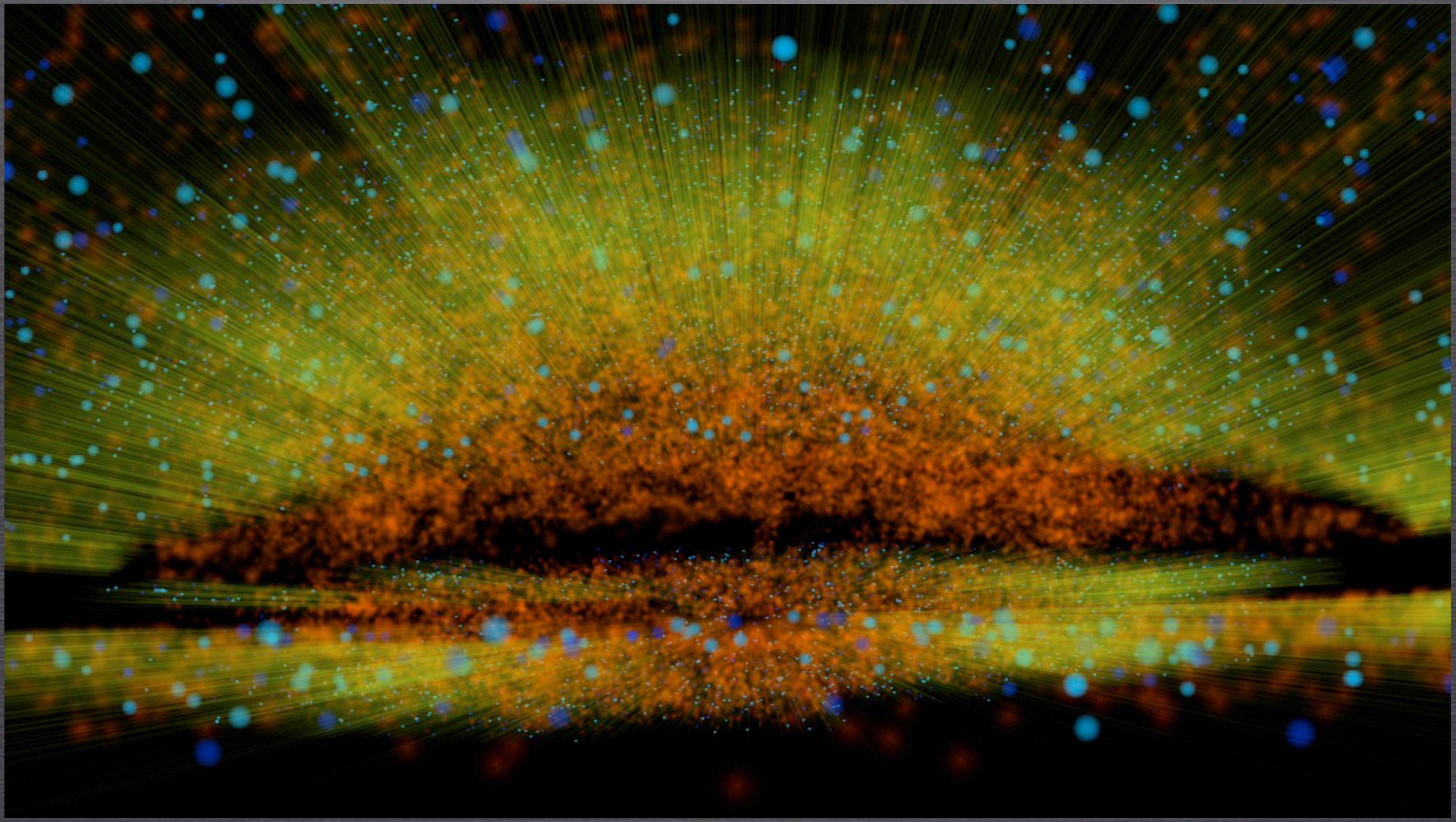
Revealing the origins and Environments of Mg II Absorbers with the SDSS and 3D-HST



Britt Lundgren
NSF Postdoctoral Fellow
University of Wisconsin-Madison

IPMU Colloquium
October 29, 2012

Outline

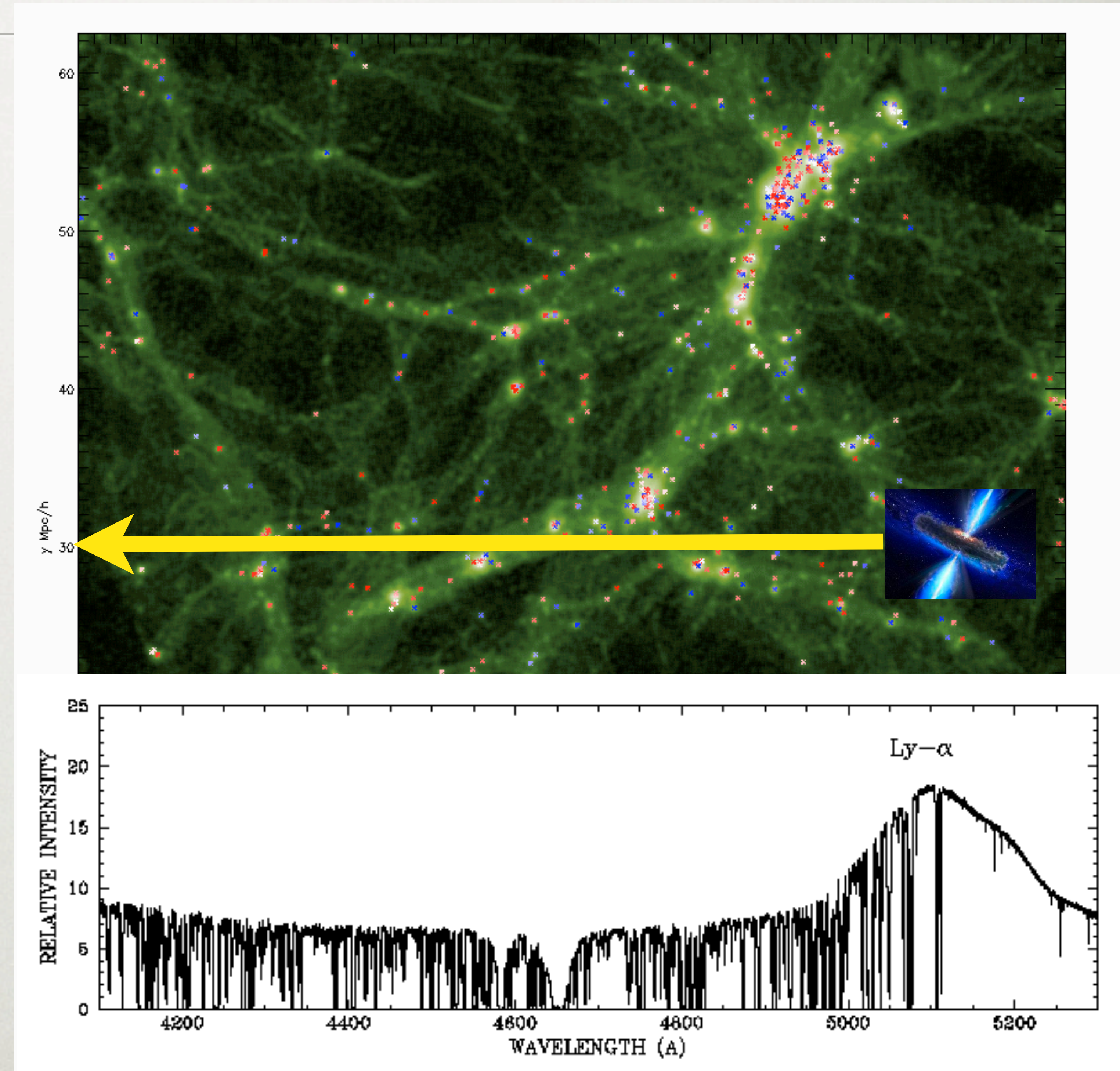
- Background & Motivation
- Statistical analyses using new large samples of Mg II
  - Stacking & Galaxy-Absorber Correlations in the SDSS
- Direct detections of Mg II host galaxies at high-z
  - New results from the 3D-HST Survey (Lundgren et al. 2012)
- Future Work

Collaborators

- Yusra Al Sayyad (U. of Washington), Robert Brunner (U. of Illinois), Alison Coil (UCSD), Scott Croom (U. Sydney), Pushpa Khare (Utkal U., India), Nikhil Padmanabhan (Yale), Gordon Richards (Drexel), Don Schneider (PSU), Jeremy Tinker (NYU), Daniel Vanden Berk (St. Vincent), Pieter van Dokkum (Yale), David Wake (Yale), Don York (U. of Chicago), *+ the greater SDSS I/II & III, 3D-HST and AUS Collaborations*

What are Quasar Absorption Lines?

- Absorption features in the spectra of quasars, produced by gas and dust
- Probes of:
    - Quasar outflows & host galaxies
    - Foreground galaxies: gas halos, disks, star-forming regions
    - Intergalactic medium



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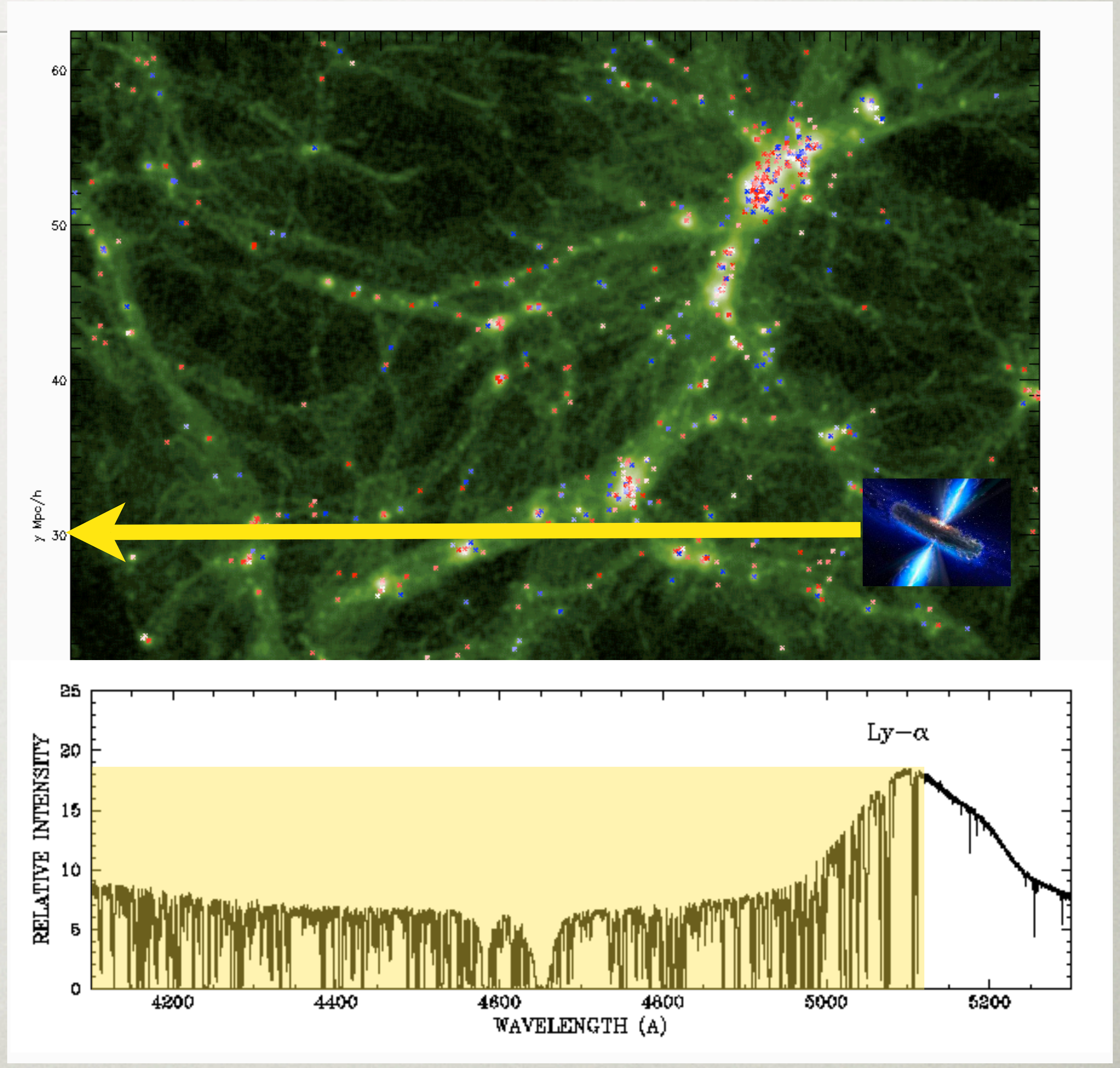

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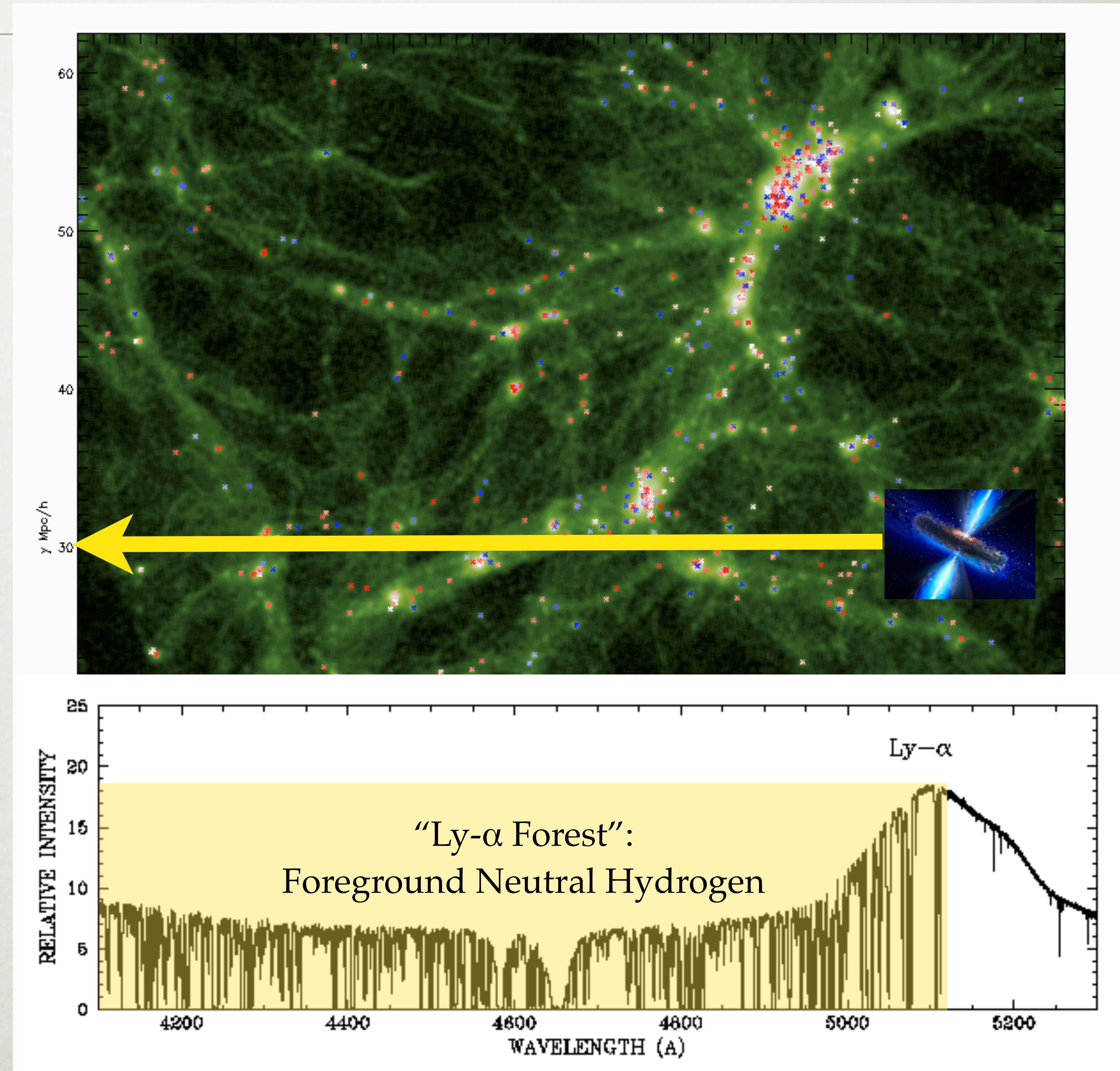

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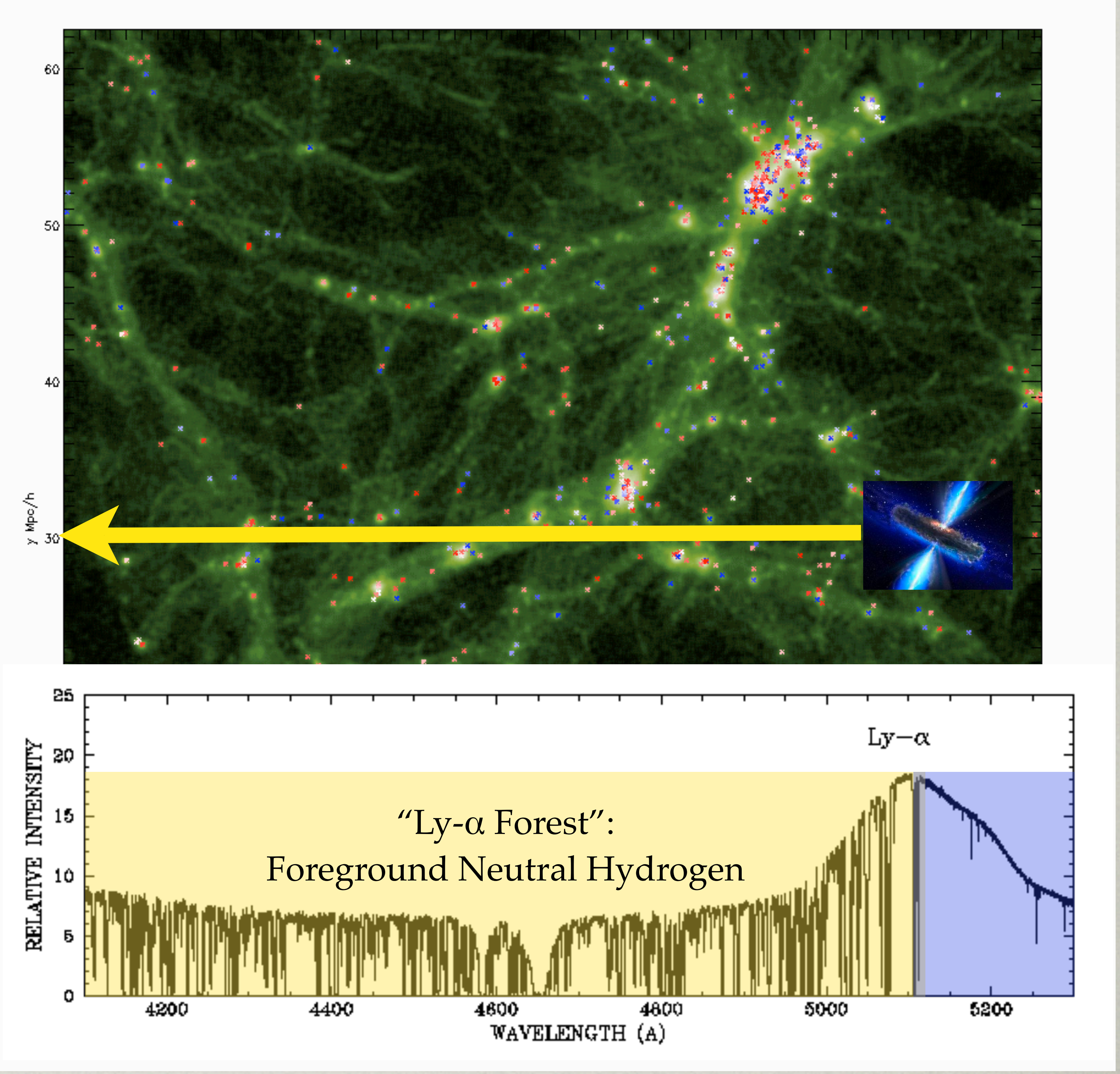

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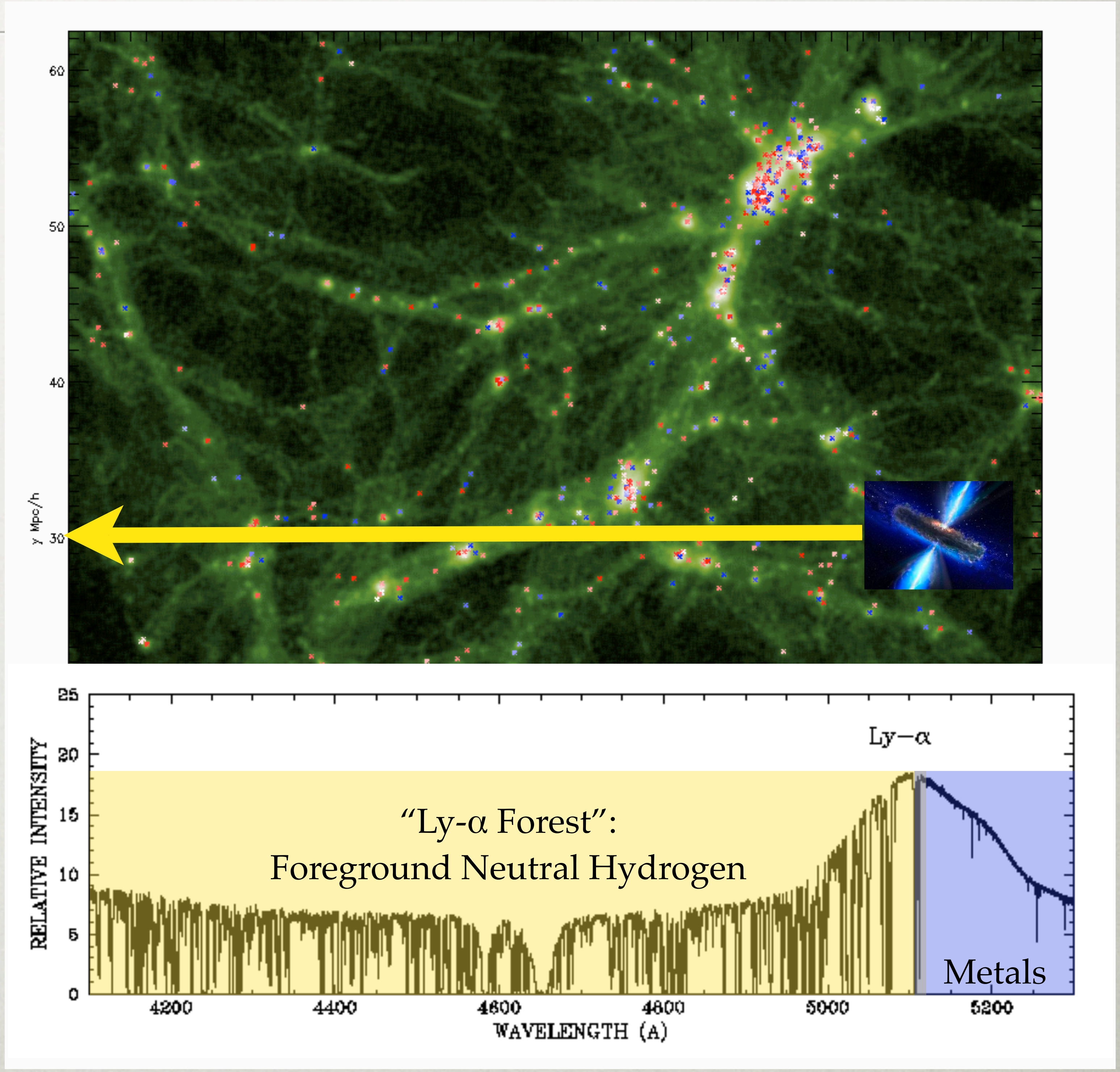


Quasar Spectra: Cosmic Core Samples

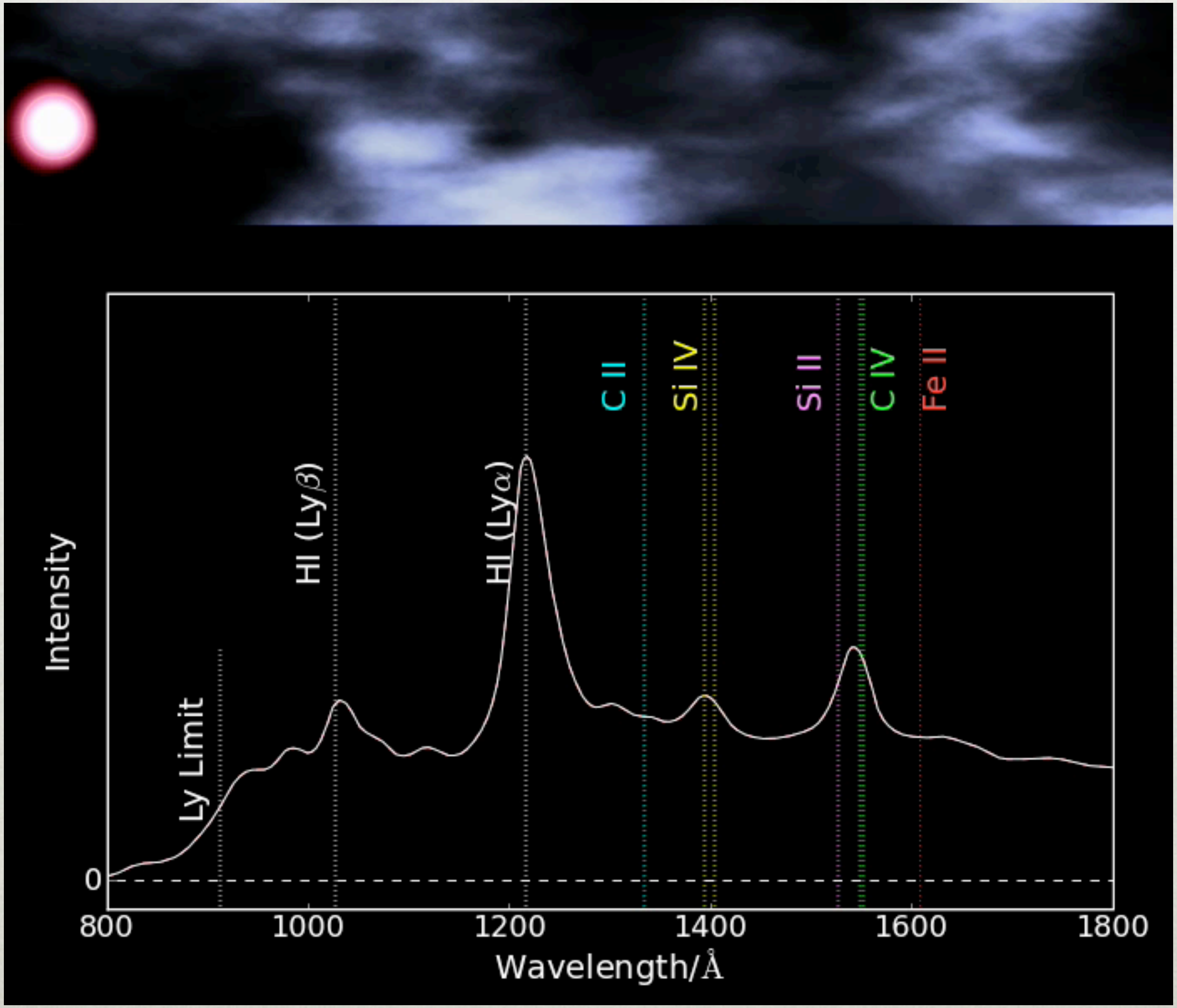
Just as ice cores from the Arctic provide a chemical history of the Earth...

The spectrum of a distant quasar can trace the evolution of the baryon content of the Universe throughout as much as 90% of cosmic history.

Quasar Spectra: Cosmic Core Samples

Animation Credit:
Andrew Pontzen, Cambridge

Quasar Spectra: Cosmic Core Samples



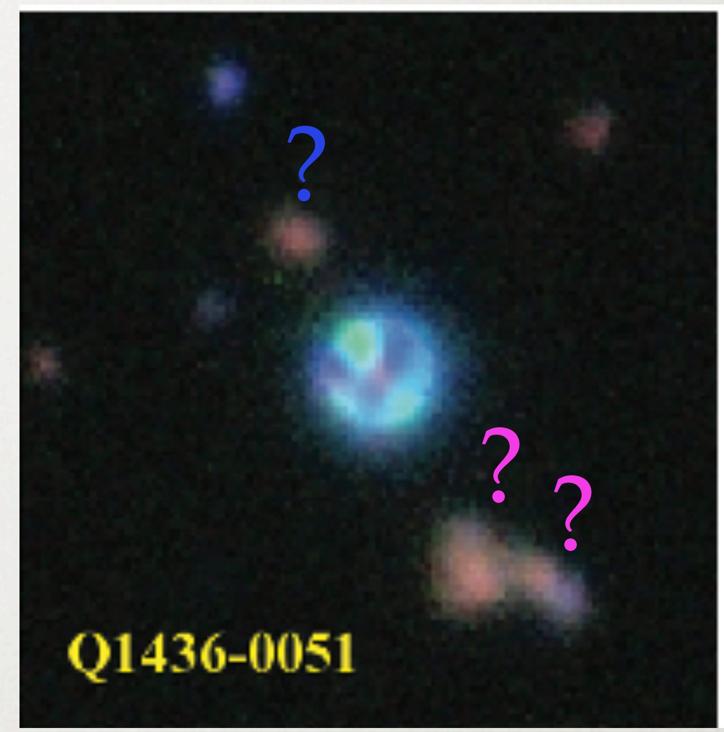
Animation Credit:
Andrew Pontzen, Cambridge

QALs as probes of galaxies and their environments

- Quasar Absorption Lines (QALs) trace *gas, not stars!*
    - The detection of luminous matter becomes more difficult at high-z... but not so for QALs
    - QALs are sensitive to wide ranges in metallicity, $N_{(HI)}$, kinematics, & ionization temperatures
- QALs provide direct, luminosity independent measurements of:
    - The gas content of galaxies ($\lesssim$ 200 kpc)
    - Galaxy environments (e.g., low luminosity satellites, tidal streams)
    - Halo-disk processes (e.g., gaseous disks, outflows, cold gas accretion)
    - IGM

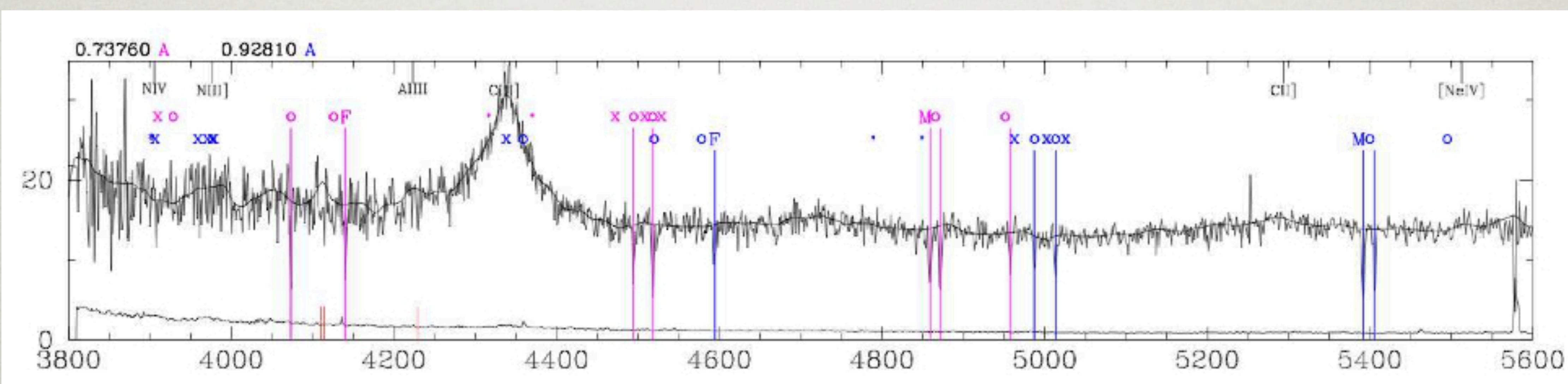
Persistent Challenges

- In theory, QALs are exceptional probes of galaxies. *However,*
    - QAL hosts are often too faint for imaging confirmation
    - It is often unclear which part of the galactic structure is being probed



z=0.738
z=0.928

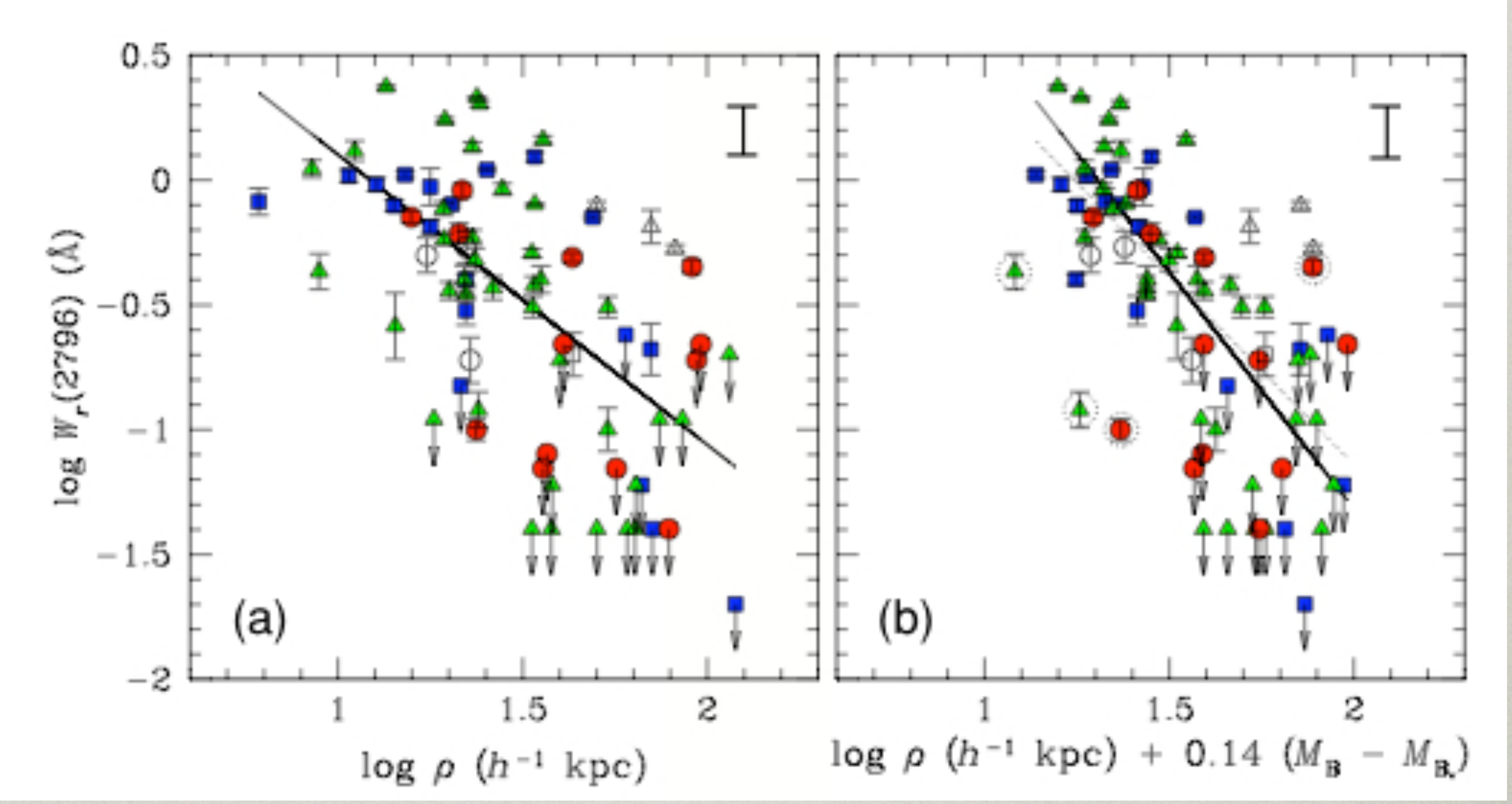
SOAR 4.1m imaging (Meiring et al. 2011) and SDSS DR7 Spectrum of Q1436-0051



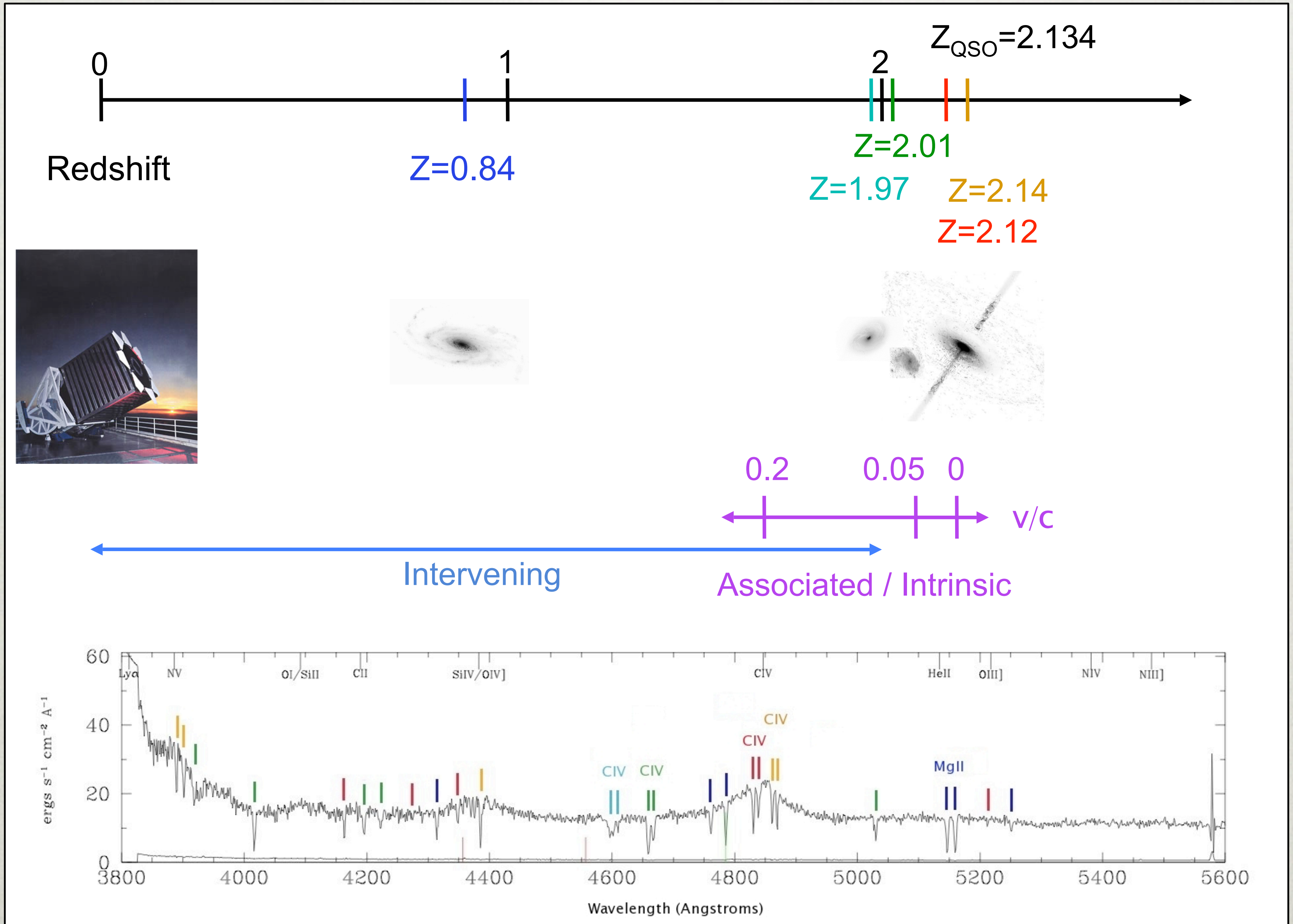
Persistent Challenges

- No obvious trends among local (z < 0.4) absorbing galaxies

Chen et al. 2010



Persistent Challenges



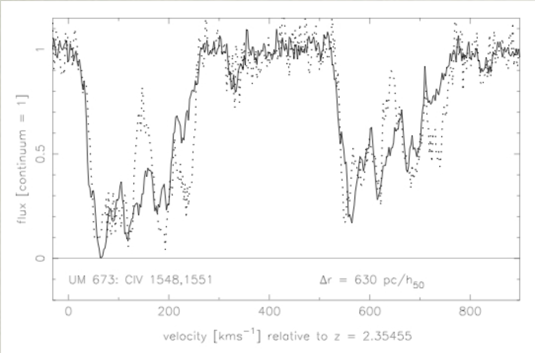
Motivation for studying QAL origins & Environments

- Outstanding questions regarding the origins and environments of QALs:
    - *How does one best distinguish quasar outflows from foreground matter in the Hubble flow?*
    - *What types of galaxies host what types of QALs?*
    - *How are QALs generally distributed in galactic haloes, and what processes do they primarily probe?*

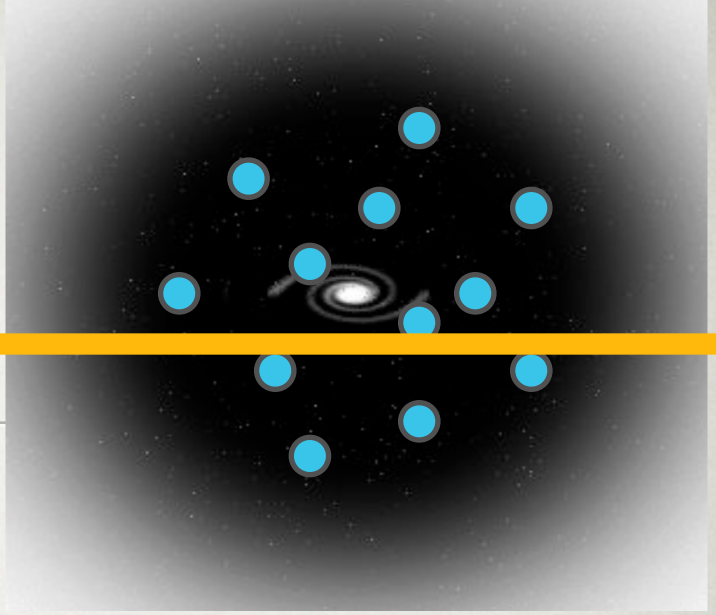
- With these determined, we can use QALs to expand our understanding of <u>gas accretion and feedback processes in galaxies and the evolution of the content & distribution of baryonic matter from high-z</u>

Mg II Absorbers

- Easily identifiable doublet (2796, 2803Å)
- Arises in photo-ionized gas with T~10,000K
  (Bergeron & Stasinska 1986; Hamann 1997)
- Prolific in optical spectra for $0.3 \lesssim z \lesssim 2.0$
- Some association with DLAs ($N_{HI} > 10^{19}$ cm^{-2})
  (Wolfe et al. 1986; Turnshek et al. 1986)
- Associated with luminous galaxies, 0.5-0.7 L*
  (Bergeron 1986; Lanzetta & Bowen 1990, 1992; Steidel et al. 1994; Zibetti et al. 2005; Nestor et al. 2007; Kacprzak et al. 2007)



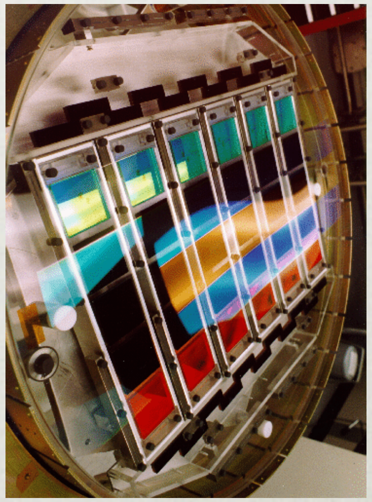
Mg II Origins



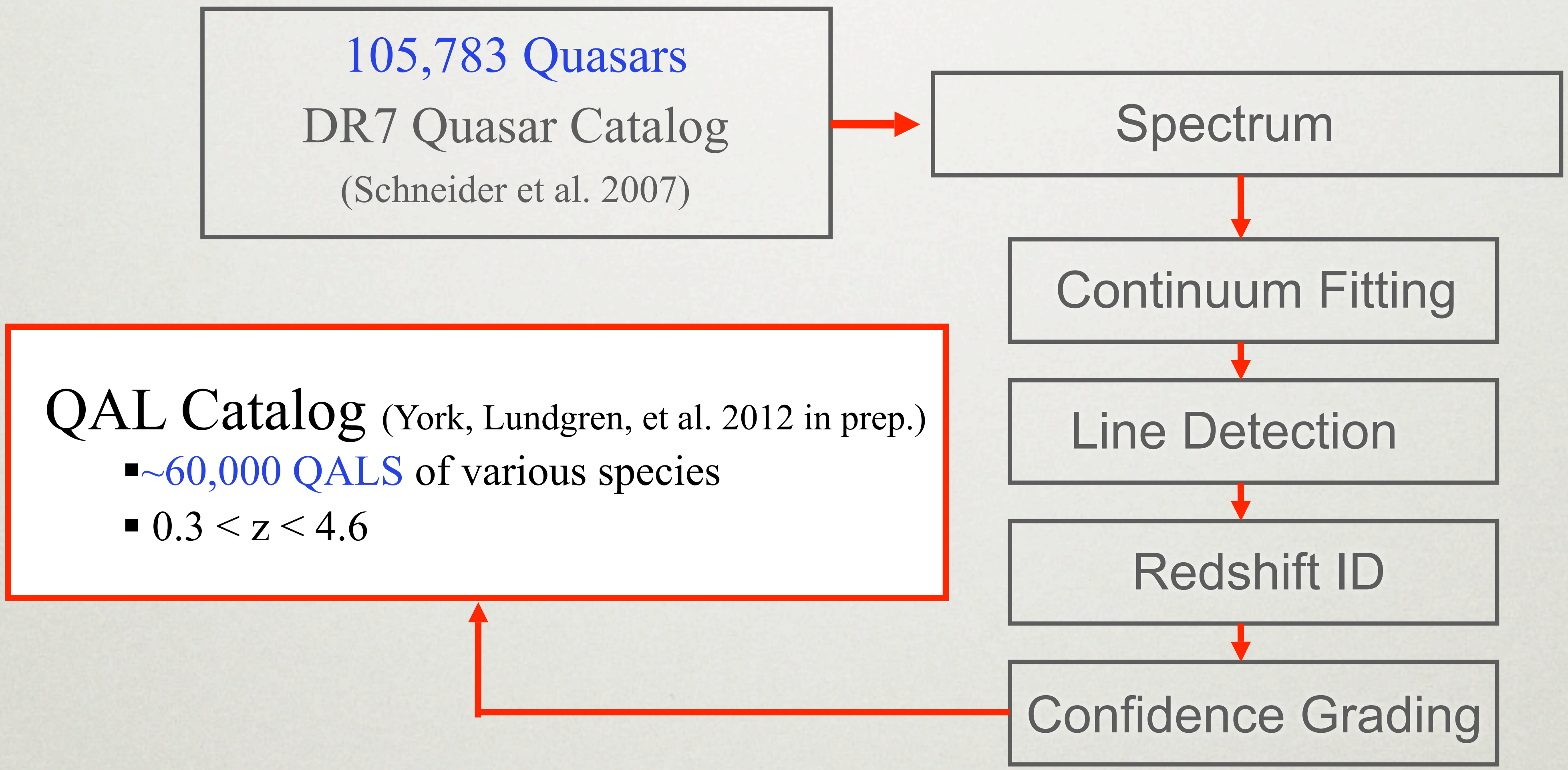
- Classical Picture:
  - kinematic structure in strong lines (e.g.,Churchill & Vogt 2001)
  - absorption equivalent width ∝ velocity dispersion of galaxy halo (e.g., Bahcall & Spitzer 1969)
- But new insights from the SDSS have tested *(and challenged)* this paradigm....

The Sloan Digital Sky Survey

- Dedicated 2.5m telescope at Apache Point Observatory, NM
- 120 megapixel camera with ugriz filter set
- Multi-object spectrograph (640 fibers)
- Seventh Data Release (DR7)
    - ~10,000 sq. degrees imaged
    - ~1 million galaxy spectra
    - ~110,000 quasar spectra

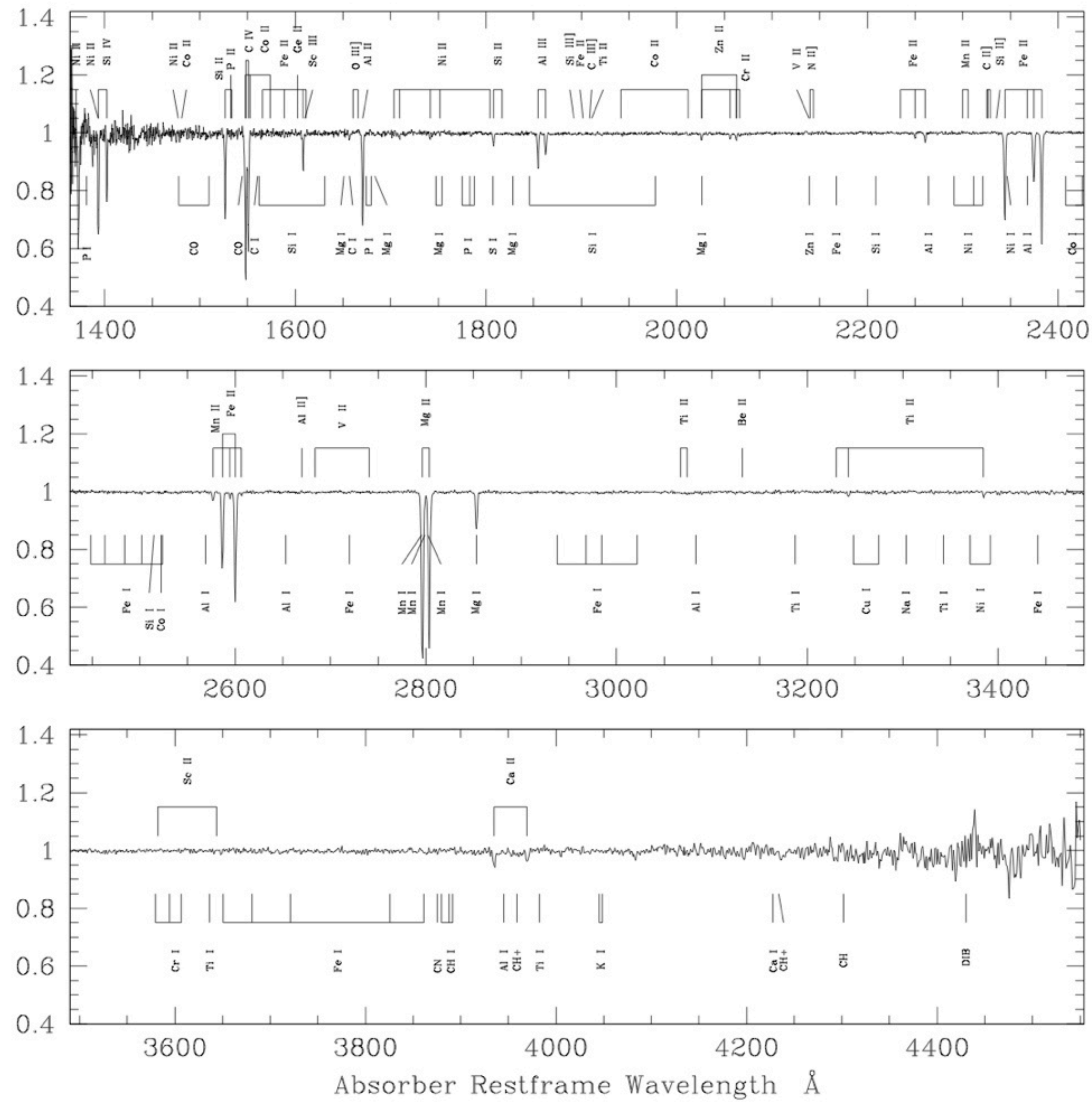


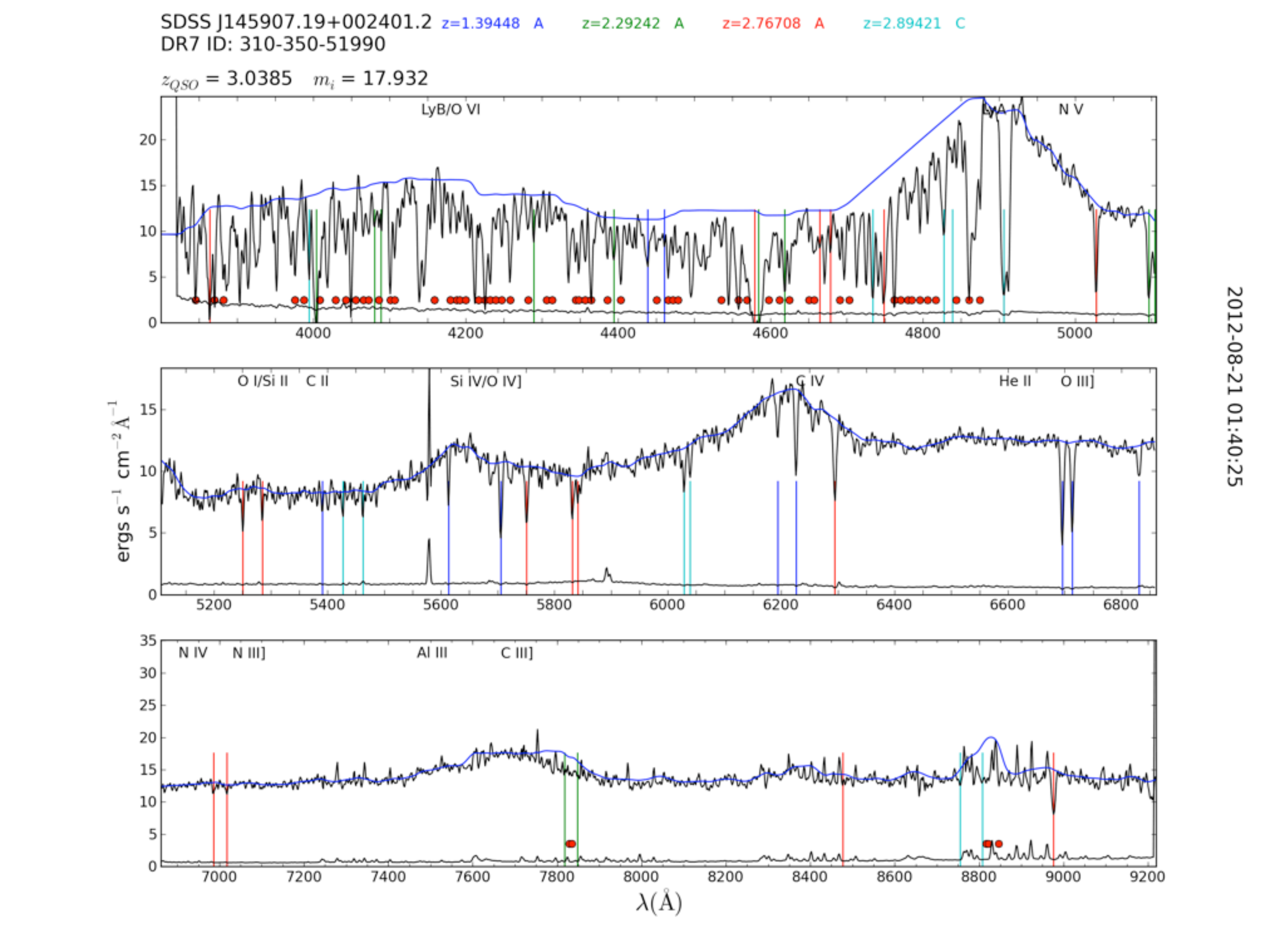
SDSS DR7 QAL pipeline

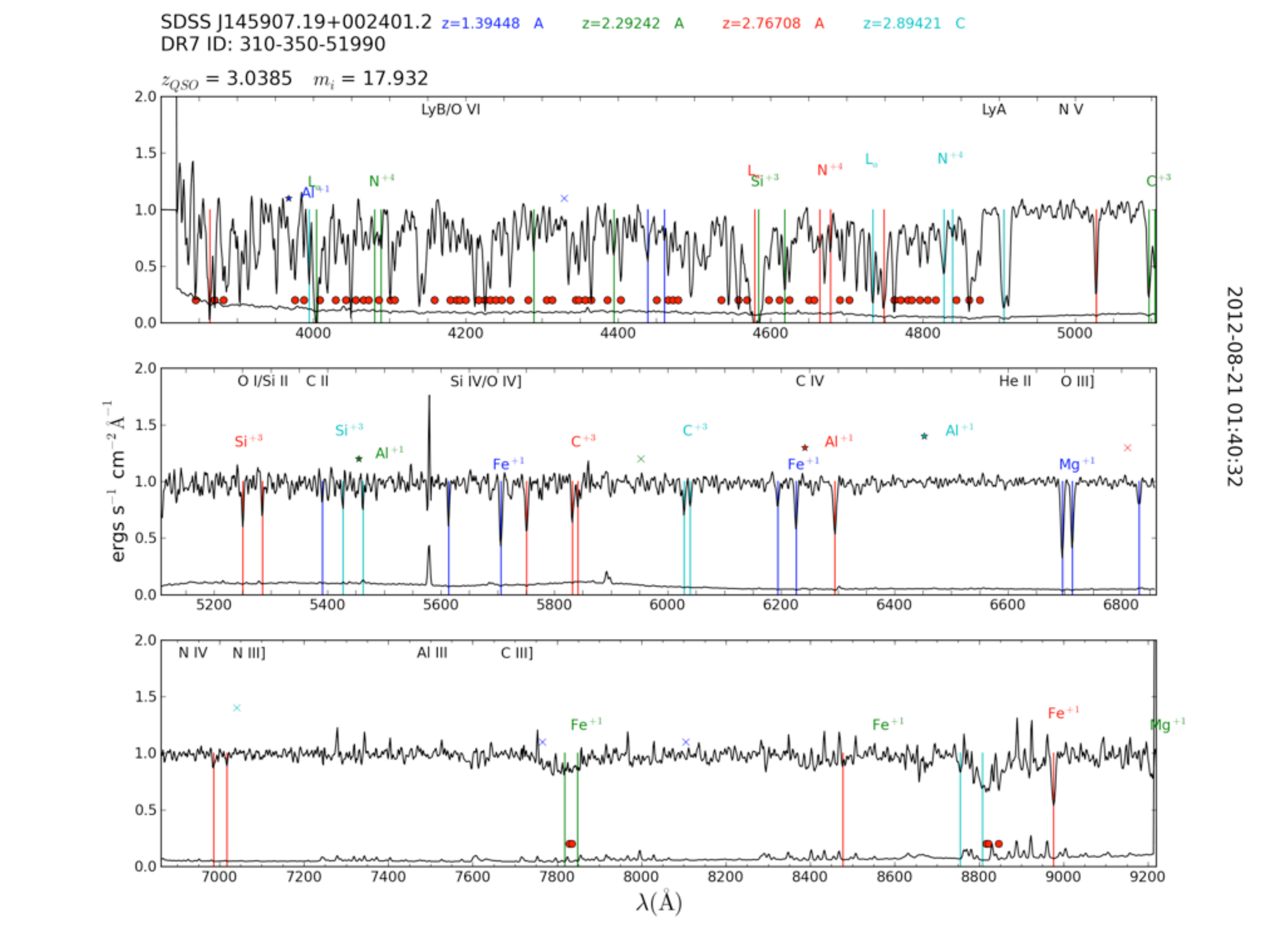


Ions identified by the SDSS DR7 absorber pipeline

(York et al. 2006)




SDSS J145907.19+002401.2
z=1.39448 A
z=2.29242 A
z=2.76708 A
z=2.89421 C
DR7 ID: 310-350-51990
z_{QSO} = 3.0385 m_i = 17.932
LyB/O VI
LyA
N V
O I/Si II
C II
Si IV/O IV]
C IV
He II
O III]
N IV
N III]
Al III
C III]
ergs s^{-1} cm^{-2} Å^{-1}
λ(Å)
2012-08-21 01:40:25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N III]
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C III]
ergs s^{-1} cm^{-2} Å^{-1}
λ(Å)
2012-08-21 01:40:32

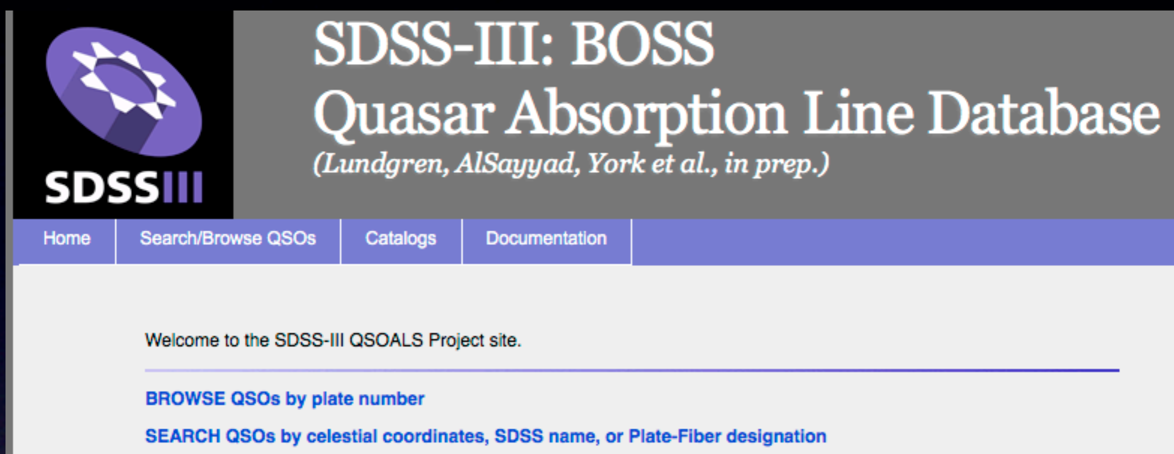
SDSS-III Baryon Oscillation Spectroscopic Survey

- 5-year survey in the SDSS-I/II footprint (10,000 deg^2)
  - 1.5M LRGs to z~1
  - ~200,000 quasars (most at $2<z<4$)
  - Upgrades to the SDSS spectrograph
    - moderately higher throughput, resolution
    - broader wavelength coverage

- DR9 Quasar Absorption Line Catalog
  - Projected identification of ~100,000 metal absorption systems by survey completion (Lundgren et al., in prep.)

Mining Metals in the BOSS Quasar Spectra

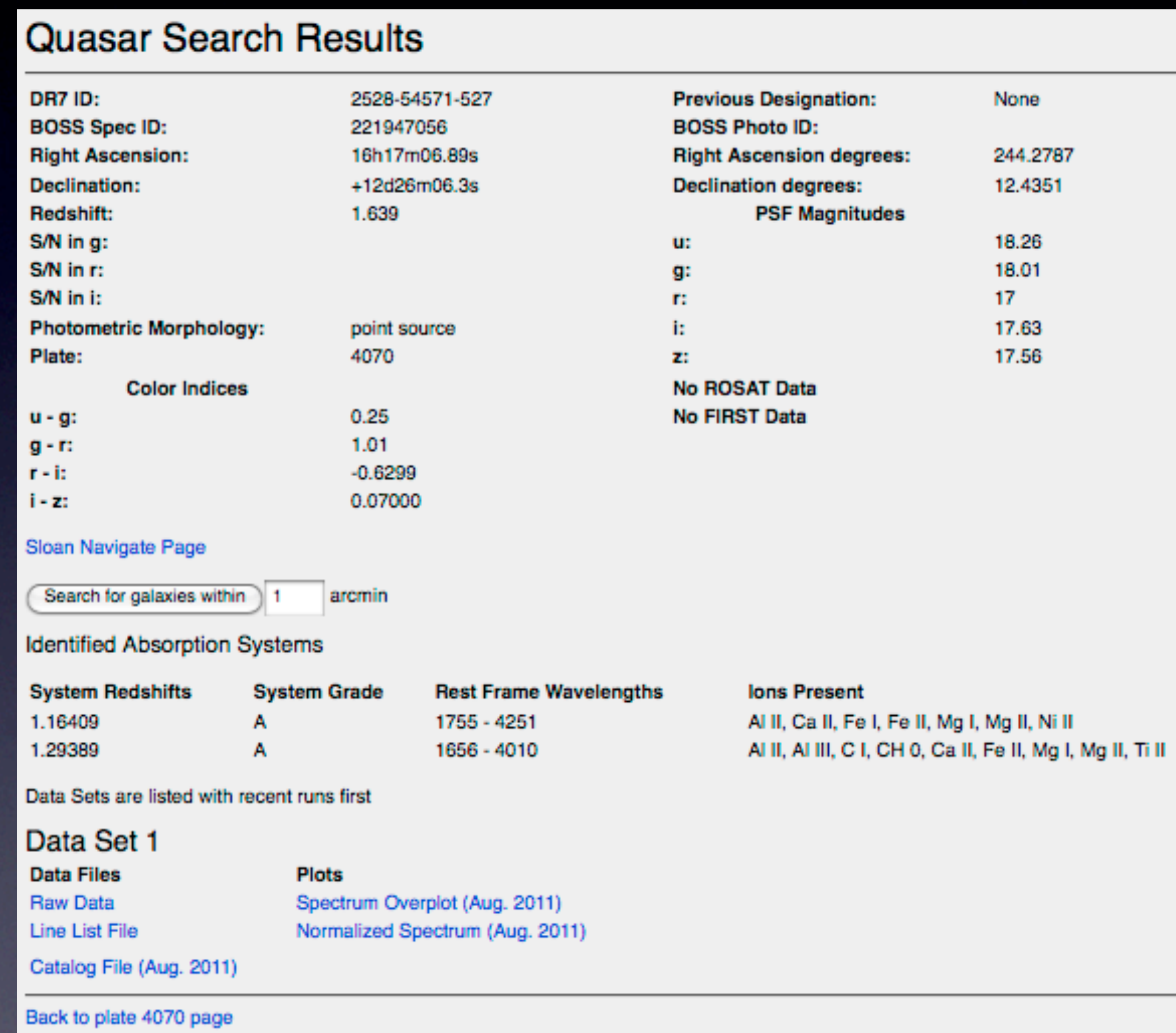
Britt Lundgren (Wisconsin), Don York (UChicago), Yusra AlSayyad (Washington)
+Project 37 co-authors, and the SDSS-III Collaboration



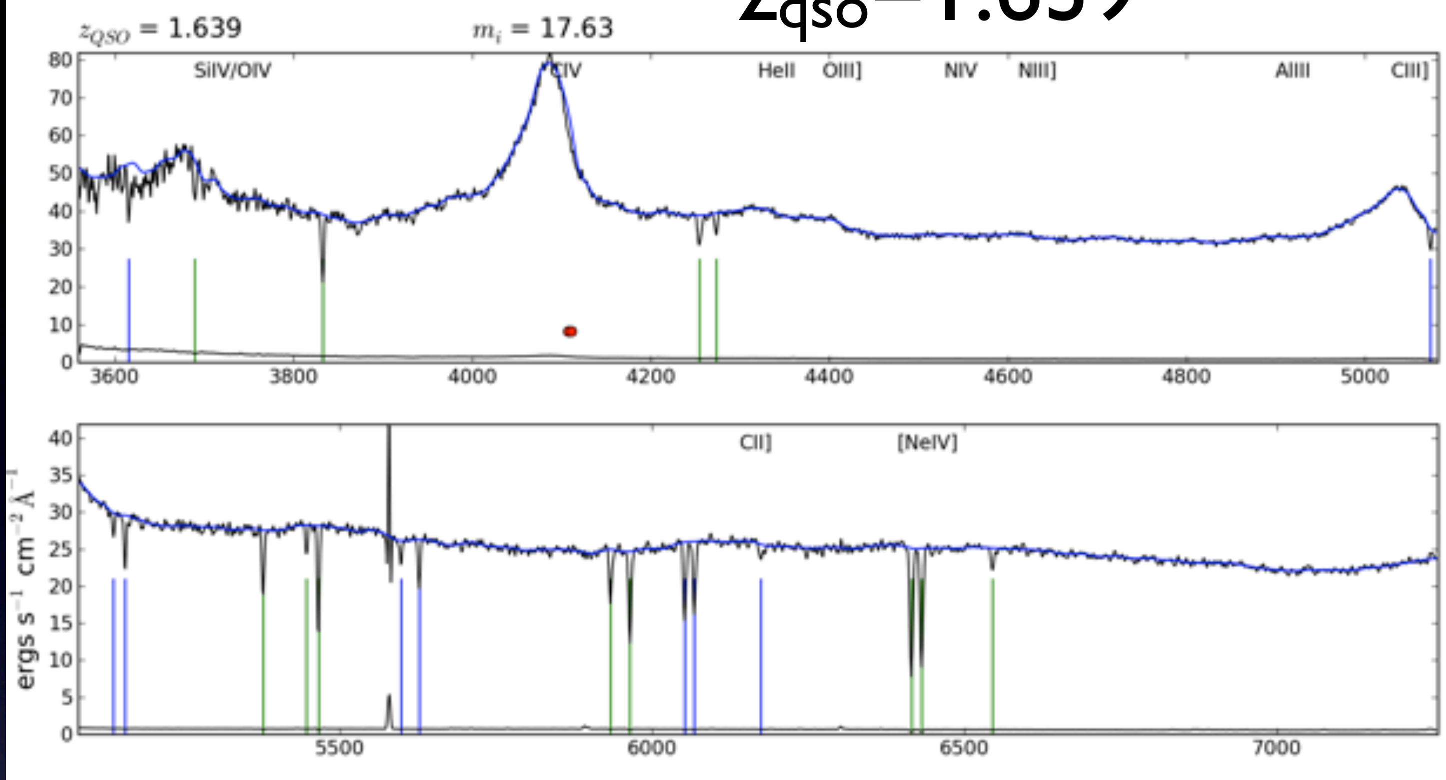
http://www.astro.yale.edu/sdss3/boss/sdss3bl/

Metal absorption line catalogs for the VAC5 quasars - modeled on DR7 database (York et al. 2012, in prep)

BOSS DR10 database now online.. feedback welcome!

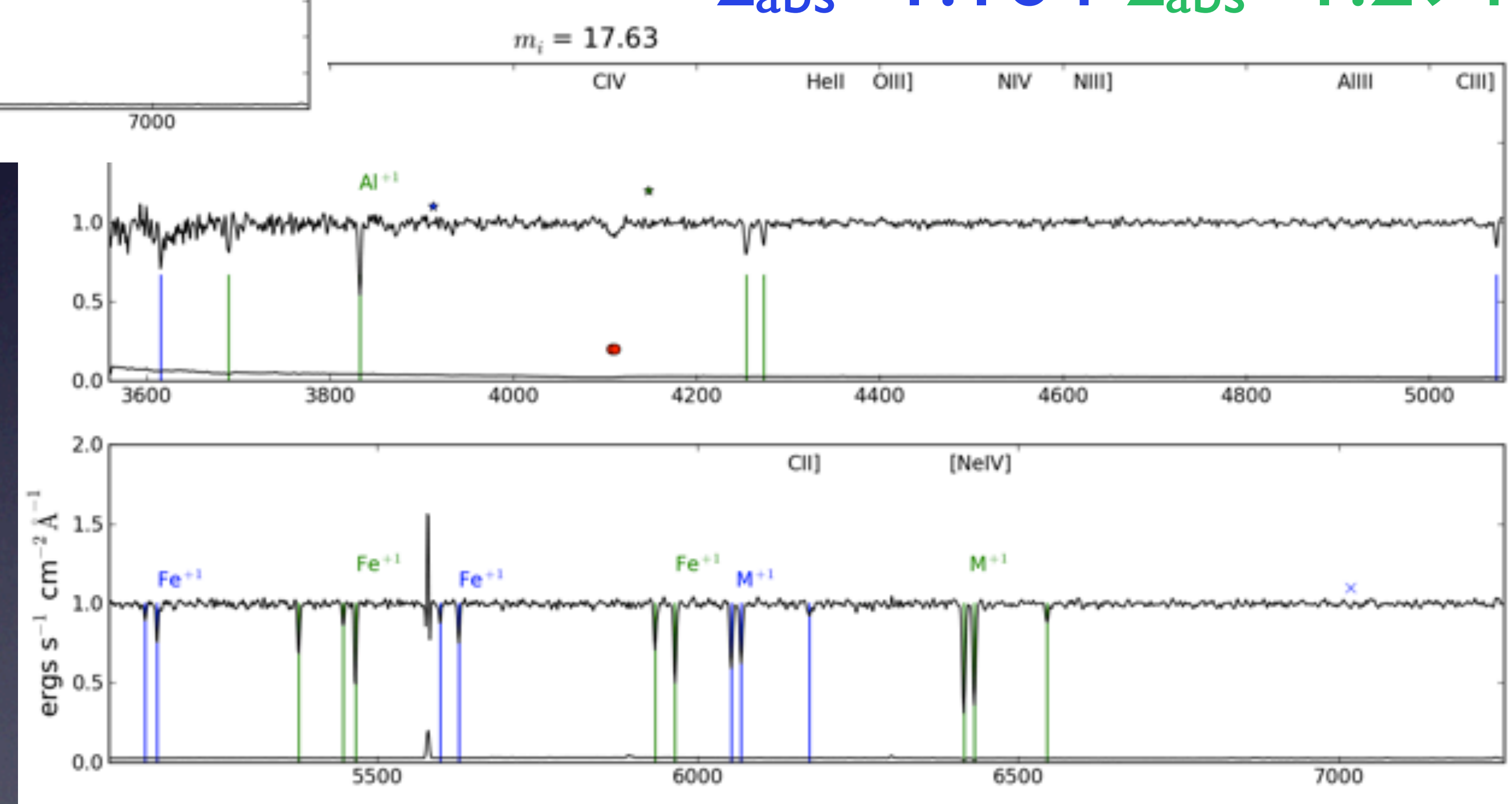


z_{qso}=1.639



Continuum-subtracted spectra and absorption line catalogs for each quasar spectrum

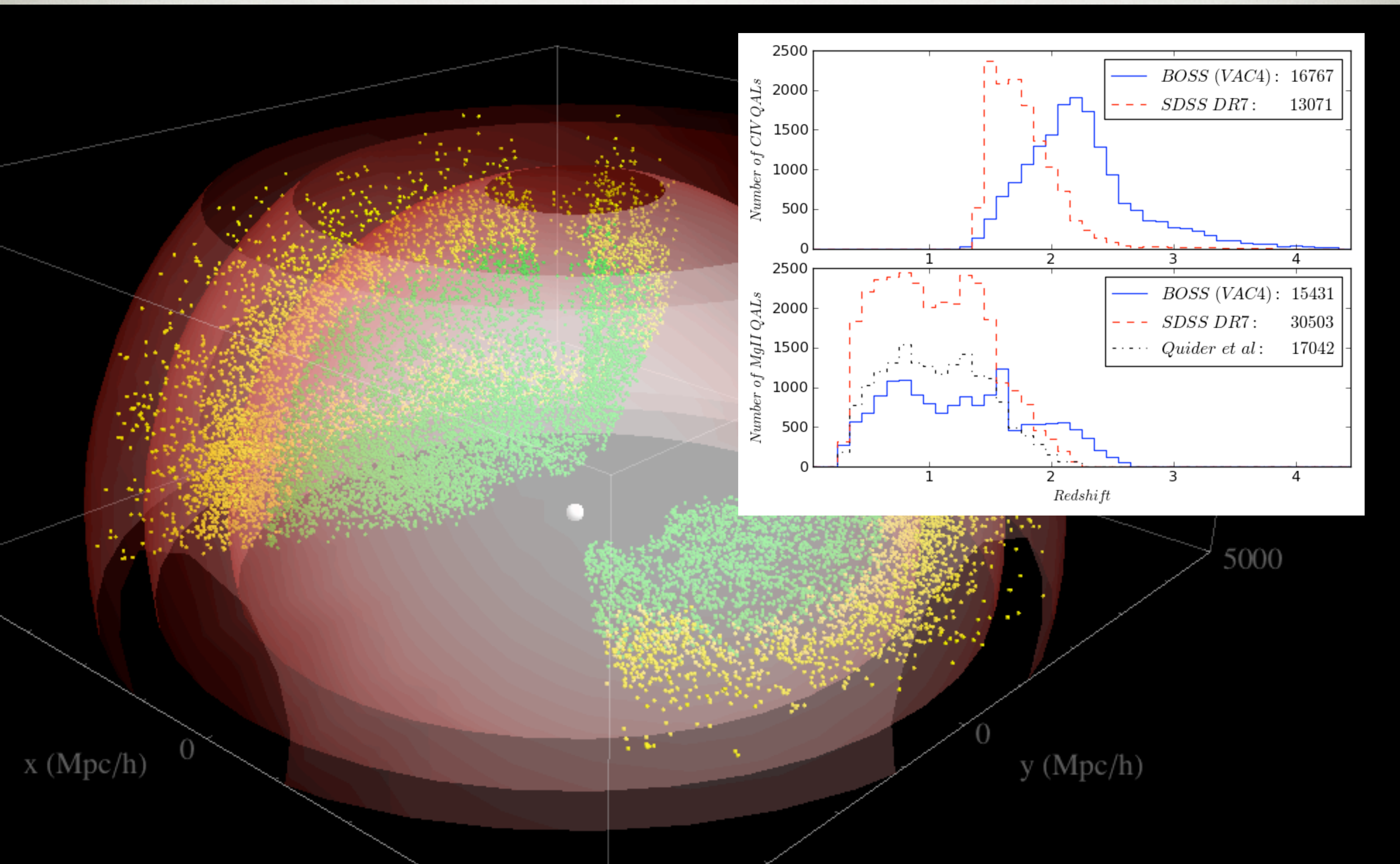
z_{abs}=1.164 z_{abs}=1.294



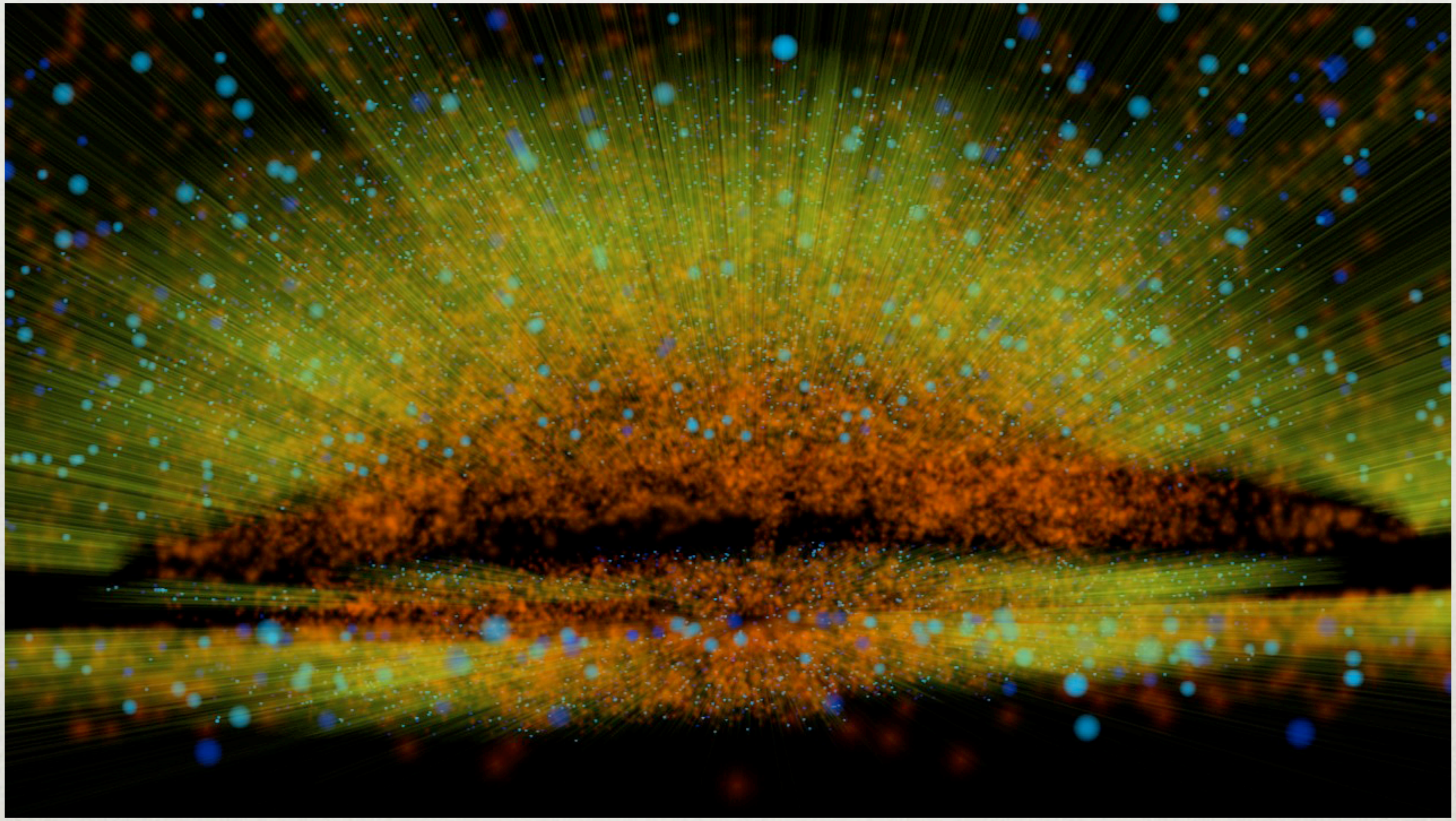

```
1 4070   88  55681 -99.0000 1.6390 17.63   0    0 -99.0 -99.000 -99 -99.000 -27.
2 SDSSJ 999999.99 +999999.9 244.2787 12.4351

3 1.16409 1755.93 4251.21 3.2 A ? ? 0.19584 ?
4 -1.00 0.13 0.08 0.05 0.05 0.06 -1.00 -1.00
5 6052.05  2.166  0.087 2796.4   Mg   II  0   0.00015   -20.52   25.0   4.36 *
5 6067.44  1.963  0.086 2803.5   Mg   II  0   0.00010   -13.70   22.7   4.27 *
5 3615.40  1.064  0.155 1670.8   Al   II  0  -0.00022    29.61    6.8   3.14 *
5 3699.11  0.288  0.091 1709.6   Ni   II  0  -0.00039    51.65    3.2   2.21 0
5 5073.21  0.595  0.051 2344.2   Fe   II  0   0.00003    -4.11   11.8   3.02 *
5 5138.12  0.436  0.072 2374.5   Fe   II  0  -0.00020    26.74    6.0   3.23 *
5 5156.60  1.049  0.070 2382.8   Fe   II  0   0.00001    -1.84   15.0   3.30 *
5 5377.34  1.417  0.073 2484.0   Fe    I  0   0.00066   -88.24   19.5   3.48 0
5 5597.93  0.531  0.064 2586.7   Fe   II  0   0.00005    -6.89    8.3   3.34 *
5 5627.24  1.074  0.061 2600.2   Fe   II  0   0.00007    -9.16   17.7   3.36 *
5 6174.13  0.582  0.122 2853.0   Mg    I  0   0.00000    -0.13    4.8   7.04 *
5 8592.57  0.301  0.097 3969.6   Ca   II  0   0.00049   -65.10    3.1   5.12 0

3 1.29389 1656.57 4010.65 3.2 A ? ? 0.13924 ?
4 -1.00 0.13 0.08 0.05 0.05 0.06 -1.00 -1.00
5 6414.93  4.032  0.077 2796.4   Mg   II  0   0.00012   -15.44   52.6   4.86 *
5 6431.24  3.709  0.076 2803.5   Mg   II  0   0.00007    -8.36   48.9   4.81 *
5 3579.28  0.515  0.123 1560.3    C    I  0   0.00004    -5.47    4.2   2.13 0
5 3689.28  0.794  0.117 1608.5   Fe   II  0  -0.00023    29.25    6.8   3.41 *
5 3832.62  1.605  0.098 1670.8   Al   II  0  -0.00001     1.81   16.4   2.92 *
5 4254.47  1.034  0.086 1854.7   Al  III  0  -0.00005     6.40   12.1   4.49 *
5 4273.28  0.534  0.070 1862.8   Al  III  0   0.00011   -13.74    7.6   2.98 *
5 5377.34  1.417  0.073 2344.2   Fe   II  0  -0.00004     4.52   19.5   3.48 0
5 5446.94  0.629  0.078 2374.5   Fe   II  0   0.00006    -7.17    8.1   3.52 *
5 5465.85  2.303  0.069 2382.8   Fe   II  0  -0.00000     0.32   33.3   3.42 *
5 5933.29  1.350  0.090 2586.7   Fe   II  0  -0.00010    12.89   15.0   3.63 *
5 5964.59  2.407  0.083 2600.2   Fe   II  0   0.00001    -0.97   28.8   3.80 *
5 6544.66  0.703  0.094 2853.0   Mg    I  0   0.00007    -9.49    7.5   4.86 *
5 7436.73  0.247  0.070 3242.9   Ti   II  0  -0.00069    88.69    3.5   4.43 0
5 9027.59  0.771  0.097 3934.8   Ca   II  0   0.00040   -50.80    7.9   5.38 0
5 9866.21  1.256  0.150 4301.5   CH    0  0  -0.00026    33.07    8.4   5.88 0
```

... to be released in parallel with the DR10 Quasar Catalog (Summer 2013)

QAL Detections in the SDSS-III BOSS Survey



3D SDSS Mg II - LRG visualization



- Credit: Mark SubbaRao (Adler Planetarium, Chicago)

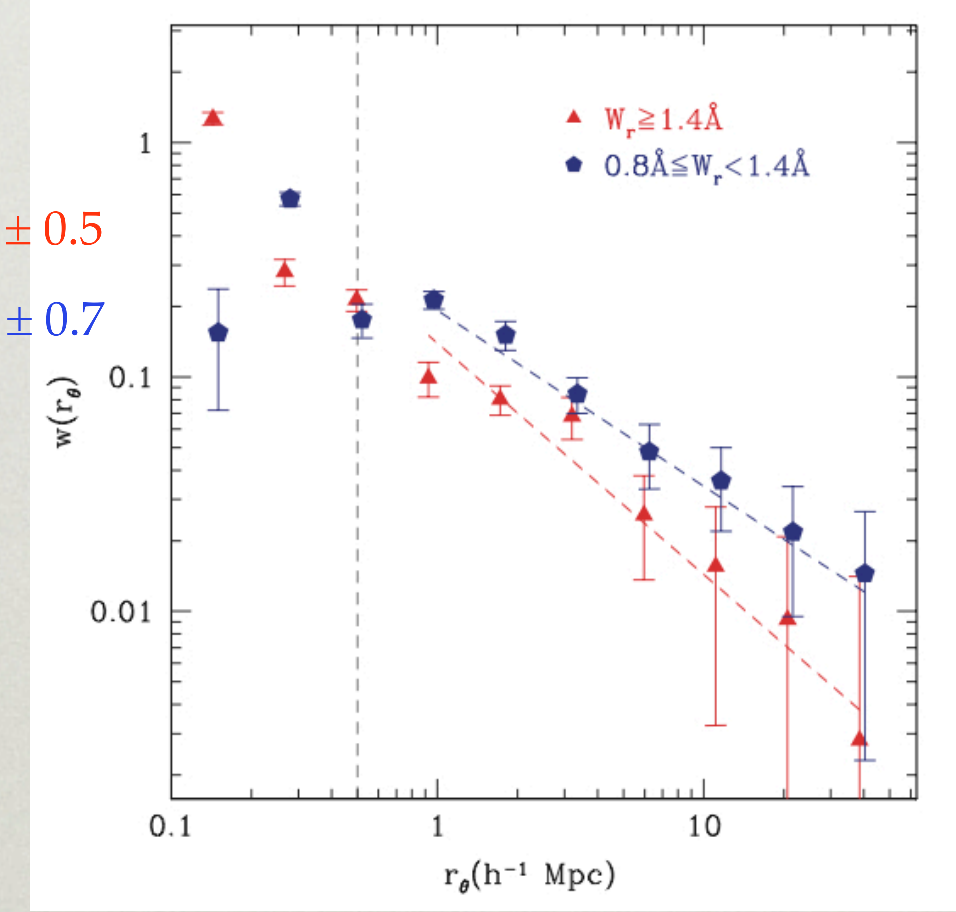
Luminous Red Galaxies vs. MgII Absorbers

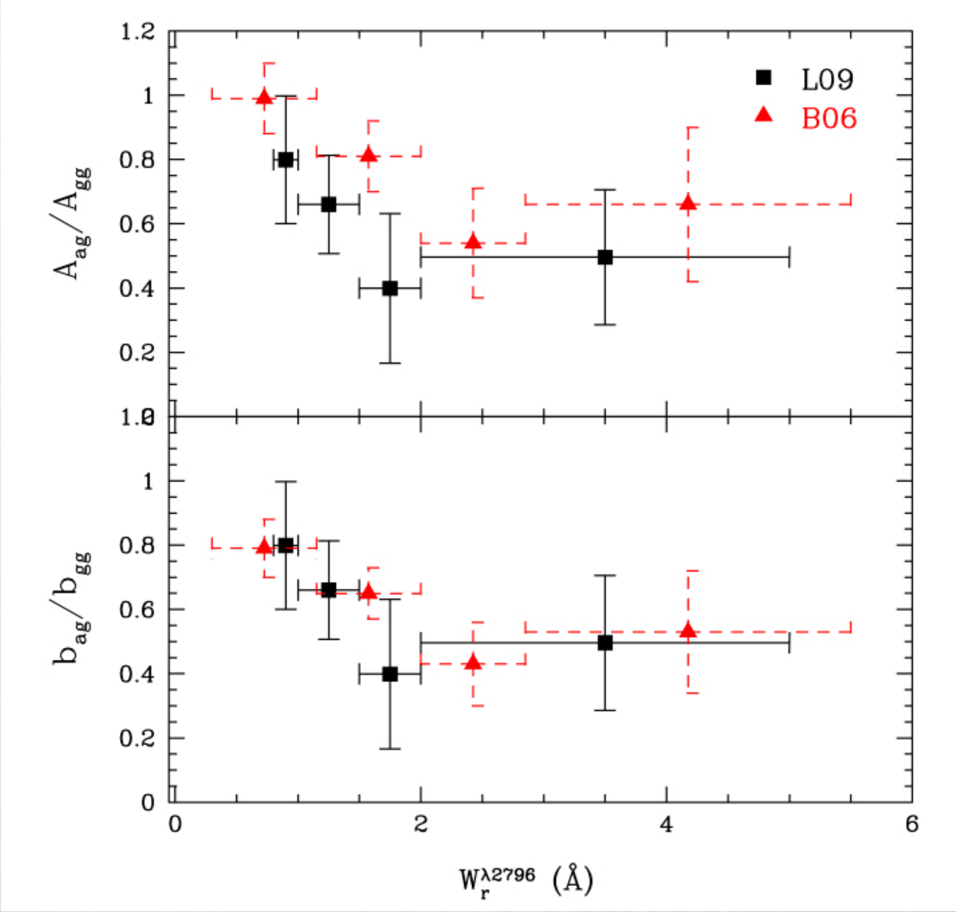
Mg II Dark Matter Halos at z~0.6

- Cross-correlations with LRGs reveal a (weak) anti-correlation between Mg II equivalent width and DM halo mass at z~0.6 (Bouché et al. 2006, Lundgren et al. 2009, Gauthier et al. 2009)

<logM> ~ 11.3 ± 0.5

<logM> ~ 12.7 ± 0.7



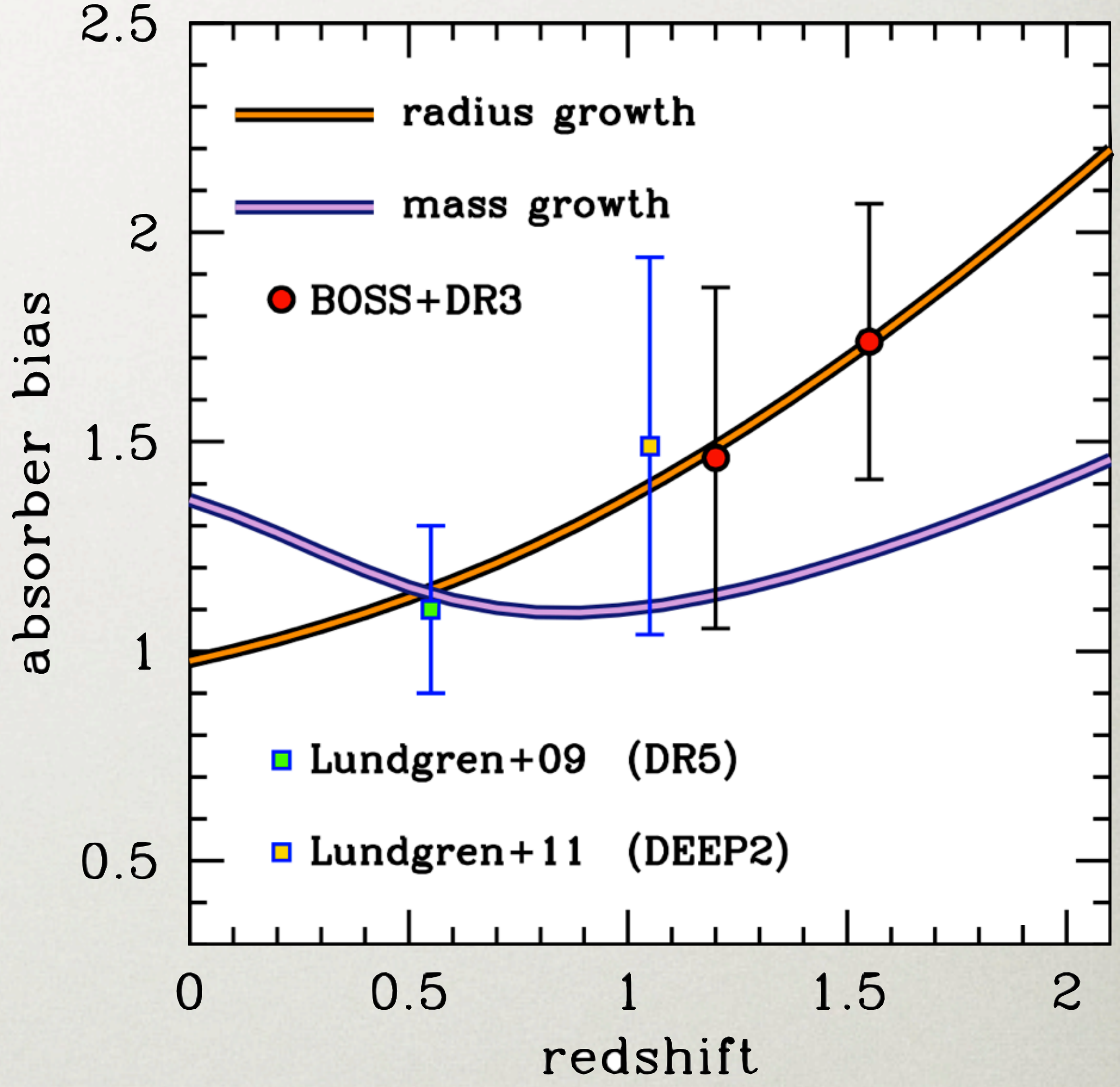


Lundgren et al. 2009

Evolution of Mg II Dark Matter Haloes

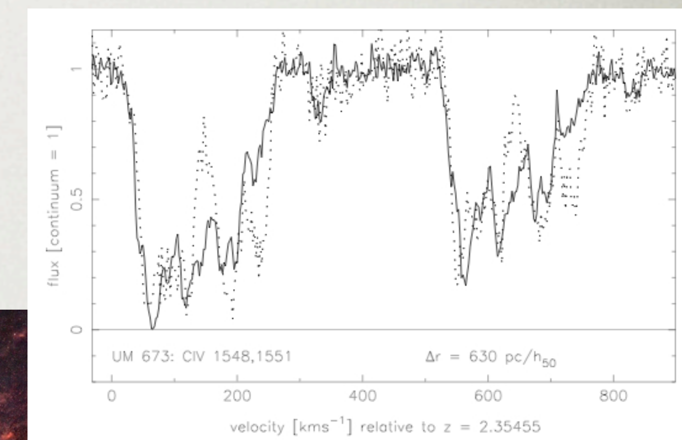
- Clustering can also constrain models of dark matter halo mass and gas radius evolution

- So far, Mg II clustering is consistent with a non-evolving DM halo mass
(Lundgren et al. 2011; Tinker, Lundgren, Wake, et al. in prep.)



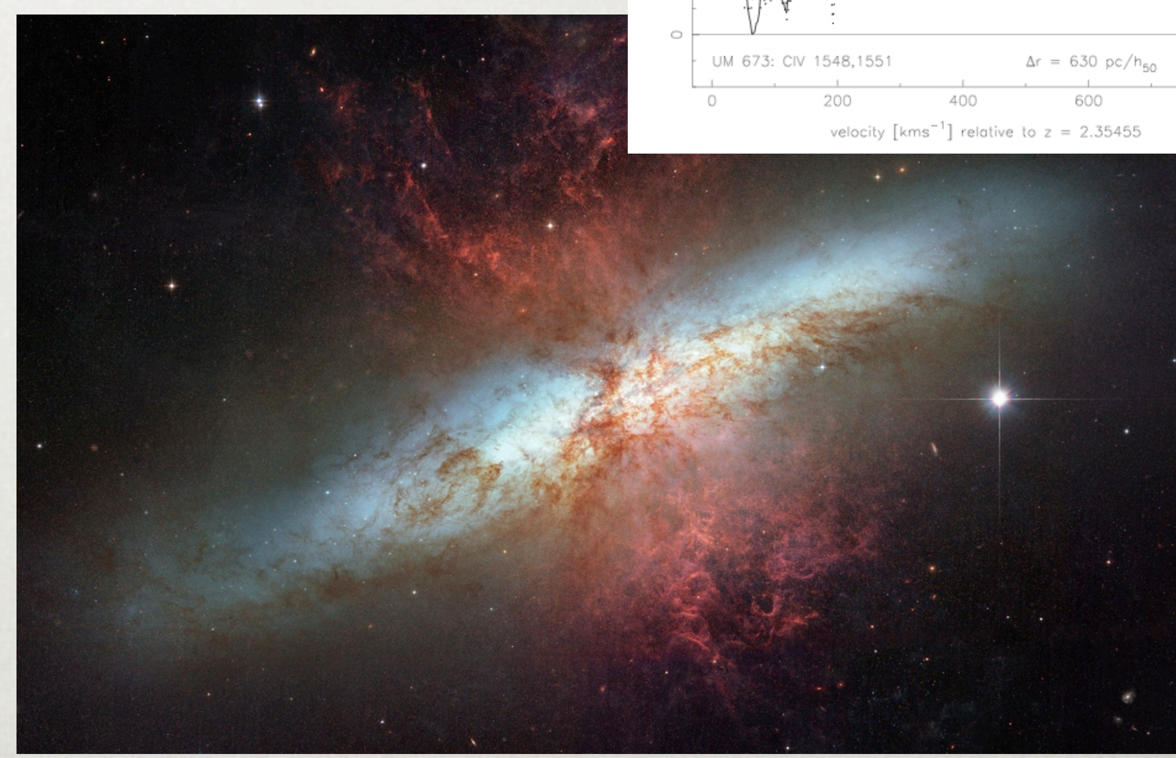
Interpretation of the W - M Anti-Correlation

- If not virialized gas in massive halos, then what's producing the large widths in these multi-component absorbers?



Super-winds from star formation?

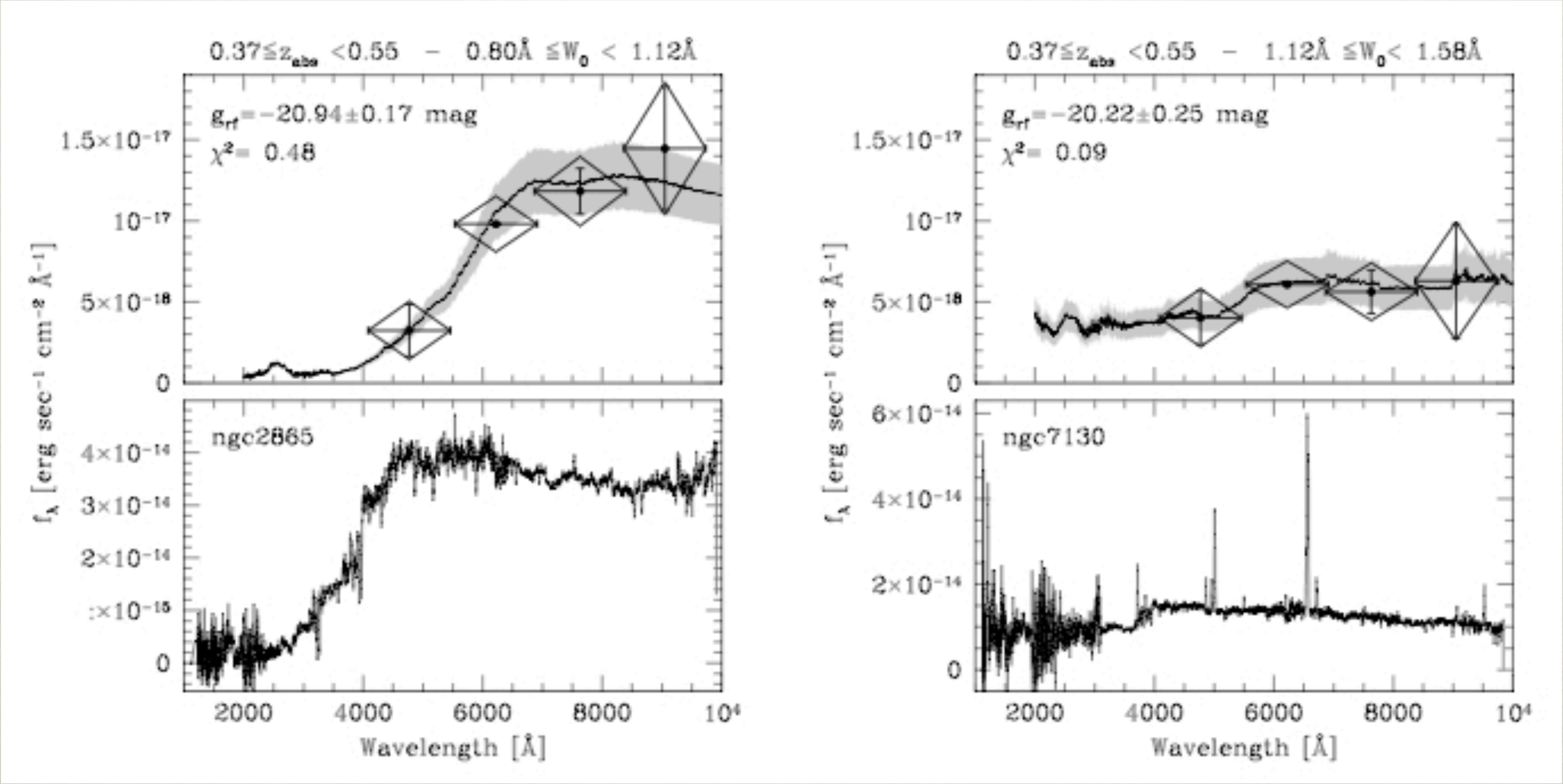
(Prochter et al. 2006; Bouche et al. 2006; Murphy et al. 2007; Nestor et al. 2010)



- Trend only observed at high-z
    - observational bias?
    - galaxy evolution?

Mg II Absorbers as Tracers of Star Formation

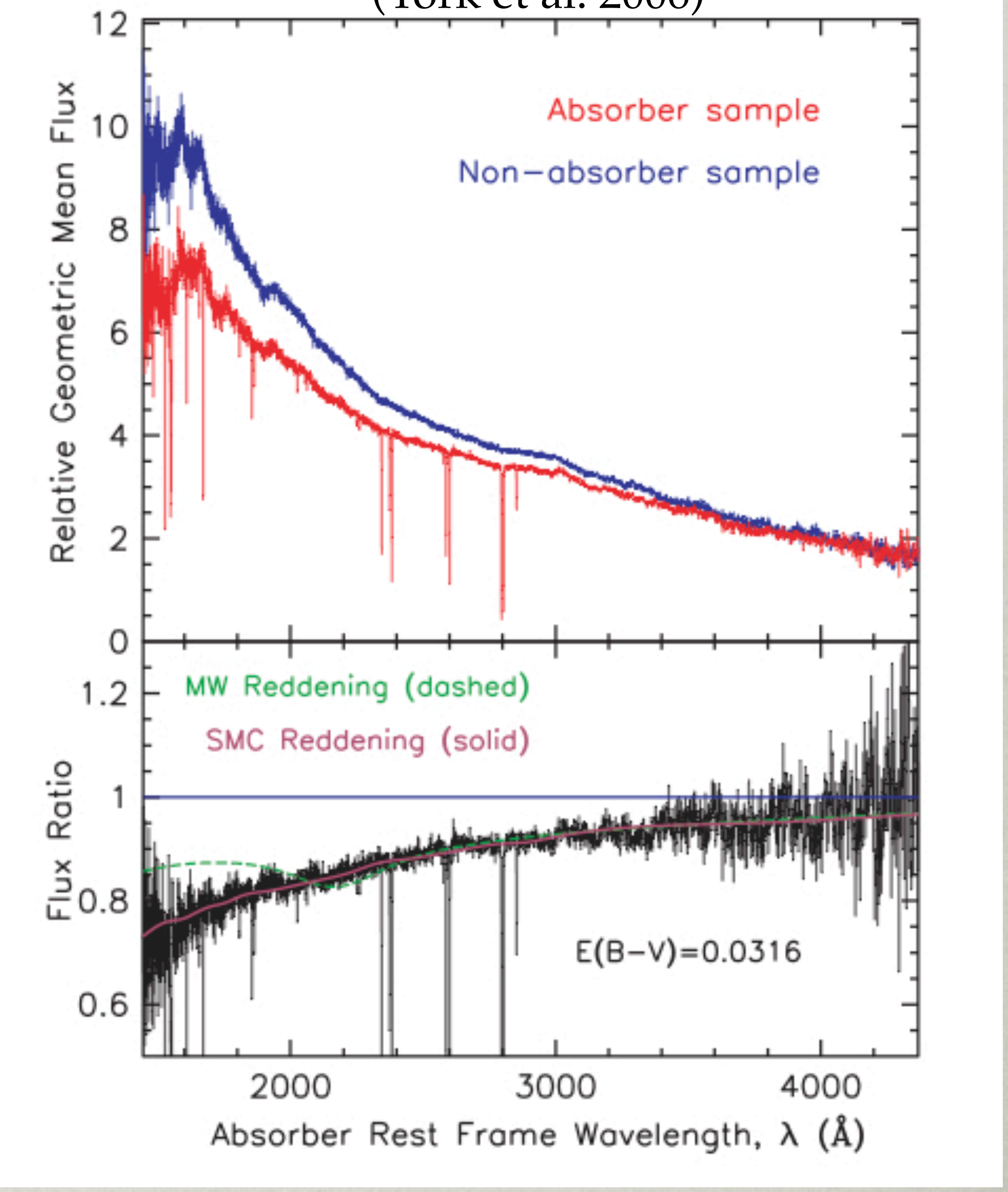
- MgII EW correlated with star-formation? (Zibetti et al. 2005)



Mg II Absorbers as Tracers of Star Formation

- Quasar sight lines with Mg II intervening absorption found to contain dust

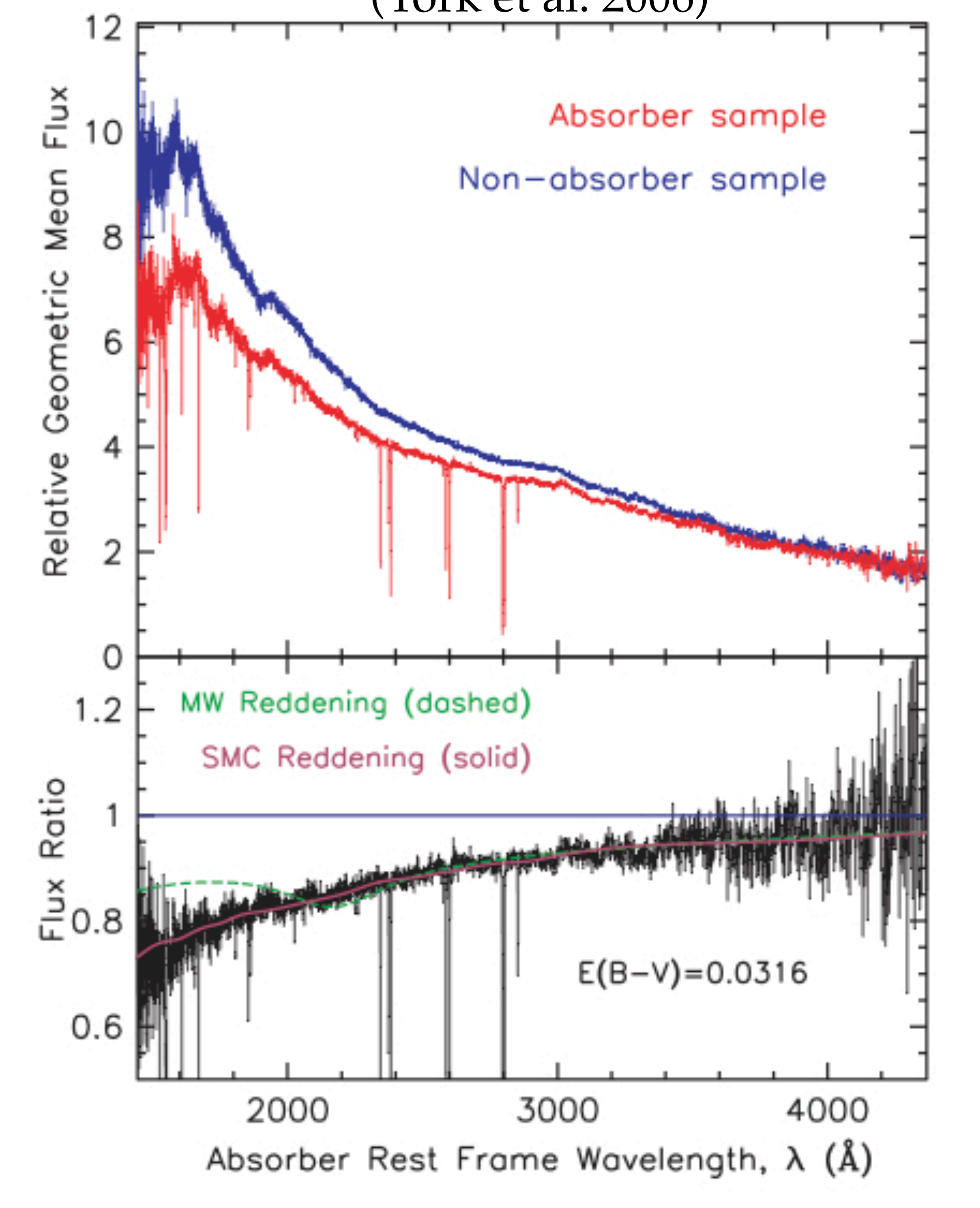
(York et al. 2006)



Mg II Absorbers as Tracers of Star Formation

- Quasar sight lines with Mg II intervening absorption found to contain dust
- Dust content, [OII] emission found to increase with Mg II equivalent width

(York et al. 2006)



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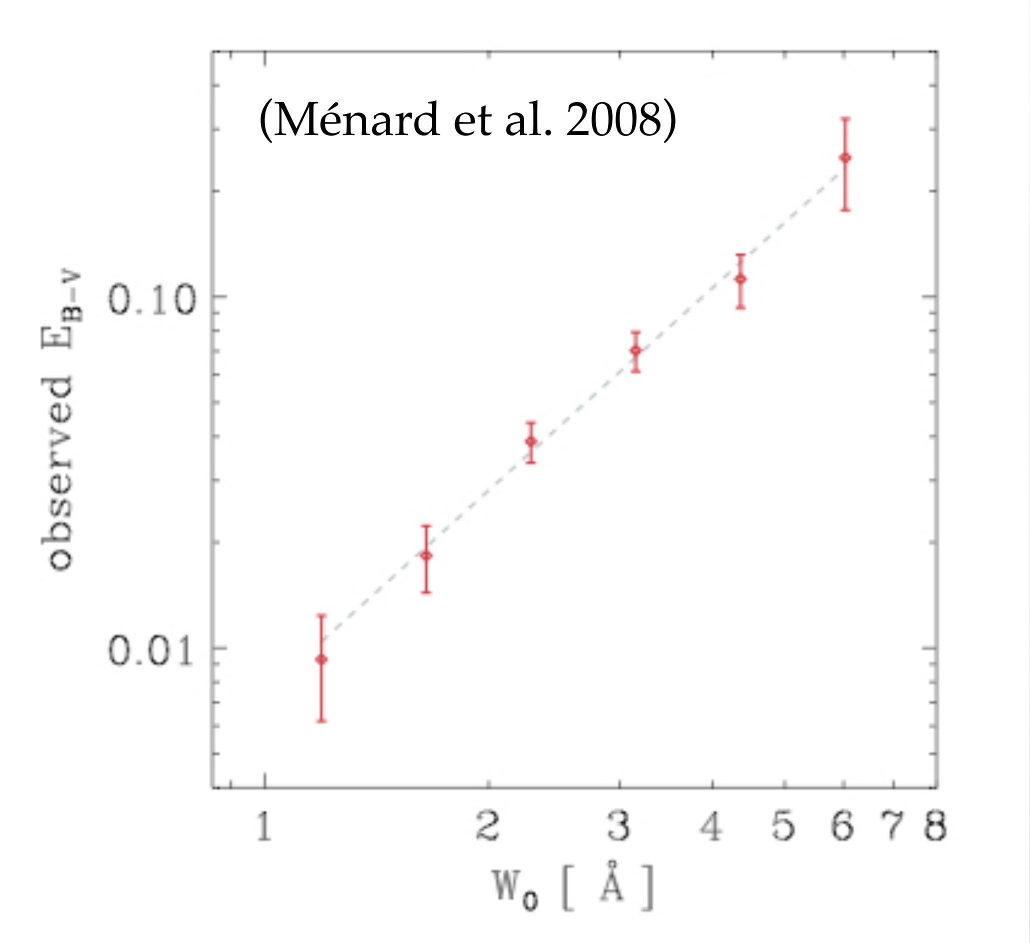

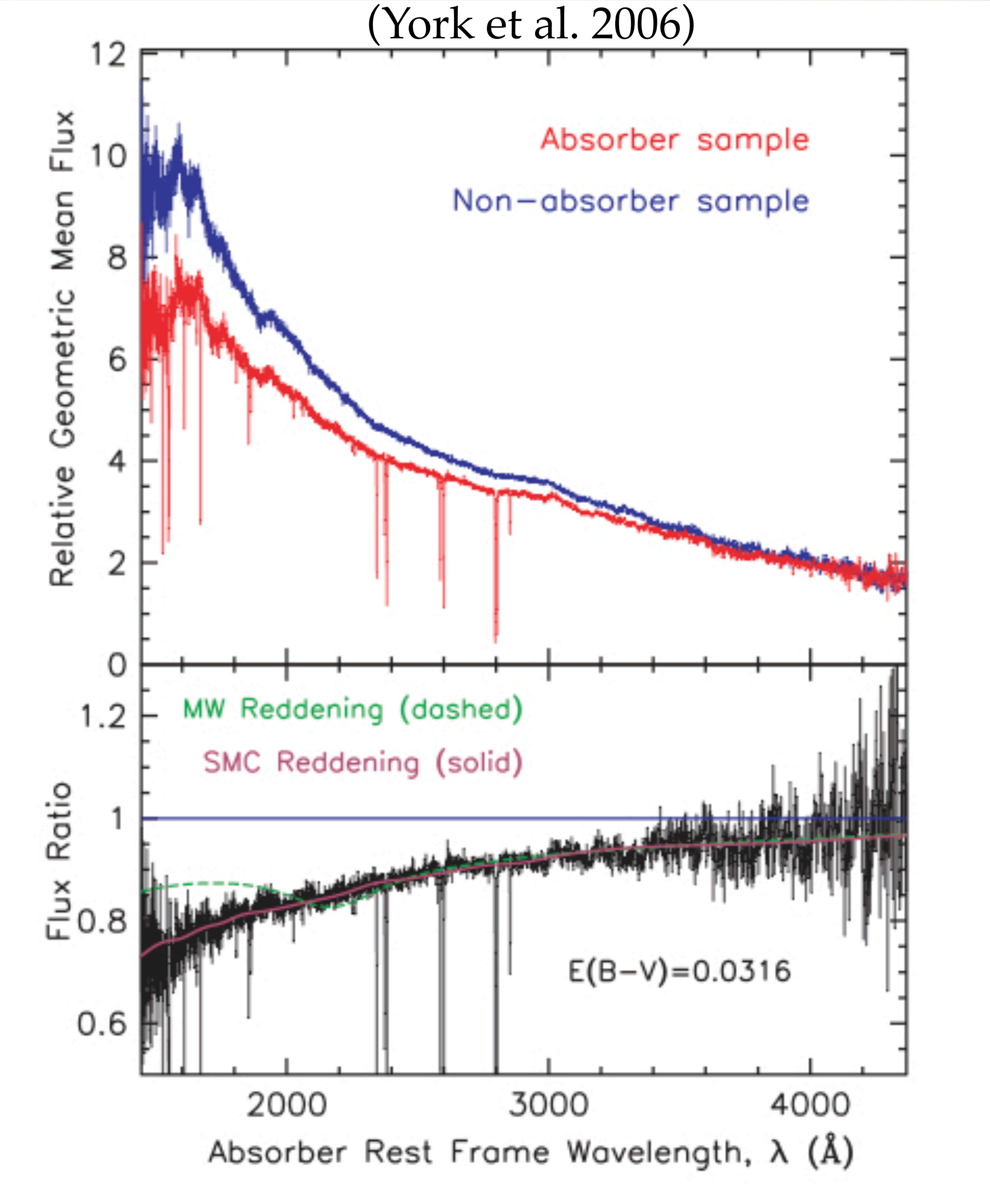

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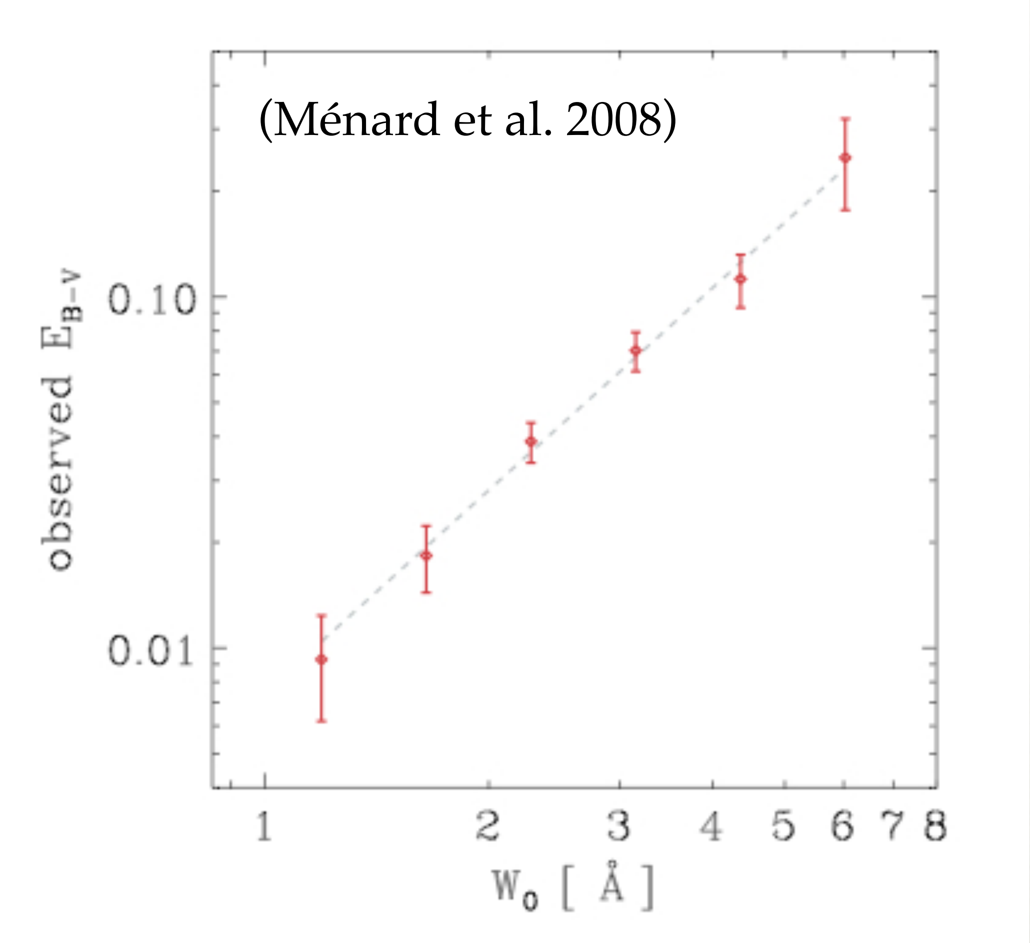
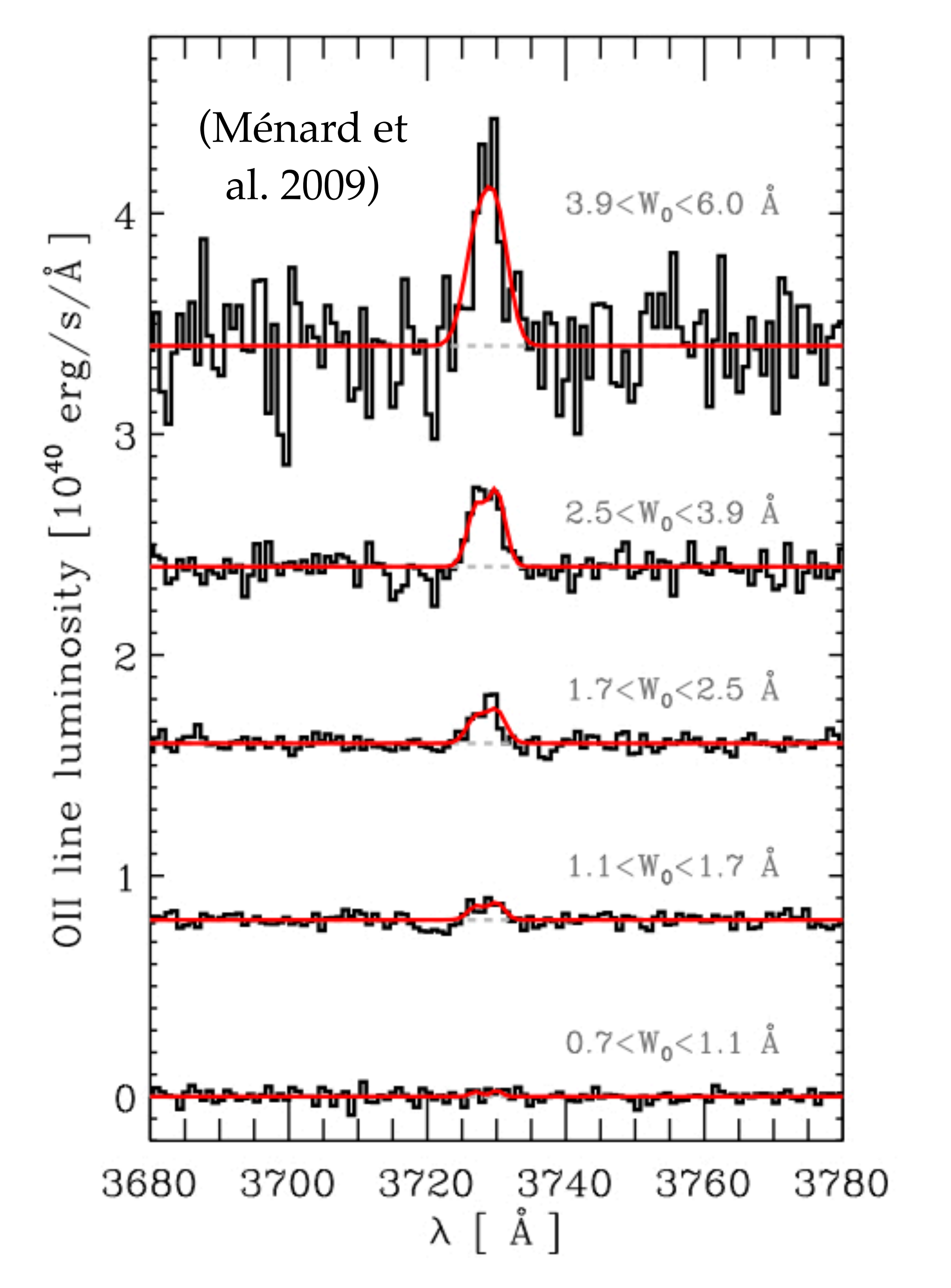
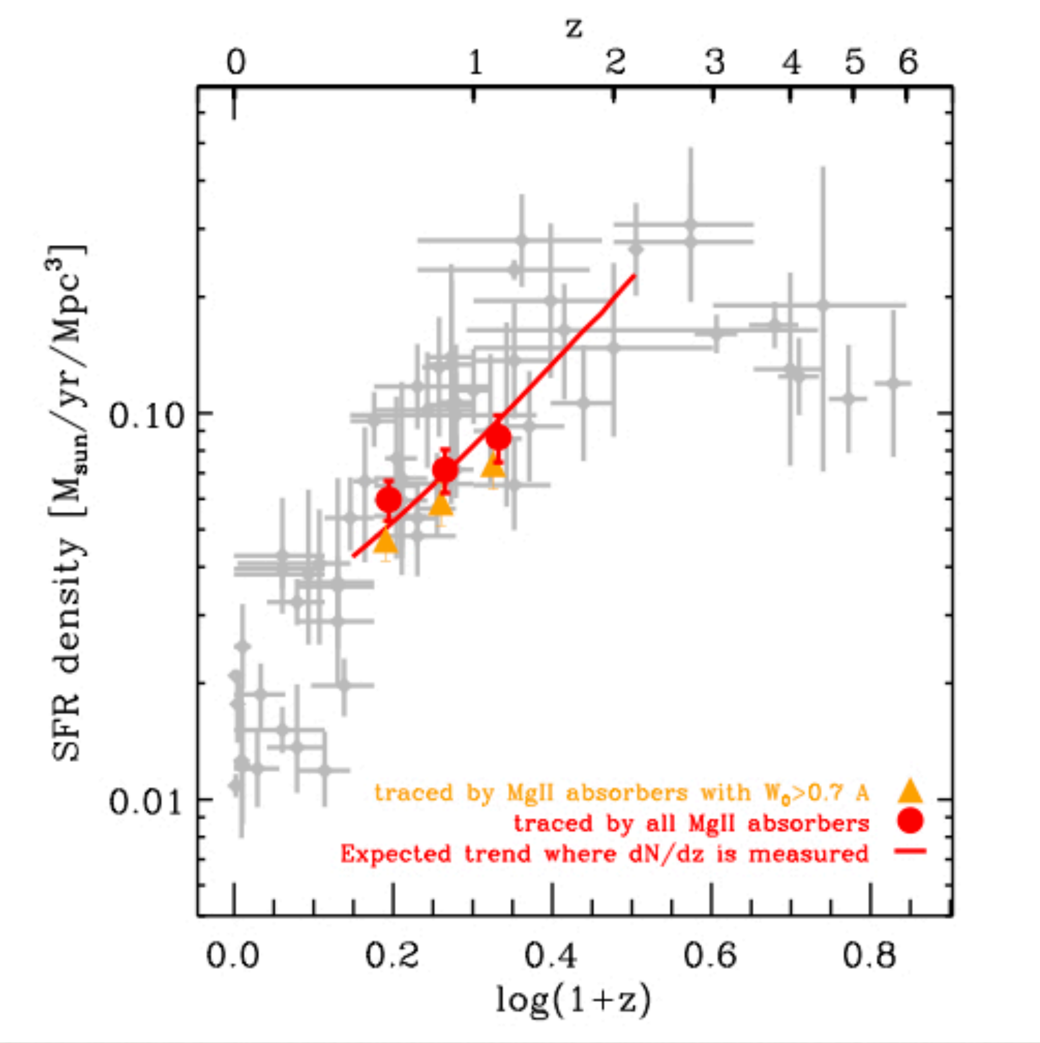




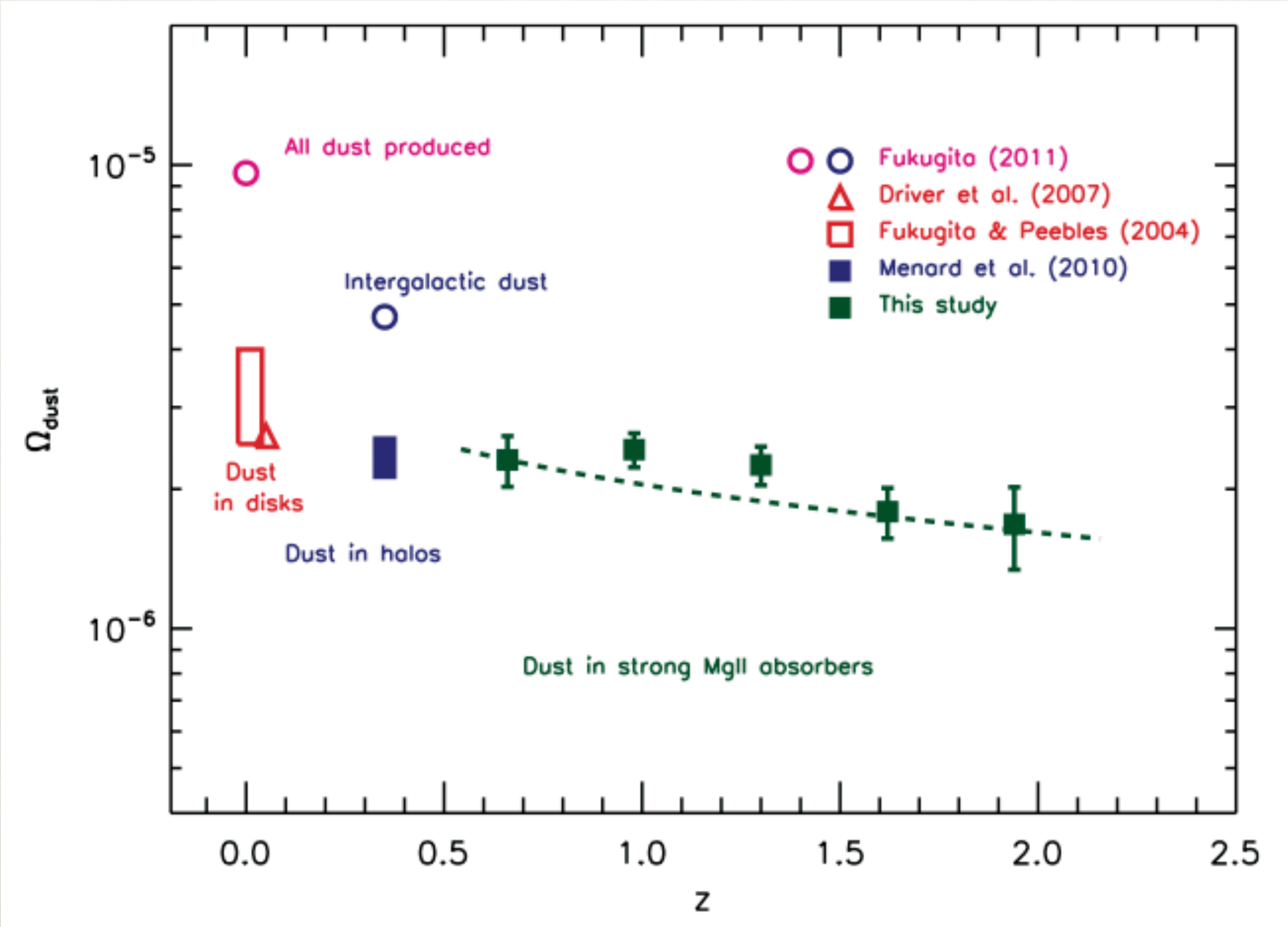
Mg II Absorbers as Tracers of Star Formation

The [OII] luminosity function predicted from dNdW/dz of MgII absorbers traces the global star formation history (Ménard et al. 2009)



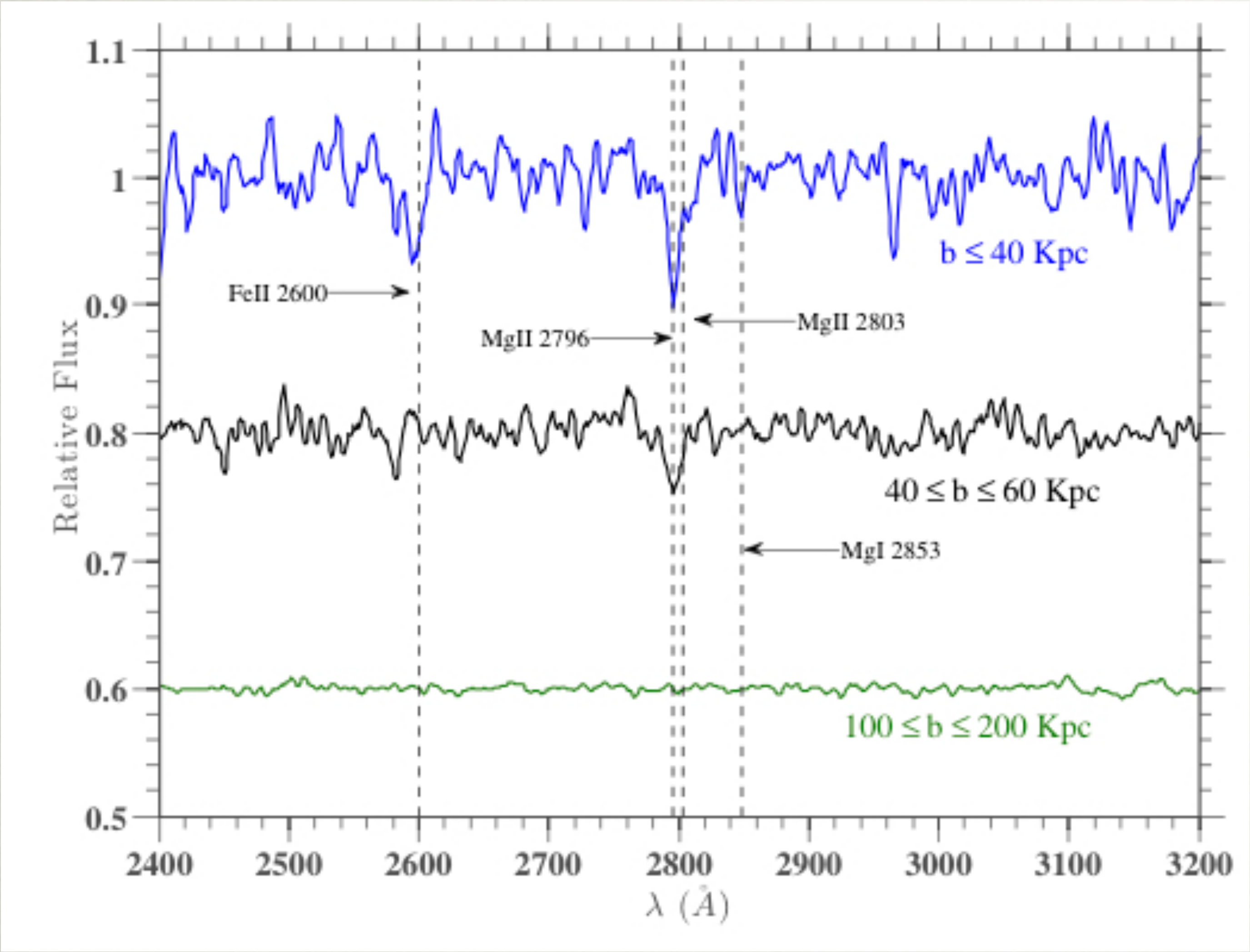
“Smoking Gun” Evidence of Outflows?

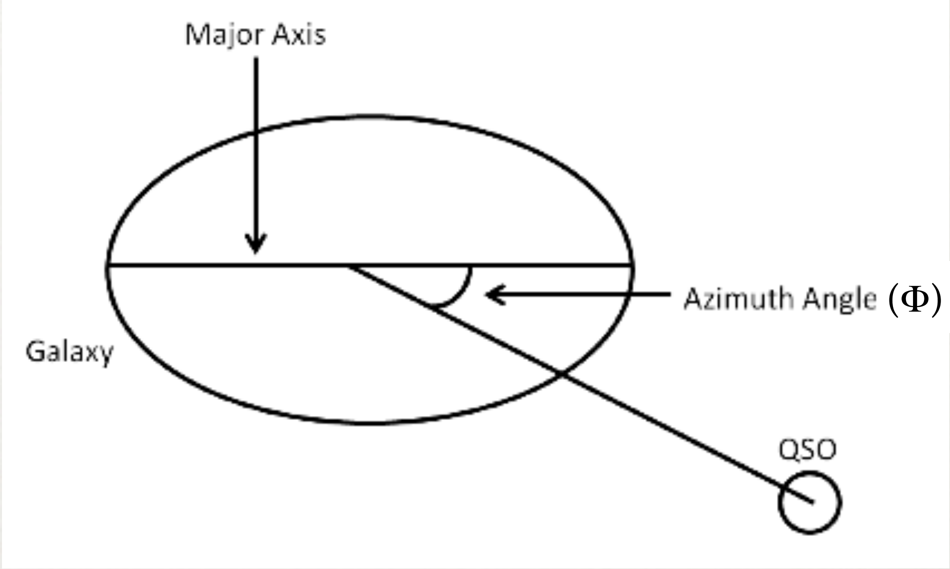
- Mg II absorbers can account for as much as 50% of the dust expelled from galaxies (Ménard & Fukugita 2012)

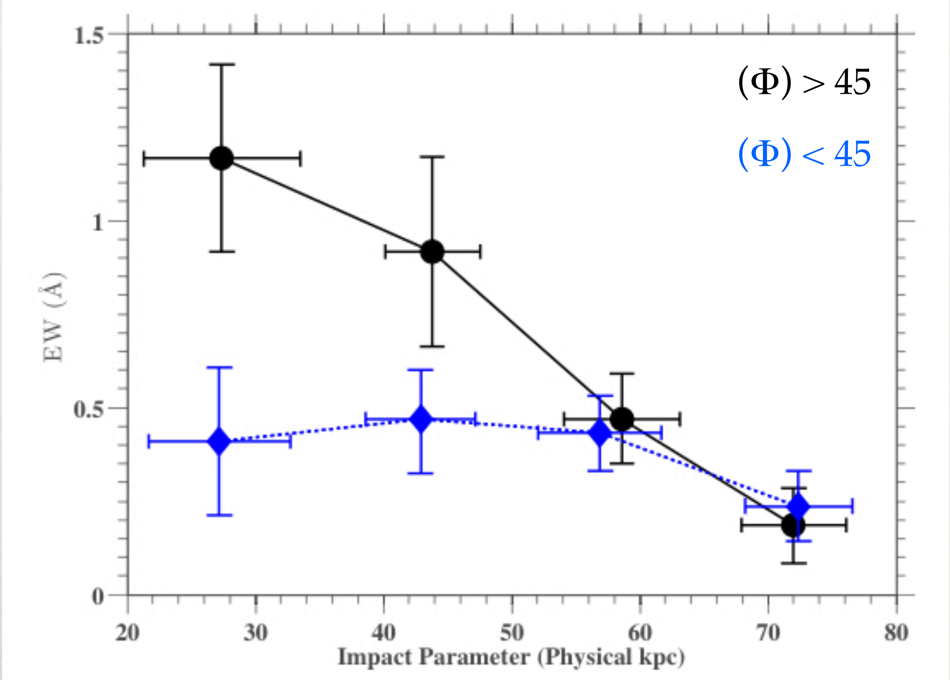


"Smoking Gun" Evidence of Outflows?

- Absorption stacks from galaxies probing 4,000 galaxies in zCOSMOS (Bordoloi et al. 2011)

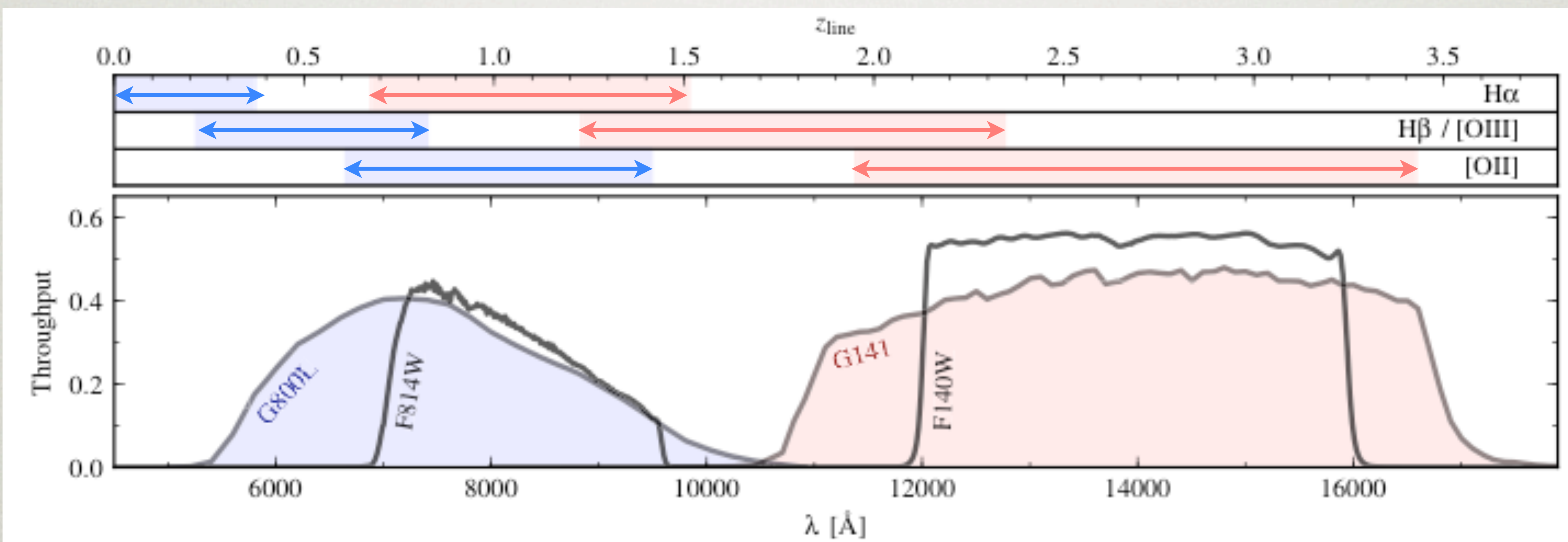






Direct Observations of Mg II Host galaxies

- **3D-HST Survey** (van Dokkum et al. 2011; Brammer et al. 2012)
  - 248 Orbit HST Program
  - WFC3 (G141 grism and F140W direct) and ACS (G800 grism and F814W)
  - 600 arcmin^2; ~10,000 galaxy redshifts at $1 < z < 3$; $\Delta z/(1+z) \sim 0.4\%$



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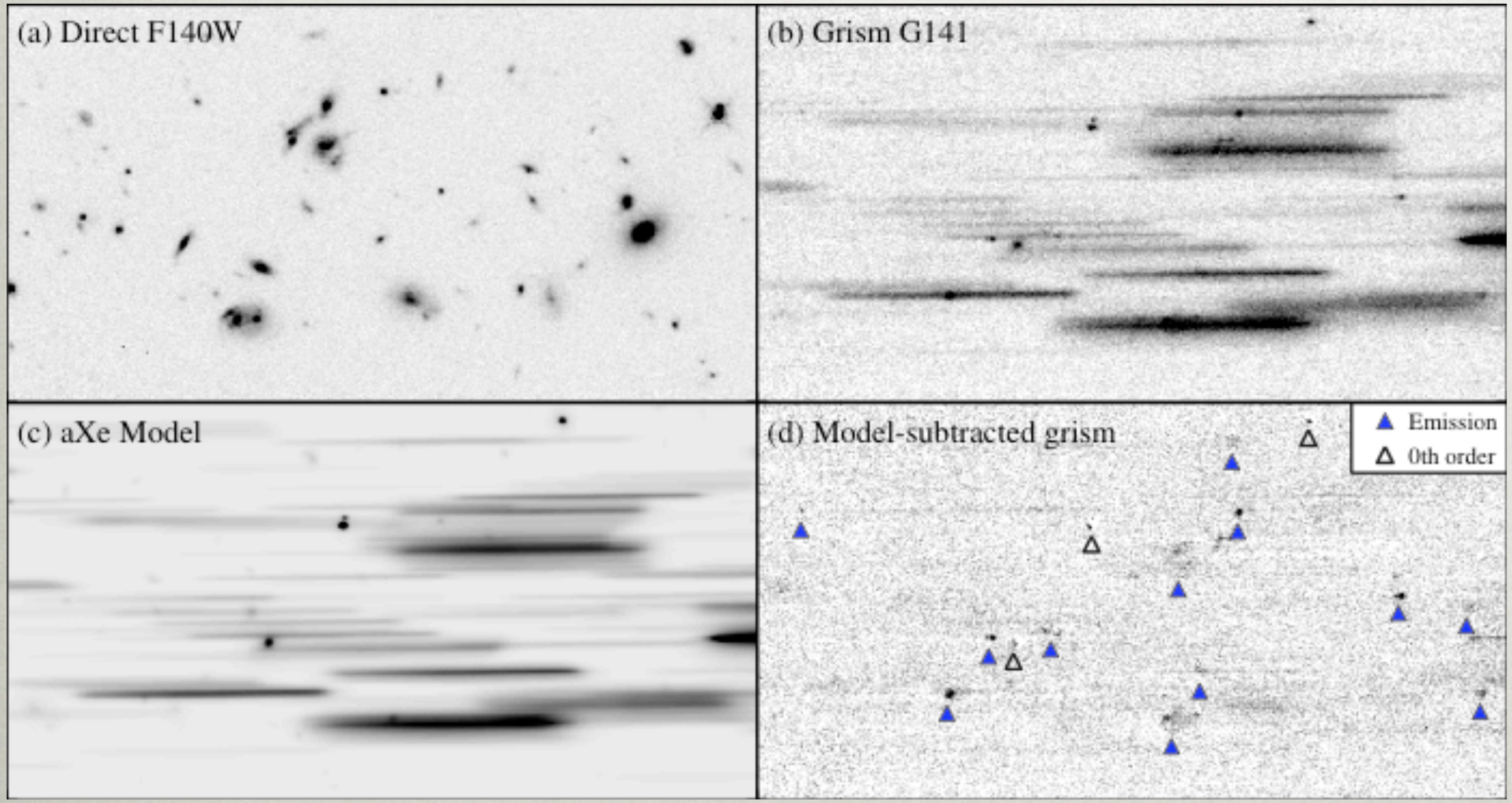
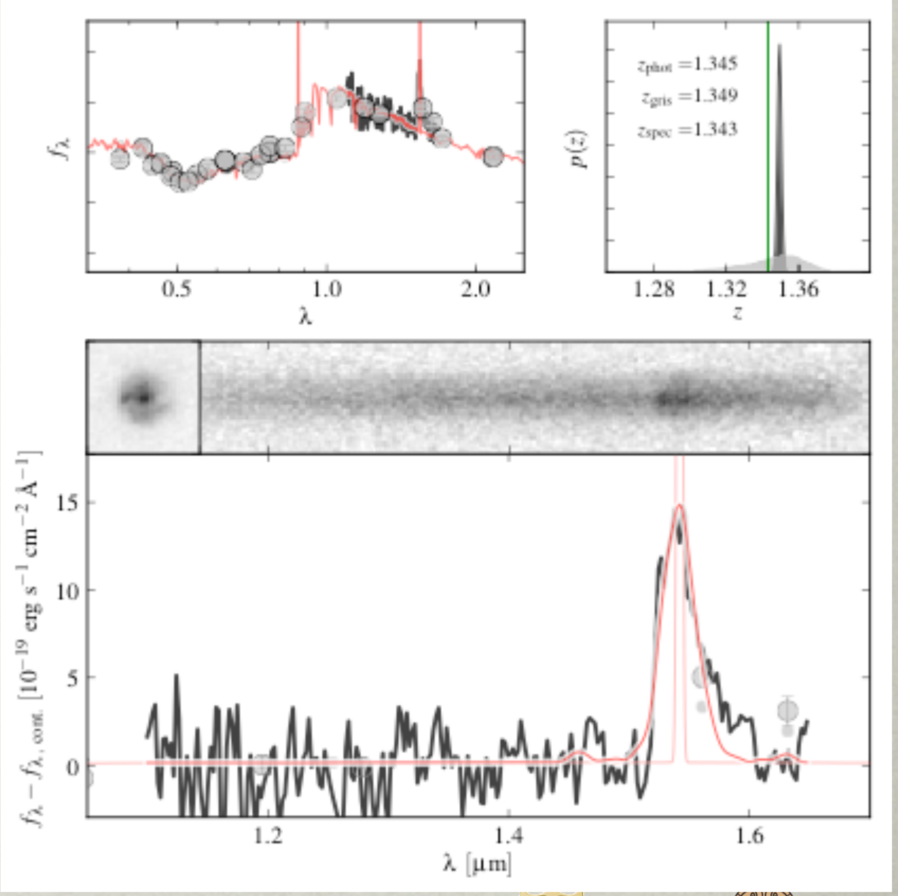
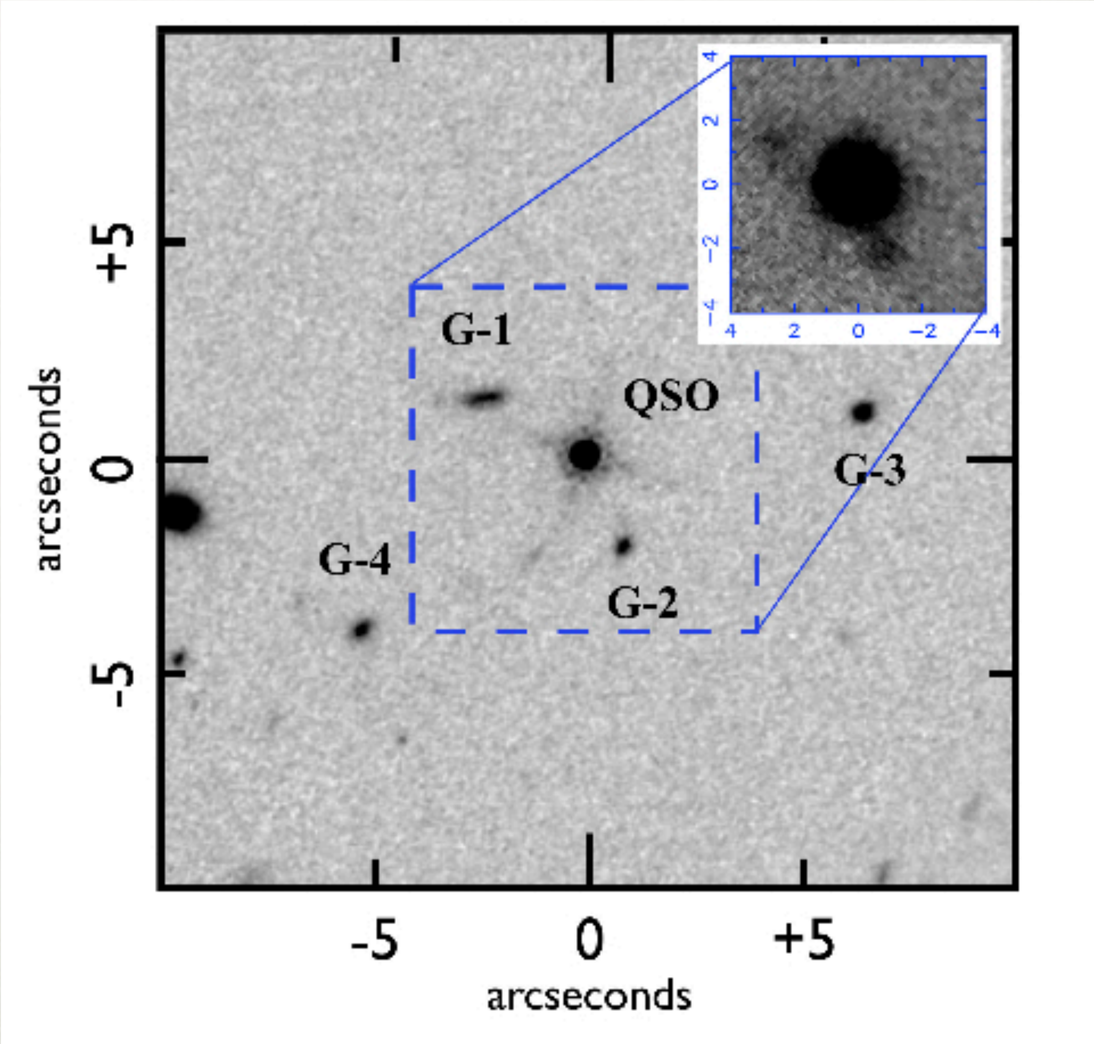




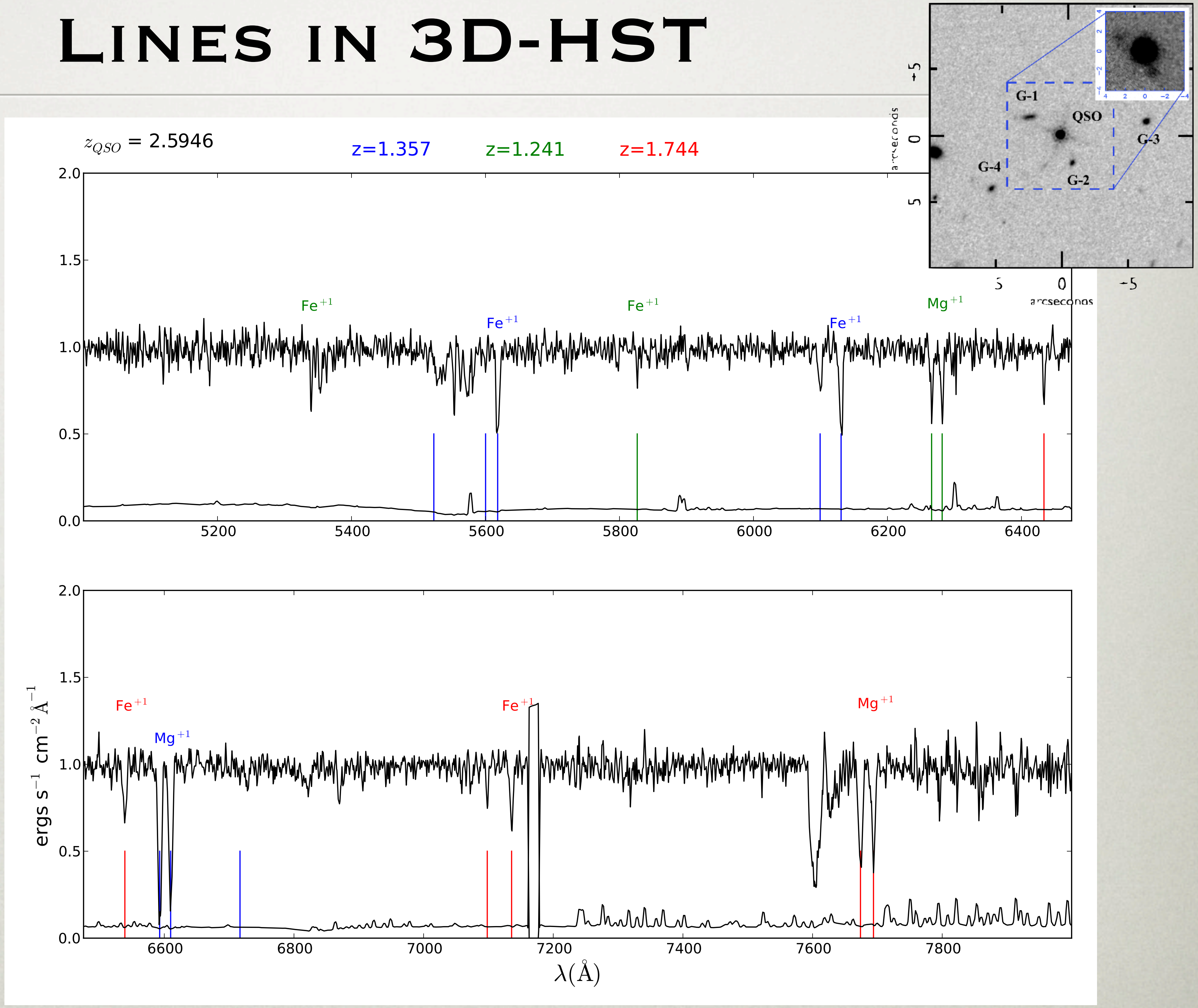
WFC3/IR Grism Observations of Mg II host galaxies at z > 1

- Advantages of HST grism data for QAL science:
  - high sensitivity, resolving power
  - capable of resolving faint galaxies in close proximity to quasar sight lines
  - large FOV for this depth



WFC3 F140W imaging of a quasar sight line in the GOODS-N grism program (Weiner et al., in prep); Team Keck Redshift Survey R-band image inset (Wirth et al. 2004)

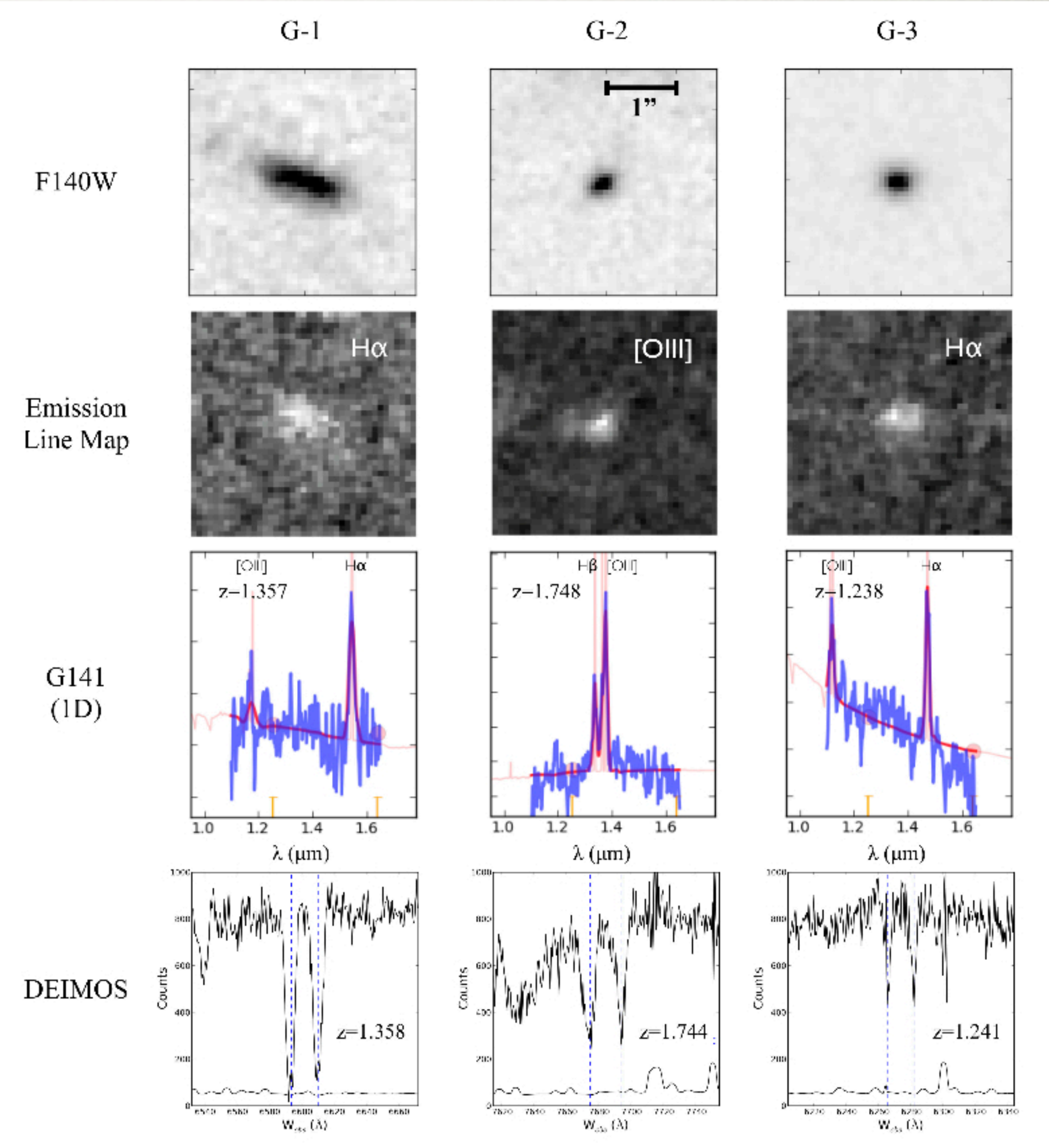
Census of Quasar Absorption Lines in 3D-HST



- A census of quasar absorption lines with W > 0.4Å in the KTRS DEIMOS spectrum reveals three strong (W_r > 0.8Å) multi-ion Mg II systems in the range 1 < z < 2

WFC3/IR Grism Observations of High-z Mg II host galaxies

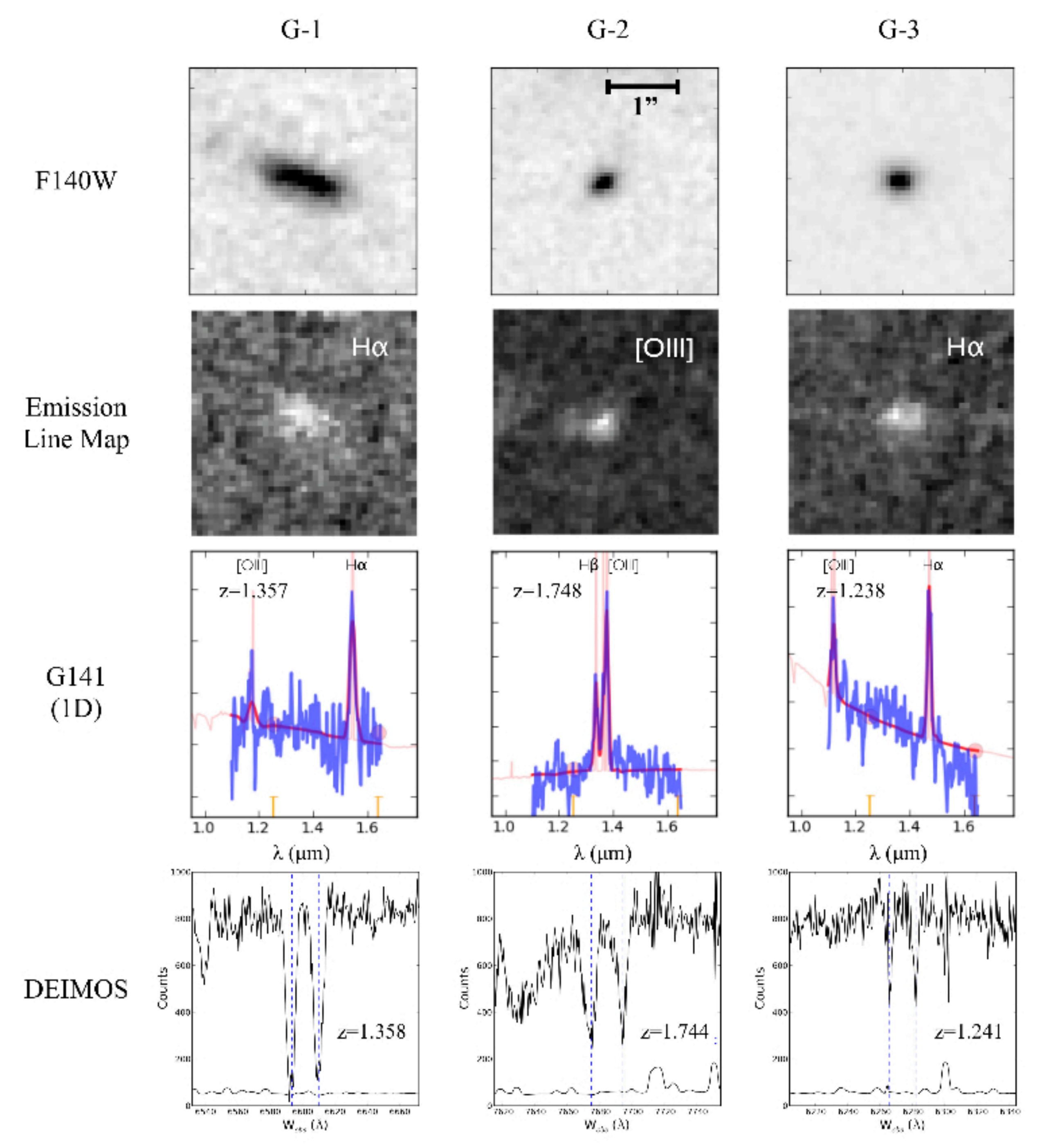
- Each identified Mg II absorption system matches to **an isolated galaxy at 1 < z < 2 identified with 3D-HST G141 grism observations with:**
    - **$\Delta z<0.004$**
    - **$20 < \rho$ (kpc) < 60**
- The spatial extent of line emission rules out a dominant contribution from an AGN



Lundgren et al. 2012

WFC3/IR Grism Observations of High-z Mg II host galaxies

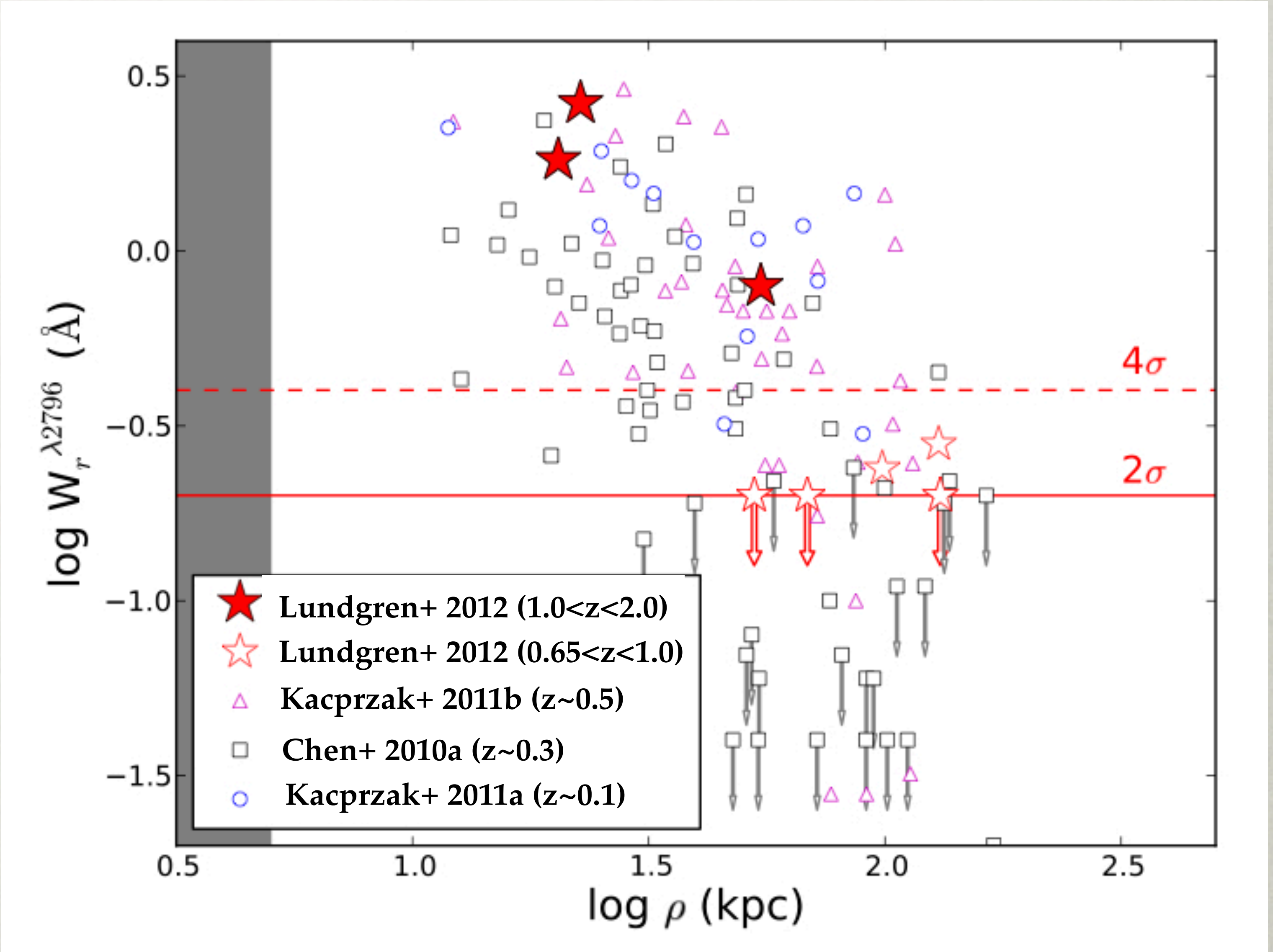
- <u>Properties of the Mg II host galaxies:</u>
  - log (M/M☉) ~ 9.75
  - SFRs > 5 M☉ / yr
  - ΣSFRs > 0.3 M☉ / yr / kpc^2
    consistent with local starbursts and LBGs, sufficient to launch large-scale winds
  - Evidence for SF-driven outflows reaching distances of at least 60 kpc around galaxies
  - Suggests prolonged SF over > 150 Myr



Lundgren et al. 2012

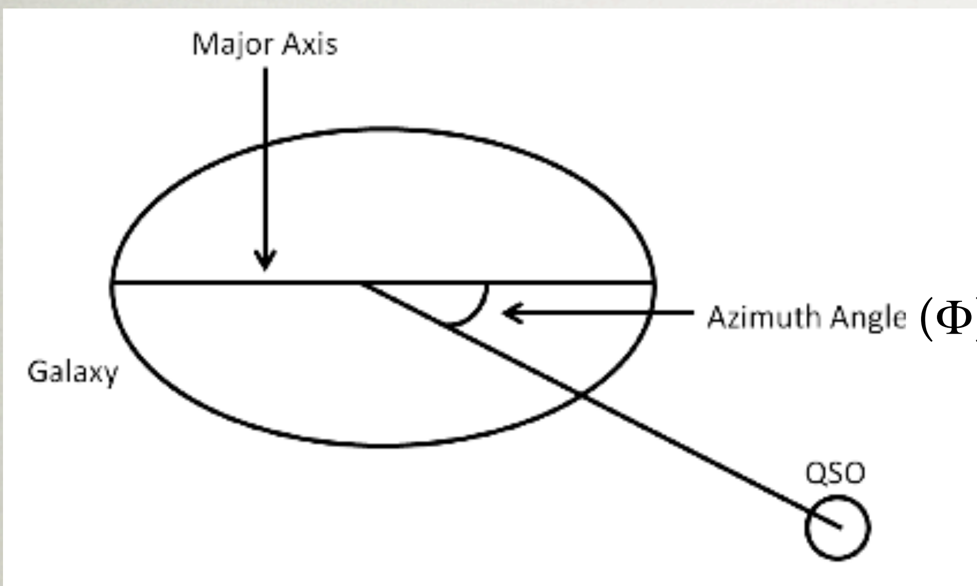
WFC3/IR Grism Observations of High-z Mg II host galaxies

- The data indicate no strong evolution in the W-ϱ relation from z~2



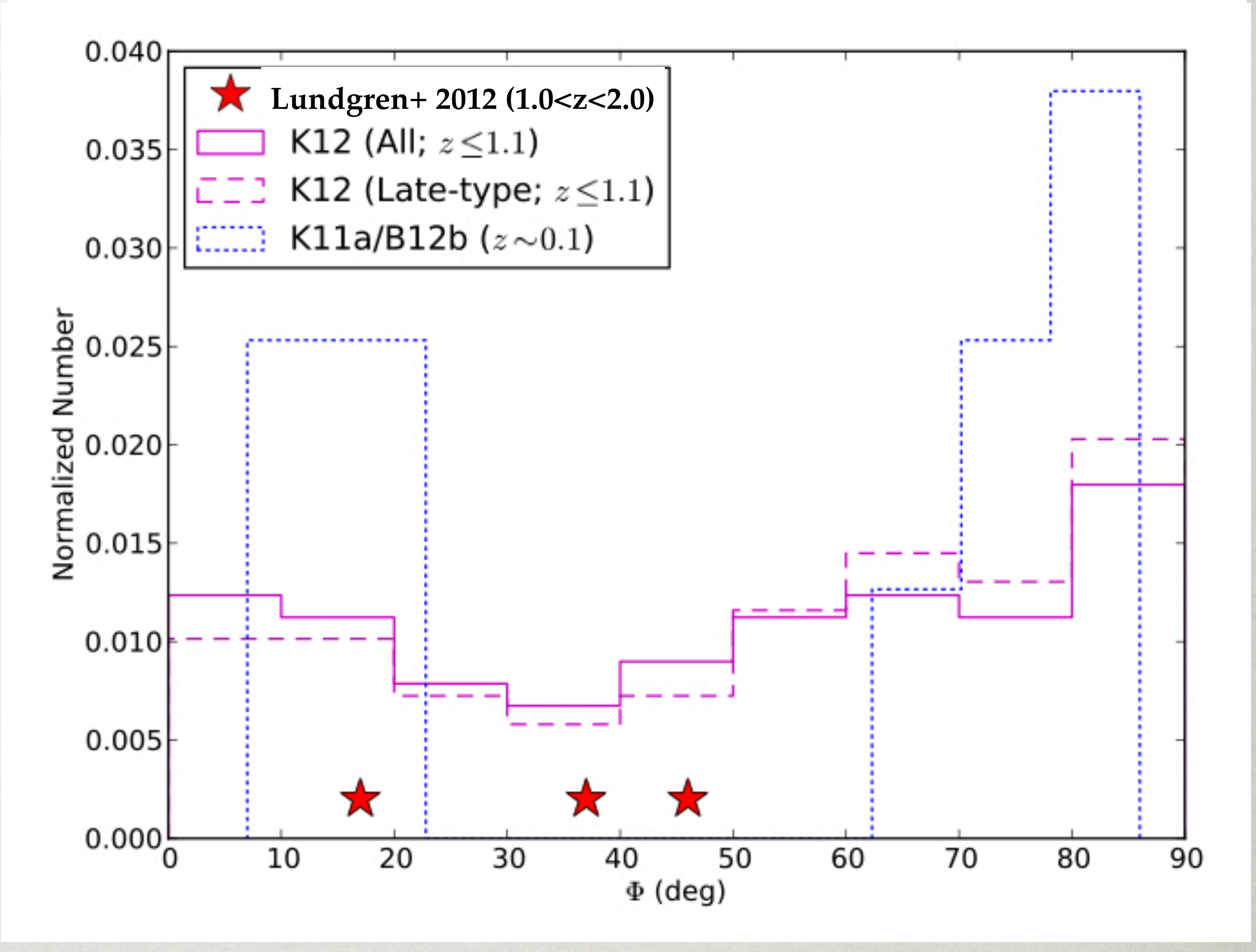
Lundgren et al. 2012

WFC3/IR Grism Observations of High-z Mg II host galaxies



- An evolving azimuthal distribution of Mg II around star-forming galaxies from z~2 ?

- Consistent with an increasing collimation of outflows with time (Law et al. 2012)



Lundgren et al. 2012

Summary

- New large absorber catalogs from the SDSS have dramatically changed our understanding of quasar absorption line origins in the past 5 years
  - Stacking analyses suggest that Mg II is a cosmic star formation indicator
  - Clustering analyses determined the typical Mg II environments and halo masses, leading to a better understanding of galaxy halo evolution to z~2.
- Direct, unbiased detections of Mg II host galaxies at z>1 from 3D-HST indicate that high-EW Mg II traces large-scale outflows from starbursting galaxies.
- New large overlapping surveys of absorbers and galaxies are on the horizon (eBOSS, PFS?), which will allow for better measurements of
  - galaxy-absorber correlations, the evolution of the IGM from z~5... more!