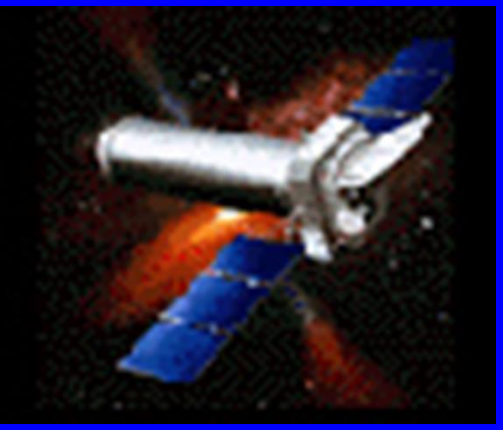
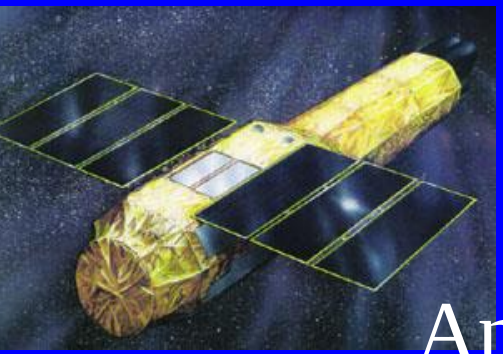
The Warm-hot Gaseous Halo of the Milky Way

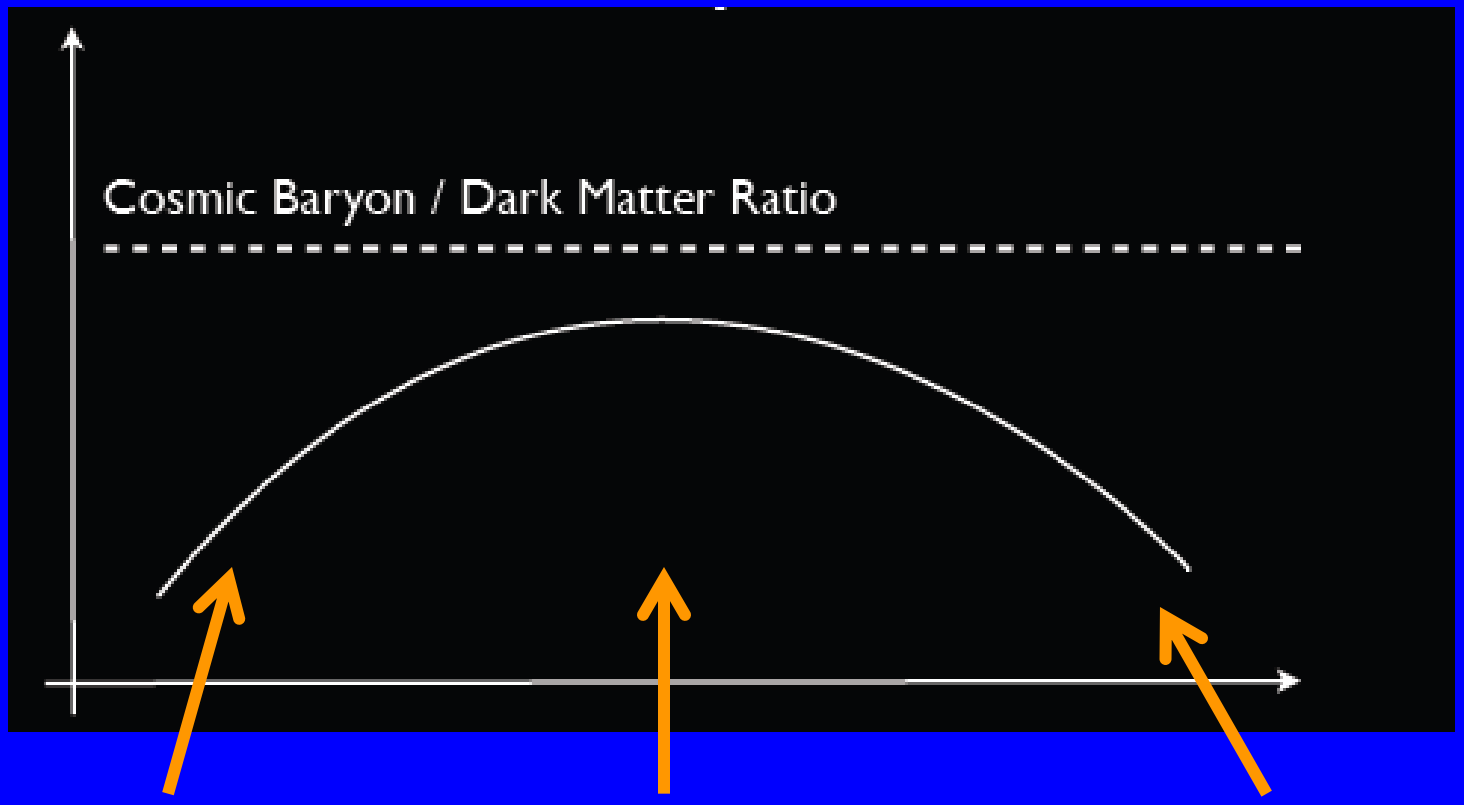


Smita Mathur
The Ohio State University



With
Anjali Gupta, Yair Krongold,
Fabrizio Nicastro, M. Galeazzi

In the low-redshift Universe, baryons are missing on all scales



Where are the Galactic missing baryons?

Local WHIM filament

scale length > 1 Mpc

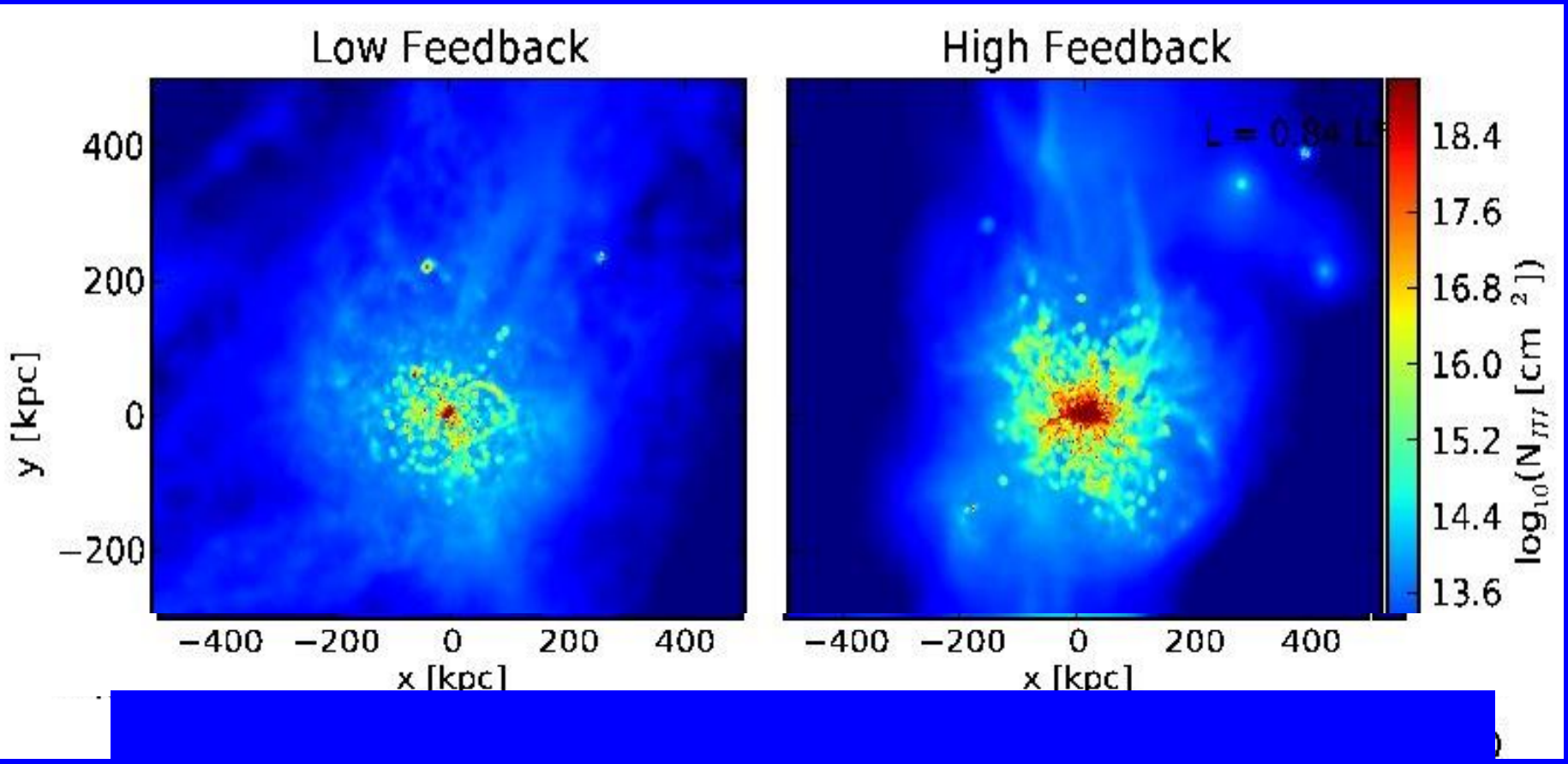
Local Group Medium

scale length of ~ 1 Mpc

Circum-Galactic Medium: extending up to the virial radius (~250kpc)

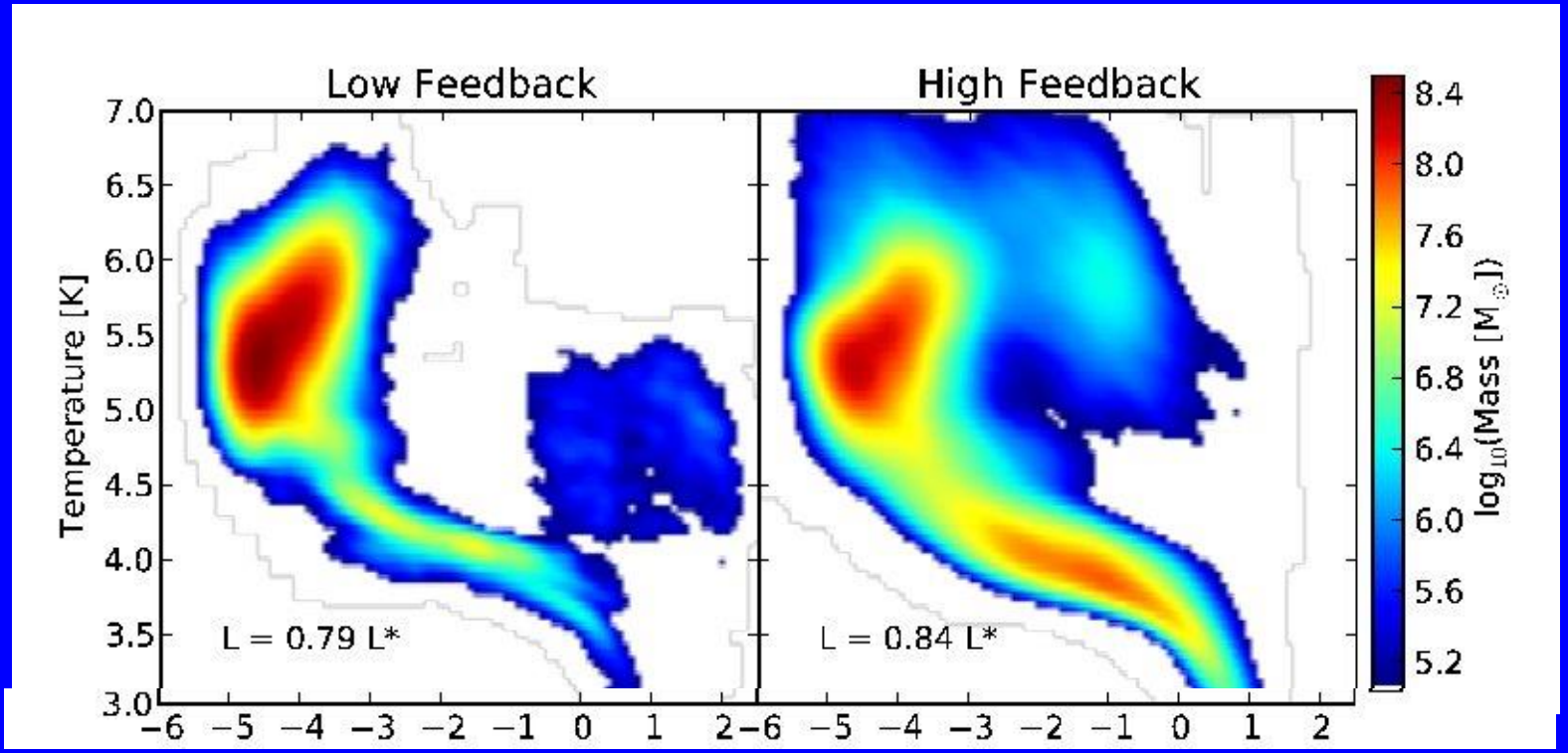
10^5 K < T < 10^7 K

Simulations of the CGM

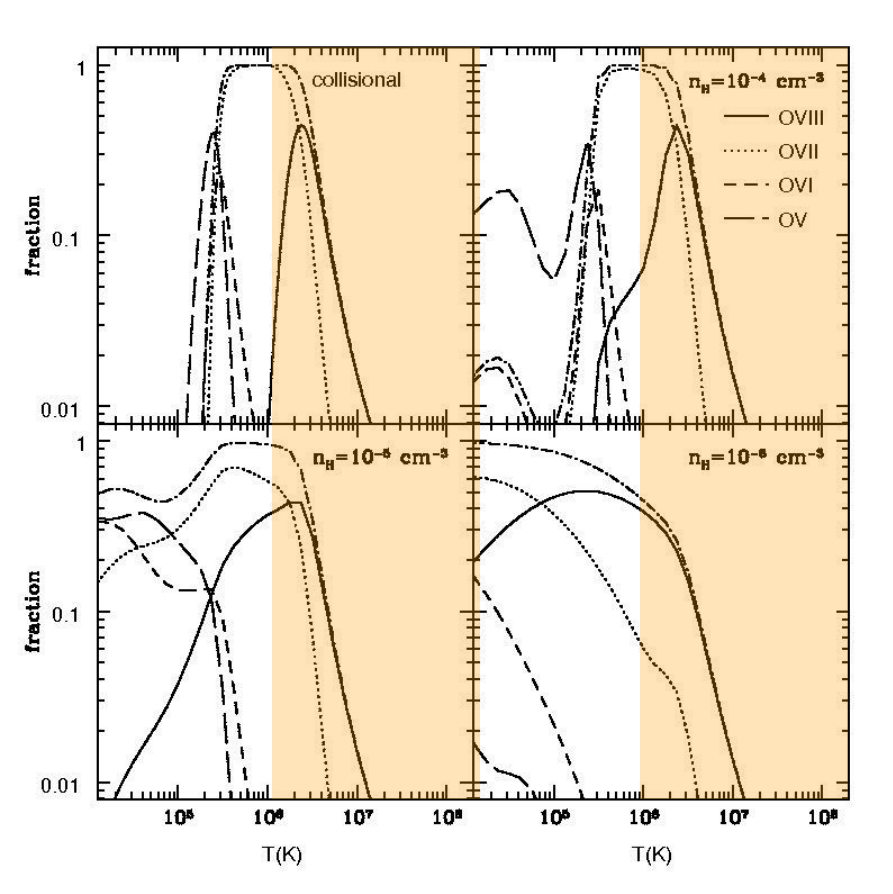


Stinson et al. 2011

Diffuse Warm-hot CGM



z = 0 X-ray Absorption

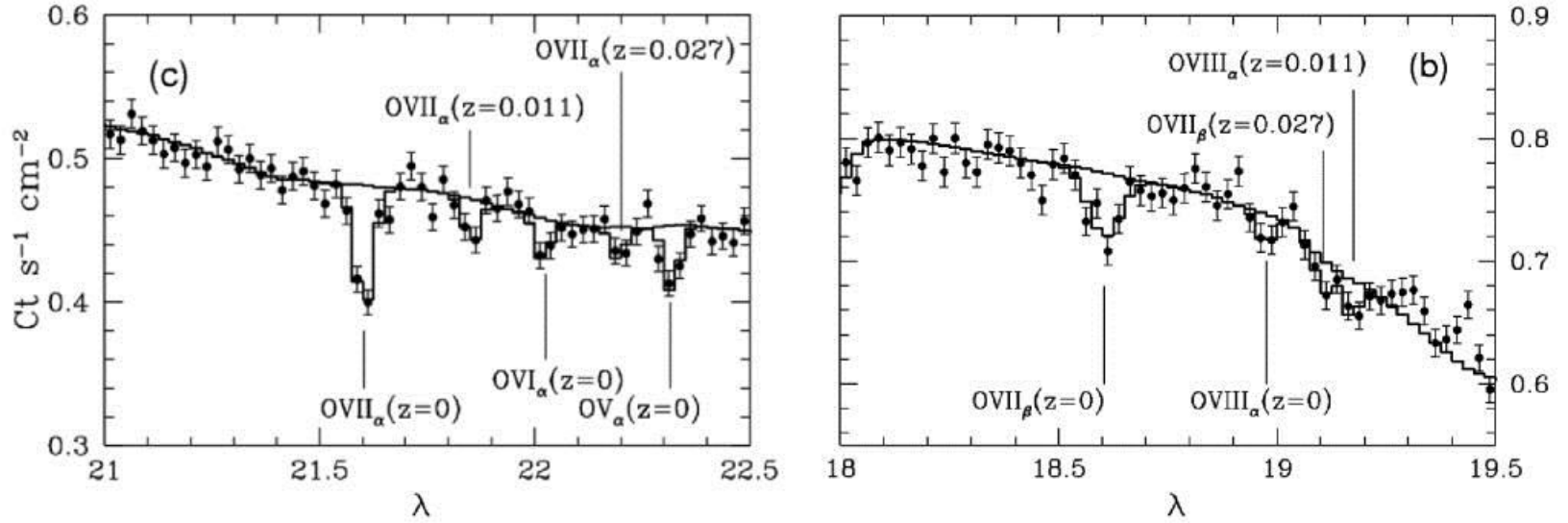


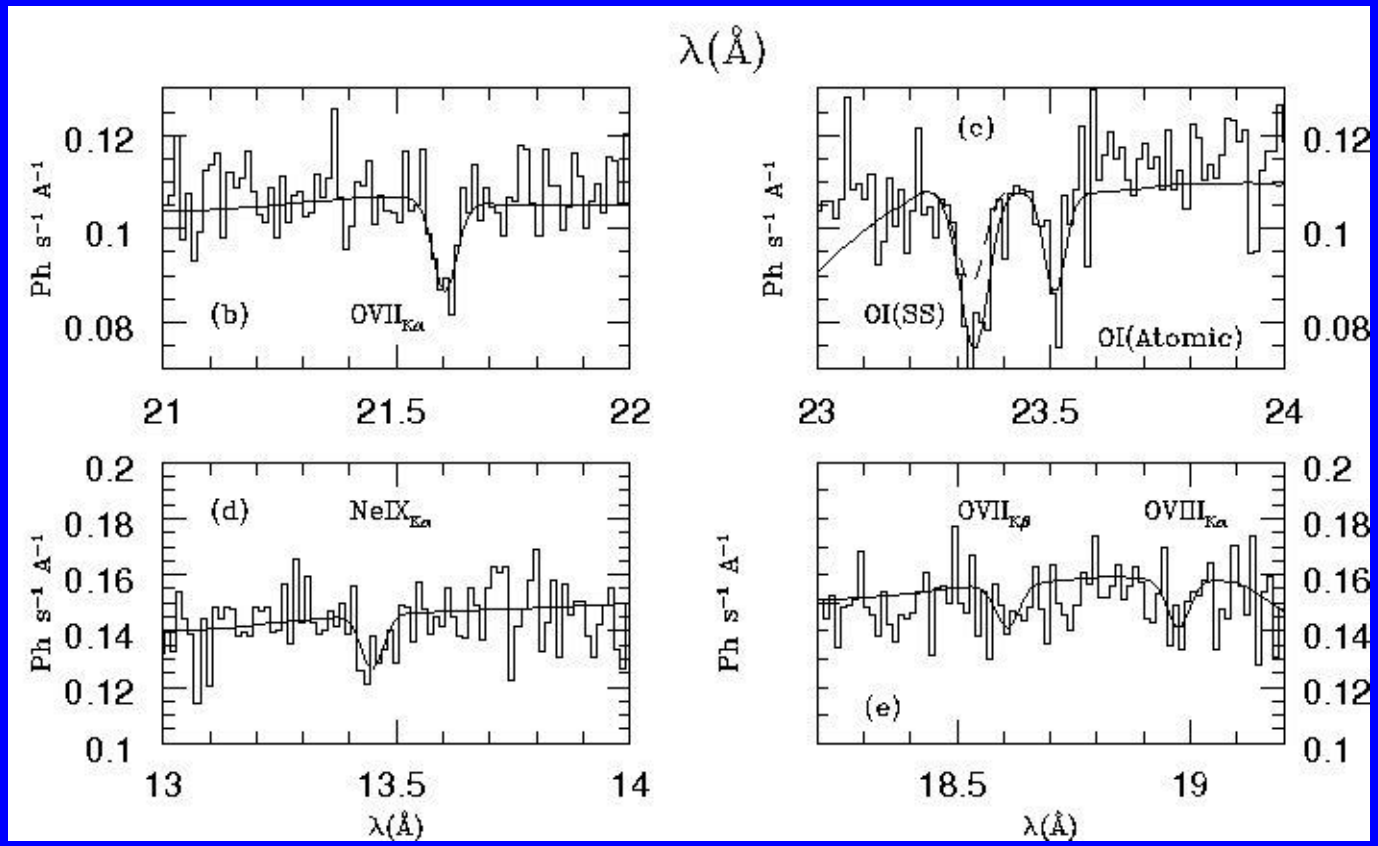
In several high S/N Chandra and XMM spectra

- ***OVII absorption (@21.60 Å)***
- ***Sometimes OVIII (@18.96 Å) and/or Ne IX (@13.44 Å)***

Mathur et al. 2003

Z=0 X-ray absorption





PKS 2155-304
Nicastro et al. 2002

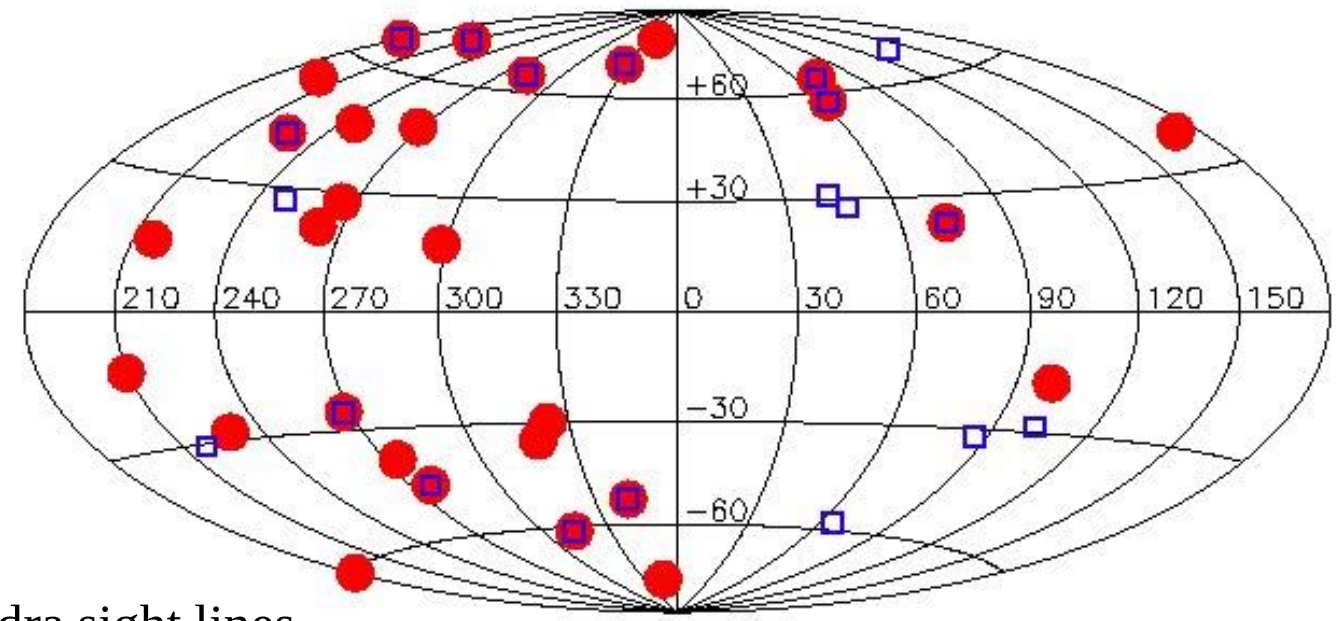
$z = 0$ X-ray Absorption

- In several high S/N Chandra spectra:
  - Mkn 421 (Williams et al. 2005)
  - Mkn 279 (Williams et al. 2006)
  - PKS 2155-304 (Nicastro et al. 2002)
  - 3C 273 (Fang et al. 2003)
  - Other sightlines with lower significance (McKernan et al 2004)
- Always OVII, sometimes other species
- Chandra-LETG resolution 700 km/s, so all lines are unresolved

Origin

- Hot Galactic Halo/Corona…
  - From galaxy formation / feedback processes
  - Some OVII seen within 50 kpc (Wang et al. 2005)
- … or Local Warm-Hot IGM?
  - Predicted by simulations (Kravtsov et al. 2002)
  - Upper limit on OVII emission implies very low density (Rasmussen et al. 2003)

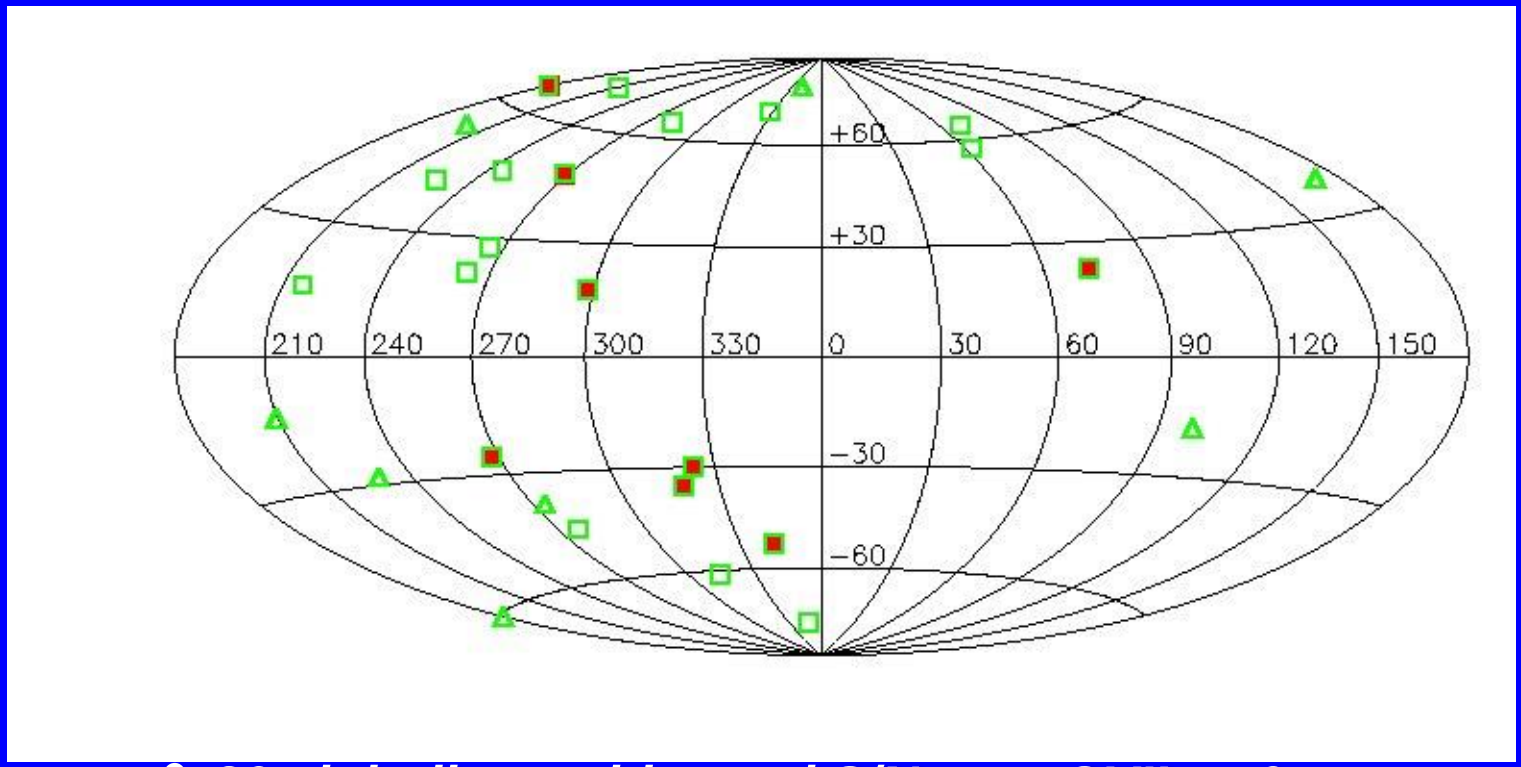
Our Chandra Survey of OVII and OVIII



Chandra sight lines

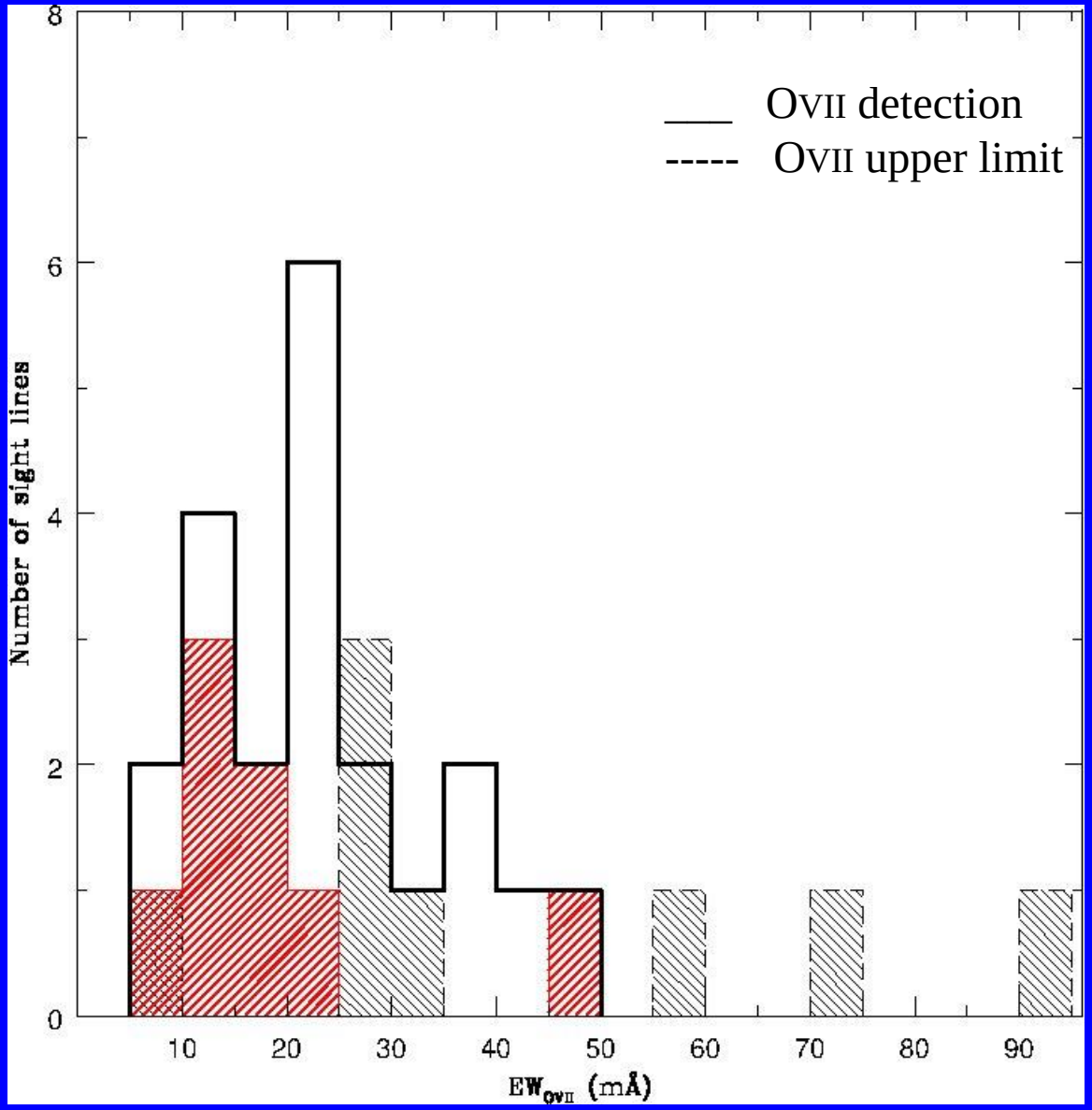
Previous OVII detection

Our Chandra Survey of OVII and OVIII

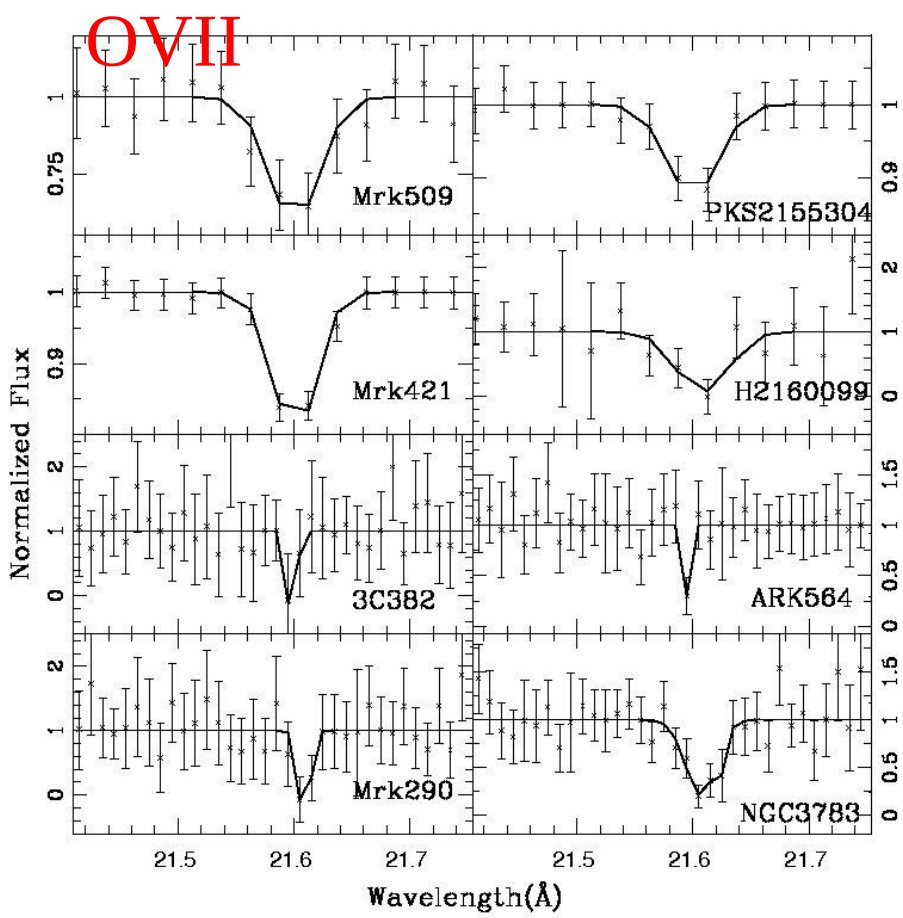


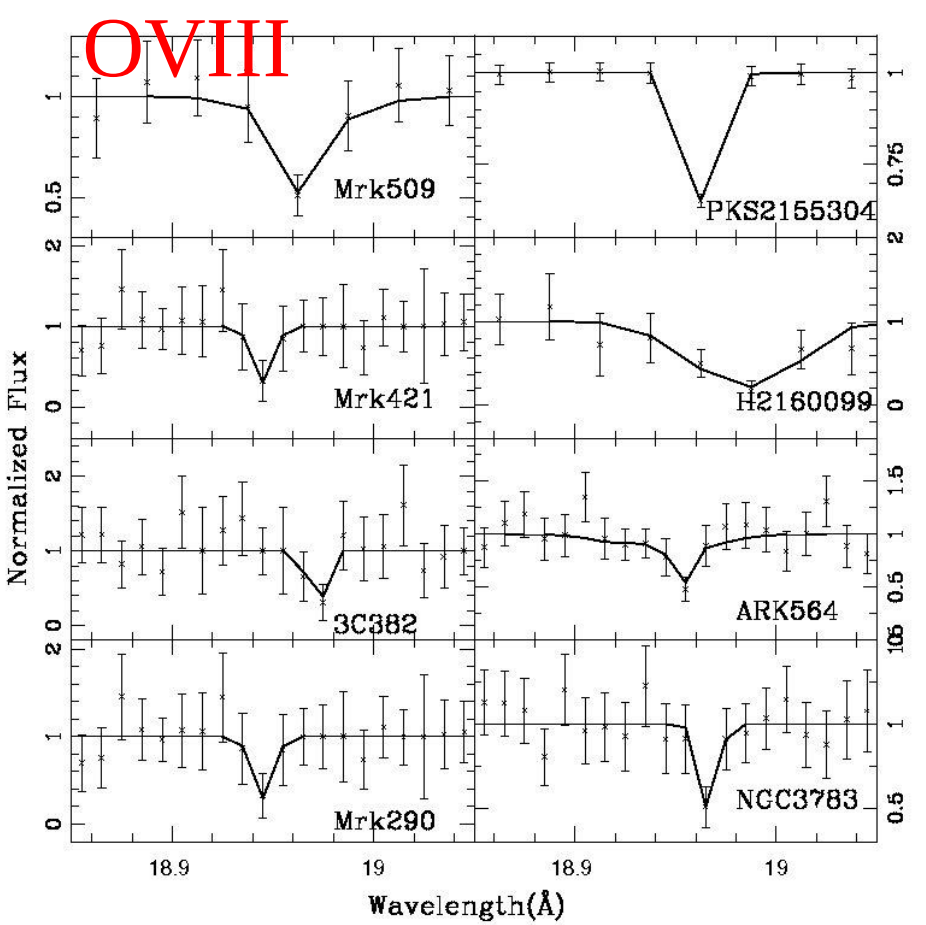
- *29 sight lines with good S/N near OVII z=0 region*
- *OVII detection in 21 sight lines*
- *OVIII detection in 8 sight lines*

OVII EW Distribution



OVII and OVIII z=0 Absorption





- *Log T = 6.1-6.4 K*

Column Density Measurement

- **Optically thin line**

  $N(\text{ion}) = 1.3 \times 10^{20} (EW/f\lambda^2)\ cm^{-2}$

- **For OVII**

  $EW(K\beta)/EW(K\alpha) = 0.156$

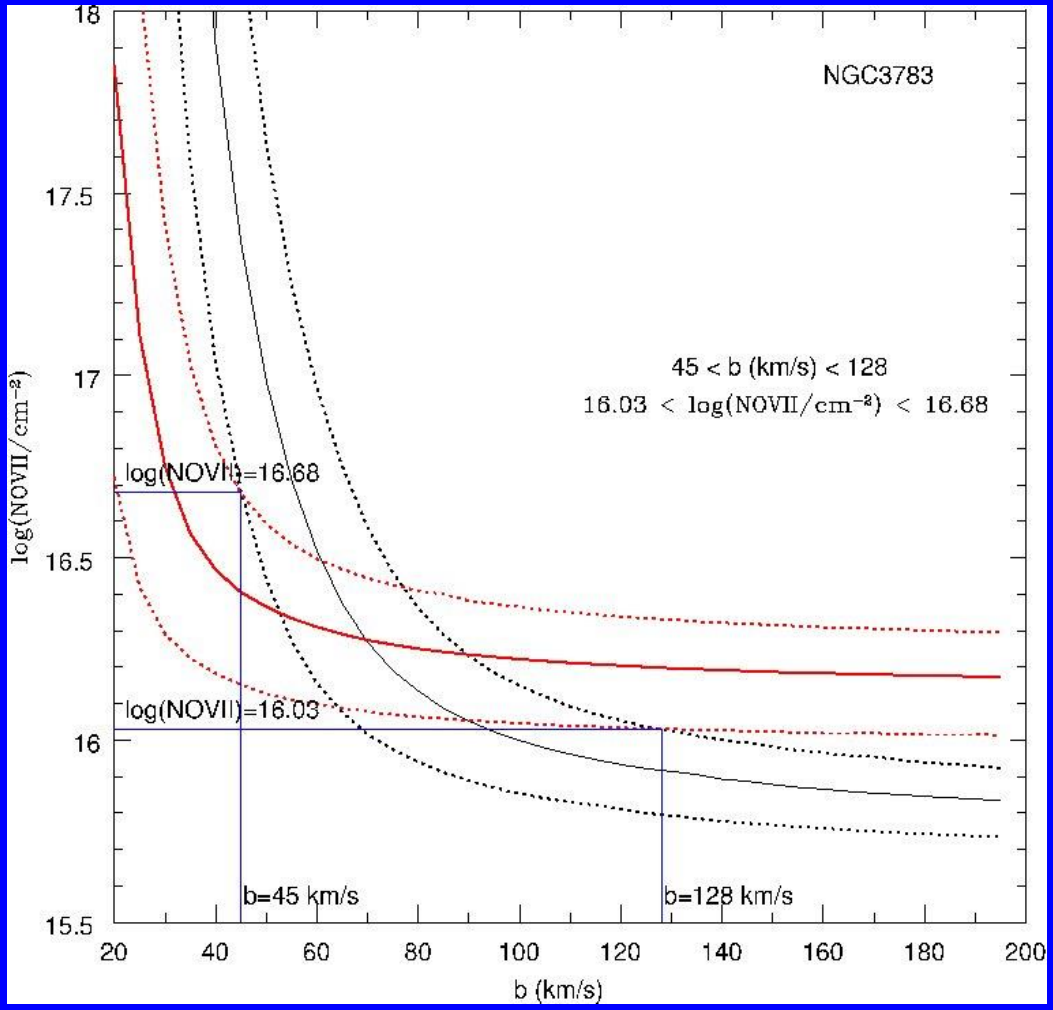
Table 2: The O VII and O VIII absorption line measurement.

Target	EW (O VII $K\alpha$) ($m\AA$)	EW (O VII $K\beta$) ($m\AA$)	EW (O VIII $K\alpha$) ($m\AA$)	O VII ($\frac{EW(K\beta)}{EW(K\alpha)}$)	b km/s	log(NO VII) cm^{-2}
Mrk290	18.9 ± 4.5	5.1 ± 3.7	8.4 ± 2.9	0.27 ± 0.21	> 55	$16.14 \pm 0.32^*$
PKS2155-304	11.6 ± 1.6	4.2 ± 1.3	6.7 ± 1.4	0.36 ± 0.12	$35 - 94$	16.09 ± 0.19
Mrk421	9.4 ± 1.1	4.6 ± 0.7	1.8 ± 0.9	0.49 ± 0.09	$24 - 55$	16.22 ± 0.23
Mrk509	23.9 ± 5.0	11.7 ± 4.1	10.3 ± 4.3	0.49 ± 0.20	$70 - 200$	16.7 ± 0.27
3C382	17.3 ± 5.0	7.8 ± 3.0	6.8 ± 3.8	0.45 ± 0.22	> 40	$16.50 \pm 0.49^*$
Ark564	12.0 ± 1.9	< 3.8	9.5 ± 4.1	...	> 20	$15.82 \pm 0.20^*$
NGC3783	14.4 ± 2.5	5.6 ± 1.6	4.5 ± 2.9	0.39 ± 0.13	$50 - 130$	16.30 ± 0.25
H2106-099	48.3 ± 18.0	< 34.2	28.8 ± 13.8	...	> 70	$16.23 \pm 0.16^*$

*Th ;h analysis

Most of OVII Kα are saturated

$log(N_{OVII})$ and b contour



- *Log N_{OVII} = 16.19 ± 0.08 cm^{-2}*

2-3 times higher than previous estimates

- **Column density $N_H = \mu\, n_e L$**

Galactic Halo Emission Measure

Henley et al. (2010) and Yoshino et al. (2009)

- **Galactic Halo temperature is fairly constant**

  $T = (1.8 - 2.4) \times 10^6$ K

- **Halo emission measure varies by an order of magnitude**

  $EM = (0.0005 – 0.005)$ cm^{-6} pc

$$EM = 0.003\ (Z/Z_{\Theta})\ \text{cm}^{-6}\ \text{pc}$$

Combining Absorption and Emission Measurement

$$n_e = (2.0 \pm 0.6) \times 10^{-4} (0.5/f_{OVII})^{-1} \text{ cm}^{-3}$$

$$R = (71.8 \pm 30.2) \; (8.51 \times 10^{-4}/(A_O/A_H))(0.5/f_{OVII})^2(Z_\Theta/Z) \text{ kpc}$$

$L > 41.6$ kpc

$n_e < 2.6 \times 10^{-4} \text{cm}^{-3}$

Mass Probed by OVII and OVIII X-ray Absorbing/Emitting Gas Phase

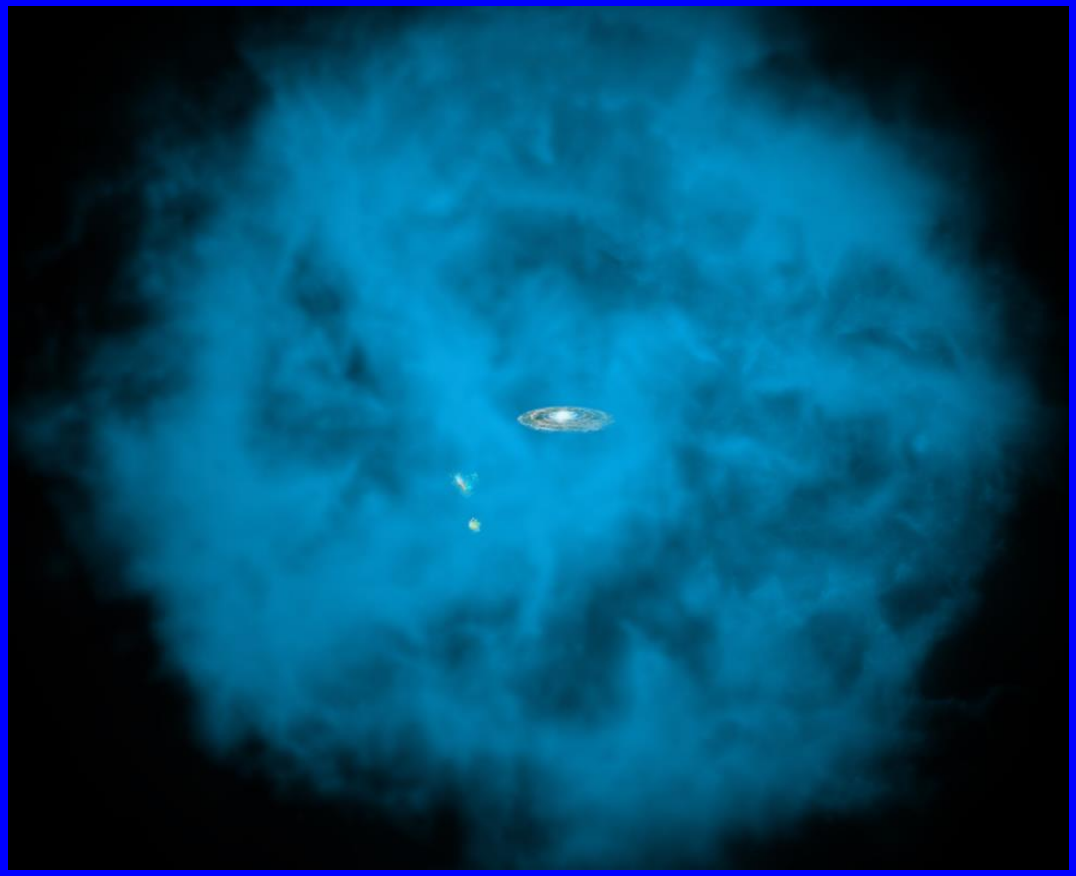
$$\mathbf{M_{total} > 1.7 \times 10^{9}}\ (fc/0.72)\ (8.51 \times 10^{-4}/(A_O/A_H))^3 (0.5/f_{OVII})^5 (Z_\Theta/Z)^3 \mathbf{M_\Theta}$$

For $Z = 0.3Z_\Theta$

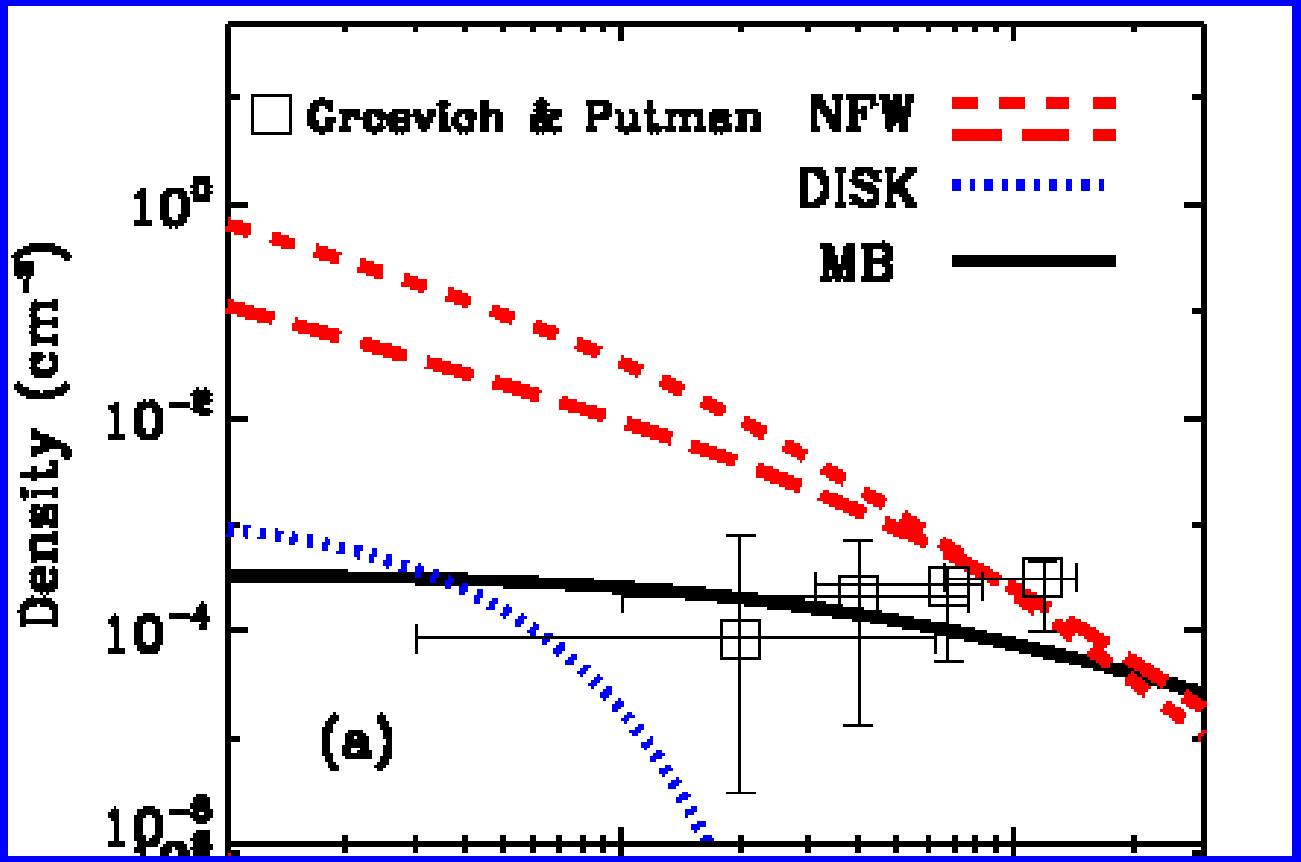
$L > 138$ kpc

$M_{total} > 6.1 \times 10^{10}\ M_\Theta$

Gupta, Mathur + 2012, 2014



Courtesy: Chandra presss office

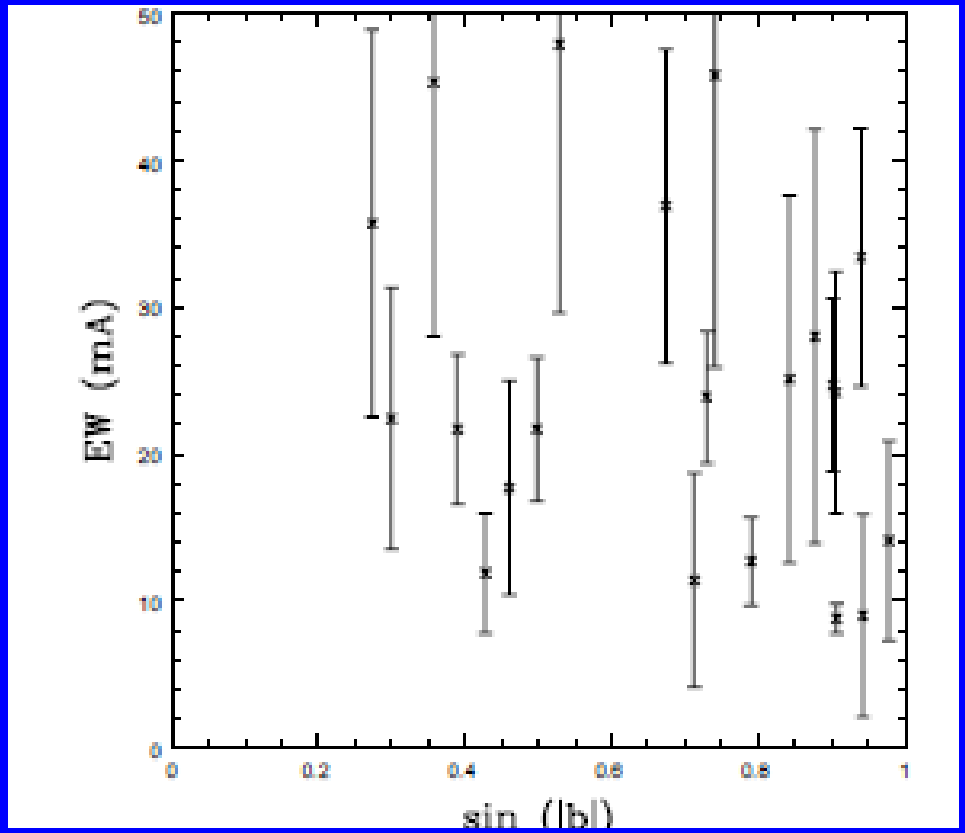


Fang, Bullock +2012

This is a robust result!

- Is the z=0 absorption mostly from the Galactic disk? **No**.
- What about the uniform density profile? **No problem: gives a lower limit on mass**.
- Are the emission and absorption at different temperatures? **No**.

….. no anticorrelation between EW and sin(b)



Future directions

- Probing the anisotropy: emission and absorption along the same sightline.

  -- New Suzaku observations

  -- New XMM-Newton Observations.
- Different density and temperature profiles: e.g. Maller-Bullock profile in NFW halo.
- Probing the multi-phase medium: other ions dominant at different temperatures.

Conclusion

- **X-rays provides evidence for hot ($T>10^6$ K) gas in and around the Milky Way.**

- **X-ray OVII and O VIII absorption lines at z=0 probe the hot gas extending over a large region around the Milky Way, with a radius of over 100 kpc.**

- **The mass content of this phase is over 10^{10} $M_\odot$.**

- **A large fraction of Galactic missing baryons are in this hot phase.**

- **Appears to be a robust result supported by theoretical models.**