- Probes to the nature of dark matter from faint (and dark) galaxies

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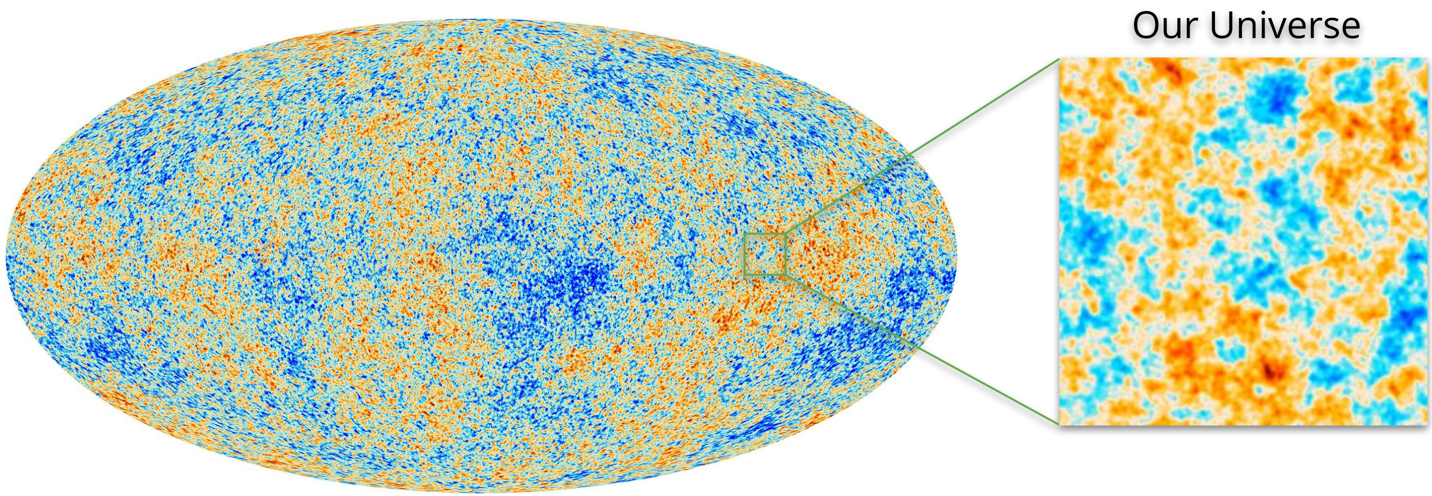
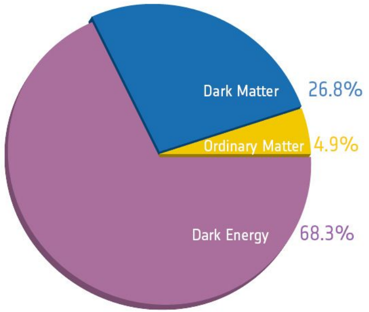
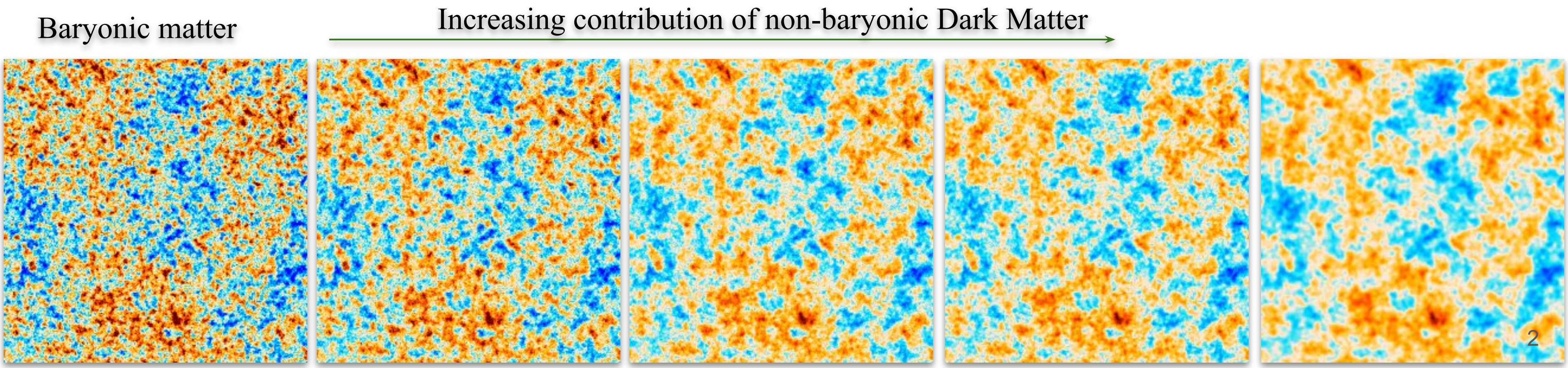
The Need for Dark Matter and Dark Energy

Planck Collaboration (2016)



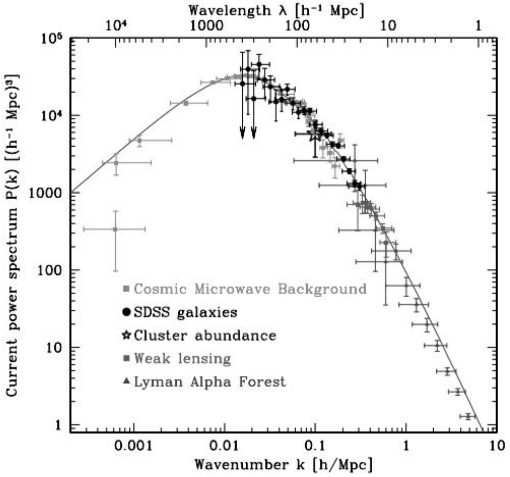




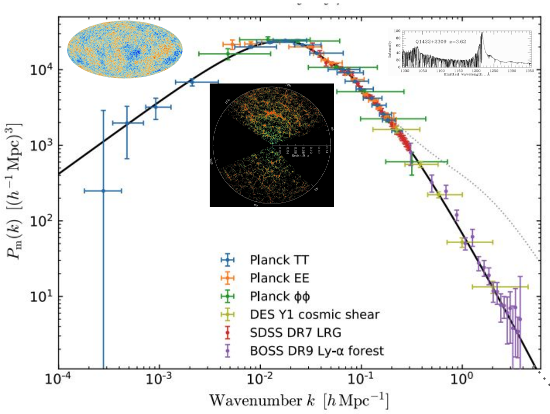
The Standard Model of Cosmology

The standard model of cosmology (ΛCDM) fits observational data over scales spanning several orders of magnitude.

Remarkably, observations taken at different times and over different scales, can be accurately described by a single curve: the ΛCDM power spectrum.



Tegmark 2004



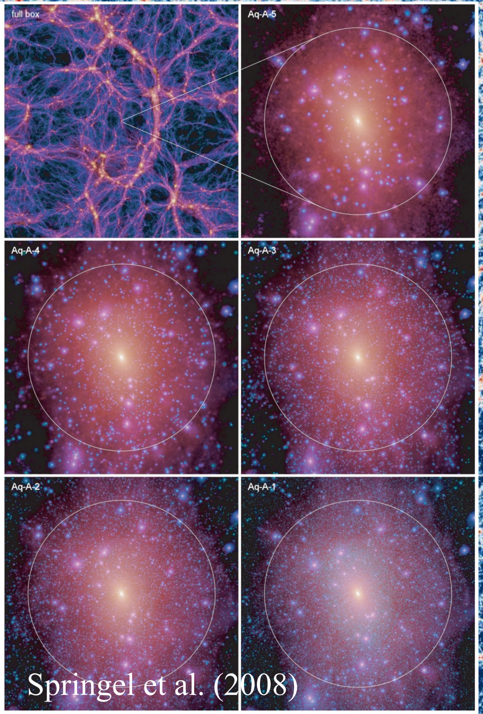
Planck collaboration (2019)

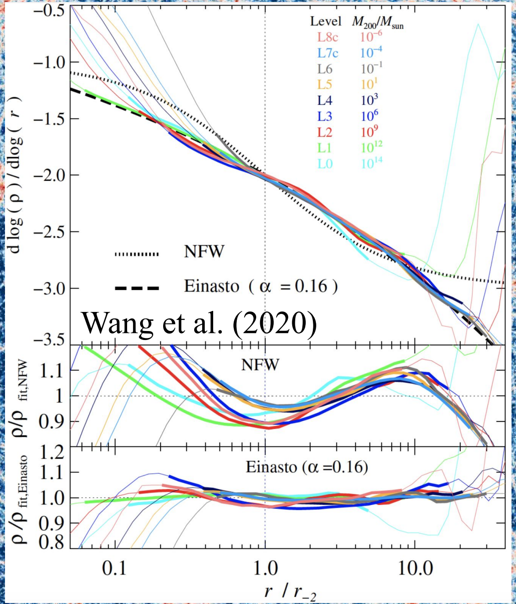
Agreement between CMB data at z~1000 and galaxy clustering at z~0 validates the paradigm of structure formation triggered by the gravitational instability of small density fluctuations.

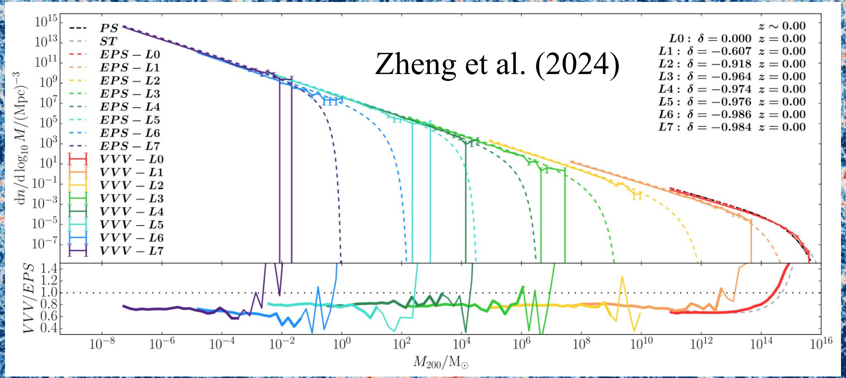
(Dwarf) galaxy scales

Any hope to rule out ΛCDM from astrophysical observations lies to the right of these plots, where we do yet not have observations!

Simulations of Structure Formation from Primordial Density Fluctuations





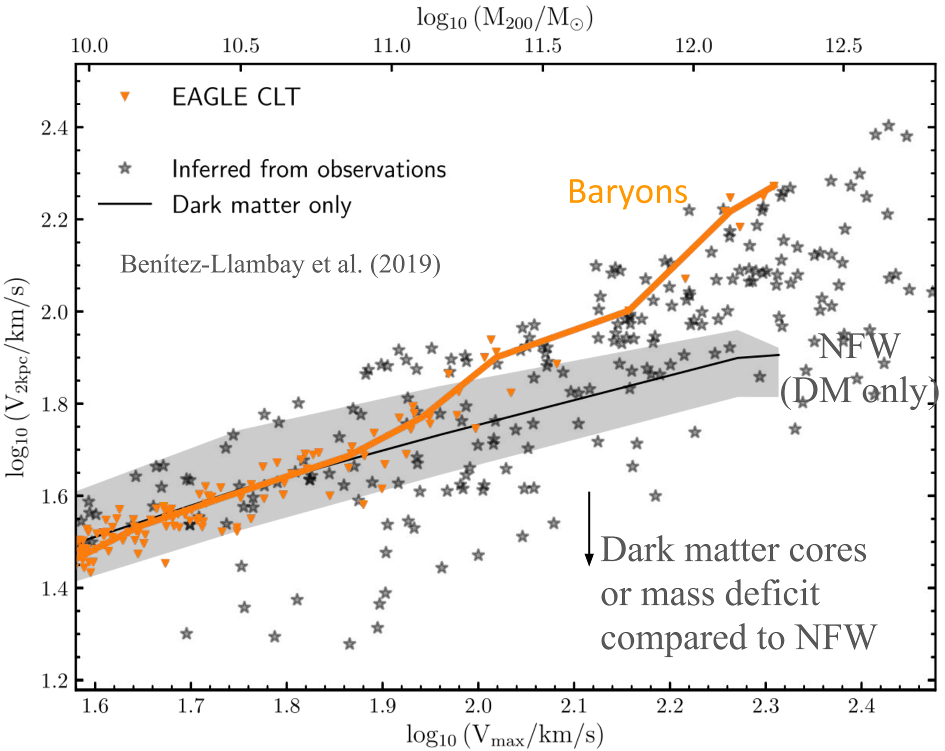


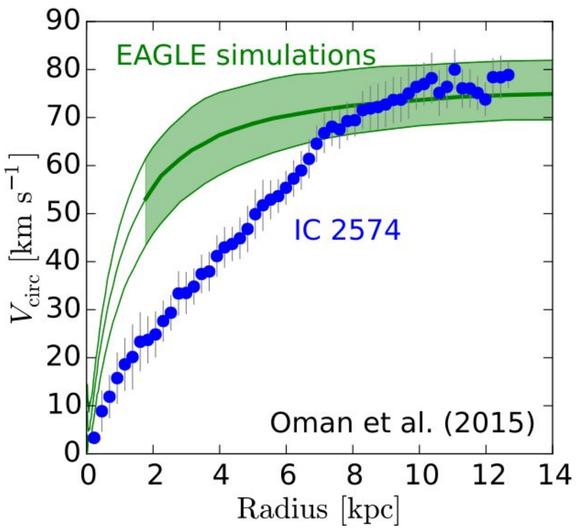
We understand the clustering properties of dark matter over all astrophysical scales.

Mass deficit in low-mass galaxies (cusp/core problem)

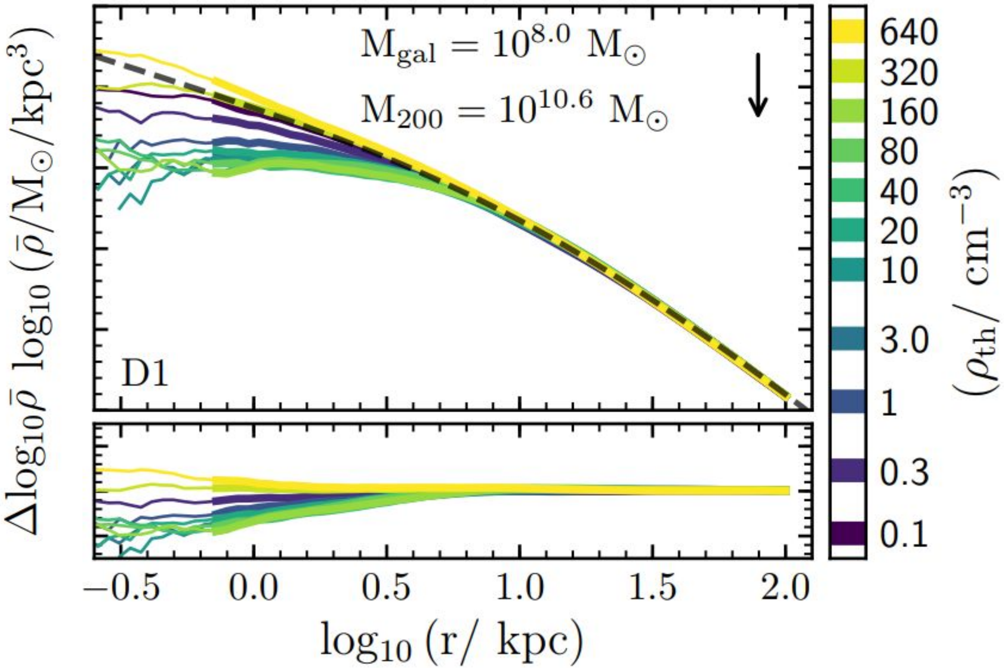
$$V_{\rm circ} = \sqrt{GM(r)/r}$$

$$V_{\rm max} = max\{V_{\rm circ}\}$$





Inner density profile of halos depend strongly on the galaxy formation model



Cores or cusps can be obtained depending on how star formation is modelled in simulations.

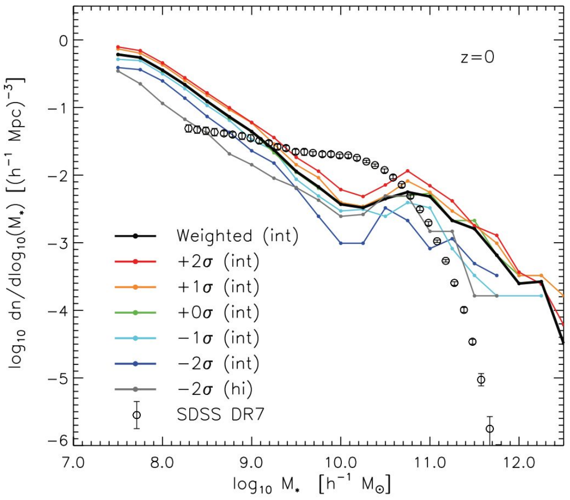
If gas does not become self-gravitating before forming stars, gravitational coupling is ineffective and dark matter halos remain cuspy.

This freedom hinders robust theoretical predictions regarding the kinematics of dwarf galaxies.

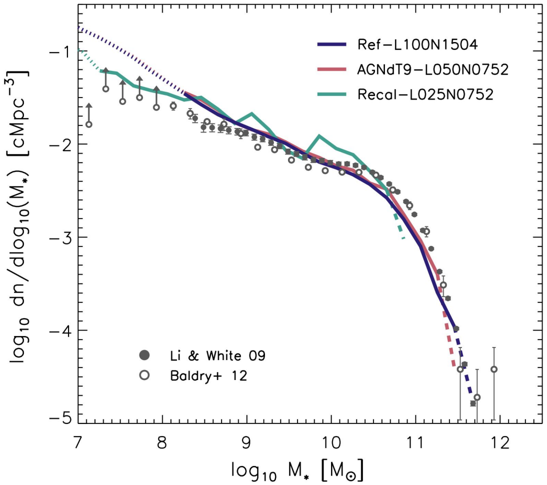
Benitez-Llambay et al. (2019)

Galaxy luminosity function depends strongly on the underlying modelling

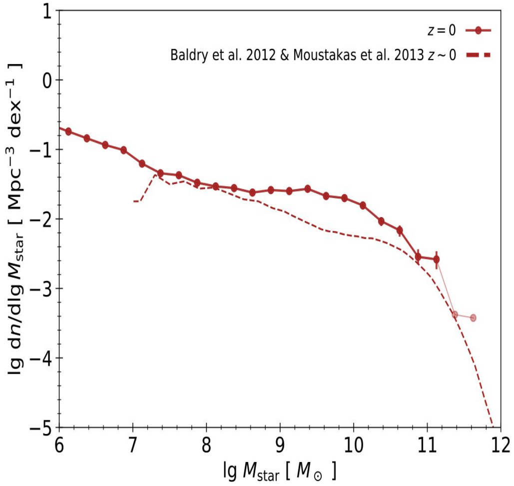
GIMIC (Crain et al. 2009)



Eagle (Schaye et al. 2015)



FIRE-box (Feldmann et al. 2023)



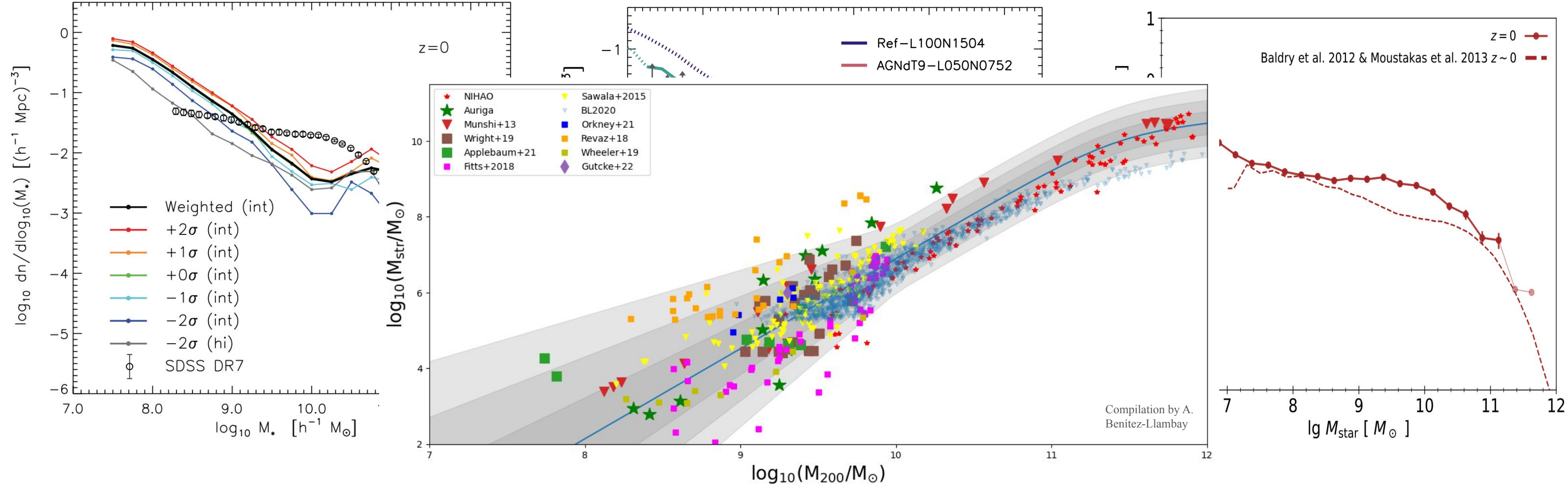
The state-of-the-art demonstrates that galaxy counts as a function of stellar mass is highly dependent on the galaxy formation (feedback) model. Unlike the halo mass function, the galaxy luminosity function cannot be predicted.

Galaxy luminosity function depends strongly on the underlying modelling

GIMIC (Crain et al. 2009)

Eagle (Schaye et al. 2015)

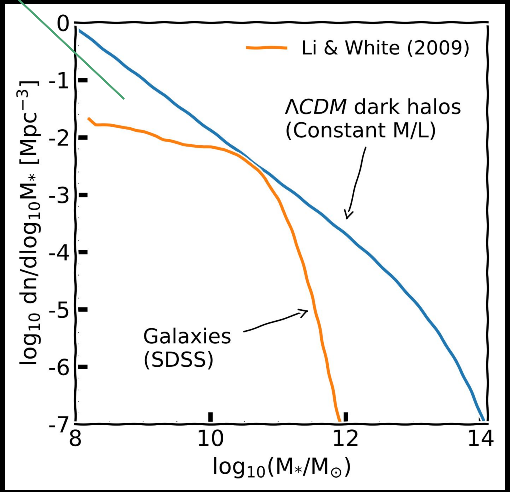
FIRE-box (Feldmann et al. 2023)



The state-of-the-art demonstrates that galaxy counts as a function of stellar mass is highly dependent on the galaxy formation (feedback) model. Unlike the halo mass function, the galaxy luminosity function cannot be predicted.

The Onset of Galaxy Formation

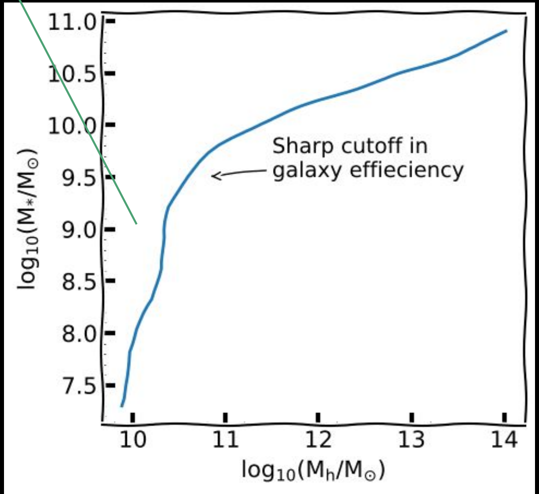
Discrepancy largely due to reionization and the UVB → Increasingly large number of starless haloes below 10^{10} $M_\odot$



The observed galaxy mass function (orange) is much flatter than the halo mass function at the faint-end. There are not enough low-mass galaxies in the Universe as collapsed low-mass dark matter halos in simulations.

The Onset of Galaxy Formation

Discrepancy largely due to reionization and the UVB → Increasingly large number of starless haloes below 10^{10} $M_\odot$



Matching galaxies and halos by abundance indicates that galaxy formation becomes increasingly inefficient, and eventually stops altogether, below a characteristic halo mass.

The onset of galaxy formation

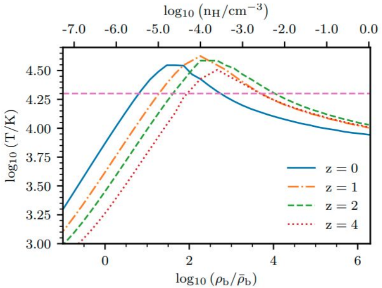
Galaxy Formation before reionization

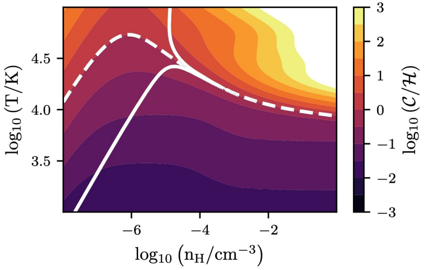
Galaxy formation proceeds only in dark matter halos for which the virial temperature is $T_{200} > 10^4$ K. Otherwise gas is fully neutral and radiative cooling is inefficient.

$$M_H^z \sim (4\times10^7\ M_\odot)\left(\frac{1+z}{11}\right)^{-3/2} \quad \text{(Atomic cooling limit)}$$

The effect of the UVB after reionization

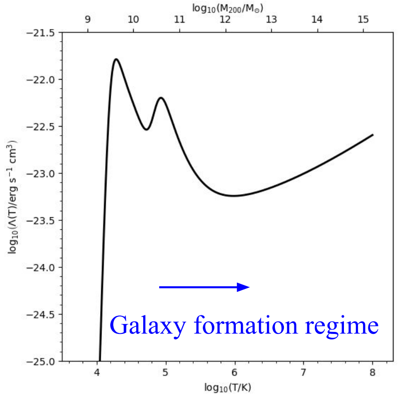
- Cooling rate is reduced because there is less neutral hydrogen at low density.
- Gas pressure is higher because the gas is hotter.
- Galaxies can only form in halos much more massive than the atomic cooling mass.



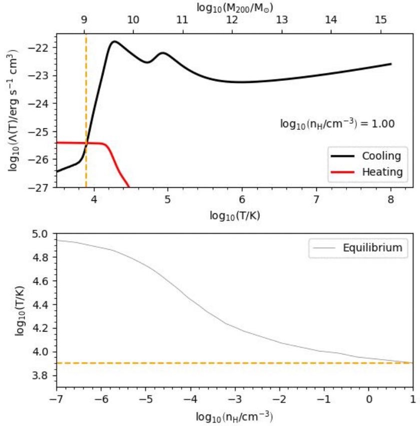


Effective equation of state arising from the UVB is well understood (e.g., Rauch 1998; Theuns 1998; Benítez-Llambay et al. 2017)

Cooling rate as a function of temperature

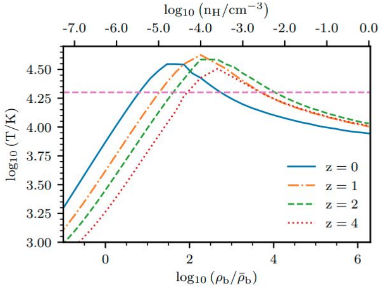


Cooling rate + external UVB



The Onset of galaxy formation under the presence of the UVB

Equation of state (10^4 K < Tvir < 10^5 K)



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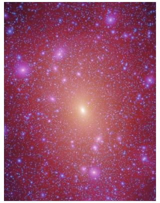
NFW halo



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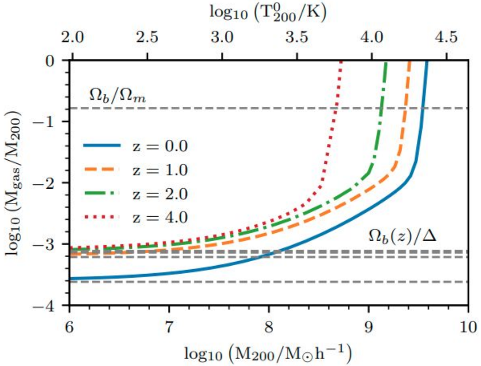
Hydrostatic equilibrium

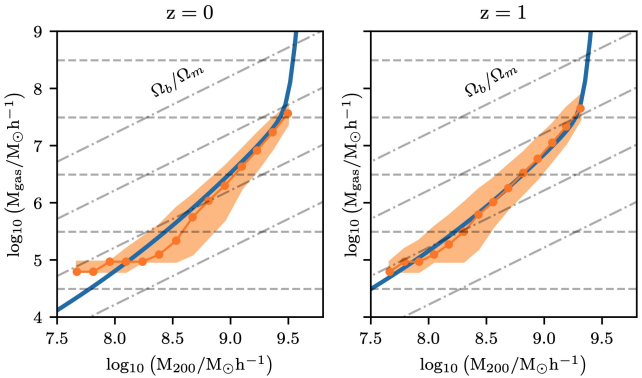
$$\frac{1}{\rho(r)}\frac{dP}{dr} = -\frac{GM_{\rm dm}(r)}{r^2}$$

RELHICS

Total gas mass in dimensionless units for various redshifts

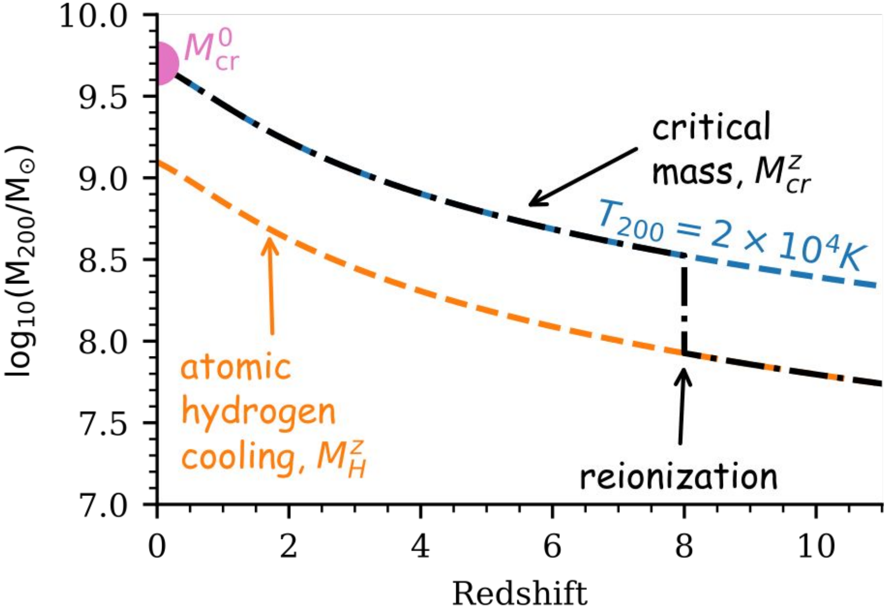


Total gas mass of "dark" gaseous halos compared to high-res cosmological simulations



Benítez-Llambay & Frenk (2020)

Qualitative description of how galaxy formation proceeds in low-mass halos



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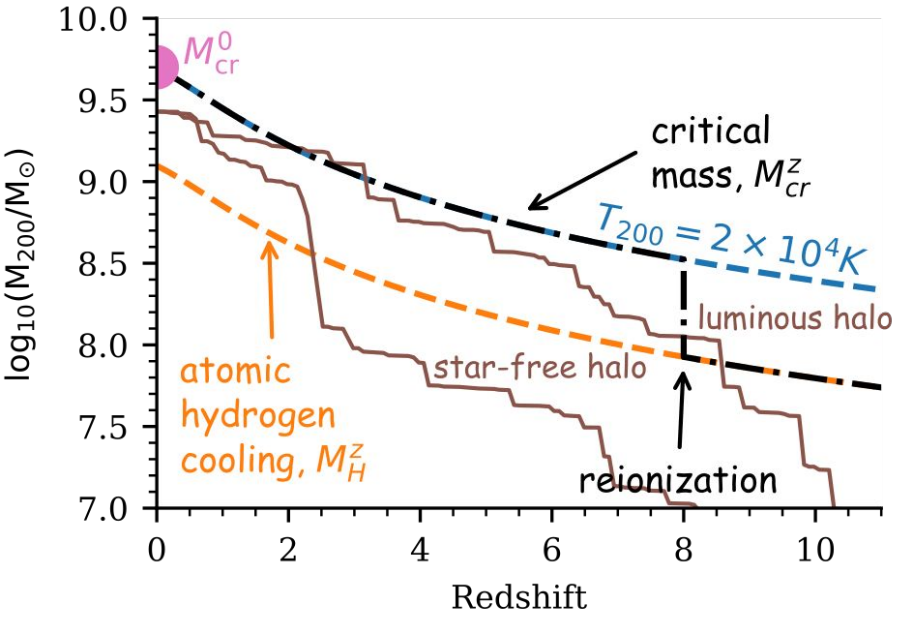
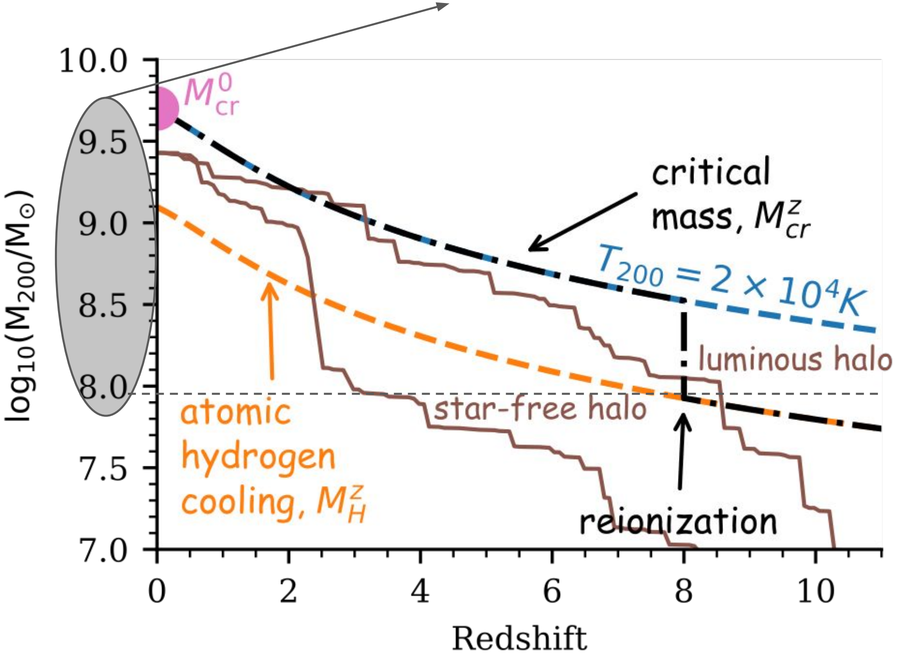


Benítez-Llambay & Frenk (2020)

Qualitative description of how galaxy formation proceeds in low-mass halos

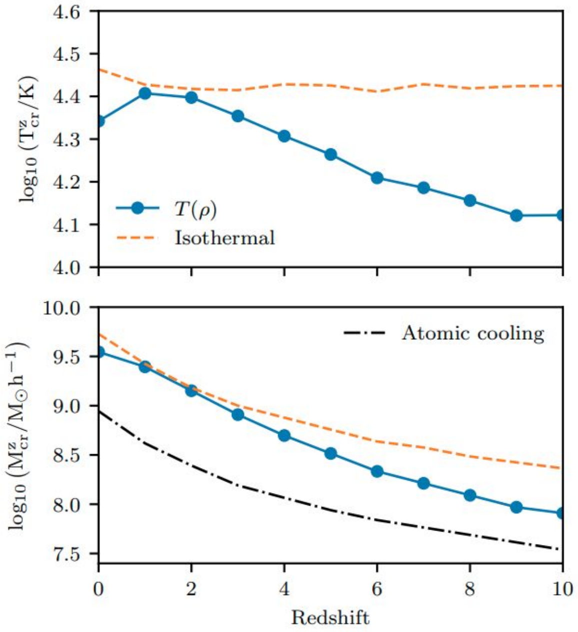
Stochastic galaxy formation below the z=0 critical mass.



Benítez-Llambay & Frenk (2020)

The critical mass for galaxy formation under the effect of the UVB

Benítez-Llambay & Frenk (2020)



Stability analysis of gas in thermal equilibrium with the UVB in the potential well of an NFW halo allows us to derive the redshift-dependent critical mass for the onset of galaxy formation.

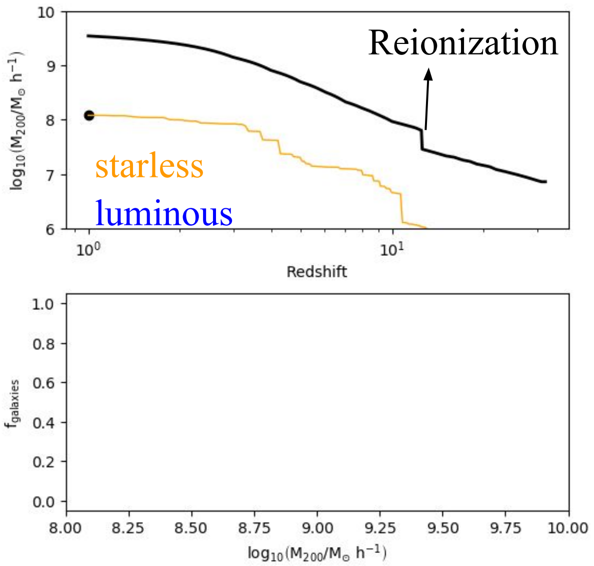
This analysis takes into account the non-linear evolution of low-mass halos and the non-trivial effect of the UVB background as a function of gas density.

For details about this framework, check: Benítez-Llambay & Frenk (2020); Pereira-Wilson et al. (2023)

We have a framework in place to calculate the critical mass above which galaxies form stars, given a UVB model and the redshift of reionization.

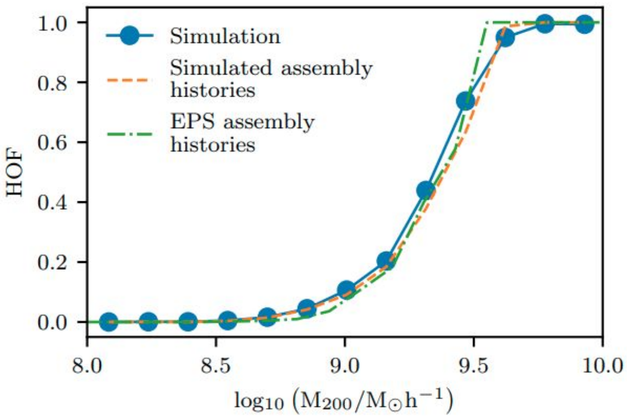
The onset of galaxy formation as a function of halo mass

CDM mass assembly histories (EPS)



Halos that do not cross the critical mass remain dark (orange), whereas halos that cross the critical mass can form stars (blue).

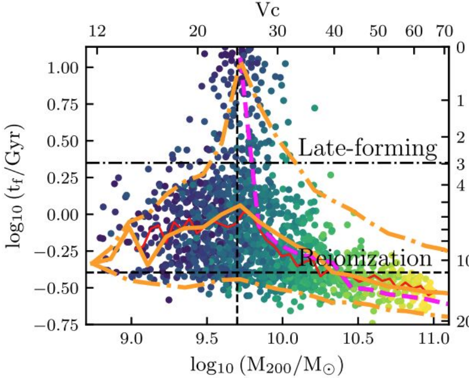
The stochastic nature of CDM mass assembly histories makes the process of galaxy formation in a narrow range of halo mass stochastic.



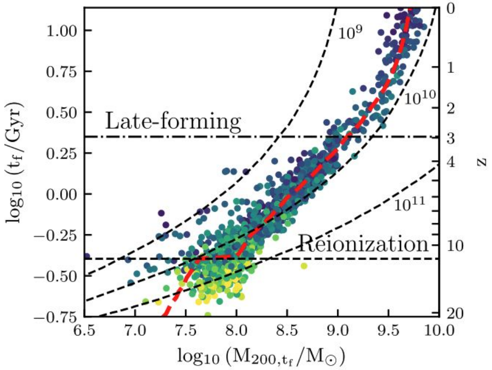
Benítez-Llambay & Frenk (2020)

When do galaxies form? Old and late-forming UFDs trace the critical mass

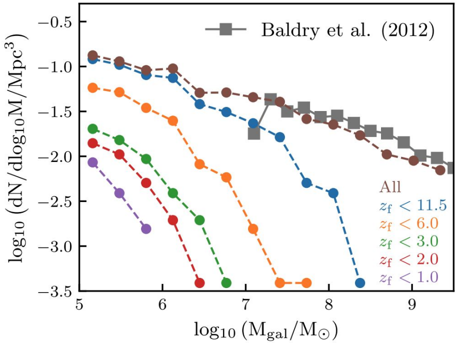
Halo mass today

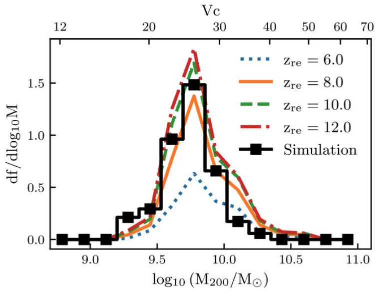


Halo mass at formation time



Stellar mass function today





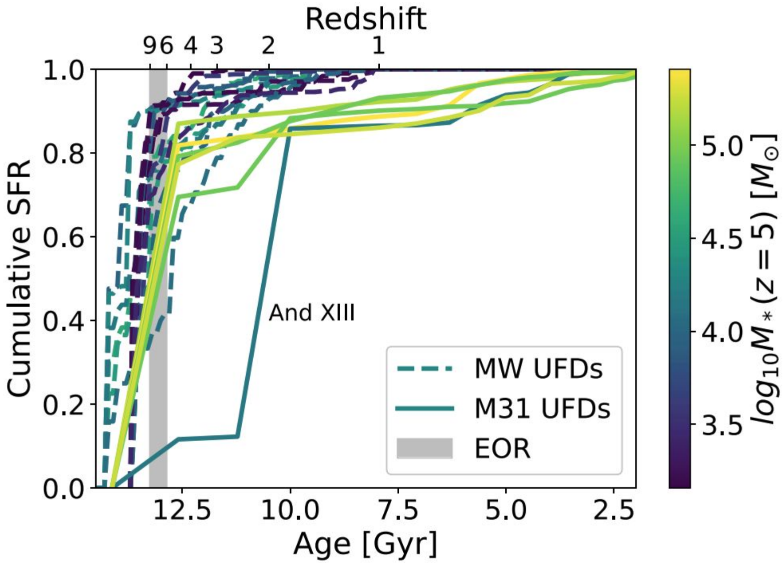
The existence of a critical mass for the onset of galaxy formation implies that the most dwarfs are uniformly old. They form before or during reionization. However, within this picture, we expect a small fraction of dwarfs forming late, after z=3.

The frequency of late-forming dwarfs is largely insensitive to the redshift of reionization of the Universe reionizes for z > 8.

Benítez-Llambay & Fumagalli (2021)

Late-forming UFDs? (And XIII)

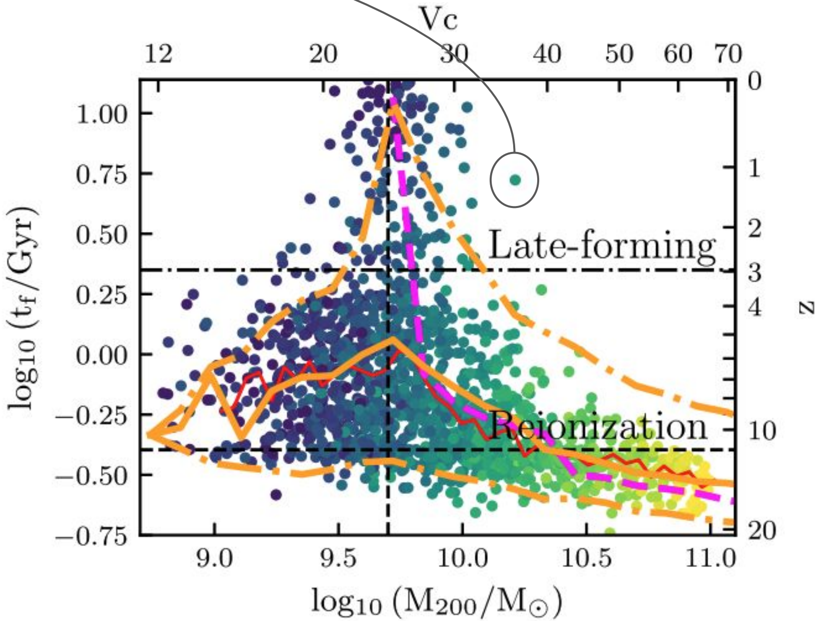
Using HST data resolving the oldest main-sequence turn-off, Savino et al. (2023) report resolved SFH of the UFD And XIII consistent with having formed more than 80% of its stars after z < 3.



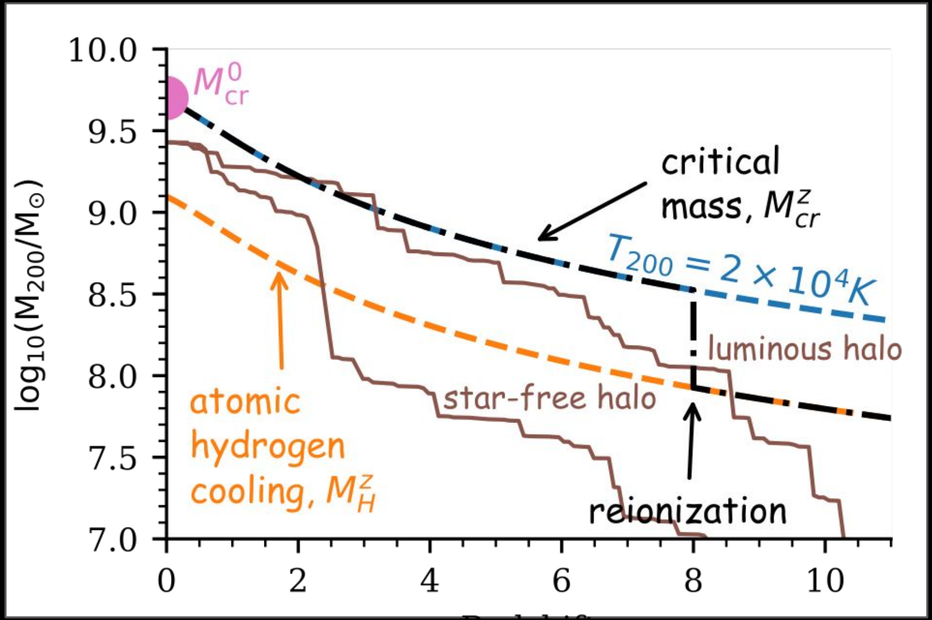
If And XIII is indeed a late-forming dwarfs as predicted in CDM, its halo mass should not be too different from the critical mass.

I Zw 18 (A late-forming galaxy)

?

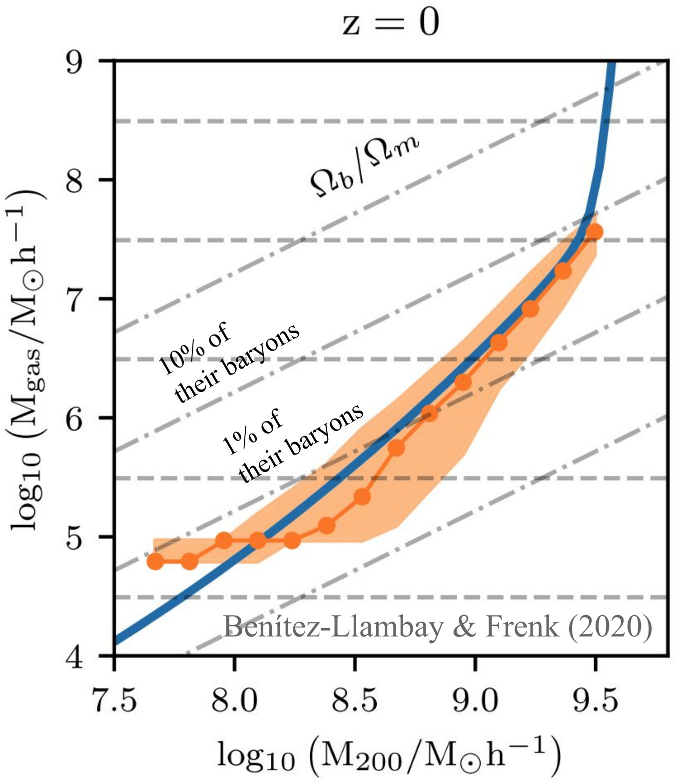


Starless dark matter halos



When galaxies do not form, the gas remains in hydrostatic equilibrium

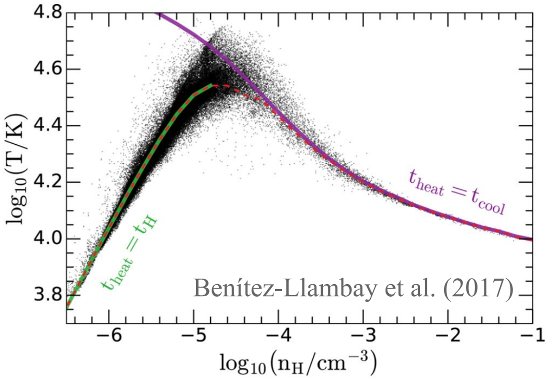
Median gas mass as a function of halo mass of starless halos



The gas of starless dark matter halos is not completely pushed out by the effect of the UVB.

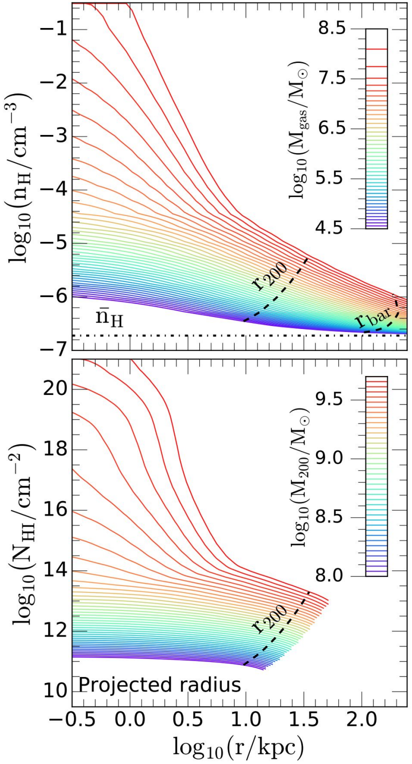
The total gas mass is significantly reduced by the effect of the UVB, but some gas remains, and the amount of gas that remains increases with halo mass.

If halos are more massive than the critical mass, the amount of gas required to sustain hydrostatic equilibrium diverges --> onset of gravitational instability.

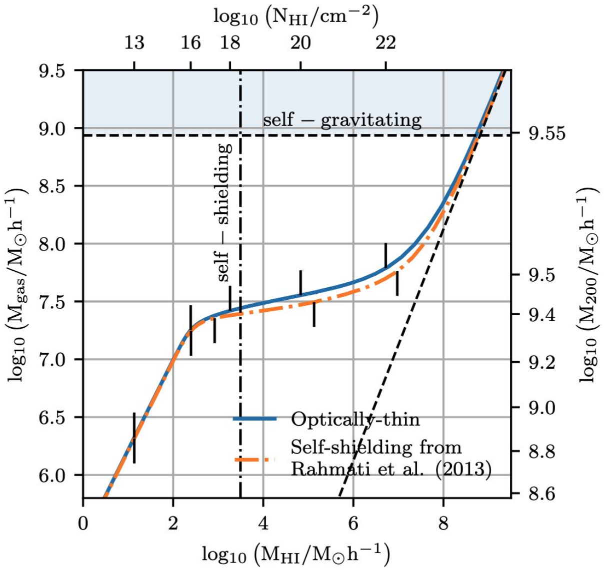


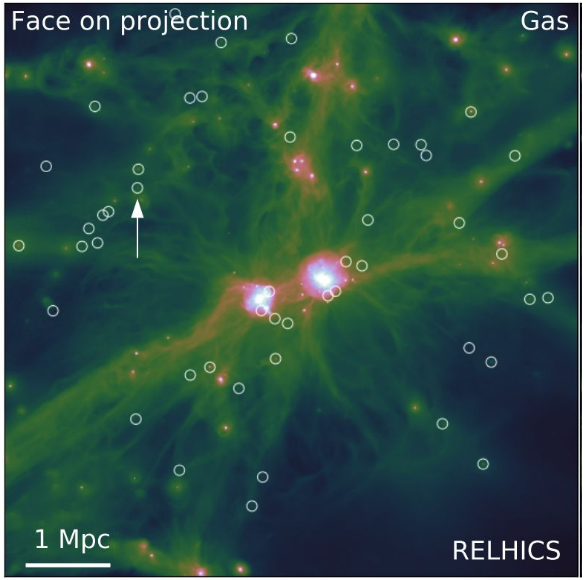
Effective equation of state arising from the UVB is well understood: e.g.: (Rauch 1998; Theuns 1998; Benítez-Llambay et al. 2017)

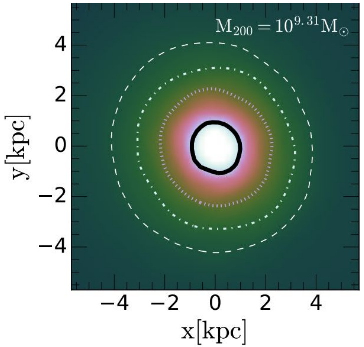
Gas properties of starless dark matter halos



Gas-rich starless halos are expected to be uniformly distributed across the sky, be round, with gas in hydrostatic equilibrium at temperature T ~ 2×10^4 K, and far from luminous galaxies.

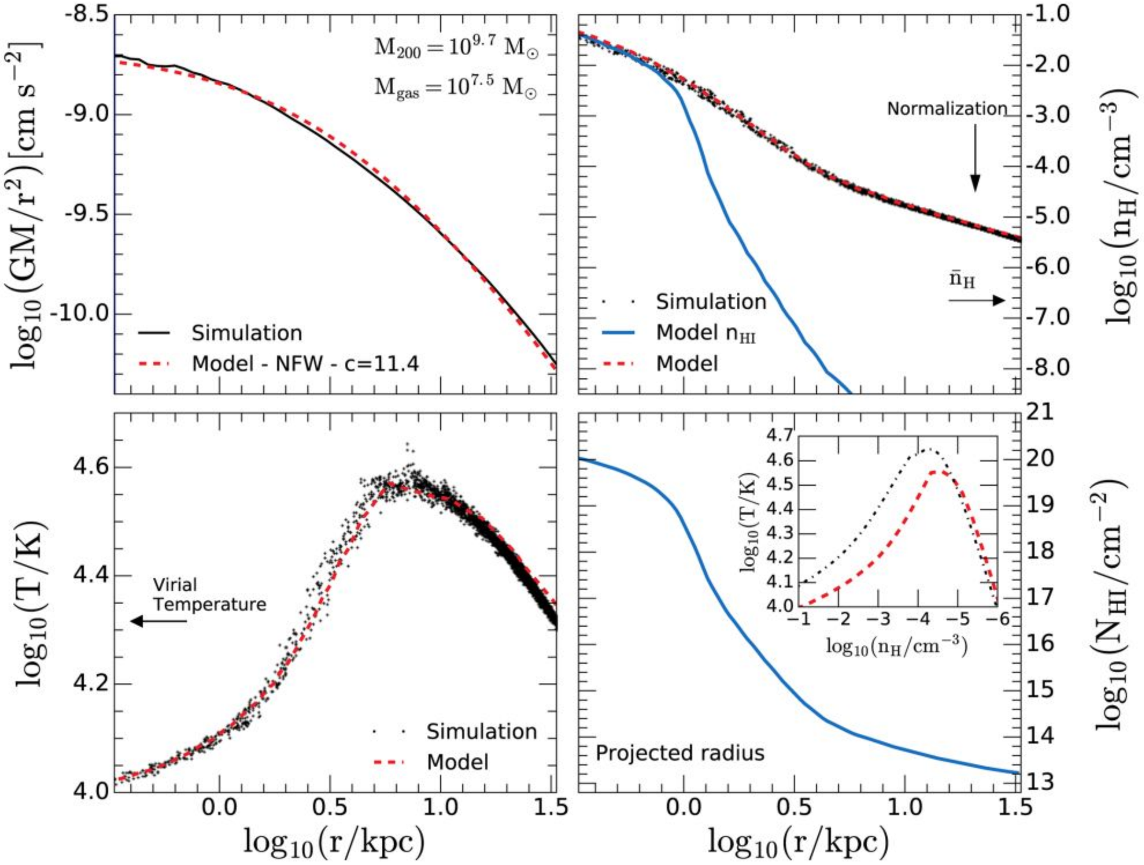


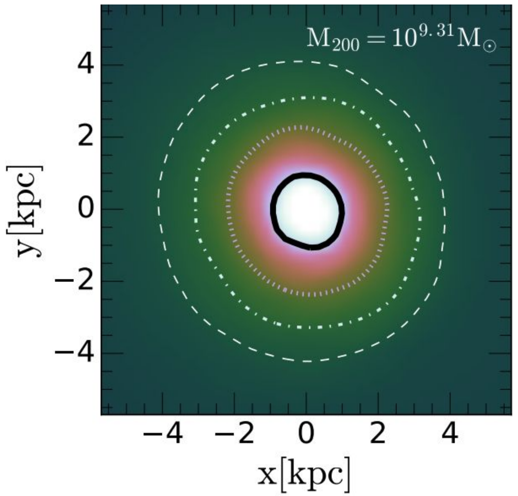




Benítez-Llambay et al. (2017)

Starless halos are well understood in simulations



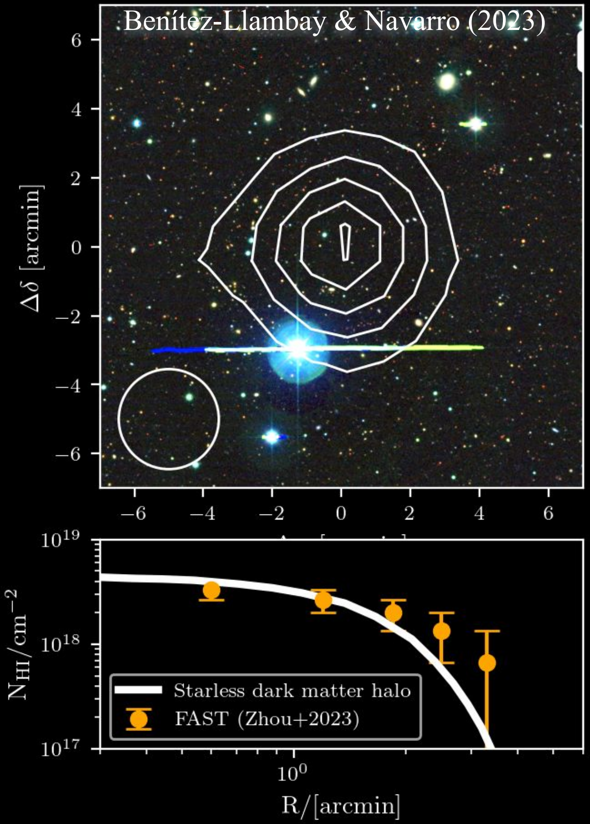


The First RELHIC detected with FAST?

Observations by Zhou et al. (2023)

Video by ABL

The First RELHIC detected with FAST?



Cloud-9, a rogue HI cloud detected near M94 by Zhou et al. (2023), without and optical counterpart brighter than 29.15 mag/arcsec^2 in the *g* band, has most of its properties consistent with expectations for a starless dark matter halo.

However, the cloud is systematically more extended in the outer parts compared to ΛCDM expectations.

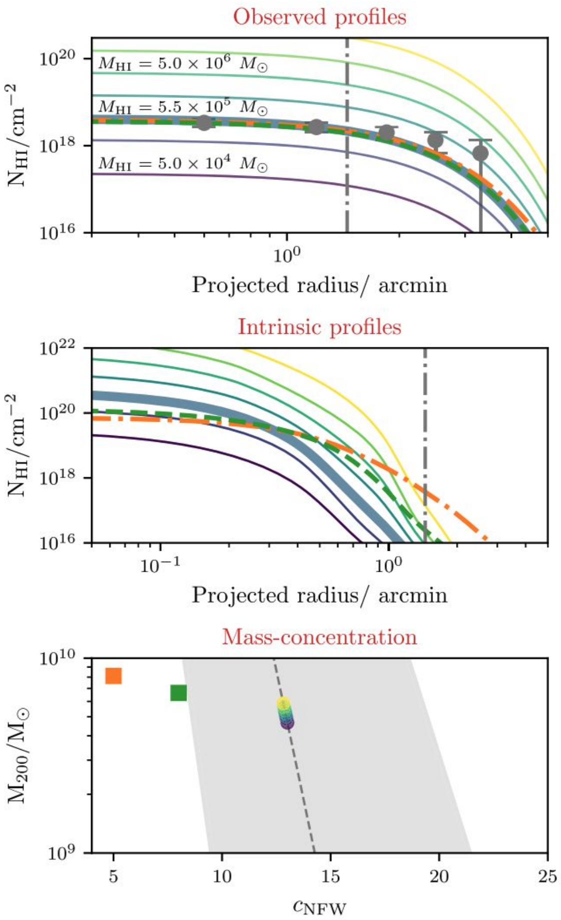
Does this signal perturbations in the outer parts of departures from ΛCDM?

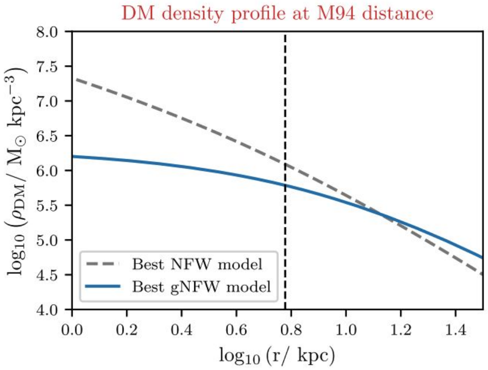
$N_{HI,0} \sim 1.0 \times 10^{20}$ cm^{-2}
$M_{HI} \sim 5.5 \times 10^5$ $M_\odot$
$M_{200} \sim 5.0 \times 10^9$ $M_\odot$

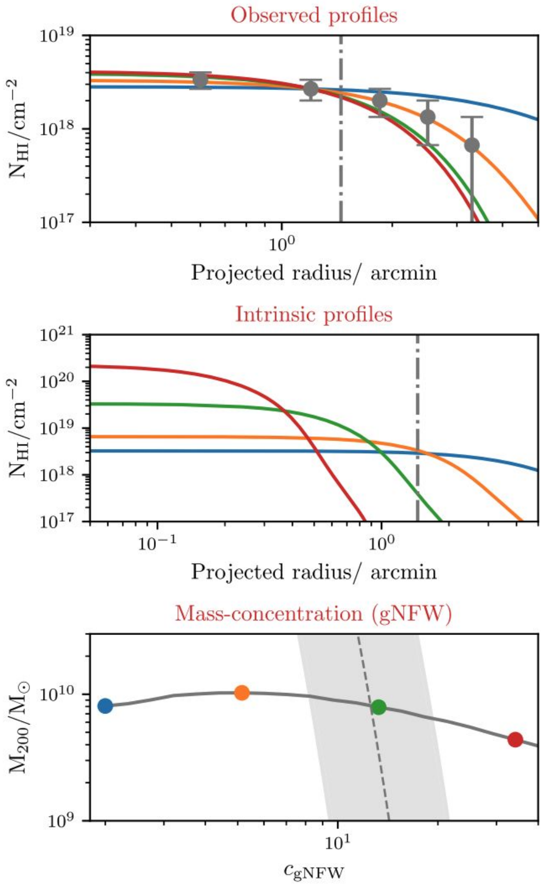
Dark matter constraints from 21 cm observations

Cuspy NFW

Cored NFW

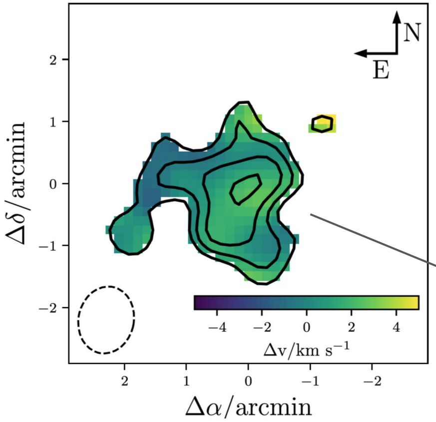






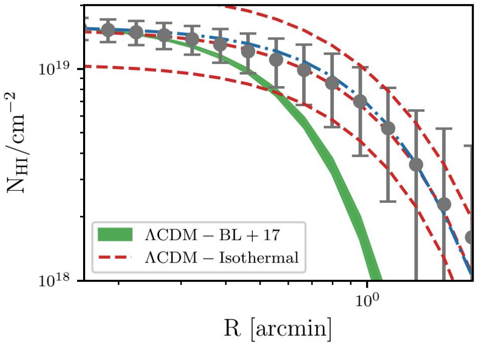
Benítez-Llambay A. & JN (2023)

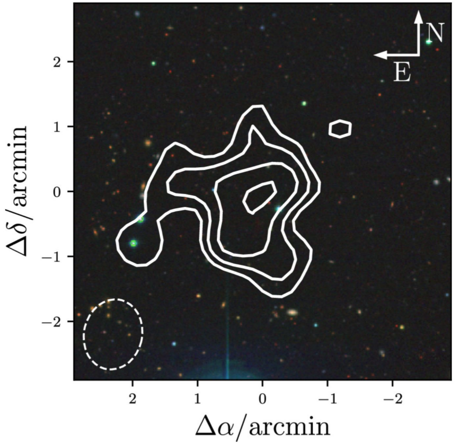
Very Large Array Observations of Cloud-9

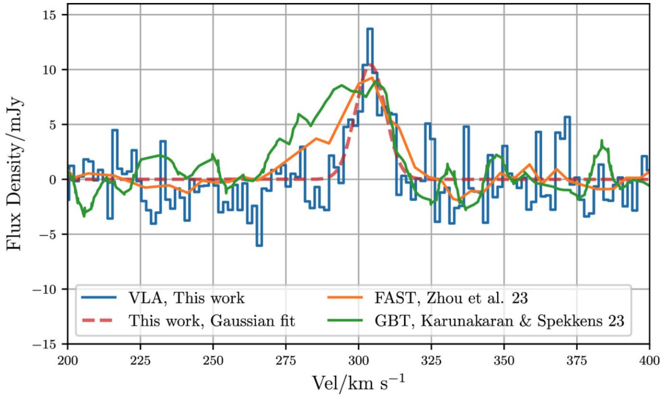


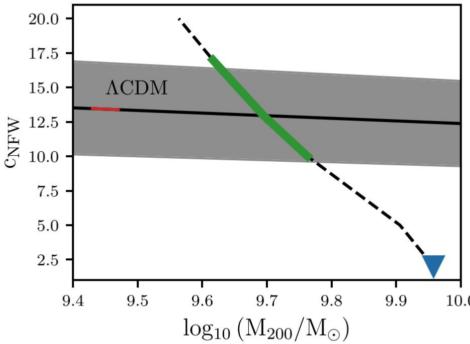
Observed with VLA, the system displays features consistent with being subject to ram pressure stripping.

The central gas distribution is still consistent with a gaseous system in hydrostatic equilibrium with a large amount of dark matter.





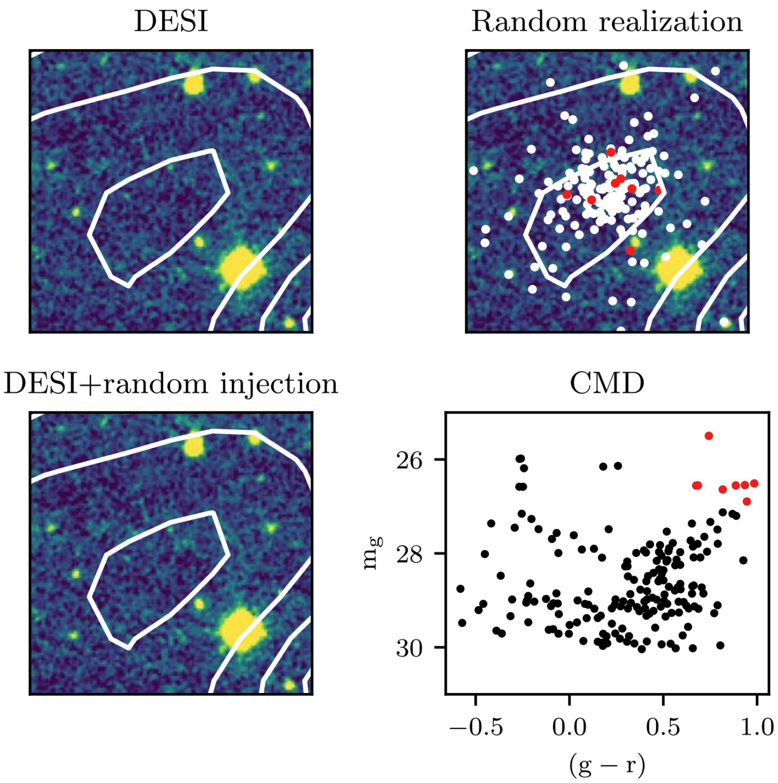


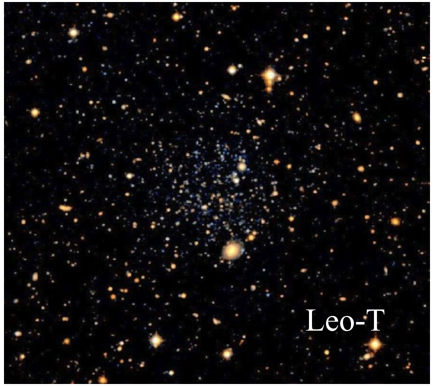


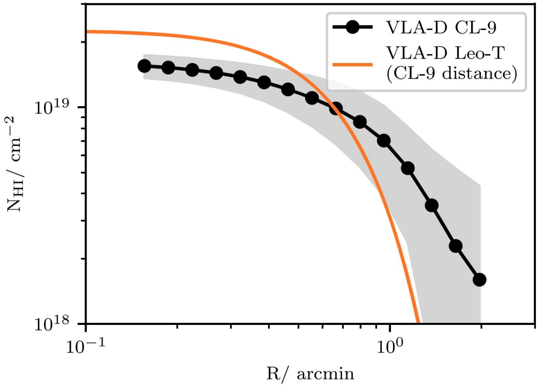
Benítez-Llambay et al. (2024)

Current limits on the stellar mass of Cloud-9

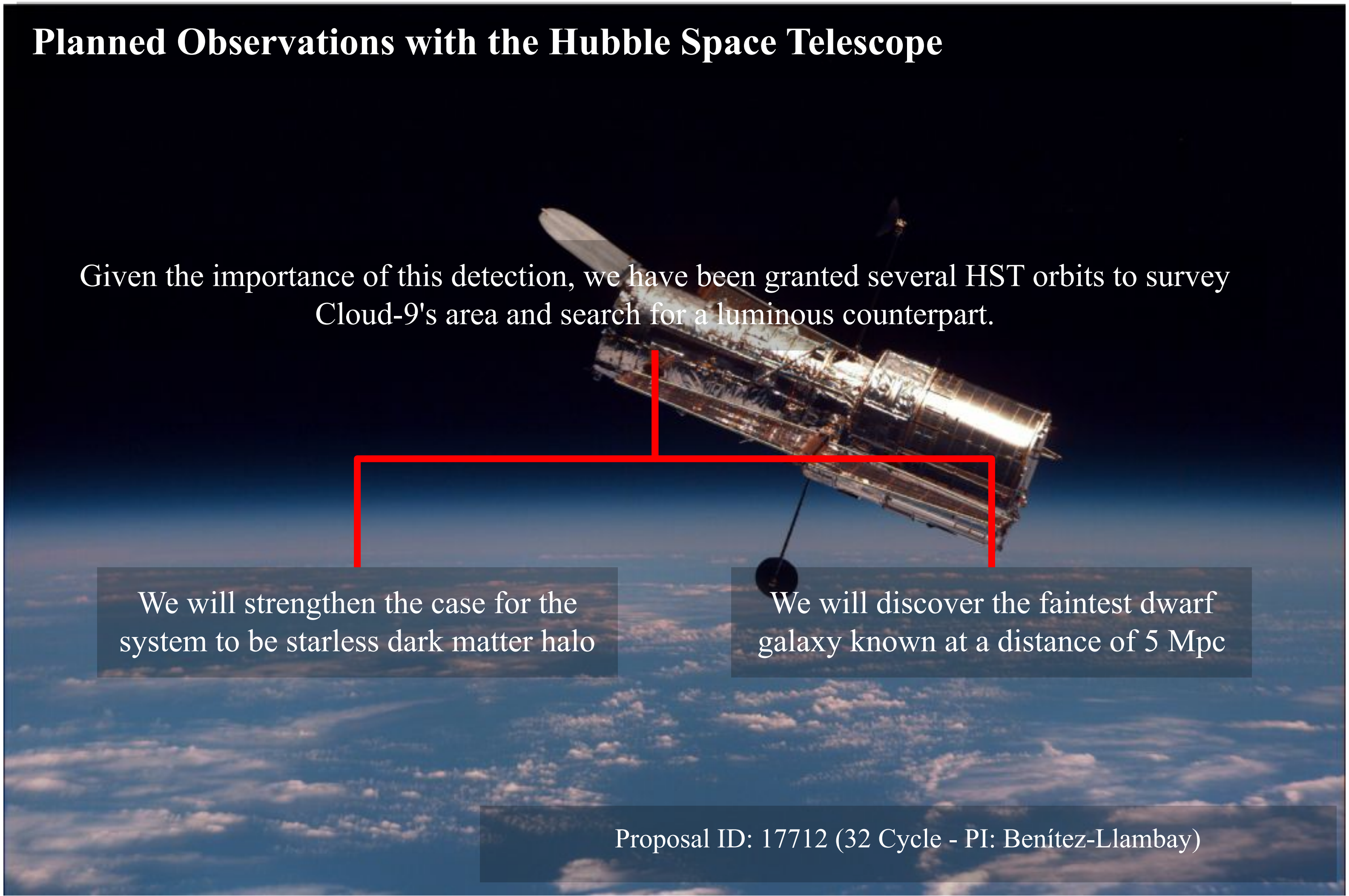
What if Cloud-9 is a Leo-T analogue, but at a distance of 5 Mpc?







Planned Observations with the Hubble Space Telescope



Given the importance of this detection, we have been granted several HST orbits to survey Cloud-9's area and search for a luminous counterpart.

We will strengthen the case for the system to be starless dark matter halo

We will discover the faintest dwarf galaxy known at a distance of 5 Mpc

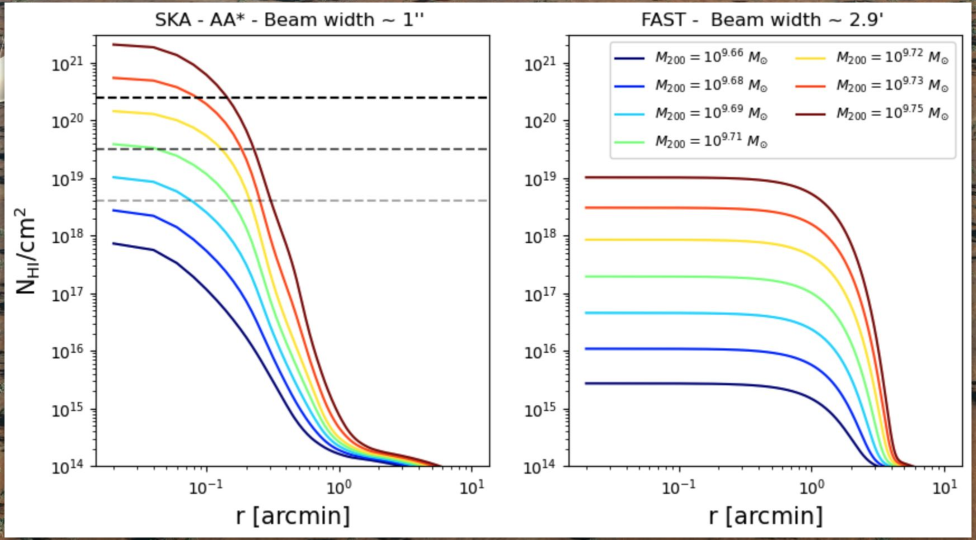
Proposal ID: 17712 (32 Cycle - PI: Benítez-Llambay)

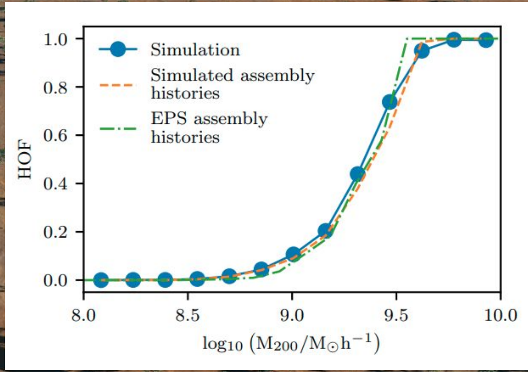
What can be probed with SKA's AA*

- Using high-resolution cosmological simulations, we find that the number density of starless dark matter halos massive enough to develop central column densities above **10^{19} cm^{-2}** is roughly **$n_R \sim 7\times10^{-3}$ Mpc^{-3}.**

- With a beam footprint of 1", we could resolve the core radius of starless systems with five beams up to a distance of roughly 40 Mpc. To find ten starless halos, this would require a survey area of approximately 220 square degrees.

- However, 8 out of 10 detections are expected to be faint quiescent dwarf galaxies. The good news is that characterising the 21 cm column density profiles of these quiescent dwarfs is expected to be equally informative about the underlying dark matter distribution!





Takeaway points

1) **Probing or ruling out ΛCDM through galaxy observations remains challenging**, as current models possess significant flexibility in accommodating observational data.

2) **Low-mass scales provide a unique opportunity to test ΛCDM's most robust predictions**, particularly regarding the number and structure of halos. This is because baryonic processes are not expected to significantly influence these halos.

3) **Predictions for the structure of starless dark matter halos are now in place** and accurately reproduce results from numerical simulations.

4) **A candidate for the first robust starless dark matter halo may have been discovered.** Upcoming Hubble observations later this month could provide further insight into its true nature.