[ \text{Ibaudo et al.} \]

\[ \log N(\text{H}I) > 17.5 \quad z \sim 1.3 \quad (\text{simulation}) \]

\[ \text{Faucher-Giguere \& Keres (2011)} \quad z \sim 2 \quad (\text{simulation}) \]

Lower limits
Upper limits

Wotta+ (2016) 

16.4 < \log N(\text{H}I) < 18.3 

z \sim 0.3 – 1

Observation

Cumulative covering factor

Impact parameter

“Low Resolution” \[[\text{Mg/H}]\]

Comparison of \([\text{Mg/H}]\) derived through our “low-resolution metallicities” using only Mg II/H I (Wotta et al. 2016) versus \([\text{X/H}]\) from detailed ionization corrections in the same absorbers (Lehner et al. 2013). The top panel shows the residuals as a function of \([\text{X/H}]\), which are in agreement with expectations based on our estimated uncertainties. Our low-resolution metallicity determinations can readily distinguish between absorbers in the low- or high-metallicity branches of the LLS MDF. We refer to this method as “low-resolution” both because the results are somewhat less precise than with detailed models and because we can rely on low-resolution UV (H I) and ground-based optical (Mg II) spectroscopy to derive these metallicities. This method is tested and calibrated over the same redshift range as our target galaxies.

“Low-resolution” metallicities are in agreement with those derived from detailed modeling.
Development of improved coatings for space telescopes allows increased capabilities in wavelength coverage, improved wavefront control, and overall efficiency. New materials with improved control of the deposition process are critical improvements that enable more science by adding targets and creating more capable instruments.

Improvements to mirror coatings suitable for large mirrors would contribute to the largest possible gains in scientific return from a Cosmic Origins Mission. First, if ultraviolet reflectivity can be improved compared to existing missions, it will add to the number of scientifically viable targets. In general, the number of targets increases dramatically as a function of minimum detectable flux. (See Figure 6.1) Second, improved coatings improve wavefront error (WFE) budgets. With an optical coating requiring less of the overall WFE, more error can be allocated to fabrication and alignment, which reduces risk and therefore cost of a mission. Third, opening the ultraviolet further toward the blue, changes and improves the fundamental science that can be accomplished. Access to wavelengths currently unavailable (such as 90–110 nm) provide data that simply cannot be accessed without the increased bandpass. (Figure 6.2) Finally, and it cannot be stated strongly enough, improved reflectivity creates more capable instruments beyond a simple increase in effective area. For example, far ultraviolet spectrographs can be cross dispersed without a significant loss of effective area, allowing high spectral resolution and broad bandpass simultaneously. That combination, compared to existing systems, reduces the observing time necessary on a target by the multiplex advantage of an echelle—well beyond the simple improved effective area throughput. Moving to multi-object systems could increase the advantage even further.

Beyond improvements to ultraviolet capability, improved coatings would be the path forward to developing systems that would produce acceptable wavefront errors for exoplanet observations. Specifically, dielectric protective coatings may have too much polarization for some current coronagraph designs. Bare metal coatings will have a smaller overall polarization effect, but there are only a few metal coatings suitable for coating a large mirror with associated handling practicalities.

1. **Optical / NIR detector development**: Optical detectors are nearly perfect for general astrophysical detections. High time resolution is critical for a small number of science cases. Improved detector radiation tolerance will extend the usable lifetime of missions, particularly for missions not in Low Earth Orbit. Leveraging the commercial developments in detectors will add capability to future missions beyond what the limited budget for technology investment can provide. Projects that...