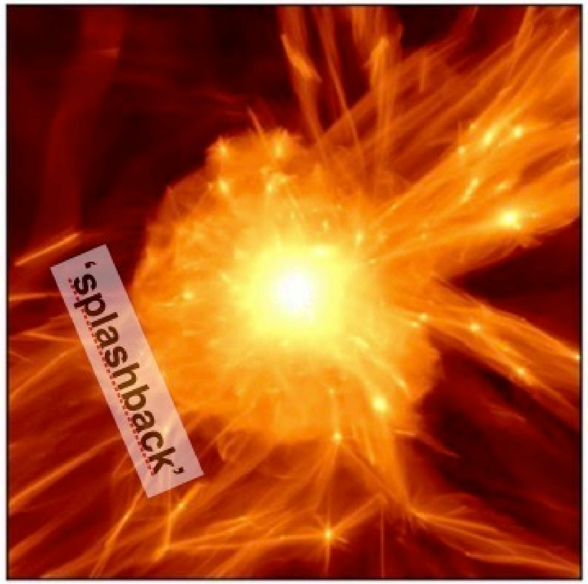
The Baryon and Metal Content of Hot Galaxy Halos

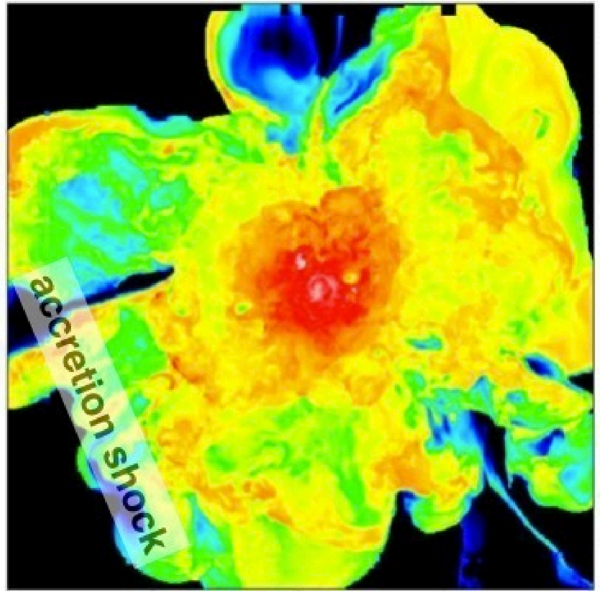
Joel N. Bregman, Edmund Hodges-Kluck, Jiangtao Li, Zhijie Qu, Yunyang Li, Mike Anderson, Xinyu Dai

Vienna, 31 August 2018
Warm and Hot Baryonic Matter in the Cosmos

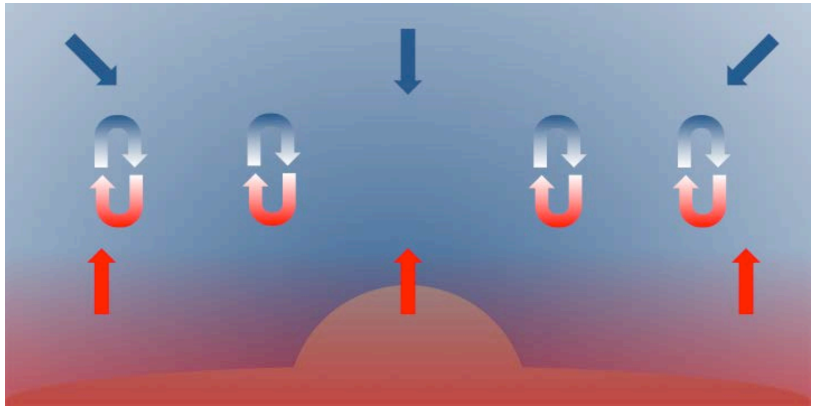
Pictures In My Mind

Springel et al. Simulations predict hot halos to ~R_{200}. Model-dependent





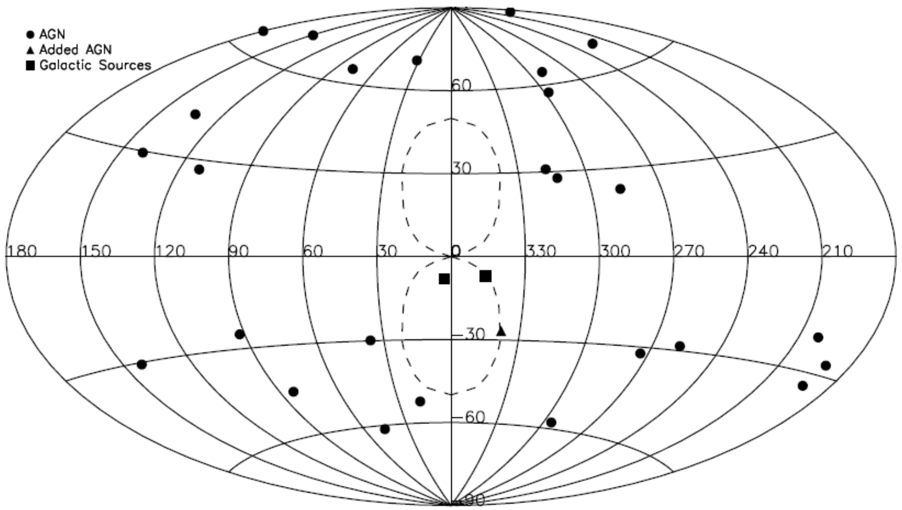
Near Galaxy Disk, ~0.05 R_{200} : Galactic Fountain(s) + accretion



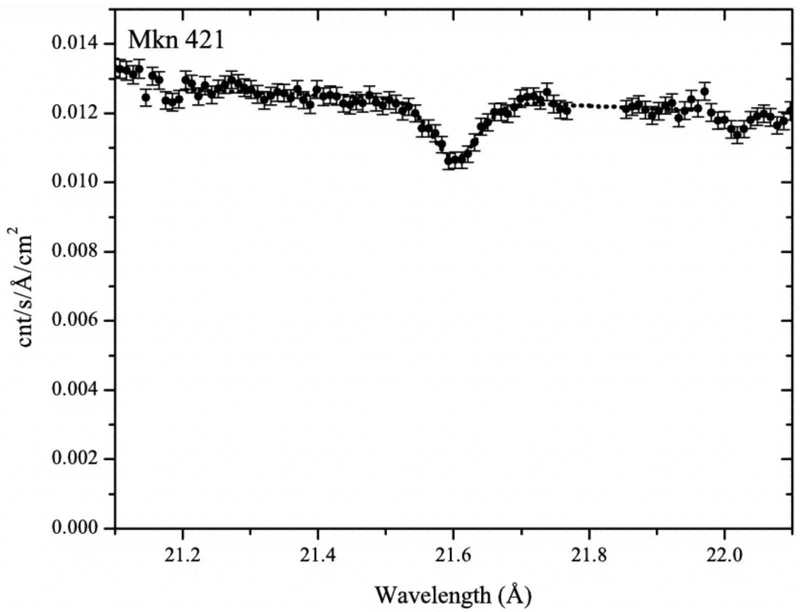
Fitting A Density Model

- OVII and OVIII absorption and emission lines (2×10^6 K) from XMM (Miller & JNB 2013, 2015; Li & JNB 2017)
- Fit a "beta" model, $n(r) = n_o \left(1 + (r/r_c)^2\right)^{-3\beta/2}$
  - $n(r) \approx n_o (r/r_c)^{-3\beta}$ (not sensitive to core radius)
  - Flattened model does not improve fit
  - Need a hole in central 1.2 kpc (Fermi bubble to the rescue)
- Also include a disk component with a scale height

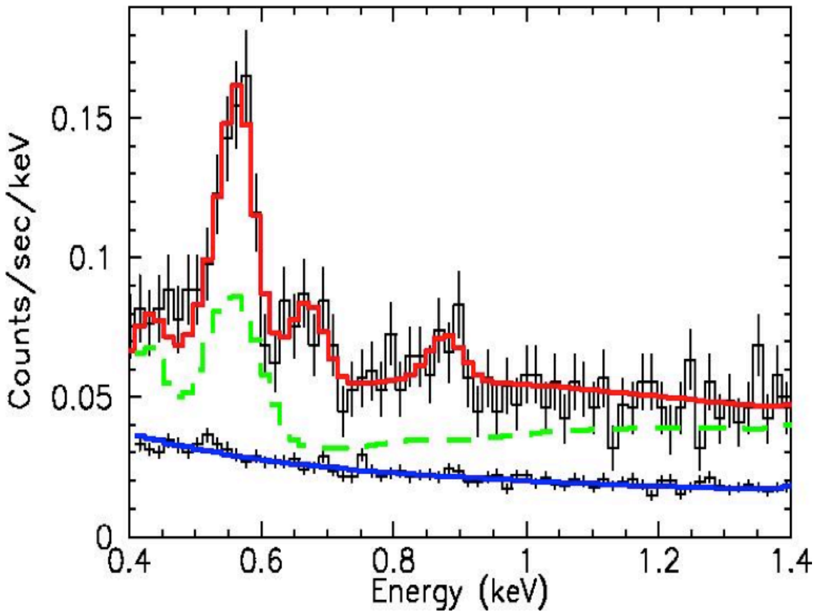
Absorption sightlines



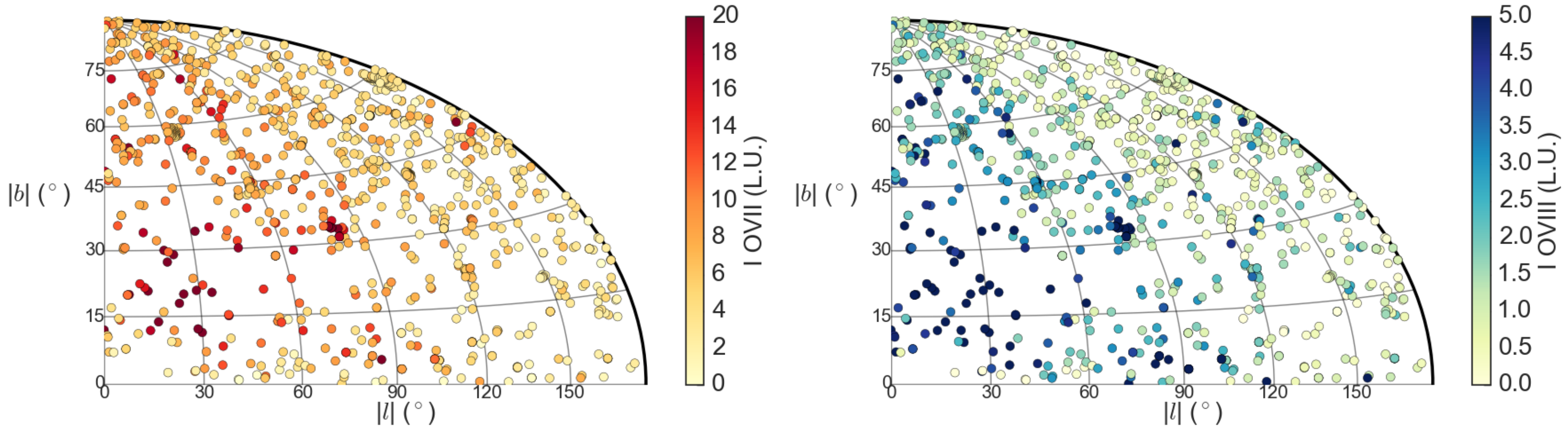
We use X-ray data to detect hot gas



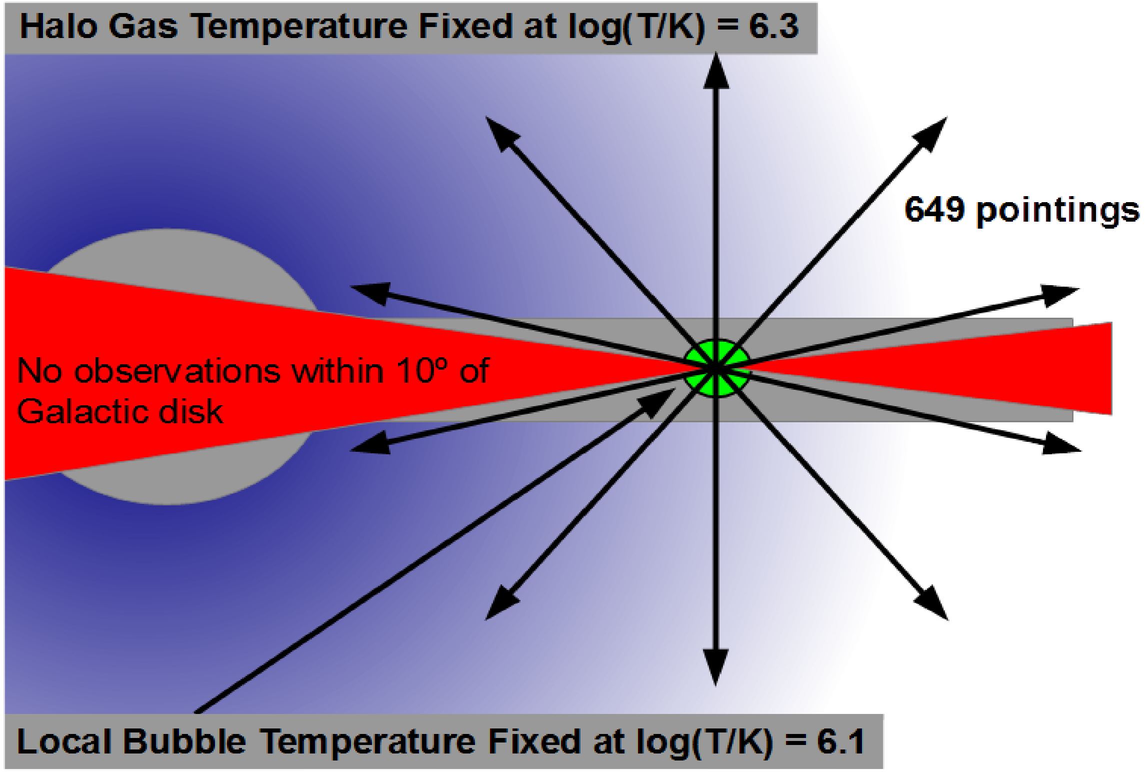
Absorption by O VII Milky Way Gas at 21.6 Å (0.56 keV) (about 30x column from O VI) Various authors: e.g., Hodges-Kluck et al. 2016)



Emission from O VII (0.56 keV) and O VIII (0.65 keV) from Milky Way
Henley & Shelton (2012, 13)

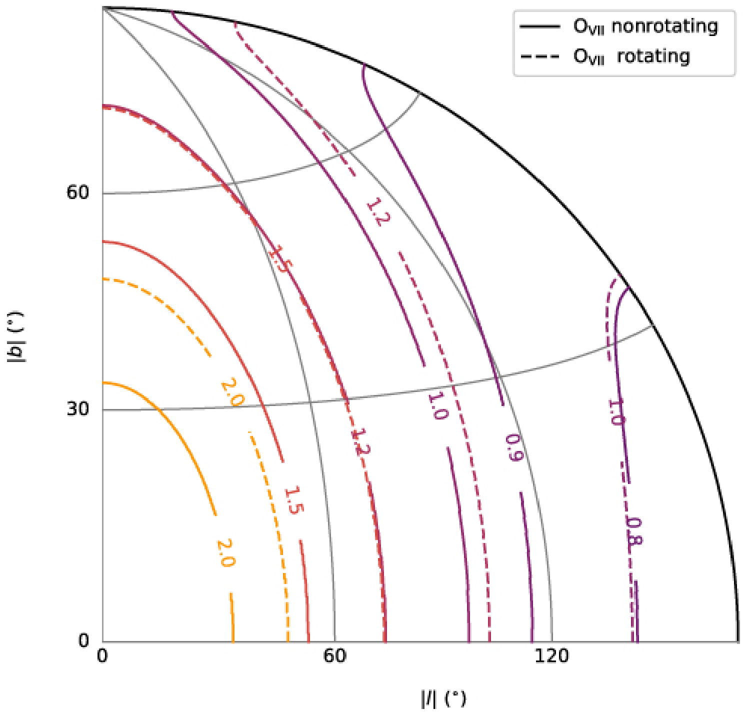


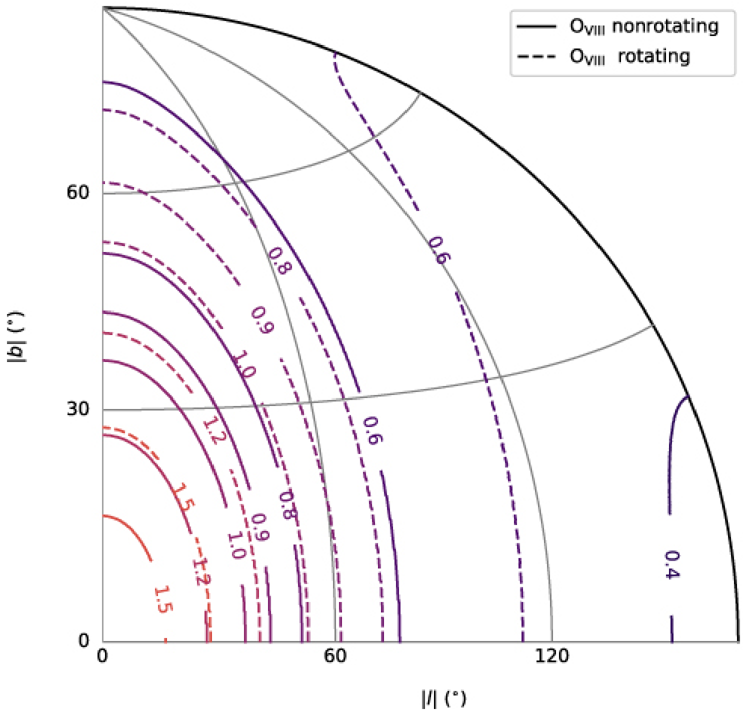
Dimmest toward anticenter
Brightening as you look across the Milky Way
Avoid Fermi Bubbles region
Henley and Shelton (2012, 13)



Optical Depth Effects

- O VII is He-like with a triplet – one resonance line
- O VIII is H-like, so we use the Ly alpha line
- Optical depths ~1; depends on rotation, Doppler b
- Yunyang Li & JNB (2017)





Masses: Optical Depth Corrections

Significant error reduction with MCRT treatment (Li & JNB 2017)

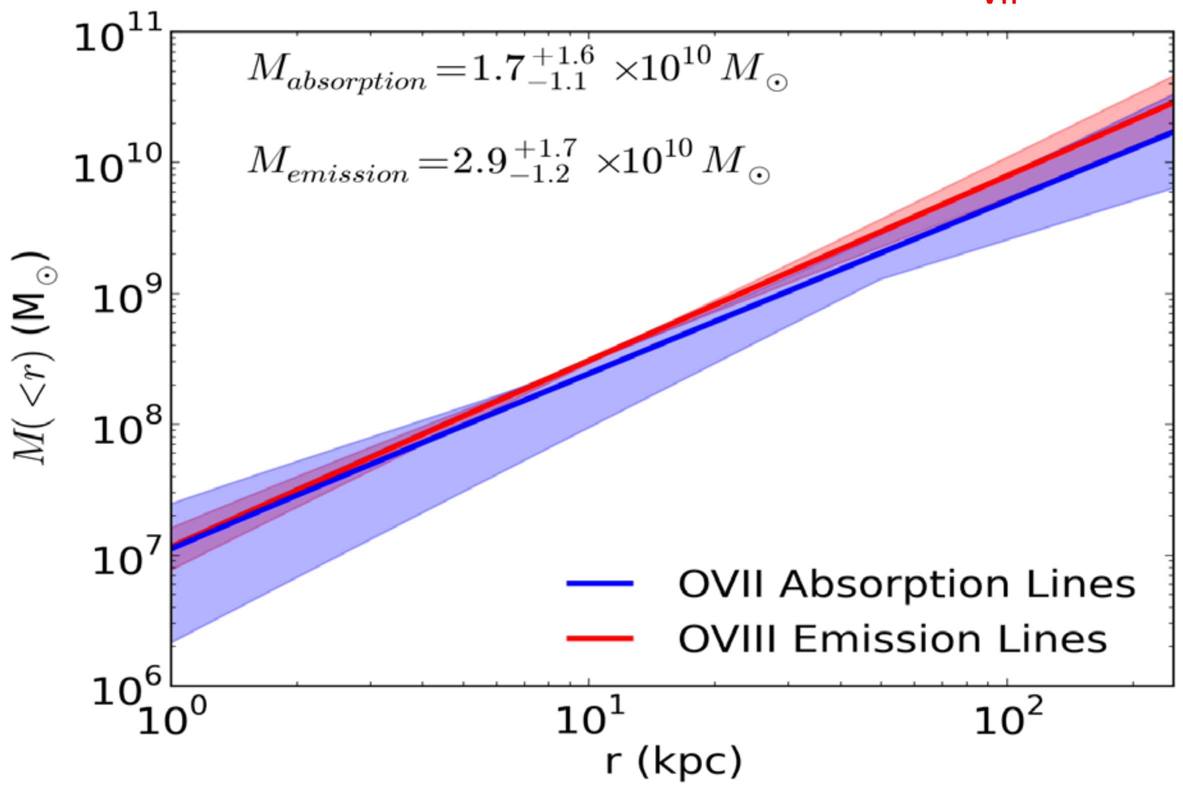
β = 0.51 +/- 0.02; $b_{turbulence}$ ~ 100 km/s; $M_{emission}$ (R_{vir}) = 2.8 +/- 0.4 E10 M_{sun}

Exponential Hot Disk: z_h ~ 1.3 kpc; M_{disk} ~1.8E8 M_{sun} (minor component)

Same results for fit with O VII lines and O VIII lines

Can't put much mass in exponential disk – overproduces X-rays

This hot halo is not the missing baryons within R_{vir}

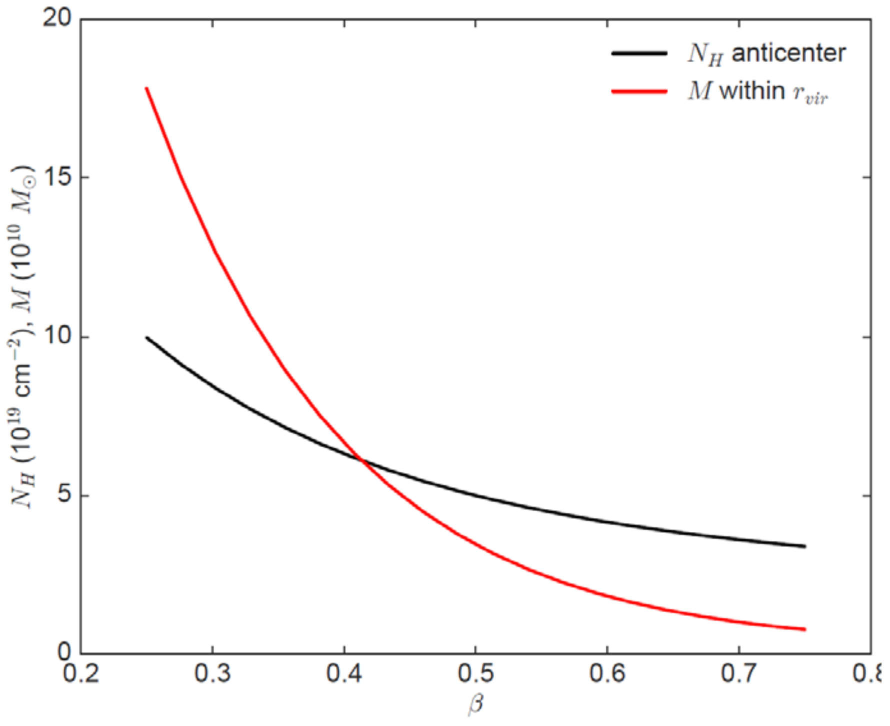


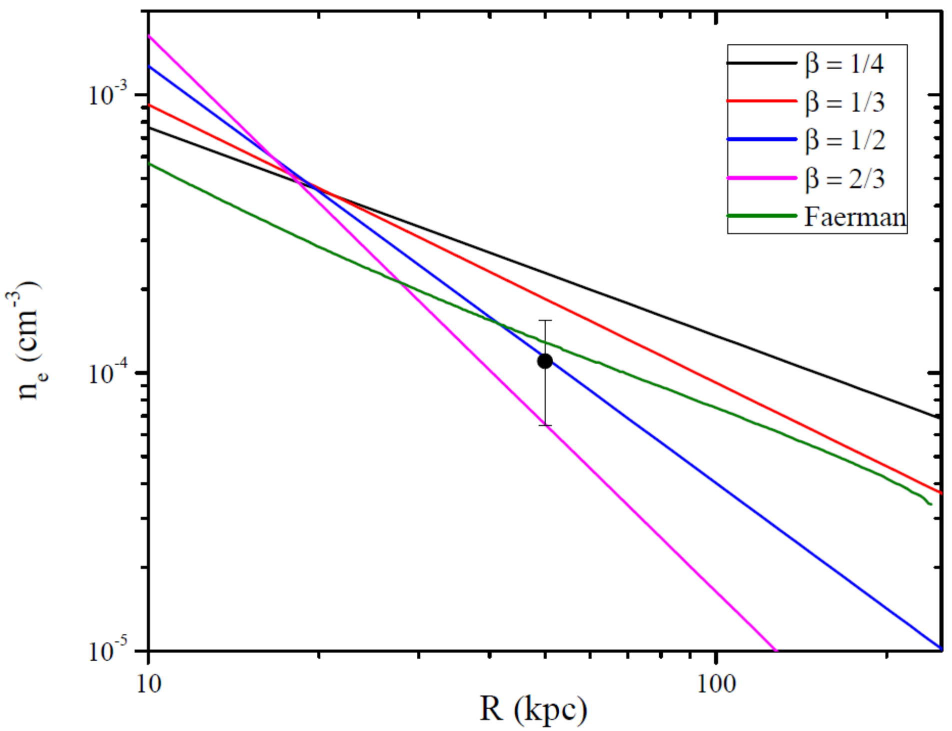
Miller & JNB
(2013, 2015)

Where are the bodies buried?

- Hot gas mass is mainly constrained within 50 kpc
- Extrapolate from 50 kpc to R_{vir} (250 kpc)
- Could the density distribution flatten significantly beyond 50 kpc?
  - This would give more mass within R_{vir}
- No evidence for this
- N(O VII) toward LMC would be about half that toward a background AGN
  - Not seen
  - Bregman et al. 2018 ApJ 862, 3

Pulsar DM + Salem et al. (2015) constraints

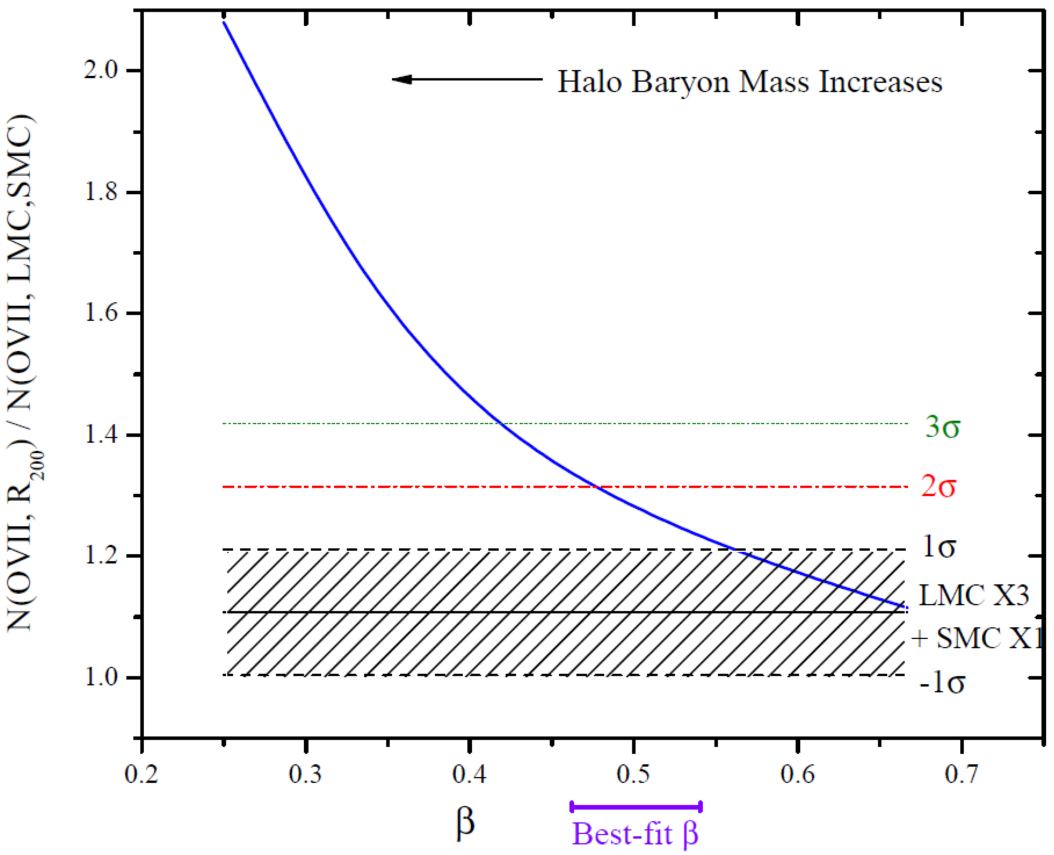




For β < 0.25 (3β < 0.75), missing baryons lie within R_{200}

But our fits show that β = 0.52 ± 0.03 (within 50 kpc)

- Another Check: Fraction of O VII lies beyond LMC/SMC
- All baryons within R_{200} – flatter density distribution – half of N(O VII) lies beyond LMC/SMC
- Not seen: results consistent with β near 0.5
- Missing baryons not hot and within R_{200}



Where are the Missing Milky Way Baryons?

- For a cosmological f_{bar} of 0.157 (Planck 2105)
  - M(stars + cold gas + dust) = 6-7 x 10^{10} $M_{\odot}$
  - M_{vir} = 1-2 x 10^{12} $M_{\odot}$
  - $M_{missing}$ = 1-3 x 10^{11} $M_{\odot}$

- If the hot gas density profile extends to the virial radius...
- M_{hot} = 3 x 10^{10} $M_{\odot}$

- Hot Halo gas contributes < 20% to the missing baryons

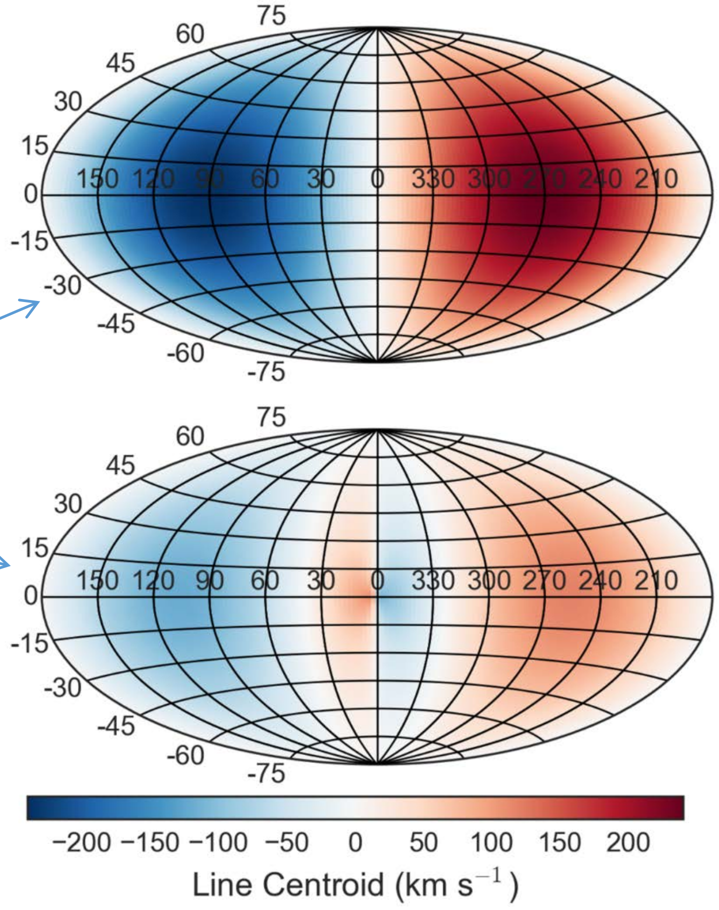
- Profile would need to extend to 2-3 R_{vir} to account for all of the Milky Way's missing baryons

Rotation of the Milky Way Hot Halo

You can see the Galaxy rotate!

Stationary Hot Halo

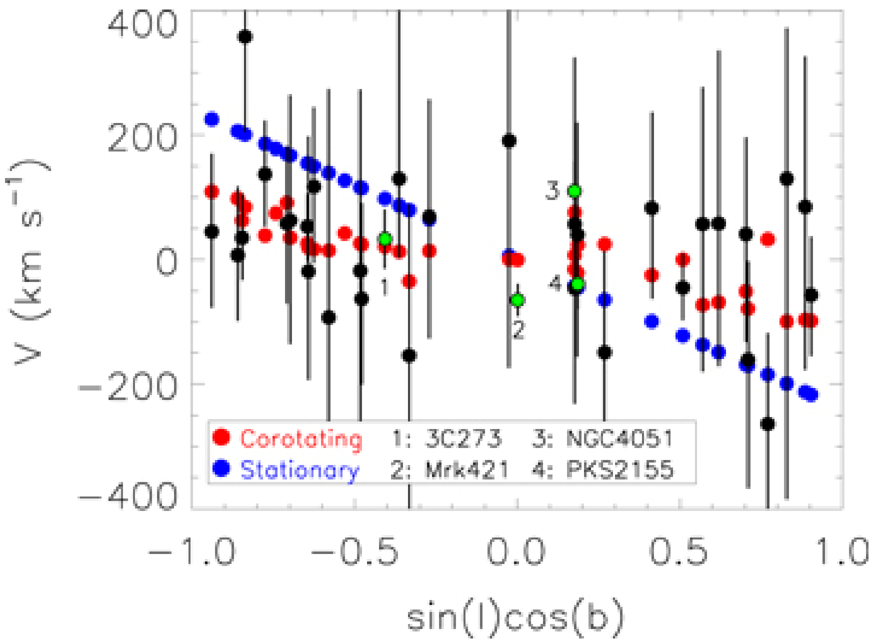
Co-Rotating Hot Halo
Miller et al. (2015)

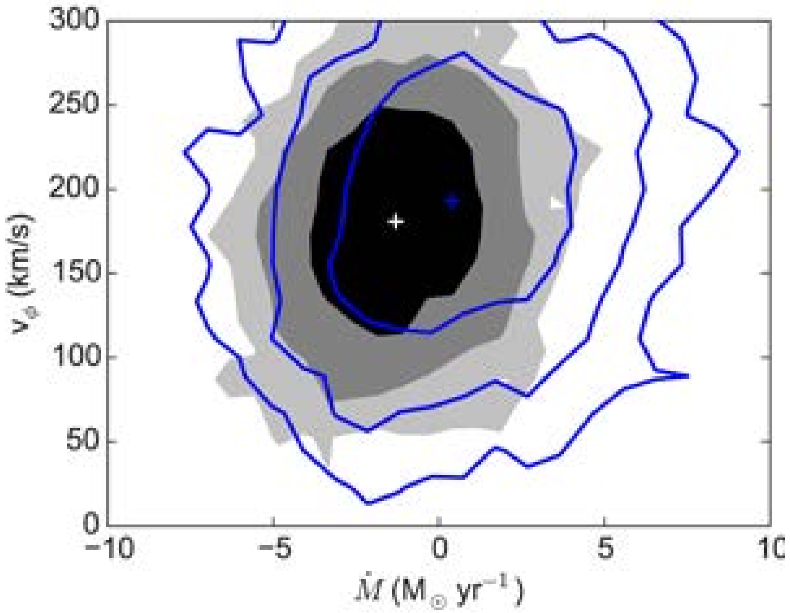


Look Up: Net Accretion or Outflow

Rotation of the Milky Way Hot Halo

- From O VII absorption line studies (Hodges-Kluck et al. 2016)
- Data exclude stationary halo
- V_{rot} = 183 +/- 41 km/s
- Most of this gas is within 50 kpc
- Accretion rate < 6 Msun/yr
- Consistent with models





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: $Z > 0.3\ Z_\odot$

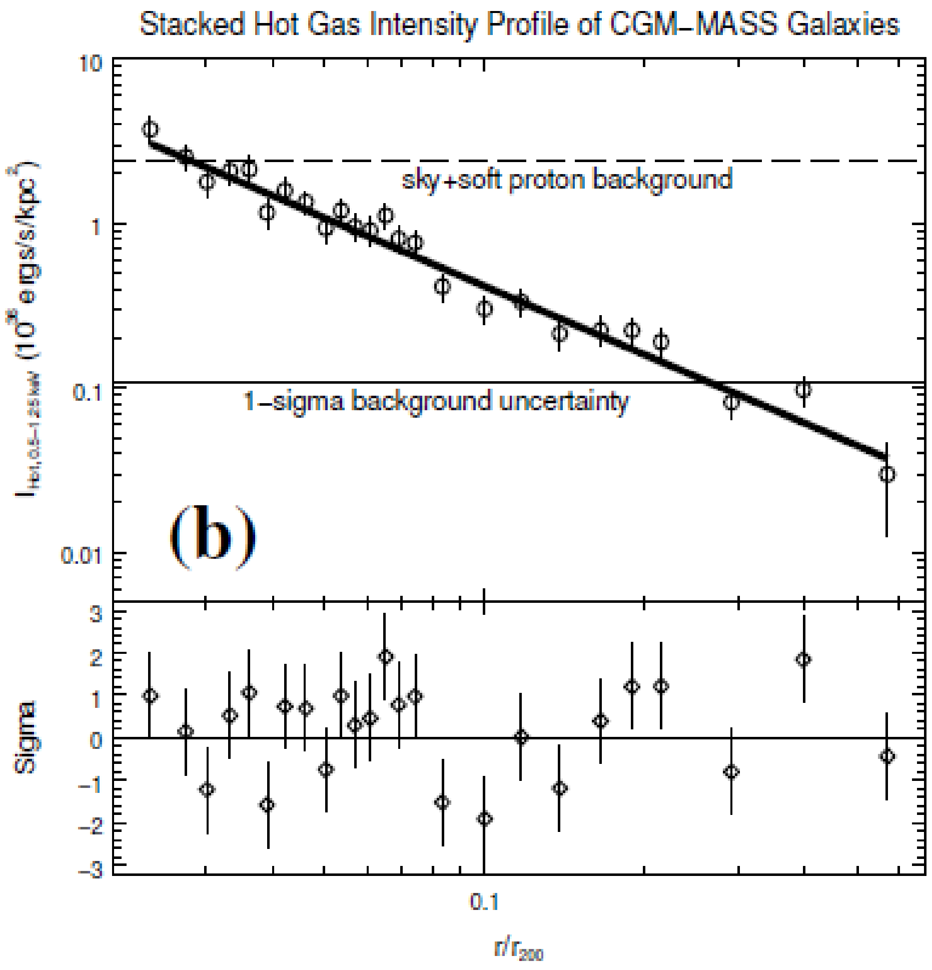
- Best fit with emission, absorption, and MCRT
  - $0.3 < Z < 0.9$ solar (JNB et al. 2018)
  - Absorption column = n(OVII) L
  - Emission measure = n_e n(OVII) L
  - Can solve for metallicity, n(OVII) / n_e

Is This Metallicity Too High?

- Not really
- Cosmic metallicity is 0.09-0.17 solar (Moaz; Shull)
- Most of these metals (80%) are unaccounted for
  - Probably in hot phase
- Missing baryons (40%) has the rest of the metals
  - Metallicity of 0.2-0.3 solar
- There will be plenty of metals to detect in the missing baryons (good for future missions)

Other Spirals Are Similar in X-Rays

- Easier to see X-rays in more massive spirals (2-6L*)
- X-ray emission seen to ~130 kpc from stacking 6 galaxies
- M_{hot} ~ 1.3E11 M_{sun}
- Missing baryons not within R_{200}
- J-T Li et al. 2018 ApJ 855, 24
- Anderson et al. 2016 MNRAS, 455, 227



Mutually Inconsistent Conclusions
(not everyone can be correct)

- The missing baryons around galaxies are….
  - Warm ionized (COS-Halos)
  - Hot (~T_{vir}) and within R_{200}
  - Hot (~T_{vir}) and extended beyond R_{200}
- Warm ionized halo gas mass may have been overestimated
  - Multi-component gas
  - Ionization not just from photons
  - Other groups get masses 3-8x lower than COS-Halos
  - Significant mass in extended disks, not halos
  - Certainly the MW and M31 do not have ~1E11 Msun of warm gas
- Most Likely (today): Hot (~T_{vir}) and extended beyond R_{200}
  - Consistent with SZ work (but the S/N is not impressive)
  - Consistent with extrapolation of X-ray data (but it's an extrapolation)

Needed For Making Progress

- Ability to Detect Galaxy Halos to 0.3-2 R_{200}
- Absorption: *Arcus* (Explorer, Phase A); launch 2023
- Absorption & Emission
  - Athena (ESO flagship); launch 2029
  - Lynx (potential NASA flagship); launch 2034
- Emission
  - HaloSat for Milky Way (10 deg); Kaaret; smallsat operating!
  - HUBS & Super-DIOS, 3’ (China & Japan); 2029
- CMB-Stage 4; late 2020’s
- UV Emission: CAFÉ (China); 2028

Things to Remember

- Milky Way Hot Gas
  - Exponential hot disk is minor component
  - Within 50 kpc, Spherical halo with $n \sim r^{-3/2}$, $v_{rot} \sim 180$ km/s, $b_{turb} \sim 100$ km/s
  - Extrapolated to R_{200}, 3E10 Msun; not the missing baryons
  - If missing baryons are hot, halo must extend to $\sim 2R_{vir}$
  - Metallicity 0.3-0.9 solar
- Other spirals have similar density profiles
- Gas around massive galaxies (stacked) seen to 130 kpc (0.4 R_{200})
- Let's get some new observatories