# Where are the missing baryons?

## CGM Properties from the COS-Halos Survey

Bili Dong, UC San Diego
CASS, April 15, 2016

The Astrophysical Journal, 792:8 (21pp), 2014 September 1 doi:10.1088/0004-637X/792/1/8


# THE COS-HALOS SURVEY: PHYSICAL CONDITIONS AND BARYONIC MASS IN THE LOW-REDSHIFT CIRCUMGALACTIC MEDIUM

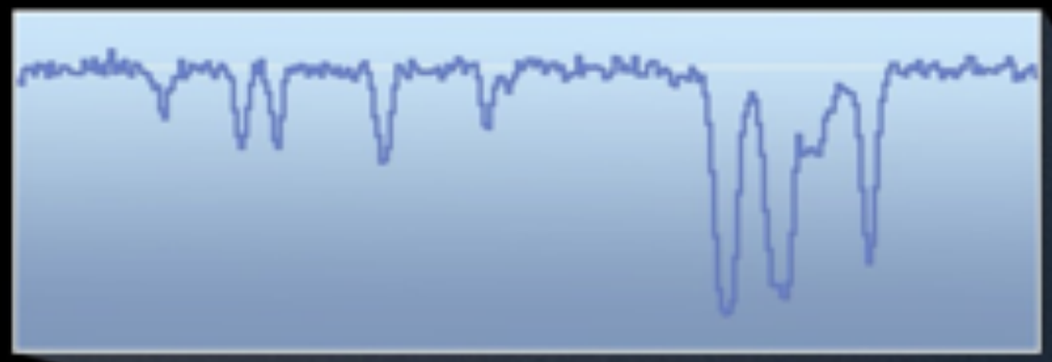
Jessica K. Werk[1,11], J. Xavier Prochaska[1], Jason Tumlinson[2], Molly S. Peeples[2], Todd M. Tripp[3], Andrew J. Fox[2], Nicolas Lehner[4], Christopher Thom[2], John M. O'Meara[5], Amanda Brady Ford[6], Rongmon Bordoloi[2], Neal Katz[3], Nicolas Tejos[1], Benjamin D. Oppenheimer[7,8], Romeel Davé[9], and David H. Weinberg[10]

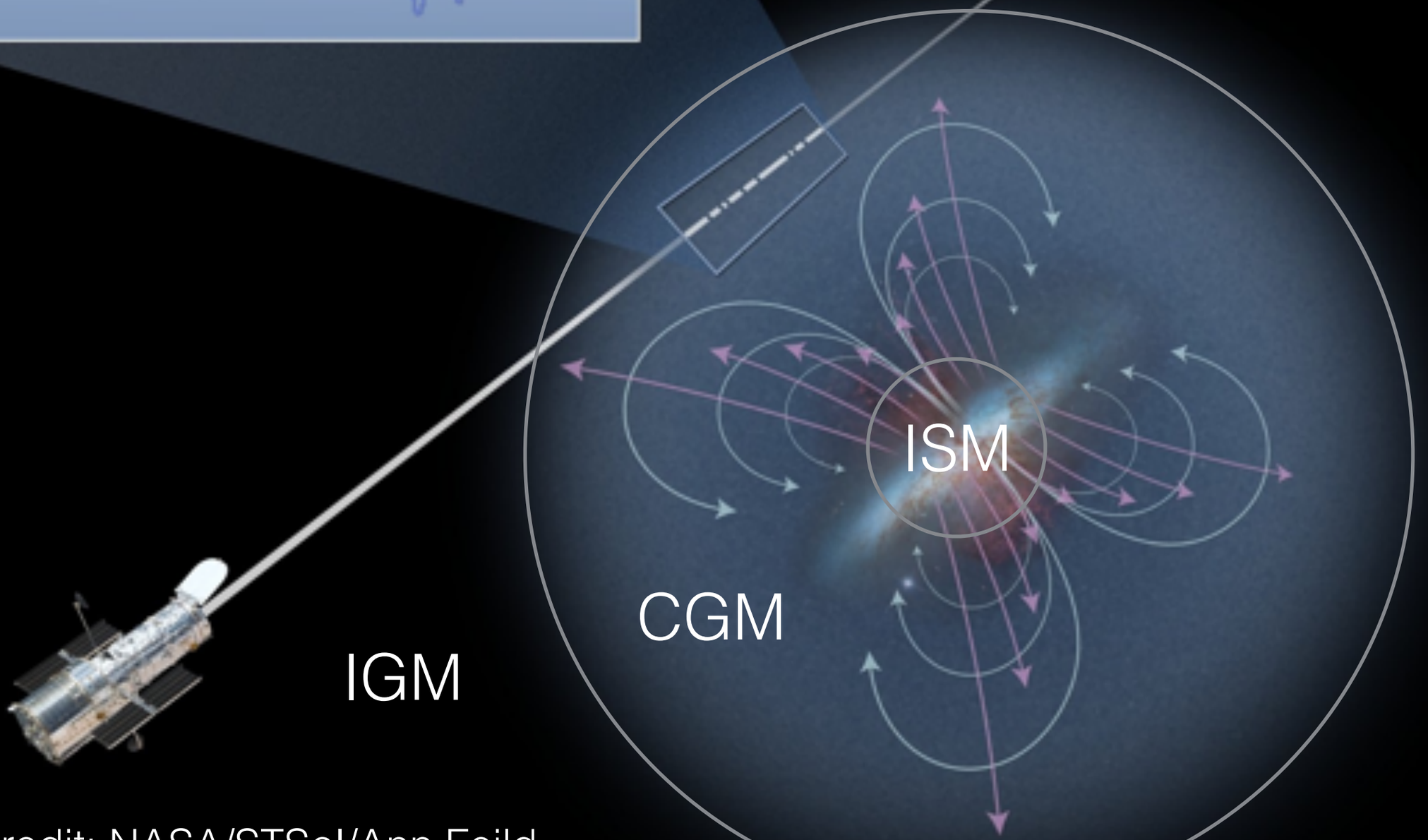
[1] UCO/Lick Observatory; University of California, Santa Cruz, CA, USA; jwerk@ucolick.org
[2] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD, USA
[3] Department of Astronomy, University of Massachusetts, Amherst, MA, USA
[4] Department of Physics and Astronomy, University of Notre Dame, South Bend, IN, USA
[5] Department of Chemistry and Physics, Saint Michael's College, Colchester, VT, USA
[6] Astronomy Department, University of Arizona, Tucson, AZ 85721, USA
[7] Leiden Observatory, Leiden University, NL-2300 RA Leiden, The Netherlands
[8] CASA, Department of Astrophysical and Planetary Sciences, University of Colorado, Boulder, CO 80309, USA
[9] University of the Western Cape, Bellville, Cape Town 7535, South Africa
[10] Department of Astronomy, The Ohio State University, Columbus, OH, USA
*Received 2014 March 4; accepted 2014 June 21; published 2014 August 8*

# The Missing Baryon Problem

- Baryon mass expected: 17% of total mass
- Baryon mass estimated: 3%-7% of total baryon mass (stars, dust, and gas in galaxies and clusters)
- Other baryonic contents:
    - Lyα forest ~ 40%
    - circumgalactic medium (CGM) ~ 25%
    - warm-hot intergalactic medium (WHIM) ~ 25%
- The halo missing baryon problem: $(M_{\text{stars, gas}} / M_{\text{DM}}) / (\Omega_b / \Omega_m)$
    - stars ~ 0.02-0.05
    - add cold ISM ~ 0.07
    - add X-ray halo gas ~ 0.08
    - missing ~ 60%

# The Circumgalactic Medium (CGM)






Graphic credit: NASA/STScI/Ann Feild

# The Circumgalactic Medium (CGM)

- CGM is a diffuse baryonic component within the dark matter halo that extends far from the inner regions to the virial radius and beyond.

- CGM gas is too diffuse to be studied in emission.

# The COS-Halos Survey

Absorption Spectrum

QSO

Method A: QSO -> Absorption Spectrum -> Galaxy @ z

Method B: Galaxy -> QSO -> Absorption Spectrum @ z

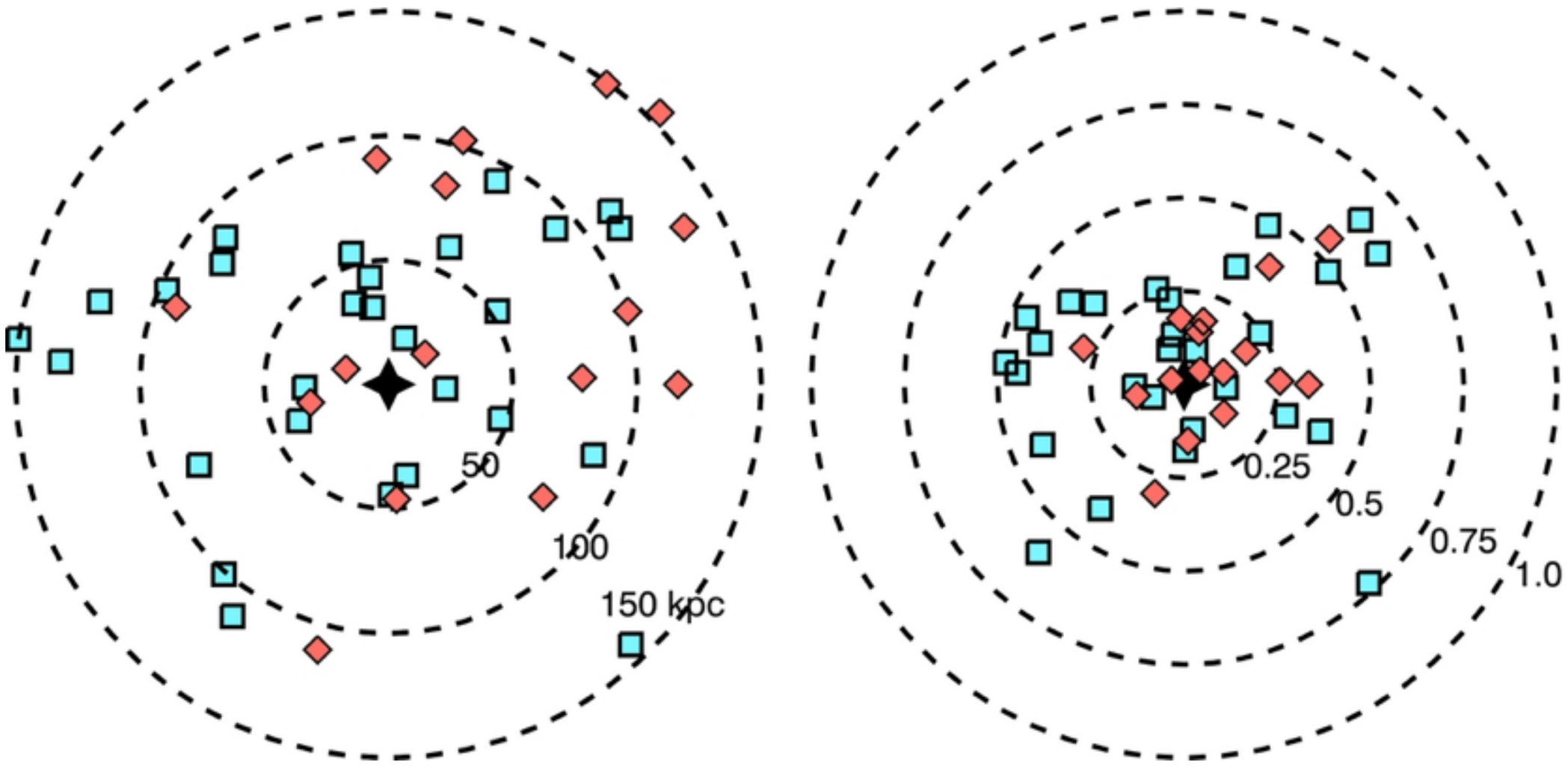
HST/COS

Galaxy

Cosmic Origins Spectrograph

Graphic credit: NASA/STScI/Ann Feild

# COS-Halos Sample




Tumlinson+2013

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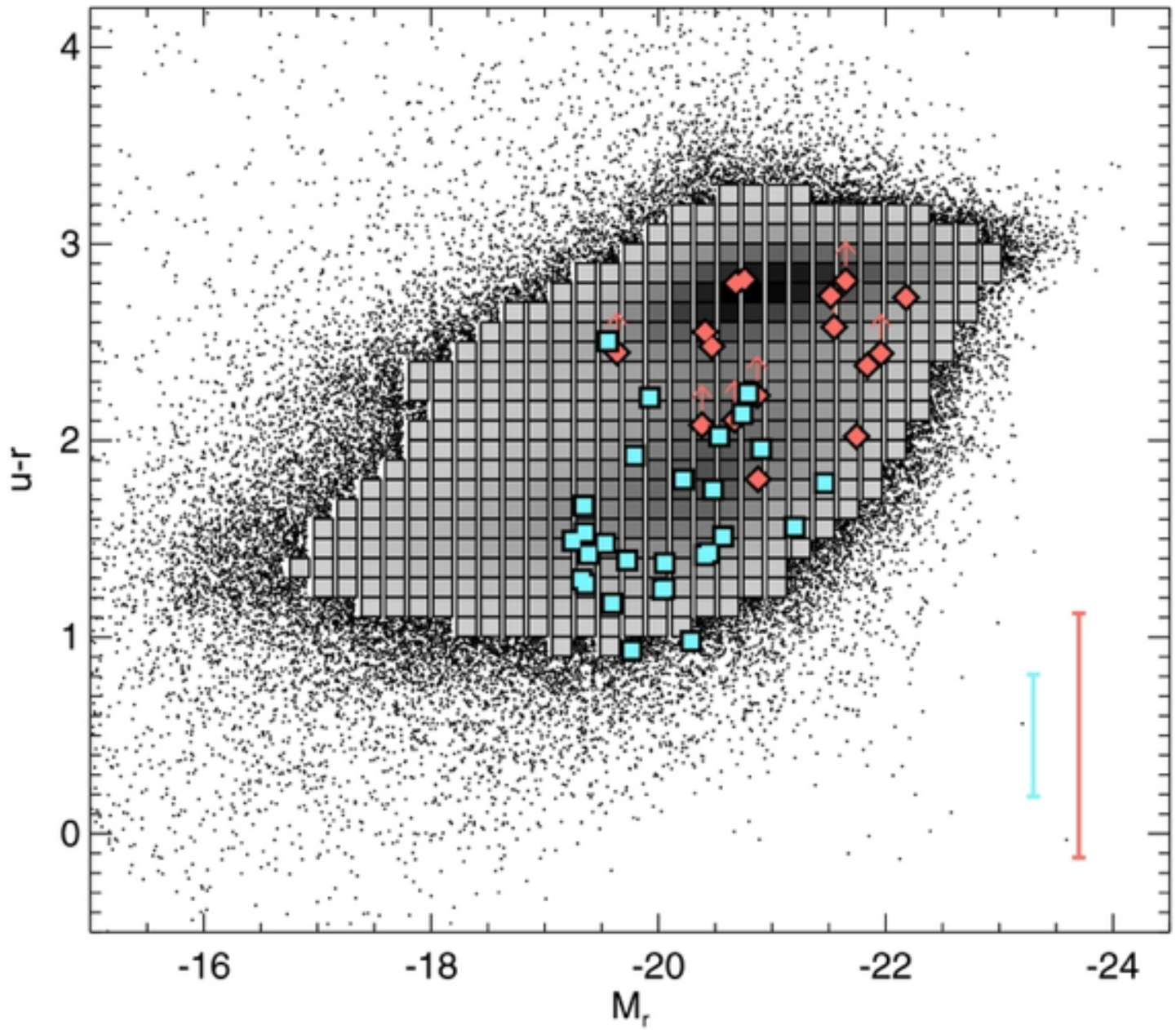
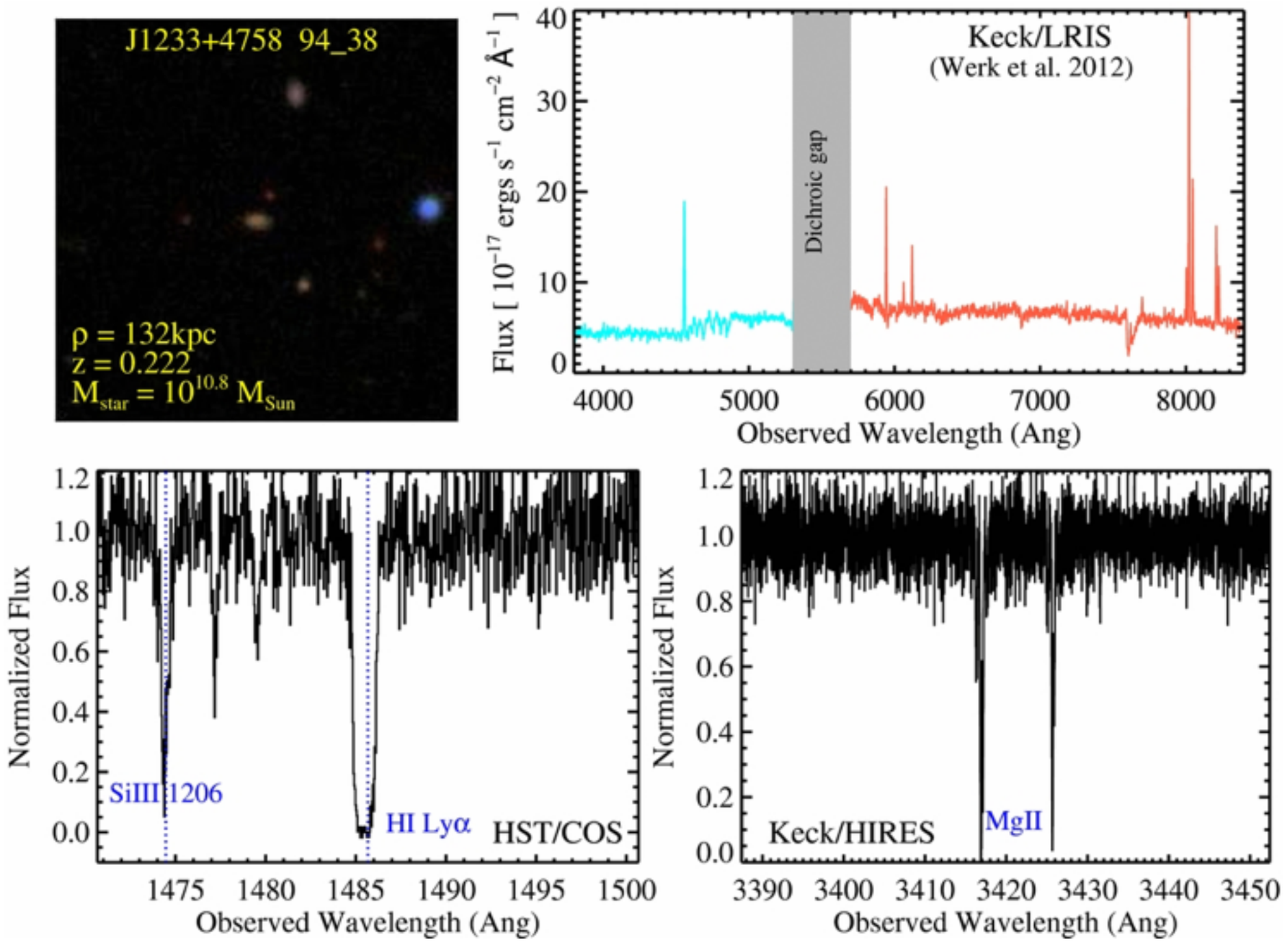



Tumlinson+2013

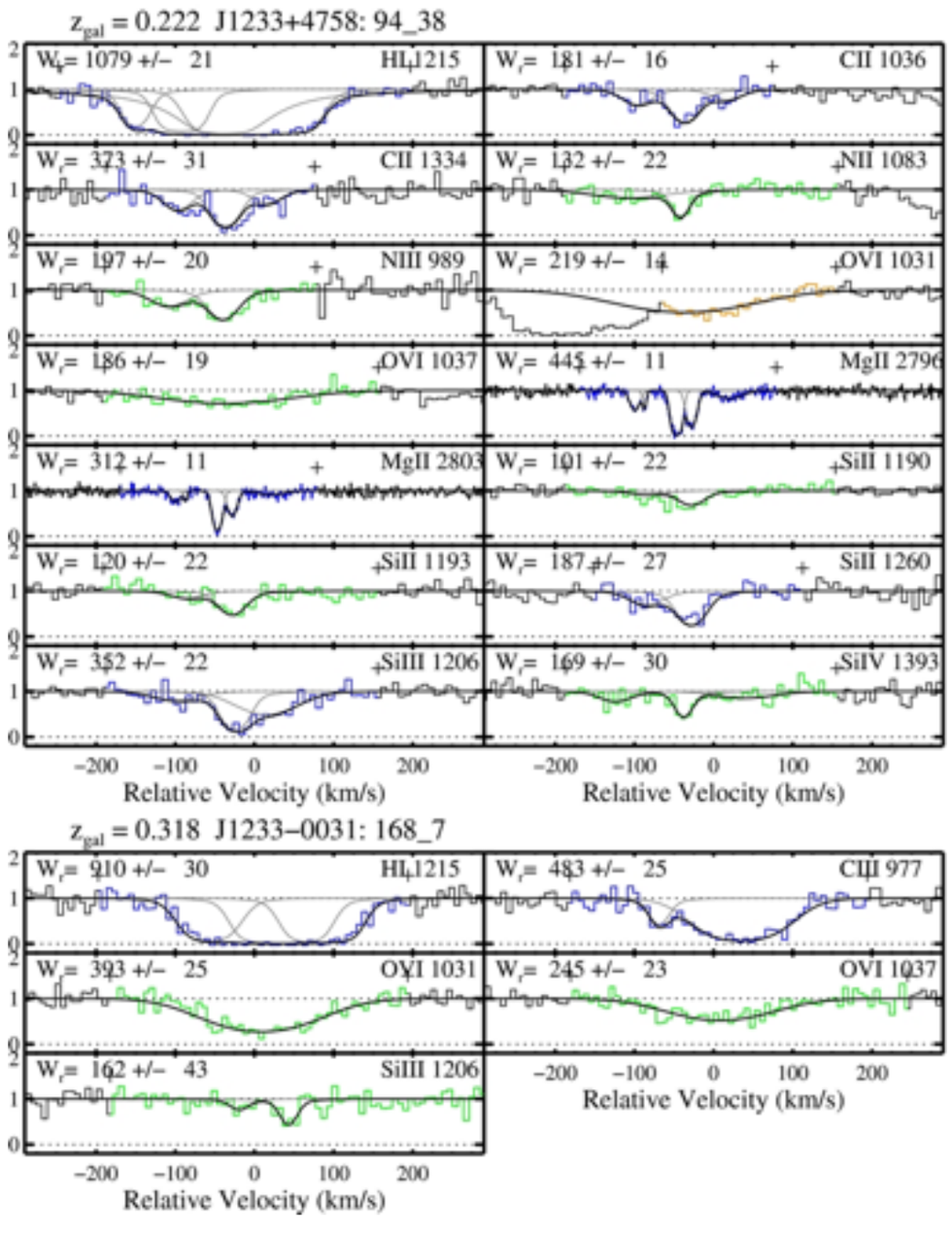
# QSO Absorption Line Spectrum




Werk+2013

# Fitting Absorption Lines

- Voigt profile fits
- Absorption lines highlighted
- good
- saturated
- blended
- bad (saturated + blended)
- +: velocity range

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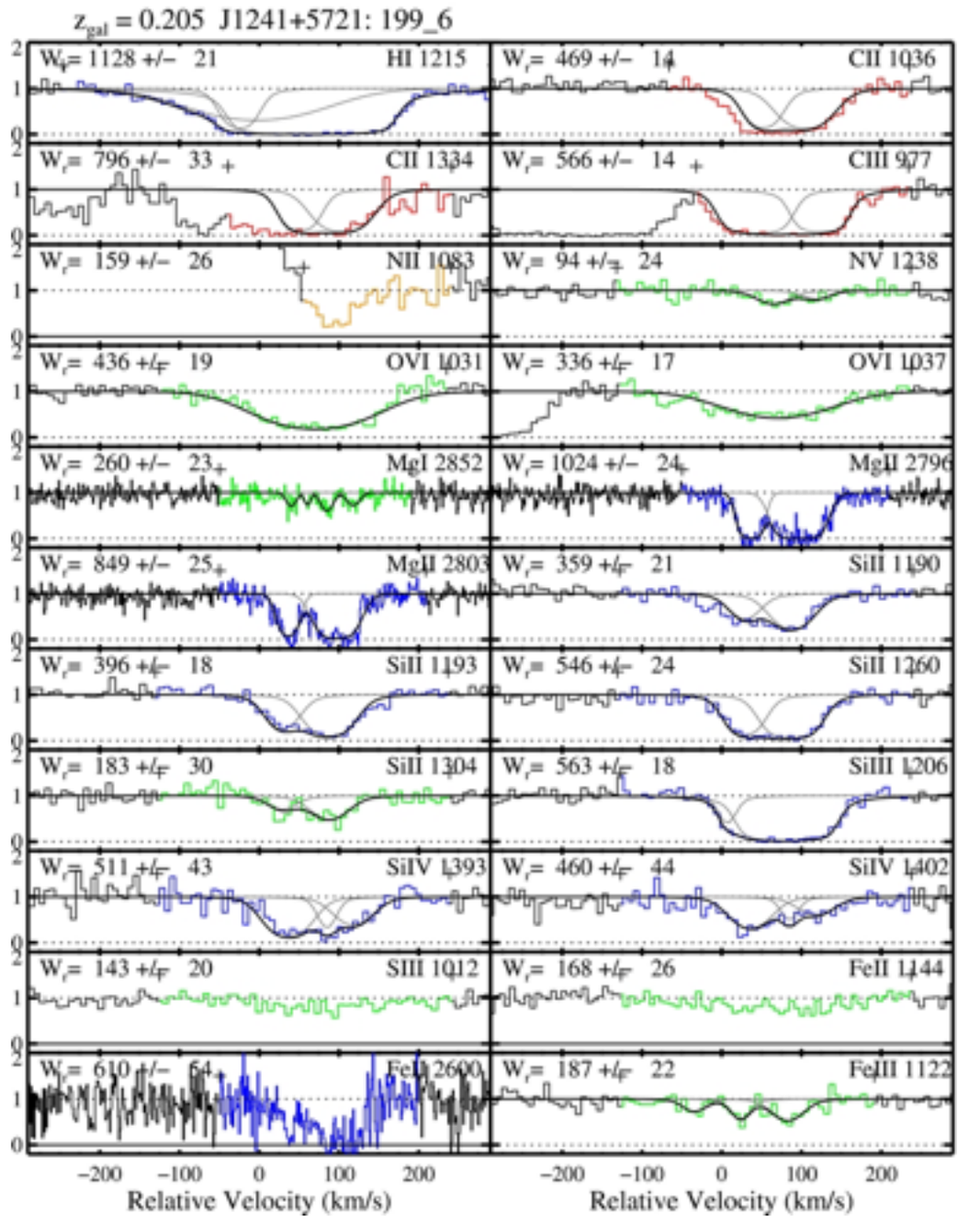
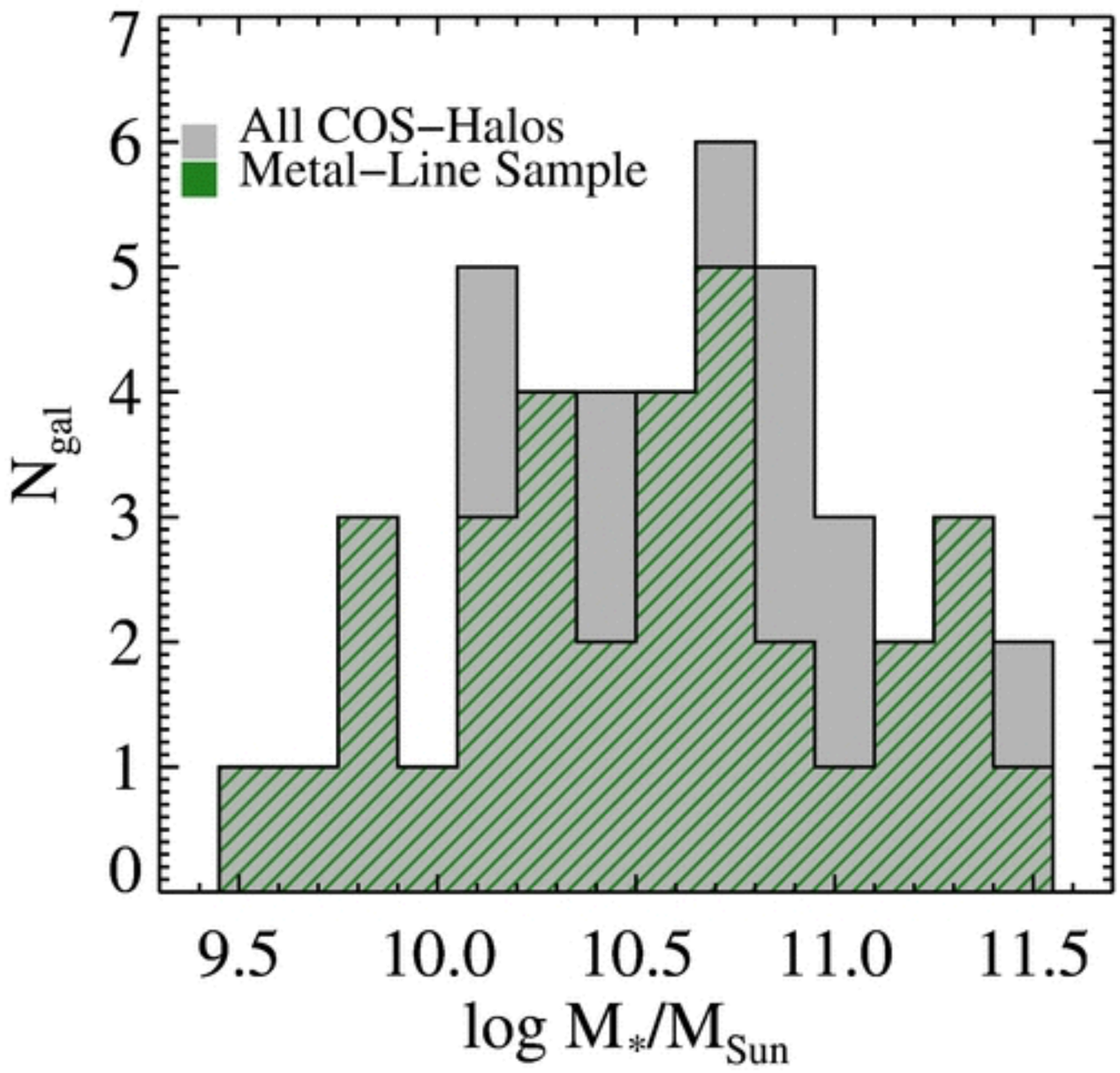



Werk+2013

# Metal-Line Sample

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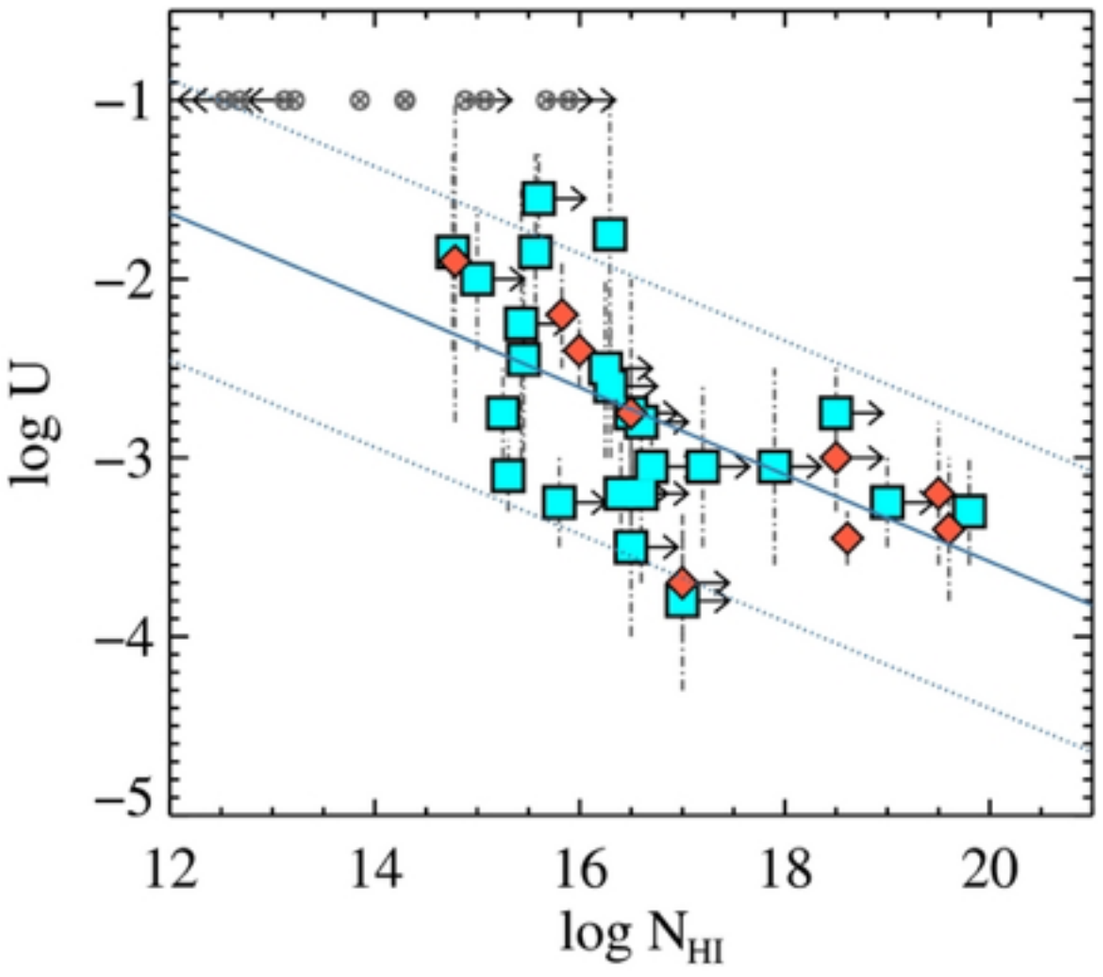
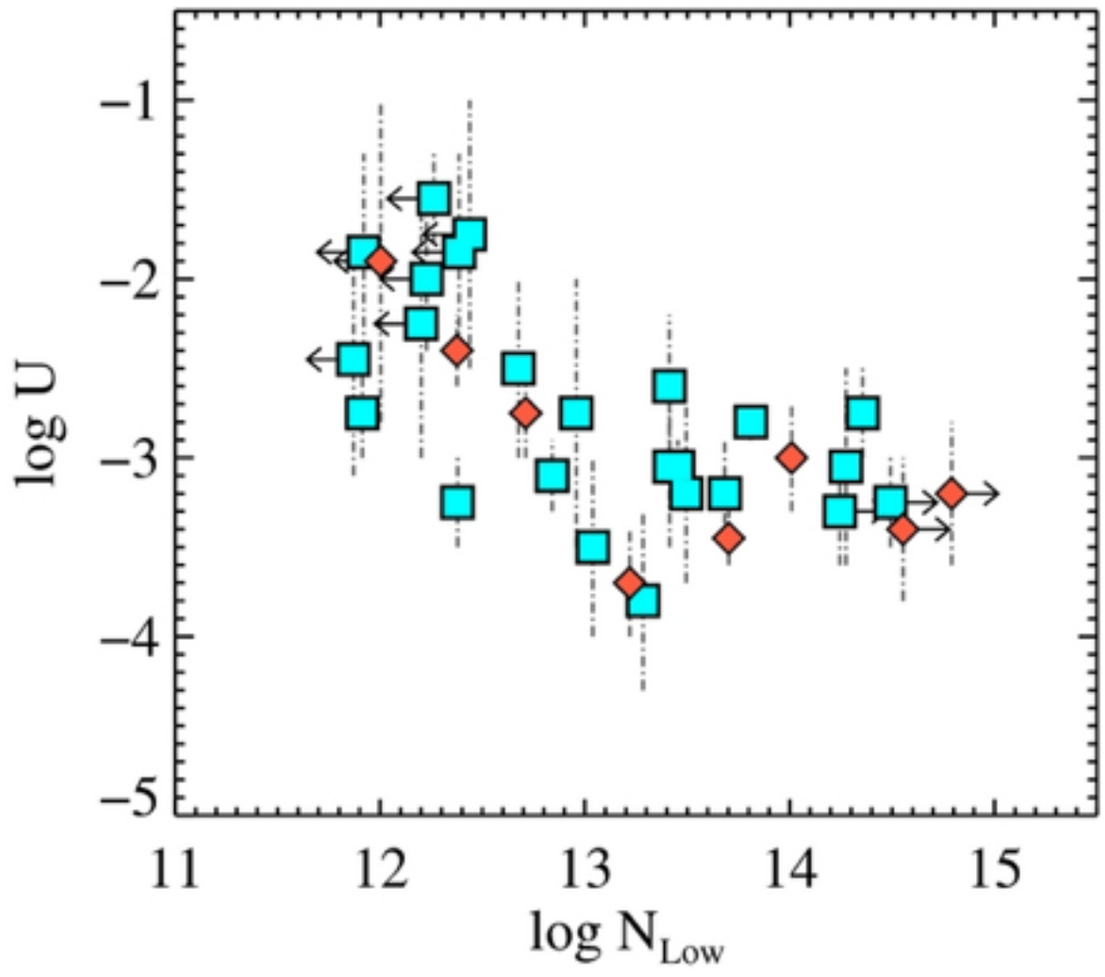
# Ionization Parameter Scaling Relations

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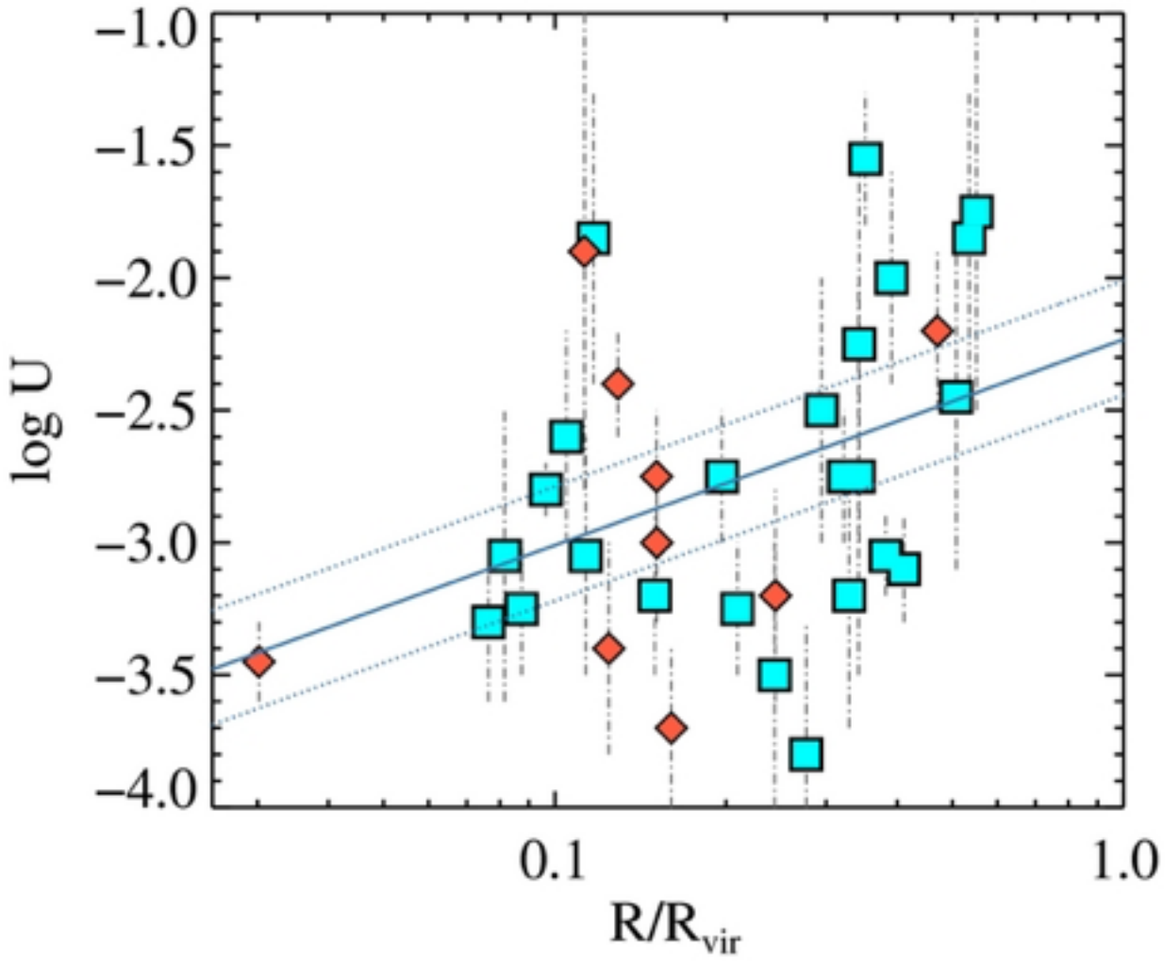
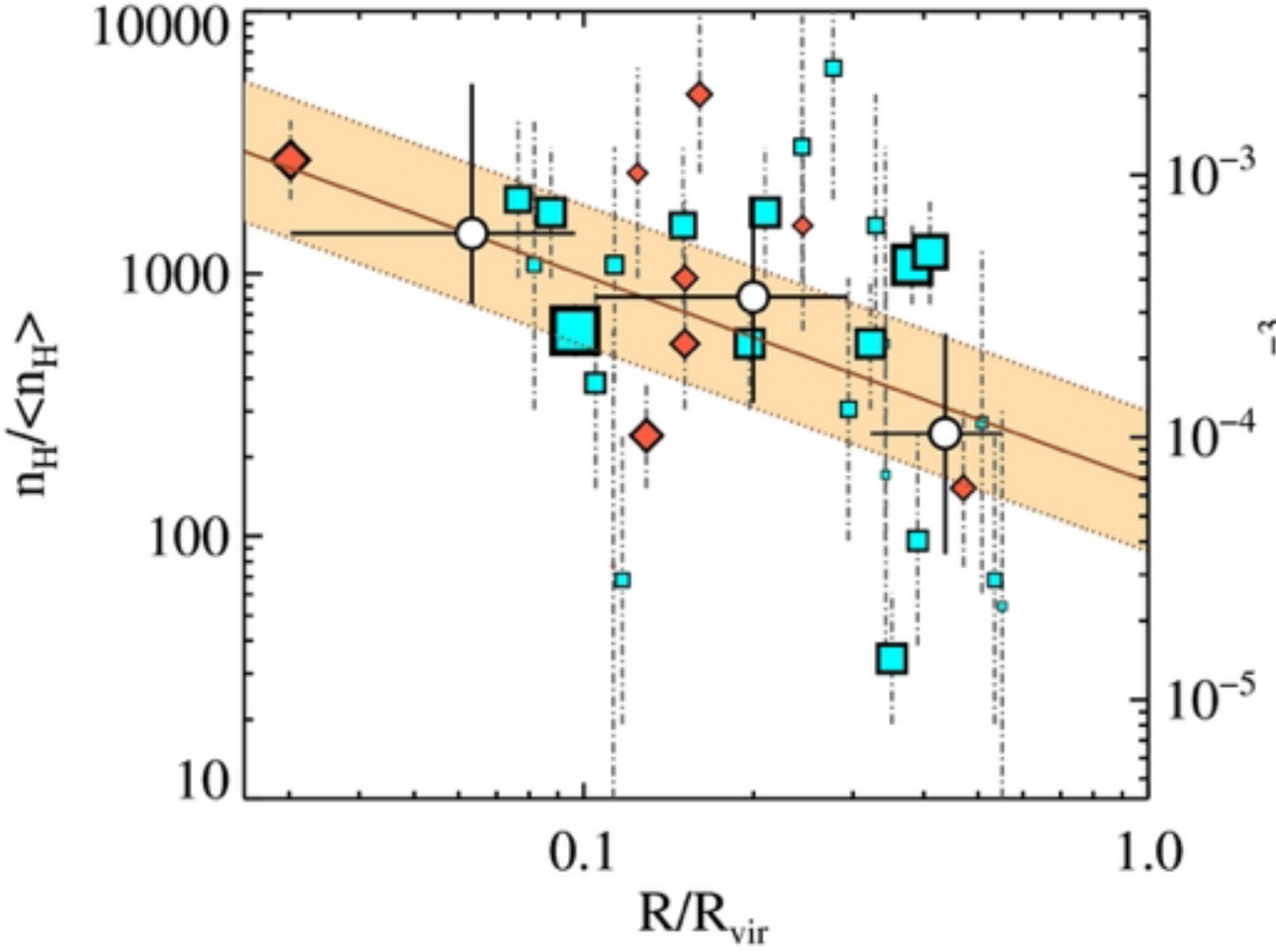
# Ionization Parameter and Volume Density Profiles

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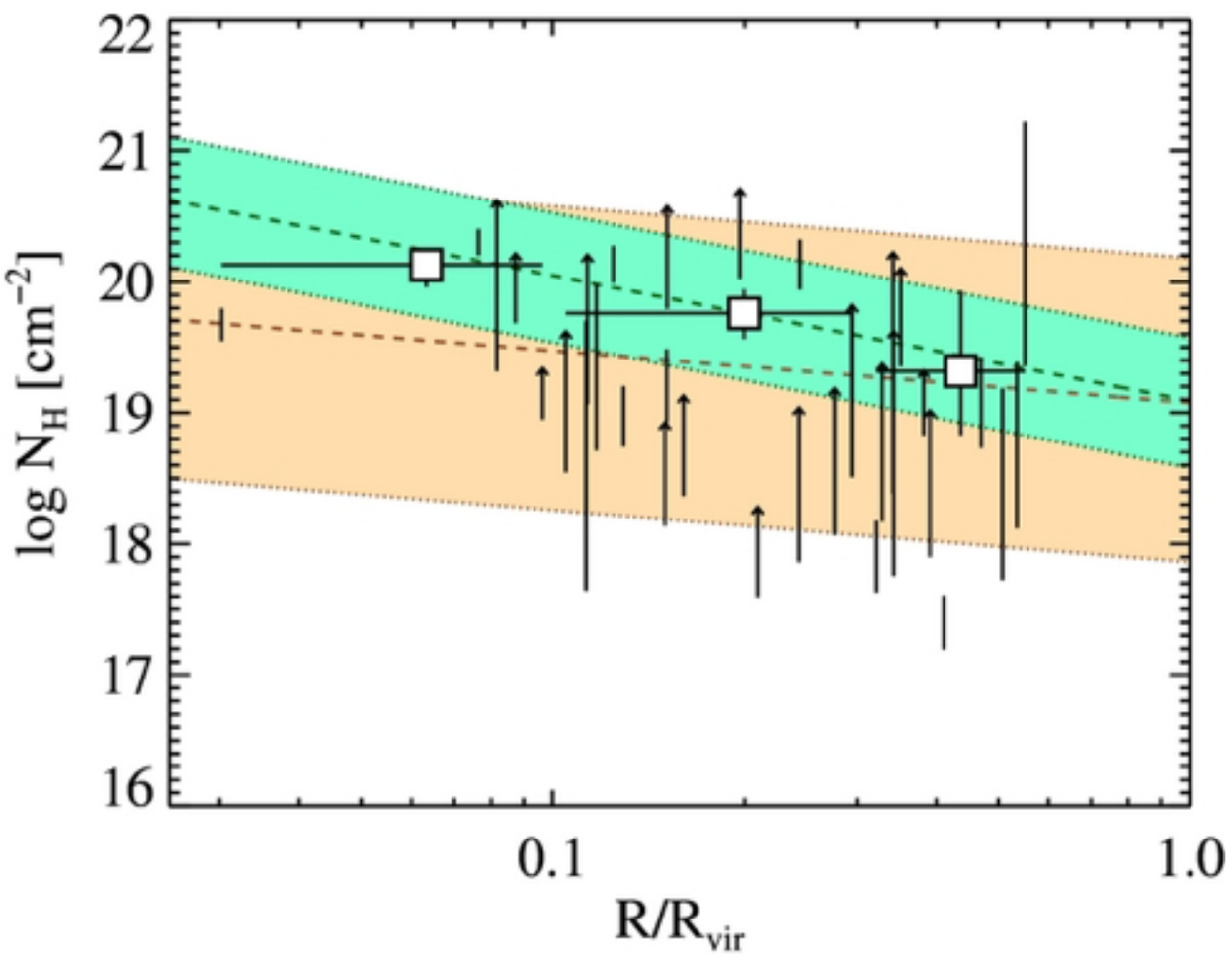
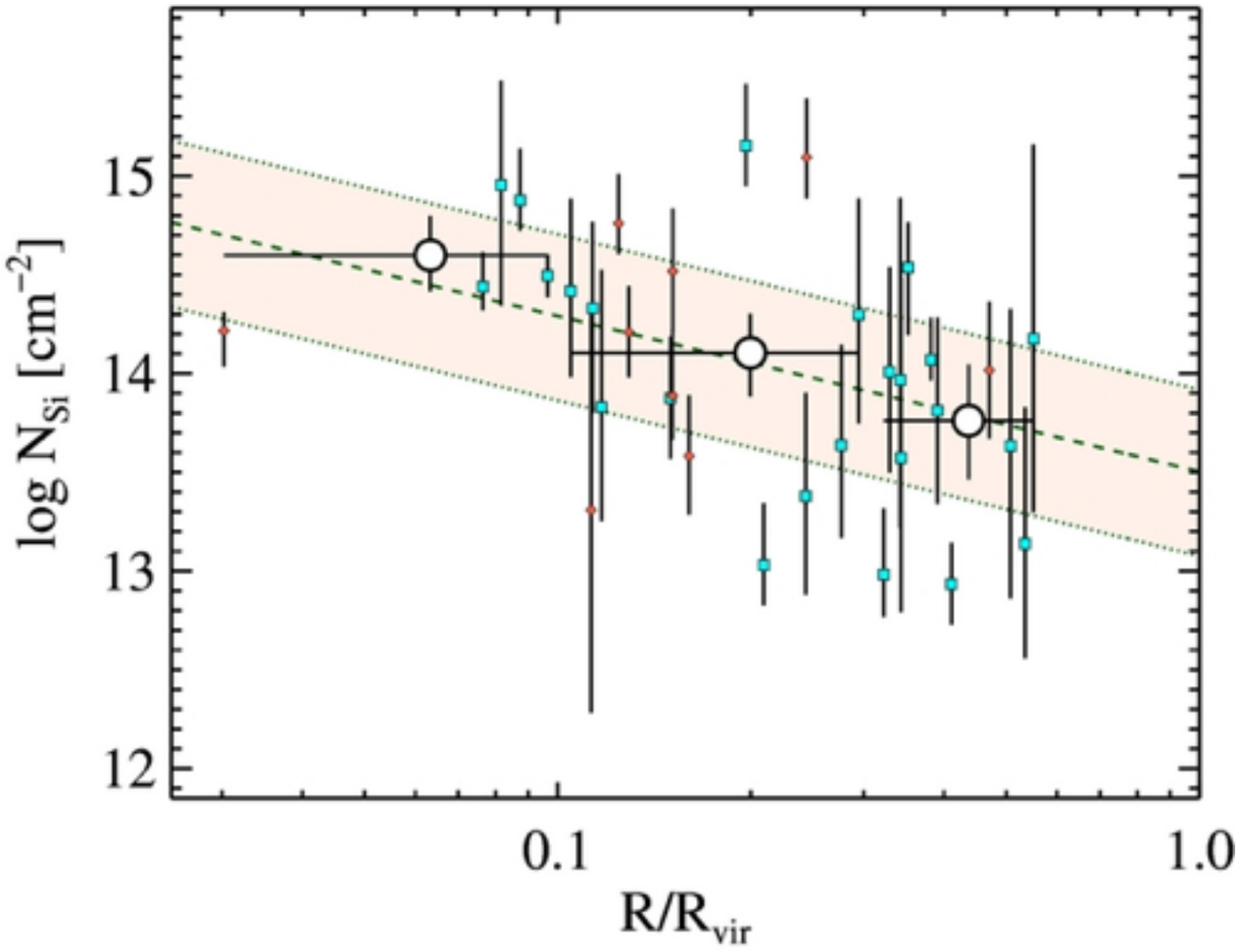
# Gas Surface Density Profiles

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# Photoionization Modeling

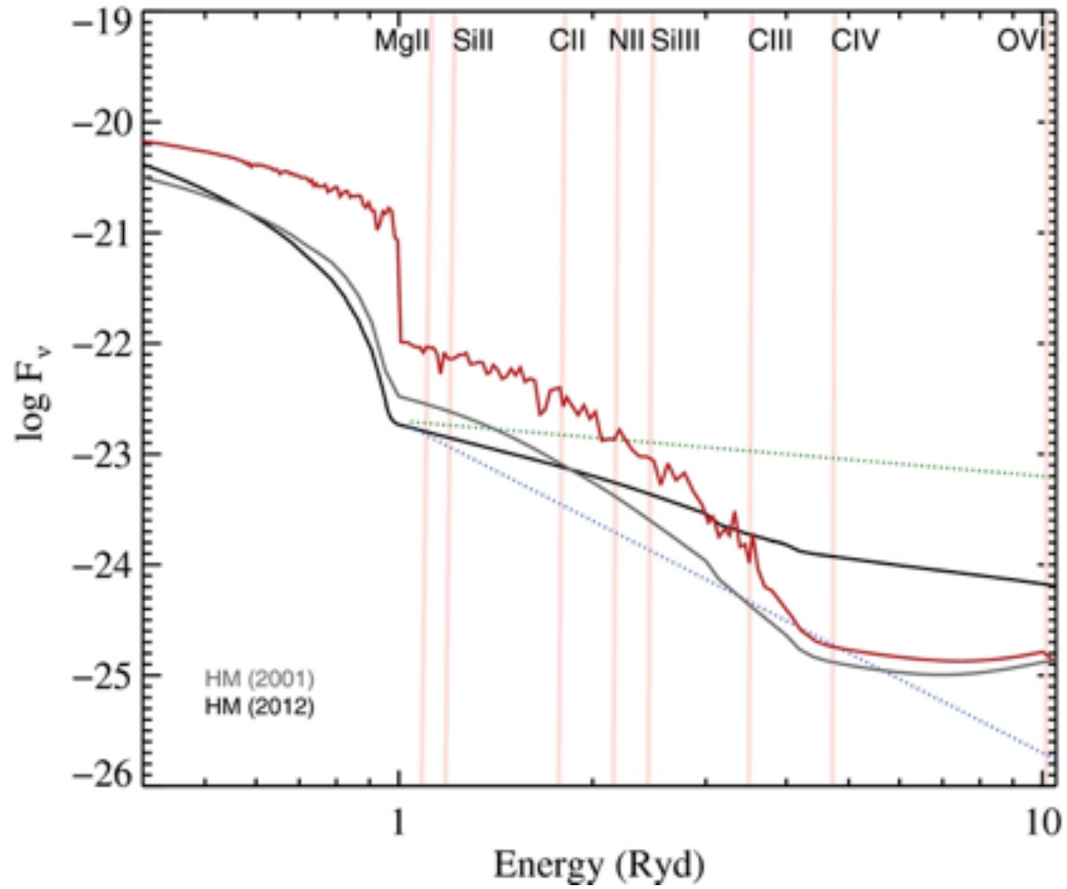
**Cloudy & Associates**

*Photoionization Simulations for the Discriminating Astrophysicist Since 1978*

CLOUDY needs to know:

- extragalactic ultra-violet background (EUVB) radiation
- galaxy background radiation
- gas metallicity
- gas density
- ionization parameter
- geometry: 10 - 160 kpc

to calculate column densities

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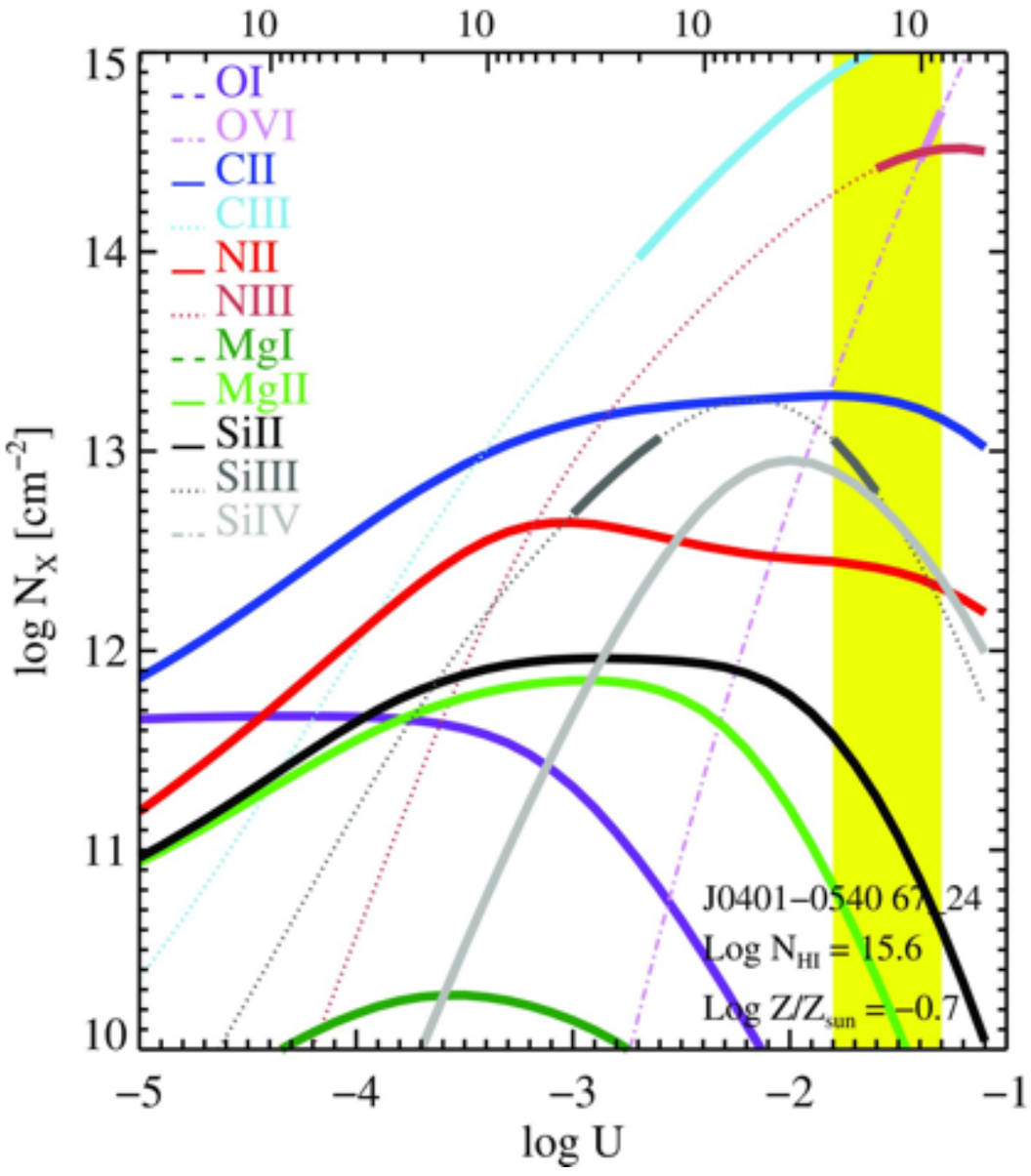


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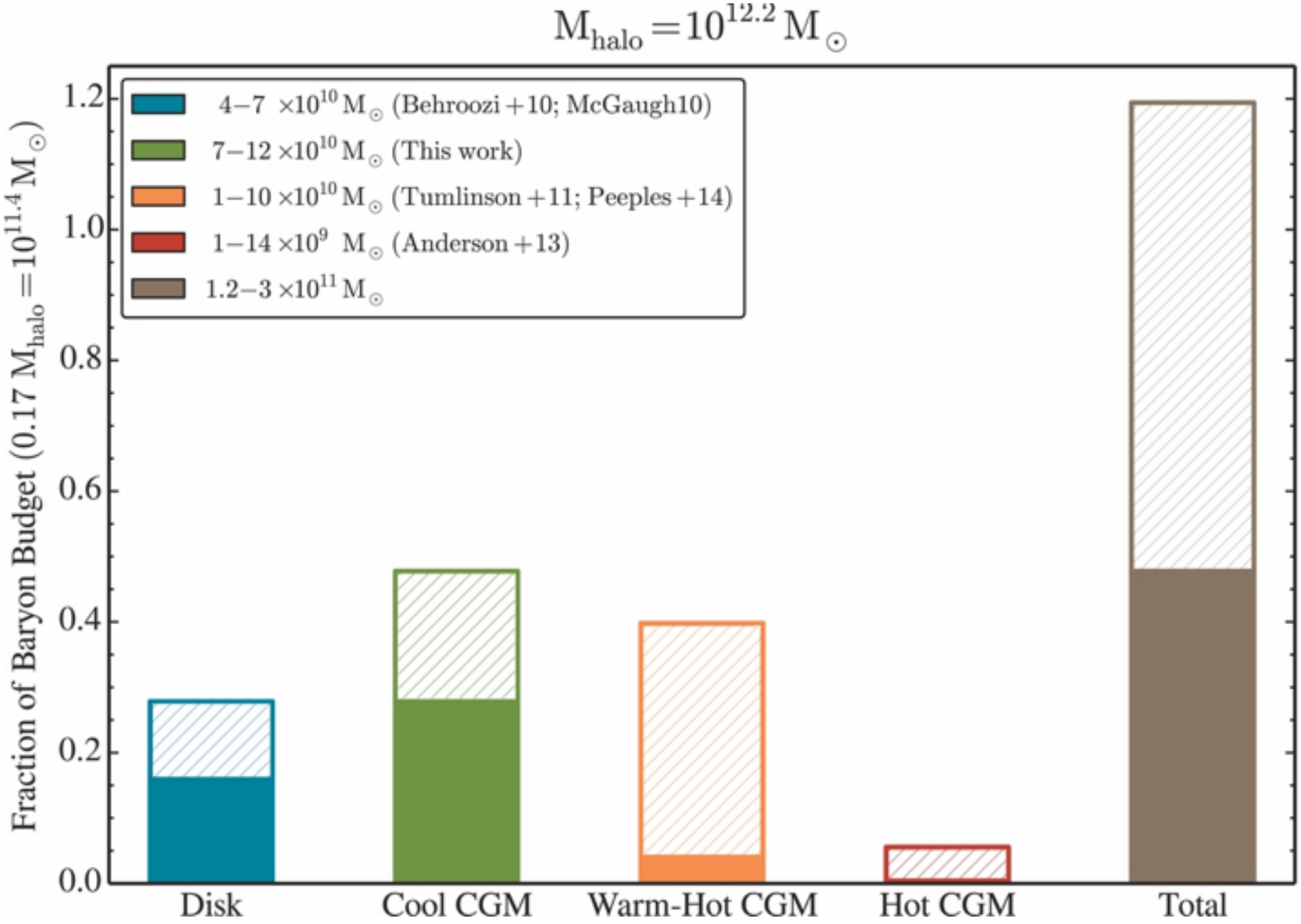
# Total Mass of the Photoionized CGM

- Integrate gas surface density profile to get mass.
- Strict Lower Limit: $2.1\times10^{10}\,M_{\odot}$
  - AODM (Apparent Optical Depth Method) H I column density
    - The lowest ionization parameter
    - 160 kpc cut off
    - Include the 11 non-detections
- Preferred Lower Limit: $6.5\times10^{10}\,M_{\odot}$
  - Preferred values for log N_HI and log U
  - Exclude the 11 non-detections

# Baryonic Budget

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Draft version April 11, 2016
Preprint typeset using LaTeX style emulateapj v. 5/2/11

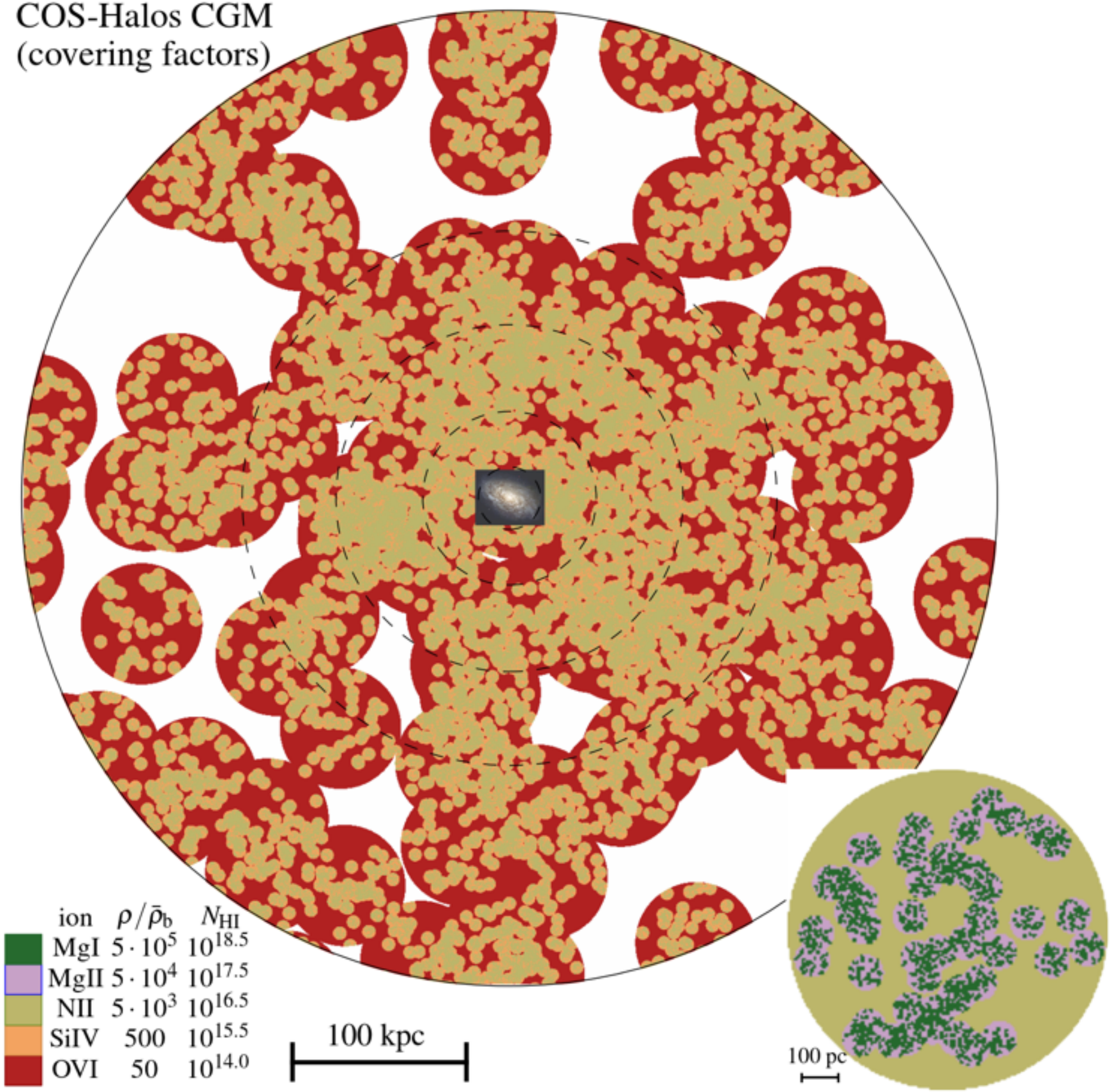
# A UNIVERSAL DENSITY STRUCTURE FOR CIRCUM-GALACTIC GAS

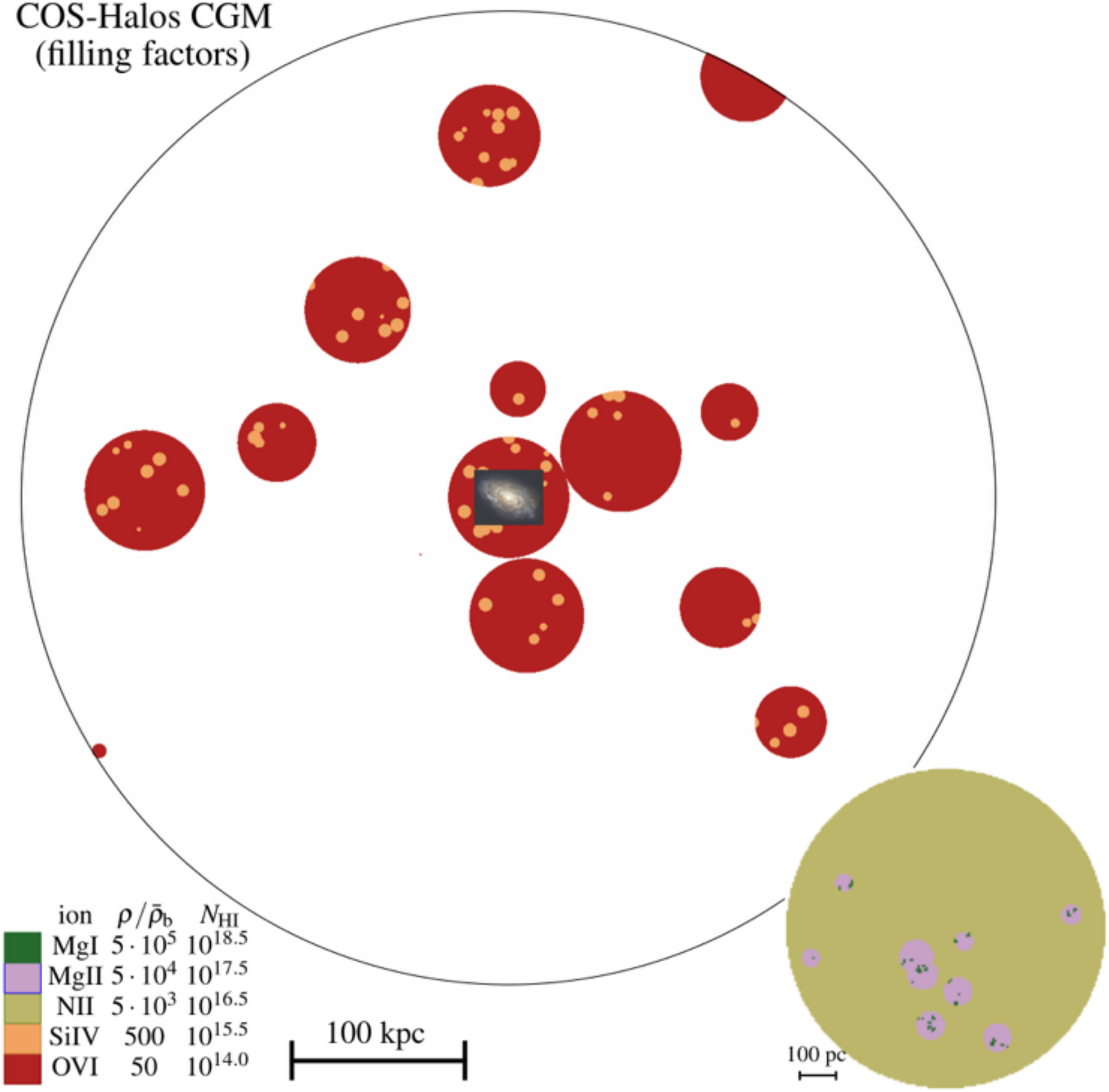
Jonathan Stern[1*†], Joseph F. Hennawi[1], J. Xavier Prochaska[2], and Jessica K. Werk[2]

*Draft version April 11, 2016*

## ABSTRACT

We develop a new method to constrain the physical conditions in the cool ($\sim 10^4$ K) circumgalactic medium (CGM) from measurements of ionic columns densities, under two main assumptions: that the cool CGM spans a large range of gas densities, and that small high-density clouds are hierarchically embedded in large low-density clouds. The new method combines (or 'stacks') the information available from different sightlines during the photoionization modeling, thus yielding significantly tighter constraints on the CGM properties compared to traditional methods which model each sightline individually. Applying this new technique to the COS-Halos survey of low-redshift $\sim L^*$ galaxies, we find that we can reproduce all observed ion columns in all 44 galaxies in the sample, from the low-ions to O VI, with a single universal density structure for the cool CGM. The gas densities span the range $50 \lesssim \rho/\bar{\rho}_b \lesssim 5 \times 10^5$ ($\bar{\rho}_b$ is the cosmic mean), while the physical size of individual clouds scales as $\sim \rho^{-1}$, from $\approx 35$ kpc of the low density O VI clouds to $\approx 6$ pc of the highest density low-ion clouds. The cloud sizes are too small for this density structure to be driven by self-gravity, thus its physical source is unclear. We find a total cool CGM mass within the virial radius of $(1.3 \pm 0.4) \times 10^{10}$ M$_\odot$ (~1% of the halo mass), distributed rather uniformly over the four decades in density. The mean cool gas density profile scales as $R^{-1.0\pm0.3}$, where $R$ is the distance from the galaxy center. We construct a 3D model of the cool CGM based on our results, which we argue are a benchmark for the CGM structure in hydrodynamic simulations. Our results can be tested by measuring the coherence scales of different ions, using absorption line measurements along multiple sightlines towards lensed quasars.





# Summary

- CGM could explain some of the ‘missing baryons’.

- CGM is still mysterious.