

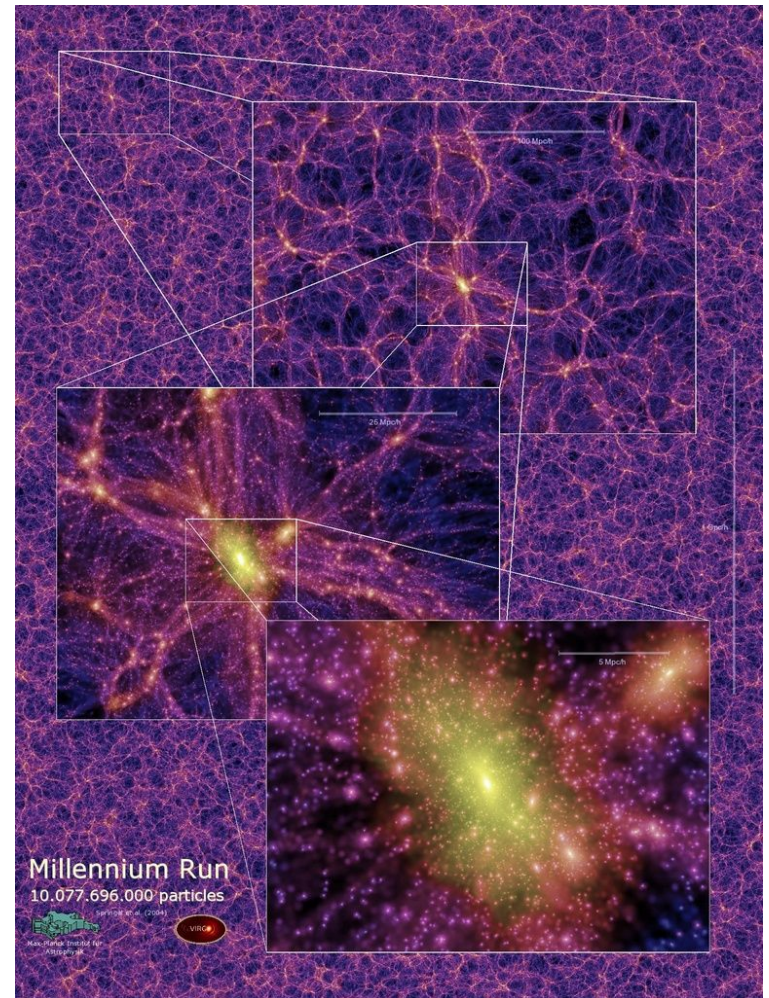
Unveiling small-scale dark matter structure with starless halos:

Are mass and concentration estimates reliable?

The prediction of Λ CDM model

In the **Cold Dark Matter (CDM)** paradigm, the number of halos massive enough to host galaxies **exceeds** the number of faint galaxies observed.

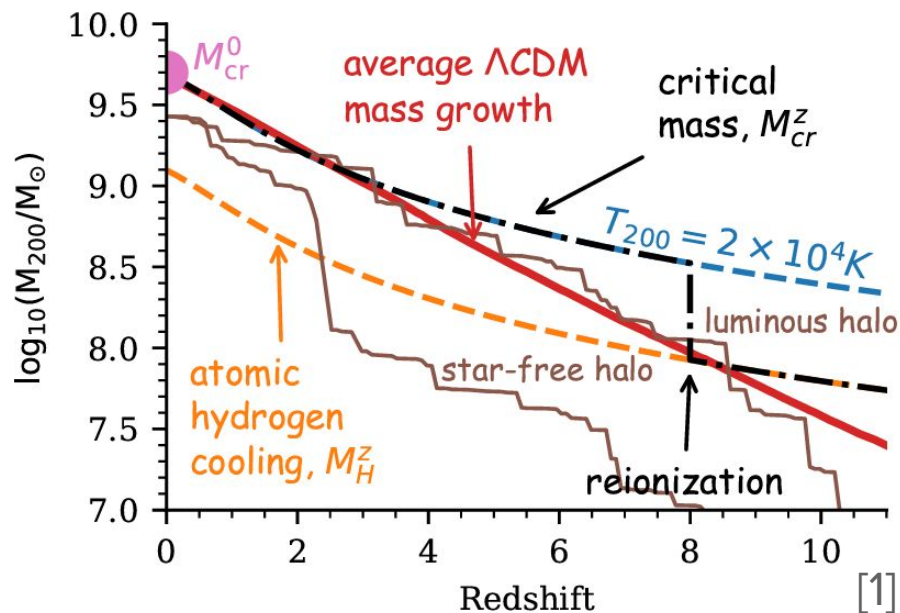
One explanation could be that halos remain **dark** because galaxies fail to form below a certain halo mass.



The UVB feedback and the filtering mass

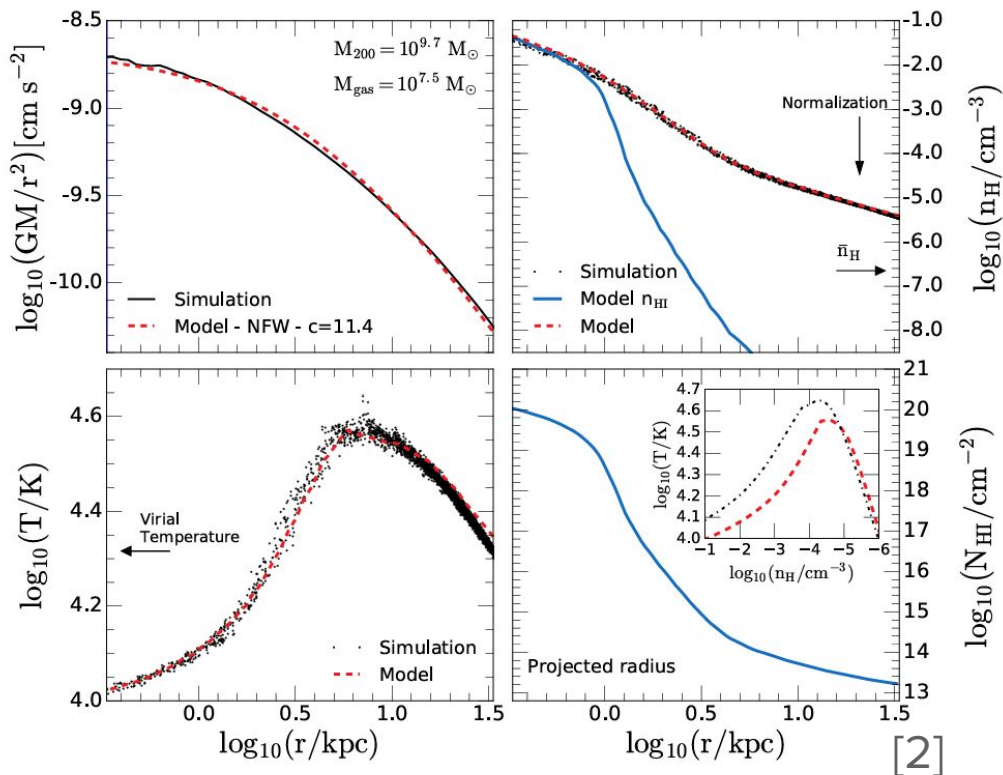
- A halo can form stars only if **gravity overcomes the gas pressure support**.
- **Before reionization:** the pressure floor is set by the efficiency of **hydrogen cooling**.
- **After reionization:** the pressure floor is maintained by the **UV background heating**.

Schematic picture of the impact of cosmic reionization on galaxy formation

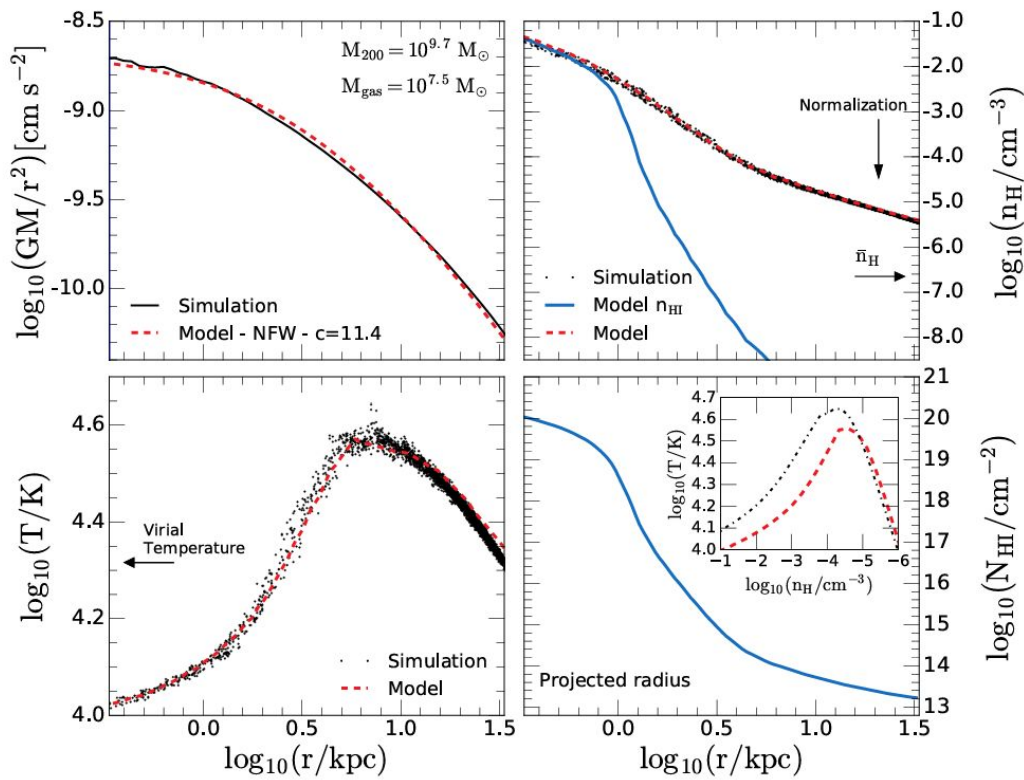


Reionization Limited HI Clouds (RELHICs)

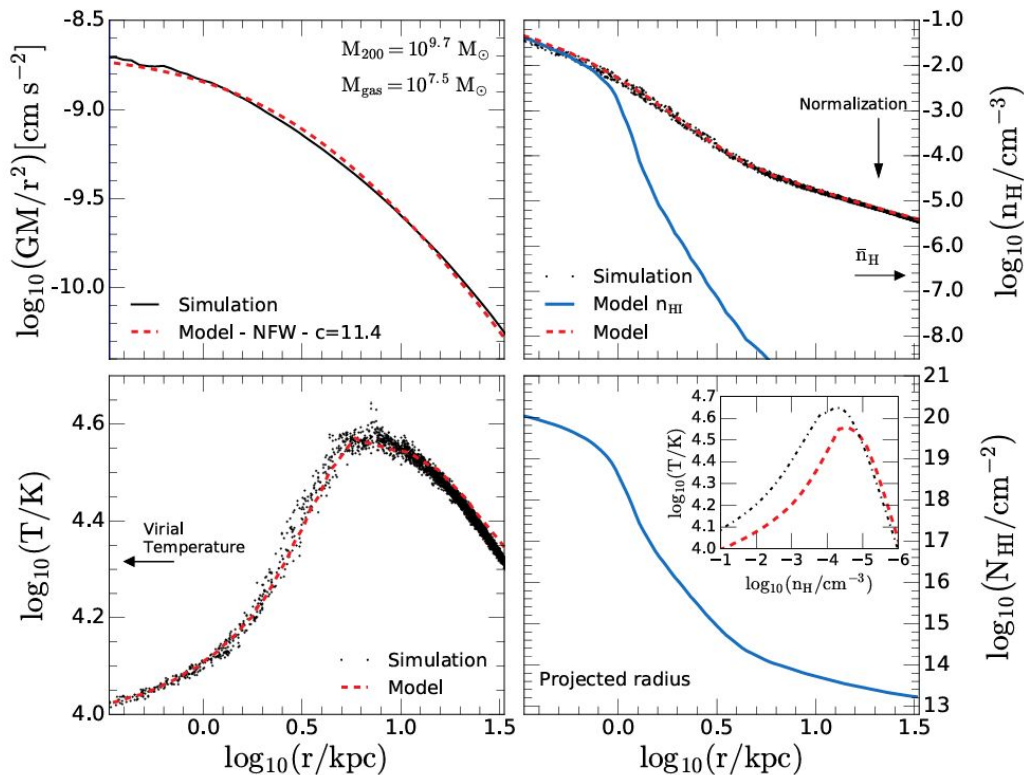
- Just below the **critical halo mass**, we can identify a class of objects whose structure is set by the balance between the **UVB heating** and the **dark matter potential well**.
- These systems are called **Reionization Limited HI Clouds (RELHICs)**.



They don't have stars within, the **DM content is pristine** and should follow NFW profile

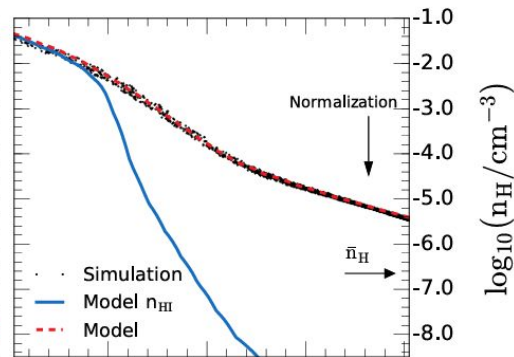
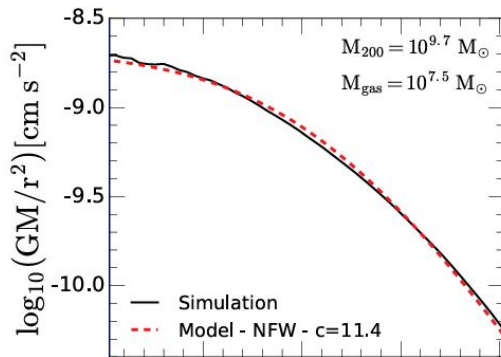


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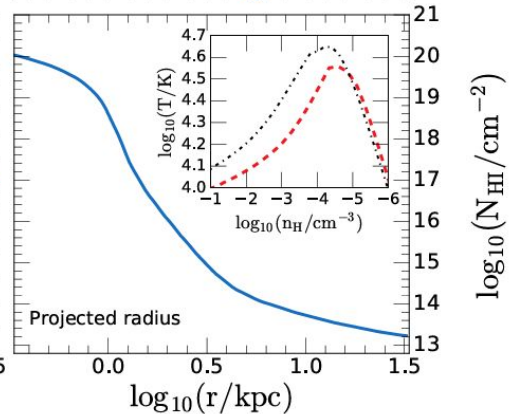
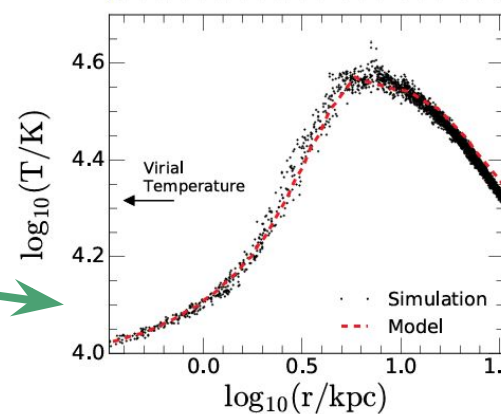
They are in **hydrostatic equilibrium**, so they are expected to be **roughly spherical**.

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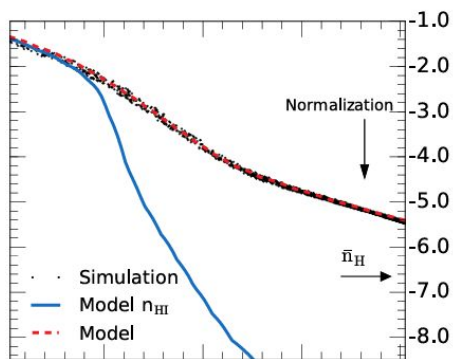
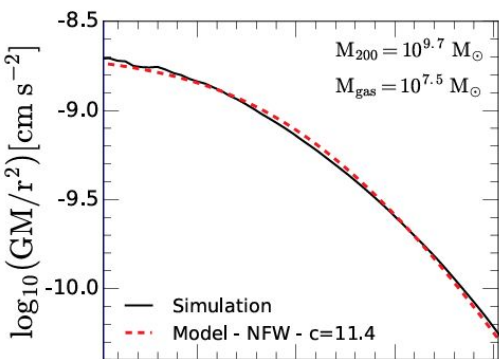
They are in **thermal equilibrium** with the UVB.



The broadening of the **HI emission** should be narrower than 20 km/s.



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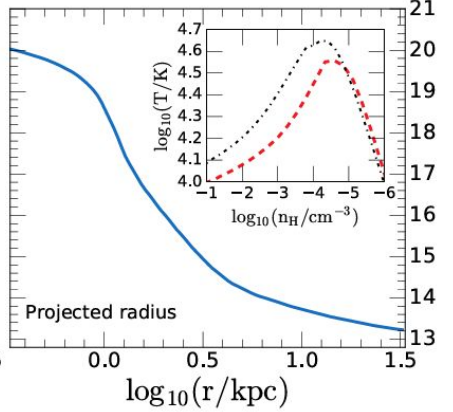
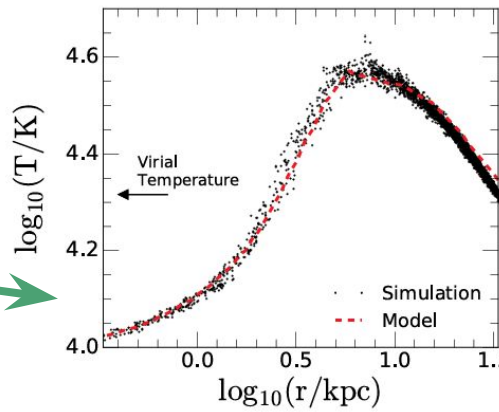


$\log_{10}(n_{\text{HI}}/\text{cm}^{-3})$



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$\log_{10}(N_{\text{HI}}/\text{cm}^{-2})$



The broadening of the **HI emission** should be narrower than 20 km/s.

They are dense and cool enough to **host HI**, with column densities **above $10^{19} N_{\text{HI}}/\text{cm}^{-2}$** , detectable by modern radio facilities.

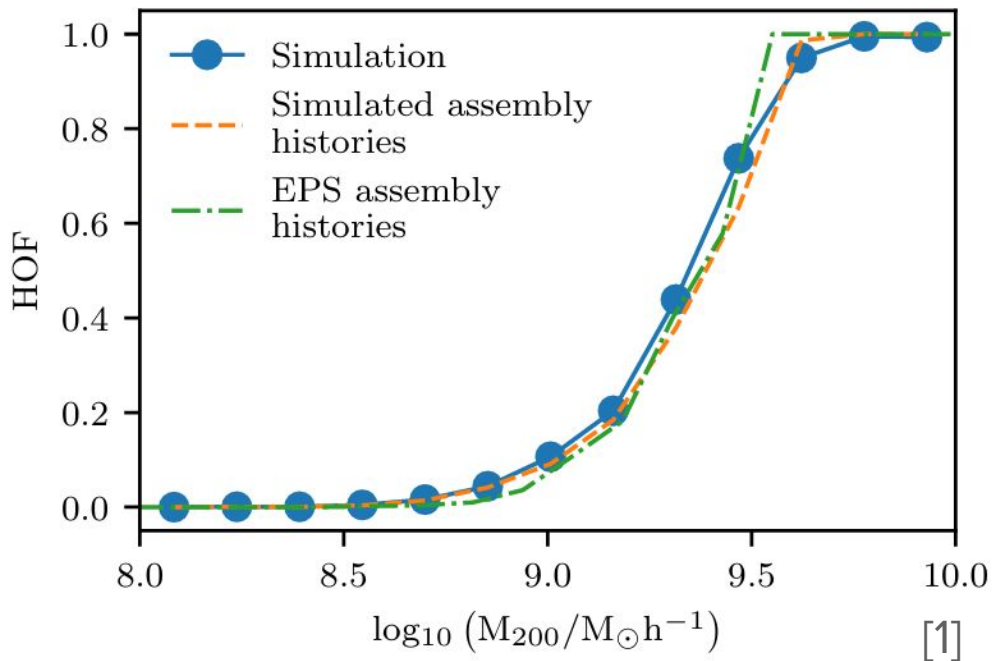
How many RELHICs are visible?

Many halos in the past **exceeded the critical mass**.

Others experienced **ram-pressure stripping** and they lost their gas.

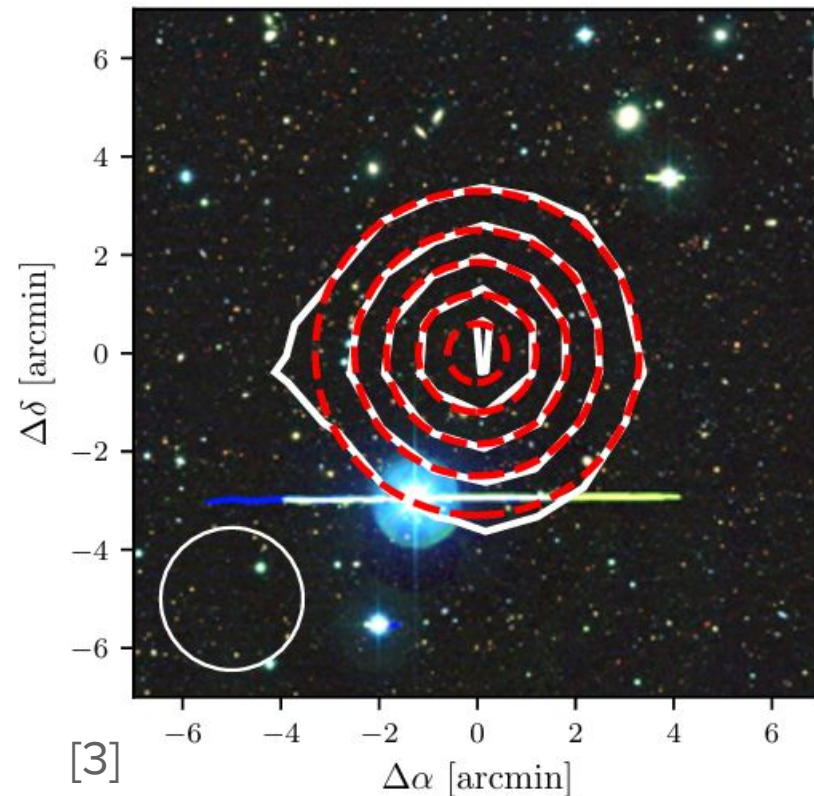
(selection of isolated systems)

As a result, within the **Local Group** we expect **≈ 1 observable RELHIC**.



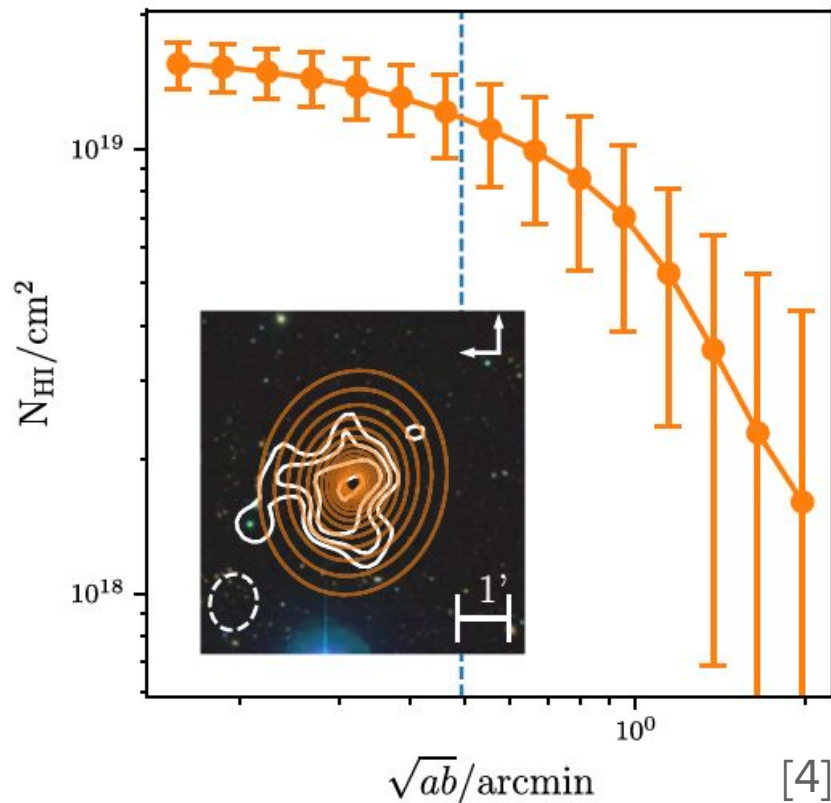
The M94 Cloud-9 candidate- FAST's observation

- **Shape:** roughly spherical
- **Central column density:** $\sim 4 \times 10^{18} N_{\text{HI}}/\text{cm}^{-2}$
- **Consistent with a RELHIC** heated by the UV background, with:
 - $M_{200} \approx 5 \times 10^9 M_{\odot} \rightarrow$ consistent with the critical mass
 - **Concentration:** $c \approx 13$
- But the **beam size** is comparable to the cloud dimension
- Cannot rule out the presence of a **stellar counterpart less massive than $10^5 M_{\odot}$.**

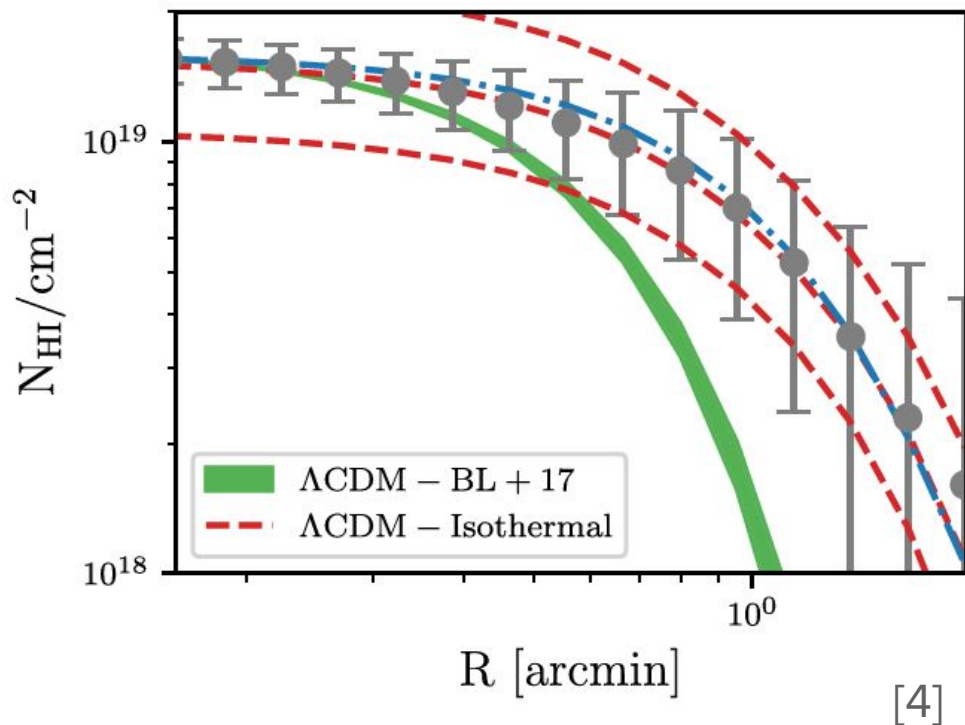


The M94 Cloud-9 candidate-VLA-D's observation

- The **VLA survey** has a **better spatial resolution** (FWHM ≈ 1.5 arcmin) compared to FAST.
- At this resolution, the **cloud no longer appears spherical**.
- Its shape is **consistent with ram pressure effects** from the environment.
- The **central column density** is measured to be $\sim 1 \times 10^{19} N_{\text{HI}}/\text{cm}^2$, higher than previous estimates.



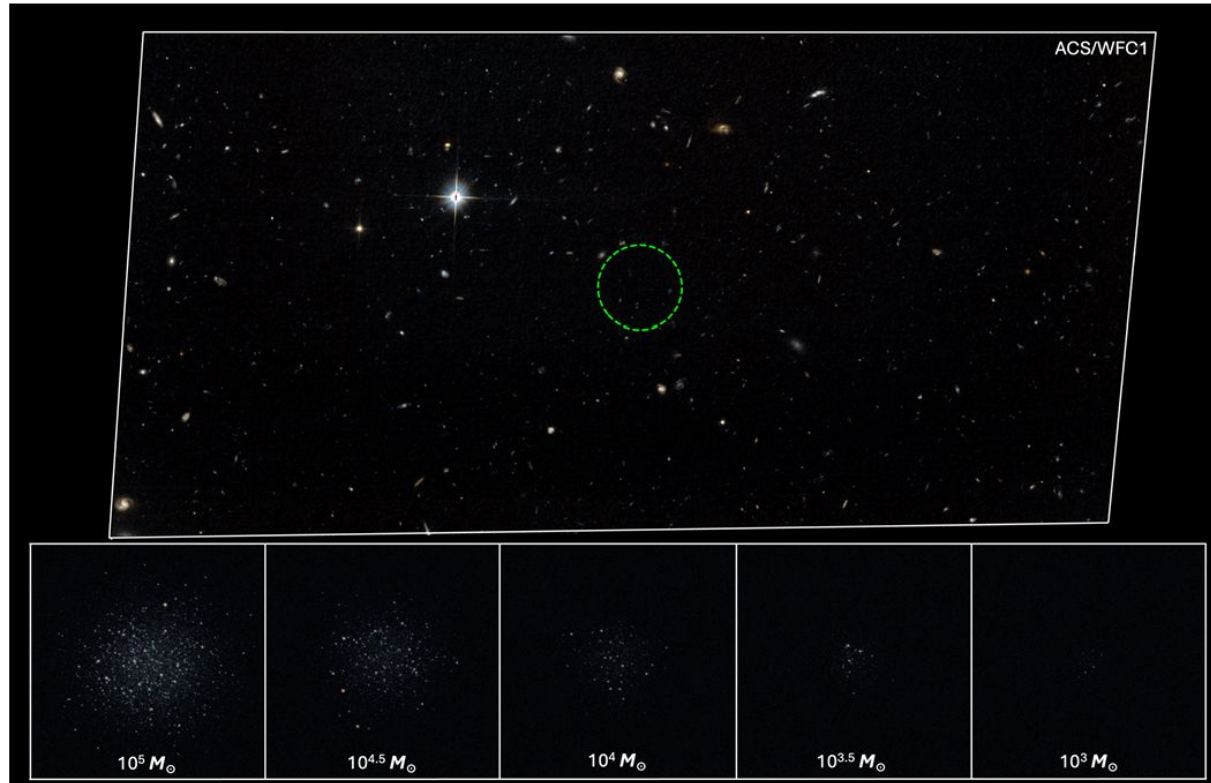
The failure of the simplest model



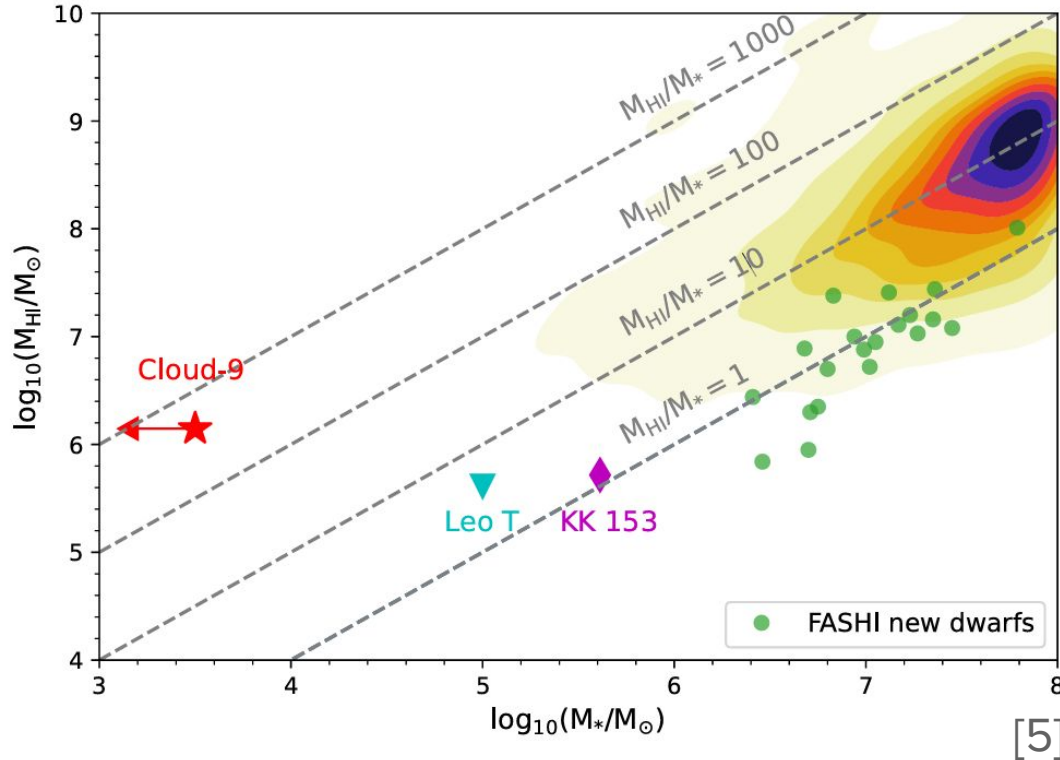
The observed Cloud-9 data of VLA-D are **not in agreement with a UVB** driven EoS, the suggested motivation is:

- The **ram pressure** of the IGM that strips the cloud's gas

The M94 Cloud-9 candidate- HST's observation



A different class from dwarfs



The recent HST observation of Cloud-9 :

- Ruled out a stellar counterpart greater than $10^{3.5} M_{\odot}$
- Find a H I-to-stellar mass ratio of $M_{\text{HI}}/M_{*} \gtrsim 443$ (Leo T and KK 153 $M_{\text{HI}}/M_{*} \lesssim 4$)

How reliable are RELHICs as probes of DM?

A systematic study using the EAGLE simulations

- We applied **nested sampling** to determine the **mass** and **concentration** of **262 simulated halos** in a **box of size ≈ 20 Mpc**.

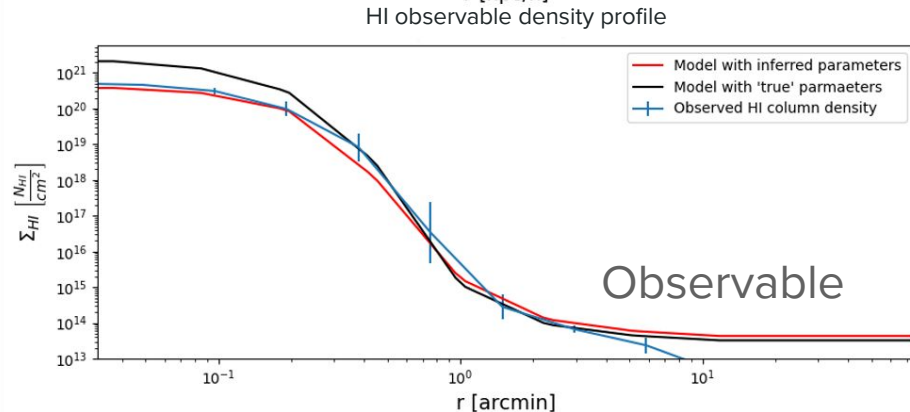
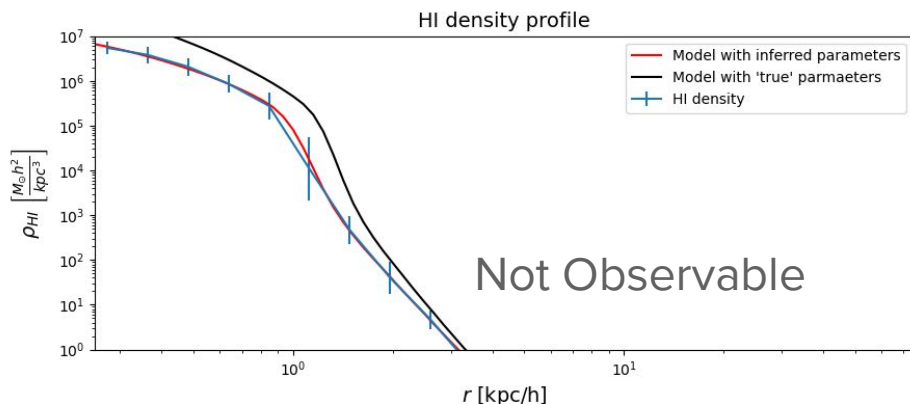
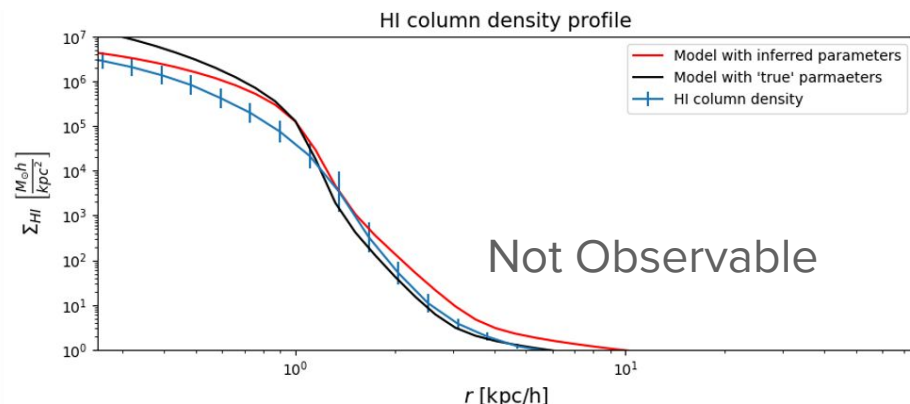
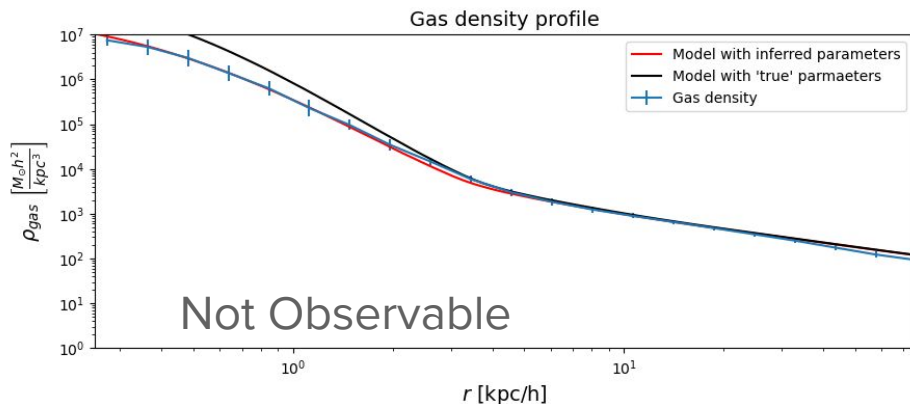
Selection criteria:

- **No stars bound.**
- **$M_{200} > 2 \times 10^9 M_{\odot}$.**
- **At least $10^7 M_{\odot}$ of gas.**

Ground truth:

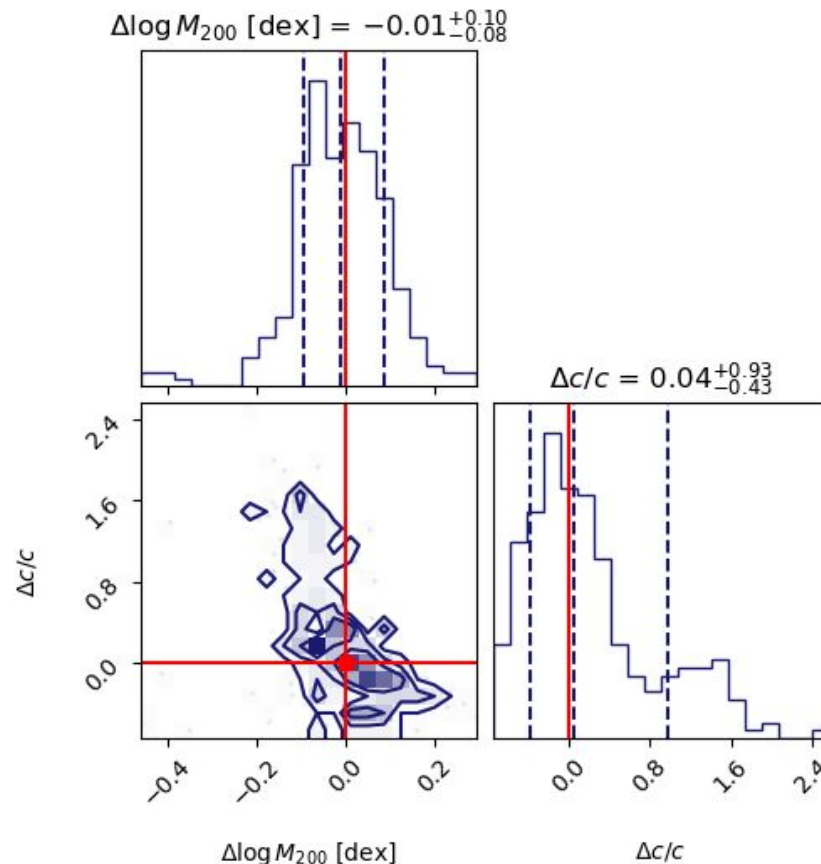
- **Virial mass** from counting DM particles.
- **Concentration** from an **NFW fit** to the DM density profile.

4 different profiles

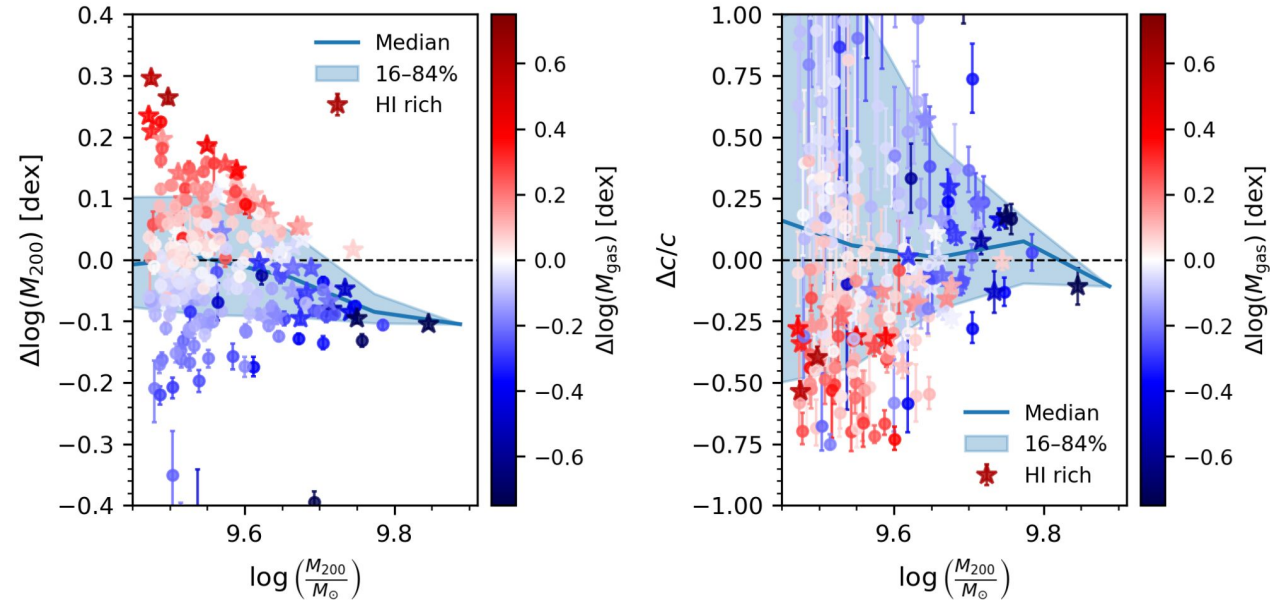


Unbiased total gas distribution

- **Unbiased distribution** of MPVs obtained.
- A faint **bimodality in concentration**, likely due to the difficulty of sampling the halo centers.
- On average, halos appear to be in **hydrostatic and thermal equilibrium**.



The gas mass correlation

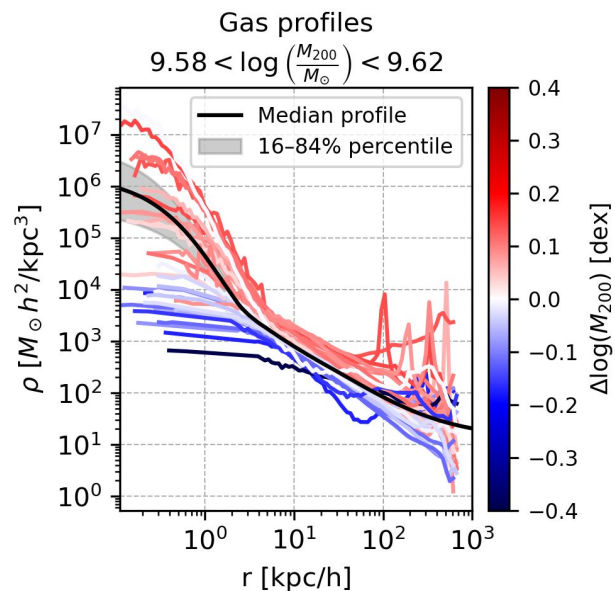
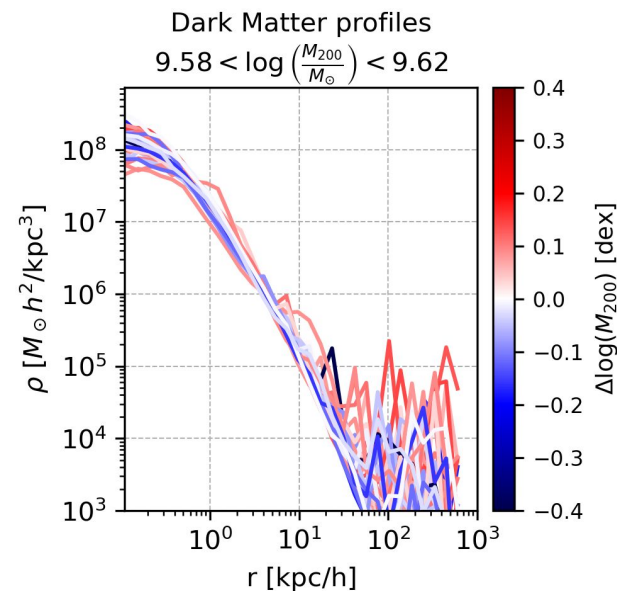


- **Gas mass residuals** correlate with the **virial mass residuals**.
- For **HI-rich halos (★)**, residuals appear **anti-correlated** with the *true* virial mass.

Question:

- *What modify the expected gas mass in the model?*

The 3th parameter



DM profiles do not correlate with the residuals.

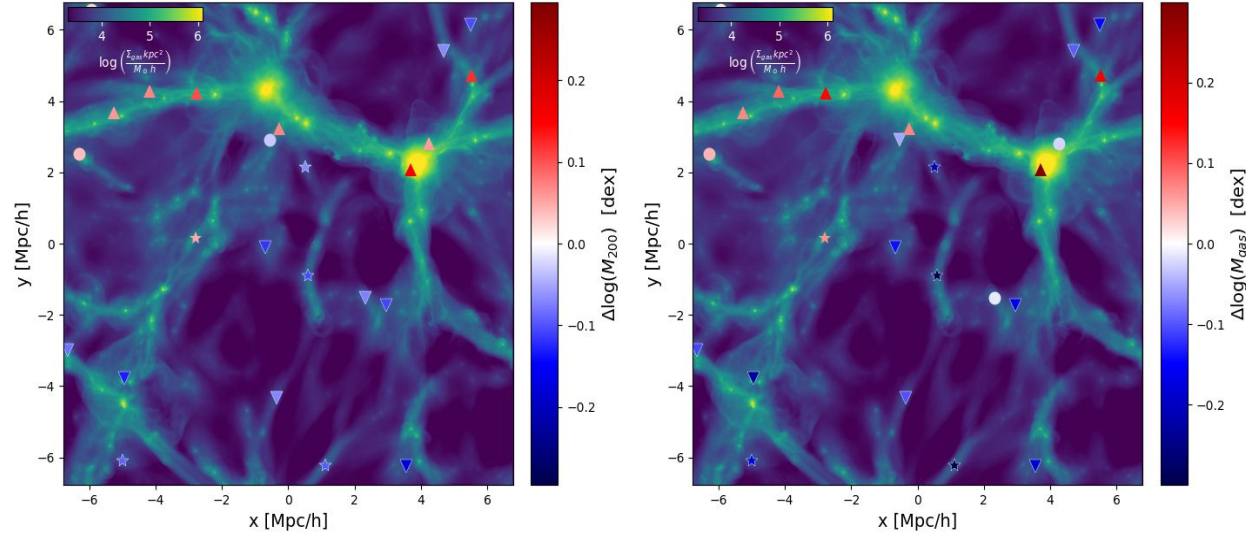
Halos with outer density lower/higher than predicted are underestimated/overestimated by the model.

BL17 model: must include external pressure

Thermal equilibrium: density \leftrightarrow pressure

Environmental Effects on Halo Mass

- Halos with **overestimated virial mass** (overdense environments) are generally **closer to the cosmic web**.
- The ones with a underestimate mass are **more isolated**.
- **Implication:** environmental density is largely determined by **halo position**.



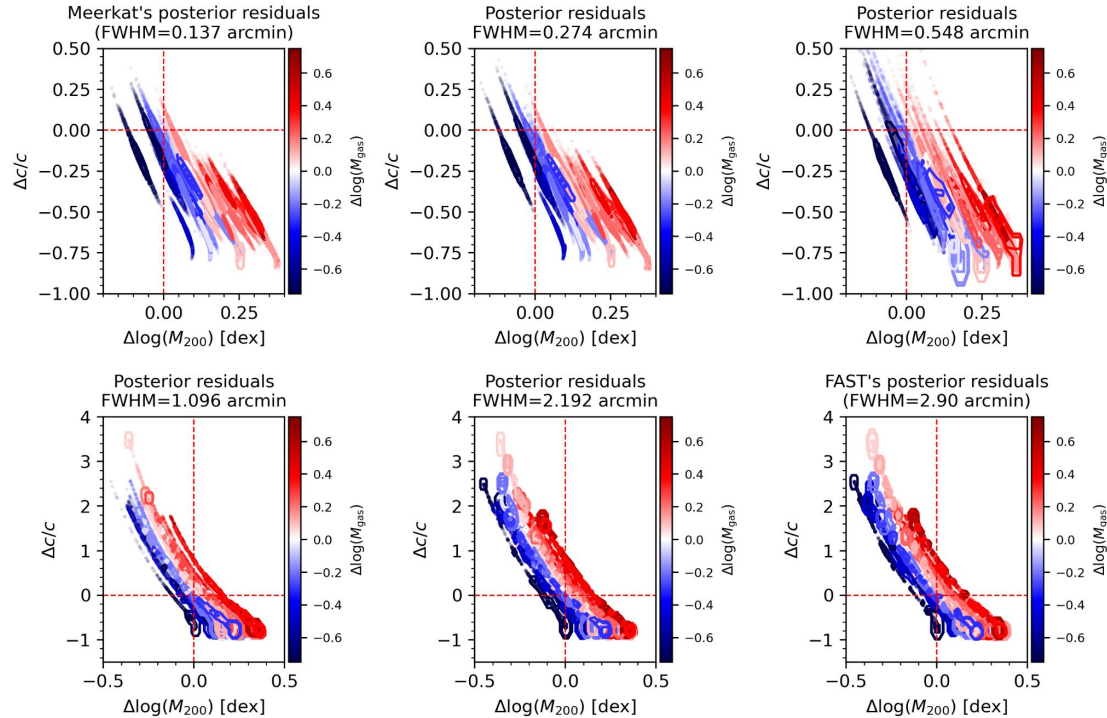
- This may explain the **discrepancy found for Cloud-9**.

What we learned

- **RELHICs** are ideal halos to test the **CDM paradigm on small scales** ($\ll 30$ kpc), as their **pristine DM distribution** is unaffected by stellar feedback.
- **From observational evidence** we know that Cloud-9 is a very strong RELHIC candidate.
- **Simulations show** that the **underlying DM distribution** can be estimated reasonably well for RELHICs **as an ensemble**.
- **Caution:** for **individual systems**, DM parameters are **biased by external pressure**.

Mock Observations of RELHICs

- Observer inside cosmological volume of 20 Mpc
- Projected the column density of RELHICs as if they are observed from this position.
- Minimal resolution to fit NFW: $\text{FWHM} \lesssim 0.5$ arcmin
- Reachable with SKA



Thank you for the attention

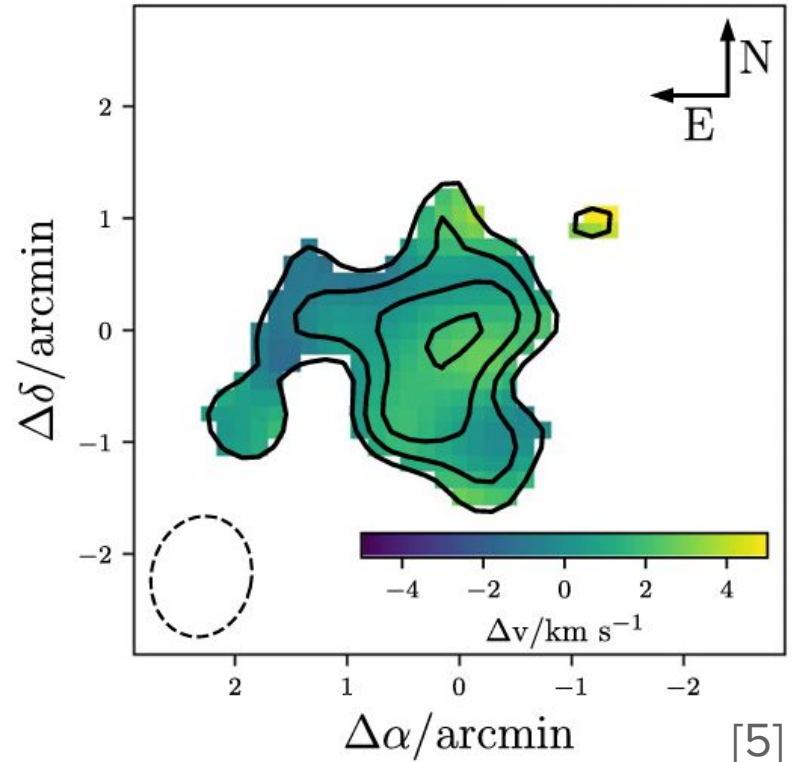
References

1. Benítez-Llambay A., Frenk C., 2020, MNRAS, 498, 4887
2. Benítez-Llambay A., Navarro J.F., Frenk C.S., et al., 2016, MNRAS, 465, 3913
3. Benítez-Llambay A., Navarro J.F., 2023, ApJ, 956, 1
4. Benítez-Llambay A., et.al, 2024, ApJ, 973, 61
5. Anand G.,et al., 2025, arXiv:2508.20157

Backup slides

Cloud-9 a non rotating systems

There is **no coherent rotation** over the sampled scales, demonstrating that the sampled gas cloud is **not supported by circular motion**



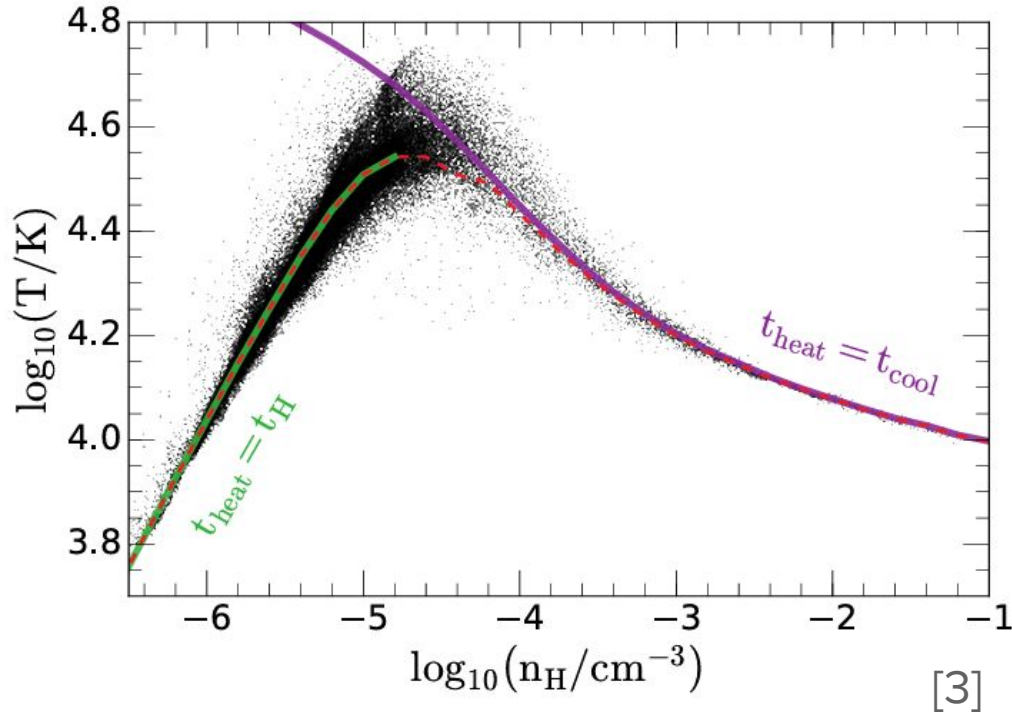
The simplest model (Llambay2017)

$$\frac{1}{\rho} \frac{dP}{dr} = -\frac{GM(r)}{r^2} \longrightarrow \rho(r) = F^{-1}[G(r)] \longrightarrow$$
$$F(\rho) = \int_{\bar{\rho}}^{\rho} \left(\frac{T}{\rho} + \frac{dT}{d\rho} \right) \Big|_{\rho'} d\rho'$$
$$G(r) = -2T_{200} \int_{\infty}^r \frac{\tilde{M}(\tilde{r}')}{\tilde{r}'^2} d\tilde{r}',$$

The model's parameters:

1. The **halo mass and concentration** that drives the potential well
2. The **Equation of State** that drives the pressure of the gas
3. The outer density that determines the outer pressure, that is assumed to be the **mean baryonic density of the universe**

The Equation of State



- At high densities ($10^{-5} n_H/\text{cm}^{-3}$ for $Z=0$) the cooling time is smaller than the Hubble time ($t_{\text{heat}} = t_{\text{cool}}$)
- At lower densities the cooling time is smaller than the Hubble time ($t_{\text{heat}} = t_{\text{Hubble}}$)

The two option (EoS-outer density)

