Hot Halos and the Missing Baryons in Galaxies

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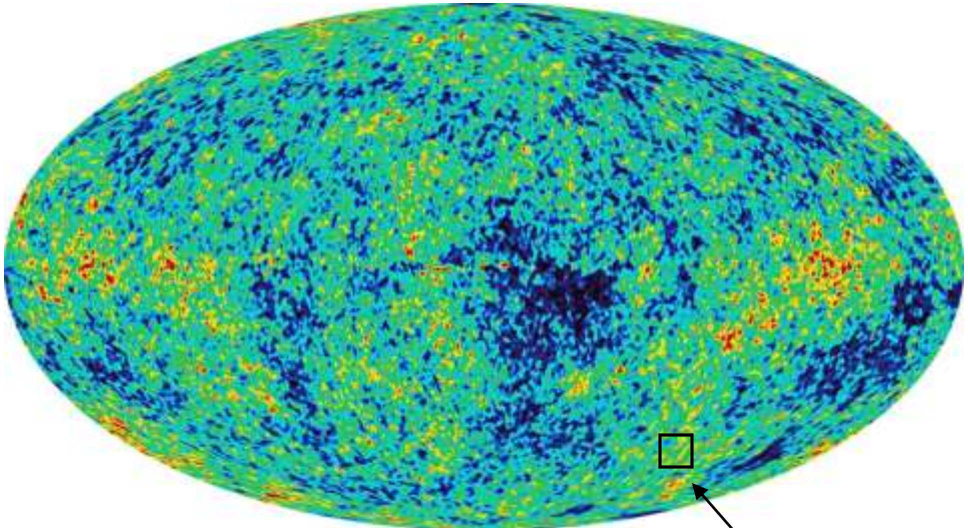
- **The Missing Baryon Problem In Galaxies**
- The Hot Milky Way Halo: Mass and Metallicity
- Extended Hot Halos Around Other Galaxies
- Where Are the Missing Baryons & How Did They Get There?
- Distinguishing Between a Galactic Fountain and Extended Hot Halo
- Accretion From Beyond a Galactic Fountain

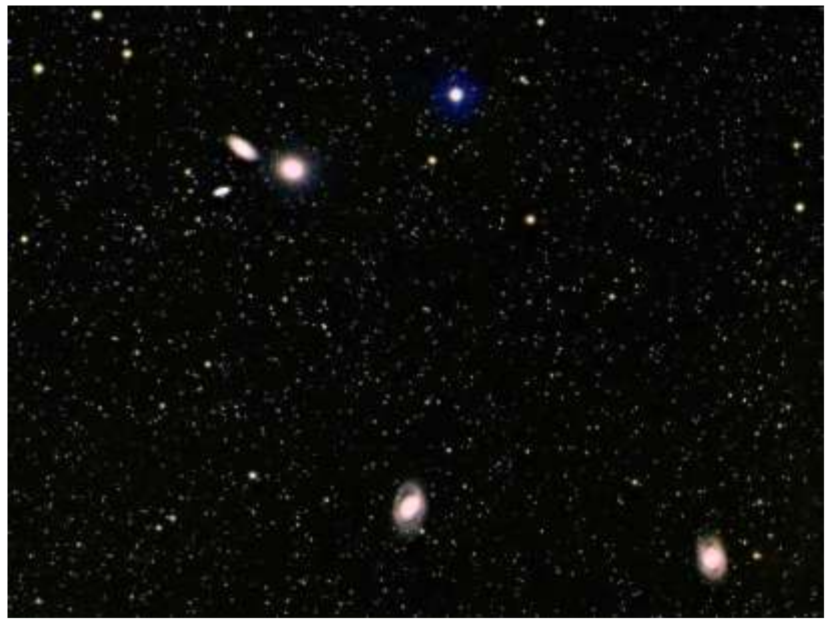
A Missing Baryon Problem



Cosmic Microwave Background (z = 1000)

The general belief was that this

Became this



But then someone counted the baryons and found otherwise….

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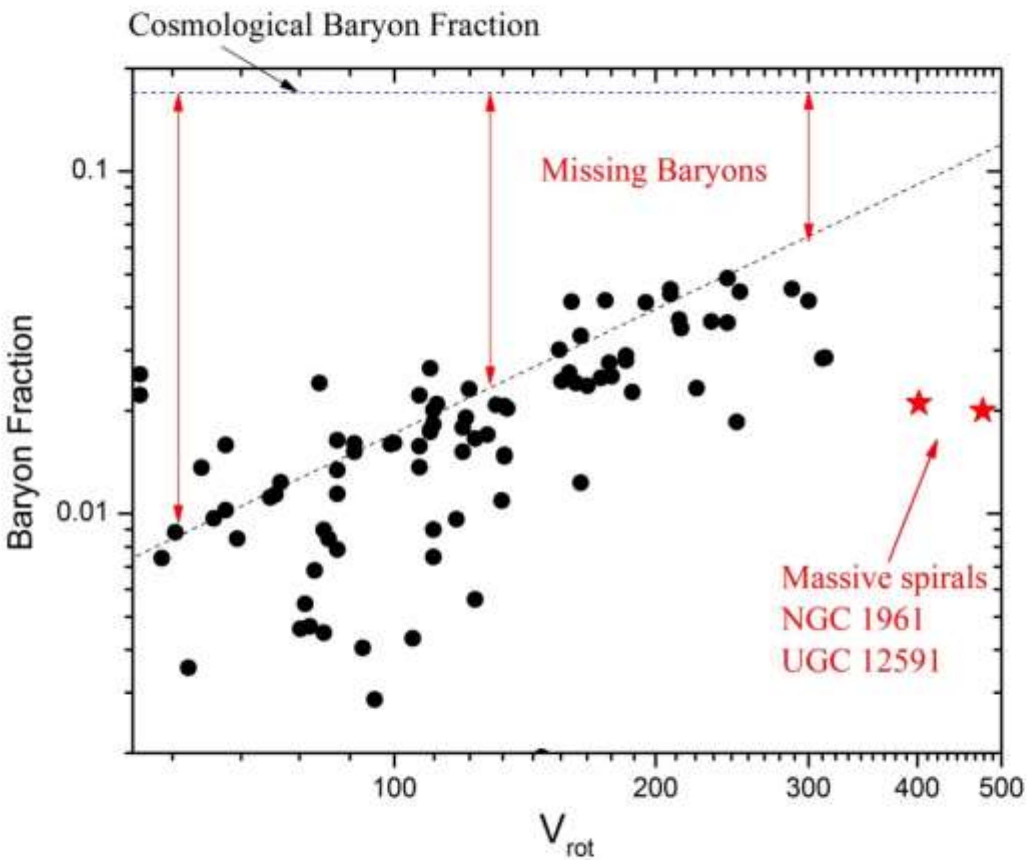
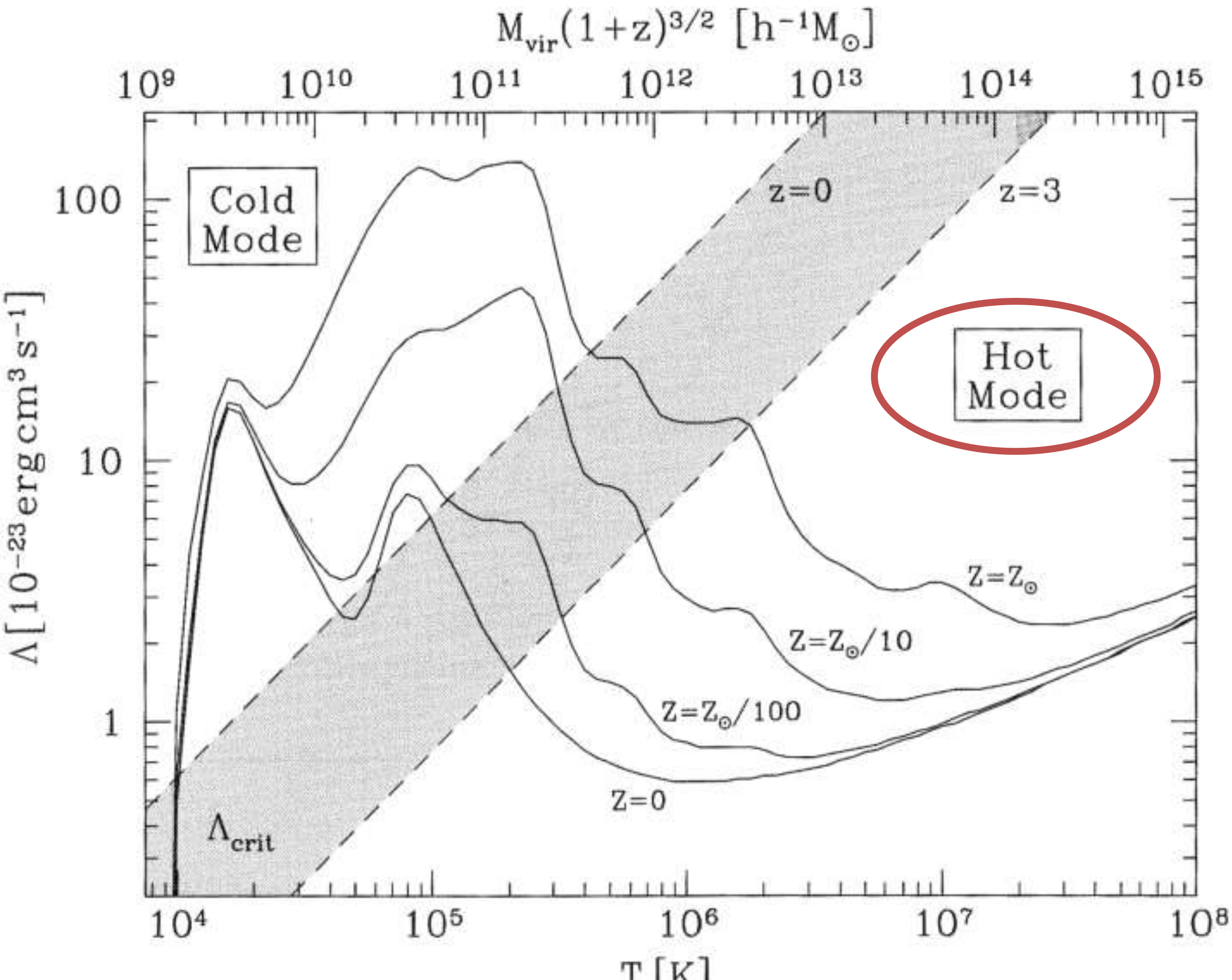


Rich clusters have nearly all their baryons.
Galaxies become increasingly baryon-poor.
"Average" spiral (like M33) is missing 90% of baryons

Where Are The Baryons?

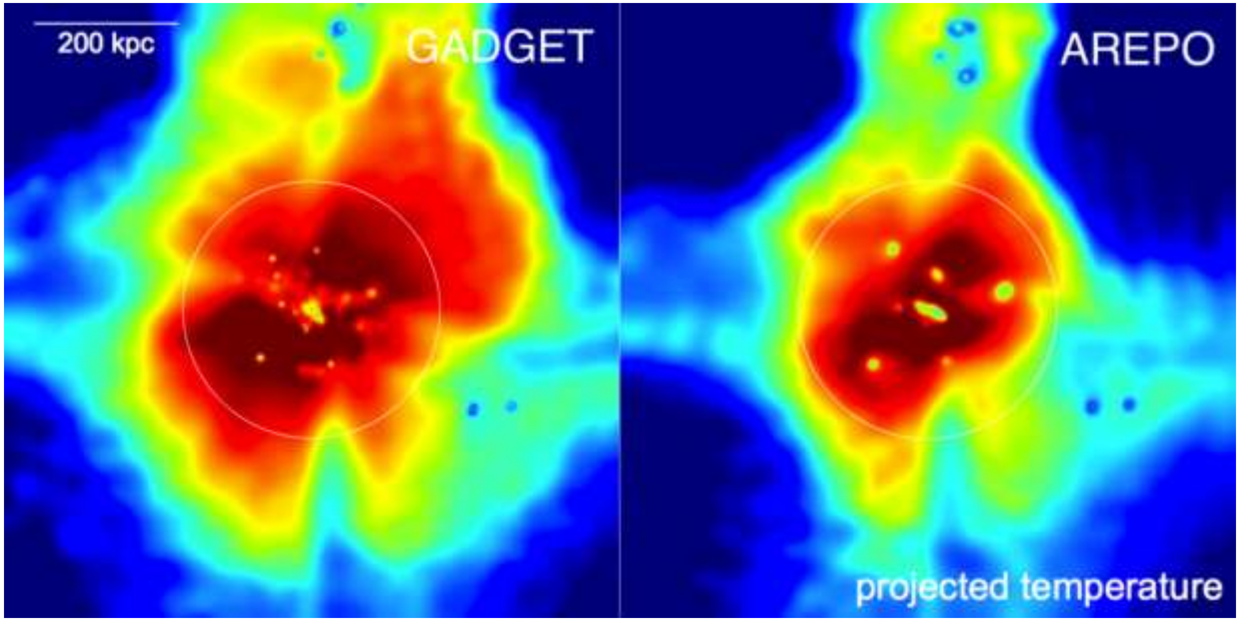
- Galaxies are missing 70-95% of their baryons
- Were the baryons expelled from galaxies?
  - Maybe they didn't fall in to begin with
- Massive galaxies (like Milky Way) accrete gas
  - Infall at the free-fall velocity
  - Accretion shock converts motion to heat
  - Massive halo of gas at about the virial temperature
  - T_{virial} ~ 1-4x10^6 K
- Basic model supported by simulations
  - Hot gas mass, radial distribution sensitive to input parameters

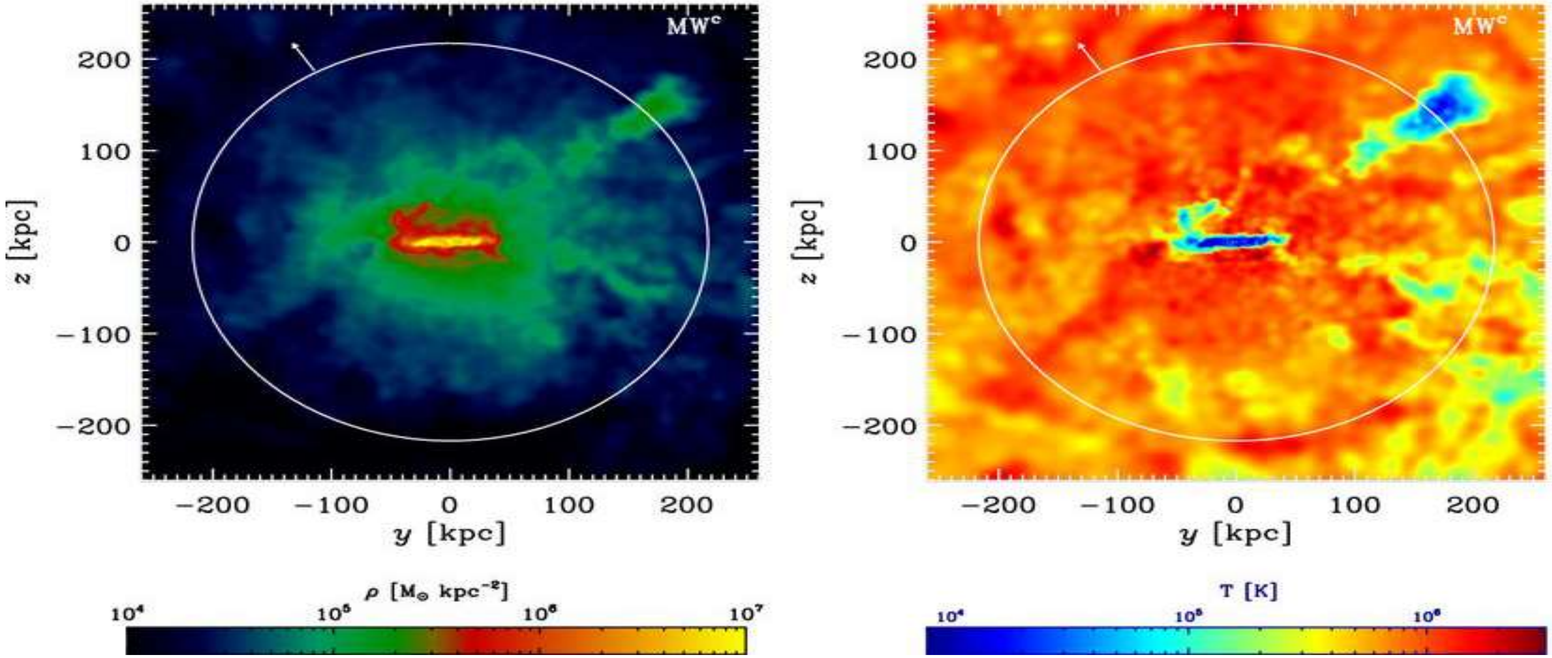
Two Modes of Accretion



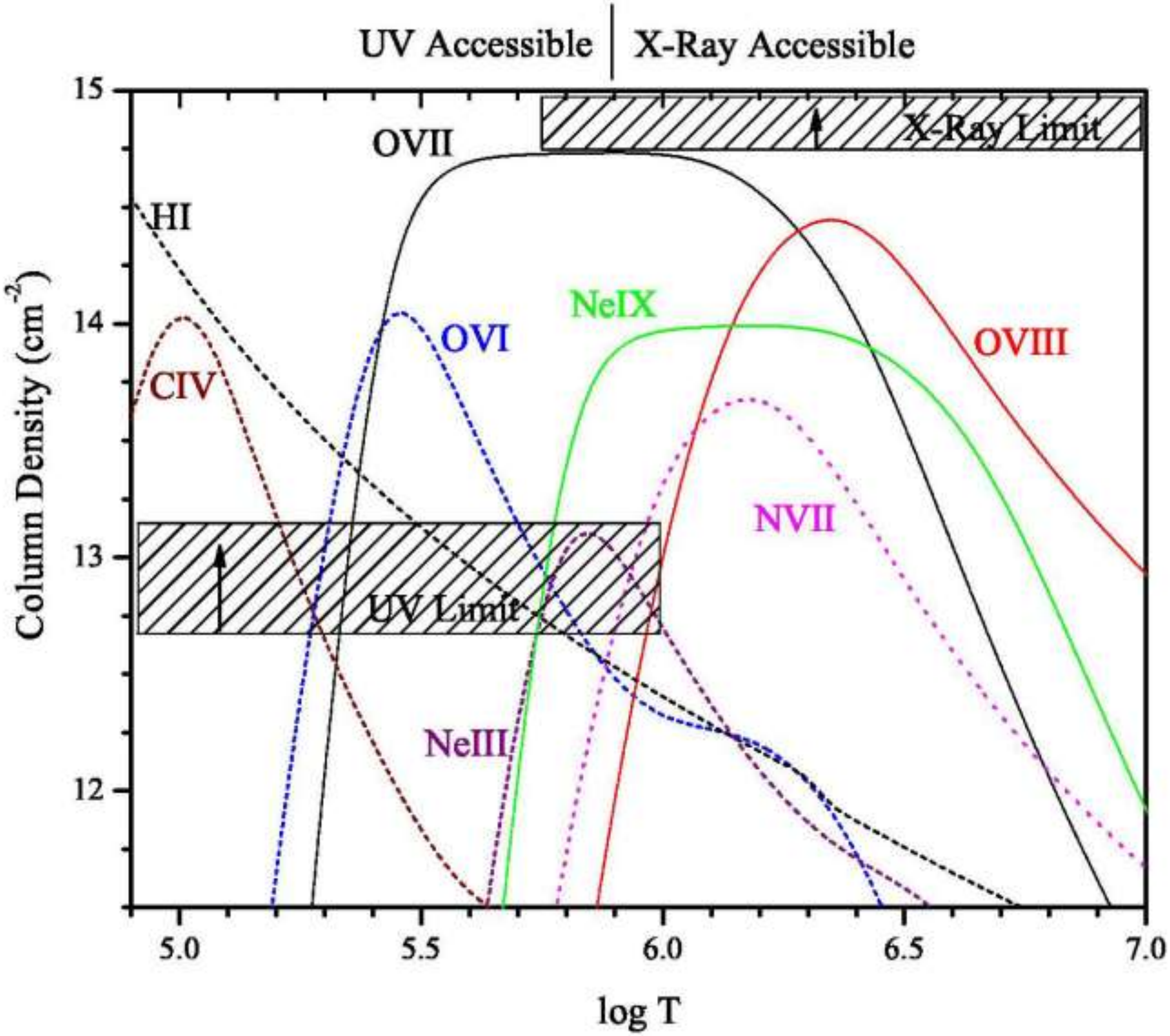
from Mo, van den Bosch, and White (2010)

Springel





Model for the Milky Way; Nuza et al. 2014



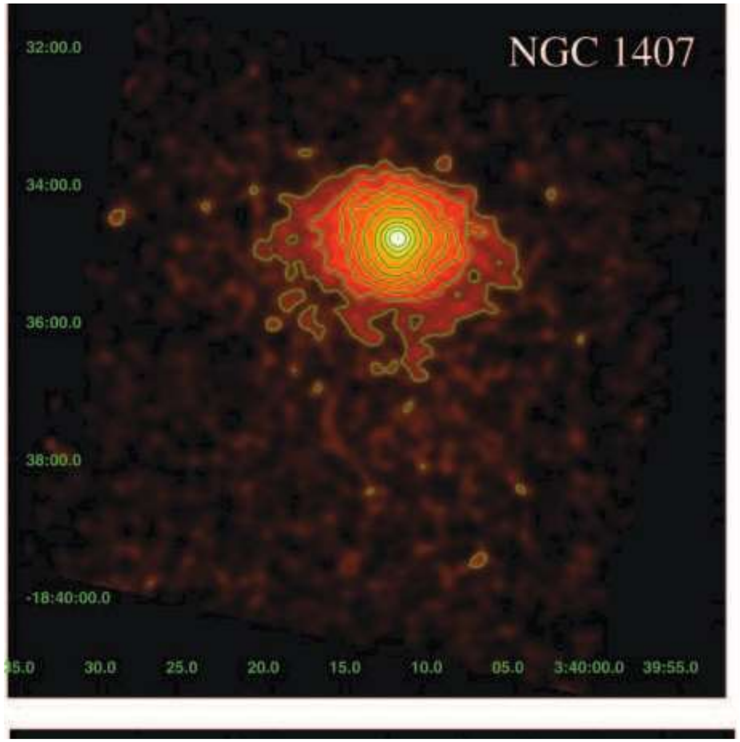
Z = 0.1 Solar

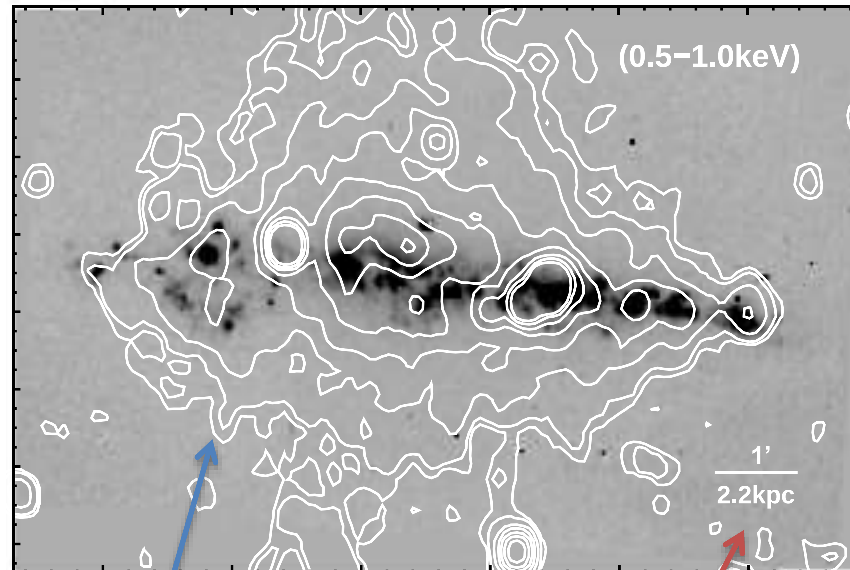
N = 10^{19} cm^{-2}

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

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

Hot Gas Around Spiral Galaxies





Tüllmann et al. 2006

Ellipticals: Hot gas out to 10 kpc often detected; separation from cluster?

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

Hot gas is seen out to much smaller radii than around ellipticals

Spirals: most likely a SN-driven outflow, and not a hot halo

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Constraints on Gas Around Milky Way

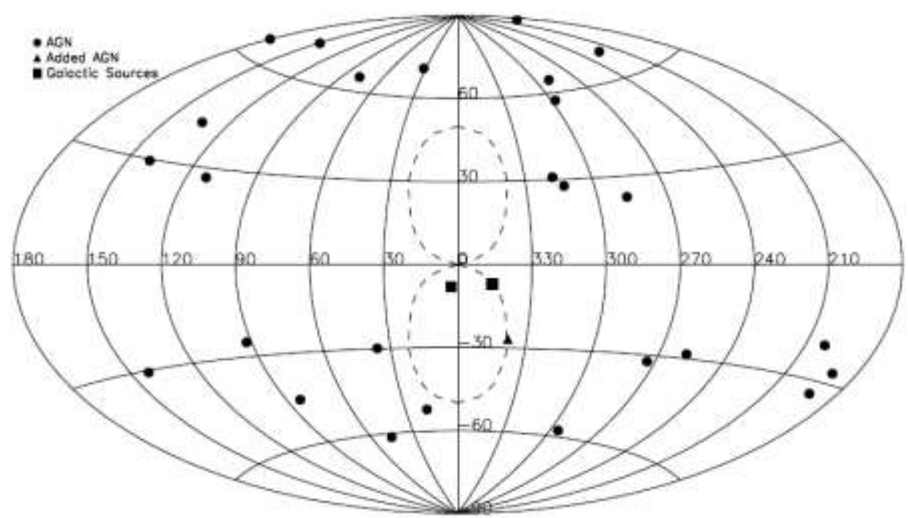
- Limits on halo gas from pulsar dispersion measure
  - Dispersion measure: integral of n_e along line of sight
  - Pulsars in LMC have a DM above that of the MW
  - Most of this could be due to the LMC environment
  - If due to path toward LMC ➔ n_e = 5E-4 cm^{-3}
  - NFW profile (concentration of 12) out to R_{virial} = 250 kpc
    - 1.5E10 $M_{\odot}$
    - 4% of the missing baryons
- Constraint from the Galactic soft X-ray background
  - Use hotter component (3E6 K)
  - NFW Profile, M_{gas} = 6E9 $M_{\odot}$
  - 2% of the missing baryons

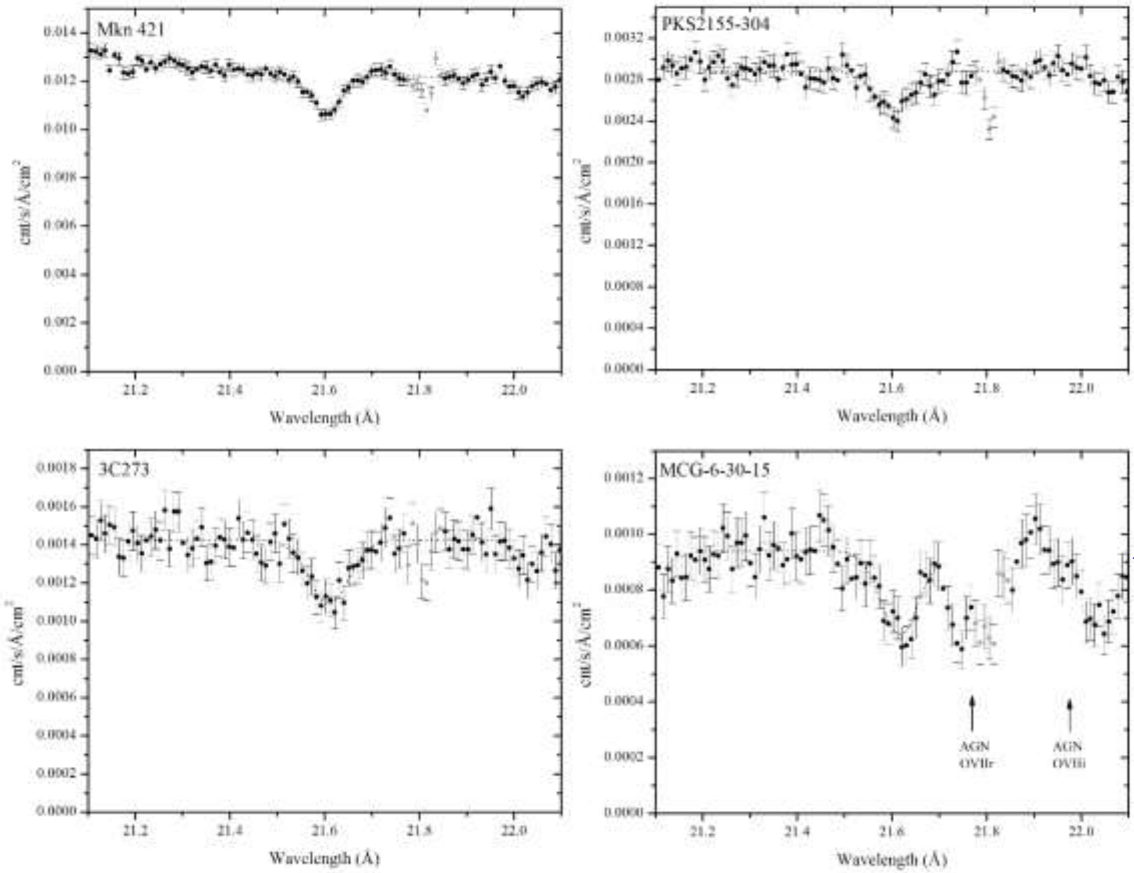
Anderson & Bregman 2010

Fitting A Density Model

- OVII and OVIII absorption and emission lines (2×10^6 K) from XMM (Miller & JNB 2013, 2014)
- Fit a "beta" model, $n(r) = n_o \, (1 + (r/r_c)^2)^{-3\beta}$
  - $n(r) \approx n_o \, (r/r_c)^{-6\beta}$ (not sensitive to core radius)
  - Flattened model does not improve fit
  - Need a hole in central 1.2 kpc (Fermi bubble to the rescue)

Absorption sightlines





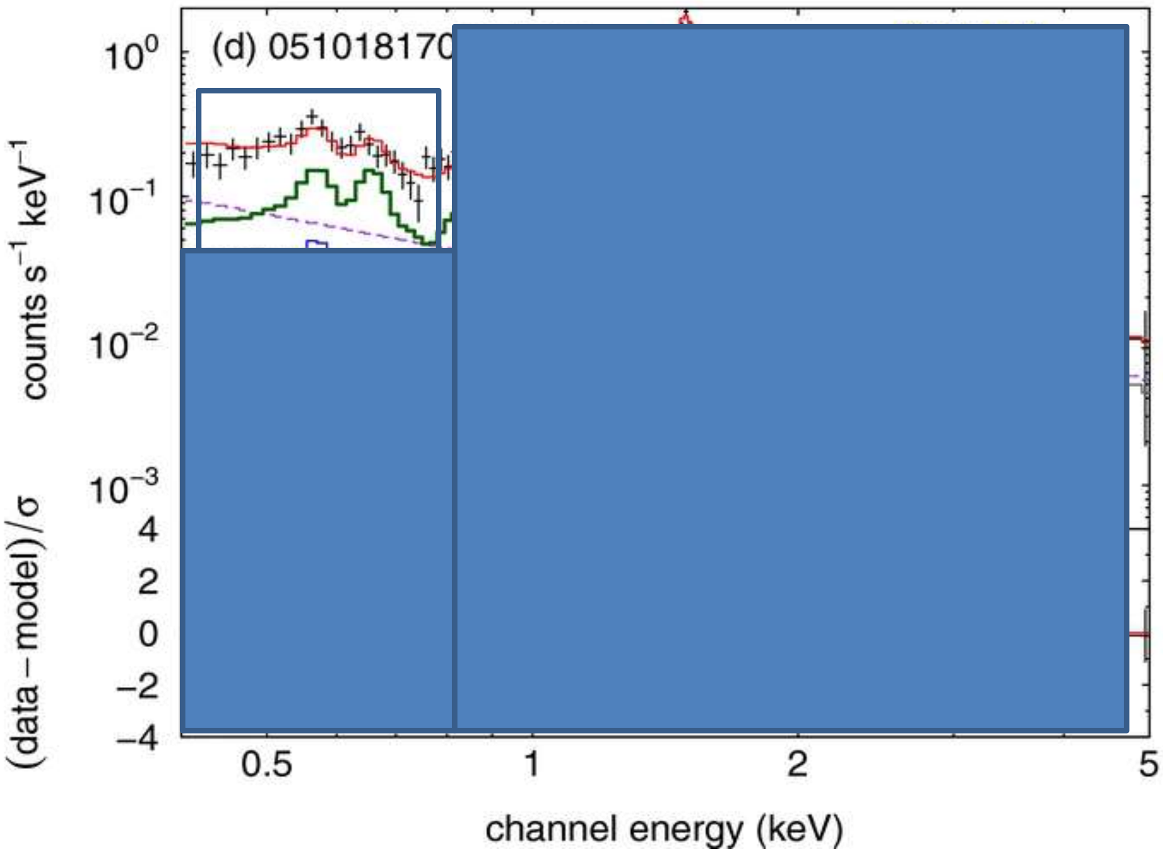
Toward Bulge

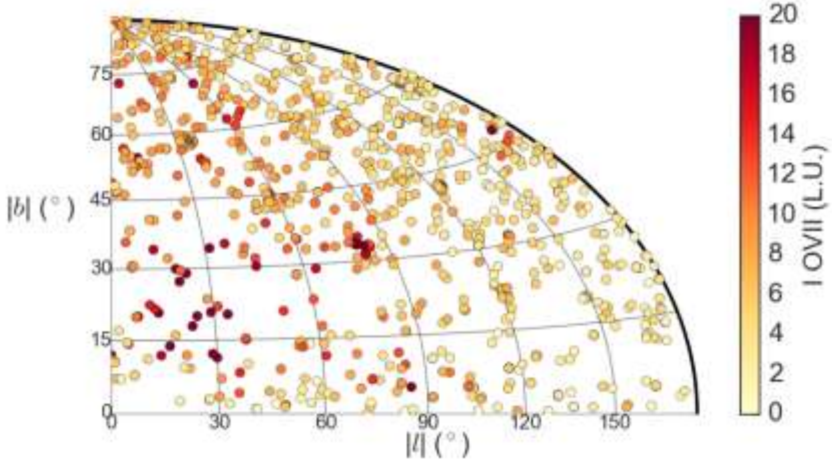
26 Target AGNs; mean EW = 22 mÅ; 17 with rms < 10 mÅ

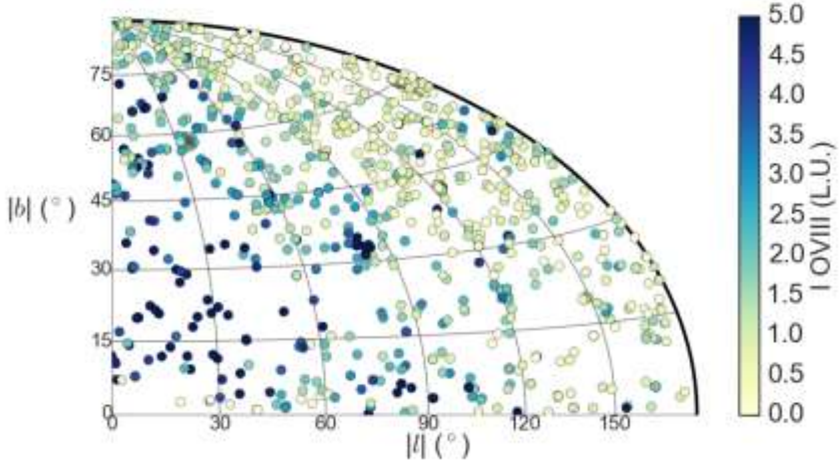
These are the 4 best.

O VII and O VII in Emission

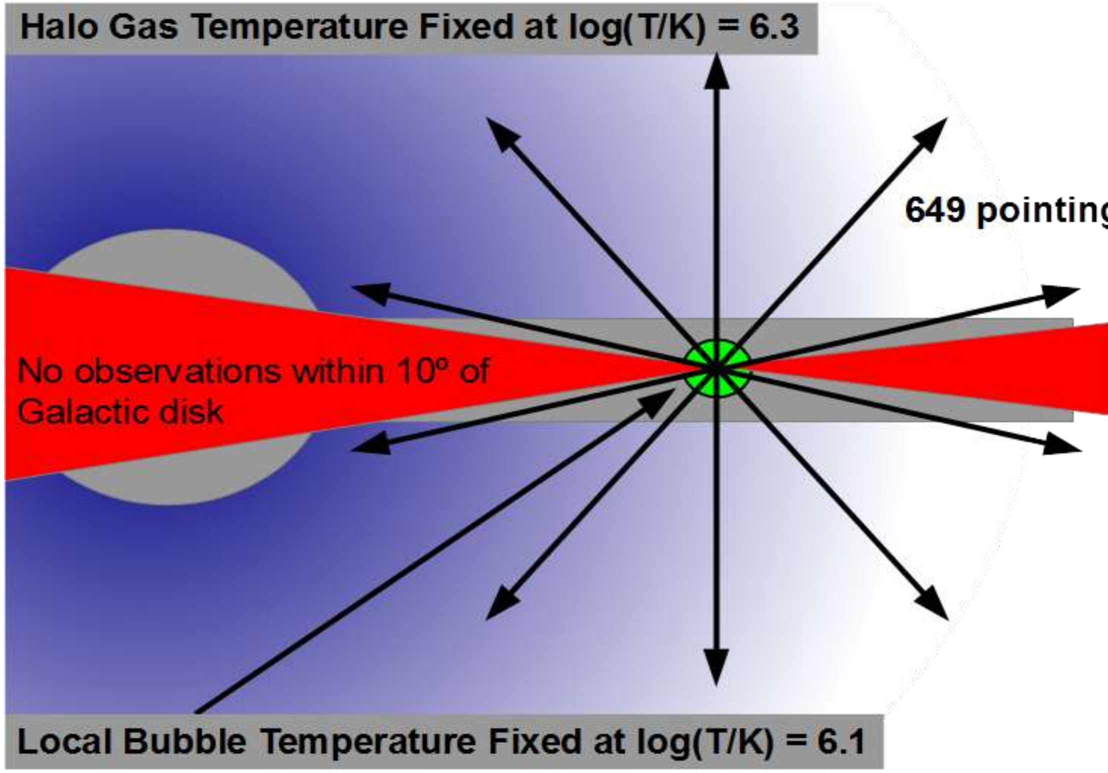
- OVII - 0.56 keV – He-like triplet emission
- OVIII - 0.65 keV – H-like Lyα emission





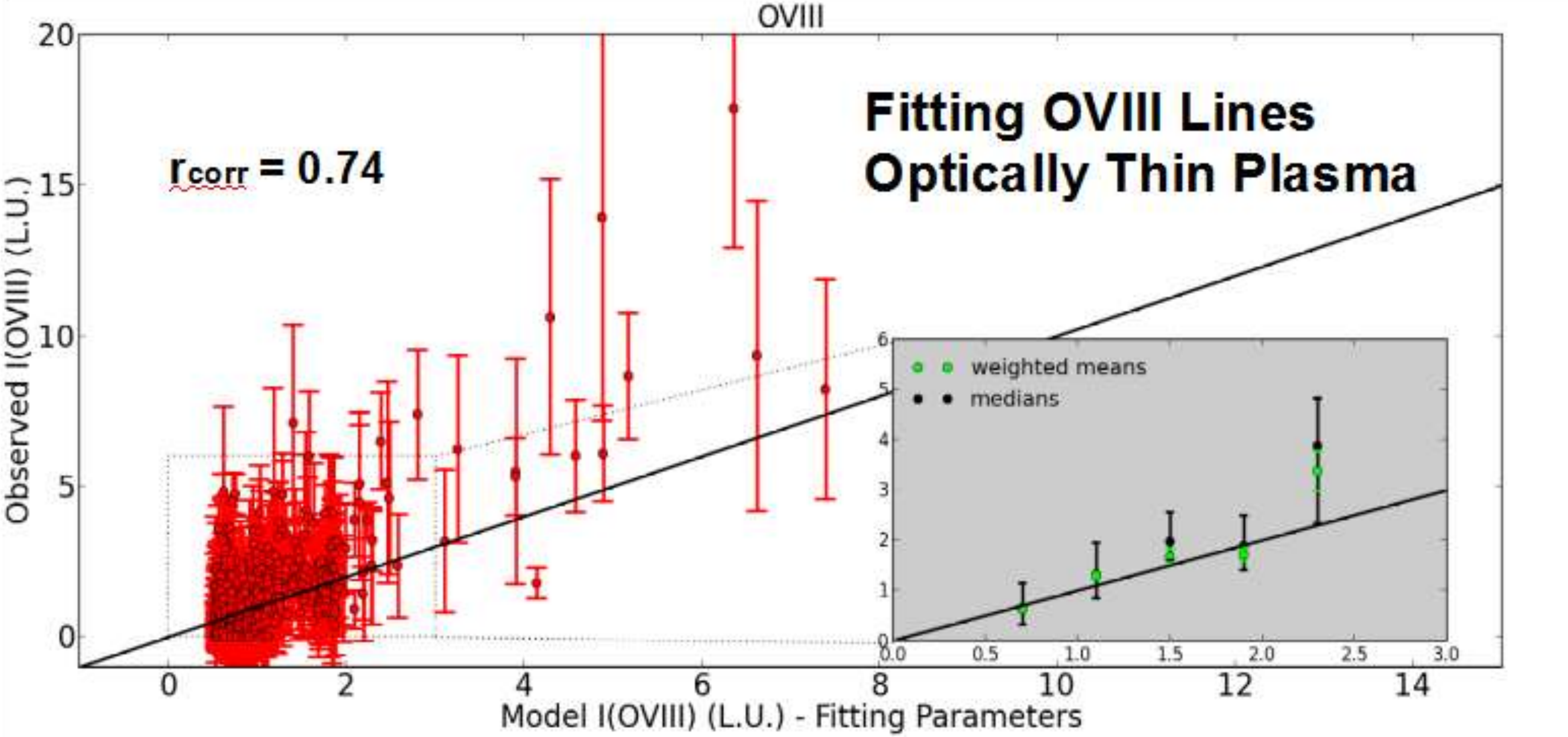


Dimmest toward anticenter
Brightening as you look across the Milky Way
Avoid Fermi Bubbles region

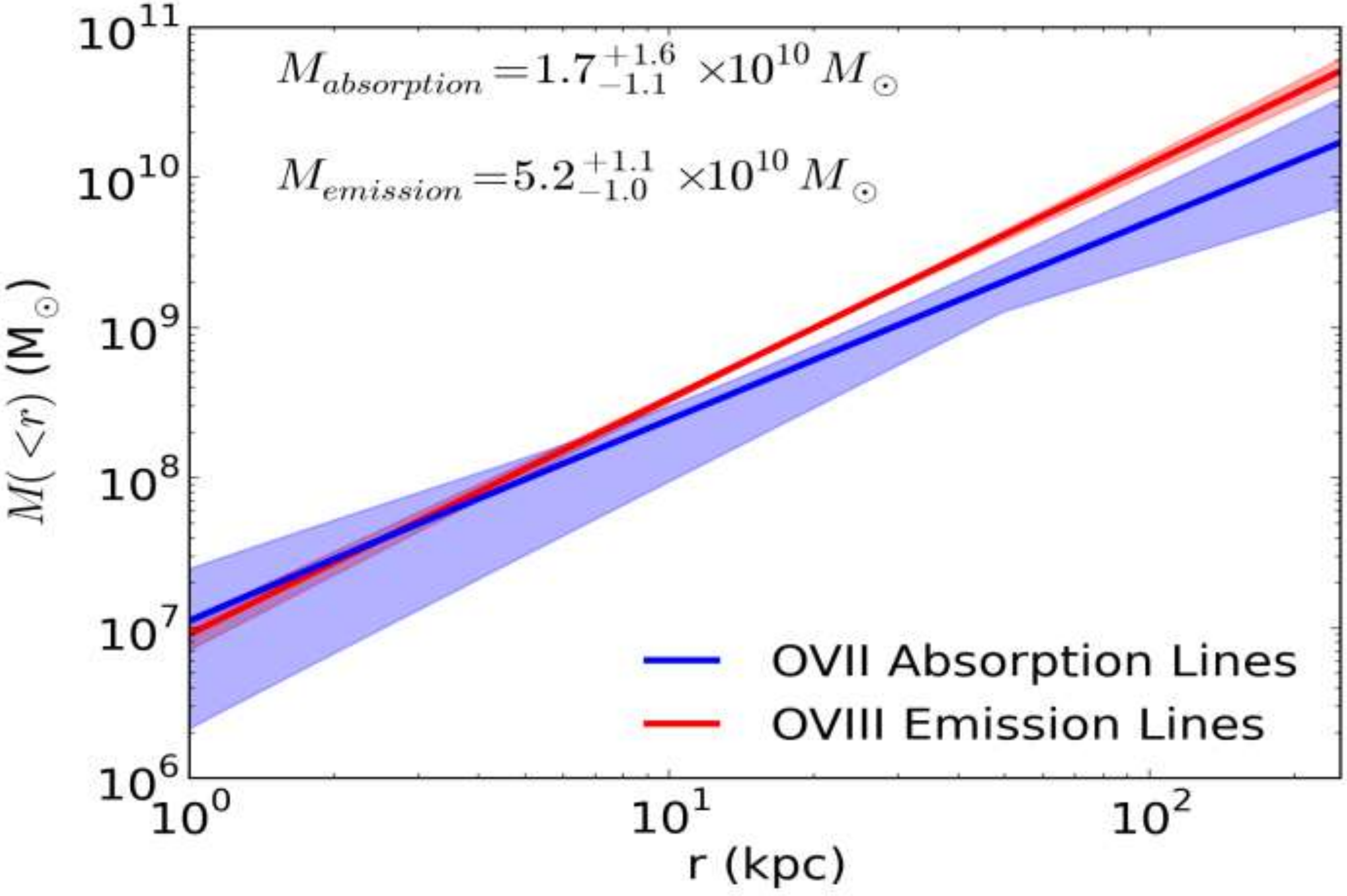


Results

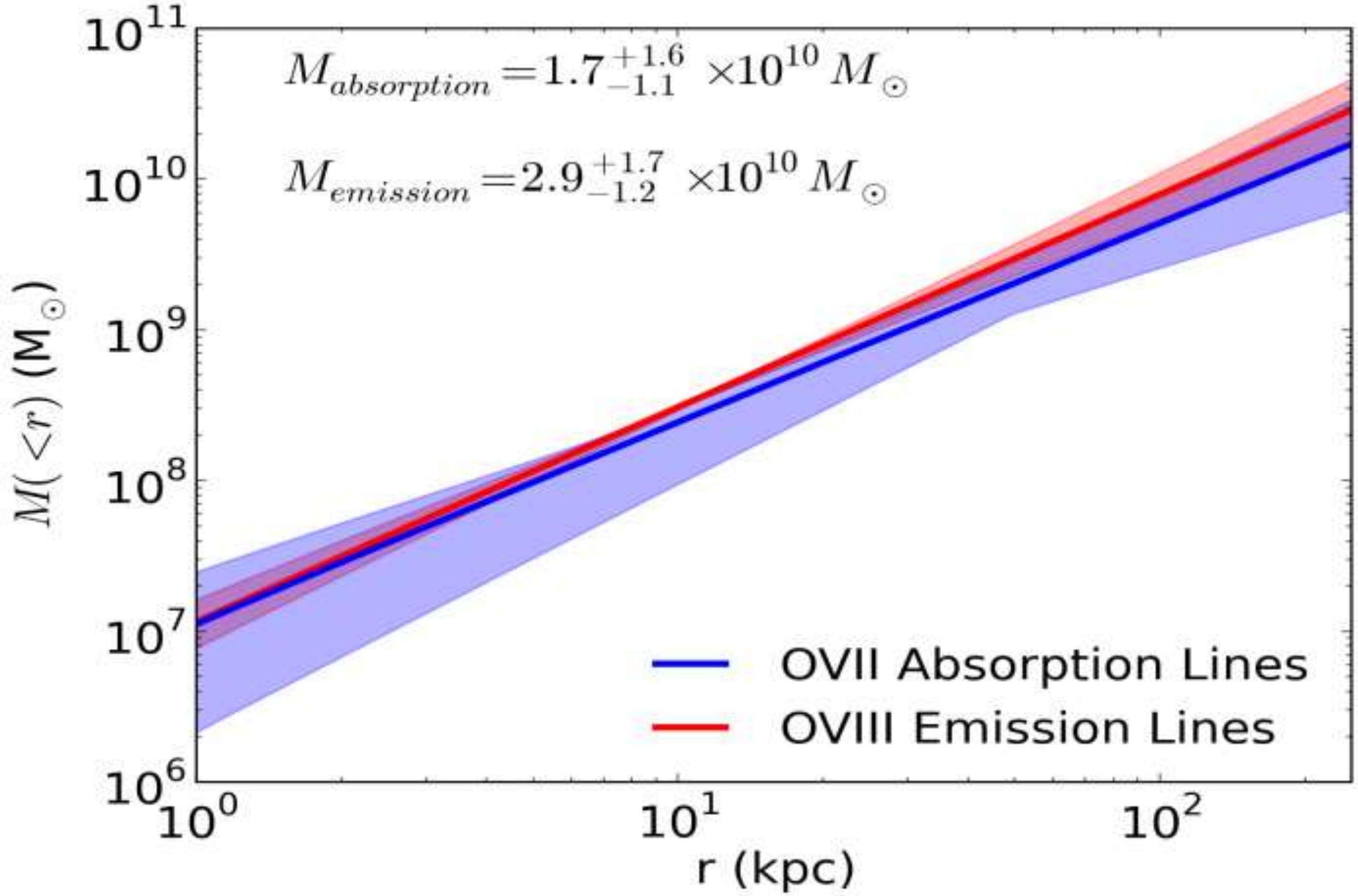
Lines Fitted	$n_o r_c^{3\beta}$ (cm^{-3} $kpc^{3\beta}$)	β	$n_{local\ bubble}$ (cm^{-3})	χ_{red}^2 (dof)
OVII	0.89 ± 0.06 x 10^{-2}	0.43 ± 0.01	3.86 ± 0.26 x 10^{-3}	4.69 (645)
OVIII	1.35 ± 0.24 x 10^{-2}	0.50 ± 0.03	No Contribution	1.08 (644)

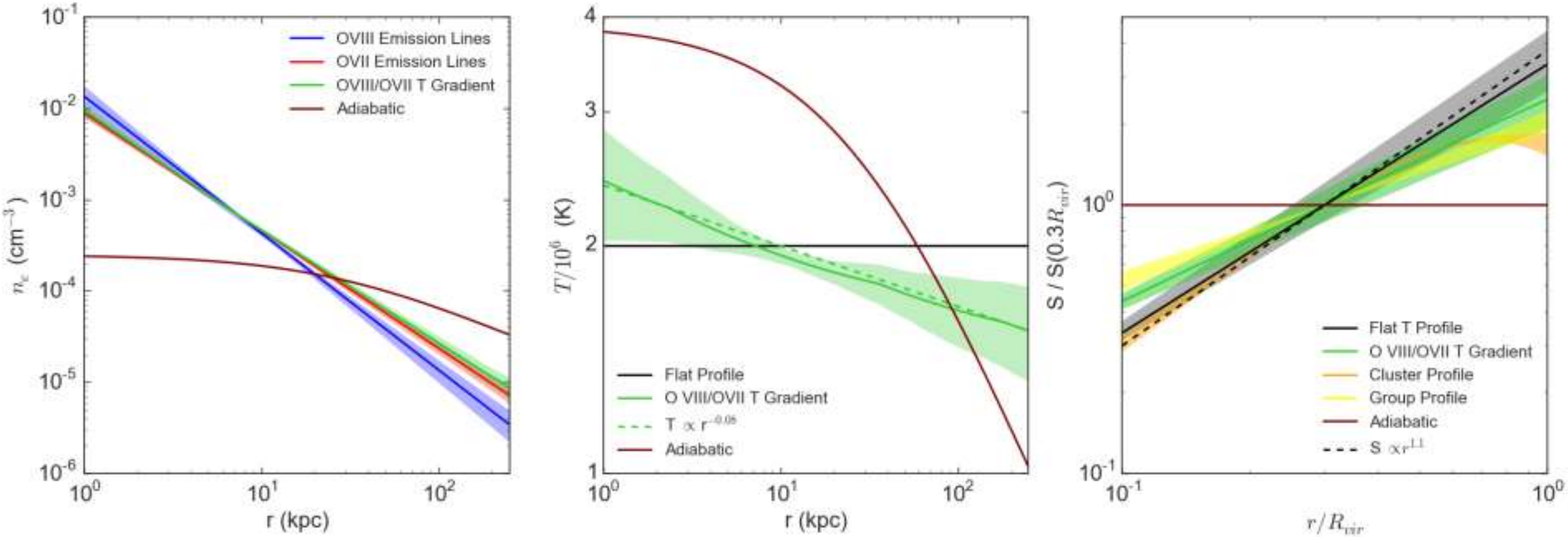


Masses: Abs + Emission



Masses: Optical Depth Correction





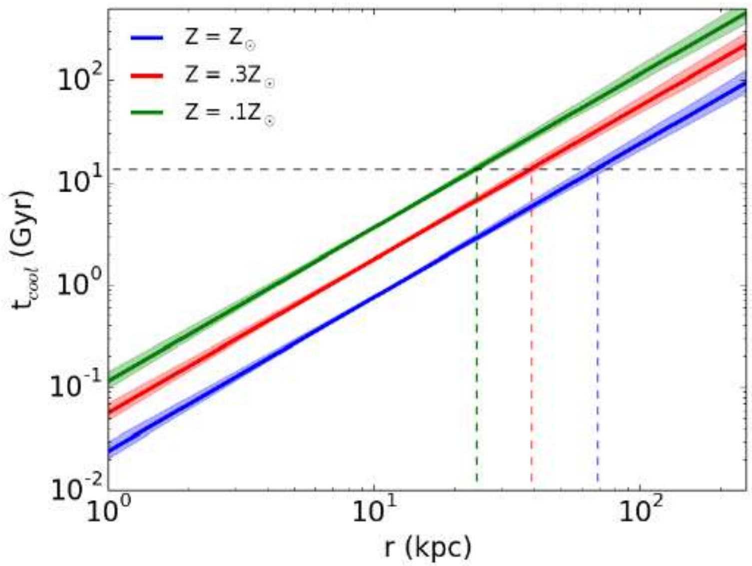
- Fit to O VIII emission is a little flatter than for O VII – can be interpreted as a T gradient
- Shallow T gradient: $T \propto r^{-0.08}$
- Entropy increases with radius like galaxy groups
- Not consistent with flattened density profile (and high T) proposed by Gupta et al. (2012), Bullock.

The Metallicity of the Halo Gas

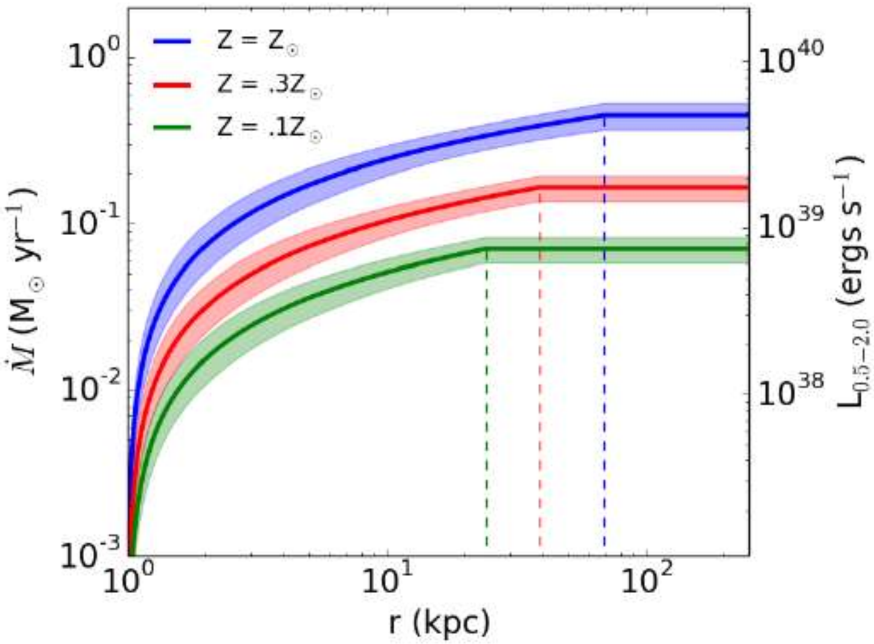
- ***Minimum*** metallicity given by the combination of the pulsar dispersion measure and O VII, O VIII absorption columns
  - Electron column to LMC fixed by pulsar DM
  - N(OVII), N(OVIII) dominated by material between LMC and MW
  - Divide one by other: $Z > 0.3\ Z_\odot$
- Shull et al. (2014): census of cool/warm gas and metals at low redshift
  - Observe about 60% of baryons (intergalactic; T < 3E5 K)
  - Missing 90% of metals
  - Mean cosmic metallicity of universe ≈ 0.16
  - Remainder of baryons (T > 3E5 K) should have $Z \approx 0.3\ Z_\odot$
- The hot medium has plenty of metals (not “pristine”)

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)



Milky Way Baryon Budget

- For a cosmological f_{bar} of 0.171 ± 0.006 (WMAP)...
  - M(stars + cold gas + dust) = 6-7 x 10^{10} $M_{\odot}$
  - Mvir = 1-2 x 10^{12} $M_{\odot}$
  - Mmiss = 1-3 x 10^{11} $M_{\odot}$

- If the density profile extends to the virial radius...
- Mhot = 2-6 x 10^{10} $M_{\odot}$

- Halo gas contributes < 20% to the missing baryons

- Profile would need to extend to 2-3 R_{vir} to account for all of the Milky Way's missing baryons

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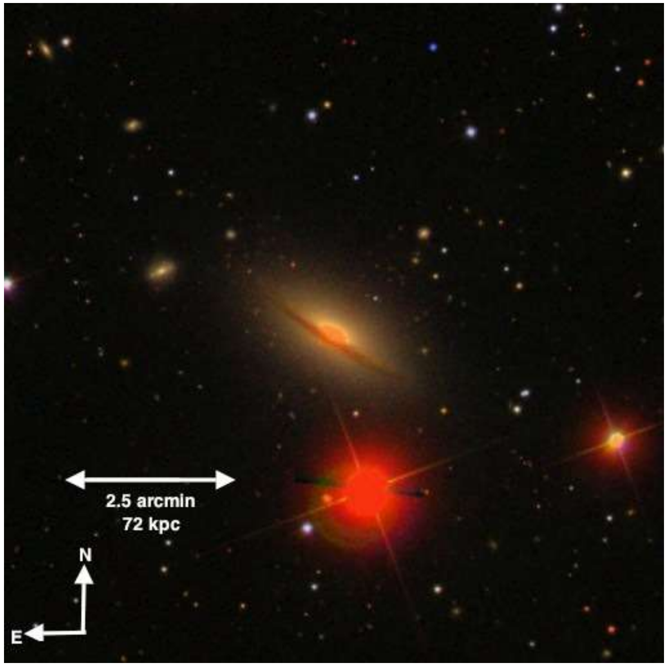
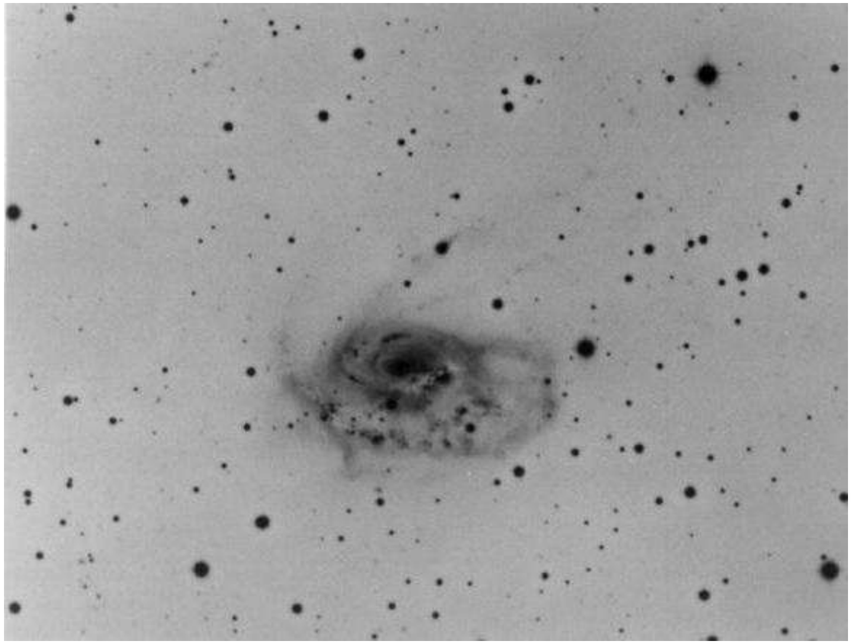
Halos Around Two Massive Galaxies NGC 1961 and UGC 12591

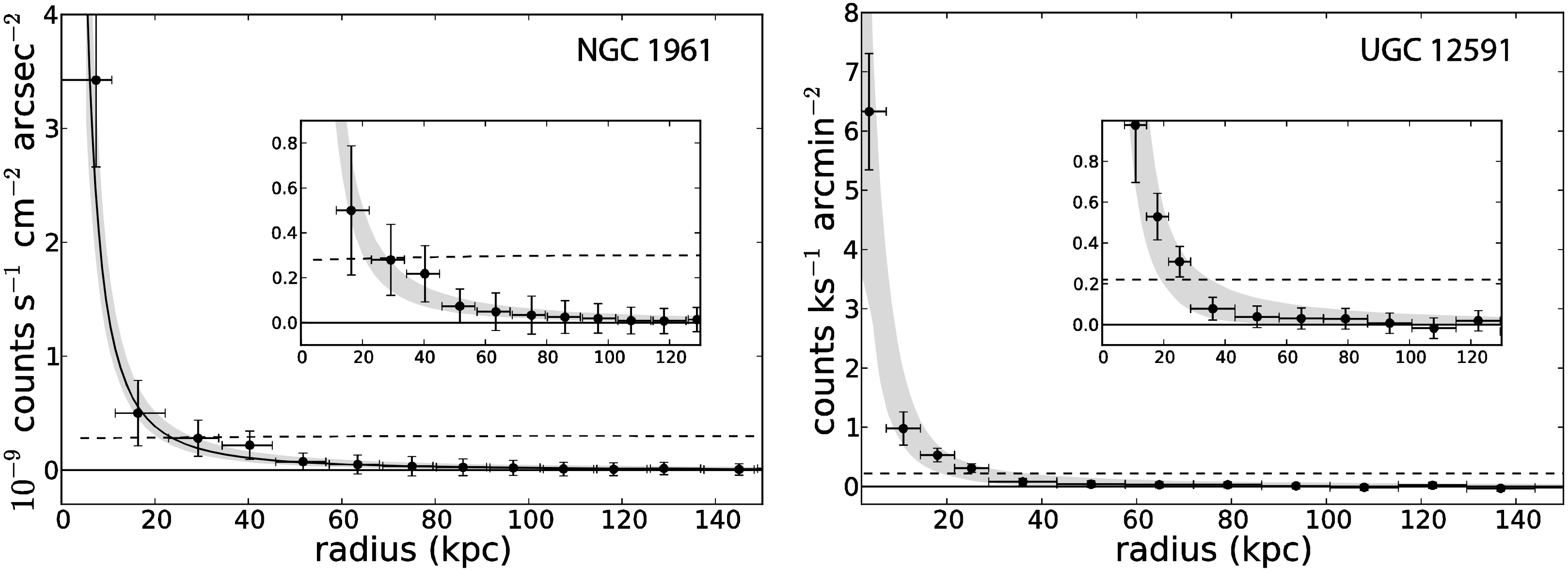




UGC 12591: Early-type spiral (left) NGC 1961: Later-type spiral (right)

Stellar Mass is 6-8x the Milky Way

Hot Halos Around Isolated Galaxies



- Hot halos detected to 50-70 kpc (optical size 20 kpc)
  - M_{gas} = 5 x 10^9 M_{sun}
  - Extrapolation to r_{virial} is about 30x (like stellar mass)
- Still far short of missing baryons; f_b = 0.024-0.029 (mean cosmological value is f_b = 0.17)

Isolated Ordinary Galaxies: The ROSAT Stacking Project

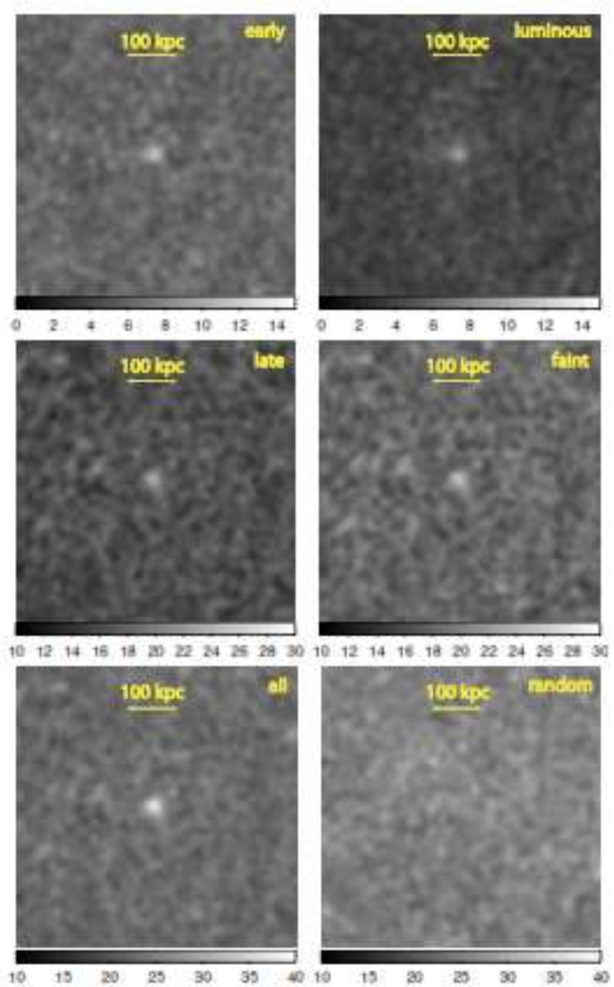
Anderson, Dai & Bregman (2012)

Stack a few thousand galaxies (1 photon each)

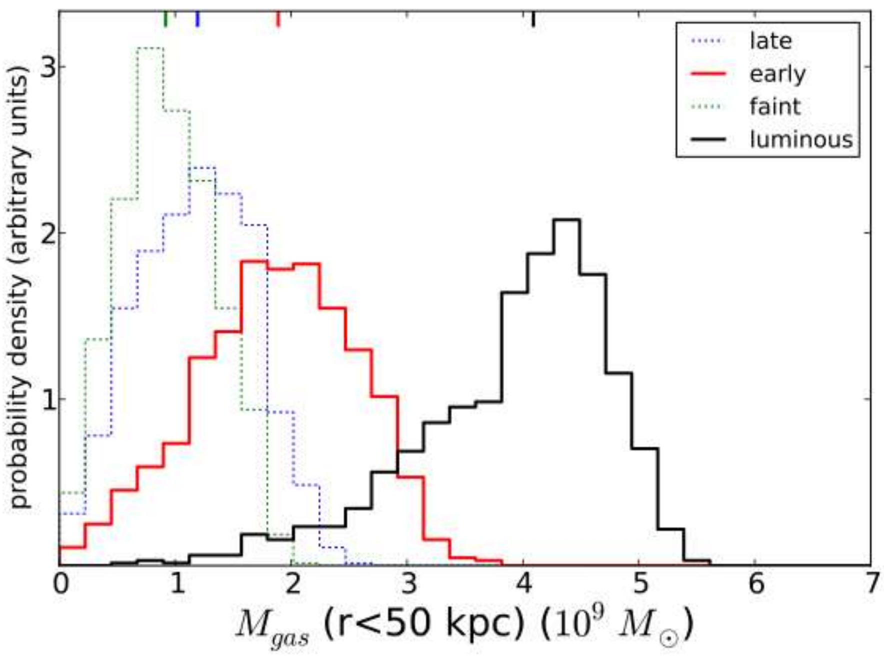
Late-type, early-type galaxies(high/low L_K)

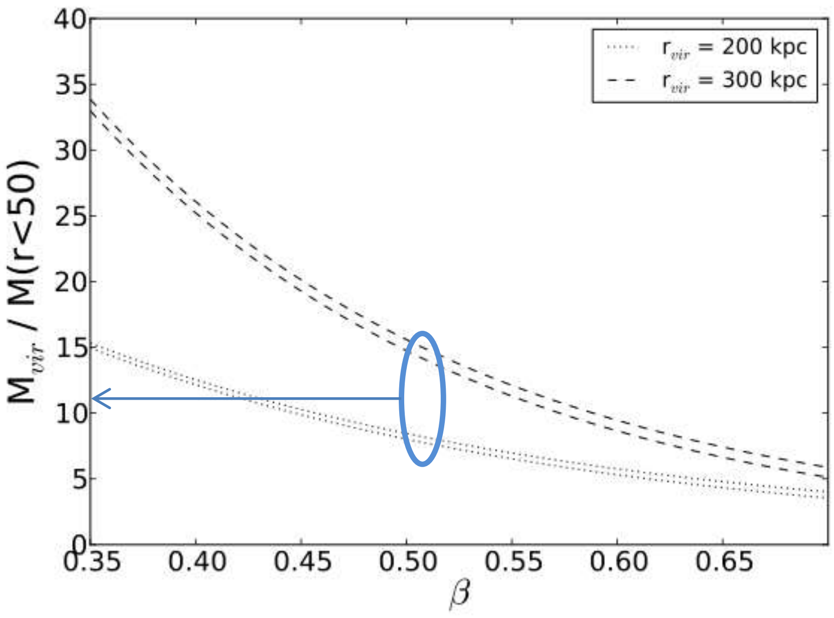
Do an endless number of simulations, tests…..

Fit: A "beta" surface brightness component, a point source (< 5 kpc) + background



Radius = 100 pix = 500 kpc = gravitational sphere of influence (virial radius)





- Mass within 50 kpc pretty well determined
- Similar to Milky Way hot gas mass (MW is ordinary)
- Extrapolation to the r_{virial} uncertain but can add 10x more mass
- Still not the missing baryons (by a factor of a few), but a lot of gas
- Have now surveyed a few individual galaxies plus stacked galaxies

Density and Mass Summary

- Also, NGC 720 (Humphreys), NGC 266 (Bogdan)
- Everyone gets the same result:
  - $\beta = ½$; $n \sim r^{-3/2}$
  - 20-30% of missing baryons within R_{virial}
- Could density law be flatter (Kauffman et al. 2008, Feldmann et al. 2012)?
  - No (inconsistent with observed S_x, T_x)
  - T also gives $n \sim r^{-3/2}$

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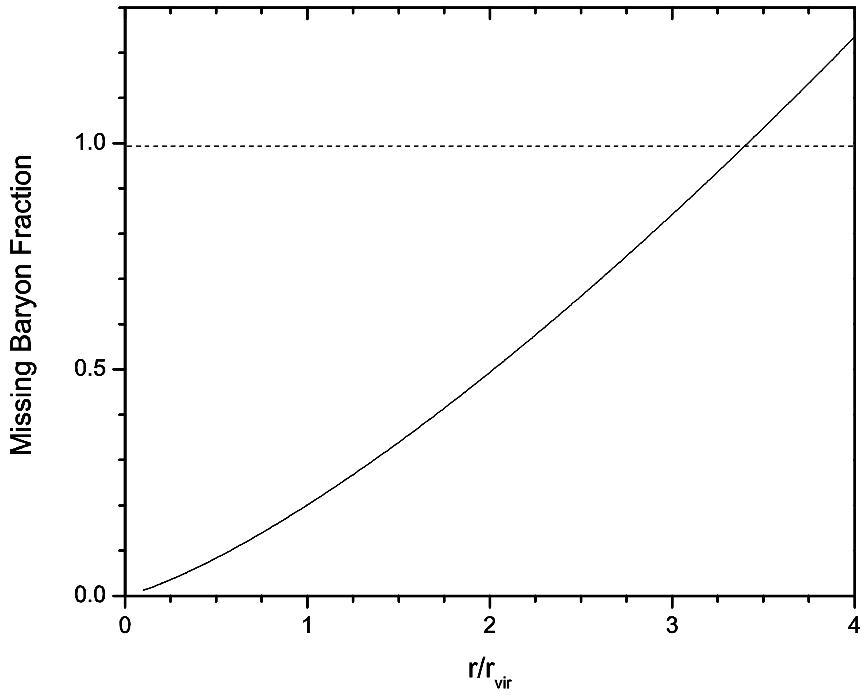
Where Are the Missing Baryons?

- Extend the $n_{gas} \sim r^{-3/2}$ law to large radius
- Extend NFW profile to large radius; $n_{DM} \sim r^{-3}$
- Radius where the DM to baryons reach cosmic ratio



Missing baryons within $3R_{virial}$

Larger if n_{gas} approaches shape of n_{DM} (as it must)

Why Are The Baryons So Extended?

- Two possibilities
- All the baryons fell into each galaxy
  - Stellar and AGN processes eject the gas
  - Must be SNe in the smaller galaxies (no AGN)
  - Missing baryon fraction independent of whether dwarf galaxy is gas-rich or star-rich
  - Mass loading has to increase rapidly with decreasing galaxy mass
  - Models sometimes do violence to physics
  - Is there an alternative?

Early Heating Prevents Infall

- Preheating in the very earliest stages of galaxy formation (before the galaxy is formed)
- Preheating by High-Mass Stellar Population (Pop 2.5)
  - $2 < Z < 8$
  - Before collapse of L* galaxy (from many dwarfs)
  - Entropy floor (preheating is 0.4-1 keV; 5-12x10^6K)
    - Need about 1 SNe per 500 $M_\odot$ of gas
- Other Consequences of this Population
  - Enrich the metals by distributed SNe
    - 0.2 Solar metals is also 1 SNe per 500 $M_\odot$ of gas
    - Widespread metal dispersal
  - Explains the extended dust distribution (Menard)
  - Needed for metallicity problem in rich galaxy clusters
  - Solves the G-dwarf
  - Not all mass is retained by poor clusters
  - May lead to mass-metallicity relationship

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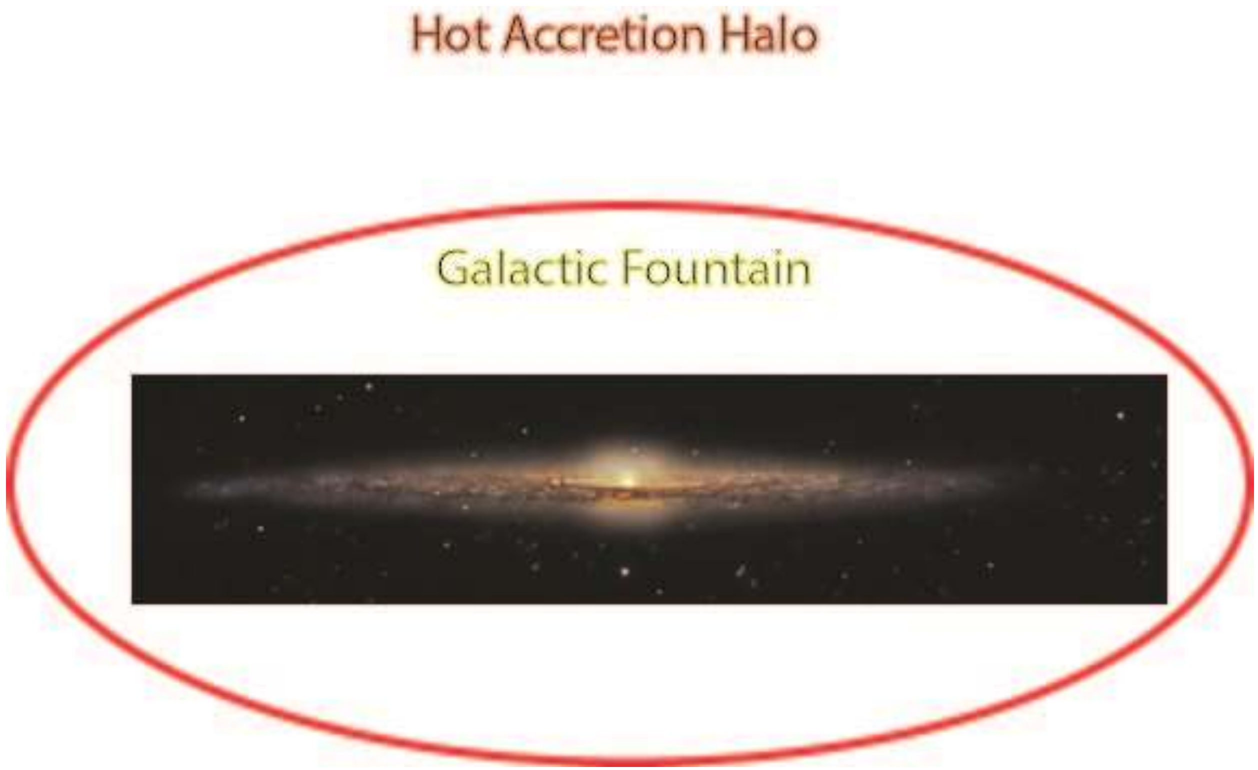
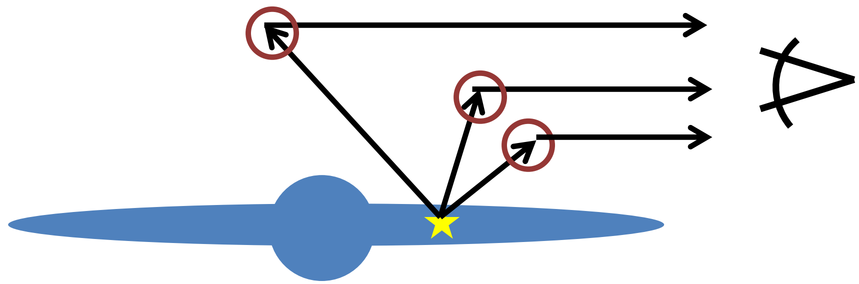
Galactic Fountain and the Hot Halo

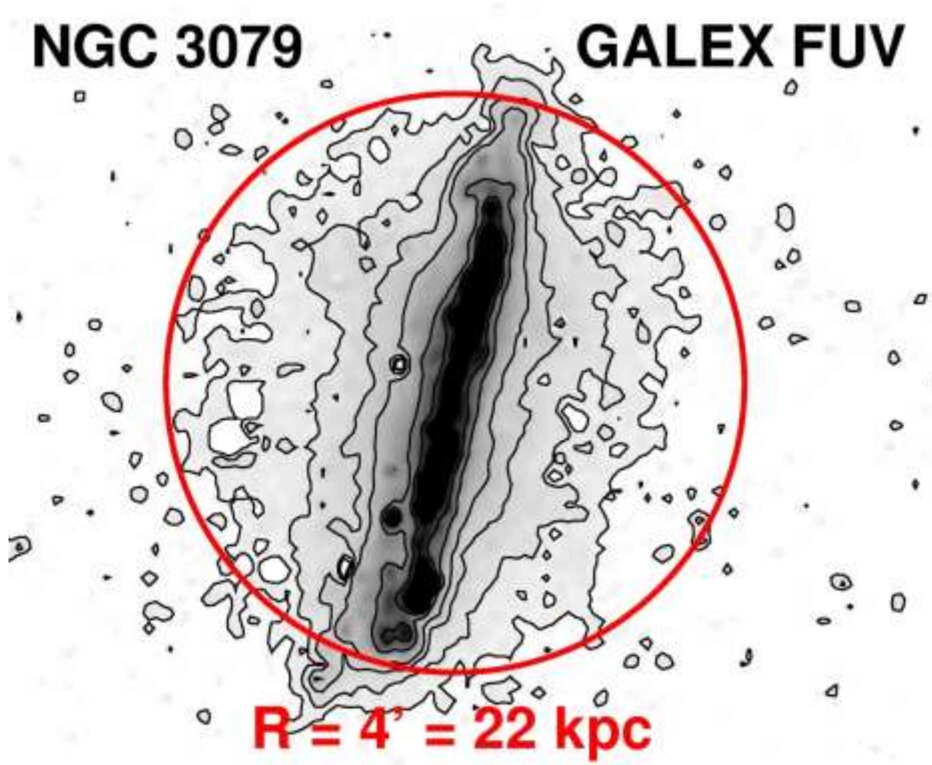
- Galactic Fountain: Due to Star Formation and SNe today
- Extended Hot Halo: Remnant of Galaxy Formation
- Where does one end and the other begin?



Explore Halo By Dust Scattering (E. Hodges-Kluck & JNB)

Extragalactic dust scatters some starlight entering the galaxy's halo into our line of sight.

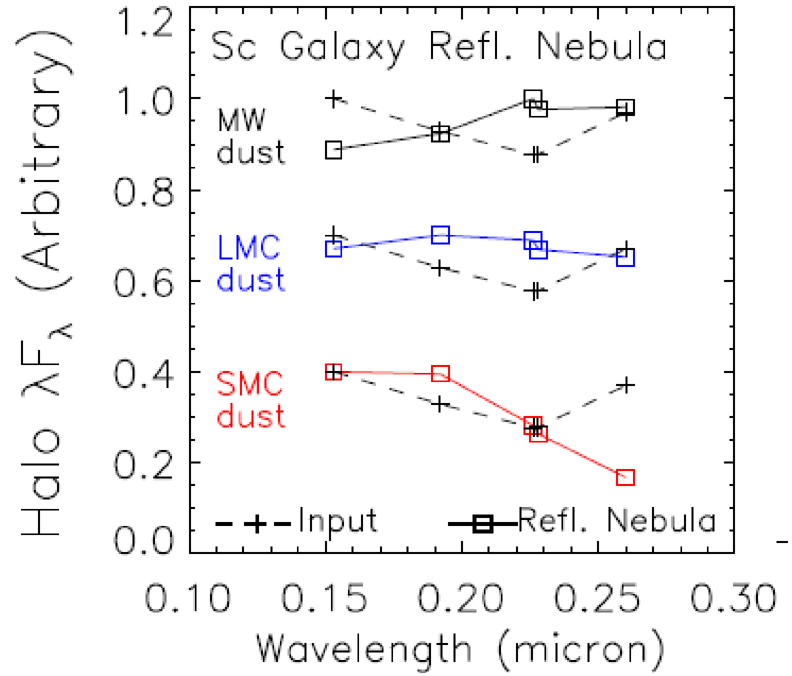




Scattering is most efficient in the UV (where the sky is also dark), so we see highly extended extragalactic reflection nebulae around highly inclined, star-forming galaxies

$$L_{halo,\lambda} = L_{gal,\lambda}(1 - e^{-\tau_{scat,\lambda}})$$

$$\tau_{scat,\lambda} = N_H \delta_{DGR} \sigma_\lambda \varpi_\lambda$$



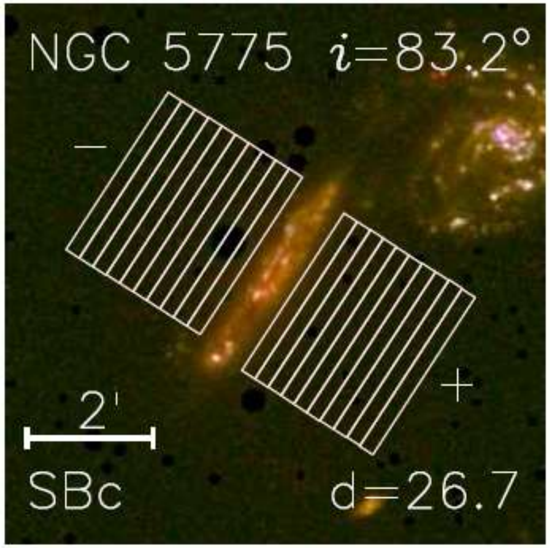
When τ << 1, as in halos,

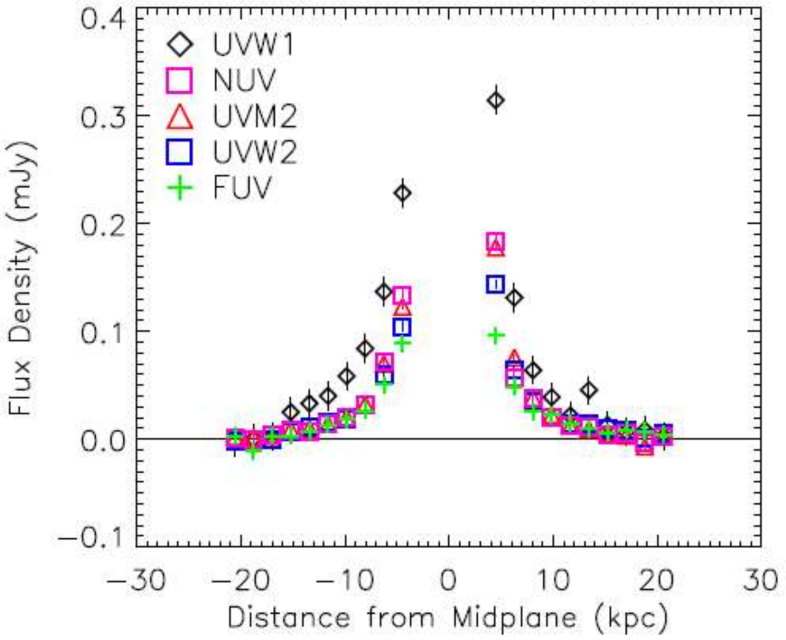
- Difference in *normalized spectra* determined by *dust type*
- Difference in *amount of light* determined by *amount of dust*

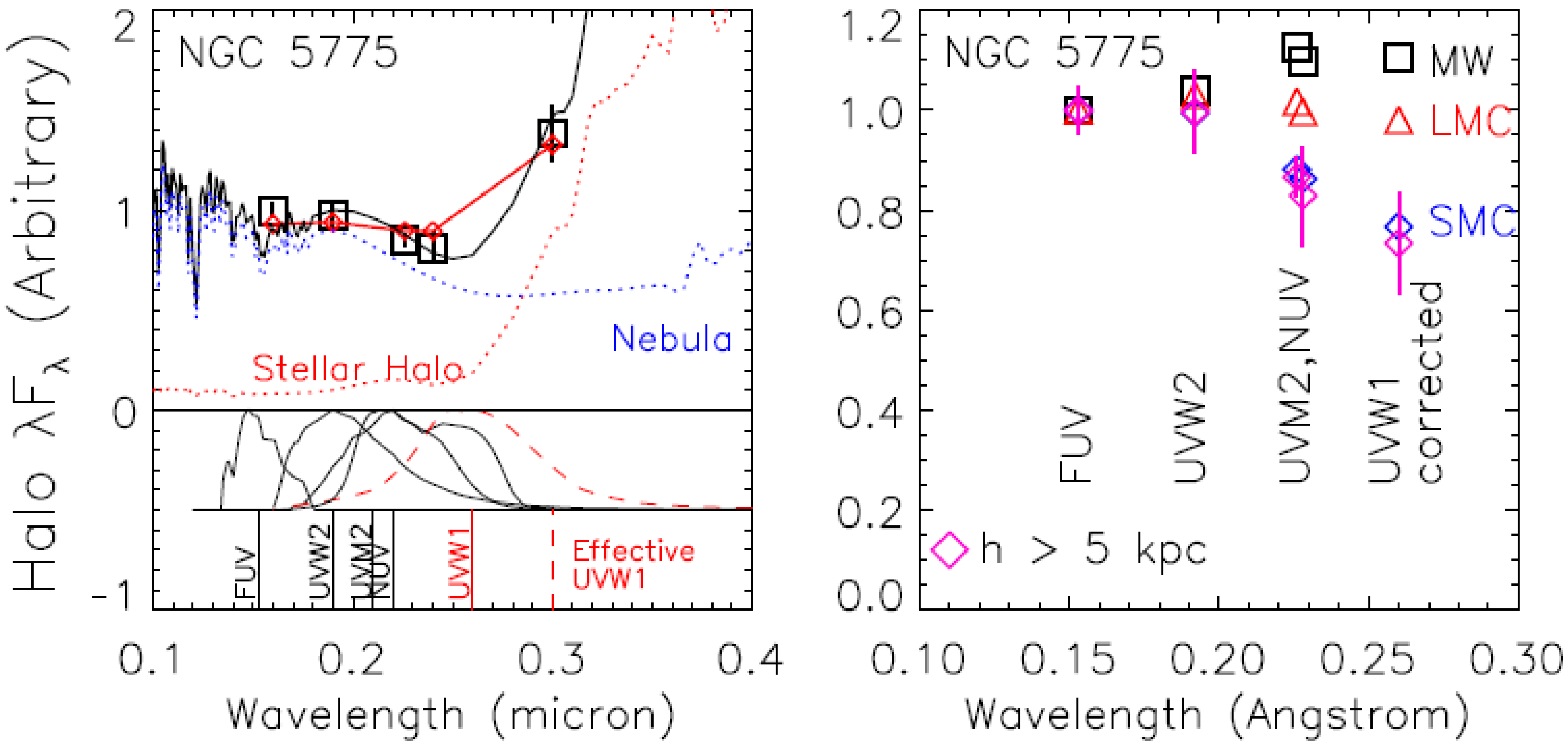
The extinction curve is determined by dust grain composition, so reflection nebulae provide a way to measure metal content! Also, we can *map* the dust-bearing gas with modest exposures.

Case Study: NGC 5775

1. Measure SED in 5 GALEX+SWIFT UV bands
2. Fit normalized SED with different dust models to find dust type
3. Use N_H to get metal content
4. Examine UV SED as a function of position (does the dust type/underlying emission change?)

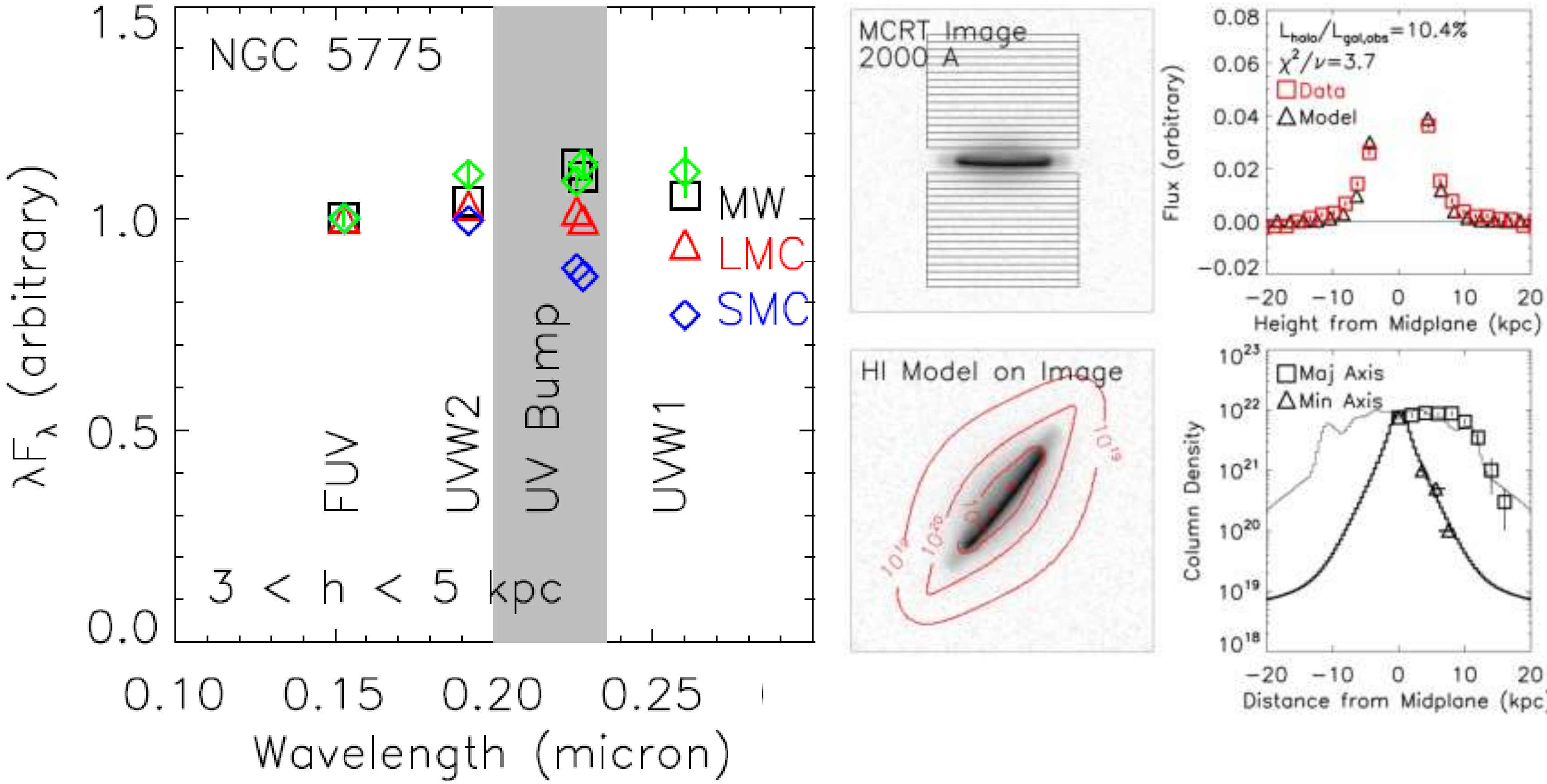




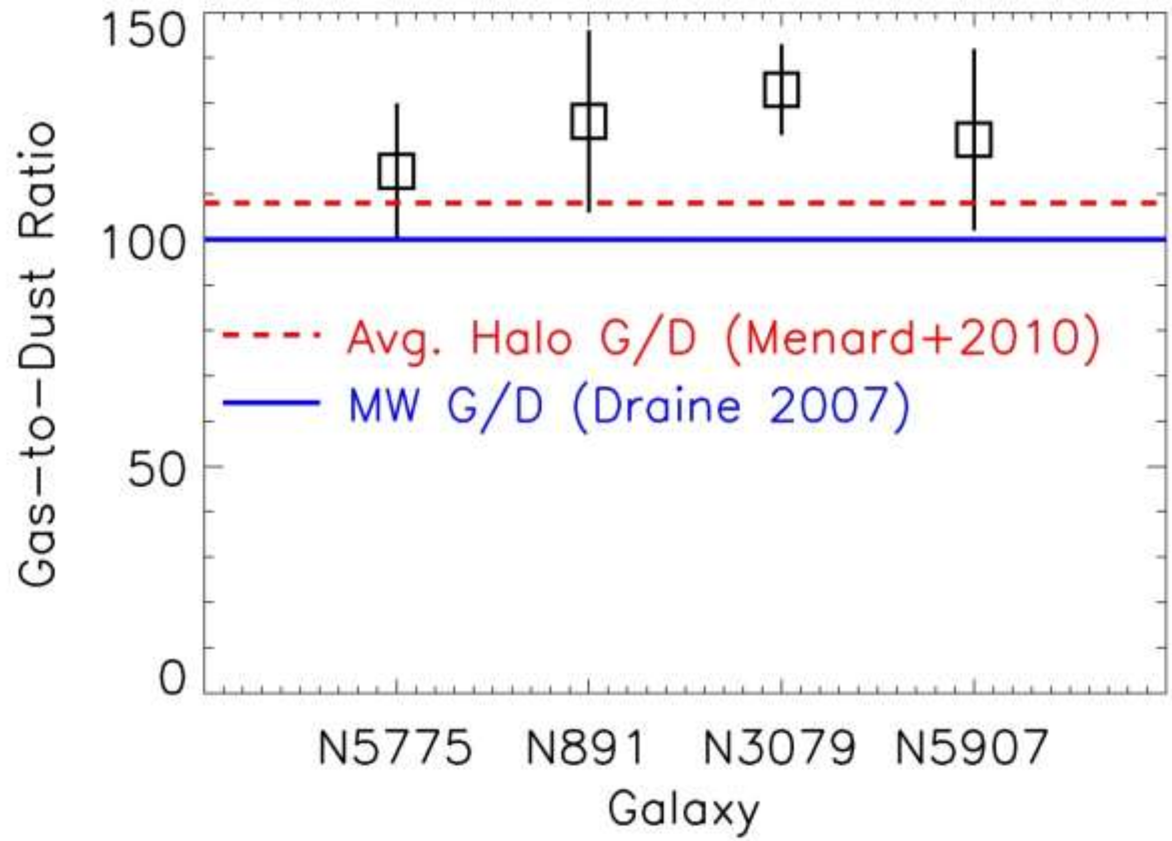


The extinction-corrected galaxy spectrum is folded through a dust model and the filter response curves to make a synthetic SED, which we compare to the observed SED. Of the three dust models shown here, the SMC model matches the halo spectrum above 5 kpc best.

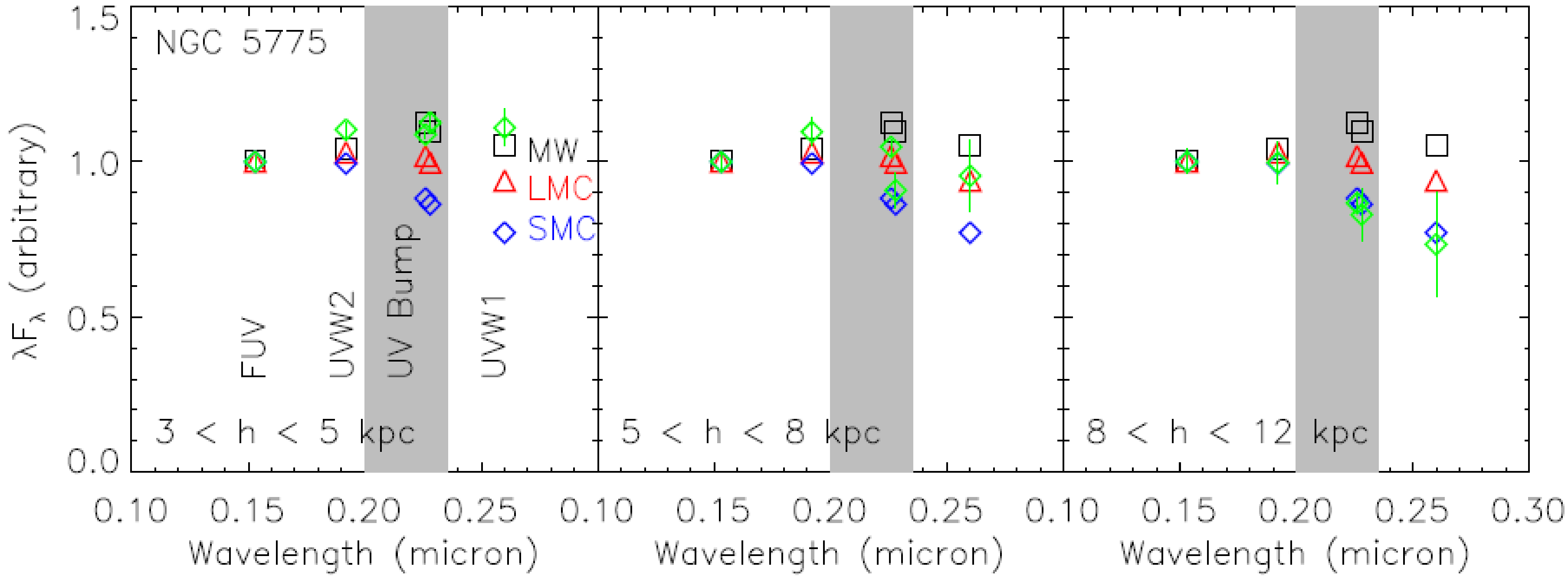
In practice, we find the best-fit carbonaceous/silicate grain fraction.



With the UV flux profile, dust type, and HI data, we can constrain the dust-to-gas ratio with Monte Carlo Radiative Transfer models, and thus the metallicity of the gas.



Near the disks of most galaxies, the composition of the dust is like Milky Way dust and the dust-to-gas ratio is similar to the Milky Way. Farther away, the measurement is more uncertain but the dust-to-gas ratio drops.

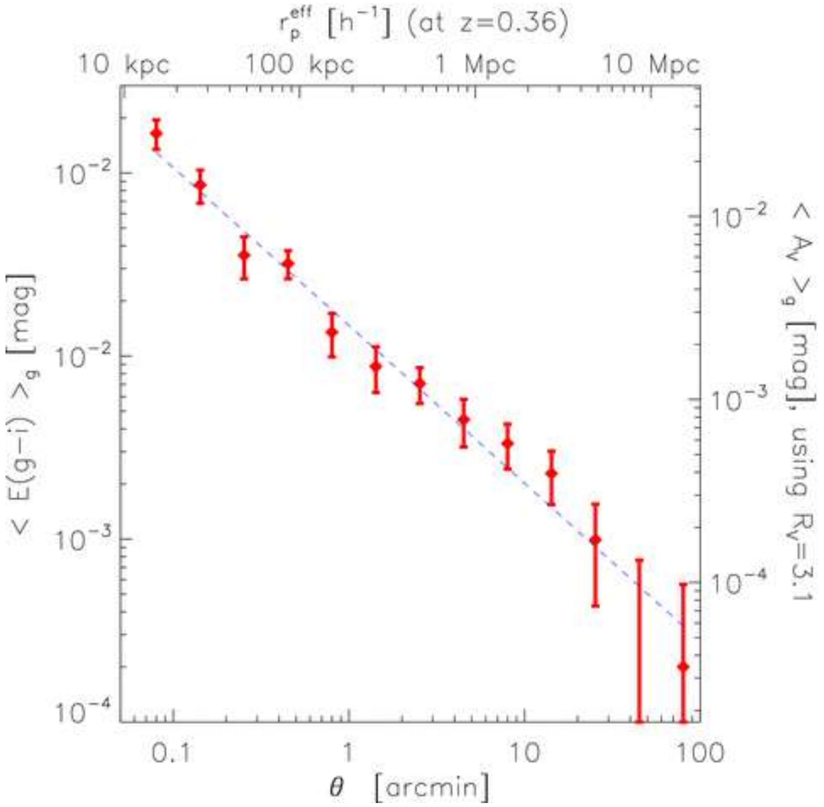


The SED (green points, normalized to FUV) gets bluer with height, changing which dust model makes the best-fit synthetic SEDs (black, red, and blue points). The best explanation for the trend with height is a smaller fraction of carbonaceous grains (more SMC-like). This could indicate dust processing or lower metallicity.

“Transition” height is about 8-10 kpc above disk: Fountain-Halo Interface?

More On Halo Metallicity

- Hot gas phase metallicity not known
- Dust extinction extends to large radius
- Divide by hot gas column to get metallicity



Ménard B et al. MNRAS 2010;405:1025-1039

- Dust-hot gas metallicity measure
- Must be more metals: in gas phase
- Metallicity significant fraction of solar, on average