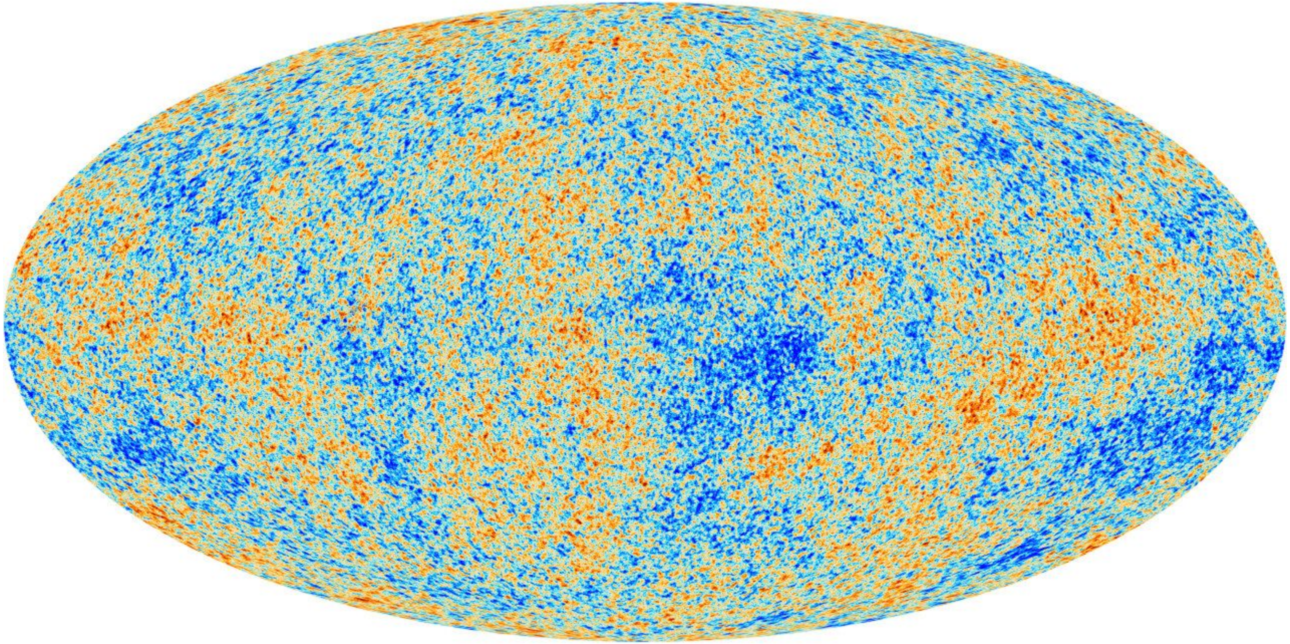
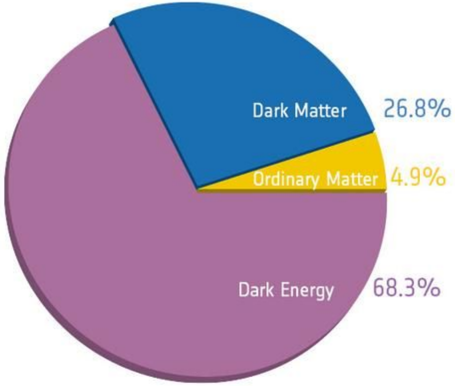
Probing ΛCDM with “dark” galaxies

- Alejandro Benítez-Llambay -

The Standard Model of Cosmology



Planck Collaboration (2016)

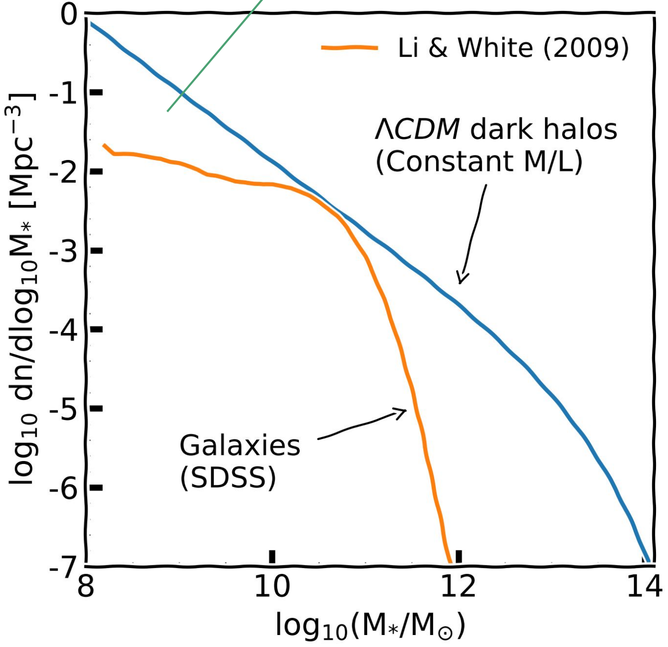


Cosmological parameters are known with high precision.

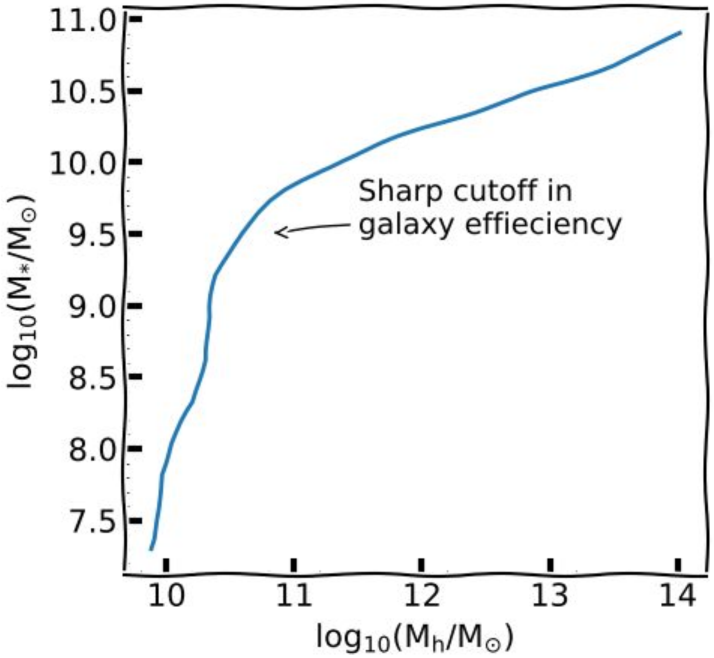
Give us the framework to construct a model of the evolution of the Universe, assuming that the main driver of structure formation is gravity.

Galaxy-halo connection

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



$$n(>M_{halo}) = n(>M_*)$$



Matching halos and galaxies by abundance
(e.g. Behroozi et al. 2013)

Density profile of low-mass halos after reionization

Toy model and the existence of "dark" dark matter halos

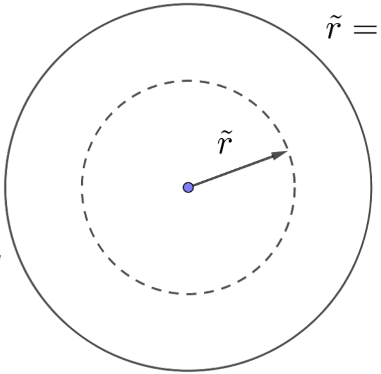
$$\frac{1}{\rho_g}\nabla P = -\nabla\phi$$

Hydrostatic equilibrium:

$$\frac{1}{\tilde{\rho}}\frac{d\tilde{\rho}}{d\tilde{r}} = -\left(\frac{V_{200}}{c_s}\right)^2 \frac{\tilde{M}(\tilde{r})}{\tilde{r}^2}$$

For isothermal gas and NFW halo, the solution is analytic

Dark matter halo



$\tilde{r} = 1$

Further out the Universe is uniform

$(\tilde{\rho} = 1)$

Quantities

$$\tilde{M} = \frac{M}{M_{200}}$$

$$\tilde{r} = \frac{r}{r_{200}}$$

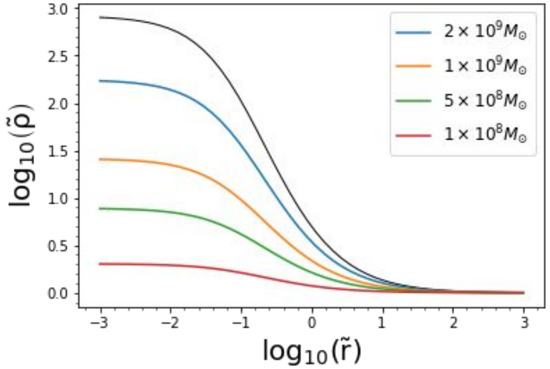
$$\tilde{\rho} = \frac{\rho}{\bar{\rho}}$$

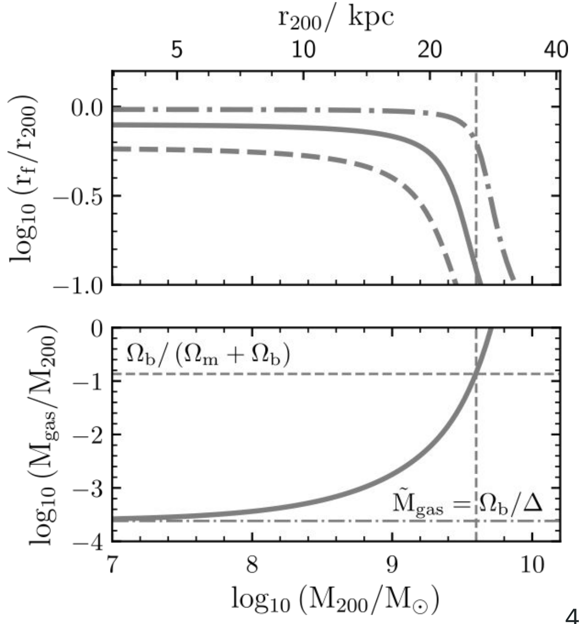
$$V_{200} \sim 30\,\frac{km}{s}\left(\frac{M_{200}}{10^{10}M_\odot}\right)^{1/3}$$

$$c_s \sim 10\,\frac{km}{s}\left(\frac{T}{10^4 K}\right)^{1/2}$$

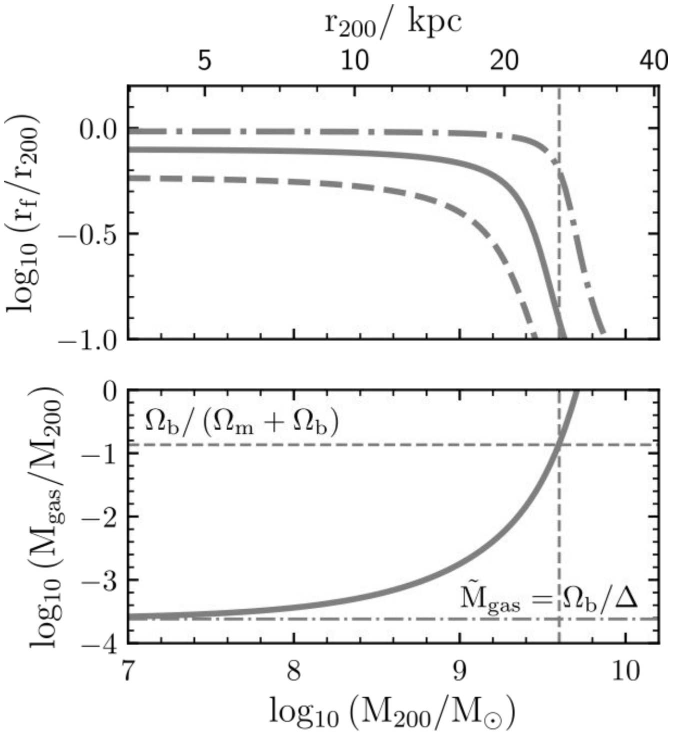
Density profile of gas

$$\tilde{\rho}(\tilde{r}) = exp\left\{\left(\frac{V_{200}}{c_s}\right)^2 \frac{1}{f(c)} \frac{ln(1+c\tilde{r})}{\tilde{r}}\right\}$$





Structural properties of “dark” galaxies

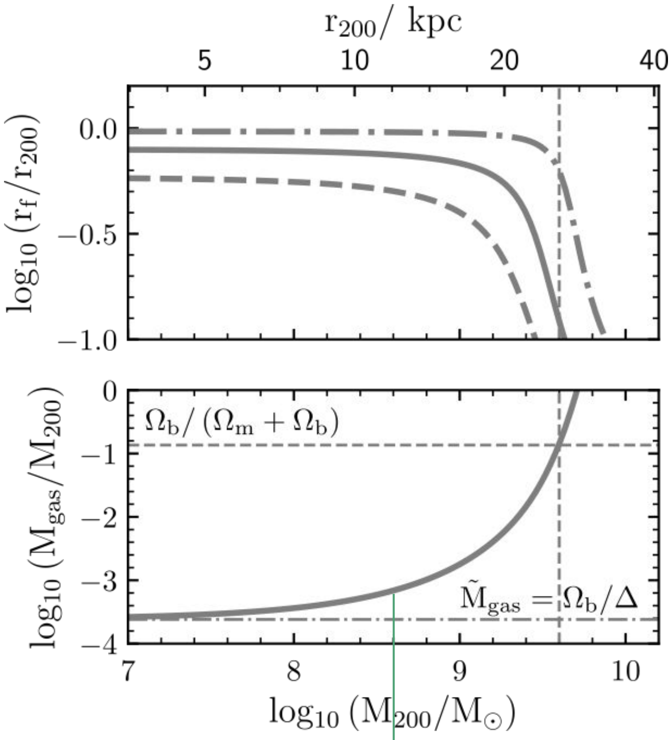


Lessons from these simple considerations

- Halos with $\mathbf{M_{200} < 10^8\ M_\odot}$ are expected to be completely devoid of gas at z=0.
- All halos with $\mathbf{M_{200} > 10^{9.6}\ M_\odot}$ are expected to host a luminous galaxy at z=0; there are not enough baryons in the Universe to provide pressure support against gravitational collapse.
- Halos with $\mathbf{M_{200} < 10^{9.6}\ M_\odot}$ may or may not host a luminous galaxy at z=0. This depends largely on the mass of the halo before reionization.
- There is a narrow range in halo mass **(3×10^8 - 5×10^9 $M_\odot$)** in which the gas neither completely escape the system nor it collapses further.

Benitez-Llambay, A. (in prep)

Structural properties of "dark" galaxies



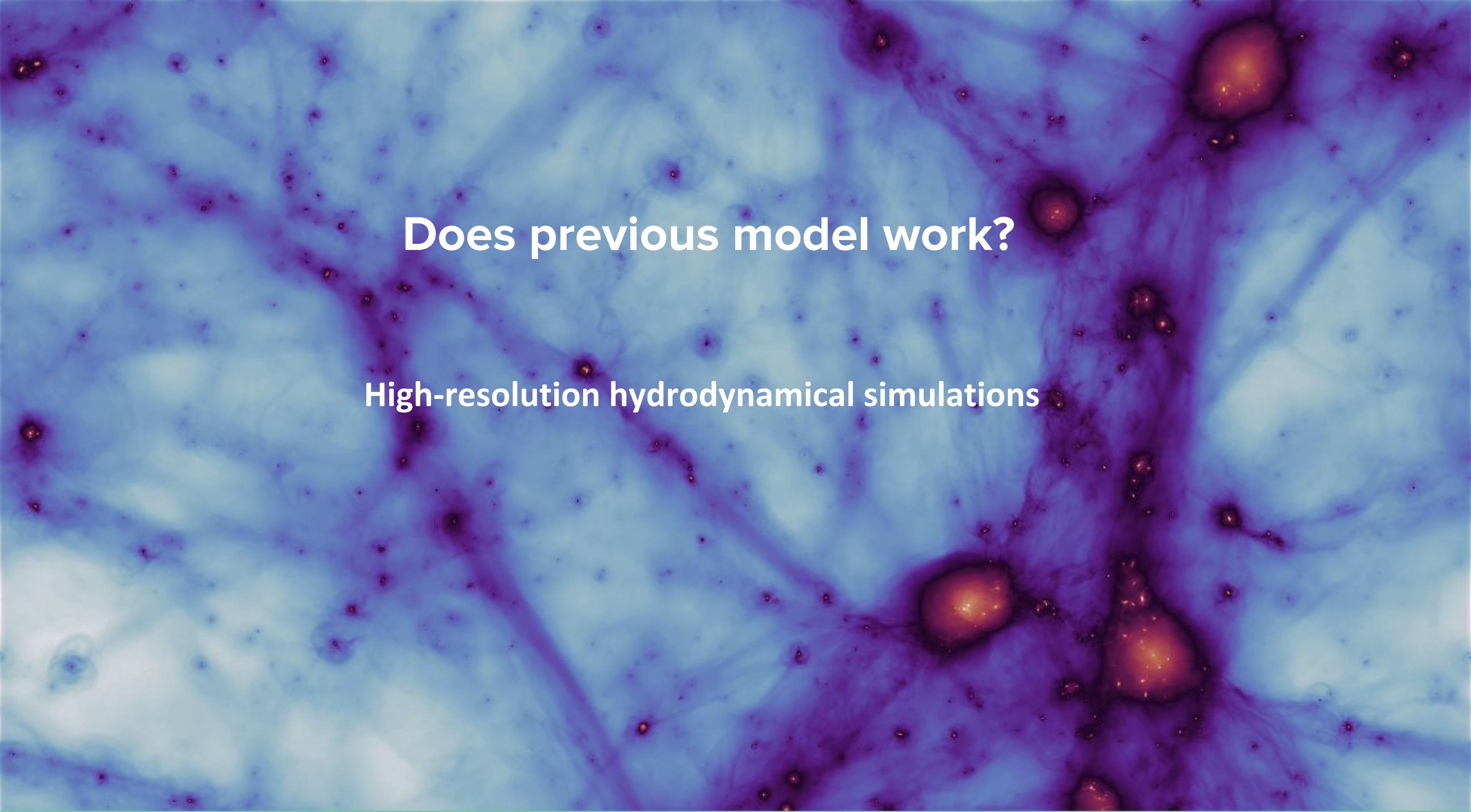
Lessons from these simple considerations

- Halos with $\mathbf{M_{200} < 10^8\ M_\odot}$ are expected to be completely devoid of gas at z=0.
- All halos with $\mathbf{M_{200} > 10^{9.6}\ M_\odot}$ are expected to host a luminous galaxy at z=0; there are not enough baryons in the Universe to provide pressure support against gravitational collapse.
- Halos with $\mathbf{M_{200} < 10^{9.6}\ M_\odot}$ may or may not host a luminous galaxy at z=0. This depends largely on the mass of the halo before reionization.
- There is a narrow range in halo mass $\mathbf{(3\times10^8 - 5\times10^9\ M_\odot)}$ in which the gas neither completely escape the system nor it collapses further.

These halos would be realised with 50 gas particles if simulated with, e.g. $10^4\ M_\odot$.

Benitez-Llambay, A. (in prep)

Does previous model work?



High-resolution hydrodynamical simulations

Testing this model with high-resolution numerical simulations

The simulation

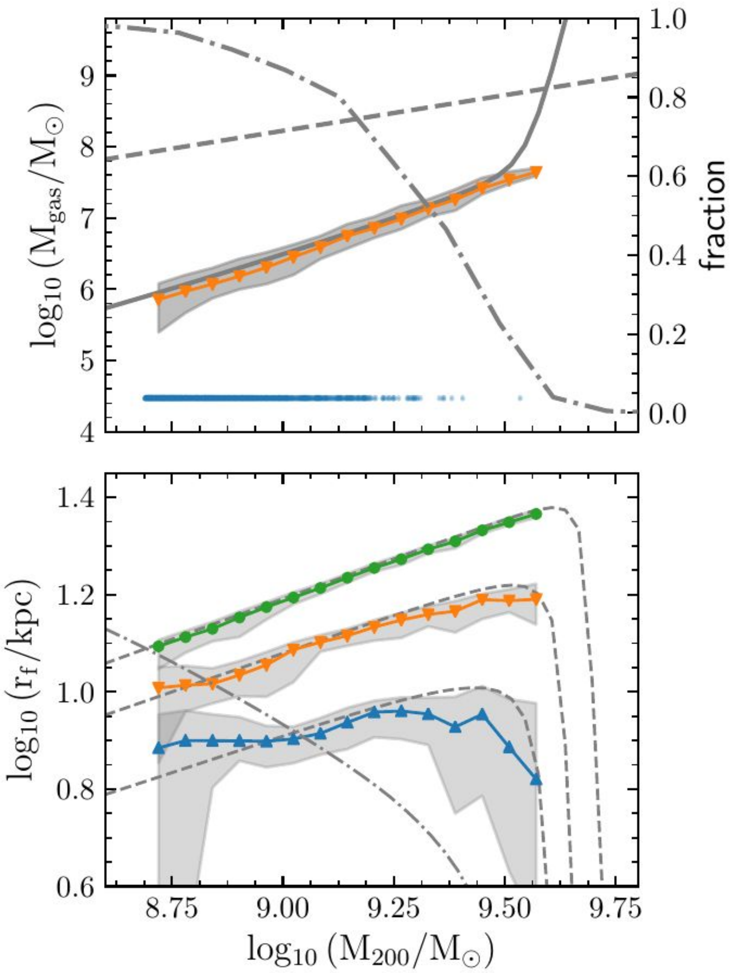
- Cosmological hydrodynamical simulation, using P-Gadget3 + EAGLE galaxy formation model.
- Box (20 Mpc)^3
- Gas particle mass ~ 10^4 $M_\odot$

Sample of dark halos:

- Only central halos, with a minimum halo mass $10^{8.75}$ $M_\odot$ (expected to be resolved by 30 gas particles)
- No bound stars within R_{200}.

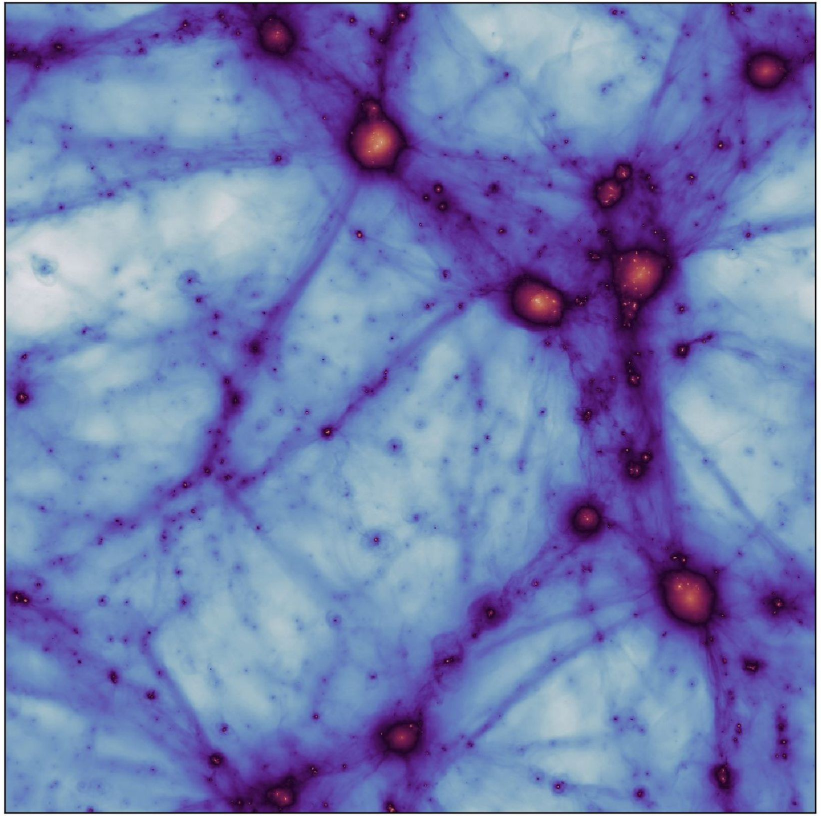
Subsample:

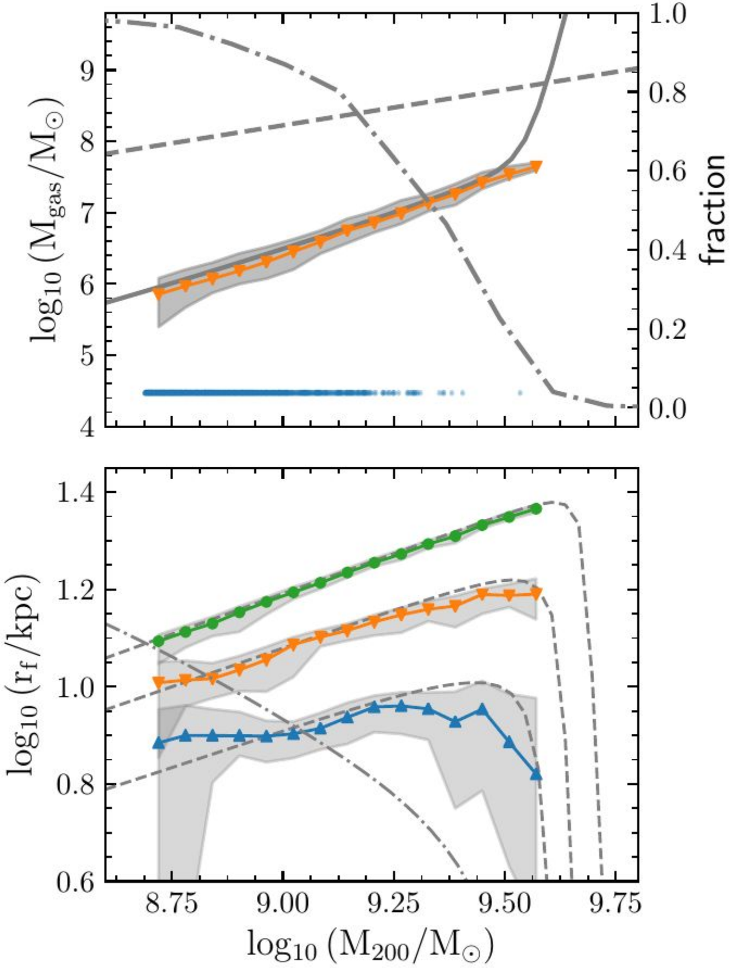
- Halos that contain more than 1 gas particle
- Halos that contain 0 bound gas particles



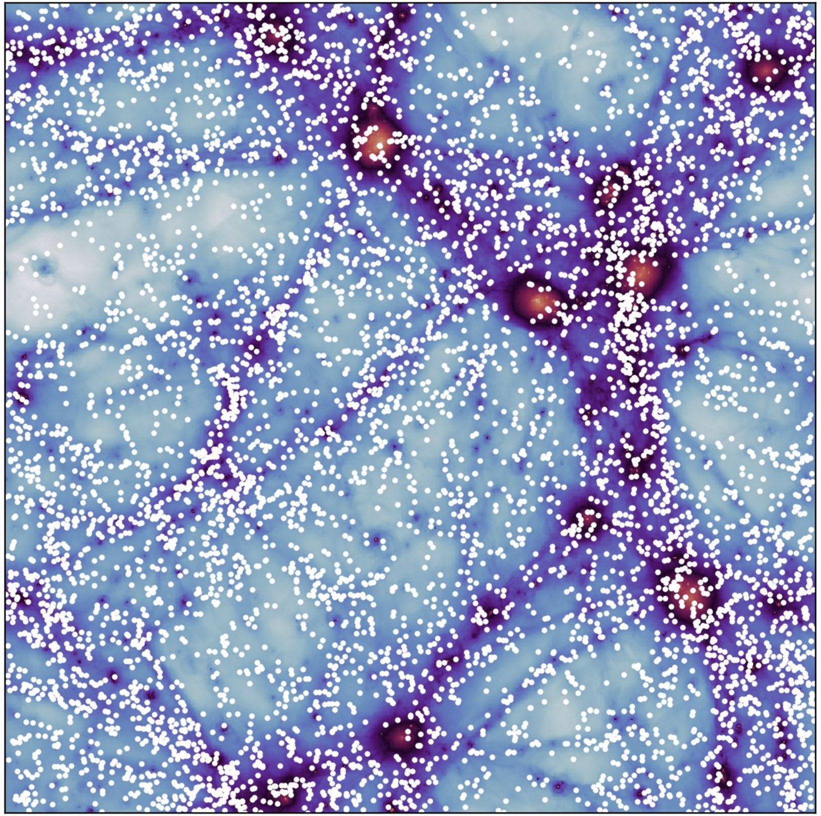
Benitez-Llambay, A. (in prep)

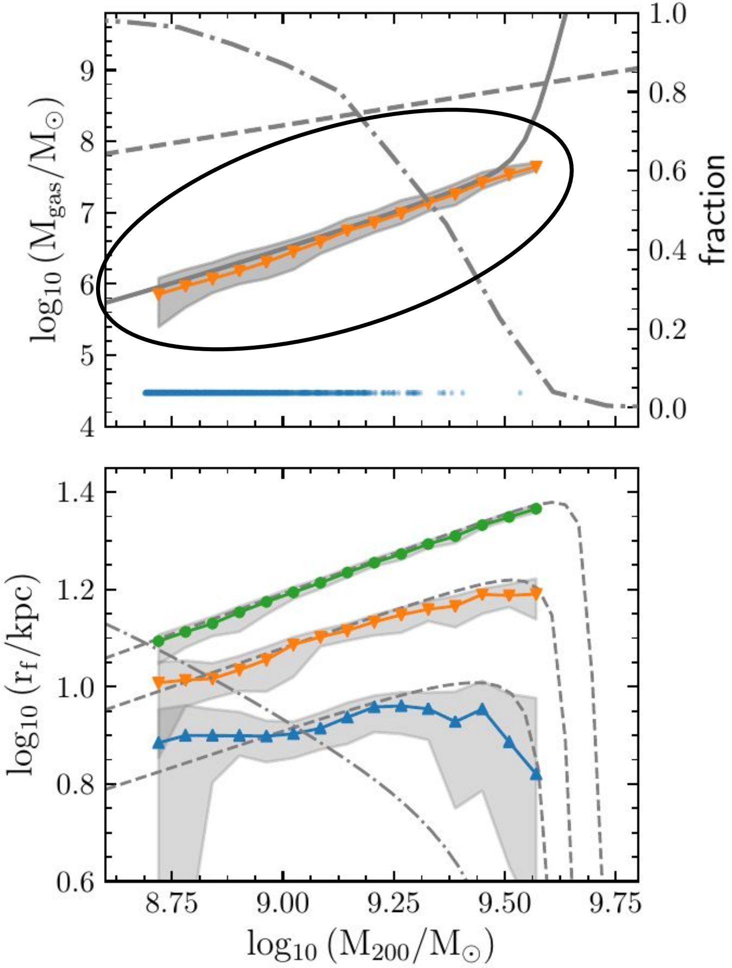
Project gas density in the simulated volume



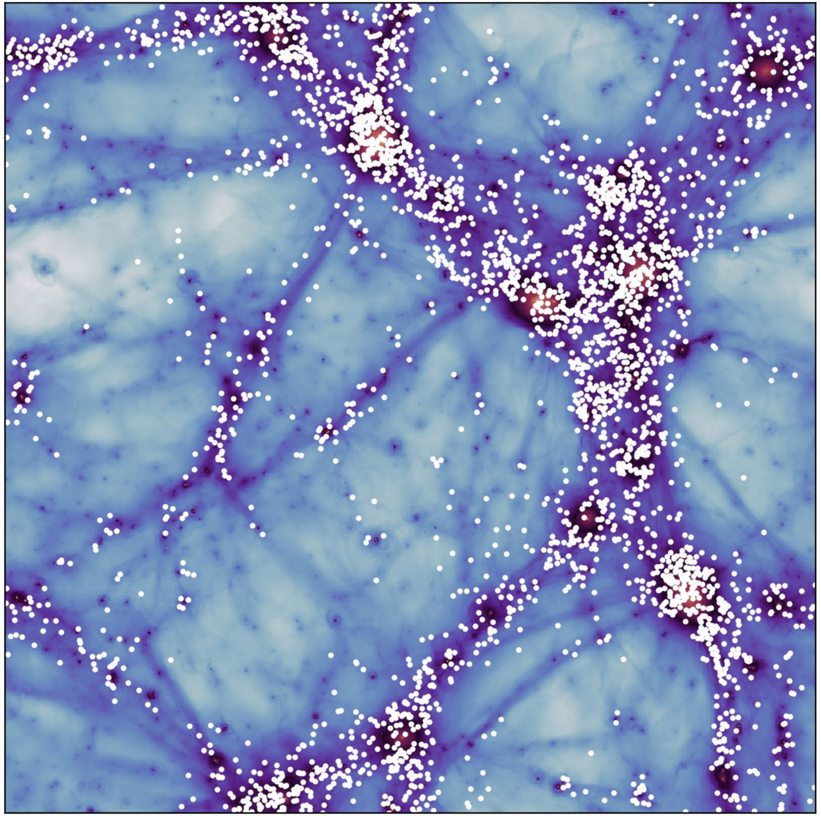


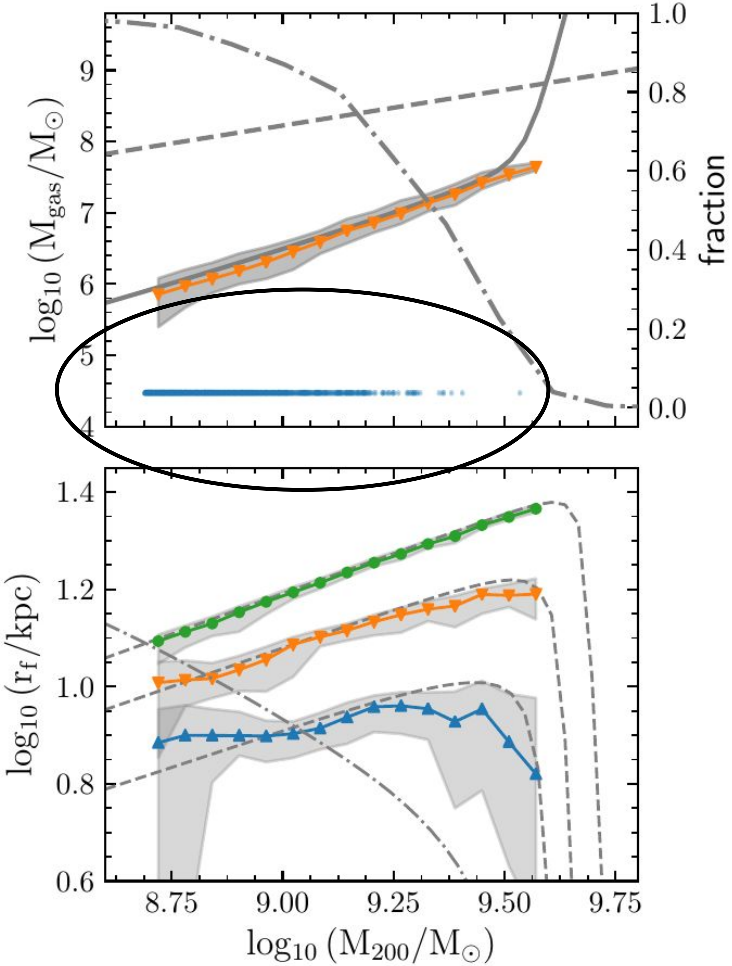
Dark galaxies that contain gas (RELHICs)
REhionization-Limited-HI-Clouds



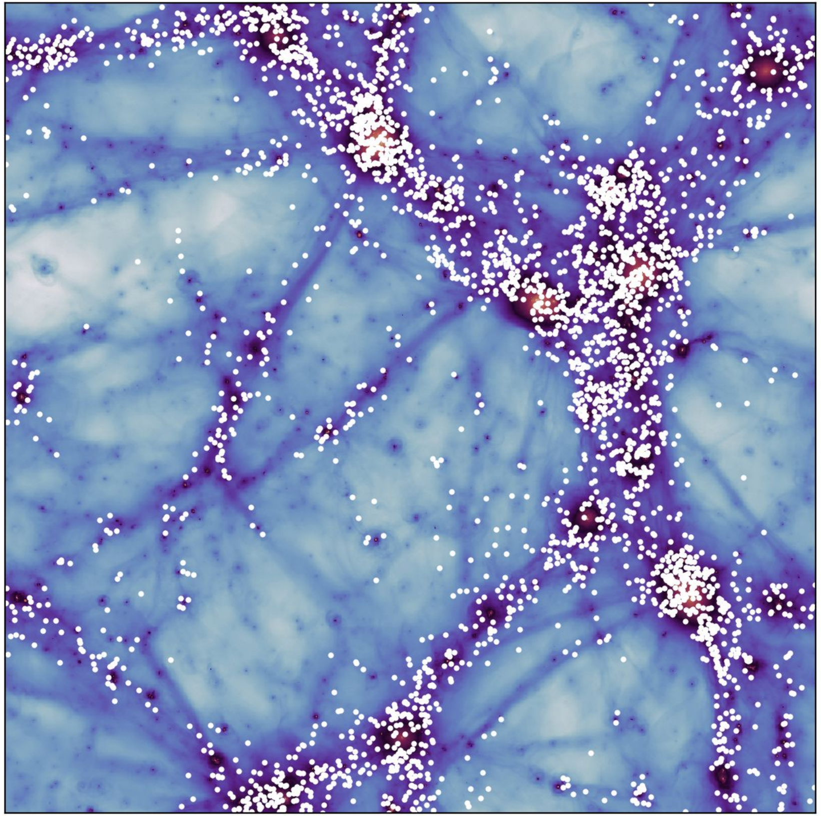


Dark galaxies without gas (COSWEBS)
"COSmic WEB Stripped halos"

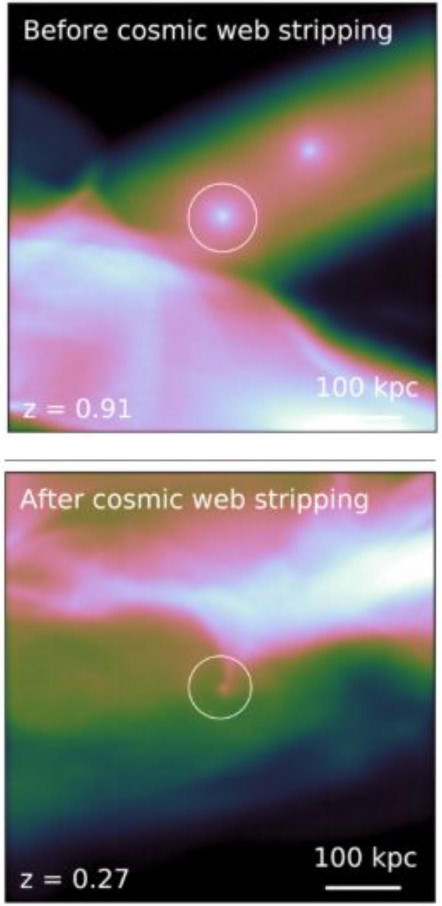




Dark galaxies without gas (COSWEBS)
"COSmic WEB Stripped halos"

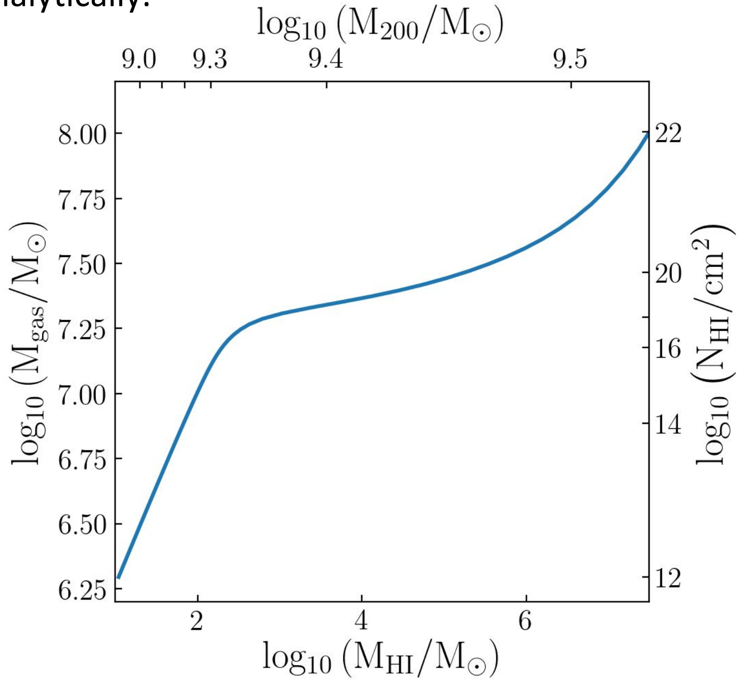


Gas stripping by the Cosmic Web and massive halos

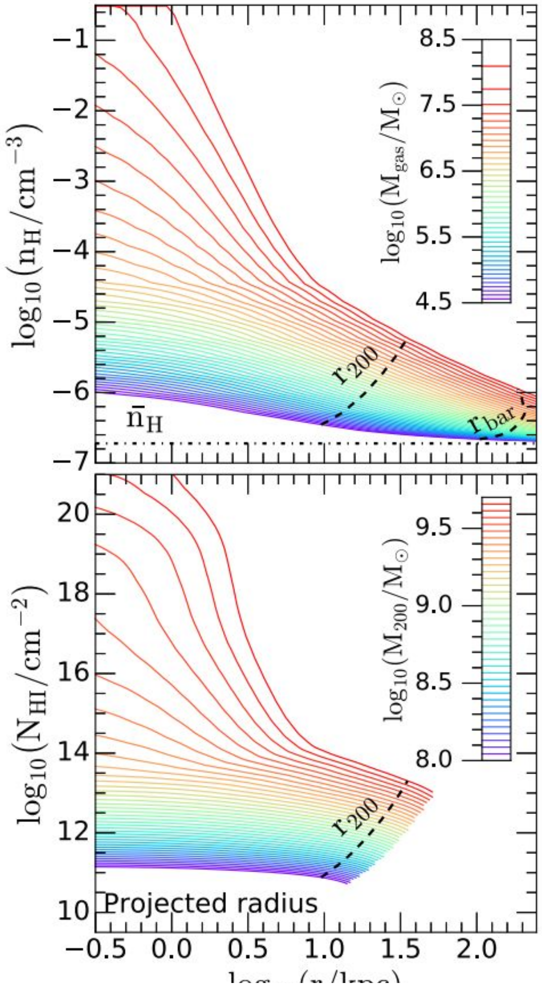


Observable properties of RELHICs

- Simulations are needed to determine the relative abundance of RELHICs and luminous galaxies.
- Structural and observable properties can be calculated analytically.



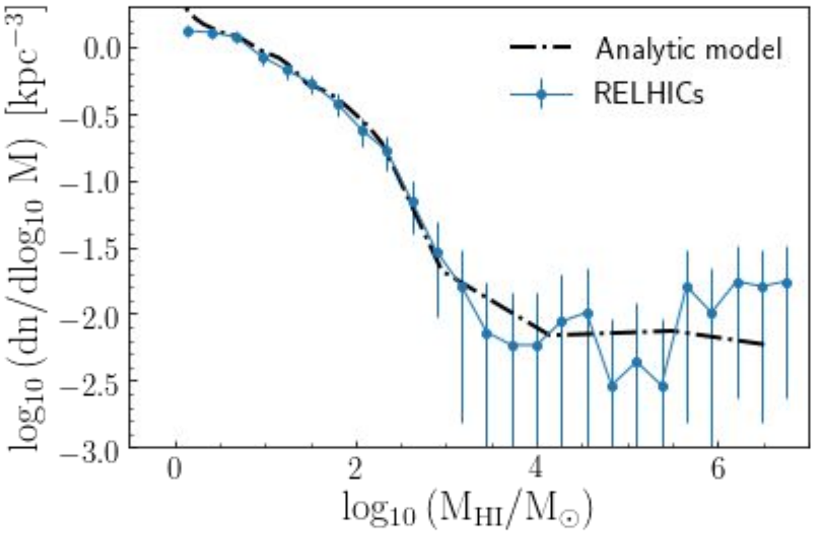
$$M_{\mathrm{HI}}/\mathrm{M}_\odot = 2.36\times 10^5\, S_{21}\, (d/\mathrm{Mpc})^2$$

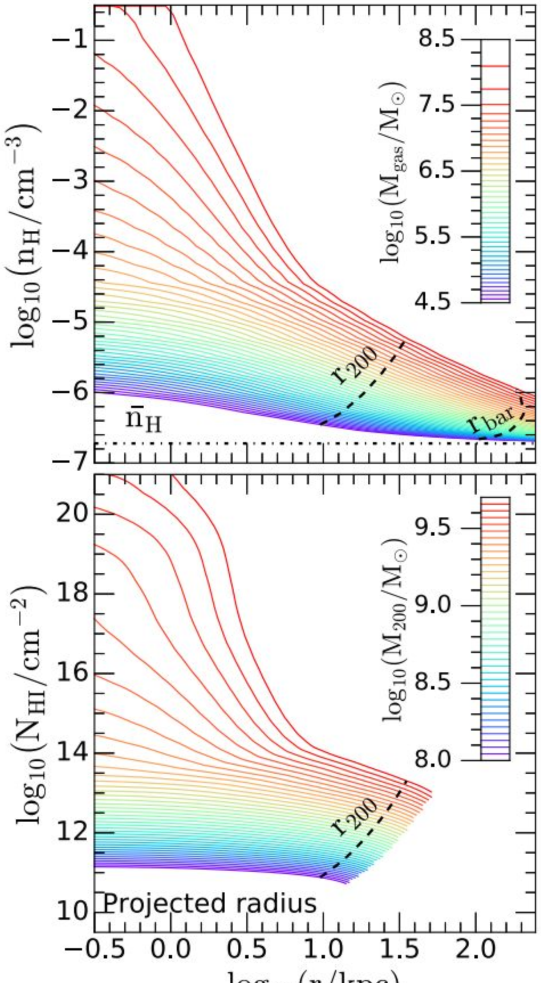


Observable properties of RELHICs

- Simulations are needed to determine the relative abundance of RELHICs and luminous galaxies.
- Structural and observable properties can be calculated analytically.

RELHICs HI-mass function





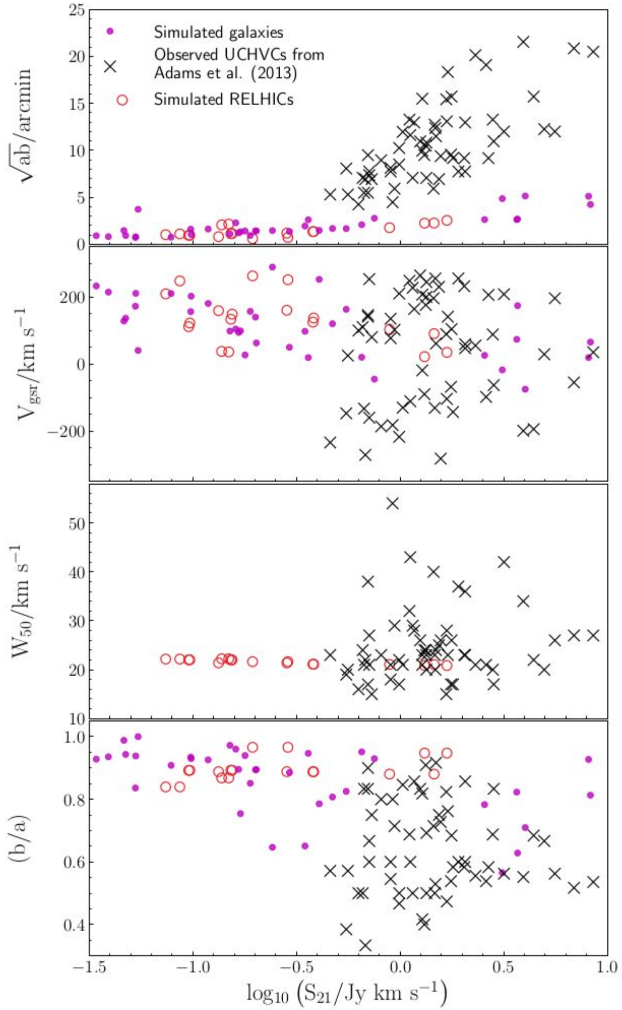
Observational signatures and comparison with existing observations

Benitez-Llambay et al. (2017)

- Properties of simulated RELHICs from the APOSTLE simulations and UCHVCs from ALFALFA (Adams et al. 2013)

- All RELHICs are round, have positive galactocentric velocities and have a well-defined thermal broadening.

- Simulated low-mass galaxies have properties compatible with some UCHVCs. After all, Leo P was discovered as an UCHVCs.



Conclusions

- ★ (ΛCDM + reionization): The Universe must have an increasingly large fraction of "dark" dark matter halos below a halo mass $M_{200} < 3x10^9 M_\odot$ at redshift z=0.

- ★ Theoretical calculations enable to predict the thermodynamics properties of these halos in detail. A simple model has proven to be successful in describing the properties of simulated RELHICs.

- ★ We predict that RELCHIs should be more common in **low-density regions** have (i) **positive galactocentric velocities,** (ii) **be round (a/b > 0.8)**, (iii) **relatively low HI fluxes**, (iv) **very small angular diameter** and (v) a **well-defined thermal broadening**.

- ★ Some UCHVCs observed by ALFALFA are consistent the properties expected for "dark" galaxies, although they tend to be larger.

- ★ Probing ΛCDM requires characterizing the population of RELHICs (need of high-resolution numerical simulations to resolve the interactions of low-mass halos with the environment). I am on it. Stay tuned!.

Check further details in: Benitez-Llambay et al. (2017)
Benitez-Llambay (2019) (in prep)