The Hot Gaseous Halos of Spiral Galaxies

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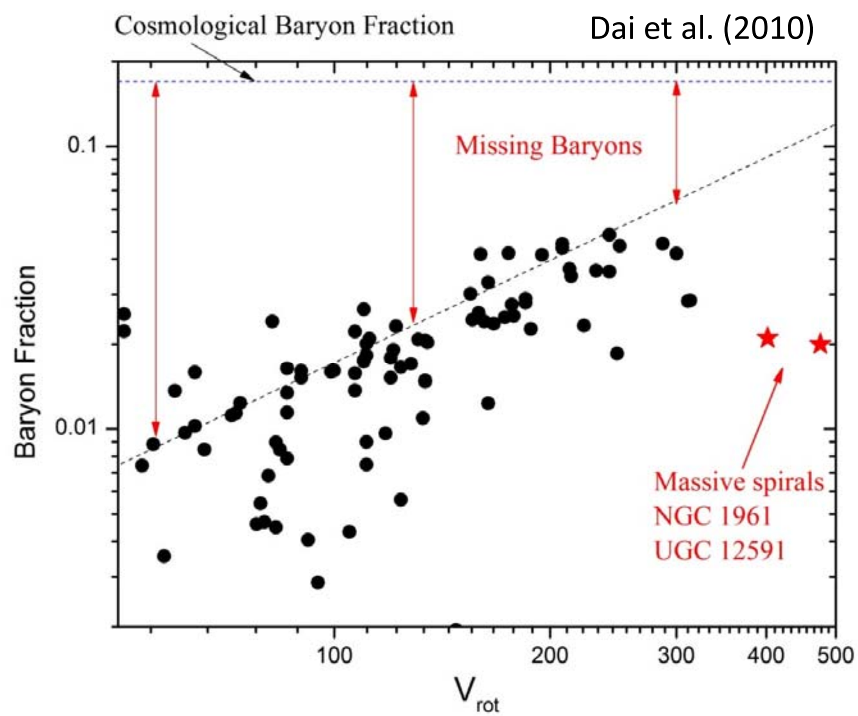
Hot Galaxy Halos and Missing Baryons

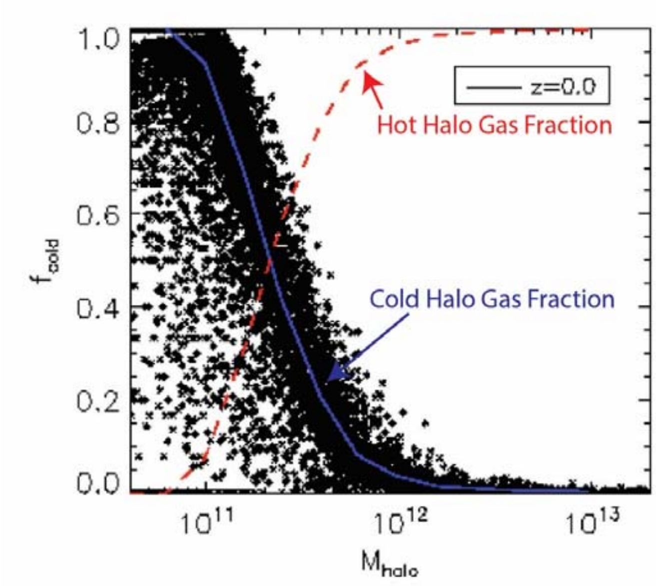
Dai et al. (2010)



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

Baryons Aren't Really Missing

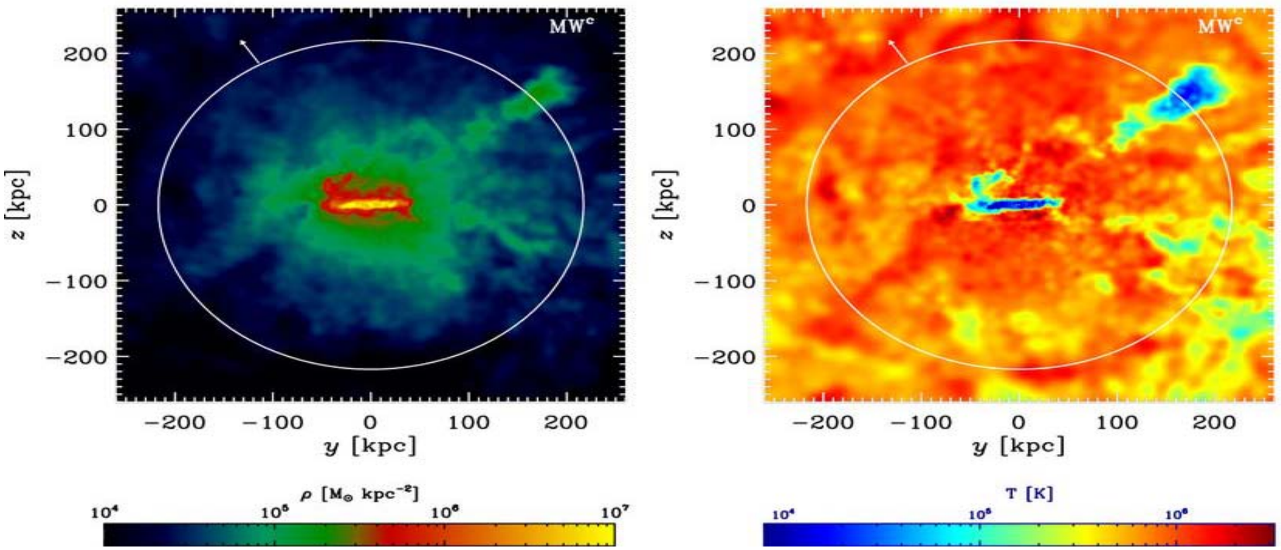
- Matter must be conserved
- Baryons are just hard to see
- Where are they?
- Models: Hot dilute gas in galaxy halos and surrounding galaxies
- Why should we care?
- It's all about galaxy formation and the formation of structure
  - Formation of structures from Dark Matter is (more or less) a solved problem
  - Baryons are different because of cooling and heating
  - Heating comes from **accretion and feedback**
- Gas should have $T \sim T_{virial}$ ➔ X-rays
- Prediction: lower mass galaxies don't have a hot halo



Keres et al. 2008

The Milky Way

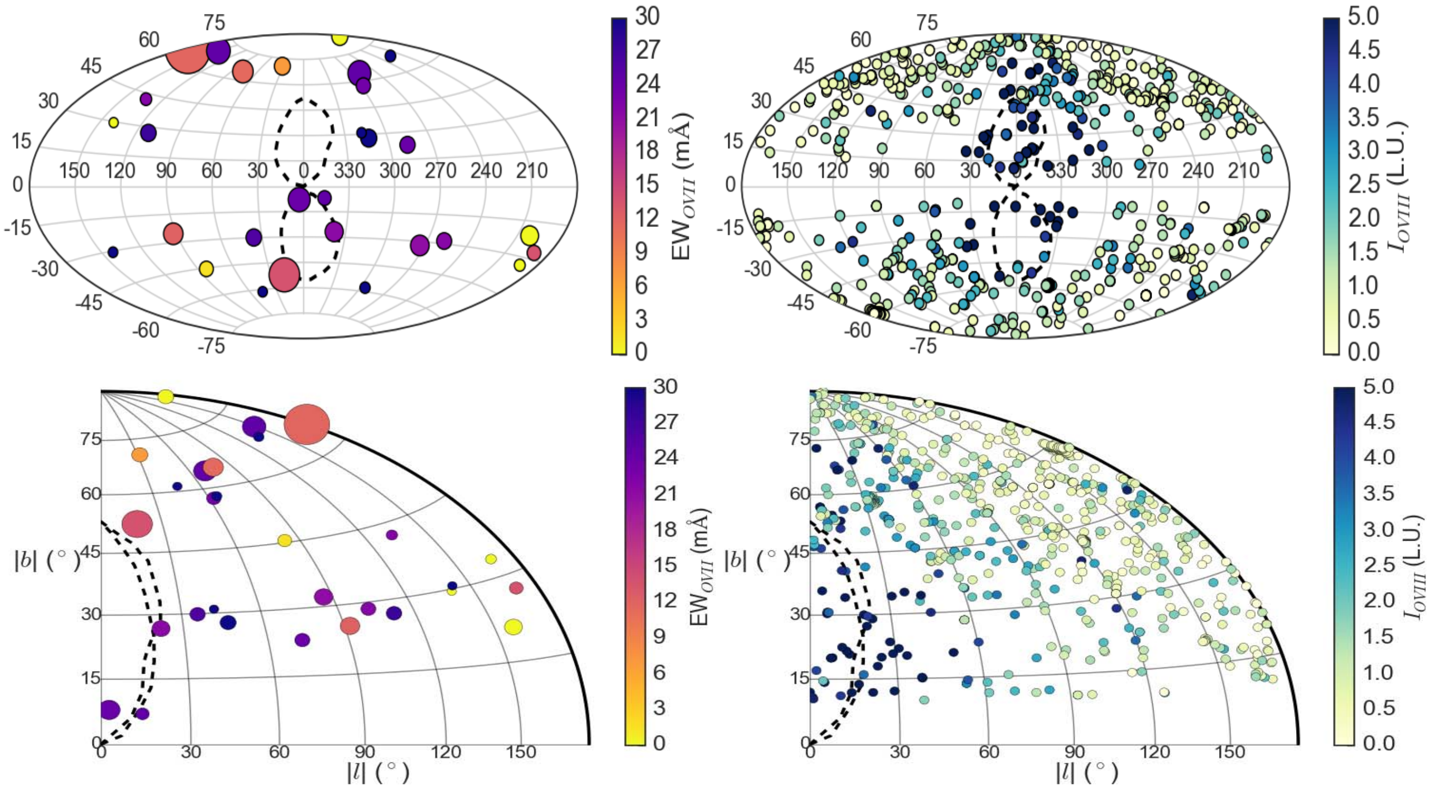
- The best data for study
- Hot Halo: mass, cooling rate, metallicity
- Rotation of the Hot Halo
- Interaction of the Fermi Bubbles with the Hot Halo



Model for the Milky Way
Nuza et al. 2014

Observations Samples

- Archival XMM data projects have produced all-sky samples of line strengths
    - Absorption lines: 26 AGN, 3 X-ray binaries
    - Emission lines: 683 sight lines from Henley & Shelton 12

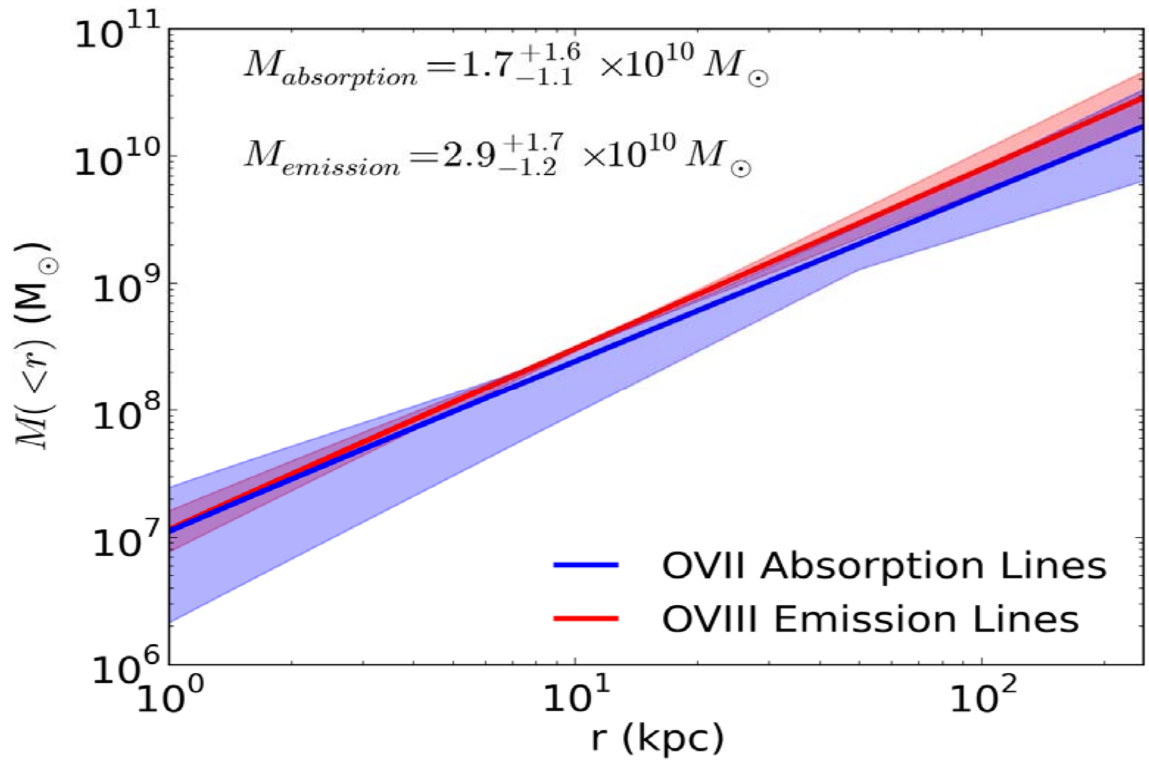


MW Halo Masses (With Optical Depth Correction)

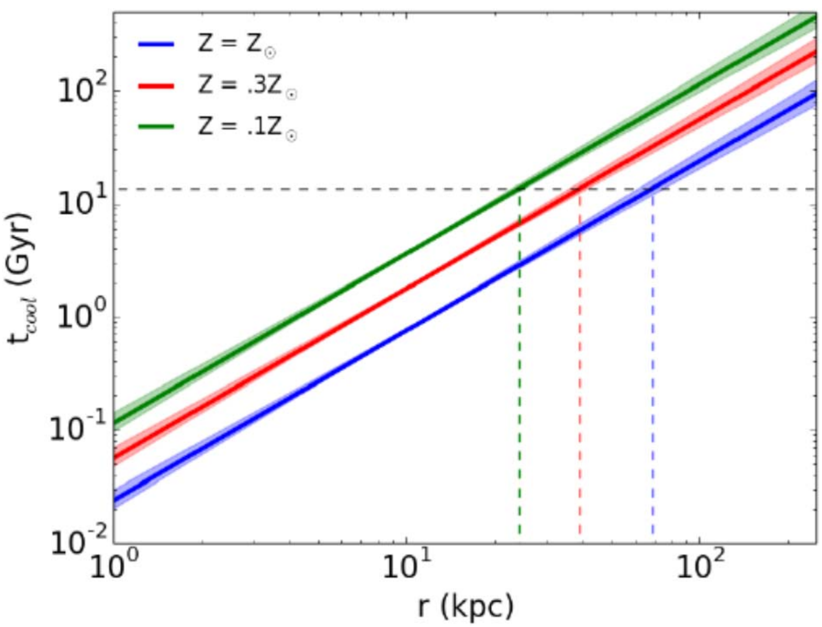
β≈ ½
n ∝ $r^{-3/2}$
Gas detected to 50 kpc
Extrapolation beyond 50 kpc

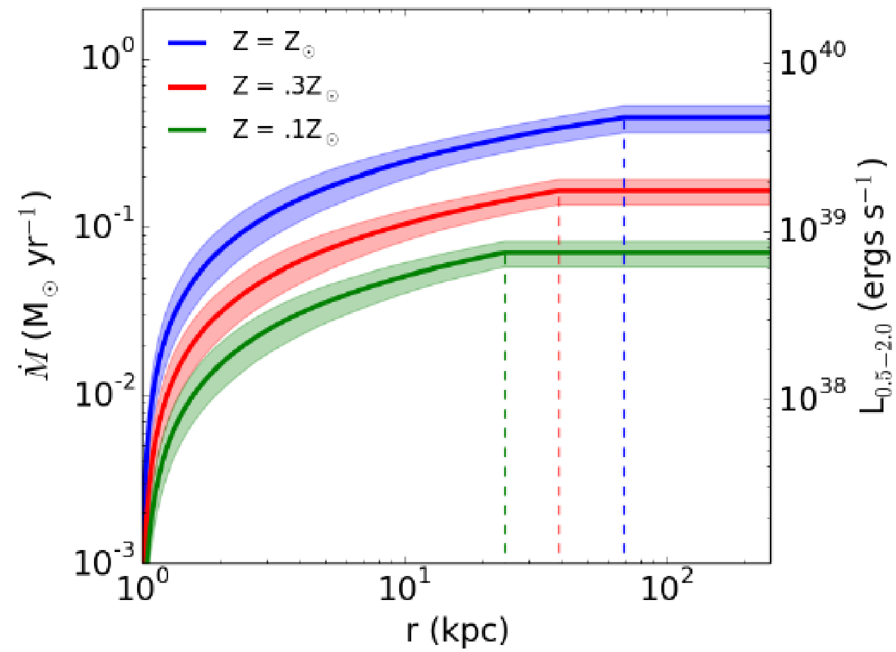
This is not the missing baryons (1-3x10^{11} $M_\odot$)

Need to extrapolate gas to 2-3R_{virial} to account for missing baryons.



Miller & Bregman 2015





Cooling time of the hot halo:

"Cooling flow" within 40 kpc

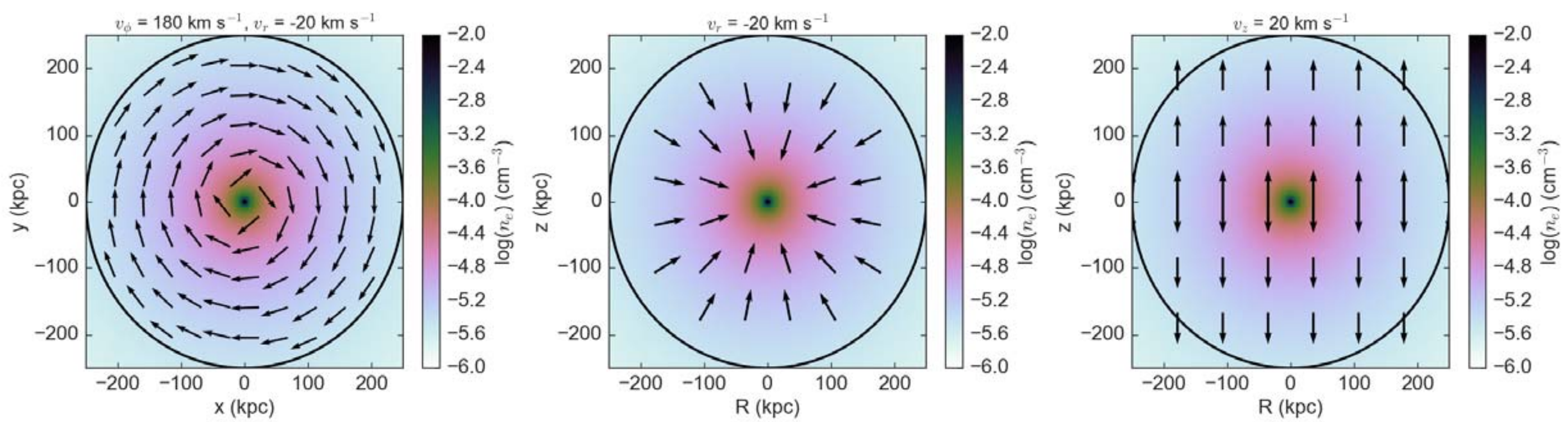
Cooling rate is about 0.2 Msun/yr (Z = 0.3 Zsun) (if cooling flows occur)

Hot Gas Kinematic Models

- Modeling absorption line shapes for bulk velocity flows
  - $v_{\Phi}(R)$ = flat rotation curve
  - $v_{r/z}(r,z)$ = constant accretion or outflow

face-on view

edge-on views



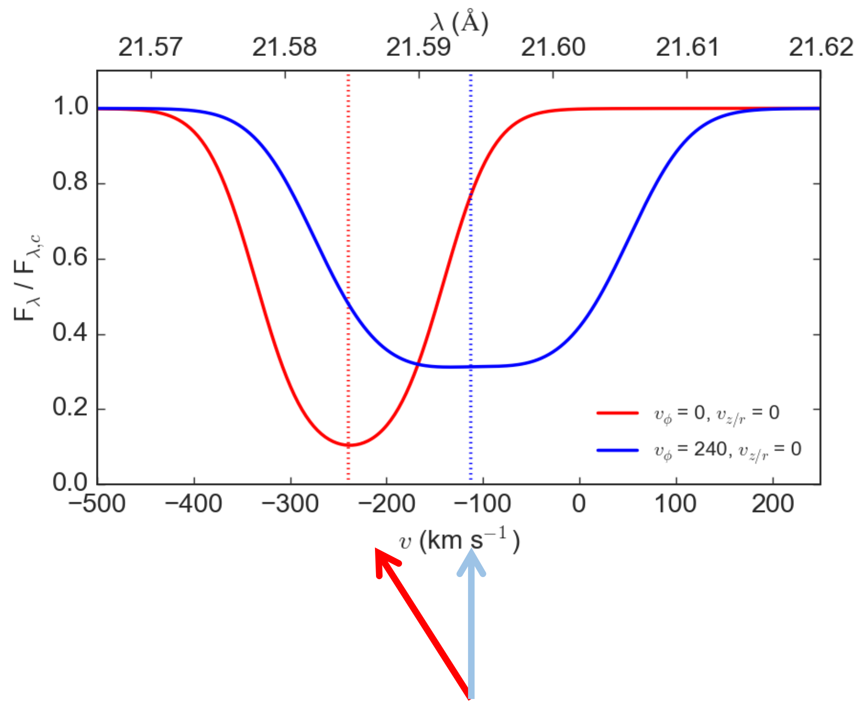
Rotation constrained by objects at various Galactic longitudes (but not high b)

Inflow/outflow constrained by looking up/down (high/low Galactic latitude)

Line of Sight Velocity Effects

- Line shapes and centroids encode information on the velocity structure

l,b = 90°, 0°
Red = stationary
Blue = corotating



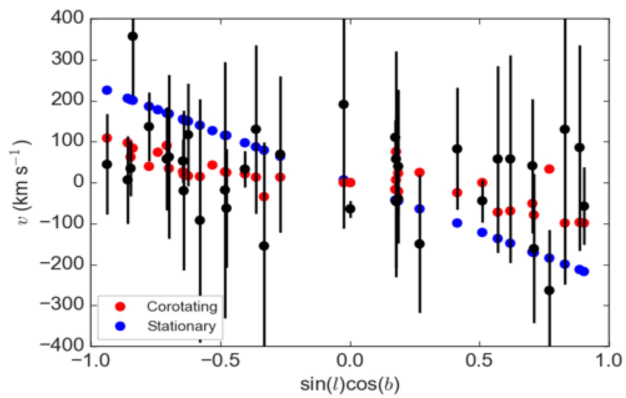
Broad line shapes similar to HI profiles for gas in the disk.

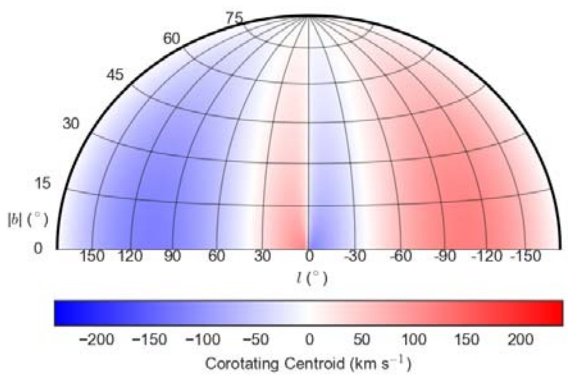
XMM RGS was not expected to have this precision but it does!

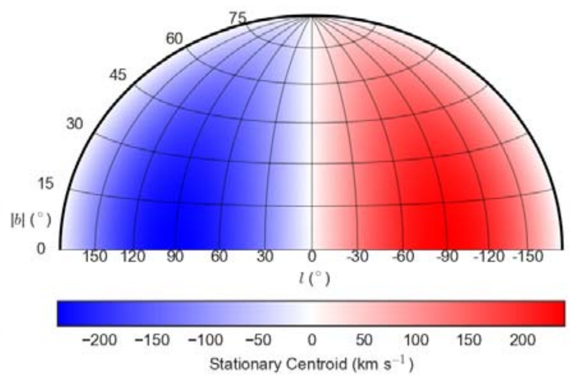
Centroid differences can be measured

Observed Line Centroids

- 37 OVII absorption line centroids from Hodges-Kluck+ 16
- Corotating model is a better fit to the data than a stationary profile
  - Best-fit model lags behind the disk with $v_{\Phi} = 183 \pm 41$ km s^{-1}







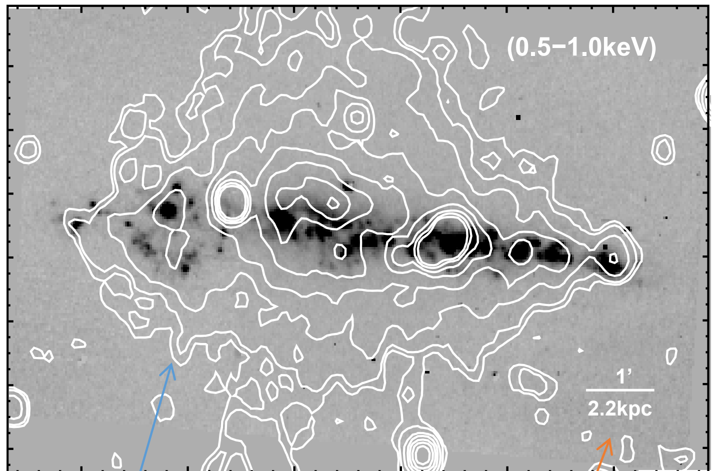
The Interaction of the Fermi Bubbles with the Hot Halo

- Elevated OVIII/OVII ration near Fermi Bubbles ➔ shocked gas

- Modeling the emission lines shows
  - thermal gas density to be $\approx 10^{-3}$ cm^{-3} and log(T) = 6.6-6.7
  - v_{exp} = 490 km s^{-1}
  - $\dot{E}$ = 2.3 x 10^{42} erg s^{-1}
  - t = 4.3 Myr

- FB origin consistent with a Sgr A* accretion event
- Not consistent with star formation origin

Hot Gas Around Spiral Galaxies



Tüllmann et al. 2006

The gas is oriented perpendicular to the disk, and is usually visible only when there is active star formation

Dilute hot halo extends to the virial radius; accreted gas. Challenging to detect.

Spirals: most likely a SN-driven galactic fountain + hot mode accretion

Global Formation Mechanisms

- Accretion Shock
  - Gas shock-heats to T_{vir} at r_{vir} as it accretes onto the dark matter halo
  - Expect spherical power law structure at ≈ 2 x 10^6 K

- Supernovae-driven 'galactic fountain'
  - Supernovae heat the ISM and break out of the disk
  - Expect an exponential disk structure confined within |z| < 10 kpc

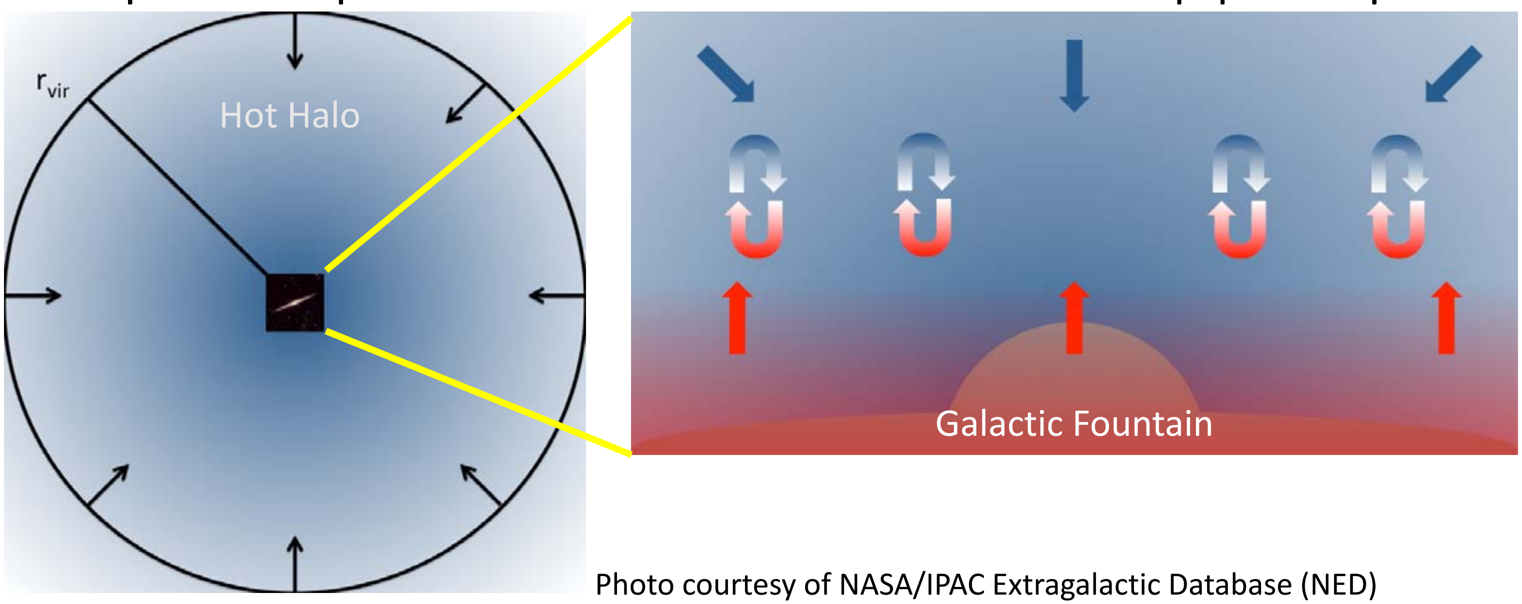
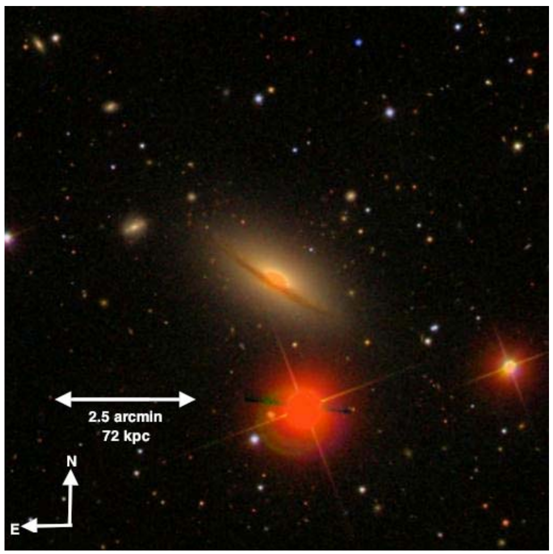
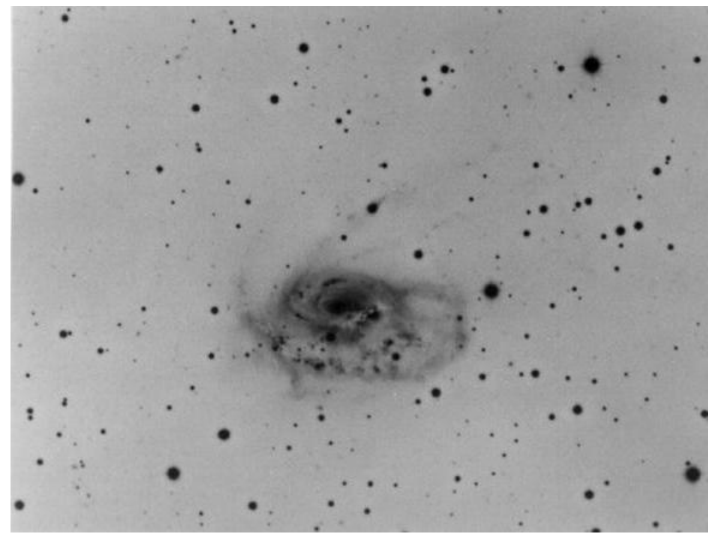


Photo courtesy of NASA/IPAC Extragalactic Database (NED)

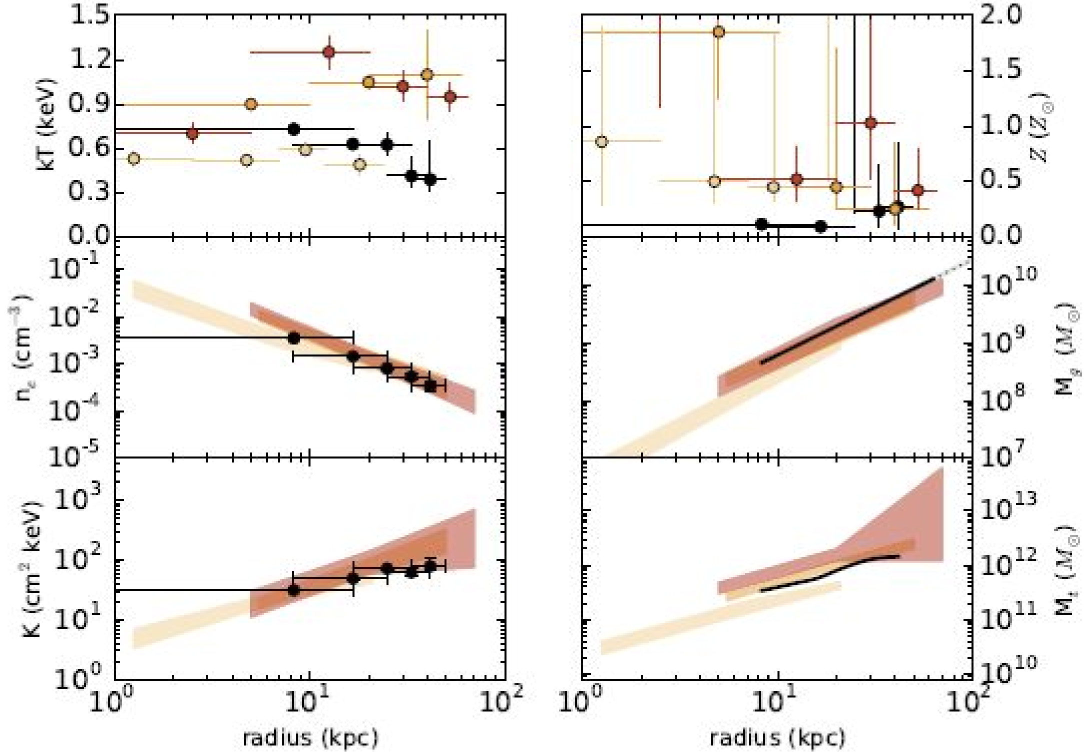
Halos Around Two Massive Galaxies NGC 1961 and UGC 12591





UGC 12591: Early-type spiral (left) NGC 1961: Later-type spiral (right)

Stellar Mass is 6-8x the Milky Way



Summary from Anderson et al. (2015); also NGC 720 (Humphreys), NGC 266 (Bogdan); UGC 12591 (Dai et al. 2015)

Metallicity of 0.1 – 0.5 Solar

Entropy increase with radius

Density and Mass Summary

- General results
  - $\beta = ½$; $n \sim r^{-3/2}$
  - 20-30% of missing baryons within R_{virial}
  - Gas mass comparable to stellar mass
  - Still missing half of the baryons (or more)
- Could density law be flatter (Kauffman et al. 2008, Feldmann et al. 2012)?
  - No (inconsistent with observed S_x, T_x)
  - T also gives $n \sim r^{-3/2}$

Summary and Conclusions

(in case you concentration is compromised after the dinner last night)

- Extended hot halos exist around spiral galaxies
  - To at least 50 kpc and probably to R_{200}
  - Comparable to (less than) stellar mass within R_{200}
  - Hot mode accretion of 0.1-0.3 $M_{\odot}$/yr (less than star formation rate)
  - Does not account for missing baryons unless extended to 2-3R_{200}
  - Metallicity of ~0.3 Solar
  - Variation in properties unknown due to small samples
- Milky Way hot halo rotates
  - About 180 km s^{-1} (60 km/s slower than the disk); could use more objects
  - Consistent with theory, but few predictions
- Fermi Bubbles shock hot halo (v = 500 km/s); AGN origin