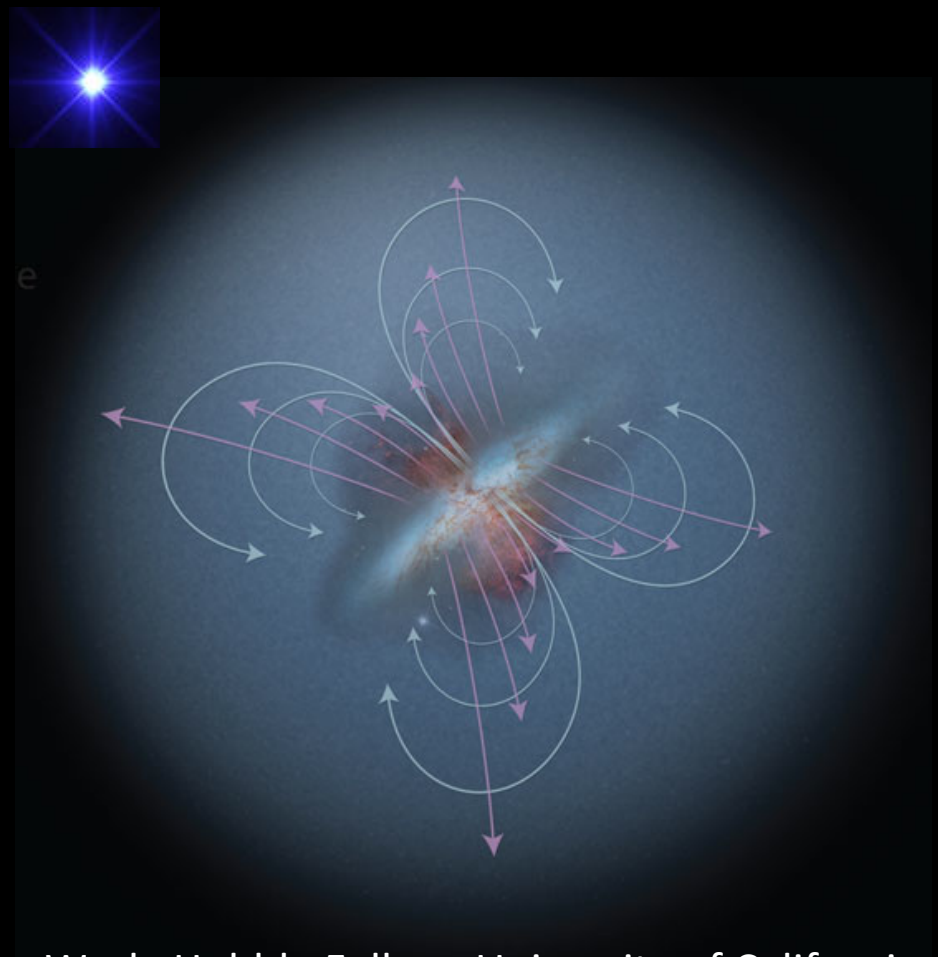
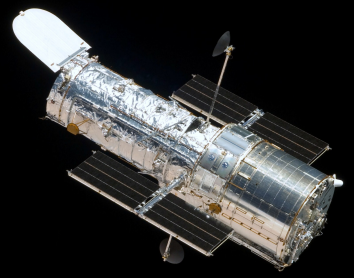
The Massive, Enriched, Cool Gaseous Envelopes Around Galaxies





Jessica Werk, Hubble Fellow, University of California, Santa Cruz

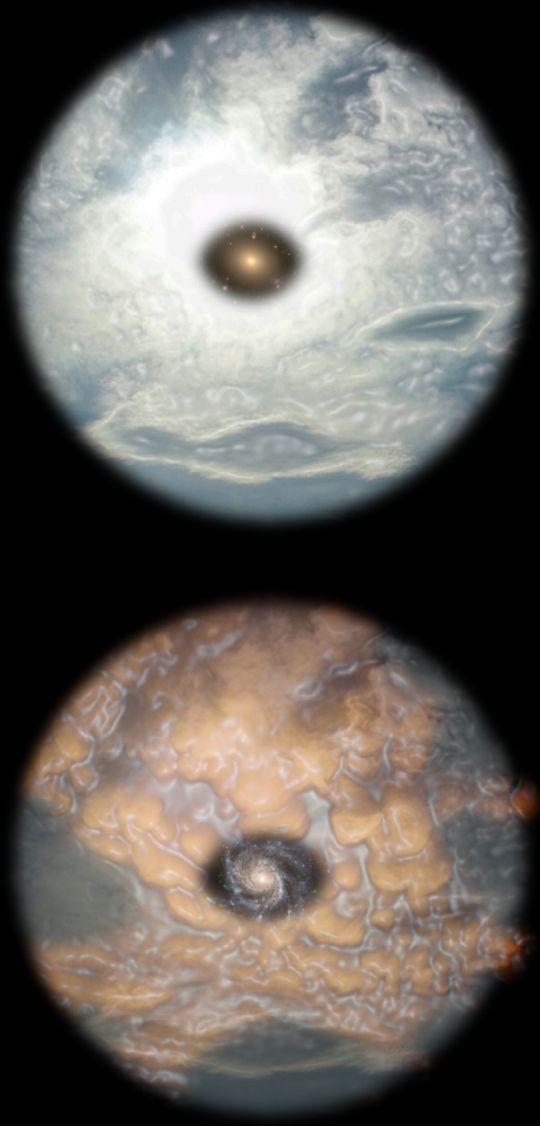
QNQ, July 2014

COS-Halos: Three Observational Realities

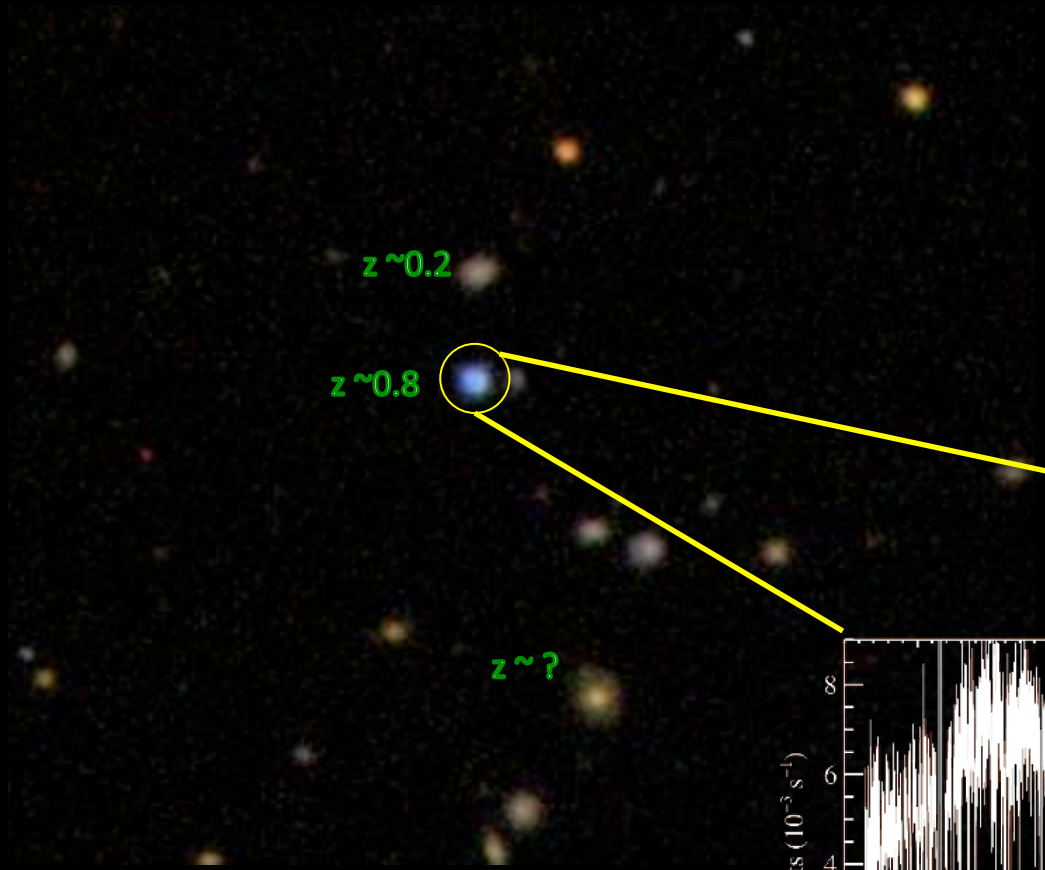
1. All L* galaxies, including quiescent galaxies, show significant HI absorption and other 'cool' metal ions to 150 kpc (Thom+12, Werk+13)

2. The cool gas is highly ionized, and metal-enriched. There is enough of it to account for > 50% of the baryon budget of an L* halo (Werk+14)

3. Red/blue dichotomy is reflected by the strong presence of OVI ('warm' gas) around SF galaxies, and its absence around non-SF galaxies (Tumlinson+11)

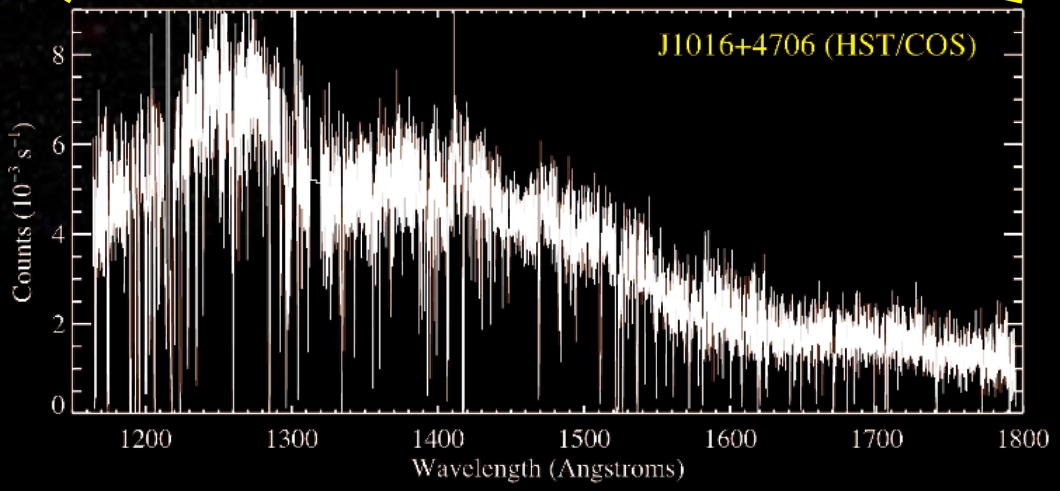


Absorption Line Experiments Using Quasars



Method A: Find absorber in spectrum, go hunting for a galaxy at the proper redshift

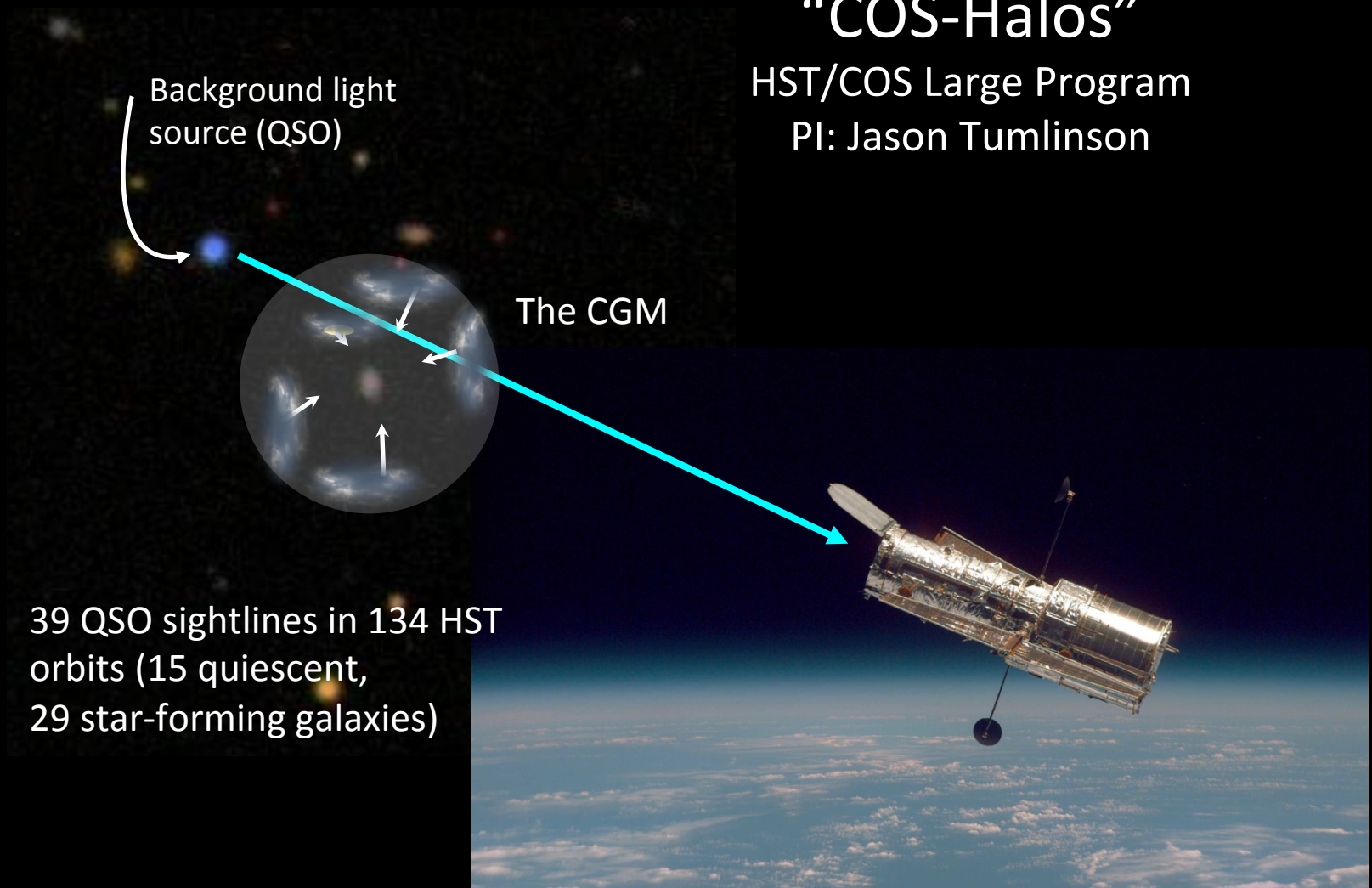
Method B: Know redshifts of nearby galaxies in projection, go hunting for absorption in the spectrum at those redshifts



Systematically Surveying the Halo Gas of Galaxies

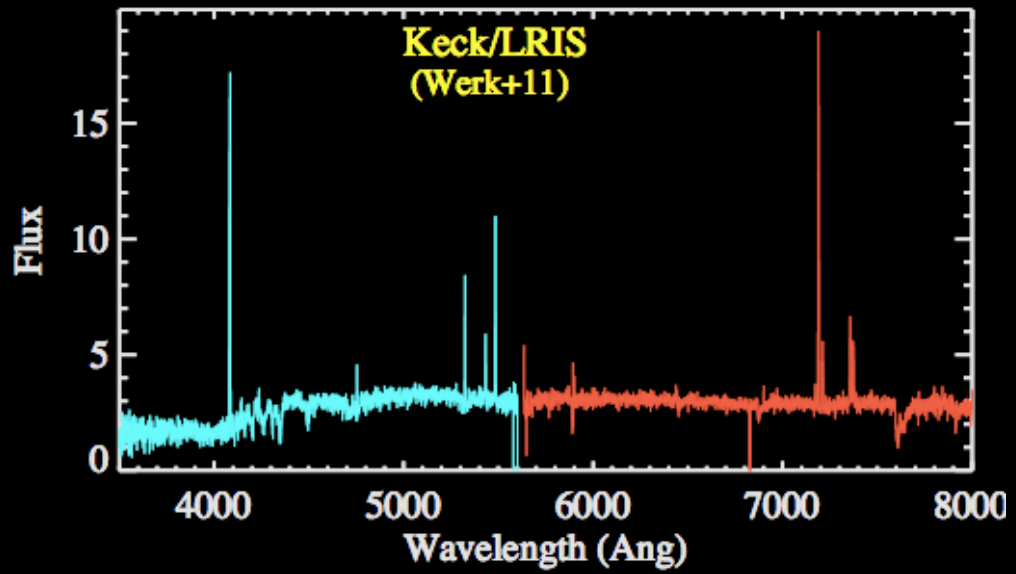
"COS-Halos"

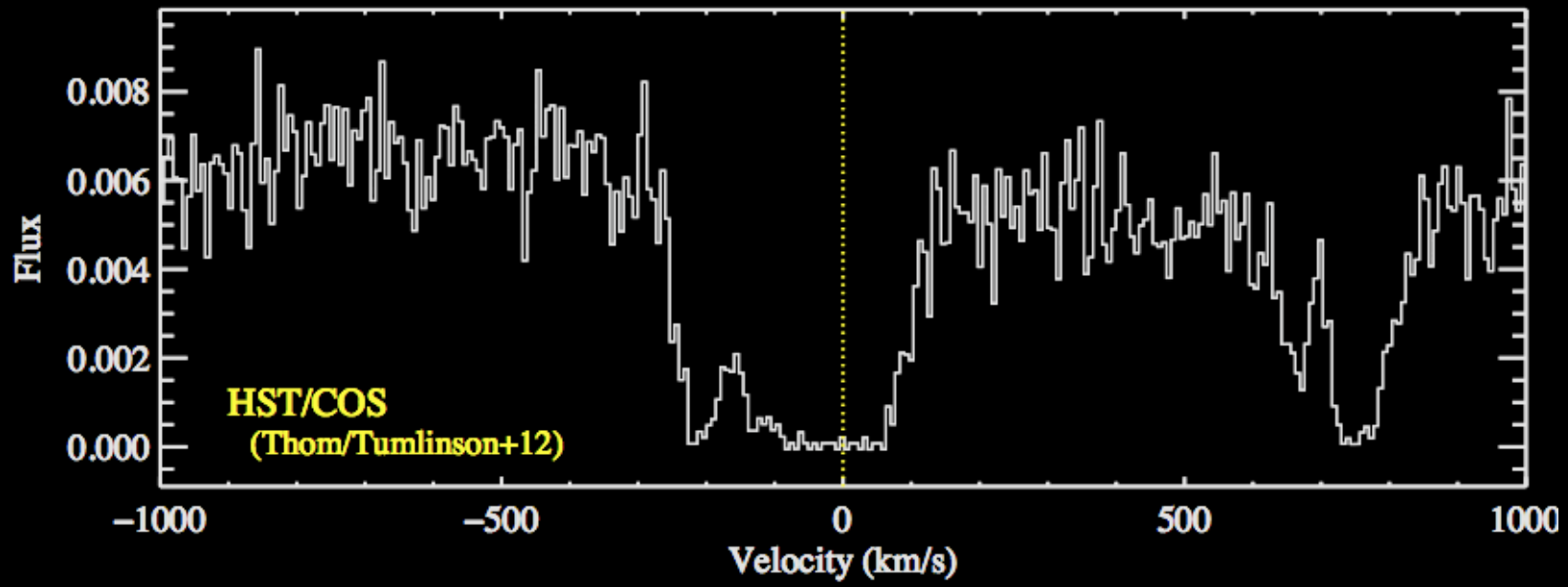
HST/COS Large Program
PI: Jason Tumlinson



39 QSO sightlines in 134 HST orbits (15 quiescent, 29 star-forming galaxies)

1. Observations of Cool Gas to 150 kpc Around z~0.2 L* Galaxies





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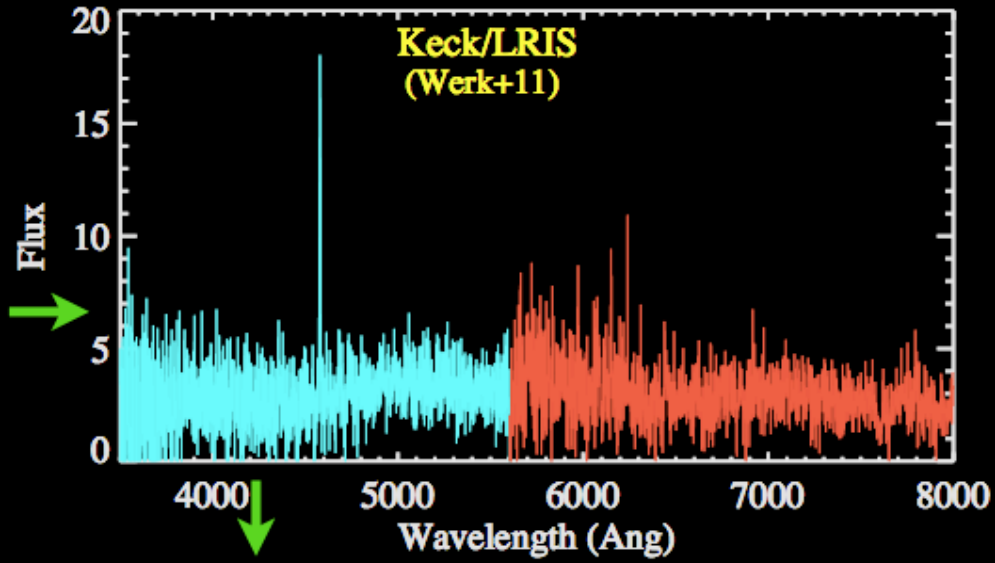

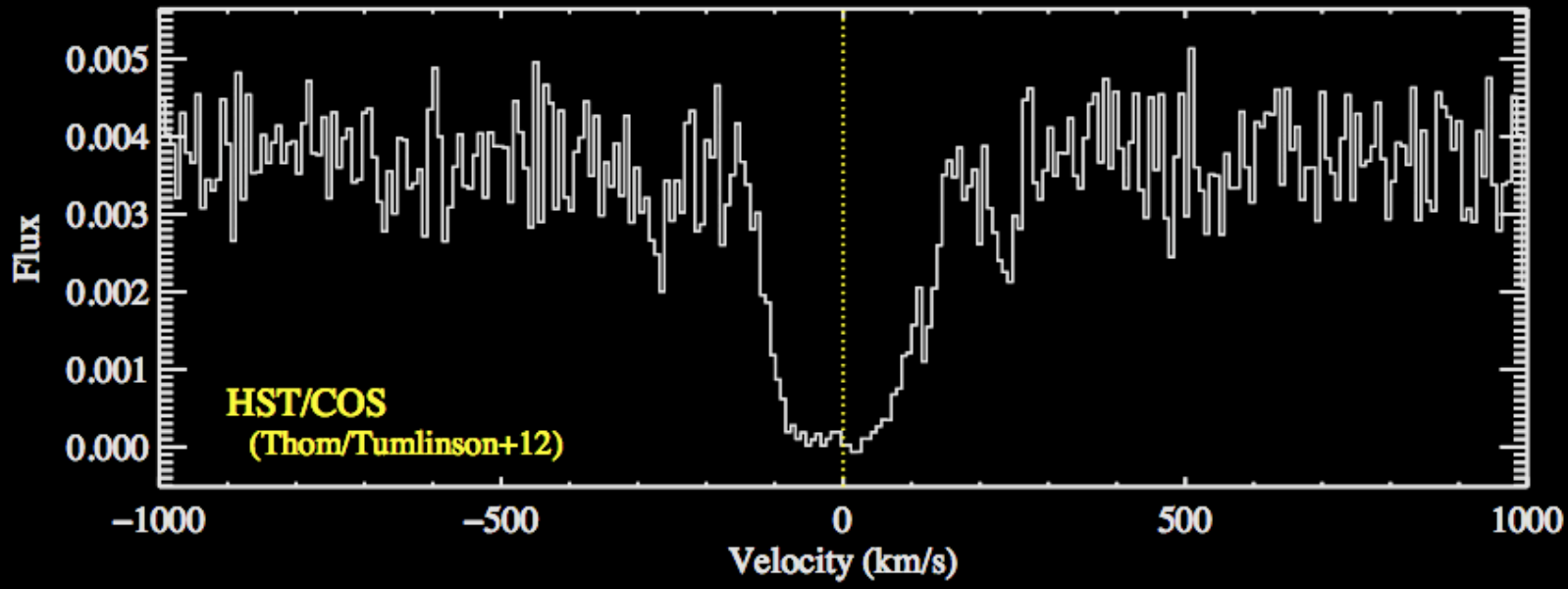

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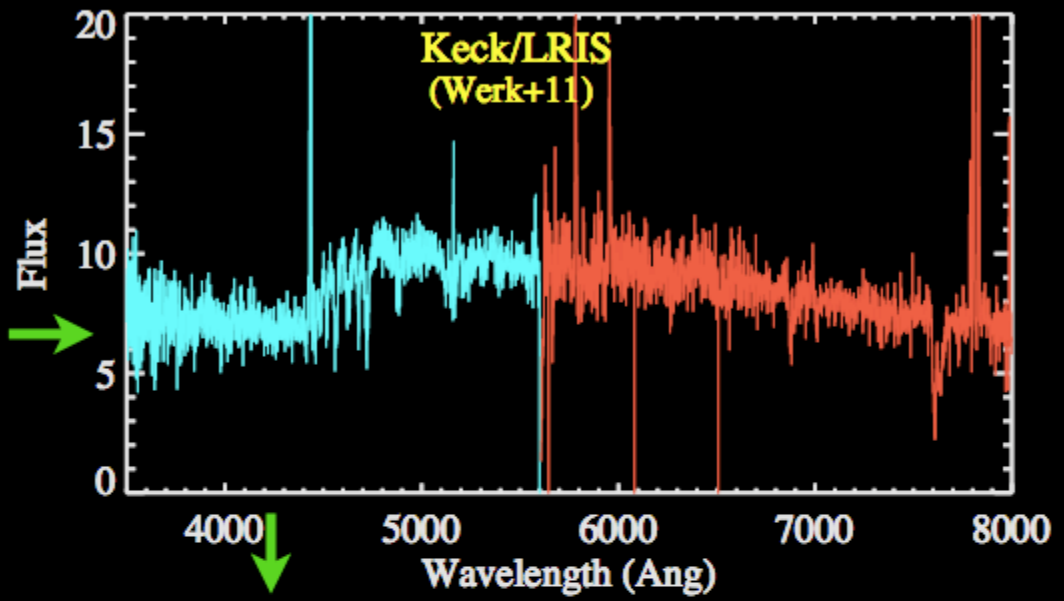

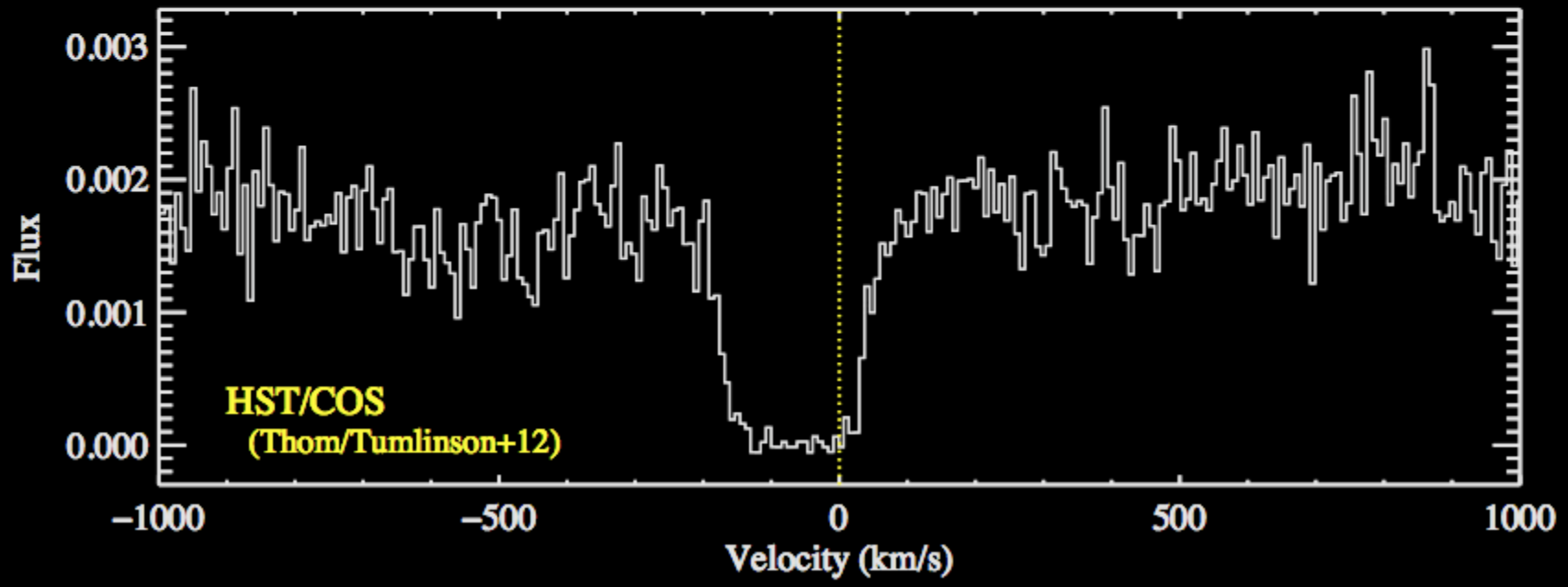

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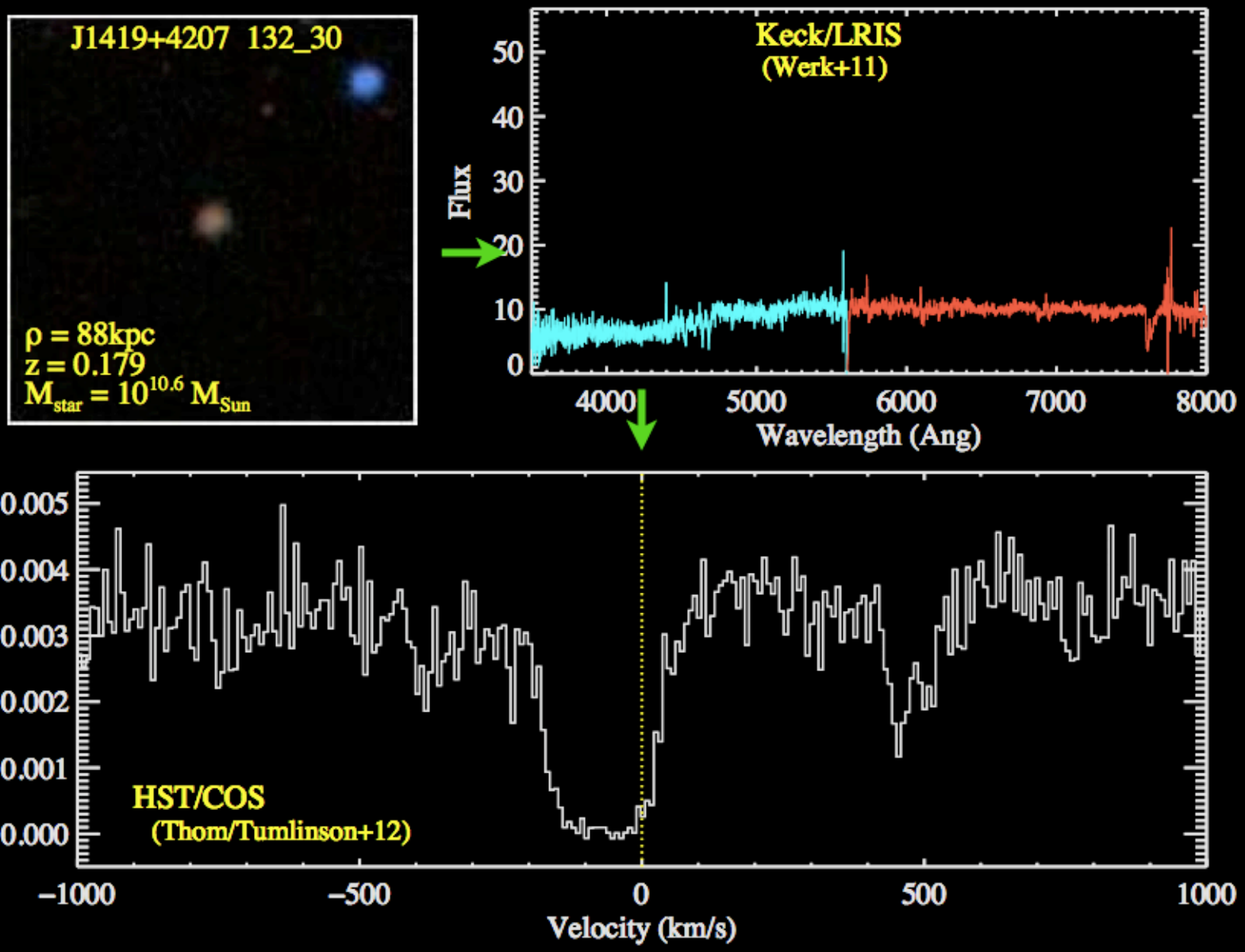
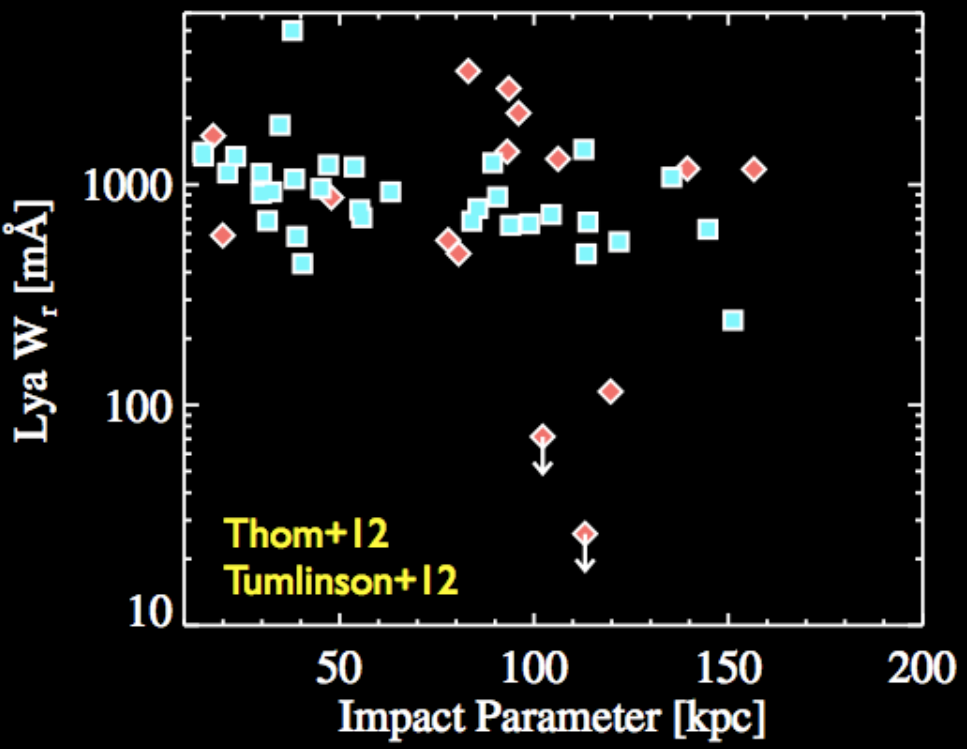
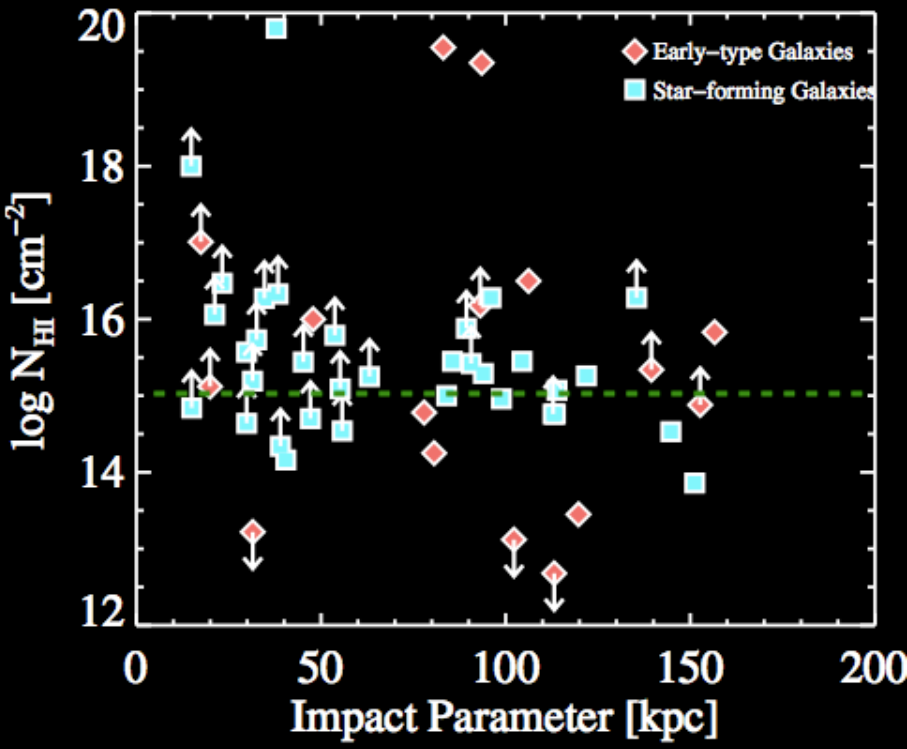


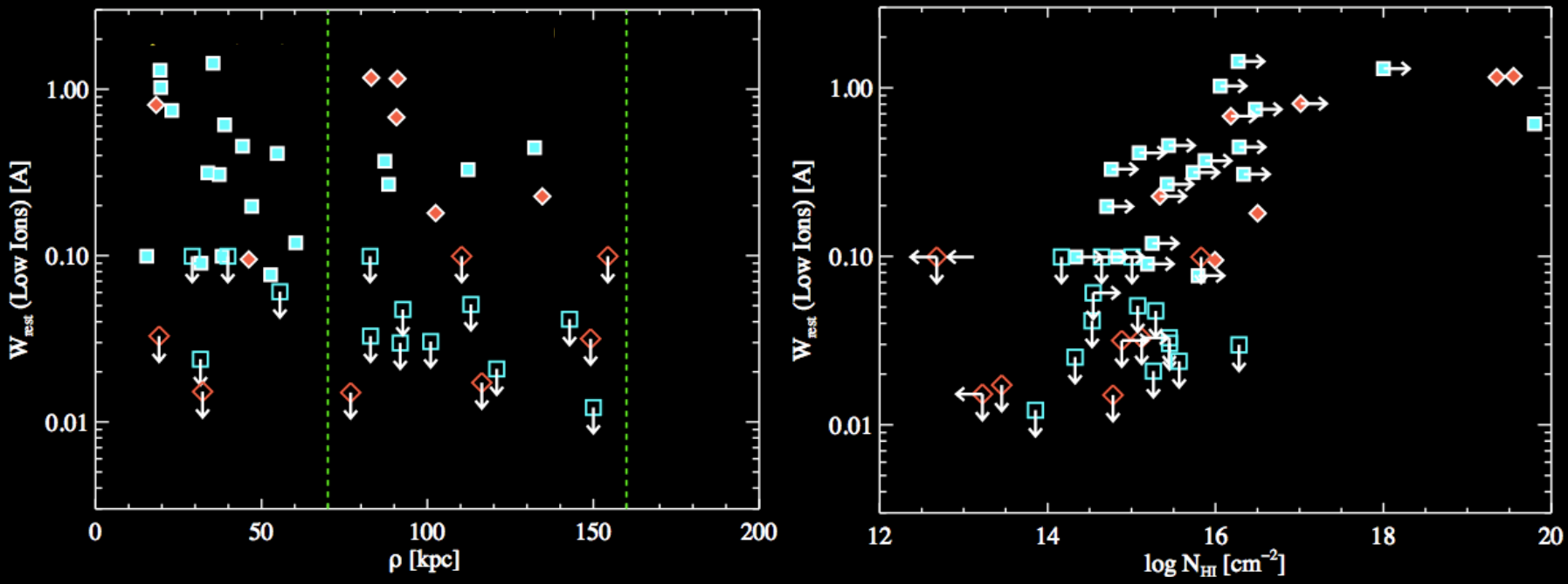
The HI Gas





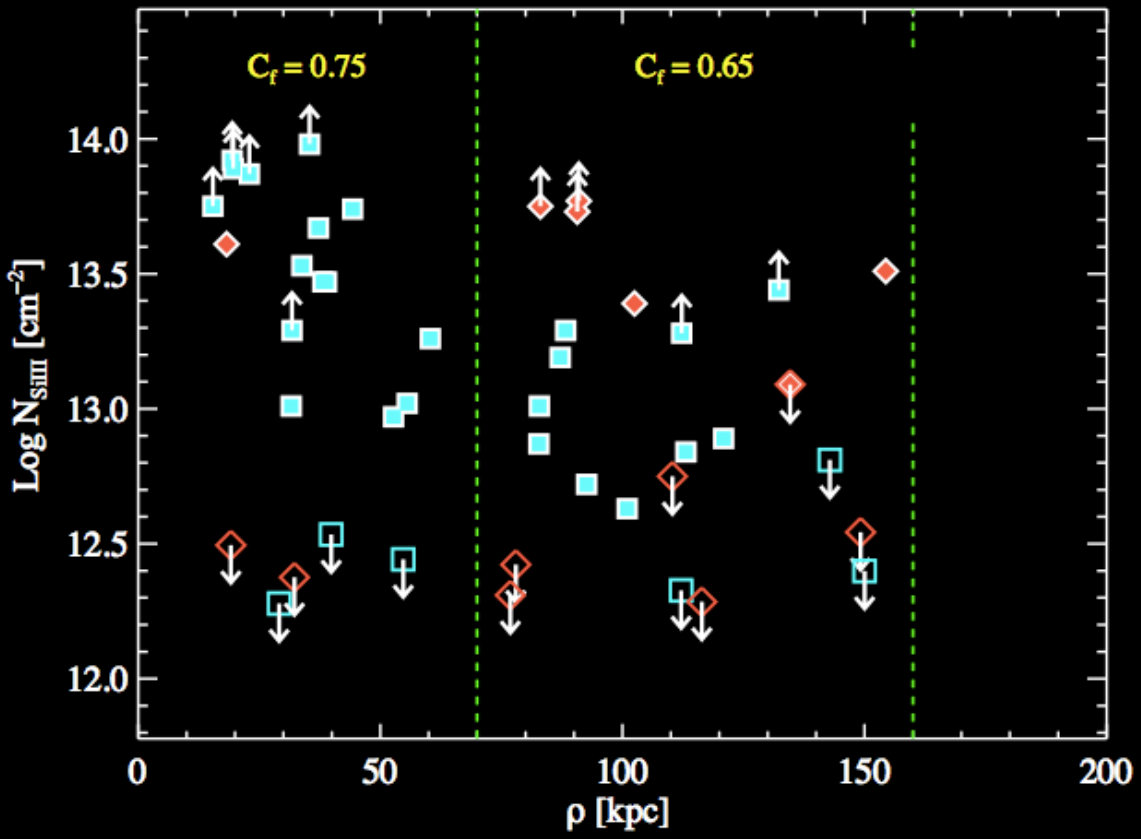
1. A cool (10^4 K) medium with high covering fraction of $N_{HI} > 10^{15}$ cm^{-2} exists around nearly every L* galaxy, even ellipticals, to 150 kpc.
2. Thus, there is no obvious suppression of cool gas around massive quiescent galaxies.

The Low Ionization State Metals



1. Low-Ion metals (Mg II) are present throughout the CGM, and have 50% covering fraction, to 150 kpc (Werk+13)
2. There is no obvious distinction between SF and quiescent galaxies
3. These low-ions seem to trace high N_{HI} (> 10^{16} cm^{-2})

The Intermediate Ionization State Metals



1. Intermediate ionization state metals (SiIII, CIII) are very common throughout the CGM, and have 70% covering fraction to 150 kpc (90% for CIII). Werk +13
2. There is no obvious distinction between SF and quiescent galaxies.
3. There is a likely trend of decreasing column with impact parameter.

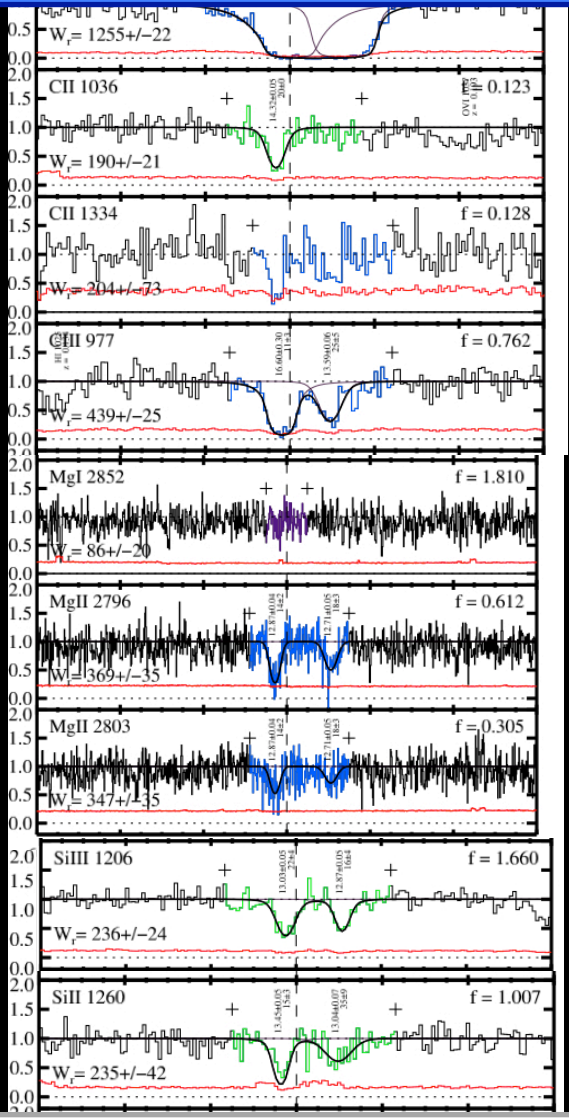
The Cool (10^4 K) CGM to 150 kpc at Low-Redshift

Facts:

1. Ubiquitous Neutral Hydrogen (HI) – Tumlinson et al. 2013

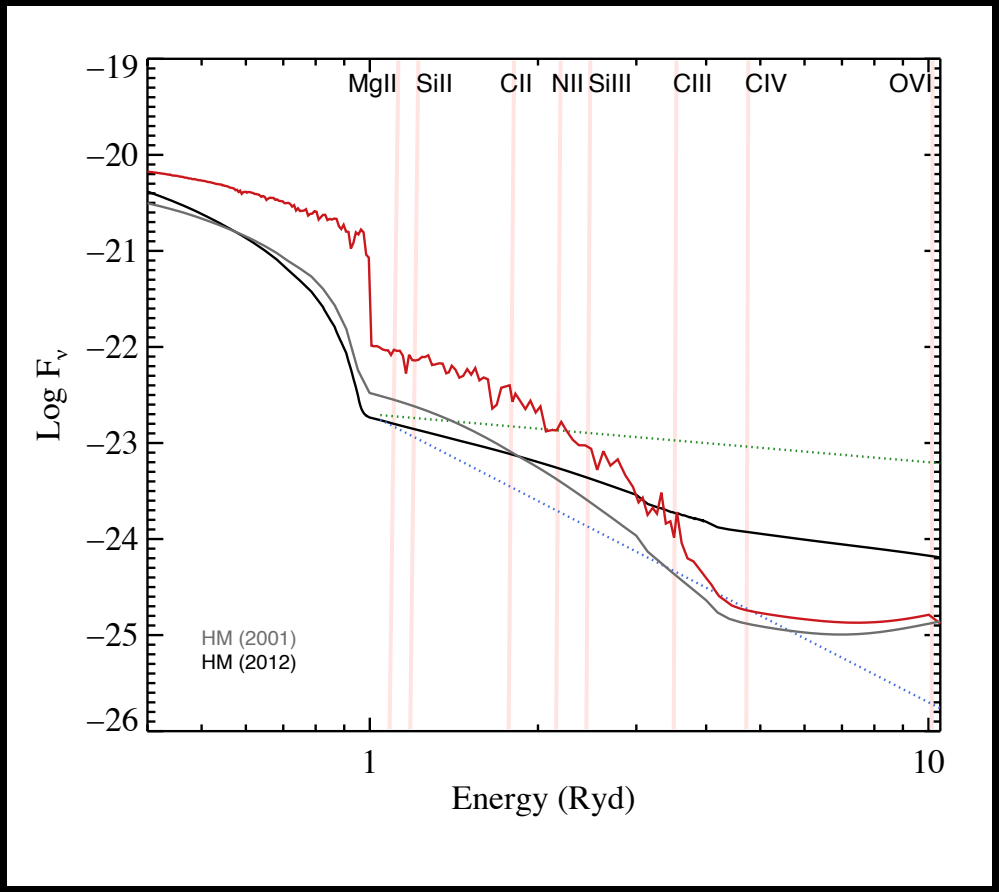
2. Lots of ionized metals: SiII, SiIII, CII, CIII,NII, NIII, MgII – Werk et al. 2013

3. Atomic Physics tells us SiII, SiIII are probably the same temperature as HI, ~ 10^4 K



→Most of the Hydrogen is Ionized (and sadly, unobservable directly) AND, we have to model it to determine the ionization fraction.

CLOUDY Photoionization Modeling



CUBA

Cosmic Ultraviolet Background

A cosmological 1D radiative transfer code by Francesco Haardt and Piero Madau

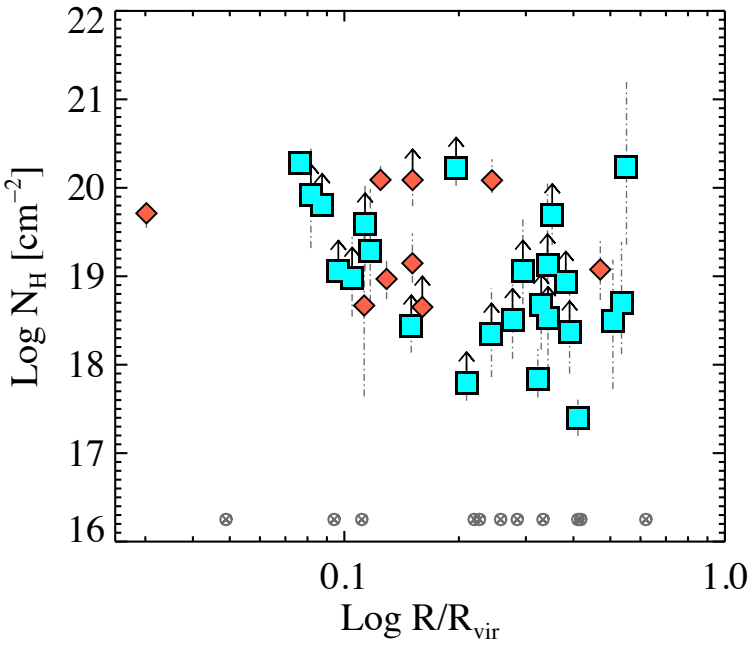
To Determine Physical Conditions:

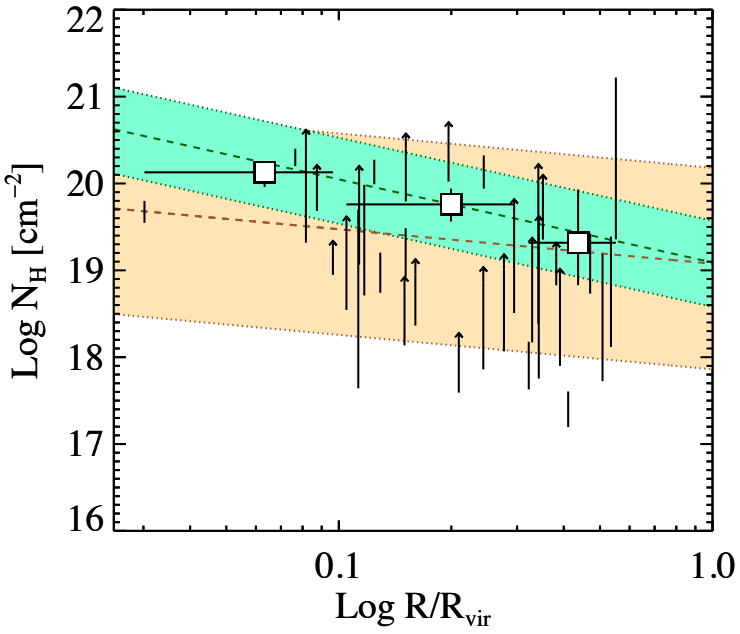
1. Ionization Parameters (robustly)
2. Gas Metallicity (not so well, since HI is saturated)
3. Gas Densities
4. Total Hydrogen Column

Cloudy & Associates

Photoionization Simulations for the Discriminating Astrophysicist Since 1978

The Surface Density of Hydrogen



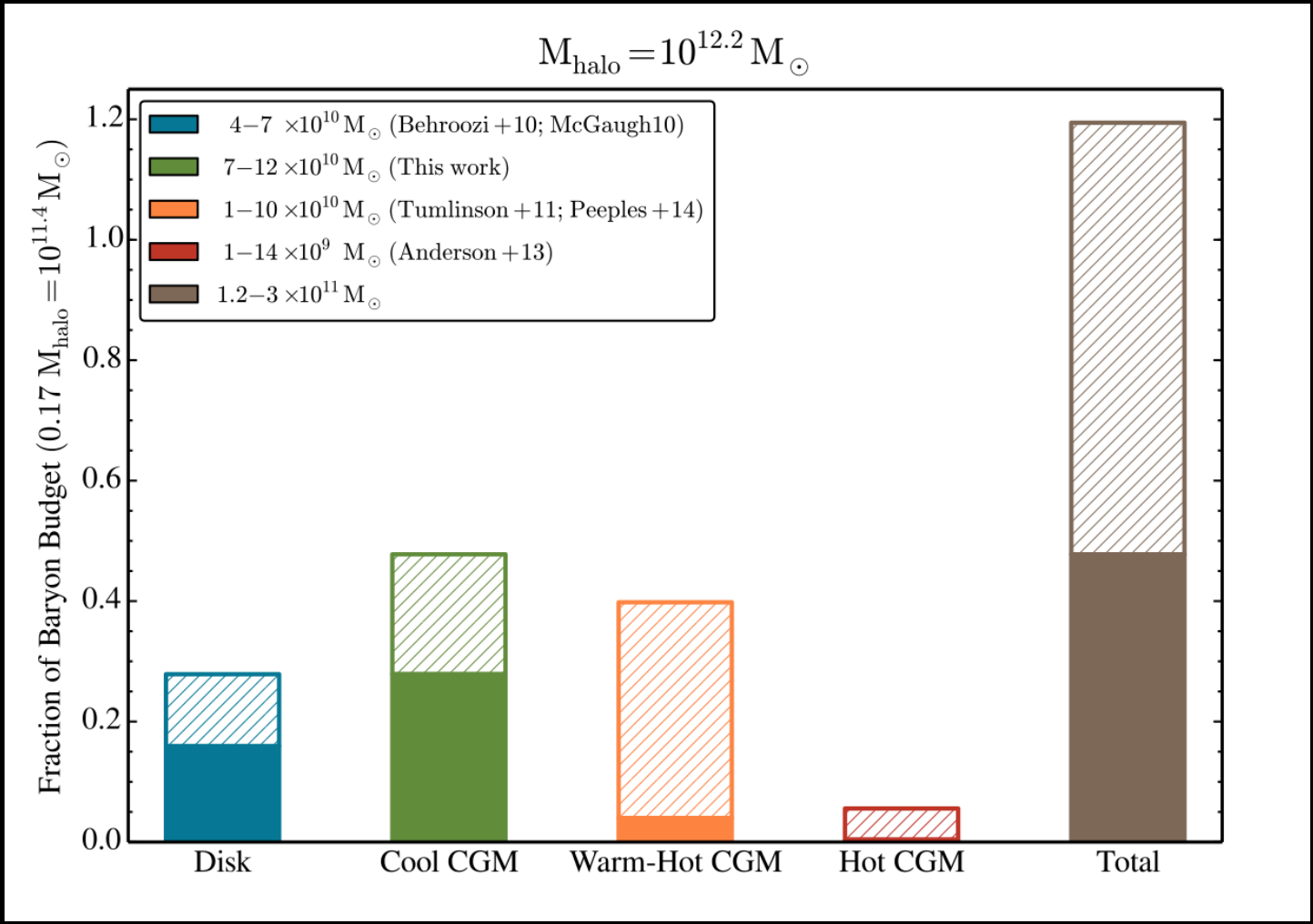


$$M_{\,10^4\mathrm{K\ CGM}} = \int 2\pi r\ \Sigma_{\mathrm{gas}}(r)\,\mathrm{d}r$$

Integrate surface density from 0 – 160 kpc, and calculate total mass:
Strict lower limit: 2 x 10^{10} $M_\odot$
Conservative Estimate: 6 x 10^{10} $M_\odot$

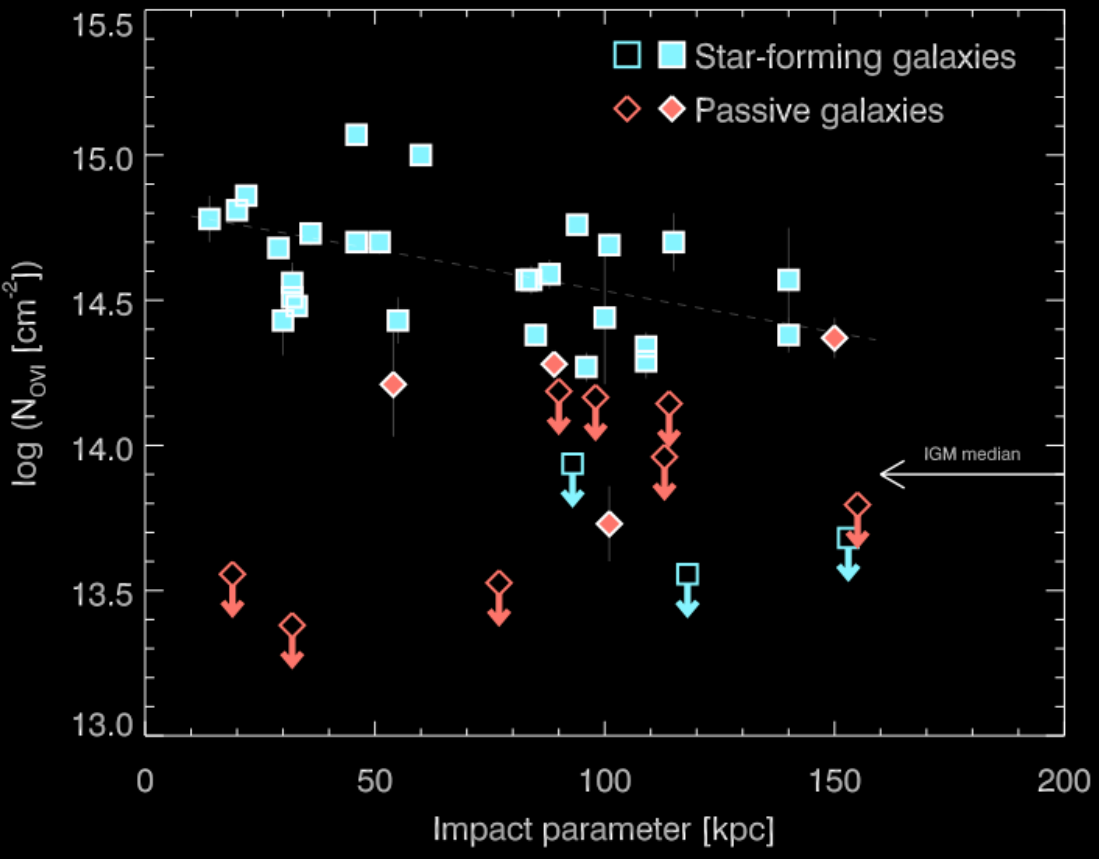
Werk+14

The Baryonic Content of the Cool CGM: What Missing Baryon Problem?



Werk+14

OVI is more common around star-forming galaxies than around non-SF galaxies (Tumlinson+11)



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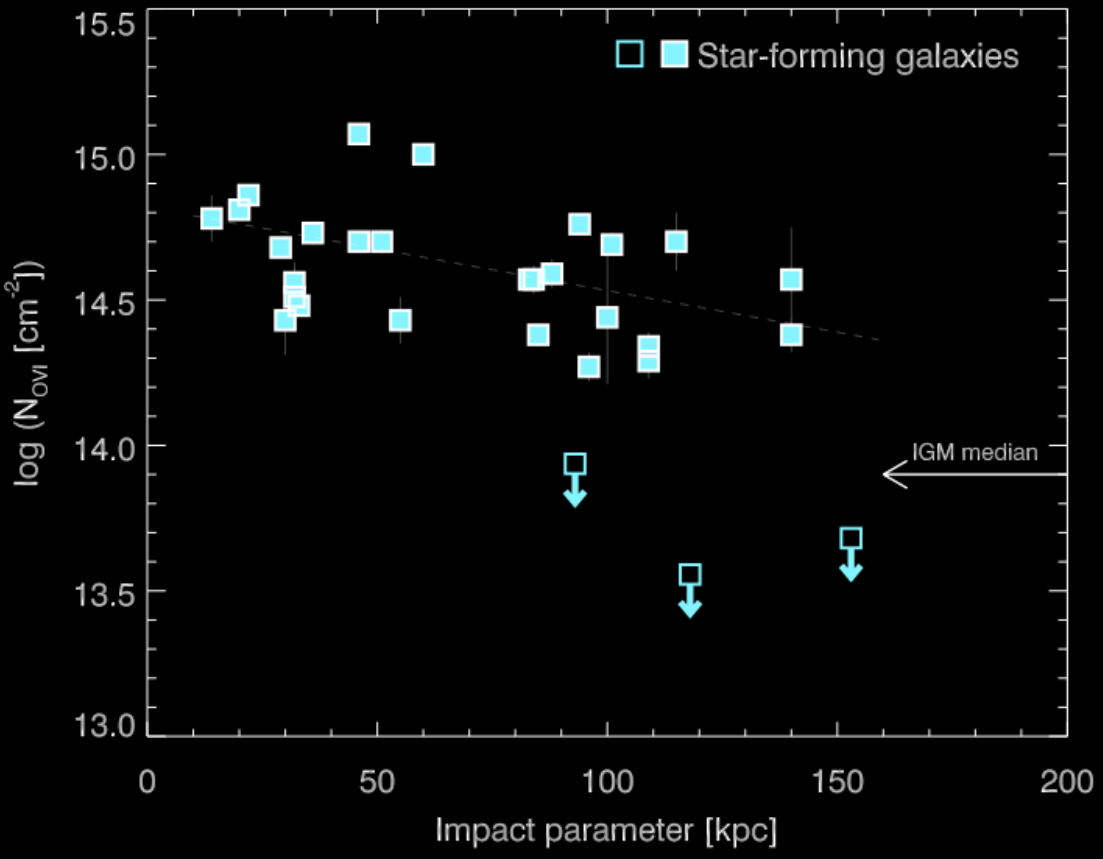

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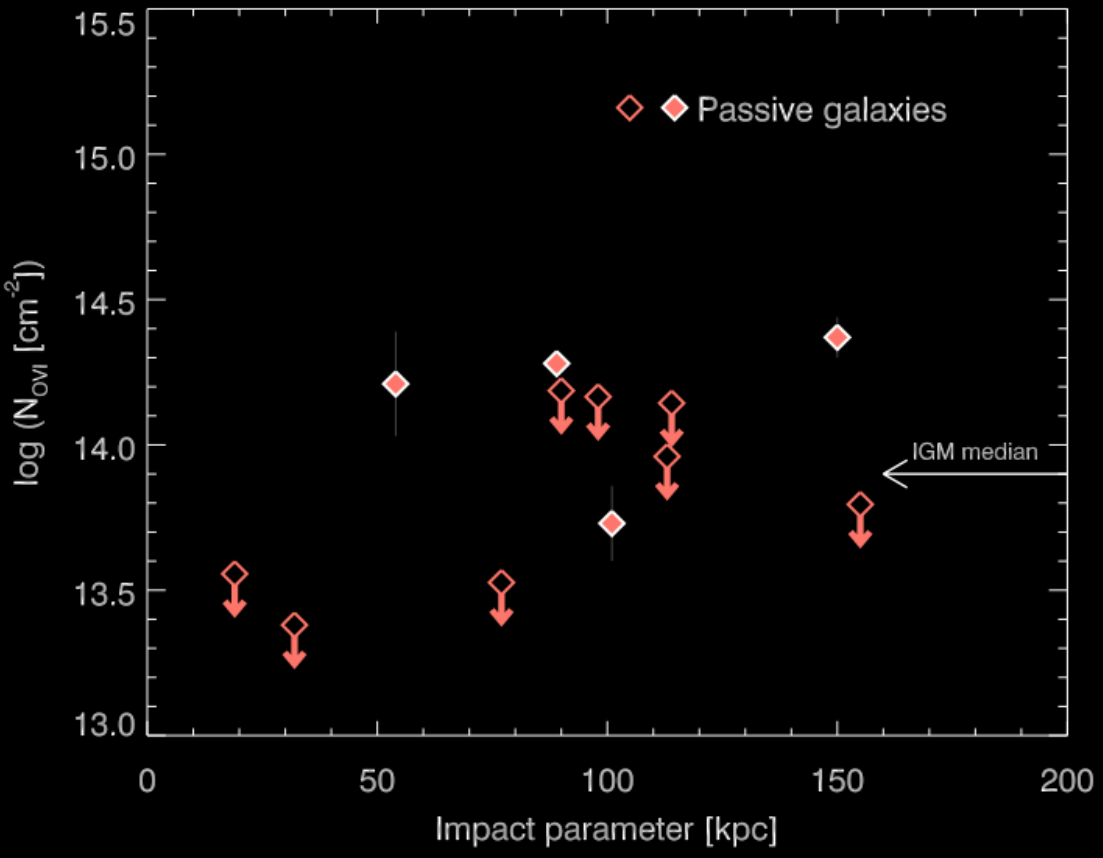

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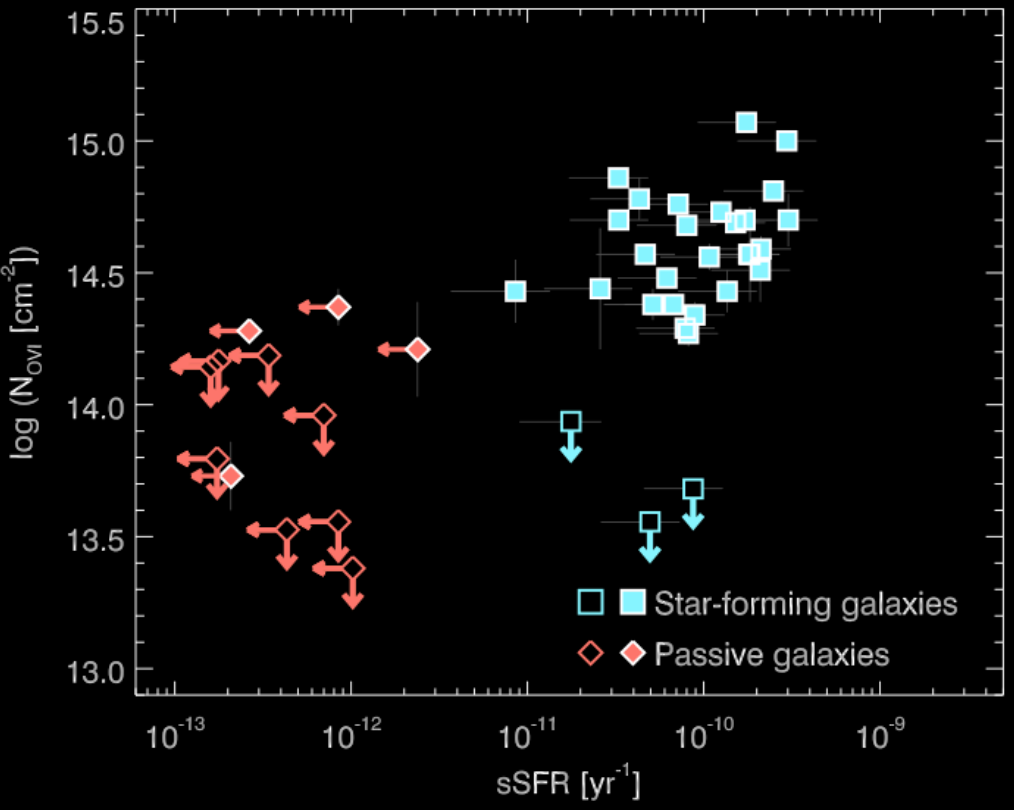


1. OVI is more common around star-forming galaxies than around massive, red, ellipticals (SF = 90%; Red = 30%) Tumlinson+11
2. There is a likely trend of decreasing column with impact parameter.

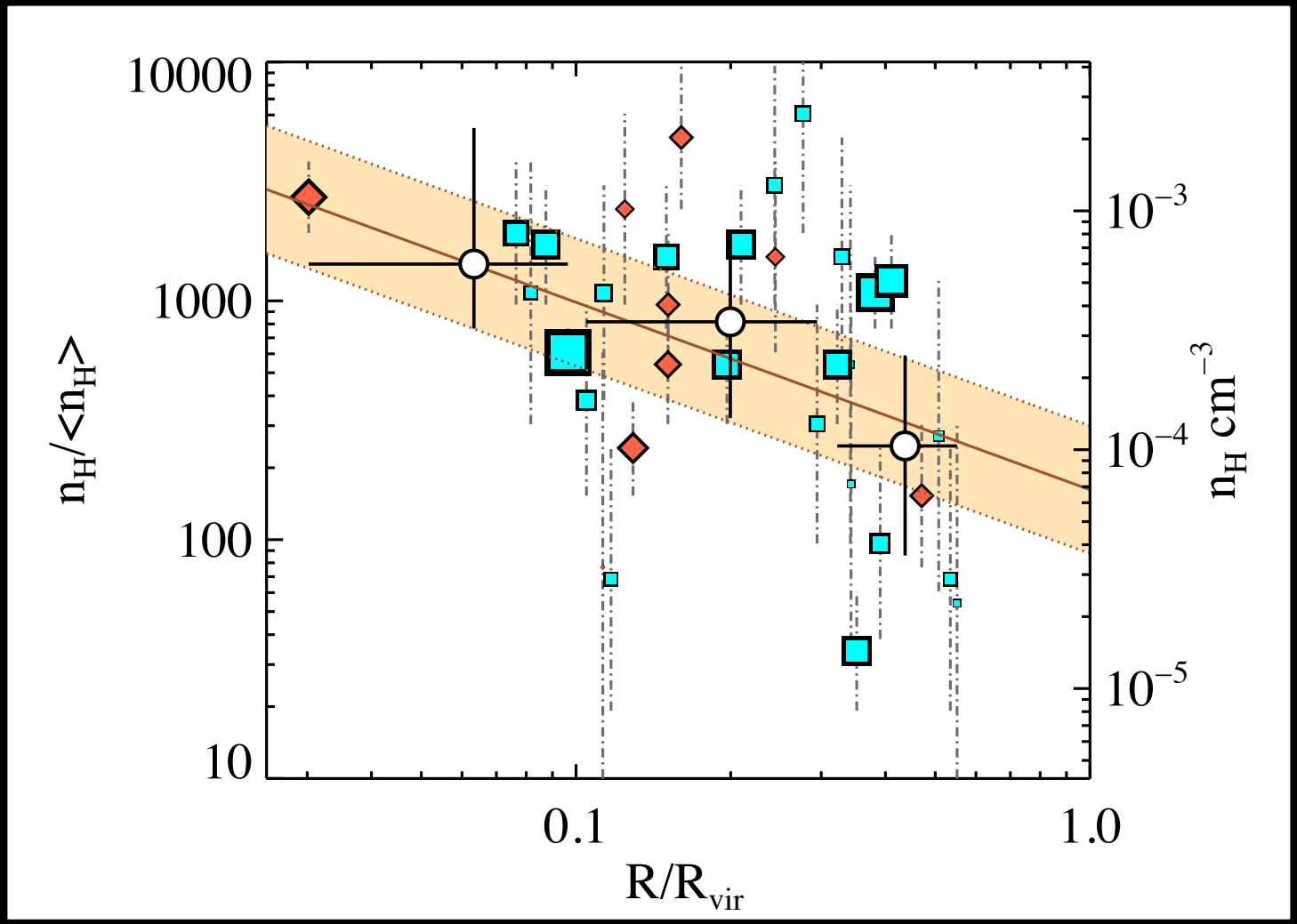
What is the Physical State of the Gas in the CGM?

1. Equilibrium considerations: What is the origin/fate of all the cool gas 10 – 150 kpc from galaxies? Will this cool gas drive new SF?

2. The Physical Conditions Giving Rise to OVI: How does OVI coexist with cool gas, and why is OVI an absent ionization state of Oxygen around "quenched" galaxies?

3. Does Environment matter?

Volume Density

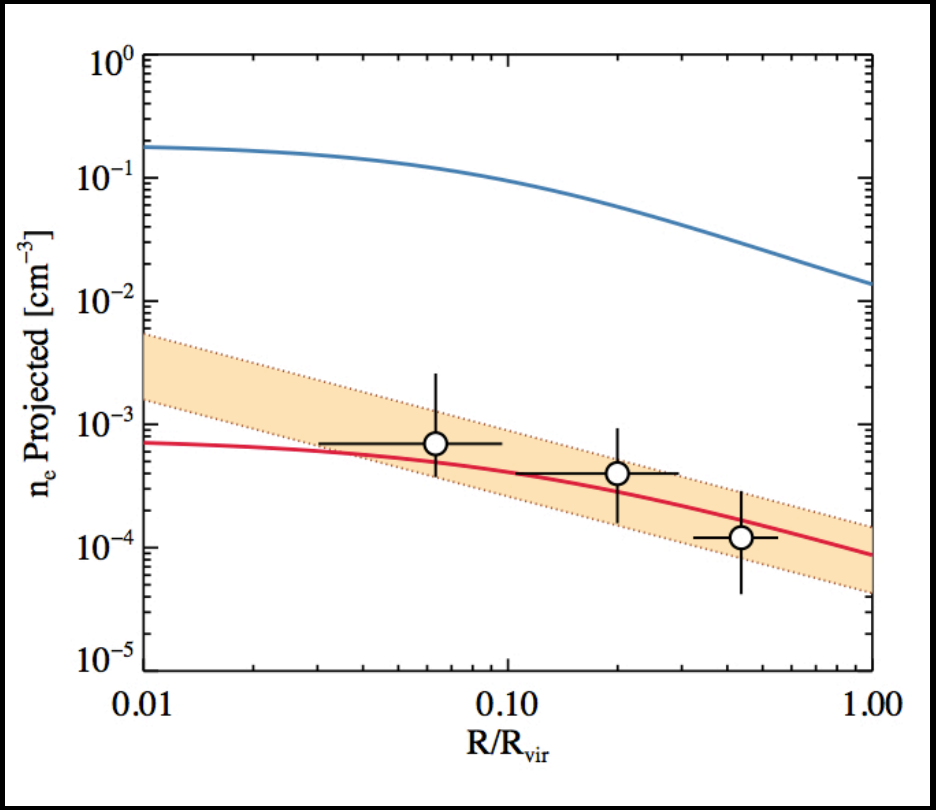


$U = \Phi_{tot} / n_H c$

Werk+14

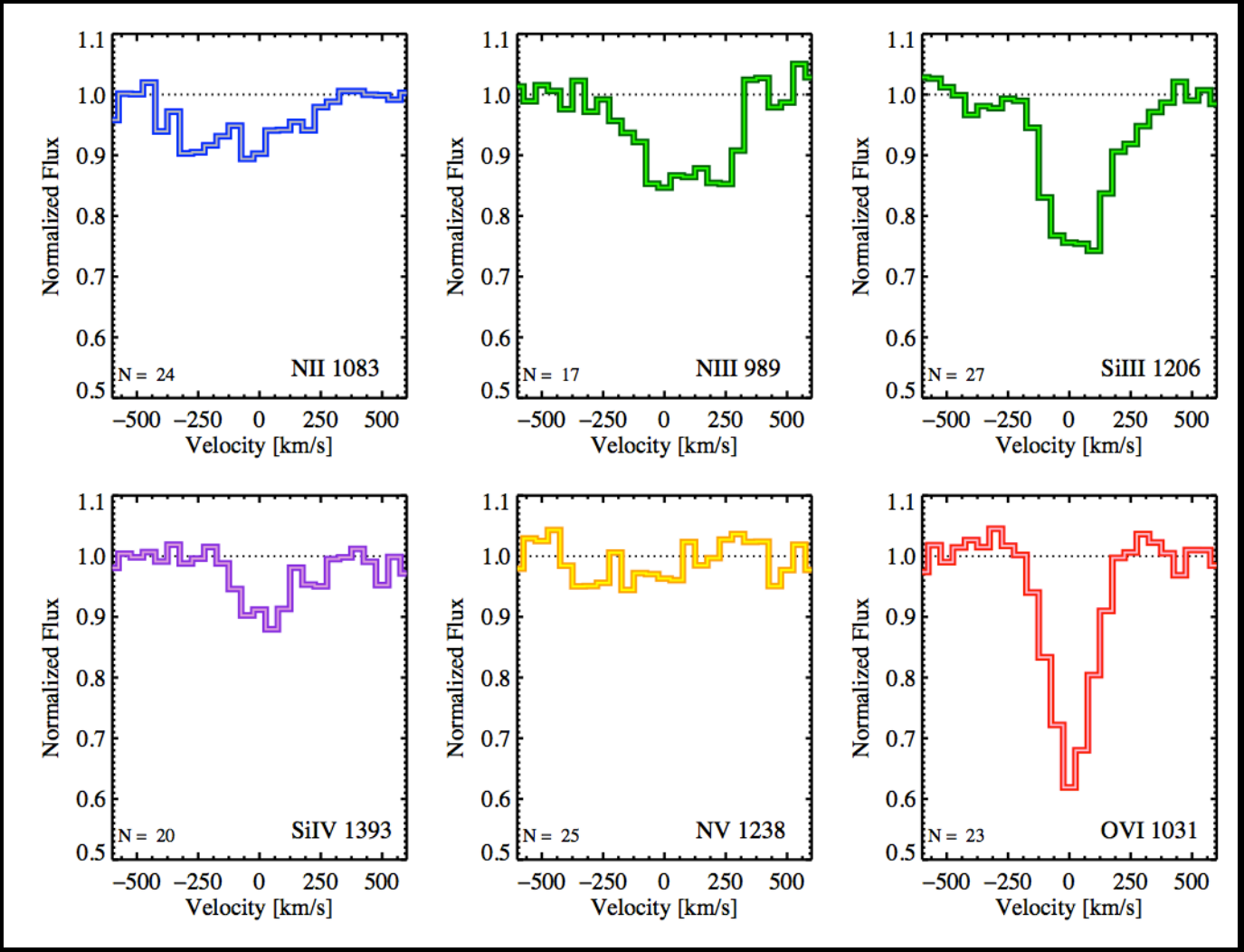
Pressure Equilibrium: Two-Phase Solutions

- Mo & Miralda-Escude 1996: Cool (10^4 K) clouds in pressure equilibrium with diffuse, hot (10^6 K) halo gas
- Maller & Bullock 2004: predict a hot gas density profile evolving adiabatically from original NFW distribution
- Cool, pressure-supported clouds condense out of hot medium



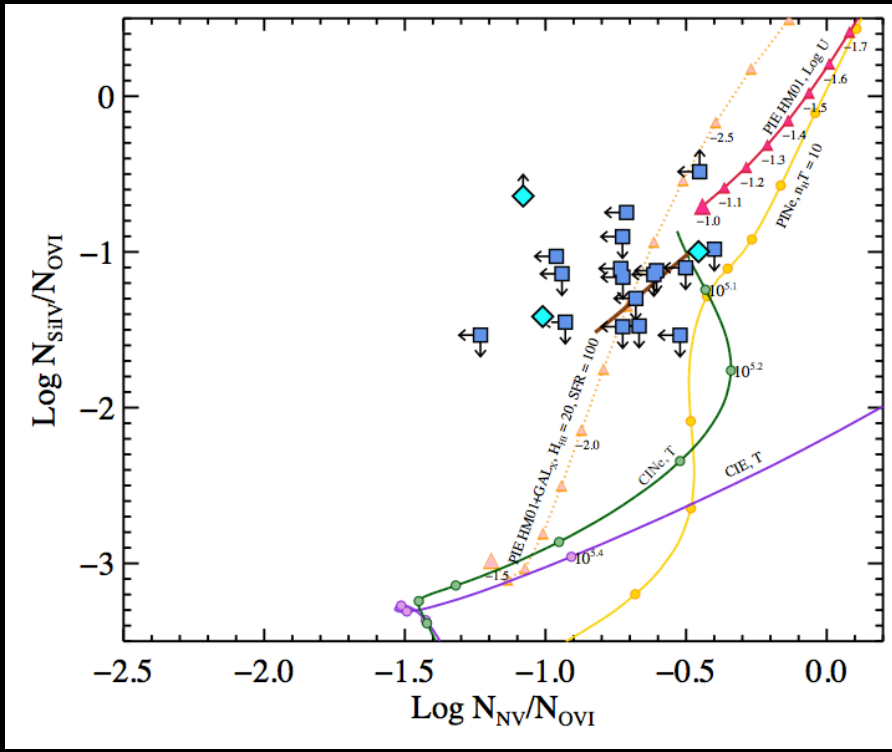
Physically, we rule out a simple model of the CGM that includes cool 10^4 K clouds in pressure equilibrium with a hot 10^6 K medium. At these densities, cooling times are short.

COS-Halos Stacks: Why No NV?

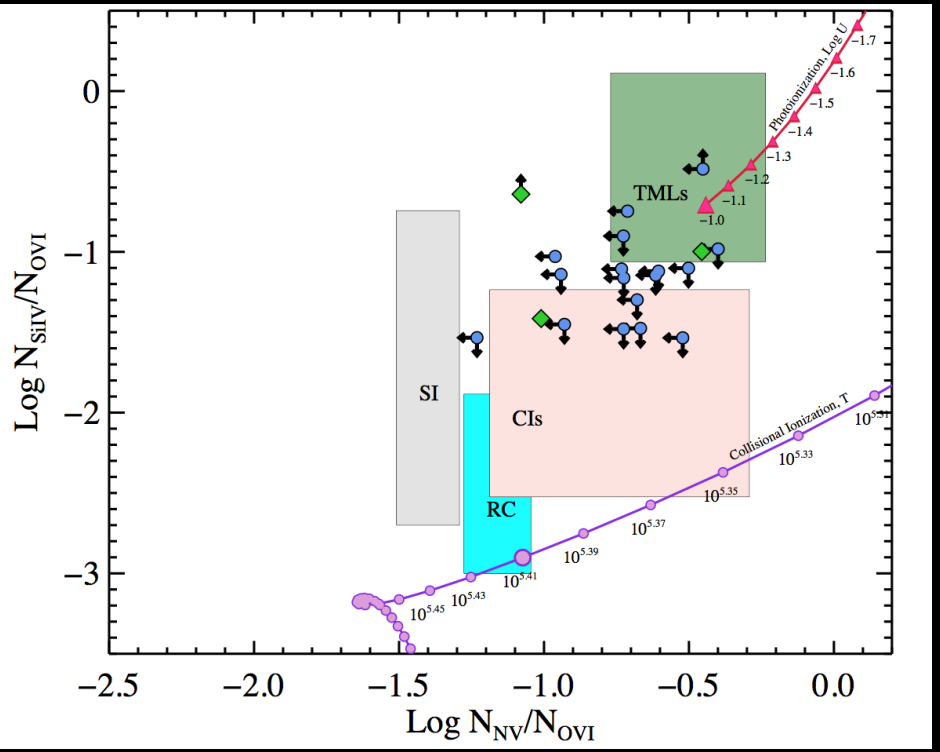


There is no NV in the CGM

Simple Models: Photo + Collisional



Exotic Models?



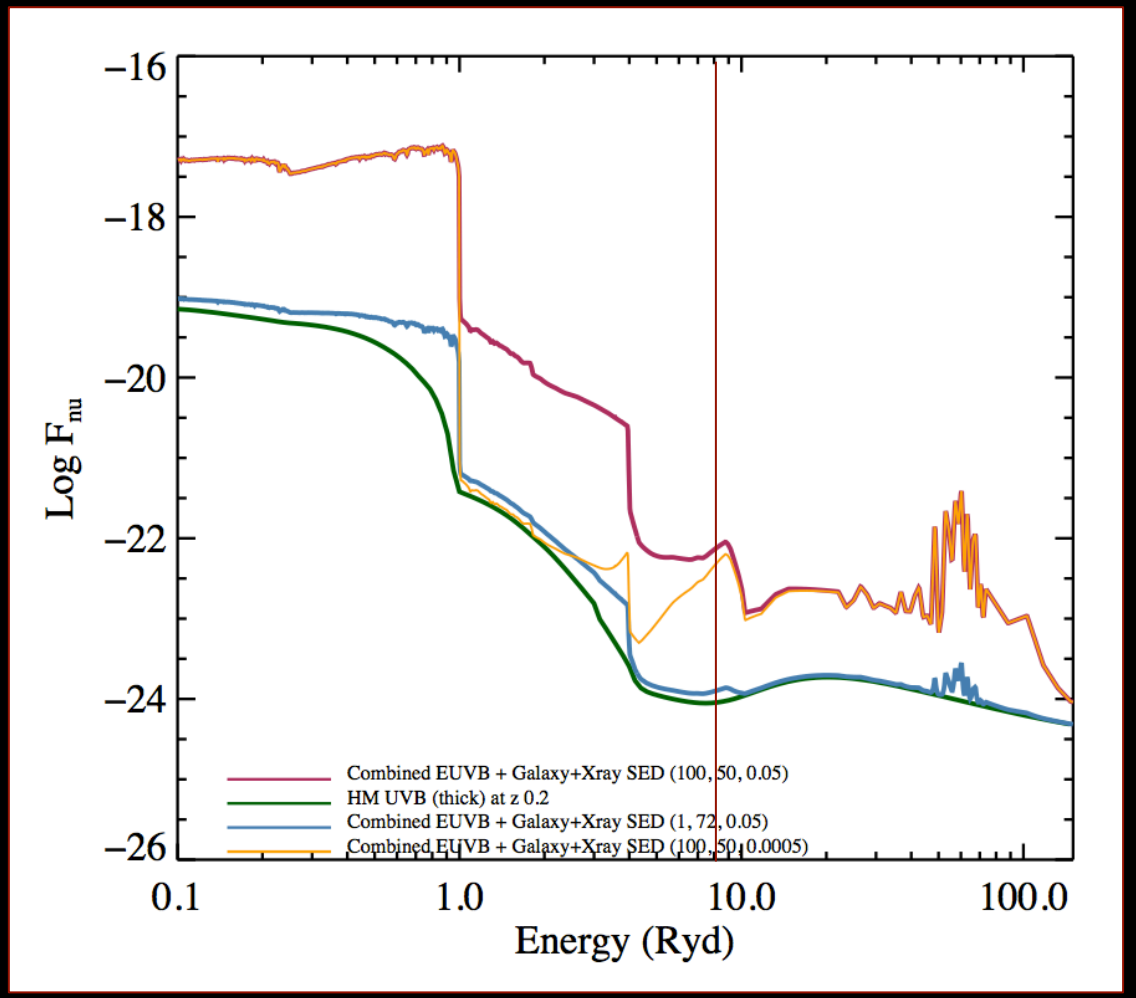
Rule out: Simple PI, PINE, CIE, CINE (too much SiIV)
PI + Soft X-rays?? (i.e. Cantalupo 2010)

Rule out: TMLs and CIs
CIs don't make enough OVI (LogN ~ 13)

Galaxy SED: Constructing a 10 Ryd Bump with Soft-Xrays

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} = 1% (or lower)
d = 50 kpc

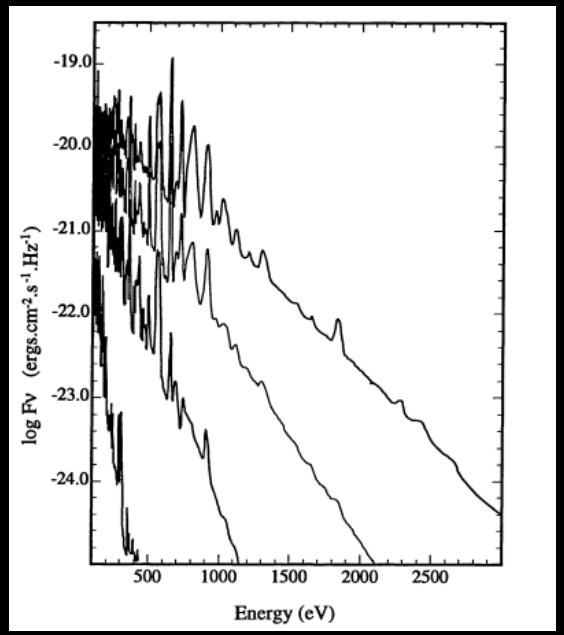


Naturally explains OVI dichotomy, but does not offer insight on quenching problem.

Shock Ionization, Radiative Cooling via Recombination

- Shock Ionization: Gas cloud moves with v > local sound speed, there is a shock front at the leading edge of the cloud, shock velocities between 200 – 500 km/s (Dopita & Sutherland 1996)
- Radiative cooling: hot gas cools down by radiative recombination (Edgar & Chevalier 1986), evolution of cooling is isochoric or isobaric.

EUV/Soft X-ray spectrum from radiative shocks



Clouds are moving fast enough to create shocks in SF galaxies. There is no shock creation in quiescent galaxies…clouds have slowed?

Summary and Conclusions

1. All L* galaxies, including quiescent galaxies, show significant HI absorption and other 'cool' ions to 150 kpc (Thom+12, Werk+13)

2. The cool gas is highly ionized, and therefore there is enough of it to account for > 50% of the baryon budget of an L* halo (Werk+14)

3. The cool gas is not in pressure equilibrium with a hot, ambient medium. Cooling times are short (~10^8 years).

4. Red/blue dichotomy is reflected by the strong presence of OVI ('warm' gas) around SF galaxies, and its absence around non-SF galaxies (Tumlinson+11)

5. OVI does not arise from simple photoionization in the presence of some EUVB. Collisional Ionization seems unlikely. It is a mystery that remains to be solved, but the absence of NV is illuminating.