Observational Evidence the CGM is Driving (and Driven by) Star Formation

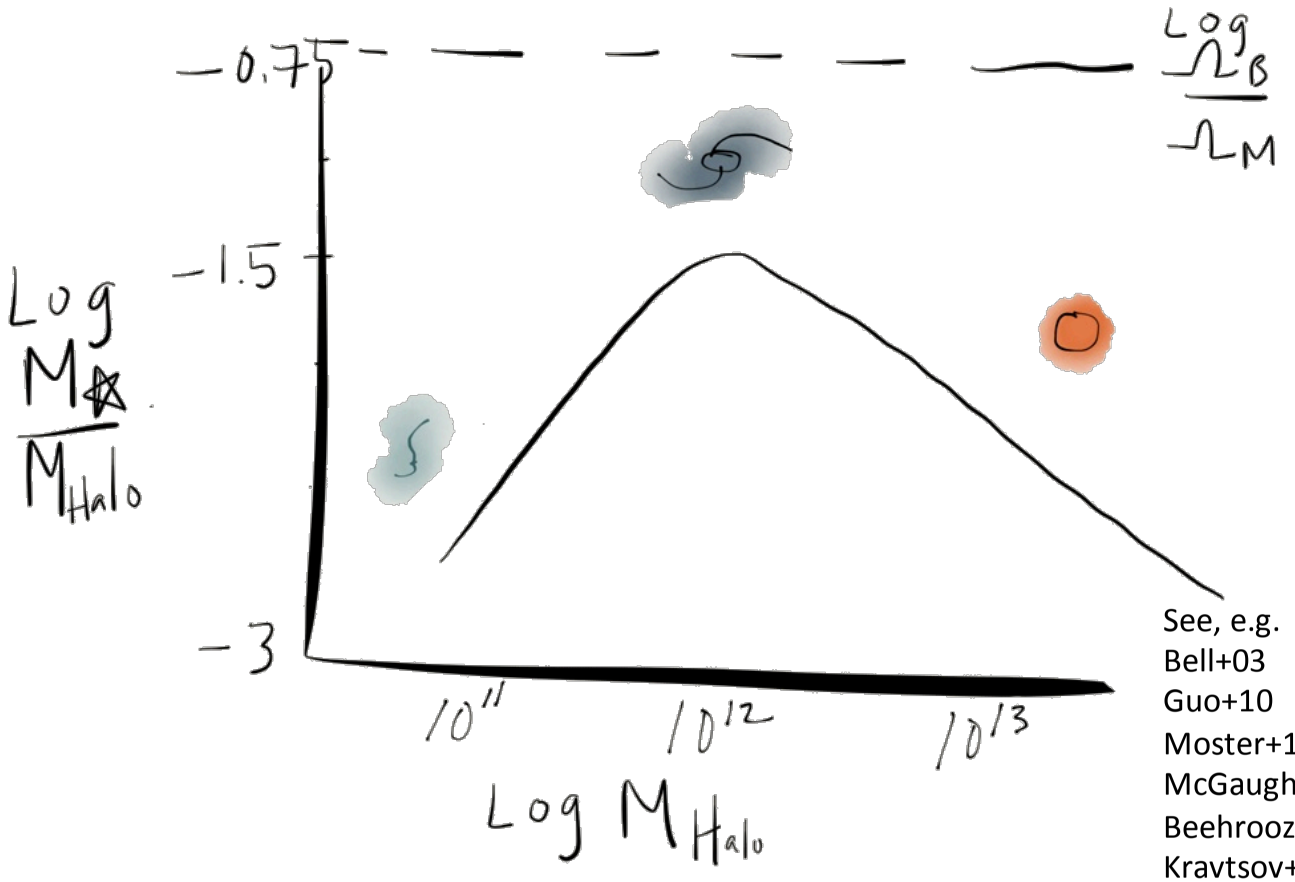
Jessica Werk, Hubble Fellow

University of California, Santa Cruz

Circumgalactic gas shapes and is shaped by the observed properties of galaxies.

Baryons and Dark Matter

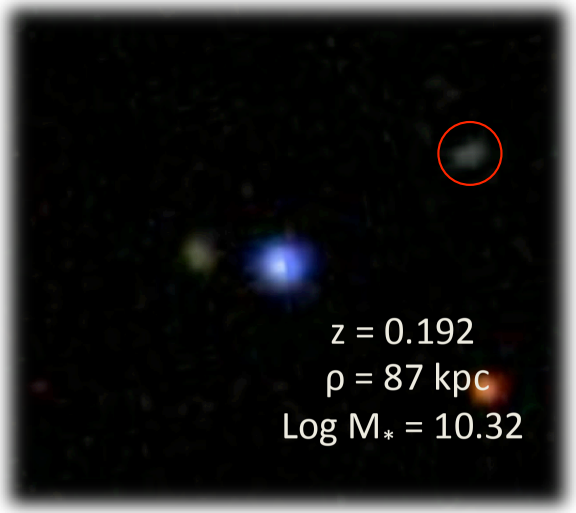
How much baryonic mass does the CGM contribute?

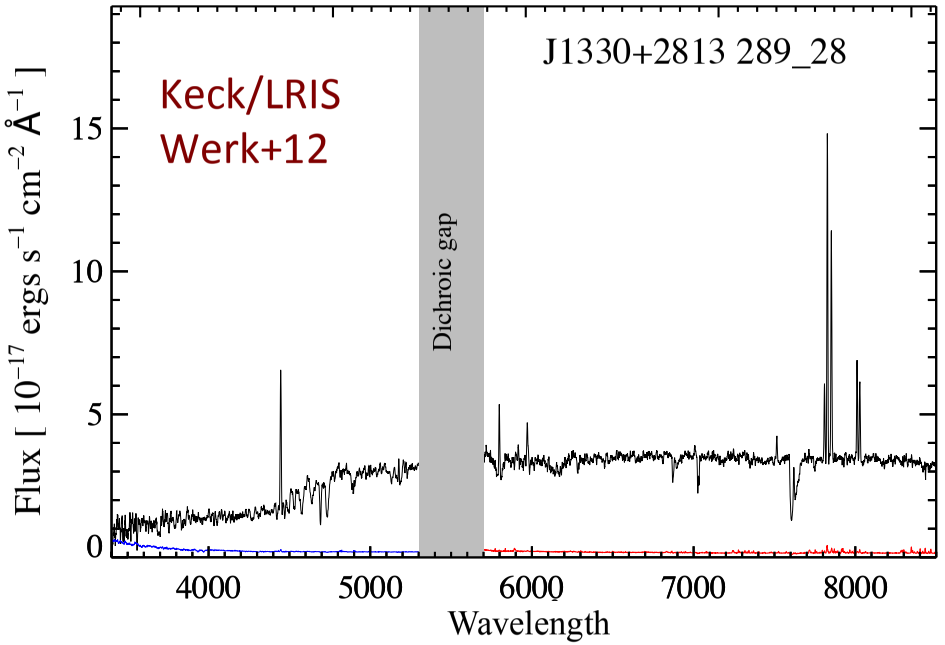


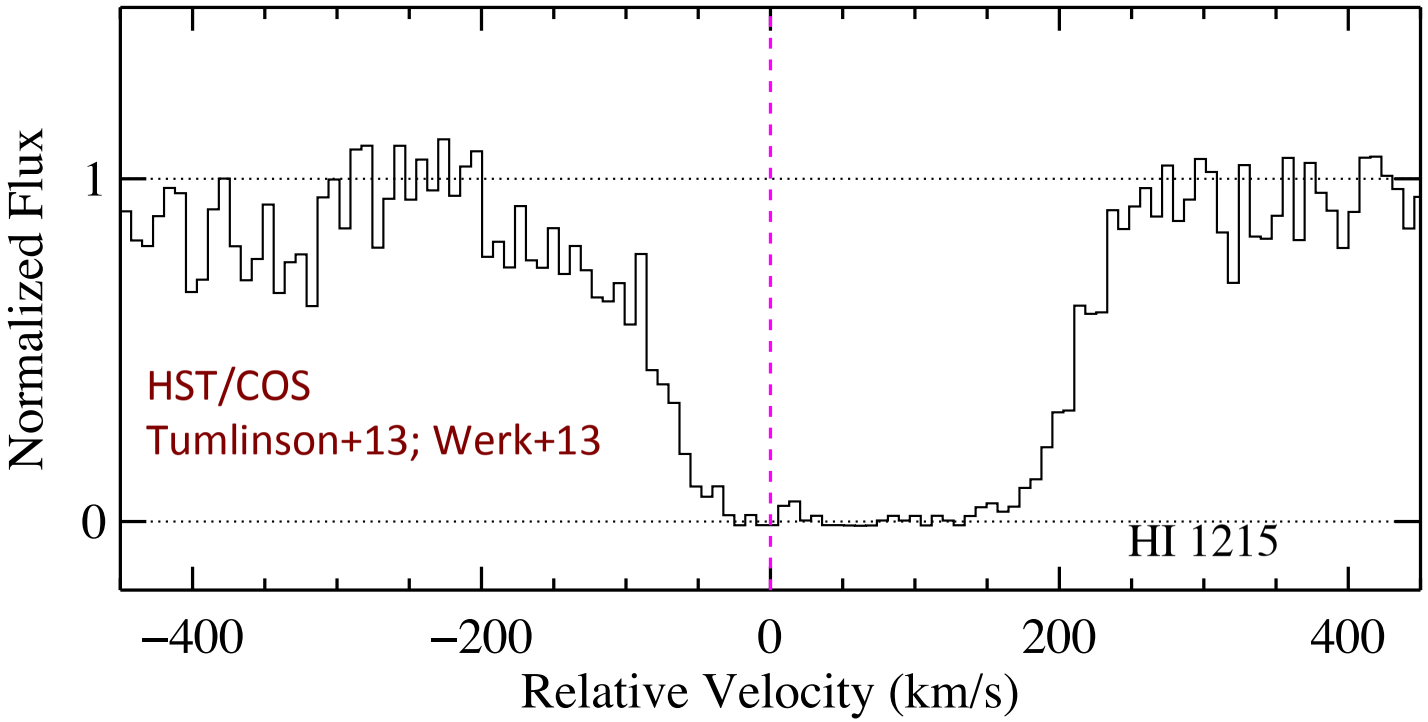
See, e.g.
Bell+03
Guo+10
Moster+10
McGaugh 10
Beehroozi+10
Kravtsov+14

Only 10- 20% of galaxy's baryons are in stars, and light does not follow dark matter

J1330+2813 289_28

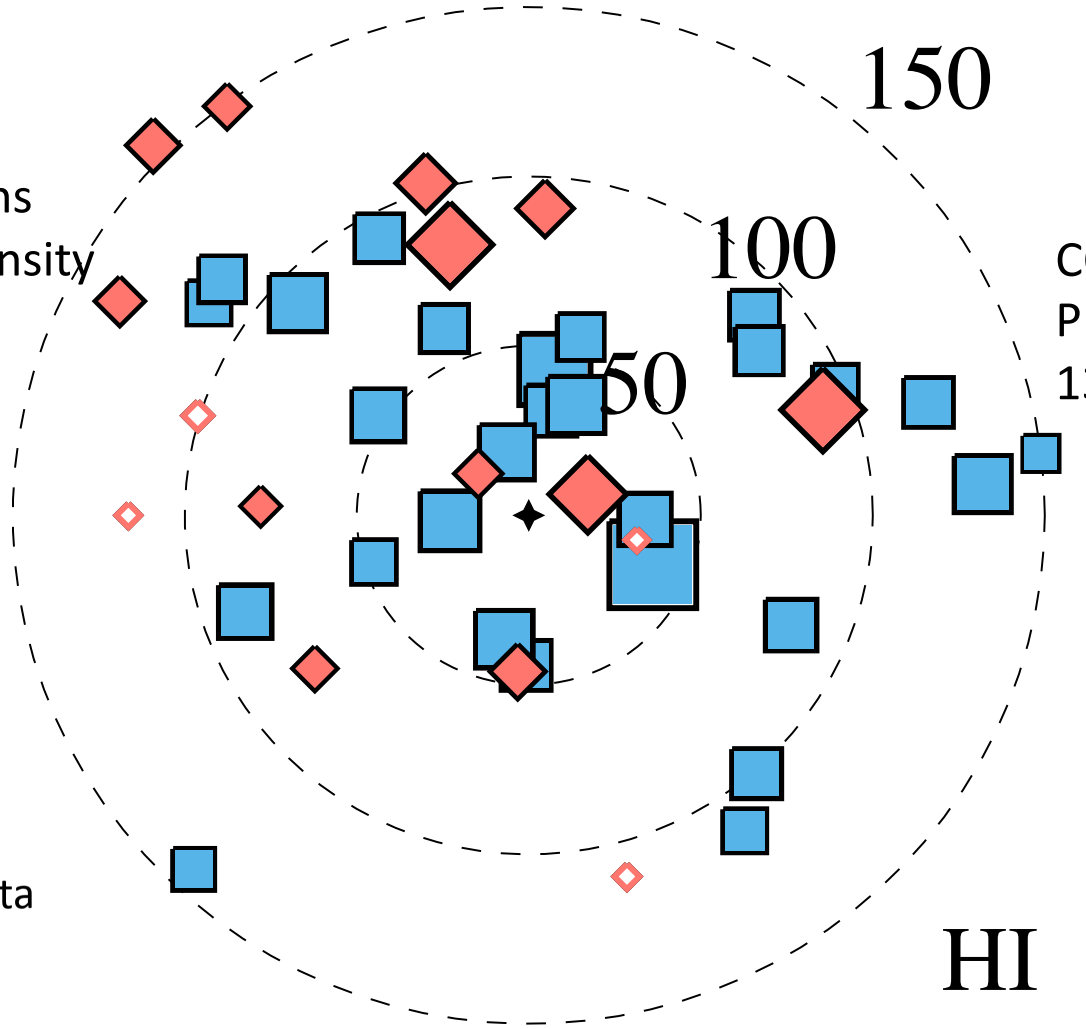






Observed Properties of the CGM: The HI Gas

= star-forming
= quiescent
= non-detections
Point size ≈ column density



COS-Halos
PI: Jason Tumlinson
134 orbits with HST/COS

Max $N_{HI} = 10^{19}$
Min $N_{HI} = 10^{14.5}$

Line saturation → many of these are lower limits

NB: Blank space = no data

A cool (10^4 K) medium with high covering fraction of $N_{HI} > 10^{15}$ cm^{-2} exists around nearly every L* galaxy, **even ellipticals**, to 150 kpc.

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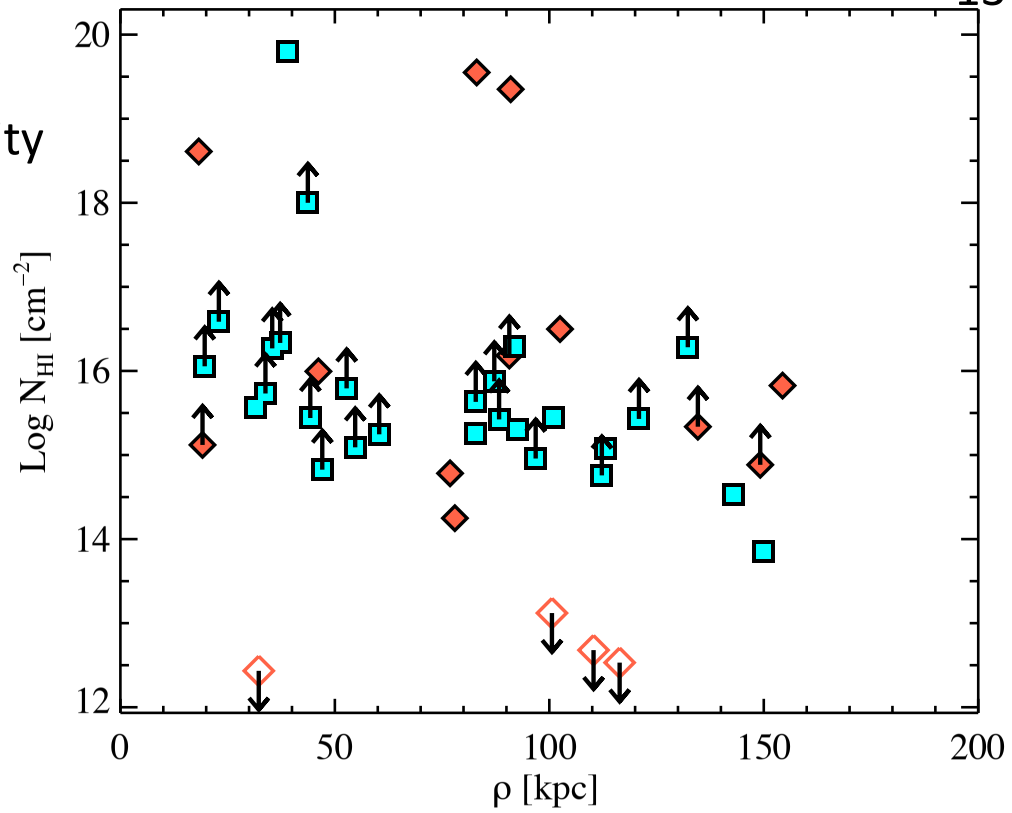

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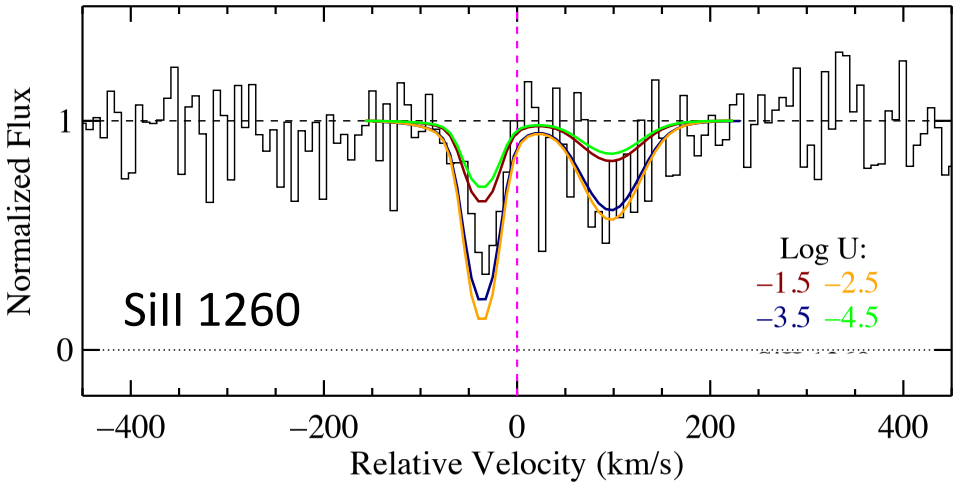
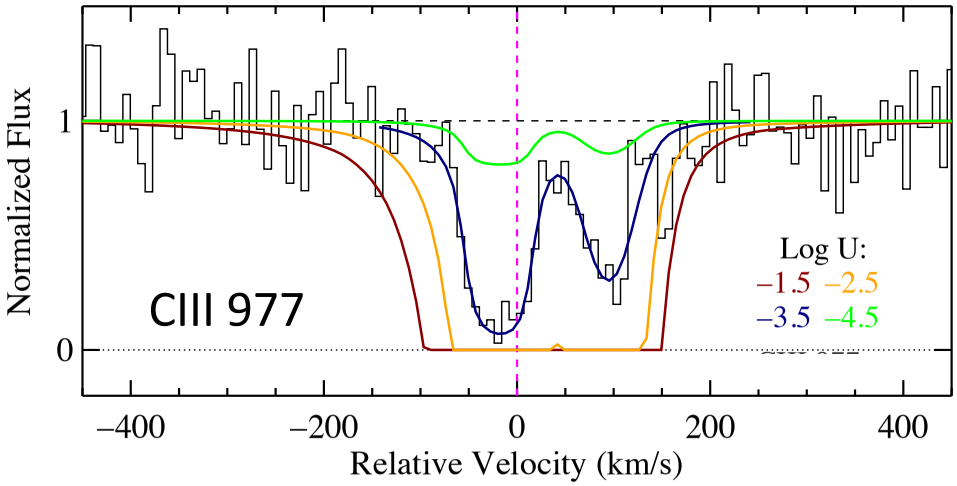
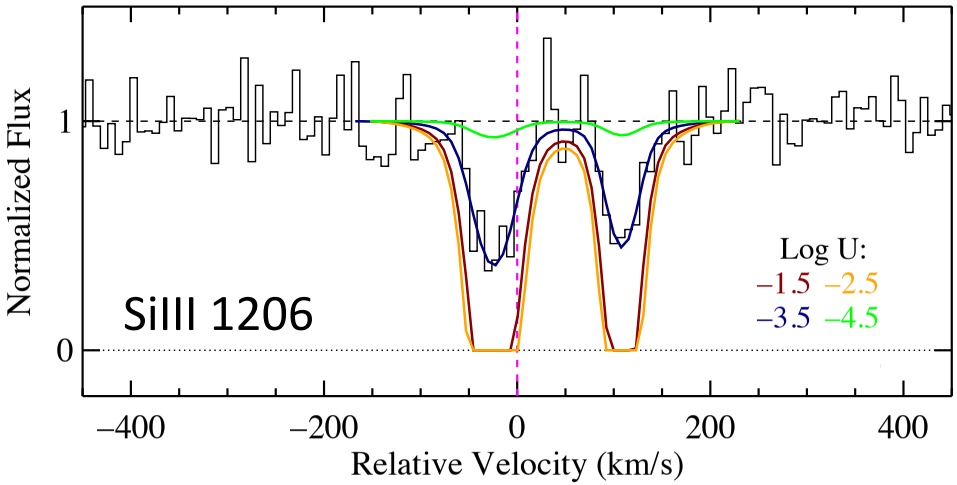
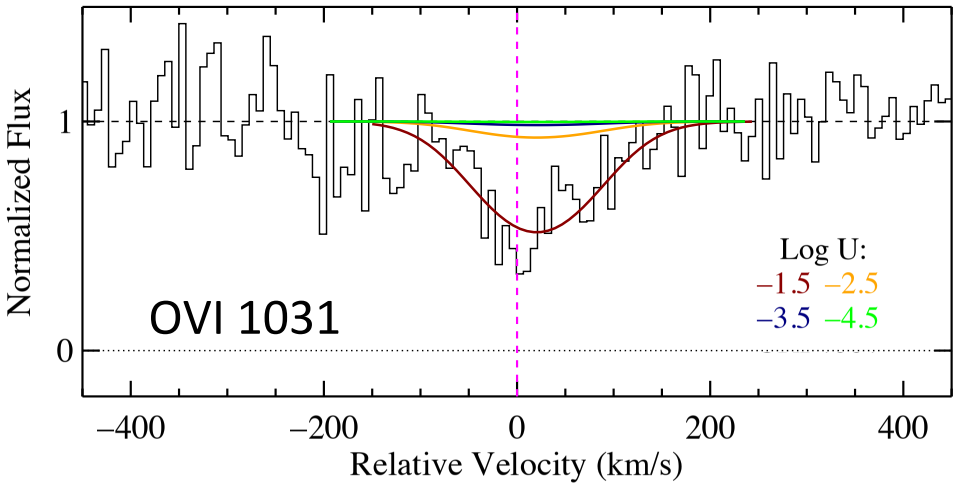
Find the Ionization Parameter

Case Study: J1330+2813 289_28







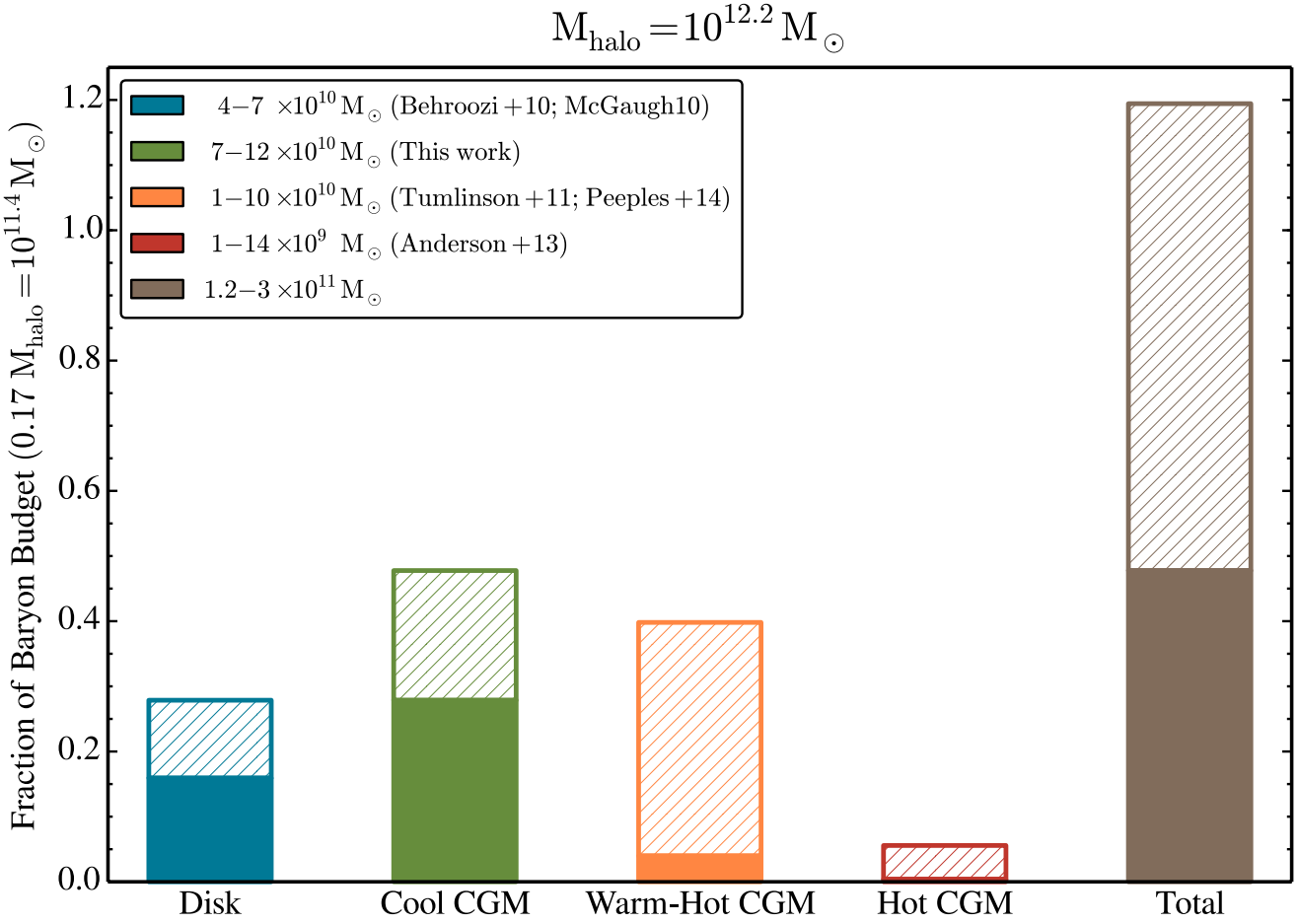


For a grid of Log N_{HI} (known = 16.6) &
Log [M/H] (Log U fairly independent of this value)

Mass of the CGM

Werk+ 2014:
$M_{CGM} > 2 \times 10^{10} M_{\odot}$

Stocke+2013:
$M_{CGM} > 10^{10} M_{\odot}$

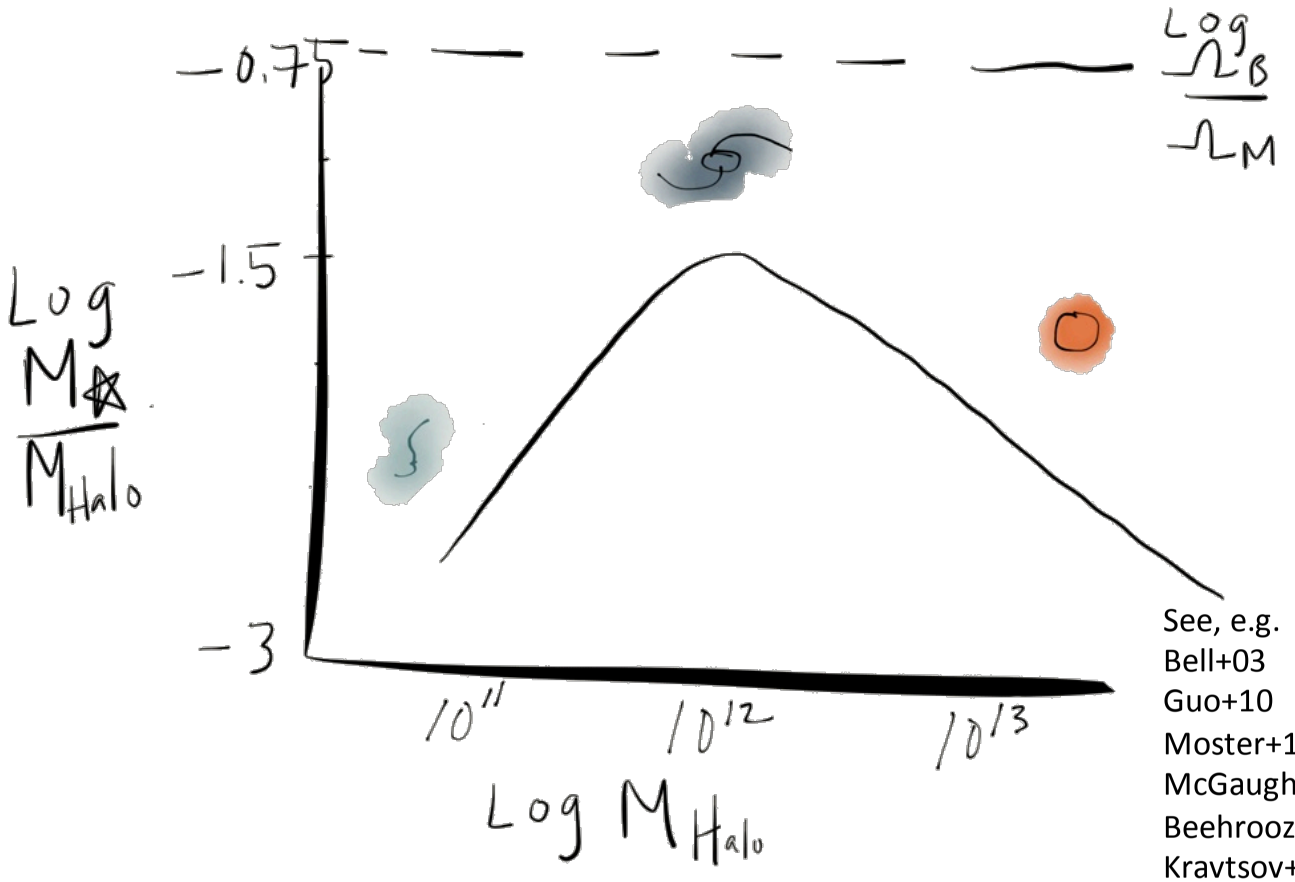


The CGM is a major reservoir of galactic baryons, containing at least as many as the disk, and within reach of closing the baryon budget around L* galaxies (Werk+14)

Baryons and Dark Matter

How much baryonic mass does the CGM contribute?

A: At least as much as the stars, potentially the rest of the missing baryons.



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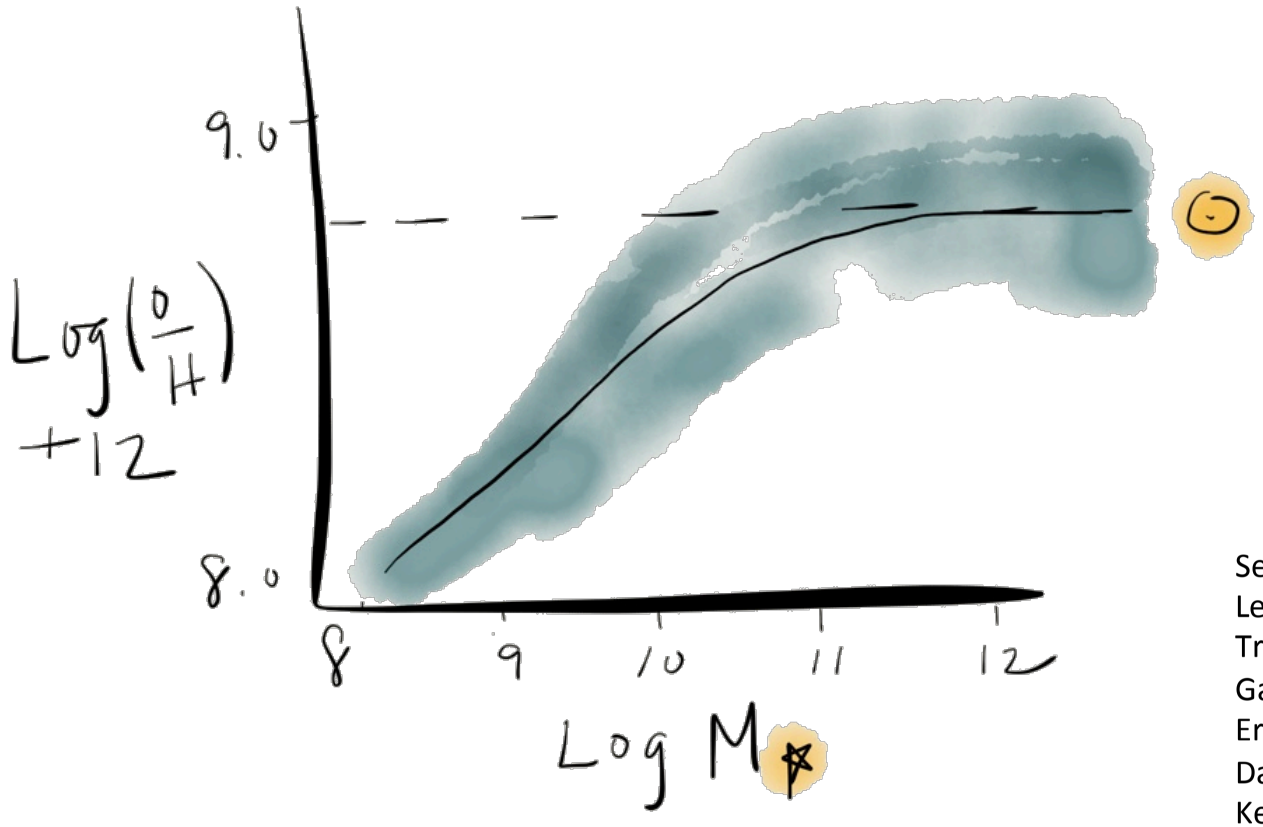
The Mass-Metallicity Relation

Can the metal content of the CGM help explain this relation?

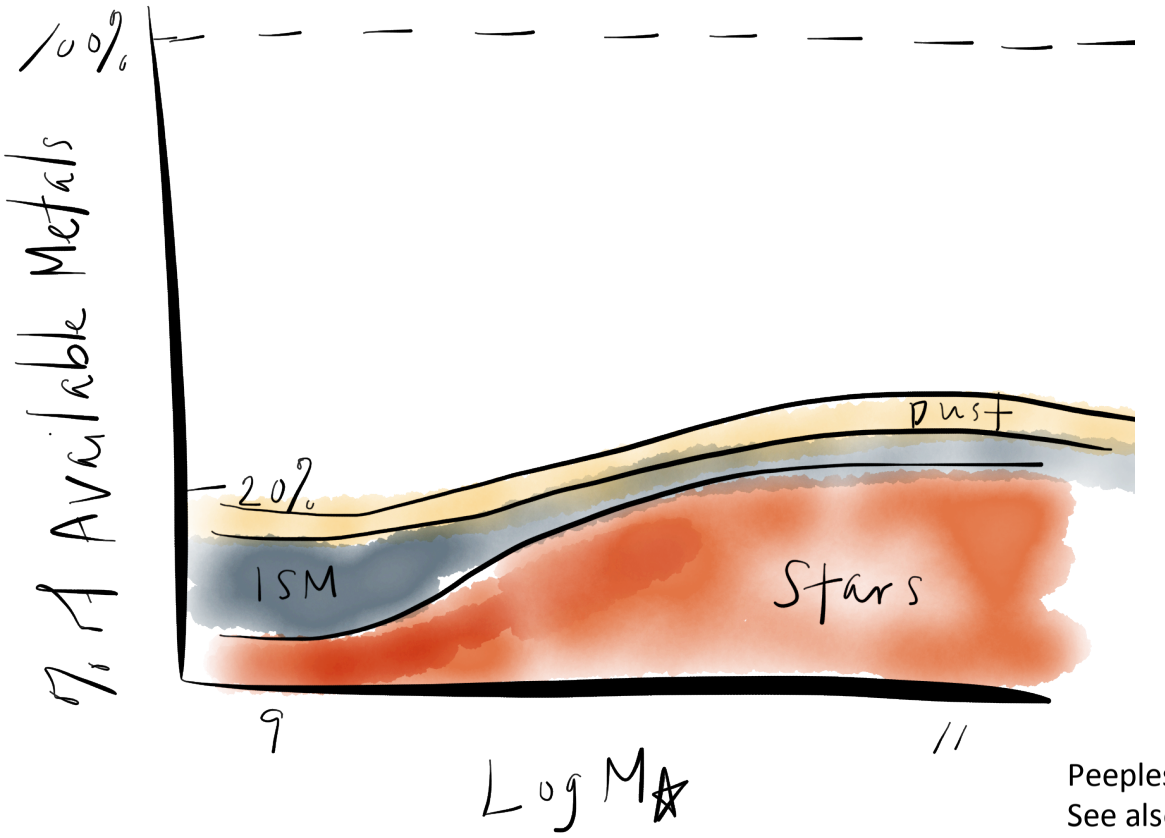


See e.g.
Lequeux+79
Tremonti+04
Gallazzi+05
Erb+06
Dalcanton 07
Kewley+08
+ many more

M-Z relation extends over three decades of stellar mass and out to z~3; Why?

The Missing Metals

Does the CGM harbor these 'missing' metals?



Peeples+14
See also: Zahid+12

Galaxies are missing ~80% of the metals they have generated over their SFHs

The Metal Mass of the CGM

Silicon (Low-Ions)

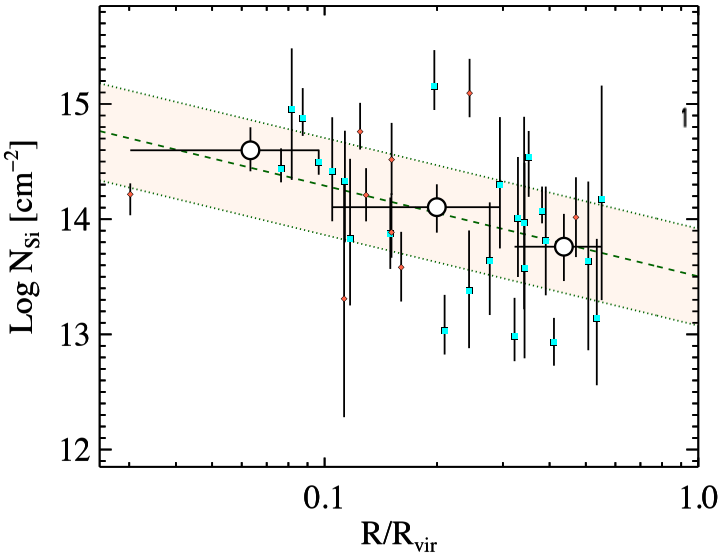
Werk+2014 (CLOUDY):
$M_{silicon}$ = 2.9 x 10^6 $M_\odot$

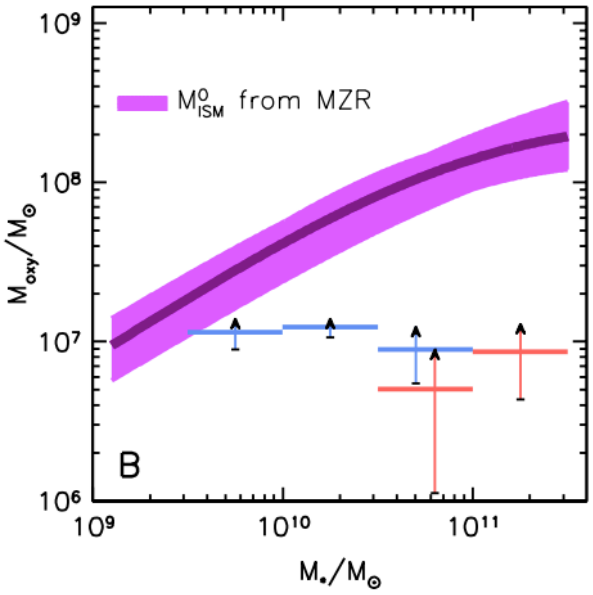
Oxygen (High-Ions):

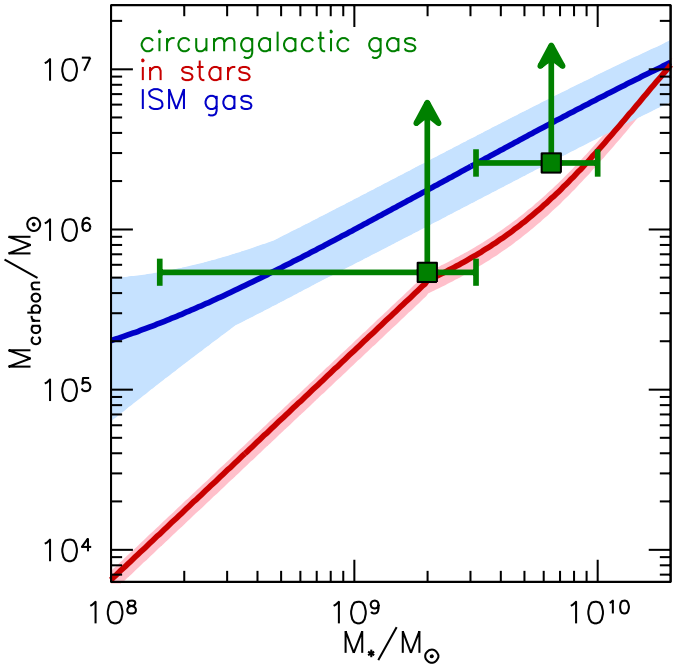
Tumlinson+2011 (max f_{OVI}):
$M_{oxy} > 1.2 \times 10^7 (0.2/f_{OVI})\ M_\odot$

Carbon (Low? High?)

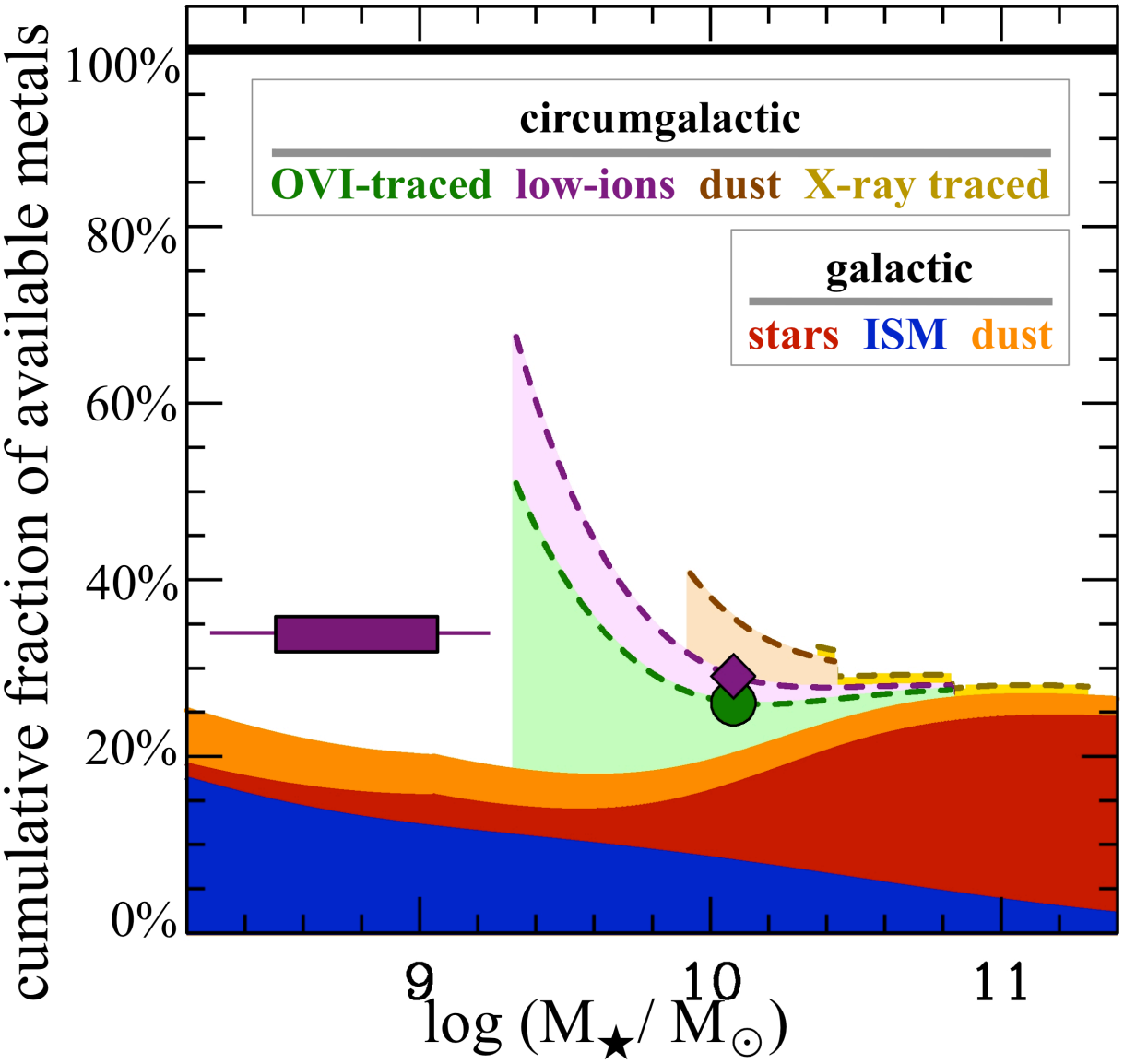
Bordoloi+2014 (max f_{CIV}):
$M_{carbon} > 1.2 \times 10^6 (0.3/f_{CIV})\ M_\odot$







Oxygen "Deficits" in Local SF Galaxies



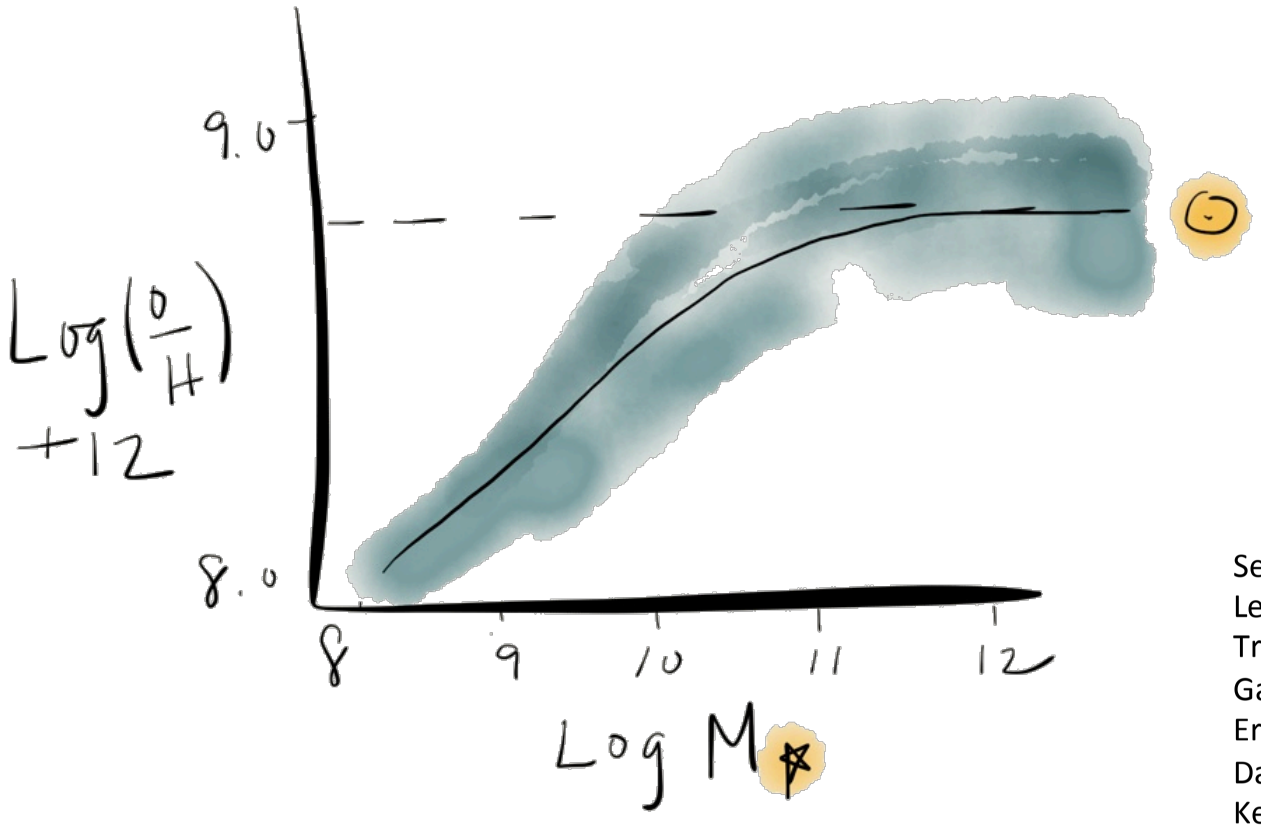
30 – 60% still missing

Peeples et al. 2014 -- Galaxy Metal Census, see also Zahid et al. 2012

The Mass-Metallicity Relation

Can the metal content of the CGM help explain this relation?

A: A substantial fraction of the metals generated by a galaxy over its lifetime are in the CGM.



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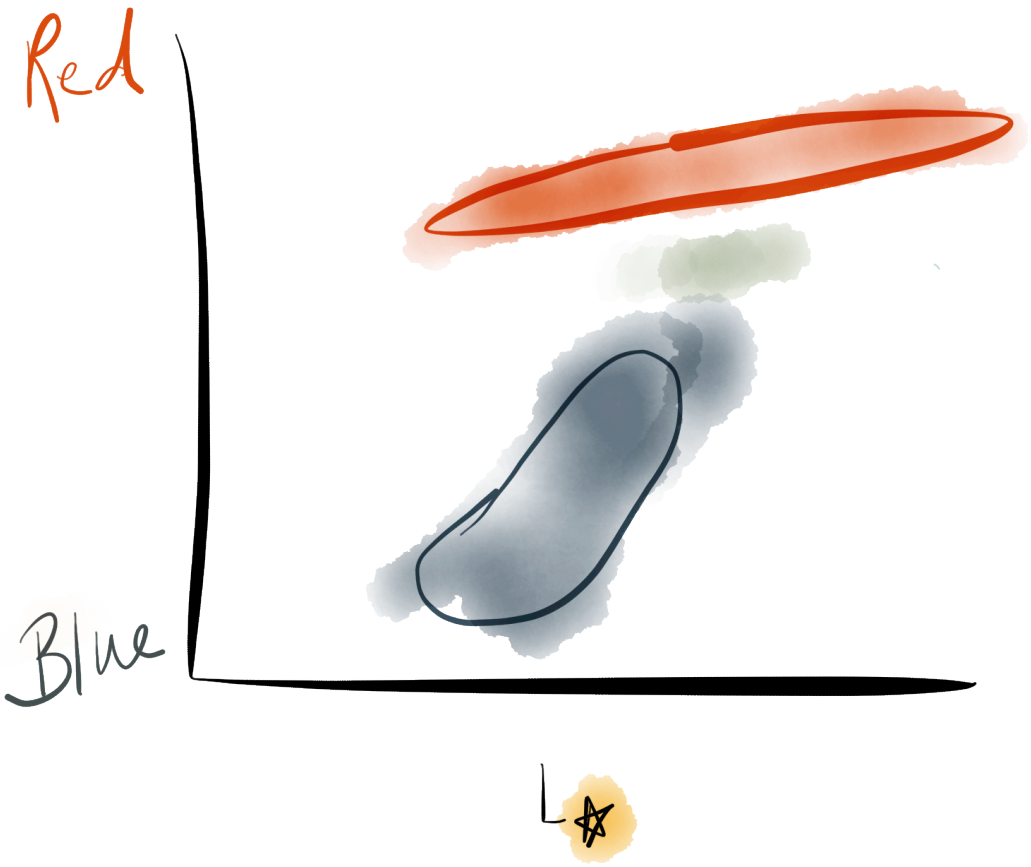
Red-Blue Dichotomy and Quenching

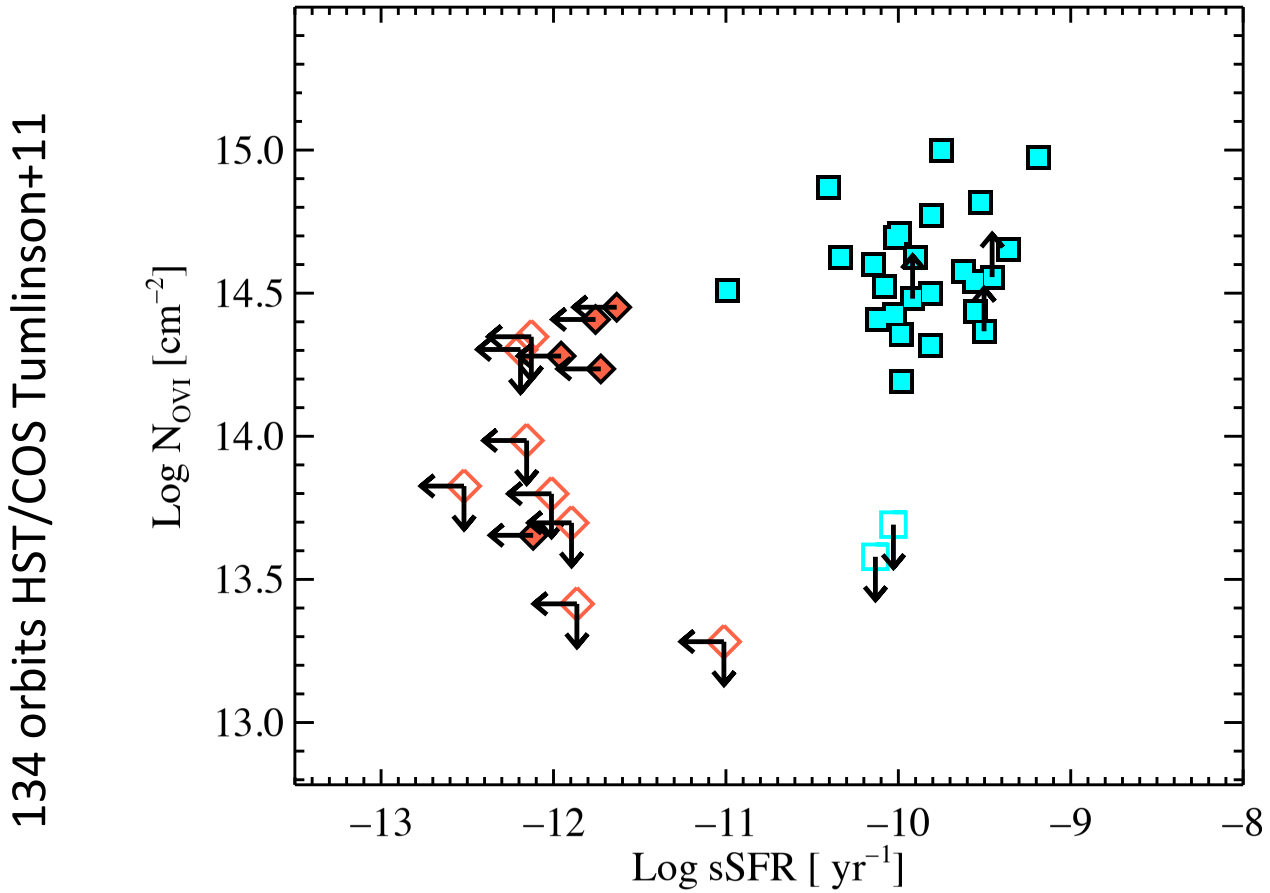
Is this dichotomy reflected by the CGM properties?



See e.g.
Mathews & Baker 71
Blanton+2003
Faber+07
Drory+09
Tomczak+14
+many more

Some galaxies eventually stop forming stars; what triggers and maintains quenching?

Highly Ionized CGM Traced by OVI Correlates with SFR



See also Bordoloi+14 for CIV

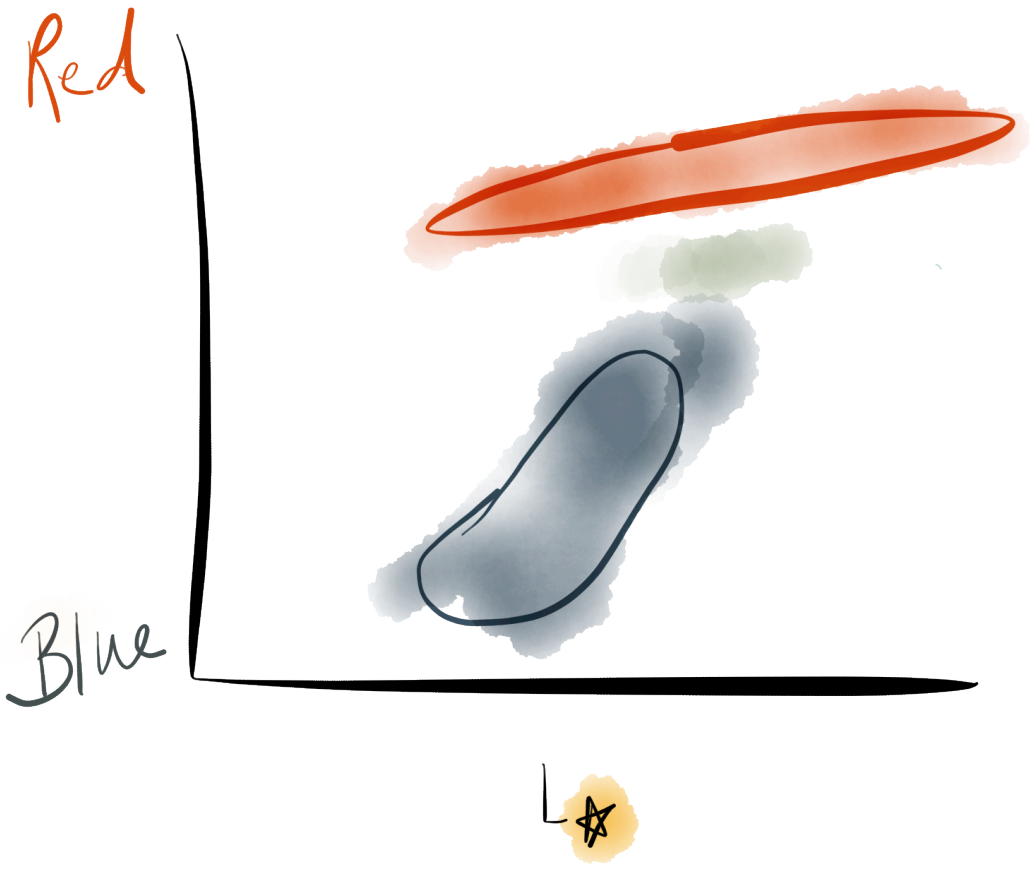
3 nights Keck LRIS - Werk+12

Quenching appears to modify the abundance of high ionization state gas in L* halos while leaving the colder gas mostly unaffected.

Red-Blue Dichotomy and Quenching

Is this dichotomy reflected by the CGM properties?

A: Yes, in the highly ionized gas phases.



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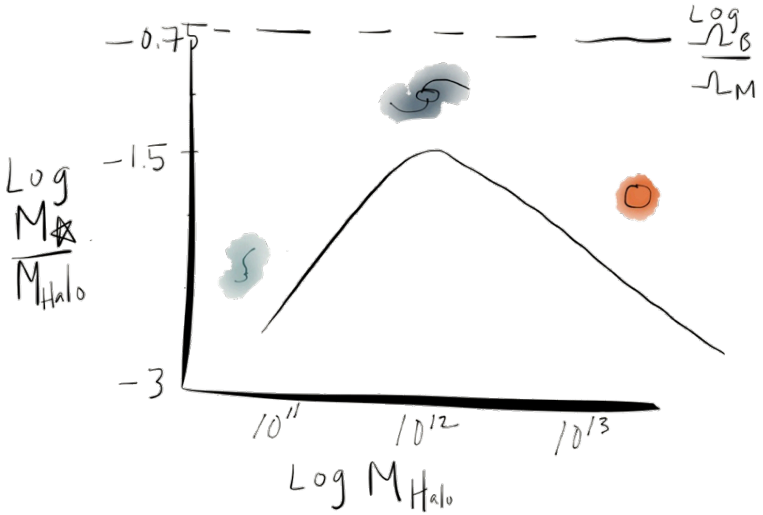
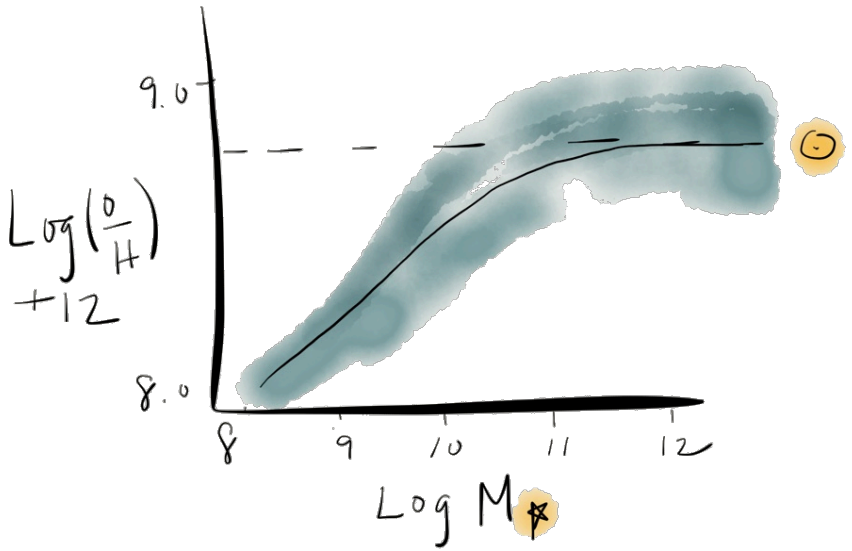
CGM Take Away

Circum-galactic gas contains a substantial fraction of baryons and metals, and its content is somehow modified by whatever process shuts down star formation in galaxies.





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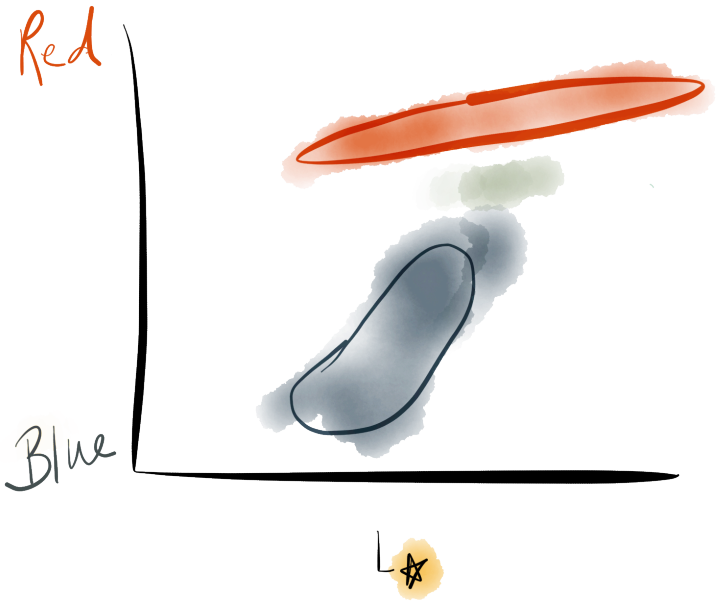
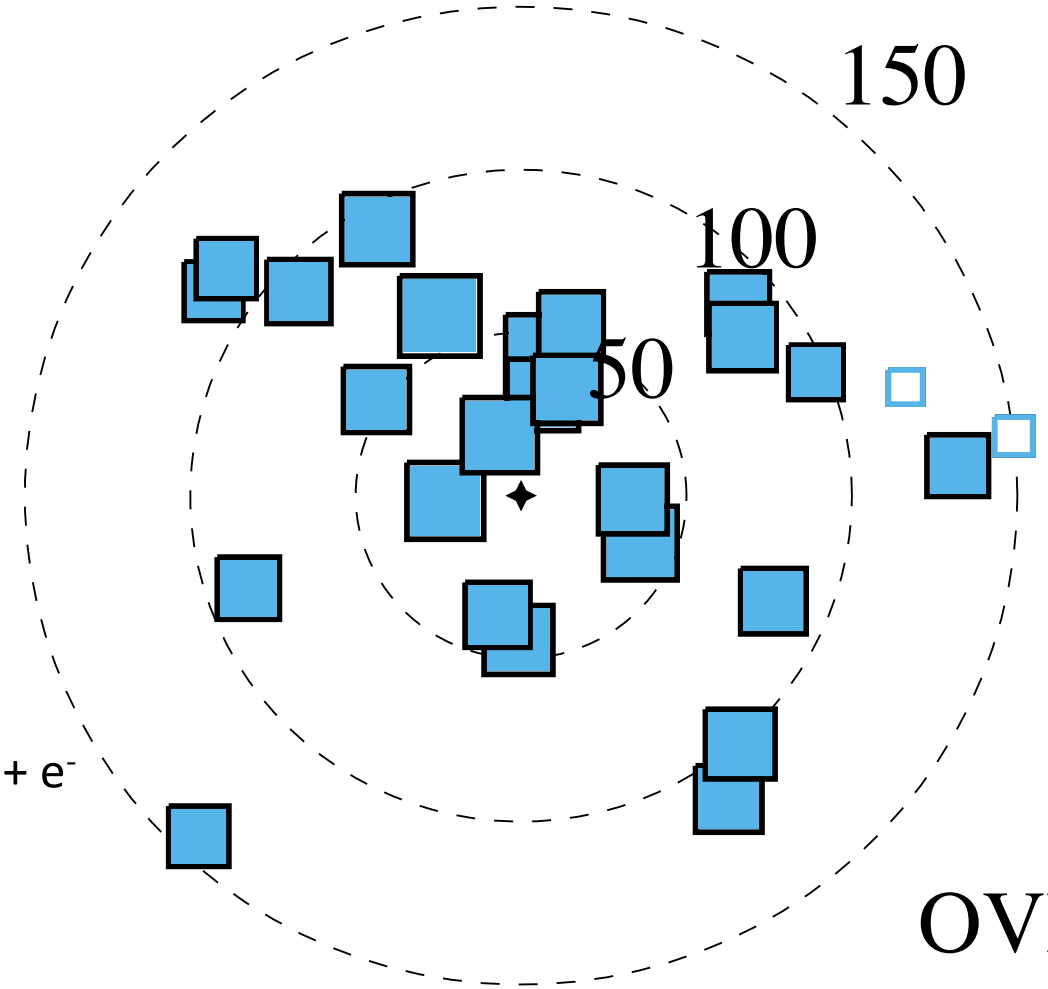


il Programma

- Physical Conditions in the Highly-Ionized CGM (aka How is OVI ionized?)

- Distribution of OVI in galaxy halos with respect to major/minor axes

Observed Properties of the CGM: The High-Ions (aka OVI)

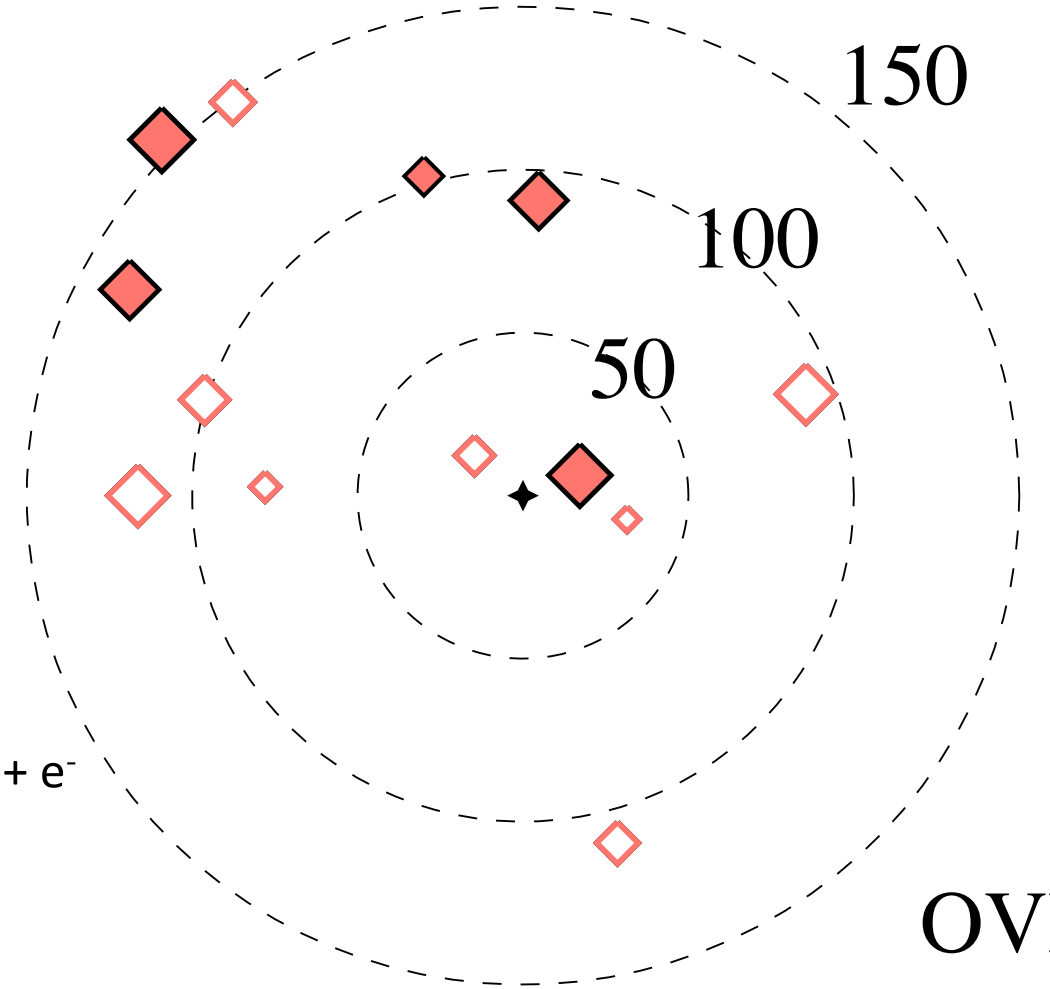


OV + 113.9eV ➔OVI + e^-

$T_{CIE} = 10^{5.5}$ K

OVI is ubiquitous in the CGM of star-forming galaxies (Tumlinson +11; Werk+12)

Observed Properties of the CGM: The High-Ions (aka OVI)



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OVI is rarely found in the CGM of quiescent galaxies, when it is, it is weak, and the incidence does not depend on impact parameter. (Tumlinson +11; Werk+12)

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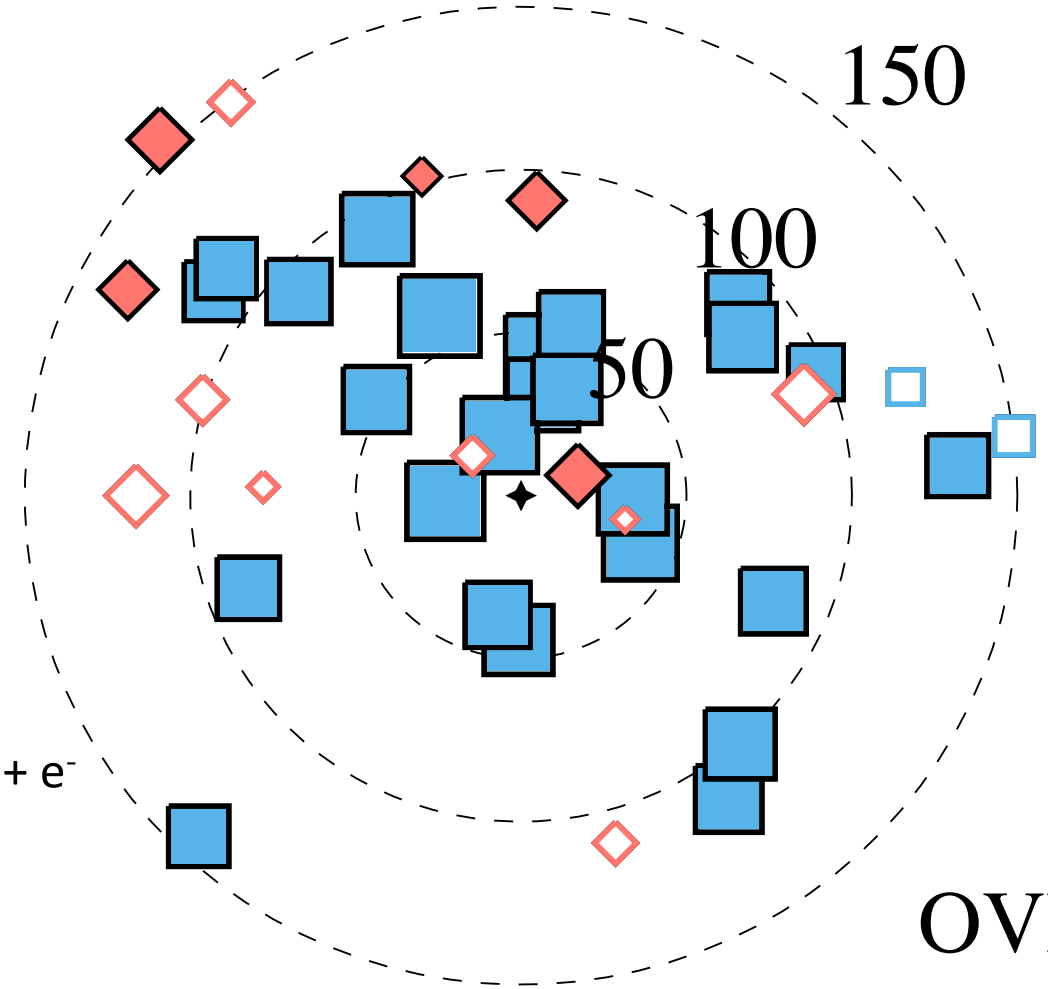

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A Possible Clue: There is no NV detected in the CGM

Other High Ions?

SiIII + 33.5eV ➔SiIV + e^-
$T_{CIE} = 10^{4.7}$K

NIV + 77.5eV ➔NV + e^-
$T_{CIE} = 10^{5.1}$K

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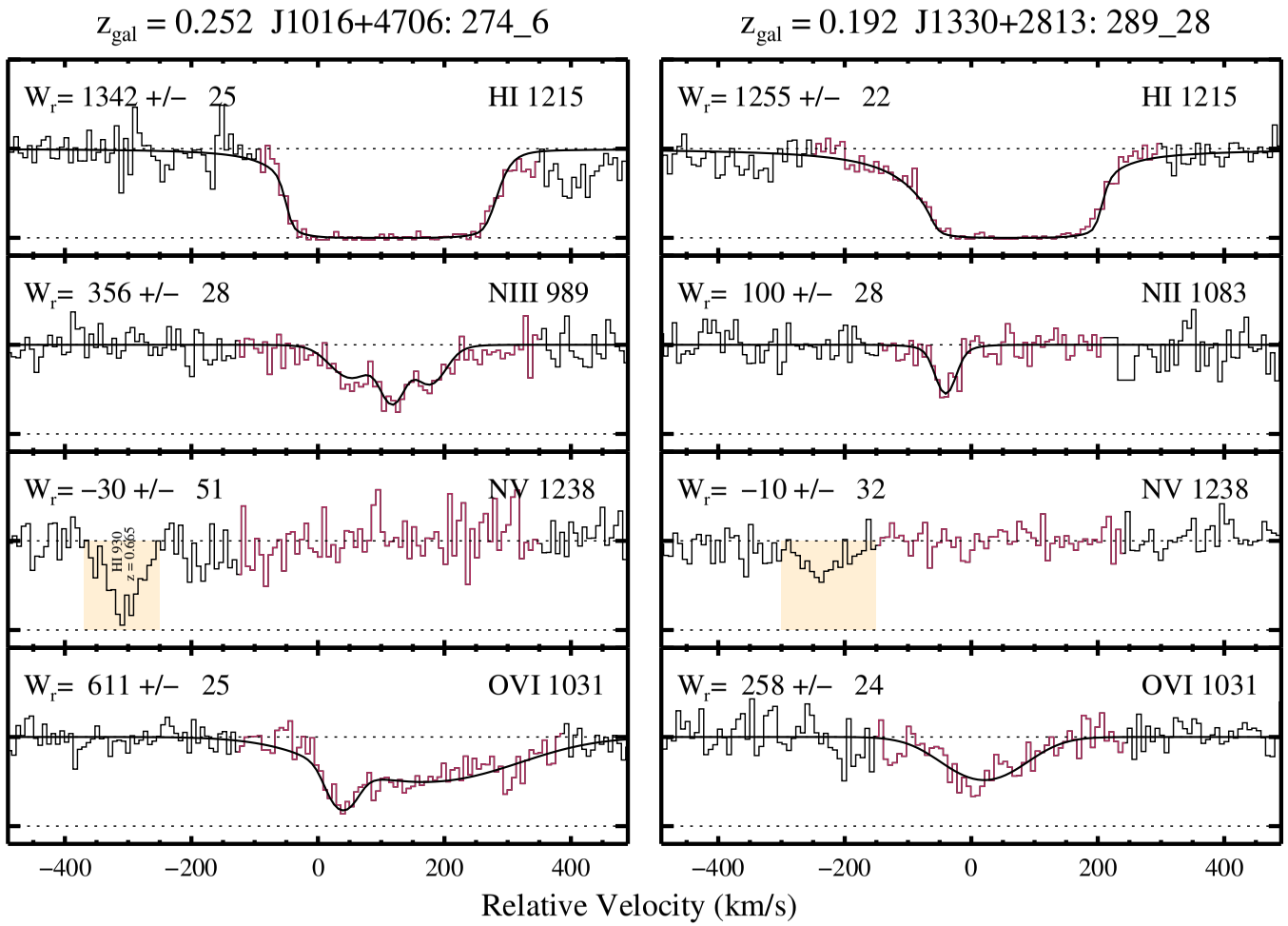
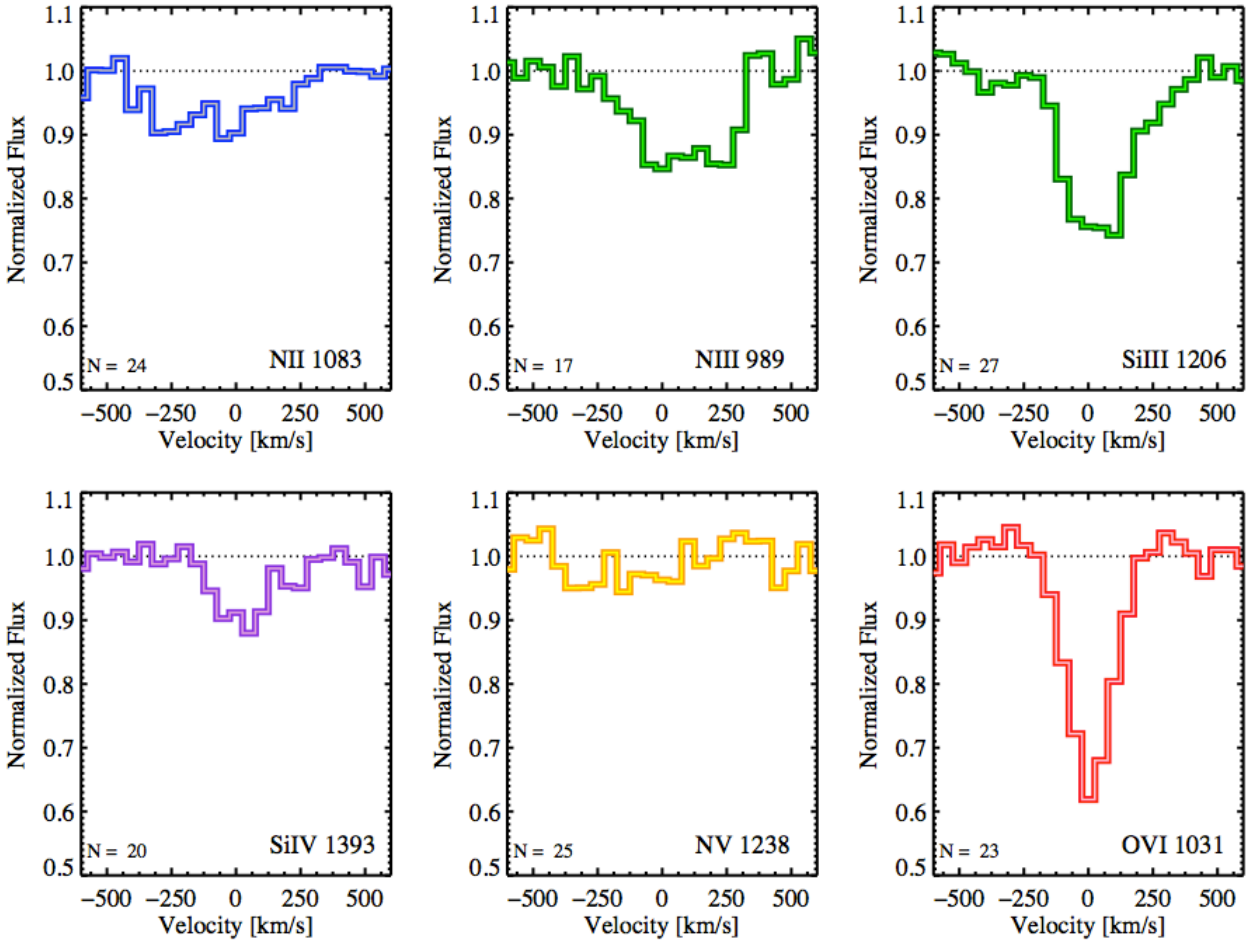


Werk+15

A Possible Clue: There is no NV detected in the CGM

COS-Halos Stacked Data



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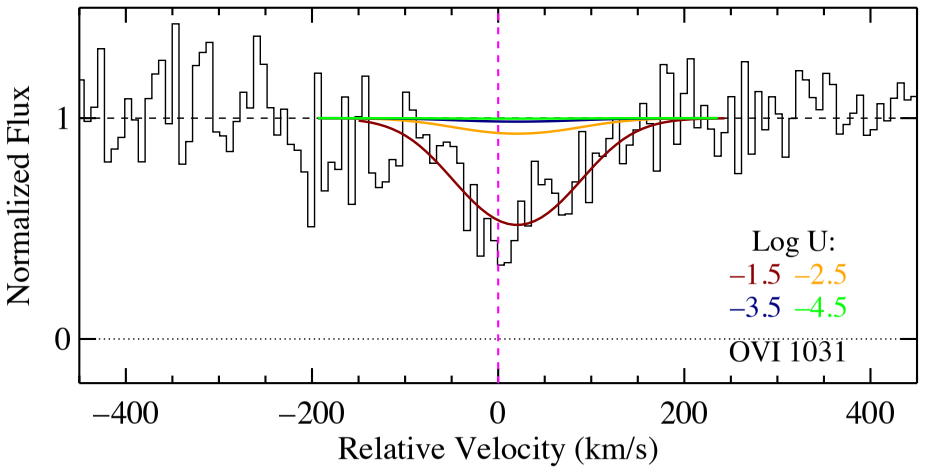
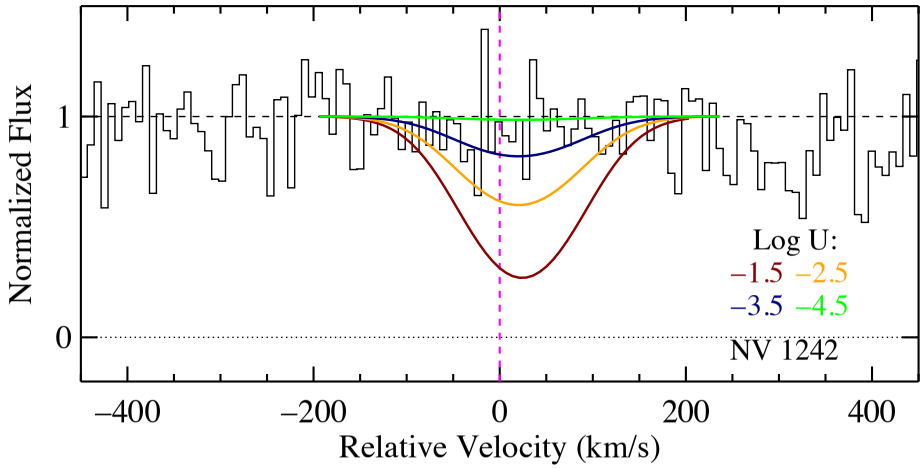
Photoionization by an EUVB predicts…





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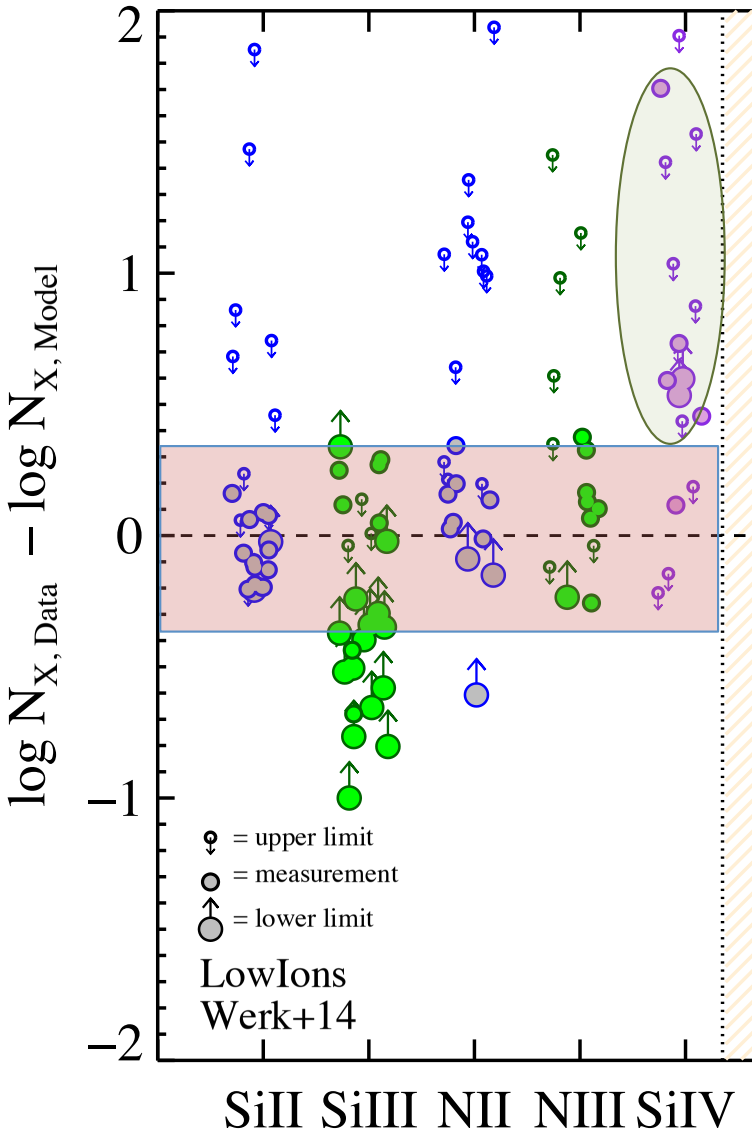
SiIV Is Not a Well-behaved Low-Ion

SiI + 8.2eV ➔SiII + e^-
$T_{CIE} = 10^{4.2}$

SiII + 16.3eV ➔SiIII + e^-
$T_{CIE} = 10^{4.5}$K

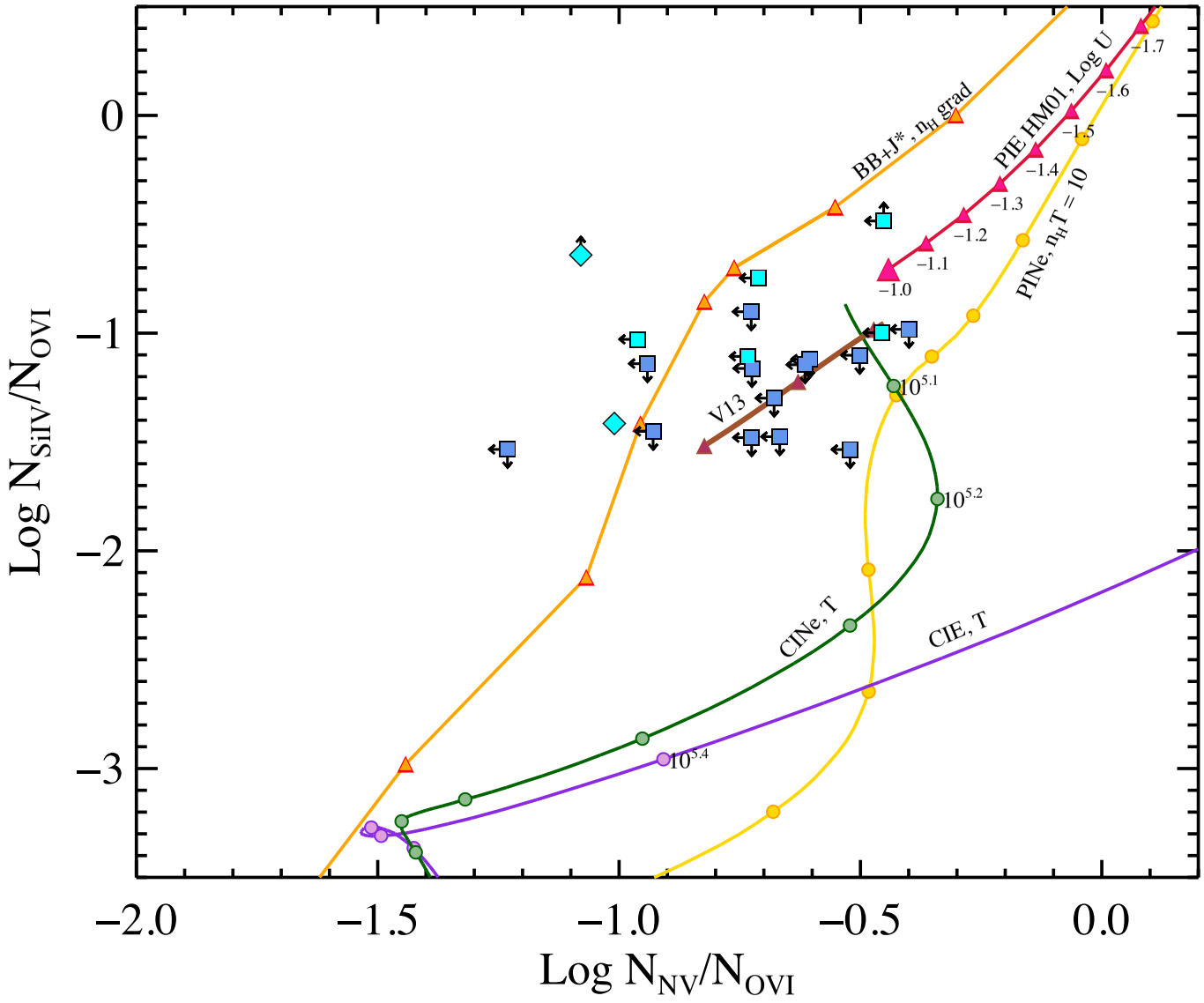
SiIII + 33.5eV ➔SiIV + e^-
$T_{CIE} = 10^{4.7}$K



See also poster by Laura Corlies

0.5 dex too much SiIV compared to best-fitting ‘low-ion’ cloudy models

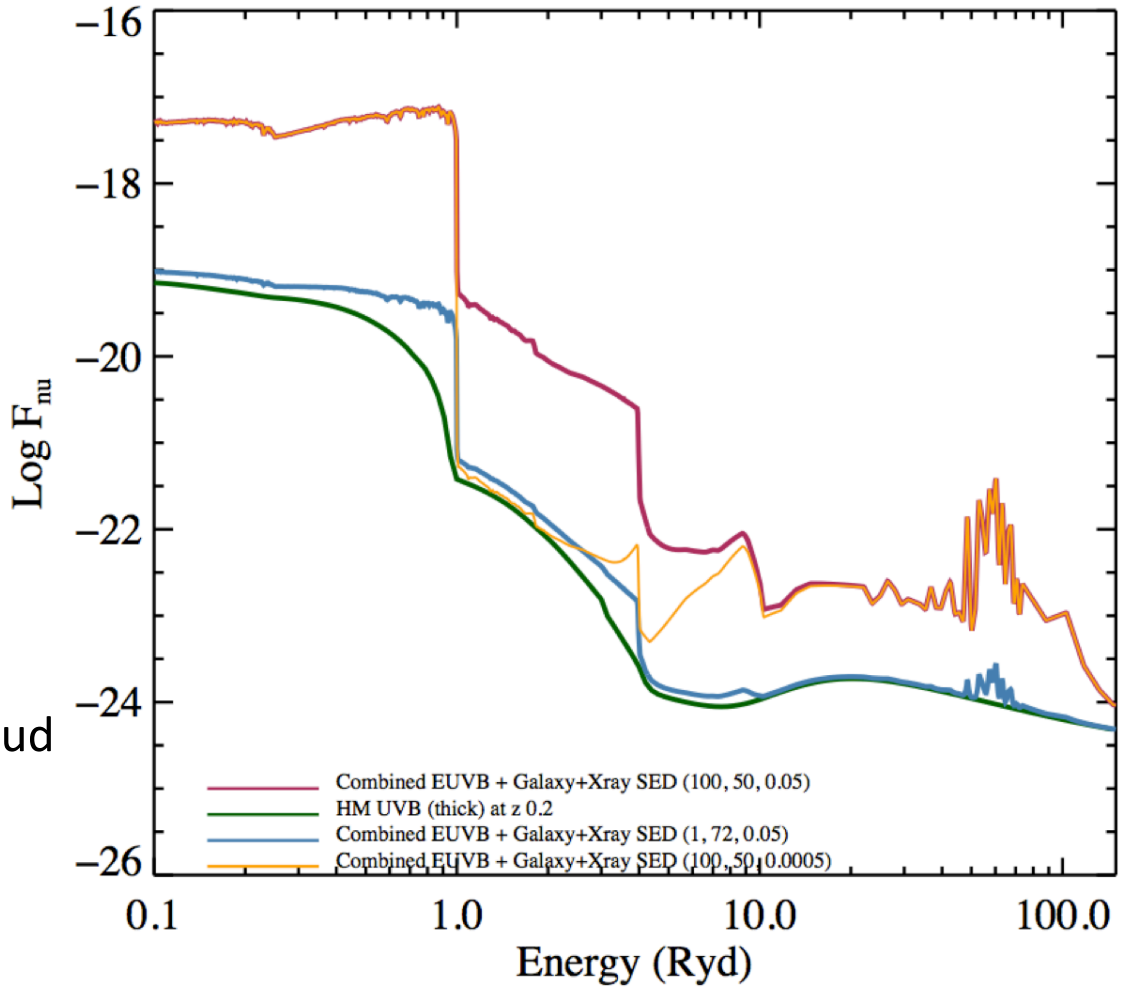
Common Ways of Getting OVI are Ruled Out by Data



Saving Photoionization: Cantalupo to the Rescue

Cantalupo 2010:
SN and XRBs produce soft x-rays
Tunables: Galaxy N_{HI}, SFR, d, f_{esc}

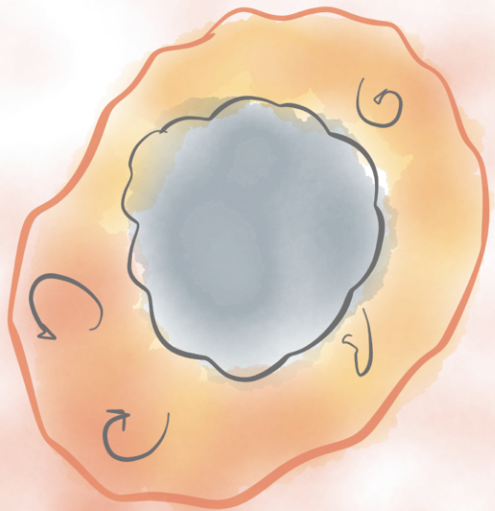
To fit NV/OVI:
Log N_{HI} = 20
SFR = 100
F_{esc} = 10% (or lower)
Steep density gradient in absorbing cloud



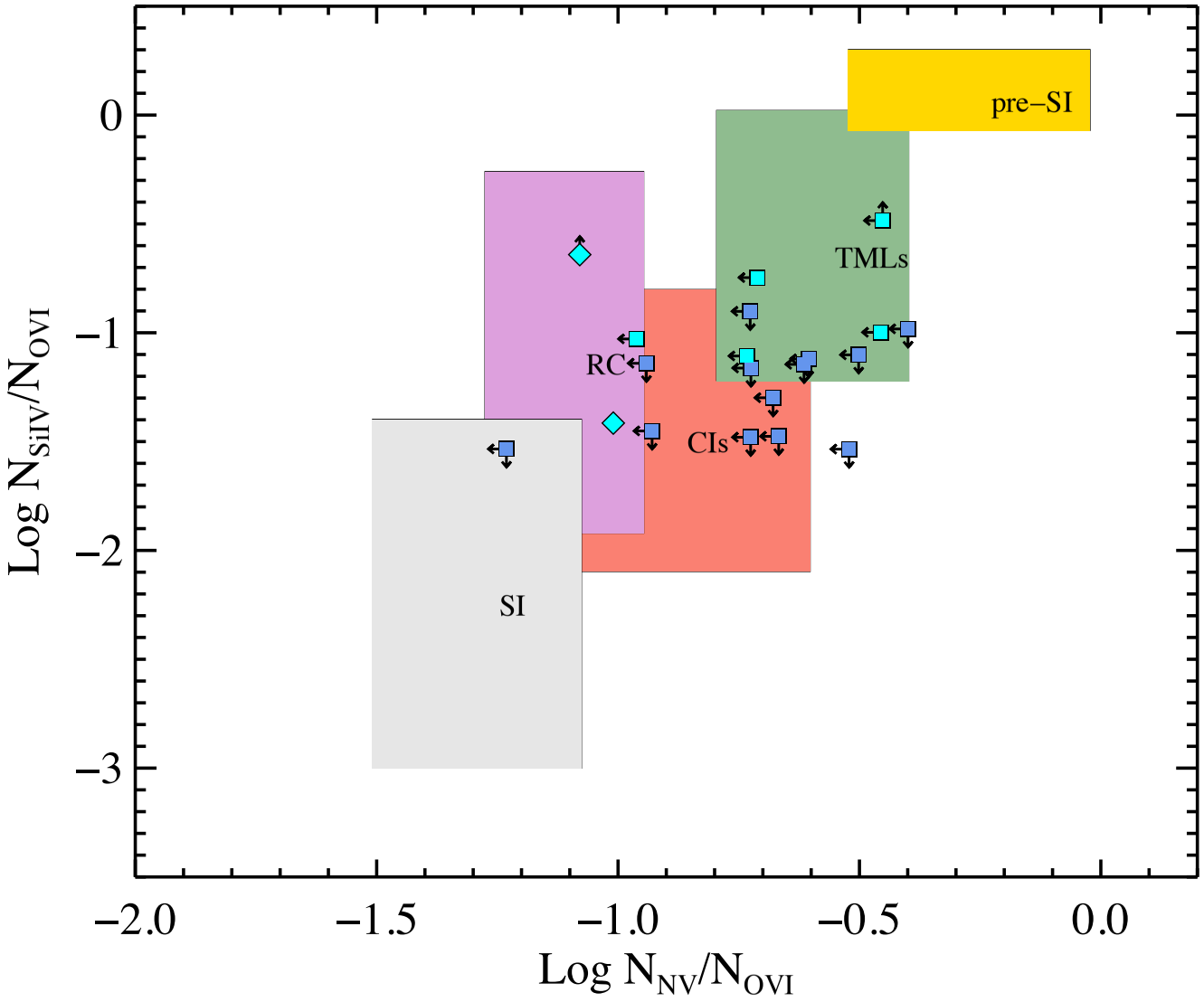
Intensity of extra component: > 2 orders of magnitude greater than EUVB at 10 Ryd

Other Non-Equilibrium Models

- Shock Ionization (Dopita 96; Gnat+09)
- Radiative cooling in a moving flow (Edgar+86; Shapiro+91):
- Turbulent Mixing Layers (Begelman+90; Slavin+93, also poster by Lucia Armillotta on disk-halo interface):
- Conductive Interfaces (Borkowski+90; Gnat+10)

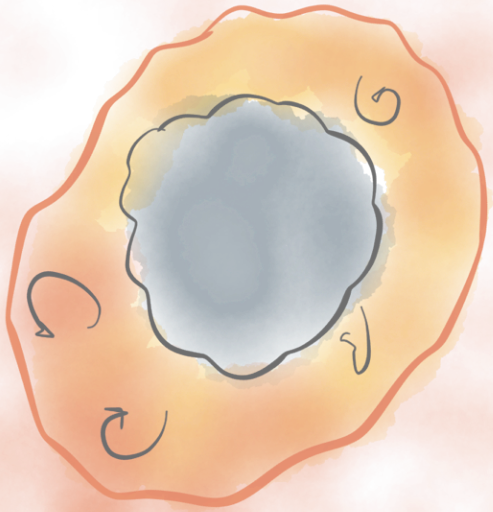


Complex Collisional Ionization Out of Equilibrium



Other Non-Equilibrium Models

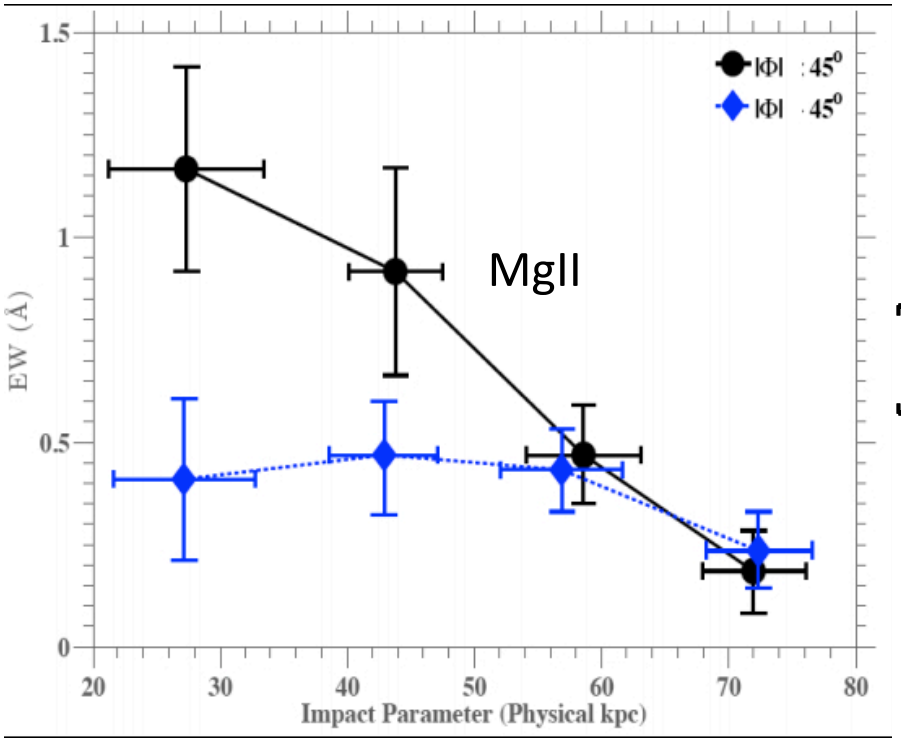
- Shock Ionization (Dopita 96; Gnat+09): Not enough SiIV
- Radiative cooling in a moving flow (Edgar+86; Shapiro+91): Correct Ratios; Column densities?
- Turbulent Mixing Layers (Begelman+90; Slavin+93): Wrong Ratios; Wrong Column densities
- Conductive Interfaces (Borkowski+90; Gnat+10): Low Total OVI Column density



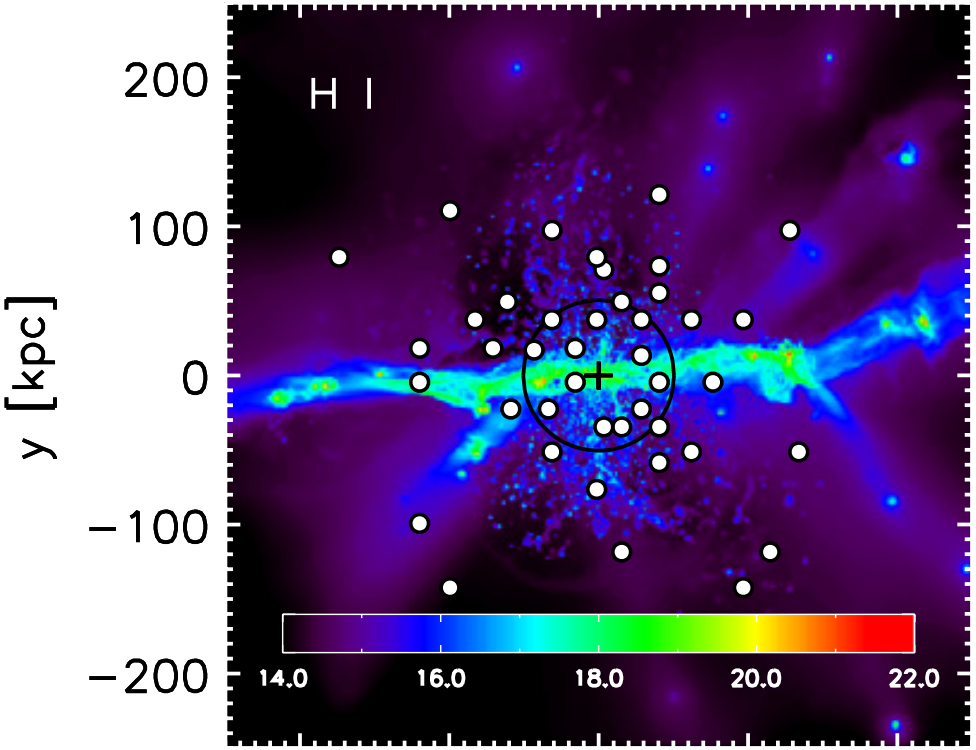
Constraining the Structure of the CGM

Recall Bouche's talk…

- Single sightlines per galaxy → one dimensional picture
- 2-D map, with basic galaxy morphological information

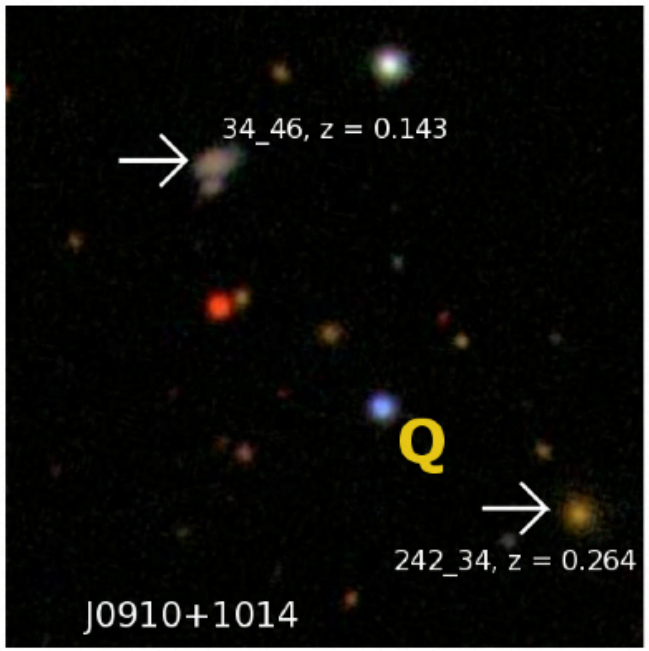


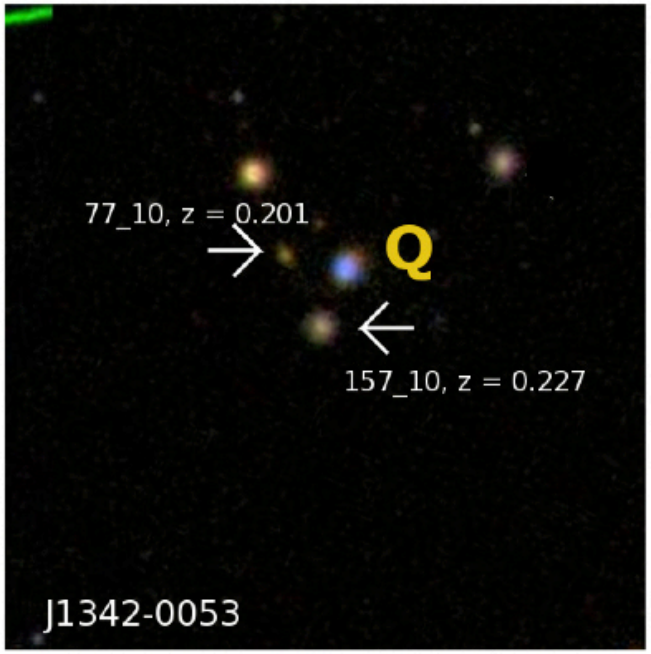
Bordoloi+11; Stacked 5000 background spectra probing 4000 galaxies in COSMOS

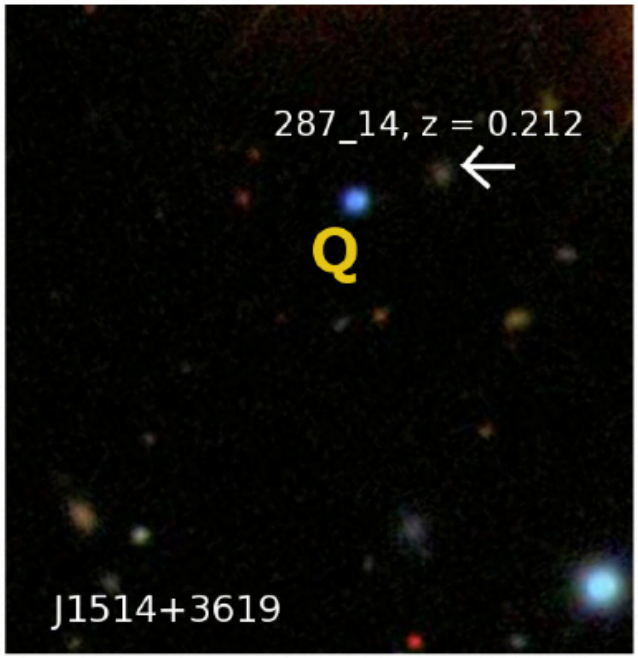


Shen+13, + COS-Halos

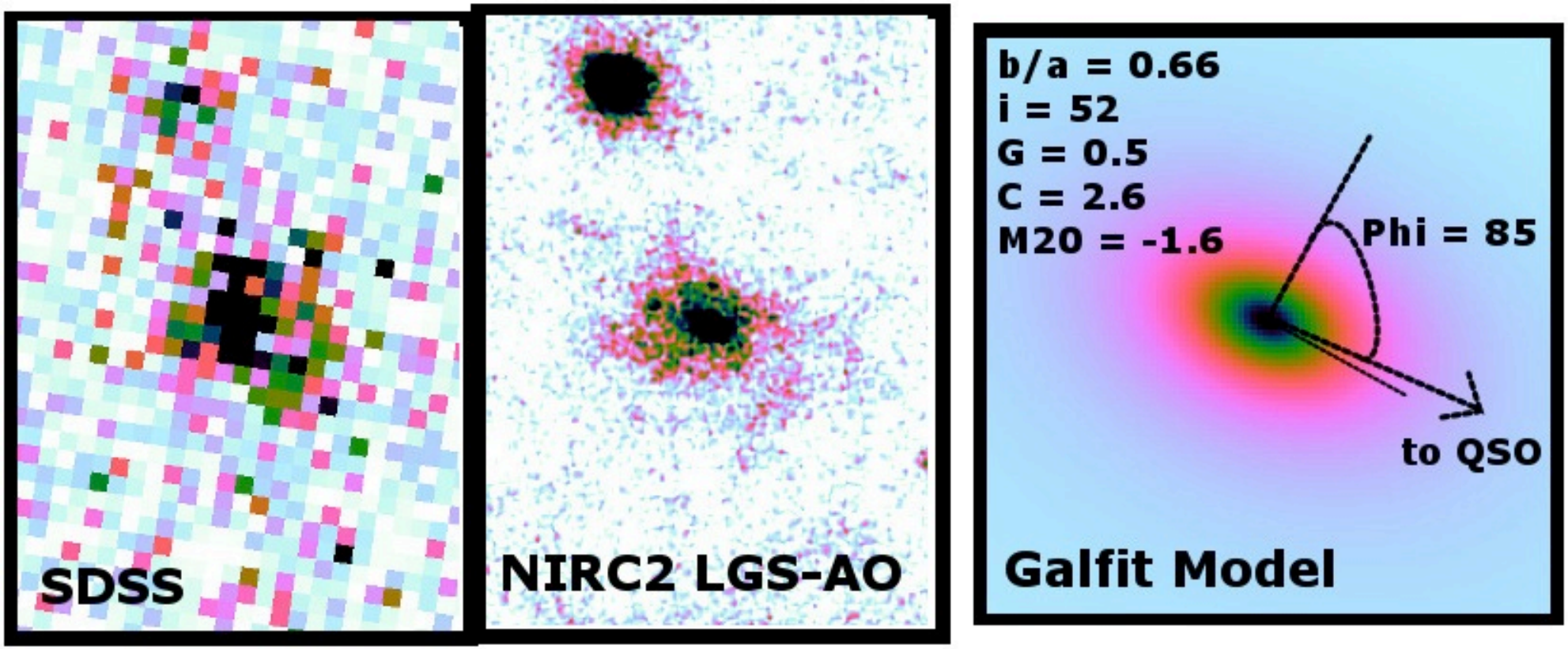
SDSS Imaging







Keck AO Imaging: K-band NIRC2 in 2014, 2015



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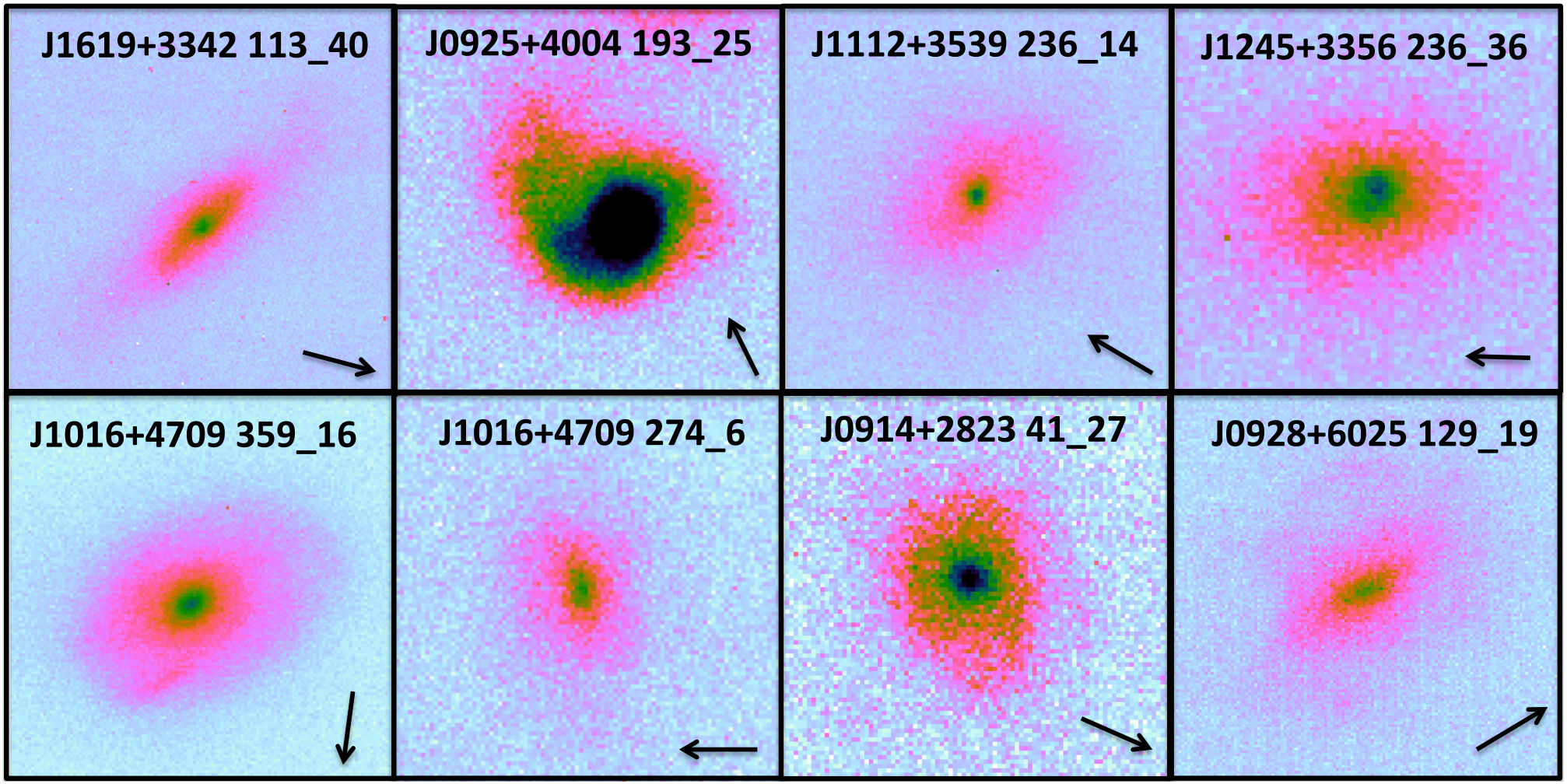
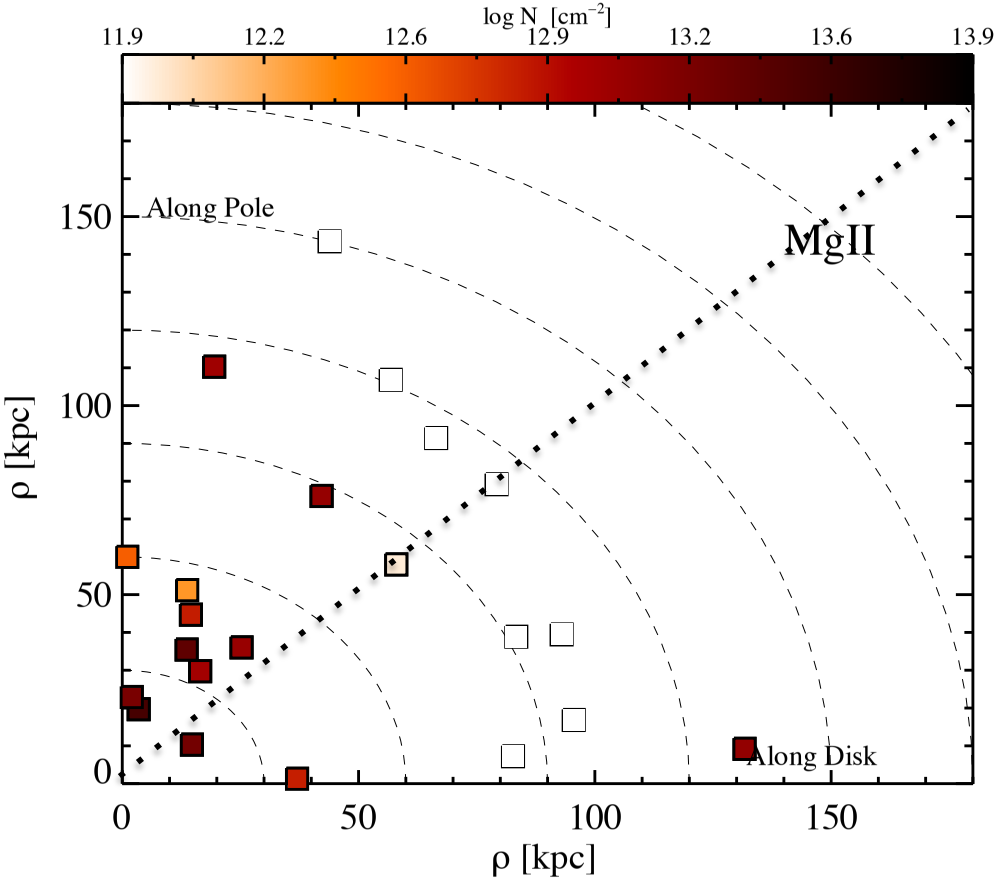


+ an HST SNAP program to image QSO fields (PI: Mulchaey) → 7 COS-Halos fields

First Map of 2-D CGM Across Ionization States, Constraints for Feedback Models



Werk+15b

Sample:
SF COS-Halos galaxies
with i > 45 degrees (non face-on)

Within 50 kpc, most COS-Halos sightlines probe the minor axis!

By ~100 kpc, the ionized metal absorption strength shows no preference for minor or major axis.

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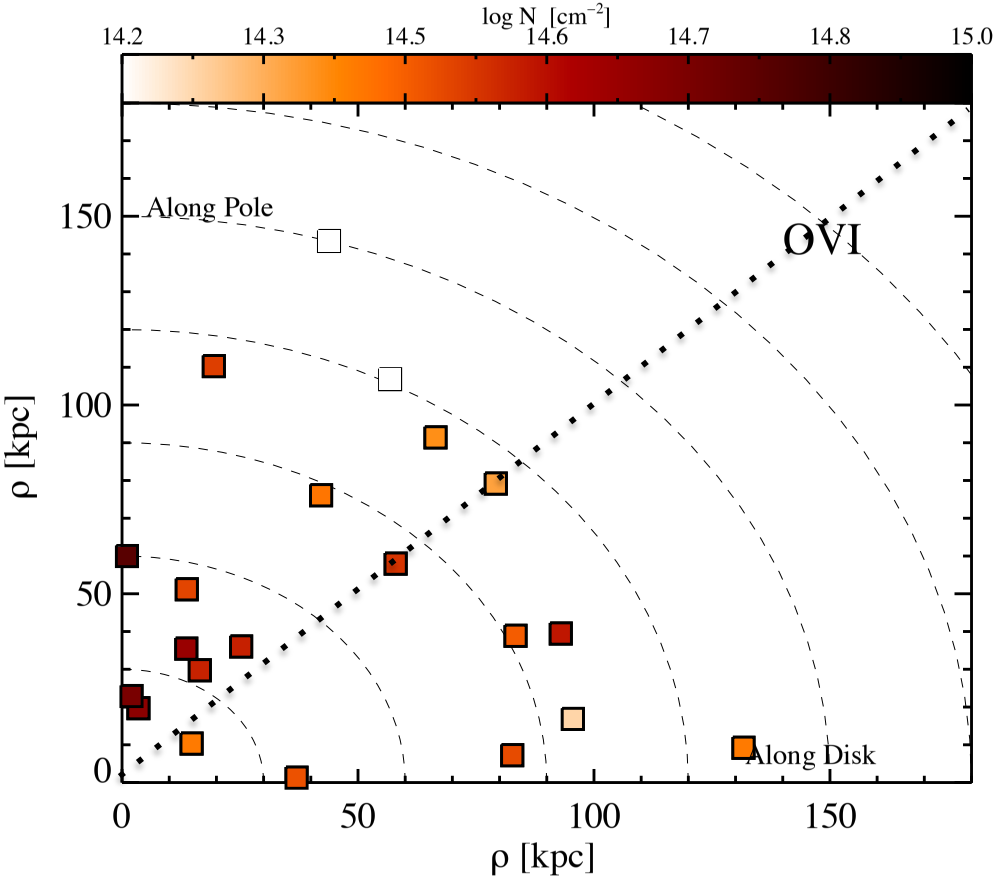

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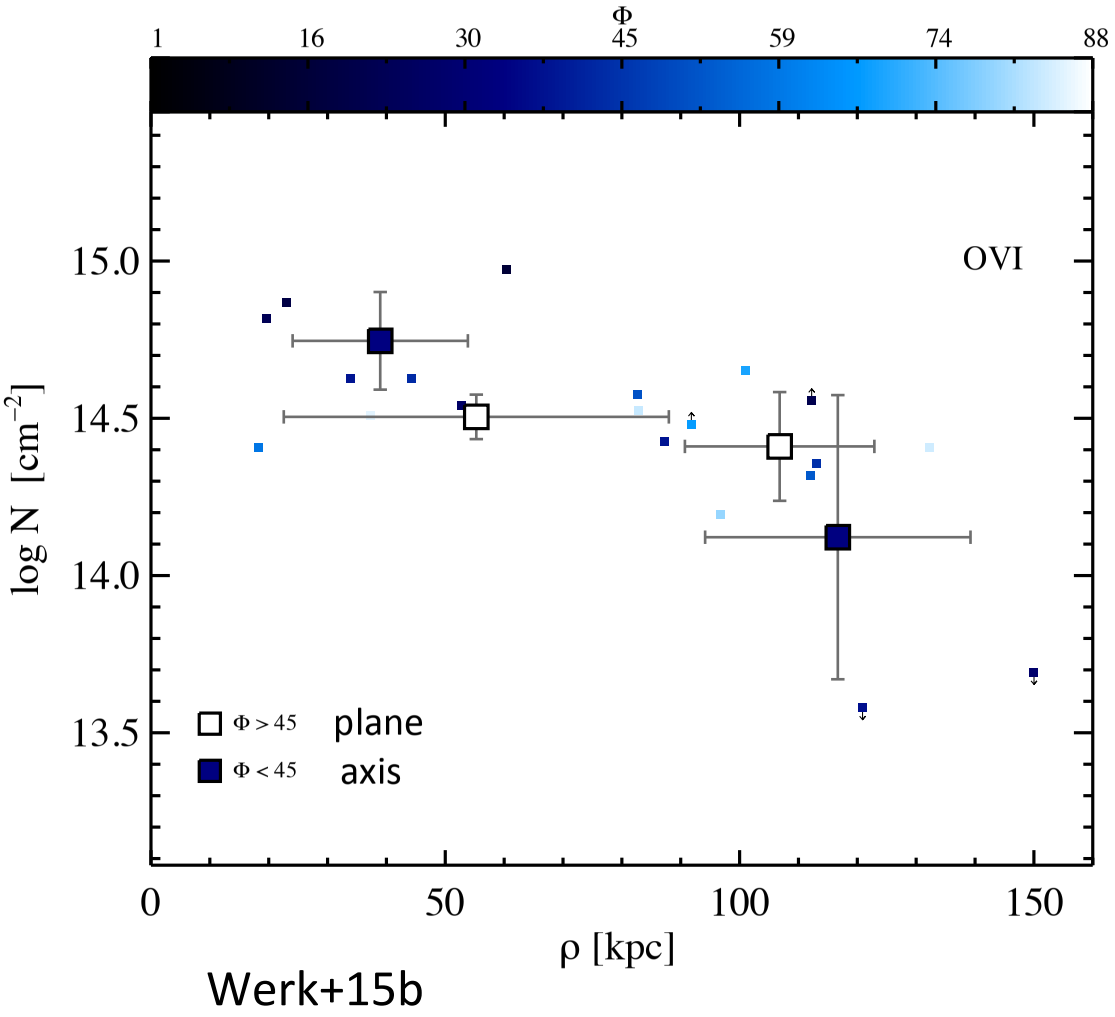

Werk+15b

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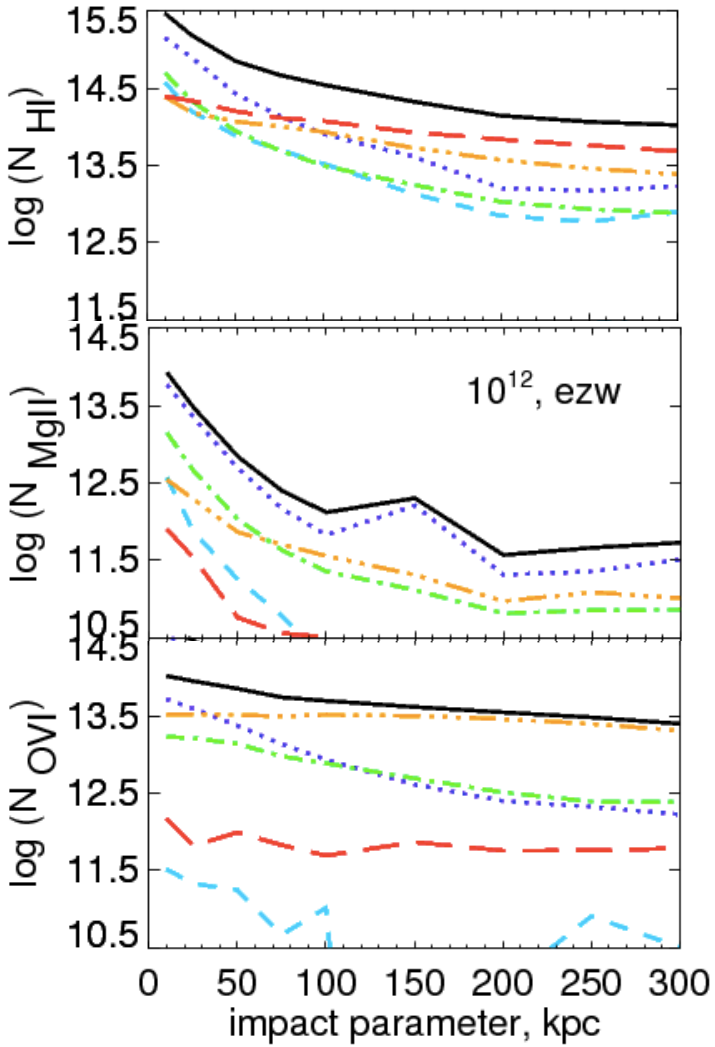
Different Phases, Different Origins

Ford+14

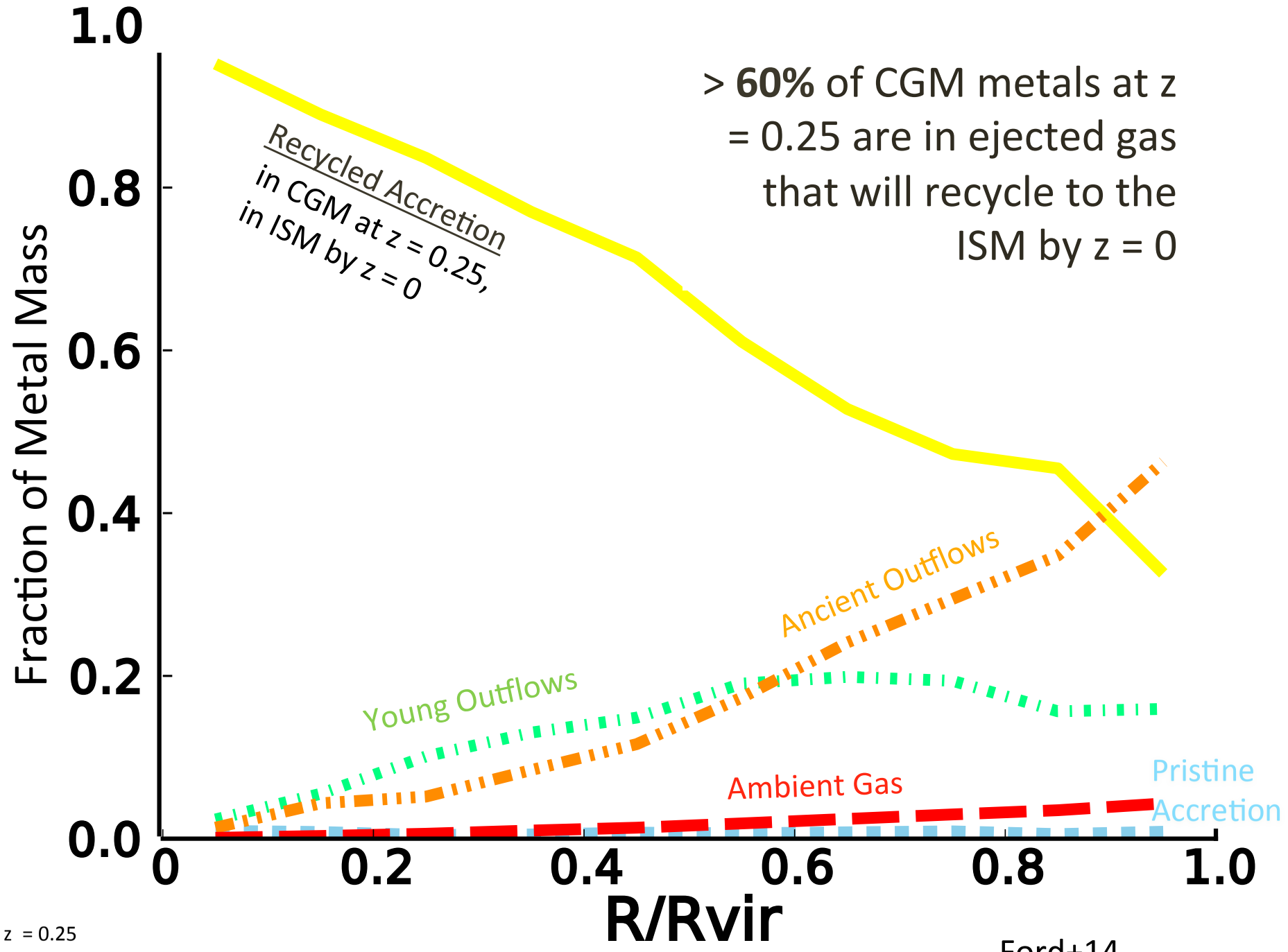
Gagdet-2 (Springel 05; Oppenheimer & Davé 2008)

Hybrid Energy-Momentum driven winds (EZW)

Track the fate of the particle rather than its velocity



PA-Pristine accretion, RA-Recycled Accretion, YO-Young Outflows, AO-Ancient Outflows, AMB-Ambient


1.0
0.8
0.6
0.4
0.2
0.0
Fraction of Metal Mass
0
0.2
0.4
0.6
0.8
1.0
R/Rvir
> 60% of CGM metals at z = 0.25 are in ejected gas that will recycle to the ISM by z = 0
Recycled Accretion in CGM at z = 0.25, in ISM by z = 0
Ancient Outflows
Young Outflows
Ambient Gas
Pristine Accretion
z = 0.25
Ford+14

Summary

- The CGM strongly influences and is influenced by the properties of the stars and gas within galaxies

- Simple photoionization by an EUVB and CIE (non-dynamical) cannot reproduce measured absorption line ratios of high ions. These two processes are what go into simulations currently.

- The 2D distribution of OVI around galaxies between 50 and 150 kpc does not depend on galaxy orientation. May support the idea that OVI is part of an 'ancient' outflow (see Ford+13)