Mitigating the optical depth degeneracy using the kinematic Sunyaev-Zel'dovich effect with CMB-S4

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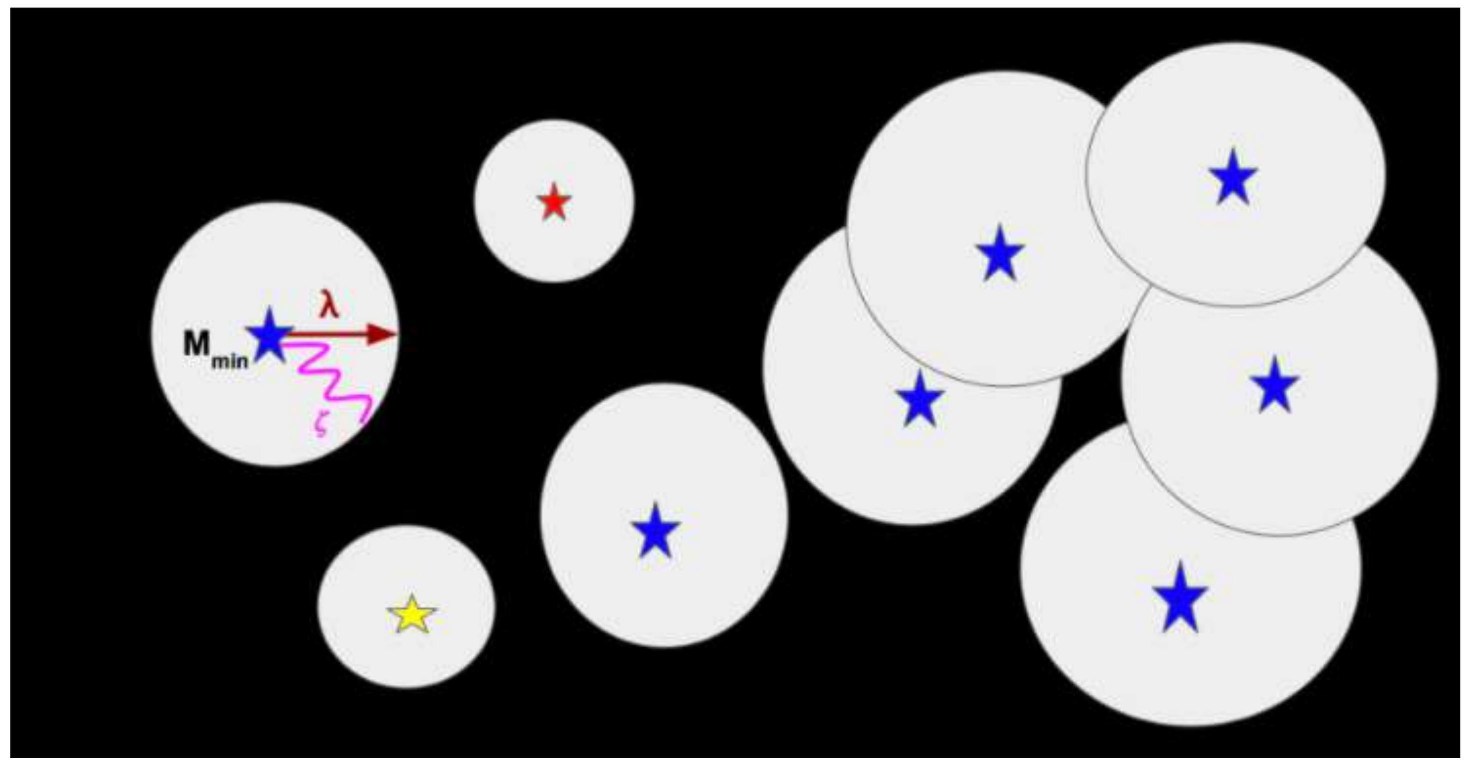
How did the first stars form, and what was their role in reionizing the universe?

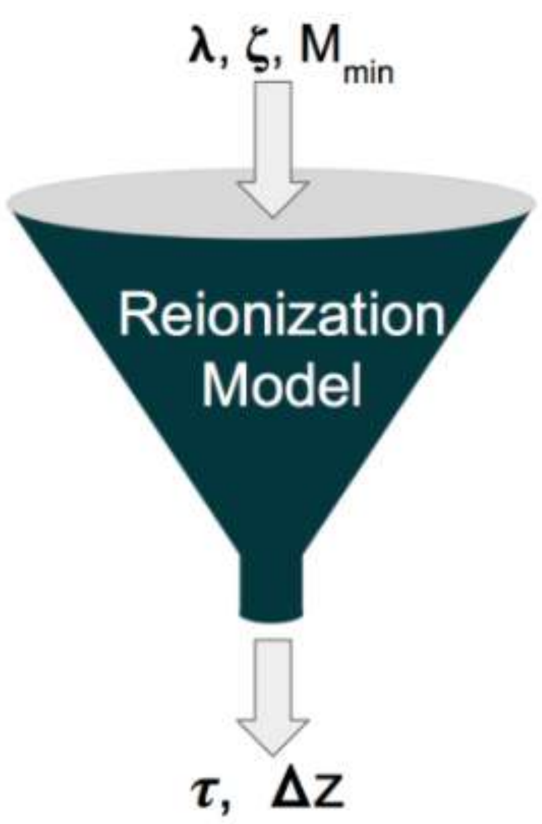
The universe is believed to reionize in patches and these patches grow as more atoms are converted to ions, and eventually overlap, until the whole universe is ionized.

Our simulation model [1] shows this process for a typical patch of the universe. The important parameters in this model are:

- **The efficiency**, **ζ**, which is the number of ionizing radiation the stars give off.
- **The mean free path**, **λ**, which is the average distance the radiation travels .
- **The mass,** M_{min} of the stars causing reionization.



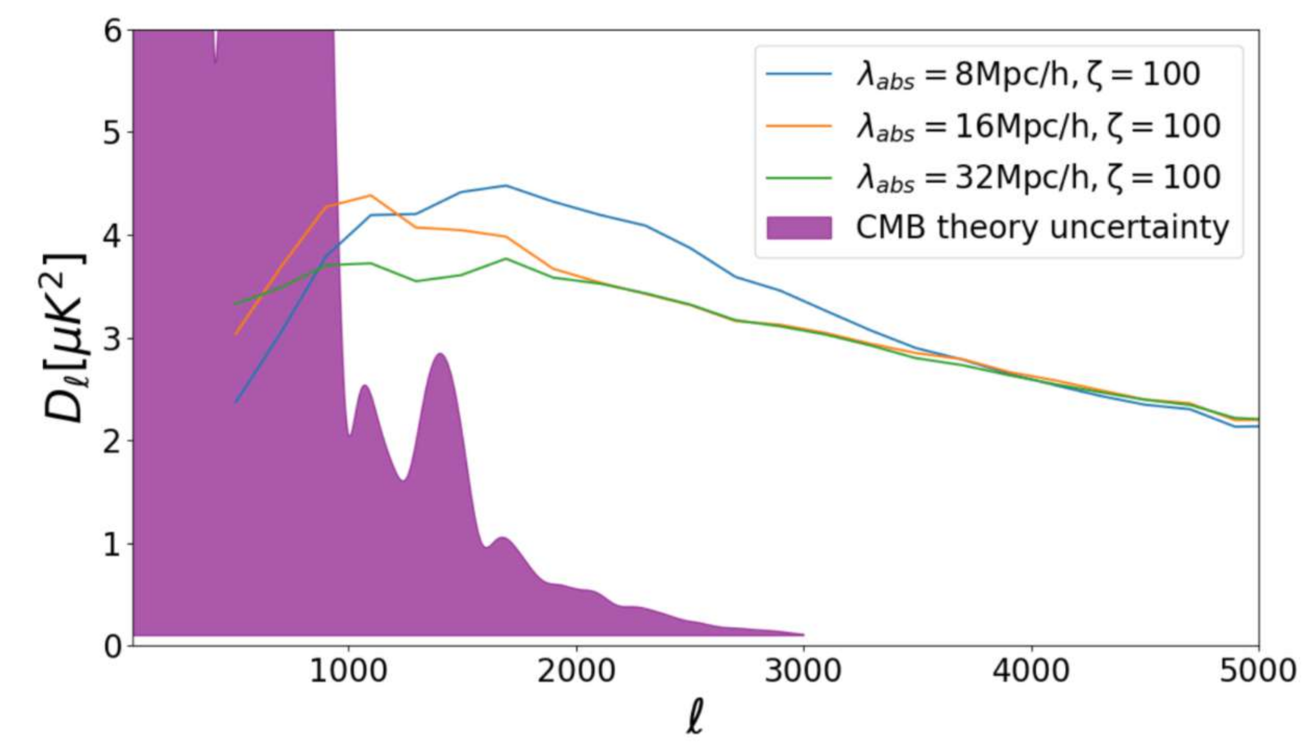
These parameters control the morphology and the history of reionization, and in turn tell us about the optical depth, $\boldsymbol{\tau}$ and the duration of reionization, **Δ**z.



Kinetic Sunyaev-Zel'dovich (kSZ) effect as a probe of reionization

The kSZ effect is the doppler boosting of CMB photons as they Compton-scatter off free electrons moving with a non-zero velocity.

This effect leaves an imprint on the CMB and careful study of this effect can provide enormous information about the EoR. The EoR kSZ signal depends sensitively on the astrophysical details of reionization, as it directly probes the distribution of free electrons.Varying the reionization parameters in the simulation produces various models of the kSZ power spectrum.



Constraints on the duration of reionization and optical depth.

We consider two statistical probes of thee EoR kSZ signal:

- The angular power spectrum (two-point function)
- A configuration of the trispectrum (four-point function) [2]

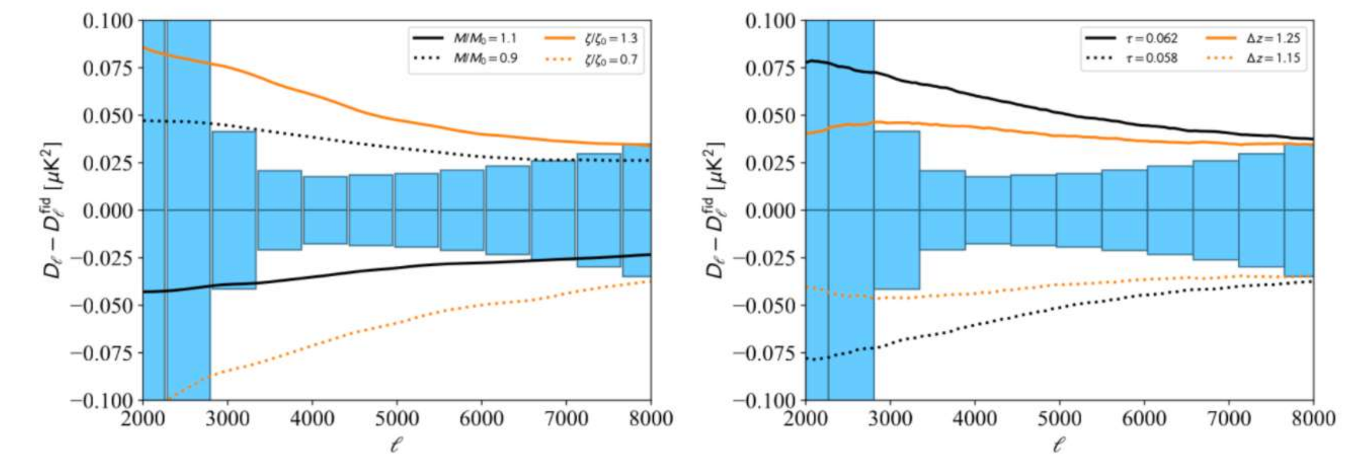
We compute the spectrum derivatives for the reionization parameters by varying the model parameters M_{min} and **ζ** and then use the chain rule to compute

$$\frac{\partial C_\ell}{\partial \tau} = \frac{\partial \zeta}{\partial \tau}\frac{\partial C_\ell}{\partial \zeta} + \frac{\partial M_{\min}}{\partial \tau}\frac{\partial C_\ell}{\partial M_{\min}}$$

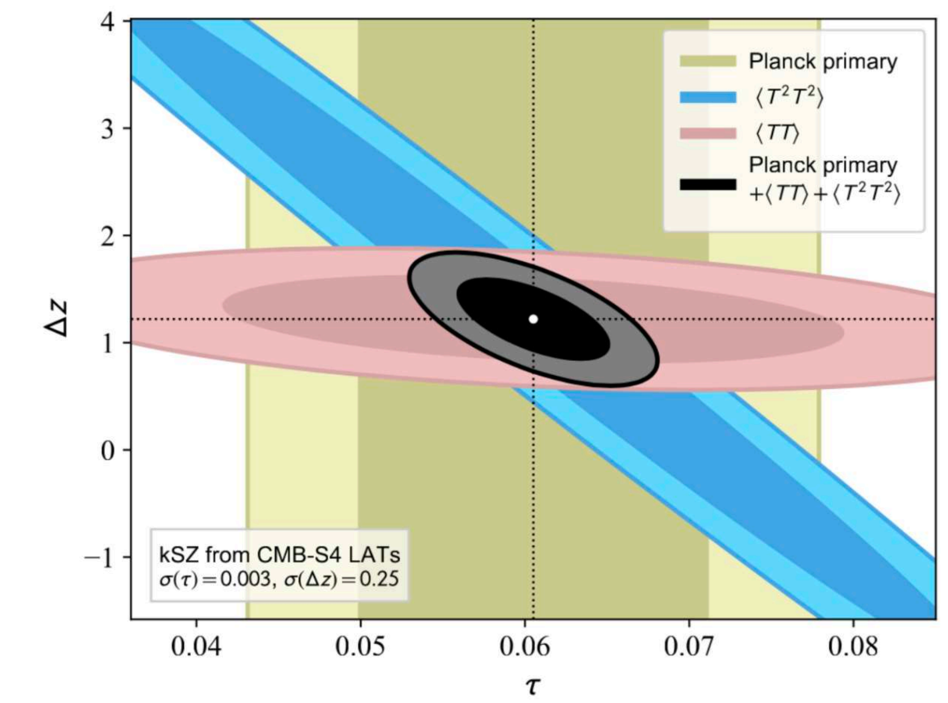
And similarly for **Δ**z. Fixing **λ** = 300 MPC/h, we perform a fisher analysis around a fiducial model with **ζ** = 70 and M_{min} = 3 x 10^9 solar mass, which yields $\boldsymbol{\tau}$ = 0.06 and **Δ**z = 1.2.

The kSZ two-point function and the reconstructed kSZ four-point function combined sufficiently breaks degeneracies between $\boldsymbol{\tau}$ and **Δ**z, yielding tight constraints on both parameters. We find $\sigma(\boldsymbol{\tau})$ = 0.003 and σ(**Δ**z) = 0.25 for a combination of CMB-S4 and Planck data.

Constraints on the duration of reionization and optical depth from CMB-S4 and Plank data.



The figure above shows the dependence of the kSZ power spectrum on reionization model parameters **ζ** and M_{min} , (left panel) and the resulting reionization history parameters $\boldsymbol{\tau}$, **Δ**z (right panel). The shaded bars show 1σ uncertainties in the power spectrum including instrumental noise and residual foregrounds for a combination of CMB-S4 and Planck, and sample variance in the primary CMB and kSZ temperature for our fiducial model.



The vertical shaded contours are 68% and 95% confidence regions from the primary CMB anisotropies measured by Planck, which constrain the optical depth to an error of $\sigma(\boldsymbol{\tau})$ = 0.007. The angled contours show forecast reionization constraints from the kSZ power spectrum (pink) and the kSZ four-point function (blue), as derived for CMB-S4 and Planck data. The black contours show forecast constraints from the combination of all three probes. The complimentary degeneracy directions of the two point and four-point function effectively break the degeneracy between the reionization parameters.

Works Cited

[1] Alvarez, M. A., & Abel, T. (2012). The effect of absorption systems on cosmic reionization. *The Astrophysical Journal*, *747*(2), 126.

[2] Smith, K. M., & Ferraro, S. (2017). Detecting patchy reionization in the cosmic microwave background. *Physical Review Letters*, *119*(2), 021301.