# Detecting Missing Baryons Around the Milky Way and External Galaxies

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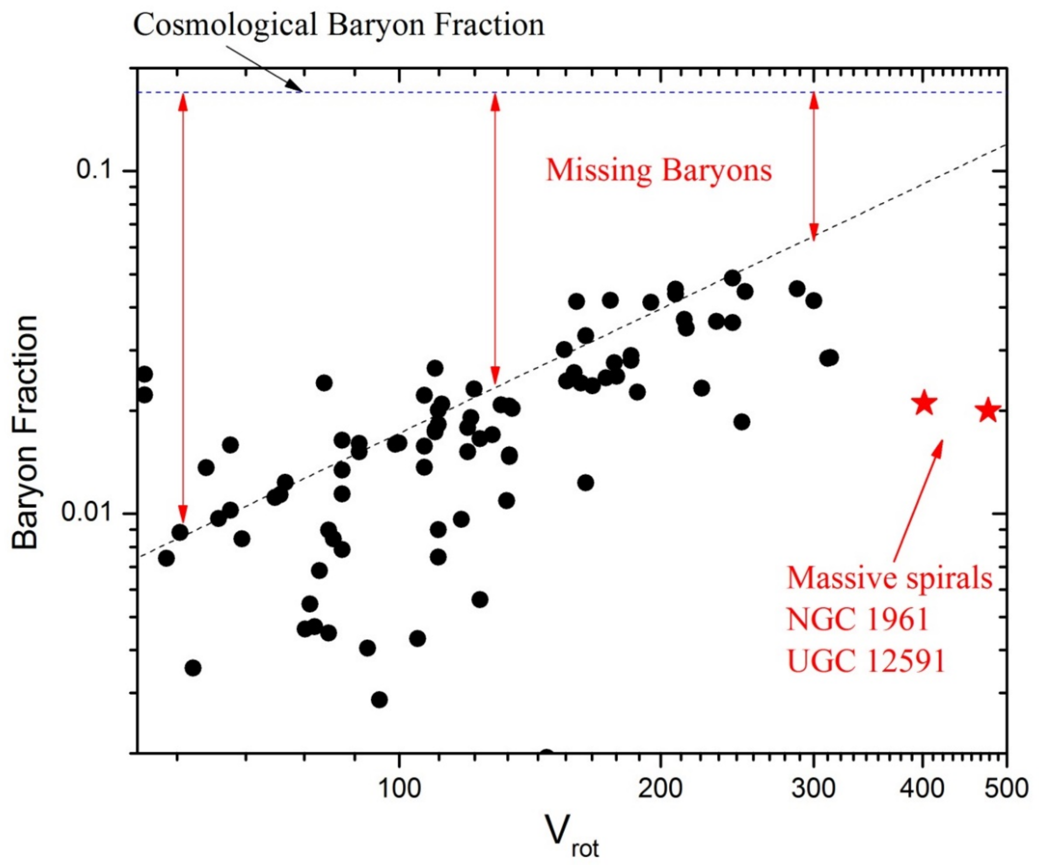
# The Missing Baryon Problem(s) at Low Redshift

- 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

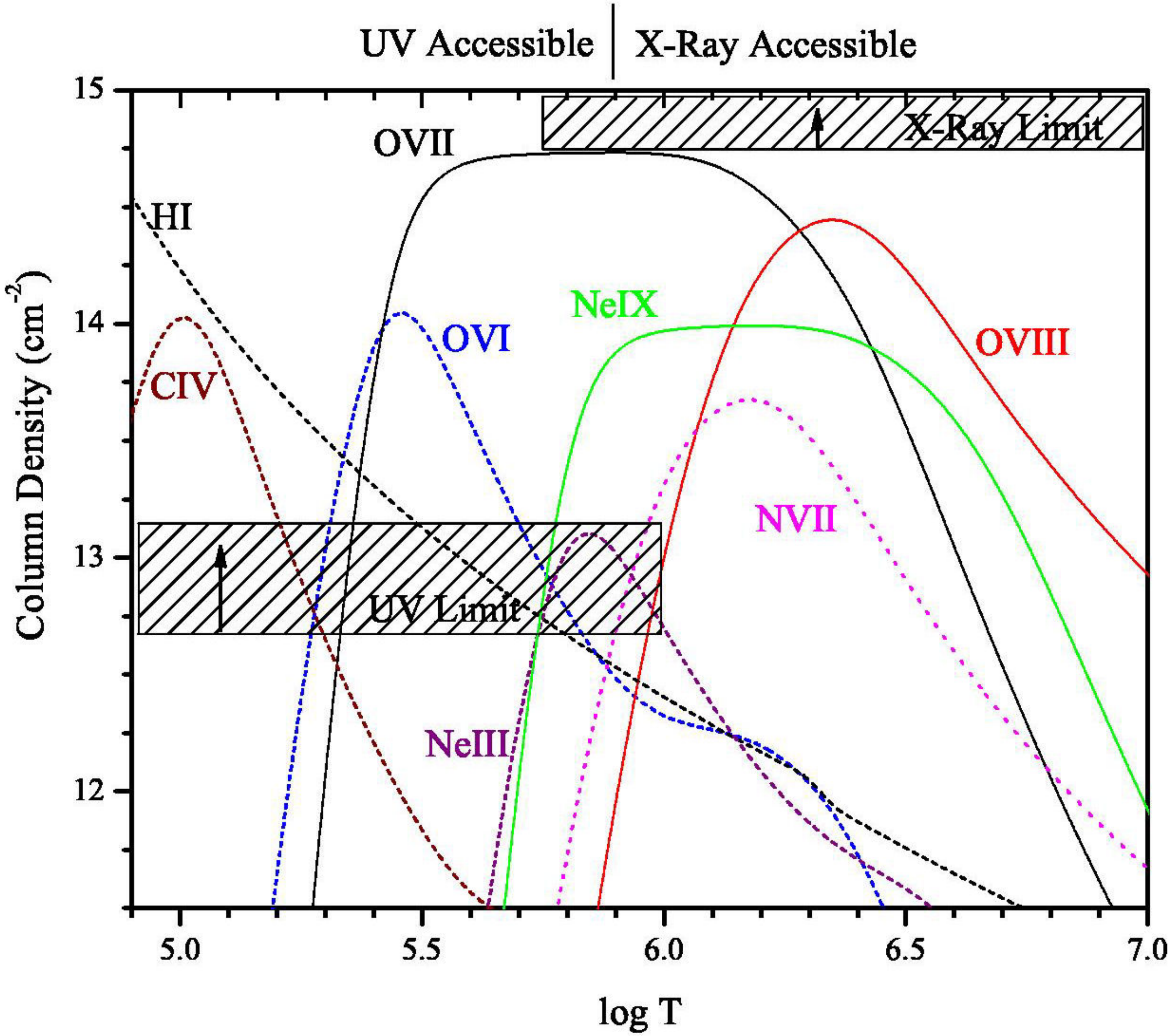
# The 3rd Problem: The Missing Metals

- 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 ($10^{6.5}$ - $10^{7}$ 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



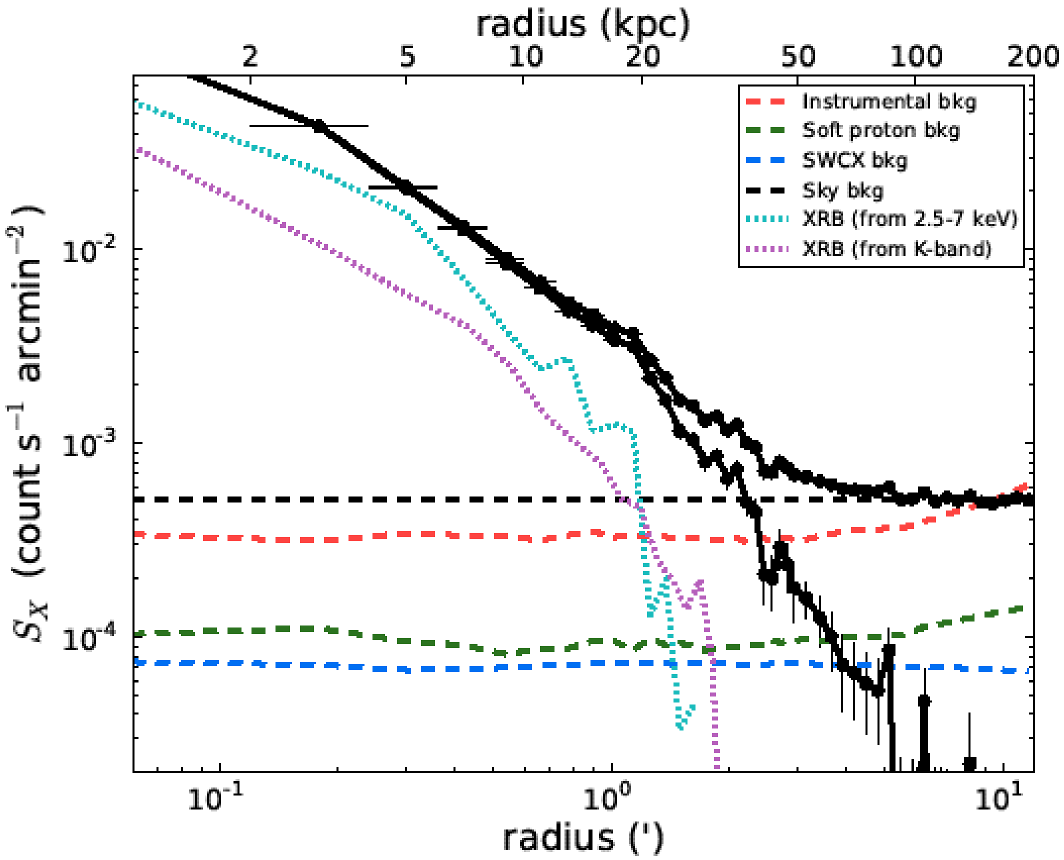

Z = 0.1 Solar

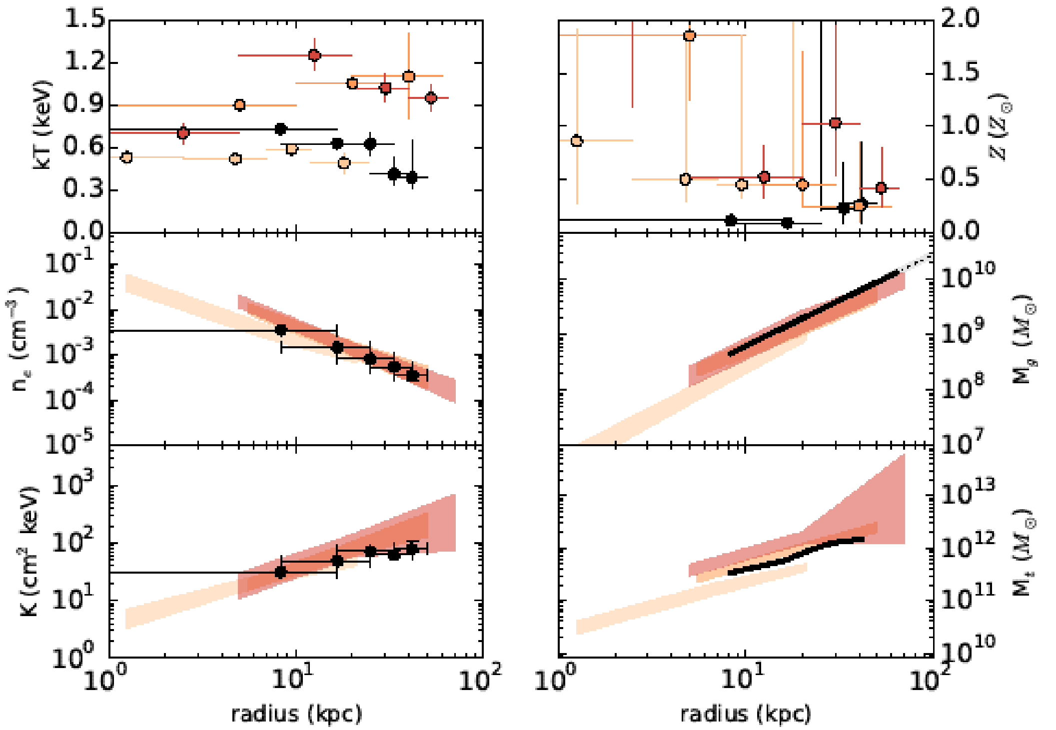
N = $10^{19}$ cm$^{-2}$

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

O VII Kα (21.6 A), O VIII Kα (19.0 A) are the best lines.

# Extended Hot Halos Around Isolated Are Detected



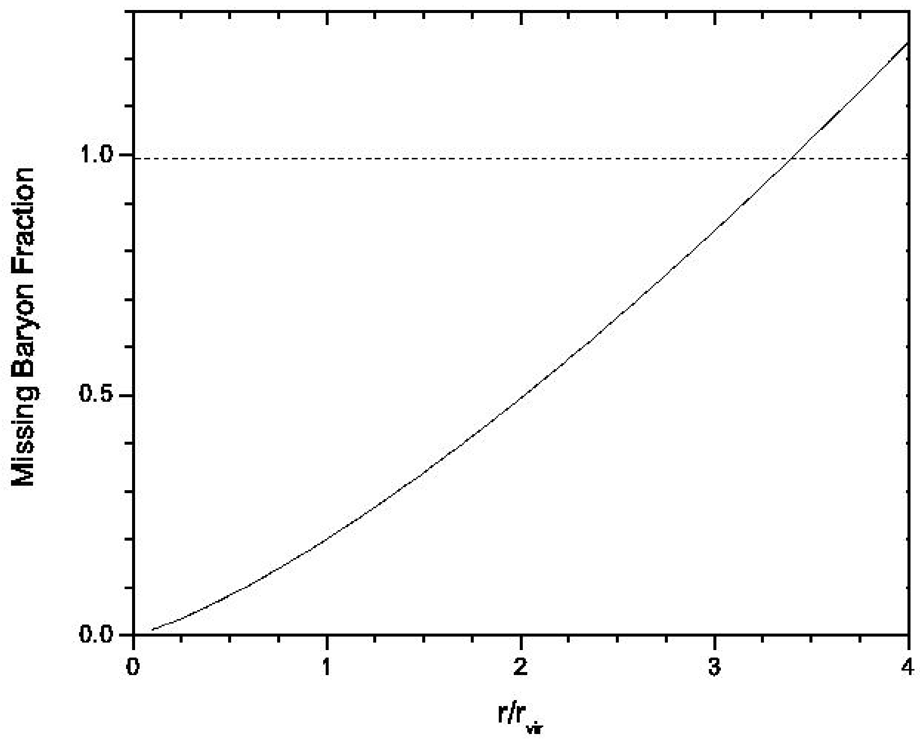

- From Anderson, Churazov, & JNB 2015 (NGC 1961; UGC 12591, others)
- 30% of baryons accounted for at virial radius (still missing most)
- Metallicities of 0.2-0.5 solar (mainly Fe)

# 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?

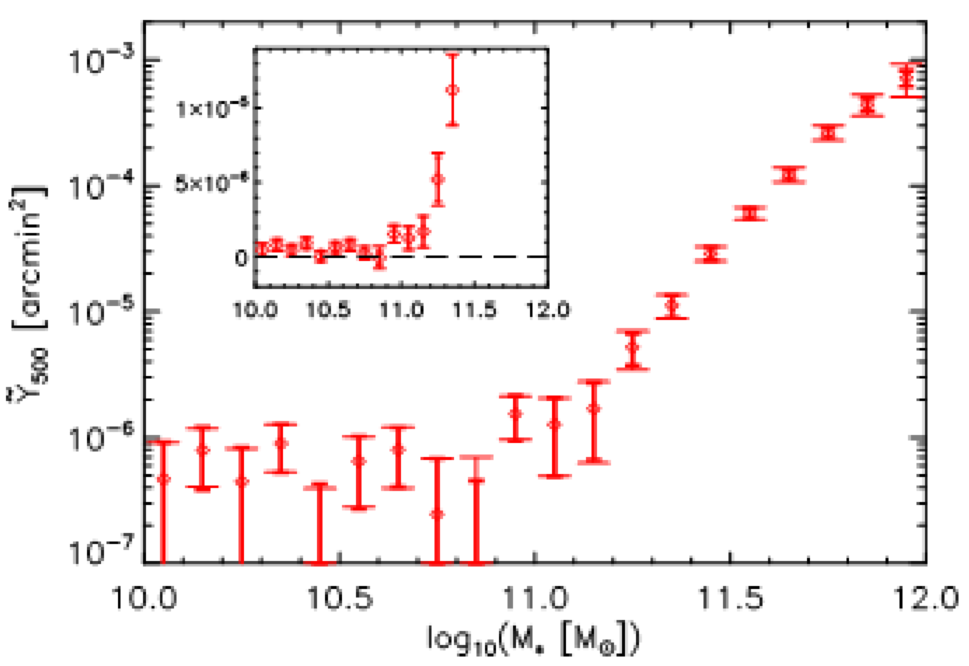
# Density and Mass Extrapolation

- Common Hot Halo Gas Properites:
  - $\beta$ = ½; n ~ $r^{-3/2}$
  - 20-30% of missing baryons within $R_{virial}$
- If extended out to 3-5$R_{virial}$ 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 $R_{virial}$?

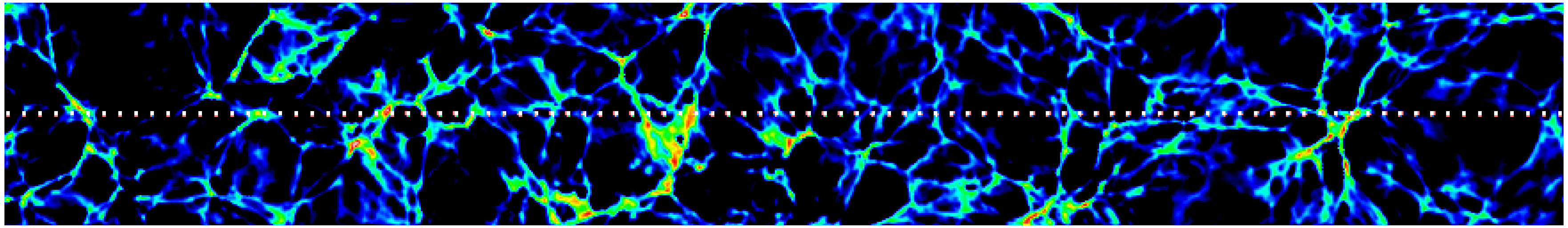


# S-Z Effect Shows Galaxy Halos are Hot

- Planck Collaboration (2014); Inter. Results XI (also Greco et al. 2015)
  - 100-217 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

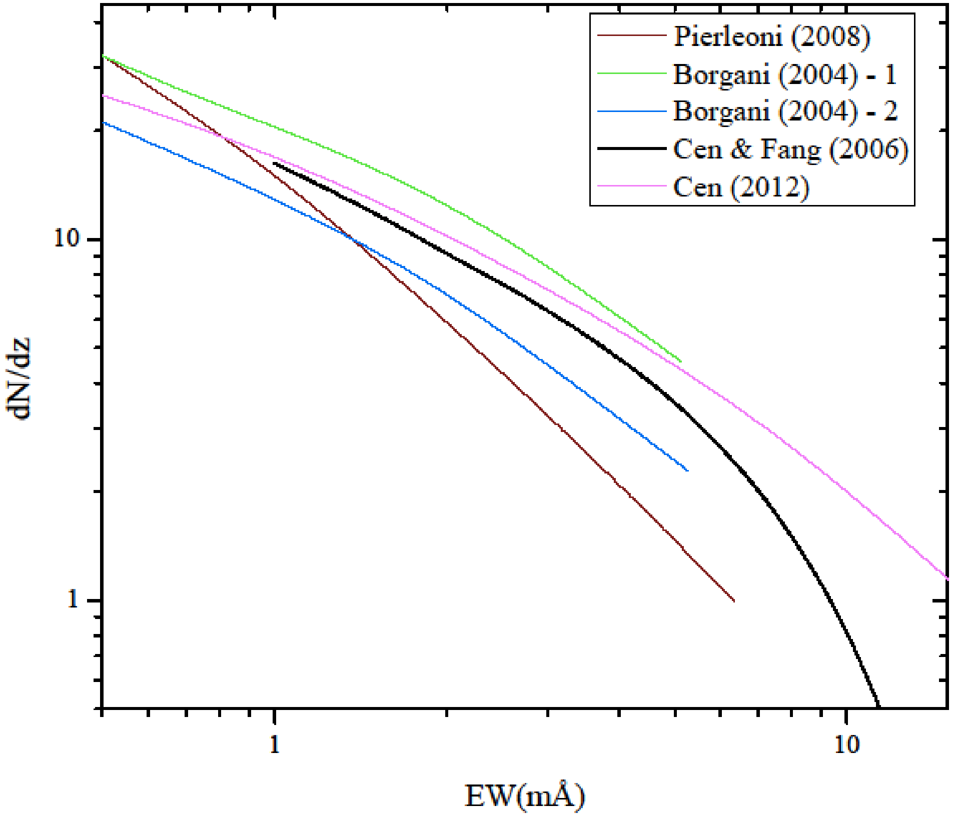


# Absorption Line Predictions



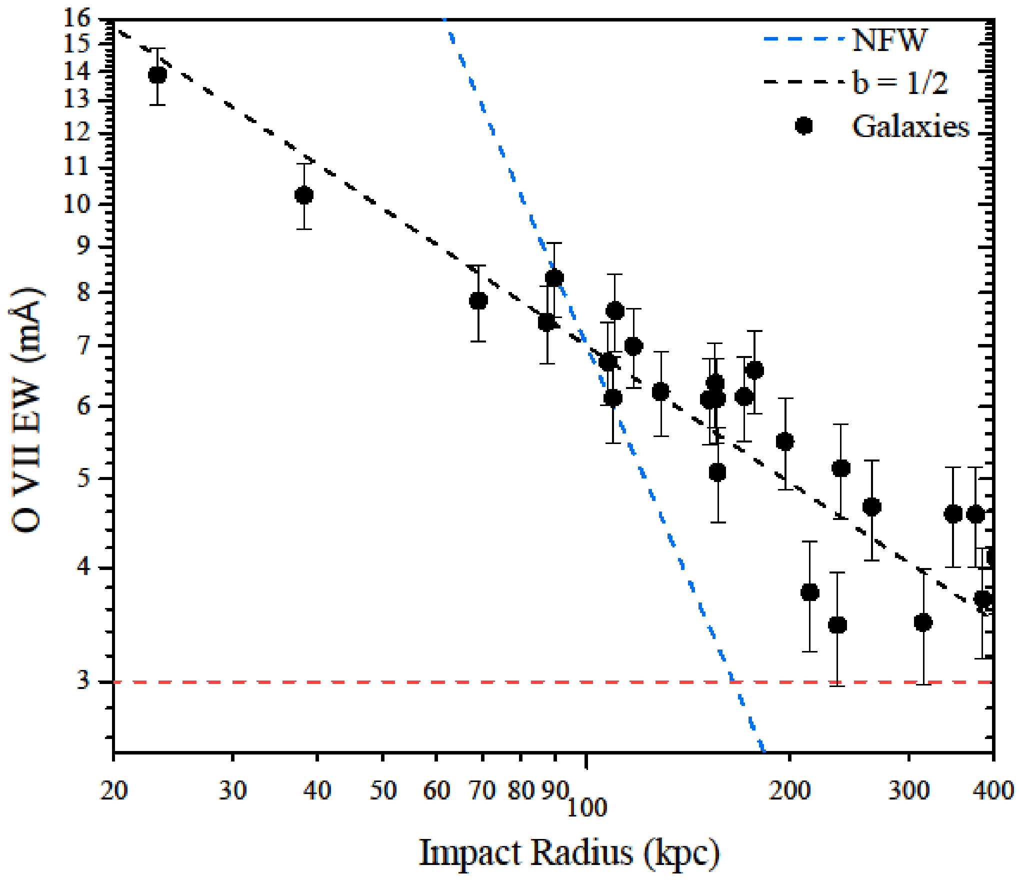
Line of sight through favorite simulation

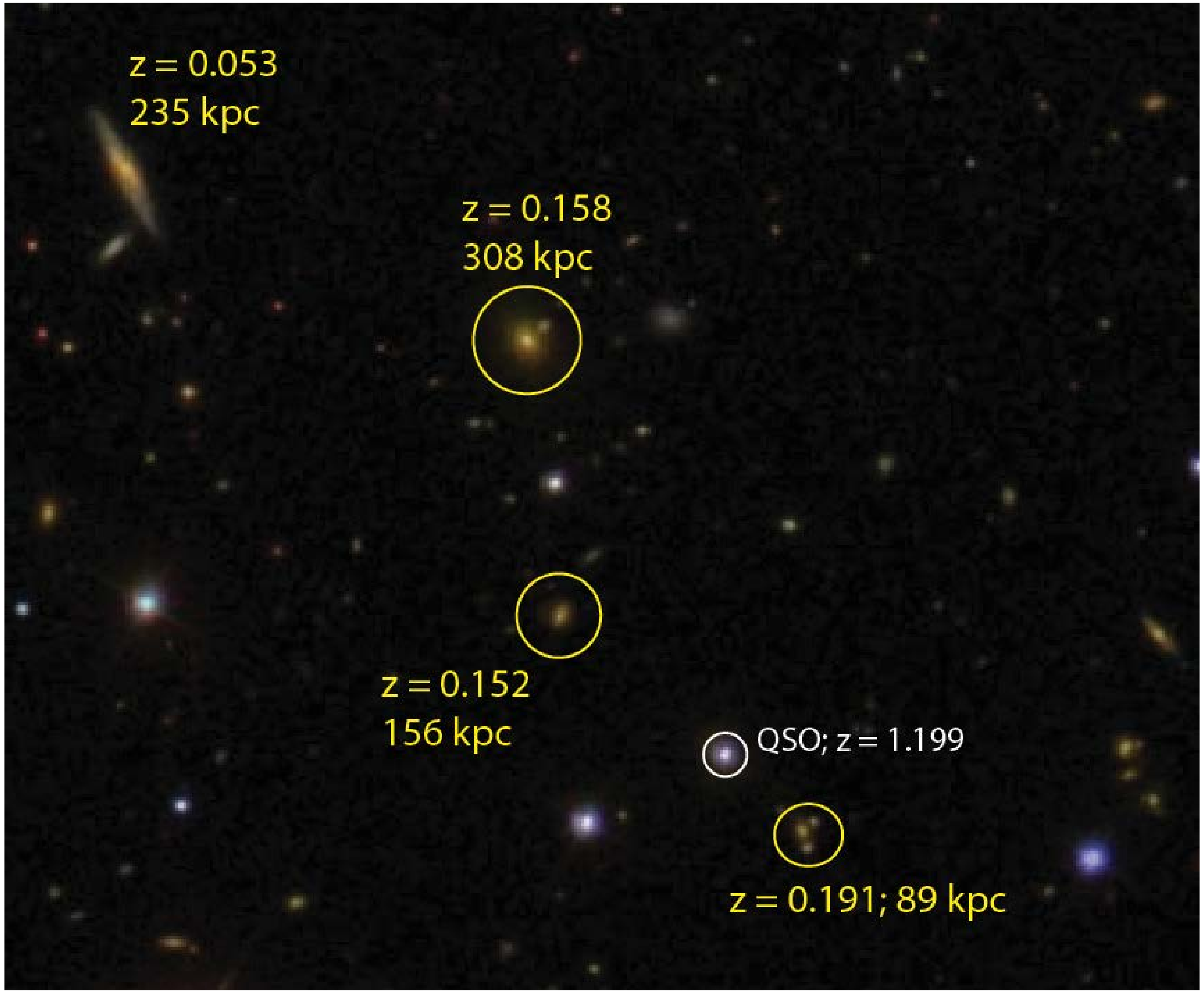
- Cosmological simulations with baryons and heating processes (Cen)
- Most absorption: outer parts of groups and from galaxy halos
- O VII: not much absorption above 10 mA
- Desirable to get down to 3 mA



# 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

# Instrumental Requirements: Calorimeter

- Science need is to detect a 3-4 mA absorption line at 5 sigma
- Athena: resolution of 250 for a 2 eV detector (2.5 eV requirement; 1.5 eV goal)
- Consider S/N of 100 per resolution element (1 sigma) without systematics
- Line width is probably about 100-200 km/s = resolution of 1500-3000
  - line under-resolved by 10x (no line shape information)
- For a 5 sigma line detection at R = 250 and S/N = 100, line depth is 0.05 and resolution element is 86 mA, so you can detect a 4.3 mA line at z = 0, or a 8.3 mA line at z = 1.
- Can map out dN/dz, galaxy halos, in 10 Msec

# Recommendations for the Athena Calorimeter

- Higher spectral resolution really helps
  - Can we obtain 1 eV resolution for a few of the pixels?
- Must be able to achieve high S/N without systematics
  - Systematics enter only when S/N > 200 would be ideal

- For emission studies, observing in lines (O VIII, Fe L) allows studies of hot galaxy halos to about (or beyond) 100 kpc
  - Need good knowledge of focused and unfocused background