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Erratum: "PAPER-64 Constraints on Reionization: The 21 cm Power Spectrum at $z = 8.4$" (2015, ApJ, 809, 61)

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In this erratum, we retract the upper limits on the 21 cm power spectrum presented in the published article. The published article reported an upper limit on $\Delta^2_{21}(k)$ of $(22.4\ \mathrm{mK})^2$ at $z = 8.4$ in the range $0.15 < k < 0.5h\ \mathrm{Mpc}^{-1}$. This analysis underestimated the level of signal loss, or attenuation of the target cosmological 21 cm signal associated with the chosen power spectrum estimator, and also underestimated the statistical error on those estimates. A revised result, with a new analysis, is presented in M. K. Kolopanis et al. (2018, in preparation). Below, we briefly summarize the errors in the original analysis and how they are corrected. For an in-depth analysis and discussion of the errors, we refer the reader to Cheng et al. (2018).

Signal loss was expected in the original analysis because the covariance matrices, $\boldsymbol{C}$, used to weight the un-normalized bandpower estimates, $\hat{\boldsymbol{q}}_\alpha$, in

$$\hat{\boldsymbol{q}}_\alpha = \boldsymbol{x}\boldsymbol{C}^{-1}\boldsymbol{Q}_\alpha\boldsymbol{C}^{-1}\boldsymbol{x} \tag{1}$$

were empirically estimated from a time-averaged finite ensemble of the data, $\boldsymbol{x}$, such that $\boldsymbol{C} \rightarrow \hat{\boldsymbol{C}}_x = \langle \boldsymbol{x}\boldsymbol{x}^\dagger\rangle_t$. While the true covariance $\boldsymbol{C}$ leads to an inherently unbiased lossless estimator of the power spectrum, using an empirically estimated $\hat{\boldsymbol{C}}$ can lead to signal loss. Specifically, weighting data by an empirically estimated covariance carries the risk of overfitting and downweighting EoR fluctuations that are coupled to the data. In Cheng et al. (2018), it is shown that these couplings are especially strong in the fringe-rate filtered PAPER-64 data set.

The first and most impactful error relates to the method by which signal loss was estimated. To assess signal loss from the empirically estimated covariance matrix, different realizations of mock cosmological signals $\boldsymbol{e}$ of known amplitudes are added to the original data to form a new data vector, $\boldsymbol{r} \equiv \boldsymbol{x} + \boldsymbol{e}$. New covariance matrices, $\hat{\boldsymbol{C}}_r = \langle \boldsymbol{r}\boldsymbol{r}^\dagger\rangle_t$, are used to estimate un-normalized bandpowers, $\hat{\boldsymbol{q}}_{\alpha,r}$, which can be written as

$$\begin{aligned}\hat{\boldsymbol{q}}_{\alpha,r} &= \boldsymbol{x}\hat{\boldsymbol{C}}_r^{-1}\boldsymbol{Q}_\alpha\hat{\boldsymbol{C}}_r^{-1}\boldsymbol{x} + \boldsymbol{x}\hat{\boldsymbol{C}}_r^{-1}\boldsymbol{Q}_\alpha\hat{\boldsymbol{C}}_r^{-1}\boldsymbol{e}\\ &+ \boldsymbol{e}\hat{\boldsymbol{C}}_r^{-1}\boldsymbol{Q}_\alpha\hat{\boldsymbol{C}}_r^{-1}\boldsymbol{x} + \boldsymbol{e}\hat{\boldsymbol{C}}_r^{-1}\boldsymbol{Q}_\alpha\hat{\boldsymbol{C}}_r^{-1}\boldsymbol{e}.\end{aligned} \tag{2}$$

The normalized power estimate can then be compared to the known injected power in $\boldsymbol{e}$ to estimate signal loss.

The key error in the previous analysis was to assume that, since $\boldsymbol{e}$ was statistically independent of $\boldsymbol{x}$, that the two middle cross-terms in Equation (2) would average to zero in an ensemble. However, as shown in Cheng et al. (2018) and Switzer et al. (2015), these cross-terms can contain significant negative power because $\hat{\boldsymbol{C}}_r$ contains information that correlates the two vectors. Ignoring these cross-terms leads to a significant underestimate of signal loss.

As a result, we presented negligible signal loss in our original analysis, when in fact approximately ~99.99% of the signal was removed (Cheng et al. 2018). Correcting for the actual signal loss is the biggest factor revising the upper limit on Δ^2_{21}.

The second mistake made in the original analysis was to underestimate the statistical errors in the reported power spectrum estimates. The original analysis used a bootstrap resampling technique on power spectral measurements over the baseline and time axes. However, fringe-rate filtering introduces significant correlations in the data along the time axis. As is discussed in Cheng et al. (2018), bootstrapping across correlated samples can result in a significant underestimate of the variation in the data if the number of resamplings is not equal to the number of independent samples in the data, as in the case of the original analysis. The error bars associated with this oversampling were underestimated by approximately a factor of 2 (in mK). The revised analysis in

M. K. Kolopanis et al. (2018, in preparation) only applies bootstrap resampling across the baseline axis to avoid this problem.

The mistake in estimating the statistical errors should have become apparent when comparing results to our theoretical thermal noise sensitivity. Unfortunately, a third miscalculation was made in estimating the thermal noise sensitivity. As detailed in Cheng et al. (2018), this miscalculation stemmed from numerous small mismatches between the idealized analysis pipeline used to estimate sensitivity and the actual analysis applied to the data. As a result, our estimated thermal noise sensitivity was approximately a factor of 3 low (in mK), leading to the mistaken impression that our error bars were consistent with the level of thermal noise.

In summary, we retract the power spectrum results shown in Figures 18 and 20 in the published article. Results that relied on the original limits, including those presented in Figure 21, are retracted. Additionally, the companion paper to the original manuscript, Pober et al. (2015), used the original limits to place constraints on the spin temperature of the intergalactic medium (IGM) at $z = 8.4$. Our revised limits do not place significant constraints on the IGM temperature, and the results of Figure 4 from Pober et al. (2015) should be disregarded. However, we note that their analysis would still be relevant should a future experiment place constraints on the 21 cm signal similar to those claimed in the published article. An updated analysis of this same data set is presented in M. K. Kolopanis et al. (2018, in preparation), where these revised results are put into context with measurements at other redshifts.

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