Title: Probing the Magneto-Ionized Circumgalactic Medium of M31 with HI and Rotation Measures

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Abstract:

The circumgalactic medium (CGM) represents both a significant reservoir of baryons around galaxies as well as the region through which gas flows on to and out of galactic disks providing fuel for continued star formation. It is, however, challenging to study due to the low densities of gas in the CGM. Previous UV absorption studies have shown that the CGM is ubiquitous around star-forming galaxies. Project AMIGA has shown that the Andromeda Galaxy (M31), specifically, has an extensive CGM, which has further been confirmed by recent results from Fast Radio Bursts. Here, we present two complementary approaches to further characterize the CGM of M31. First, using archival rotation measure (RM) measurements of background radio point sources projected within the virial radius of M31, we present evidence of the existence of a magneto-ionized plasma extending out to $\gtrsim$100 kpc from M31. Second, using HI observations from the Green Bank Telescope (GBT) and MeerKAT, we show evidence of infalling gas being disrupted by the hot CGM at similar distances. Both observations confirm the presence of an extended, hot, ionized, and magnetized CGM around M31.

Probing the magneto-ionized Circumgalactic Medium of M31 with HI and Rotation Measures

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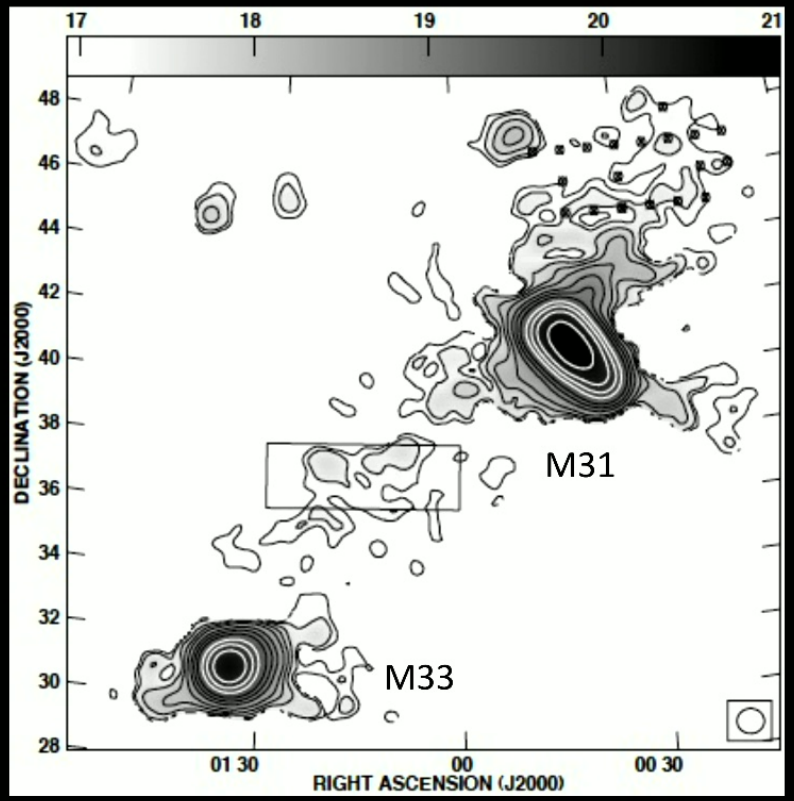
Why Andromeda's (M31) CGM?

- Closest analog to the Milky Way:
  - $M_{200} \cong 10^{12}\ M_{\odot}$
  - D=780 kpc
- Big on the sky, easy to resolve features:
  - $R_{virial} \cong 300$ kpc (22°)
  - many probes of CGM
  - 1'= 226 pc
- Allows for excellent M_{HI} and N_{HI} sensitivity.

HI Mapping of M31's CGM

- Braun & Thilker (2004) found a large HI structure appearing to connect M31 and M33 at 49', 40 km/s resolution.
- This $N_{HI} > 10^{17}$ cm^{-2} filamentary structure sits within the warm-hot ionized CGM.

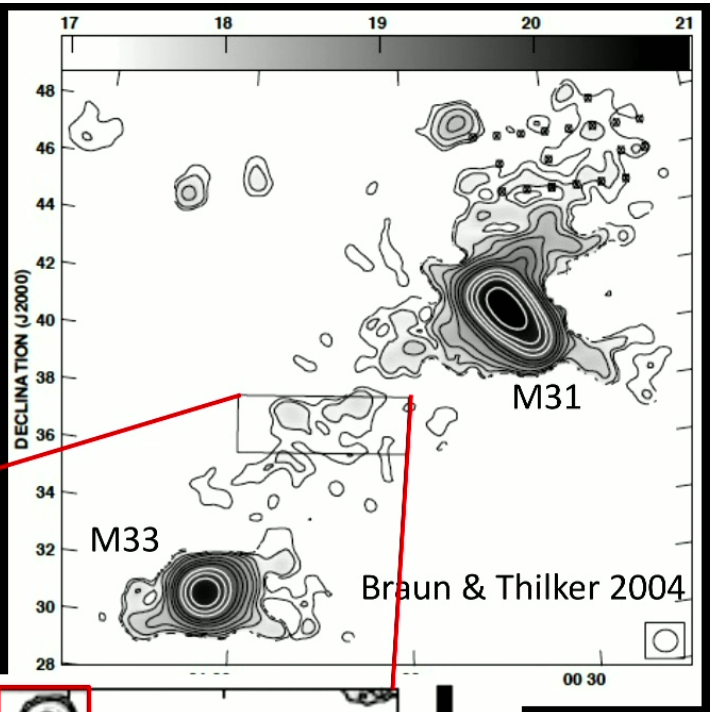


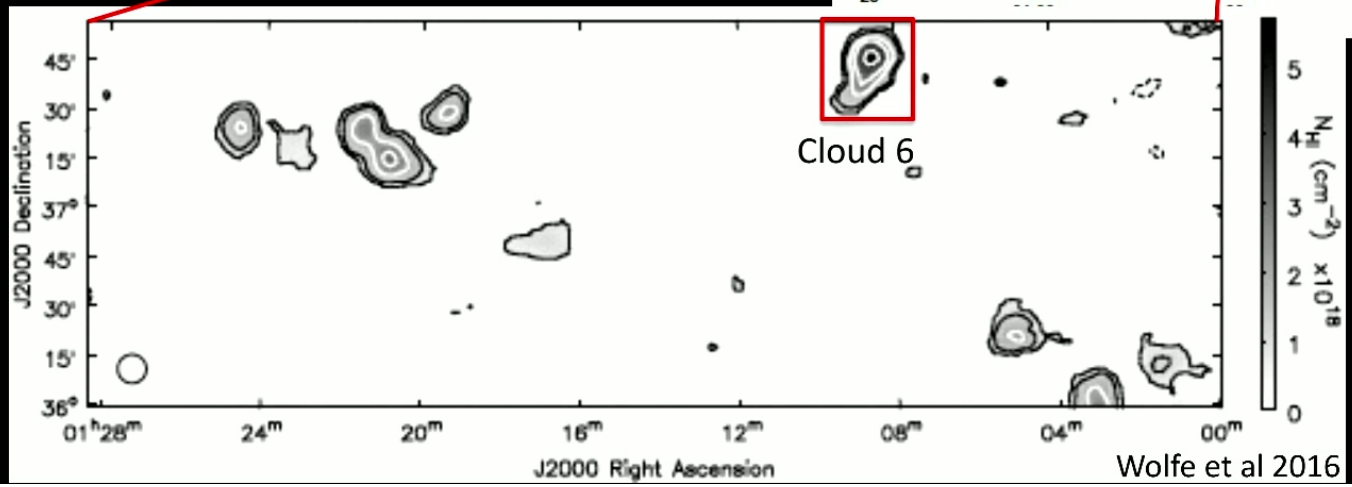
Braun & Thilker 2004

At higher resolution…

With GBT at 9.1', 5.2 km/s resolution:

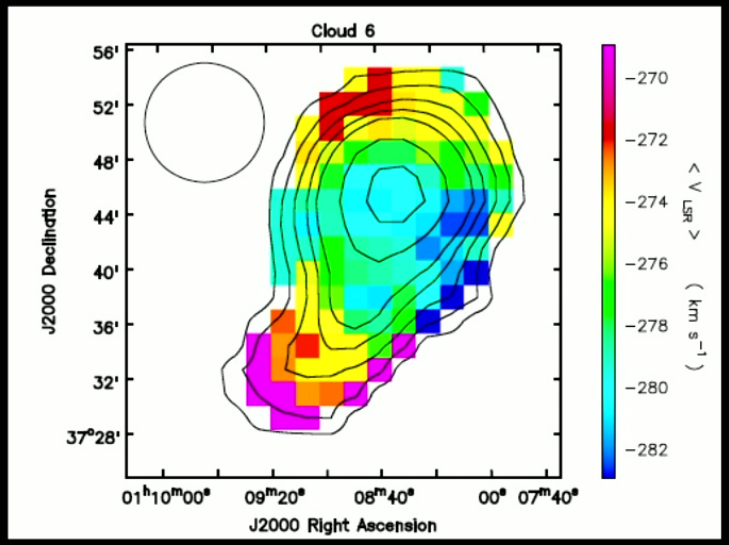
- Despite its initial appearance in BT04, even at $N_{HI} \sim 10^{17}$ cm^{-2}, this gas is clumpy with $M_{HI} \sim 10^5$ $M_\odot$ for the clumps.

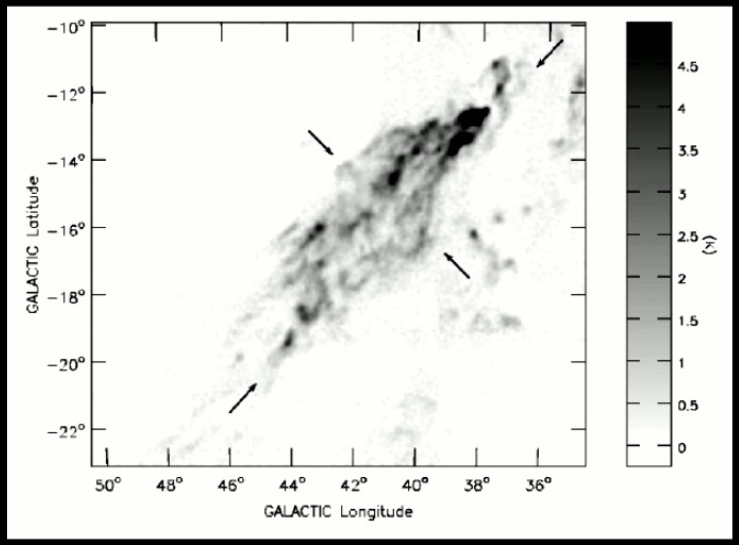




Cloud 6

- Similar extent as Smith's Cloud (a Milky Way high-velocity cloud), ~3 kpc (Lockman 2008).
- M_{HI} is 10x lower though.
- Minimal coherent velocity structure (at 5.2 km/s resolution).
- MeerKAT can help!





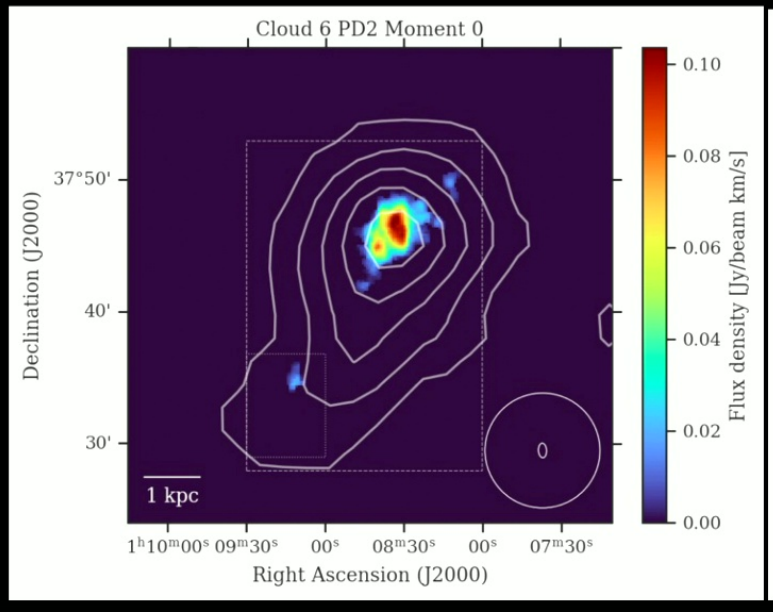
MeerKAT:
An interferometer with single-dish sensitivity

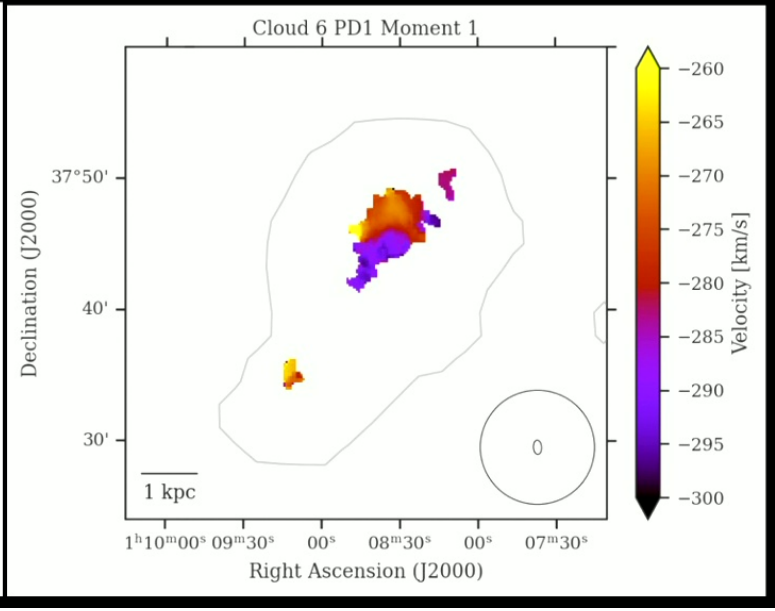
MeerKAT is capable of imaging HI at $N_{HI} < 10^{18}$ cm^{-2} across its 1 deg^2 FoV at ~6—90”

MeerKAT HI Observations of Cloud 6

- GBT HI map becomes even more clumpy and shows signs of velocity gradient indicative of ram pressure stripping.
- Recover about 50% of the HI flux.

Kummer et al. in prep

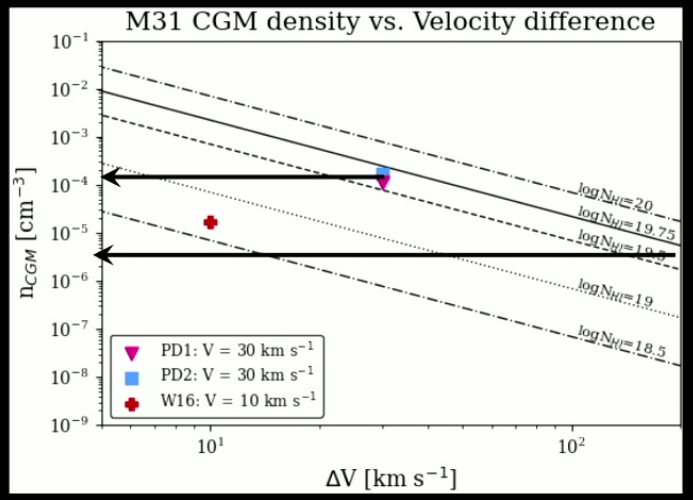




Ram Pressure Stripping

$$\rho_{CGM} V^2 = 2\pi G \Sigma_{mass} \Sigma_{HI}$$

- We assume that cloud is only HI.
- Based on observed peak N_{HI} and velocity gradient across cloud, derive n_{CGM}~10^{-4} cm^{-3} at R ~ 96 kpc.
- Even for larger ΔV, still get reasonable n_{CGM}~ 5x10^{-6} cm^{-3}
- Broadly consistent with AMIGA estimates of M_{CGM} and Prochaska & Zheng (2019) mNFW DM estimates.



Kummer et al. in prep

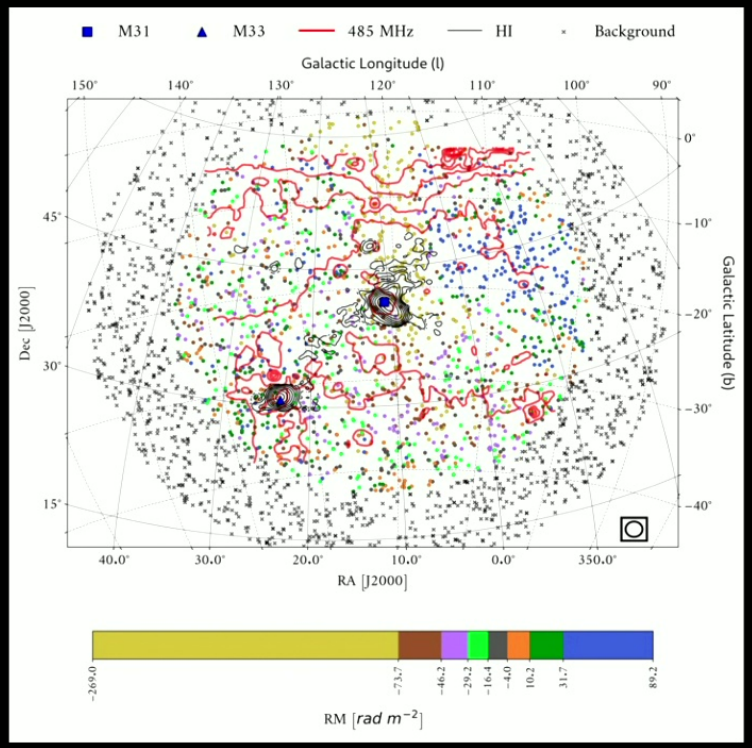
But, this is only probing the CGM at one location...

How do we get a wider view?

The bigger CGM picture?

- We want to be able to probe the full extent of M31's CGM and trace the main component of it, the ionized gas.
- AMIGA (see Lehner talk on Thursday) has ~ 50 sightlines. A few FRBs probe CGM.
- Can use ~1800+ rotation measures (RM) from Taylor et al. (2009) to study out to R_{virial}.

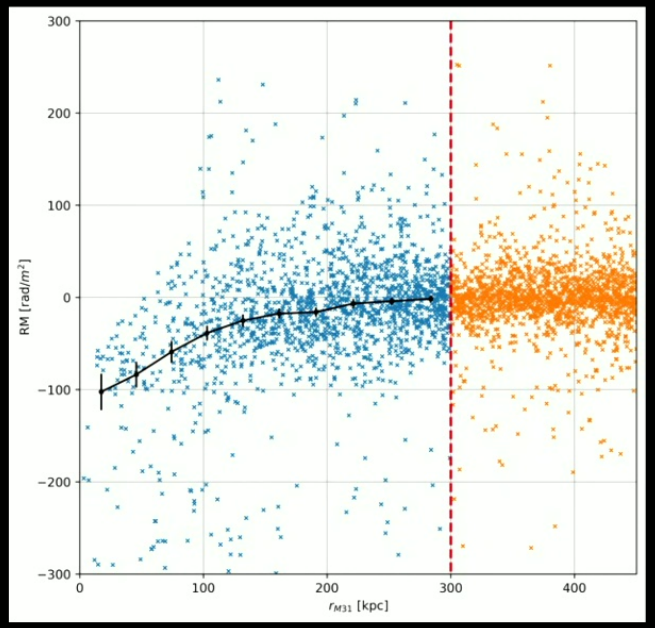
$$RM \sim \int n_e B_{\parallel} dl$$

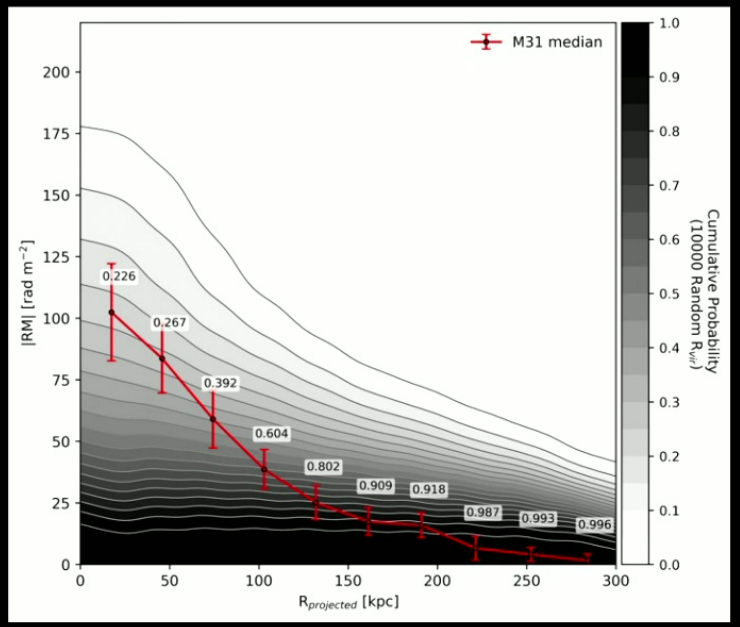


Pisano, Njoroge, Taylor, in prep

M31's CGM

- Correct for Milky Way foreground and exclude low-latitude RM values.
- Clear excess in RM out to ~100+ kpc (projected) of M31 compared to random directions!
- Can confirm both ionized gas & B-field in CGM of M31!





Pisano, Njoroge, Taylor, in prep

What about the B-field?

"Magnetic fields are never the answer"

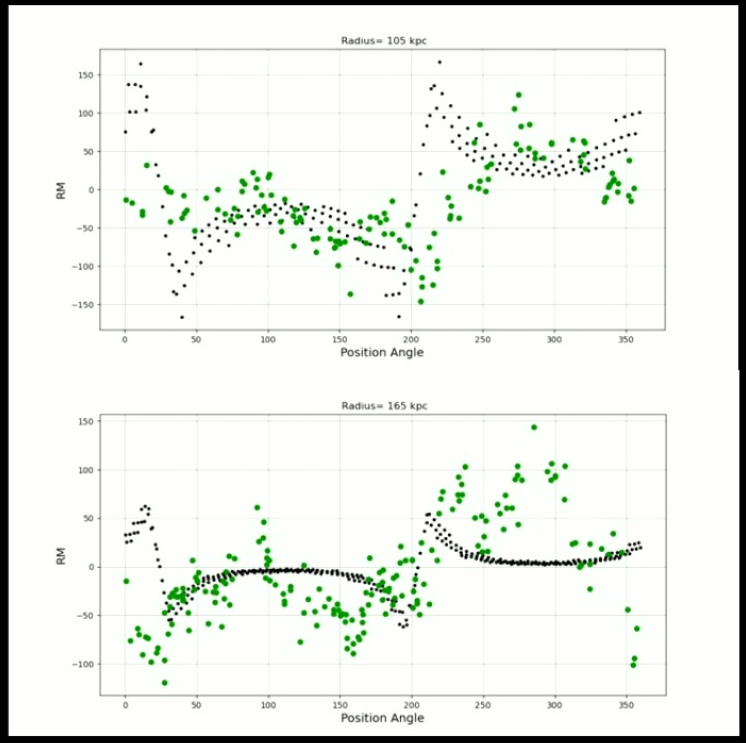
"Magnetic fields are the last refuge of the scoundrel"

D.J. Pisano

(on numerous occasions)

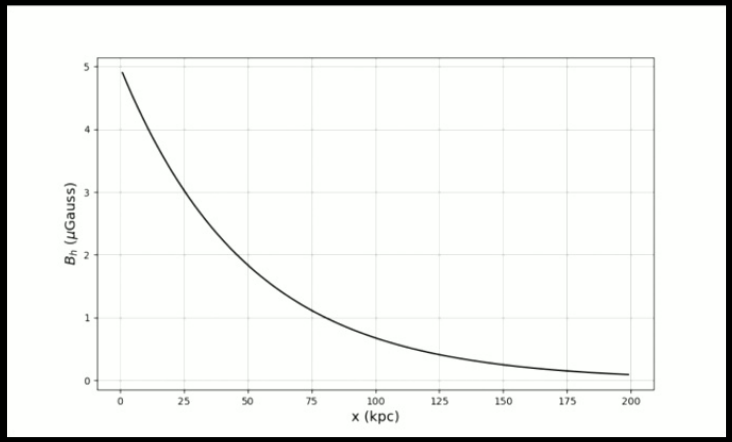
A simple B-field model

- Azimuthal field in disk
- Pure vertical field with an exponential scale height of ~ 50 kpc
- mNFW model for n_e (Prochaska & Zheng 2019).



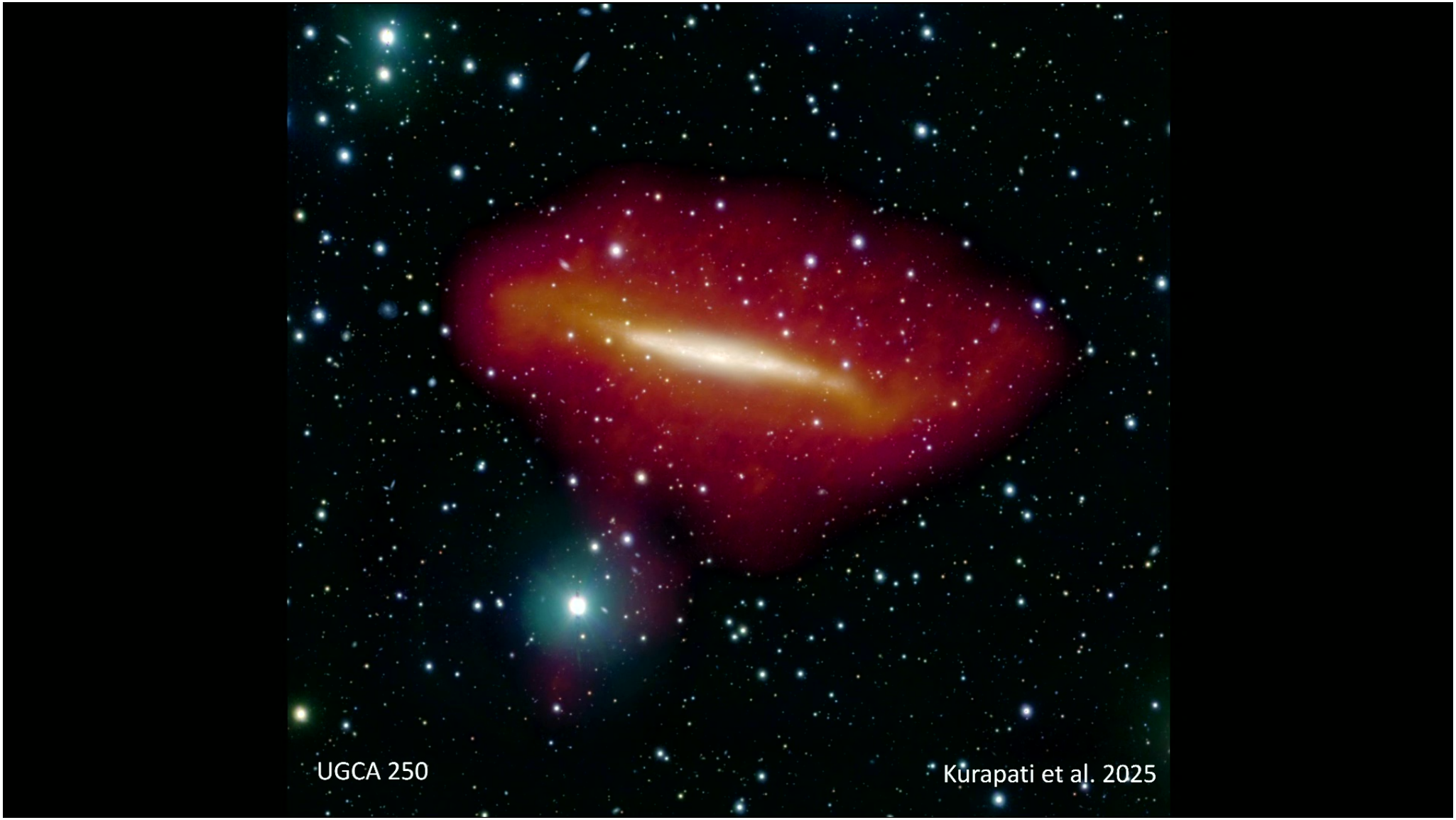
M31's CGM Magnetic Field

- Using these constraints, get B ~ 0.5μG at R ~ 100 kpc.
- In equipartition, expect B ~ 1μG for T~10^5 K.
- Still need to try more realistic (toroidal, poloidal, etc) models.



Conclusions

- MeerKAT is an amazing instrument for mapping and analysing HI at high resolution and extremely low-N_{HI} making it perfect for mapping the CGM of nearby galaxies.
- MeerKAT data of HI cloud around M31 is showing signature of interaction with surrounding dense CGM at expected densities. Implies local n_{CGM}~10^{-4} cm^{-3} at R_{M31}~96 kpc
- Archival RM data gives evidence of magneto-ionized plasma out to ~100+ kpc. With constraints from HI, implies B-field of ~0.5μG. Shows promise for future MeerKAT/SKA studies of the CGM of external galaxies.


UGCA 250
Kurapati et al. 2025