ULTRAVIOLET ASTRONOMY IN THE XXI CENTURY

e-Workshop 2020 – October 27-29

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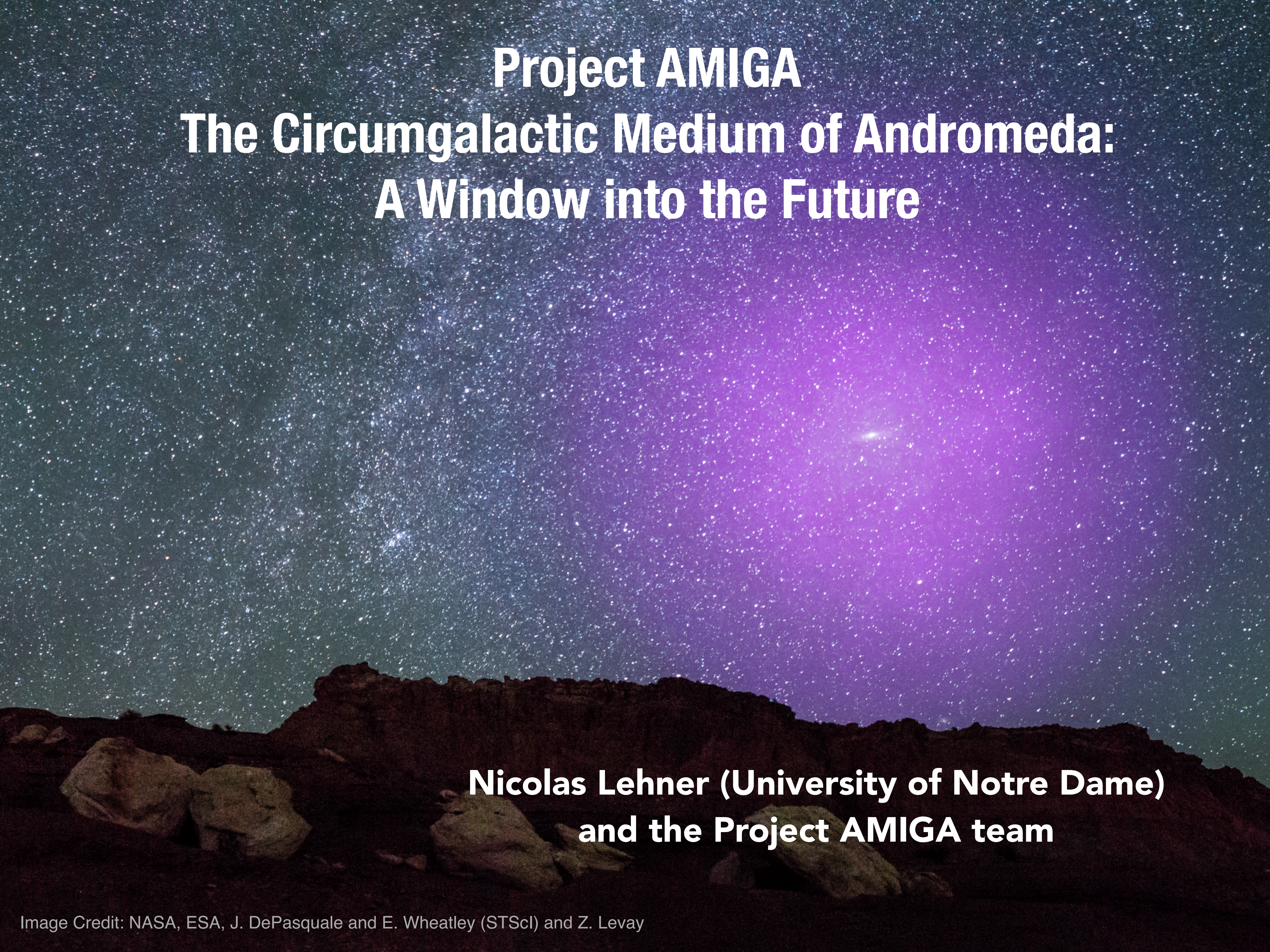

Image Credit: NASA, ESA, J. DePasquale and E. Wheatley (STScI) and Z. Levay

Project AMIGA (Absorption Maps of Ionized Gas toward Andromeda)

THE ASTROPHYSICAL JOURNAL, 900:9 (44pp), 2020 September 1
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Project AMIGA: The Circumgalactic Medium of Andromeda*

Nicolas Lehner[1], Samantha C. Berek[1,2,20], J. Christopher Howk[1], Bart P. Wakker[3], Jason Tumlinson[4,5], Edward B. Jenkins[6], J. Xavier Prochaska[7], Ramona Augustin[4], Suoqing Ji[8], Claude-André Faucher-Giguère[9], Zachary Hafen[9], Molly S. Peeples[4,5], Kat A. Barger[10], Michelle A. Berg[1], Rongmon Bordoloi[11], Thomas M. Brown[4], Andrew J. Fox[12], Karoline M. Gilbert[4,5], Puragra Guhathakurta[7], Jason S. Kalirai[13], Felix J. Lockman[14], John M. O'Meara[15], D. J. Pisano[16,17,21], Joseph Ribaudo[18], and Jessica K. Werk[19]

THE ASTROPHYSICAL JOURNAL, 846:141 (15pp), 2017 September 10
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Project AMIGA: A Minimal Covering Factor for Optically Thick Circumgalactic Gas around the Andromeda Galaxy

J. Christopher Howk[1,2], Christopher B. Wotta[1], Michelle A. Berg[1], Nicolas Lehner[1], Felix J. Lockman[3], Zachary Hafen[4], D. J. Pisano[5,6], Claude-André Faucher-Giguère[4], Bart P. Wakker[7], J. Xavier Prochaska[8,9], Spencer A. Wolfe[5,6], Joseph Ribaudo[10], Kathleen A. Barger[11], Lauren Corlies[12], Andrew J. Fox[13], Puragra Guhathakurta[8,9], Edward B. Jenkins[14], Jason Kalirai[12,13], John M. O'Meara[15], Molly S. Peeples[12,13], Kyle R. Stewart[16], and Jay Strader[17]

THE ASTRONOMICAL JOURNAL, 156:230 (23pp), 2018 November
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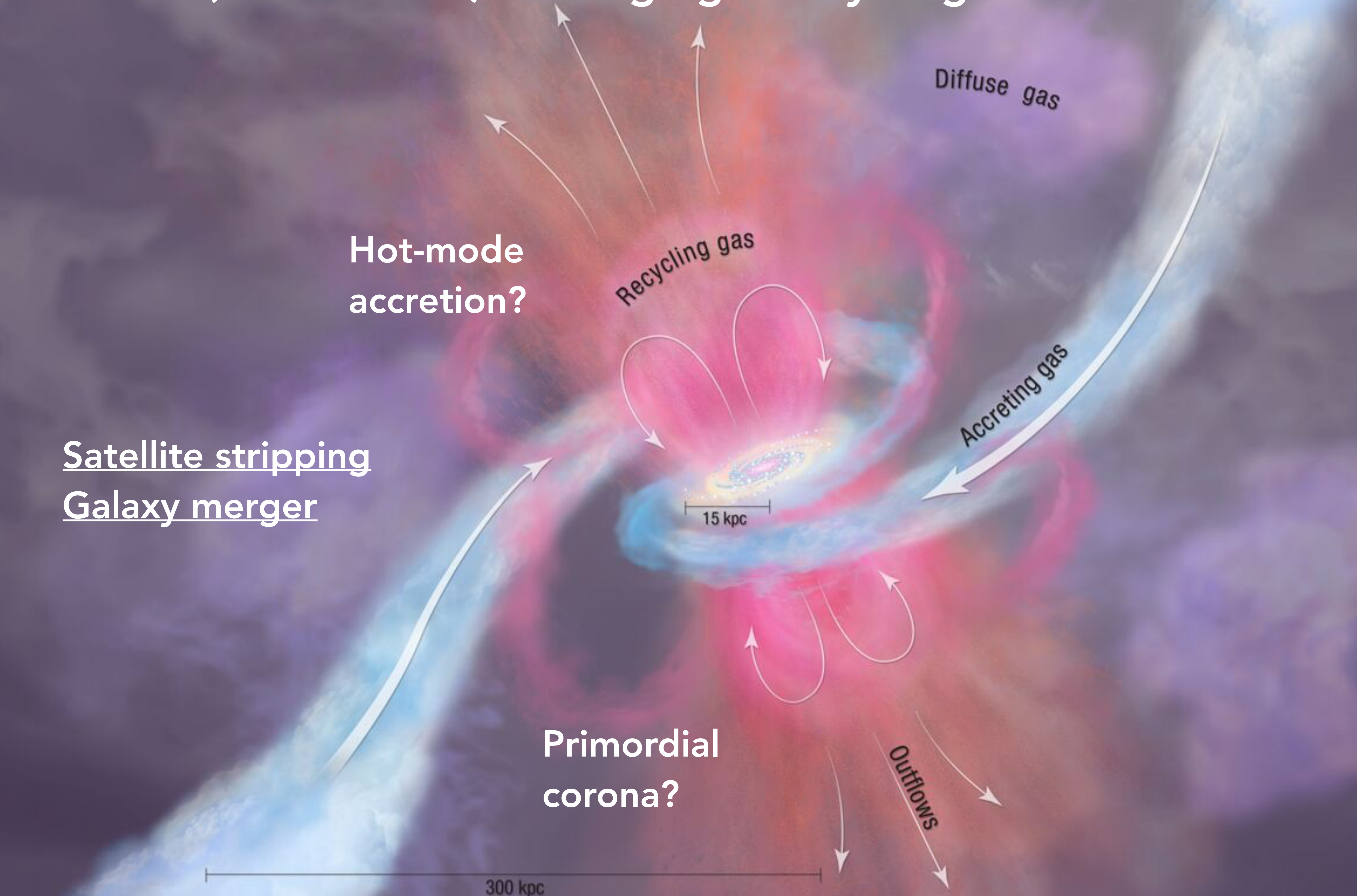
Project AMIGA: Distance and Metallicity Gradients along Andromeda's Giant Southern Stream from the Red Clump*

Roger E. Cohen[1], Jason S. Kalirai[1], Karoline M. Gilbert[1,2], Puragra Guhathakurta[3], Molly S. Peeples[1], Nicolas Lehner[4], Thomas M. Brown[1], Luciana Bianchi[2], Kathleen A. Barger[5], and John M. O'Meara[6]

Galaxies (=disk+CGM) are huge gas recycling factories



Tumlinson, Peeples, Werk (2017)

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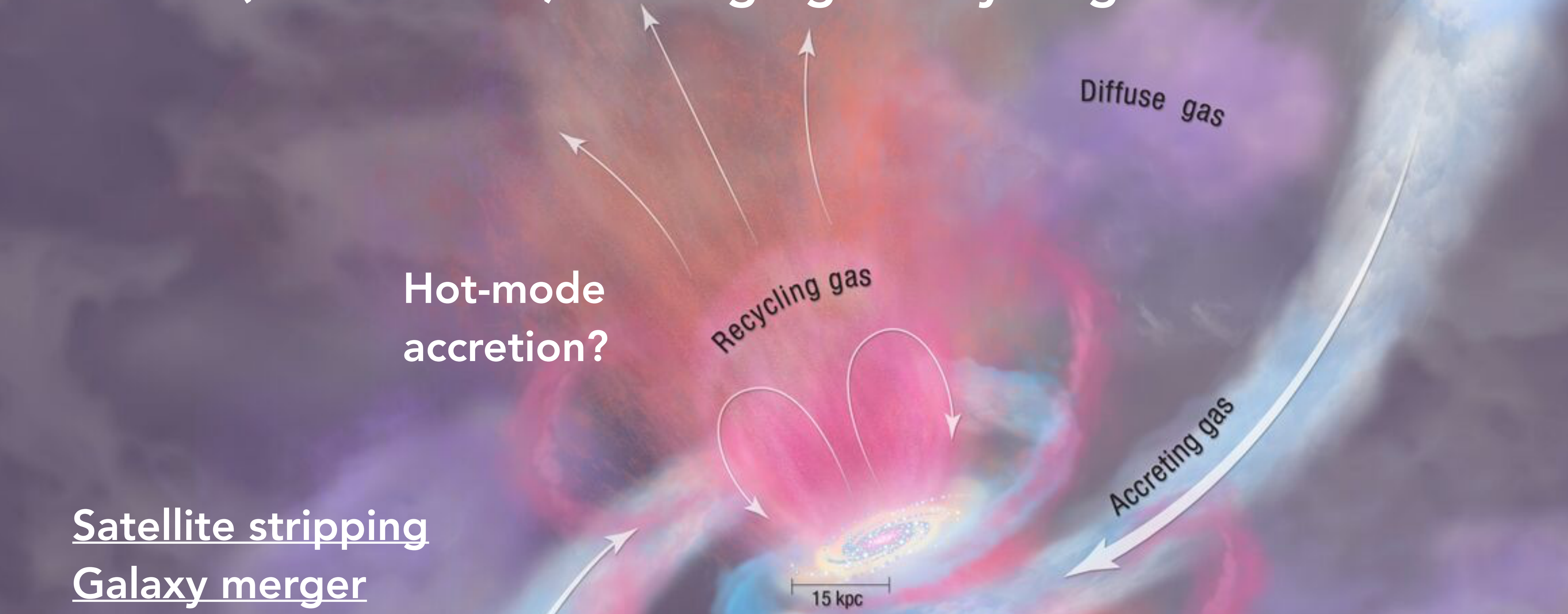
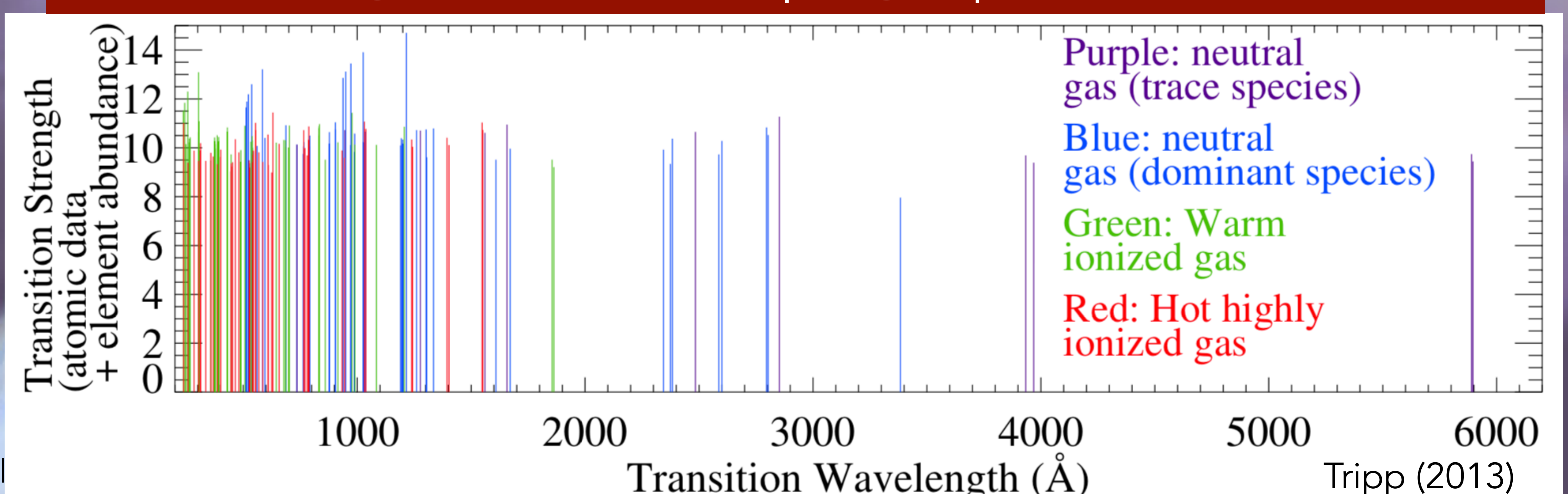


Hot-mode accretion?

Satellite stripping

Galaxy merger

The CGM of galaxies has multiple gas-phases: hot, warm, cool

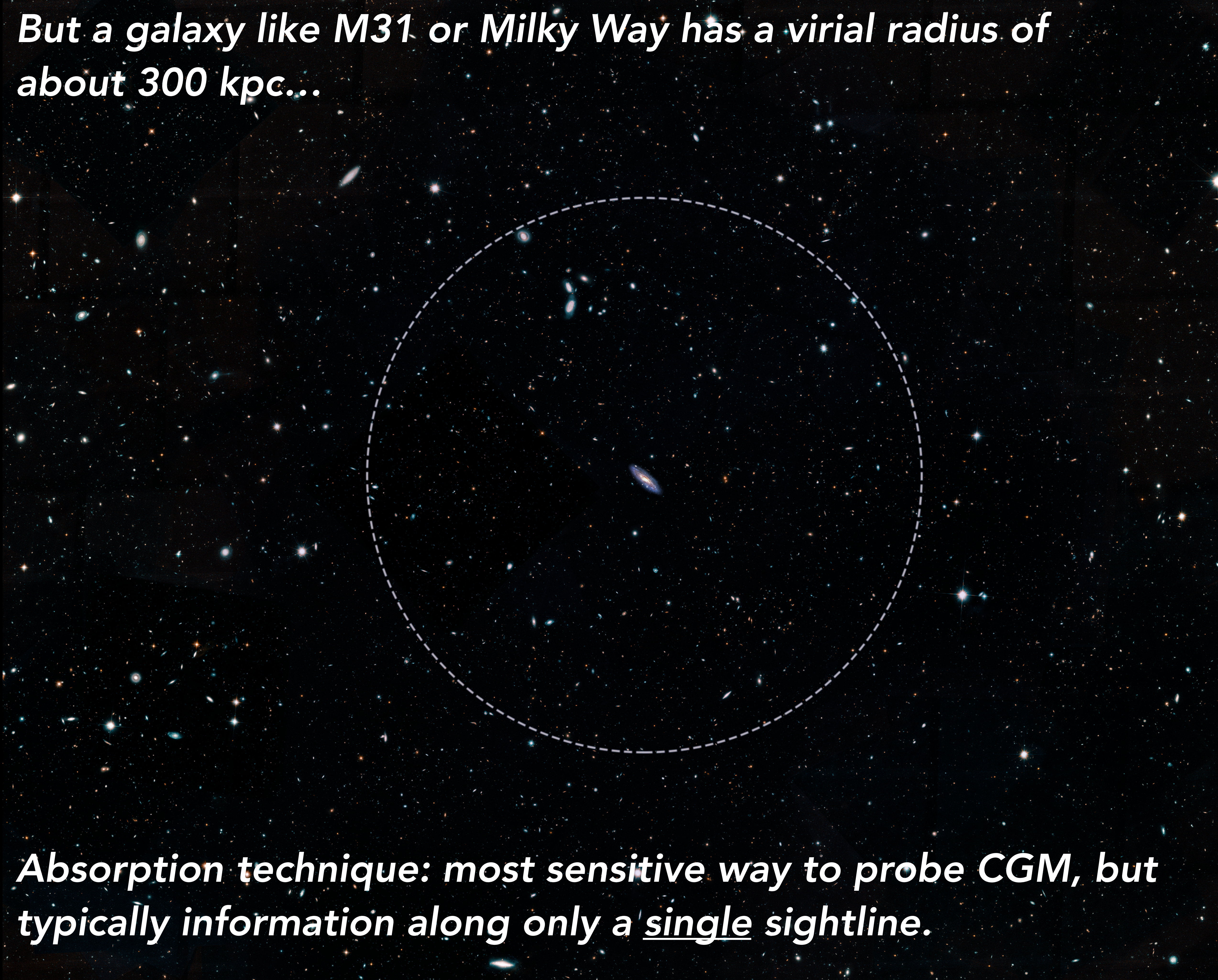


Tripp (2013)

Tumlinson, Peepl

Characterizing the CGM of galaxies

Emission observations (e.g. HI, X-rays) in the local universe are usually not very sensitive beyond 50 kpc.


But a galaxy like M31 or Milky Way has a virial radius of about 300 kpc…
Absorption technique: most sensitive way to probe CGM, but typically information along only a <u>single</u> sightline.

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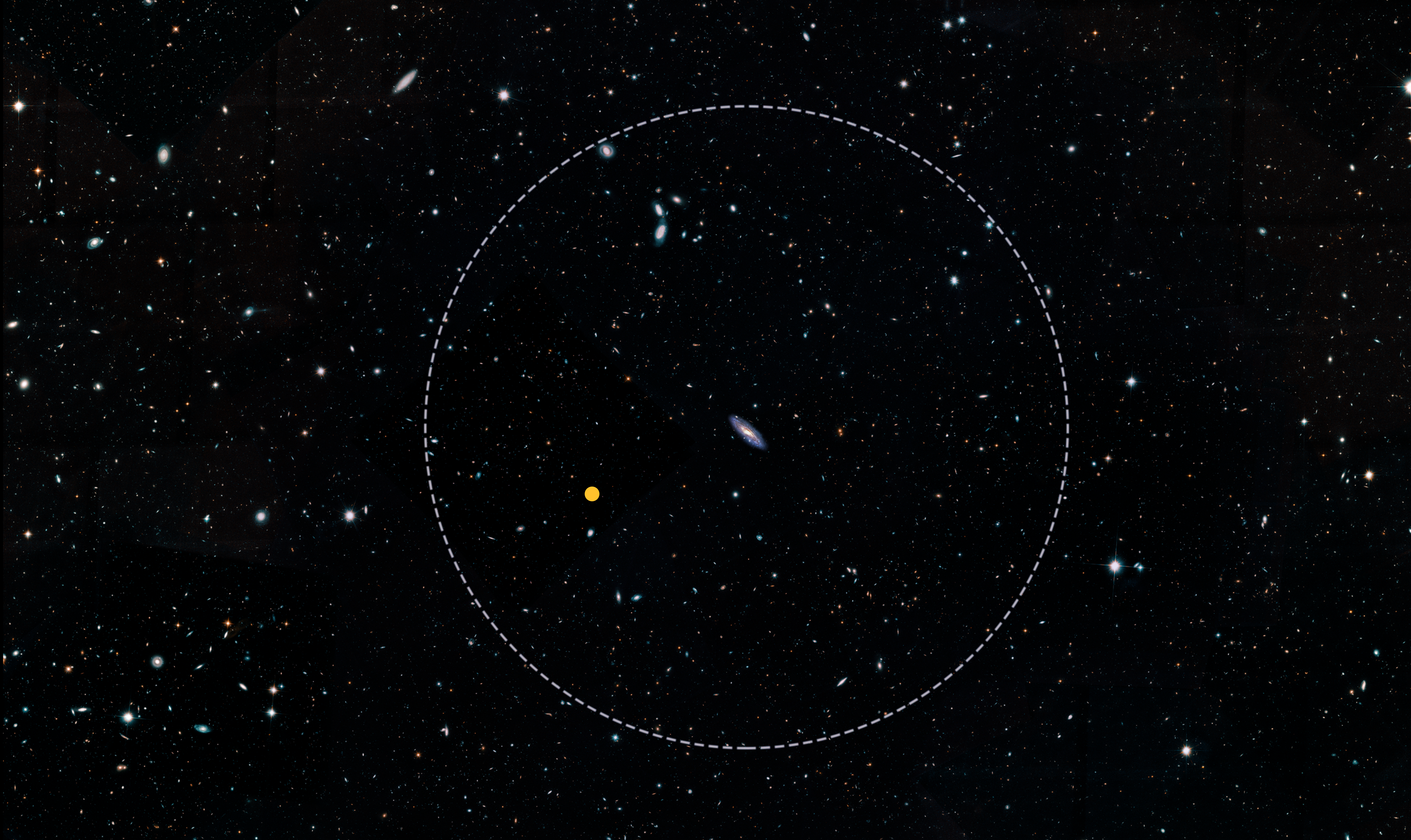

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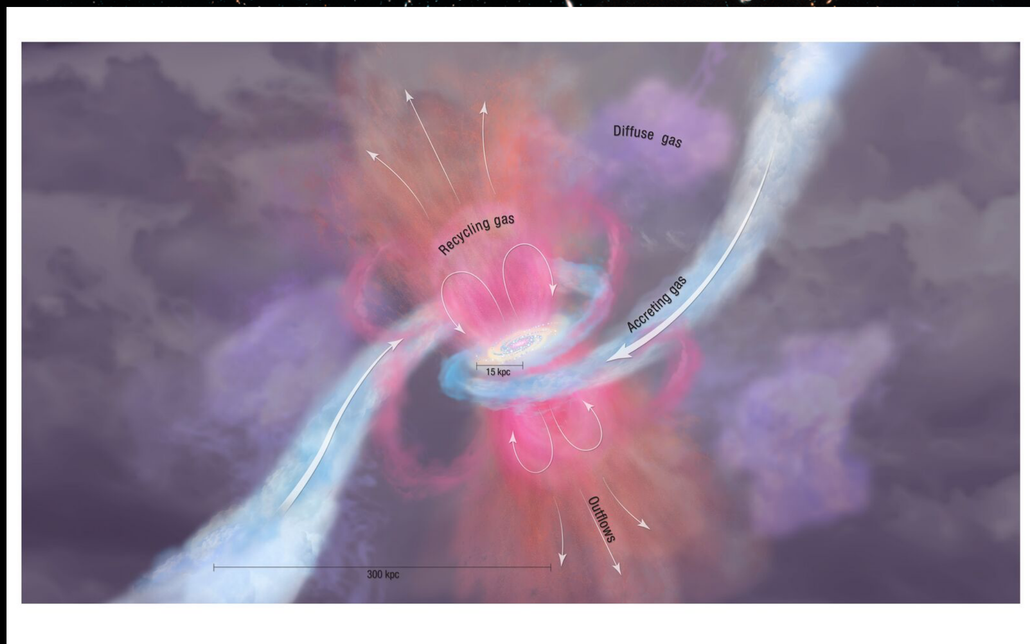

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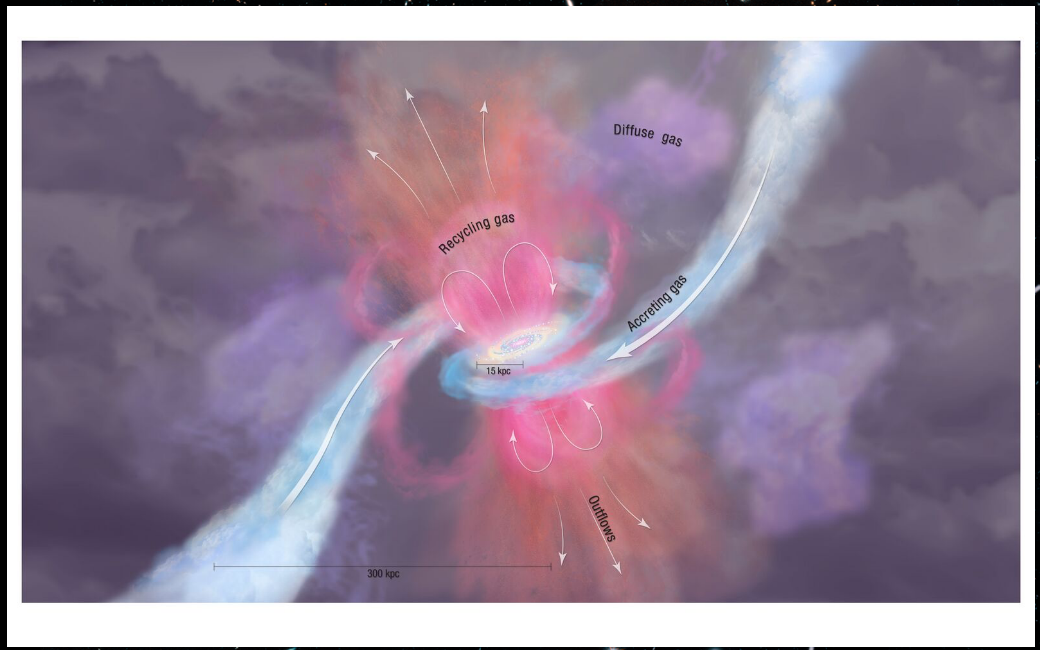
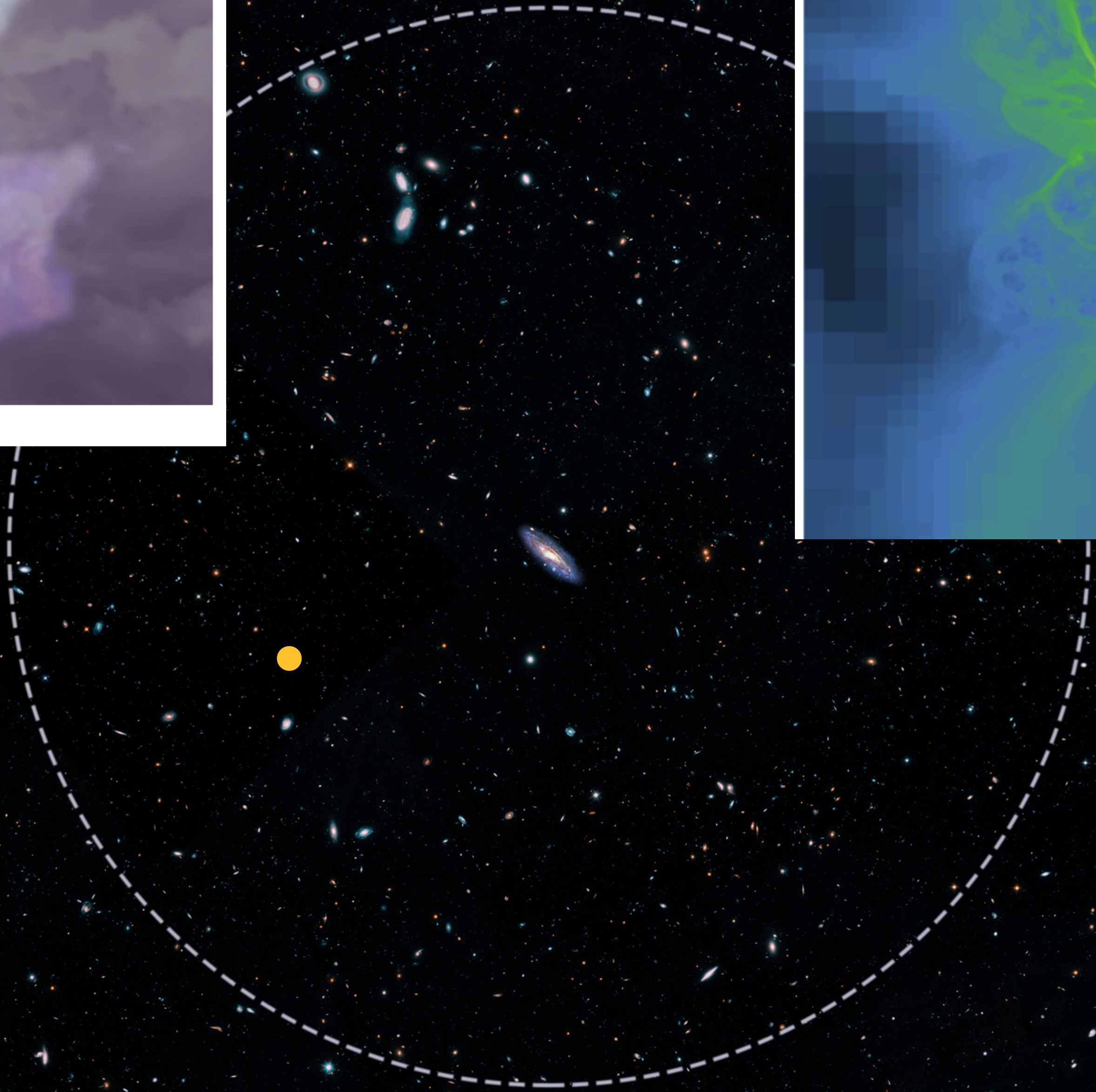
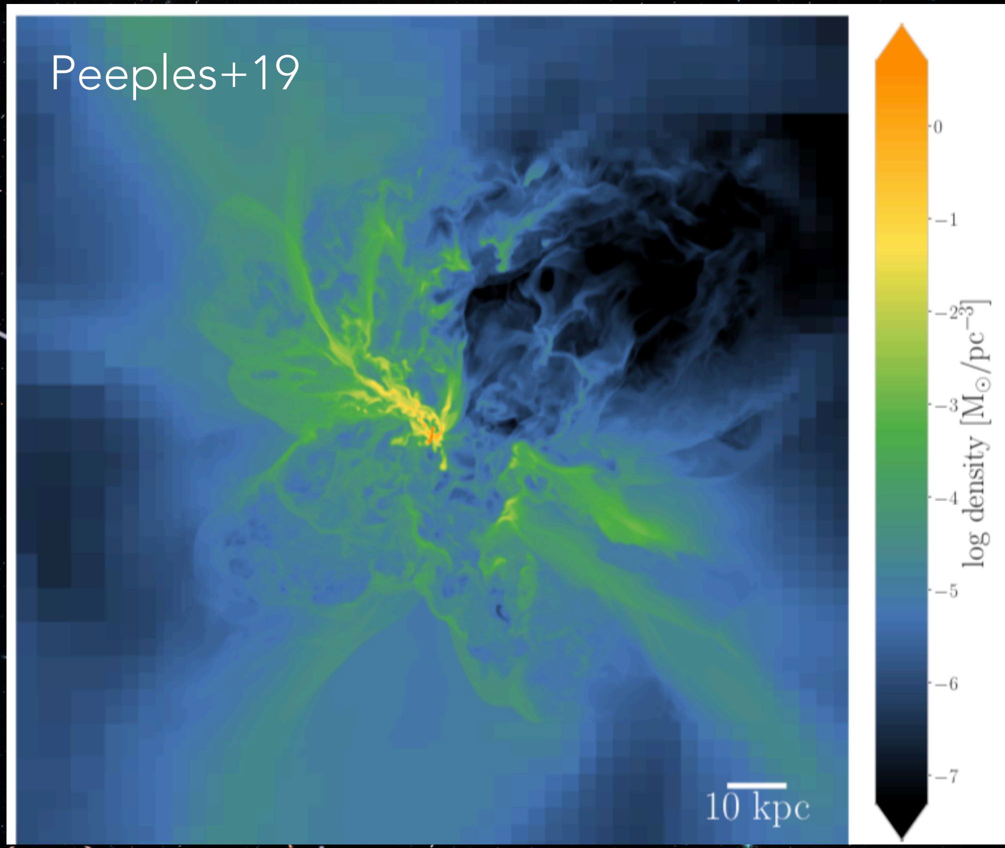
But a galaxy like M31 or Milky Way has a virial radius of about 300 kpc…







Absorption technique: most sensitive way to probe CGM, but typically information along only a <u>single</u> sightline.

What we really want to have is information from multiple sightlines

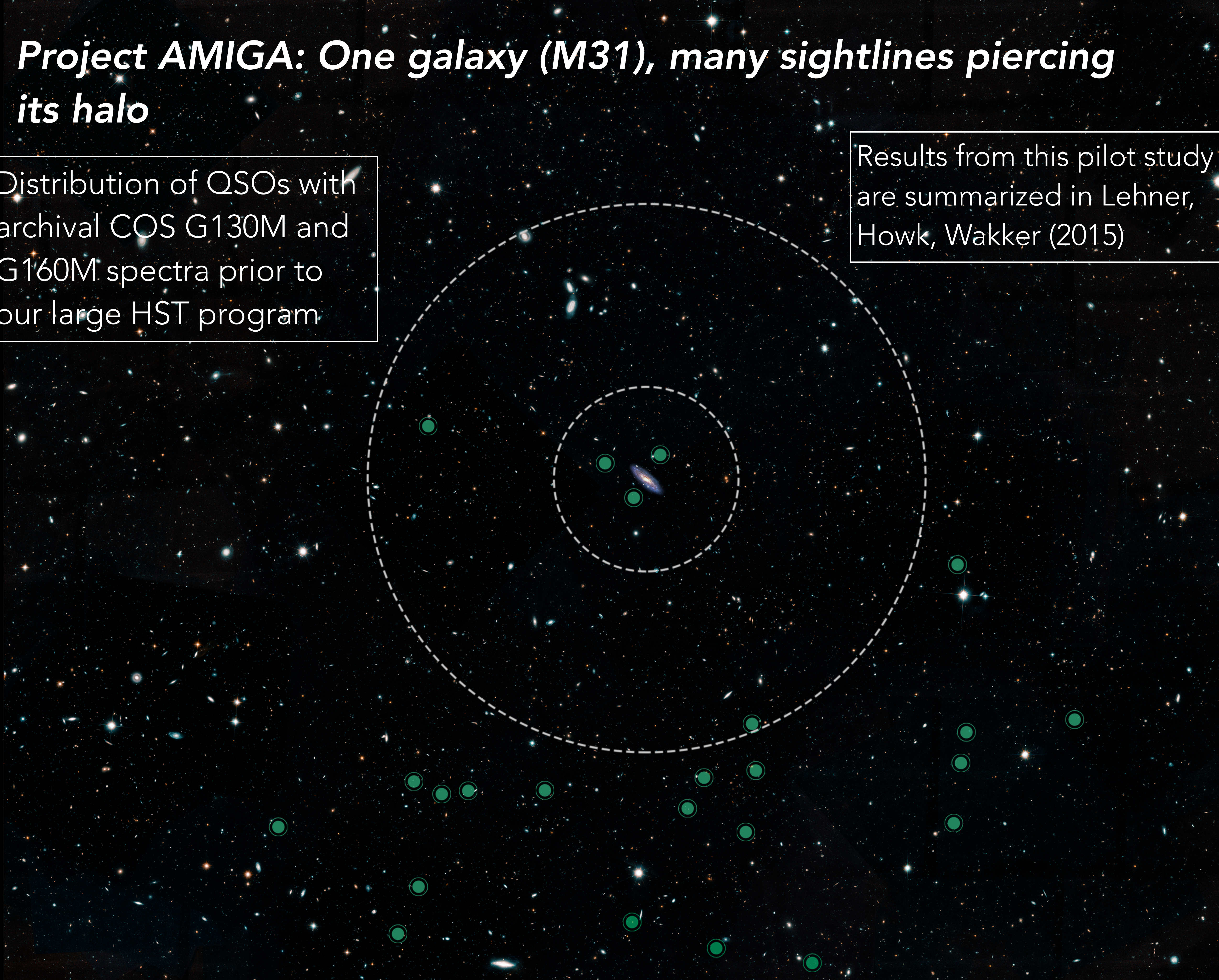
Since we rarely can do that, we assemble many galaxies with <u>single sightline</u> piercing them to capture "statistical" properties of the CGM(s) of galaxies.

But galaxies are not the same: mass, environments, star formation, orientation, etc. and may not be observed at the same epoch

Project AMIGA: One galaxy (M31)…

Project AMIGA: One galaxy (M31), many sightlines piercing its halo

Distribution of QSOs with archival COS G130M and G160M spectra prior to our large HST program



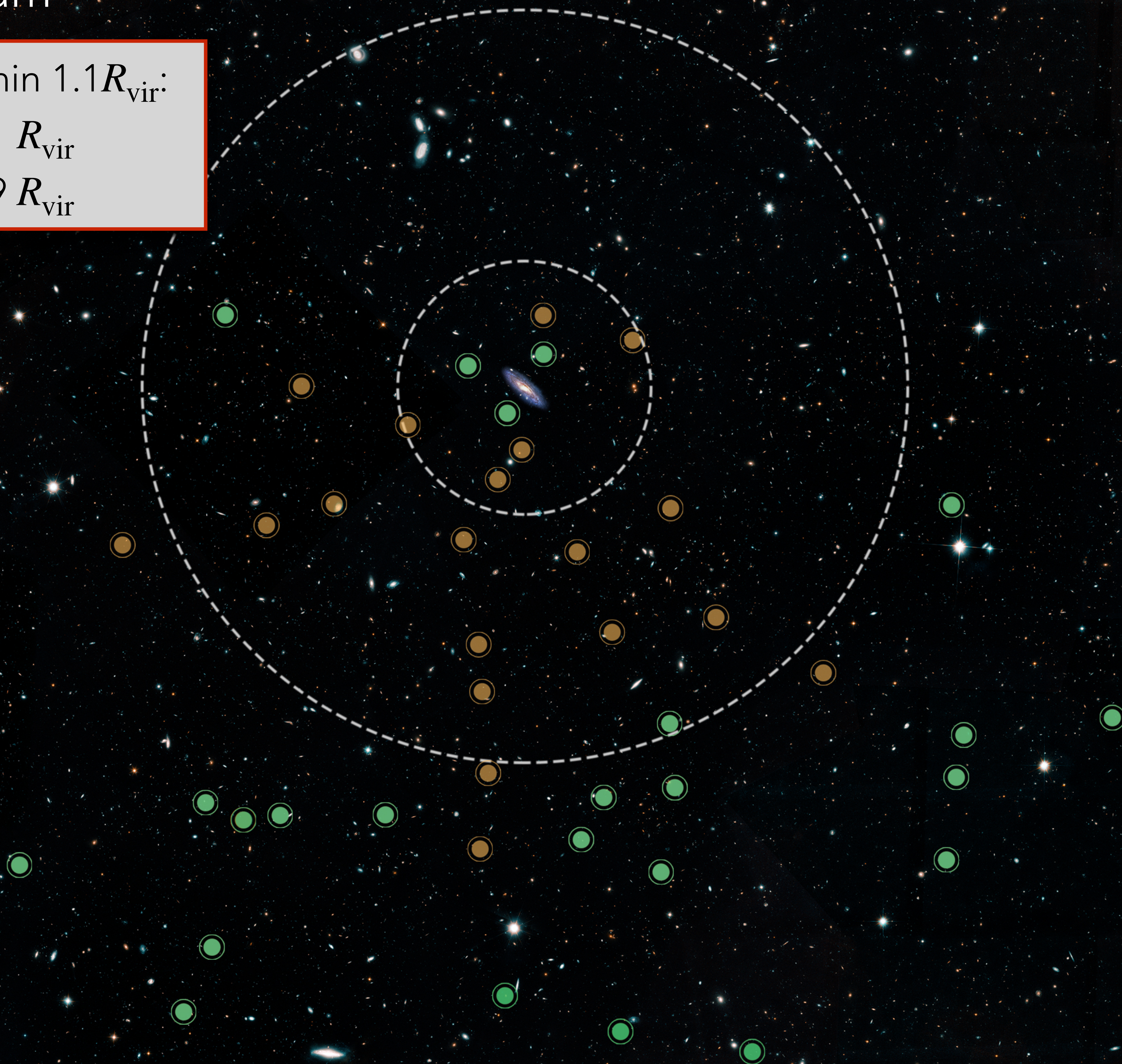
Results from this pilot study are summarized in Lehner, Howk, Wakker (2015)

Project AMIGA

Large HST Program

18 targeted QSOs within $1.1R_{\rm vir}$:

- 25 QSOs within 1.1 $R_{\rm vir}$
- 43 QSOs within 1.9 $R_{\rm vir}$



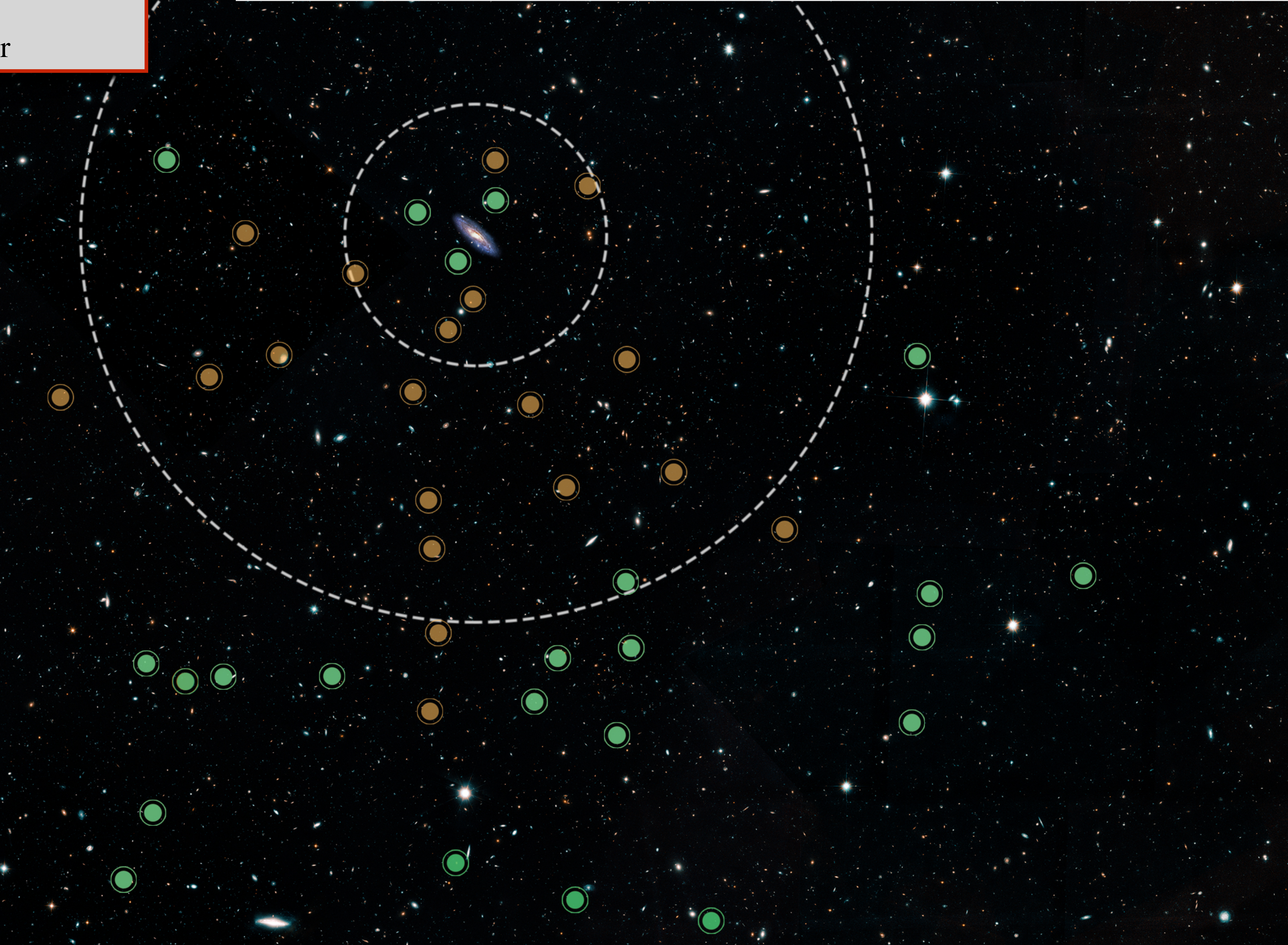
Project AMIGA

Large HST Program

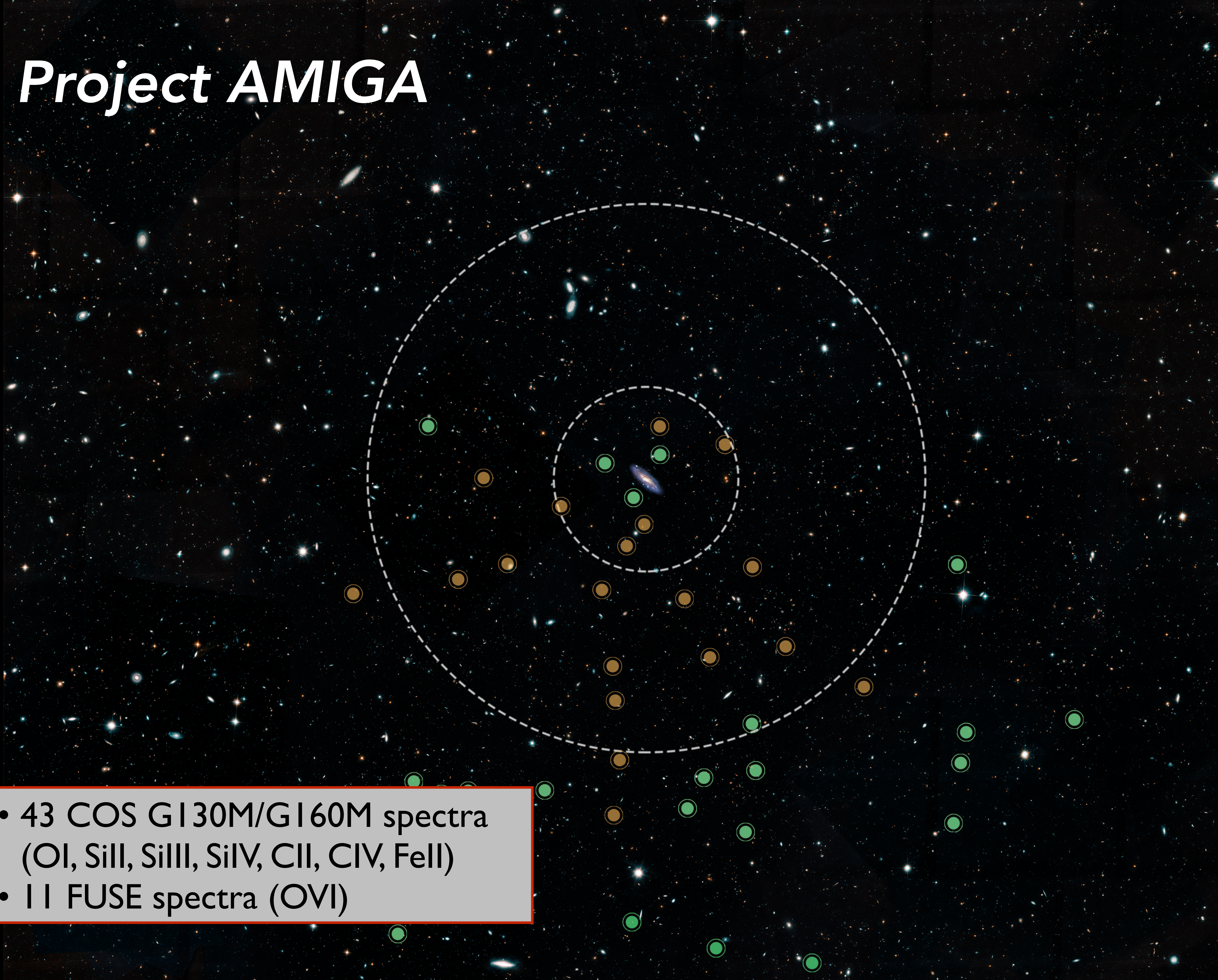
18 targeted QSOs within $1.1 R_{\rm vir}$:
- 25 QSOs within 1.1 $R_{\rm vir}$
- 43 QSOs within 1.9 $R_{\rm vir}$

"Follow the metals":

- first determination in absorption of the extent of a single galaxy halo.
- first maps of the velocities, surface densities, ionized fraction, gas-phases as a function of R and azimuth for a single galaxy halo.

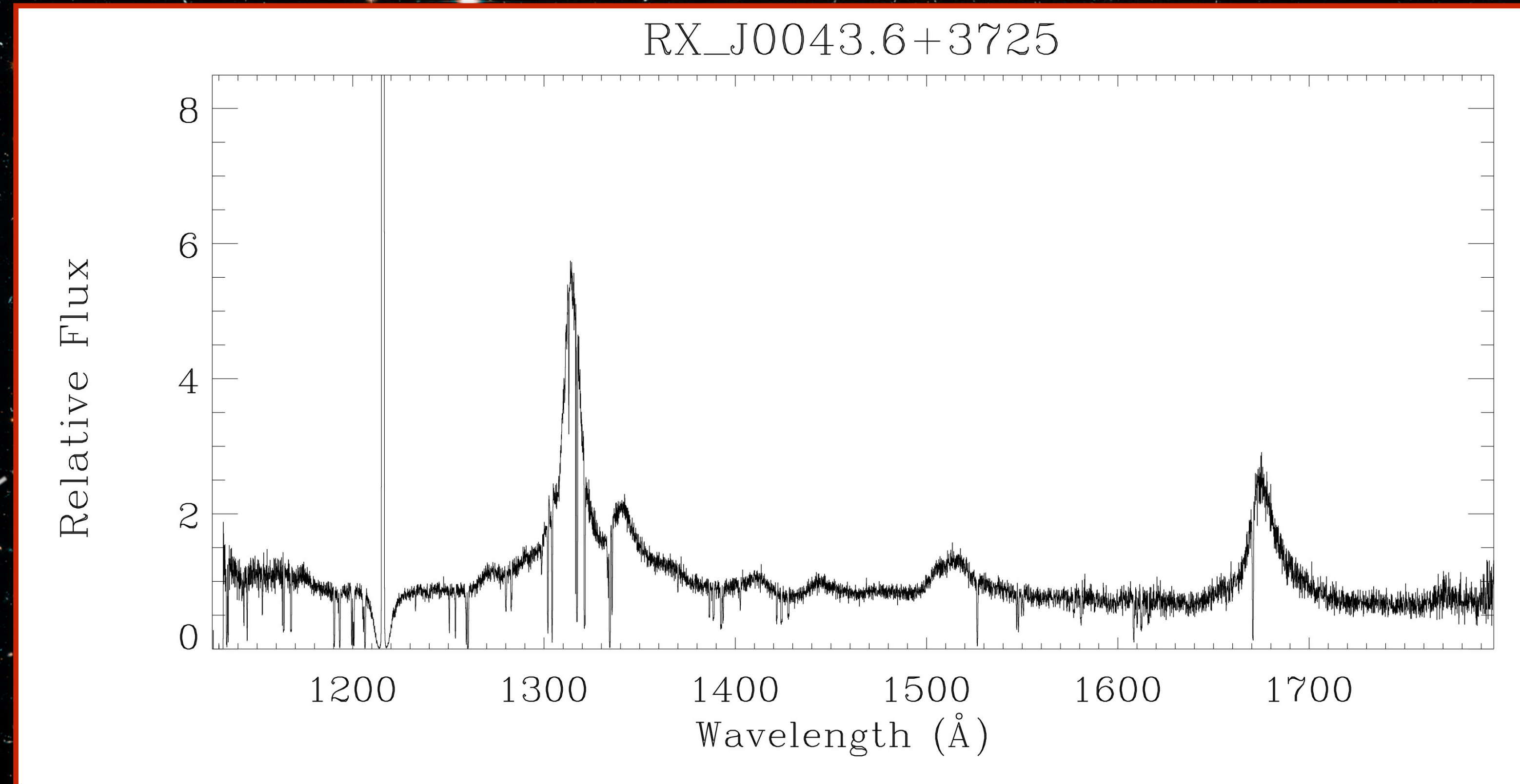


Project AMIGA



- 43 COS G130M/G160M spectra (OI, SiII, SiIII, SiIV, CII, CIV, FeII)
- 11 FUSE spectra (OVI)

Project AMIGA



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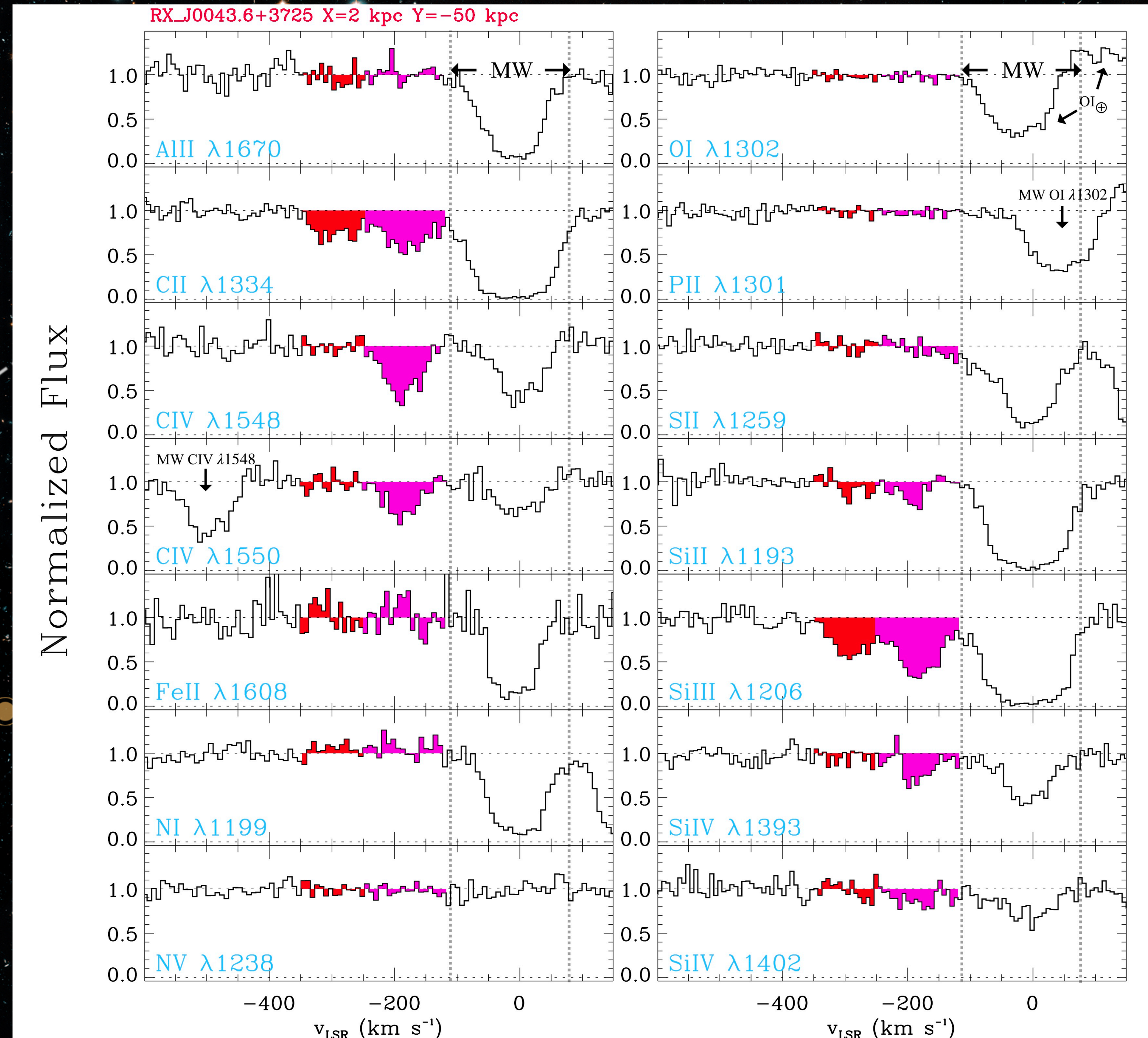

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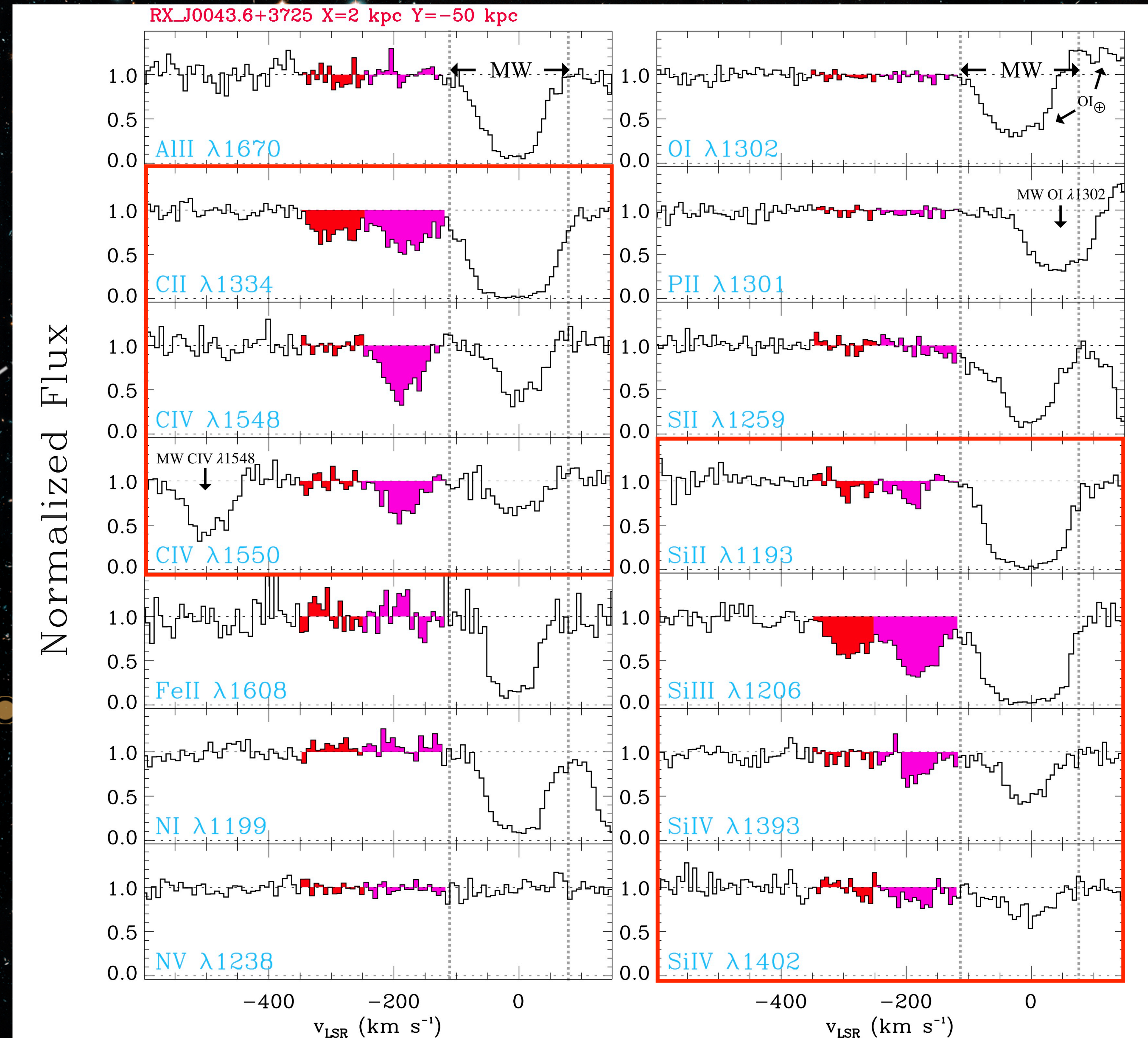

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How big is the CGM of M31?

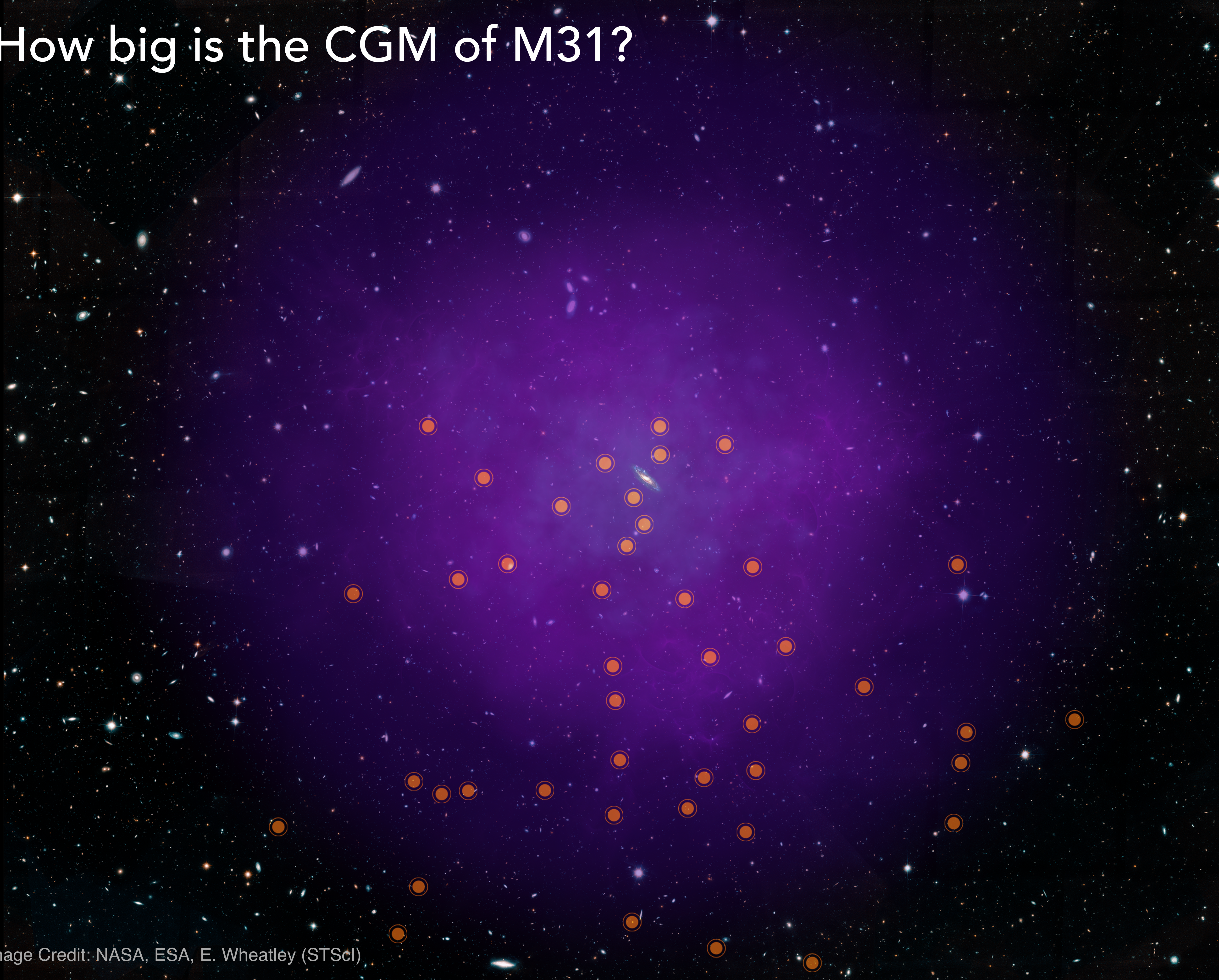
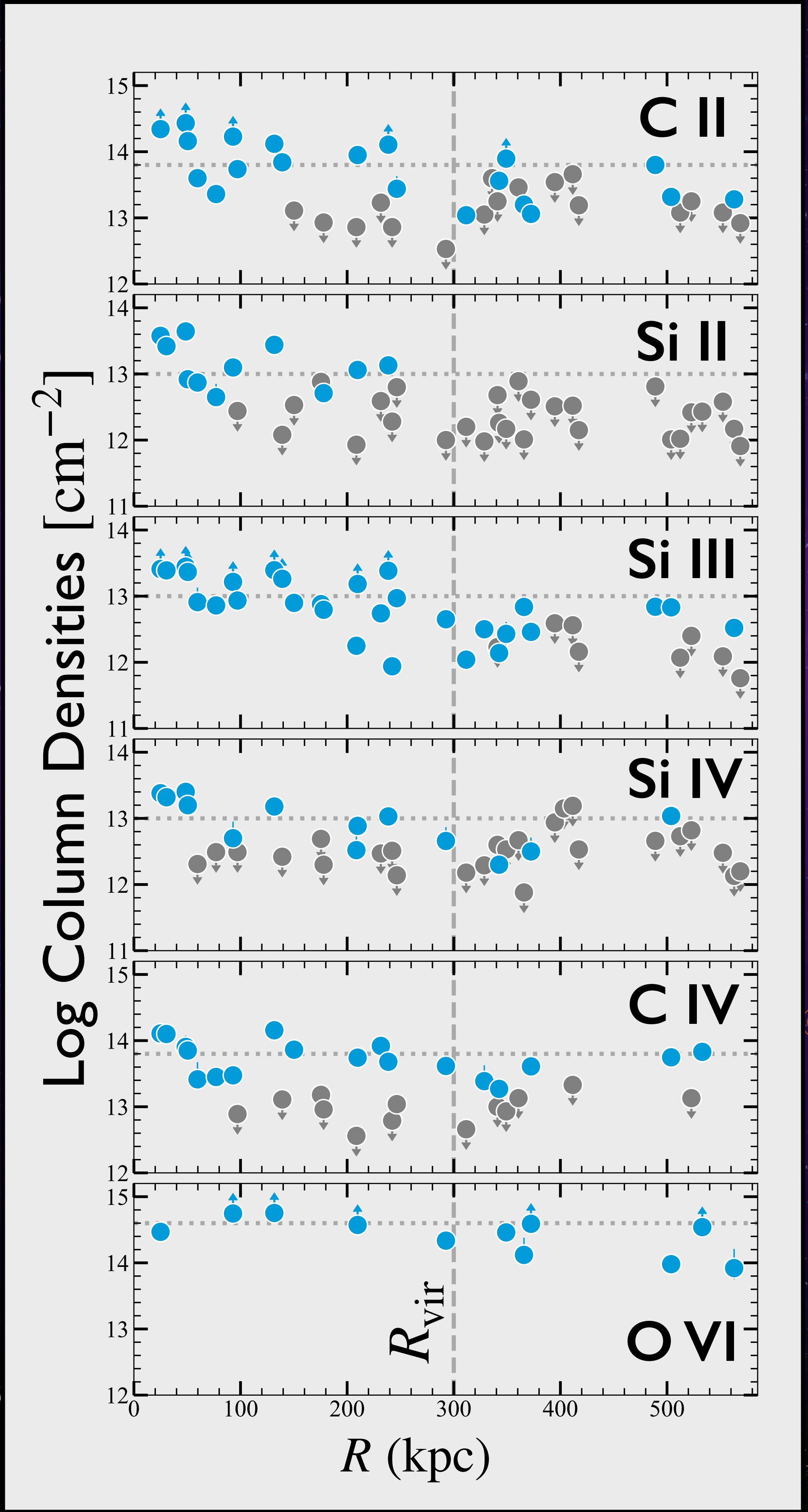


Image Credit: NASA, ESA, E. Wheatley (STScI)

How big is the CGM of M31?

Detection of M31 CGM gas

No detection of M31 CGM



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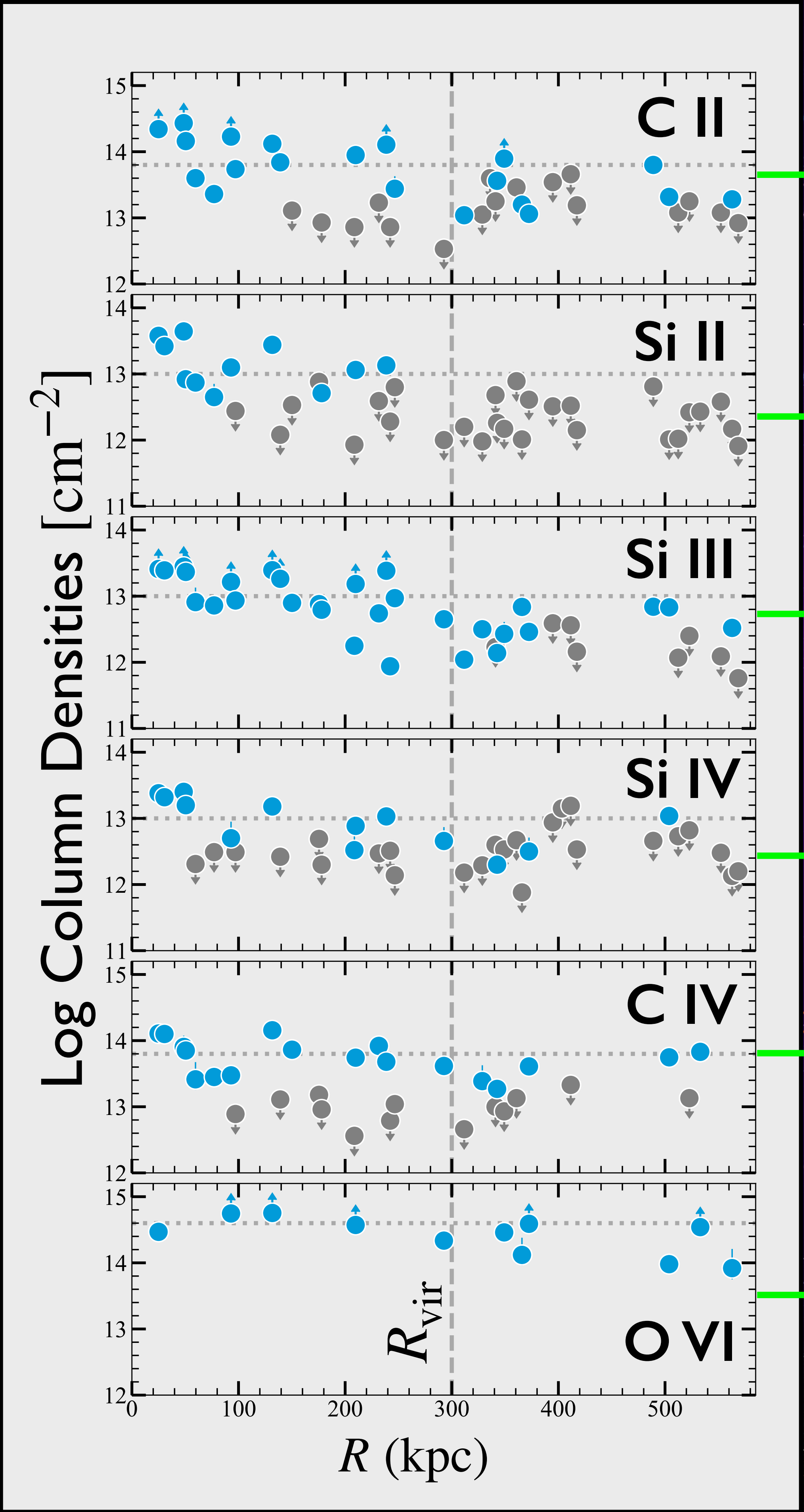

low ions: probe of ~10^3-10^4 K neutral and ionized gas

Intermediate ions: probe of ~10^3-$10^{4.5}$ K ionized gas

high ions: probe of ~$10^{4.5}$-$10^{5.5}$ K ionized gas

Image Credit: NASA, ESA, E. Wheatley (STScI)

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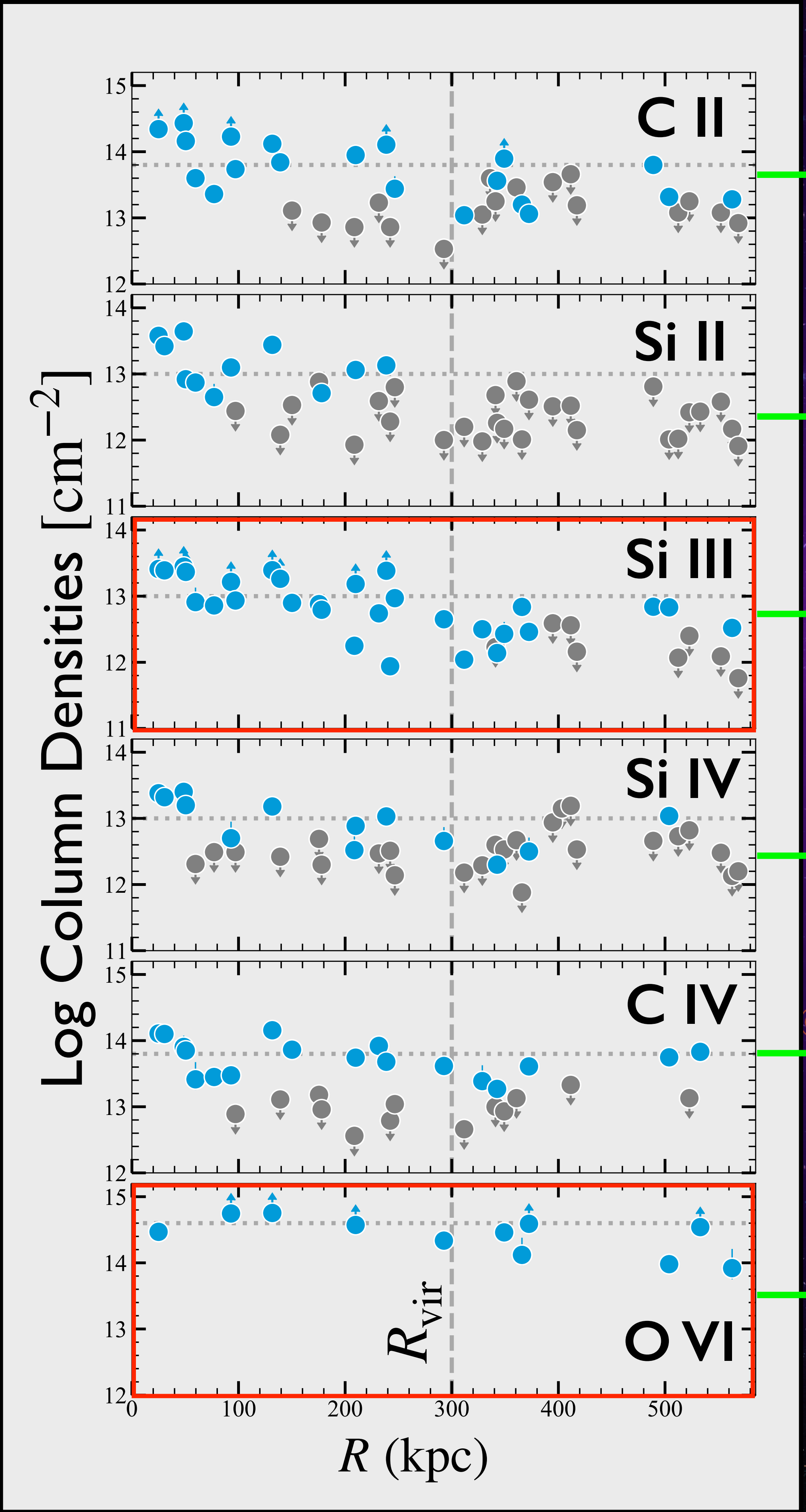

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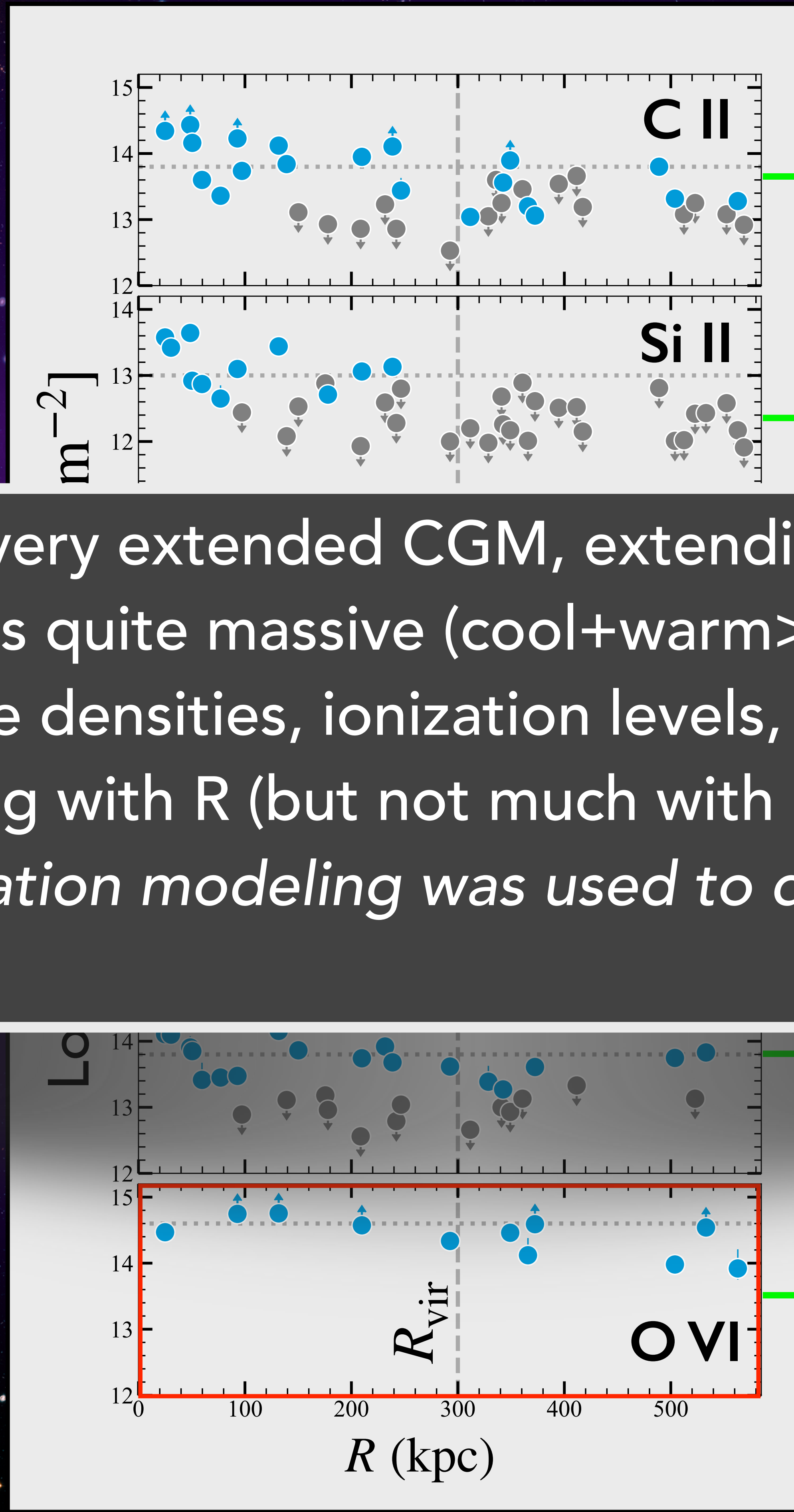


low ions: probe of ~10^3-10^4 K neutral and ionized gas

high ions: probe of ~$10^{4.5}$-$10^{5.5}$ K ionized gas

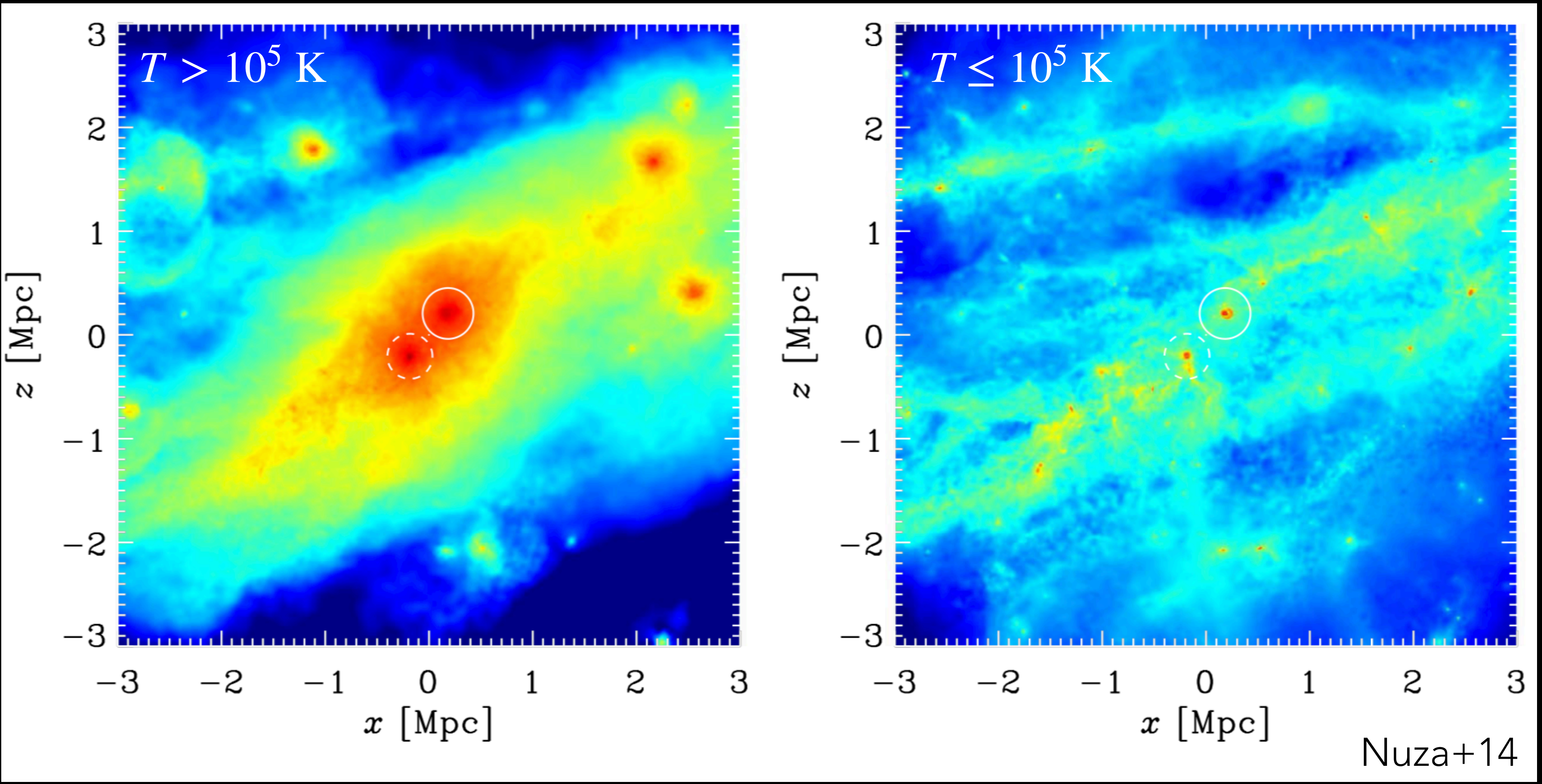
- M31 has a very extended CGM, extending beyond R_{vir}.
- M31 CGM is quite massive (cool+warm>4×10^{10} M_{sun}).
- M31 surface densities, ionization levels, and kinematic are changing with R (but not much with azimuth).

NB: *no ionization modeling was used to derive these properties.*

Image Credit: NASA, ESA, E. Wheatley (STScI)

Zoom-in cosmological simulations: widespread of multiple gas-phases in the CGM of galaxies that also depends on R

CLUES



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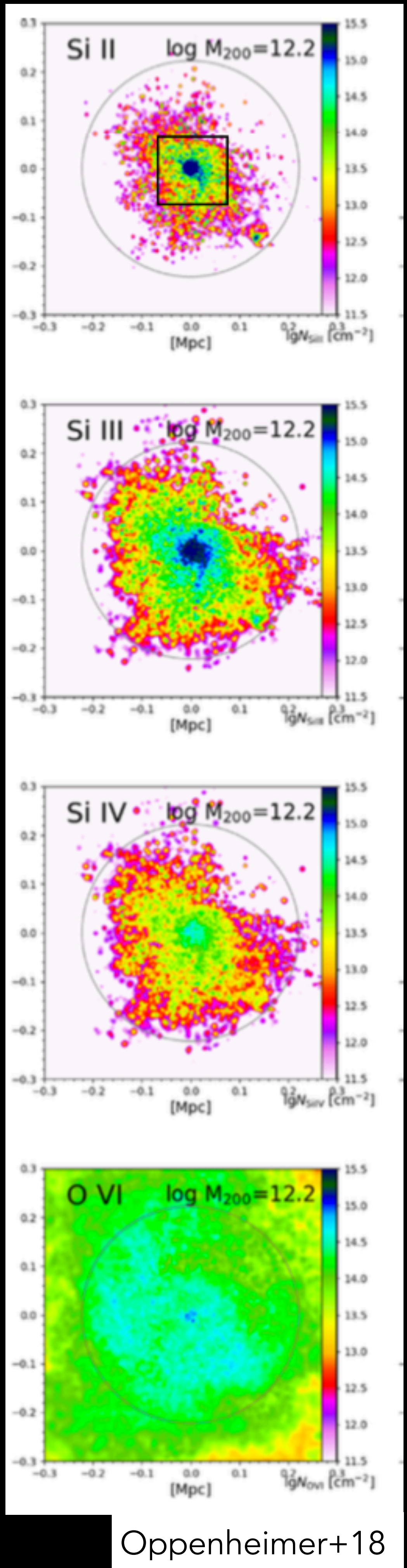
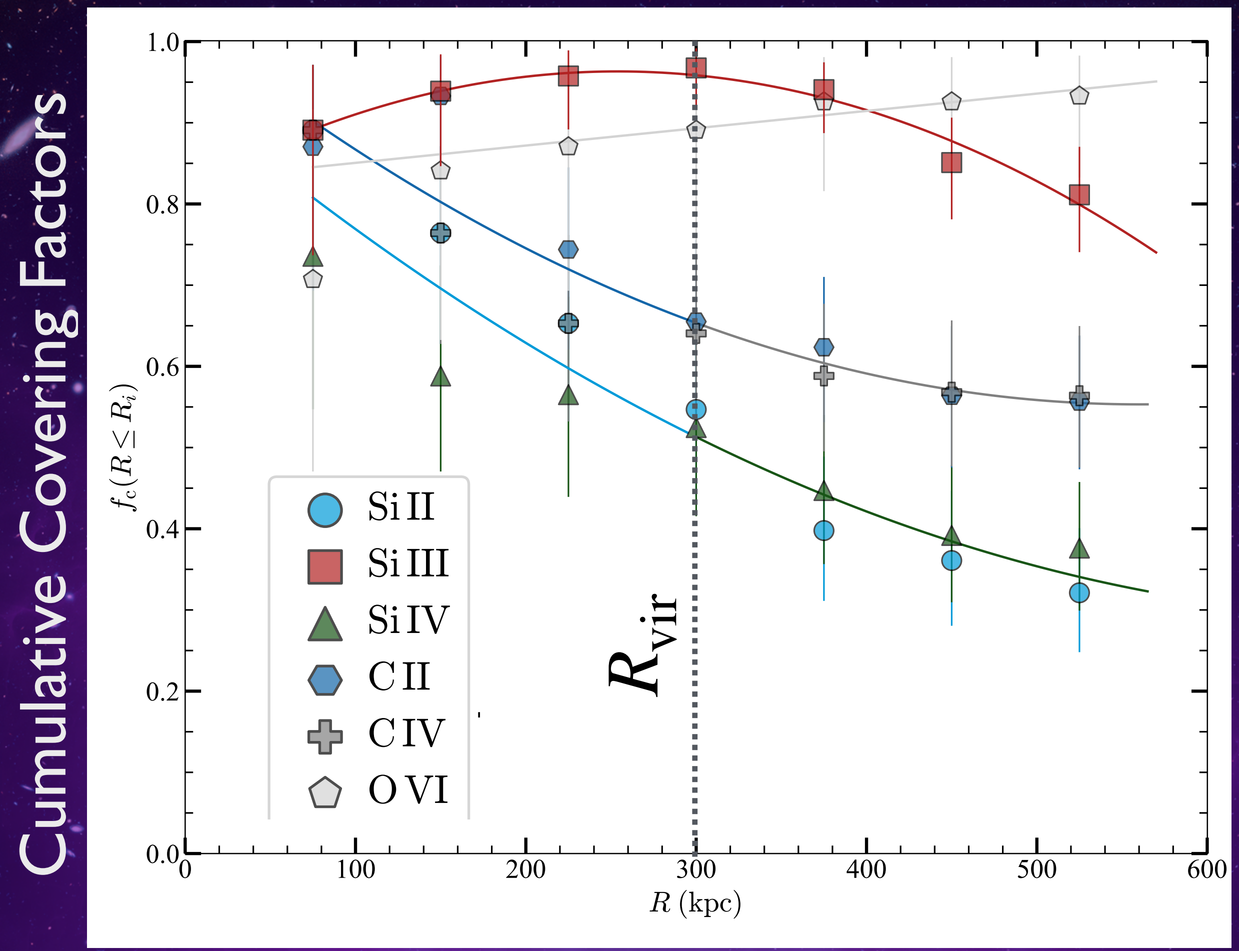


Qualitative similarities in the distribution of the CGM properties between Project AMIGA and zoom-in simulations, but there are key quantitative differences (Lehner+2020).

UV observations are key to sensitively probe the CGM

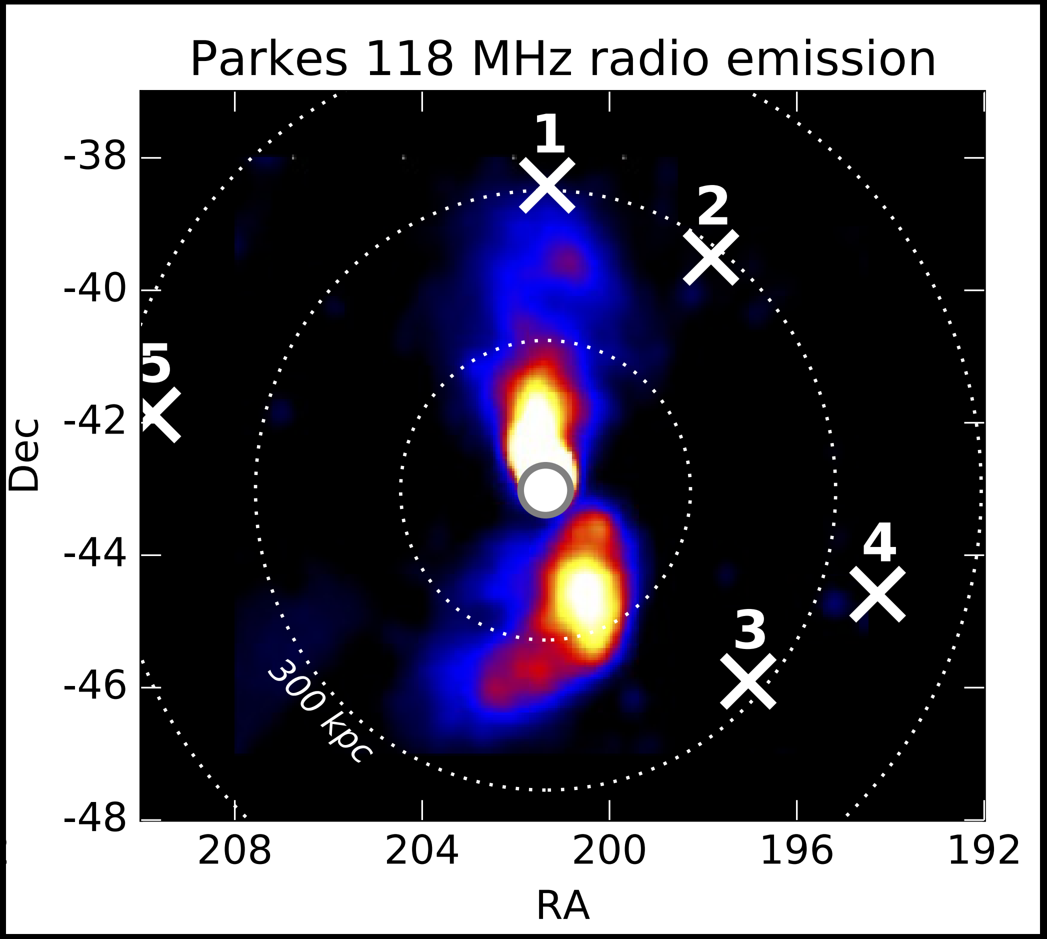


Si III and O VI are quite remarkable relative to the other ions and HI.

Deep HI emission is not detected down to 17.5 dex (Howk+17): HI surveys will need to be more sensitive than $N(\mathrm{H\,I}) \ll 10^{17}\ \mathrm{cm}^{-2}$ to hope to detect CGM gas well beyond 20–30 kpc.

What will it take to do this experiment toward other galaxies?

Example: Cen A (about 5x farther away than M31)



See also, e.g., Bowen+2016, Keeney+2013 for other examples.

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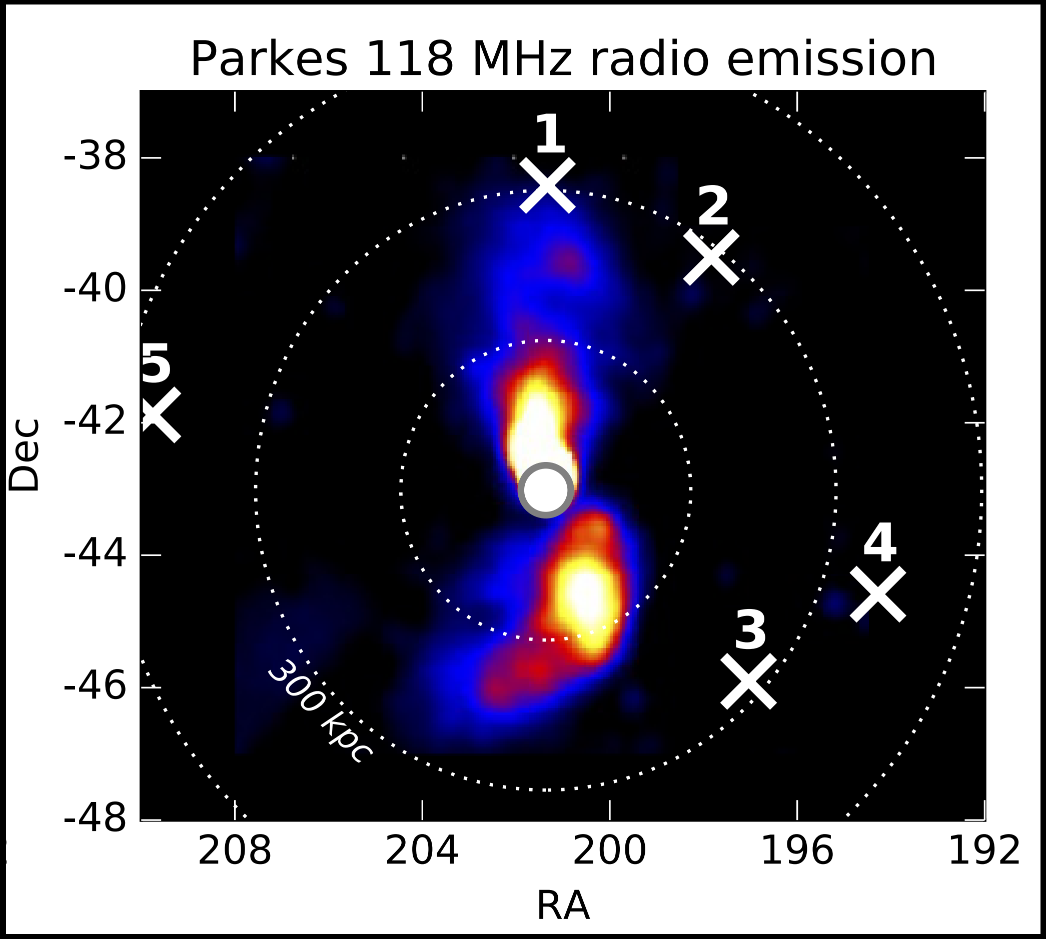

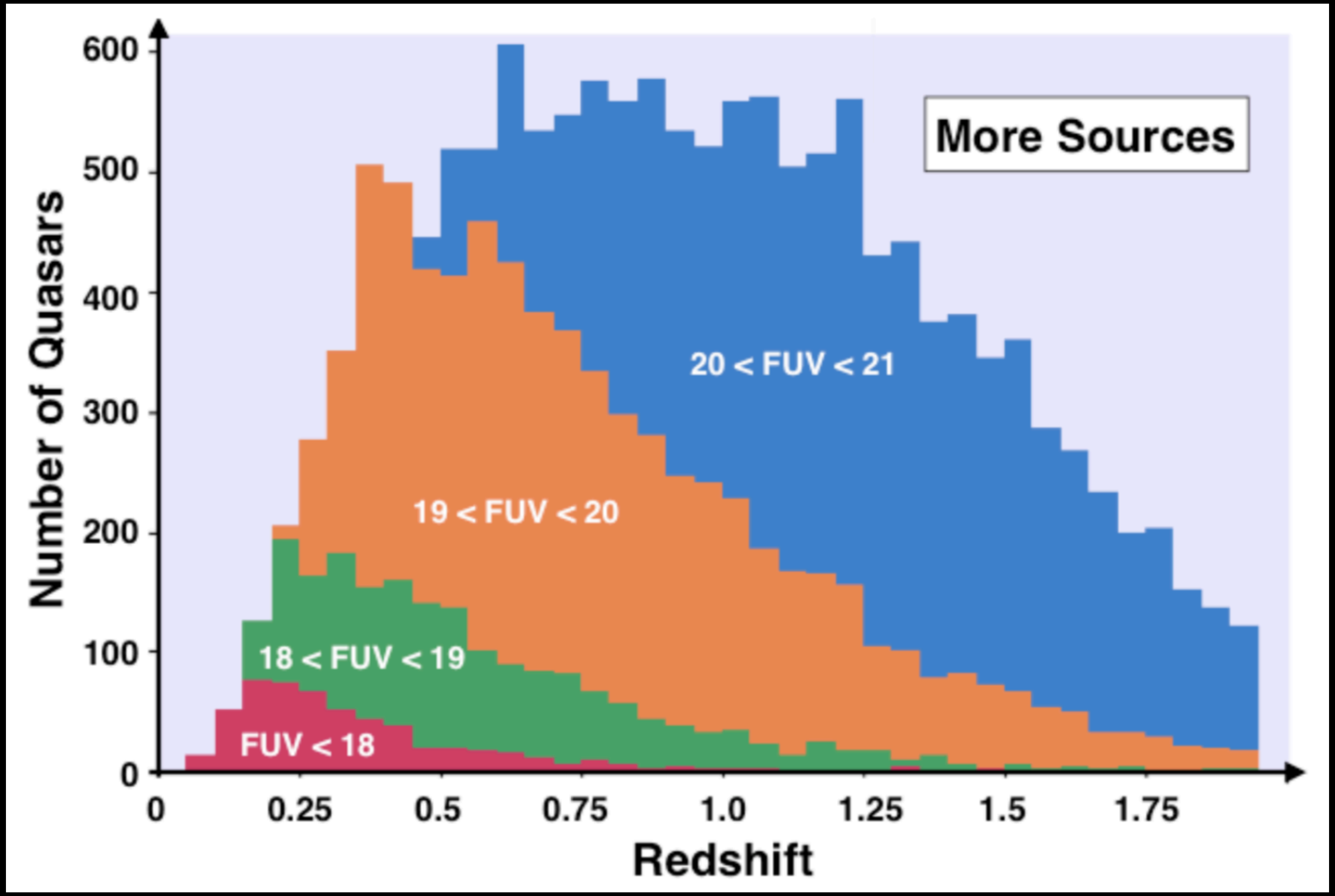

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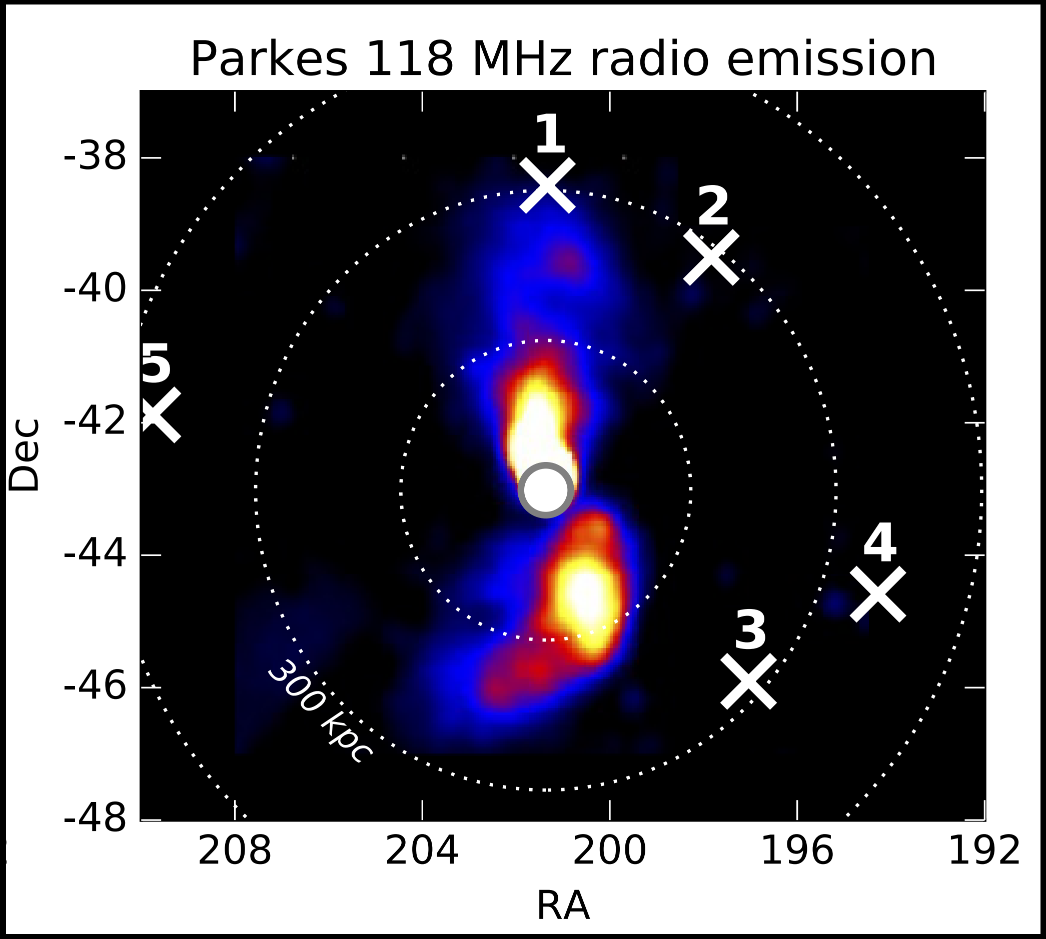

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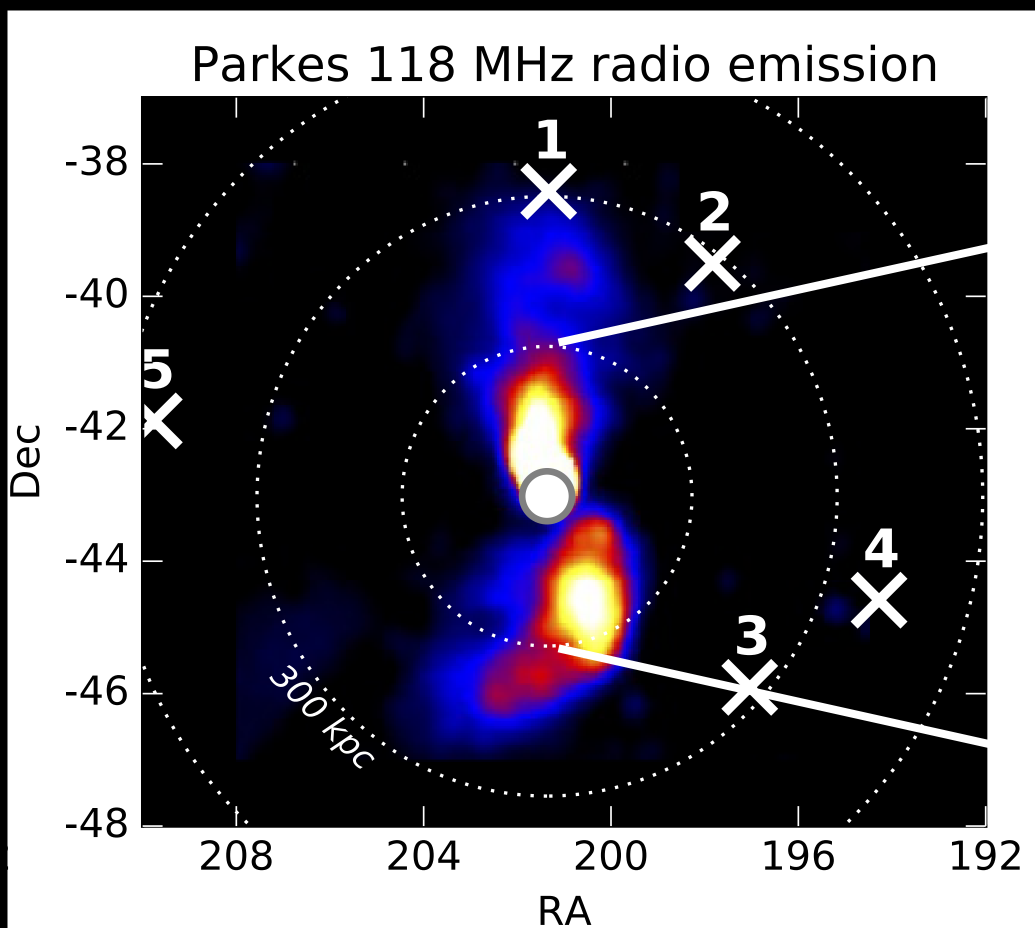

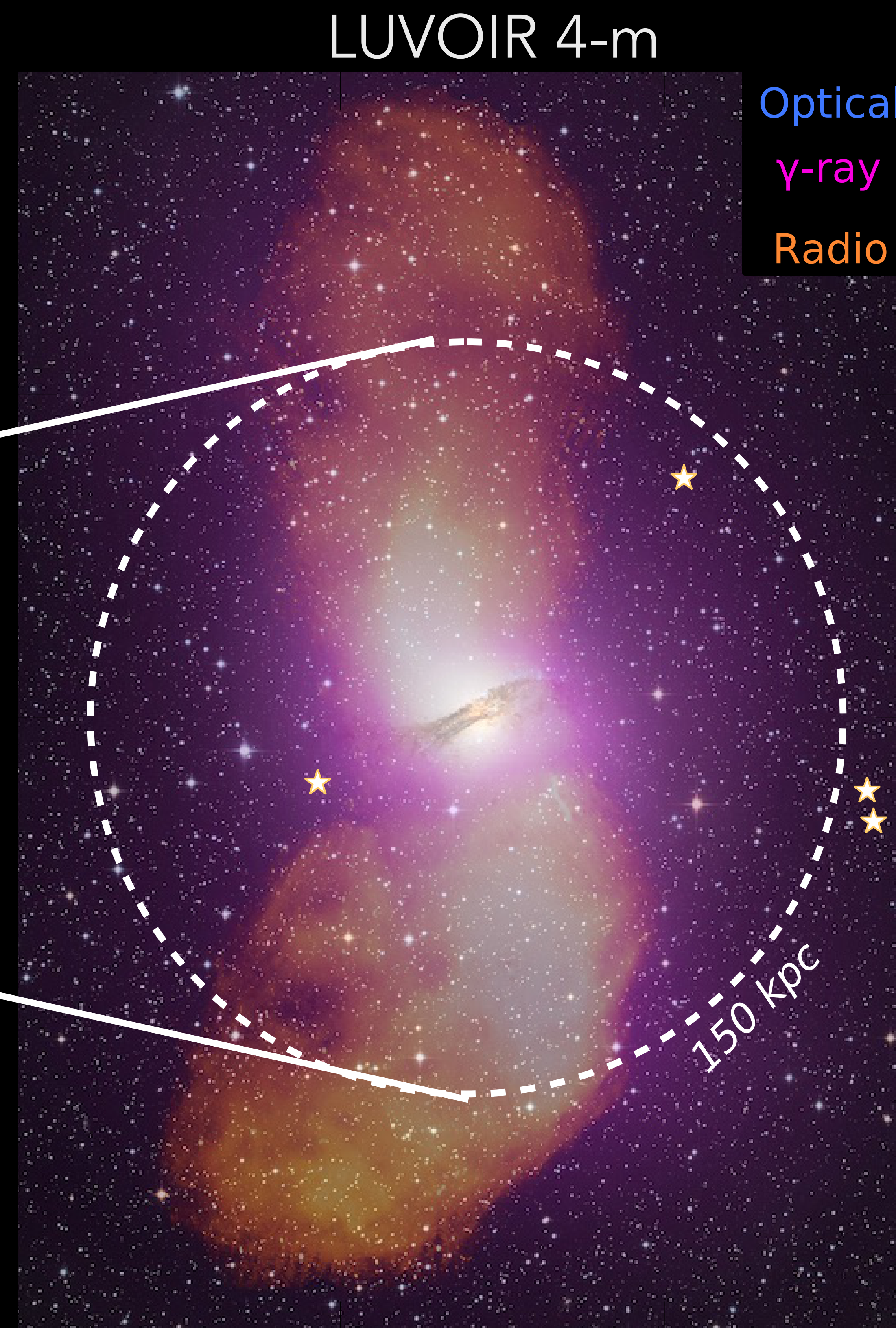

Courtesy Chris Howk (Fig. 5.5—LUVOIR interim report)

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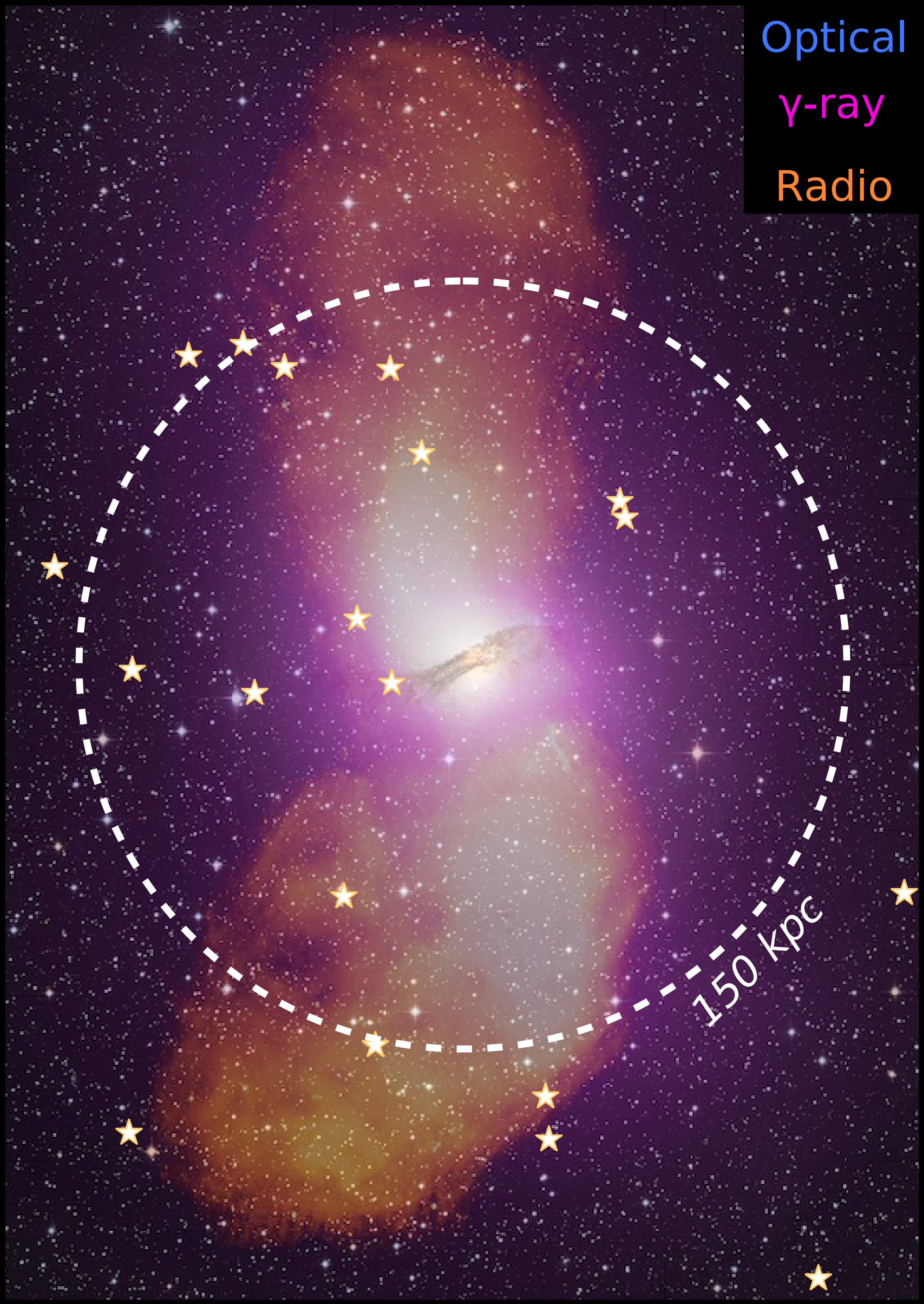
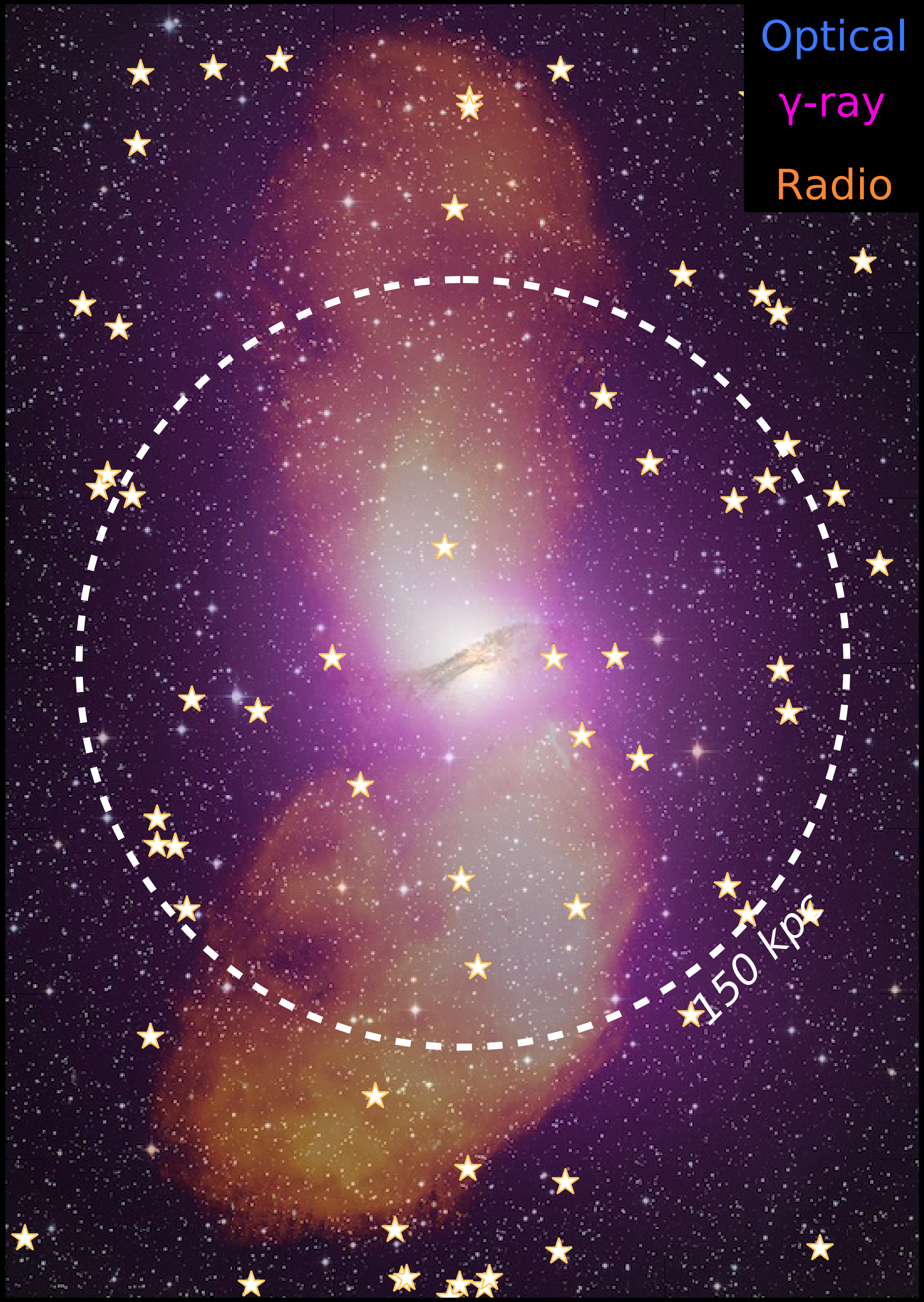
LUVOIR 6-m



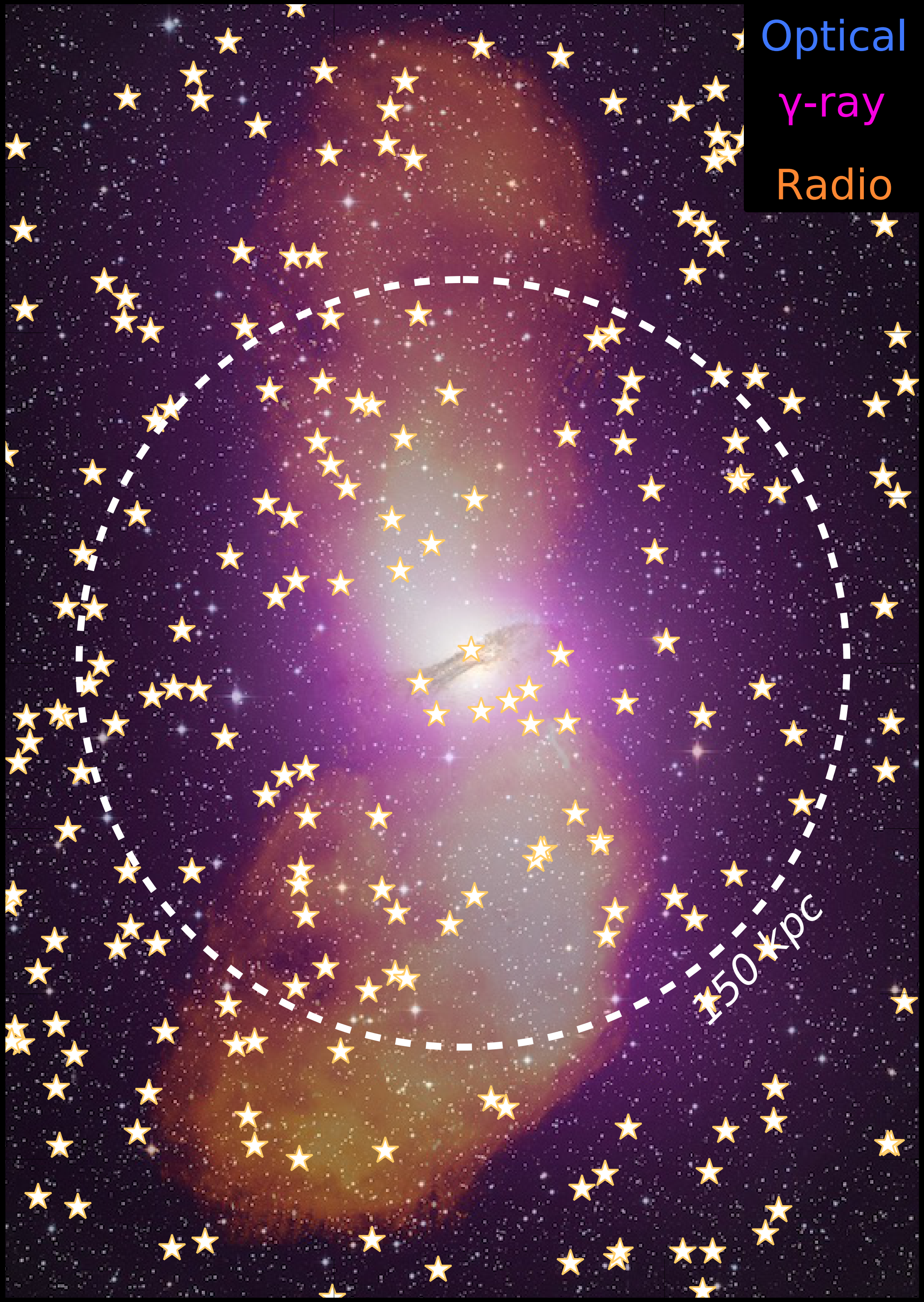
Courtesy Chris Howk (Fig. 5.5—LUVOIR interim report)

LUVOIR 9-m



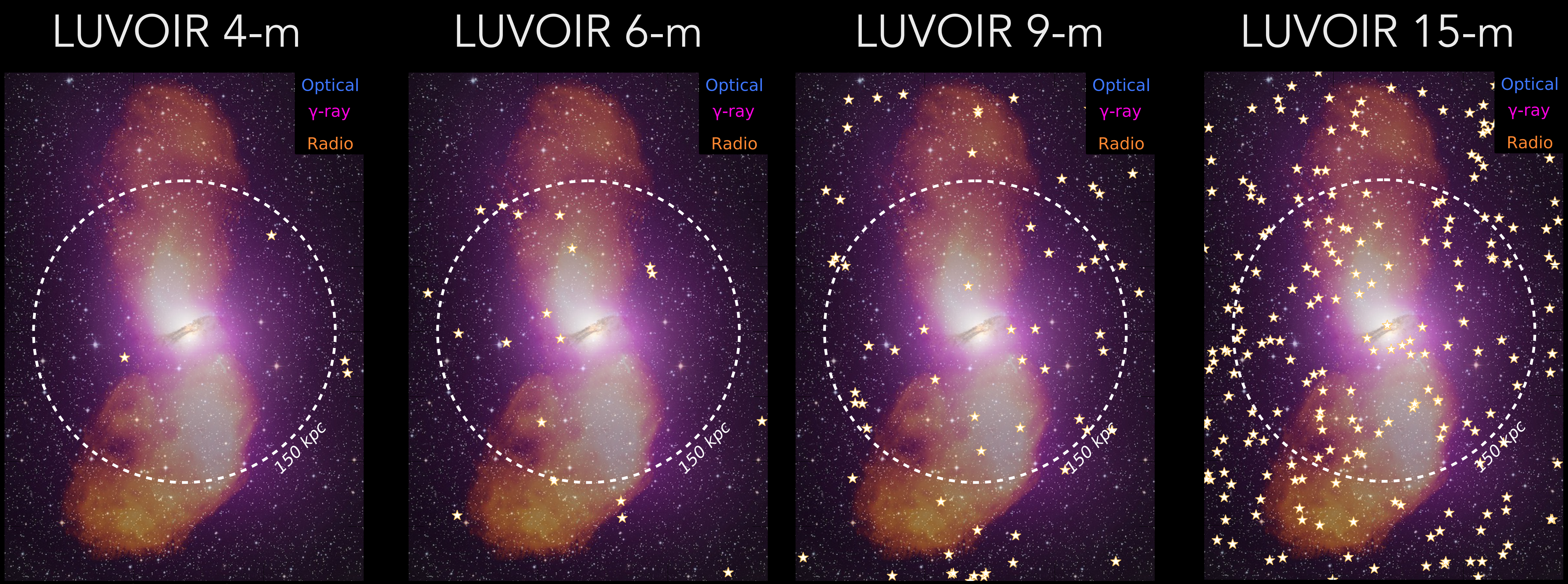
Courtesy Chris Howk (Fig. 5.5—LUVOIR interim report)

LUVOIR 15-m



Courtesy Chris Howk (Fig. 5.5—LUVOIR interim report)

It will take a much bigger telescope to "zoom-in" on the CGM of galaxies beyond M31!



Courtesy Chris Howk (Fig. 5.5—LUVOIR interim report)

Background galaxies are ten times more numerous and can also be used to map the CGM gas.

With UV coverage, high spatial resolution, and extreme sensitivity, IFU techniques will also provide the first maps of the CGM.

Summary

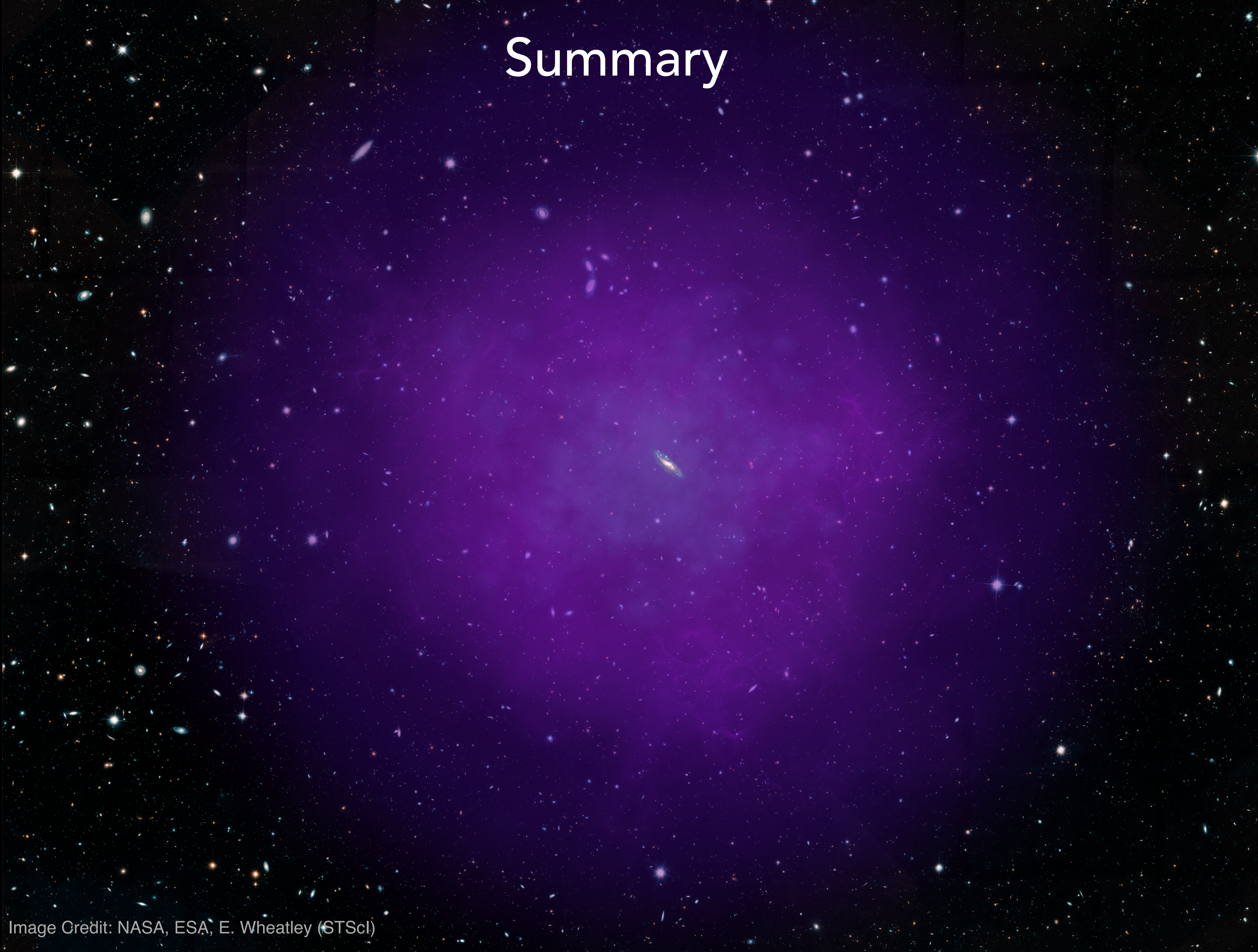


Image Credit: NASA, ESA, E. Wheatley (STScI)

Summary

- Project AMIGA is an unique experiment that has targeted the CGM of M31 with 43 sightlines:
    - Andromeda hosts a massive, extended metal-enriched halo of cool and warm-hot gas. It is so extended that MW and M31 CGMs most likely already overlap.
    - The M31 CGM gas has a complex structure that varies with R.

Image Credit: NASA, ESA, E. Wheatley (STScI)

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Image Credit: NASA, ESA, E. Wheatley (STScI)

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- With Project AMIGA, we demonstrate that probing the CGM of galaxies with *multiple sightlines is key to unravel its complexity, nature, and its relationships with the stellar disks of galaxies. A larger, more sensitive UV telescope will be need to observe galaxies beyond M31.*

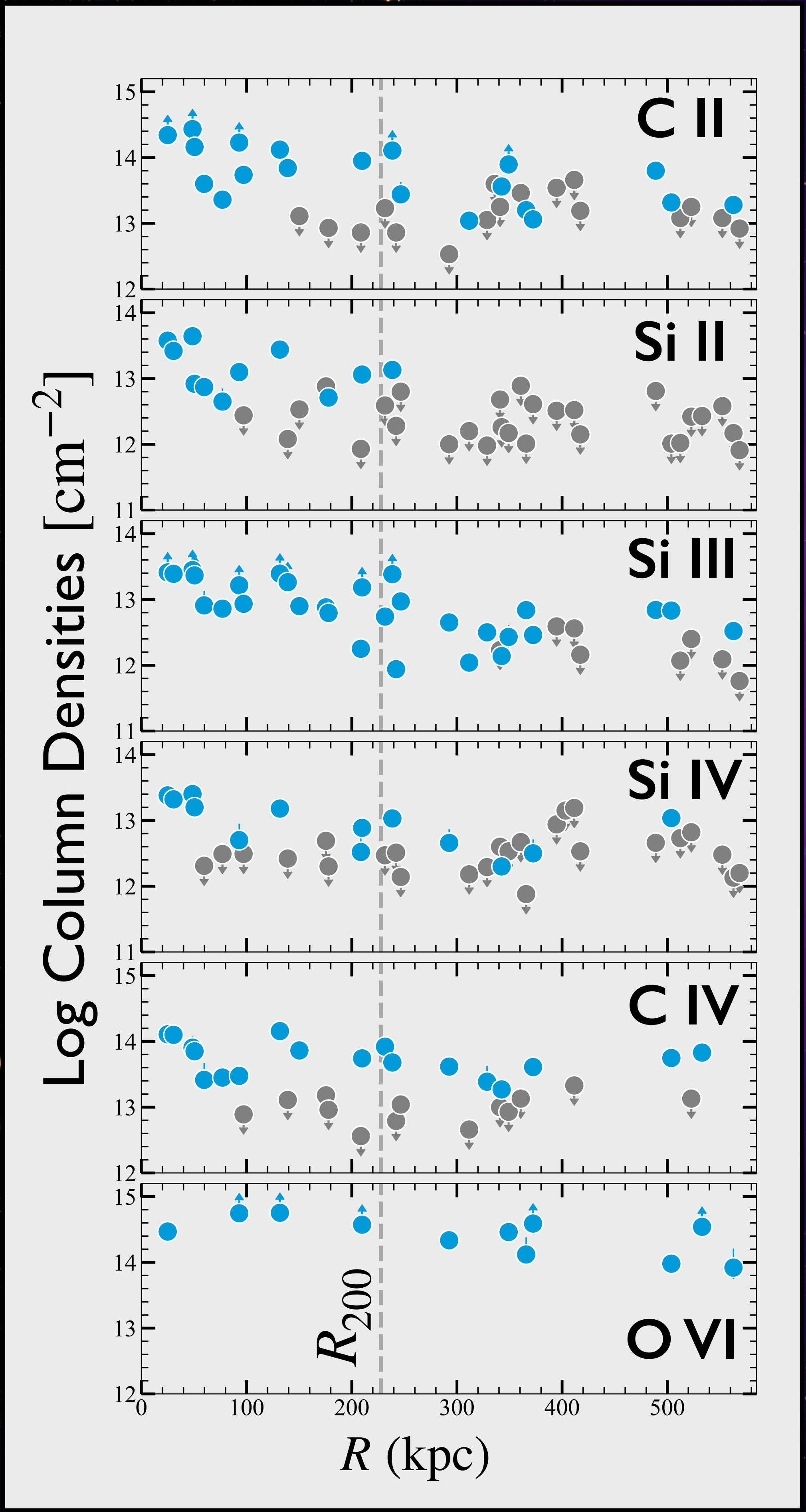
Image Credit: NASA, ESA, E. Wheatley (STScI)

Thank you!

Check out the NASA press release:
https://hubblesite.org/contents/news-releases/2020/news-2020-46

Credit: NASA, ESA, and E. Wheatley (STScI) / J.C. Howk (University of Notre Dame); constellations from Stellarium; Milky Way © Axel Mellinger

How massive is the CGM of M31?



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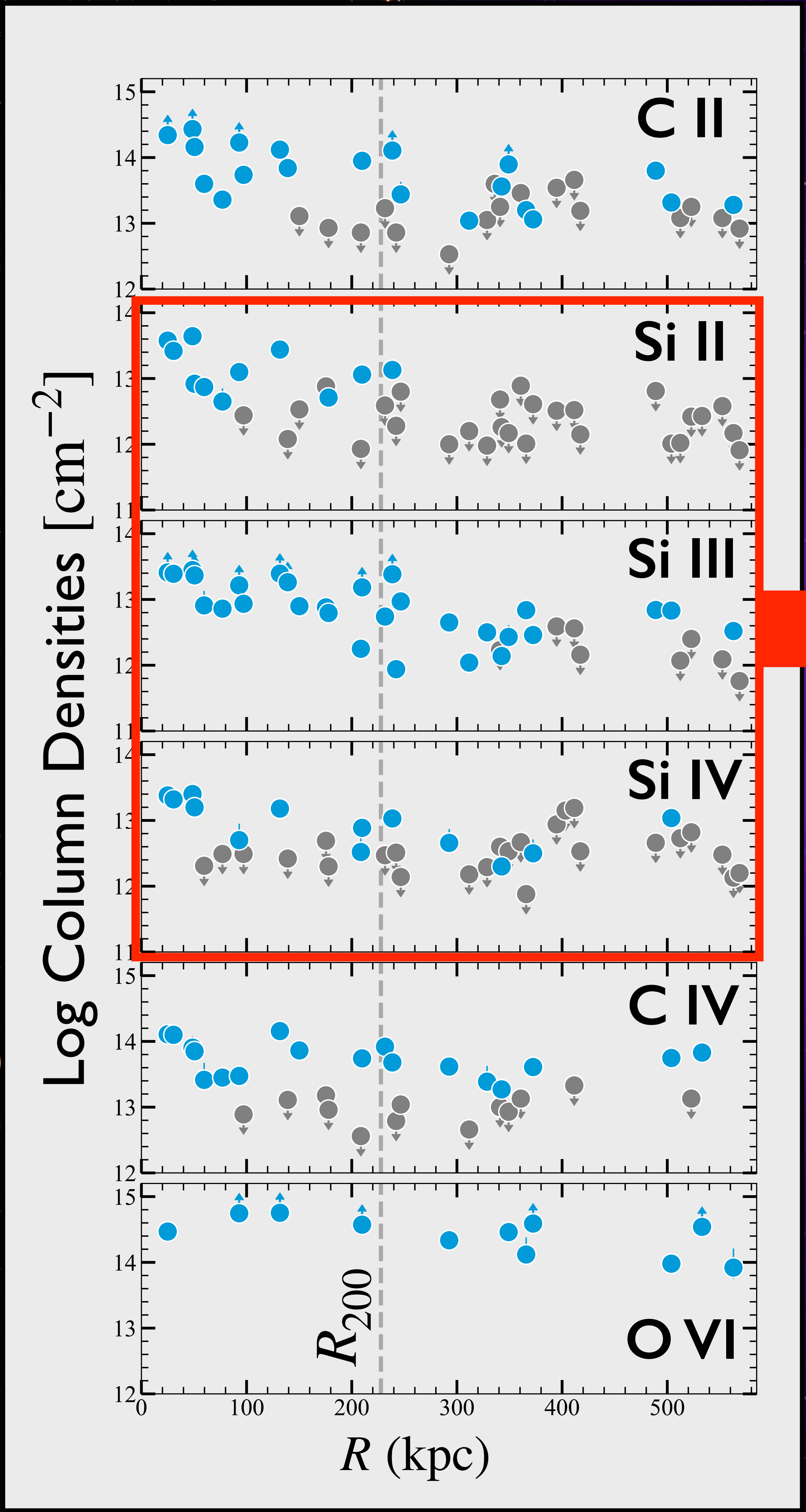

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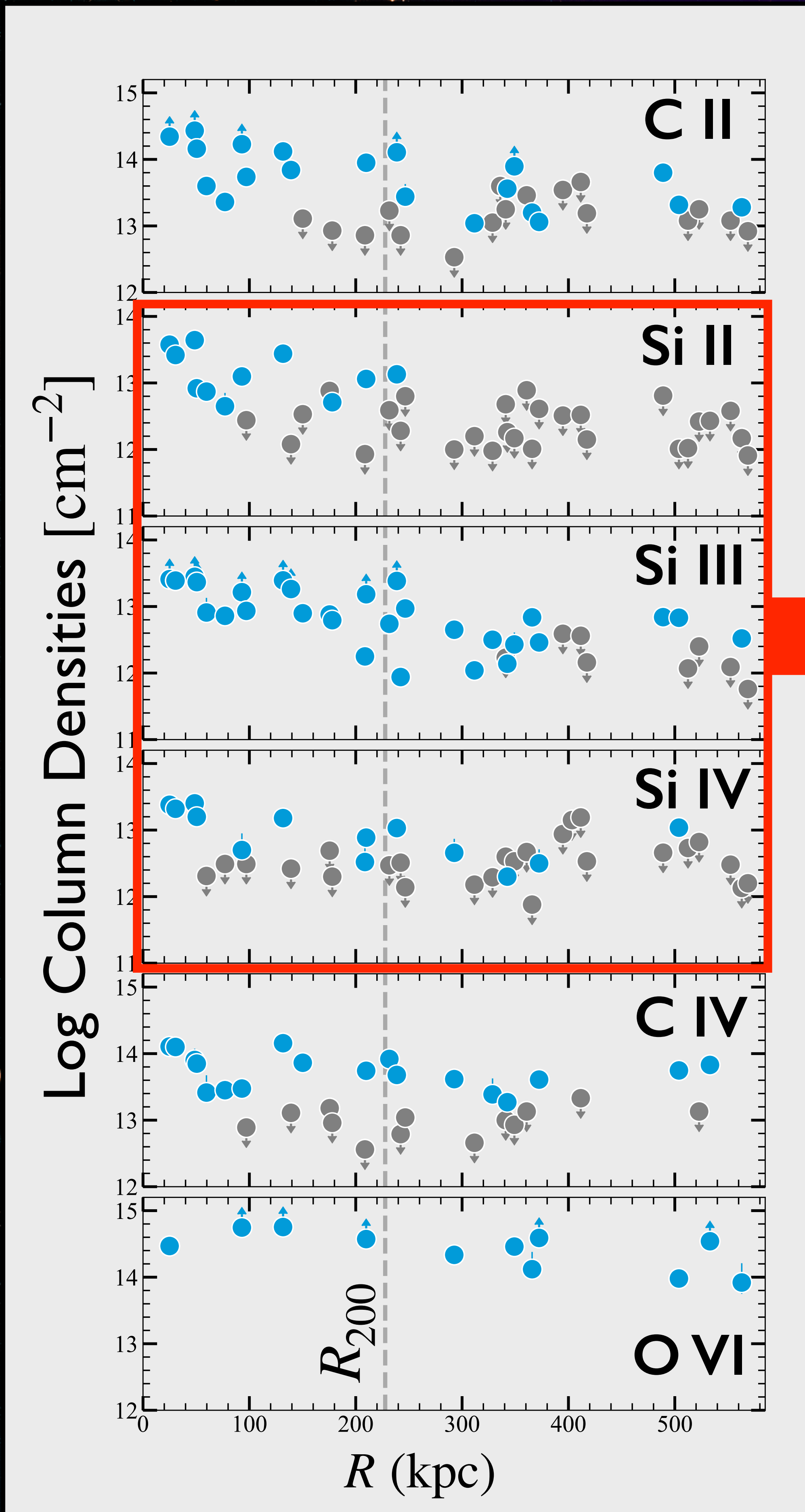

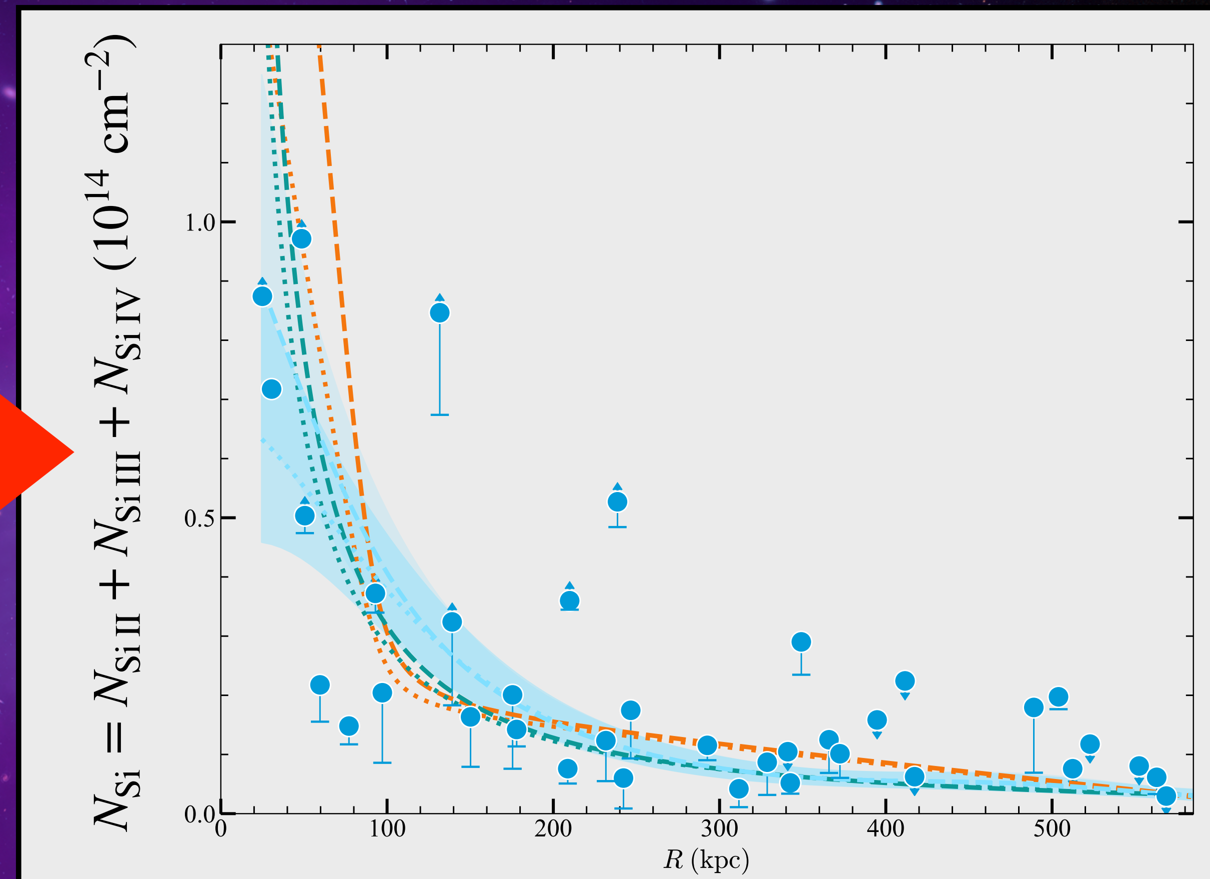

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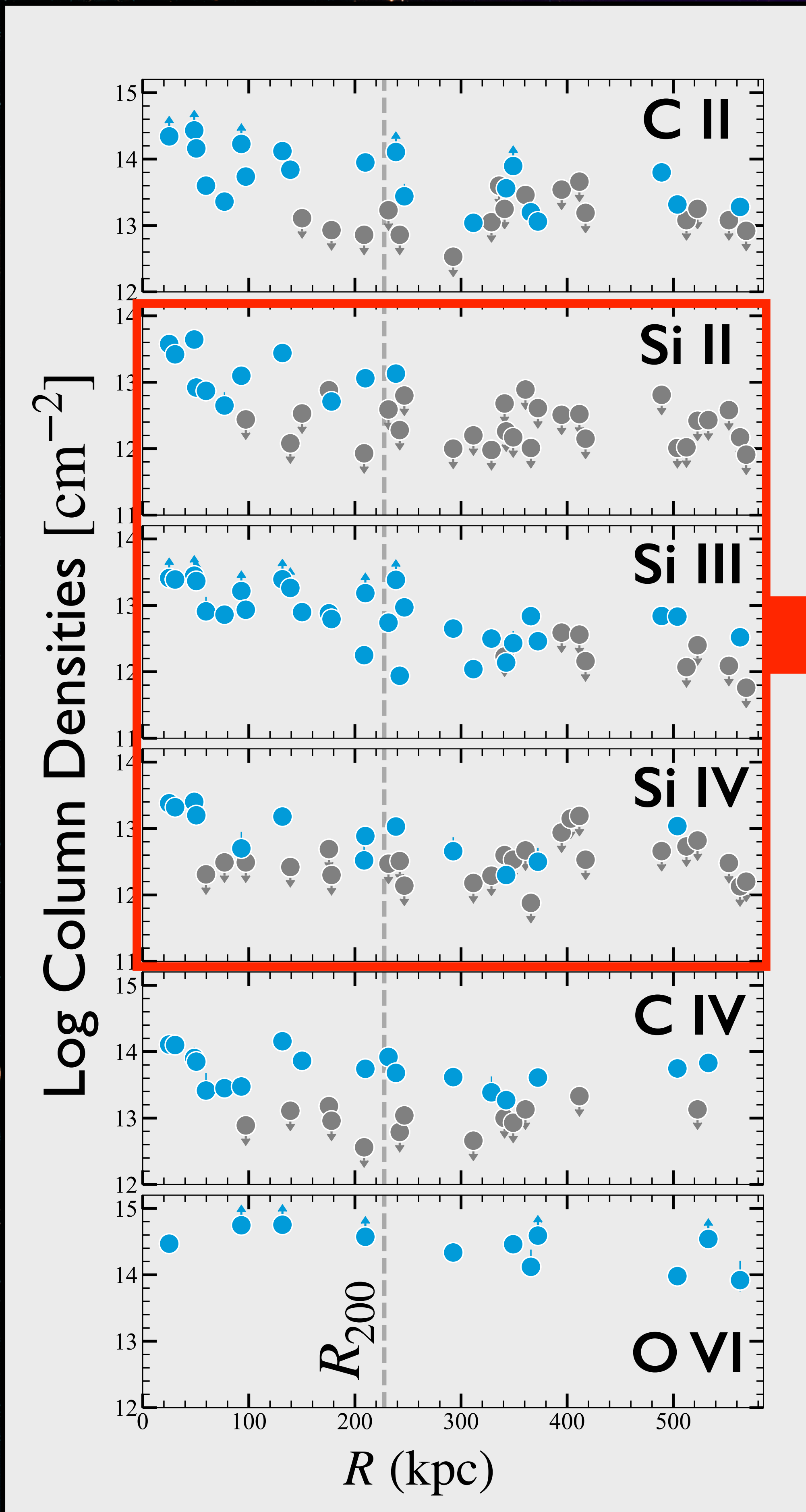
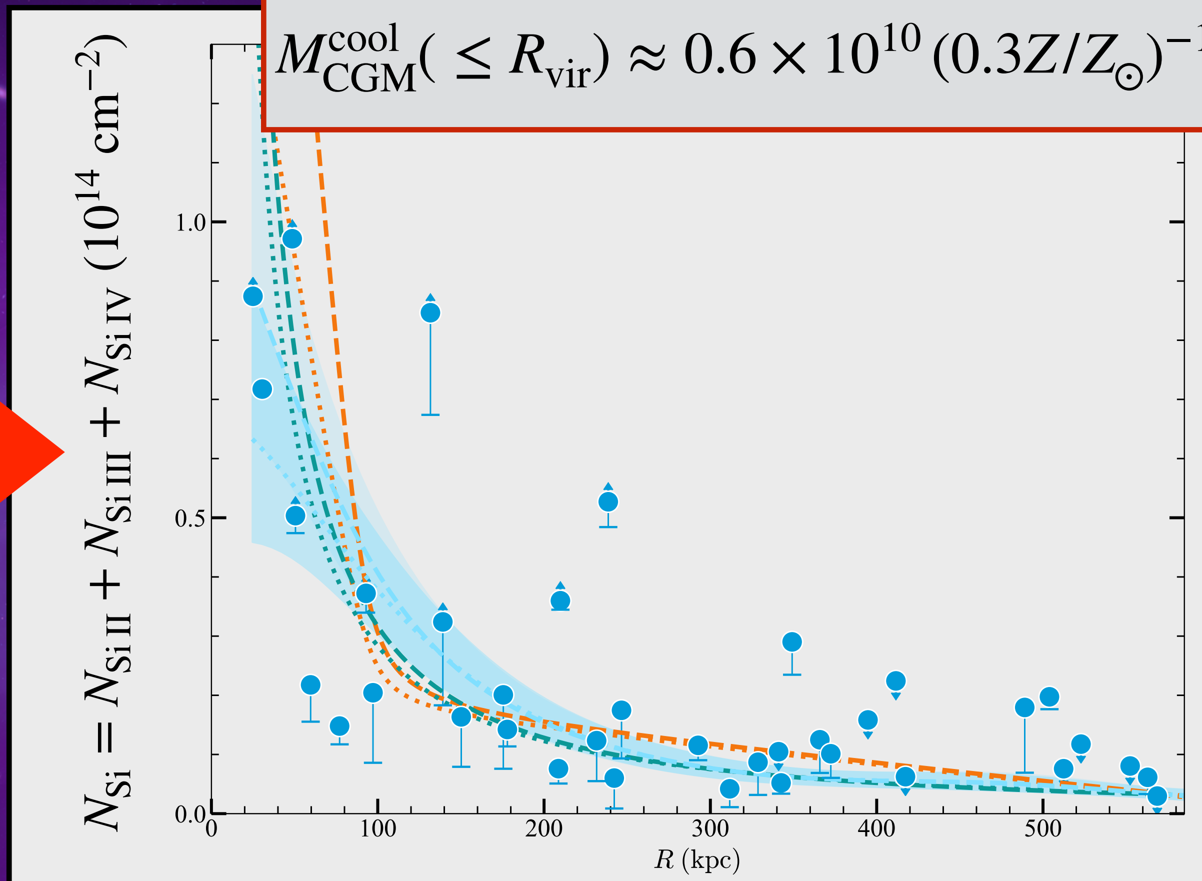


Detection of M31 CGM gas

No detection of M31 CGM

$$M_Z^{\rm cool}(\leq R_{\rm vir}) \approx 2 \times 10^7\ {\rm M}_\odot$$

$$M_{\rm CGM}^{\rm cool}(\leq R_{\rm vir}) \approx 0.6 \times 10^{10}\,(0.3Z/Z_\odot)^{-1}\ {\rm M}_\odot$$



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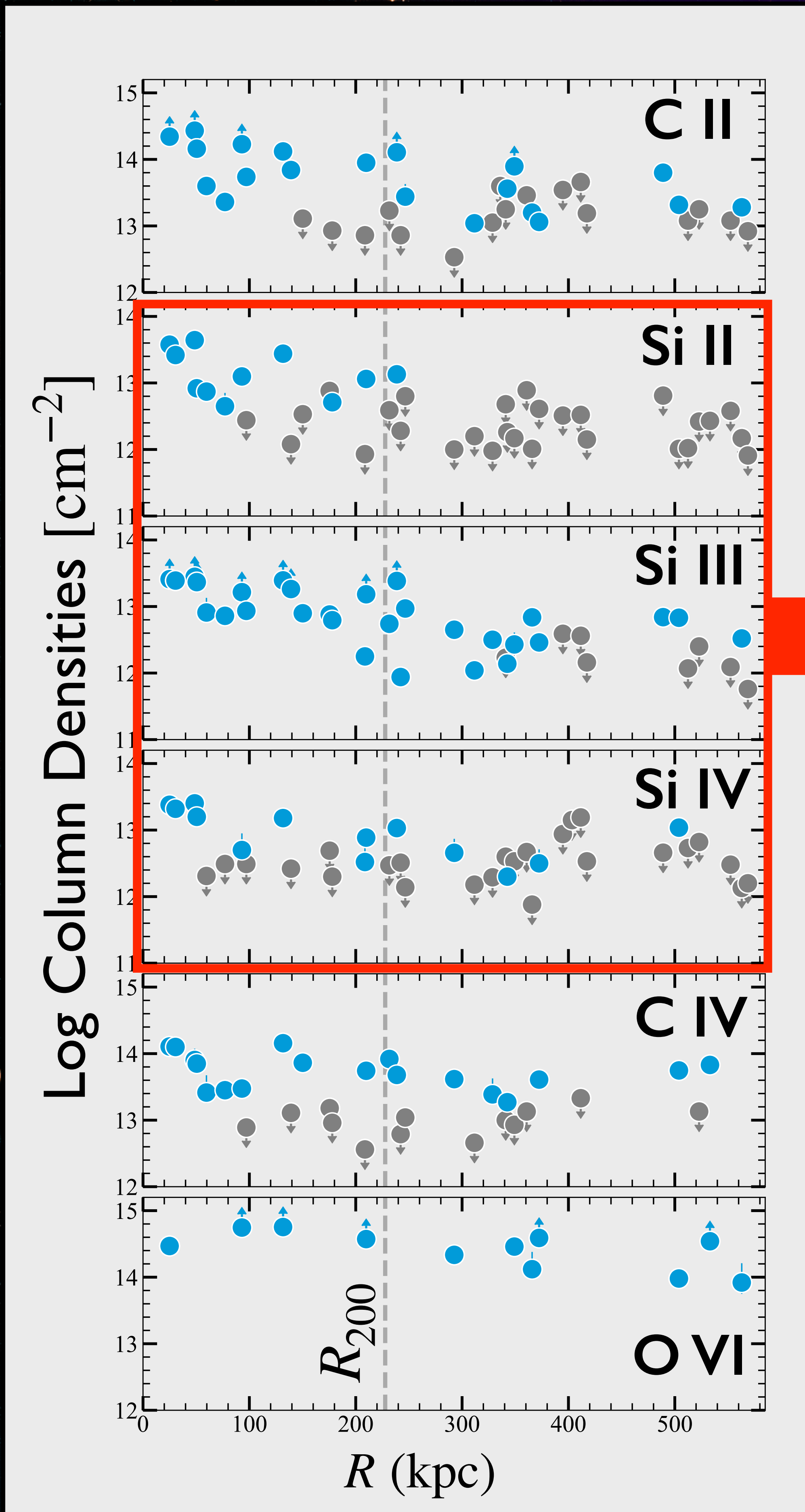

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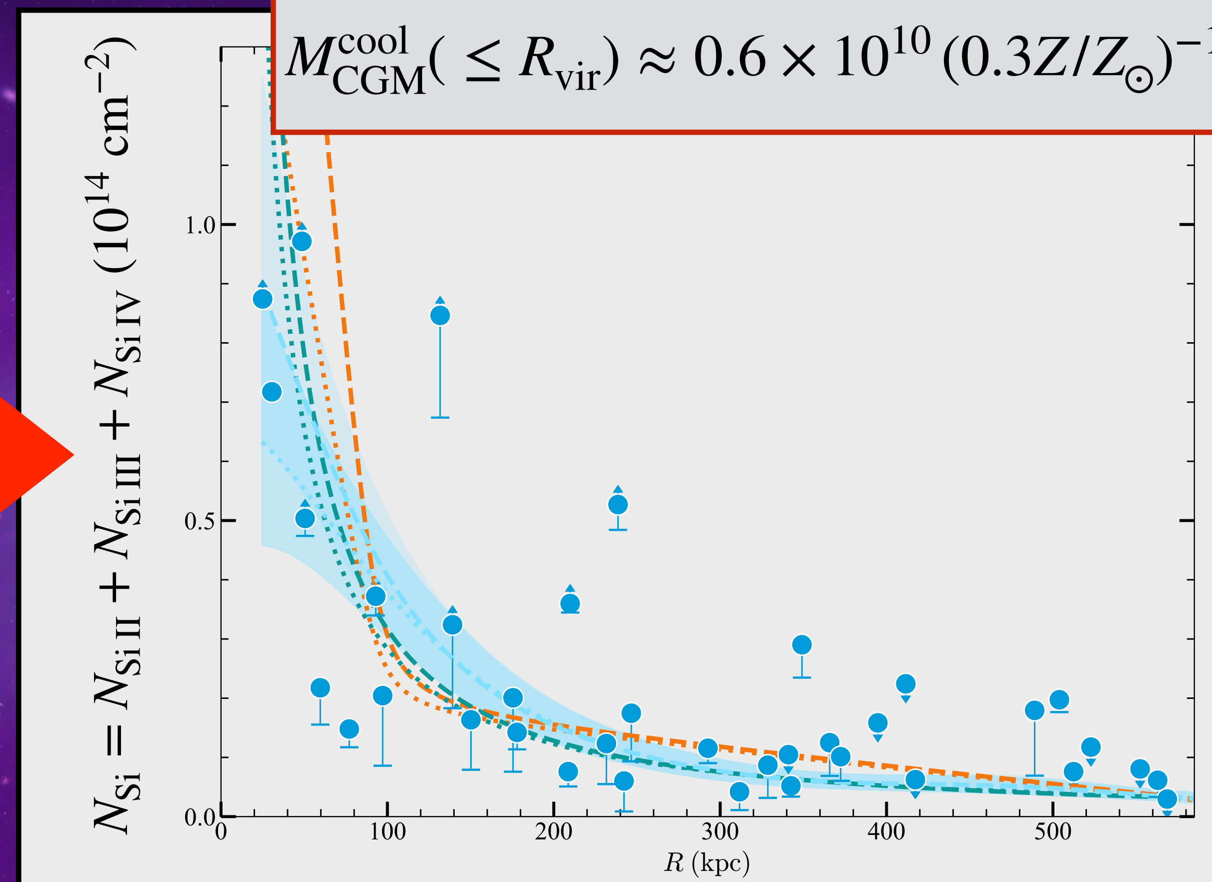
No detection of M31 CGM

$$M_Z^{\rm cool}(\leq R_{\rm vir}) \approx 2\times10^7\ {\rm M}_\odot$$

$$M_{\rm CGM}^{\rm cool}(\leq R_{\rm vir}) \approx 0.6\times10^{10}\,(0.3Z/Z_\odot)^{-1}\ {\rm M}_\odot$$

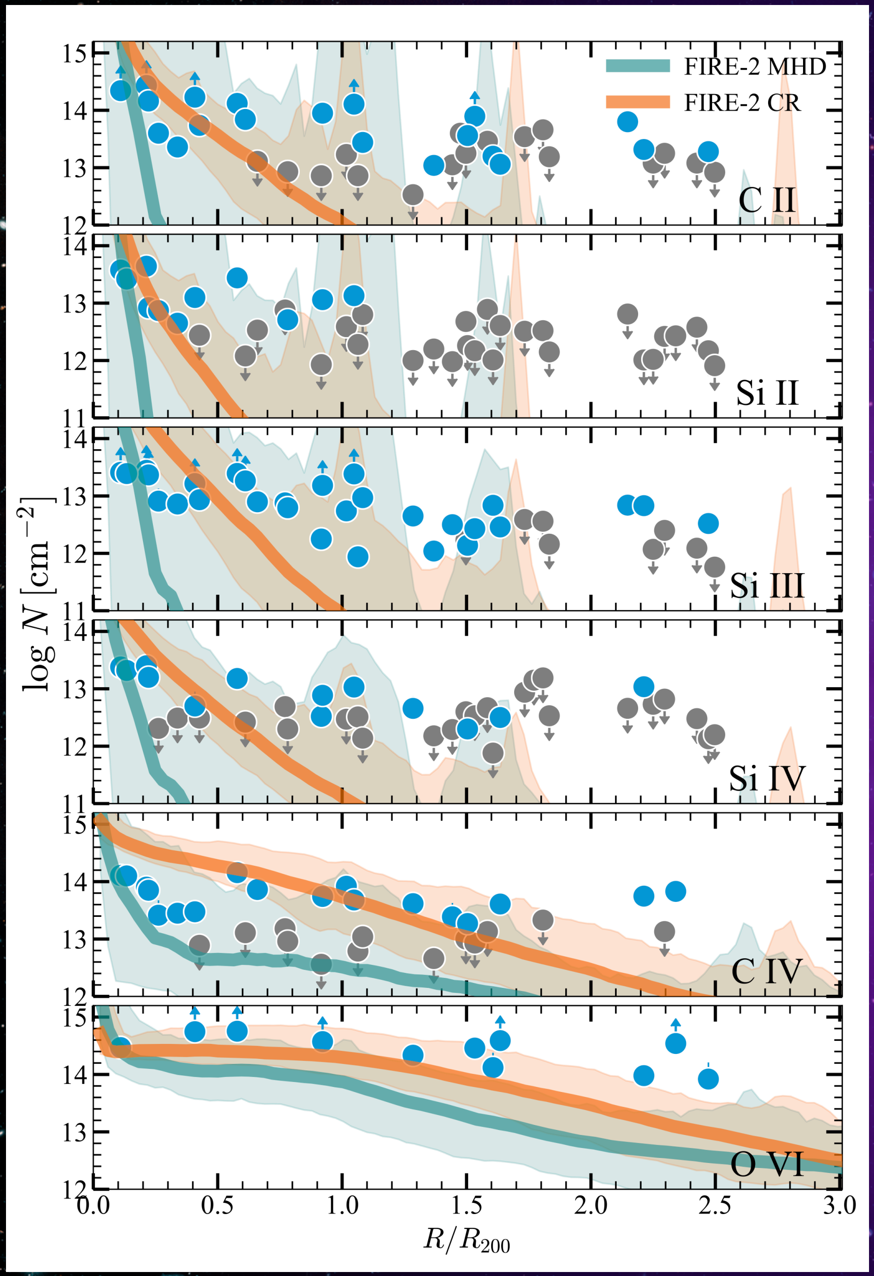


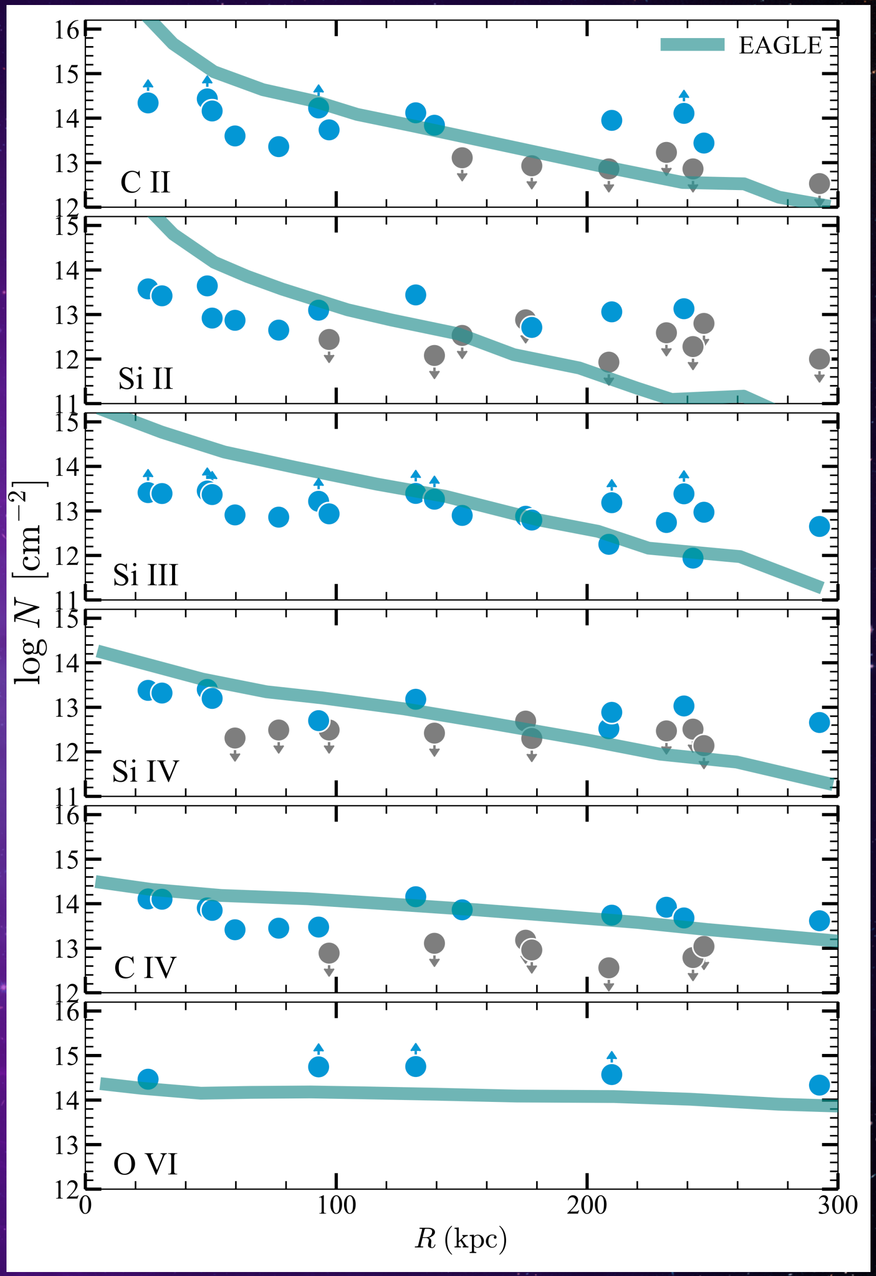
Combining with OVI (nearly constant with R)

$$M_Z^{\rm cool+warm}(\leq R_{\rm vir}) \gtrsim 10^8\ {\rm M}_\odot$$

$$M_{\rm CGM}^{\rm cool+warm}(\leq R_{\rm vir}) \gtrsim 4\times10^{10}\,(0.3Z/Z_\odot)^{-1}\ {\rm M}_\odot$$

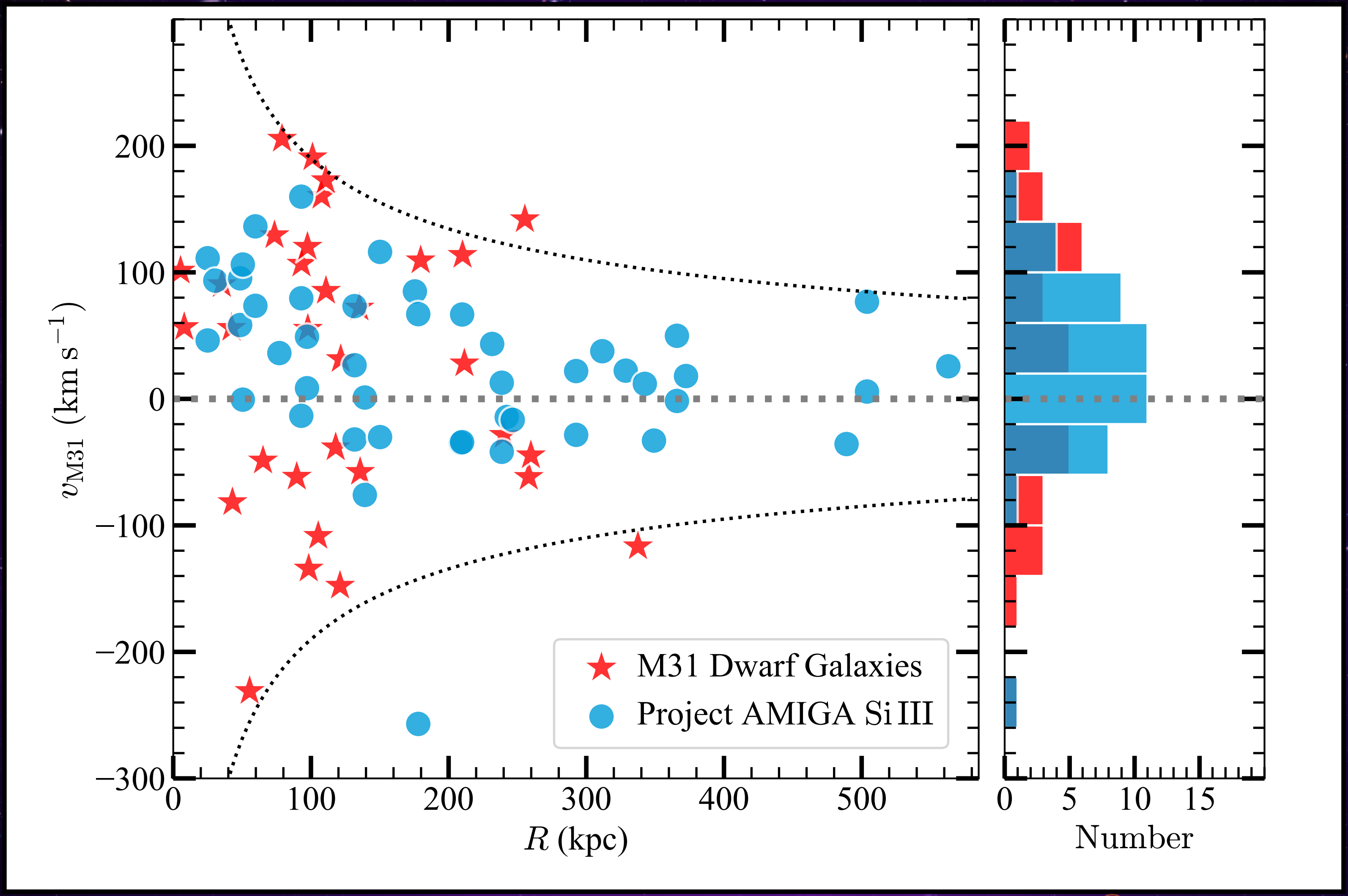
Results can be directly **quantitatively** compared with zoom-in cosmological simulations





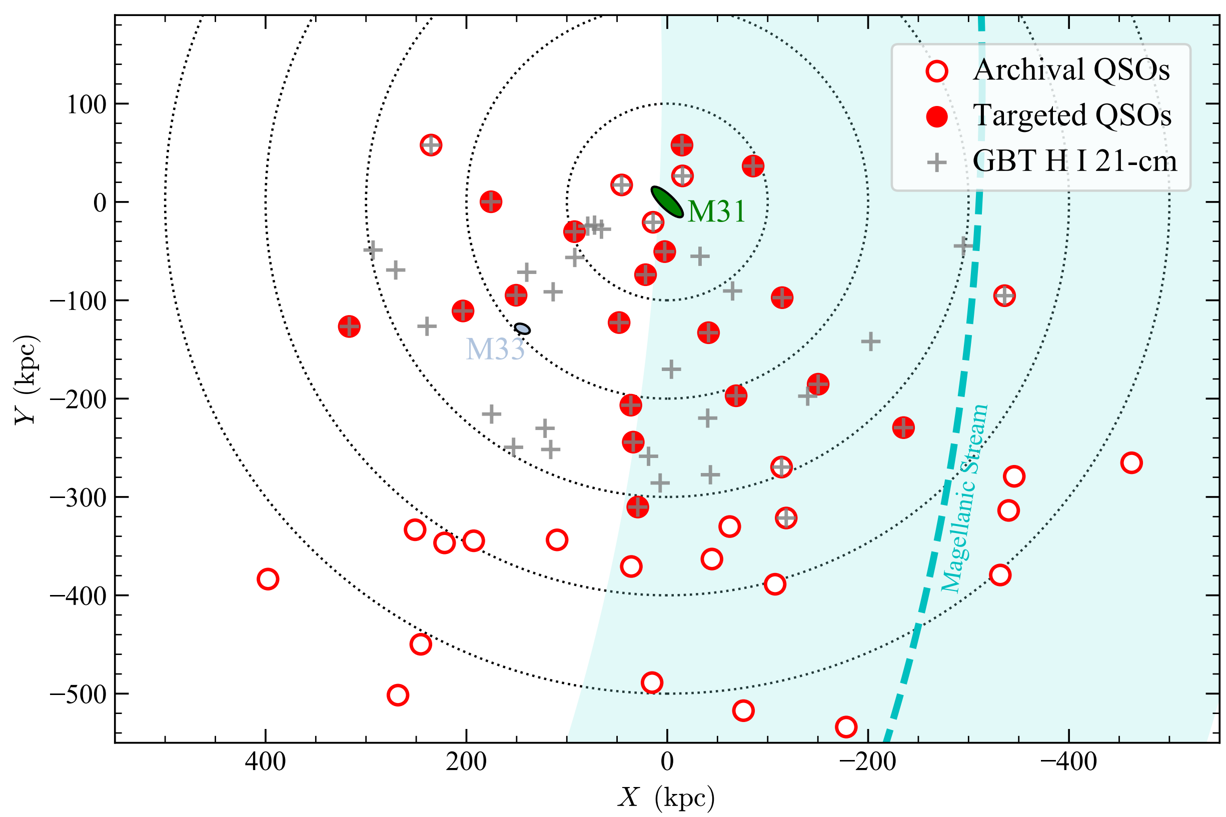
But note that only the galaxy masses are similar between the observed and simulated galaxies here.

Similar velocity distributions between CGM gas and dwarf satellites



Several absorbers are also within close spatial and velocity proximity of the dwarfs. However, none of the properties of the absorbers in close proximity to these dwarf galaxies show any peculiarity that would associate them with the CGM of these satellites rather than the CGM of M31.

Association of the absorption with M31 CGM



components associated with MS