Missing Baryons Around Galaxies And Through The Universe

Joel Bregman

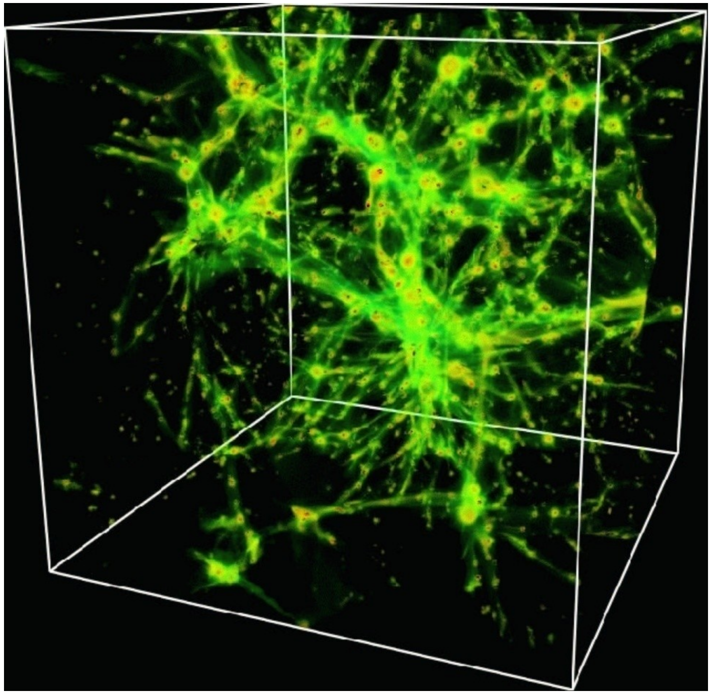
University of Michigan

Collaborators: Mike Anderson, Xinyu Dai, Matt Miller, Edmund Hodges-Kluck, Xinyu Dai, Zhijie Qu, Yunyang Li

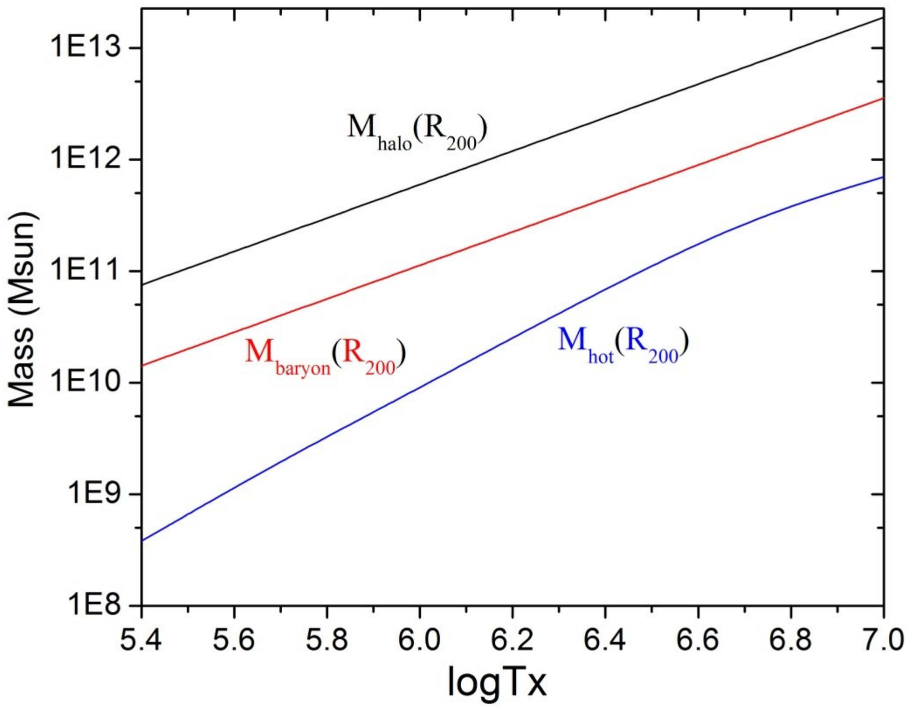
- Astrophysical reasons for caring about Missing Hot Baryons
- What have we already learned about Missing Hot Baryons in galaxies and the Universe?
- New insights before Lynx launches
- The Lynx contributions

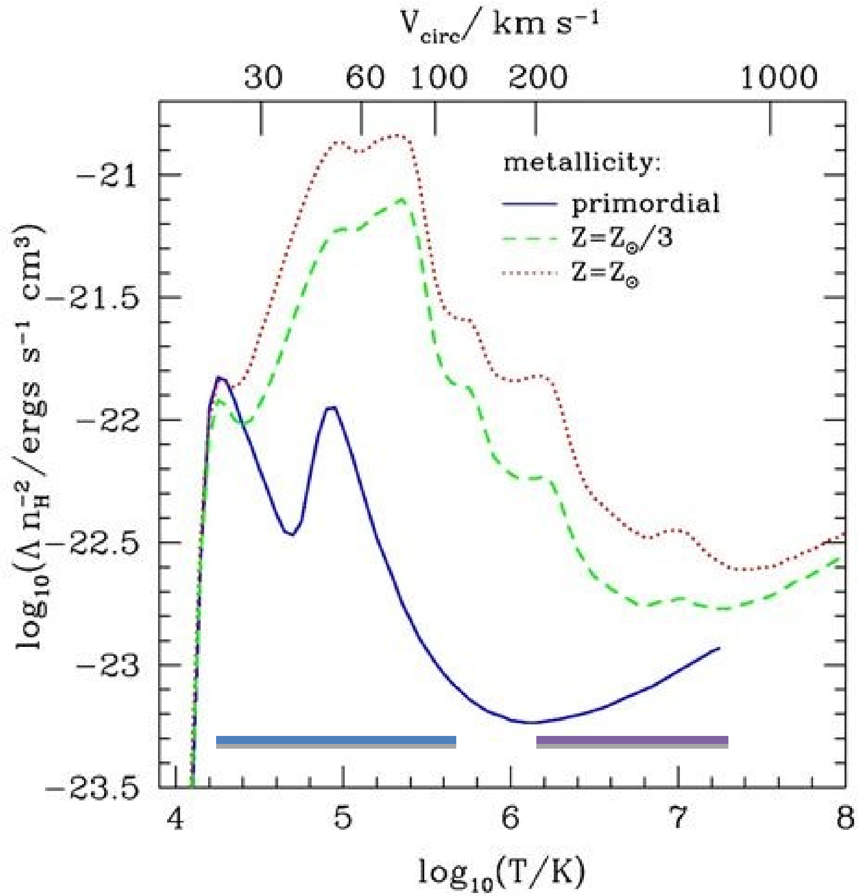
The Astrophysics

- Formation of the Cosmic Web
  - For overdensities ~ 30 - 180
  - Collapse of filaments
  - T ~ 1-10x10^5 K
- Virialized objects
  - Collapse for overdensities > 180
  - Filaments drain into virialized regions
  - T > 10^5 K
  - Baryons would follow dark matter if not for cooling (T, n, Z) and feedback



Importance of Radiative Cooling





M_{hot} vs T_X Prediction (JNB)
Depends on Feedback, Z
Not Yet Tested!

Low T, high cooling rate low Mgas halo

Higher T lower cooling high Mgas halo

- Importance of hot halo
  - Reservoir of gas to cool onto disk and make stars
  - “Pressure release valve” for feedback
- Feedback critical to modifying hot halo
  - SNe and AGNs provides feedback
  - amount of feedback and timing matters
  - Outflow from galaxy (but to what radius?)
  - Circulation pattern within R_{200}
    - but at what rate?
- *Measure hot halo properties to infer heating and galaxy evolution*

Could Gas Be Hot Beyond R_{200}?

- Accretion shocks – splashback radius
  - – Gas hot to 1.2-1.5R_{200}
  - – Hot filaments draining in
- Early heating of gas
  - – SN occur before deep potential well formed
  - – Most heated gas never falls in
  - – Major modification of galaxy formation/evolution
- Winds
  - – Can push out gas; reheating at terminal shock
- **Great uncertainties here**

- Answers to astrophysical issues
  - require measuring n, T, metallicity, entropy out to ~R_{200} and beyond
- *This can all be done with X-ray observations*

- Observations we need
  - Unbiased absorption line survey of hot gas along random sight lines
    - Cosmic web, galaxies, and galaxy groups
  - Studies of hot gas around individual galaxies and groups

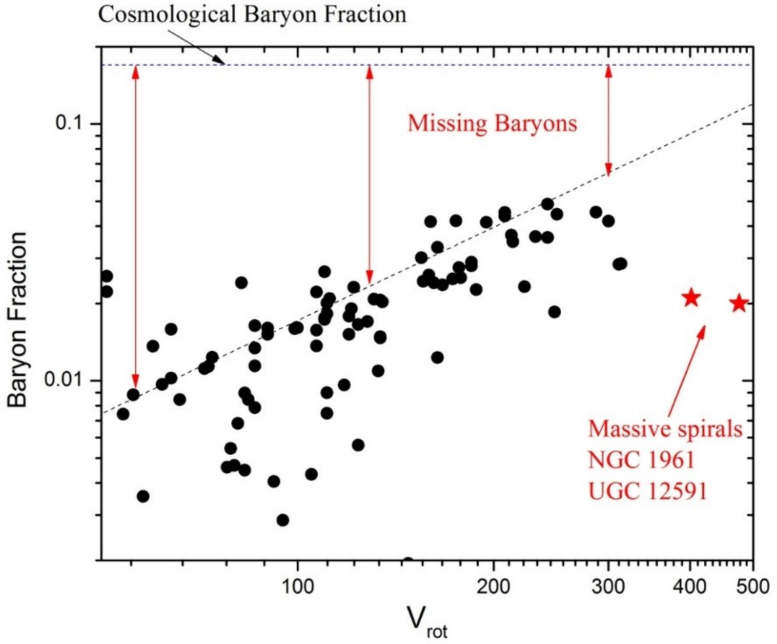
- Astrophysical reasons for caring about Missing Hot Baryons
- What have we already learned about Missing Hot Baryons in galaxies and the Universe?
- New insights before Lynx launches
- The Lynx contributions

What Do We Know Today?

- Count up the baryons in the Universe
  - <10% in stars and cold gas in galaxies
- Census Along Sightlines
  - Add in mass from UV absorption line studies (through O VI)
  - About half of the baryons still missing
  - No O VII, O VIII detections along sightlines
    - Current instruments too insensitive
- Virialized systems are about 60% of the Dark Matter
  - Are the baryons missing from virialized and non-virialized systems?
- The Missing Metals Problem is Worse!
  - Shull et al. (2014): takes cosmic SFR and calculates metals produced
  - Missing 90% of metals
  - Similar results by Maoz et al. (2014) from SNe
  - Mean cosmic metallicity of universe ≈ 0.09-0.16
  - **Remainder of baryons (T > 3E5 K) should have $Z \approx 0.2\text{-}0.3\ Z_{sun}$**
- The hot medium has plenty of metals (not "pristine") – good for observers!

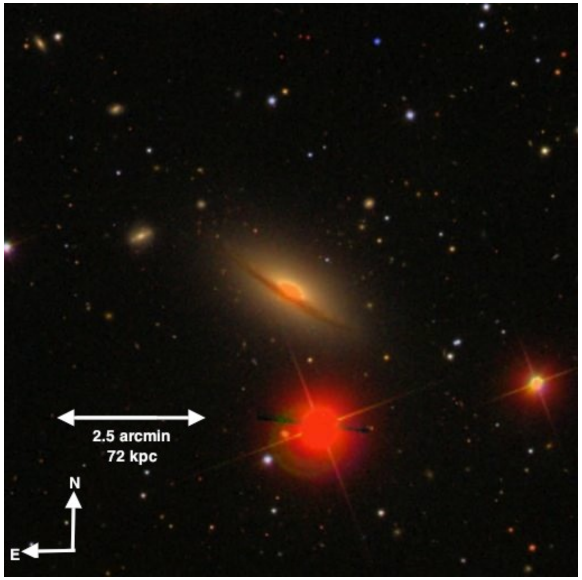
Hot Halos in Virialized Systems

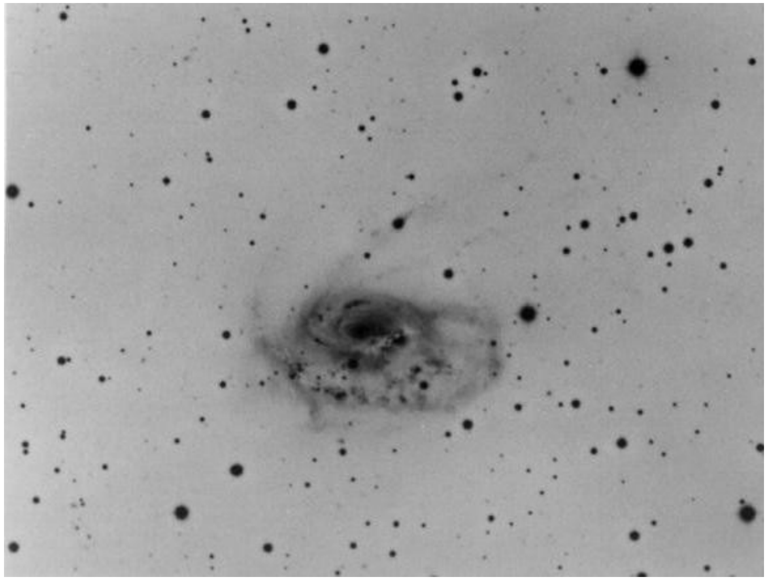
- Rich clusters have nearly all their baryons.
- Galaxies: count up stars + disk gas
- Galaxies missing 70-95% of baryons
- Galaxies become increasingly baryon-poor for lower mass.
- L* galaxy missing ~$10^{11.3}$ M_{sun} of baryons!
  - 4x more mass than the stars
  - 20x more than the cold disk gas



Dai et al. 2010; McGaugh et al. 2010

Halos Around Two Massive Galaxies: NGC 1961 and UGC 12591



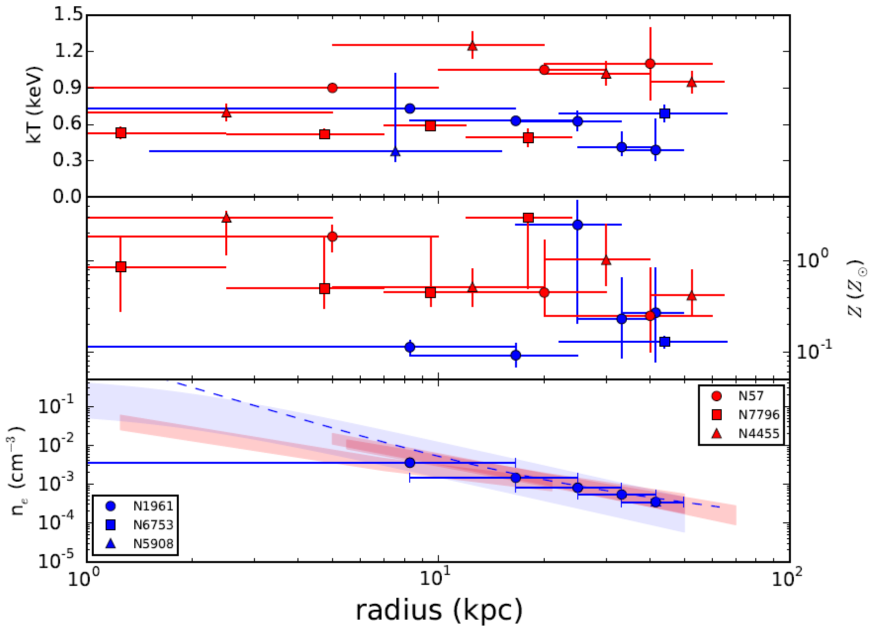


UGC 12591: Early-type spiral (left)   NGC 1961: Later-type spiral (right)

Stellar Mass is 6-8x the Milky Way

- Detections out to 50-70 kpc
  - 0.15-0.2 R_{virial}
- Density consistent with beta ≈ ½
  - $n \sim r^{-3/2}$
  - No flattening with r (possible steepening)
- Gas Masses 0.5-1 x M* to R_{virial}
  - Extrapolation at contant beta
  - A big reservoir of gas
  - Not the missing baryons (>50% missing)
- T ≈ 1.4 T_{virial}
  - Suggests some heating
- Metalicity
  - 0.1-0.3 Solar in spirals
  - 0.3-1 Solar in early-type galaxies

Summary of 3 isolated early-type galaxies and 3 massive spirals.



Bregman, Anderson, Miller… (2017); Bogdan; O'Sullivan

From 0.2R_{200} to R_{200}

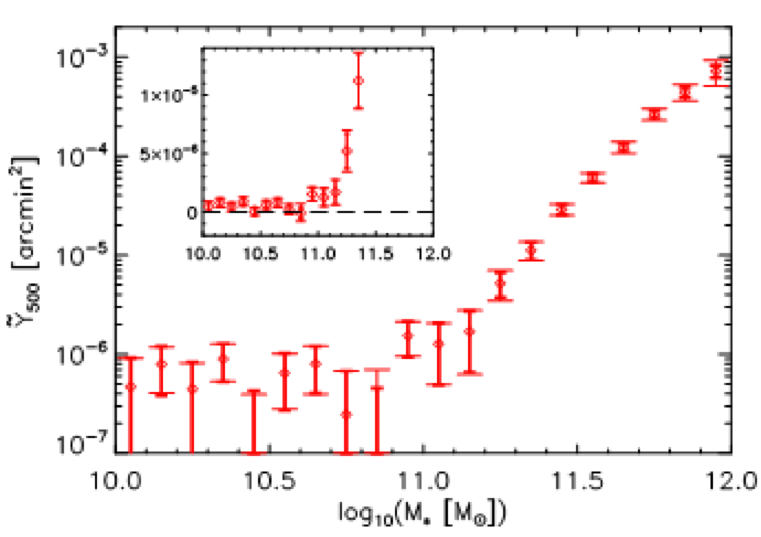
- Hot gas mass within 50 kpc is ~5E9 Msun
- Extrapolate to R_{200}
  - Have to adopt a density distribution
  - Density has same slope within 50 kpc and > 50 kpc
    - Probably wrong but simple
  - Simulations: density steepens with R
  - If isothermal to R_{200}, density flattens (Faerman et al. 2017)
- Constant density slope
  - $M_{gas}(R_{200}) \sim M_{star}$
  - $M_{gas} + M_{star}$ at R_{200} still only 50% of baryons (at best)
- Need to measure density law directly from X-ray observations

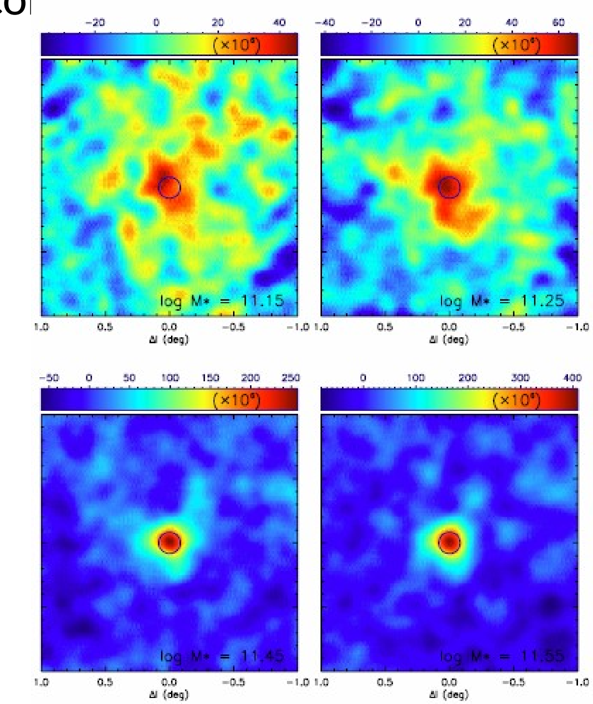
Are the Missing Baryons Warm (~10^4 K)?

- Detections in UV: COS-Halos
  - Line strengths + Cloudy column densities
  - Interpreted by team as most of the missing baryons in the halo
  - Conversion to columns have issues
  - Reinterpreted by two groups to get 5x lower masses
    - Now less mass than stellar mass
  - Likely seeing large stable disks to 50 kpc (also seen in 21 cm HI and in models) + a halo with less gas mass (JNB 2017)
- Lower redshift absorption studies get lower gas masses
- Bottom Line
  - Significant gas in disks but few times less than M_{star}
  - Modest mass in halo, but less than disk
  - N(OVI) about 1/10 of N(OVII)
  - **Warm gas does not dominate halo gas distribution**

Are the Missing Baryons Hot?

- Hot gas can create a Sunyaev-Zeldovich signal
  - Y parameter is just product of M_{gas} and T_X
    - $T_X \approx T_{virial}$, so we just measure M_{gas}
  - Can't detect systems with M_h < 3E14 M_{sun}
  - Stack galaxies in M_{star} bins (Planck 2013)
  - Only detect massive galaxies ($\log M_{star}$ >11.1)
  - Implies most of the baryons in massive galaxies are hot
  - Gas appears extended in stack and in cross-correlations (Greco 2015; Van Waerbeke 2014; Ma 2015)





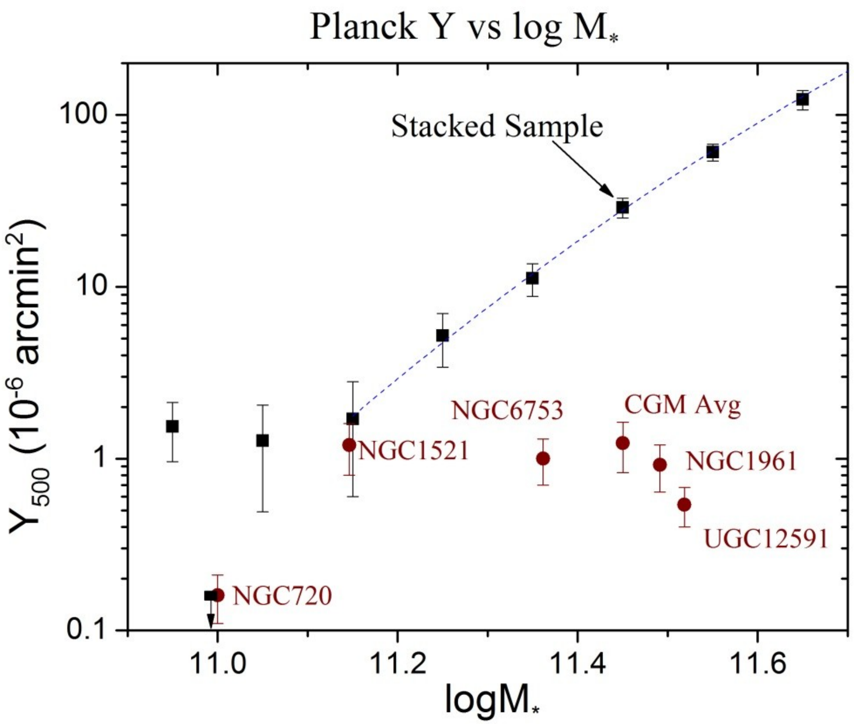
Does the SZ Signal Make Sense?

- Individual galaxies should be point sources
  - The Planck beam is 10’, but $2R_{200}$ = 4’
- Individual galaxies observed in X-rays have much smaller Y parameter (extrapolated to R_{200})

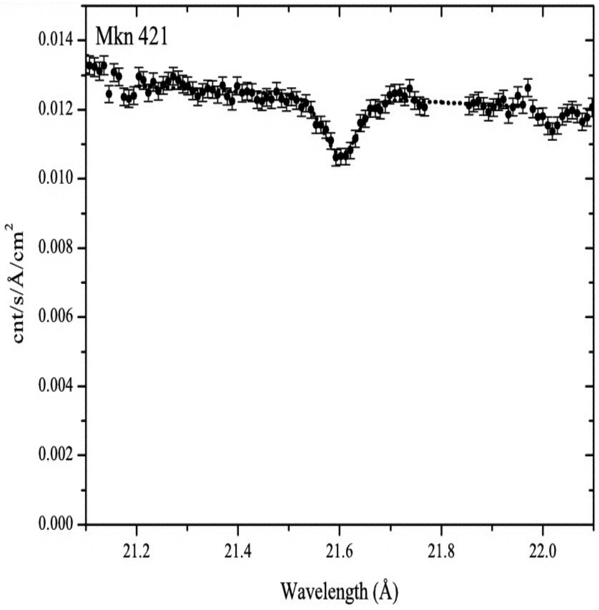
Resolution?

1. Our galaxies are outliers relative to stack sample. Stack sample galaxies – usually in groups/clusters.
2. Was the correction for group contamination too small?

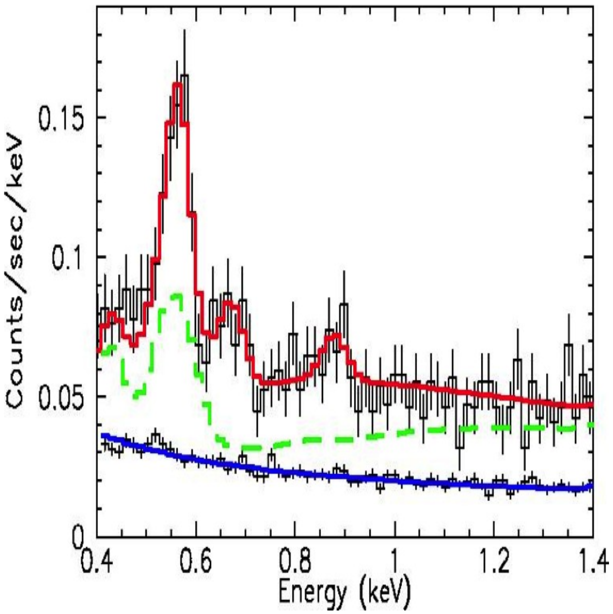
Maybe the gas out to R_{200} and beyond is hot.



Milky Way Hot Gas in X-rays
(emission and absorption)



Absorption by O VII MW gas
30 sightlines; 3 really good ones
(about 10x column from O VI)



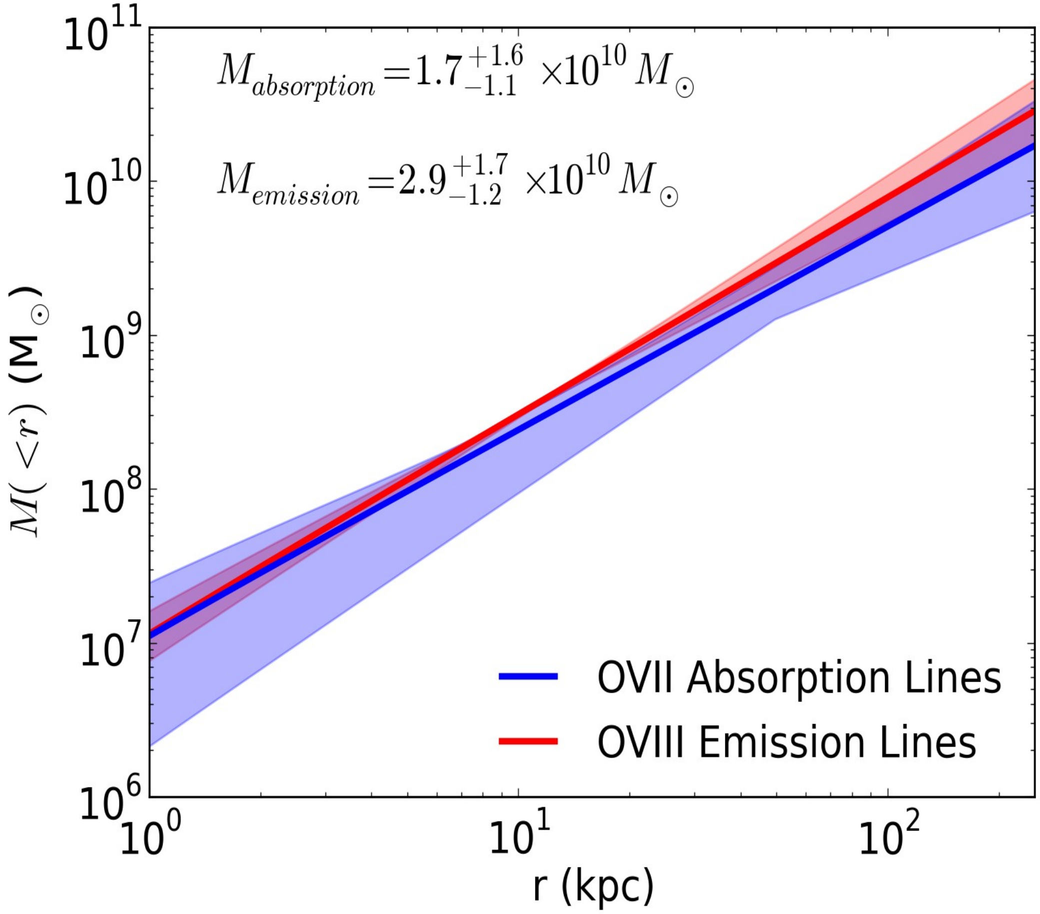
Emission from O VII (0.56 keV) and O VIII (0.65 keV) from Milky Way; 650 sightlines

Fit parametric beta model to get n_e vs r; T_X from spectra

Mostly, sensitive to gas < 50 kpc from Sun (Miller 2015; Hodges-Kluck 2016; Li 2017)

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 – measure the EW toward the LMC
  - Divide one by other: $Z > 0.3\ Z_{sun}$
  - About the same as the external galaxies



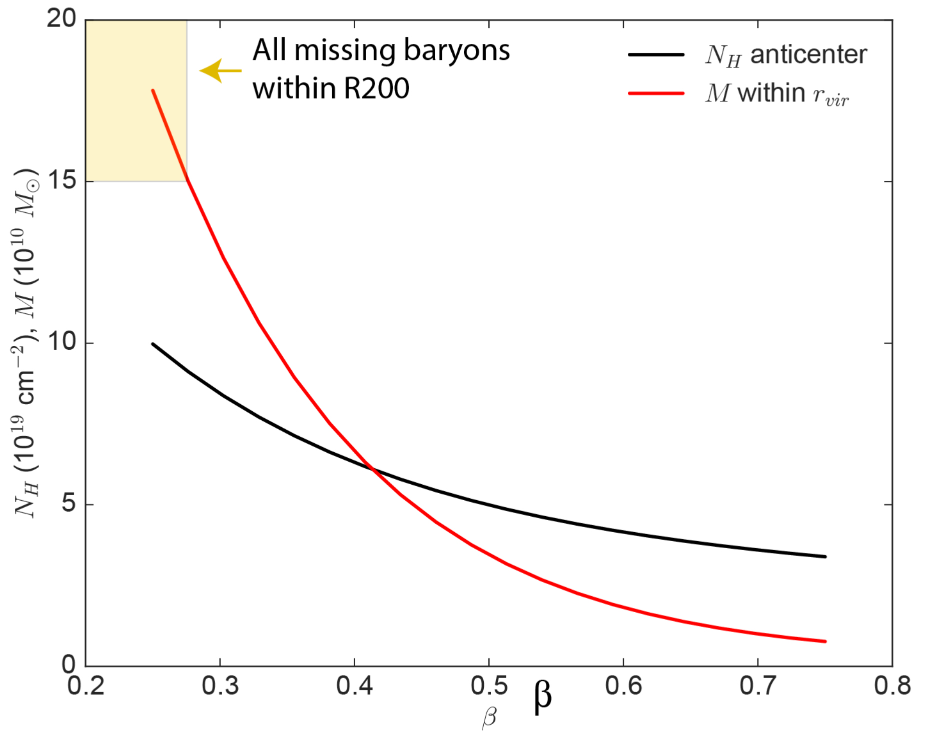
Extrapolate to 250 kpc

Masses considerable but a bit less than M_{star} (5×10^{10} M_{sun})

Still missing at least half the baryons

Fitting More Baryons Into R_{200}

- Make density law flatter beyond 50 kpc
  - Density power law pretty well constrained within 50 kpc
- If all missing baryons are within R_{200} , beta < 0.3 (flat density law)
- If beta ≈ 0.5, baryons must extend beyond R_{200}
- Measuring density law beyond 50 kpc is crucial

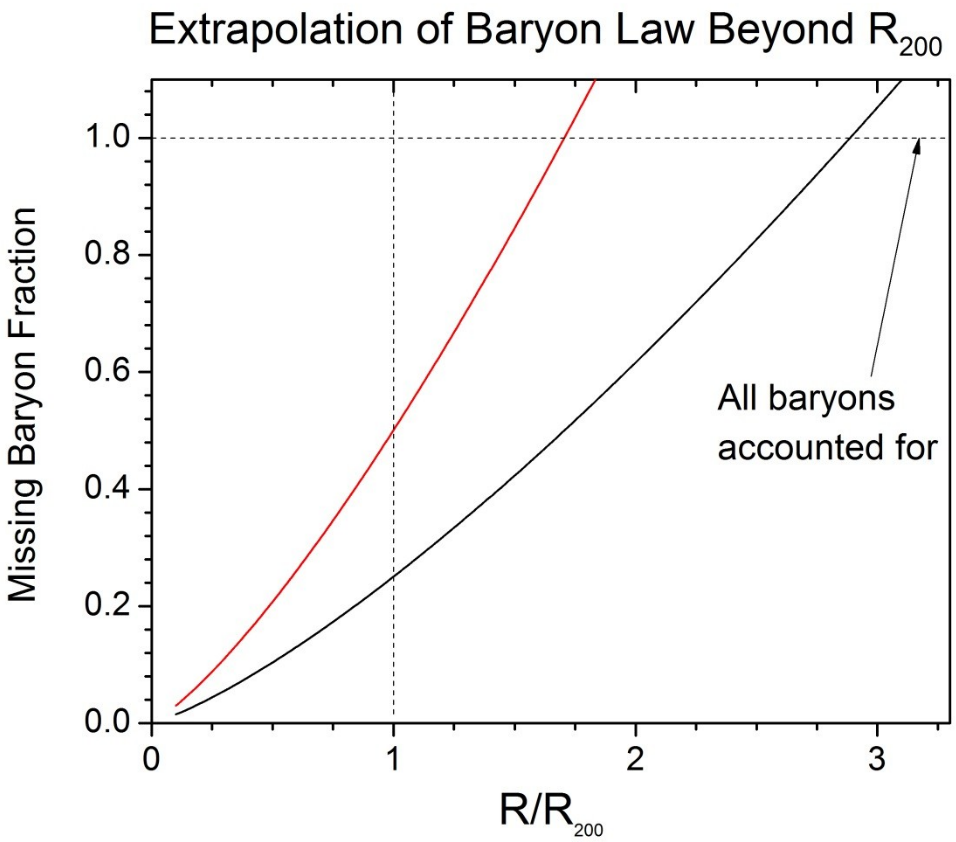


Flat
High T≈ T_{vir}/beta

Steep
T ~ T_{vir}

Where Do The Missing Baryons Lie?

- Extrapolate $n_{gas} \sim r^{-3/2}$ law to large radius (beta ≈ ½)
- Missing baryons within 1.7-3R_{200}
- Too many extrapolations – need new data!



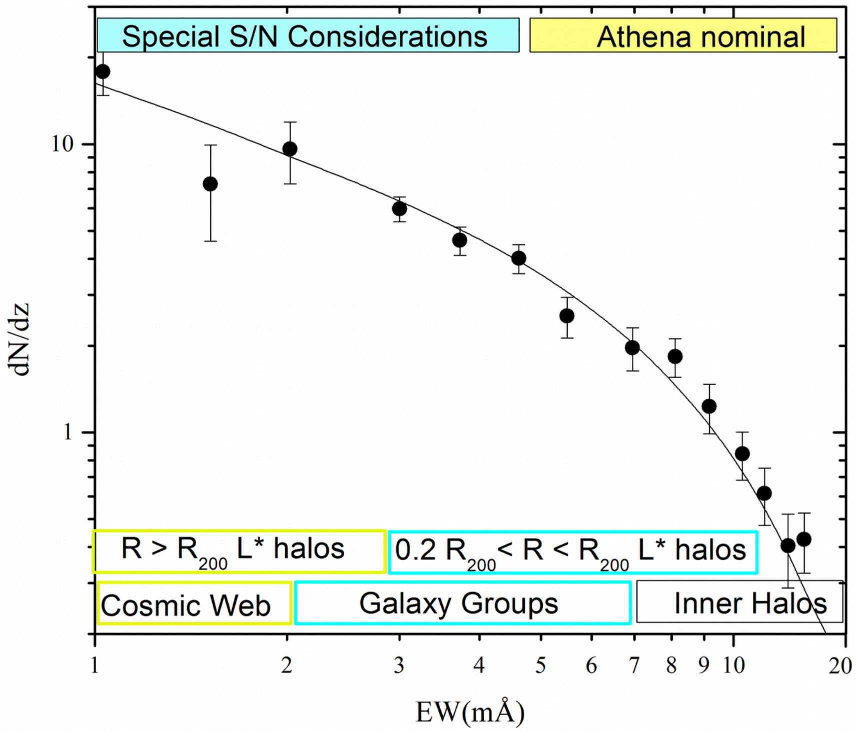
- Astrophysical reasons for caring about Missing Hot Baryons
- What have we already learned about Missing Hot Baryons in galaxies and the Universe?
- New insights before Lynx launches
- The Lynx contributions

What Will We Learn Before Lynx?

- UV Absorption Line Studies (HST)
  - The big studies are done; modest progress at best
- JWST, Euclid, WFIRST, Giant ground-based telescopes
  - Not much progress here either
- Improvements in SZ studies
  - Higher angular resolution (but may be resolved already)
  - Subtraction of Galactic dust signal – primary systematic
  - Anticipated improvement in M_{halo} : 3-6x
  - Still will need stacks ~10^3; <u>no individual galaxies</u>

Before Lynx, cont.

- Athena
  - Cosmological census: absorption to 5 mA in O VII
    - Likely absorption from inner parts of galaxies (<100 kpc)
    - Won’t detect outer parts of galaxies or WHIM

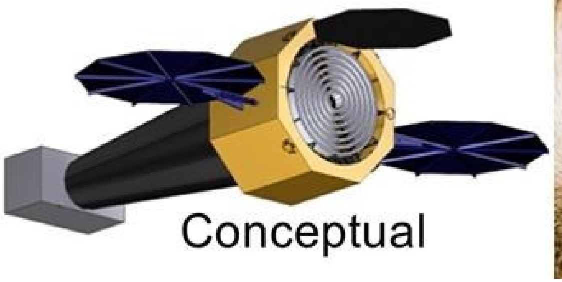


If Arcus MIDEX selected (high resolution X-ray spectroscopy), should go down to 3 mA (or better).

Lynx will go to 1 mA, or better.

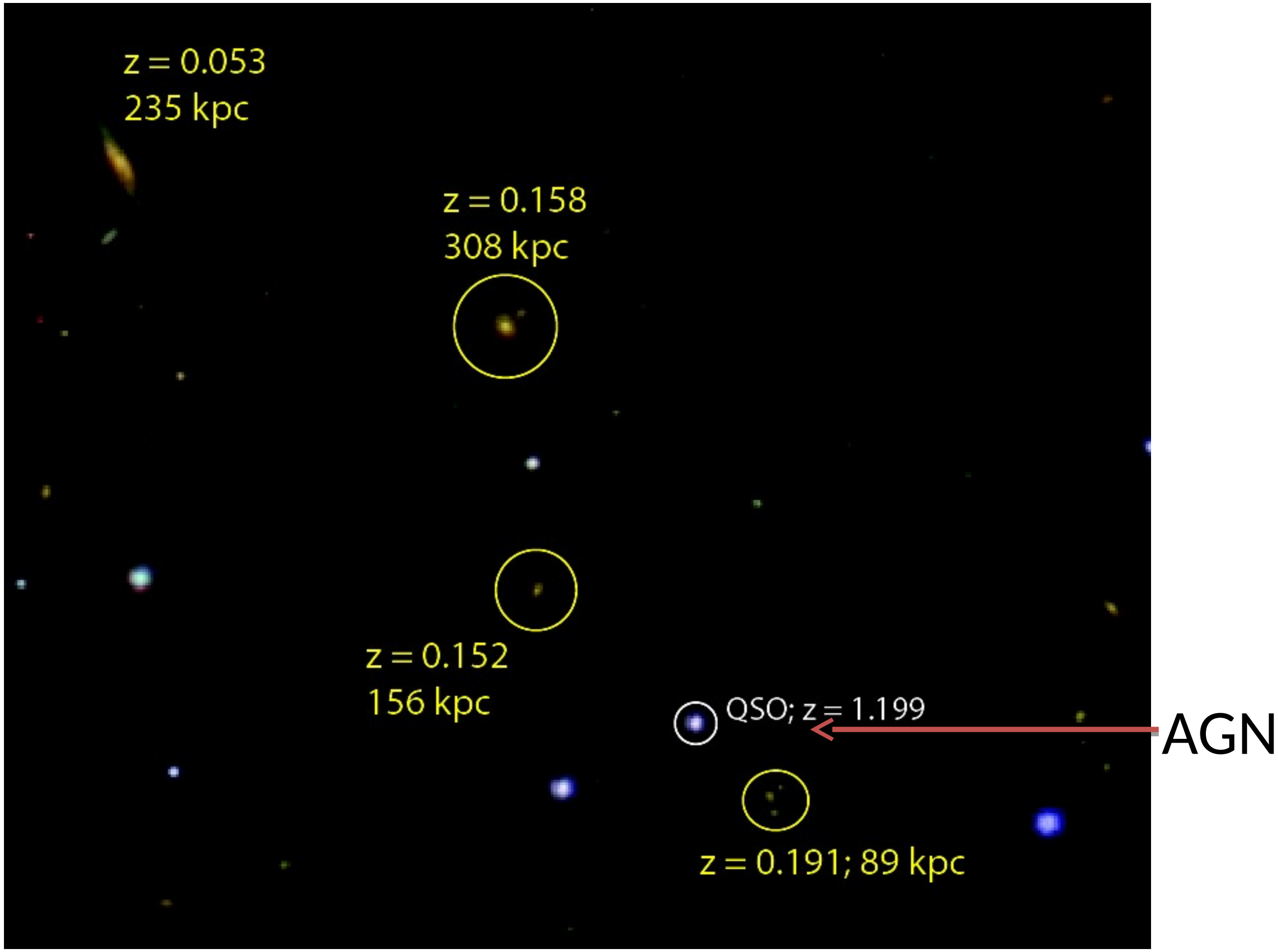
- Athena for individual galaxies in emission
  - Much better define gas properties within 50 kpc
    - T_X, density, metallicity to good accuracy
  - Some emission line information out to 100 kpc
    - Long observations with small XIFU
  - Observations out to a good fraction of R_{200} would take 10+ Msec per object

- Astrophysical reasons for caring about Missing Hot Baryons
- What have we already learned about Missing Hot Baryons in galaxies and the Universe?
- New insights before Lynx launches
- **The Lynx contributions**



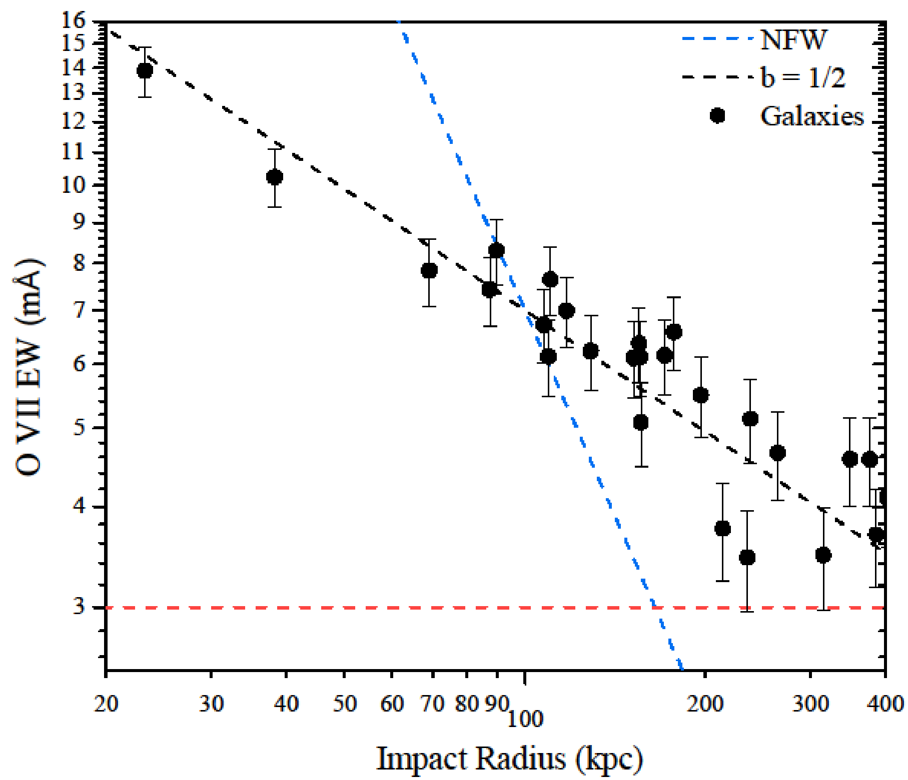
- Lynx improvements for Halo Emission
  - The 20' IFU is ***16x*** larger fov than Athena
  - Imaging of individual galaxies to D ~ 100 Mpc will go out to ~$R_{200;}$ 1 Msec observations
    - Probably about 0.5R_{200} if you want to know n, Z, T_x
    - Out to R_{200} (and possibly beyond) if you just want to detect hot gas emission (and get T_X)
  - Detect X-ray halos to z ~1 by stacking!
    - Cosmological evolution

Lynx will be able to detect hot halos against bright AGNs (example field)



Put the MW Halo Around External Galaxies

- Extrapolated beyond virial radius (JNB 2015)
- Can detect gas beyond R_{200}
- Studies go to z ~ 1.5 – *cosmological evolution*



Lynx: Milky Way Hot Halo

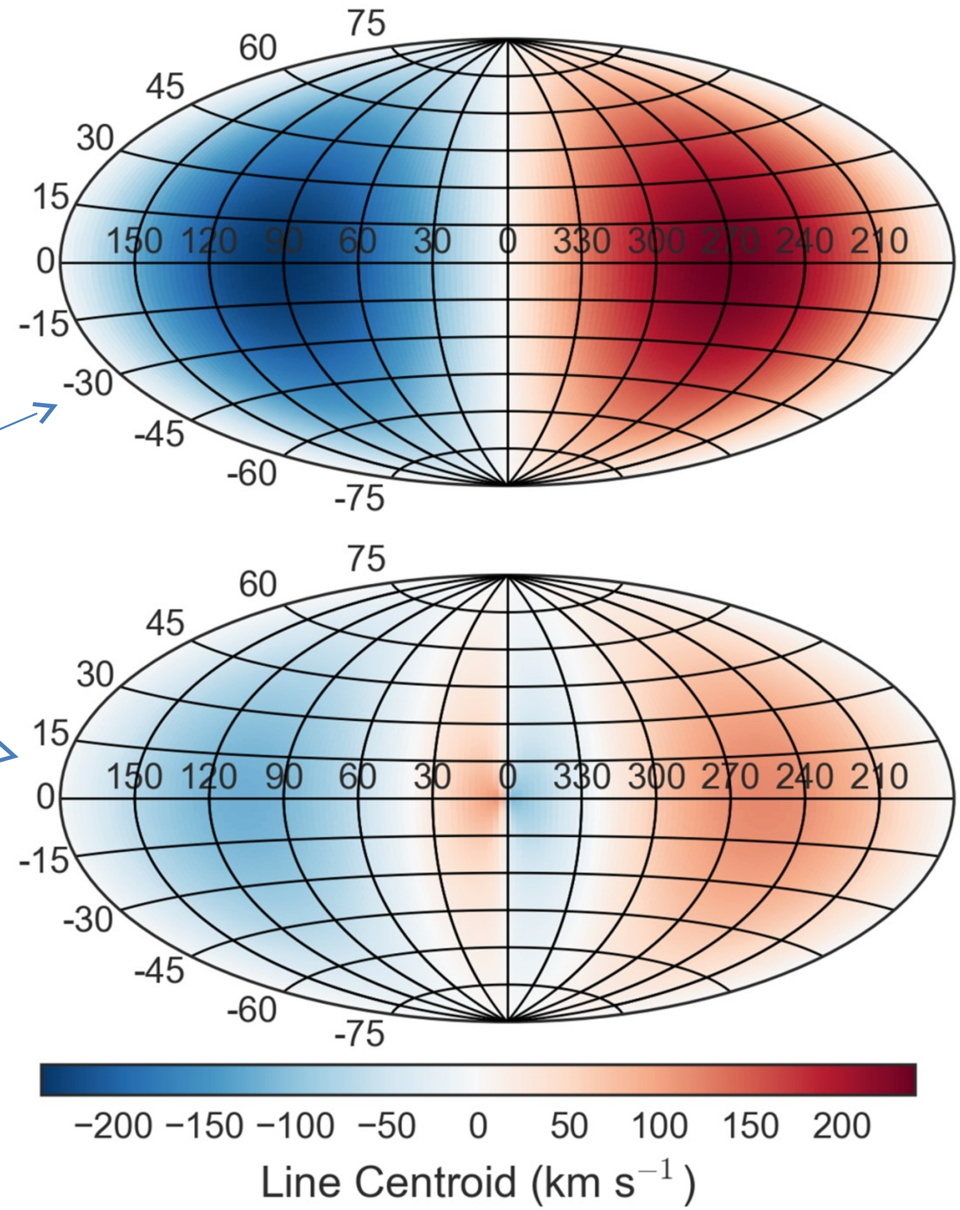
- Dynamics of the halo (currently poorly known; 180 +/- 40 km/s)
  - Line shapes from Lynx
  - rotation vs radius
  - infall/outflow rate (~30 km/s)
  - Turbulence (feedback); ~50-100 km/s
- Optical depth effects in the strongest lines (partly Athena)
  - Affects gas mass determination and metallicity
  - Measure second strongest line from each ion; split triplets
- Metallicity and Temperature vs radius
  - Parts of lines maps to radius
  - Possible with high S/N abs lines + known emissivities

You can see the Galaxy rotate!

Stationary Hot Halo

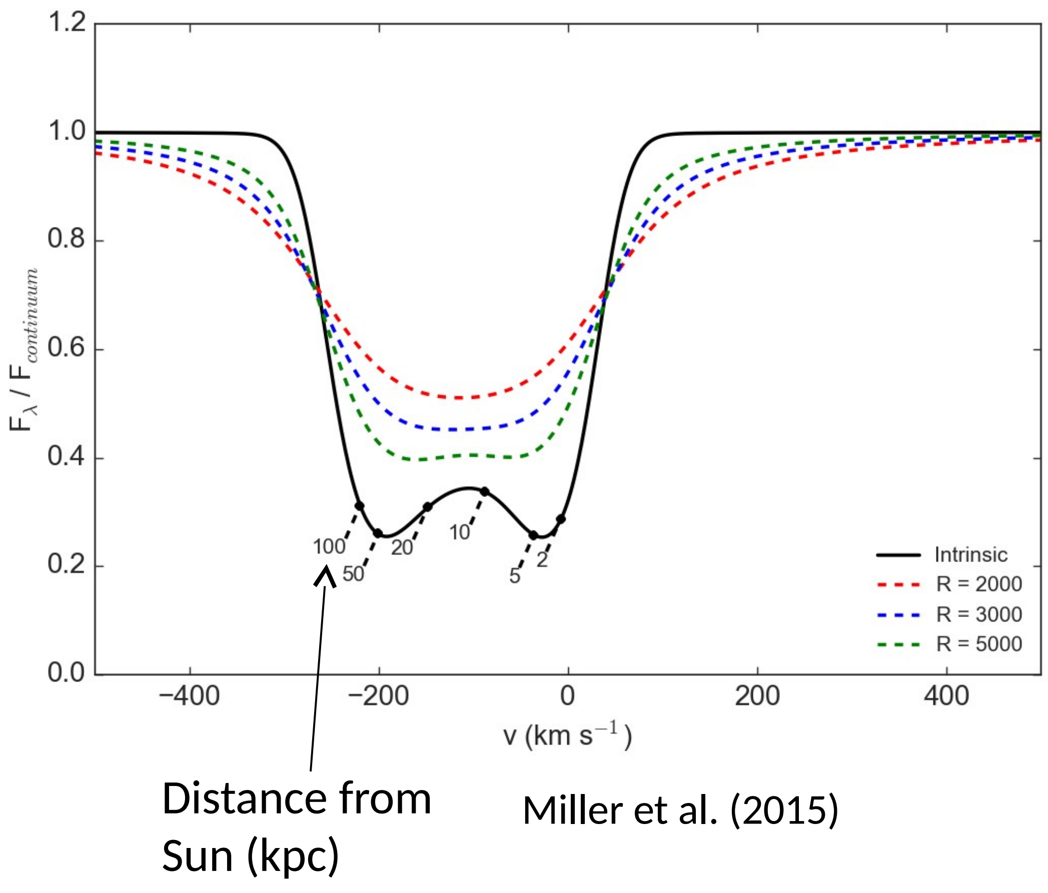
Co-Rotating Hot Halo

Miller et al. (2015)



Map the Galaxy Rotation Vs Radius

- X-Ray Rotation Curve
  - Higher spectral resolution (*R*) essential
  - Doppler b = 45 km/s
  - Shown l = 90, b = 0
- Line location maps to radius
  - Line ratios give T(r)
- Need *R* ~ 5000 or greater
  - And high S/N
  - Athena inadequate, *R* = 300
  - *R* ~ 10,000 would be even better



Miller et al. (2015)

Summary: Advances with Lynx

- Census of hot absorbing gas in Universe
  - Galaxy halos (and beyond), galaxy groups, Cosmic Web
  - As a function of redshift to z ~ 1.5
- Galaxy halos in emission and absorption
  - M_{gas} T_X and metals distribution to large radii
  - Galaxy evolution, z = 0 – 1
- Dynamics of hot galactic halos and groups
  - Rotation, turbulence, accretion rate