This talk tells you two stories:

1. The identification of massive amounts of cold ($T \approx 10^4$ K), dense ($N_{\text{HI}} > 10^{20}$ cm$^{-2}$), gas at $z \approx 1.6$, not associated with, and chemically more pristine than, the ISM in the galaxies.
   a) Gas from earlier generations of stars, possibly with a top-hat IMF?
   b) There is tentative evidence that this gas accretes onto star-forming galaxies. Feeding cold accretion?

2. Even with 10-m telescopes, it is possible to study gas exchange, between galaxies and the IGM at high redshift, including accretion (it just takes some effort).
Absorption spectroscopy very sensitive to the presence of gas; one needs a source with blue, featureless spectrum to back-illuminate the gas.

Vast body of knowledge from QSO absorption systems to leverage on.

Blue SF galaxies (e.g. LBNG) are $\approx 10^3$ more numerous than QSO; one is virtually guaranteed to find some (how many depends on the sensitivity one can reach) in the background of any preselected structure.

The GOODS observer.

Observed optical spectrum.

Galaxy over-density @ $z \approx 1.6$, with its IGM.

Rest-frame far UV spectrum.

SF galaxy @ $z \approx 3.5$. 

Galaxy Absorption Systems
We targeted a large overdensity of galaxies at $z \approx 1.6$, looking for evidence of accreting gas (GOODS ESO FORS2 spectra)

- Naïvely, higher chance of detection in node of cosmic web

- We searched for intervening MgII absorption systems in the spectra of background LBG at $3 < z < 3.5$

- MgII traces $10^4$ KHI gas

- Much higher spatial sampling than using QSO

- Detected absorption in three LBG

- LBG roughly aligned, with separations of $\approx 150$ kpc (G2-G3) and $\approx 1$ Mpc (G1 to G2,3)
The LBG Absorption Line Systems

- Found 4 intervening absorption line systems in the spectra of 3 LBG at z>3, out of a total 21 galaxies with z<24.6

- The lines, which have S/N>10 and are resolved with 12<FWHM<45 Å, do not match any known features at the redshift of the LBG

- Large observed equivalent width:
  - G1: 24±4 Å
  - G2a: 23±5 Å
  - G2b: 14±5 Å
  - G3: 26±78 Å
To investigate the nature of the absorption features,

- we have stacked them after registering their central wavelength to the MgII λ 2795–2803 rest-frame central wavelength (2800 Å)
- we clearly detect a doublet (λ λ 2796–2802 Å) with rest-frame equivalent width \( W_r = 6.3\pm1.5 \) Å
- This makes the stack (as well as the individual systems) ultra-strong MgII absorption systems (\( W_r > 3 \) Å)

Absorption takes place in outflow with \( v = 350 \) km/s (systemic redshift from [OII])
What kind of gas can produce the observed MgII absorption systems? Lessons from QSO studies

- MgII absorption systems form in the warm (T \approx 10^4 \text{ K}) optically-thick HI medium that produces Lyman-Limit Systems (N_{\text{HI}}>10^{19} \text{ cm}^{-2})

- Strong MgII systems ($W_r>0.3$ Å) form in the gaseous halos of bright, massive galaxies ($L/L^*>0.3$) of all spectral types at impact parameter $d<70$ kpc (e.g. Steidel et al. 2002; Churchill et al. 2005)

  - A few strong MgII absorption systems appear not to have an associated galaxy, bright or otherwise, however (e.g. Tripp & Bowen 2005; see also Fumagalli et al. 2010)

- Ultra-strong MgII systems ($W_r>3$ Å) form in the halos of massive galaxies at $d<40$ kpc (Nestor et al. 2007); the strongest absorbers ($W_r>5$ Å) also form in the wind of SF galaxies with $L/L^*>4$ (Nestor et al. 2007; Tremonti et al. 2007)

- Most, at least 60% but likely as many as 90% of those with $W_r>5$ Å, are Damped Lyman Alpha absorbers, i.e. ($N_{\text{HI}}>2 \times 10^{20} \text{ cm}^{-2}$)
Our absorbing gas appears to be located at the edge of the overdensity

Small number statistics and selection bias due to band of sky lines at \( \lambda \lambda 7250-7400 \) Å might play a role.

Gas will, in general, be moving relative to the galaxies at \( \approx \text{several} \ 10^2 \) km/s.

Effect might very well be physical, however.

Spectroscopic sample now also includes the ESO VLT/FORS2 GMASS: \( m_{4.5 \mu m} \leq 23.0 \) (roughly \( M > 4 \times 10^9 \) M\(_\odot\) at \( z = 1.6 \)), \( \approx 50\% \) complete.
Are Galaxies Responsible for our MgII absorbers?

- There are no spectroscopically-confirmed galaxies with $d < 210$ kpc from the LOS to any of the three LBG in either the FORS2 sample or the GMASS one.

- We have explored the field around the LOS to each LBG using the GOODS ACS z-band images and recent ultra-deep U and R-band images from VTL/VIMOS (1-$\sigma$ SB fluctuations $\mu \approx 30$ mag arcsec$^{-2}$) together with photometric redshifts.

  - The LBG are undetected in the U band, providing unrestricted visibility to possible faint galaxies at $z \approx 1.61$ overlapping with the LBG isophotes.

- We found no galaxy that could plausibly be held responsible for the absorption systems, based on what we know from QSO studies.
The LOS to G1:
circled and labeled galaxies have $1.5 < \zphot < 1.7$ in at least one of our two photo-z catalogs

The LBG (center) is undetected in the U band: no galaxy is on top of it

10419:
z=27.2, $L/L^*=0.02$

10479:
z=26.5, $L/L^*=0.05$

10895:
z=23.5, $L/L^*=0.36$
(but $b \approx 80$ kpc: too far for ultra-strong)

Concentric circles have 10, 50, 100 kpc radius

This faint galaxy is undetected in the ACS image: $z<28.2$ or roughly $0.01 L^*$ if at $z \approx 1.6$

This galaxy is undetected in the U band: at the same redshift as the LBG
The LOS to G2
(the one with 2 absorbers):
circled and labeled galaxies have $1.5 < z_{\text{phot}} < 1.7$ in at least one of our two photo-z catalogs.

The LBG is not detected in the U band: no galaxy is on top of it.

14131:
$z=25.4$, $L/L^*=0.1$
$b\approx 25$ kpc

14524:
$z=27.3$, $L/L^*=0.025$

14526:
$z=26.6$, $L/L^*=0.05$

Concentric circles have 10, 50, 100 kpc radius.

14131 is too faint to plausibly cause ultra-strong MgII absorption.

In any case, it can only account for one of the two absorbers of G2.

These galaxies are not or barely detected in the U band: at same or similar redshift as the LBG.
The LOS to G1:
circled and labeled galaxies have $1.5 < z_{\text{phot}} < 1.7$ in at least one of our two photo-z catalogs

The LBG is not detected in the U band: no galaxy is on top of it

14871:
z = 27.7; $L/L^* = 0.02$
d $\approx 25$ kpc

14876:
z = 26.0; $L/L^* = 0.04$
d $\approx 11$ kpc

Both 1471 and 14876 are very faint to be plausible hosts of ultra-strong absorbers. 14976 has very short impact parameter, though.

Concentric circles have 10, 50, 100 kpc radius

Note that Nestor et al. (2007) estimate that the disk of the MW would NOT be capable of ultra-strong MgII absorption
The absorbing gas seems to be chemically more pristine than the galaxies’ ISM

- Fe II trough not detected in the stacked spectrum of the four MgII absorbers:
  - $W_{\text{FeII}}/W_{\text{MgII}} < 1/9$

- The detected gas is expected to be similarly dense and hot as the ISM in the star-forming galaxies at similar redshift

- The lack of Fe features likely implies that the “intra-overdensity” gas is chemically more pristine than that in the IGM (outflows) of star-forming galaxies at the same redshift
We have looked for independent evidence of the existence and nature of the gas

- We have stacked all the GMASS spectra at $z > 1.65$, i.e. in the background of the overdensity (119 galaxies, $T_{\text{exp}} \approx 2071$ hr)

- There is one well detected feature in correspondence with the peak in the redshift distribution at the wavelength of MgII.

- (as well as another one nearby to one of the absorbers)

- Consider that not all galaxies might have absorption (strong dilution effect)

- MgII is detected, but FeII still not detected!
We saw that the absorbing gas seems to be chemically "different" than the galaxies' ISM.

- Not possible to translate the equivalent width ratio into elemental abundance ratio, because the lines are almost certainly saturated.

- Since the FeII is not detected, however, and in saturated lines the column density is underestimated, the observed $W_r$ ratio of Fe to is a crude lower limit to the elemental abundance ratio:
  
  $$[\text{Mg/Fe}] > \log\left(\frac{W_{\text{MgII}}}{W_{\text{FeII}}}\right) \approx \log(6.3/1.5) = 0.623$$

- For comparison, $-0.3 < [\alpha/\text{Fe}] < 0.5$ in galaxies (Recchi et al. 2009; Samson & Northeast 2008; Thomas et al. 2005) and DLA, including metal poor ones.

- Thus, it appears that the MgII absorbing trough is chemically different: more pristine or enriched by stars with a very top-heavy IMF (lots of $\alpha$-elements but little Fe).
[\alpha/\text{Fe}] ratio in galaxies
Sansom & Northeast 2008 ($37 < \sigma < 236$ km/s)
Thomas et al. 2005 ($50 < \sigma < 360$ km/s)

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure.png}
\caption{Histogram of MgII absorbers with respect to $[\alpha/\text{Fe}]$.
The red and black histograms represent different velocity ranges.
MgII absorbers are indicated by the arrow.}
\end{figure}
Tentative evidence for accretion

- Accretion should look like an extension of the MgII absorption feature and/or additional discrete absorption features toward redder wavelengths

- Possible evidence for such features in the 16 FORS2 stack of overdensity galaxies at z=1.6

- Also observed in the 119 GMASS stack: discrete absorption feature detected at same wavelength as FORS2 stack.

- Possible residual MgII emission from low-level AGN (Liner or Seyfert 2) might hide red extension. AGN suspected for residual emission in FeII
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• Different from Steidel et al.: this is a stacked spectrum, probing a range of impact parameters.
How much gas is there?

- From the resolved nature of LBG, we can set a crude lower limit to the mass of absorbing clouds:

\[ M \approx 5 \times 10^8 \times \left( \frac{N_{HI}}{10^{20}} \right) \times \left( \frac{D}{10 \text{kpc}} \right)^2 M_\odot \]

- \( D \) is the physical size subtended by the LBG at \( z \approx 1.6 \).

- If the covering factor is crudely \( C_f \approx 4/21 = 0.2 \), over the projected area of the three absorbers (\( D \approx 1 \text{ Mpc} \)) the HI mass is:

\[ M \approx 1 \times 10^{12} M_\odot \]
In Conclusion

- We have found evidence of massive amounts of HI gas with \( T \approx 10^4 \) K, i.e. at the expected temperature of the gas believed to feed “cold accretion”, within a galaxy overdensity at \( z \approx 1.6 \).

- This gas does not seem to be directly associated with galaxies and appears to be chemically younger, i.e. depleted of Fe relative to \( \alpha\)-elements, relative to the ISM of galaxies (either halo gas or outflows).

- The projected gas covering factor in the overdensity appears to be roughly \( C_F \approx 0.2 \). Together with the resolved nature of the LBG, this implies as much as \( \approx 10^{12} \, M_\odot \) of gas in an area with a projected diameter \( D \approx 1 \, \text{Mpc} \).

- There is tentative evidence that this gas is accreting onto star-forming galaxies of the overdensity, maybe feeding “cold accretion”?