Snowmass2021 - Letter of Interest

Primordial Non-Gaussianity with Millimeter-Wave Line Intensity Mapping

Thematic Areas:

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

Contact Information:
Kirit S. Karkare (University of Chicago) [kkarkare@kicp.uchicago.edu]

Authors:
Pete Barry (Argonne National Laboratory), Clarence Chang (Argonne National Laboratory), Abigail Crites (University of Toronto), Kirit S. Karkare (University of Chicago), Garrett K. Keating (Center for Astrophysics | Harvard & Smithsonian), Jeff McMahon (University of Chicago), Azadeh Moradinezhad Dizgah (University of Geneva), Erik Shirokoff (University of Chicago), Adam Anderson (Fermilab), Bradford A. Benson (Fermilab, University of Chicago), Simeon Bird (UCR), Patrick C. Breysse (New York University), Geoffrey Bower (ASIAA), Tom Cecil (Argonne National Laboratory), Tzu-Ching Chang (Jet Propulsion Laboratory, California Institute of Technology), Jacques Delabrouille (CNRS/IN2P3, Laboratoire APC, France & CEA/IRFU, France & USTC, China), Olivier Dore (Jet Propulsion Laboratory, California Institute of Technology), Yan Gong (National Astronomical Observatories, Chinese Academy of Sciences), Salman Habib (Argonne National Laboratory), Ely D. Kovetz (Ben-Gurion University, Israel), Adam Lidz (University of Pennsylvania), Dan P. Marrone (University of Arizonna), Marta Silva (University of Oslo), Sara M. Simon (Fermilab), Francisco Villaescusa-Navarro (Princeton University), Gensheng Wang (Argonne National Laboratory), Kimmy Wu (SLAC), Michael Zemcov (Rochester Institute of Technology)

Abstract:
We propose constraining primordial non-Gaussianity (PNG) using the new technique of mm-wave line intensity mapping (LIM). A dedicated instrument featuring hundreds on-chip mm-wave spectrometers could probe multi-field inflation at a sensitivity competitive with next-generation optical galaxy surveys, while a further scaling-up could approach the cosmic variance limit. Measurements of the scale-dependent line bias on extremely large scales could be performed in both the angular and radial directions, constraining local-shape non-Gaussianity with larger volumes than galaxy surveys and providing a critical cross-check with independent astrophysical and instrumental systematics. Higher-order statistics such as the bispectrum, which uniquely constrain other PNG shapes, would similarly benefit from a large increase in mode count and higher redshifts where nonlinearities are smaller.

Summary

Primordial non-Gaussianity (PNG) offers a unique view into the physics of inflation, and can be probed in multiple ways using large-scale structure (LSS). In this LOI, we advocate for testing PNG with millimeter-wave line intensity mapping (LIM), which offers the potential to reach higher redshifts and survey volumes than planned galaxy surveys. We summarize the science case and observational technique, describe a strawman instrument optimized for the scale-dependent bias observable, and outline the efforts necessary to realize PNG constraints with mm-wave LIM.

Primordial Non-Gaussianity

Inflation is the leading paradigm for explaining the origin of structure and initial conditions of the Universe. While the simplest inflationary models predict a Gaussian distribution of primordial perturbations, others can produce non-Gaussian fluctuations, generally parametrized by an amplitude $f_{\rm NL}$ and a shape function. Of particular interest is the "local shape" PNG, since single-field inflation generally produces $f_{\rm NL}^{\rm loc} \ll 1$, *Detection of $f_{\rm NL}^{\rm loc} \sim O(1)$ is thus considered a smoking-gun for multi-field models of inflation.* Planck's constraint of $\sigma(f_{\rm NL}^{\rm loc}) \sim 5$ is cosmic variance limited, and tighter limits are only possible through the larger volume of LSS[1].

One of the most prominent effects of local PNG is a scale-dependent bias in the power spectrum of biased tracers of dark matter such as galaxies or line intensity, most easily observable at large scales ($1/k^2$). Next-generation widefield optical surveys that are sensitive to this feature, such as LSST[2] and SPHEREx[3], are expected to approach the theoretically-significant $\sigma(f_{\rm NL}^{\rm loc}) \sim 1$. However, projection uncertainties are significant and observational systematics on very large scales are difficult to mitigate[4–7]. To achieve the tightest possible constraints on PNG, we are motivated to

- Use as many tracers of LSS as possible—both to minimize the effect of systematics[8–10] and to improve precision (i.e., cosmic variance cancellation[11]).
- Maximize available cosmological volume by extending LSS tracer redshift reach (typically $z < 3$ for next-generation galaxy surveys).

In addition to the scale-dependent bias, on which we focus in this LOI, we also note that higher-order statistics such as the line bispectrum will also benefit: at high redshift, nonlinearities of growth of structure are smaller, so perturbative theoretical models are expected to be valid over a wider range of scales. This offers a unique opportunity for constraining the early-Universe mechanism driving inflation.

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[12]. 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. LIM at mm wavelengths—targeting far-IR emission lines such as the CO rotational ladder or the [CII] ionized carbon fine structure line—is extremely promising. Ground-based observations can detect structure over the entire $0 < z < 9$ redshift range (including multiple measurements of the same structure using different CO lines) using field-proven CMB heritage techniques, and on-chip mm-wave spectrometers offer a straightforward path towards improving sensitivity by the orders of magnitude needed to constrain cosmology. See the associated Overview[13] and Facilities LOIs[14] for more details.

An Optimized Straw-Man Instrument

An instrument that targets the large-scale galaxy bias from primordial non-Gaussianity must be optimized[15] to measure large scales, in both the angular and radial directions, with high sensitivity and low systematics. In particular, we require measuring down to $\ell \sim 20$ ($k \sim 10^{-2.5}\ h\,\mathrm{Mpc}^{-1}$). Below we present a straw-man instrument design, which adopts heritage from CMB instruments.

- **Small aperture**: A large aperture is unnecessary since only large angular scales need to be resolved. To minimize large-scale optical systematics, the cryostat should be unobstructed and easy to shield. An on-axis $\sim$ 0.5 m refracting telescope, similar to BICEP3 in formfactor[16], would provide a compromise between large focal plane area/field of view (30°) and the ability to use a continuously-rotating mount if necessary. A small aperture also allows multiple levels of co-moving and fixed shields to minimize ground pickup, and low-cost duplication of cryostats.
- **Focal plane and optics**: A densely-packed focal plane of wide-bandwidth, moderate-resolution mm-wave spectrometers covering 80–310 GHz would be sensitive to CO from $0 < z < 5$ and [CII] from $5 < z < 9$. While only modest spectral resolution ($R \gtrsim 10$) is required in principle, in practice higher resolution is preferable for foreground removal and component separation; other LIM experiments will likely feature $R \gtrsim 300$. Wideband optics, anti-reflection coated for this entire range, have been demonstrated in SPT-3G[17]. Precise knowledge of the spectral response is necessary to isolate large-scale modes along the line of sight and can be obtained by Fourier Transform Spectroscopy *in situ*.
- **Site**: Deployment at an excellent mm-wave site is essential; there are two outstanding candidates with CMB heritage. The South Pole offers an extremely stable atmosphere during the Polar winter, while the Atacama desert allows for wider sky coverage.

Roadmap

Three major efforts are required to enable LIM-based f_{NL} constraints competitive with galaxy surveys[18,19]:

First, *on-chip millimeter-wave spectrometers* offer the only reasonable path towards the order of magnitude sensitivity increases necessary to constrain PNG. While individual on-chip spectrometers can now be fabricated, significant effort is needed to develop densely-packed focal planes with hundreds of spectrometers, each with hundreds of spectral channels. With targeted effort, this development could be completed in 3–5 years; see the Detectors[20] and Facilities LOIs[14] for further details.

Second, *theory predictions for the strengths of the CO and [CII] lines as a function of redshift* must be solidified; current models for line brightnesses vary by more than an order of magnitude. Recent mm-wave LIM detections from pathfinder experiments constrain this range to closer to a factor of a few[21,22]. With projected line brightnesses, spectral energy distributions, and biases with LSS in hand, reliable f_{NL} forecasts and clearer understanding of improvements when cross-correlating with other tracers will be possible; see the associated cross-correlations LOI[23].

Finally, *better understanding of the ability of ground-based observations to recover $\ell \sim 20$ in intensity* is needed[24,25]. Large angular scale measurements are typically made from space or balloons due to the large impact of atmospheric fluctuations. Fast scan modulation, e.g. using a continuously rotating mount and helium rotary joint, may be necessary. Spectroscopic data in each spatial pixel may enable removal of atmospheric lines or the use of only quiet parts of the mm-wave spectrum for the f_{NL} analysis.

References

[1] P. D. Meerburg *et al.*, "Primordial Non-Gaussianity," *Bull. Am. Astron. Soc.* **51** no. 3, (May, 2019) 107, arXiv:1903.04409 [astro-ph.CO].

[2] LSST Science Collaboration, "LSST Science Book, Version 2.0," *arXiv e-prints* (Dec., 2009) arXiv:0912.0201, arXiv:0912.0201 [astro-ph.IM].

[3] O. Doré *et al.*, "Cosmology with the SPHEREX All-Sky Spectral Survey," *arXiv e-prints* (Dec., 2014) arXiv:1412.4872, arXiv:1412.4872 [astro-ph.CO].

[4] **BOSS** Collaboration, A. J. Ross *et al.*, "The clustering of galaxies in the SDSS-III Baryon Oscillation Spectroscopic Survey: Analysis of potential systematics," *Mon. Not. Roy. Astron. Soc.* **424** (2012) 564, arXiv:1203.6499 [astro-ph.CO].

[5] A. R. Pullen and C. M. Hirata, "Systematic effects in large-scale angular power spectra of photometric quasars and implications for constraining primordial nongaussianity," *Publ. Astron. Soc. Pac.* **125** (2013) 705–718, arXiv:1212.4500 [astro-ph.CO].

[6] B. Leistedt, H. V. Peiris, D. J. Mortlock, A. Benoit-Lévy, and A. Pontzen, "Estimating the large-scale angular power spectrum in the presence of systematics: a case study of Sloan Digital Sky Survey quasars," *Mon. Not. Roy. Astron. Soc.* **435** (2013) 1857, arXiv:1306.0005 [astro-ph.CO].

[7] D. Alonso, P. Bull, P. G. Ferreira, R. Maartens, and M. Santos, "Ultra large-scale cosmology in next-generation experiments with single tracers," *Astrophys. J.* **814** no. 2, (2015) 145, arXiv:1505.07596 [astro-ph.CO].

[8] T. Giannantonio, A. J. Ross, W. J. Percival, R. Crittenden, D. Bacher, M. Kilbinger, R. Nichol, and J. Weller, "Improved Primordial Non-Gaussianity Constraints from Measurements of Galaxy Clustering and the Integrated Sachs-Wolfe Effect," *Phys. Rev. D* **89** no. 2, (2014) 023511, arXiv:1303.1349 [astro-ph.CO].

[9] T. Giannantonio and W. J. Percival, "Using correlations between CMB lensing and large-scale structure to measure primordial non-Gaussianity," *Mon. Not. Roy. Astron. Soc.* **441** (2014) L16–L20, arXiv:1312.5154 [astro-ph.CO].

[10] M. Schmittfull and U. Seljak, "Parameter constraints from cross-correlation of CMB lensing with galaxy clustering," *Phys. Rev. D* **97** no. 12, (2018) 123540, arXiv:1710.09465 [astro-ph.CO].

[11] U. Seljak, "Extracting primordial non-gaussianity without cosmic variance," *Phys. Rev. Lett.* **102** (2009) 021302, arXiv:0807.1770 [astro-ph].

[12] E. D. Kovetz *et al.*, "Line-Intensity Mapping: 2017 Status Report," *arXiv e-prints* (Sept., 2017) arXiv:1709.09066, arXiv:1709.09066 [astro-ph.CO].

[13] K. S. Karkare *et al.*, "Cosmology with Millimeter-Wave Line Intensity Mapping," *Snowmass LOI* .

[14] K. S. Karkare *et al.*, "Millimeter-Wave Line Intensity Mapping Facilities," *Snowmass LOI* .

[15] R. de Putter and O. Doré, "Designing an inflation galaxy survey: How to measure σ (f_{NL})$\sim$1 using scale-dependent galaxy bias," *Phys. Rev. D* **95** no. 12, (June, 2017) 123513, arXiv:1412.3854 [astro-ph.CO].

[16] Z. Ahmed *et al.*, "BICEP3: a 95GHz refracting telescope for degree-scale CMB polarization," in *Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VII*, vol. 9153 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, p. 91531N. Aug., 2014. arXiv:1407.5928 [astro-ph.IM].

[17] A. Nadolski *et al.*, "Broadband anti-reflective coatings for cosmic microwave background experiments," in *Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy IX*, vol. 10708 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, p. 1070843. July, 2018. arXiv:1809.00030 [astro-ph.IM].

[18] A. Moradinezhad Dizgah, G. K. Keating, and A. Fialkov, "Probing Cosmic Origins with CO and [C II] Emission Lines," *Astrophys. J. Lett.* **870** no. 1, (Jan., 2019) L4, arXiv:1801.10178 [astro-ph.CO].

[19] A. Moradinezhad Dizgah and G. K. Keating, "Line Intensity Mapping with [C II] and CO(1-0) as Probes of Primordial Non-Gaussianity," *Astrophys. J.* **872** no. 2, (Feb., 2019) 126, arXiv:1810.02850 [astro-ph.CO].

[20] E. Shirokoff *et al.*, "Kinetic Inductance Detectors for Long-Wavelength Photon Detection," *Snowmass LOI* .

[21] G. K. Keating *et al.*, "An Intensity Mapping Detection of Aggregate CO Line Emission at 3 mm," *Astrophysical Journal (in press)* , arXiv:2008.08087 [astro-ph.GA].

[22] G. K. Keating *et al.*, "COPSS II: The Molecular Gas Content of Ten Million Cubic Megaparsecs at Redshift z$\sim$3," *Astrophysical Journal* **830** no. 1, (Oct., 2016) 34, arXiv:1605.03971 [astro-ph.GA].

[23] A. Moradinezhad Dizgah *et al.*, "Synergies Between Millimeter-Wavelength Intensity Mapping with Radio, Optical, and Microwave Observations," *Snowmass LOI* .

[24] O. P. Lay and N. W. Halverson, "The Impact of Atmospheric Fluctuations on Degree-Scale Imaging of the Cosmic Microwave Background," **543** no. 2, (Nov., 2000) 787–798, arXiv:astro-ph/9905369 [astro-ph].

[25] D. Barkats, R. Bowens-Rubin, W. H. Clay, T. Culp, R. Hills, J. M. Kovac, N. A. Larsen, S. Paine, C. D. Sheehy, and A. G. Vieregg, "High-precision scanning water vapor radiometers for cosmic microwave background site characterization and comparison," in *Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy IX*, vol. 10708 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, p. 107082E. July, 2018. arXiv:1808.01349 [astro-ph.IM].