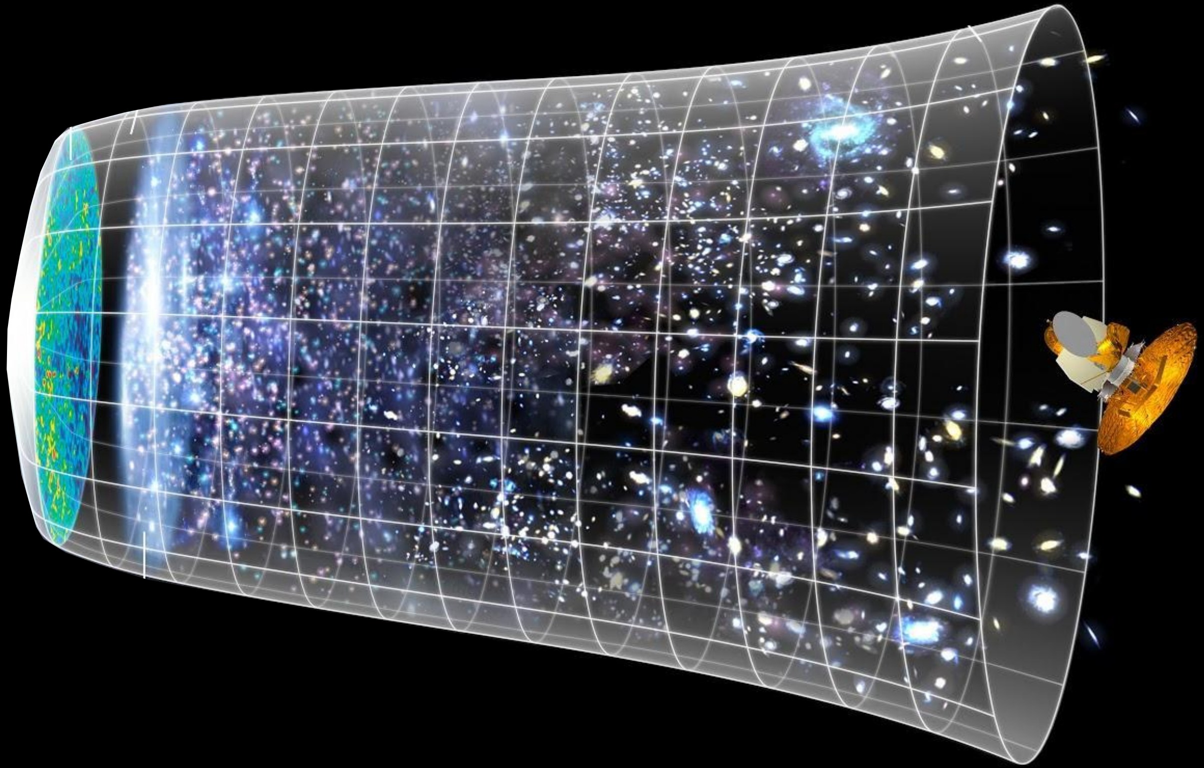
On-Chip Millimeter-Wave Spectroscopy for Line Intensity Mapping: SuperSpec and SPT-SLIM

Kirit S. Karkare

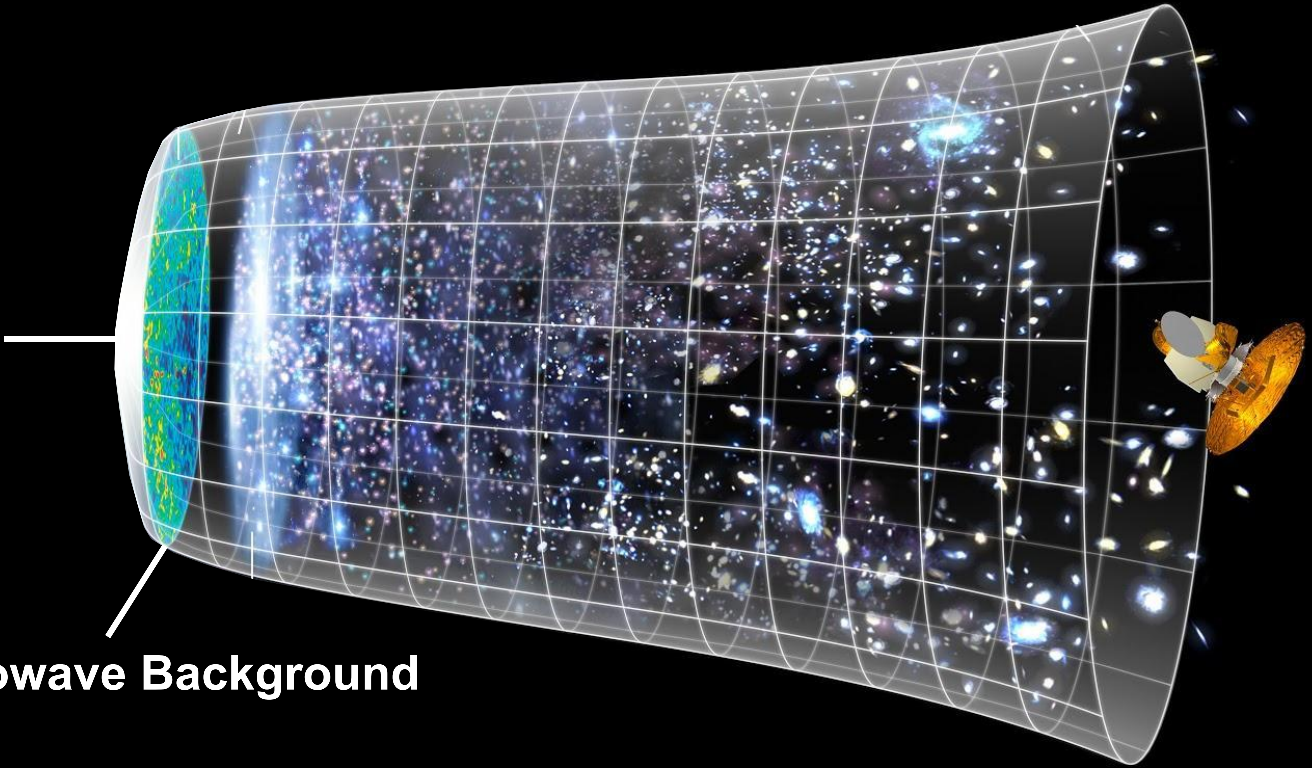
LBNL, 2026-12-12

Modern Cosmological Picture



NASA/WMAP
Science Team

Modern Cosmological Picture



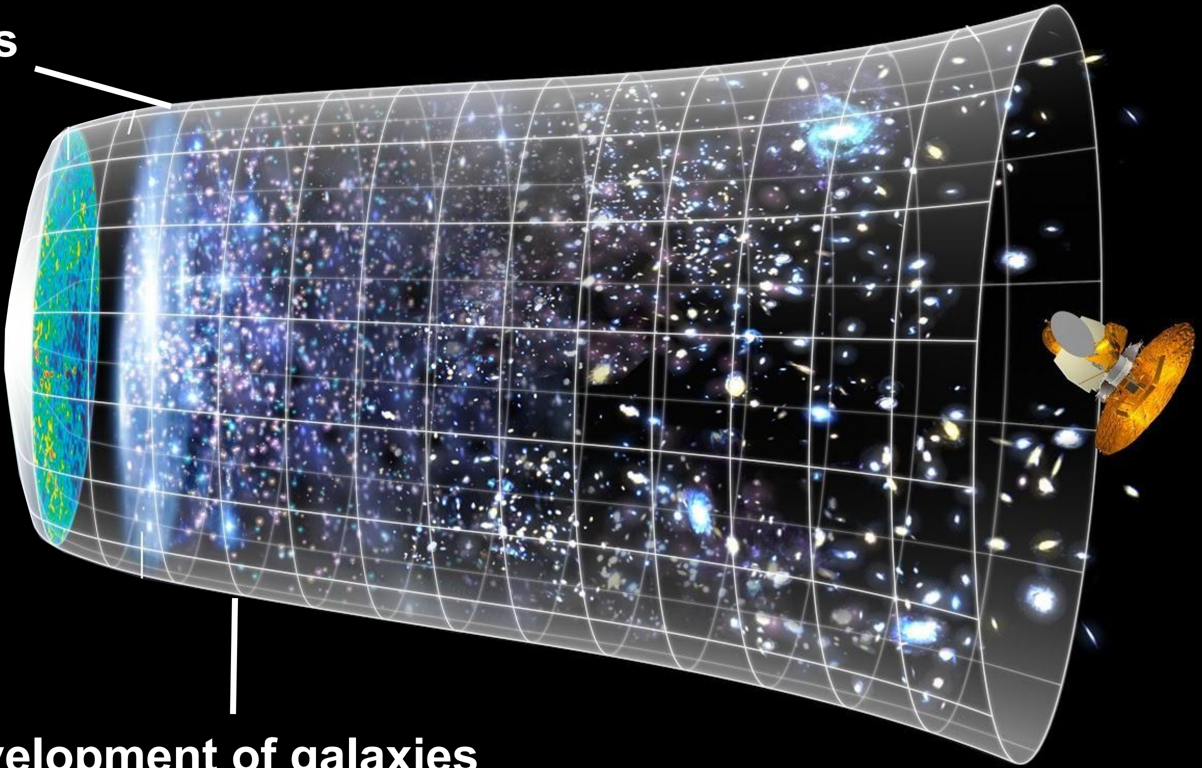
Early hot, dense state

Cosmic Microwave Background
380,000 yr

NASA/WMAP
Science Team

Modern Cosmological Picture

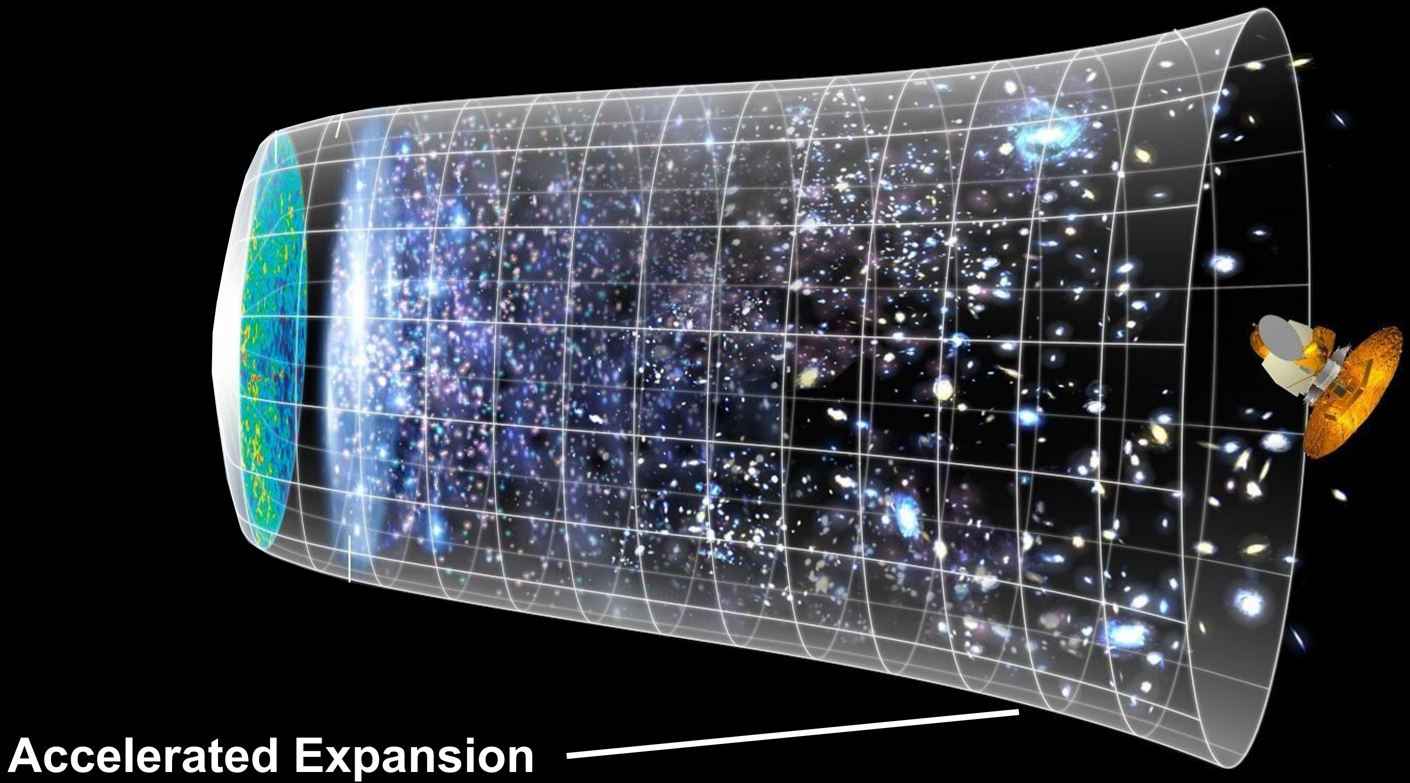
First stars
~400 Myr



Development of galaxies
Reionization

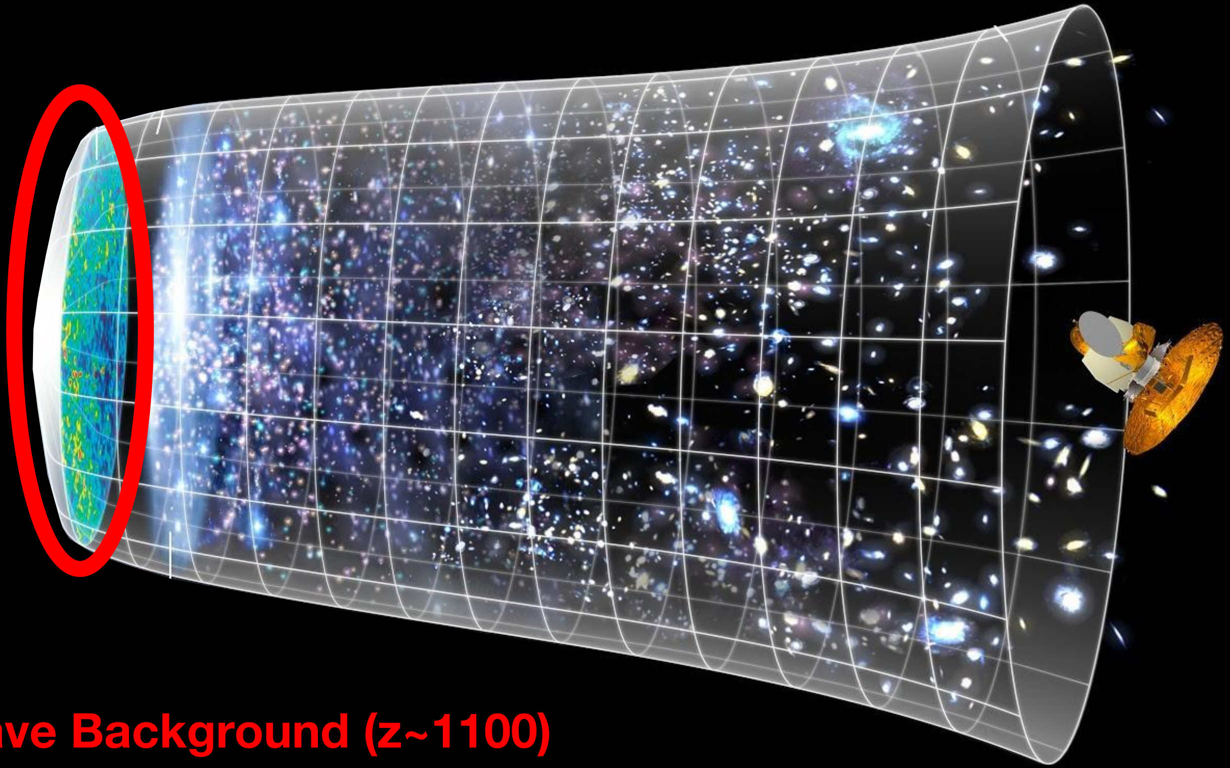
NASA/WMAP
Science Team

Modern Cosmological Picture



NASA/WMAP Science Team

Observational Probes

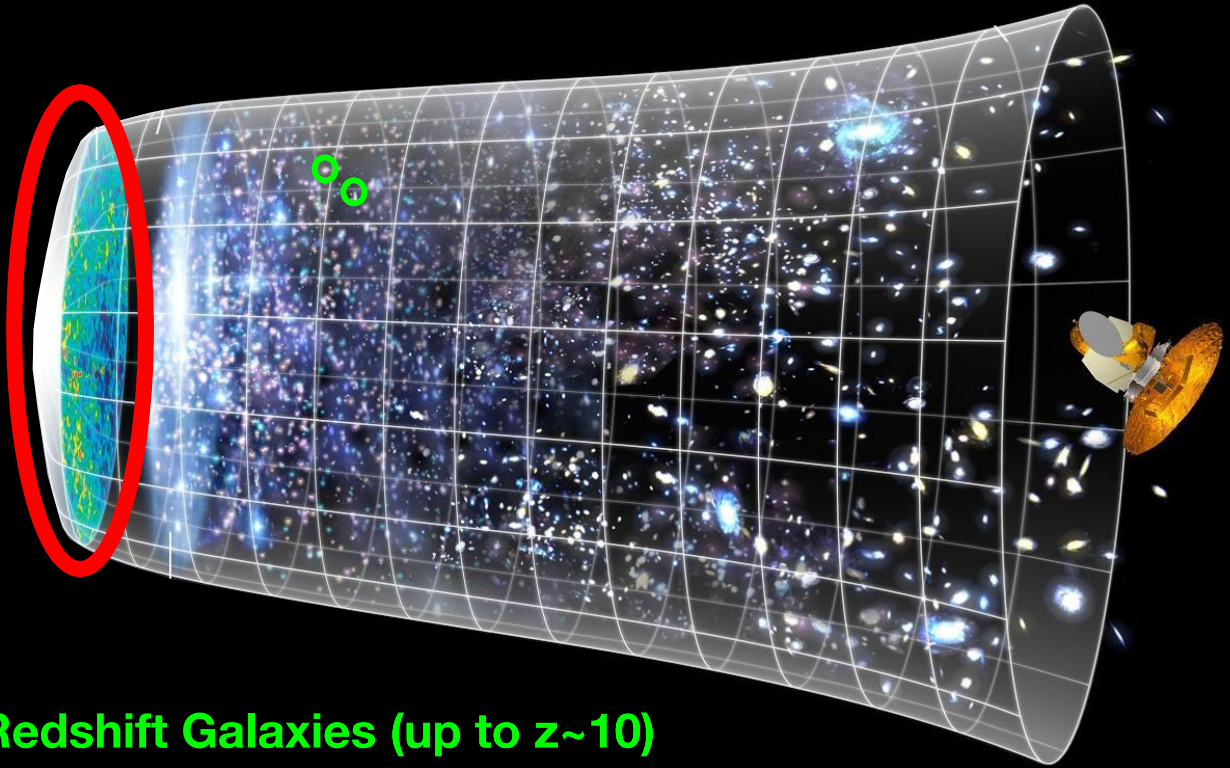


Cosmic Microwave Background (z~1100)

Initial conditions

NASA/WMAP
Science Team

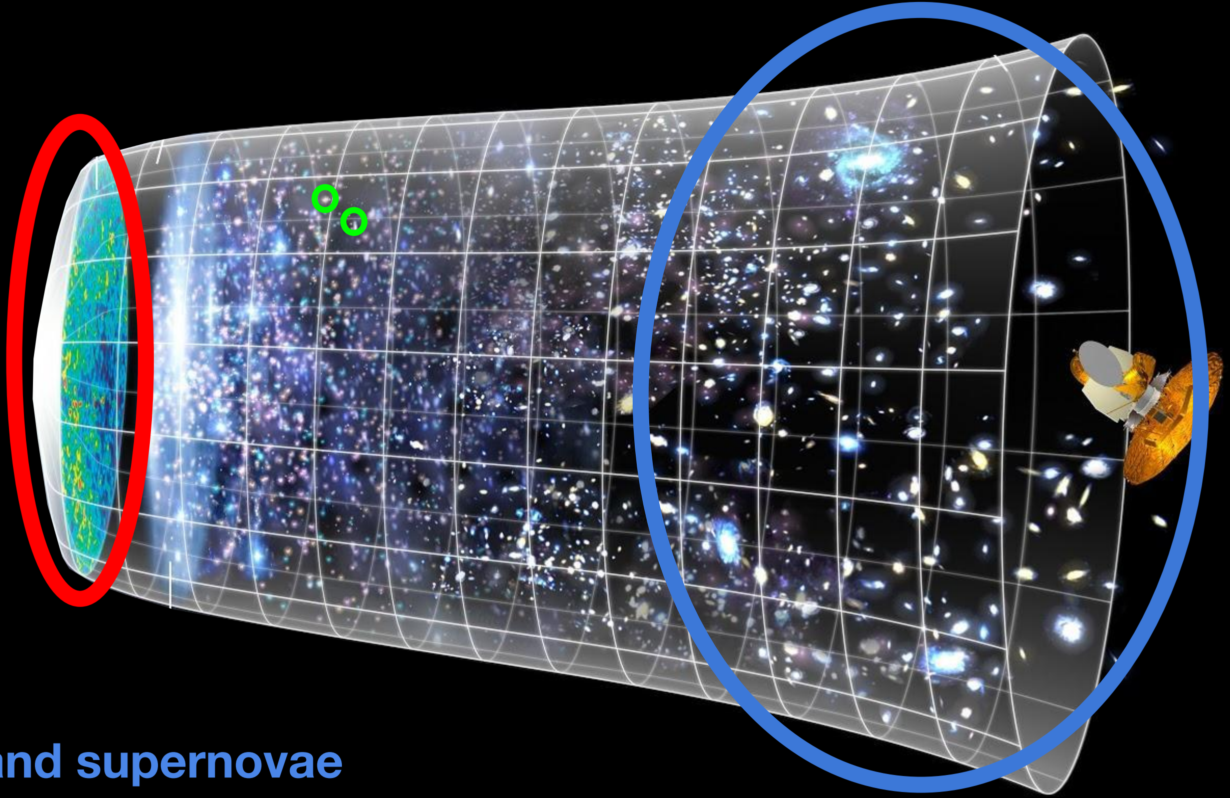
Observational Probes



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

NASA/WMAP Science Team

Observational Probes

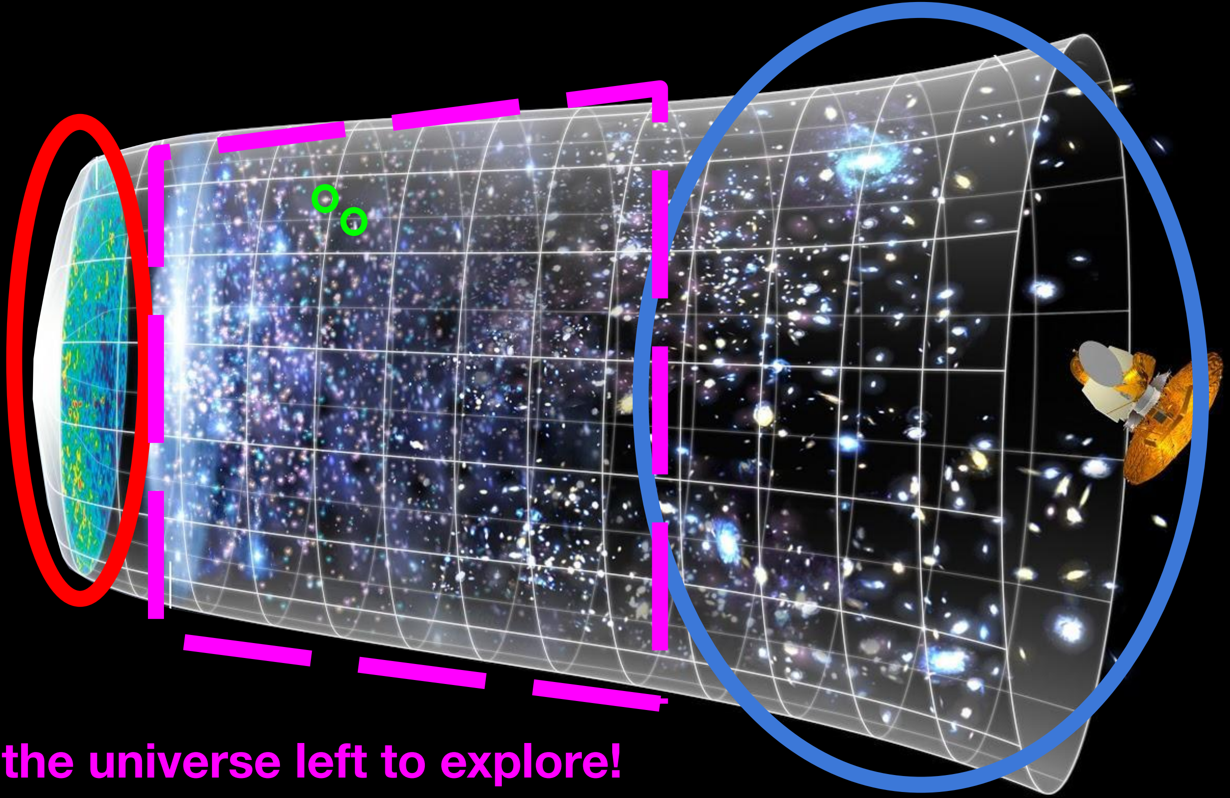


Galaxy surveys and supernovae

Late-time large-scale structure, Hubble rate

NASA/WMAP
Science Team

Observational Probes

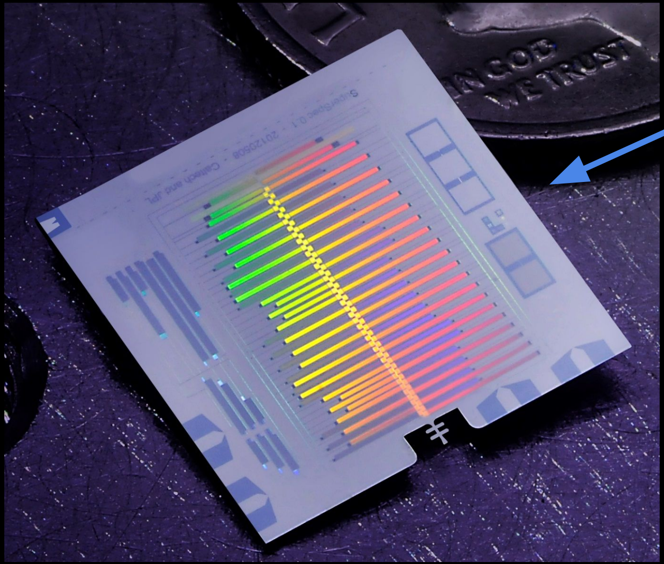


Huge fraction of the universe left to explore!

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?



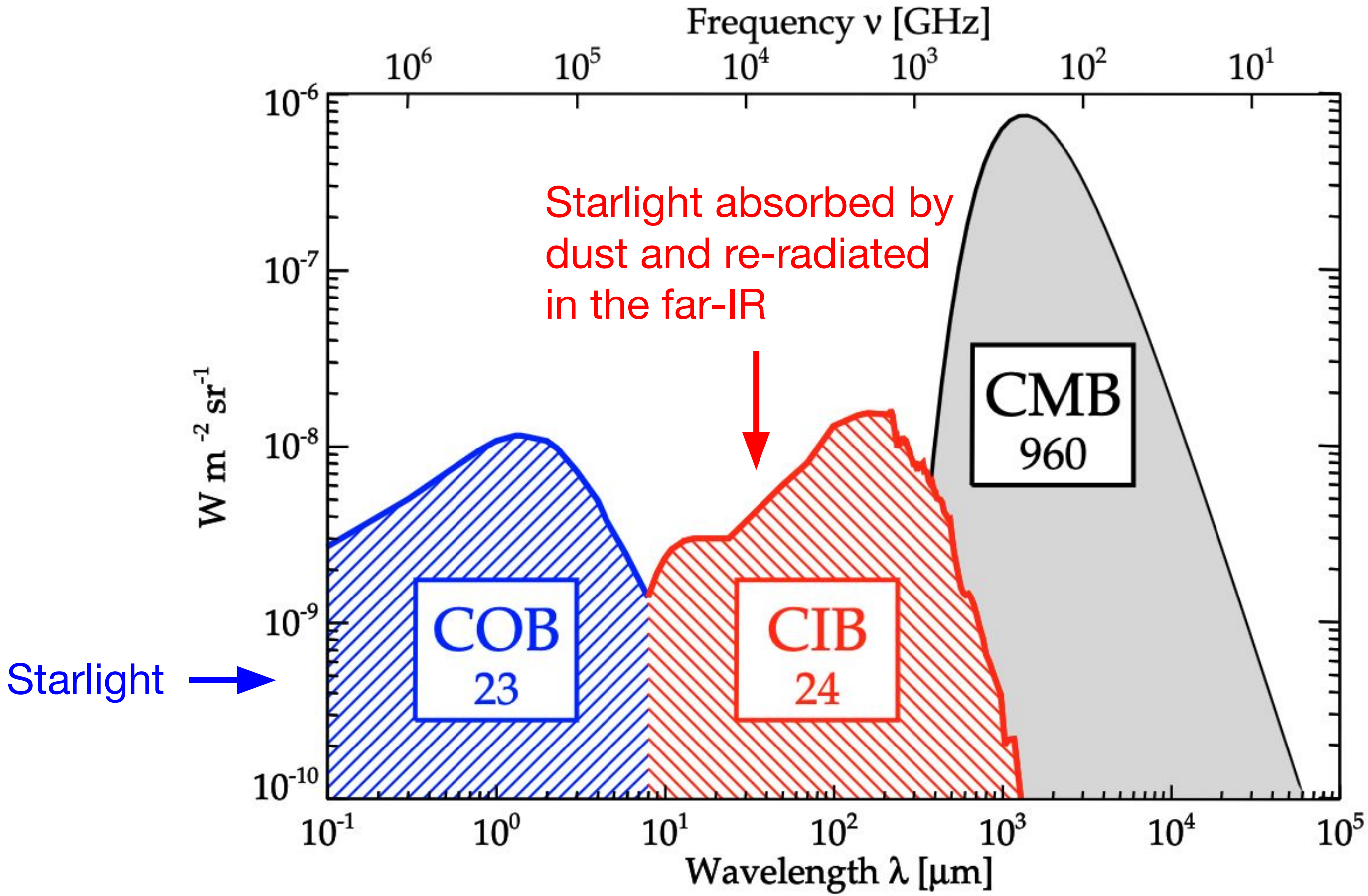
We are now developing the technology (on-chip superconducting millimeter-wave spectrometers)

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.

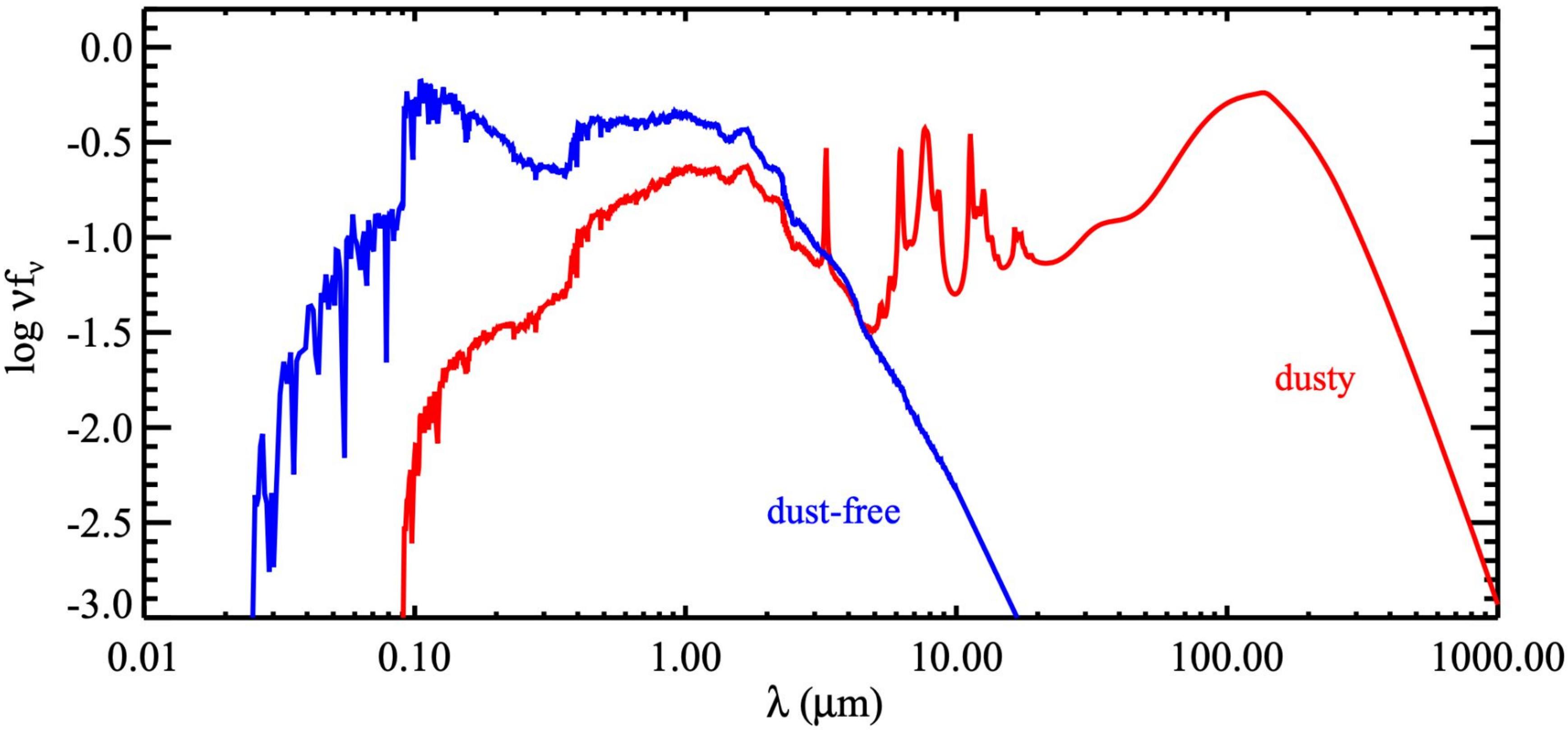
Far-IR is Important!

Dole+ 2006



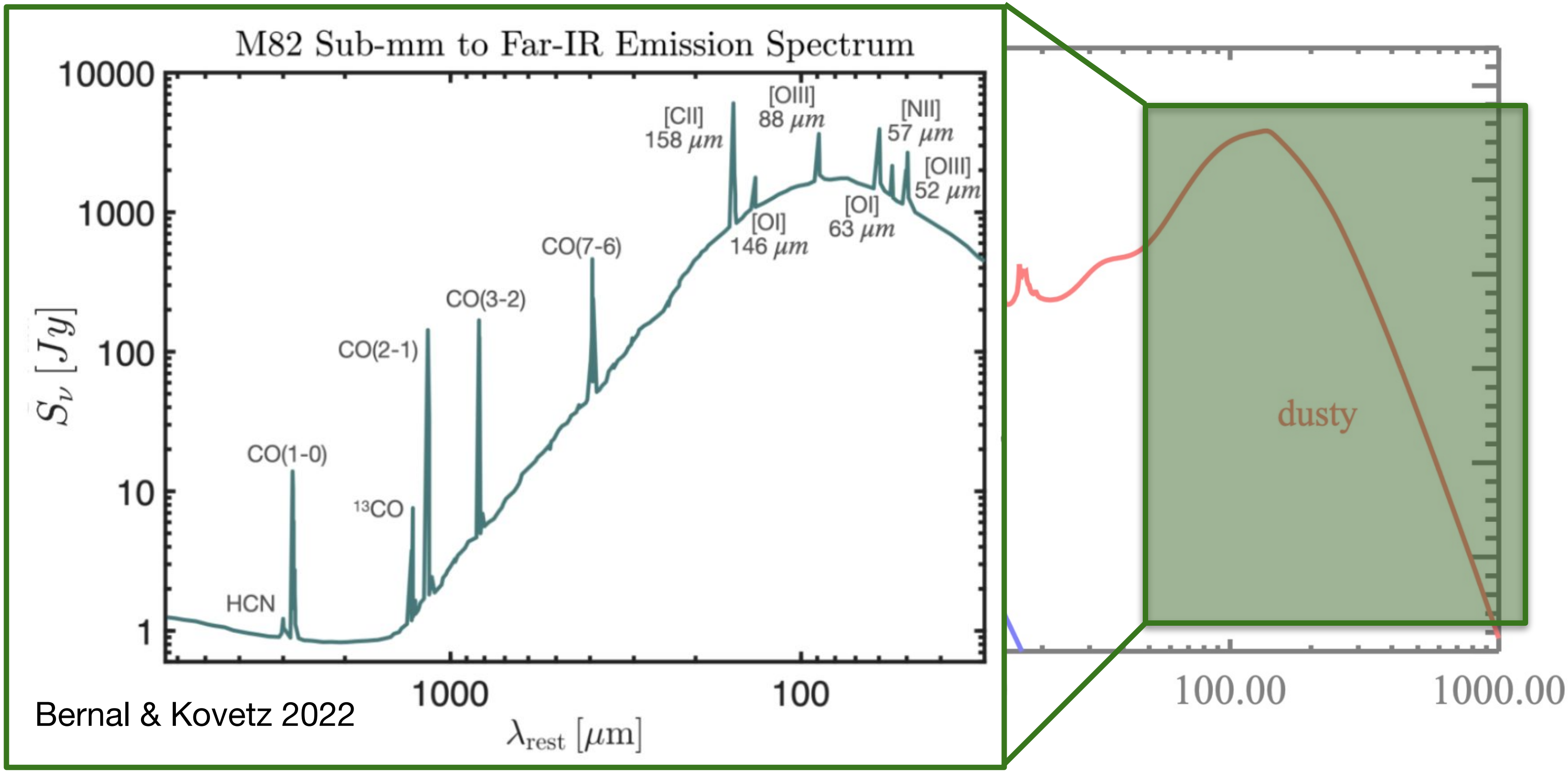
Far-IR is Important!

Conroy ARA&A 2013



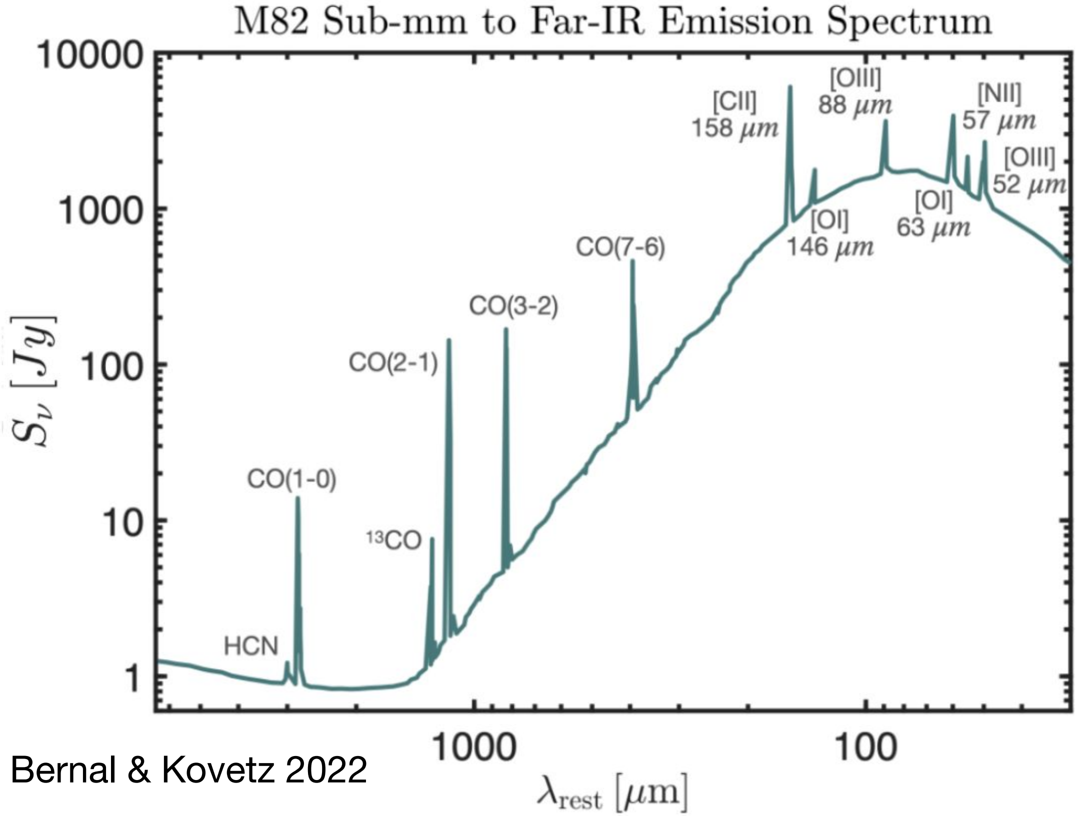
Far-IR is Important!

Conroy ARA&A 2013

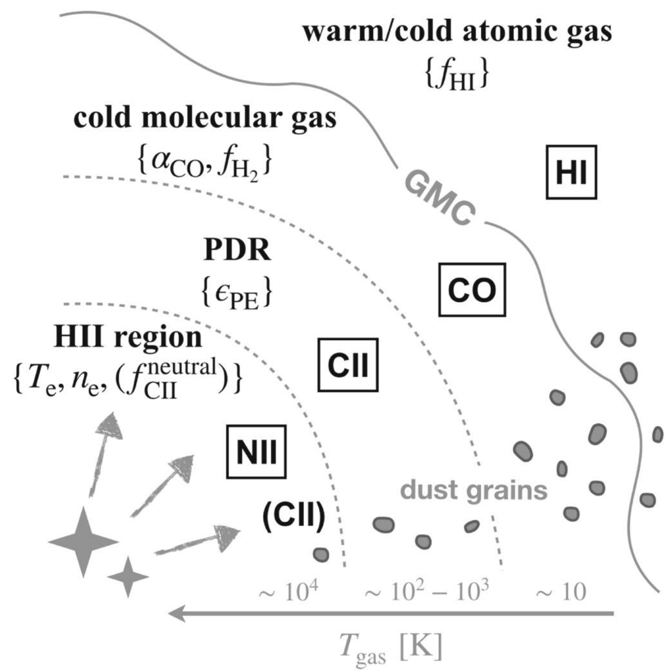


Bernal & Kovetz 2022

Far-IR is Important!

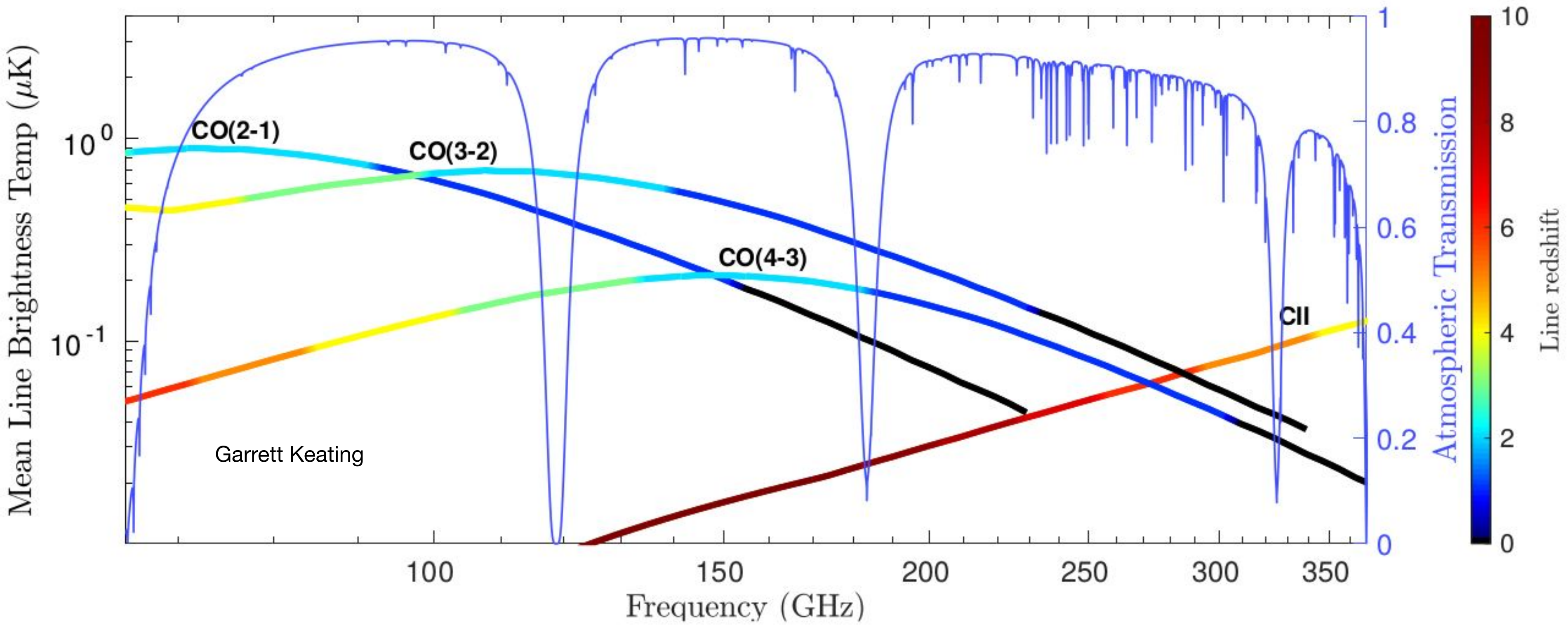


Bernal & Kovetz 2022

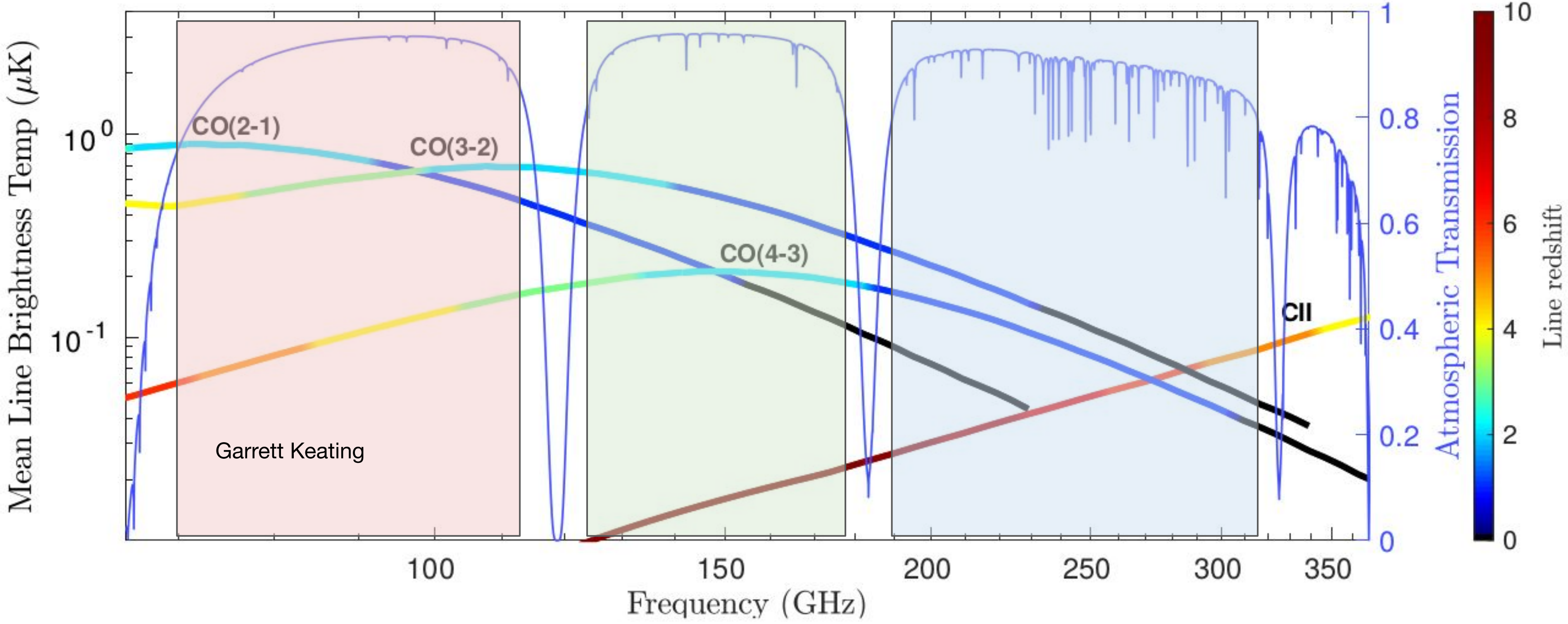


Sun+ 2019

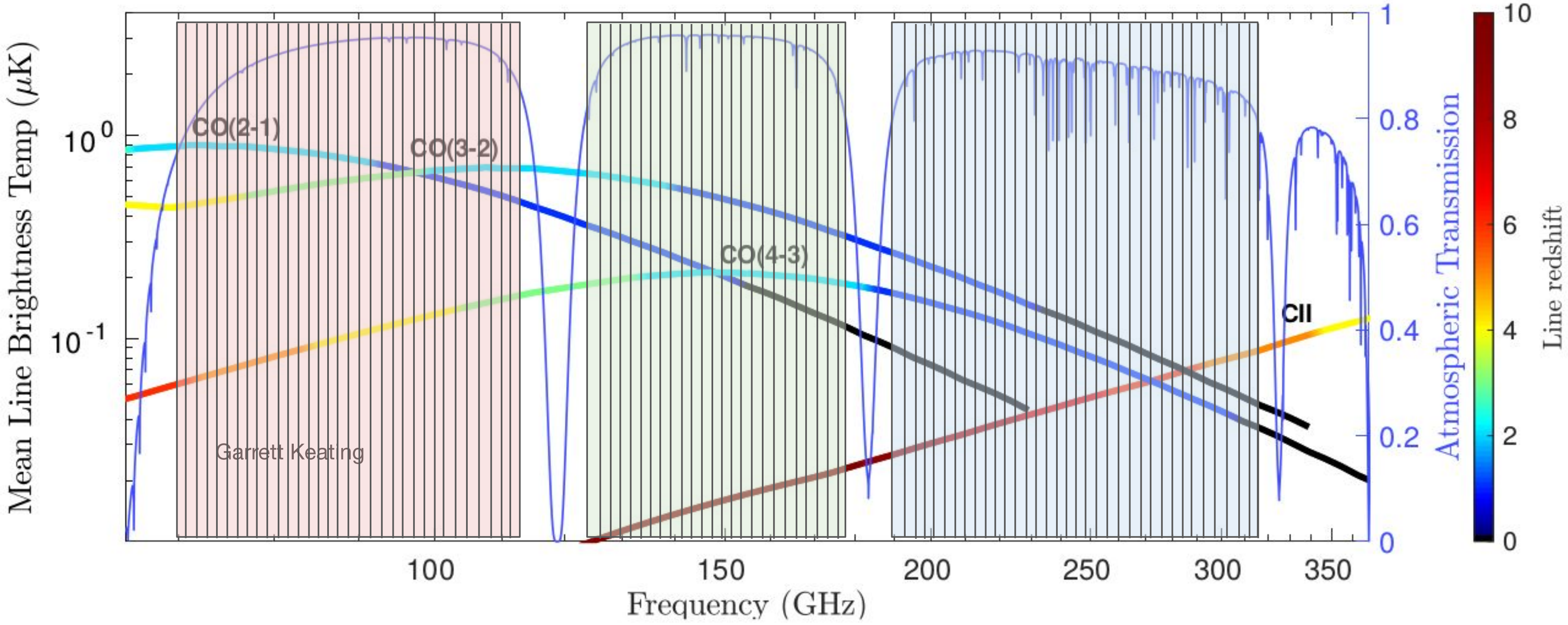
Wide Redshift Coverage in the Millimeter Range



Wide Redshift Coverage in the Millimeter Range



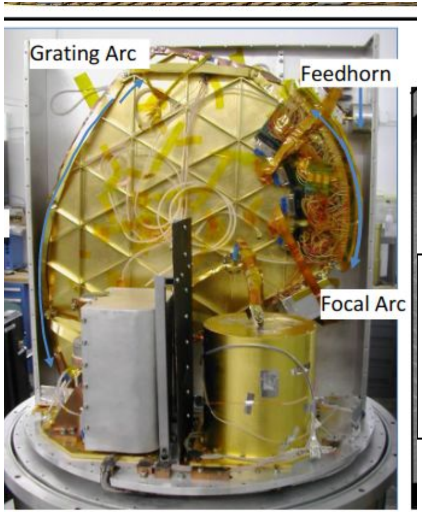
Wide Redshift Coverage in the Millimeter Range



State-of-the-art Millimeter-Wave Spectrometers

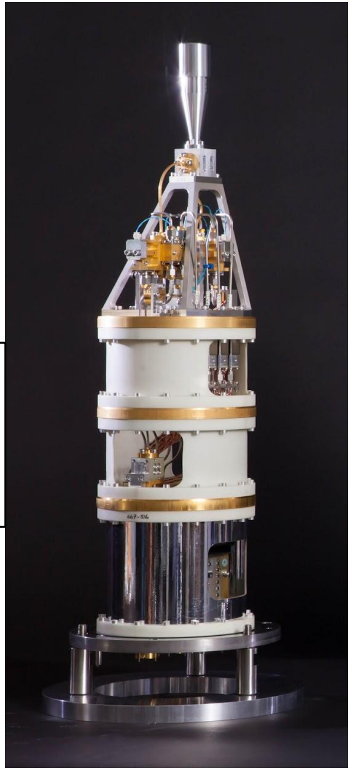
To detect **large numbers** of optically-faint, far-IR-bright galaxies at high redshift, we need wide-band mm-wave spectroscopy, with many pixels for sensitivity.

Current instrumentation is insufficient!



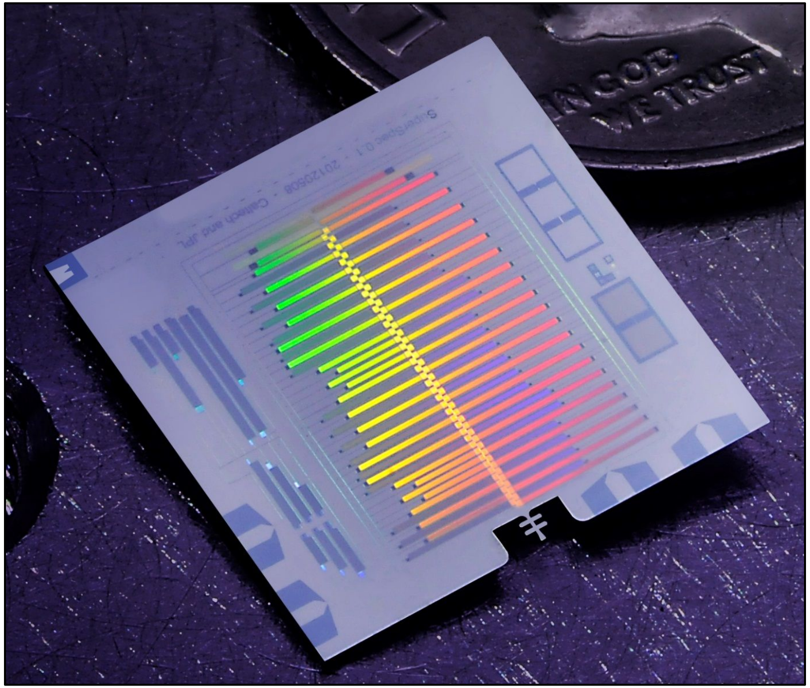
Z-Spec diffraction grating: Wide bandwidth…but the size of a table!

Matt Bradford



ALMA heterodyne receiver: high resolution, but limited bandwidth and bulky.

SuperSpec (Superconducting Spectrometer)



Developing a compact, scalable mm-wave spectrometer

Caltech/JPL
C. M. Bradford
S. Hailey-Dunsheath
R. Janssen
E. Kane
H. LeDuc
J. Zmuidzinas

Boston University
K. S. Karkare
A. Lapuente
S. Savorgnano
A. Tan

GSFC
J. Glenn

NIST
J. Wheeler

University of Chicago
R. McGeehan
E. Shirokoff

Arizona State University
K. Massingill
P. Mauskopf

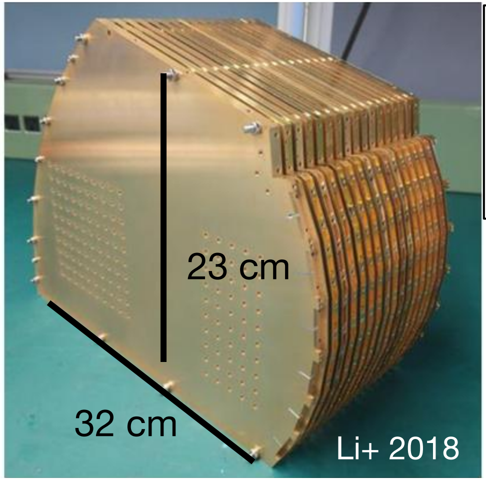
Cardiff University
P. Barry
S. Doyle
C. Tucker

UC Santa Barbara
J. Redford

Dalhousie University
S. Chapman

Spectrometer Design

Minimize detector volume by printing the spectrometer on a silicon wafer.



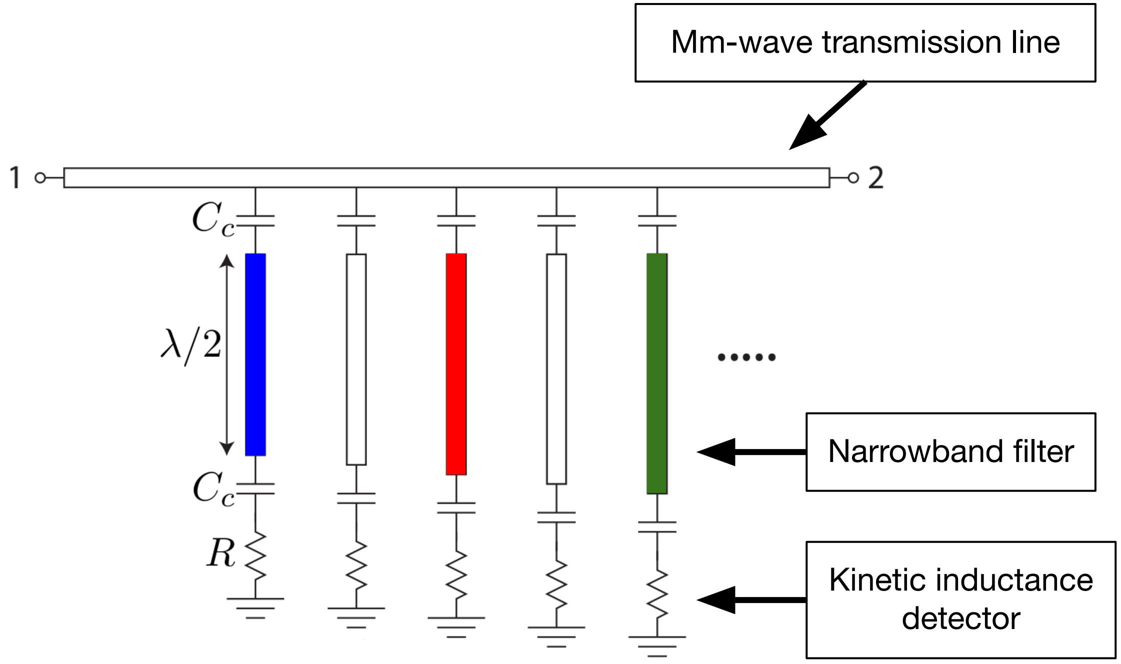
TIME grating:
32 x 23 x 1 cm
~ 736 cm^3

SuperSpec:
3.6 x 5.7 x 0.05 cm
~ 1 cm^3

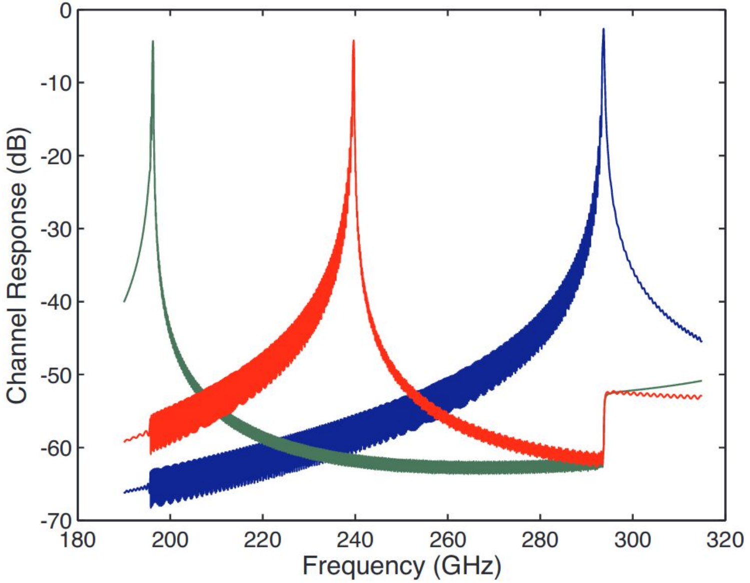
Maximize sensitivity with superconducting **kinetic inductance detectors**.

Detect [CII] from reionization-era galaxies: 180-310 GHz, R=λ/Δλ=300 resolution.

A Filter-Bank Spectrometer

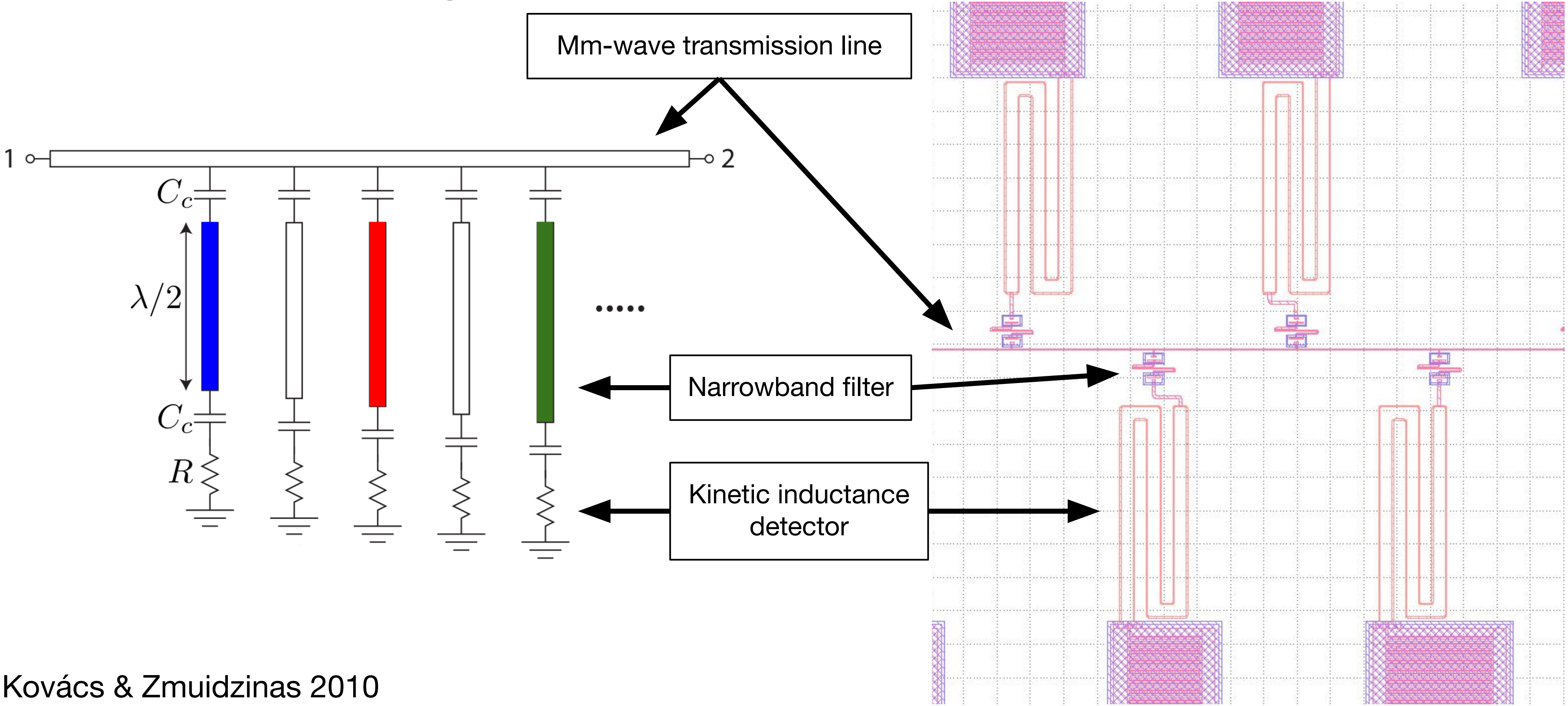


Filter Profiles



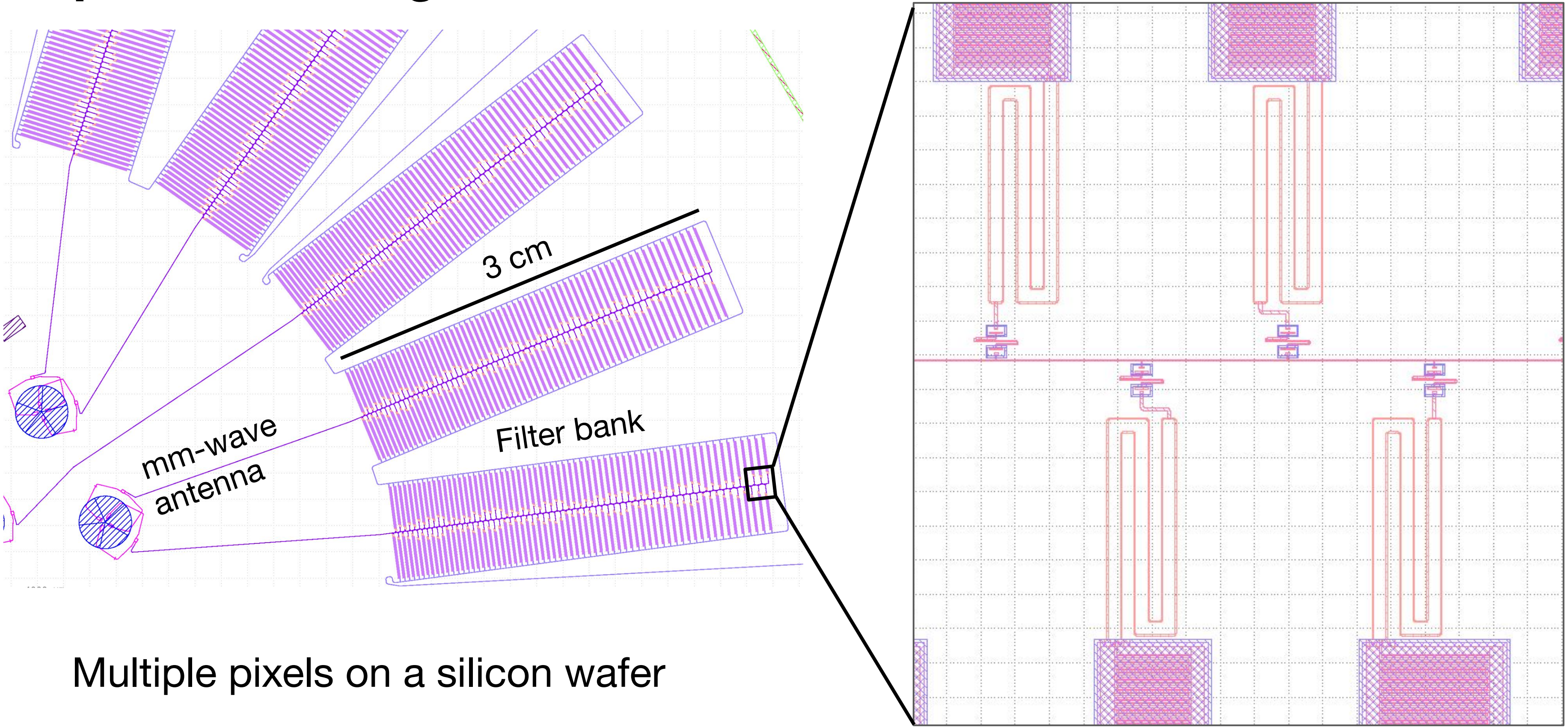
Kovács & Zmuidzinas 2010

A Filter-Bank Spectrometer Realized with Thin-Film Superconducting Circuits



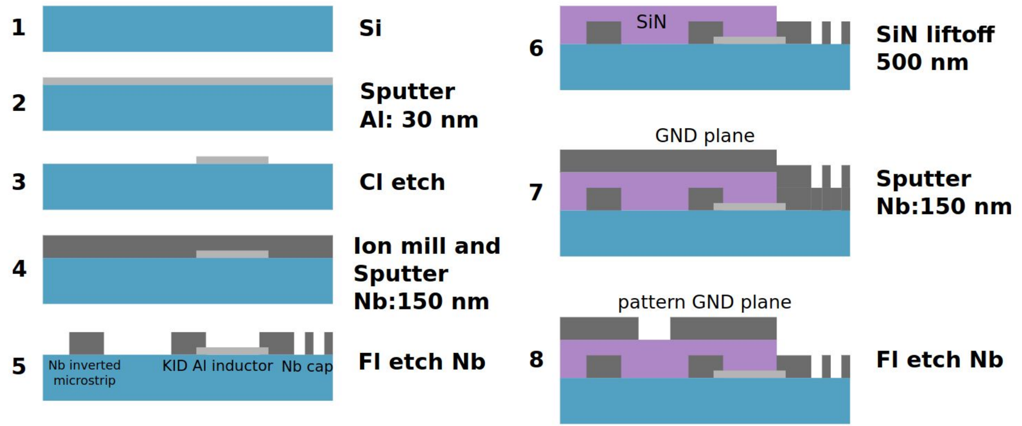
Kovács & Zmuidzinas 2010

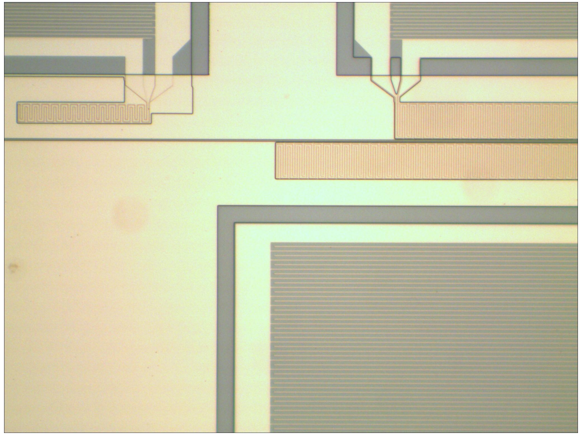
A Filter-Bank Spectrometer Realized with Thin-Film Superconducting Circuits



Multiple pixels on a silicon wafer

Detector Fabrication

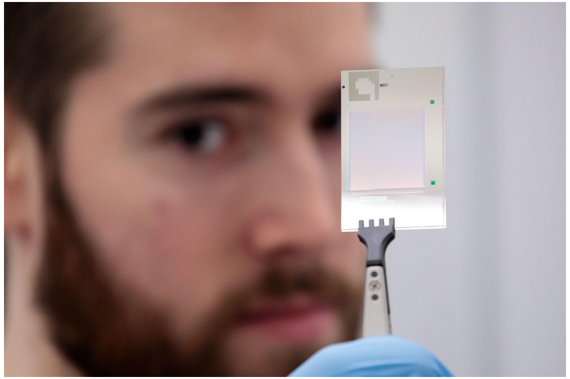




Use superconducting thin films:
Niobium, Aluminum, Titanium Nitride…

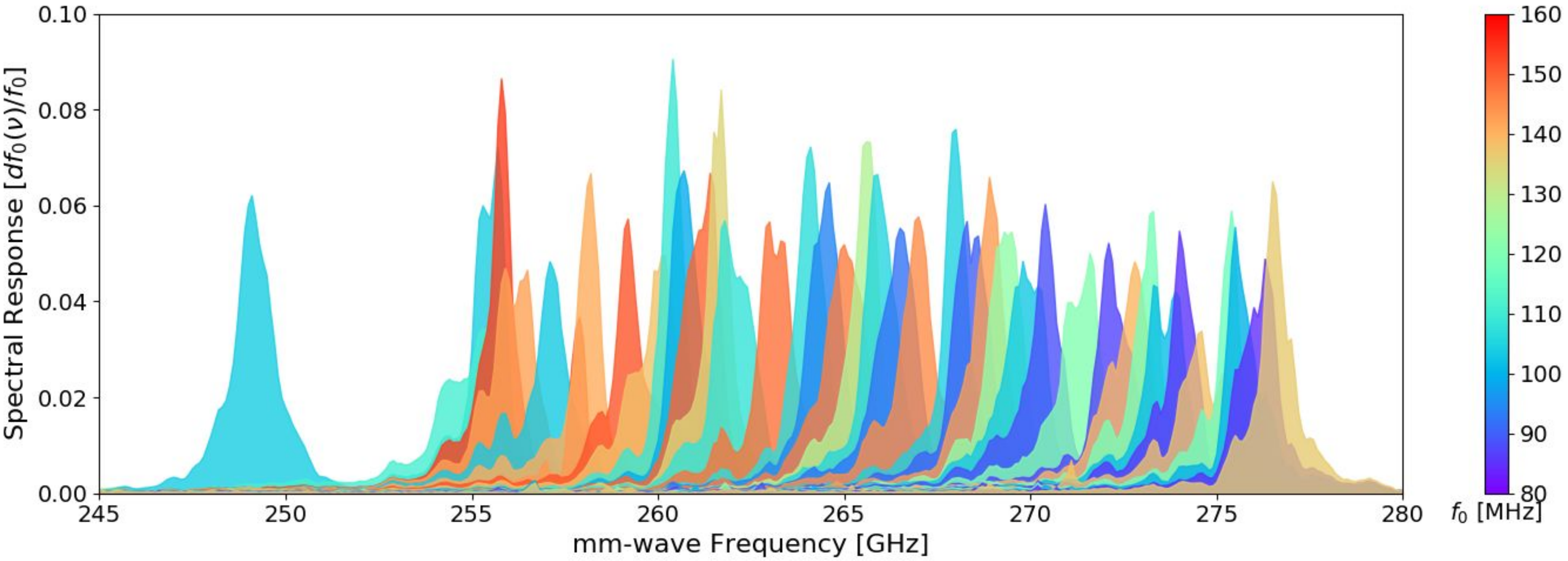
JPL Microdevices Laboratory and
UChicago Pritzker Nanofabrication Facility

Ryan McGeehan
UChicago Ph.D. 2023



The Spectrometer Works!

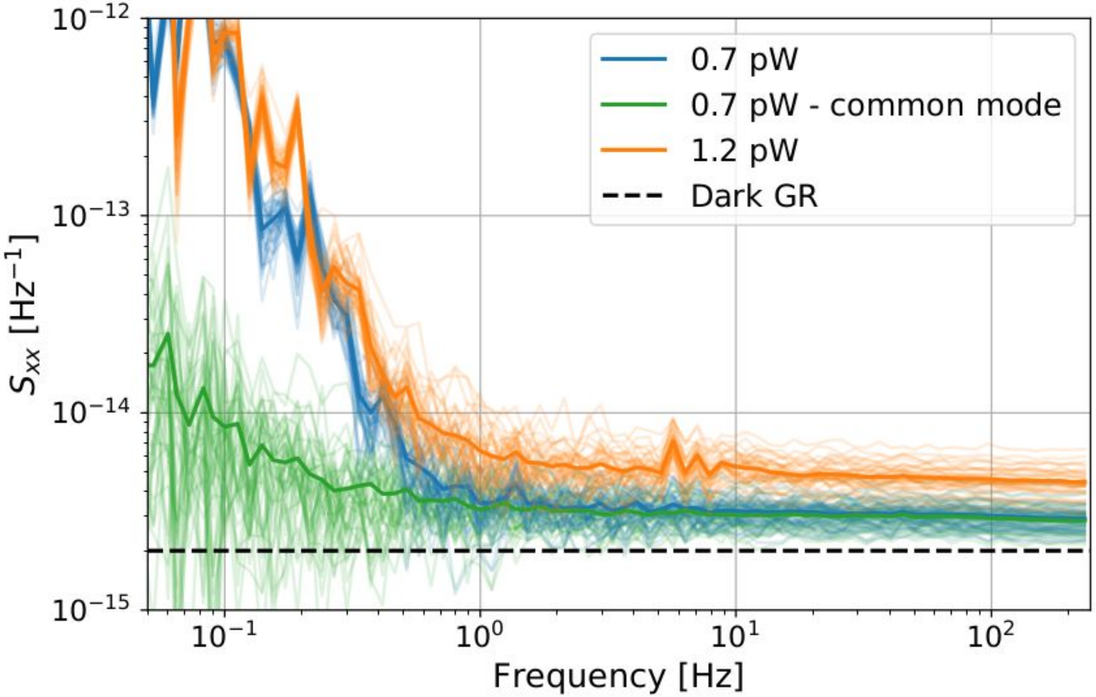
Karkare+ J. Low Temp. Phys.
2002.04542



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

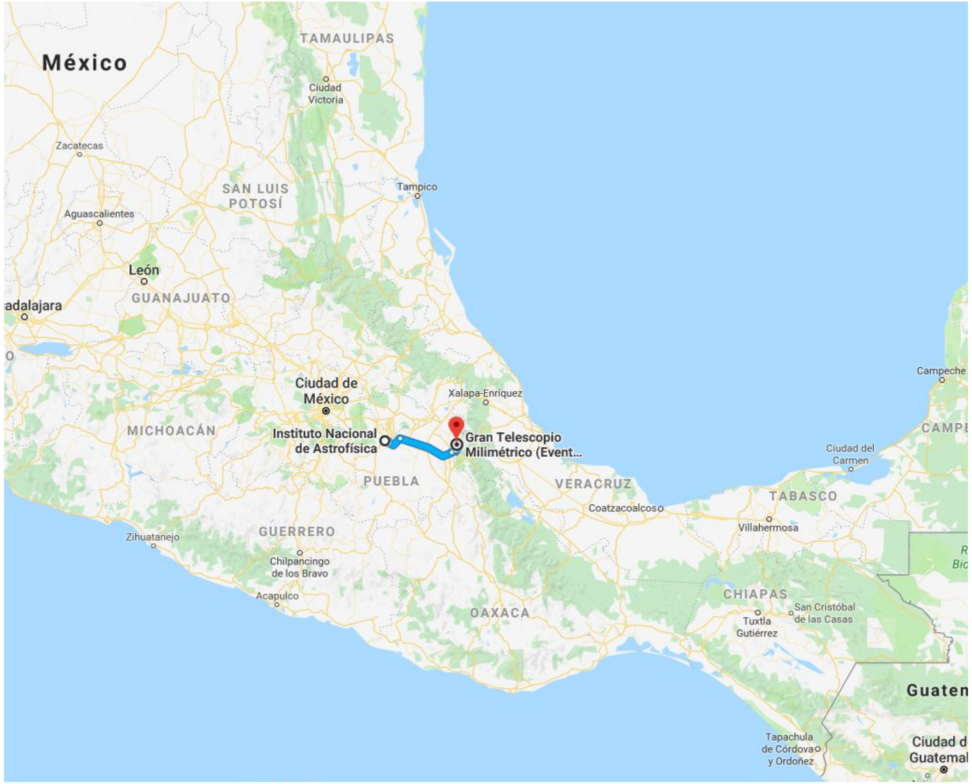
The Spectrometer Works!

Karkare+ J. Low Temp. Phys.
2002.04542



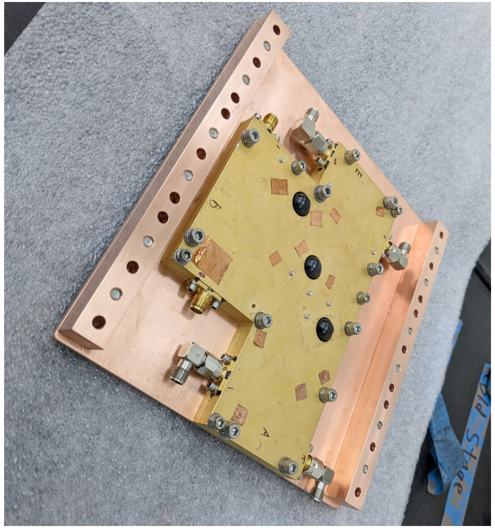
Noise levels are low enough for observations at ground-based observatories (i.e., *photon noise dominated)*.

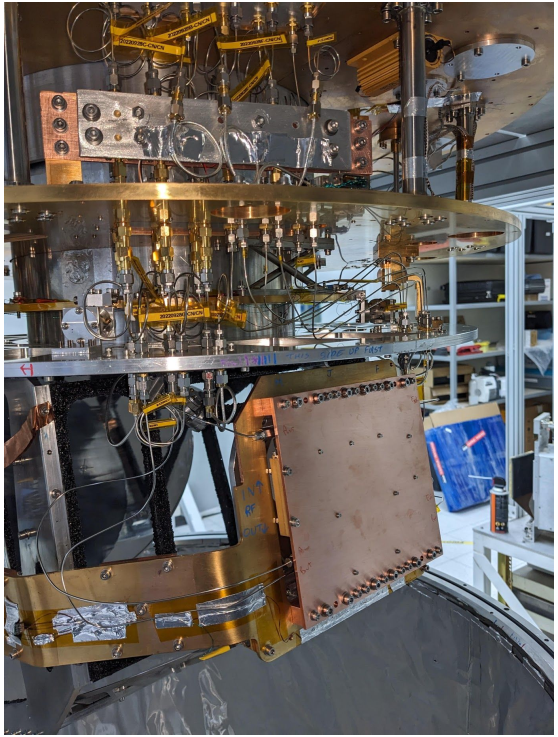
Demonstration at the Large Millimeter Telescope

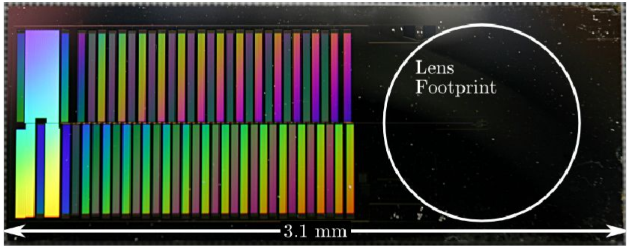


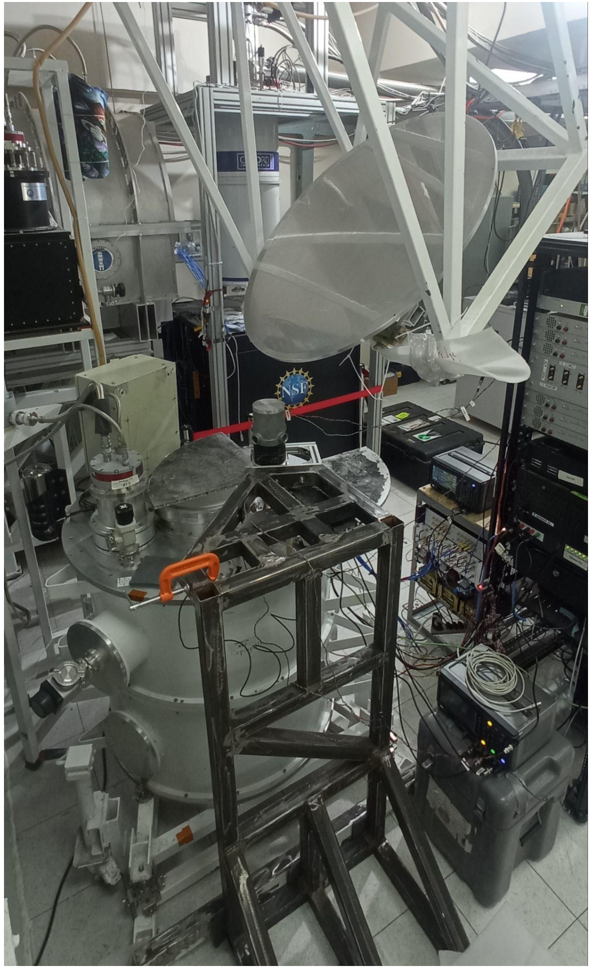
Summer 2025

Three **SuperSpec** devices installed in the **MUSCAT** cryostat → **SuMAC** (SuperSpec/MUSCAT Collaboration)

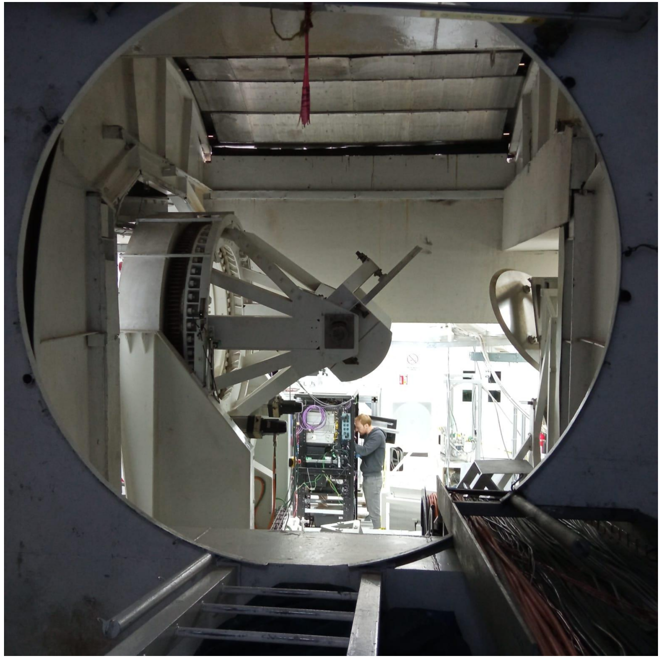






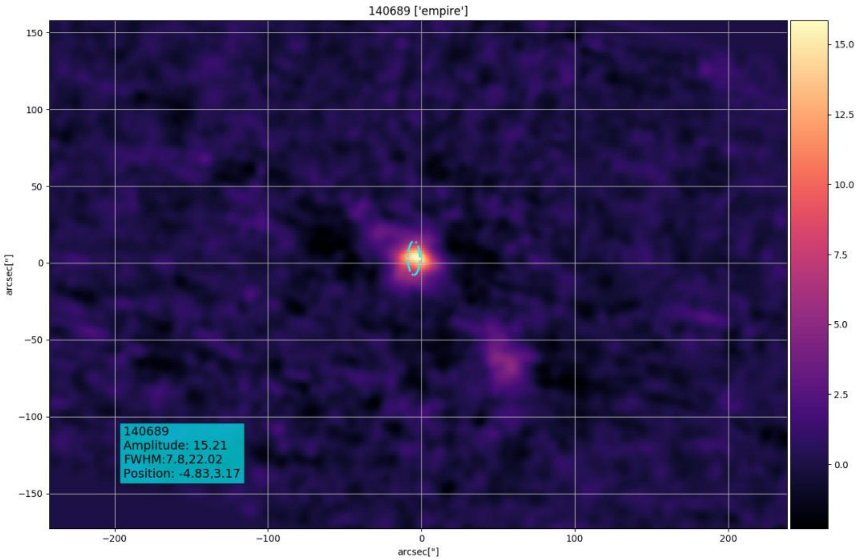


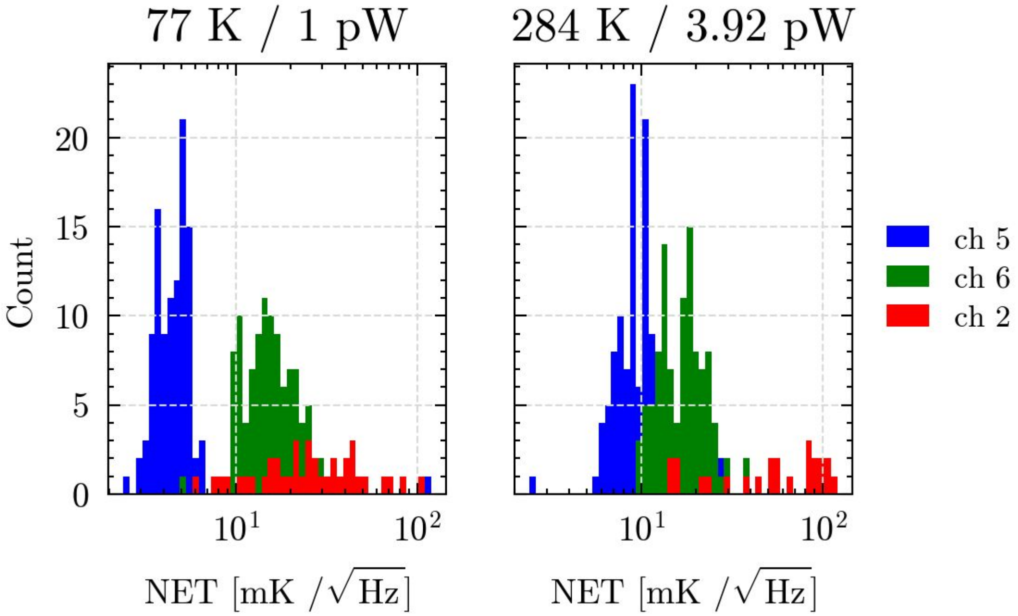
Summer 2025



Preliminary Results

Alex Lapuente

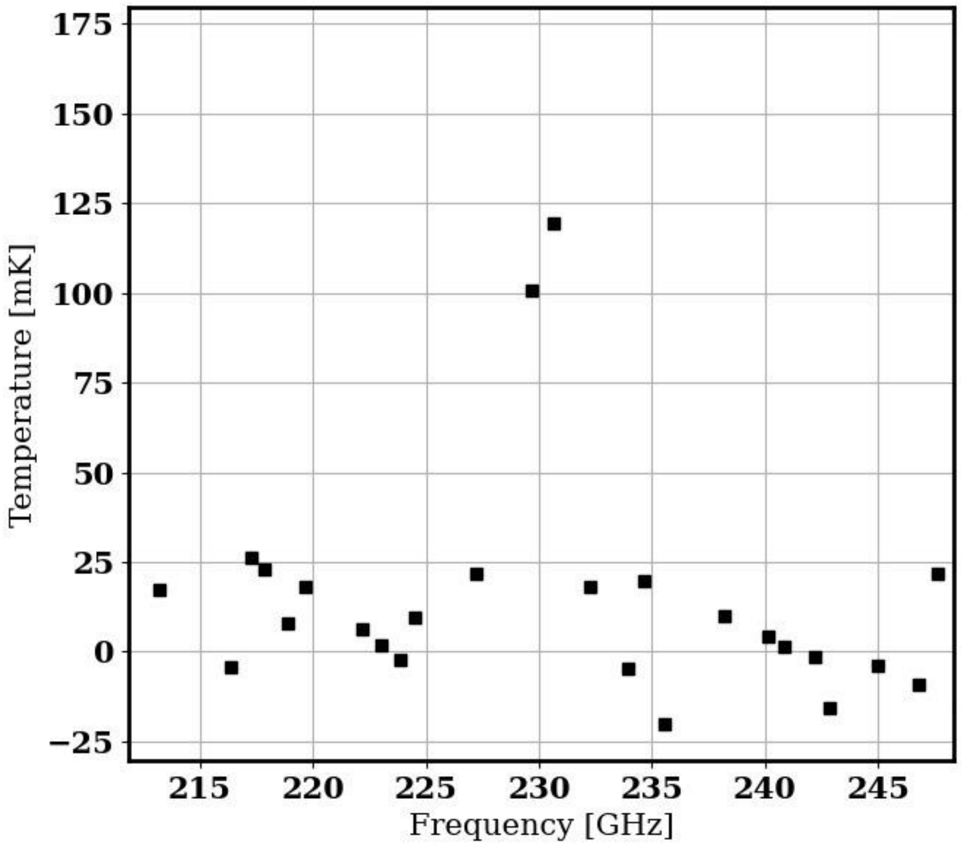




Orion K-L

Note that bandwidths are much smaller than typical CMB detectors

Preliminary Results



Detection of CO(2-1) in NGC 253!

Marcial Tapia

Recap: Millimeter-Wave Spectroscopy

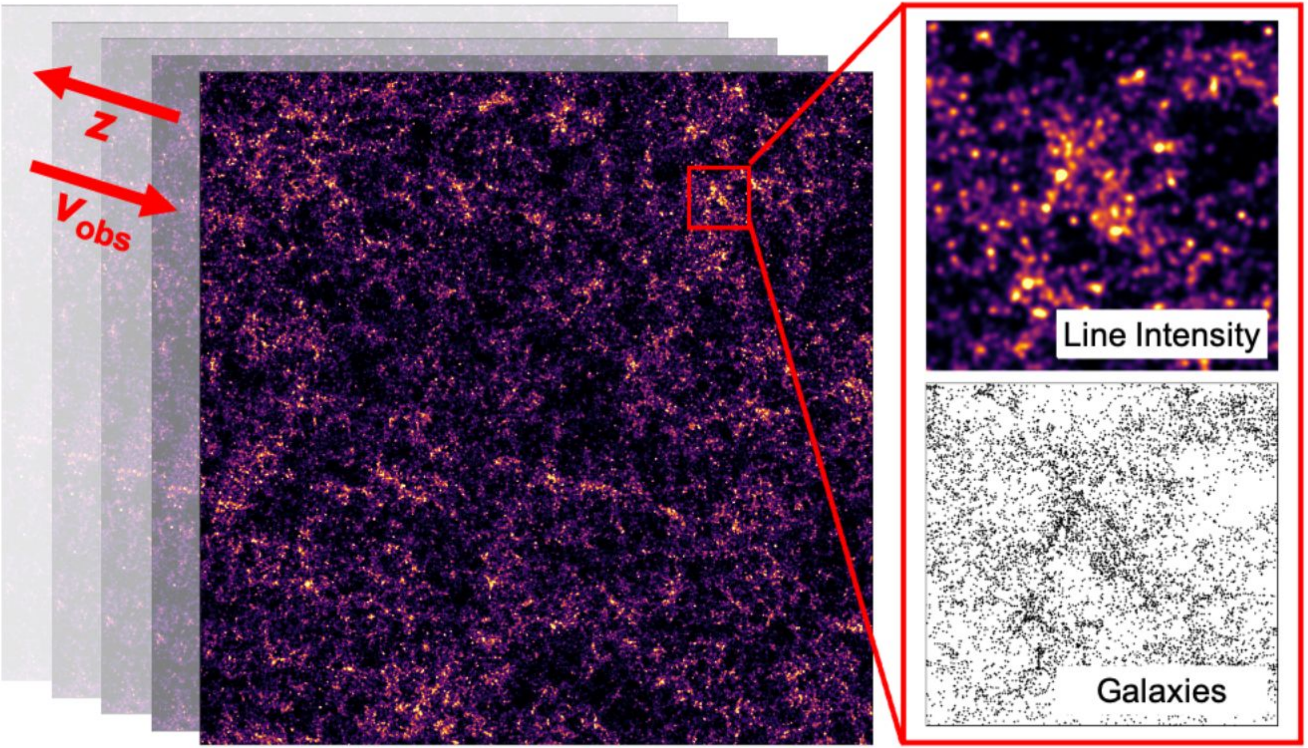
With SuperSpec we've developed **on-chip mm-wave spectrometer technology**, enabling multi-pixel, wide-bandwidth observations of optically-faint (but far-IR bright), high-redshift galaxies.

Surveys at the LMT and other large telescopes will provide a direct view of the star formation activity in reionization-era galaxies…

…but what about the galaxies that are too faint to be directly detected?

Line Intensity Mapping (LIM)

Karkare+ 2203.07258
mm-wave LIM white paper



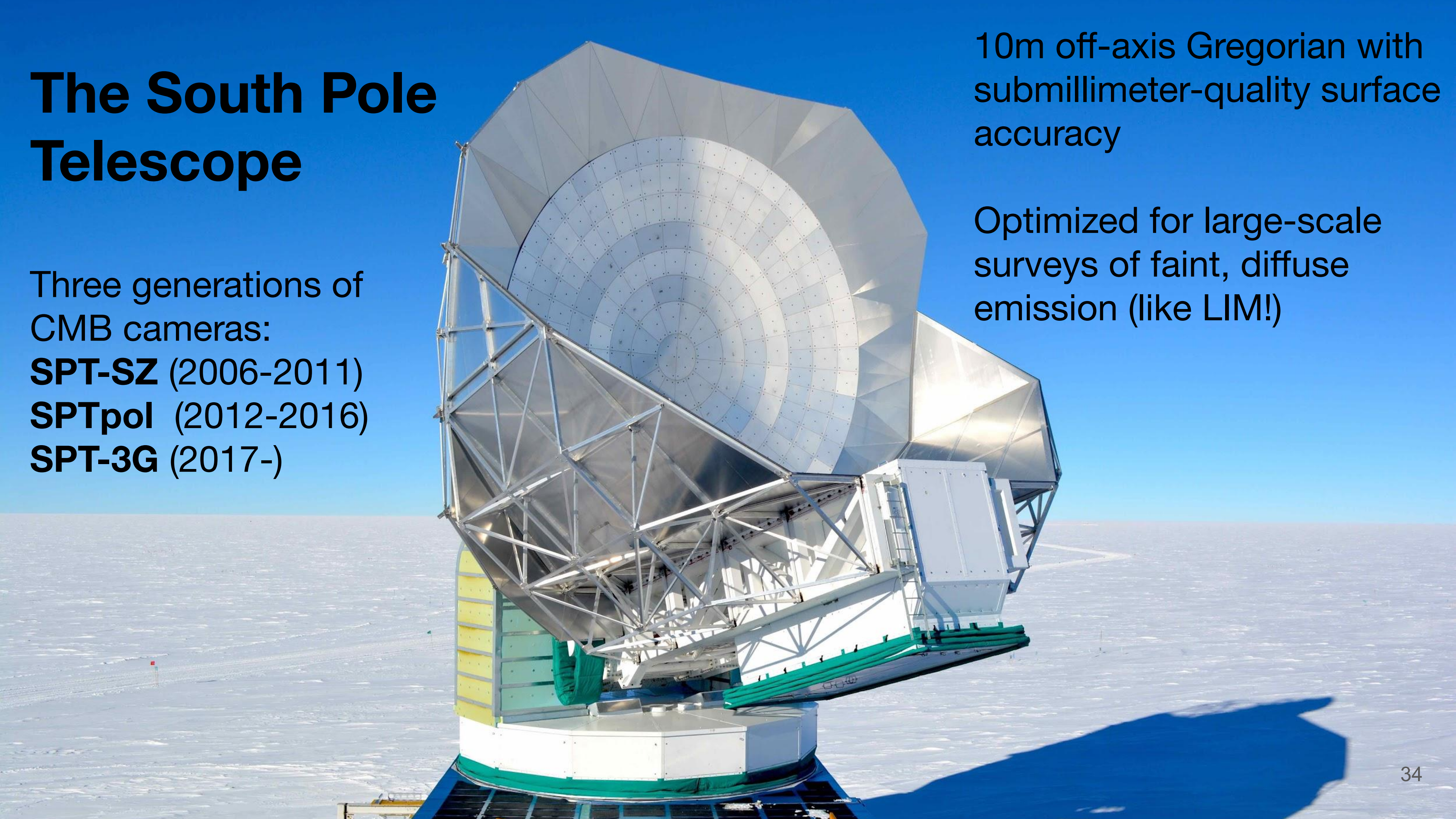
Integrate over individual sources while retaining large-scale cosmology.

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

Works with any line:
21cm, CO/[CII], Hα/Lyα

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!)

The SPT Shirokoff Line Intensity Mapper (SPT-SLIM)

Argonne
T. Cecil
C. Chang
C. Yu

Boston U.
A. Lapuente
A. Tan
K. S. Karkare

Cardiff
P. Barry
C. Benson
G. Robson

CfA
G. Keating

Student
Postdoc
co-PI

Fermilab
A. Anderson
B. Benson
M. Young

McGill
M. Adamic
M. Dobbs
M. Rouble

U. Arizona
D. Kim
D. Marrone

U. Chicago
E. Brooks
J. Carlstrom
K. Dibert
K. Fichman
J. Zebrowski

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.

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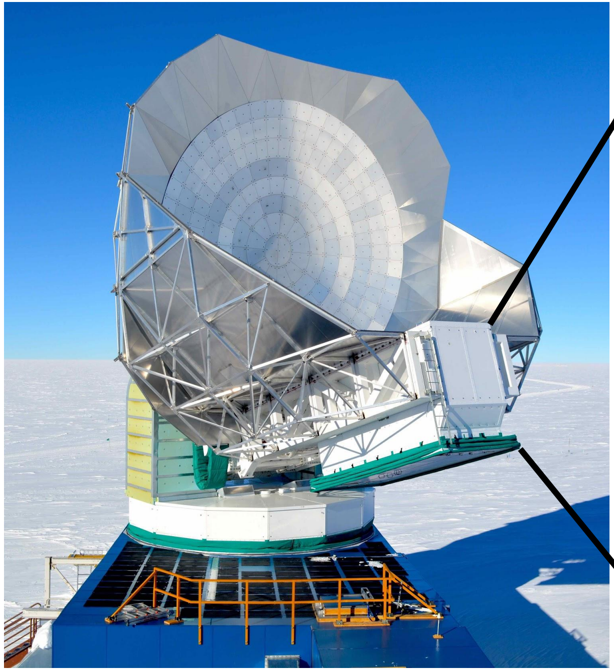
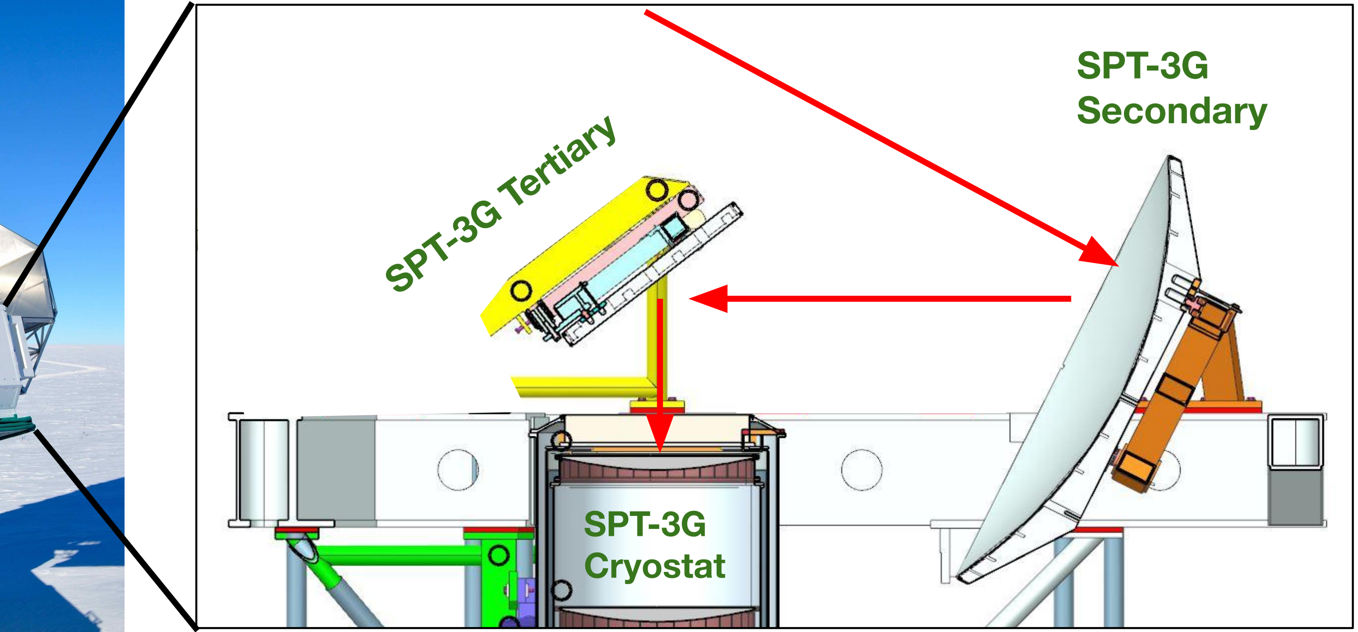
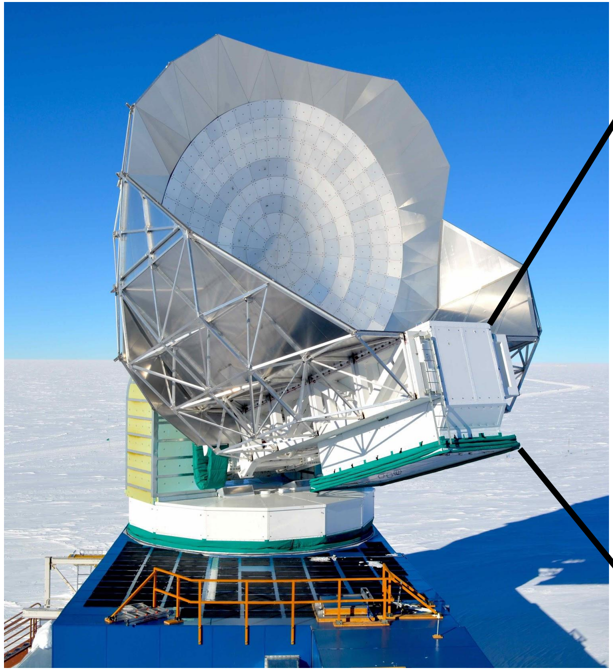


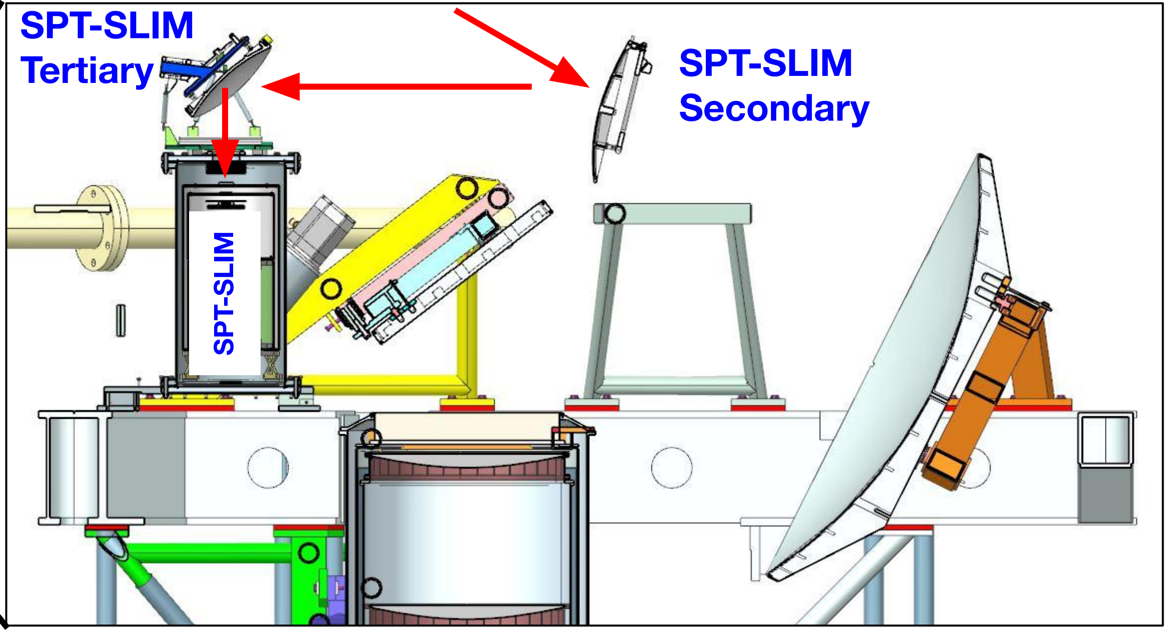


In normal operation, light from the primary is reflected into the receiver cabin, and then into the SPT-3G cryostat…

Karkare+ J. Low Temp. Phys. 2111.04631

The SPT Shirokoff Line Intensity Mapper (SPT-SLIM)





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

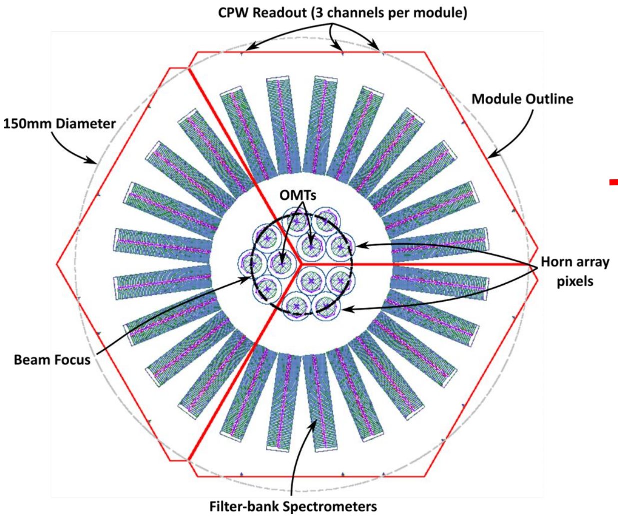
Karkare+ J. Low Temp. Phys.
2111.04631

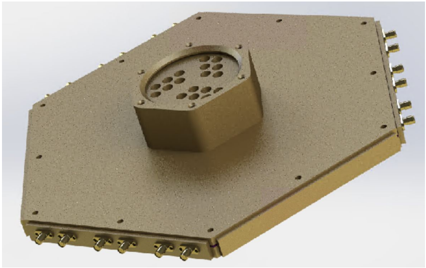
Don Mitchell

The SPT-SLIM Instrument

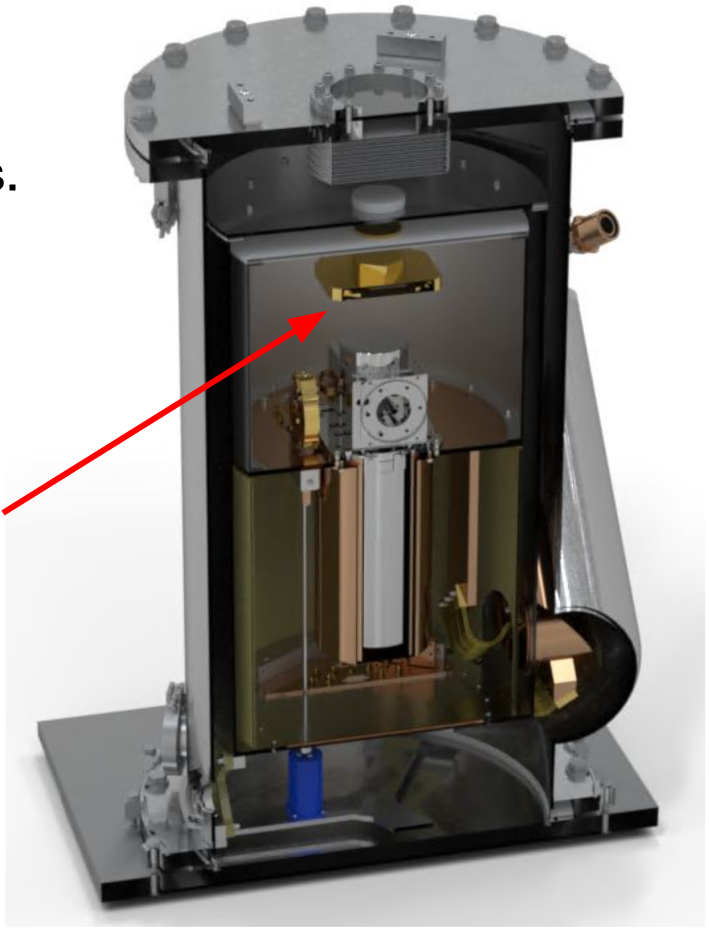
An on-chip mm-wave integral field unit (IFU):
9 dual-pol pixels, each feeding two spectrometers.

Compact cryostat holds detectors at 100 mK with an adiabatic demagnetization refrigerator.

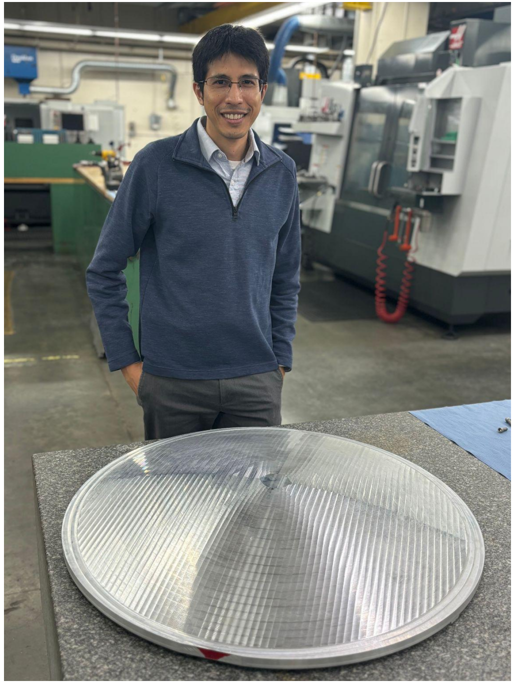


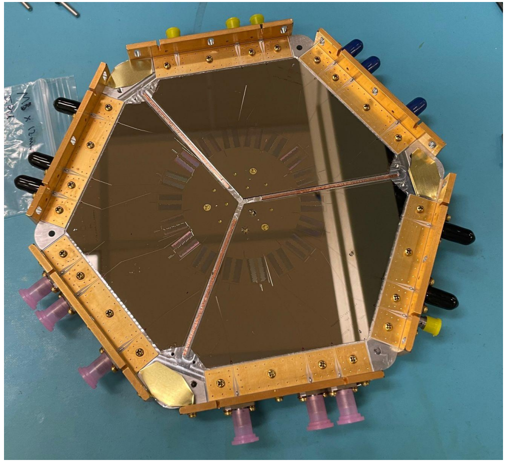


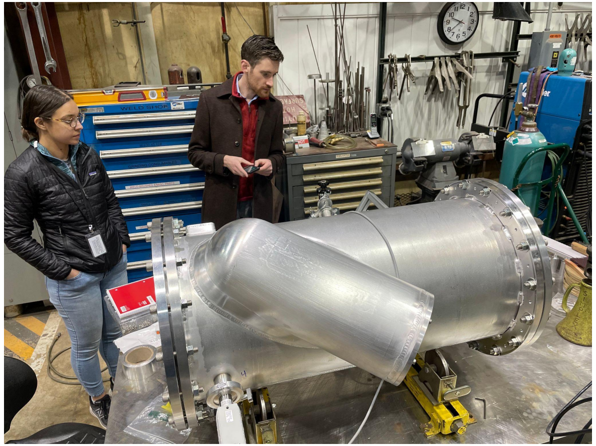
Pete Barry,
Gethin Robson

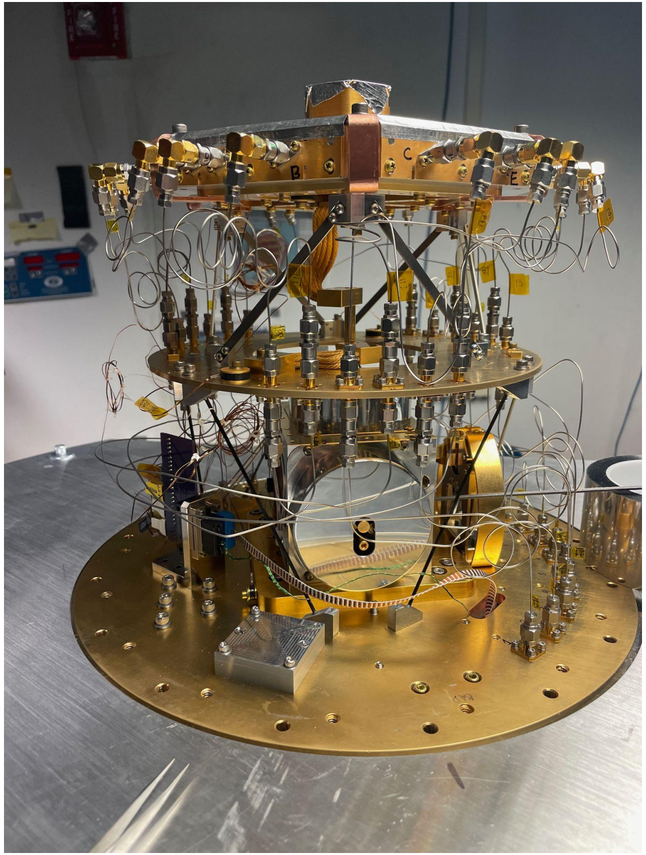


The SPT-SLIM Instrument



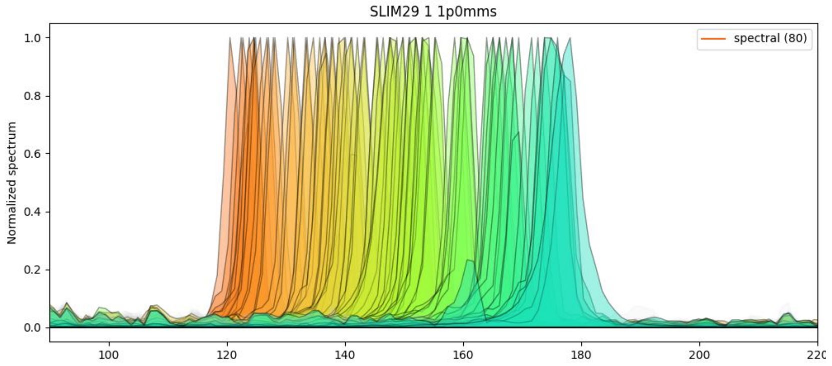


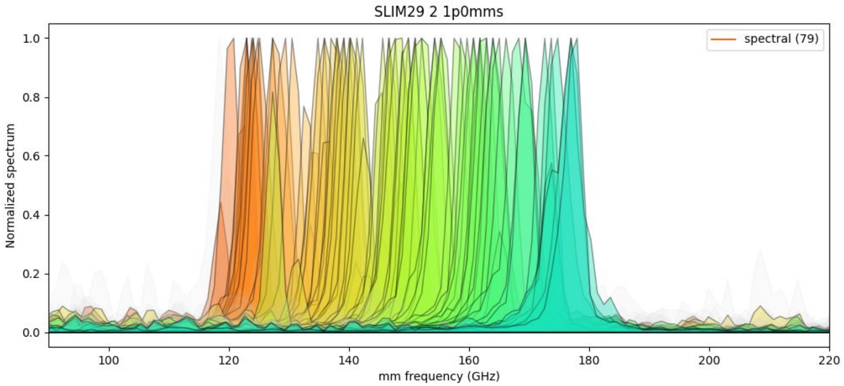


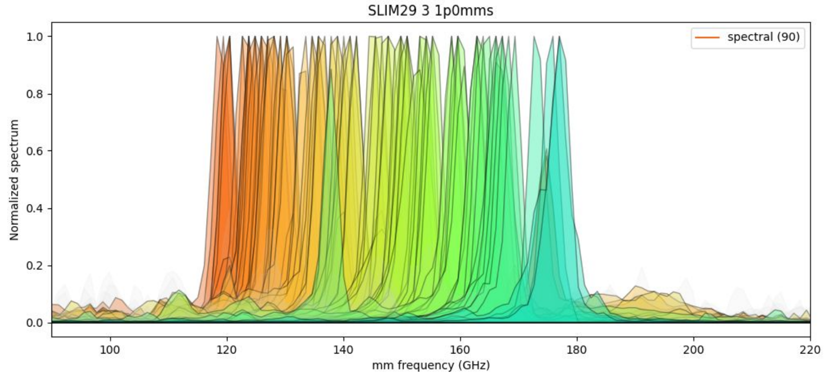


The SPT-SLIM Spectrometers

Spectrometers designed to cover 120–180 GHz with R~100 resolution targeting CO(2-1), (3-2), (4-3) from 0.5 < z < 2.5







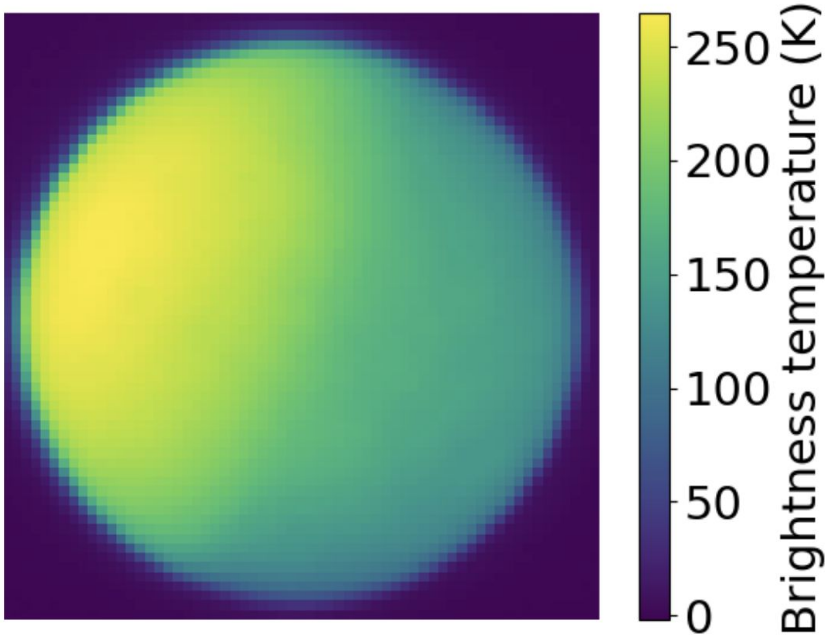
To our knowledge, this is the first multi-pixel on-chip mm-wave spectrometer array.

Kyra Fichman, Karia Dibert, Tyler Natoli, Cyndia Yu

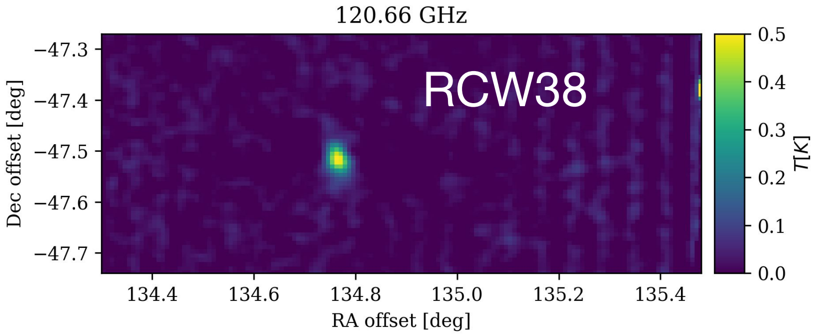
Installation in January 2025!

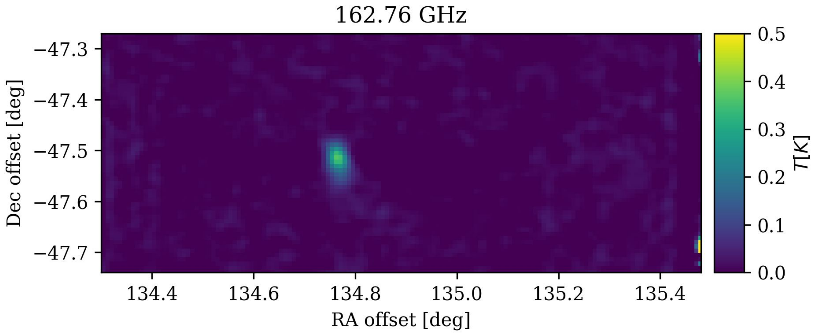
Adam Anderson

First-Light Images

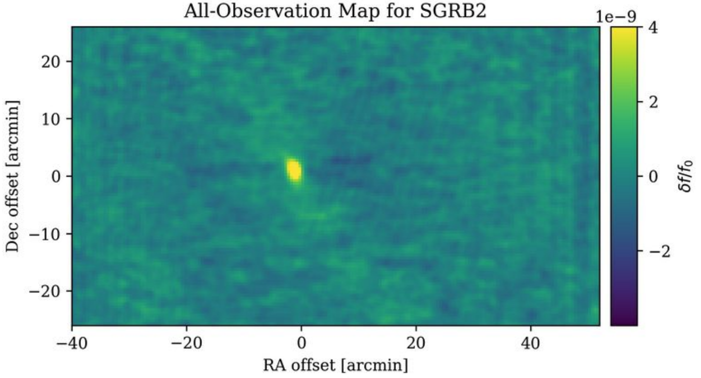


Karia Dibert





Jessica Zebrowski
Alex Lapuente



First-Season Accomplishments

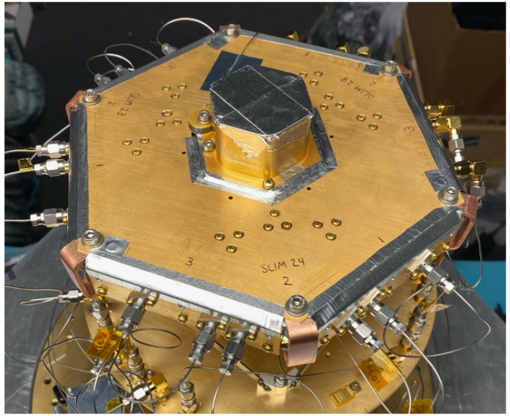
Successful engineering run, leading to the **firs** **detections of astronomical objects with a multi-pixel on-chip spectrometer!** (despite cargo delays and extremely limited on-sky time)

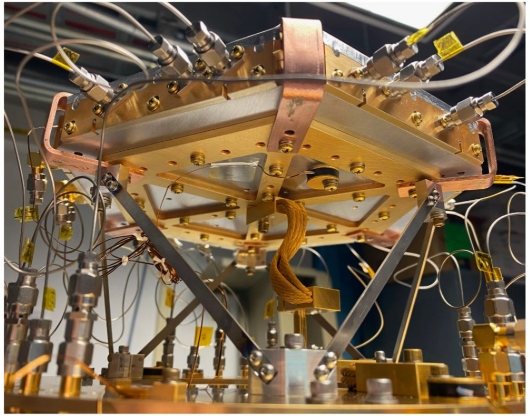
3 papers from the first year:

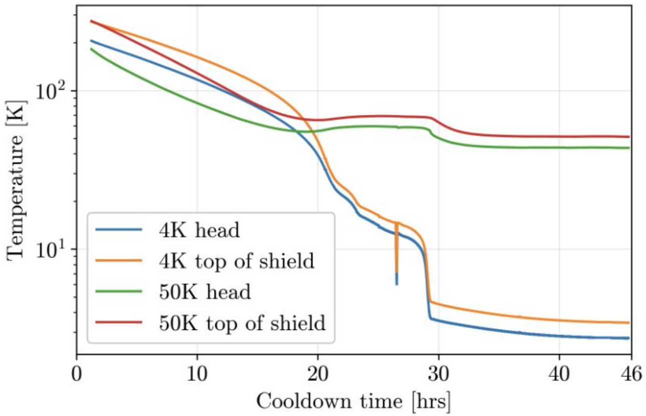
- Cryostat thermal performance
- Characterization of filter-bank spectrometers
- Demonstration of an atmospheric-based calibration routine

Paper 1: Cryostat (Matt Young)

arxiv:2510.14219



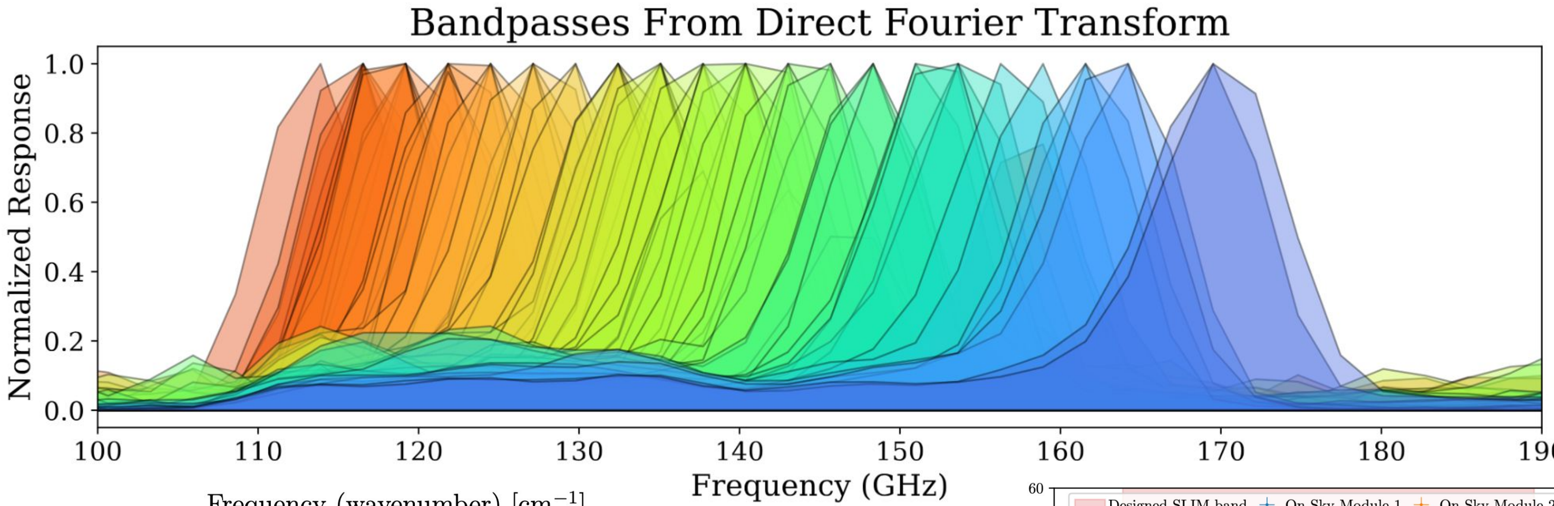


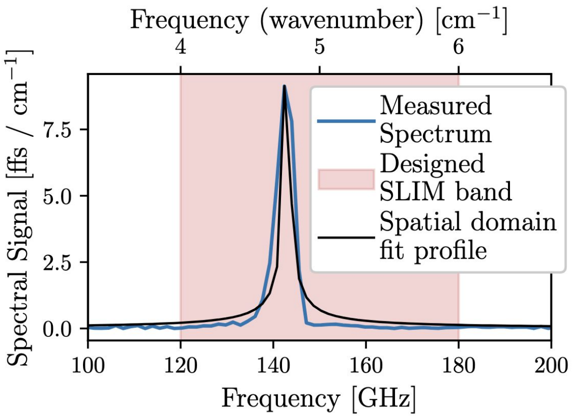


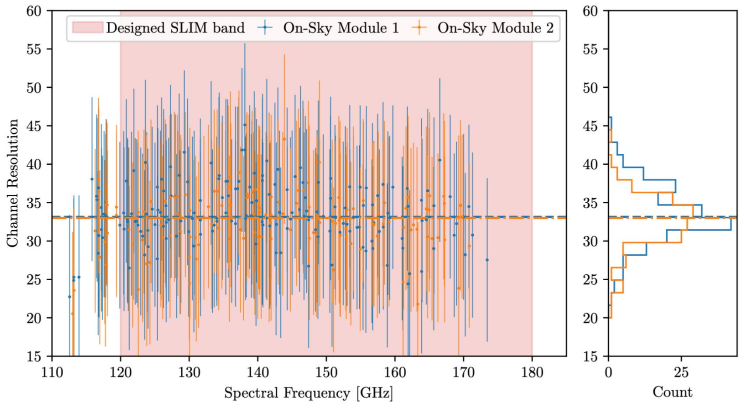
Stage	Modeled load					Measured load
	Conductive	Wiring	Radiative	Optical	Total	Total
50K	2.65 W	0.13 W	11.5 W	0.25 W	14.5 W	15 W
4K	101 mW	136 mW	7 mW	321 mW	113 mW	110 mW
GGG	9.33 μW	5.30 μW	0.21 μW	0 μW	14.8 μW	17.0 μW
FAA	0.93 μW	0.28 μW	0.42 μW	0.01 μW	1.62 μW	2.20 μW

Paper 2: Spectrometers (Chris Benson)

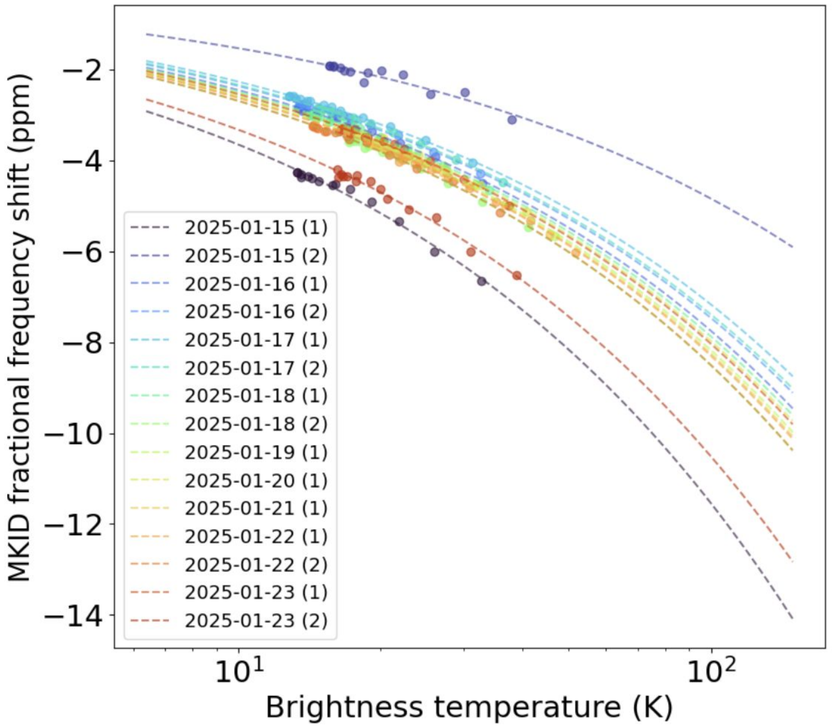
arxiv:2509.02245

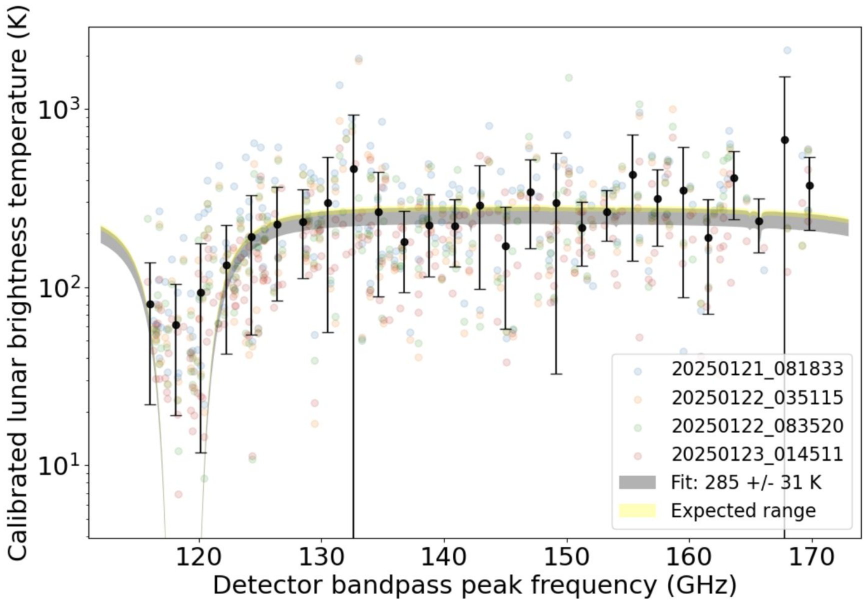






Paper 3: Atmospheric Calibration (Karia Dibert)





arxiv:2510.14220

Takeaways and Looking Forward

In our engineering season, we successfully built **an instrument that works end-to-end** and deployed the first multi-pixel on-chip spectrometer.

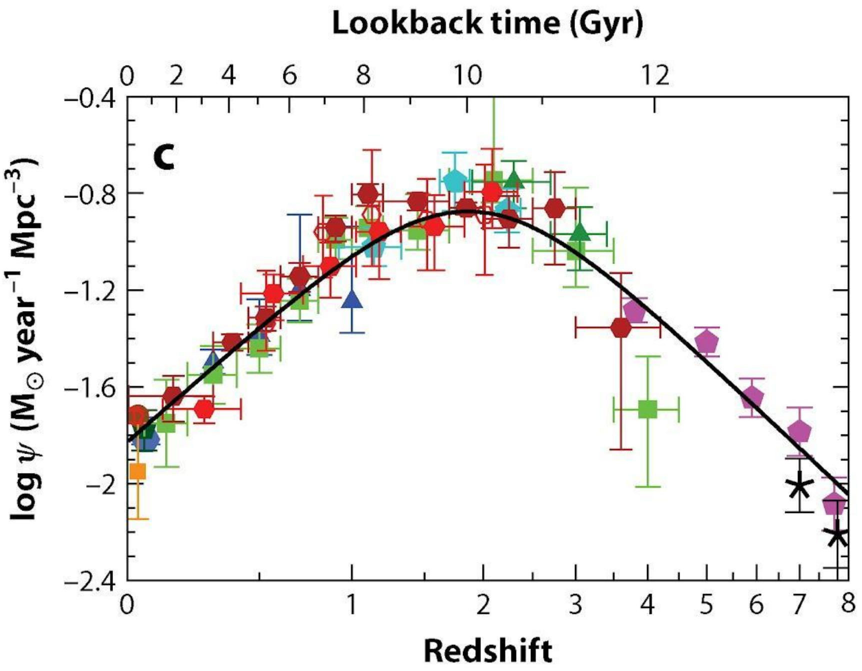
However, the detectors were not sensitive enough to do LIM science. After analyzing first-season data, this is now well-understood:

- **Dielectric loss** was several times higher than expected, reducing spectrometer resolution and optical efficiency
- **Detector responsivity** was low due to a conservative fabrication choice
- **Resonator quality factors** were lower than expected

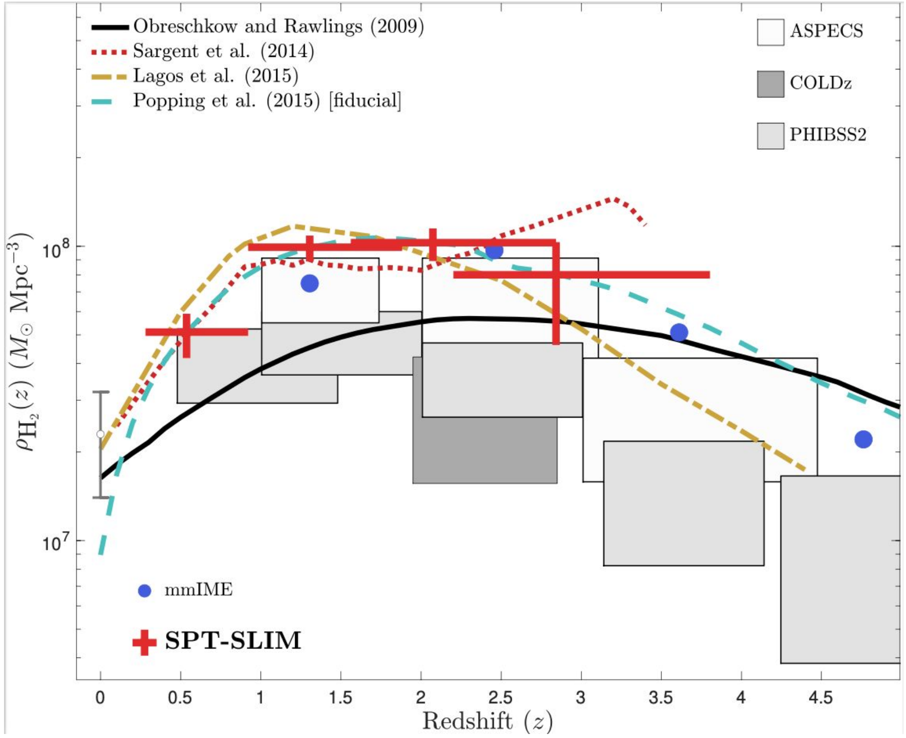
We've identified straightforward fixes to each of these issues (*in most cases having already demonstrated the ideal parameters on test devices!*).

With these improvements, we expect next season's focal plane to be substantially more sensitive and capable of the LIM science we proposed.

Constraints on Cosmic Star Formation History



Madau & Dickinson 2014



Garrett Keating

Recap: SPT-SLIM

LIM detects the aggregate emission from faint, unresolved galaxies in 3D, enabling efficient surveys of large volumes and high redshifts.

With SPT-SLIM, we're learning how to use on-chip spectrometers for this measurement…

…but these are all still relatively small-volume surveys.

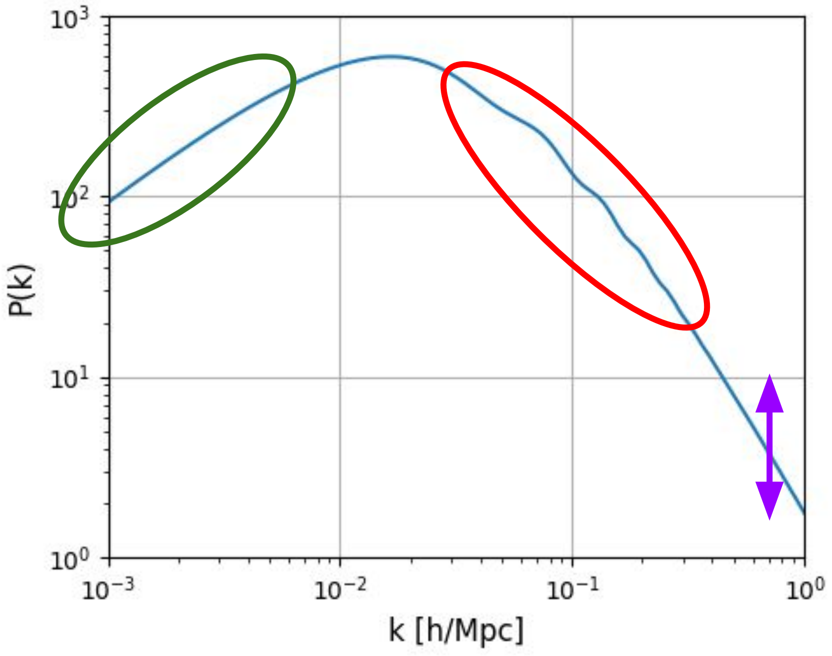
How can we get to next-generation cosmology with LIM?

Large-Scale Structure Constrains Our Cosmological Model

Primordial non-Gaussianity
(multi-field inflation)

Expansion history
(dark energy/modified gravity)

Massive neutrinos



How much sensitivity do we need?

	Spec-hrs
	Timescale
	Example
Neutrino masses	$\sigma(M_\nu)$ [eV]
Dark energy	$\sigma(w_0)$ incl. z>3
Inflation	Primordial FoM

For Snowmass, we forecast the sensitivity required for mm-wave LIM to provide competitive cosmological constraints.

Calculated as a function of *spectrometer-hours* – a rough measure of survey depth.

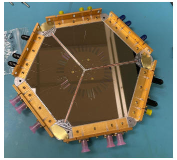
Karkare+ 2203.07258
Snowmass white paper

How much sensitivity do we need?

	Spec-hrs	$\lesssim 10^5$
	Timescale	2025
	Example	TIME, SPT-SLIM
Neutrino masses	$\sigma(M_\nu)$ [eV]	
Dark energy	$\sigma(w_0)$ incl. $z>3$	
Inflation	Primordial FoM	

10s of spectrometers, limited deployments.

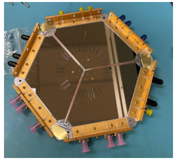
First detections of power spectra.
CO/[CII] luminosity functions.

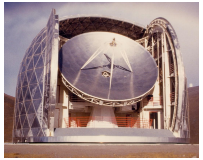


Karkare+ 2203.07258
Snowmass white paper

How much sensitivity do we need?

Spec-hrs	$\lesssim 10^5$	10^6
Timescale	2025	2028
Example	TIME, SPT-SLIM	TIME-Ext
Neutrino masses: $\sigma(M_\nu)$ [eV]		0.047
Dark energy: $\sigma(w_0)$ incl. z>3		0.03
Inflation: Primordial FoM		0.1



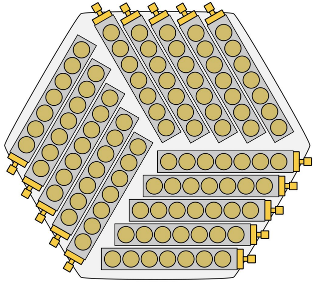


Pathfinder instruments at dedicated facilities.

Characterize the **high-redshift multi-phase ISM** (including cold molecular gas).

Karkare+ 2203.07258
Snowmass white paper

How much sensitivity do we need?



Spec-hrs	$\lesssim 10^5$	10^6	10^7
Timescale	2025	2028	2030
Example	TIME, SPT-SLIM	TIME-Ext	CCAT, one tube
$\sigma(M_\nu)$ [eV]		0.047	0.028
$\sigma(w_0)$ incl. z>3		0.03	0.013
Primordial FoM		0.1	1

Neutrino masses

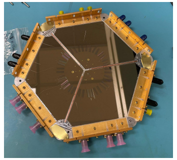
Dark energy

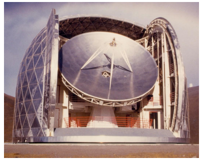
Inflation

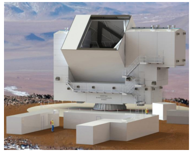
Focal plane with ~hundred spectrometers

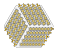
Competing with galaxy surveys, but including high redshifts.
Image the EoR. Constrain dynamical DE models.

DESI: FoM ~ 1









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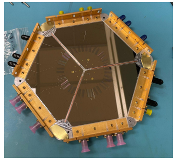
Snowmass white paper

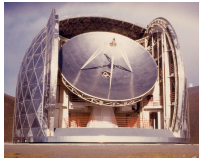
How much sensitivity do we need?

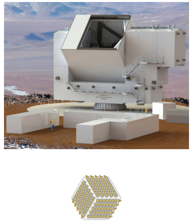
	Spec-hrs	$\lesssim 10^5$	10^6	10^7	10^8
	Timescale	2025	2028	2030	2033
	Example	TIME, SPT-SLIM	TIME-Ext	CCAT, one tube	CCAT, 7 tubes
Neutrino masses	$\sigma(M_\nu)$ [eV]		0.047	0.028	0.013
Dark energy	$\sigma(w_0)$ incl. $z>3$		0.03	0.013	0.005
Inflation	Primordial FoM		0.1	1	10

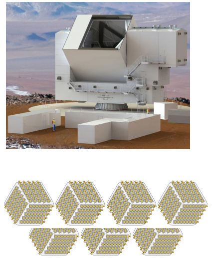
Comparable to next-gen surveys, but including higher redshifts.

MegaMapper: FoM ~ 10









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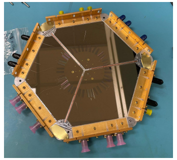
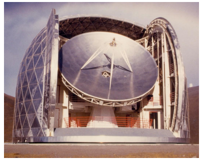
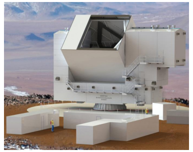
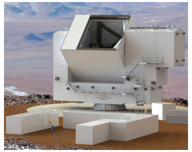
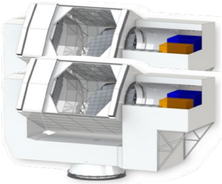
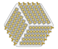
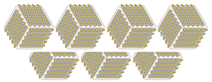
Snowmass white paper

How much sensitivity do we need?

Well beyond DESI/LSST!

	Spec-hrs	$\lesssim 10^5$	10^6	10^7	10^8	10^9
	Timescale	2025	2028	2030	2033	2040
	Example	TIME, SPT-SLIM	TIME-Ext	CCAT, one tube	CCAT, 7 tubes	CMB-S4 85 tubes
Neutrino masses	$\sigma(M_\nu)$ [eV]		0.047	0.028	0.013	0.007
Dark energy	$\sigma(w_0)$ incl. $z>3$		0.03	0.013	0.005	0.003
Inflation	Primordial FoM		0.1	1	10	100

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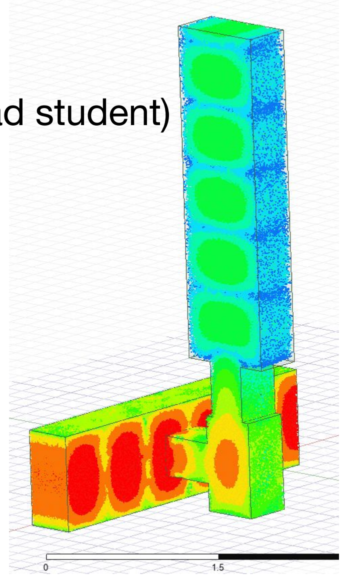
Snowmass white paper

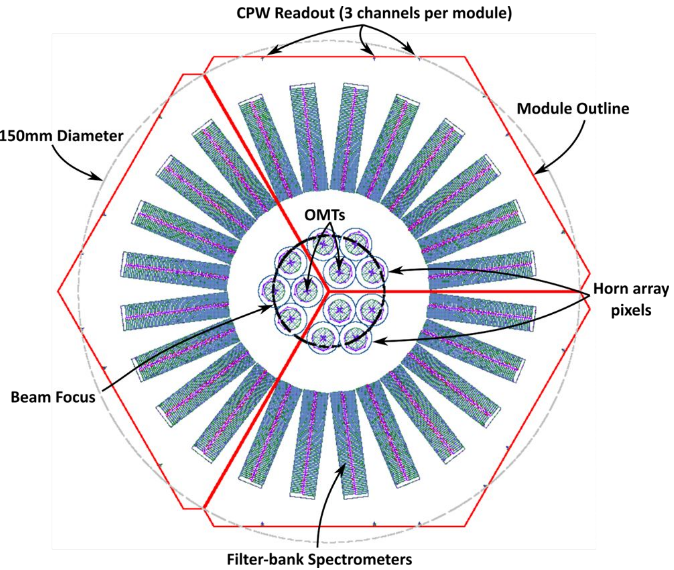
How do we get there?

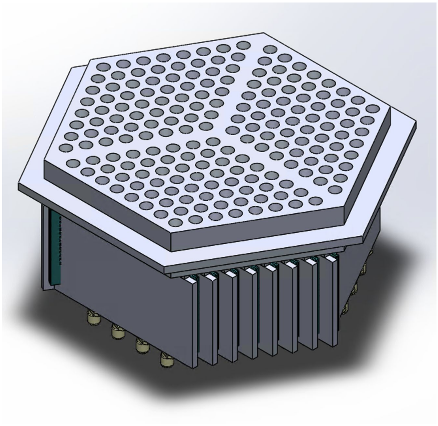
Pete Barry
Annie Tan (BU grad student)



Major challenges in improving:

- Sensitivity/spectral resolution (low-loss dielectrics)
- Detector multiplexing (higher Qs, readout electronics)
- Packing density (creative focal plane geometries)





Summary

Far-IR lines are sensitive to high-redshift galaxies. LIM at mm wavelengths can probe cosmic structure over an extremely wide redshift range from the ground.

On-chip spectrometers are now on sky! SuperSpec and SPT-SLIM both saw first light in 2025 - stay tuned for sensitivity, noise, etc. Anticipate more deployments in the next few years.

We are working to improve spectrometer performance for next-generation LIM experiments, which will have the sensitivity answer the fundamental mysteries of our cosmological model beyond the reach of CMB and galaxy surveys.