Peer Review Report on "Robust CMB B-mode Analysis with Needlet-ILC"

A Variational Consistency Assessment

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(Dated: December 22, 2025)

This report evaluates the manuscript entitled "Robust CMB B-mode analysis with Needlet-ILC and simulation-based inference". The assessment focuses on structural consistency, variational closure, physical completeness, and dependence on non-generative model assumptions. The conclusion is that the work is not based on a self-contained physical theory and relies entirely on phenomenological parametrizations. Recommendation: Reject.

REFEREE REPORT

The manuscript entitled "Quantifying the impact of beam chromaticity on large-scale B-mode science for the Simons Observatory" presents an end-to-end simulation pipeline for evaluating the imprint of beam chromaticity on the recovery of the tensor-to-scalar ratio r from CMB polarization measurements.

The work is technically detailed; however, the manuscript suffers from several structural issues that undermine its scientific validity as a contribution to fundamental cosmology. My recommendation is **Reject**, for the reasons detailed below.

1. Model self-referentiality

The entire analysis is performed on simulated skies whose statistical properties (CMB realization, dust, synchrotron, spectral indices, spatial correlations) are not derived from first principles but imposed *a priori*. As a consequence, the beam-induced bias is evaluated within a self-referential system: the sky model, its foreground complexity, and its statistical structure coincide with those assumed by the component-separation algorithm. This makes the study unable to reveal inconsistencies or unmodelled effects, since the inference pipeline is calibrated on the same assumptions used to generate the data.

2. Lack of variational or physical closure

No fundamental field equation or variational functional is specified for the sky components. Dust SEDs, synchrotron slopes, spatial correlations, and frequency decoherence parameters are introduced phenomenologically. Since these degrees of freedom are not tied to a dynamical or variational structure, the pipeline cannot in principle test physical proposals for r. All outputs are conditioned on prior assumptions rather than on physical derivations.

3. Gaussian likelihood applied to non-Gaussian fields

Foregrounds are known to be non-Gaussian, anisotropic, and correlated across scales. The manuscript acknowledges this but retains a Gaussian likelihood for the power spectra. This choice analytically suppresses non-Gaussian systematics but does not model them. Therefore, the quoted uncertainties on r are necessarily underestimates and cannot be interpreted as robust constraints.

4. Beam modelling remains idealised

The beam simulations used here are produced under assumptions of optical ideality and do not reflect realistic non-idealities, alignment variations, or HWP-induced leakage. The authors explicitly acknowledge that the real instrument will deviate more strongly from ideality. Thus, the reported chromaticity bias cannot be extrapolated to the actual instrument.

5. Absorption of systematics into foreground parameters

The component-separation pipeline (BBPower/NaMaster) absorbs a wide class of systematic errors into effective dust or synchrotron parameters. This makes the bias on r apparently small but prevents the identification of the underlying cause. A small reported bias does not indicate physical robustness but rather reflects the flexibility of the parametrization.

6. No demonstrable sensitivity to primordial tensors

The quoted constraints on r remain fully consistent with zero and strongly prior-dependent. Given the modelling choices, the pipeline does not demonstrate that the experiment can isolate primordial B modes from component degeneracies.

Conclusion

The manuscript does not provide physically testable predictions, does not identify observable signatures independent of model assumptions, and does not demonstrate that beam chromaticity can be robustly evaluated without a first-principles description of sky components.

For these reasons, I recommend **Reject**.

APPENDIX A: VARIATIONAL REQUIREMENTS FOR A CONSISTENT TREATMENT OF CMB POLARIZATION

A physically complete analysis of sky polarization requires that all observables (CMB temperature, polarization, dust emission, synchrotron emission, beam response, frequency decorrelation) arise from a variational principle. In particular, one must specify a functional $\mathcal{F}$ whose extrema generate:

1. the sky fields and their correlations;
2. their frequency dependence (SEDs);
3. their spatial statistics;
4. their interaction with the optical system (beam, HWP, bandpass).

Without such a structure, each component is introduced as a free template rather than as the solution of a well-defined physical problem.

The manuscript under review does not provide such a functional. Foreground SEDs are imposed, not derived. Beam chromaticity is introduced via numerical optics but not linked to a field-theoretic framework. No closure relation exists between sky components and instrumental response.

For completeness, we outline below the general variational structure that a consistent theory must satisfy.

A.1 Variational Closure Condition

Let Ψ_i denote the fundamental fields generating all sky observables, and let Γ encode the coherence structure. A closed variational formulation must satisfy:

$$\frac{\delta}{\delta\Psi^\dagger(x)}\left\{\left|\sum_{i,j}\Psi_i^\dagger\Gamma\Psi_j\right|^2 - \lambda_1\sum_i(\Psi_i^\dagger\Psi_i - 1)^2 - \lambda_2\sum_{i,j,k}\mathrm{Tr}\left[\Gamma(\Psi_i\Psi_j^\dagger - \Psi_k\Psi_i^\dagger)\right]^2\right\} = 0.$$

This condition ensures:

1. *emergent frequency spectra* rather than imposed SED templates;

2. *self-consistent spatial correlations* instead of Gaussian approximations;
3. *dust and synchrotron fields as coherent excitations*, not as external nuisance components;
4. *beam interaction as a coherent mapping* rather than a synthetic convolution.

A.2 Consequences for beam chromaticity

In a closed variational structure, beam response is not an external function of frequency. Instead, it emerges from the coherent mapping:

$$B_\nu(x) = \Psi^\dagger(x)\,\Gamma_\nu\,\Psi(x),$$

with Γ_ν determining the frequency response. Thus, chromaticity is *not* a perturbation but an intrinsic geometric feature.

The manuscript's approach, which treats chromaticity as a small correction to an ideal beam, cannot capture this structure and therefore cannot assess its physical impact on r.

A.3 Implications

A simulation pipeline lacking variational closure cannot meaningfully quantify the bias induced by beam chromaticity, since neither the sky model nor the instrument model arises from a unified physical description.

Therefore, the numerical results in the manuscript cannot be interpreted as constraints on primordial tensors.