

The background of the slide is a deep space image. It features a bright, multi-colored star with a prominent cross-shaped diffraction pattern on the left side. To the right of the star is a large, glowing purple nebula. The rest of the background is dark, filled with numerous small, distant galaxies and stars.

Uncovering Starless Dark Matter Halos in the Era of Roman

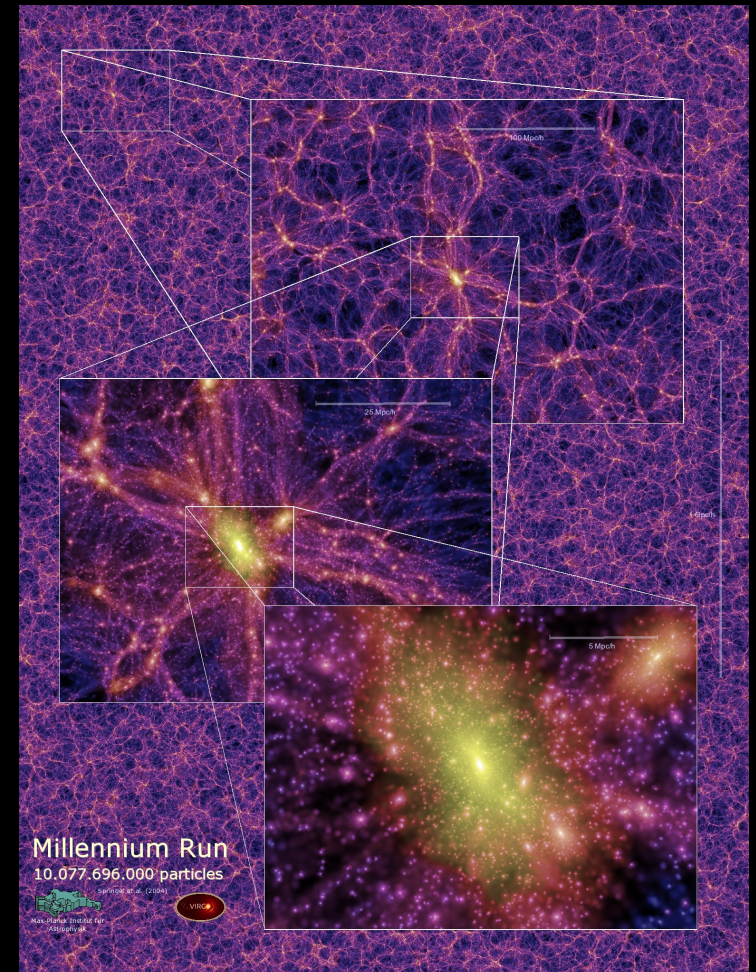
Gagandeep Anand (STScI)

With Alejandro Benítez-Llambay, Rachael Beaton, Andrew Fox, Julio Navarro, and Elena D'Onghia

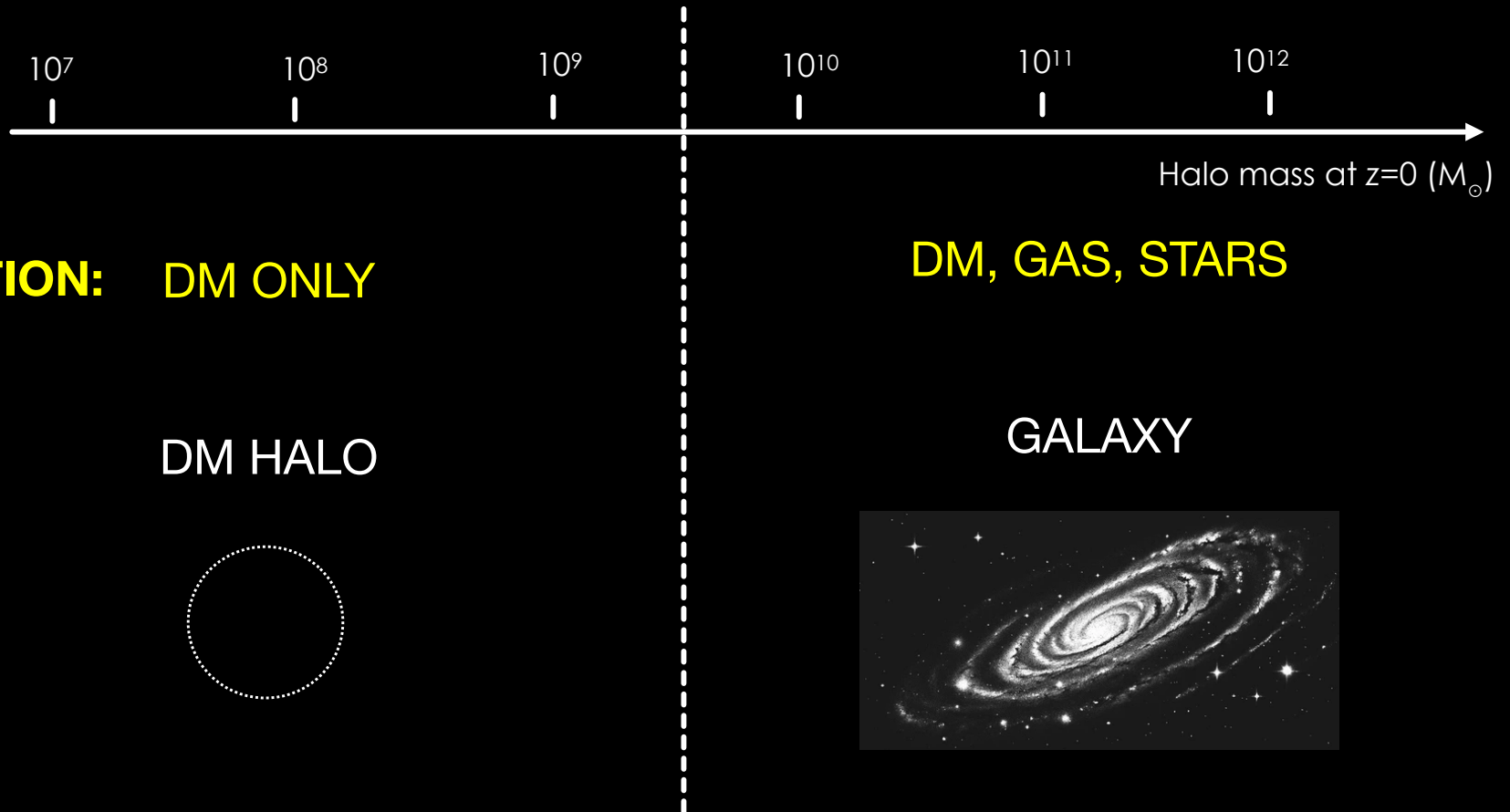
Shifting Landscapes in Astrophysics: New Frontiers to Explore with Roman, July 16th, 2026

Dark Matter Halos

- The prevailing Lambda Cold Dark Matter (Λ CDM) cosmology makes predictions about the existence of dark matter halos over a wide range of mass scales
- Galaxies are formed within these dark matter halos, and hence come in many sizes
 - The Roman Space Telescope in particular will contribute greatly to the detection and characterization of the faint end of this mass regime.
 - However, not all masses of dark matter halos are expected to form galaxies with gas and stars



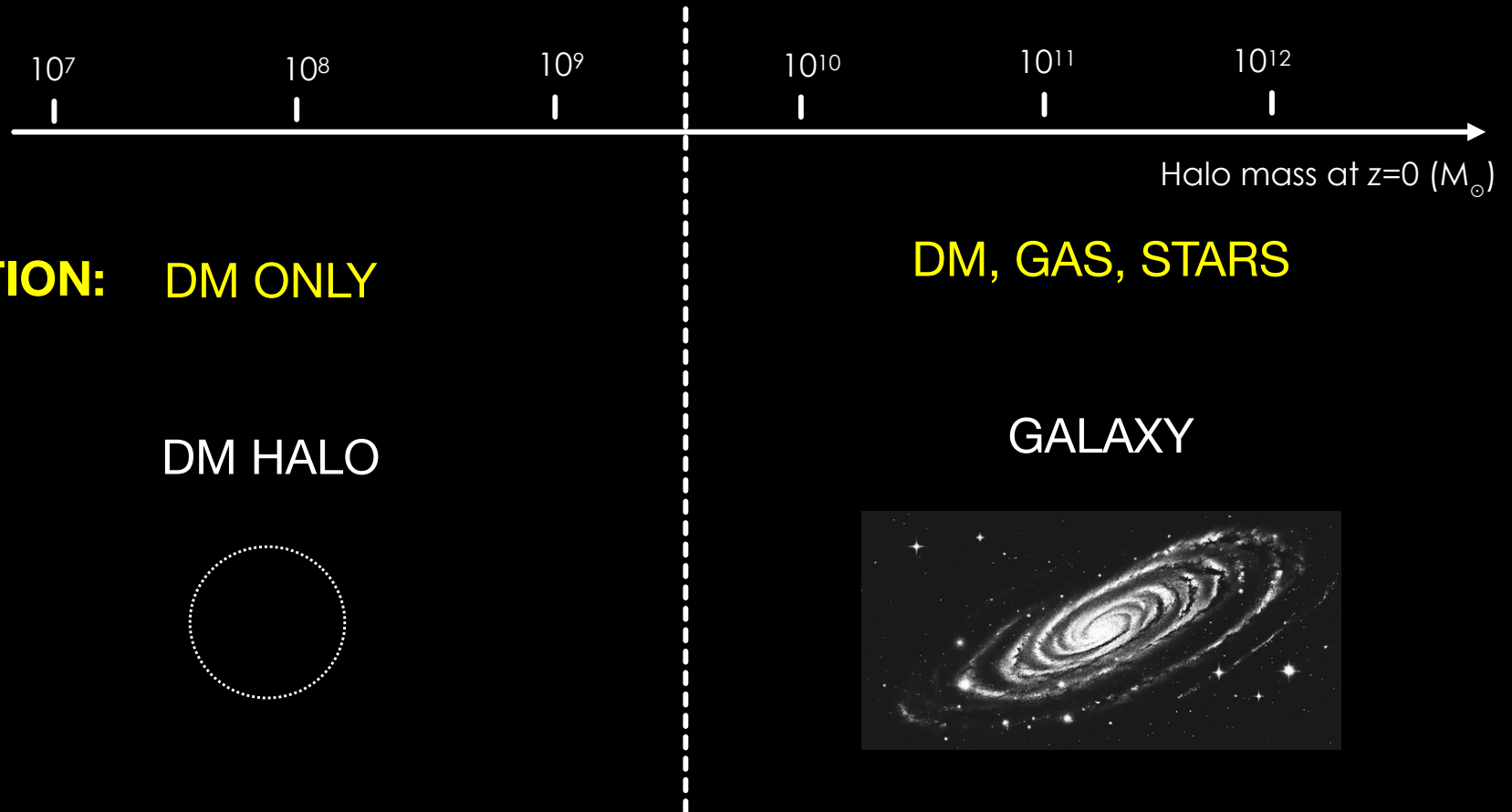
TWO TYPES OF DARK MATTER HALOS ARE PREDICTED COMPOSITION DEPEND ON MASS



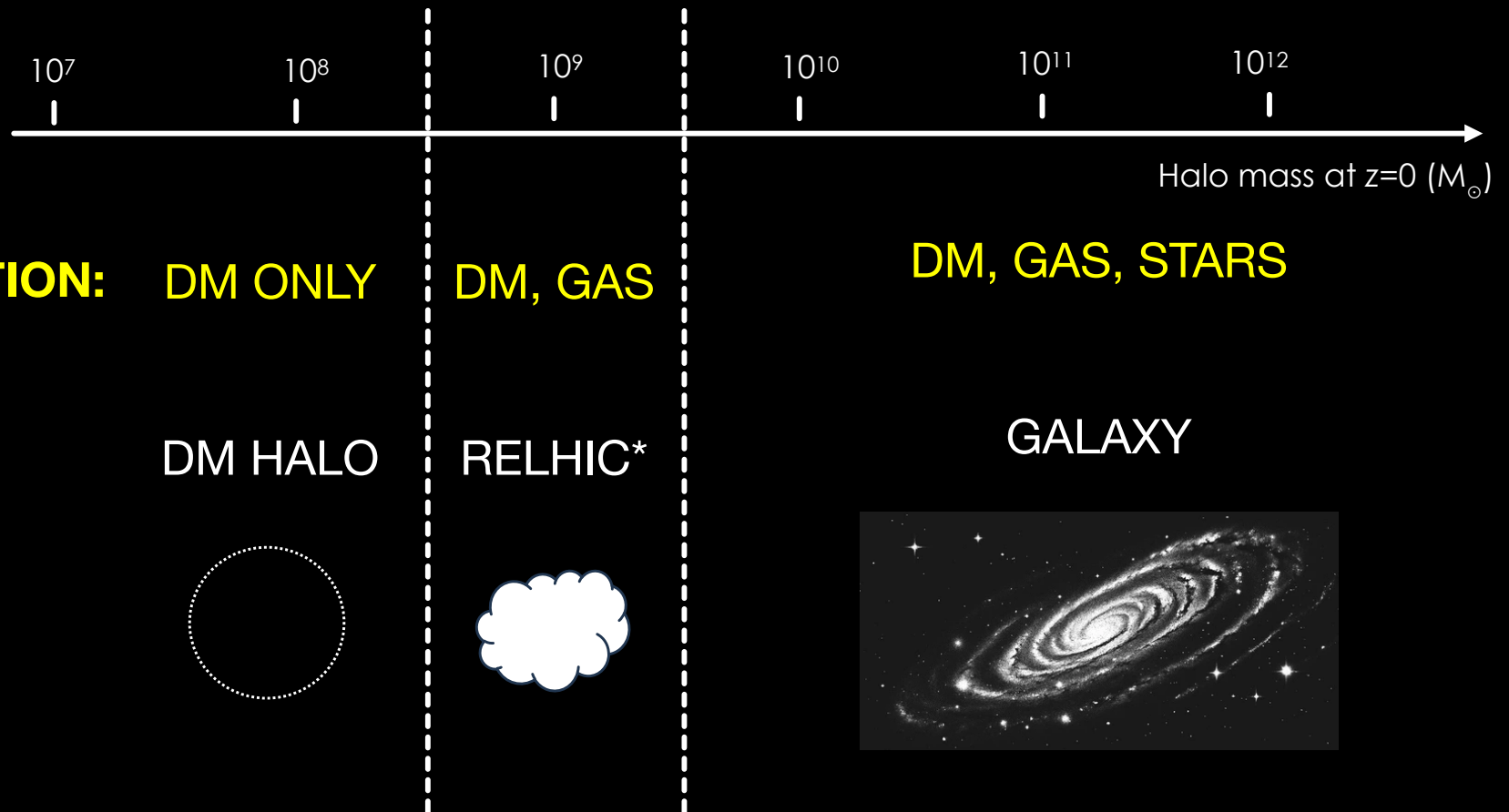
Λ CDM RELHICs

- Dark matter halos more massive than $M_{\text{crit},0} \sim 5 \times 10^9 M_{\odot}$ should all host stars
 - On the contrary, if they are less massive, and have never exceeded $M_{\text{crit}}(z)$, then these halos should lack stars entirely
 - Notably, for the upper mass end of starless halos, their conditions (high density and low gas temperature) allow for hydrogen recombination in their cores, making them visible at 21cm
- Predicted in prior theoretical work (e.g. Sternberg+02), and recently given the name REionization Limited HI Clouds (RELHICs) by Benitez-Llambay+17

TWO THREE TYPES OF DARK MATTER HALOS ARE PREDICTED COMPOSITION DEPEND ON MASS



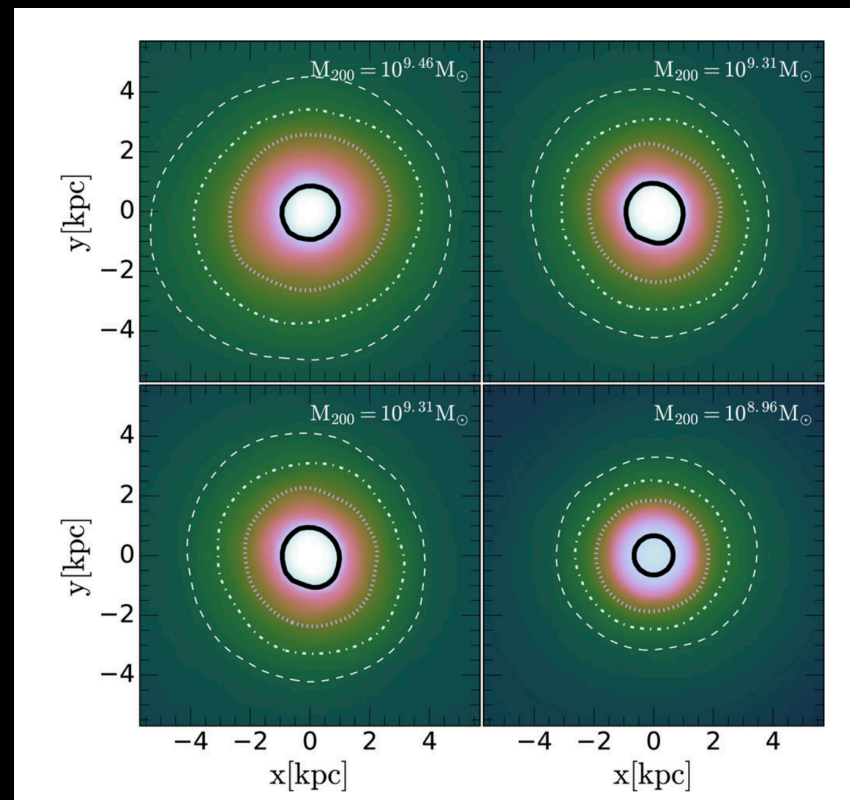
TWO THREE TYPES OF DARK MATTER HALOS ARE PREDICTED COMPOSITION DEPEND ON MASS



* Benitez-Llambay+ 2017

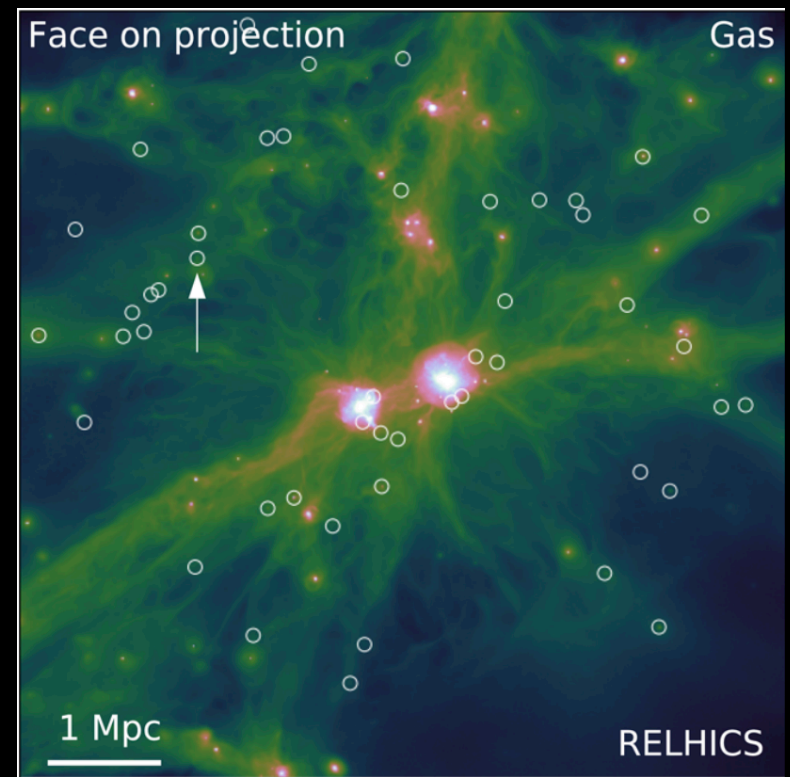
Λ CDM RELHICs

- RELHICs (REionization Limited HI Clouds; Benitez-Llambay+17) examined in APOSTLE simulations:
 - Nearly spherical extragalactic gas clouds in hydrostatic equilibrium, and thermal equilibrium with the ultraviolet background
 - Dynamically cold (narrow HI linewidths, $W_{50} \approx 20$ km/s)
 - Centrally concentrated radial profiles
 - Dark, or lacking in stellar content
 - Reside in low-density regions, including outskirts of massive galaxies



Λ CDM RELHICs

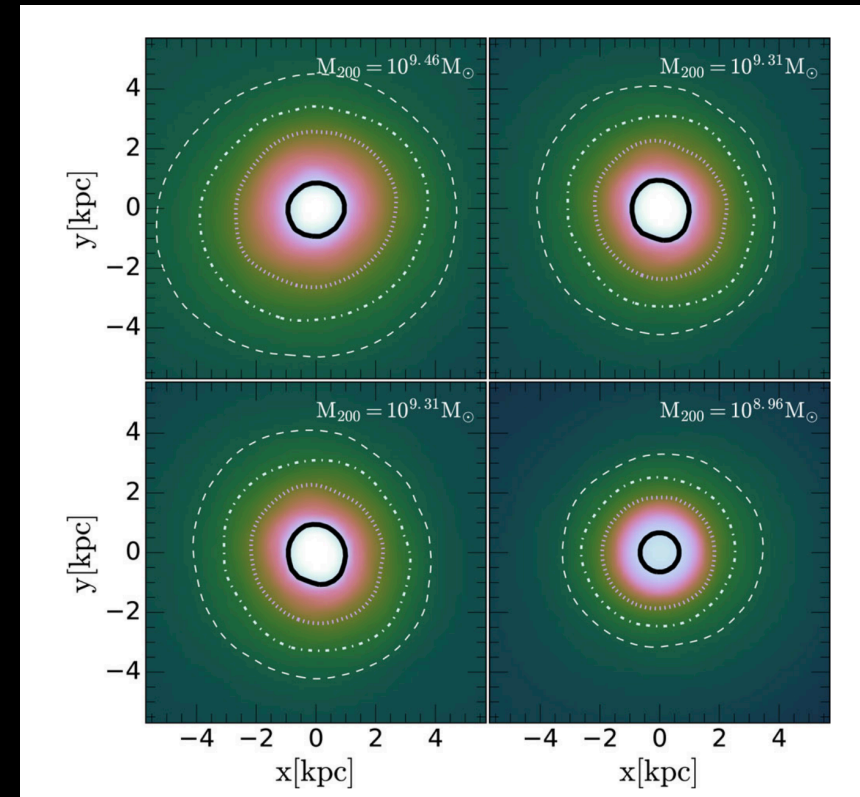
- Where are they?
 - Reside in low-density regions, including outskirts of massive galaxies
- Finding a genuine RELHIC would:
 - Confirm a cornerstone prediction of Λ CDM, namely the existence of bound collapsed structures in a mass regime below galaxies
 - Provide novel paths to studying Λ CDM on the smallest scales, without many of the complications from systems that contain stars (García-Bethencourt+26, Turini+26, Moreno+26)



APOSTLE

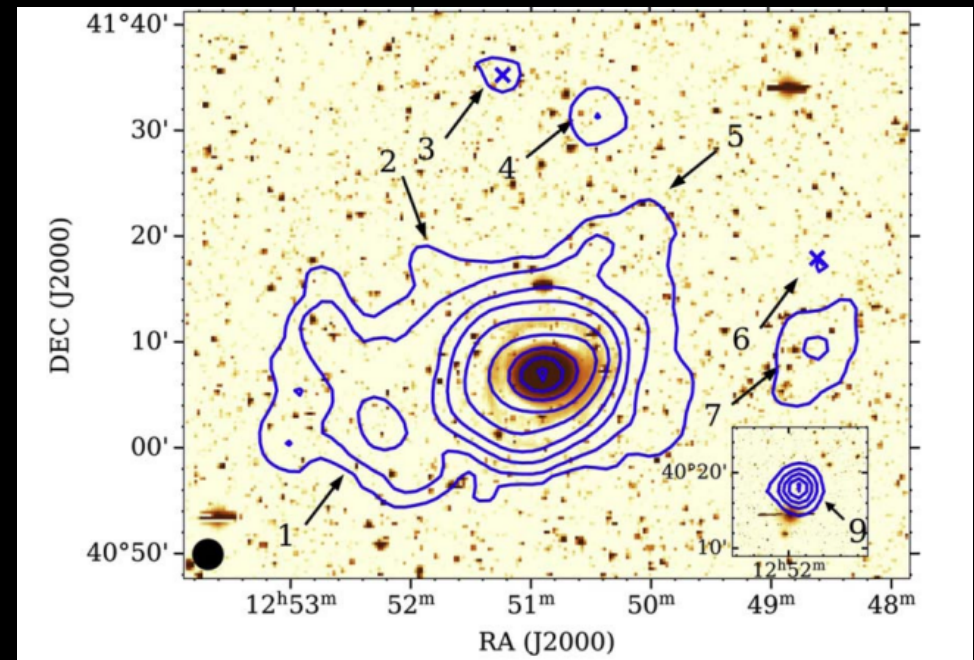
Λ CDM RELHICs

- Distinct from objects such as high velocity clouds or ultra-compact high velocity clouds around the Milky Way (e.g. Adams+13)
- These objects are too extended, irregular, bright, or with linewidths too broad to match the RELHIC criteria
- Strong candidate objects have been scarce, as RELHICs are predicted to have relatively low HI fluxes (not well-matched to existing large HI surveys, e.g. ALFALFA)



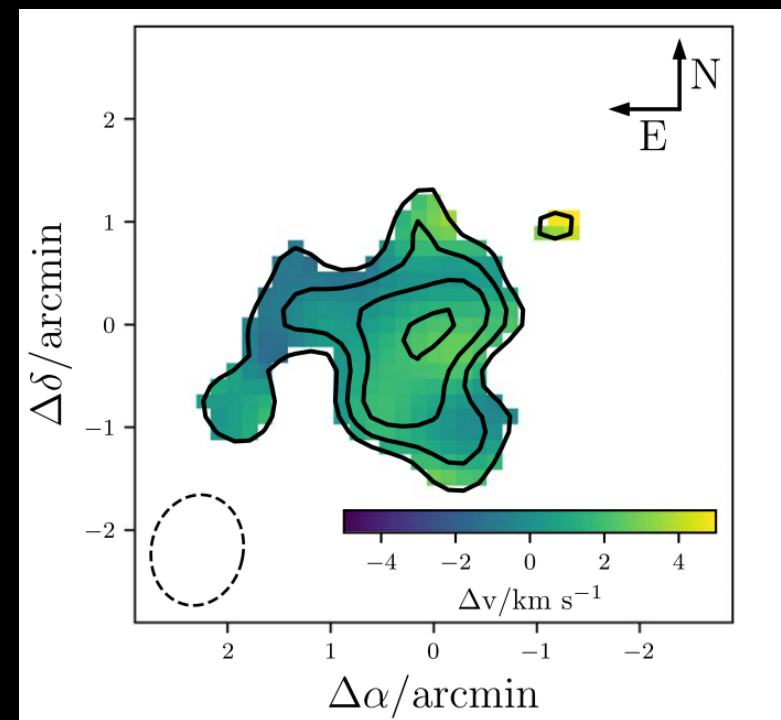
Cloud-9: Discovery of a RELHIC Candidate with FAST

- Zhou+23 used the Five-hundred-meter Aperture Spherical radio Telescope (FAST) to obtain high-sensitivity HI observations around M94 (D=4.4 Mpc)
- Several detected HI clouds, Cloud-9 turned out to be a compelling RELHIC candidate:
 - Outskirts of M94 system (> 70 kpc)
 - Dynamically cold (12 km/s line width)
 - Nearly spherical
 - No optical counterpart (in ground-based imaging)



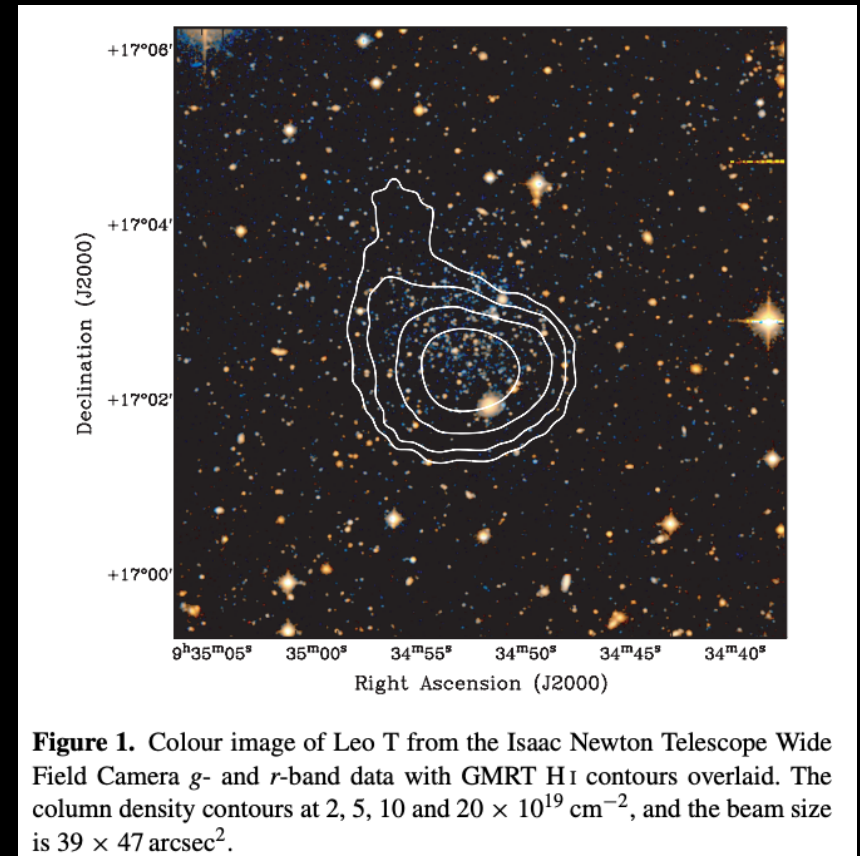
Cloud-9: Follow-up with VLA + GBT

- After the initial FAST discovery of Cloud-9, confirmation of the object was provided by both VLA (Benitez-Llambay+24) and the GBT (Karunakaran & Spekkens 24)
- High resolution VLA observations reveal non-spherical structure
 - Still consistent with RELHIC interpretation, as could be due to ram pressure given the ~ 70 kpc proximity to the massive host (M94)
- At the distance of M94, Cloud-9 requires a substantial amount of mass beyond its HI content ($\sim 10^6 M_\odot$) to remain in hydrostatic equilibrium
 - Inferred total halo mass is very close to $M_{\text{crit},0}$ ($\sim 5 \times 10^9 M_\odot$)



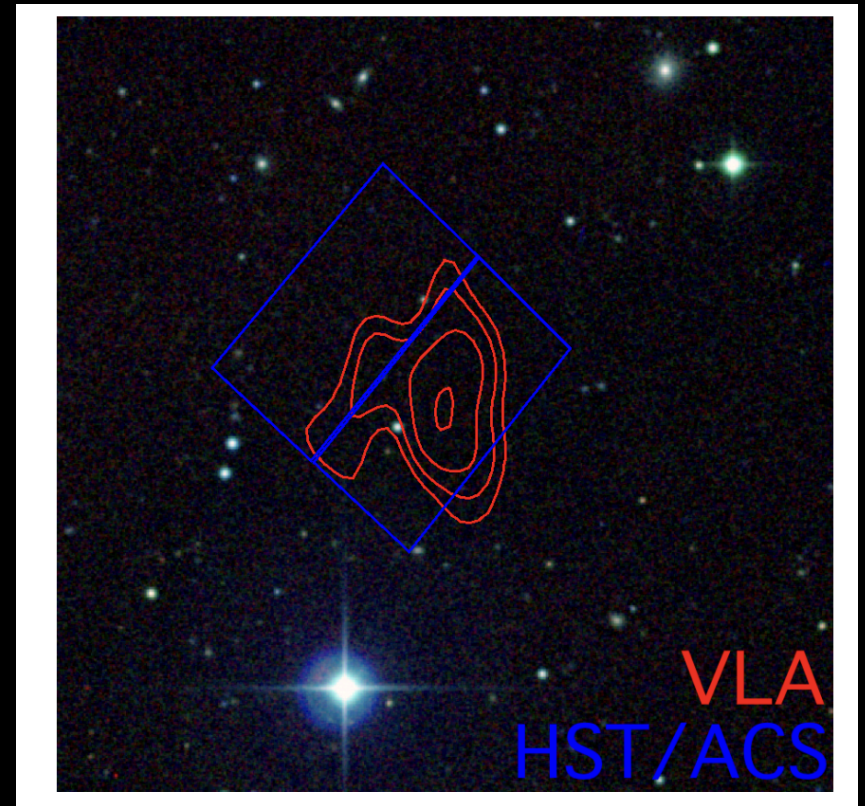
Cloud-9: A faint, low-mass dwarf galaxy?

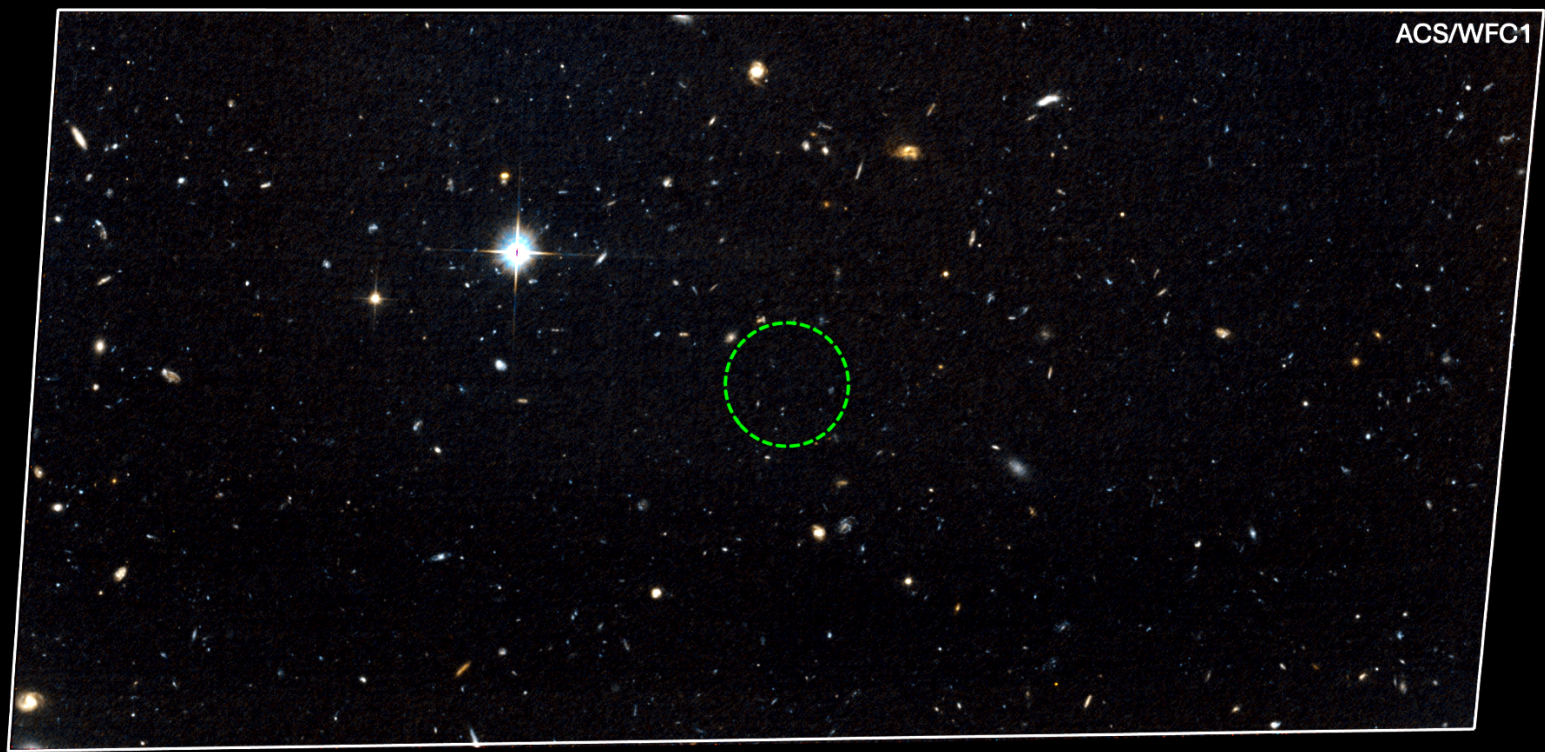
- An alternative explanation involves that Cloud-9 is a galaxy with stars, but not detectable by the ground-based observations available
- An appropriate analogue would be the dwarf galaxy Leo T, an HI rich dwarf galaxy in the Local Group
 - Cloud 9 and Leo T have a similar inner HI density
 - The existing ground-based data for Cloud 9 have a faint limit of just above Leo T's stellar mass ($\sim 10^5 M_{\odot}$) at the distance of M94



HST/ACS Observations

- HST program (GO-17712; PI Benitez-Llambay) to observe Cloud-9 for eight orbits with HST/ACS
 - Either detect a stellar counterpart, or bring down the stellar mass limit by 1-2 orders of magnitude to rule out a Leo T analog
- ArtPop software used (Greco & Danieli 2021) to simulate dwarf galaxy images, based on our observing conditions (telescope parameters, exposure times, PSFs, etc.)
- Separately, performed point-spread function photometry to measure point source population, along with detailed artificial star experiments to quantify photometric errors and completeness levels





Leo T Analog
(to scale)

$10^5 M_{\odot}$

$10^{4.5} M_{\odot}$

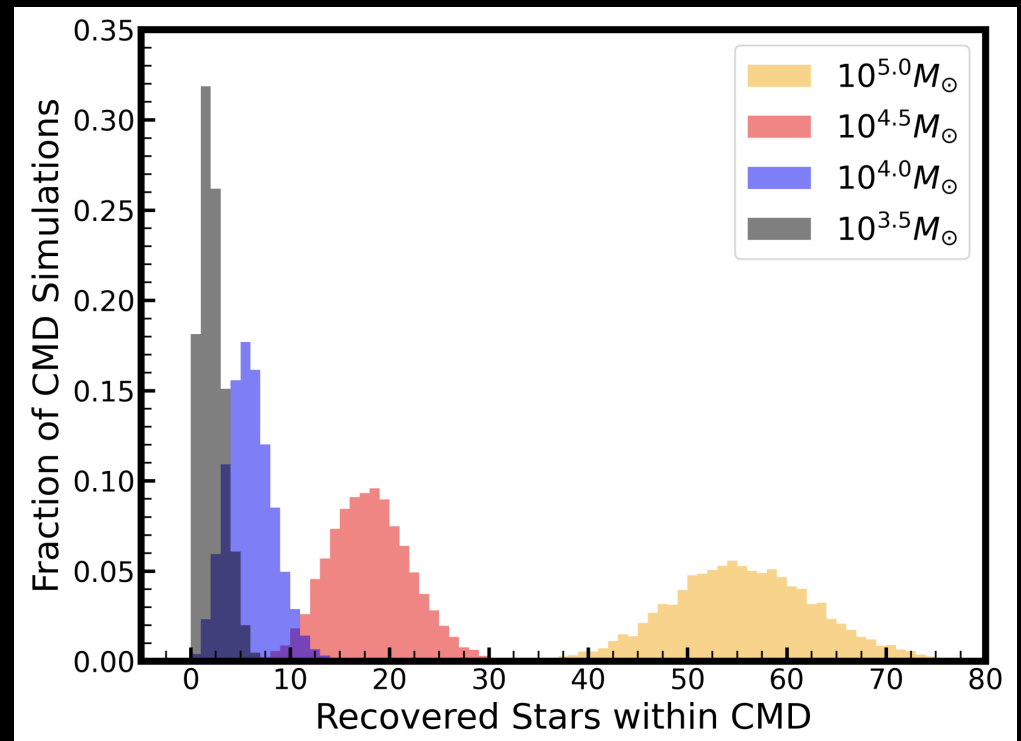
$10^4 M_{\odot}$

$10^{3.5} M_{\odot}$

$10^3 M_{\odot}$

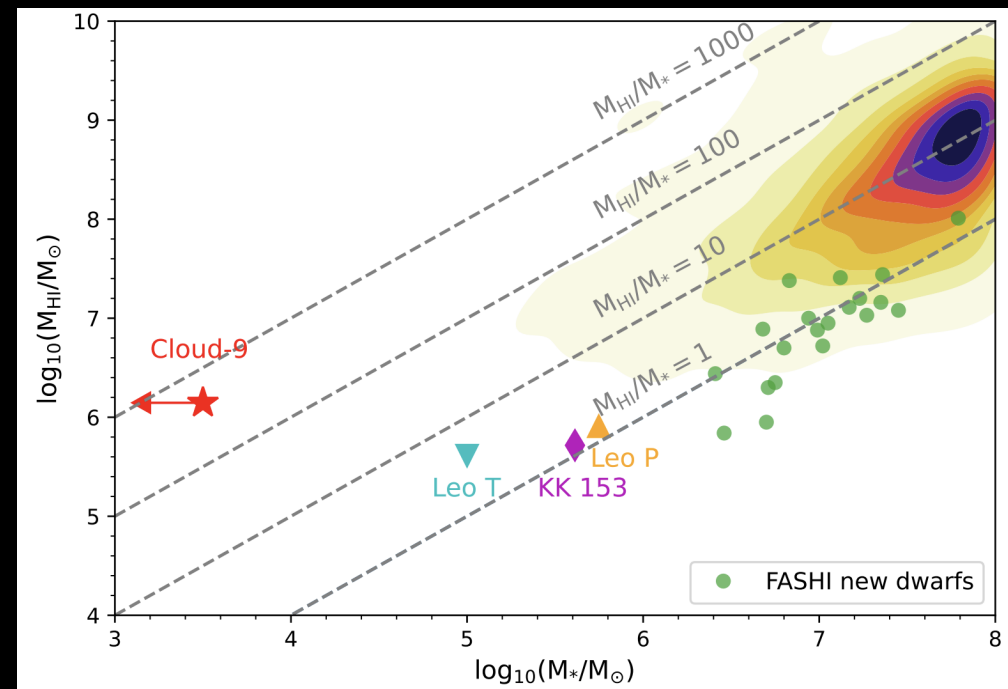
HST/ACS Observations

- More quantitatively, we also used ArtPop to generate synthetic photometry drawn from MIST isochrones for a range of input stellar masses for an old stellar population (conservative route)
- Applied our observational selection functions to these simulations (photometric errors, bias, incompleteness)
- Results allow us rule out a $10^4 M_{\odot}$ stellar mass counterpart with 99.5% confidence, with a baseline upper limit of $10^{3.5} M_{\odot}$



Cloud-9's Properties

- Given the absence of any stellar counterpart down to a very low stellar mass ($10^{3.5} M_{\odot}$), we believe Cloud-9 is likely the first known RELHIC
- There are ultra-faint dwarfs with stellar masses near/below this limit, but none have anywhere near the HI content ($\sim 1.4 \times 10^6 M_{\odot}$) seen with Cloud-9
- $M_{\text{HI}}/M_{*} \gtrsim 443$, exceeding known values for dwarf galaxies with similar HI content by orders of magnitude



Cloud-9 as a Genuine Starless DM Halo

Very strong evidence in favor of Cloud-9 as a genuine starless dark matter halo:

- **Location:** >70 kpc from galaxy
- **Radial velocity:** 304 km/s, matching M94's of 308 km/s
- **Morphology*:** round, symmetric
- **Lack of stars:** $M_* < 10^{3.5} M_\odot$
- **Radial profile:** Centrally concentrated
- **Central H I column density:** $1.6 \times 10^{19} \text{ cm}^{-2}$
- **H I mass:** $\sim 10^6 M_\odot$
- **Narrow H I linewidth:** 12 km/s; kinematically cold
- **Inferred DM mass:** $\sim 10^{9.7} M_\odot$; very close to critical mass at $z=0$

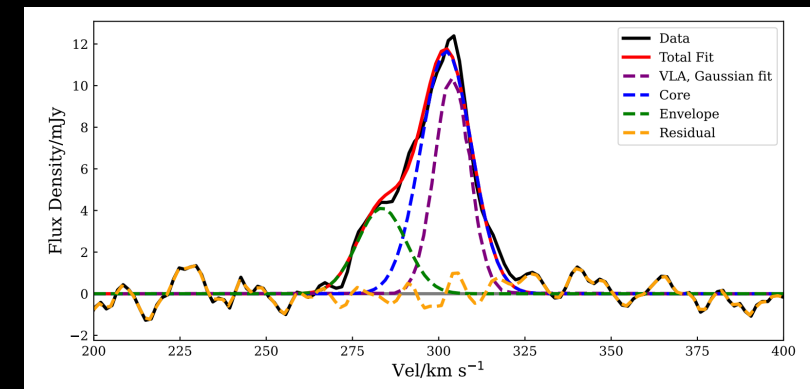
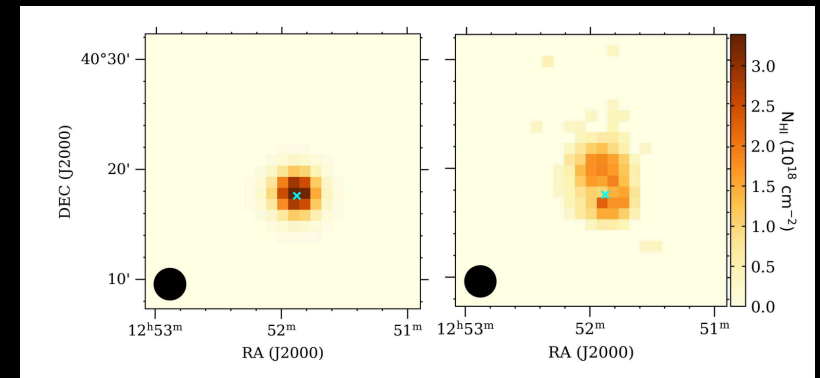


The properties above match the Benitez-Llambay+ 2017 RELHIC model

- However, the extent of the gas in Cloud-9 is $\sim 2\times$ larger than the model predicts. The central core of Cloud-9 is largely consistent with predictions, but the extended component may be due to ongoing interactions with M94.

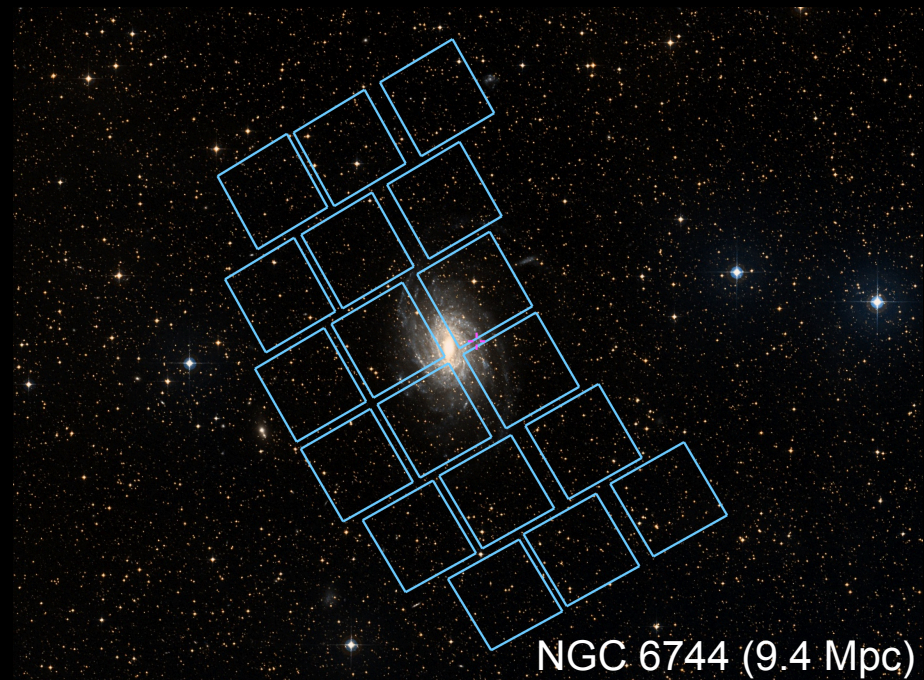
Cloud-9 as a Genuine Starless DM Halo

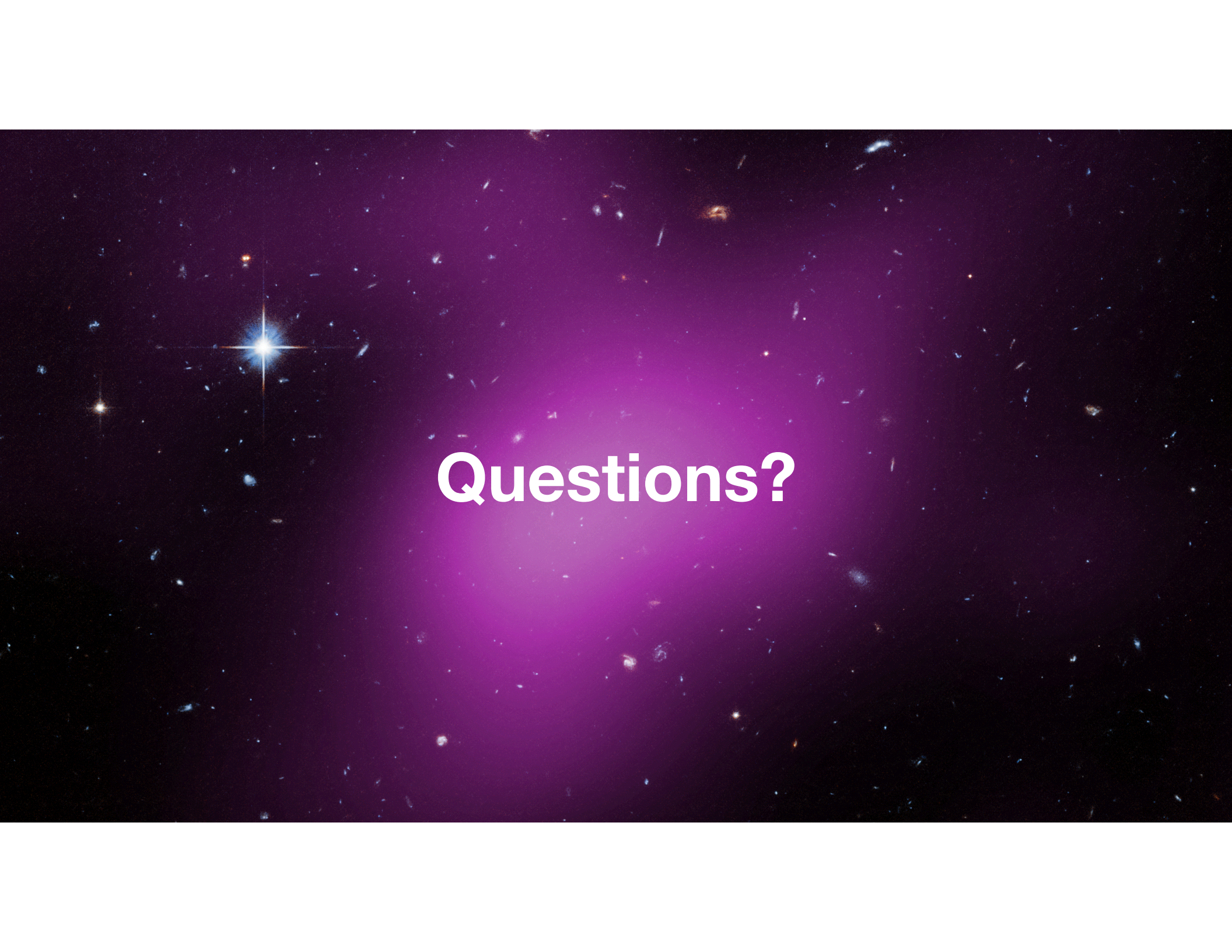
- Paper last week by Zhou+26 present new FAST data combined with VLA imaging to reveal a clear two-component structure of the gas
 - Outer, extended HI envelope with a clear velocity gradient (but no ordered rotation)
 - Inner, dynamically quiescent core with narrow linewidth
- Natural explanation appears to be a that the inner core is held together by a large amount of non-baryonic matter, whereas the outer envelope appears to be stripped gas.
- RELHIC object undergoing interaction with the CGM of M94



A Roman Survey of Nearby Galaxies

- A future Roman GAS program of nearby galaxies would enable an immense amount of science that could not be done with other facilities at this scale
 - Detailed characterization of resolved star formation in all types of galactic environments
 - Studies of resolved stellar halos, providing key insights into galactic assembly processes
 - A baseline imaging campaign for identification of progenitor stars to future supernovae and direct-collapse black holes
 - Robust measurements of galaxy distances to ground observed measurements, determine 3D structures and flows, and stress-test the Hubble tension
 - Detection and characterization of complete satellite populations well into the ultra-faint regime
 - With future HI surveys (e.g. SKA), many more starless dark matter halo candidates will be discovered, and Roman can help efficiently determine if they are genuinely starless
 - And so much more!



A deep space photograph featuring a prominent purple nebula in the center. The nebula has a bright, glowing core and diffuse, wispy edges. The surrounding space is dark, filled with numerous distant galaxies and stars. A bright star with a four-pointed diffraction pattern is visible on the left side of the image. The word "Questions?" is written in a large, white, sans-serif font across the middle of the image, partially overlapping the nebula.

Questions?

Backup Slides

Summary of Cloud-9 Properties

Basic Properties: H I size: 1' or 1.4 kpc; H I velocity width: 12 km s⁻¹ (from VLA), H I mass: $\sim 10^6 M_{\odot}$
Distance: 4.4 Mpc, Radial Velocity: 304 km s⁻¹; Projected Distance from M94: ~ 70 kpc
Dark matter mass: $5 \times 10^9 M_{\odot}$ (to remain in hydrostatic equilibrium)
Stellar mass: $< 10^{3.5} M_{\odot}$

Evidence for RELHIC: Starless, dynamically cold, smooth radial profile (H I column vs radius), symmetric morphology, location (outer M94 system)

Other scenarios:

Foreground HVC or Magellanic Stream: ruled out based on kinematics & sky location

“Vanilla” H I cloud in the M94 CGM: harder to rule out

cloud at $n, T = 2 \times 10^{-2} \text{ cm}^{-3}, 10^4 \text{ K}$ would be in pressure equil. with hot CGM at $2 \times 10^{-4} \text{ cm}^{-3}, 10^6 \text{ K}$ (plausible values)

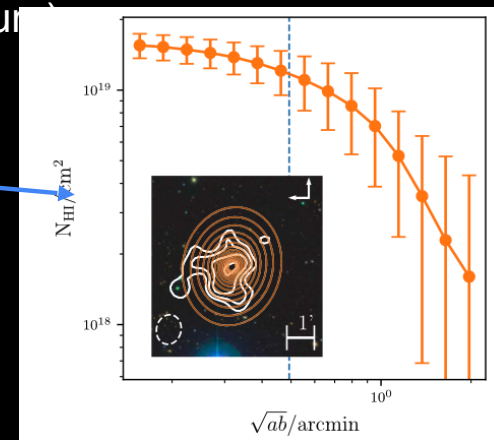
lifetime against ram pressure stripping would be a few 10s of Myr

High-Velocity Cloud (HVC) analog around M94 (variation of previous scenario): hard to rule out, but:

MW HVCs are found within ~ 10 -15 kpc, not 70 kpc

MW HVCs have irregular radial profiles, not smoothly decreasing, symmetric radial profile like Cloud-9

MW HVCs have broader kinematics (not surprising as they're closer to the galaxy)



Alternative Explanations?

- Offset of the stellar populations from the HI gas? (Anand+25)
 - Ram-pressure interactions could induce a mild offset (the HI morphology is only mildly asymmetrical)
 - We tested out to 1 kpc (comparable to the extent of the compact HI core), and found no statistical overdensity when compared to the background chip
- A neutral gas cloud in pressure equilibrium with M94's circumgalactic medium? (Anand+25)
 - Such a configuration would be unstable, lasting ~ 10 s of Myrs only
- Foreground (MW) high-velocity cloud, or association with the Magellanic Stream?

Alternative Explanations?

- M94 HVC? (Benitez Llambay+24, Zhou+26)
 - Two component (compact core + extended envelope) is hard to square with this explanation
 - Timescale arguments disfavor as well, >50 kpc from M94's outer disk, travel time ~ 200 -500 Myr, disruption timescale ~ 100 Myr
- HVC initially accreting onto M94 system? (Zhou+26)
 - Without significant gravitational potential, subject to rapid ionization and disruption
- Tidal debris? (Zhou+23, Benitez Llambay+24, Zhou+26)
 - Similar to arguments against HVC, including timescale (potential merger in M94 system ~ 5 Gyr ago)

Cloud-9: Sky Location on all-sky HVC Map

