The critical halo mass for Population III stars

Dependence on Lyman-Werner radiation, baryon-dark matter streaming, and redshift

Mihir Kulkarni, Columbia University

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M_{crit} : Critical halo mass for Population III stars

- Minimum halo mass required to host sufficient cold-dense gas to form stars.
- Expected to be 10^5-10^7 $M_\odot$ in ΛCDM.
- Can increase based on the environment and in turn delay Pop III star formation.
- Very important for semi-analytic models to make observational predictions.

arxiv:2010.04169

Effect of Lyman-Werner radiation

- Molecular hydrogen is necessary for gas cooling in minihalos.
- LW photons (11.2 - 13.6 eV) can dissociate molecular hydrogen.
- In the presence of LW radiation, molecular hydrogen is destroyed and star formation is suppressed.
- Massive halos can self-shield from LW radiation (Wolcott-Green+19).
- Pop III stars form only in massive halos increasing M_{crit} and delay Pop III star formation.

Effect of baryon-dark matter streaming velocity

- First pointed out by Tseliakhovich & Hirata 2010.
- Prior to recombination, baryons were coupled with radiation whereas DM fluctuations grew, resulting in a net streaming velocity between them.
- Coherent over a scale of 3-5 comoving Mpc.
- Maxwell-Boltzmann distribution with RMS ~ 30 km/s at $z = 1100$.
- Decreases with time as $V_{bc} \propto (1+z)$.

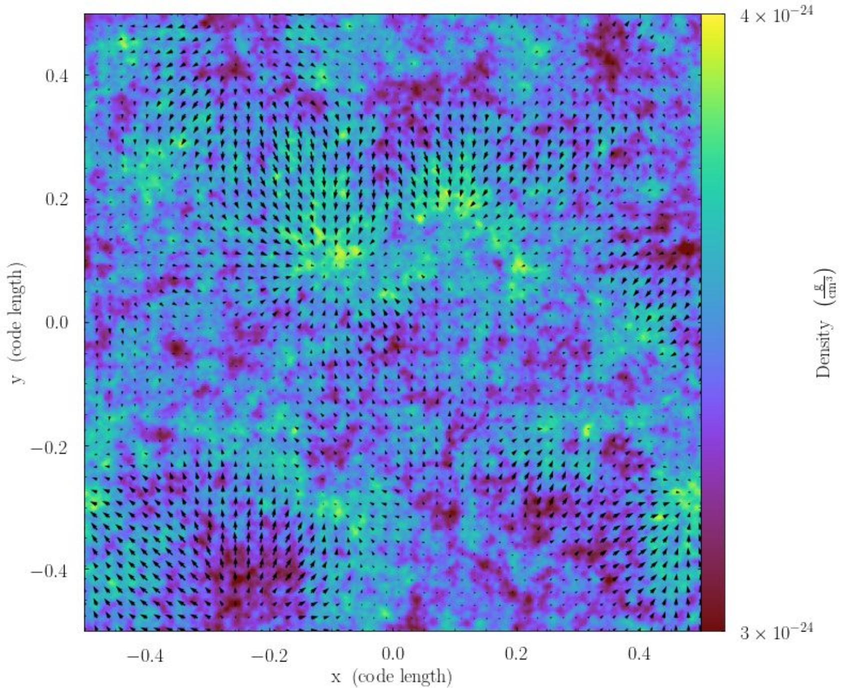
In the regions with high streaming velocity

- Halos are **gas poor** with a lower maximum density.
- Halos need to be more massive with deeper potential wells to have high gas densities.
- M_{crit} is increased and Pop III star formation is delayed.

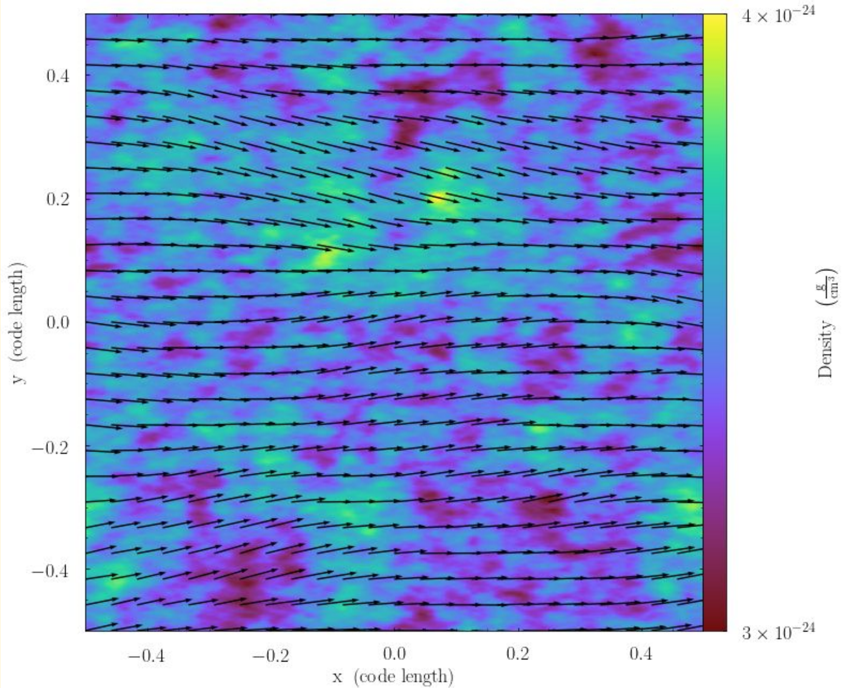
Effect of baryon-dark matter streaming velocity

ICs using CICASS

Without streaming



With streaming

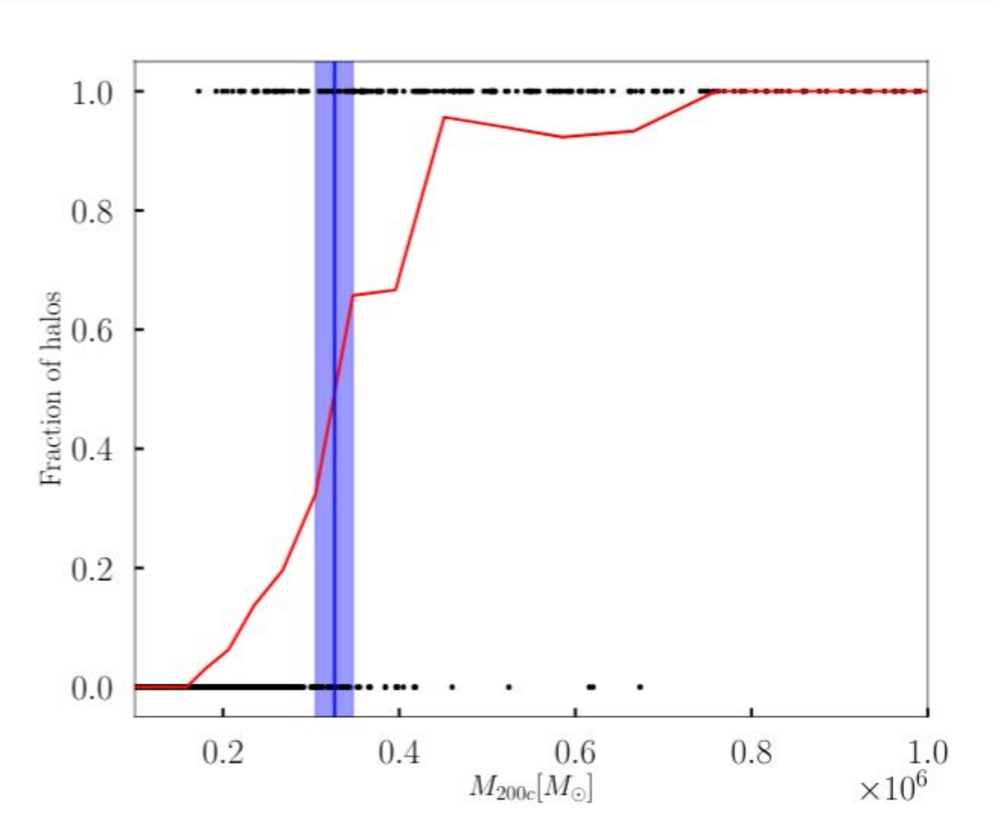


Simulations set-up

- Cosmological simulations of comoving box size 0.5 (1) h^{-1} Mpc using ENZO.
- Primordial chemistry
- Initial conditions using CICASS (McQuinn & O'Leary 2012)
- DM particle mass 100 (800) $M_{\odot}$
- Spatial resolution ~ 22 comoving pc.
- Cold-dense gas ($T < 0.5\ T_{vir}$, $n > 100\ cm^{-3}$).
- $J_{21} = 10^{-21}$ erg s^{-1} $cm^{-2} Hz^{-1} Sr^{-1}$.

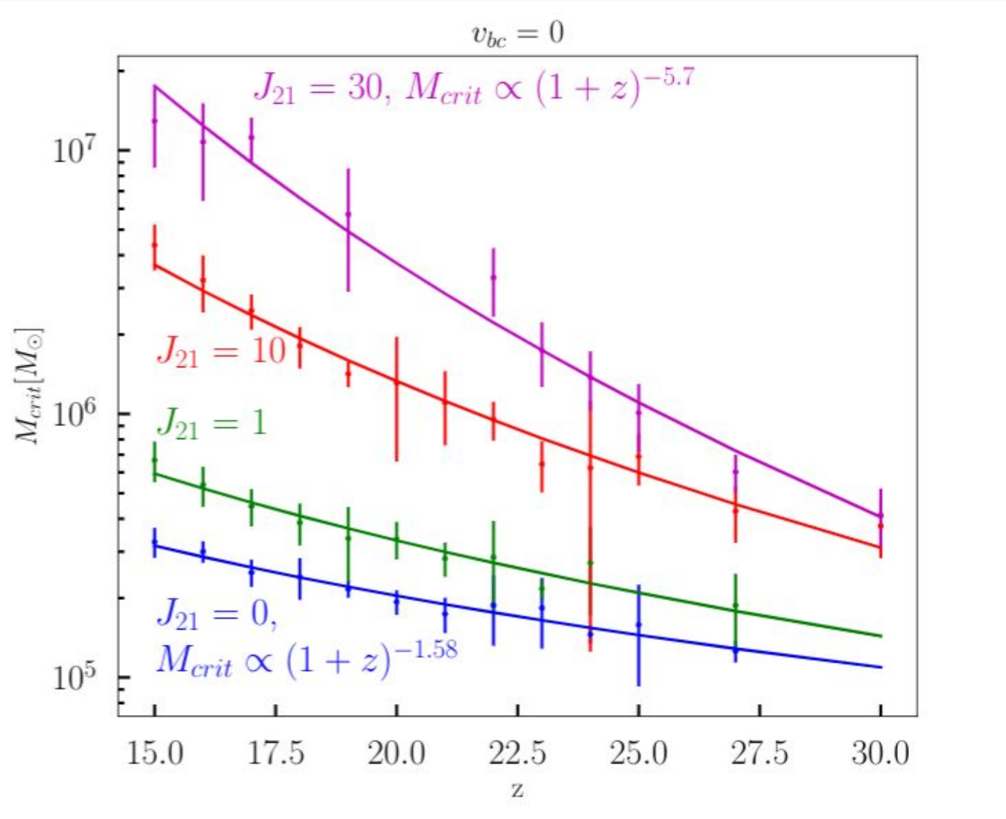
	$J_{21} = 0$	$J_{21} = 1$	$J_{21} = 10$	$J_{21} = 30$
$v_{bc} = 0$	✓	✓	✓	✓
$v_{bc} = 1\sigma$	✓	✓	✓	
$v_{bc} = 2\sigma$	✓	✓		

Identifying M_{crit}



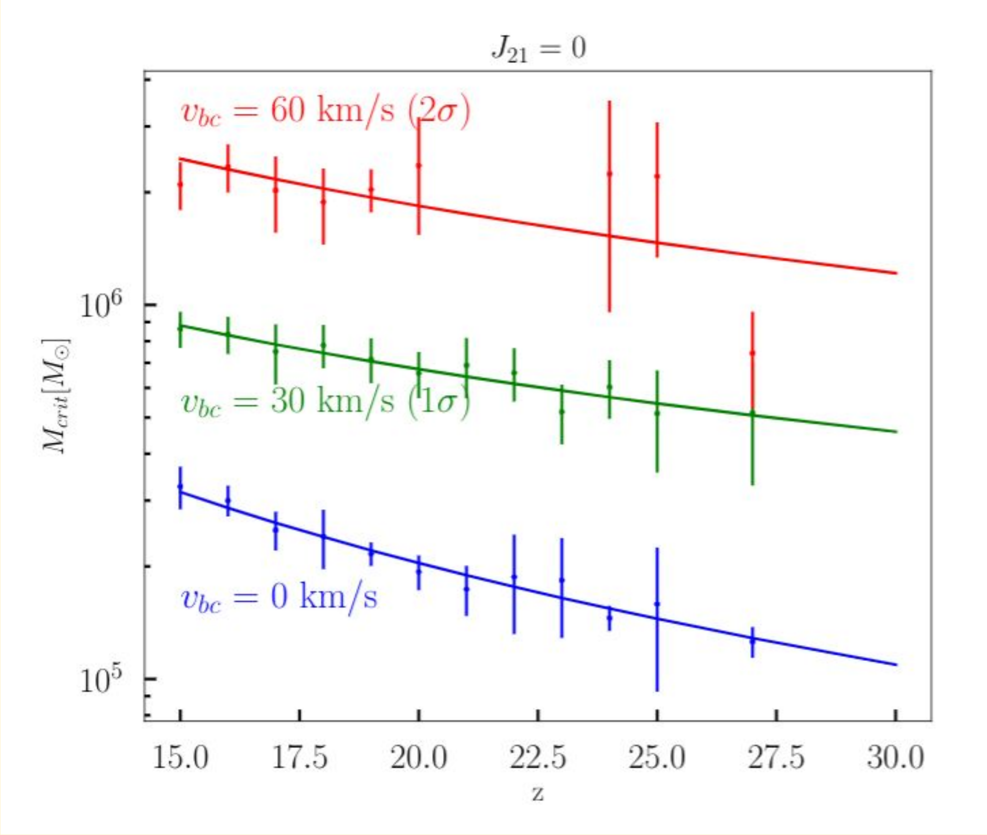
- Mass where half of the halos have cold-dense gas.
- Scatter corresponding to the mass range with 25%-75% of halos with cold-dense gas.

Dependence on LW radiation



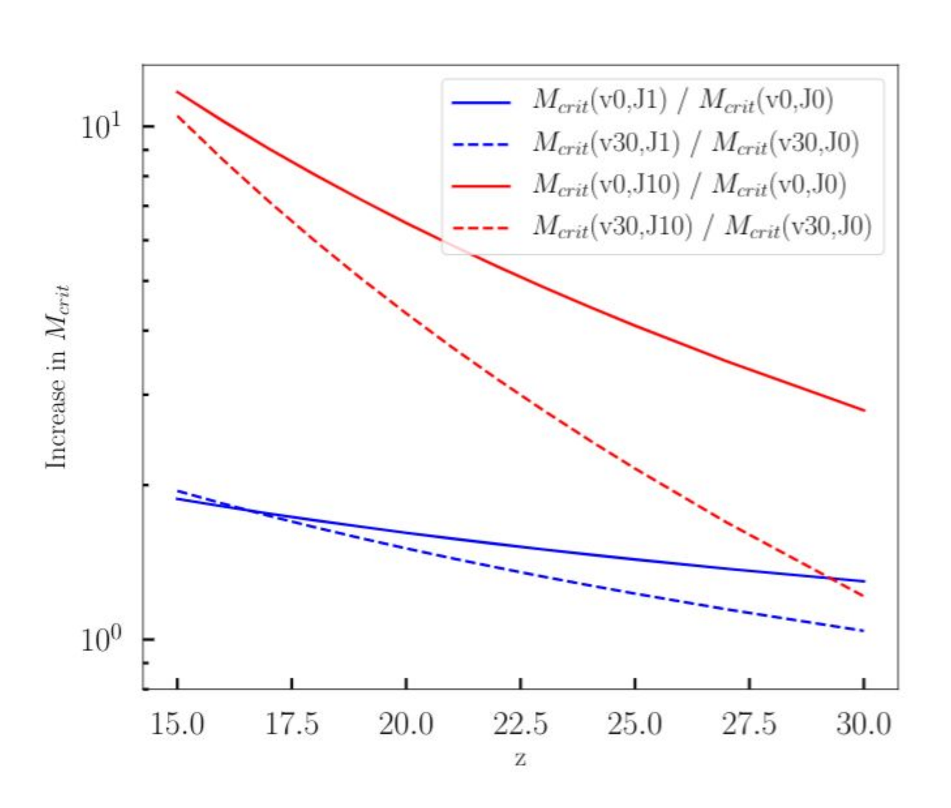
- For J_{LW}=0, consistent with a fixed virial temperature.
- M_{crit} increases with LW flux.
- Steeper z-dependence with high LW flux.
- Self-shielding of H_2 is important.

Dependence on streaming velocity



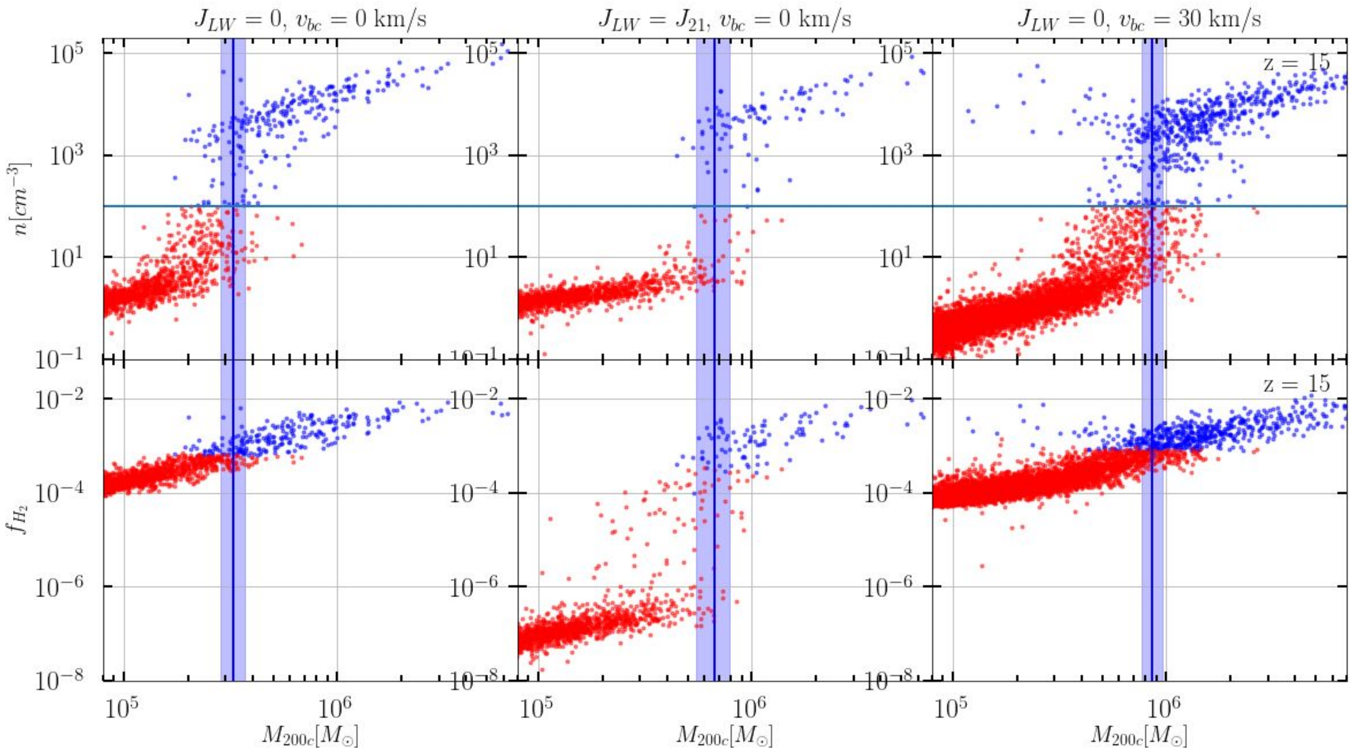
- M_{crit} is higher in the high streaming velocity environment.
- z-dependence becomes less steep in presence of streaming velocity.
- Expected as $v_{bc} \propto (1+z)$.

M_{crit} in presence of J_{LW} and v_{bc}



- **Solid lines** denote increase in M_{crit} because of LW flux in the **absence of streaming**.
- **Dashed lines** denote a similar increase in the **presence of streaming**.
- Effects are **not** multiplicative.
- Combination of LW flux and streaming velocity is **less effective** than the simple multiplicative assumption.

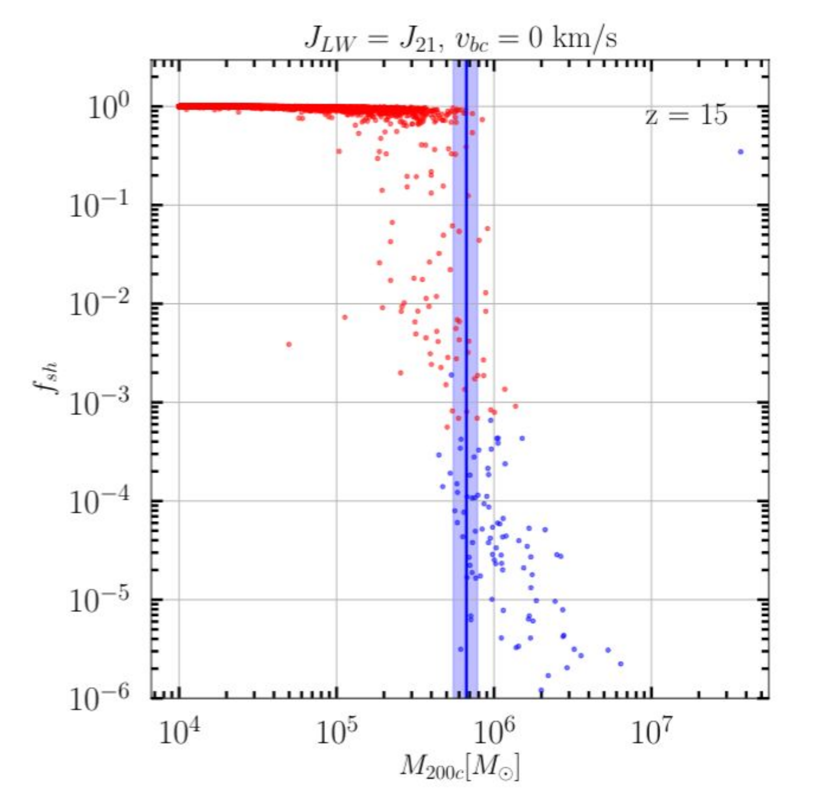
Quantities at the center of the halos



Trends for the warm halos can be used to understand the effects of LW flux and streaming on M_{crit}.

Gas density starts to increase in halos less massive than M_{crit}.

Self-shielding of molecular hydrogen



- Halos less massive than M_{crit} also have significant self-shielding leading to increased gas densities.
- Molecular hydrogen appear to be in equilibrium.
- At high-z: higher gas density $\longrightarrow$ better self-shielding $\longrightarrow$ higher H_2 fraction $\longrightarrow$ steeper z-dependence for M_{crit}.

Summary

1. Clear redshift dependence of $M_{crit} \propto (1+z)^{-1.58}$ consistent with a fixed virial temperature in absence of LW radiation and streaming velocity.
2. LW background increases M_{crit} and also increases z-dependence slope up to -5.7 for $J_{LW} = 30\ J_{21}$.
3. Self-shielding of gas from LW radiation is important and results in M_{crit} significantly smaller than previous works.
4. Effects on M_{crit} from LW radiation and streaming velocity are not entirely independent. The combined impact appears to be less than if they were operating independently.
5. We provide a fit for $M_{crit}(J_{LW}, v_{bc}, z)$ which can be used by semi-analytic models of early galaxy formation.