# Snowmass2021 - Letter of Interest

# *Synergies between Millimeter-Wave Line Intensity Mapping with Radio, Optical and Microwave Observations*

**Thematic Areas:**

■ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
■ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe

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**Abstract:** Line intensity mapping is a powerful emerging observational technique to map the large scale structure (LSS) over a wide range of scales and redshifts, largely inaccessible by other probes. We advocate leveraging synergies between line intensity mapping (LIM) at millimeter wavelengths as a novel probe of LSS, and the more well-established observations of optical galaxy surveys and weak lensing of the Cosmic Microwave Background (CMB). We also discuss the complementarity of intensity maps with different lines, in particular mm-wavelength lines and the 21-cm line. Combining various LSS probes, all tracing the same underlying dark matter distribution while having different systematics and foregrounds, can lead to significant enhancements in the scientific reach of individual probes. The expected scientific gain is the result of mitigation of degeneracies between cosmological parameters, sample variance cancellation in some cases, control of systematics and improved calibration of nuisance parameters. Mm-wave LIM over a redshift range of $0 < z < 9$ uniquely offers a multitude of cross-correlation opportunities at low and high redshifts, which in turn can significantly improve the precision and robustness of the constraints on cosmological parameters including primordial non-Gaussianity, the effective number of relativistic species, the sum of neutrino masses, and the dark energy equation of state.

## Overview

The large-scale structure (LSS) of the universe carries invaluable information on the origin, evolution and composition of the universe. Line intensity mapping (LIM)[1;2] is an emerging observational technique to map the LSS over a significant fraction of the sky and extended redshift epochs, largely inaccessible to other probes of the LSS. Instead of resolving individual sources, LIM relies on detecting the cumulative emission of molecular and atomic spectral lines from galaxies or the intergalactic medium. Measurements of line frequency together with spatial fluctuations in the line intensity provide a 3D map of the underlying dark matter distribution. In this letter we advocate mm-wave LIM of far-IR emission lines (CO rotational ladder and [CII] ionized carbon fine structure line) as new cosmological probes. In particular, we highlight the synergies and complementarity of mm-wavelength LIM with other probes of LSS, specifically with optical galaxy surveys, CMB lensing and 21-cm intensity maps. For the science discussed here, we consider ground-based mm-wavelength facilities, which can detect structure over the entire $0 < z < 10$ redshift range. We refer to[3;4] for more details of the envisioned surveys.

Various probes of LSS trace the same underlying dark matter distribution using different tracers and observational techniques. Combinations of probes, including their cross-correlations, lead to significant enhancement in precision and robustness of cosmological constraints from individual ones at *no added cost*. This is due to (a) reducing statistical errors by adding more modes, breaking parameter degeneracies and cosmic variance cancellation in some cases, (b) calibrating nuisance parameters such as galaxy/line bias and line mean brightness temperature, and (c) better control of systematics and foregrounds which are expected to be largely uncorrelated between different probes. Additionally, the cross-correlations between different probes offer consistency tests of the theoretical models of the observables as well as of the individual data sets.

The large sky coverage, wide redshift range (including the ability to perform internal cross-correlations of different tracers of the same structure), and high spectral resolution of mm-wave LIM makes it particularly powerful for cross-correlations with other LSS probes. Below, we discuss some of the expected science returns from three classes of cross-correlations, highlighting the distinctive advantages of mm-wave LIM. While a large fraction of our discussions focuses on 2-point statistics, given the non-linear and non-Gaussian nature of the LSS (in particular at lower redshifts and small scales), higher-order auto and cross statistics like the bispectrum can significantly help to break degeneracies among cosmological parameters and nuisance parameters, as well as probing physics not imprinted on the 2-point statistics like equilateral primordial non-Gaussianity. In the context of LIM, while there have been a few recent studies considering 3-point cross-statistics[5;6], extensive work is still needed to fully explore their potential.

## Expected Science Returns

1. **Optical galaxy surveys:** upcoming photometric and spectroscopic surveys (LSST[7], DESI[8], EUCLID[9], SPHEREx[10]) will provide an unprecedented volume of high-precision data at $z < 3$. Cross-correlation of this rich data with mm-wave LIM can significantly enhance the scientific return of these surveys in several ways including (a) control of systematics and a more robust measurement of cosmological parameters. For example, large-scale systematics (Galactic dust extinction, stellar contamination, etc.), the main difficulties in constraining primordial non-Gaussianity from clustering power spectrum[11], impact the cross-correlations less. With large sky and redshift coverage, LIM well-matches both galaxy and quasar samples, (b) improved calibration of the redshift distribution of galaxies in imaging surveys, reducing uncertainties in photometric redshift measurements ("clustering-based" redshift estimation[12–14]). The strength of LIM for this task is twofold: accurate measurement of redshifts (thanks to the high-precision measurement of the line frequencies), and wide

redshift coverage extending well beyond the spectroscopic surveys. Furthermore, mm-wave LIM may offer some advantages over 21cm for clustering redshifts: multiple CO lines in the same survey could provide higher confidence for redshift estimation, and mm-wave receivers at 10 m-class dishes would have significantly higher angular resolution (∼arcminute) than single-dish 21cm measurements.

2. **21cm intensity maps**: cross-correlations of 21cm with other probes are expected to be much less affected by Galactic foregrounds than 21cm auto-spectra[5;15;16]. At $z > 3$, intensity maps with other lines (e.g., CO and [CII] lines) are the only tracers for cross-correlating with 21cm to provide a convincing evidence of the cosmological origin of high-redshift 21cm detection. Furthermore, multi-line cross correlations provide additional information on the Epoch of Reionization[17] (e.g., constraining the size of ionized bubbles by tracing the scale at which the cross correlation changes sign[18] and constraining properties of the ionizing sources), allowing astrophysics to be "marginalized out" in cosmological constraints. Considering higher-order cross-statistics (ex. between [CII] and 21cm) can help in reliably extracting 21 cm bias factors[5].
3. **CMB lensing maps**: weak lensing of the CMB is theoretically a very clean signal but only provides information projected along the line of sight. Cross-correlation with other tracers of matter at known redshifts would provide tomographic information of CMB lensing. Given the broad CMB lensing kernel with significant weighting beyond $z \sim 2$, cross-correlations with LIM offers distinct advantages over spectroscopic galaxy surveys which are limited to $z < 2$. However, the potential of this cross-correlation can only be unlocked if in intensity maps the large-scale modes along the line of sight, that are highly contaminated by foregrounds, can be retrieved via reconstruction methods[19–23]. Cross-correlations between the reconstructed mm-wave LIM and upcoming CMB surveys (Simons Observatory[24] and CMB-S4[25]), can significantly improve the constraints on cosmological parameters by probing redshift evolution of growth of structure to constrain dark energy/modified gravity and neutrino mass, by mitigating degeneracies between growth, line bias and mean brightness temperature, and by allowing for efficient cosmic variance cancellation in constraints on local non-Gaussianity and growth rate[26–28].

## Challenges and Roadmap

There have been a number of early detections of CO and CII line intensity in auto-spectra and cross-correlations with other probes[29–33]. Several upcoming experiments (TIME[34], CONCERTO[35], COMAP[36]) will provide higher-fidelity detection of CO and [CII] signal. However, due to their limited sensitivity, small sky and frequency coverage, these first generation surveys will not provide cosmological constraints. To realize the science goals discussed here, development of next generation of wide-field mm-wave facilities with significantly higher detector counts is required, for which on-chip spectrometers provide a promising path[3;4]. To fully take advantage of the power of the combined LSS probes, coordinated survey planning and joint data analysis is essential. The design of the new line intensity facilities need maximal overlap in their footprint on the sky with galaxy and CMB surveys.

One critical challenge affecting the usefulness of LIM cross-correlations, in particular with CMB and galaxy lensing, is that the projected probes are only sensitive to large-scale modes along the line of sight, which are contaminated by continuum foregrounds in LIM surveys. Reconstruction of the large-scale modes using their impact on small-scale fluctuations[19–23] can provide a mean to overcome this challenge and fully exploit the potential of the combined statistics.

Furthermore, the strength of the line signal, its redshift evolution and its dependence on astrophysics is not well-established and theoretical models of the signal differ by an order of magnitude. The first generation of LIM surveys will play an important role in this direction by reducing the modeling uncertainties.

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