Exploring Galaxy Halos and the Cosmic Web Through X-ray Spectroscopy

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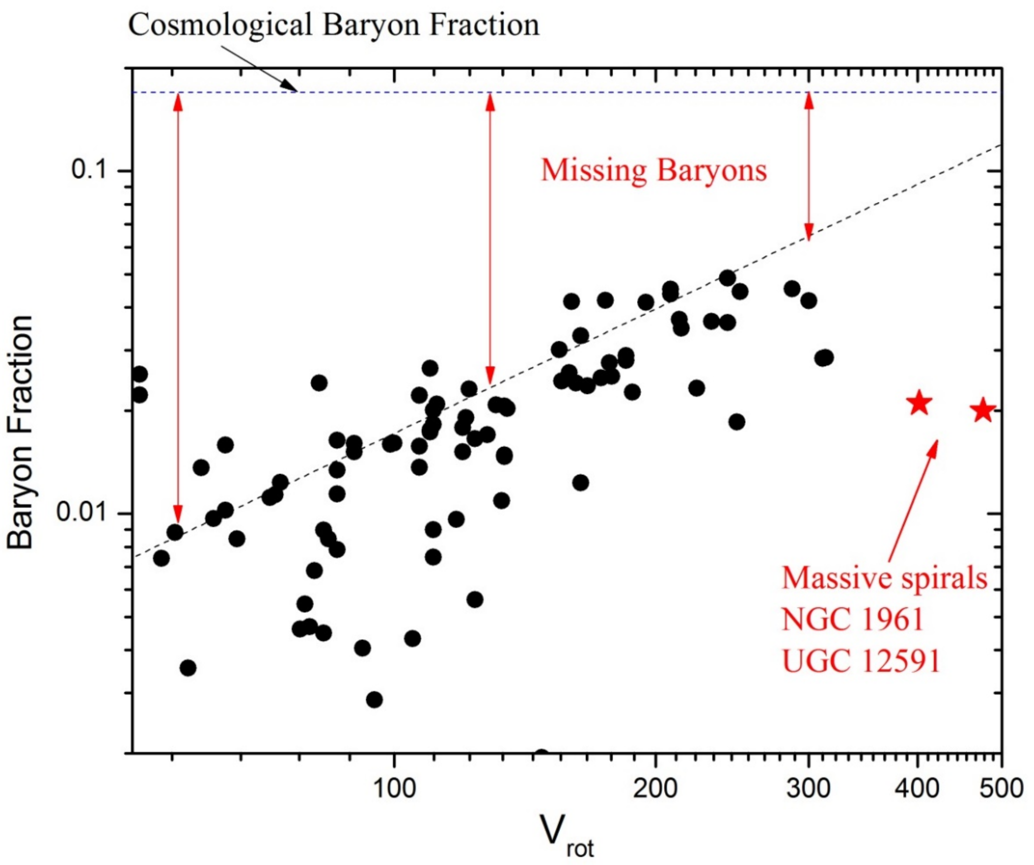
The Missing Baryon Problem(s) at Low Redshift

- Galaxies (stars and cold gas) are 10% of the Cosmic Baryons
- About 50% of the known baryons are in gaseous form
  - Galaxy clusters and groups
  - UV absorption line studies
    - galaxy halos and beyond
    - $T < 5\times10^5$ K (includes O VI)
- 1st Missing Baryon Problem: Where are the rest of the baryons?

The 2nd Missing Baryon Problem: Individual Galaxies are Missing Most of their Baryons



Rich clusters have nearly all their baryons.
Galaxies become increasingly baryon-poor.
"Average" spiral (like M33) is missing 90% of baryons

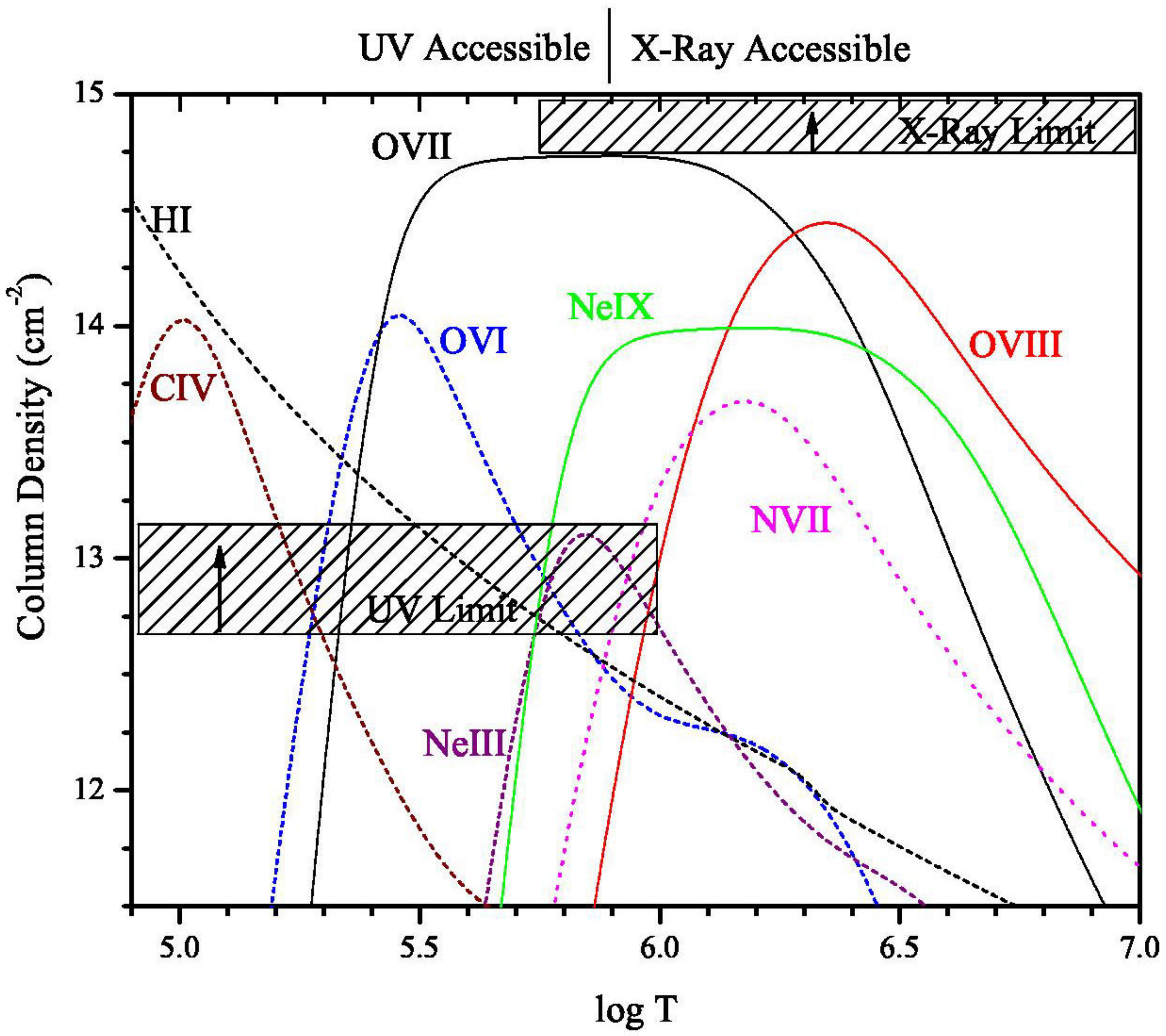
The 3rd Problem: The Missing Metals

- Calculate the Mass of Metals produced over cosmic time
- Compare to baryon density of universe to form a Cosmic Metallicity of the Universe
  - From supernovae (Maoz): 0.09 solar
  - From cosmic star formation history (Shull): 0.16 solar
- Count up all the metals from the visible stars, metal absorption lines, cold disk gas, hot group/cluster gas
  - Calculate the observed cosmic metallicity
  - Result is about 0.015 solar – we are missing 90% of the metals!

Suggested Resolution of these 3 Problems

- Extensive Previously Undetected Hot Gas Halos (10^6 - 10^7 K) exist around galaxies (Fukugita & Peebles 2006)
- The Cosmic Web has a lot of hot gas
- This hot medium must have an average metallicity of 0.2-0.3 solar to account for the metals in the Universe

- How do we detect this gas?
- X-ray absorption and emission lines, mainly O VII, O VIII, Fe L



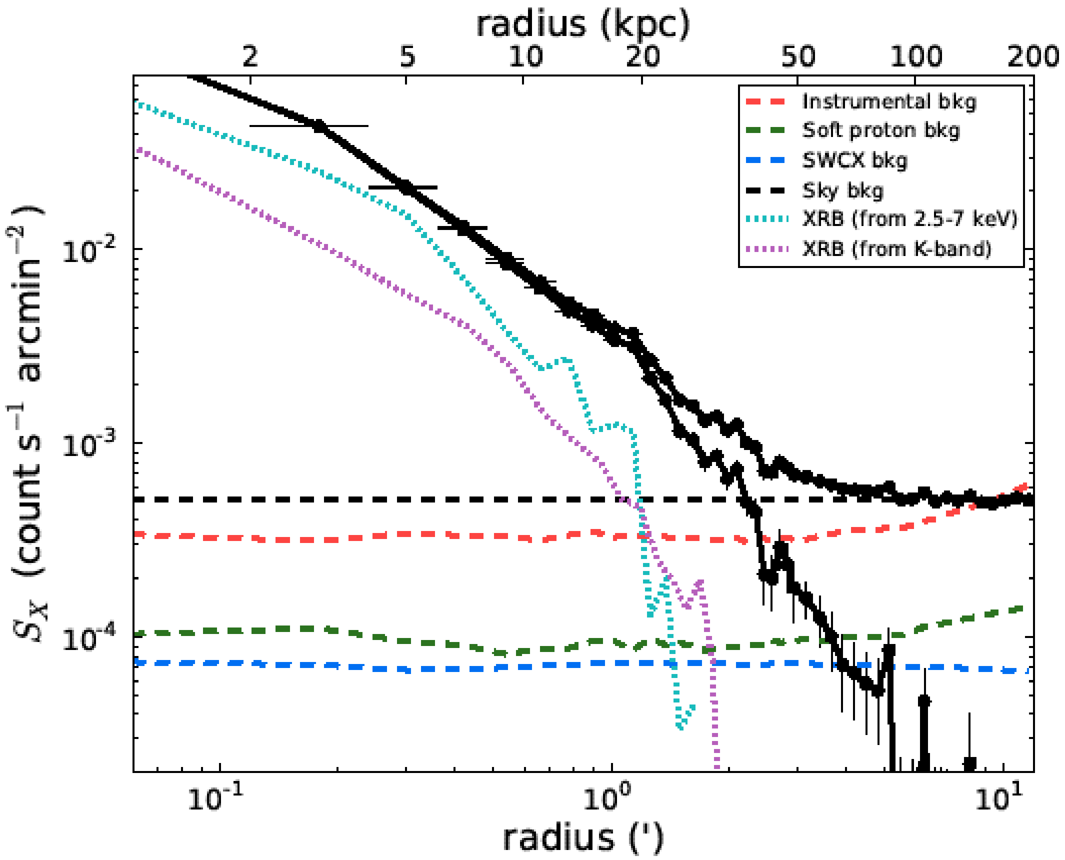
Z = 0.1 Solar

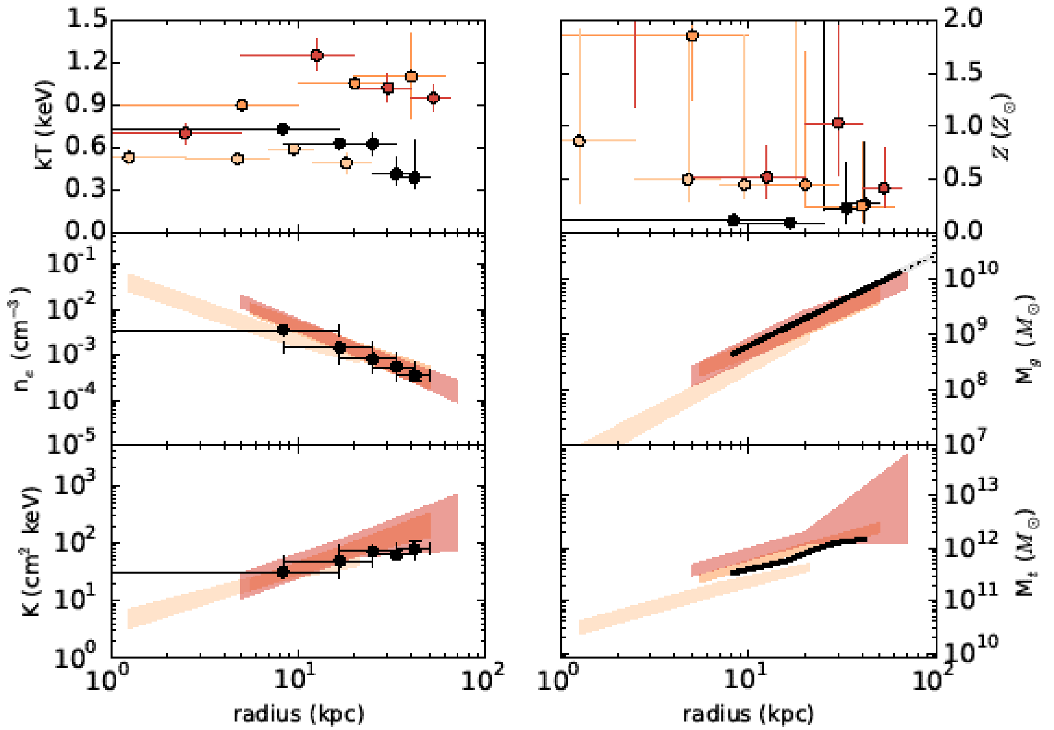
N = 10^{19} cm^{-2}

To find the rest of the baryons in absorption, need to work in the X-rays;

Best lines: O VII Heα (21.6 A), O VIII Kα (19.0 A); C VI (33.7 A), C V (40.3 A) are next

Extended Hot Halos Around Isolated Are Detected





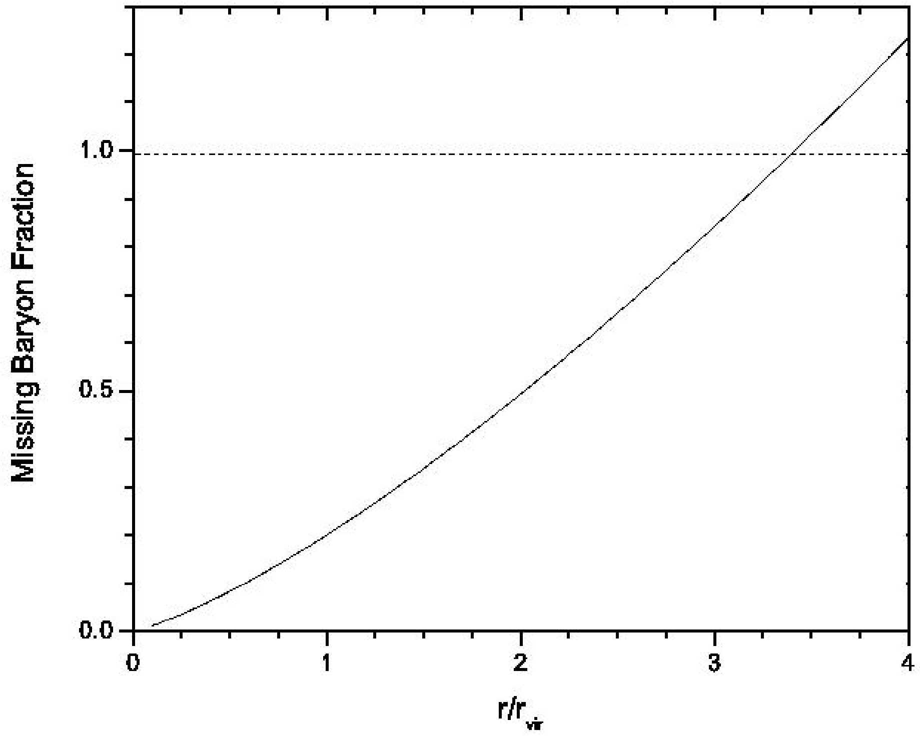
- From Anderson, Churazov, & JNB 2015 (NGC 1961; UGC 12591, others)
- 30% of baryons accounted for at virial radius (still missing most)
- Metallicities of 0.2-0.5 solar (mainly Fe)

Milky Way Baryon Budget

- From studies of Emission Lines and Absorption Lines (Miller & JNB 2015)
- For a cosmological f_{bar} of 0.157 (Planck 2105)
  - M(stars + cold gas + dust) = 6-7 x 10^{10} $M_{\odot}$
  - M_{virial} = 1-2 x 10^{12} $M_{\odot}$
  - $M_{missing}$ = 1-3 x 10^{11} $M_{\odot}$
- If the density profile extends to the virial radius...
- M_{hot} = 2-6 x 10^{10} $M_{\odot}$
- Halo gas contributes < 20% to the missing baryons
- Where's the rest?

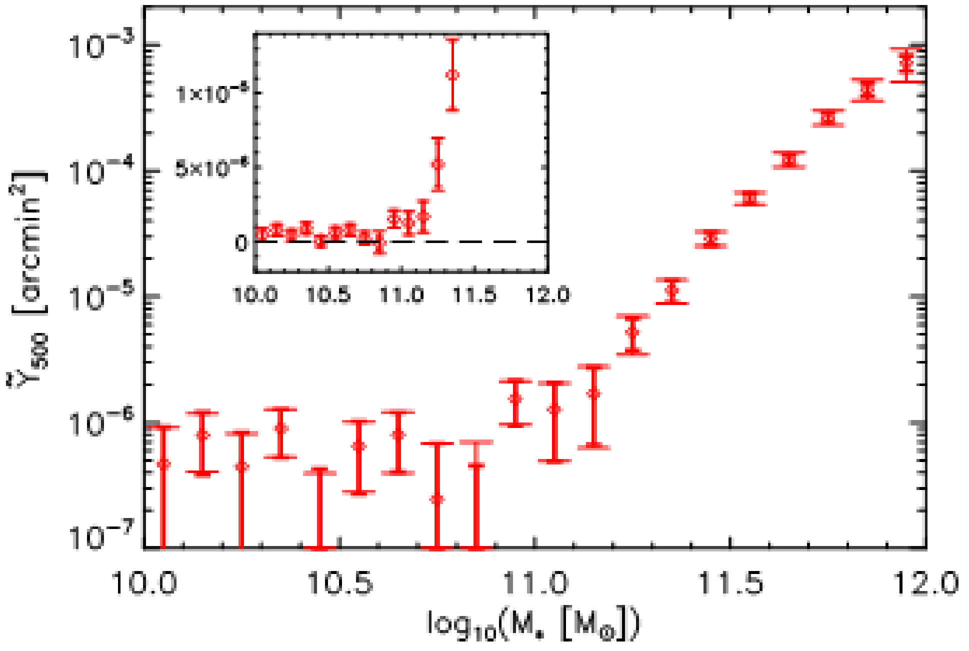
Density and Mass Extrapolation

- Common Hot Halo Gas Properites:
  - $\beta = ½$; $n \sim r^{-3/2}$
  - 20-30% of missing baryons within R_{virial}
- If extended out to 3-5R_{virial} can account for all the baryons
- No reason for baryons to be hot beyond R_{virial}
- Concerns: profile may steepen?
- Is the gas hot beyond R_{virial}?



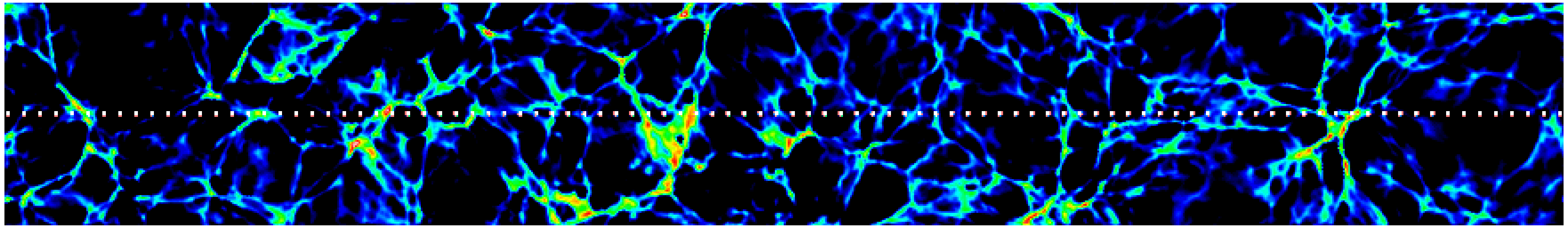
S-Z Effect Shows Galaxy Halos are Hot

- Planck Collaboration (2014); Inter. Results XI (also Greco et al. 2015)
  - 100-353 GHz; resolution 10’
  - Galaxy catalog of Blanton (2005); 260,000
  - Locally Brightest Galaxies -- Stacked
  - Massive galaxies
  - $Y_{500} \propto T_{virial} M_{gas}$
  - Signal for log M* > 11.2
  - Found the baryons!
  - Missing baryons are hot



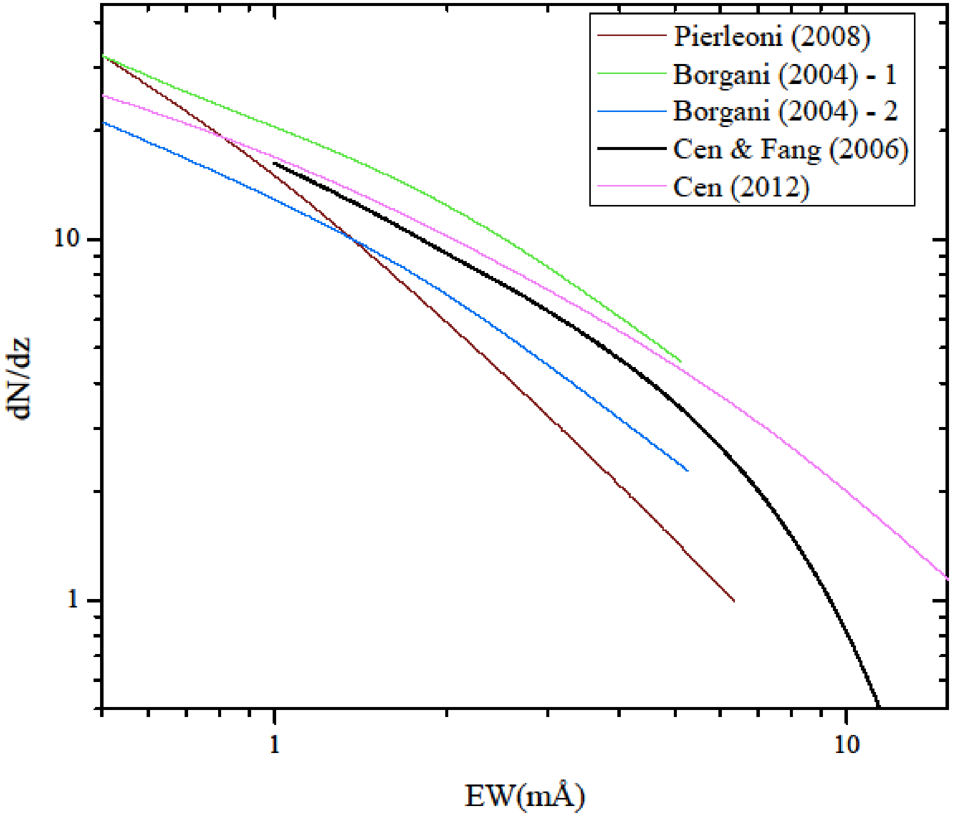
- Hot baryons extend beyond R_{virial}
- Not much room for a massive cold gas halo (COS-Halos)

Absorption Line Predictions



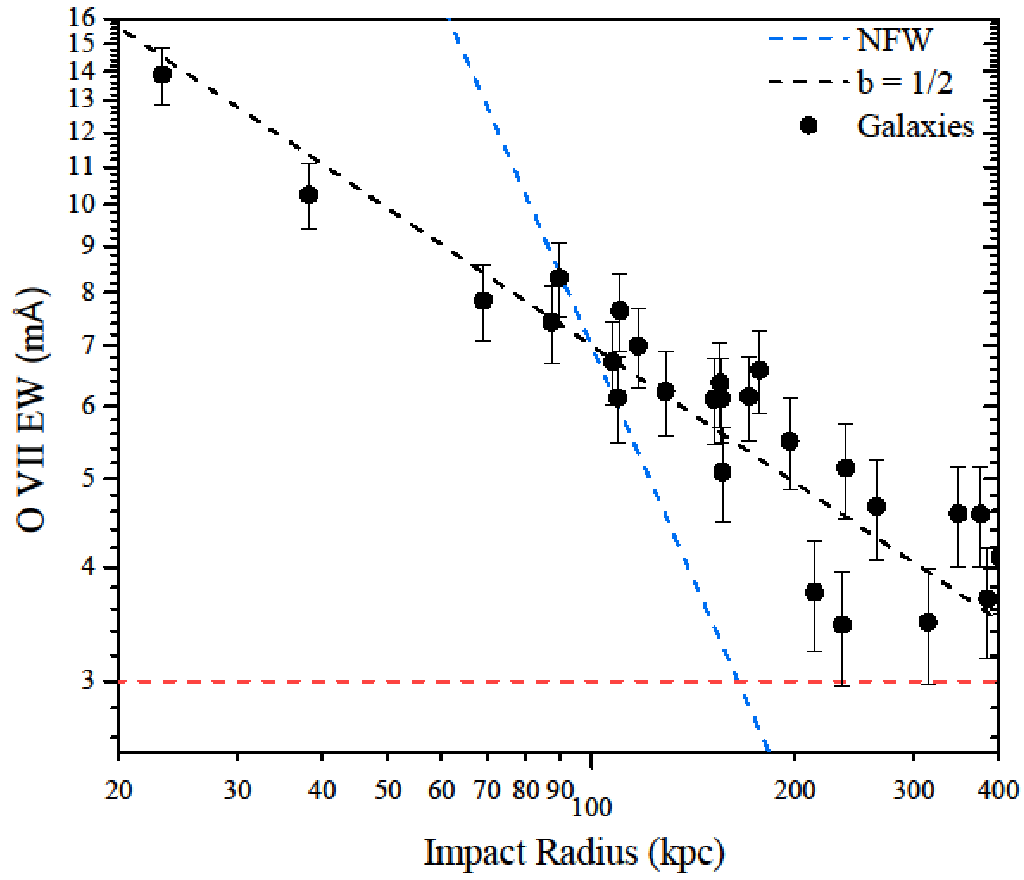
Line of sight through favorite simulation

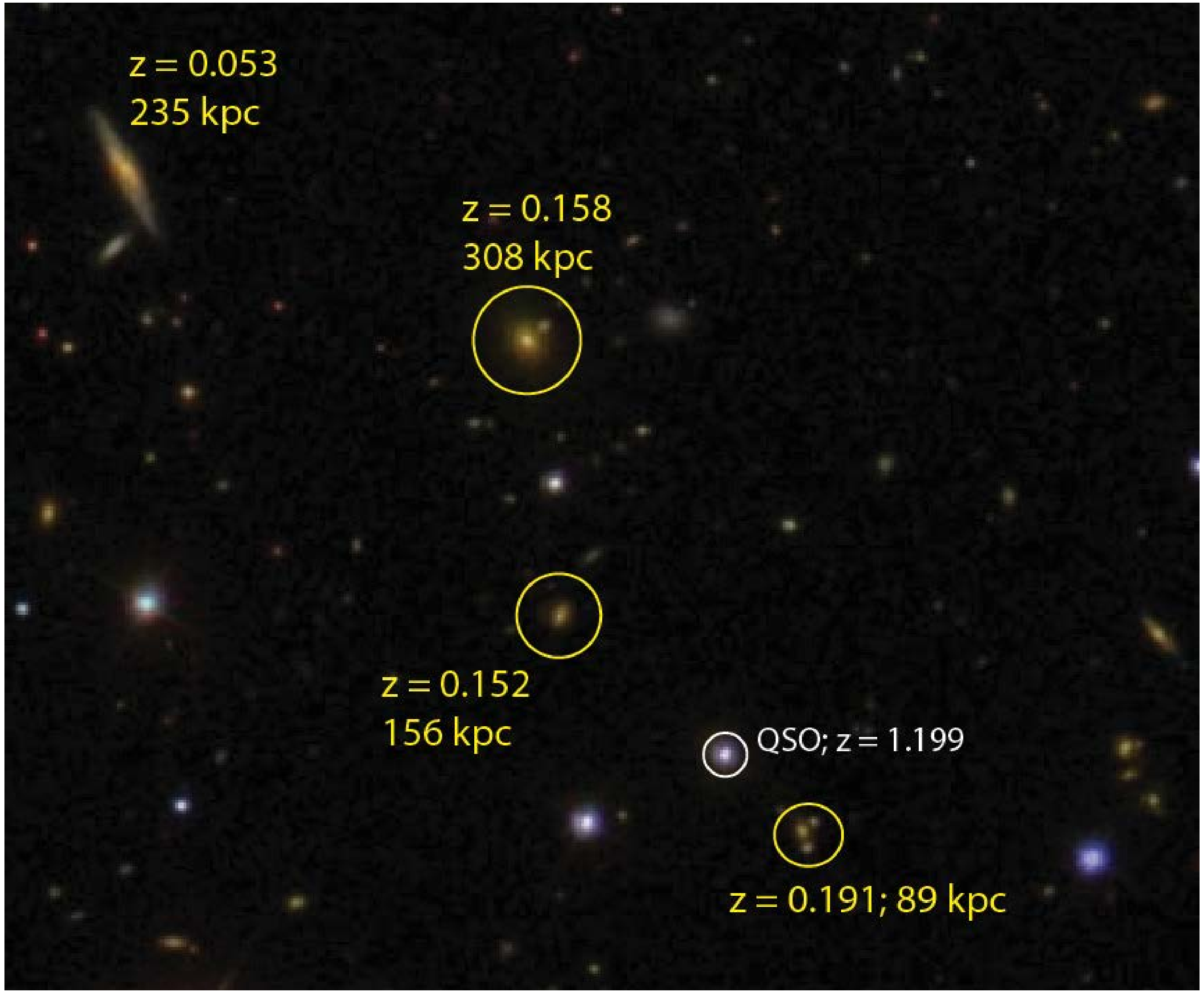
- Cosmological simulations with baryons and heating processes (Cen)
- Most absorption: outer parts of groups and from galaxy halos
- O VII: not much absorption above 10 mA
- Desirable to get down to 3 mA



Put the MW Halo Around Other Galaxies

- Extrapolated beyond virial radius
- Absorption lines produced to large radius at > 3 mA
- Actual calculated absorption against the brightest background AGNs
- Bregman et al. (2015)



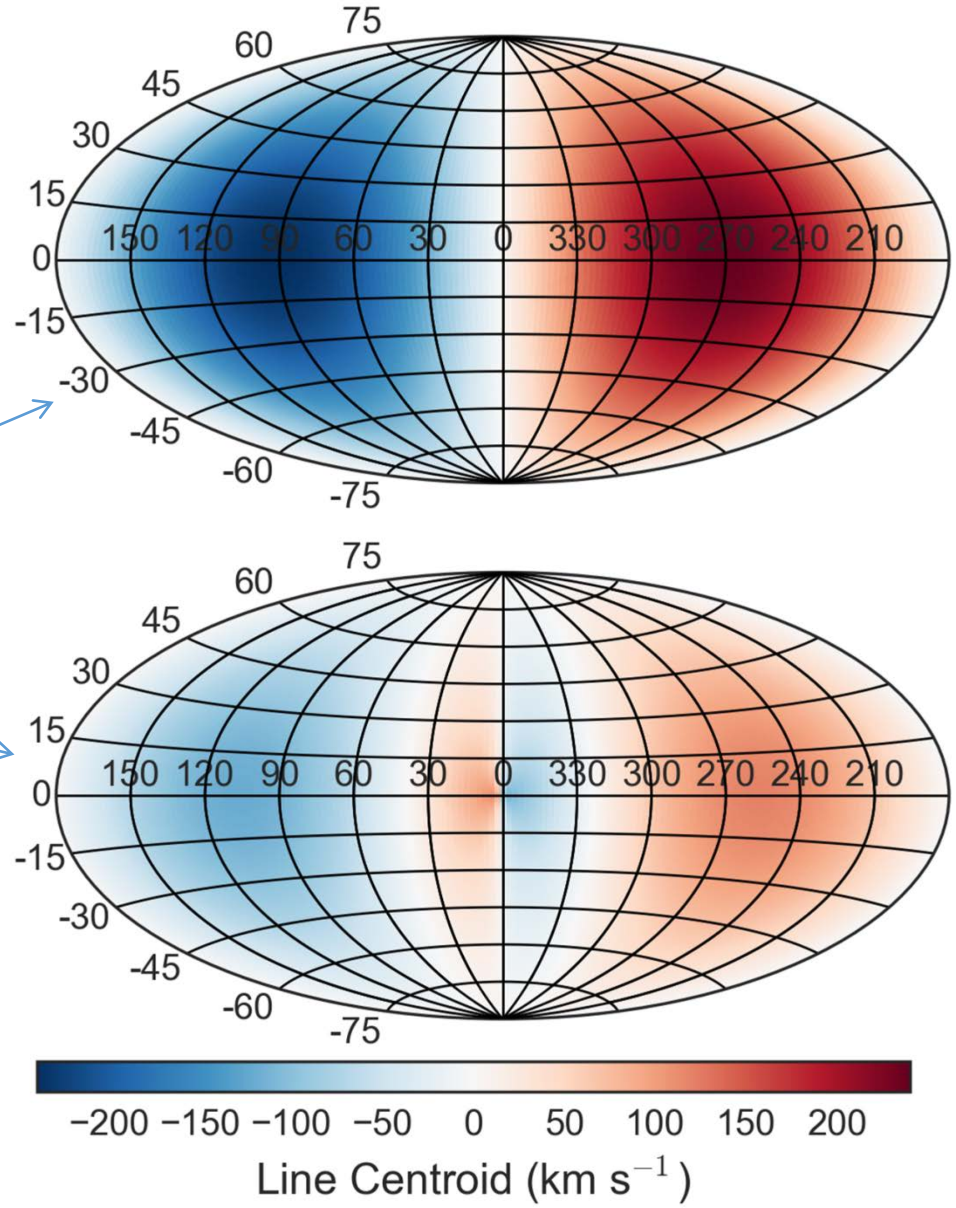

z = 0.053
235 kpc
z = 0.158
308 kpc
z = 0.152
156 kpc
QSO; z = 1.199
z = 0.191; 89 kpc

You can see the Galaxy rotate!

Stationary Hot Halo

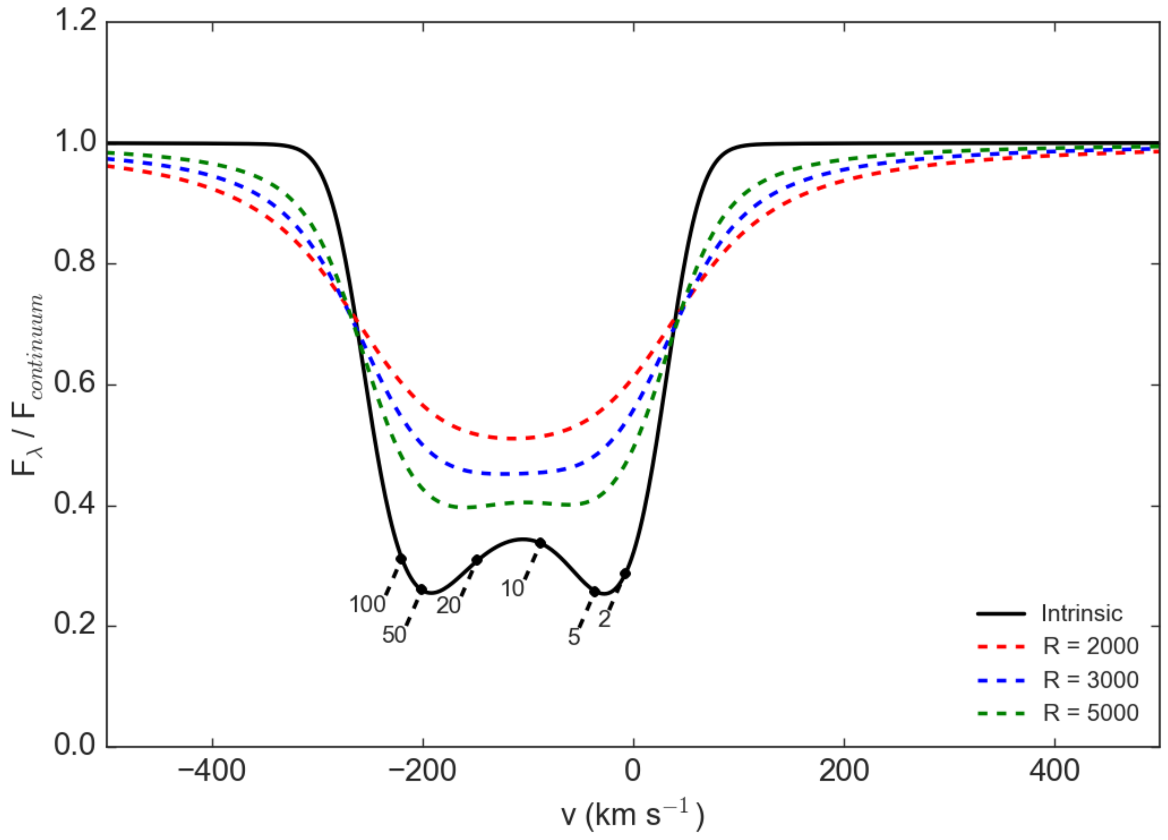
Co-Rotating Hot Halo

Miller et al. (2015)



Map the Galaxy Rotation Vs Radius

- X-Ray Rotation Curve
  - Like 21 cm line structures
  - Higher resolution essential
  - Doppler b = 45 km/s
  - Shown l = 90, b = 0
  - Miller et al. (2015)



Detectability of Unresolved Absorption Lines

Observatory	Instrument	Type	Resolution	Aeff	R x Aeff	EW limit
			(at 0.5 keV)	cm^2	10^3	mA
Chandra	LETG/ACIS-S	Grating	500	11	5.5	47
XMM-Newton	RGS	Grating	420	45	18.0	26
Athena	X-IFU	Calorimeter	250	8200	2,050	4 [2.5]
X-Ray Surveyor		Grating	5000	4000	20,000	1 [0.76]

Exposure time of 0.3 Msec, 0.5-2 keV flux of 1E-11 $erg/cm^2/s$.
EW limit is for a 4 sigma detection.

Observational Demands: X-Ray Surveyor

- Minimal science need is to detect a 4 mA absorption line at 5 sigma
  - Map out dN/dz in one line, O VII
  - Trivially met – can be done in ~ 1 Msec
  - easily go down to 1 mA
- Measure local dN/dz in O VII, O VIII, C V, C VI with a range of an order of magnitude in EW (2-20 mA)
  - Some detections of N V, N VI, Ne IX, Fe XXVII
  - Yields metal mass distribution vs temperature
  - 30-60 targets; less than 5 Msec
- Determine redshift distribution of dN/dz to z = 1
  - Simulations predict a decrease in hot gas mass with z
  - About 3 Msec

Absorption Programs, cont.

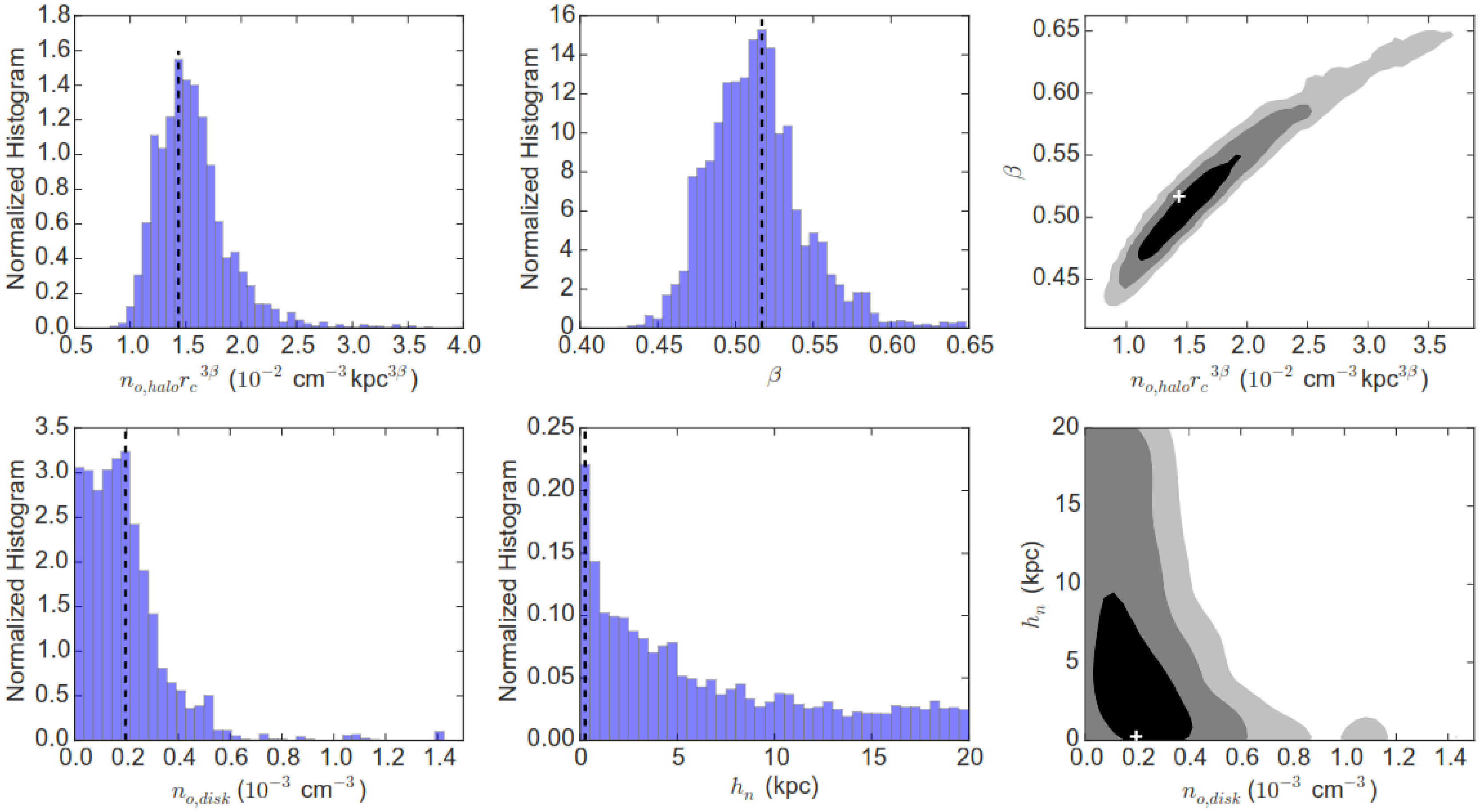
- Define absorbing properties of galaxy halos
  - Mostly obtained from above surveys
  - Add sight lines of specific background AGNs near galaxies
    - 5-10 sight lines behind M31 (1 Msec)
- Determine absorbing gas in galaxy groups
  - Get this for free from above survey (could add specific pointings; < 1 Msec)
- Absorption by outer parts of galaxy clusters
  - Need specific pointings (but < 1 Msec)
- Milky Way Studies
  - Dynamics of the halo: rotation vs radius, infall/outflow rate, turbulence
  - Resolves optical depth effects
  - Metallicity vs radius
  - Get this for free with above survey (add some pointings across Galaxy)

So Let’s Build Something Already!

Table 2. Ions and Absorption Lines

Ion	λ Å	E keV	f_{ik}	[X/H]	Rel O VII	$\log T_{min}$	$\log T_{max}$	MW	IGM	z_{max}
C V	40.26	0.308	0.647	8.59	1.24	5	6.1	X	X	0.23
C VI	33.73	0.368	0.416	8.59	0.39	5.75	6.35	X	X	0.47
N VI	28.79	0.431	0.674	7.93	0.20	5.2	6.3	X		0.72
N VII	24.80	0.500	1.090	7.93	0.15	5.9	6.6	X		1.00
O VII	21.60	0.574	0.695	8.74	1.00	5.4	6.5	X	X	1.30
OVIII	18.97	0.654	0.416	8.74	0.25	6.1	6.8	X	X	1.62
Fe XVII	15.02	0.826	2.310	7.45	0.08	6.25	7	X		2.30
Ne IX	13.45	0.922	0.721	8.00	0.12	5.7	6.9	X		2.69
Fe XX	12.82	0.967	0.520	7.45	0.01	6.75	7.2			2.87
Mg XI	9.169	1.352	0.741	7.54	0.03	5.95	7.1			4.41
Si XIII	6.648	1.860	0.747	7.54	0.02	6.2	7.25			6.44

Note. — The oscillator strength, f_{ik}, is given in the fourth column. The sixth column is a guide to the relative absorption line strength and is the product of the oscillator strength, wavelength, abundance, and the maximum ion fraction possible for the ion. T_{min} and T_{max} are the temperatures where the ion falls to one-tenth its maximum value, indicating the useful temperature range of the ion. The most likely lines used for Milky Way (MW) and extragalactic studies (IGM) are denoted in columns 9, 10, while the maximum practical redshift is given in the last column.



- Exponential disk accounts for < 10% of the O VII column in most directions (in absorption); much less in emission.
  - Hodges-Kluck et al. (2015)