Probing the "Baryon Cycle" using Quasar Absorption Line Spectroscopy

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Outline

- An Overview
  - Why do we care?
  - How to probe?
  - The Challenges
- Part-I: A Survey of Weak Mg II Absorbers' Analogs
- Part-II: MUSE-QuBES (Quasar-field Blind Emission Line Surveys)
- Part-III: Probing the outskirts of galaxy clusters using QAL spectroscopy
- What to look forward to?

Where are the baryons?

More than 90% of the cosmic baryons reside outside of galaxies in a diffuse phase (Fukugita+98, Fukugita & Peebles '04)

- Baryon census at $z < 0.4$ has found (Shull+12):
  - $\Longrightarrow$ Collapsed Objects (including the CGM): $\approx$18%
  - $\Longrightarrow$ Photoionized IGM ($\sim 10^4$ K): $\approx$28%
  - $\Longrightarrow$ Collisionally ionized IGM ($\sim 10^{5-6}$ K): $\approx$25%

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- Baryons are also missing from the halos of nearby collapsed objects (≈50%) ($\boldsymbol{M}_{\rm star,\ gas}/\boldsymbol{M}_{\rm DM} < \Omega_{\rm b}/\Omega_{\rm m}$)
  - $\Longrightarrow$ "halo missing baryon problem" (McGaugh+10)
  - $\Longrightarrow$ The CGM can account for the baryons missing from halos (Werk+14)

The study of the IGM/CGM is thus extremely important!

- Galaxies at low-z show a bimodal distribution in the color-magnitude diagram
  $\Longrightarrow$ Passively evolving red-sequence galaxies (Elliptical)
  $\Longrightarrow$ Blue-cloud galaxies actively forming stars (Spiral)

What causes such a dichotomy? How and when do galaxies become passive? How do blue-cloud galaxies sustain their star formation?

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- The cosmic star formation rate density (SFRD) of galaxies shows a peak at $z \sim 2$ and declines by a factor of > 10 at both higher and lower redshifts (Madau & Dickinson, 2014)

Why are galaxies more efficient in forming stars at a certain epoch?

The puzzles

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• Theoretical studies have found that the star-formation efficiency is maximum for halos with $M_{\rm h} \sim 10^{12} M_{\odot}$ at any epoch (Behroozi+13)

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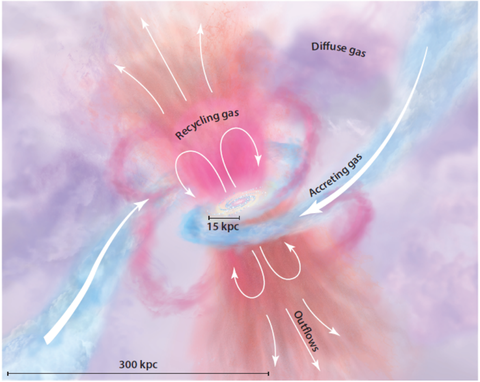
Answers to all these puzzles may lie in the processes through which galaxies acquire, expel, and recycle their gas (i.e. the "baryon cycle")

Baryon cycle happens in the CGM!

The CGM

- A reservoir of diffuse gas and metals surrounding galaxies
  - ⟹ Outside the disks/ISM and inside the virial radii (likely to be bound)
- It is dynamic
  - ⟹ Gas accretion, outflows, and recycling take place here
- It is complex
  - ⟹ The CGM shows complex ionization and chemical structures
- It is multiphase
  - ⟹ Different regions can have different densities and temperatures



Tumlinson+17, ARAA

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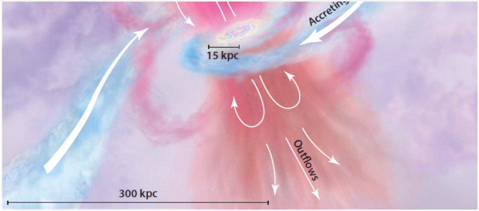
Chemical/physical conditions of the CGM preserve a record of the "baryon cycle"
QSO absorption line spectroscopy is the only way to probe the tenuous gas in the CGM

It will remain challenging even for the next generation large telescopes!



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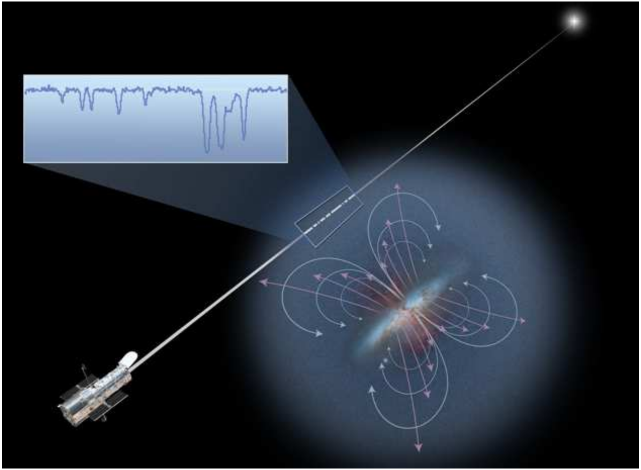
QSO spectrum: cosmic rainbow!



★ ***Extremely powerful tool to probe diffuse gas in the universe*** ★

QSO spectrum: cosmic rainbow!

Why I love QAL spectroscopy?

- ★ Luminosity unbiased way to probe cosmic structures
- ★ Probe parts of the universe that are otherwise NOT visible
- ★ Trace cosmic evolution
- ★ Probe a wide variety of astrophysical environments

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$\Longrightarrow$ Density, n_{H}: 10^{-5} – 10^{5} cm^{-3} (10 orders of magnitude!)
$\Longrightarrow$ Temperature, T: 100 – 10^{6} K (4 orders of magnitude!)
$\Longrightarrow$ Metallicity, Z: 10^{-3} – 10 $Z_{\odot}$ (4 orders of magnitude!)
$\Longrightarrow$ Size, L: sub-pc – a few 100 kpc (6 orders of magnitude!)

Quite remarkable!

★ ***Extremely powerful tool to probe diffuse gas in the universe*** ★

The challenges

- The main drawback of QAL technique: pencil beam sightline

  $\Longrightarrow$ No information across the line of sight
  $\Longrightarrow$ A large sample of QSO-galaxy pairs is required

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- The main challenges to build a statistically significant sample of QSO-galaxy pairs:

  High-z : detecting host-galaxies
  $\Longrightarrow$ Now we have MUSE/KCWI! (Optical IFUs with large FoV)

  Low-z : building a large sample of QSO spectra to cover the UV (∼900-1600Å) lines
  $\Longrightarrow$ Now we have HST/COS! (1150–1800 Å, $R \sim 18$ km s^{-1})

Two complementary approaches:

1. Absorber-centric: (Part-I)
   - (a) Build a sample of absorbers with interesting properties
   - (b) Search for galaxies at the same redshift around the background QSO
2. Galaxy-centric: (Part-II & Part-III)
   - (a) Build a sample of galaxies with well-defined properties (mass, SFR, color)
   - (b) Search for targeted absorption in the spectrum of a nearby background QSO

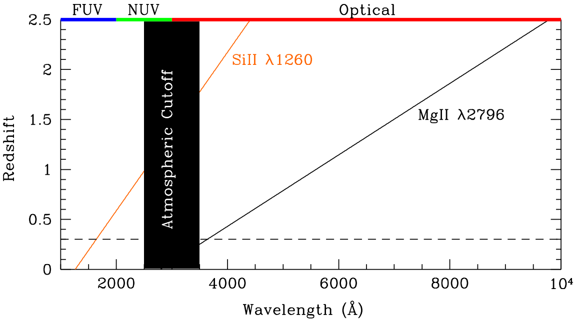
Part-i: An HST/COS survey of weak Mg II absorbers' analogs

Collaborators: Jane Charlton, Chris Churchill, Gloria Fonseca, Anand Narayanan, Philipp Richter, Amber Roberts, Benjamin Rosenwasser

Publications: Muzahid+17 (arXiv:1709.03999; MNRAS submitted)

Mg II analogs

- Mg II absorbers are the most well-studied ($z \approx 0.4$–7.0)
- Weak Mg II absorbers (W_r <300 mÅ) at high-z show very high metallicities (Rigby+02)
- Mg II $\lambda\lambda$2796,2803 lines are not accessible below $z < 0.3$



- Si II λ1260 is used as a proxy

  $\Longrightarrow$ Si^{28}_{14} and Mg^{24}_{12} are α-process elements

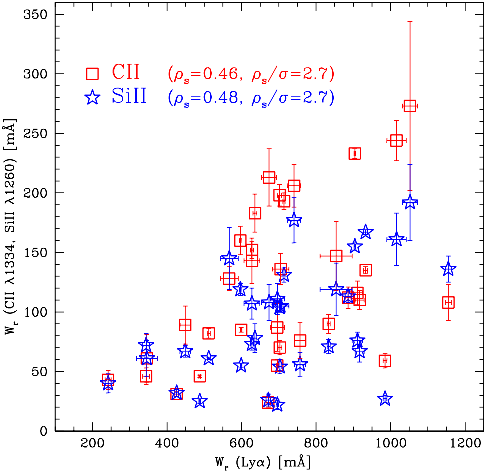
  $\Longrightarrow$ Creation IPs: 8.1 and 7.6 eV, respectively

  $\Longrightarrow$ Destruction IPs: 16.3 and 15.0 eV, respectively

  $\Longrightarrow$ [Si/H] = −4.49 and [Mg/H] = −4.40

- Si II and Mg II arise from the same gas phase

- Searched for Si II λ1260 and C II λ1334 lines in $\approx$ 400 COS spectra (S/N $>$ 5)
- Both Si II and C II lines are detected at $> 3\sigma$
- $\boldsymbol{W}_{\rm r}$(Si II λ1260) $<$ 200 mÅ and $\boldsymbol{W}_{\rm r}$(C II λ1334) $<$ 300 mÅ: Weak Mg II Analogs



The Sample

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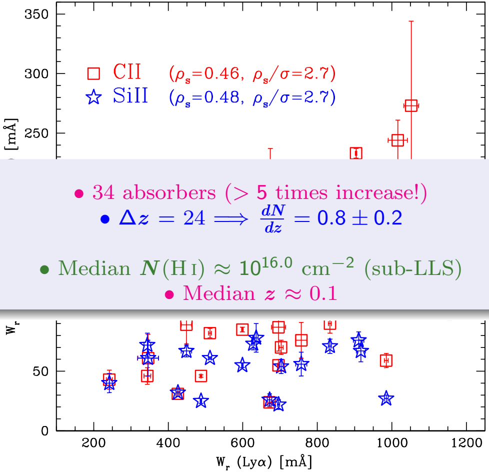


- 34 absorbers (> 5 times increase!)
- $\Delta z = 24 \Longrightarrow \frac{dN}{dz} = 0.8 \pm 0.2$

- Median N(H I) $\approx 10^{16.0}$ cm^{-2} (sub-LLS)
- Median $z \approx 0.1$

PI Models

- Assumptions:

Plane parallel geometry
UVB at $z = 0.1$ (KS 2015)
Solar relative abundances
Gas is dust free

- Density/Ionization parameter:

$N(\text{Si III})/N(\text{Si II})$

$\log n_{\rm H} = -3.3$ to -2.4
Median ($\log n_{\rm H}$) $= -2.8$

- Si-abundance:

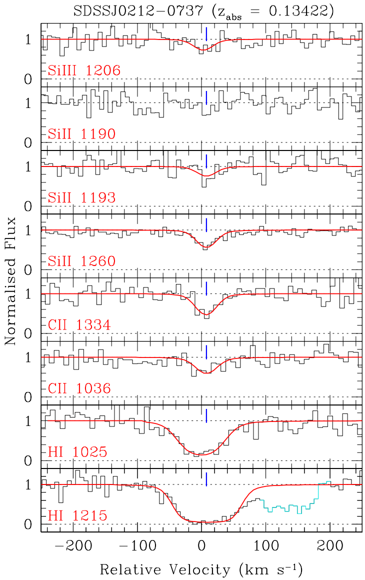
$\log\,[N(\text{Si II})/N(\text{H I})] + \log\,[f(\text{H I})/f(\text{Si II})] - \log\,(\text{Si/H})_\odot$

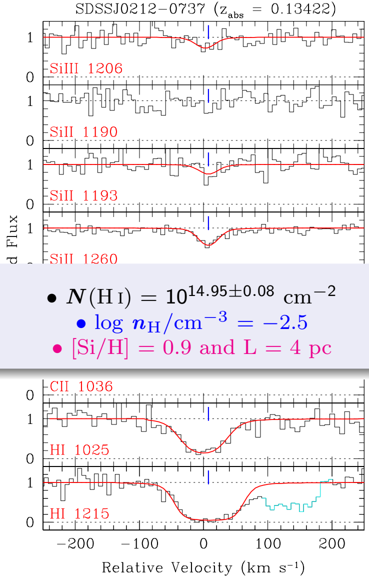
[Si/H] $= -2.5$ to $+1.6$
Median [Si/H] $= 0.0$ (solar!)

- Thickness:

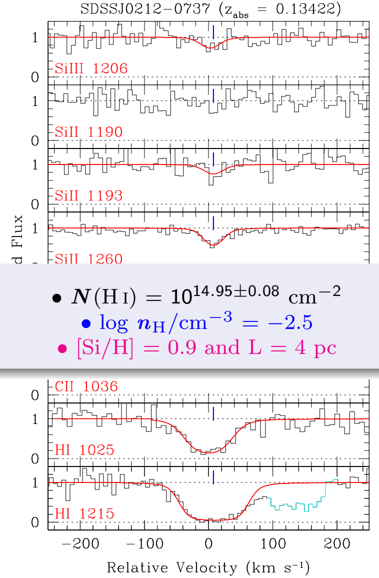
$N(\text{H I})/[f(\text{H I}) \times n_{\rm H}]$

$L = 1$ pc to 50 kpc
Median $L = 500$ pc


SDSSJ0212−0737 (z_{abs} = 0.13422)
SiIII 1206
SiII 1190
SiII 1193
SiII 1260
CII 1334
CII 1036
HI 1025
HI 1215
Normalised Flux
Relative Velocity (km s^{-1})
−200
−100
0
100
200
0
1



- $N(\mathrm{H\,I}) = 10^{14.95\pm0.08}$ cm^{-2}
- $\log n_{\mathrm{H}}/\mathrm{cm}^{-3} = -2.5$
- [Si/H] = 0.9 and L = 4 pc



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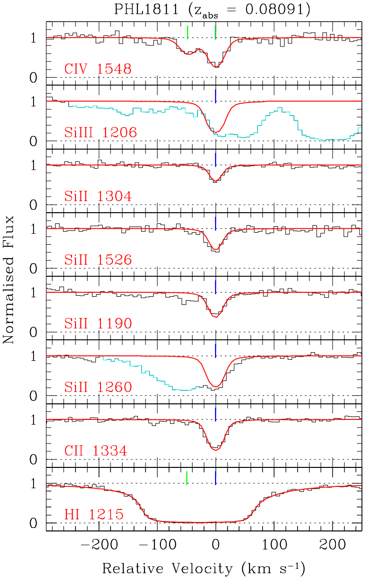
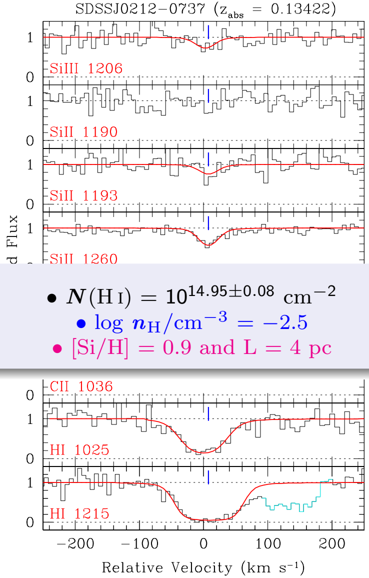
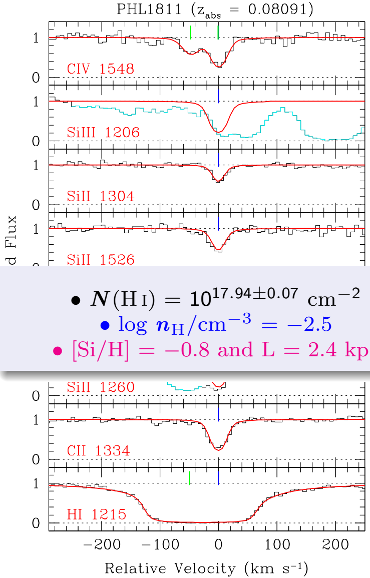


Examples





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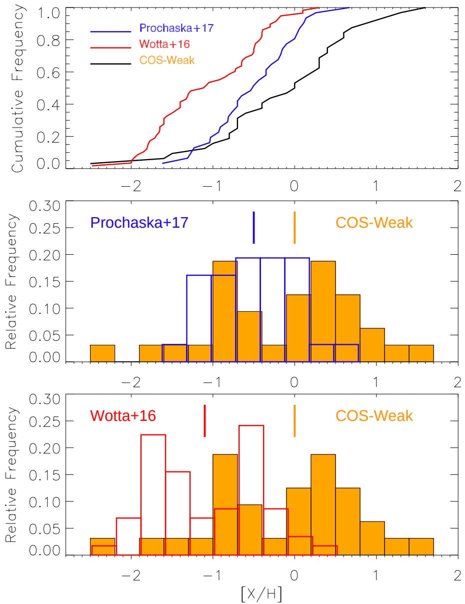
- [Si/H] = 0.9 and L = 4 pc

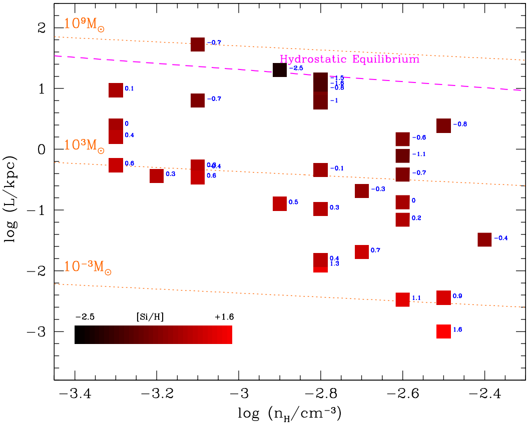
- $N(\mathrm{H\,I}) = 10^{17.94\pm0.07}$ cm^{-2}
- $\log n_{\mathrm{H}}/\mathrm{cm}^{-3} = -2.5$
- [Si/H] = −0.8 and L = 2.4 kpc



- Wotta+16:
  $\Longrightarrow$ H I-selected (LLS/pLLS)
  $\Longrightarrow$ Median [X/H] $= -1.1$
  $\Longrightarrow$ $f([\mathrm{X/H}] \geq 0)$: $\approx 3\%$

- Prochaska+17:
  $\Longrightarrow$ Galaxy-selected ($\sim L_*$)
  $\Longrightarrow$ Median [X/H] $= -0.5$
  $\Longrightarrow$ $f([\mathrm{X/H}] \geq 0)$: $\approx 22\%$

Weak absorbers are significantly more metal-rich!



- $L_J \sim$ 15 kpc $(n_H/10^{-2.8}\text{cm}^{-3})^{-1/2}\ (T_4)^{1/2}\ (f_g/0.16)^{1/2}$ (Schaye 2001)

Weak absorbers are too tiny (contain little mass) to be in hydrostatic equilibrium!

- Free expansion time scale: $t_{exp} \sim L/c_s \sim 10^7$yr $(L/100$ pc$)\ (T_4)^{-1/2} \ll t_{Hubble}$!!

Weak absorbers are transient in nature!

★ Cosmological Significance:

- $dN/dz = n_{\mathrm{cl}} \times \pi R_{\mathrm{cl}}^2 \times \frac{c}{H_0} \frac{(1+z)^2}{\sqrt{(1+z^3)\Omega_{\mathrm{M}}+\Omega_{\Lambda}}}$
- $R_{\mathrm{cl}} \equiv L/2 \sim 250$ pc & $dN/dz \approx 0.8 \Longrightarrow n_{\mathrm{cl}} \sim 10^3\ \mathrm{Mpc}^{-3}$
- $n_{\mathrm{gal}} \sim 10^{-2}\ \mathrm{Mpc}^{-3}$ (Down to $0.01 L_*$; Blanton+03)

Weak absorbers' population is huge!

Results

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★ Connection to Galaxies:

If the weak absorbers are associated with the CGM of $z \approx 0.1$ galaxies:

- Halo radius, $R_{\rm halo} \sim 130$ kpc $(\frac{dN/dz}{0.8})^{1/2} \times (\frac{n_{\rm gal}}{10^{-2}\ {\rm Mpc}^{-3}})^{-1/2} \times C_{\rm f}^{-1/2}$

Weak absorbers are widespread in galaxy halos!

- Search for galaxies in SDSS:

$\Longrightarrow$ ± 500 km s^{-1} and within 1 Mpc
$\Longrightarrow$ Spectroscopic completeness: $> 1.2 L_*$
$\Longrightarrow$ 26/34 fields are covered by SDSS

$\Longrightarrow$ A total of 75 galaxies are found!
$\Longrightarrow$ Only 6 are found in 26 random fields

A significant galaxy overdensity is seen around the weak absorbers!

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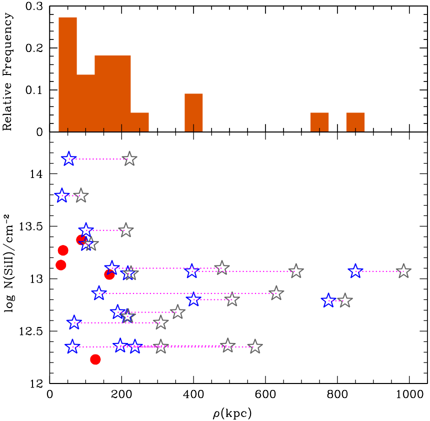
- 22/34 absorbers have host-galaxy info
- Median impact parameter $\approx$ 170 kpc
- 17/22 ($\approx$ 80%) show 2 or more galaxies!

Weak absorbers live in galaxy groups!



Origins?

☐ Weak absorbers show high metallicity and live in group environments:

★ Stripping

★ Galactic/AGN Outflow

- ISM clouds swept-up by hot-wind material via ram/radiation pressure
  (Zubovas+14, Schneider+17, Heckman+17)

- In-situ formation from hot-wind via thermal instabilities ($t_{\rm cool} < t_{\rm dyn}$)
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- "Shattering" (McCourt+16)
  - Cooling perturbation ($\sim 10^6$ K) is shattered into "cloudlets"
  - Characteristic Size: $l_{\rm cloudlet} \sim 0.1{\rm pc}\ (n_{\rm H}/{\rm cm}^{-3})^{-1}$
  - Column Density: $N_{\rm cloudlet} = n_{\rm H} l_{\rm cloudlet} \sim 10^{17.5}\ {\rm cm}^{-2}$
  - $N_{\rm cloudlet} \approx N_{\rm H} \sim 10^{18}\ {\rm cm}^{-2}$!
  - Recall that the weak absorbers' population must have been huge

"Shattering" scenario is consistent with the weak absorbers' properties!

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■ Clouds will be destroyed via:

- Hydrodynamical instabilities (K-H, R-T)
- Wind–cloud interaction

Next generation simulations with sub-pc/pc-scale resolution are essential...

Part-ii: MUSE-QuBES Surveys

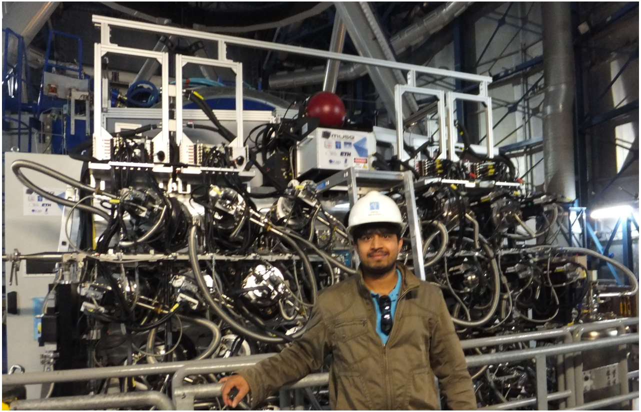
Collaborators: Joop Schaye, Marike Seager, Lorrie Straka, Sean Johnson, Martin Wendt + MUSE consortium

Publications: Johnson+ in prep.; Muzahid+in prep.; Seager+ in prep.; Straka+ in prep.; Wendt+ in prep.

MUSE

- Integral-field spectrograph (Imager + **Spectrograph**) on VLT/UT4
  - FoV: $1' \times 1'$ (WFM); $7.5'' \times 7.5''$ (NFM)
  - 24 sub-fields, each is fed into an integral-field unit (IFU)
  - Spatial sampling: $0.2'' \times 0.2''$ $\Longrightarrow$ contains $\sim$ 1 lakh spectra!
  - Spectral coverage: 4750–9350 Å; $\boldsymbol{R} \sim 3000$
- Adaptive optics system "GALACSI" has been commissioned recently

MUSE



MUSE-QuBES I
(Low-z)

- 16 MUSE fields (Depths: 2–10 hrs)
- 65 hrs of MUSE GTO observations

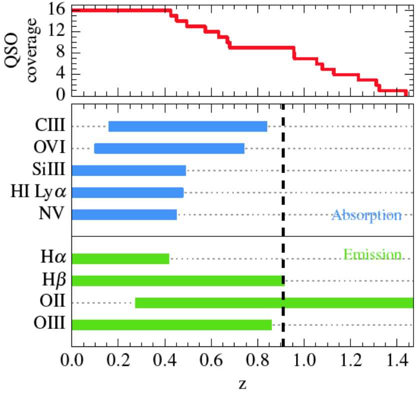
- Hα: 0.0–0.4
- [O III]: 0.0–0.9
- [O II]: 0.3–1.5

- 16 HST/COS spectra of QSOs
- $z_{\rm qso}$: 0.4–1.5
- Targeted lines: H I, O VI, Si III, C III, N V

$\approx$ 200 galaxies are detected ($z < z_{\rm qso}$)
(continuum selected; SExtractor)

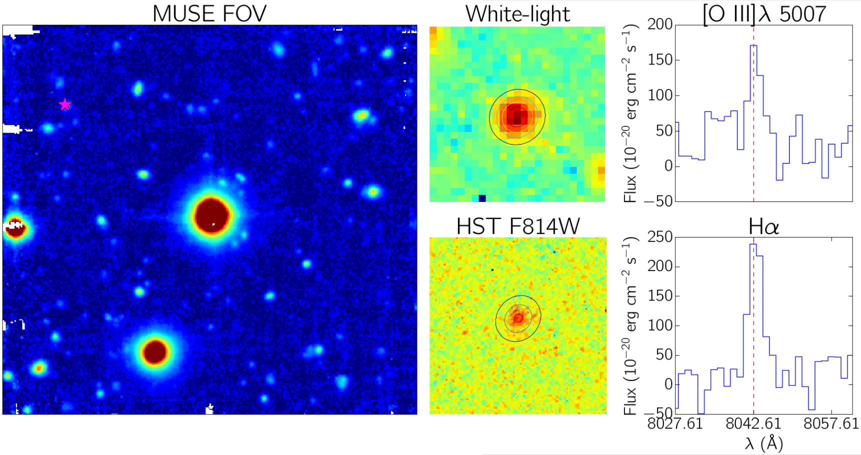
- Ancillary Data:

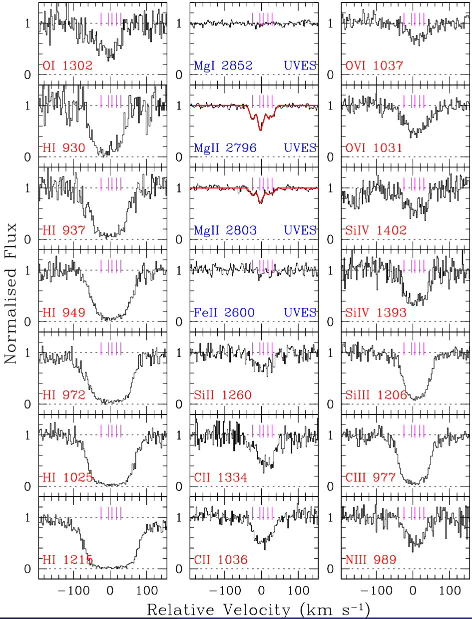
HST/ACS (for all): Galaxy morphology
VLT/UVES (for some): Kinematics
IMACS, LDSS3 (for some): More galaxies



HE0153–4520, $z_{\rm qso} = 0.451$; $z_{\rm gal} = 0.2252$, $\rho = 102$ kpc

Data: VLT/MUSE and HST/ACS





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VLT/UVES
and
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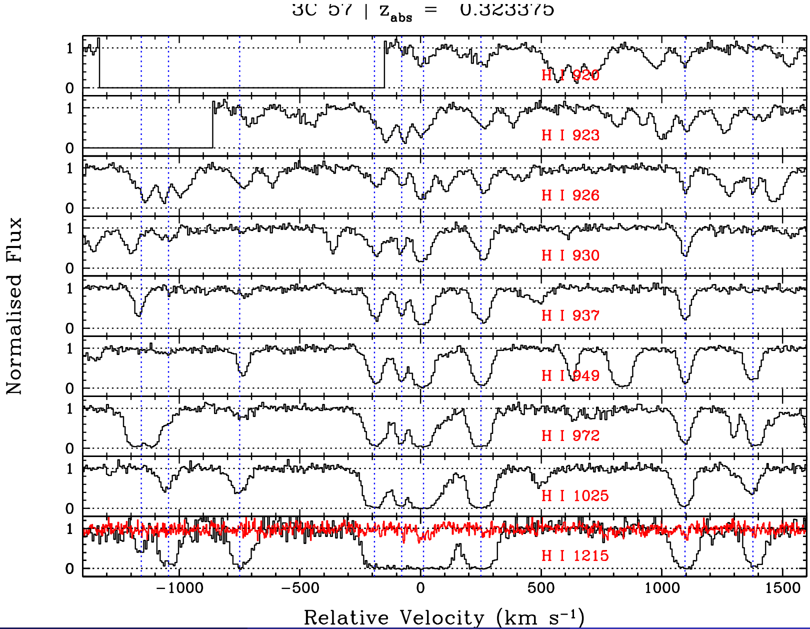
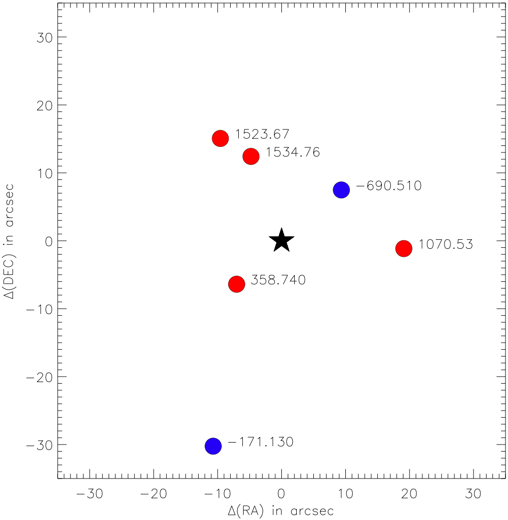
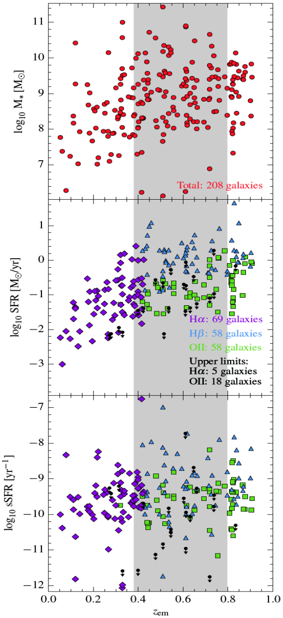
MUSE-QuBES I: Absorber-centric approach– an example





Muzahid+ (in prep.)



- $\boldsymbol{M_*}$: Pseudo broad-band filters (FAST; Kriek+09)
  - $\Longrightarrow$ SPS model (Bruzual & Charlot '03)
  - $\Longrightarrow$ IMF (Chabrier '03)
  - $\Longrightarrow$ Exponentially declining SFH
  - $\Longrightarrow$ Calzetti+00 dust law
- $\boldsymbol{M_*} \longrightarrow \boldsymbol{M}_{\rm vir}$ (Moster+13) $\longrightarrow \boldsymbol{R}_{\rm vir}$
- SFR
  - $\Longrightarrow$ Hα (Kennicutt '98)
  - $\Longrightarrow$ [O II] (Kewley+04)

⋆ Median $\boldsymbol{M_*} = 10^{8.9}\boldsymbol{M_\odot}$ (Low Mass!)

⋆ Median $\boldsymbol{M}_{\rm vir} = 10^{11.1}\boldsymbol{M_\odot}$

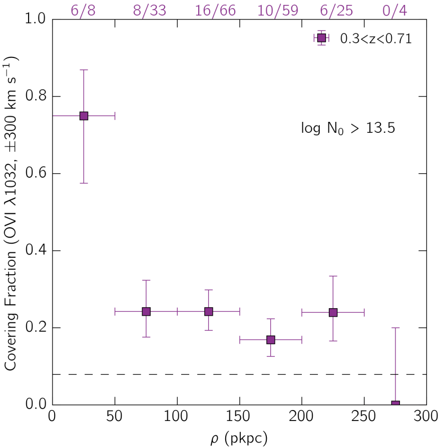
⋆ Median $\boldsymbol{R}_{\rm vir}$ =86 kpc

⋆ Median SFR = 0.2 $\boldsymbol{M_\odot}$/yr

⋆ Median sSFR = $10^{-9.6}$/yr

⋆ Median $\boldsymbol{L} = 0.1\ \boldsymbol{L_*}$

MUSE-QuBES I: Preliminary Results

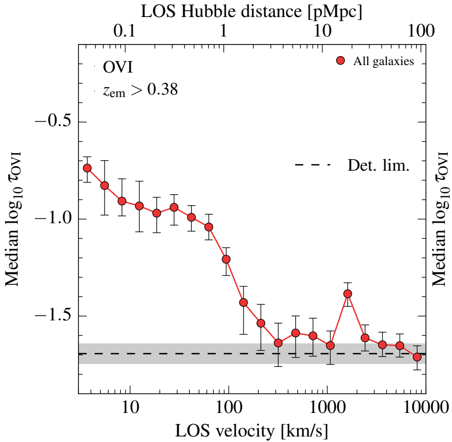


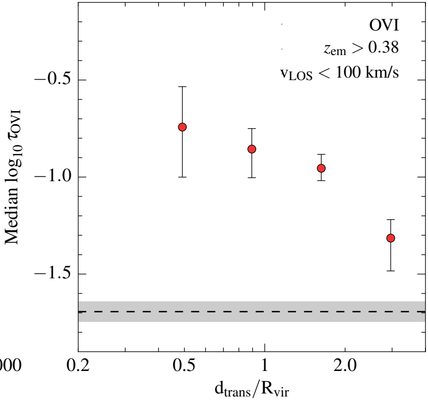
Straka+ (in prep.)

★ $C_f(< 150 \text{ kpc}) = 0.28 \pm 0.05$: considerably lower than the COS-Halos (75%; Werk+13)

Mass? Redshift? Environment?

Spectral Stacking (Seager+ in prep.)





Characteristic peculiar velocity ~200 km s^{-1}

O VI is widespread out to $2\boldsymbol{R}_{vir}$

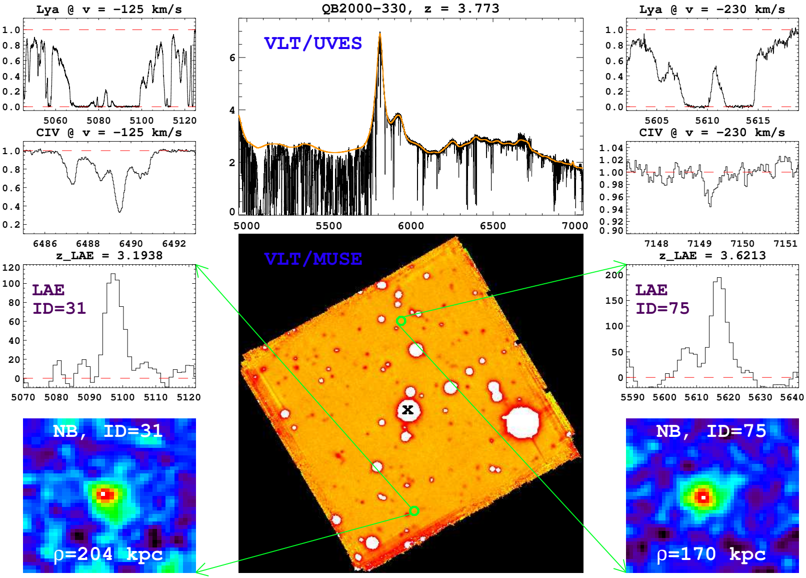
MUSE-QuBES II
(High-z)

• 8 MUSE fields (Depths: 2–10 hrs)
• 51 hrs of MUSE GTO observations

• Lyα: 2.9–3.8

• 8 VLT/UVES spectra of QSOs
• $z_{\rm qso}$: 3.7–3.9
• Targeted lines: H I, C IV, Si IV, N V

$\approx$ 150 LAEs are expected ($z < z_{\rm qso}$)
(pure line emitters; LSDCat (Herenz+16), CubEx (Cantalupo, In prep.))



QB2000−330, z = 3.773
VLT/UVES
VLT/MUSE
Lya @ v = -125 km/s
CIV @ v = -125 km/s
z_LAE = 3.1938
LAE
ID=31
NB, ID=31
ρ=204 kpc
Lya @ v = -230 km/s
CIV @ v = -230 km/s
z_LAE = 3.6213
LAE
ID=75
NB, ID=75
ρ=170 kpc
x

Issues in preparing LAE catalog

- How to find an optimal threshold S/N for the software used? ("selection function")
  ⟹ "Purity" (1 – #Obj –ve cube / #Obj +ve cube) : required well-behaved noise
  ⟹ Recovery fraction of "fake" source

- Classification (When do you call it a Lyα emitter?)
  ⟹ Check for all possible contaminants ([O II], [O III], C III], Mg II, Hβ etc.)
  ⟹ Checking by multiple people

work in progress!

Future Plan: JWST/NIRSpec observations for the rest-frame optical nebular emission lines
⟹ accurate galaxy redshift
⟹ SFR, M_*, metallicity

Part-iii: Probing the cluster outskirts (CCM)

Collaborators: Jane Charlton, Daisuke Nagai, Joop Schaye, and Raghunathan Srianand

Publications: Muzahid+17, ApJL; Muzahid+ (in prep.)

The CCM

- Galaxy clusters are well-studied out to virial radii (ICM; $r < r_{500}$) using X-ray/Radio
- Outskirts of clusters are too tenuous to detect in emission, particularly at high-z
- Cluster outskirts ($r > r_{500}$) are important:
  - $\Longrightarrow$ Gas flow processes
  - $\Longrightarrow$ Cluster feedback
  - $\Longrightarrow$ Evolution of galaxies in the most massive haloes

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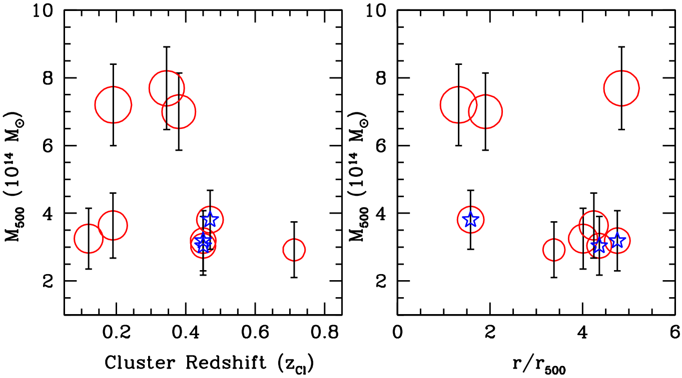
  - ⟹ Gas flow processes
  - ⟹ Cluster feedback
  - ⟹ Evolution of galaxies in the most massive haloes
- We built a sample of QSO-cluster pairs by cross-correlating Bleem+15 & Monroe+16



We got 15 orbits of HST/COS data as a pilot program!

Probing Warm-Hot Gas in the Outskirts of Galaxy Clusters Using Quasar Absorption Lines
HST Proposal 14655

Sowgat Muzahid
The Pennsylvania State University

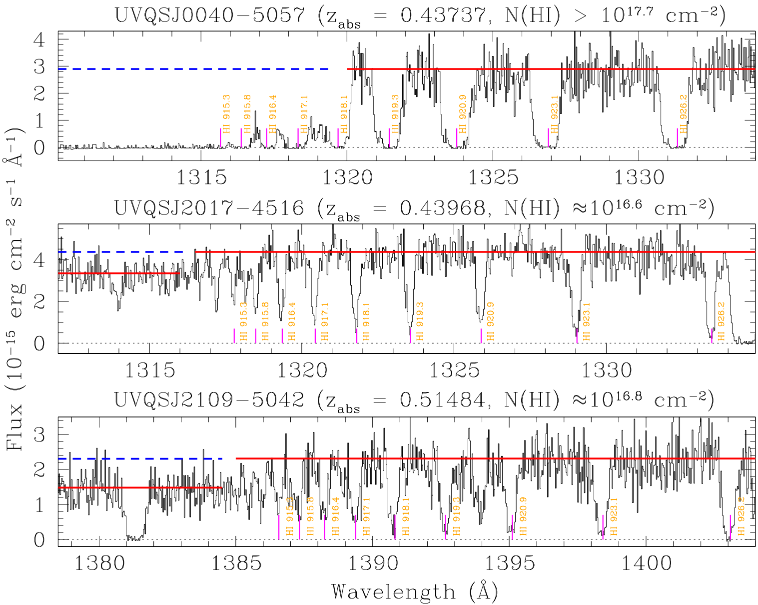
Cycle: 24
Category:
Proposal type: GO
Status:

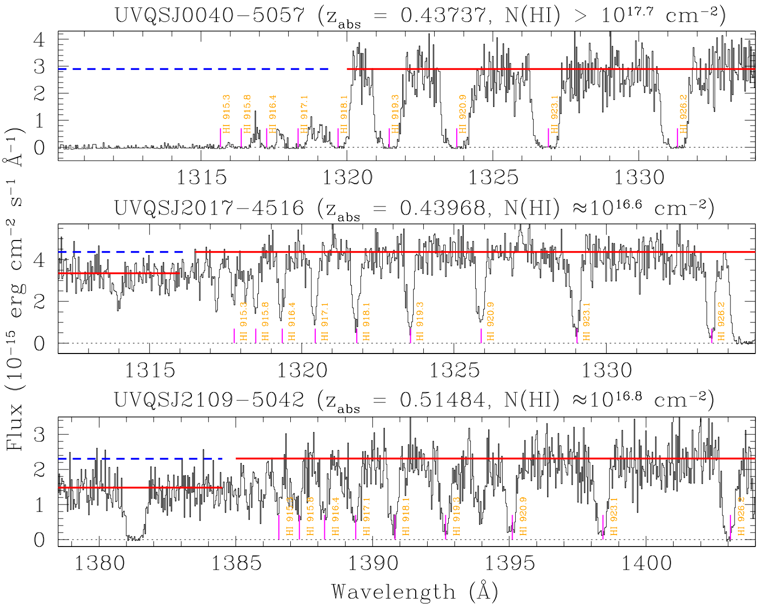
HST Proposal Information:
about this proposal
about other proposals by this PI

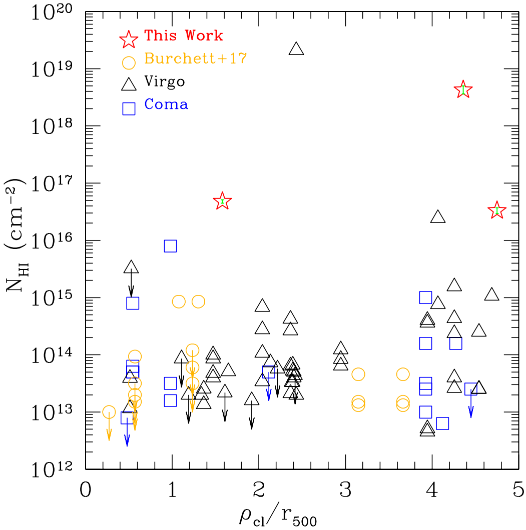
Proposal Abstract

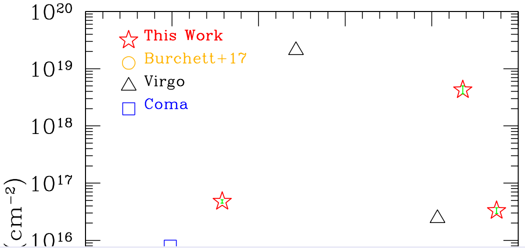
By cross-correlating the recently published sample of clusters by Bleem+15 from the 2500 deg^2 South Pole Telescope Sunyaev-Zel'dovich effect survey and the sample of all-sky UV-bright QSOs by Monroe+16, we have constructed a sample of 9 QSO-cluster pairs in the redshift range 0.1<z<0.7. In all cases the QSOs are in the background and at impact parameters of r ~(1-5)r_500 (r_500 being the radius within which the mean matter density is 500 times the critical density of the universe). This sample gives us a unique opportunity to probe unexplored cluster outskirts. Here we propose to obtain 3 QSO spectra as a pilot program that will probe the warm-hot gas, with log (T/K) = 5-6, via the OVI and NeVIII absorption lines, in the outskirts of 3 clusters at z~0.46. Recent cosmological hydrodynamical simulations suggest that the outskirts of galaxy clusters beyond r >r_500 are "cosmic melting pots", where galaxies and groups of galaxies are stripped of their metal-rich gas by tidal forces and ram pressure provided by the cluster atmosphere. This enriches the ICM with heavy elements and dissipates heat, thus establishing the overall thermodynamical and chemical structures of galaxy clusters. These simulations predict that the warm-hot gas atmosphere extends out to the accretion shock located at r ~(4-5)r_500, and that it is too cool to be probed via X-ray emission. Detecting this warm-hot gas in the outskirts of galaxy clusters will not only help account for some of the "missing baryons", but it will also advance our understanding of the physics of galaxy clusters and their use as cosmological and astrophysical laboratories.;

The CCM: Results




UVQSJ0040−5057 (z_{abs} = 0.43737, N(HI) > $10^{17.7}$ cm^{-2})
HI 915.3
HI 915.8
HI 916.4
HI 917.1
HI 918.1
HI 919.3
HI 920.9
HI 923.1
HI 926.2
1315
1320
1325
1330
UVQSJ2017−4516 (z_{abs} = 0.43968, N(HI) ≈$10^{16.6}$ cm^{-2})
1315
1320
1325
1330
UVQSJ2109−5042 (z_{abs} = 0.51484, N(HI) ≈$10^{16.8}$ cm^{-2})
1380
1385
1390
1395
1400
Flux (10^{-15} erg cm^{-2} s^{-1} Å^{-1})
Wavelength (Å)


This Work
Burchett+17
Virgo
Coma
N_{HI} (cm^{-2})
ρ_{cl}/r_{500}
10^{20}
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
0
1
2
3
4
5



Only 2.8% of the Coma/Virgo/other cluster sightlines show log N(H I) > 16.0

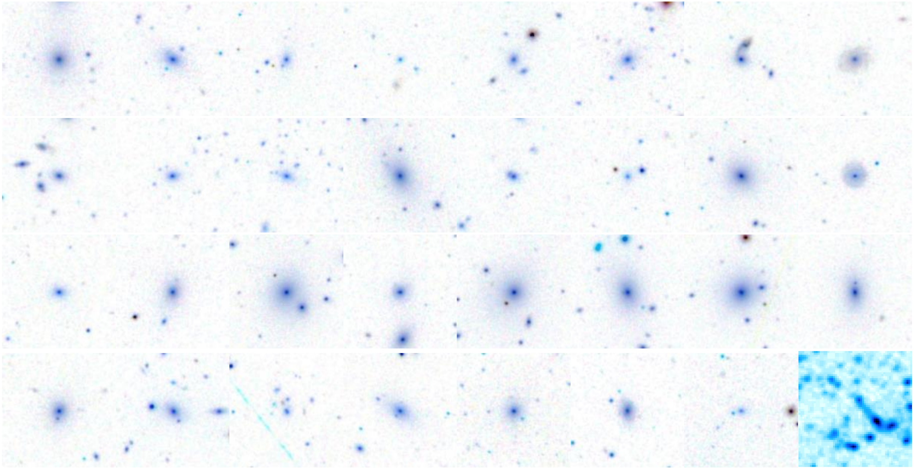
The outskirts of the SZ-selected clusters are remarkably rich in cool gas!

Strong low- (C II, Si II) and intermediate- (N III, C III) ionization metal lines are also present, suggesting high metallicity gas

(analysis is in progress!)

The CCM: Future Plans

We have found 32 new QSO-cluster pairs (non-SZE cluster)
We will propose for more HST time in the upcoming cycle



Next generation facilities

★ UV: LUVOIR (∼50 times more UV sensitivity)
★ Optical/IR: TMT, GMT, E-ELT, LSST, GAIA (operating)
★ IR: JWST
★ X-ray: Athena, Lynx

Next decade will be a "golden era"!

CCM studies in the next decade

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■ My main focus will be:

- How does the CGM change with galaxy environment (isolated, groups, clusters)?
- How does the CGM evolve? (redshift evolution)

■ Current CGM surveys are severely limited by:

∗ Number of available UV-bright QSOs
∗ Lack of uniform spectroscopic surveys of galaxies

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- ESO-GAIA: observe 500,000 QSOs up to $z \sim 5$
- LSST: reveal a large repository of galaxies/QSOs in the southern sky
- LUVOIR: observe ∼100 times more UV-bright QSOs at $R > 50{,}000$
- JWST/NIRSpec (and ALMA): will bring an avalanche of high-z galaxies

The number of QSO-galaxy, QSO-groups, QSO-cluster pairs will be increased dramatically!

The role of 30-m class telescopes (TMT)

Key: huge light gathering power

- High-resolution spectrograph: (High Resolution Optical Spectrometer; HROS)
  - ⋆ Fainter QSOs (and even galaxies!)
    - $\Longrightarrow$ Multiple sightlines through a single halo (both galaxies and QSOs)
    - $\Longrightarrow$ Small scale structures
  - ⋆ Super-high S/N (>1000) QSO spectra
    - $\Longrightarrow$ Metal lines in the under-dense regions ($\delta \ll 10$)

Obtaining high-quality spectra of background UV-bright sources will be highly time-effective!

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- Multi-object spectrograph with large FoV:
  - ∗ Wide-Field Optical Spectrometer (WFOS): first-light instrument
    3000–10,000 Å, 40 sq-arcmin FoV, long-slit/short-slit of 100s of objects
  - ∗ Infrared Imaging Spectrograph (IRIS): first-light instrument
    0.84–2.4μ, $34'' \times 34''$ FoV, IFU

  Search for galaxies around the background UV-bright source will be very easy!

The future looks exciting!!

The future looks exciting!!

T H A N K S