Cosmology with Next-Generation Millimeter-wave Spectrometers

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Temperature-to-Polarization Leakage in the BK15 $r$ constraint

Using far-field beam maps and the Planck $T$ map, calculate $T\rightarrow P$ leakage and propagate through $r$ analysis.

Estimate a bias on the recovered $r$ value of

$$\Delta r = 0.0027 \pm 0.0019 \quad \text{...compare to BK15 statistical} \quad \sigma(r) = 0.020$$

arXiv: 1904.01640

Ground Shield Analysis for CMB-S4 SATS

Compared geometry of forebaffles and ground shields needed to satisfy double-diffraction criterion (minimize far-sidelobe coupling to ground)

Fed directly into cryostat configuration decision -> “Extended Hybrid”
"Intensity Mapping" (IM): using (relatively) low angular resolution observations to measure large-scale structure, *without needing to resolve individual sources*. CIB is a classic example.

"Line Intensity Mapping" (LIM): the above, but targeting a spectral line so that observed wavelength maps directly to redshift. Requires moderate-resolution spectroscopy, but again no need to resolve individual sources.
We have galaxy surveys - why consider LIM?

- Almost all the cosmology you can do with a galaxy survey, you can do with LIM!
- **Efficiency:** Every photon “counts” -- i.e., does not need to be detected above a flux threshold -- so large volumes can be surveyed much more quickly. Especially useful for extending to higher redshifts -> more modes.

- **Multi-tracer:** At lower redshift, LIM surveys will overlap with optical surveys and trace the same structure, allowing for e.g., cosmic variance cancellation.
- **Systematics:** Most LIM surveys use observational techniques that are very different from galaxy surveys, so cross-correlations are robust.
- **Astrophysics:** In addition to cosmology from LSS, each line probes a different phase of the ISM/IGM and can inform high-z star formation, reionization physics, etc...

CMB: $\ell^2 \sim 10^7$ modes

HI Stage 2 White paper
1810.09572
LIM at mm wavelengths

Far-IR lines excited by absorbed stellar radiation, emitted on top of the dust continuum. Known to exist at high redshift (ALMA), good tracers of star formation.

In particular: detectable from the ground at mm-wave CO (distinct ladder structure), [CII] (very bright)
Our focus: LIM at mm wavelengths

A single instrument, covering ground-based CMB frequencies (80-300 GHz) is in principle sensitive to [CII] and CO over the entire range of $0 < z < 10$.

Just add moderate-resolution spectroscopy to access/isolate modes along the line of sight ($R > 100$, ~few GHz or better resolution).

Line separation is the major analysis challenge.
“Shovel-ready” Wideband mm-wave Spectrometers

Fourier Transform Spectrometer (CONCERTO) neel.cnrs.fr

Fabry-Perot (CCAT-p)
1807.00058

Grating Spectrometer (TIME)
Abby Crites

High-Resolution Long-λ FPI for HIRMES

- Scanning PZT (with mechanical motion multiplier)
- Moving flex-vane stage
- Flex-vane stage
- Fixed part of flex-vane stage

Transmission

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
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<tbody>
<tr>
<td>180</td>
</tr>
<tr>
<td>3rd</td>
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</tbody>
</table>

Output Power [dB]

- Predicted
- Measured

16 Spatial Pixel x 60 Spectral Pixel Grating Spectrometer
The SuperSpec Team

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The SuperSpec On-chip mm-wave Spectrometer

Take favorable aspects of a grating spectrometer (wide bandwidth, high sensitivity) and put it on a silicon wafer.

Eventually could approach CMB efficiency with filled focal planes, i.e. hundreds of spectrometers on a single 6” chip.

Suitable for filled focal planes (intensity mapping) or steered multi-object spectrographs.

Compare one spectrometer:

TIME grating, R~200:
32 x 23 x 1 cm ~ 736 cm³

SuperSpec, R~300:
3.6 x 5.7 x 0.05 cm ~ 1 cm³
The SuperSpec Concept

A general filter-bank (cochlear) spectrometer printed on a silicon wafer

Incoming broadband radiation sorted by narrowband $\lambda/2$ filters

Each channel couples to a separate power detector

Channel width/spacing independently adjustable via feature geometry

Kovacs and Zmuidzinas 2010
Photon noise dominated for ground-based observations.

**Chicago effort**: detector testing, readout development, analysis pipeline, interface with telescope.
Large Millimeter Telescope

James Lowenthal/UMass
SuperSpec @ LMT

Pre-COVID Status: Ready to ship instrument to LMT in Spring 2020 for a Summer observing run - we should be on the mountain right now!

Goals:
1. Demonstrate that SuperSpec can produce a spectrum of individual high-redshift galaxies
2. Understand noise performance to feed back into detector development
3. Develop on-sky calibration routines for spectroscopic MKIDs

Jason Glenn
Matt Bradford
Scaling Up Focal Planes

Pete Barry

Diagram showing the layout of spectrometers and other components in a focal plane array.
Next-Generation LIM Surveys

Projections: 500x spectrometers, 80-310 GHz, 4 years, 1000 deg\(^2\) from South Pole

<table>
<thead>
<tr>
<th>Expansion History Constraints</th>
<th>z</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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<tr>
<td>%</td>
<td>0.3</td>
<td>0.5</td>
<td>1.4</td>
<td>1.2</td>
<td></td>
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**Percent-level measurements** of the BAO at \(z > 3\), constraining time-varying EOS + some early dark energy models (dependent on true line intensity)

Plus many more science cases:

**Cosmology**: primordial power spectrum features, neutrinos, modified gravity, B-mode delensing (Karkare PRD, [arXiv:1908.08128](https://arxiv.org/abs/1908.08128))

**Astrophysics**: reionization with HI, high-z star formation, molecular gas, dusty galaxies
Summary

Millimeter-wave spectroscopy detects early star-forming galaxies through their far-IR emission lines, and will be a unique probe of cosmology and astrophysics beyond the reach of traditional galaxy surveys...

...but current mm-wave spectrometers are large and hard to scale up.

The SuperSpec on-chip spectrometer will enable filled focal planes with orders of magnitude more detectors than current instruments.

First demonstration of a R~300, 6-spectrometer receiver covering 200-300 GHz at the Large Millimeter Telescope is imminent!

In the next few years:

- Filled, multi-spectrometer focal planes
- Sensitivity for both astrophysics and cosmology!