Exploring the High-Redshift Universe with Line Intensity Mapping

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Observational Probes

Cosmic Microwave Background (z~1100)
Initial conditions

NASA/WMAP
Science Team
Observational Probes

Individual High-Redshift Galaxies (up to z~10)
Bright, massive objects
Observational Probes

Galaxy surveys and supernovae (z~2)
Late-time large-scale structure, Hubble rate

NASA/WMAP Science Team
Observational Probes

Huge fraction of the universe left to explore!

NASA/WMAP Science Team
The high-redshift, large-volume universe is the key to answering foundational questions in cosmology:

- How did the universe transition from neutral to ionized?
- How did galaxies build up stars and evolve to their current state?
- Did the universe begin with inflation?
- What is the nature of dark energy and dark matter?

KICP is playing a major role in developing the technology (on-chip superconducting millimeter-wave spectrometers) and the observational technique of line intensity mapping with a series of experiments (SuperSpec, SPT-SLIM, SPT-3G+, …) to efficiently detect the complete population of faint, high-redshift galaxies over the full sky.
The Epoch of Reionization

What did the first galaxies look like? How did they change during the first billion years?

When and how did they drive the phase change? What was the morphology of their interaction with the intergalactic medium?

Loeb 2006
The Epoch of Reionization

Neutral hydrogen + a tracer of early galaxies gives the “ultimate” view of reionization dynamics

Dumitru+ 2019
Large-Scale Structure Constrains Our Cosmological Model

**Primordial non-Gaussianity**
Did inflation involve multiple fields?

**Expansion History**
Is the dark energy equation of state \((w=-1)\) constant?

**Growth of Structure**
Does the neutrino have a normal or inverted hierarchy?
Why High Redshift?

More volume, better statistics.

"Primordial Figure of Merit" scales with precision on inflationary physics
Why High Redshift?

Wide redshift coverage probes different epochs and alleviates parameter degeneracies.

Moradinezhad Dizgah, Keating, Karkare et al.
ApJ 2110.000140
Getting to High Redshift

Why not just use existing galaxy surveys?

- High-redshift galaxies are dust-attenuated and redshifted out of ground-based optical bands
- Objects get fainter at higher redshift and are harder to detect against a noisy background
Getting to High Redshift

Why not just use existing galaxy surveys?

- High-redshift galaxies are dust-attenuated and redshifted out of ground-based optical bands → millimeter-wave
- Objects get fainter at higher redshift and are harder to detect against a noisy background → line intensity mapping
Far-IR is Important!

Conroy ARA&A 2013
Far-IR is Important!

M82 Sub-mm to Far-IR Emission Spectrum

\[ S_\nu [\text{Jy}] \]

\[ \lambda_{\text{rest}} [\text{\mu m}] \]

Bernal & Kovetz 2022

Conroy ARA&A 2013
Wide Redshift Coverage in the Millimeter Range

Garrett Keating
Wide Redshift Coverage in the Millimeter Range
Wide Redshift Coverage in the Millimeter Range
Developing a compact, scalable mm-wave spectrometer
Erik Shirokoff, astronomer who built instruments to map the universe, 1979-2023

Remembered as patient and generous teacher and mentor

Assoc. Prof. Erik Shirokoff, a University of Chicago astronomer who built instruments to understand the earliest ages of the universe, died Jan. 26. He was 43.
A Filter-Bank Spectrometer Realized with Thin-Film Superconducting Circuits

Kovács & Zmuidzinas 2010
Detector Fabrication

UChicago Pritzker Nanofabrication Facility

Ryan McGeehan, UChicago Ph.D. 2023
SuperSpec design and fabrication
Device Characterization
The Spectrometer Works!

Each channel sees a different mm-wave frequency with R~275 spectral resolution.
On-Sky Demonstration

We are now deploying a 6-spectrometer receiver to the 50-meter Large Millimeter Telescope in Mexico – an ideal facility for pointed observations of high-z galaxies.
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Line Intensity Mapping (LIM)

Integrate over individual sources while retaining large-scale cosmology.

Spectroscopic observations provide redshifts.

Much more efficient than object detection at high redshift (the low-SNR regime).

Karkare+ 2203.07258
mm-wave LIM white paper
Galaxy Detection vs LIM

Galaxy detection mode:
Use a telescope with high angular resolution (relatively large dish) to resolve individual objects.

An object is detected when it reaches some threshold (maybe $5\sigma$).

The fundamental data product is a catalog of objects.
Galaxy Detection vs LIM

Intensity mapping mode:
Use a telescope with lower angular resolution (small dish) matched to the scales that you care about.

Every (large) pixel has some noise value.

The fundamental data product is a map with error estimates.
Galaxy Detection vs LIM

Galaxy detection is optimal in the high SNR regime, while intensity mapping is optimal in the low SNR regime (e.g., high redshifts).

Nothing stops us from doing intensity mapping with high-resolution data (just operate on the map before object detection)!

But if we are less interested in small scales, LIM is usually more economical: smaller dish and less observation time needed.
The South Pole Telescope

Three generations of CMB cameras:
- **SPT-SZ** (2006-2011)
- **SPTpol** (2012-2016)
- **SPT-3G** (2017-)

10m off-axis Gregorian with submillimeter-quality surface accuracy

Optimized for large-scale surveys of faint, diffuse emission (like LIM!)
Deploy a LIM pathfinder to the South Pole Telescope during the austral summer season (Nov–Feb) while SPT-3G is not observing.

Demonstrate the enabling technology of on-chip spectrometers for the LIM measurement.

Fully funded by NSF and Fermilab in 2021.
In normal operation, light from the primary is reflected into the receiver cabin, and then into the SPT-3G cryostat...
The SPT Summertime Line Intensity Mapper (SPT-SLIM)

...but there is also room for a small auxiliary receiver. Just install a pickoff mirror!

Karkare+ J. Low Temp. Phys. 2111.04631
Verifying the Fit  (with the help of wecutfoam.com)
The SPT-SLIM Instrument

The first mm-wave integral field unit (IFU): 12 spatial-spectral pixels.

Compact cryostat holds detectors at 100 mK with an adiabatic demagnetization refrigerator.
The SPT-SLIM Instrument
The SPT-SLIM Detectors

Each spectrometer covers 120–180 GHz with R~200 resolution targeting CO(2-1), (3-2), (4-3) from $0.5 < z < 2.5$. 

Elyssa Brooks, Karia Dibert, Kyra Fichman
Next-generation cosmological constraints (primordial non-Gaussianity, dark energy equation of state, neutrino masses) are possible with 2-3 orders of magnitude improvement.

Reionization astrophysics possible with ~1.
LIM Cosmology

SPT-SLIM pathfinder **2025**

SPT-3G+ **2028** (1 tube) **2032** (7 tubes)

CMB-S4-like with spectrometers **2038** (85 tubes)

Karkare+ 2203.07258 Snowmass white paper

Neutrino masses

- Planck constraint
- Optimal Sky Area (deg^2)

Spectrometer-Hours

- Interlopers
- No Interlopers
Community Support for LIM is Growing

December 2023: the P5 report endorses LIM as a promising new direction for particle physics!

Recommendation 4e:

Conduct R&D efforts to define and enable new projects in the next decade, including detectors for an $e^+e^-$ Higgs factory and 10 TeV pCM collider, Spec-S5, DUNE FD4, Mu2e-II, Advanced Muon Facility, and Line Intensity Mapping (sections 3.1, 3.2, 4.2, 5.1, 5.2, and 6.3).

4.2.6 – Future Opportunities: Line Intensity Mapping & Gravitational Waves

Line intensity mapping (LIM) techniques are potentially a valuable future method to address key particle physics science cases during the next twenty years by probing the expansion history and the growth of structure deep in the matter-dominated era when the first galaxies were forming. LIM observations of this era could enable tests of the theory of inflation by providing a precise map of the primordial hydrogen gas which is theoretically clean for interpretation. This technique has the potential to access an earlier epoch in the universe than Spec-S5. Work to prove the viability of this method (encompassing both analysis and instrumentation) should continue with multi-agency support (Recommendation 4e), including low-cost instrumentation development competed through the DOE R&D program. DOE has already partnered with NASA to construct one pathfinder LIM experiment, LuSEE-Night, and there are exciting opportunities for investment in ground-based activities in the coming decade.
Summary

LIM at mm wavelengths can probe cosmic structure over an extremely wide redshift range from the ground.

We are developing on-chip mm-wave spectrometers to make this measurement: stay tuned for updates from SuperSpec and SPT-SLIM!

Next-generation LIM experiments will have the sensitivity answer the fundamental mysteries of our cosmological model beyond the reach of CMB and galaxy surveys.

KICP was the perfect place to start a new project and is playing a major role in developing this field!