Snowmass2021 - Letter of Interest

Millimeter-Wave Line Intensity Mapping Facilities

Thematic Areas:

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

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Abstract:
Line intensity mapping (LIM) at millimeter wavelengths is a promising new probe of large-scale structure (LSS). Next-generation surveys will significantly extend the available cosmological volume, improving precision on cosmological parameters by accessing the matter-dominated epoch of the Universe's evolution, and providing an observable complementary to other high-z probes such as 21 cm. We outline the science thresholds that future mm-wave LIM experiments could cross and the scales of facilities required to cross them. These scaling challenges are well-matched to those now being achieved by CMB-S4.

Overview

Line intensity mapping (LIM) at millimeter wavelengths has the potential to measure large-scale structure well beyond the reach of optical galaxy surveys, improving cosmological constraints from large-scale structure (LSS) measurements. Mm-wave LIM builds on the successful heritage of cosmic microwave background (CMB) experiments, which over the last 30 years have demonstrated precise, background-limited measurements of faint, diffuse structure over large sky areas with low systematics. In this LOI we outline specific science thresholds that these measurements could cross, projected spectrometer counts necessary to cross them, and the technical developments that would enable such spectrometer counts.

Science Thresholds

Critical science thresholds could be crossed by detecting high-redshift CO or [CII] with mm-wave LIM, either independently or in cross-correlation with other tracers. Many are in common with proposed next-generation CMB [1], galaxy surveys, or 21 cm experiments[2]—see the associated mm-wave LIM cosmology[3], $f_{\rm NL}$ [4], and cross-correlation[5] LOIs for further details. Table 1 lists several specific cases:

Topic	**Measurement**	**Threshold**
Inflation	Primordial non-Gaussianity	$\sigma(f_{\rm NL}^{\rm loc}) < 1,\ \sigma(f_{\rm NL}^{\rm eq}) < 10,\ \sigma(f_{\rm NL}^{\rm orth}) < 10$
Dark Energy	Expansion history at $z > 3$	$\sigma(\alpha_{\rm BAO}) < 0.01$
Neutrinos	Sum of neutrino masses	$\sigma(\Sigma m_\nu) < 0.03$ eV
Light Relics	Effective number of relativistic species	$\sigma(N_{\rm eff}) < 0.03$

Table 1: Science thresholds that could be crossed with mm-wave LIM in combination with Planck and next-generation CMB/LSS experiments. Many other cases exist that are not mentioned here.

Scales of Future Facilities

Mm-wave detectors are largely limited by the atmospheric background and not their intrinsic noise, as demonstrated with current CMB experiments. We expect this to remain true for spectrometers even at high spectral resolution (low detector bandwidth)—i.e., sensitivity is determined by detector count. Current experiments use a variety of spectrometer technologies, and will likely produce first detections of both clustering and shot noise power spectra. But none are scalable by the orders of magnitude necessary to cross the thresholds listed above. We instead anticipate that future instruments will be powered by *on-chip mm-wave spectrometers*[6]—with both the spectrometer and the detector lithographed on a silicon wafer—enabling optimally-packed focal planes and the ability to scale up detector count similar to CMB experiments.

Table 2 outlines possible experimental stages defined by spectrometer count. A "spectrometer" consists of a single spatial pixel which fully samples 80–310 GHz with frequency channels of width $\Delta\nu = \nu/R$. R is the resolving power; we take $R = 300$, demonstrated by SuperSpec[7]. For each stage we indicate an approximate timescale to deploying the indicated spectrometer count, a representative instrument, and which science threshold it could cross (assuming line strengths consistent with recent observations[8] and $\sim 10^4$ hr integration time). For the primordial non-Gaussianity science goal, we assume a compact on-axis refractor optimized to measure $\ell \sim 20$ (BICEP-like)[4]. For the other goals we assume the use of proven mm-wave platforms such as the South Pole Telescope (SPT-like) or the Simons Observatory Large Aperture Telescope (SO LAT), and a receiver comprising a set of optics tubes, each hosting a spectroscopic focal plane. Figure 1 shows representative CMB-equivalent map depths for a "Large-scale" survey; we note that the recent detection of CO shot noise fluctuations at 100 GHz had a map depth of ~ 800 μK-arcmin[8], so experiments beyond the "Detection" stage are expected to be signal-dominated.

Stage	**Time**	**Spec. Count**	**Example**	**Science Threshold**
Detection	Now	10–50	TIME[9], CONCERTO[10], CCAT-p[11]	Clustering power spectrum
Small-scale	2-4 yr	100–500	SPT-like, 1 tube × 400 spec. BICEP-like, 400 spec.	$\sigma(\alpha_{\mathrm{BAO}}) < 0.01$ at $z \sim 3$ $\sigma(f_{\mathrm{NL}}^{\mathrm{loc}}) < 3$
Large-scale	4-8 yr	1000–5000 10000–50000	Filled SPT/ACT, 7 tubes × 400 spec. SO/CMB-S4 LAT, 85 tubes × 400 spec.	$\sigma(\Sigma m_\nu) < 0.036$ (+ Planck) $\sigma(N_{\mathrm{eff}}) < 0.07$ (+ Planck)

Table 2: Stages of future mm-wave LIM experiments. Note that "Small-scale" and "Large-scale" refer to spectrometer count and not angular scales. "Time" indicates rough time to start of operations given sufficient investment. The science thresholds are approximate and conservative—they are single-tracer, ignore cross-correlations, and only consider up to $k_{\max} = 0.2$ (smaller scales are accessible with the anticipated angular and spectral resolution).

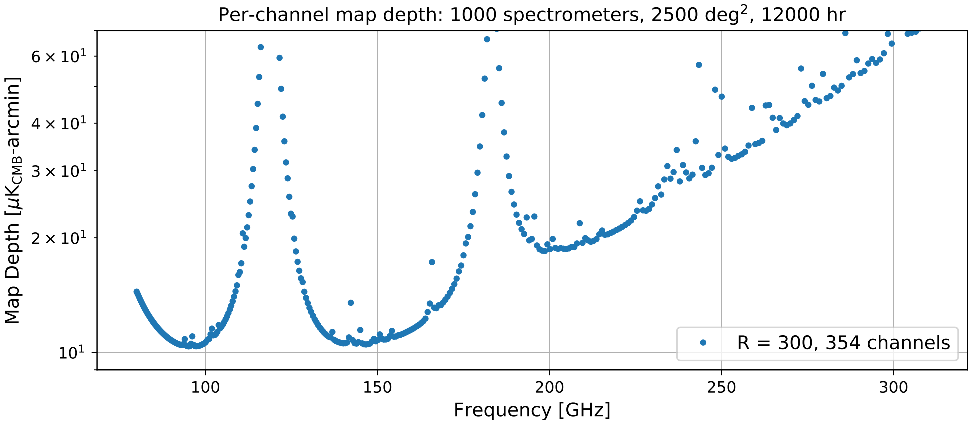

Figure 1: Map depths for a "Large-scale" experiment (1000 spectrometers observing a 2500 deg^2 patch for 12000 hr from the South Pole) in μK$_{\mathrm{CMB}}$-arcmin. Each dot is a separate $R = 300$ frequency channel.

Technologies

While first-generation prototype mm-wave on-chip spectrometers are now being demonstrated[7,12], there are a number of technical advances that will enable the sensitivity necessary to cross the aforementioned science thresholds; see the Detectors LOI[6]. Both leverage the considerable investment made in CMB experiments over the last few decades.

- **Detector Count**: Improvements in both spectral and spatial sampling of the available focal plane area are required to achieve the detector counts outlined above. Optimization of the spectrometer resolution to match the expected spectral linewidth will need development of new low-loss dielectric materials, while innovative spectrometer design and layout will be key to enabling high-density close-packed arrays for this new class of mm-wave imaging spectrometers. **2-4 years**.
- **Readout**: Spectroscopic pixels require significantly more detectors than their broadband counterparts; an array with $1000 \times R \sim 300$ spectrometers would have a detector count approaching that of the entire CMB-S4 experiment. Readout development will be essential to the success of future spectroscopic instruments; new technologies based on state-of-the-art FPGA platforms, such as the RF system-on-chip, are set to dramatically reduce overall readout costs to \$1–2 per channel. **2-4 years**.

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