Where are the Baryons in the Local Group

Joel N. Bregman, Univ. of Michigan

1. What are the Missing Baryons?
2. Looking for Missing Baryons in Emission
3. Looking for Missing Baryons in Absorption
4. Have we found the Missing Baryons?

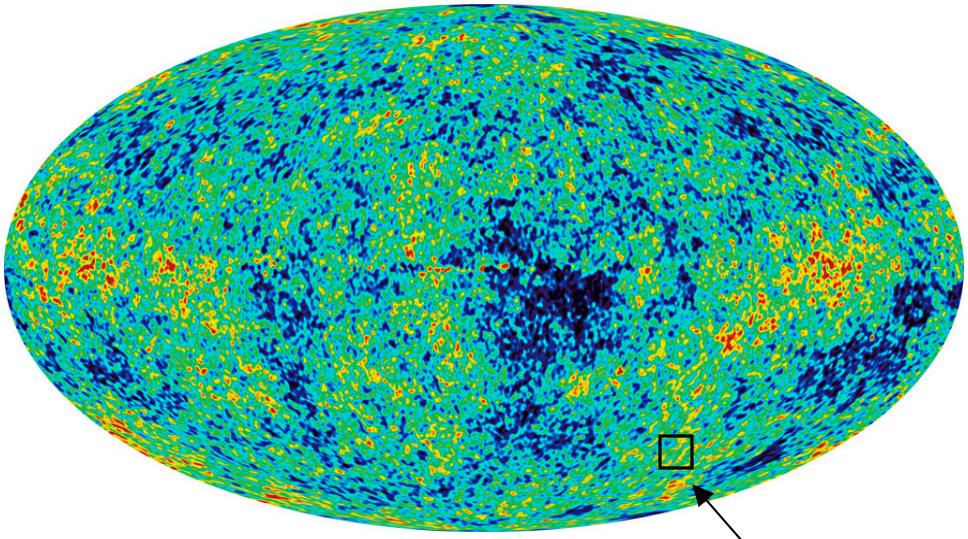
The Guilty Party

Eric Miller Jimmy Irwin

Renato Dupke Edward Lloyd-Davies Birgit Otte

6 Years of Science with Chandra Symposium

Missing Baryons



Cosmic Microwave Background (z = 1000)

The general belief was that this

Became this →

But then someone counted the baryons and found otherwise….

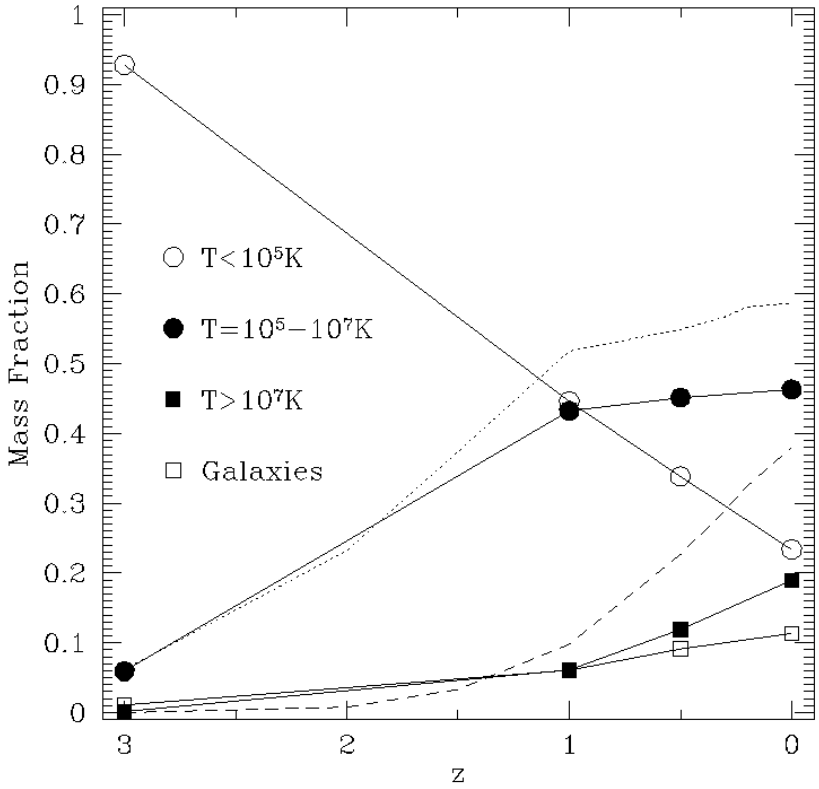
The Missing Baryon Problem

The mass in baryons, Ω_b is determined from Big Bang Nucleosynthesis and at lower redshift (z = 3), from quasar absorption line studies (they agree).

Today, the mass in galaxies and cold gas only account for ~20% of the baryons.

Most of the baryons are still gas.

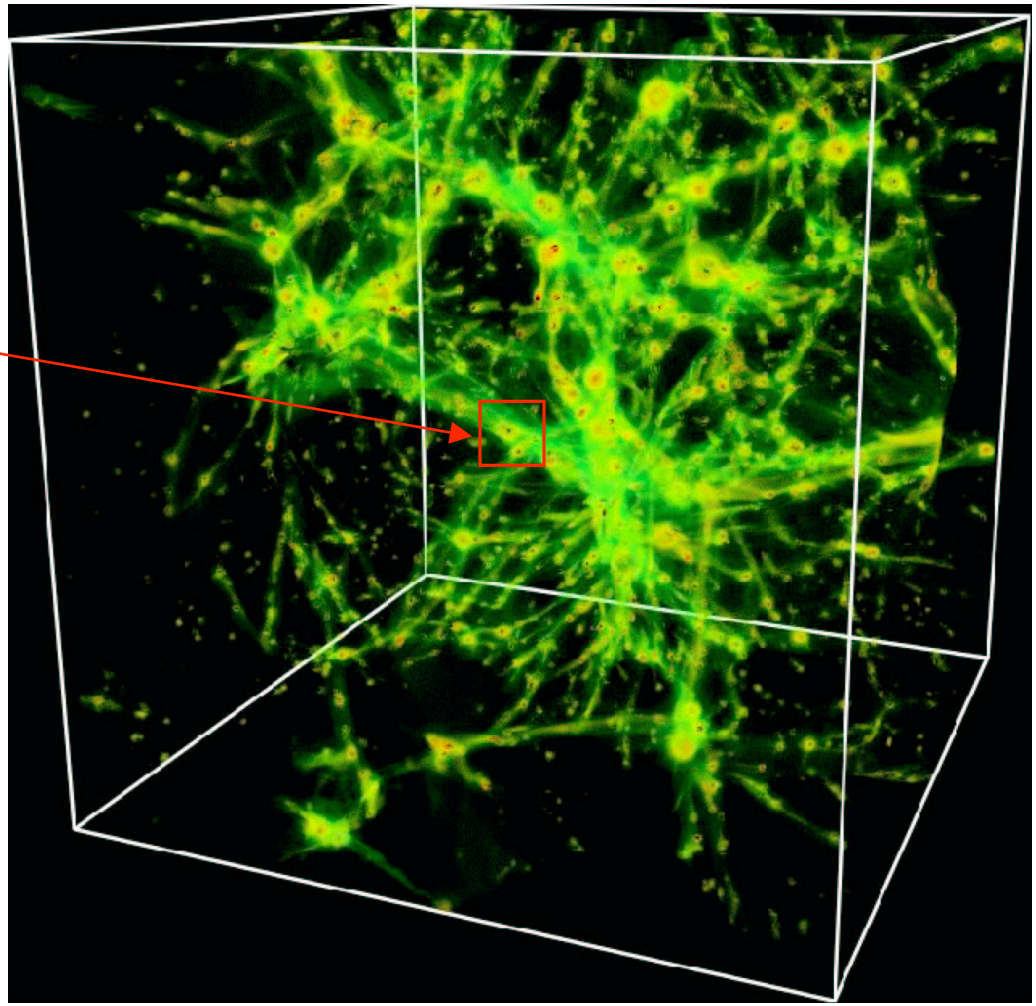
They're not missing, they are just hot (10^5-10^7 K).



Figures from Cen (1999), Cen and Ostriker (1999); see also Fukugita, Hogan, and Peebles (1998), Croft et al. (2001), Voit, Evrard, and Bryan (2001)

This cosmological simulation shows hot gas in filaments, groups, and clusters.

Just like
Home (LG)



Just Enough Physics

In external galaxies, you only make emission observations.

(sensitive to n^2, so you don't see the low density gas, which may be a lot of mass)

In the Milky Way, you can observe the X-ray gas in both

emission ($EM = n^2L$) and

absorption ($N = nL$); against the brightest AGNs

Model EWs to get n, L separately => gas mass

Combine emission and absorption and solve for n, L.

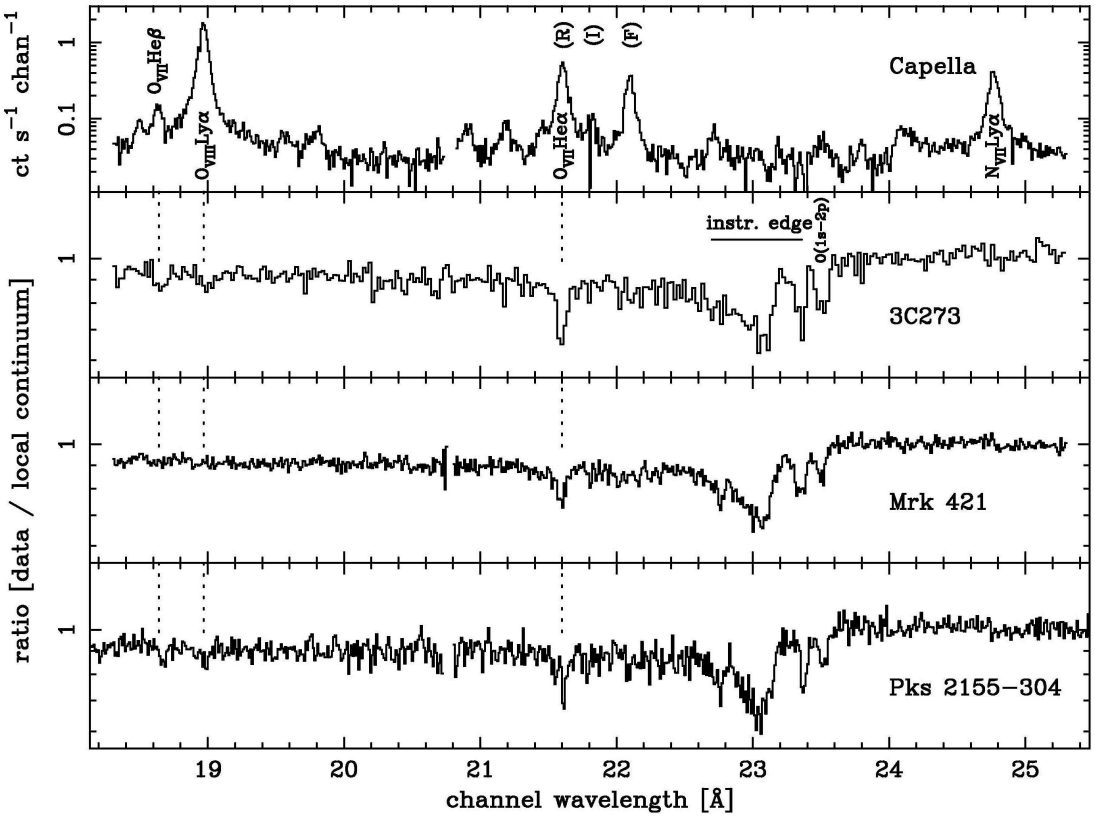
Depending on how you do this….

$10\ kpc < L < 3\ Mpc$, so a range of 10^7 in the gas mass

X-Ray Absorption against AGNs

Chandra (Nicastro et al. 2001); XMM (Rasmussen et al. 2003)

Absorption by OVII and OVIII in addition to AGN features.

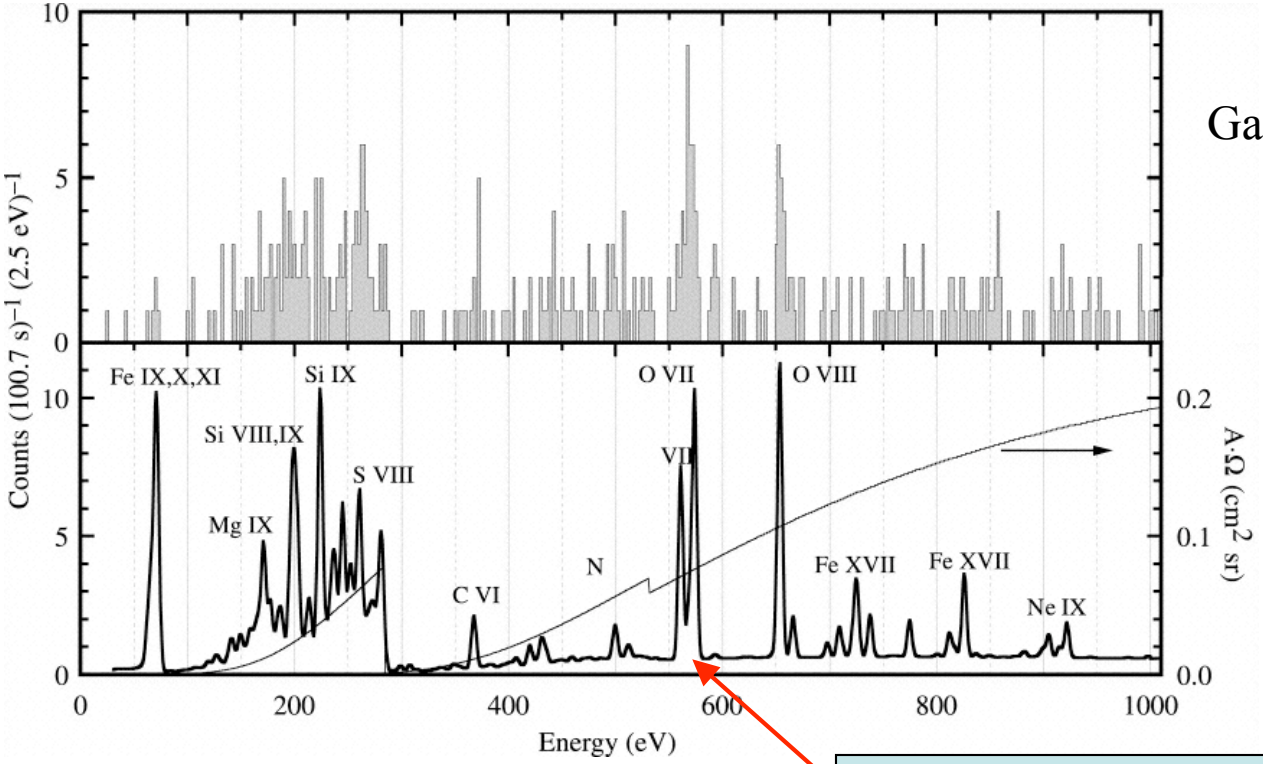


Behar et al. 2003

X-Ray Emission (Sanders et al. 2001; McCammon et al. 2002)

OVII, OVIII too hot to come from the Local Bubble;

➔ Milky Way halo



Gas is 1-2E6 K

Remember this OVII line(s)

Interpreting the Data to get Masses and Sizes

Here's how it works

pick the lines you want to fit

(e.g., OVI, OVII, OVIII absorption/emission lines)

pick a model (photoionization or collisional ionization)

solve for T, n, L so that you fit the lines

Nicastro et al. (2002)

OVI, OVII, OVIII abs lines are cospatial (same T, n, L)

$n \approx 6 \times 10^{-6}$ cm^{-3}; L ≈ 3 Mpc; $T \sim 10^{5.7}$ K; [O/H]=0.3

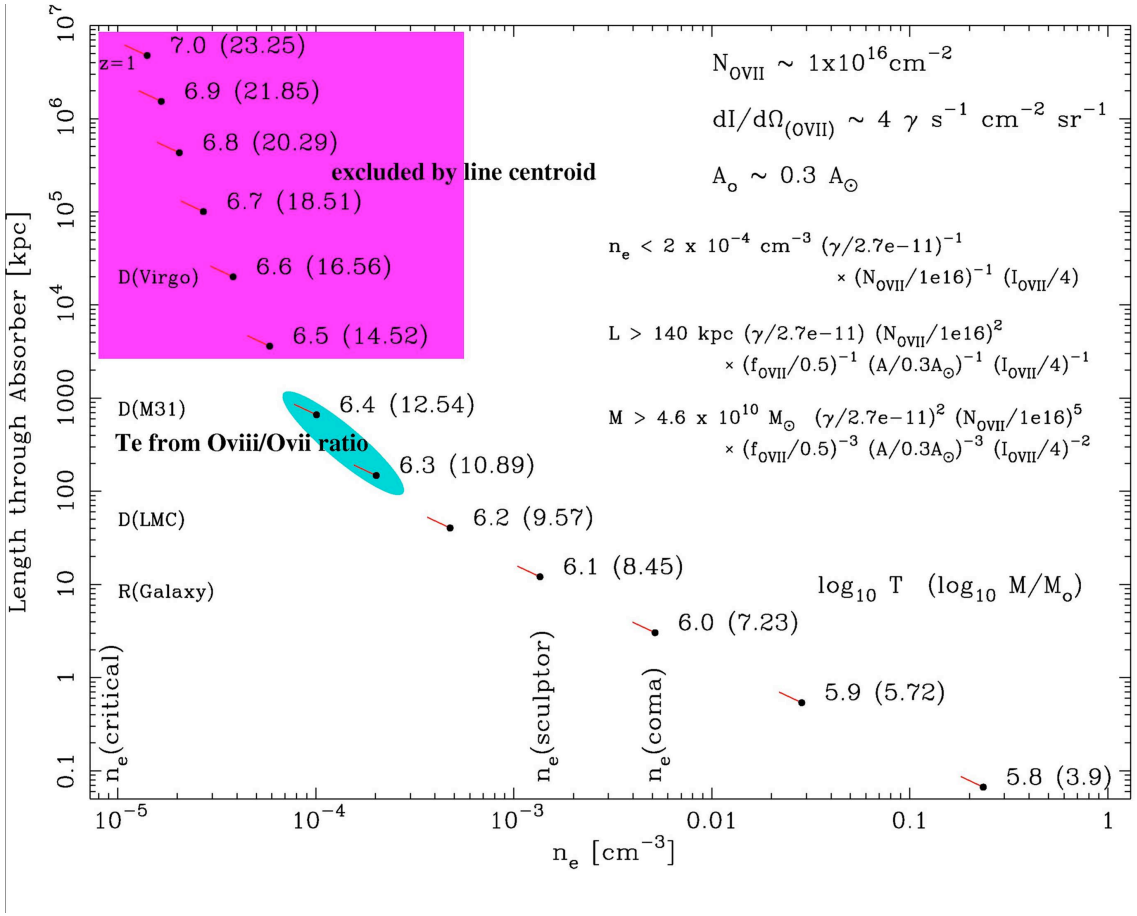
very massive Local Group halo ~10^{12} Msolar

important in terms of the missing baryons

Local Group Model

Rasmussen, Kahn et al. (2003)

Assume that OVII, OVIII abs lines are cospatial
include the emission, but only as an upper limit
$n < 2E\text{-}4\ cm^{-3}$; $L > 140$ kpc; $M > 5E10$ Msolar
more hot gas than all the gas remaining in galaxies



Sanders and McCammon (2002)

assume that OVII emission and absorption are cospatial

don't over-produce OVI, OVIII

L = 50-100 kpc; n = 2-6E-4 cm^{-3}; M ~5E9 Msolar

this is the Galactic Halo model

Like Goldilocks, I wonder which is "just right".

Galactic Halo Model:

distribution largely spherical around the MW
column densities similar in all directions
might see evidence for the shape of the Galaxy

Local Group Model

Local Group is elongated along the MW-M31 axis
columns greater along this axis and especially toward M31
(the long way through the LG)
Concern: M31 may have its own extended halo

Group simulation like the Local Group (Moore) shows elongation of matter .

Column enhancement along major axis ~2-3x perpendicular to axis

Observations

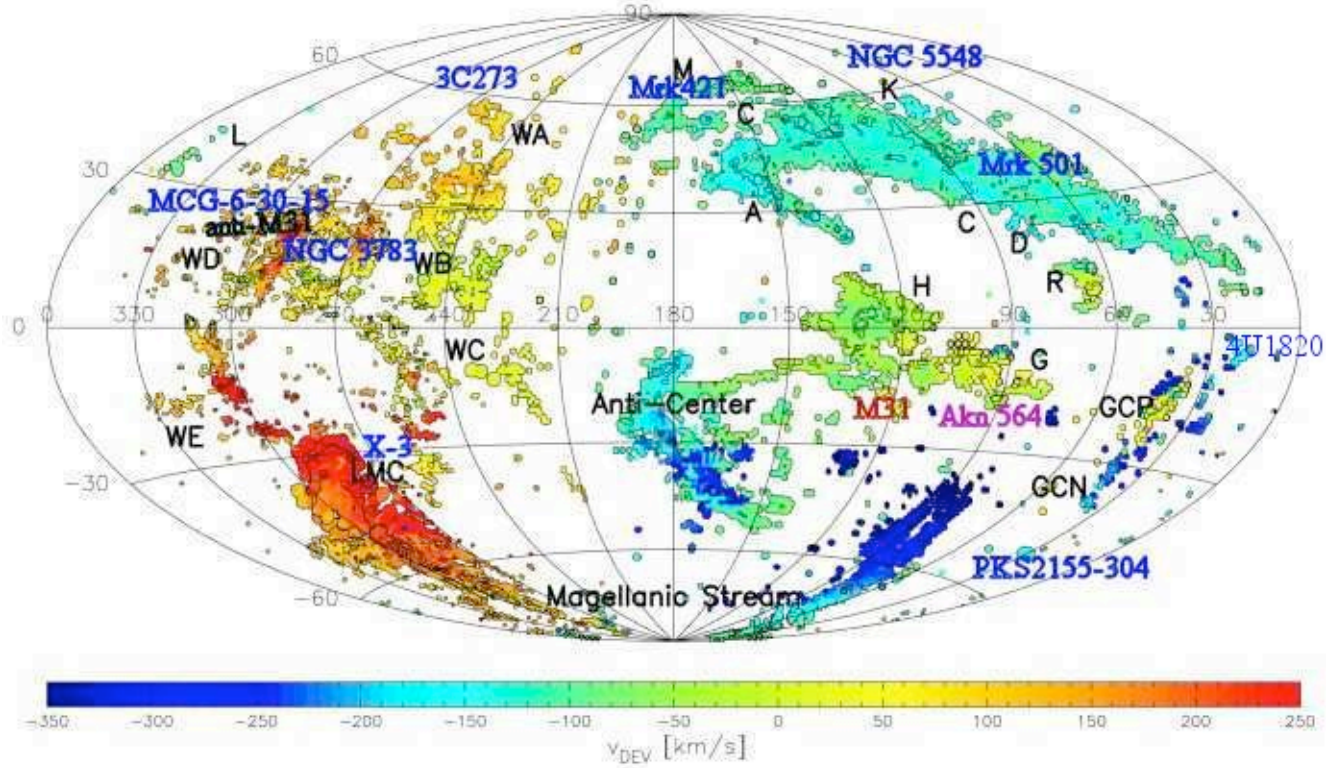
OVII absorption line observations at 21.6 Å

not many AGNs to use (up to 15; 10 observed; Long obs.)

most AGNs are well away from the MW-M31 axis

2 near the anti-M31 position (MCG-6-15-30; NGC 3783)

Akn 564 is the best toward M31 (the most important object)

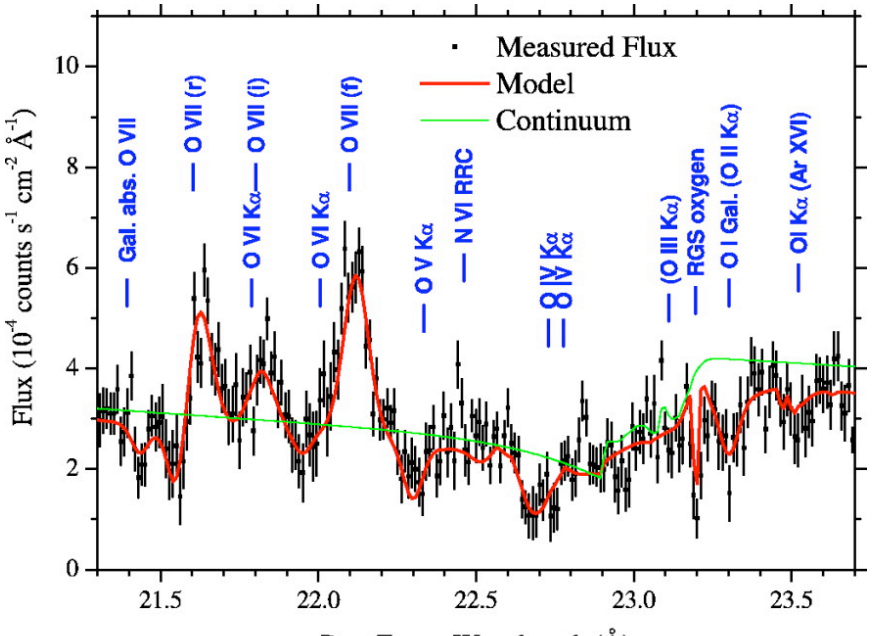


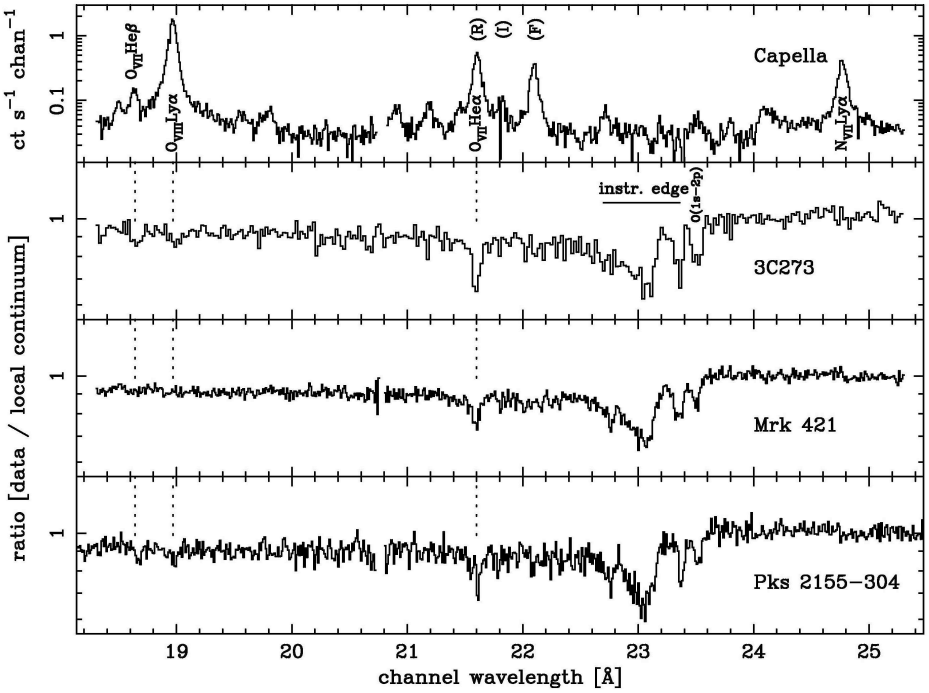
The Tricky Bits

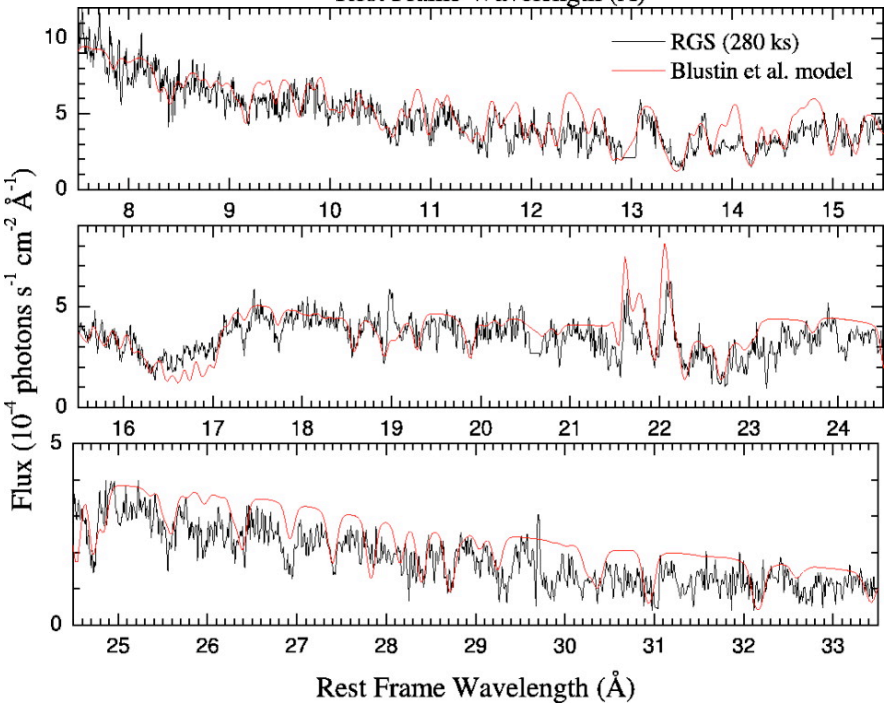
Not too difficult if you have a featureless, BL Lac – type continuum

Most AGNs have emission and absorption of their own.

Some redshift objects are problematic.





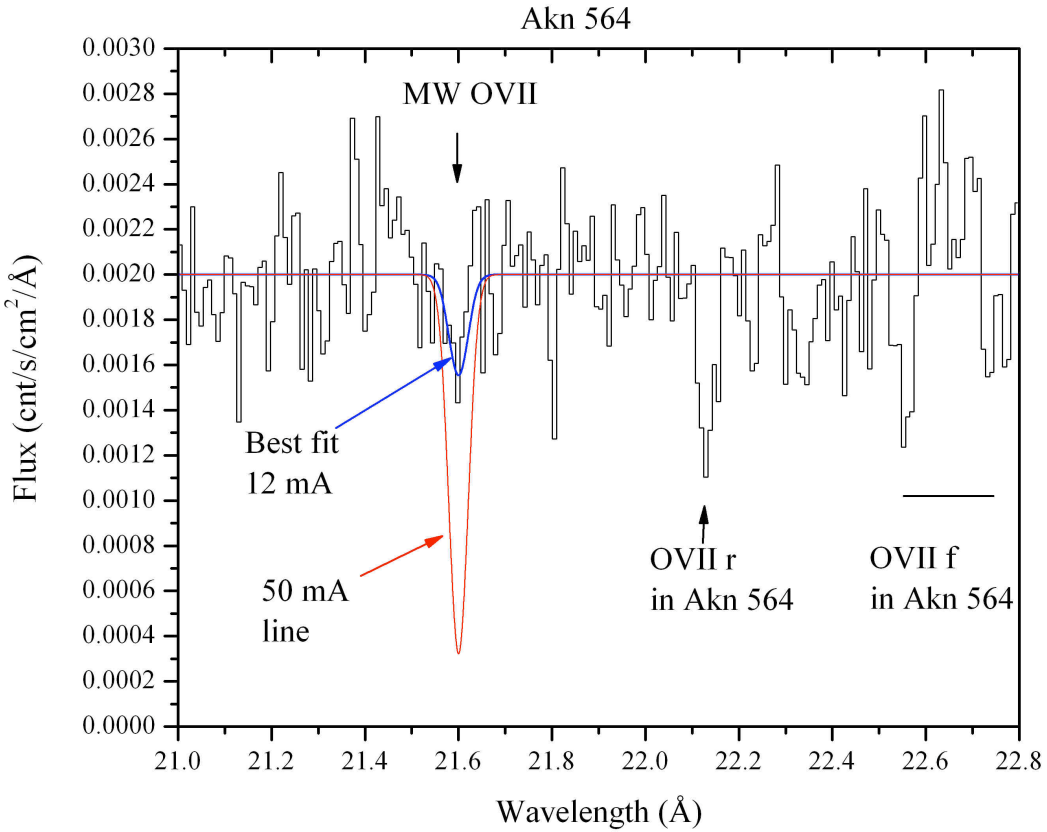


Akn 564

29º from M31 (0.35 Mpc) 71 ksec observation with XMM RGS

OVII EW is typical of ordinary lines of sight

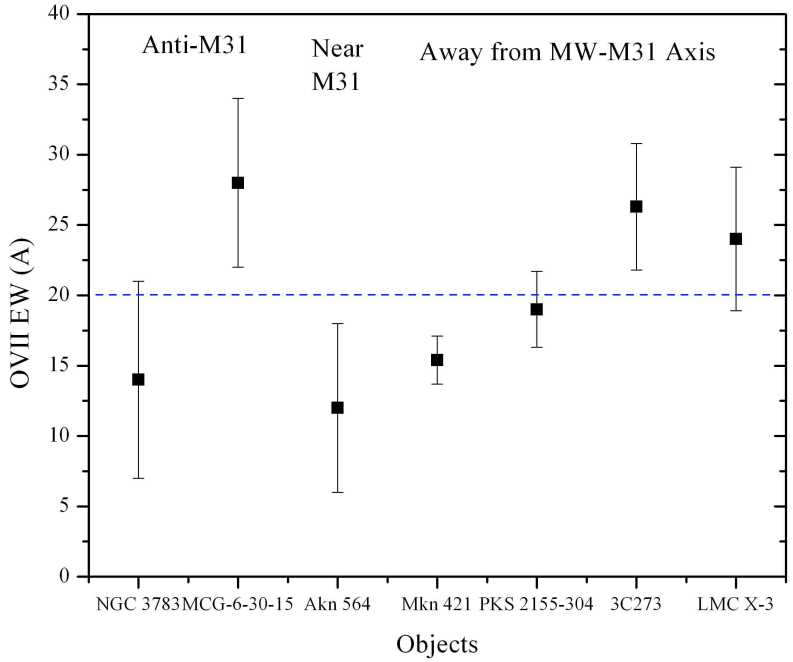
No evidence for enhanced absorption along this line of sight (no evidence of an extended M31 halo or of a Local Group medium)

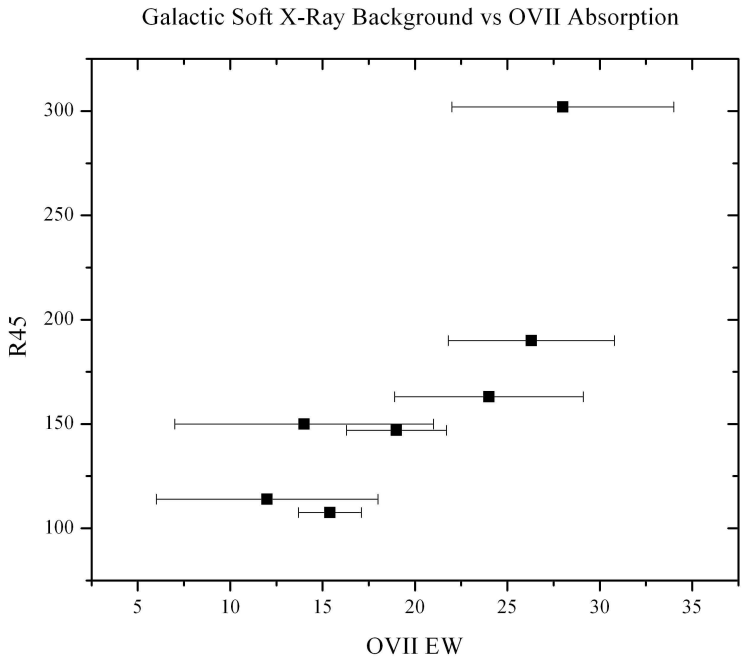


For objects away from the MW-M31 axis, average EW = 20 mÅ and the other objects are consistent with this value.

No evidence for enhancements of 2-3 times in any direction (40-60 mÅ) except 4U1820 (45 mÅ, d = 9.7 kpc), but this passes through the bulge (Benjamin)

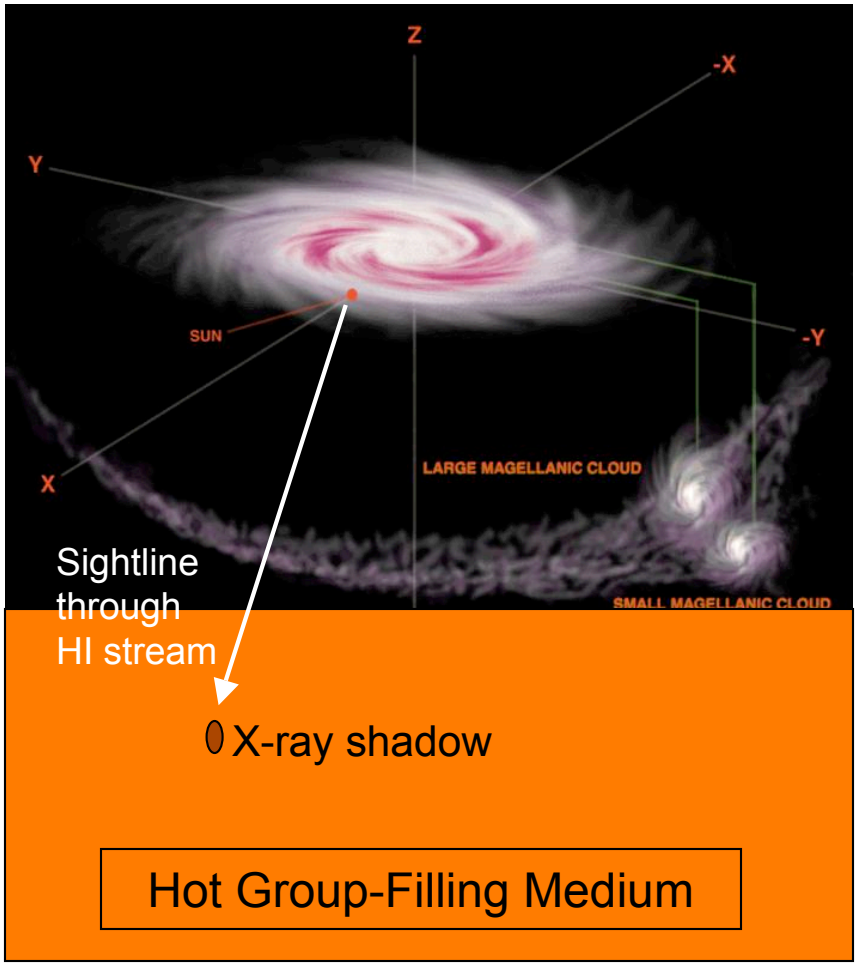
This supports the Galactic Halo model rather than the Local Group model.



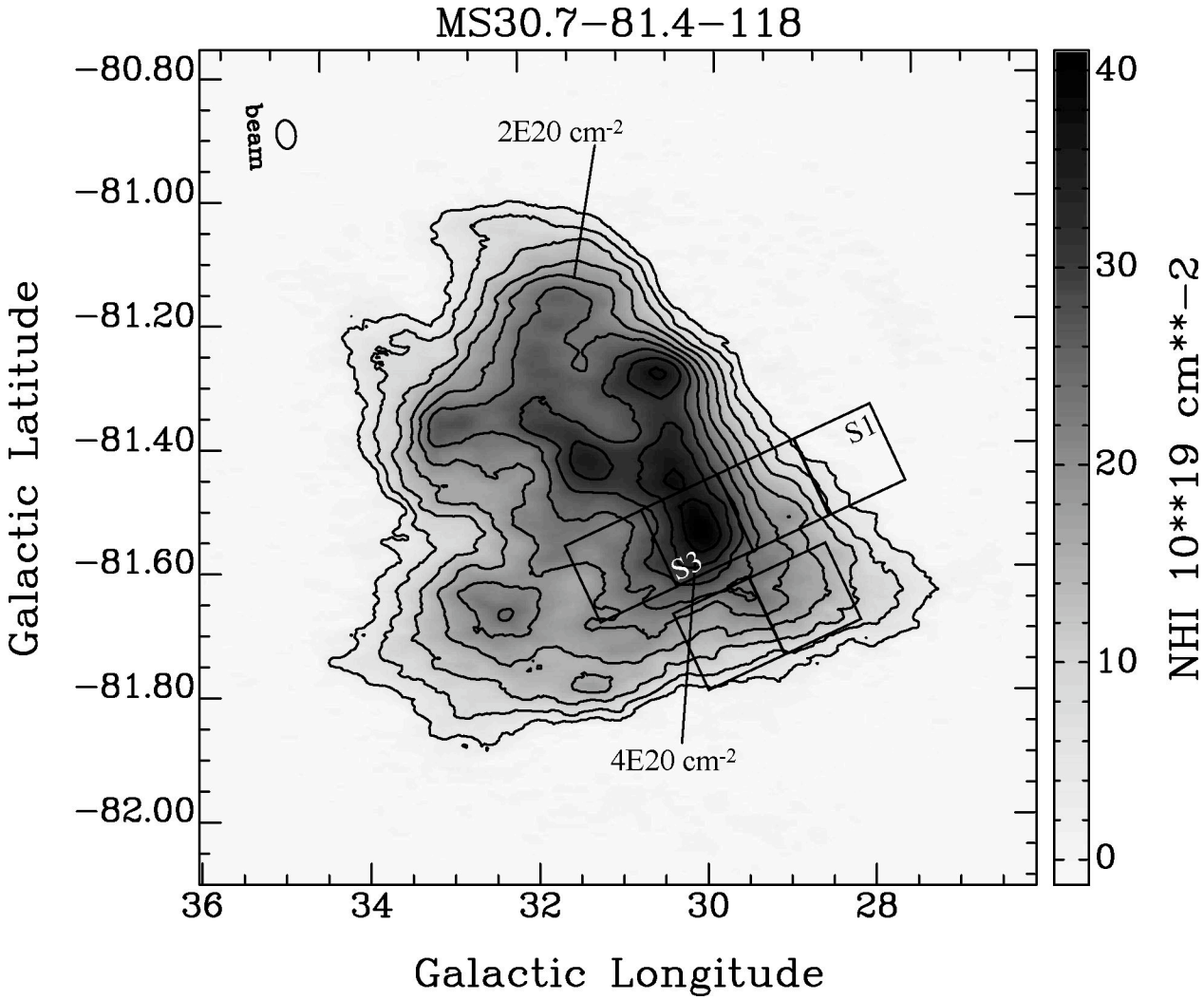


The Local Group vs Halo Model Through X-ray Emission Studies

- This uses the concept that cold gas will absorb X-ray emission from behind it, creating a "shadow"
- Chandra and XMM Observations of two objects
  - Compact High Velocity Cloud
  - HI Cloud in the Magellanic Stream
- Putman, Bruens, Moore



HI Clump in the Magellanic Stream



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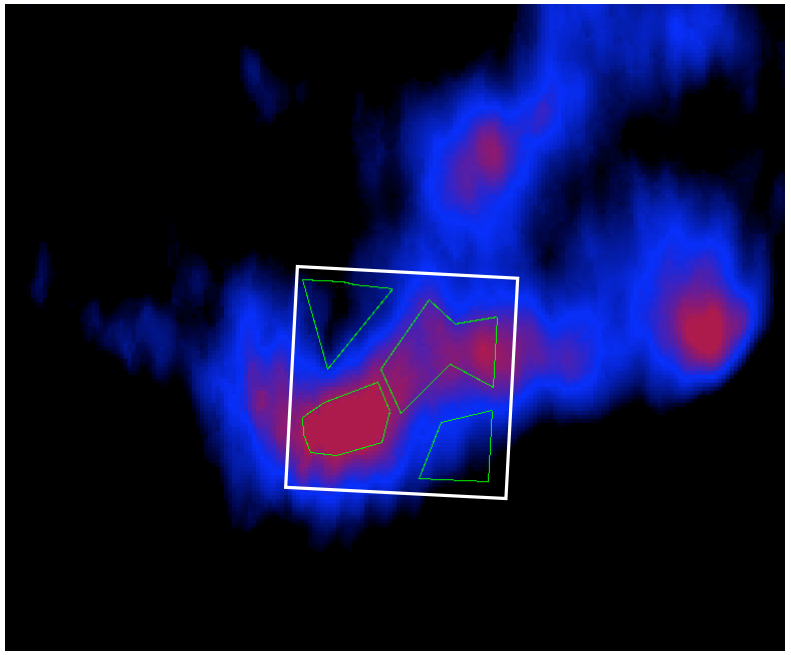
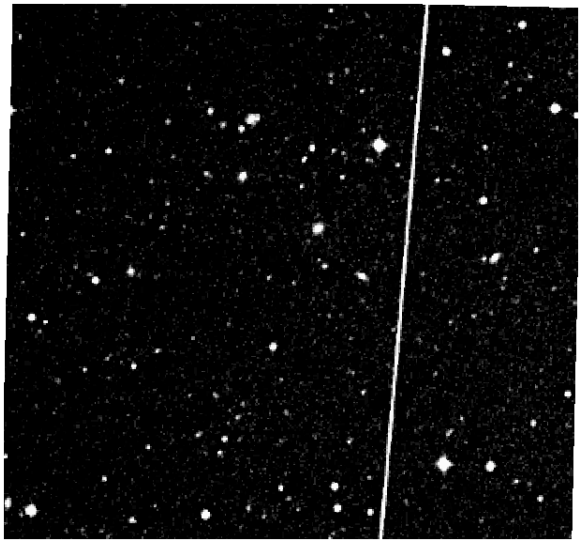




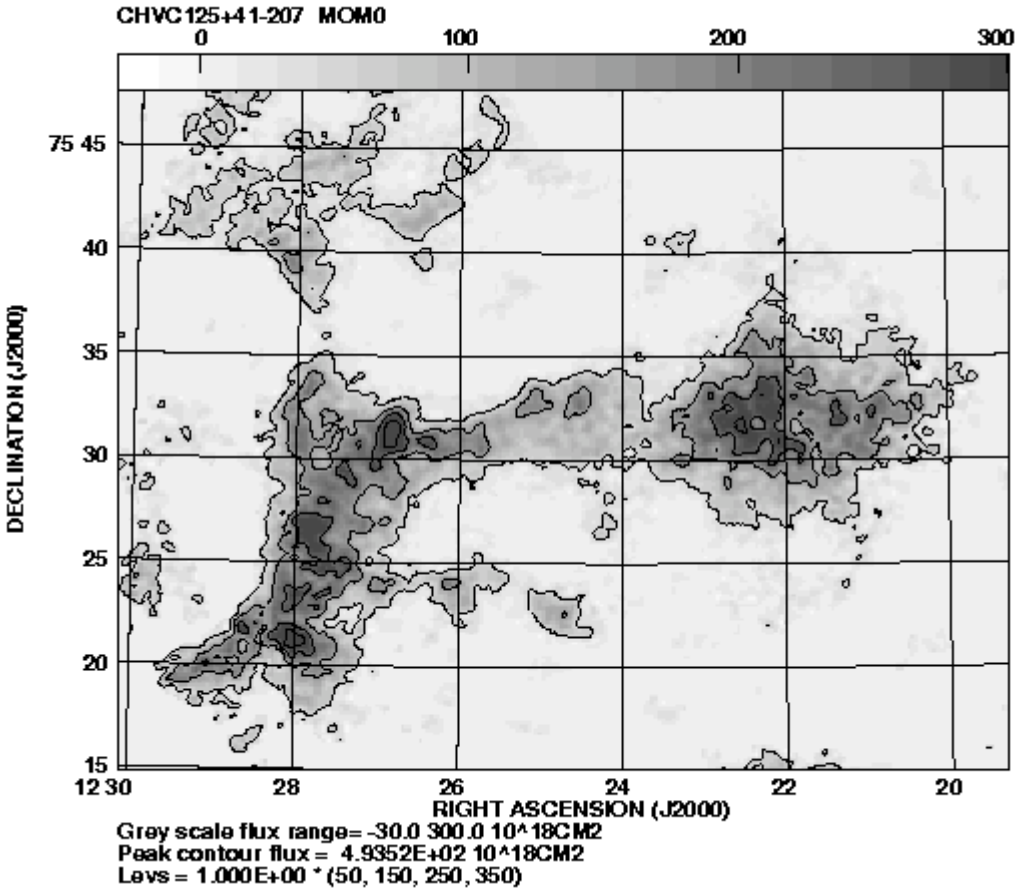
Location of S3 chip on HI cloud.

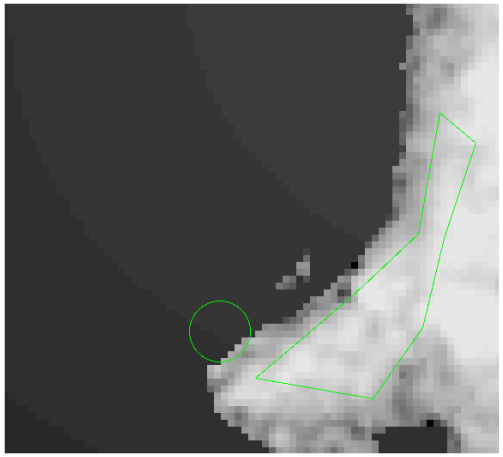
Dull optically.

No shadow seen (1.4 _ brightening)

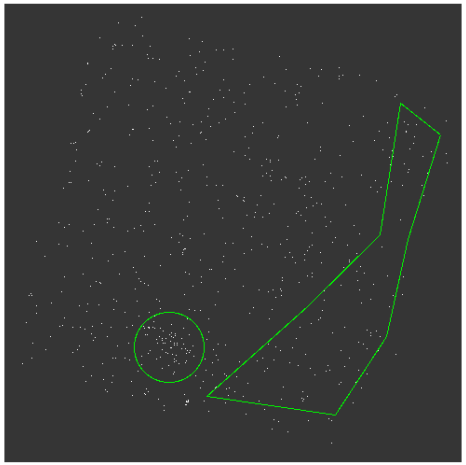
Compact HVC

- Distance not well known (~50 kpc)

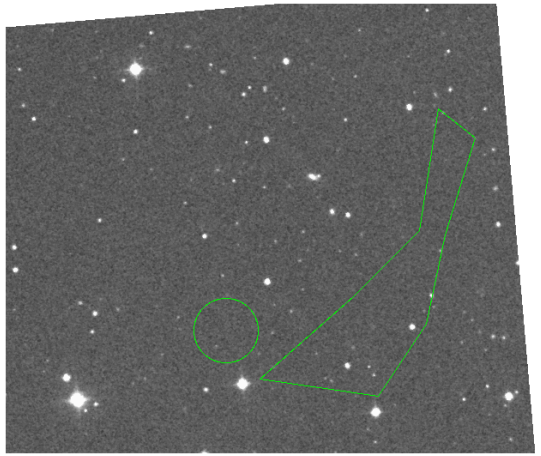




HI



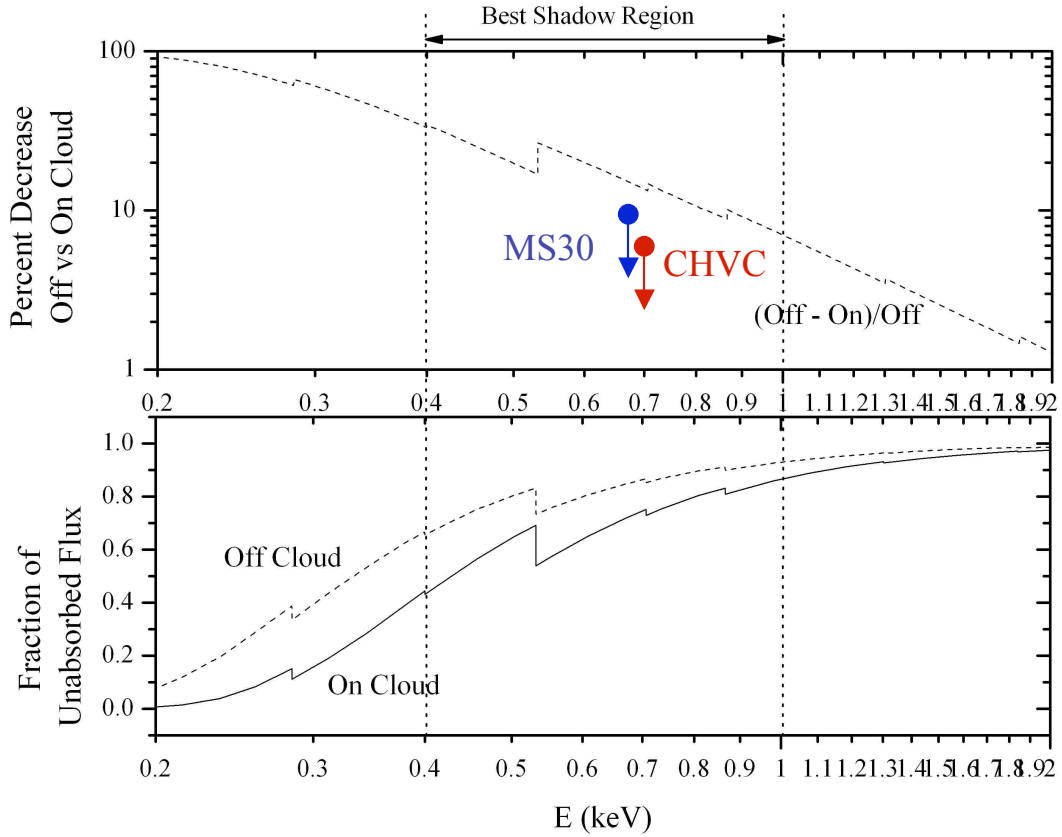
X-ray



Optical

No shadow here either.

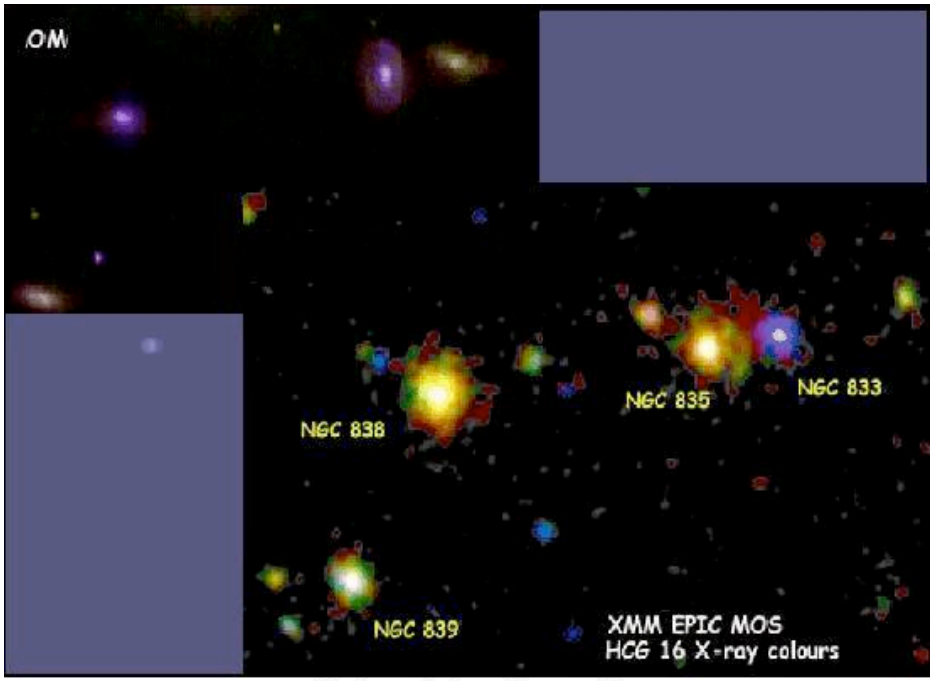
- Best effective region to look for shadow is 0.4-1 keV
- The CHVC and Magellanic Stream measurements are upper limits.
- Both results support the Galactic Halo model, not the Local Group Model



Absorption and Emission results favor the Galactic Halo model (50-100 kpc; gas mass < 1E10 Msolar)

M31 halo < 350 kpc

These sizes are similar to UV metal absorption line sizes (100 kpc; Shull, Tomlinson, Bowen …)



Hickson Galaxy Group 16

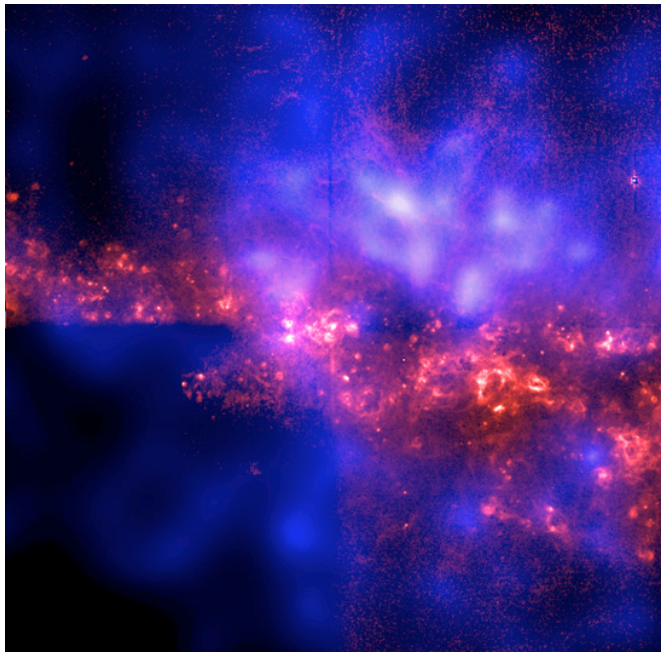
European Space Agency

Hot gas is present around galaxies

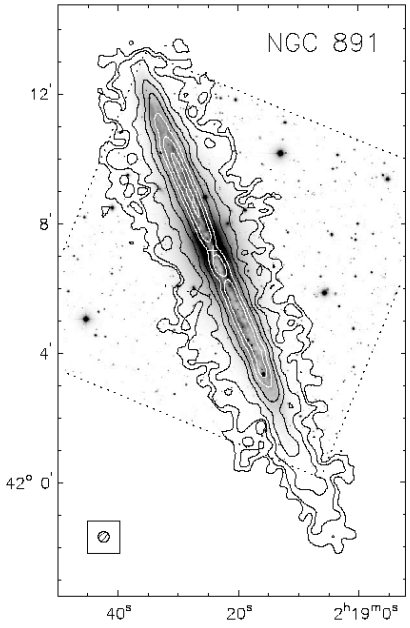
10^6-10^7 K; approaches hydro equilibrium

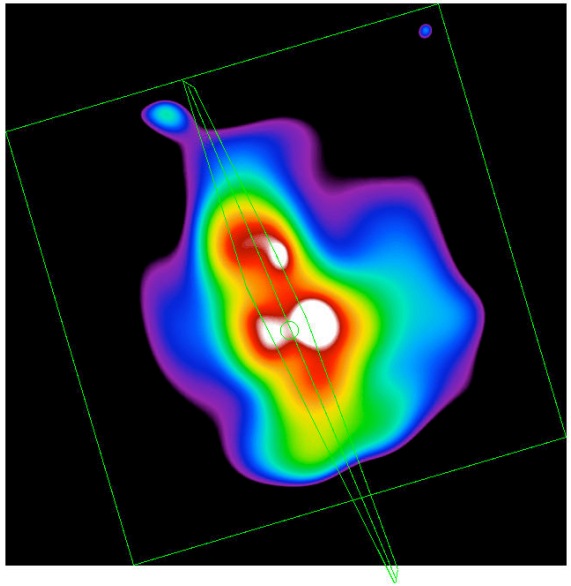
NGC 4631 (Wang et al. 2002); blue+purple are Chandra data; red+white are from HST images

Extent of the gas is 8 kpc. Gas masses are modest 10^8 Msolar. $10^{39.3}$ erg/sec



Optical and HI; Swaters





X-Ray emission; JNB+JAI