Title: From Disk to IGM: A Comprehensive Mapping of Andromeda's Circumgalactic Medium

Speakers: Nicolas Lehner

Collection/Series: Cosmic Ecosystems

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Abstract:

Project AMIGA (Absorption Maps In the Gas of Andromeda) provides an unprecedented view of the circumgalactic medium (CGM) of our nearest large galaxy neighbor. Using 55 sightlines obtained largely from two large HST COS programs, we map Andromeda's CGM across distances spanning from 10 to 570 kpc, nearly reaching twice its virial radius (Rvir=300 kpc). Using extensive diagnostics of different gas phases (OI/VI, SiII/III/IV, CII/CIV, FeII, AlII), this study uniquely bridges the smaller scales of the CGM with its largest scales extending into the intergalactic medium (IGM). In this talk, I will demonstrate how gas complexity and gas-phase structures significantly change with impact parameters but show little variation with azimuth relative to major/minor projected axes. Our program can differentiate components associated with the thick disk from those in the CGM, providing crucial insights for characterizing gas phases and accurately determining the total mass of Andromeda's CGM. I will place these findings in the broader context of other CGM observations, recent cosmological zoom simulations of Milky Way-mass galaxies at z~0, and how this pathfinder study may inform next-generation observations of the CGM/IGM with HWO.


From Disk to IGM: A Comprehensive Mapping of Andromeda's Circumgalactic Medium
Nicolas Lehner
(University of Notre Dame)
and the Project AMIGA Team
Image Credit: NASA, ESA, E. Wheatley (STScI)

Project AMIGA (Absorption Maps of Ionized Gas toward Andromeda)

The Astrophysical Journal, 804:79 (21pp), 2015 May 10 doi:10.1088/0004-637X/804/2/79

EVIDENCE FOR A MASSIVE, EXTENDED CIRCUMGALACTIC MEDIUM AROUND THE ANDROMEDA GALAXY*

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Pre-AMIGA

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Project AMIGA: A Minimal Covering Factor for Optically Thick Circumgalactic Gas around the Andromeda Galaxy

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The Astrophysical Journal, 900:9 (44pp), 2020 September 1 https://doi.org/10.3847/1538-4357/aba49c

Project AMIGA: The Circumgalactic Medium of Andromeda*

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Project AMIGA: H I and H II Covering Factors of the Circumgalactic Gas Around Andromeda*

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Project AMIGA: The Inner Circumgalactic Medium of Andromeda from Thick Disk to Halo*

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Project AMIGA: Distance and Metallicity Gradients along Andromeda's Giant Southern Stream from the Red Clump*

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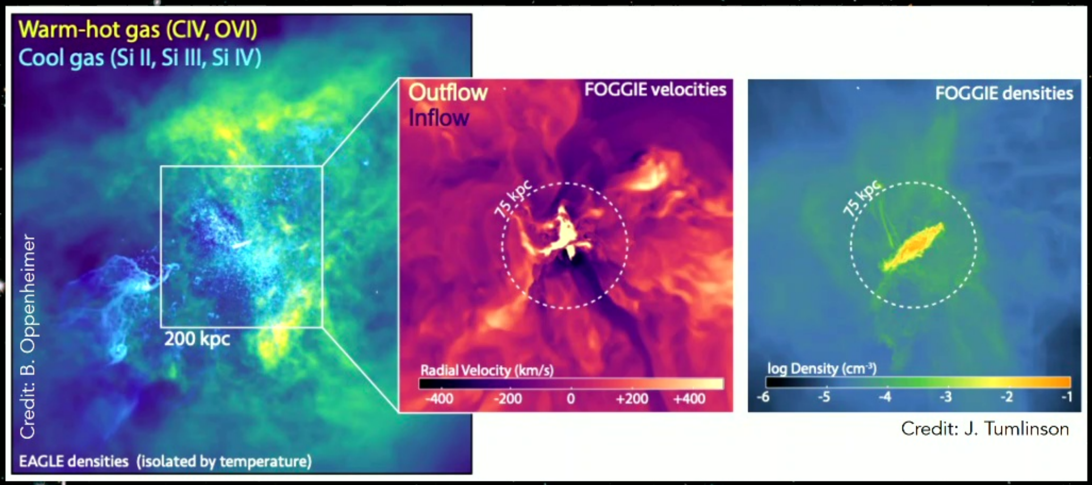
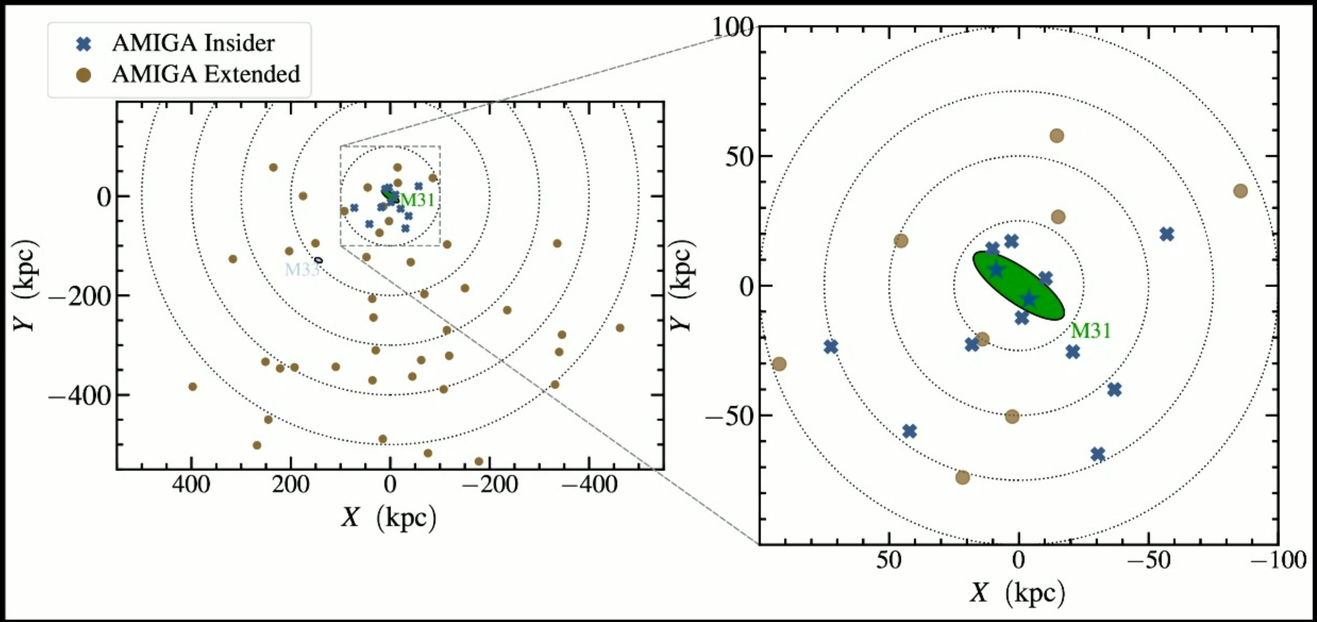
The problem: CGM sampling



- **Limited spatial sampling**: Most CGM studies rely on single quasar sightlines per galaxy, providing only one "core sample" through each halo.
- **Statistical averaging can mask real variations**: Our understanding comes from ensemble averages across many galaxies, making it difficult to distinguish real trends from confusion with other uncontrolled variables.
- **Inner-outer CGM connection gap**: Emission studies offer spatial coverage but only in the inner regions, with insufficient sensitivity to reach the outer CGM.

Project AMIGA: Many Sightlines, One Galaxy

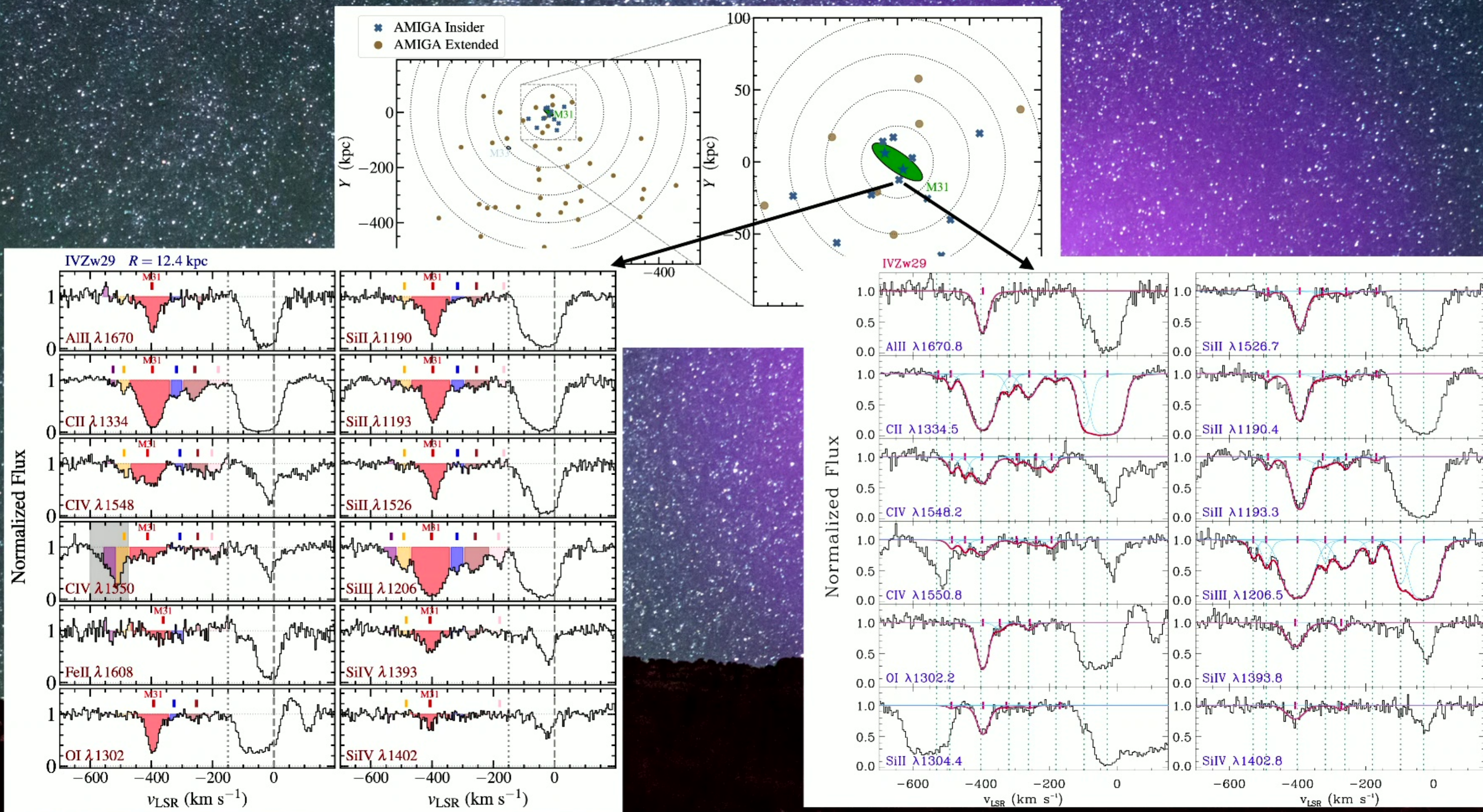


Connecting the inner CGM to outer CGM

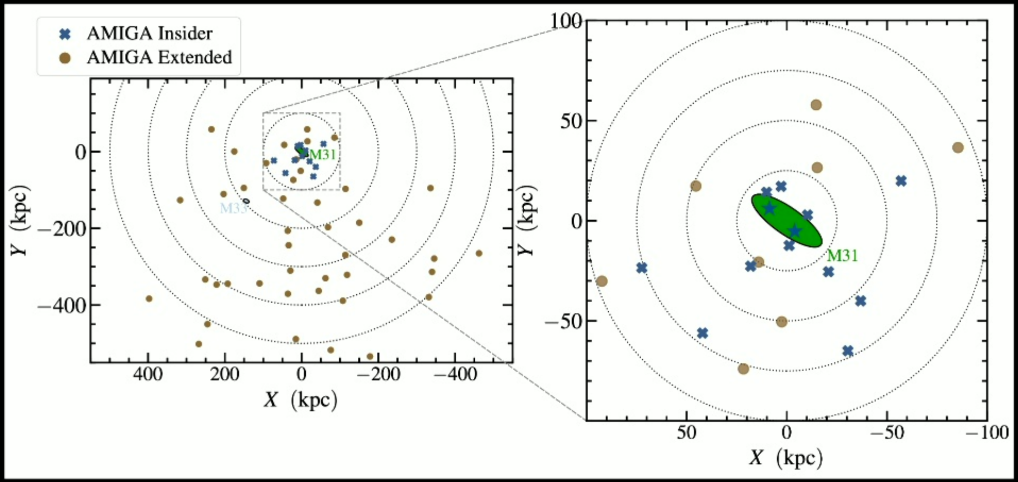
M31 as a CGM laboratory: 54 QSOs from disk to 2Rvir (+2 stars)

Two dedicated Large HST COS G130M/G160M programs (230 orbits, PI: Lehner) mapping the inner CGM (~75 kpc, 0.25Rvir) and out to the virial radius (300 kpc) + archival COS spectra (beyond R_{vir}).

Project AMIGA (Absorption Maps of Ionized Gas toward Andromeda)



Project AMIGA: Dissecting a Single Galaxy's CGM



Metals as tracer particles:

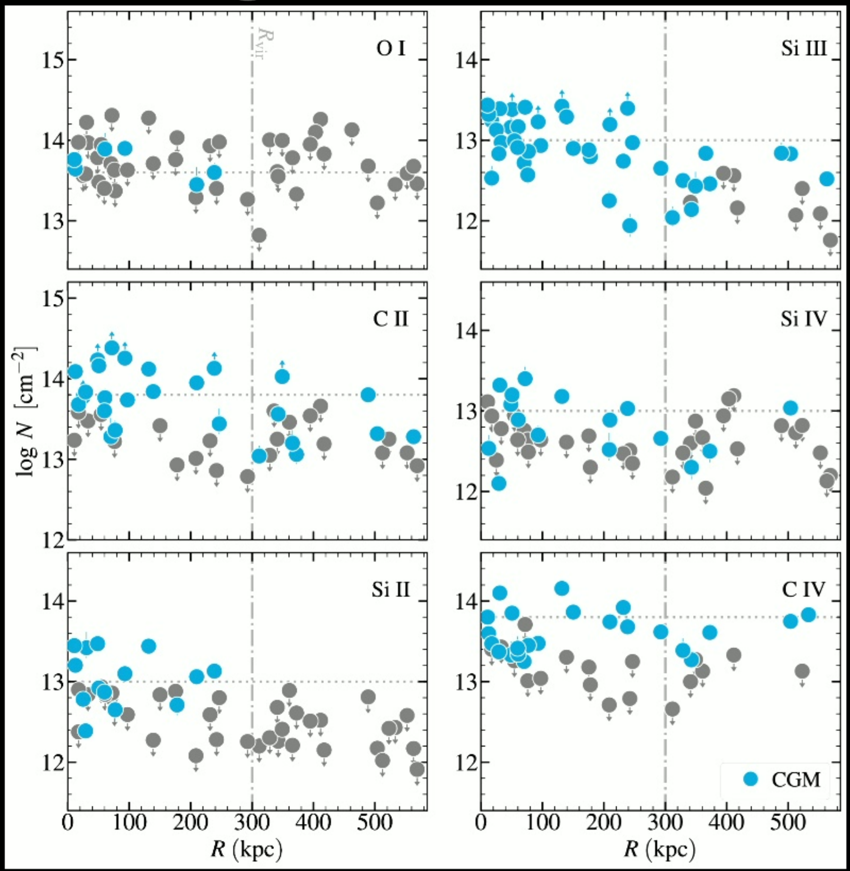
➡ **Defining CGM boundaries**: The first sensitive determination of where a single galaxy's halo begins and ends.

➡ **Comprehensive CGM "cartography"**: The first maps of gas velocities, surface densities, ionization states, and multi-phase structure as a function of radius and azimuth for an individual galaxy from disk to 2Rvir.

➡ **Connecting disk and halo physics**: Understanding how galactic processes drive CGM structure by tracing the disk-halo interface.

➡ **Testing CGM models**: Distinguishing between competing models of CGM formation.

M31's CGM: Strong Radial Trends and More Complex Inner Regions than the Outer CGM



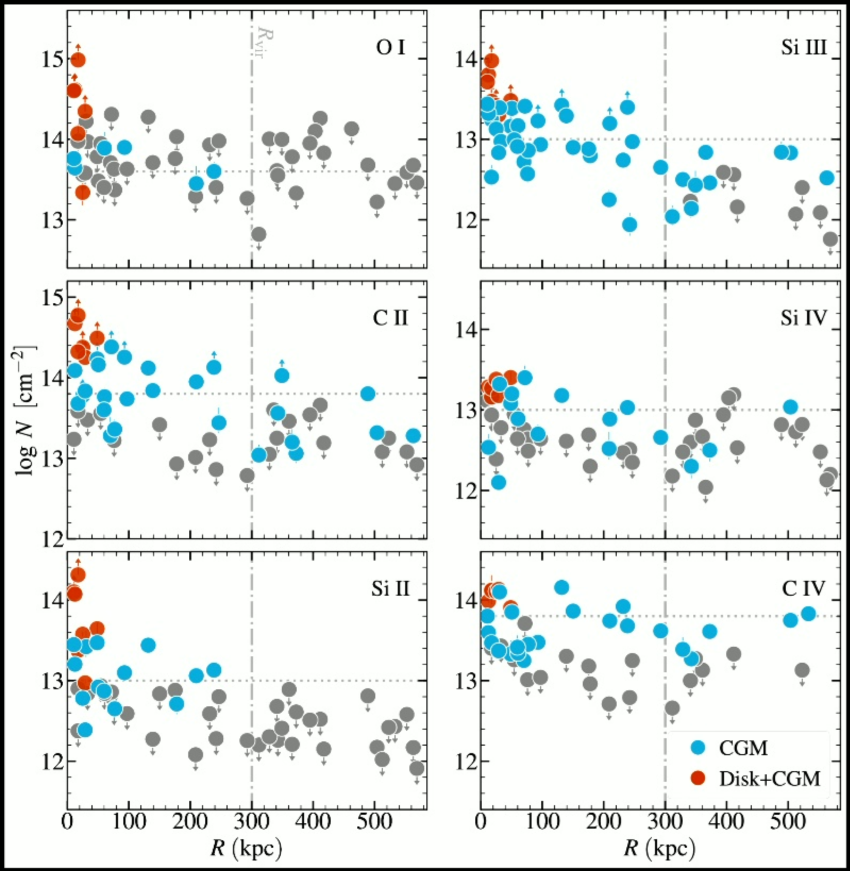
Lehner+2015, 2020, 2025

Extended reach: CGM detected beyond Rvir for some ionic species
Radial dependence: Strong dependence of column densities and ionization properties with R.
More complex inner regions: Multi-phase gas structure with high covering factors for all ions at R < 0.5Rvir,
Significant scatter: Large intrinsic variations at any radii.

Inner CGM has a more complex multiphase gas-structure than outer regions

- $R < 50$ kpc: $\langle \log N_{\rm Si\,II}/N_{\rm Si\,III}\rangle = (-0.18 \pm 0.05) \pm 0.16$ and $\langle \log N_{\rm Si\,IV}/N_{\rm Si\,III}\rangle = (-0.52 \pm 0.06) \pm 0.12$;
- $R \geq 50$ kpc: $\langle \log N_{\rm Si\,II}/N_{\rm Si\,III}\rangle = (-0.56 \pm 0.06) \pm 0.12$ and $\langle \log N_{\rm Si\,IV}/N_{\rm Si\,III}\rangle = (-0.60 \pm 0.08) \pm 0.24$.

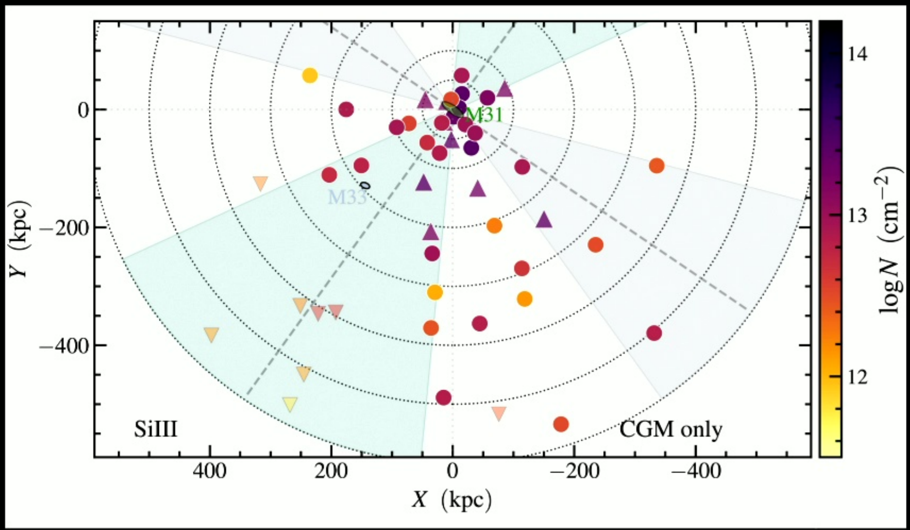
Disk-CGM Transition



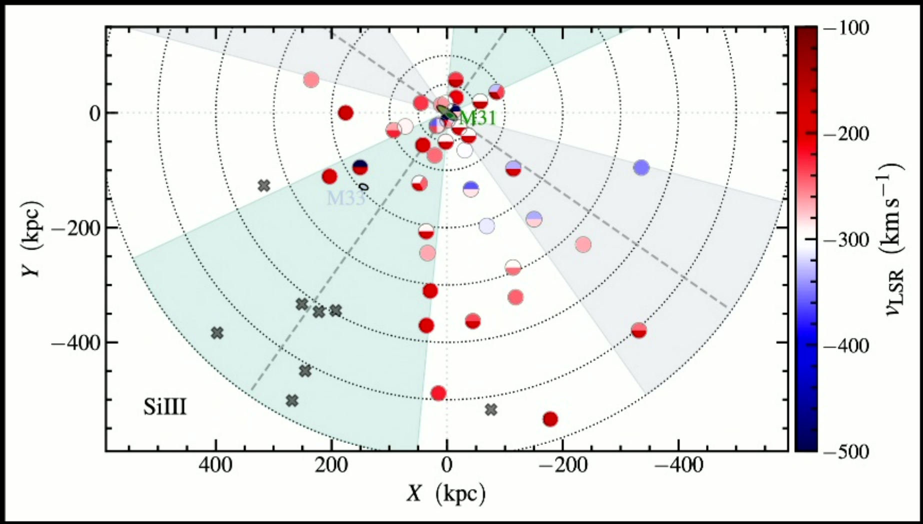
Lehner+ 2025

Low and intermediate ions show enhanced column densities in thick disk components compared to CGM gas at the same radii, while high ions remain comparable between disk and CGM phases.

Radial Dominance: No Strong Azimuthal CGM Patterns in M31



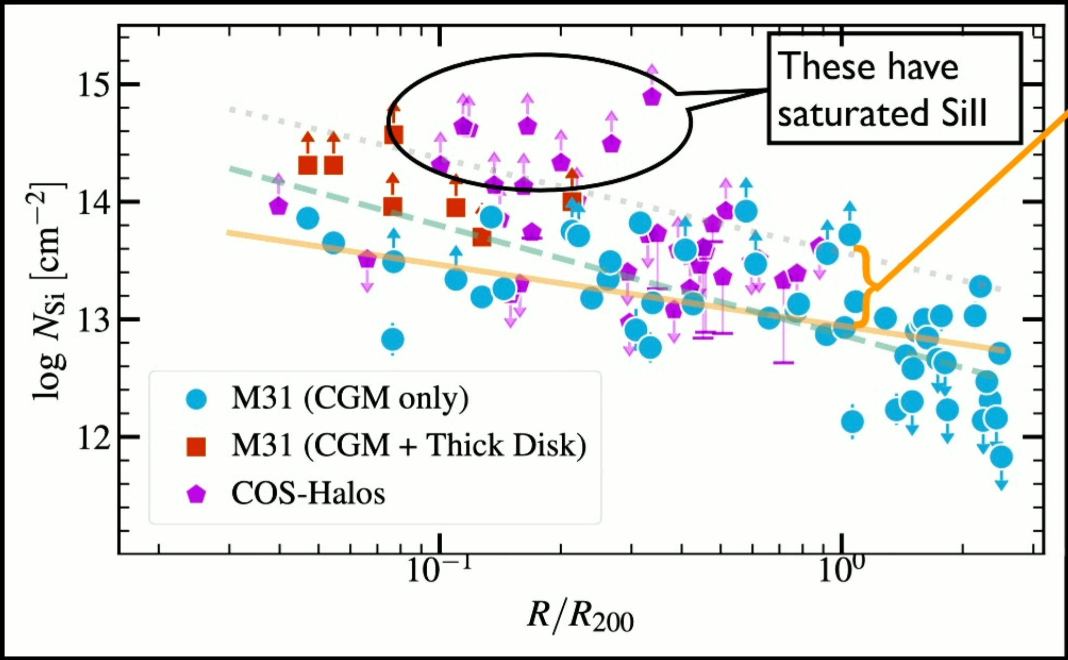
Total column densities



Velocities in each component

No significant azimuthal dependence detected for any ion species, suggesting M31's CGM is shaped by radial processes (cooling flows (Stern+2017), precipitations (Voit+2017), IGM accretion (Afruni+2022)) rather than disk-aligned, such as bipolar outflows.

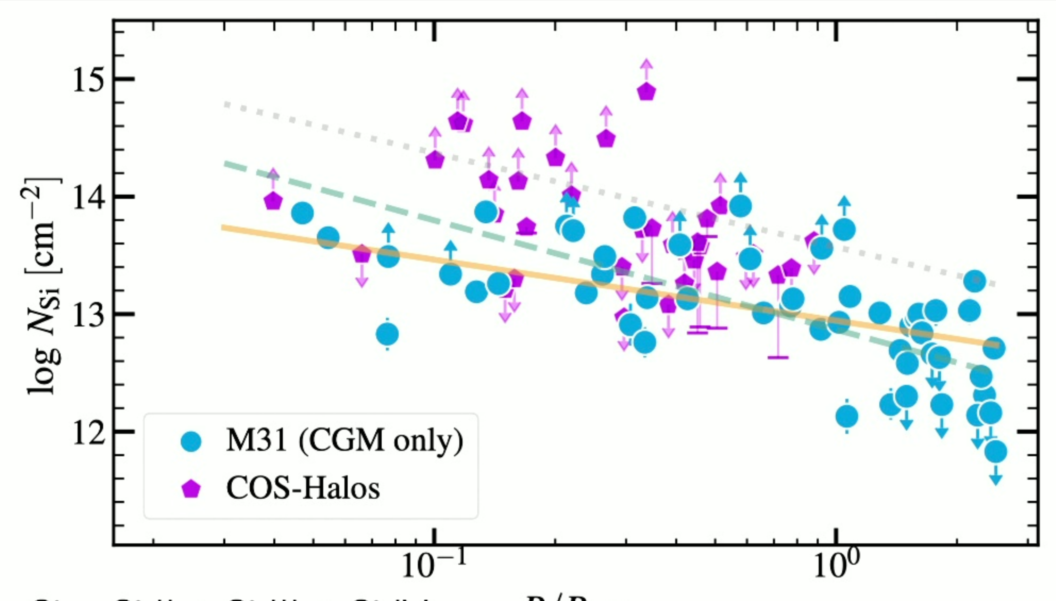
Comparison with the COS-Halos L* galaxies at z~0.2



COS-Halos cool CGM mass exceeds that of M31 by a factor of ~15 within R_{vir}.

Si = Si II + Si III + Si IV — Cool CGM

M31 has a depleted cool CGM in the inner region compared to COS-Halos galaxies

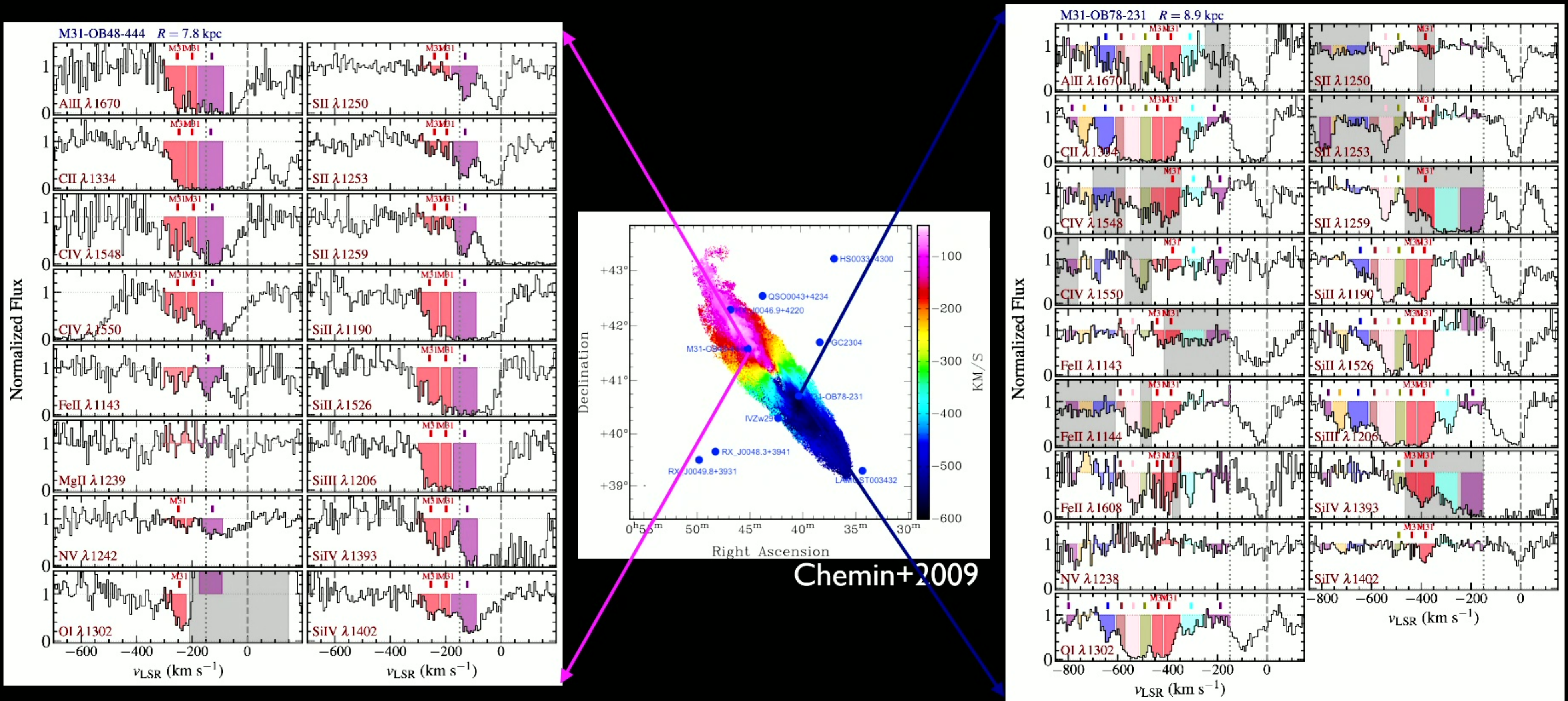


Si = Si II + Si III + Si IV

- **Contamination from nearby galaxies**: COS-Halos may include absorption from unrelated nearby gas-rich dwarf galaxies along the sightline (*unlikely to explain all the differences*).

- **Halo mass threshold effect**: M31's higher halo mass (~10^{12} solar masses) has crossed the threshold where hot gas dominates the inner CGM, while most COS-Halos galaxies have lower-mass halos still dominated by cool, turbulent gas (see Jonathan Stern's talk, see also Bish et al. 2022 with lower CIV in the MW CGM).

M31 star–QSO pair: determination of the flow origins



- COMPLEX KINEMATICS: Significant departures from simple rotation
- ACTIVE GAS CYCLING: Evidence for both inflows and outflows in the inner regions

Summary

***Project AMIGA** is a unique experiment that has targeted the CGM of M31 with 54 QSO sightlines (and 2 stars, stay tuned!):*

- There's a boundary at R<30 kpc where M31's thick disk transitions to the CGM: low-energy ions show higher column densities in the thick disk, while high-energy ions have similar column densities in both regions.
- All ion column densities decrease with R, with lower-energy ions dropping off more steeply
- The inner CGM shows a more complex, multi-phase gas structure compared to the simpler outer regions
- No significant azimuthal preferences were found, *suggesting radial processes such as cooling flows or precipitations dominate over bipolar disk-driven outflows.*

CGM mass estimates: The metal cool CGM mass **within R_{vir} is $(1.9 \pm 0.3_{stat} \pm 0.7_{sys}) \times 10^7$ $M_\odot$**, leading to a cool gas CGM mass of $\sim 6 \times 10^9 (Z/0.3\ Z_\odot)^{-1}$ $M_\odot$. *The warmer OVI-bearing gas may have at least 10 times more mass.*

Comparison with other surveys: Compared to COS-Halos L* galaxies, M31's inner CGM has lower Si column densities in the inner regions and less cool gas mass, possibly due to its higher halo mass.