# Optical Depth from 21 cm

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## I. INTRODUCTION

- Reionization is not only an interesting epoch to study in its own right, but also because it's a nuisance for the CMB. If we can understand reionization, we can predict $\tau_{CMB}$. We can then send our prediction to our CMB friends so that they no longer have to marginalize over it. In turn, that gives us better cosmological constraints on the other parameters. This paper is timely because we have next-generation instruments (like HERA!) coming online.

## II. TAU PREDICTIONS

- What does it take to predict tau? Emphasize the point that Jonathan made: it's the density-weighted ionization fraction that counts. So it's more complicated than just integrating an ionization history. Perhaps this would be a good place to add Jonathan's nice plots from global inside-out, outside-in, local... etc.?

Roughly speaking, we envision a multi-stage process for using 21 cm measurements for constraining $\tau_{\rm CMB}$. First, qualitatively different models are distinguished from one another with coarse measurements of the power spectrum or even higher order statistics **[ACL: Cite Watkinson and Pritchard]**. Having selected a single model out of many, one then uses precision power spectrum measurements to fix free parameters within the model. The correlated ionization and density fields of the model can then be predicted from simulations, and the optical depth estimated. This simulation-derived optical depth may, however, deviate from the "true" value of $\tau_{\rm CMB}$ in our Universe because simulations depend on random realizations of density fields. If this "simulation variance" on $\tau_{\rm CMB}$ is small enough to be tolerable, one may immediately feed the derived value of $\tau_{\rm CMB}$ into broader cosmological parameter estimations. On the other hand, if the simulation variance is large, it becomes necessary to directly measure the realization of $\tau_{\rm CMB}$ that represents our Universe. To do so, we propose using power spectrum measurements to restrict the space of possible reionization histories, enabling a principal component-based parameterization that can then be precisely constrained using a global signal measurement. Through the linearity arguments presented above **[ACL: Make sure these are included, or discuss them here]**, these essentially constitute a direct measurement of the optical depth.

### A. Tau predictions from power spectrum measurements

- Power spectrum measurements are a rather poor way of doing it, but they're the most promising short-term observable. So we're choosing to take a look at it, even though it's quite model dependent. It'll essentially require tying the measurements to simulations. We assume that large qualitative changes to reionization physics have already been ruled out in an earlier model selection step.
- Talk about the models and why it's ok to ignore spin temperature (basically ionization frac is too low when spin temperature effects are important). But maybe we should quantify this a little.
- Point out the interesting feature where the degeneracies in 21cm don't compromise our ability to predict tau.

Of course, no probe of reionization is perfect, and any practical measurement will come with its attendant errors and degeneracies. For example, in **[ACL: Cite Jonnie and Grieg & Mesinger]** it was shown that except in the extremely high signal-to-noise regime, fits to theoretical model parameters from 21 cm power spectrum measurements are prone to strong degeneracies if performed at a single redshift. Multi-redshift observations break these degeneracies to a great extent, enabling for instance $\sim$ 10% level constraints **[ACL: Check numbers]** from upcoming instruments like HERA. However, some degeneracy will remain, as evidenced by the elliptical contours shown in Figure **??**, which show some example 68% and 95% confidence regions on $T_{\rm vir}$ and $\zeta$ constraints. These are derived from Fisher matrix forecasts assuming multi-redshift power spectrum measurements performed by HERA **[ACL: Specify a lot more what went into this calculation, especially regarding foregrounds]**. There is clearly a degeneracy that persists between the two parameter.

Fortunately, these residual degeneracies have relatively impact on one's ability to predict $\tau$. Performing a simulation of the ionization field for every point in the parameter space shown in Figure , the relevant integral **[ACL: Reference the equation]** can be evaluated to give predictions for $\tau$. The resulting solid color contours in Figure are seen to be quite closely aligned to elliptical contours, suggesting that a very precise value for $\tau$ can be obtained from 21 cm measurements even in the face of degeneracies.

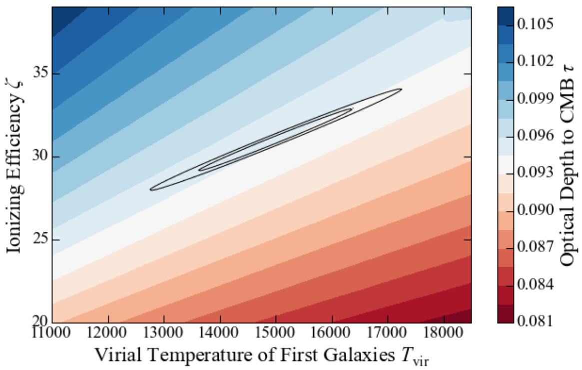


FIG. 1. asdf

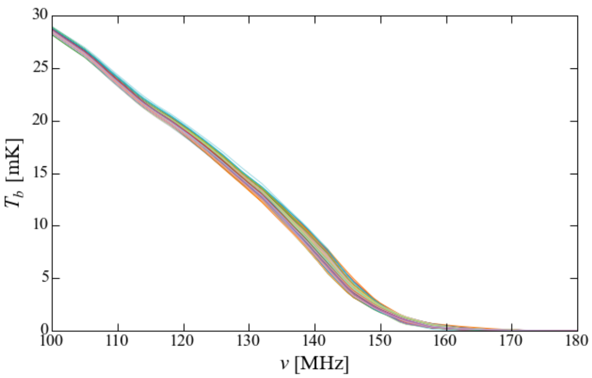


FIG. 2. asdf

- Show $\tau$ predictions for both a WMAP-style redshift and a (probably lower tau) Planck redshift.
- Talk about whether a bigger array does much better.

### B. Tau predictions from global signal measurements

- Show that global signal measurements can get to precisely the quantity we need. But we need to limit the number of degrees of freedom in our fits in order for it to work.
- Power spectrum measurements can help to provide a basis for global signal measurements. Show PCA modes for deviations from fiducial signal.
- Some forecasts for constraining these deviation modes. Show different foreground subtraction scenarios.
- Point out the fact that by making a direct measurement, we avoid the problem of cosmic variance, since we're essentially measuring "our" tau, in our branch of the multiverse.

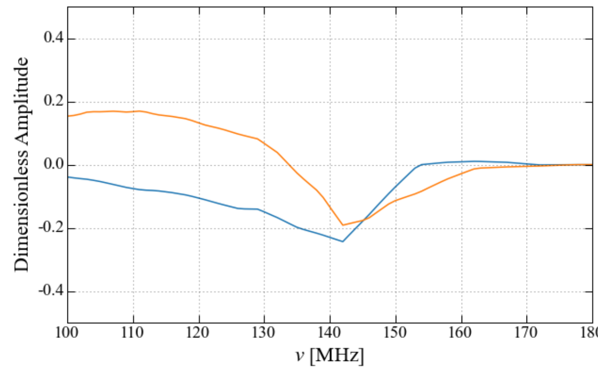


FIG. 3. asdf

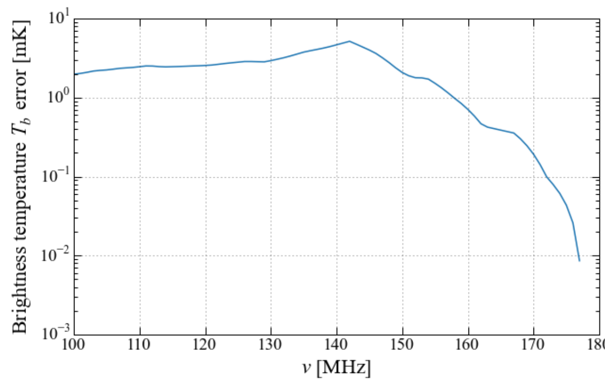


FIG. 4. asdf

### C. Summary of tau predictions

- Provide a table summarizing values.

## III. IMPROVEMENTS IN THE CMB

### A. Degeneracy breaking

Highlight some specific examples.

- How might it be helpful to no longer have the $A_s$ and $\tau$ degeneracy?
- What about B-modes? Reionization bump predictions need $\tau$, so consistency tests are helped by 21cm. Also discuss Mortonson & Hu (2008) and how inflationary parameters are biased if reionization not modeled correctly.

## IV. PREDICTIONS FOR $x_{HI}$

Mention how even thought it's not $x_{HI}$ that's directly relevant for $\tau$, the same measurements mentioned ear-

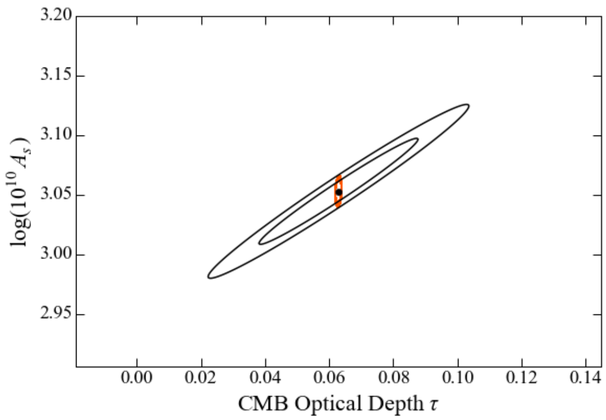


FIG. 5. asdf

lier might provide a way to probe the ionized fraction (particularly the power spectrum measurements).

- Show some projections for $x_{HI}$.
- Talk about how this can be very complementary to optical/IR measurements.

## V. CONCLUSIONS

Summarize our main points.

## ACKNOWLEDGMENTS