Snowmass2021 - Letter of Interest

Cosmology with Millimeter-Wave Line Intensity Mapping

Thematic Areas:

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

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Abstract:

We propose development of a new cosmological probe: mm-wave line intensity mapping (LIM). *This technique has the potential to measure the large-scale structure (LSS) of the Universe to significantly higher redshifts and larger scales than future galaxy surveys.* Such measurements bear on key open questions in fundamental physics and complement existing LSS probes by providing additional measurements of the same cosmic structure with independent systematics. The primary required technical advance is the development of large-format arrays of mm-wave spectrometers, achievable in the next decade. Significant cosmological impact can be realized by deploying these arrays on excellent mm-wave platforms.

Summary

Line Intensity Mapping (LIM) at millimeter wavelengths is a promising new cosmological observable. In this Letter of Interest (LOI), we outline the science cases that large-scale structure (LSS) measurements with mm-wave LIM could address, briefly describe the technique, summarize synergies with other LSS probes, and describe the state of the field and the technical developments necessary for competitive cosmological constraints using next-generation facilities. Additional information is presented in associated mm-wave LIM LOIs addressing primordial non-Gaussianity[1], cross-correlations[2], facilities[3], and detectors[4].

Cosmology with LSS

Measurements of LSS are a key component of the standard cosmological model. By probing the statistics of the matter distribution as a function of redshift, mm-wave LIM is sensitive to many topics in fundamental physics, including but not limited to:

- **Inflation**: primordial non-Gaussianity using scale-dependent line bias and higher-order statistics; features in the primordial power spectrum
- **Dark Energy**: expansion history using baryon acoustic oscillations (BAO)
- **Growth of Structure**: testing General Relativity vs modified gravity using the growth rate
- **Neutrinos**: sum of neutrino masses using the amplitude of fluctuations and expansion rate
- **Light Relics**: number of relativistic species using the BAO phase and full-shape power spectra

While these are common to all large-volume LSS probes, using multiple techniques is advantageous: cross-correlating different tracers of the same structure can improve on the cosmic variance limit, independent systematics cancel, and using multiple lines makes it possible to test the separation of the astrophysics and cosmology driving the signals. Indeed, for some goals such as primordial non-Gaussianity, cross-correlation may be necessary to cross critical physically-motivated thresholds with sufficient systematic rigor.

Millimeter-Wave Line Intensity Mapping

The LIM technique uses low angular resolution, spectroscopic observations of an atomic or molecular emission line to trace the large-scale fluctuations in the matter distribution[5]. LIM does not require individual sources to be resolved, and can therefore efficiently measure cosmological modes beyond the redshift reach of galaxy surveys by detecting *all* line-emitting sources in aggregate. Knowledge of the rest-frame wavelength uniquely maps the spectral direction to redshift, providing a 3D data cube. Several lines have been considered, with the neutral hydrogen 21 cm transition the most developed.

LIM at *mm wavelengths* detects far-IR emission lines—e.g., the CO rotational ladder or the [CII] ionized carbon fine structure line—known tracers of LSS which at high z are redshifted into the mm-wave atmospheric window and detectable from the ground. CMB experiments have decades of experience performing high-sensitivity, low-systematics measurements of faint, diffuse structure in this wavelength range; all that is needed is to add moderate-resolution spectroscopy ($R \gtrsim 300$) to existing broadband detectors.

Next-generation receivers at established mm-wave observing sites, featuring thousands of mm-wave spectrometers in the 80–310 GHz atmospheric window, could detect all of LSS out to $z \sim 10$ using CO and [CII]. This corresponds to a factor of ~ 4 increase in cosmological volume over existing galaxy surveys, probing deeply into the matter-dominated epoch ($z > 2$) where nonlinearities due to structure formation are smaller, and provides a complementary measurement of lower redshifts. A 500-spectrometer focal plane at the South Pole Telescope would constrain the expansion history to percent-level precision at $z > 3$—an epoch in which we have no measurements—discriminating between models of early dark energy[6]. A receiver optimized to measure the largest angular scales accessible from the ground ($\ell \sim 20$) would provide competitive constraints on primordial non-Gaussianity[1,7,8].

Synergy with Other Probes

Mm-wave LIM complements other LSS probes and offers distinct advantages of its own[2]:

- **Galaxy surveys**: *Photometric*—mm-wave LIM will survey large sky areas well-matched to photometric surveys with much higher spectral resolution. Where observations overlap, "clustering redshifts" can be used to calibrate photometric redshifts, improving a major systematic. *Spectroscopic*—LIM's intermediate spectral resolution will connect high-precision spectroscopic redshifts over small areas to photometric redshifts over large areas. Cross-correlation of mm-wave LIM with spectroscopic surveys can confirm that detected fluctuations are indeed from the target lines. Moreover, LIM provides clustering information useful for interpreting sparse galaxy survey data.
- **21 cm**: Both 21 cm and mm-wave LIM probe similar angular and radial scales, and cover wide redshift ranges. At high redshift ($z > 3$), mm-wave is a viable method for measuring large scales; cross-correlation will be a vital check that any detected 21 cm signal is cosmological.
- **CMB lensing**: Cross-correlating high-redshift mm-wave LIM (where redshifts are known) with integrated CMB lensing (which has a wide redshift kernel) will provide unique tomographic information beyond the reach of galaxy surveys, constraining the redshift evolution of structure growth.
- **Instrumental systematics**: Mm-wave LIM uses a different observational strategy from other probes (superconducting detectors, continuous scanning), so in cross-correlation instrumental systematics will not bias the cosmological signal. In particular, large-scale systematics in galaxy surveys are a major concern, which the addition of mm-wave data optimized for large angles—as informed by CMB experiments focusing on low ℓ—may ameliorate.
- **Astrophysical systematics**: Since different astrophysical processes produce the various LSS observables considered here, cross-correlation enables marginalization over astrophysical "nuisance parameters," such as galaxy bias, to isolate the underlying cosmological signal. Multiwavelength observations will similarly allow robust modeling and removal of Galactic foregrounds.

Roadmap

Several mm-wave LIM experiments exist or are planned (TIME[9], CONCERTO[10], CCAT-p[11]). While these efforts could achieve first detections, first-generation instruments featuring tens of spectrometers are not sensitive enough to probe fundamental cosmology. Since mm-wave detectors are now background-limited, just as in CMB, the only option is to significantly increase detector count.

On-chip mm-wave spectrometers are poised to enable this sensitivity increase. Unlike existing mm-wave spectrometers (grating, Fourier Transform), in on-chip designs both the spectrometer and detector are lithographed on a silicon wafer, enabling extremely high packing densities similar to CMB focal planes. The use of superconducting microwave resonators is key to realizing high detector counts. First demonstrations of this technology are now taking place (SuperSpec[12], DESHIMA[13]) but significant development is needed before full focal planes with hundreds of spectrometers can be fielded. *With targeted effort, this development could be completed in 3-5 years*; see the Detectors[4] and Facilities LOIs[3] for further details.

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