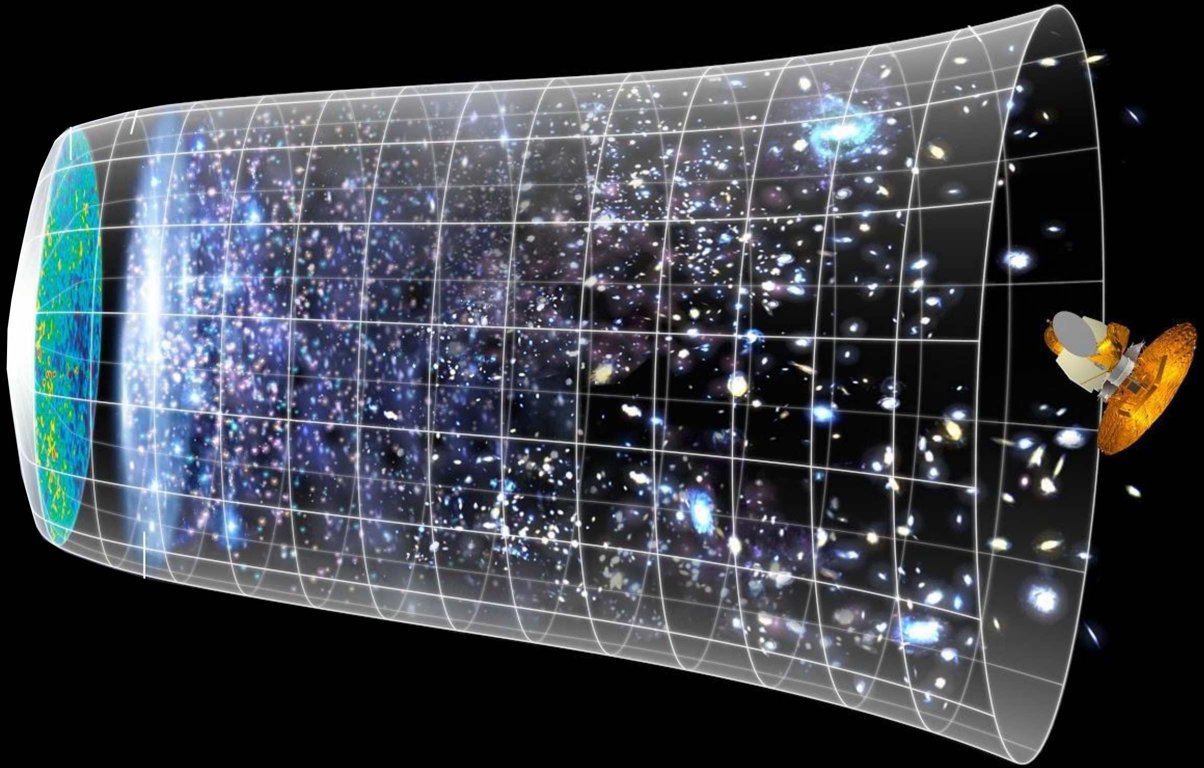
Exploring the High-Redshift Universe with SPT-SLIM and Millimeter-Wave Line Intensity Mapping

Kirit S. Karkare (SLAC/KIPAC)
UC Berkeley, 2024-02-13

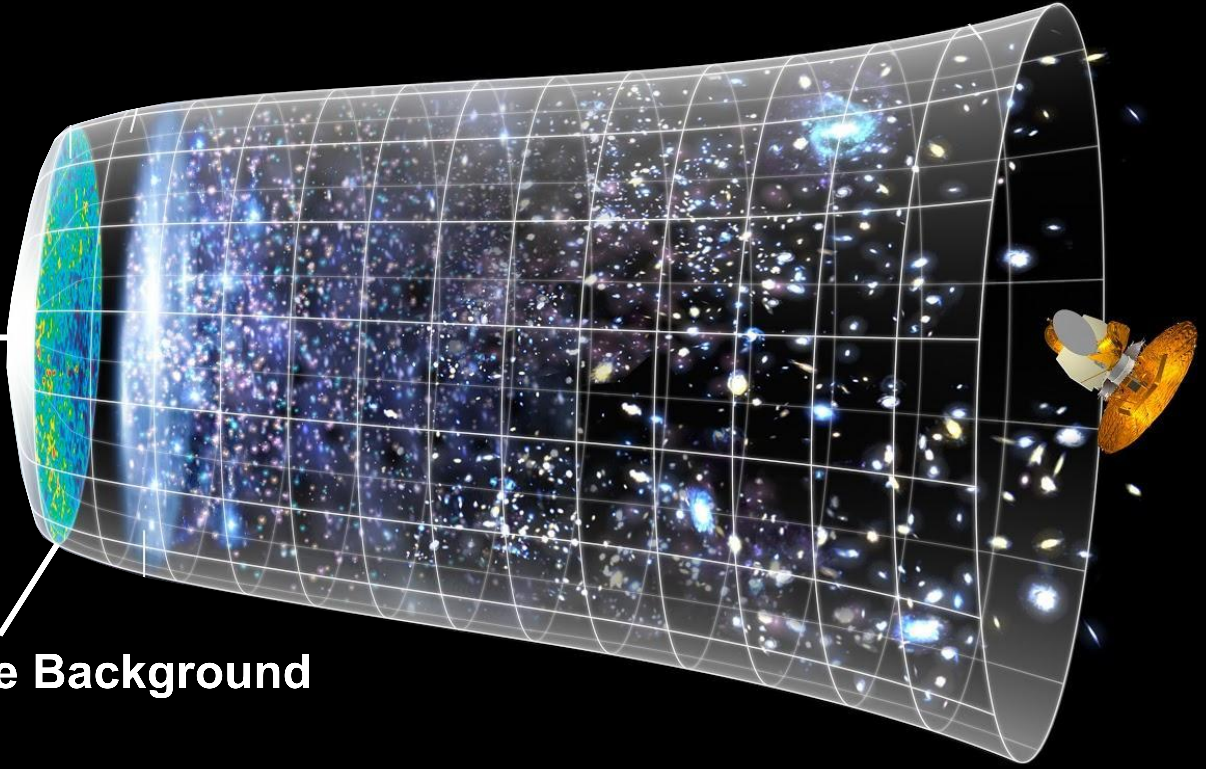
Modern Cosmological Picture



NASA/WMAP
Science Team

Modern Cosmological Picture

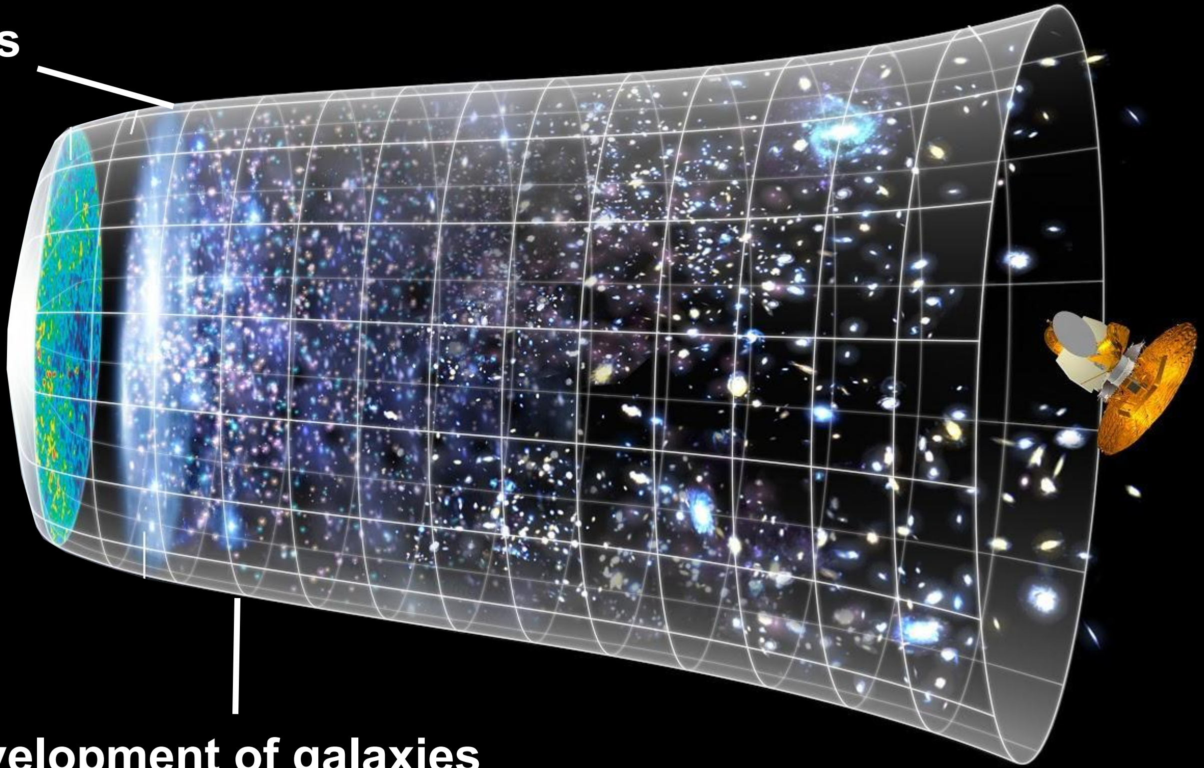
Early hot,
dense state



Cosmic Microwave Background
380,000 yr

NASA/WMAP
Science Team

Modern Cosmological Picture

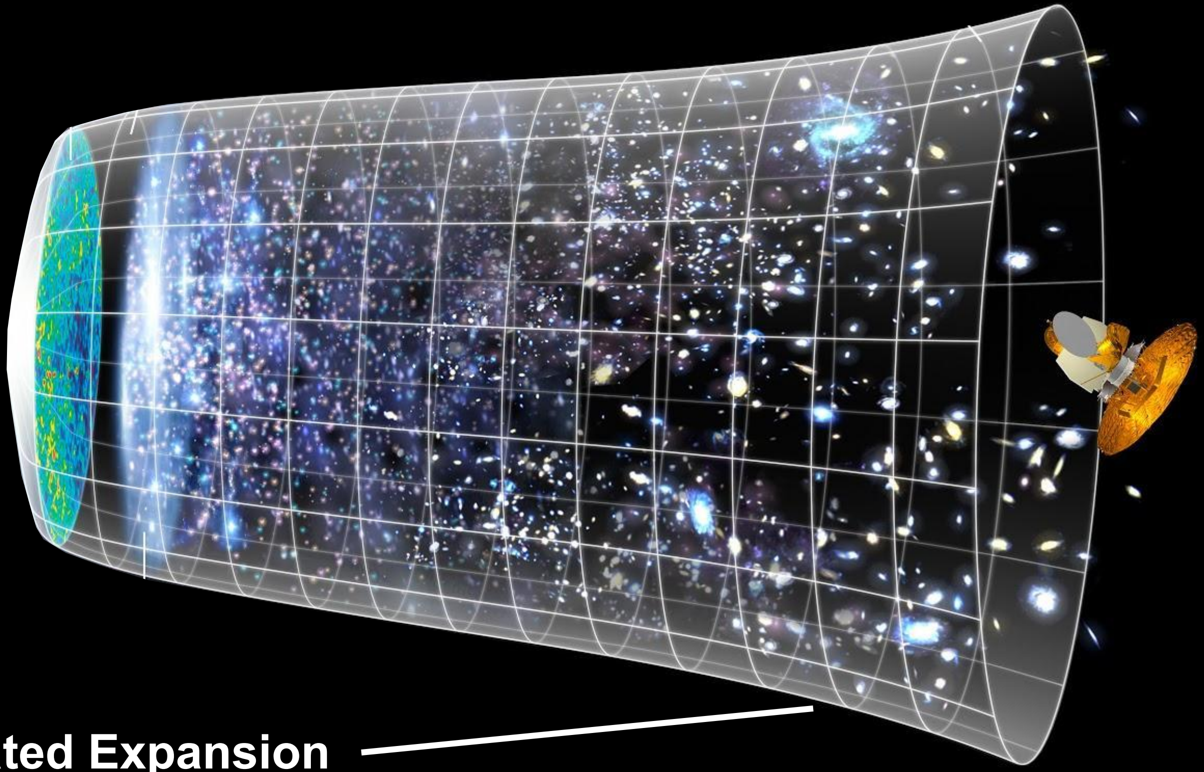


First stars
~400 Myr

Development of galaxies
Reionization

NASA/WMAP
Science Team

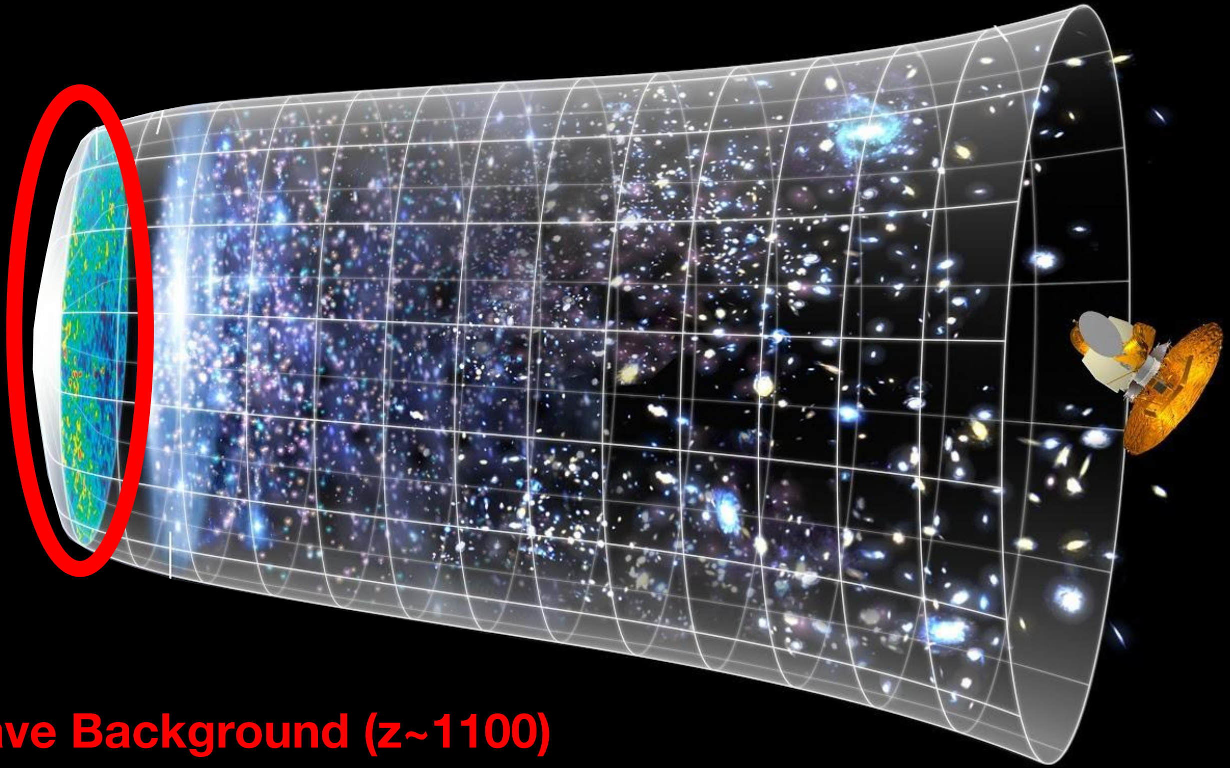
Modern Cosmological Picture



Accelerated Expansion

NASA/WMAP
Science Team

Observational Probes

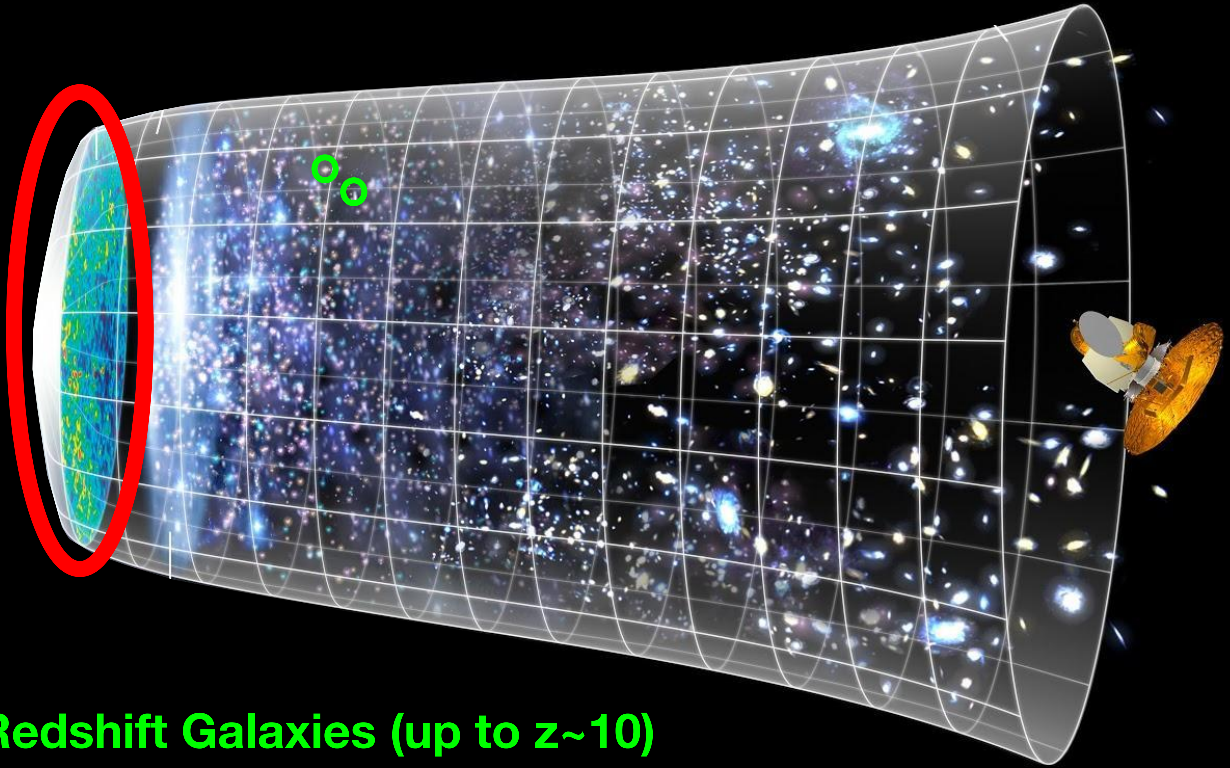


Cosmic Microwave Background (z~1100)

Initial conditions

NASA/WMAP
Science Team

Observational Probes

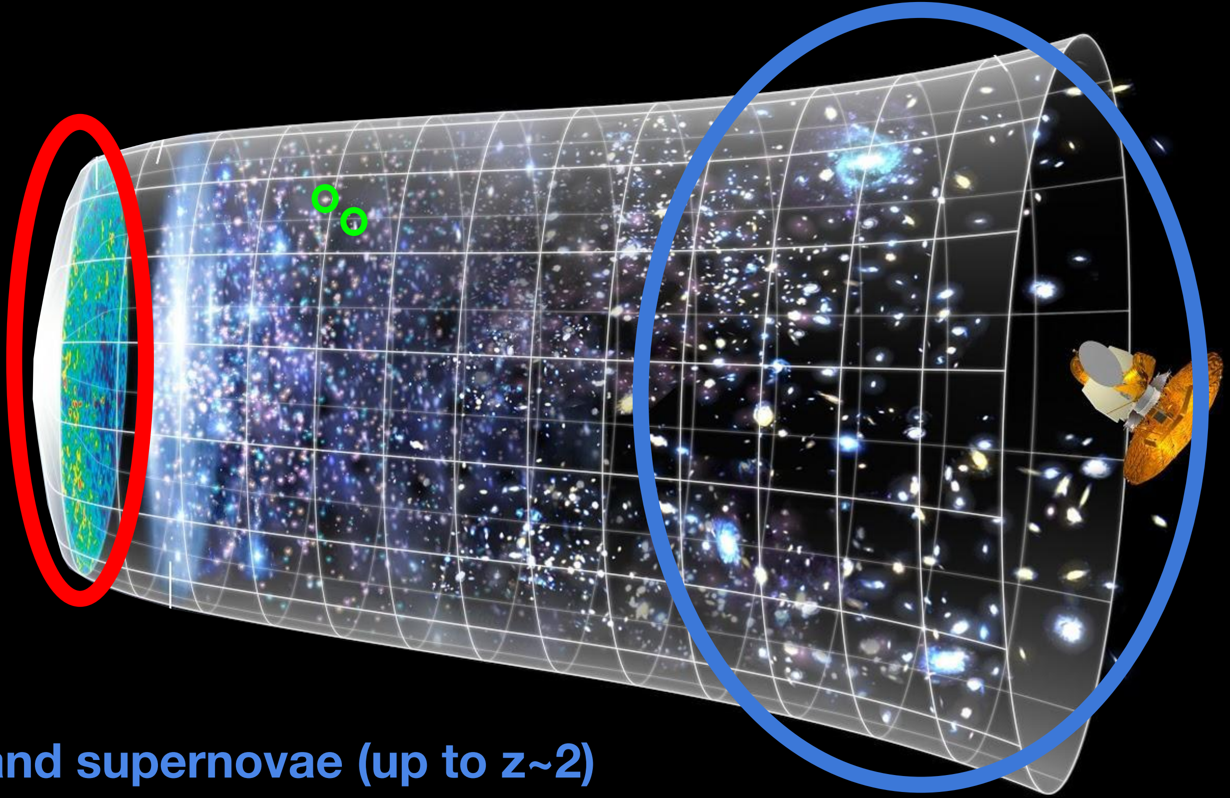


Individual High-Redshift Galaxies (up to z~10)

Atypical bright, massive objects

NASA/WMAP Science Team

Observational Probes

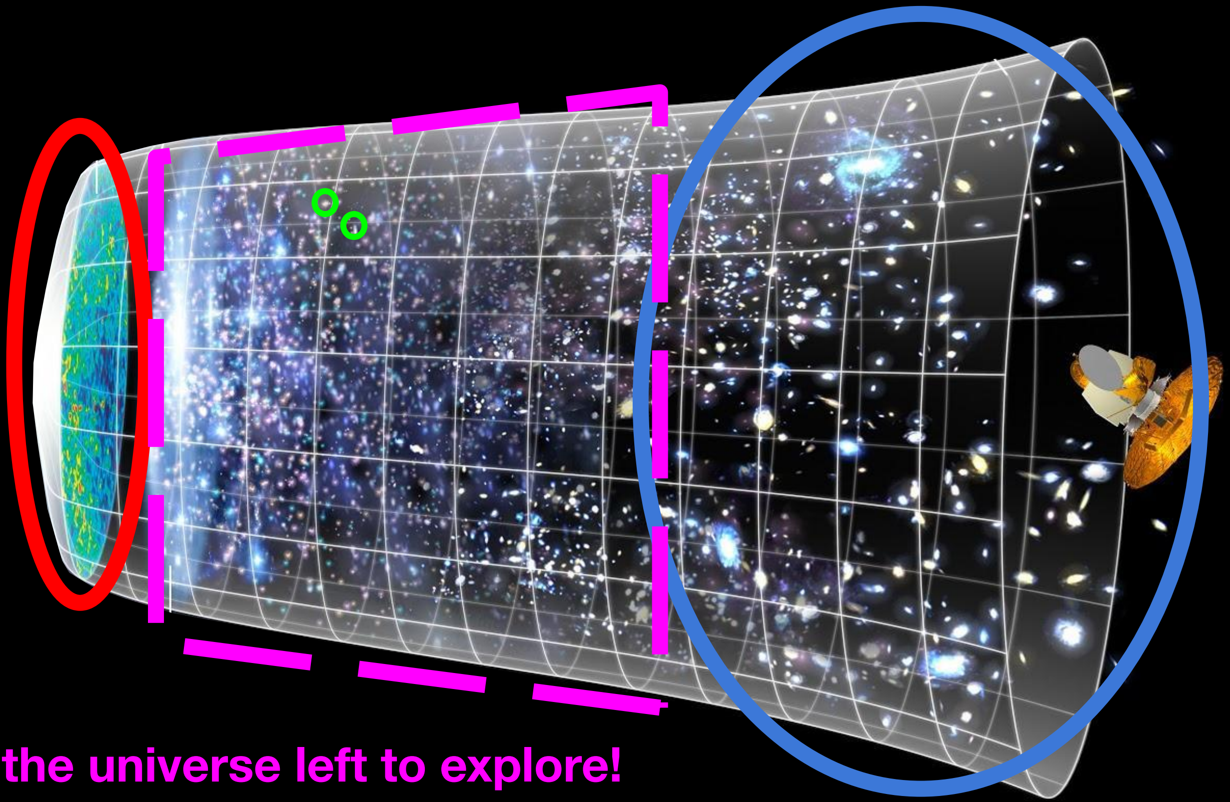


Galaxy surveys and supernovae (up to z~2)

Late-time large-scale structure, Hubble rate

NASA/WMAP Science Team

Observational Probes

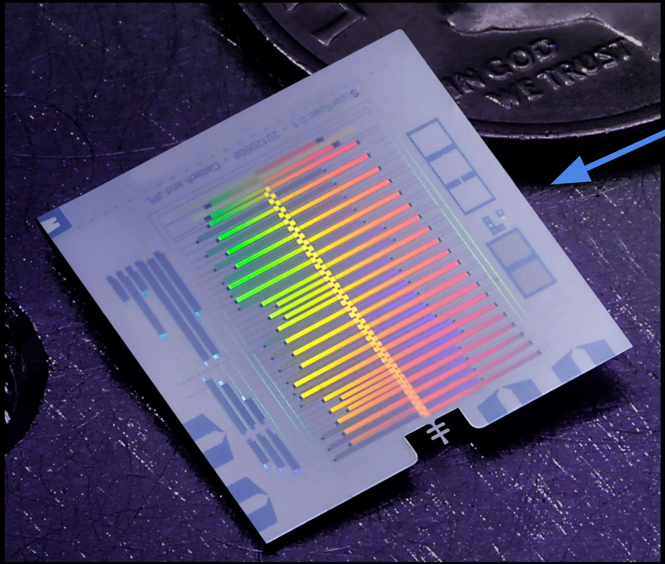


Huge fraction of the universe left to explore!

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?



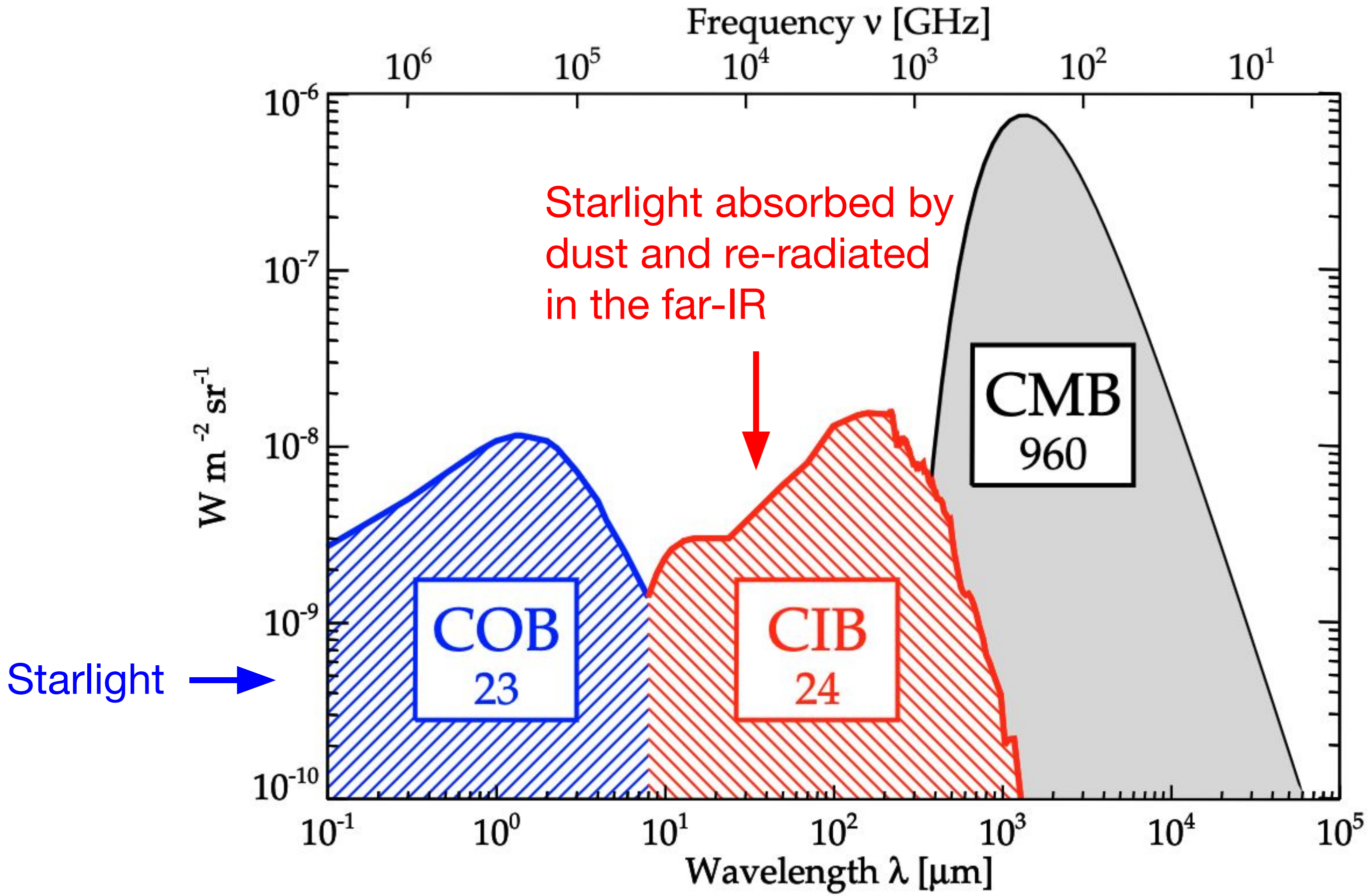
We are now developing the technology (on-chip superconducting millimeter-wave spectrometers)

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.

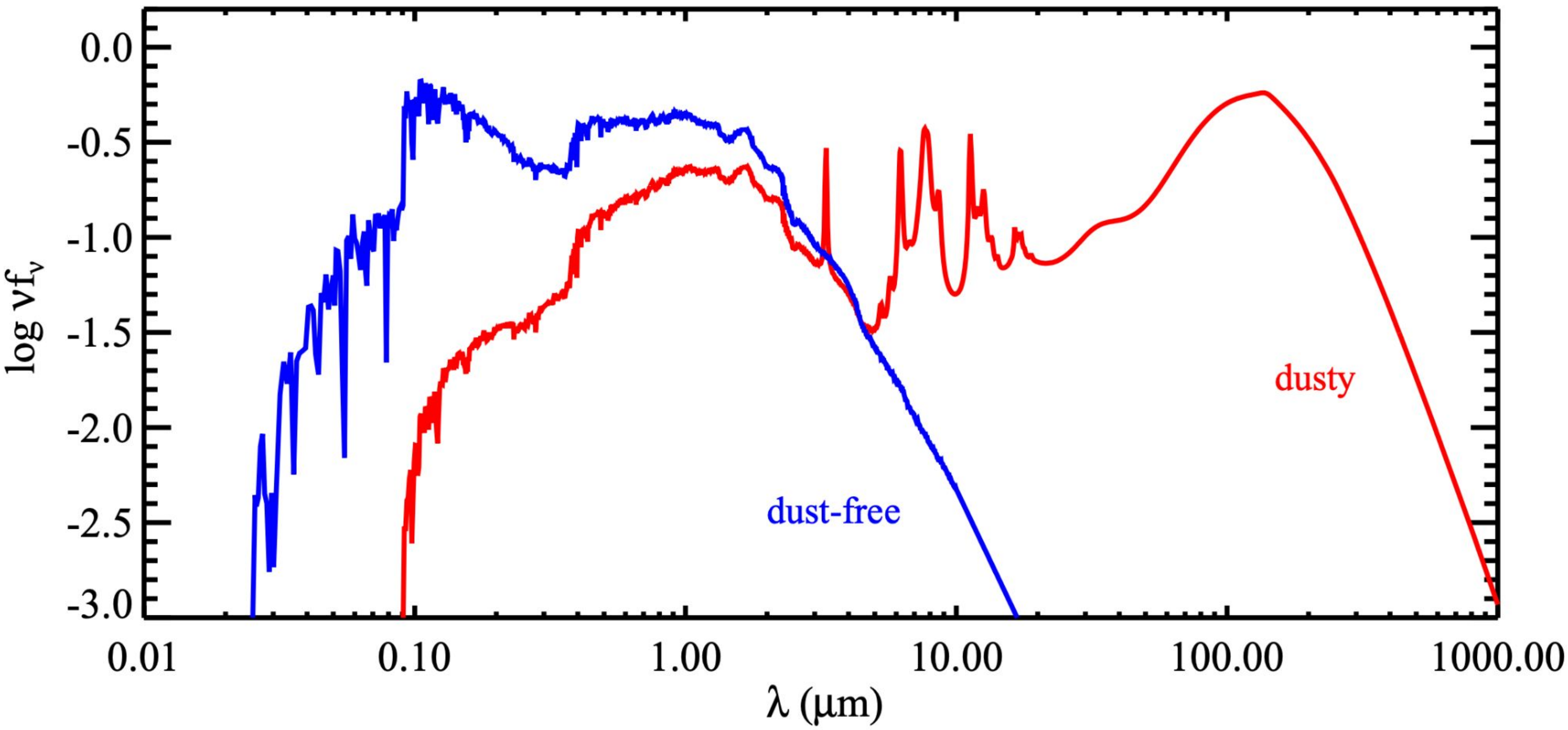
Far-IR is Important!

Dole+ 2006



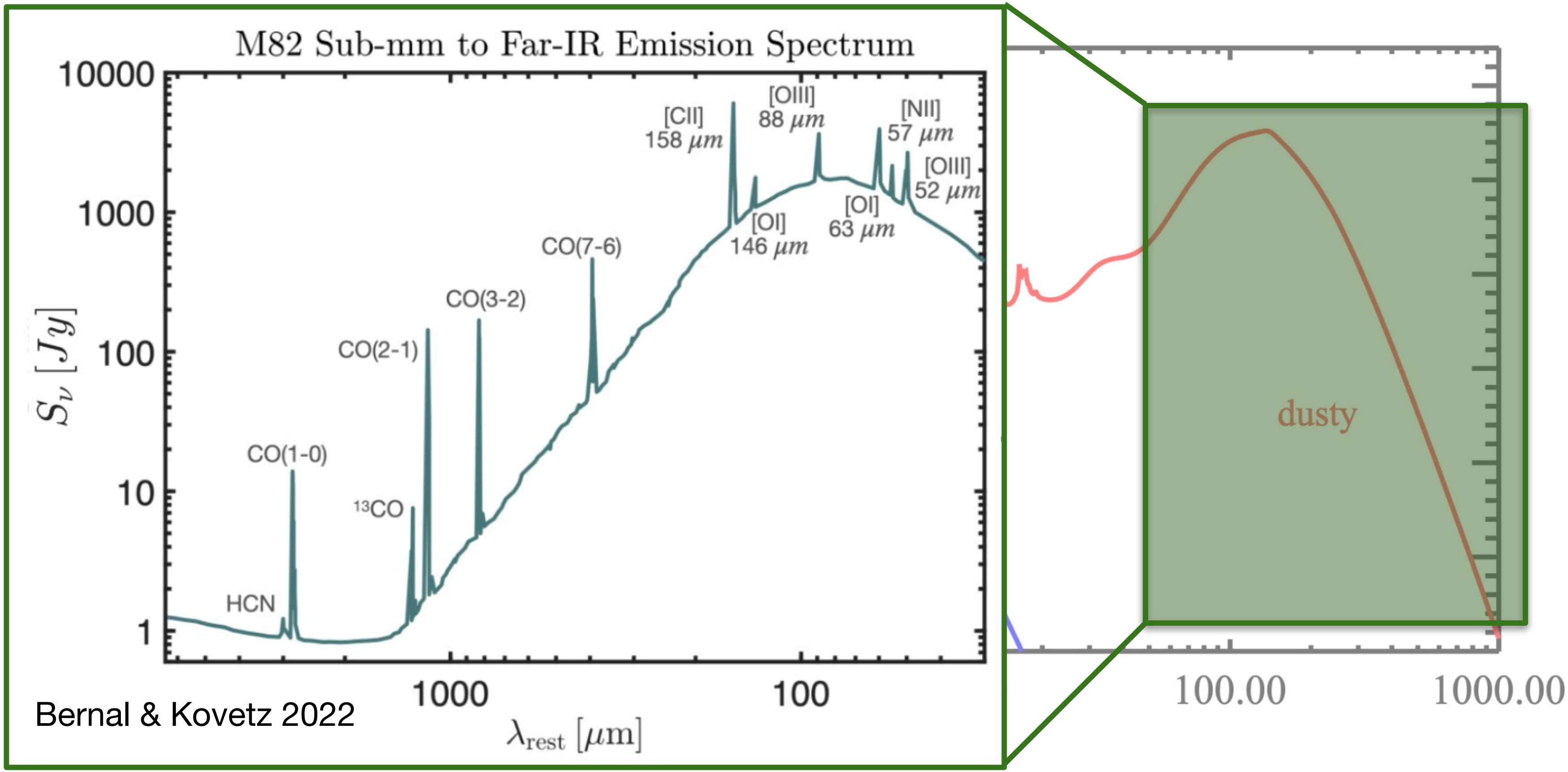
Far-IR is Important!

Conroy ARA&A 2013

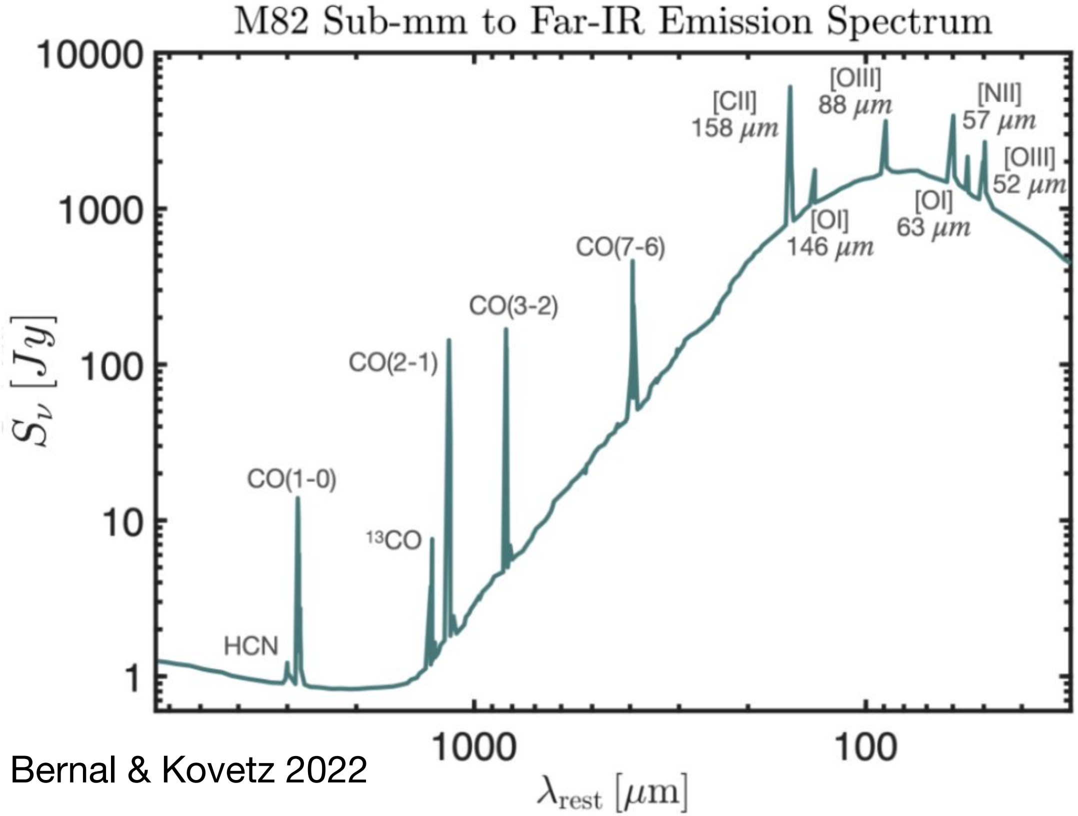


Far-IR is Important!

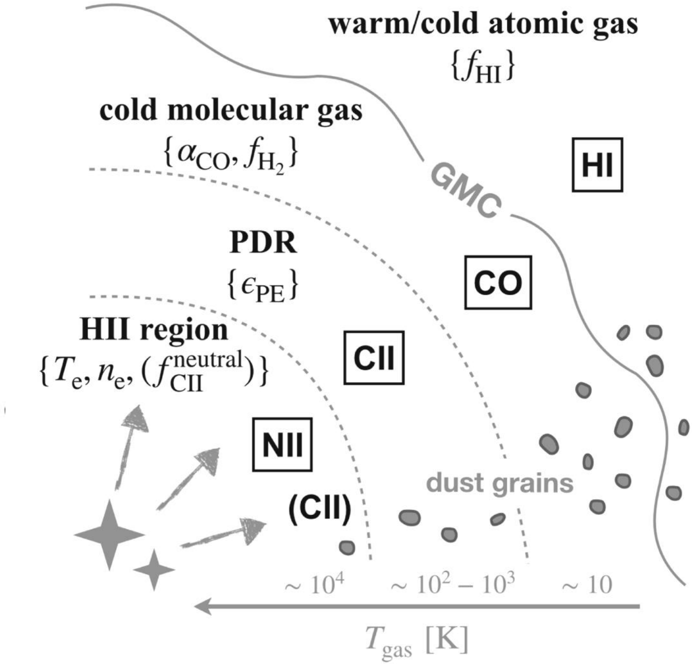
Conroy ARA&A 2013



Far-IR is Important!

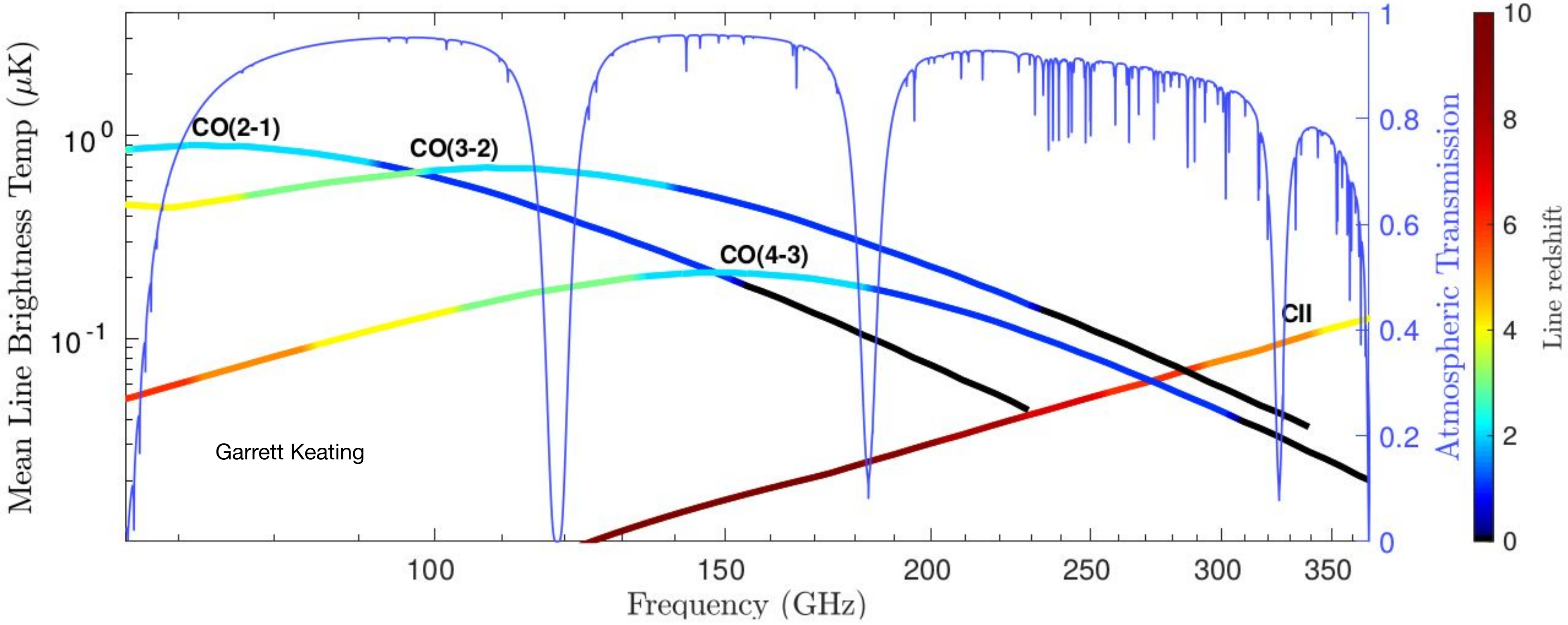


Bernal & Kovetz 2022

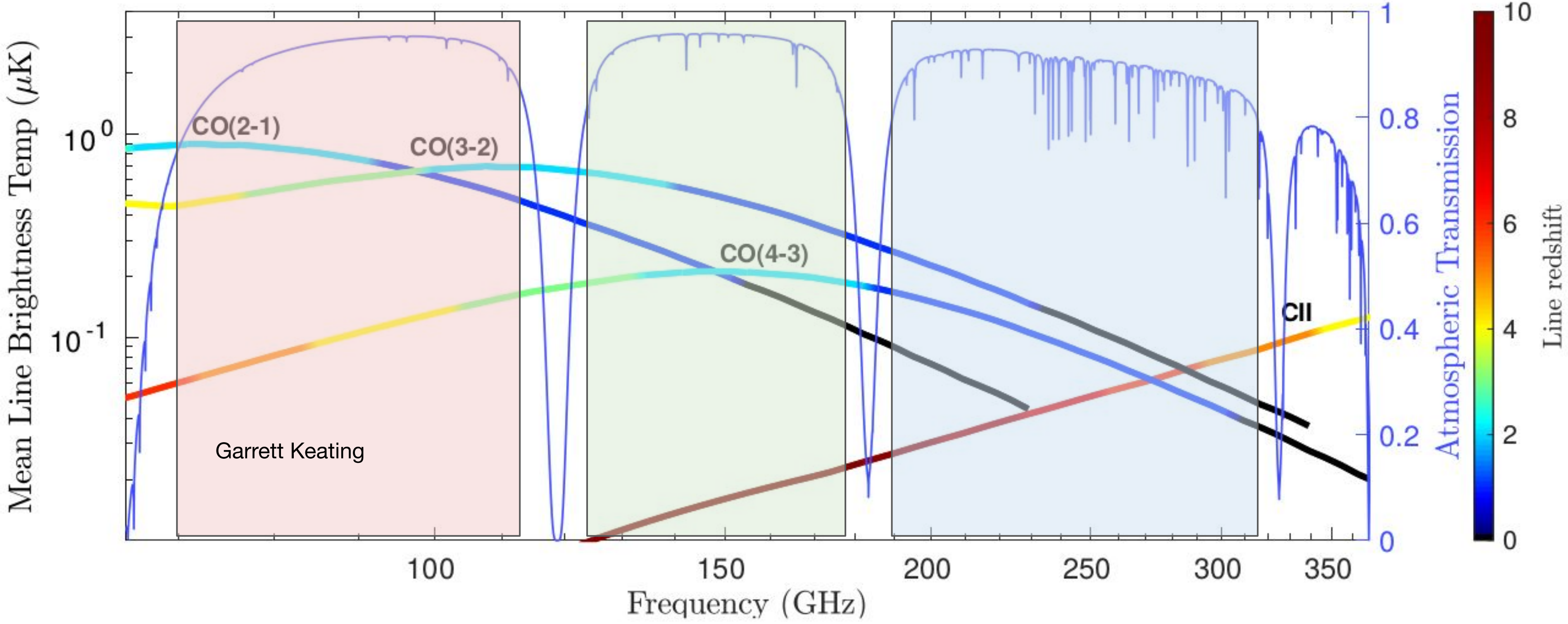


Sun+ 2019

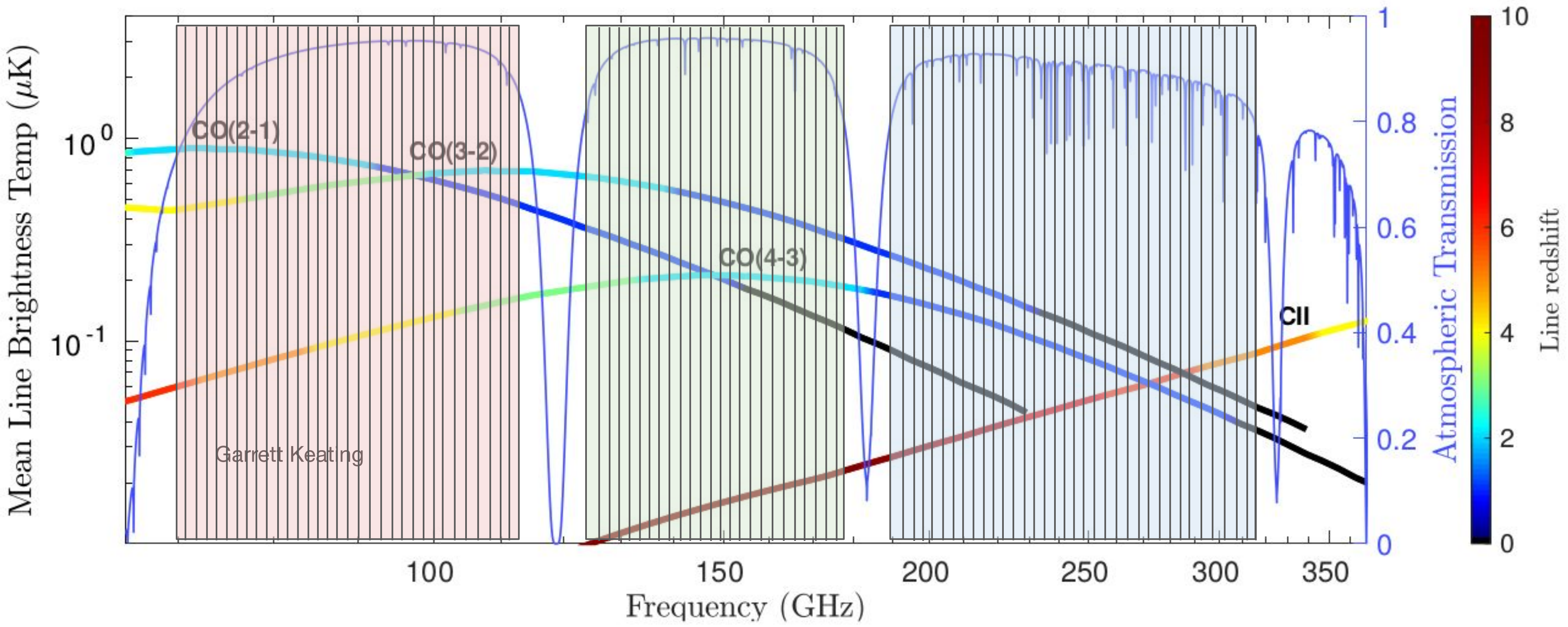
Wide Redshift Coverage in the Millimeter Range



Wide Redshift Coverage in the Millimeter Range



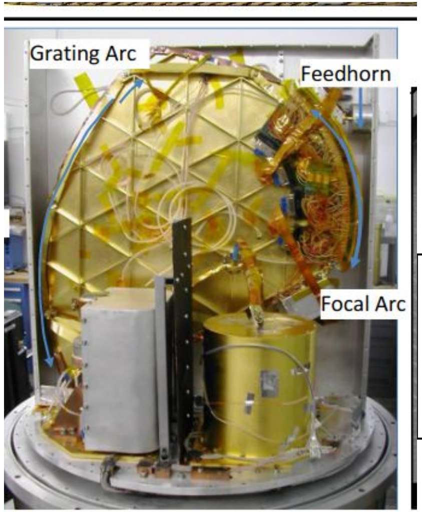
Wide Redshift Coverage in the Millimeter Range



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.

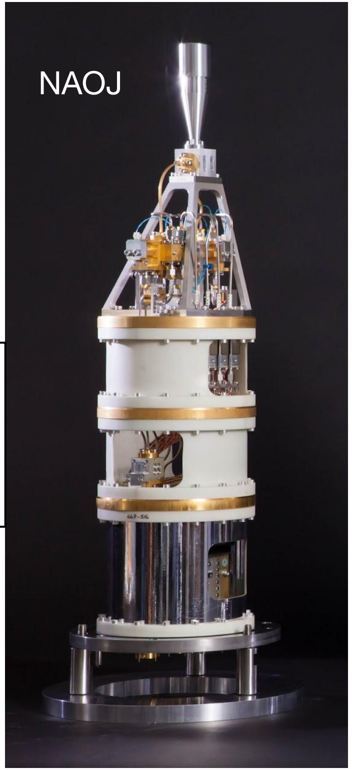
Current instrumentation is insufficient!



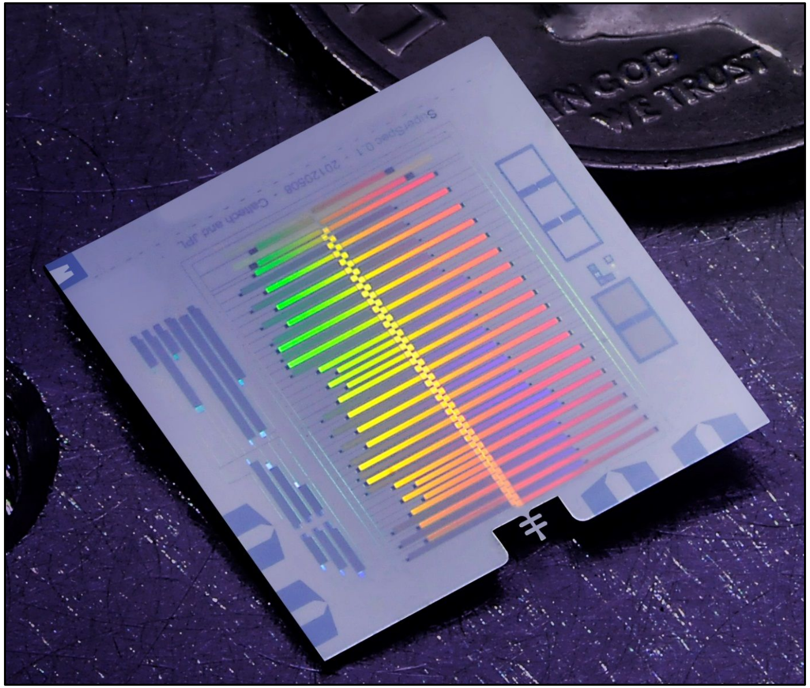
Z-Spec diffraction grating: Wide bandwidth…but the size of a table!

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

Stanford/SLAC
K. S. Karkare

GSFC
J. Glenn

NIST
J. Wheeler

University of Chicago
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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

SuperSpec (Superconducting Spectrometer)

uchicago news

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.

By Louise Lerner
Feb 3, 2023

University of Chicago
R. McGeehan
E. Shirokoff

Arizona State University
K. Massingill
P. Mauskopf

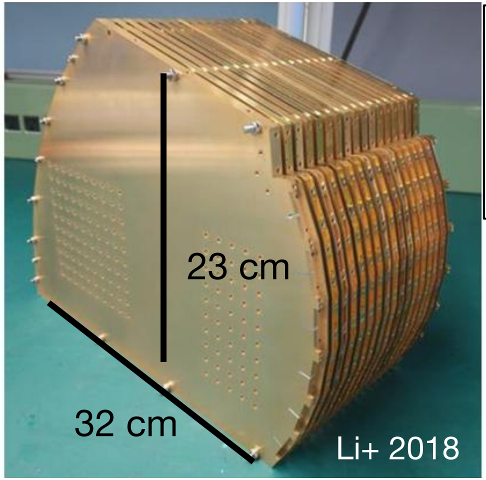
Cardiff University
P. Barry
S. Doyle
C. Tucker

UC Santa Barbara
J. Redford

Dalhousie University
S. Chapman

Design Requirements

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



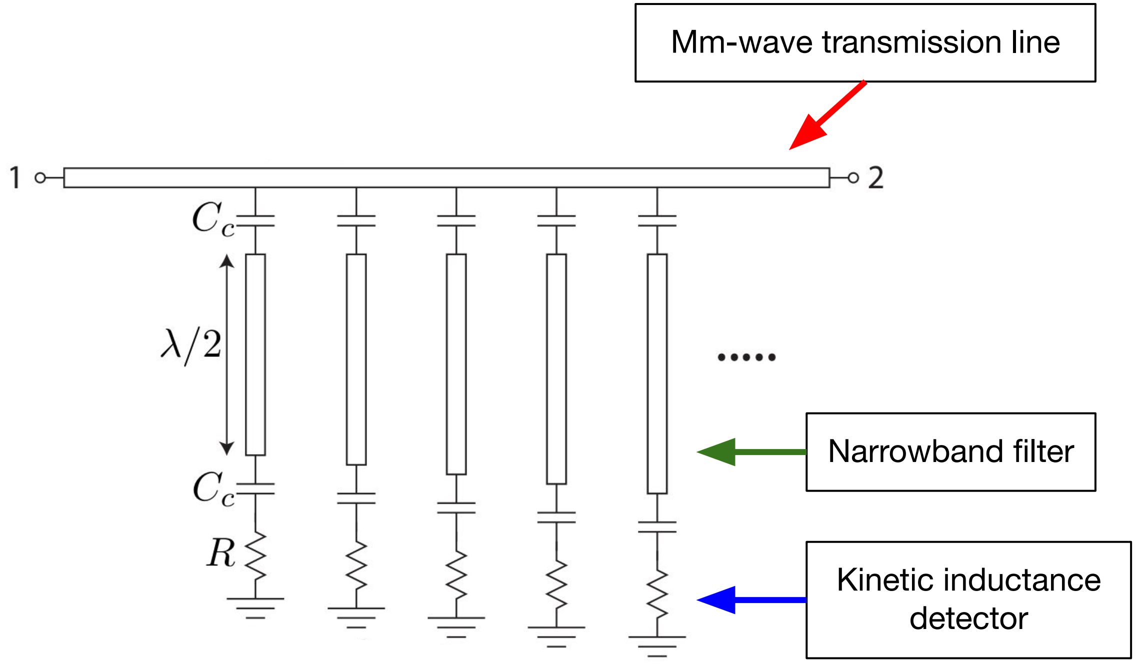
TIME grating:
32 x 23 x 1 cm
~ 736 cm^3

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

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

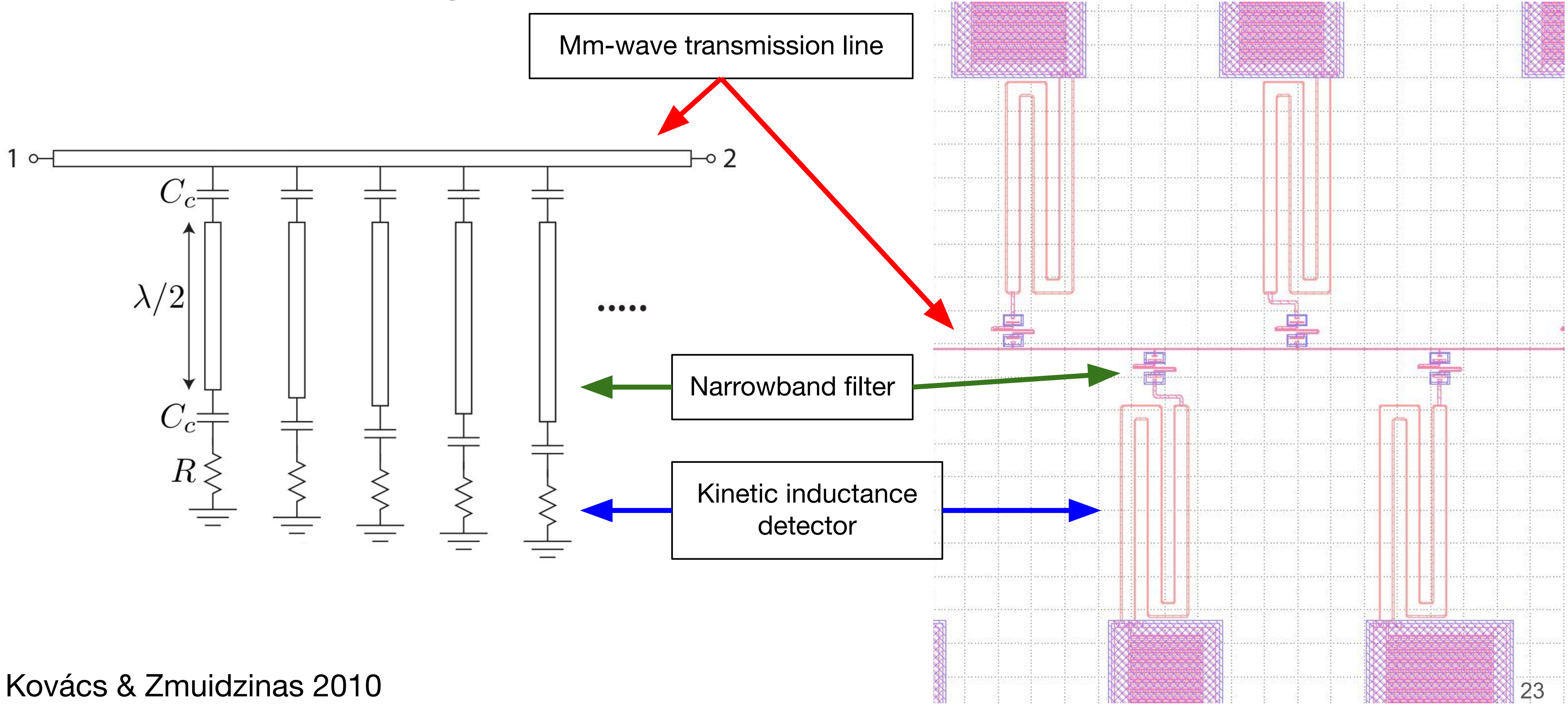
Detect [CII] from reionization-era galaxies: 180-310 GHz, R=λ/Δλ=300 resolution.

A Filter-Bank Spectrometer



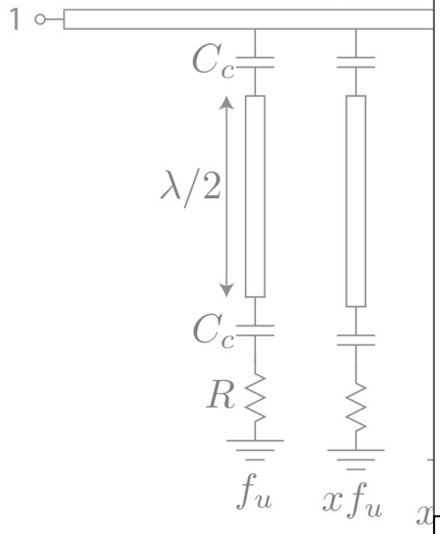
Kovács & Zmuidzinas 2010

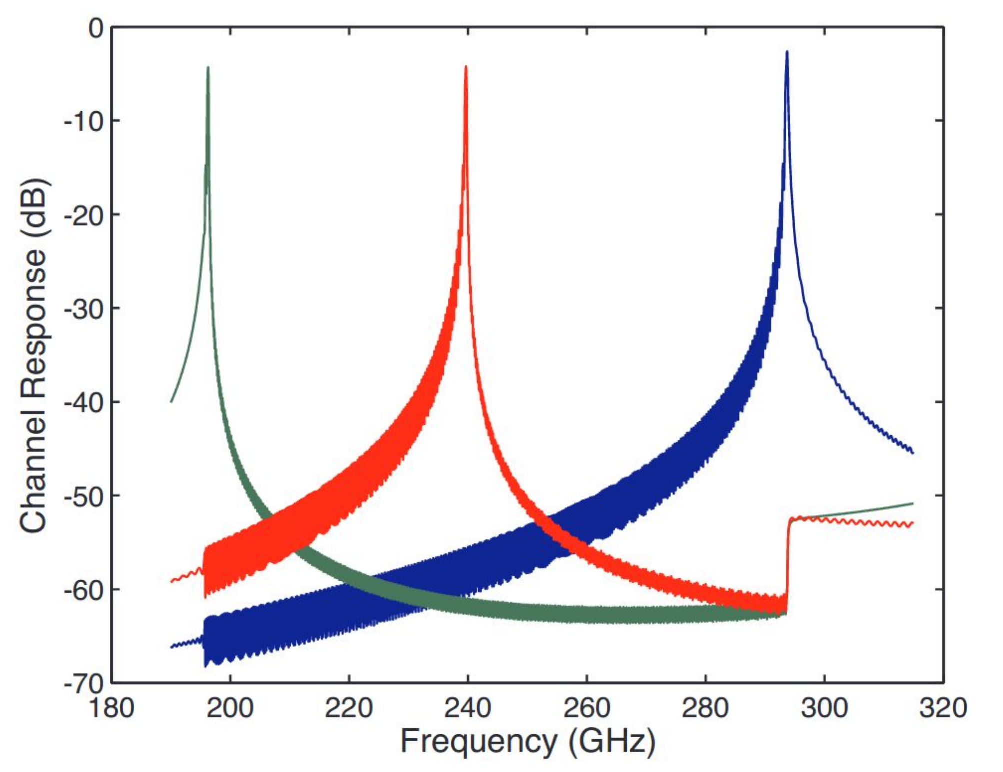
A Filter-Bank Spectrometer Realized with Thin-Film Superconducting Circuits

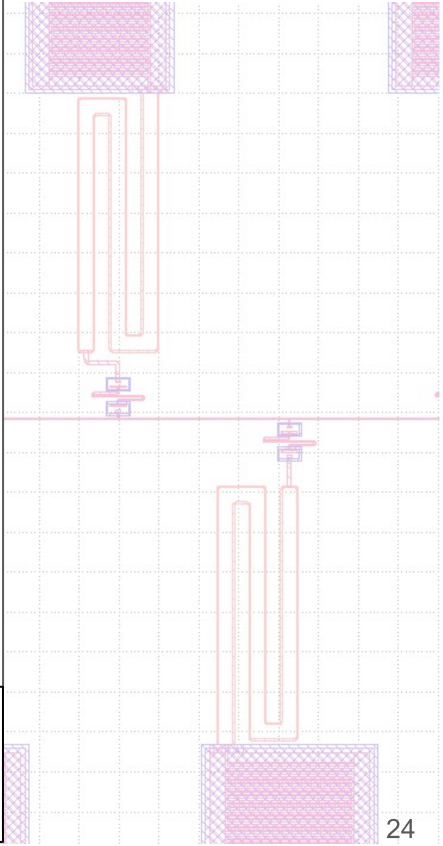


Kovács & Zmuidzinas 2010

A Filter-Bank Spectrometer Realized with Thin-Film Superconduc





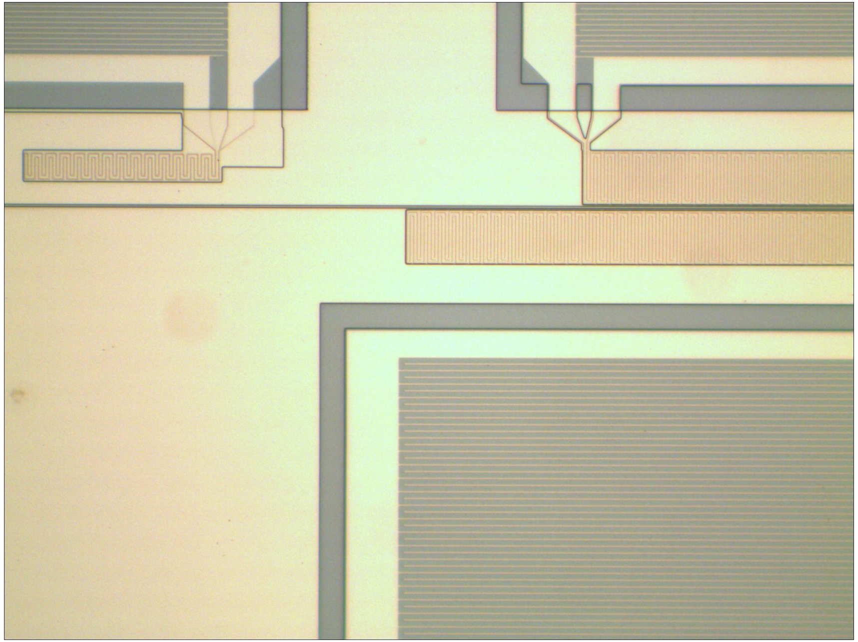


We can tune filter profiles by changing the detector geometry and material properties.

Kovács & Zmuidzinas 201

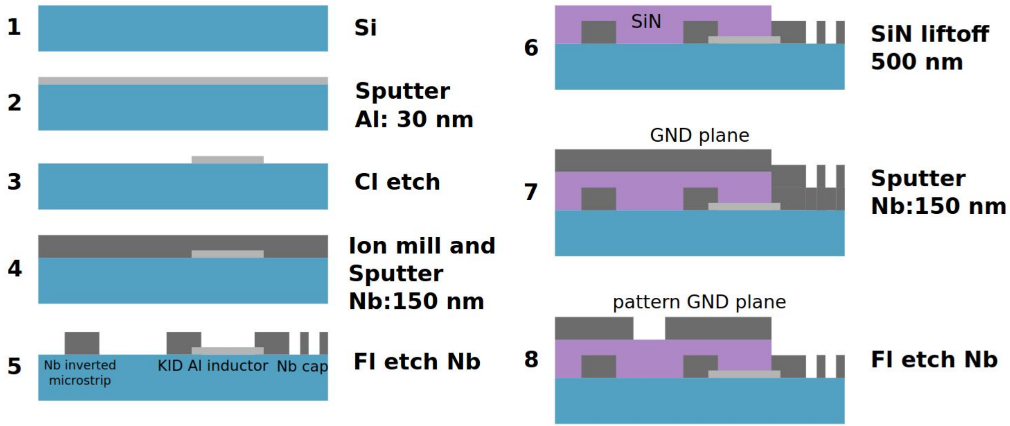
Detector Fabrication

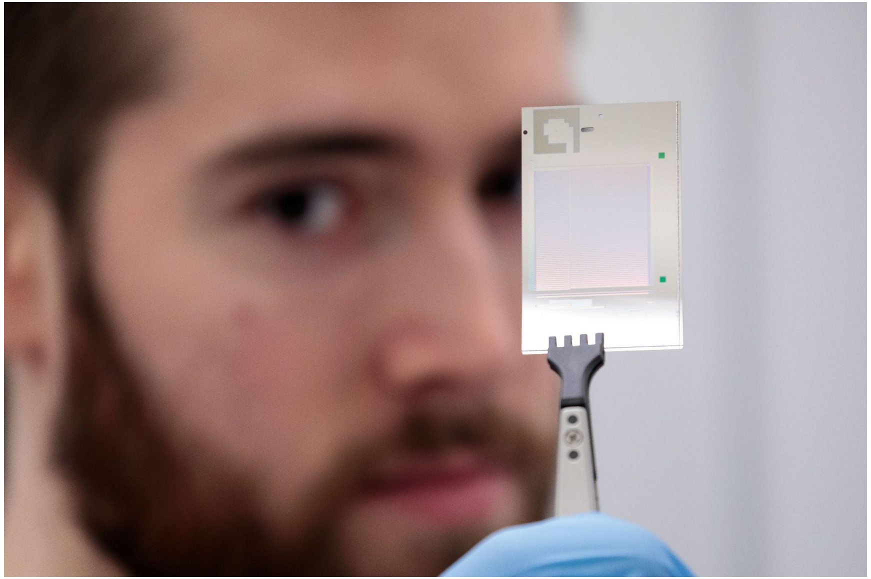
JPL Microdevices Laboratory and
UChicago Pritzker Nanofabrication Facility



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

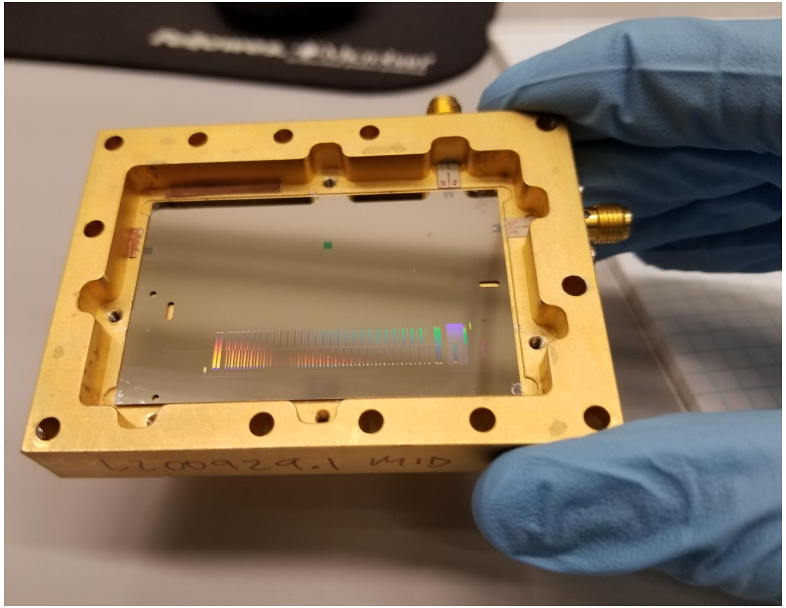
Detector Fabrication

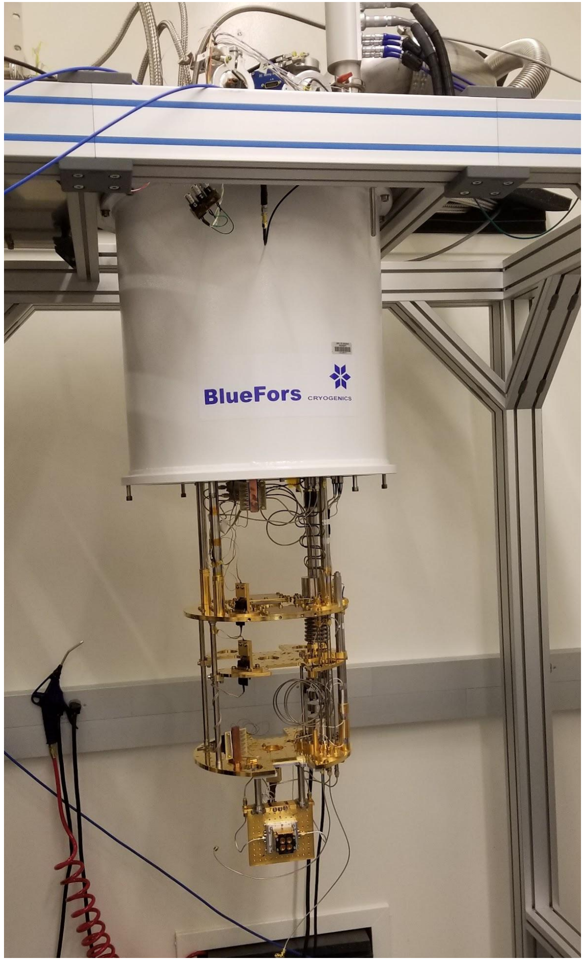




Ryan McGeehan, UChicago Ph.D. 2023
SuperSpec design and fabrication

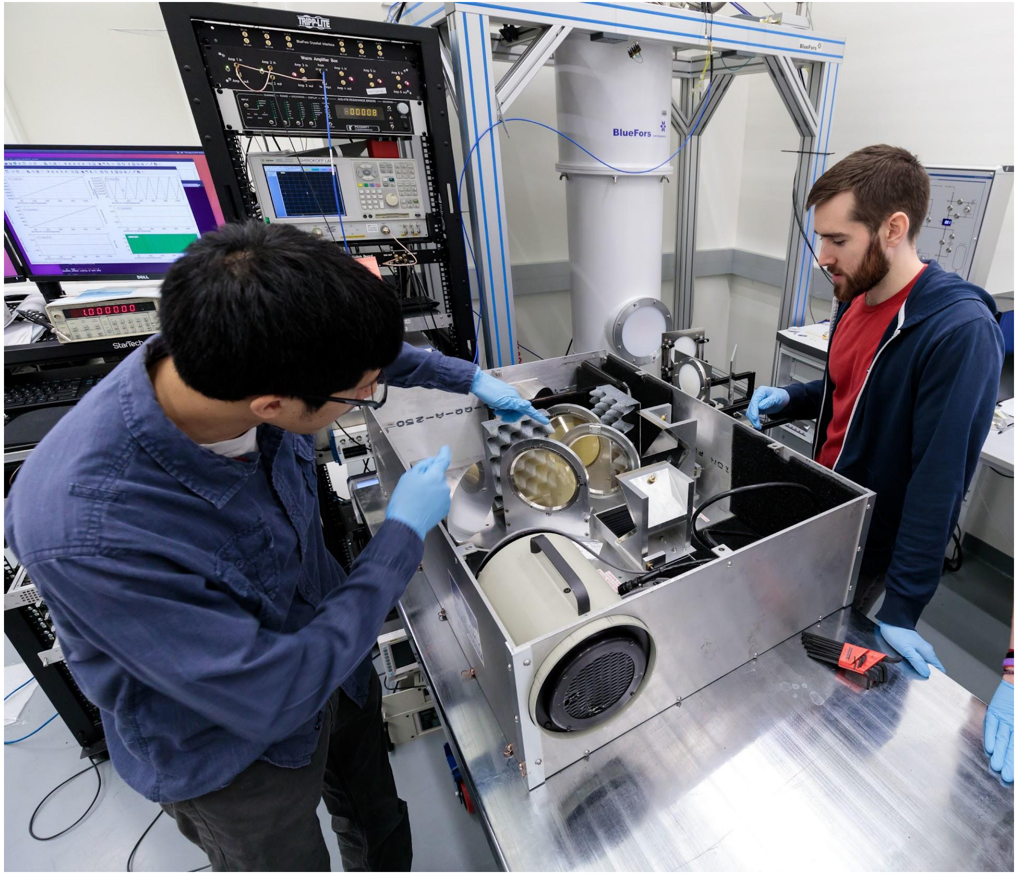
Device Characterization



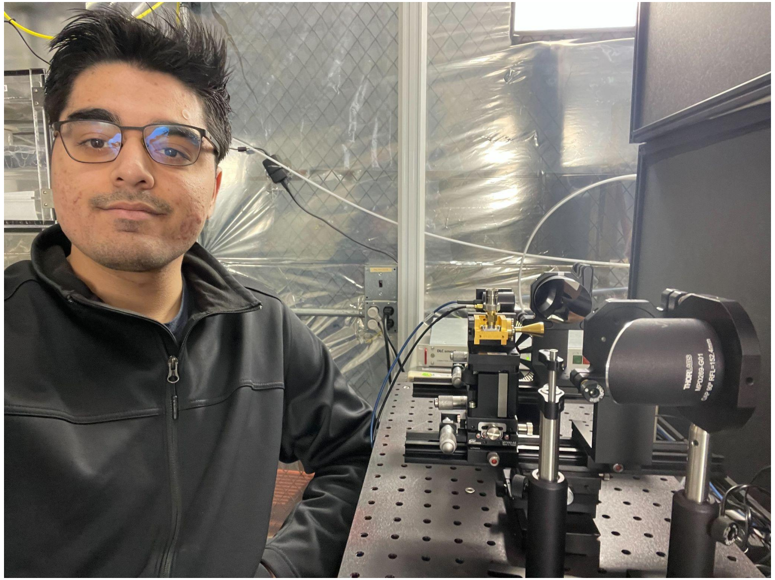


Test devices in a helium dilution refrigerator
(~100 mK required for optimal operation)

Device Characterization: spectral profiles



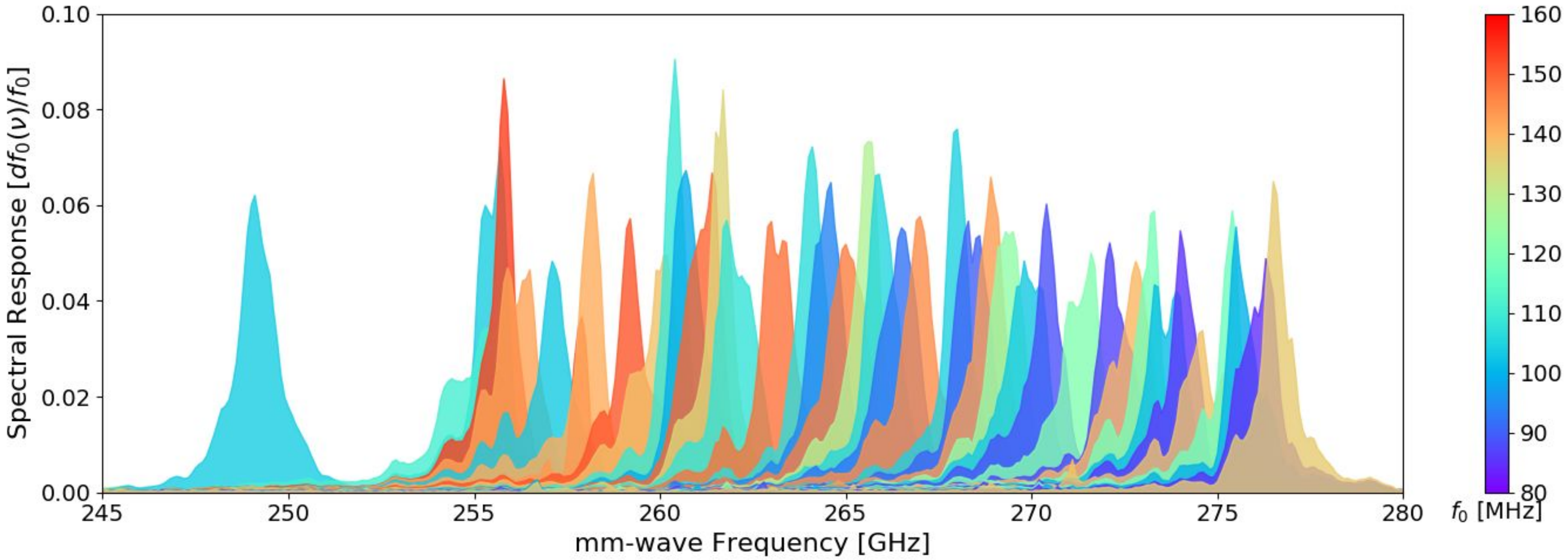
Fourier Transform spectroscopy and narrowband THz source



Abraar Saleem, KIPAC Post-bac

The Spectrometer Works!

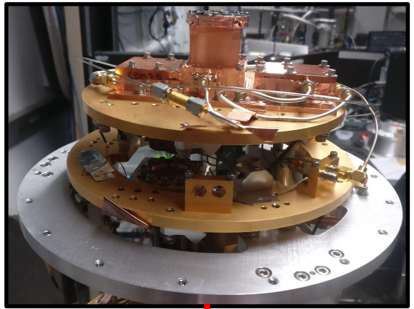
Karkare+ J. Low Temp. Phys.
2002.04542

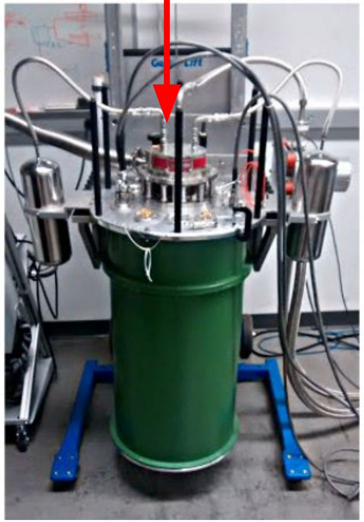


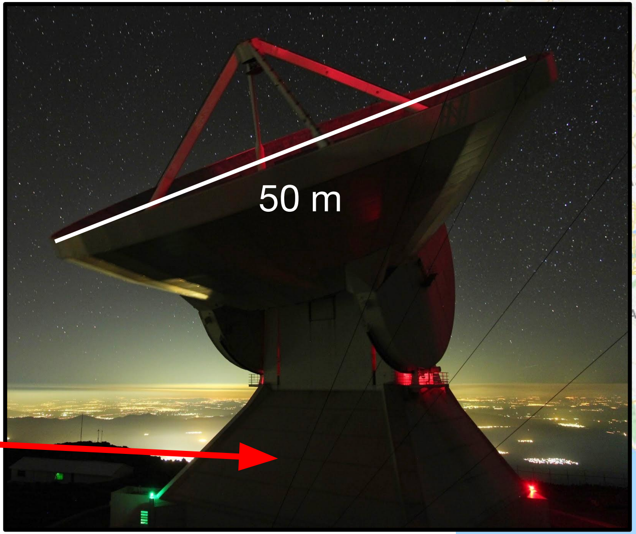
Each channel sees a different mm-wave frequency with R~275 spectral resolution.

On-Sky Demonstration

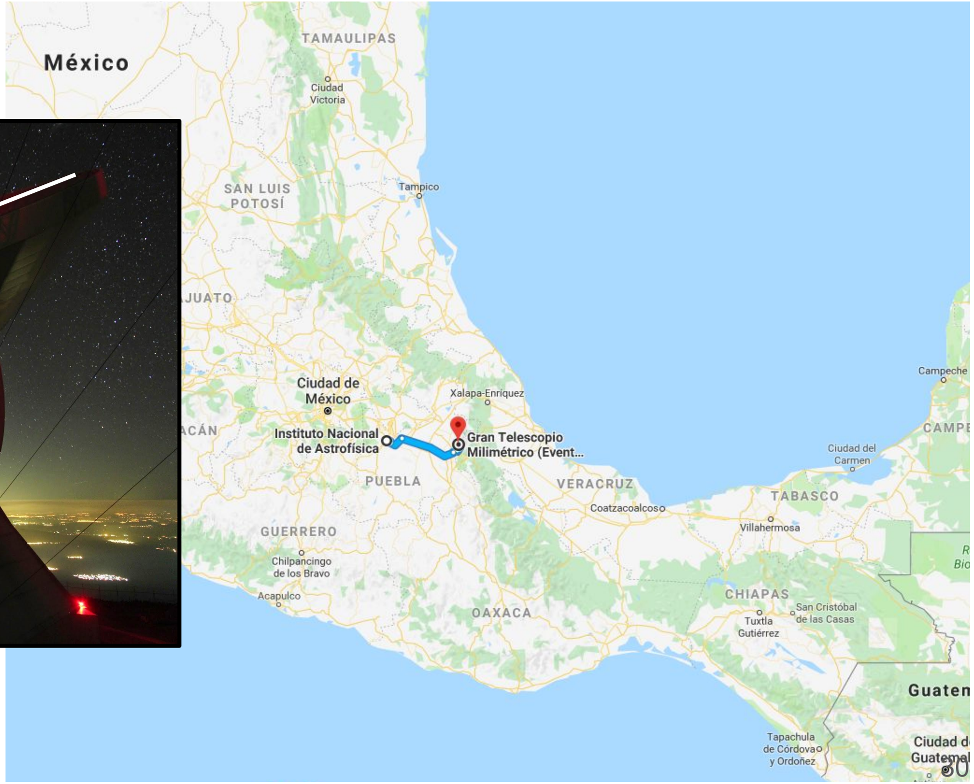
We are now deploying a 6-spectrometer receiver to the Large Millimeter Telescope in Mexico – an ideal facility for pointed observations of high-z galaxies.







lmtgtm.org



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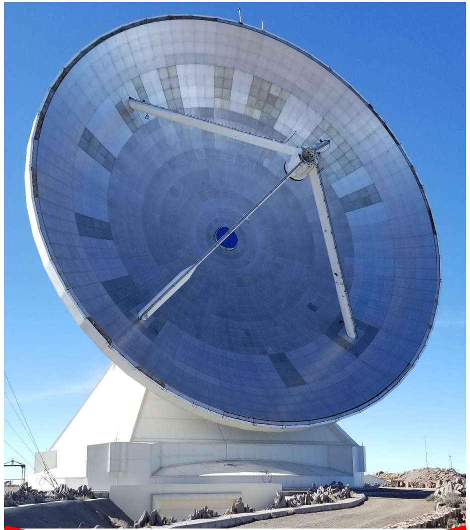

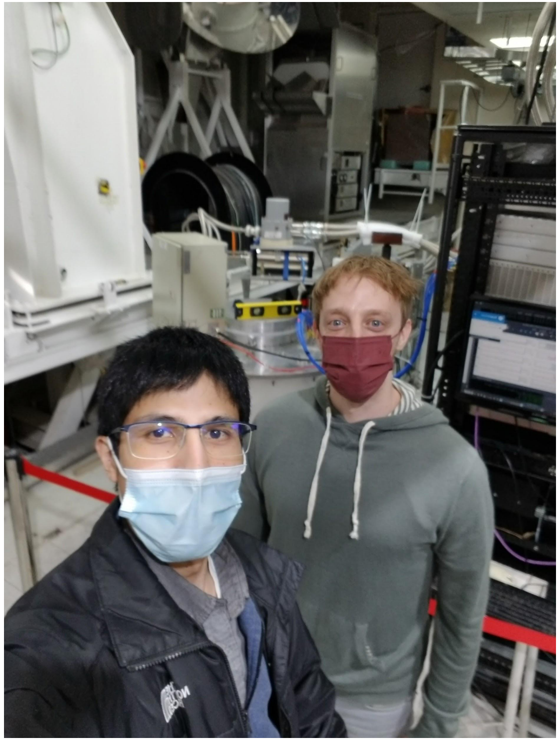

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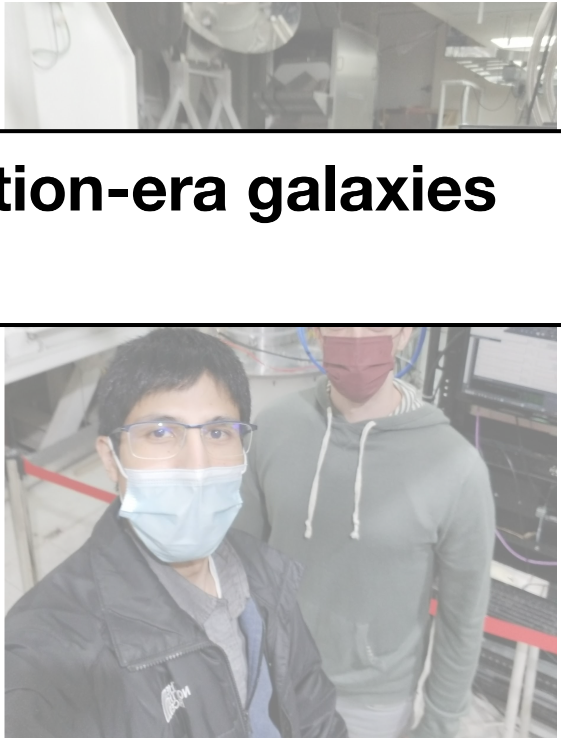


First light and detections of reionization-era galaxies coming soon!

Part 1 Recap: Millimeter-Wave Spectroscopy

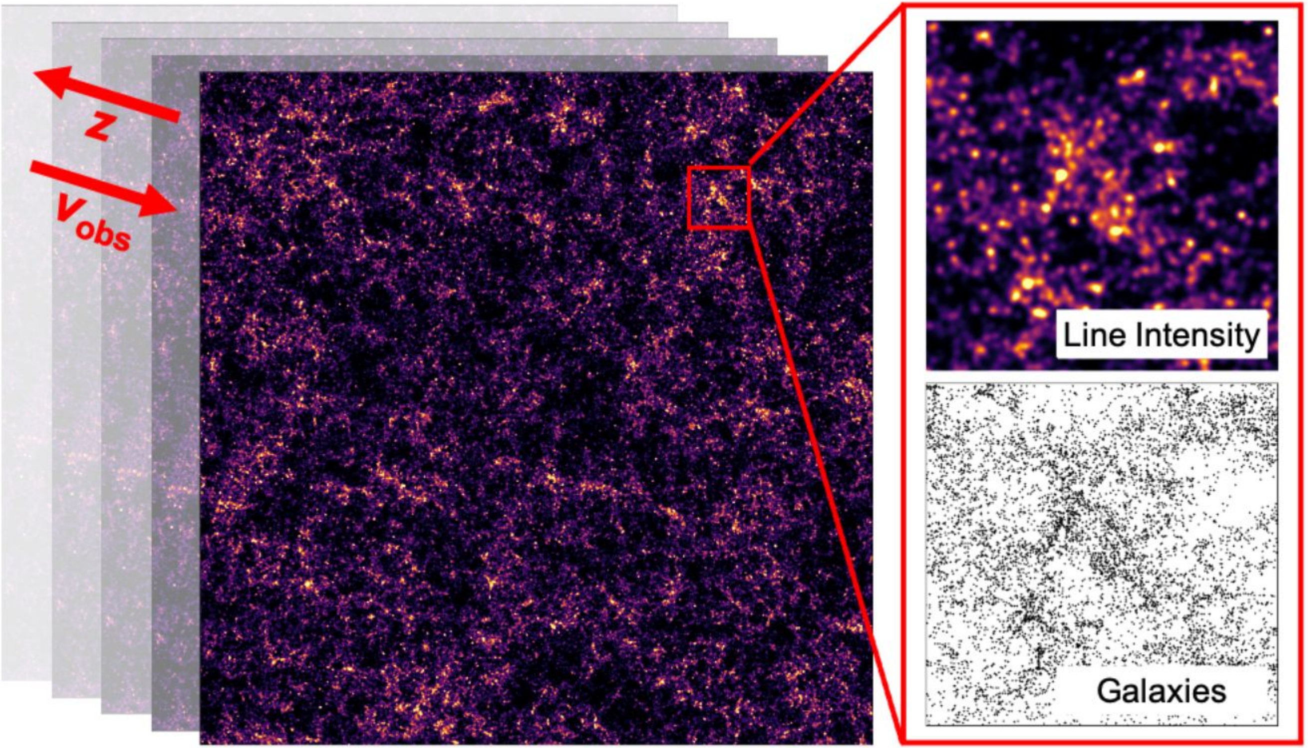
With SuperSpec we've developed **on-chip mm-wave spectrometer technology**, enabling multi-pixel, wide-bandwidth observations of optically-faint (but far-IR bright), high-redshift galaxies.

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).

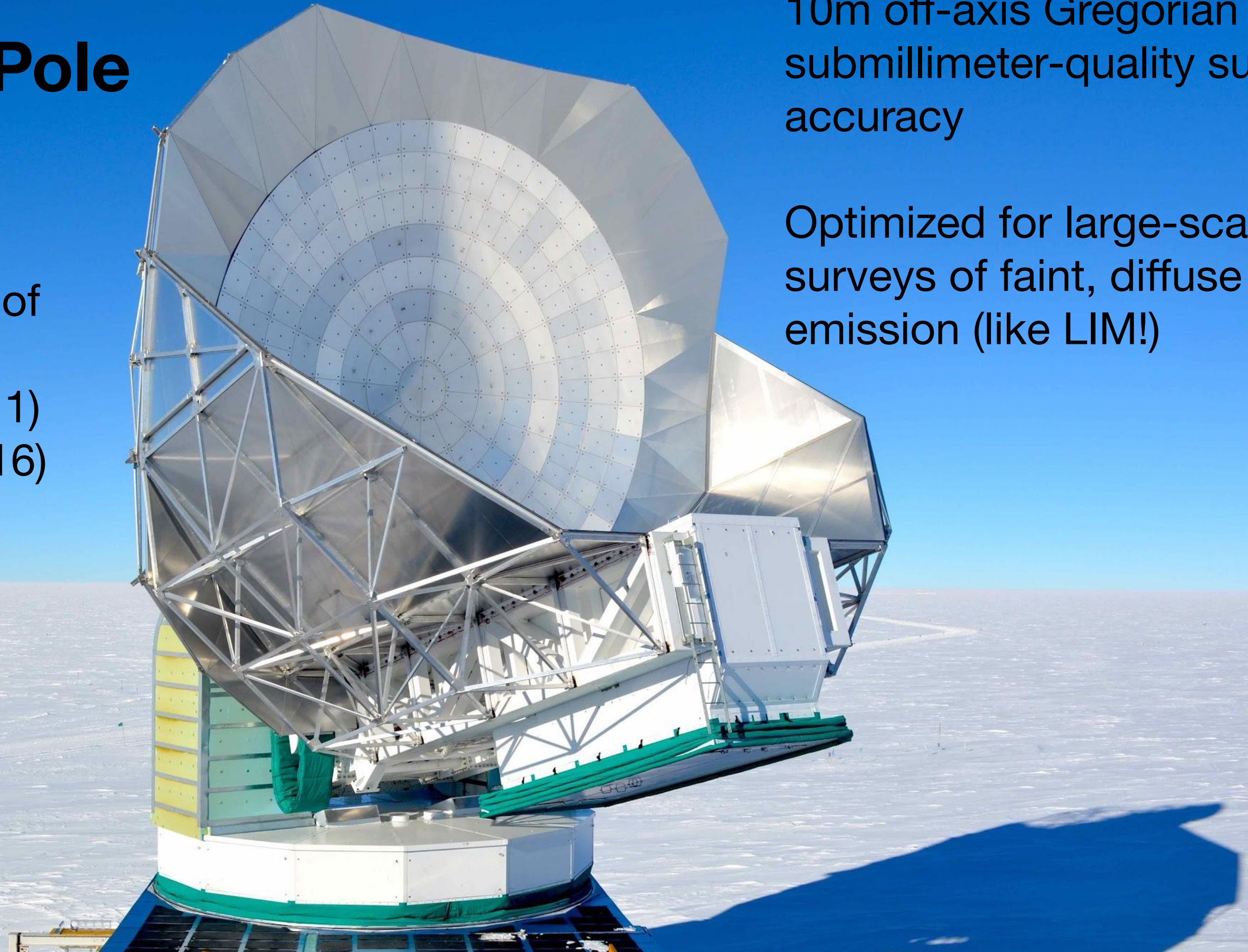
Works with any line:
21cm, CO/[CII], Hα/Lyα

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 Summertime Line Intensity Mapper (SPT-SLIM)

Argonne
T. Cecil
C. Chang
Z. Pan

Cardiff
P. Barry
G. Robson

CfA
G. Keating

Fermilab
A. Anderson
B. Benson
M. Young

McGill
M. Adamic
M. Dobbs
M. Rouble

SLAC/Stanford
K. S. Karkare
A. Saleem
C. Zhang
Z. Zhang

U. Arizona
D. Kim
D. Marrone

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

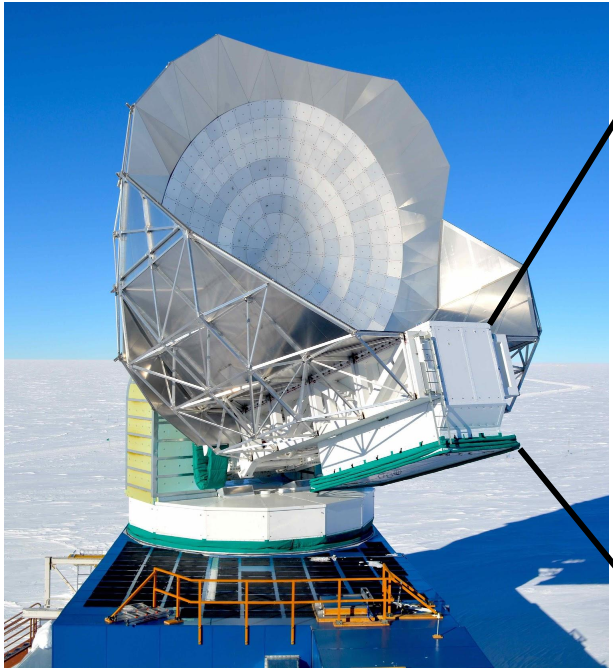
Student
Postdoc
co-PI

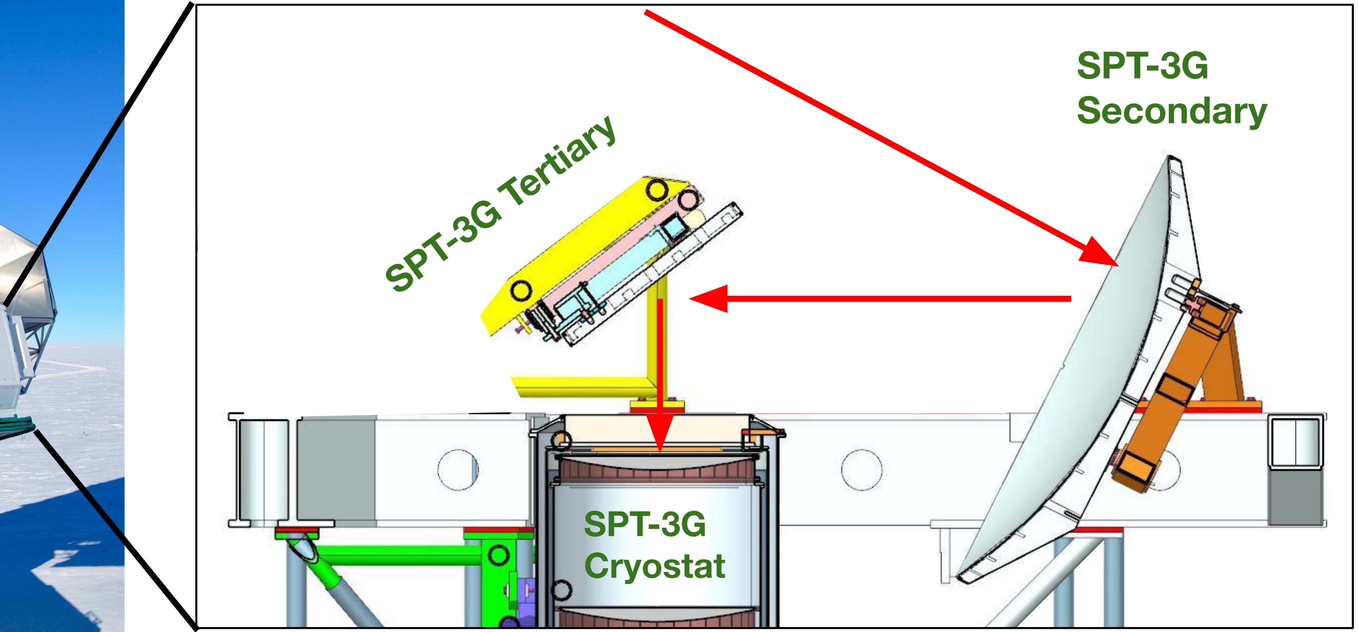
Deploy a LIM pathfinder to the South Pole Telescope during the austral summer season (Nov–Feb) while SPT-3G is not observing.

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

Fully funded by NSF and Fermilab in 2021.

The SPT Summertime Line Intensity Mapper (SPT-SLIM)

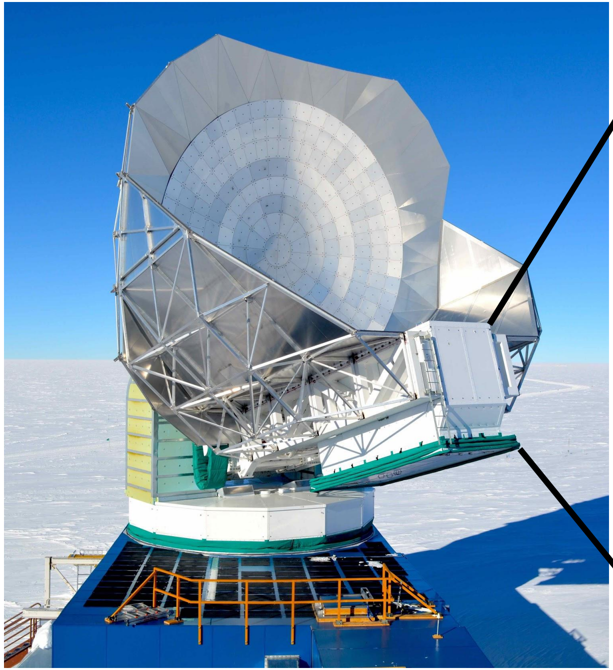


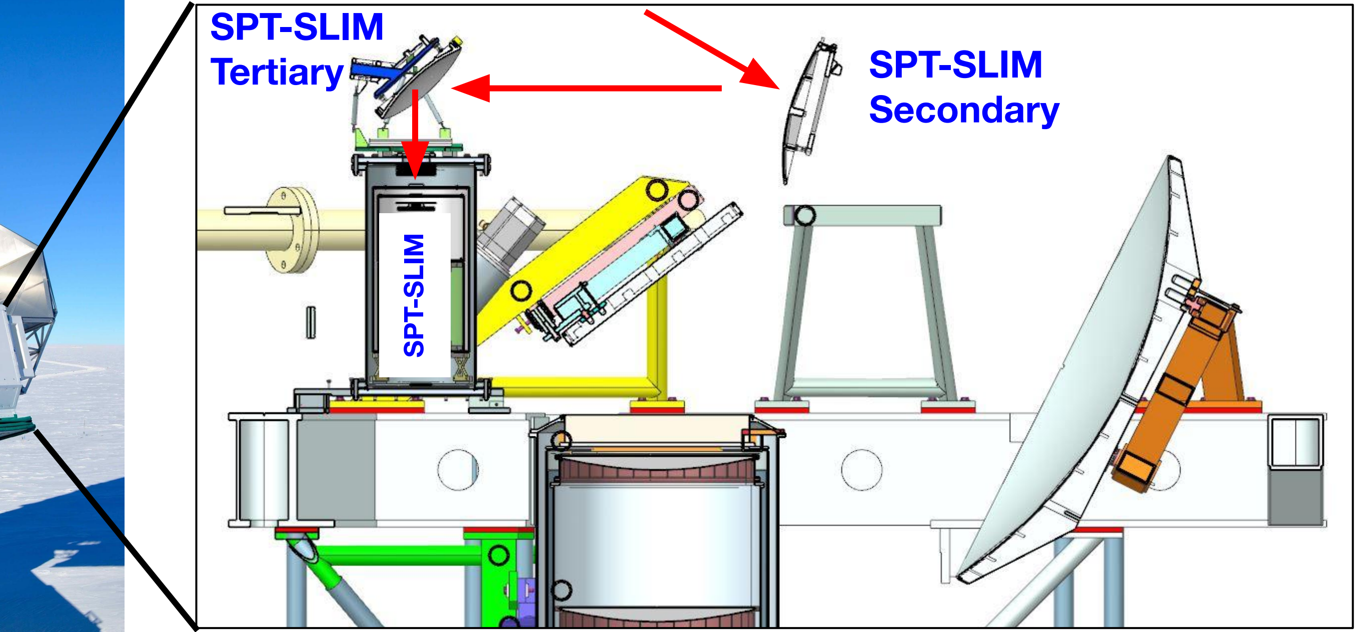


In normal operation, light from the primary is reflected into the receiver cabin, and then into the SPT-3G cryostat…

Karkare+ J. Low Temp. Phys.
2111.04631

The SPT 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)

Comments

foamlinx 11w

Telescope Prototype to be placed in the South Pole, for making images and measure the Cosmic Microwave Background light. How cool is that? #telescope #telescopes #cmb #prototype #prototypes #prototyping #foamprototype #cosmic #cosmiclight #southpole #data #props #mockup #mockups #mockupdesign #foammodel #bigband #science #southpolestation #energy #science #scientist #cnc #machining #router #cncroutercutting

Verifying the Fit (with the help of wecutfoam.com)

Comments

foamlinx 11w
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astronomy_beginner 11w
It sound crazy
Reply Send

foamlinx 11w
Haha I know, the future is now! Science fiction is no longer fiction
Reply Send

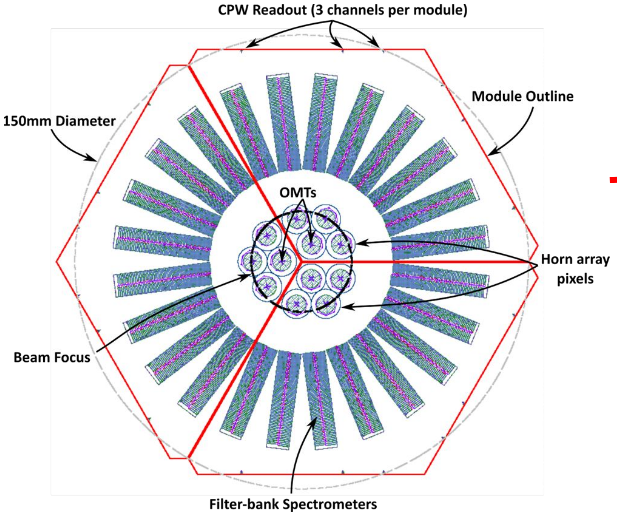
Verifying the Fit (with the help of wecutfoam.com)

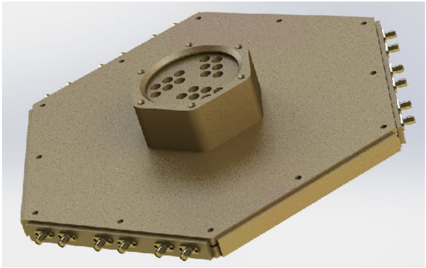
Don Mitchell

The SPT-SLIM Instrument

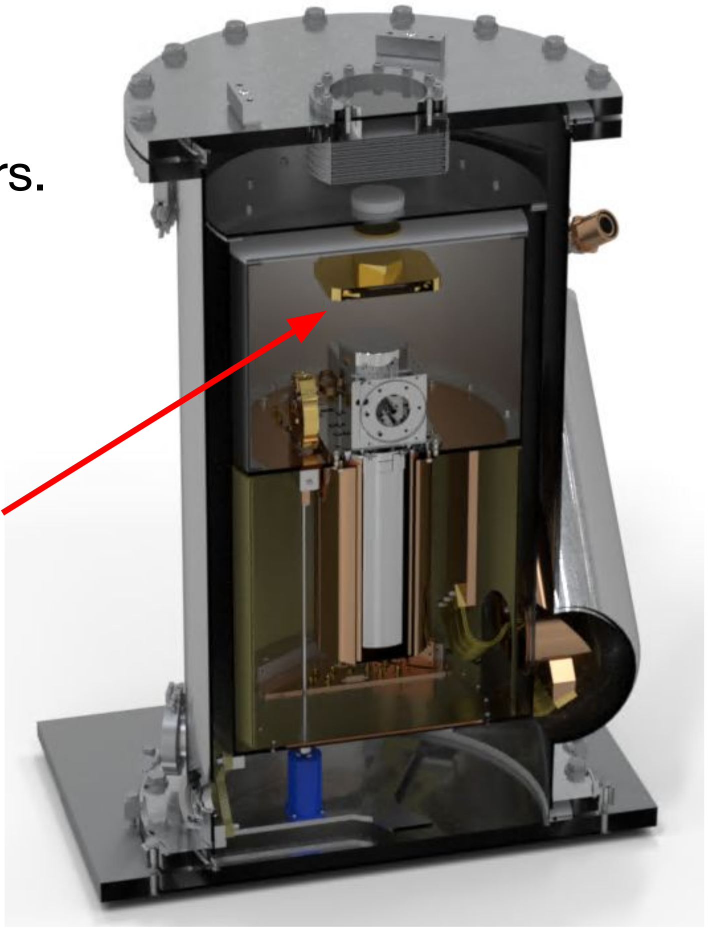
The first mm-wave integral field unit (IFU):
12 dual-pol pixels, each feeding two spectrometers.

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





Pete Barry,
Gethin Robson

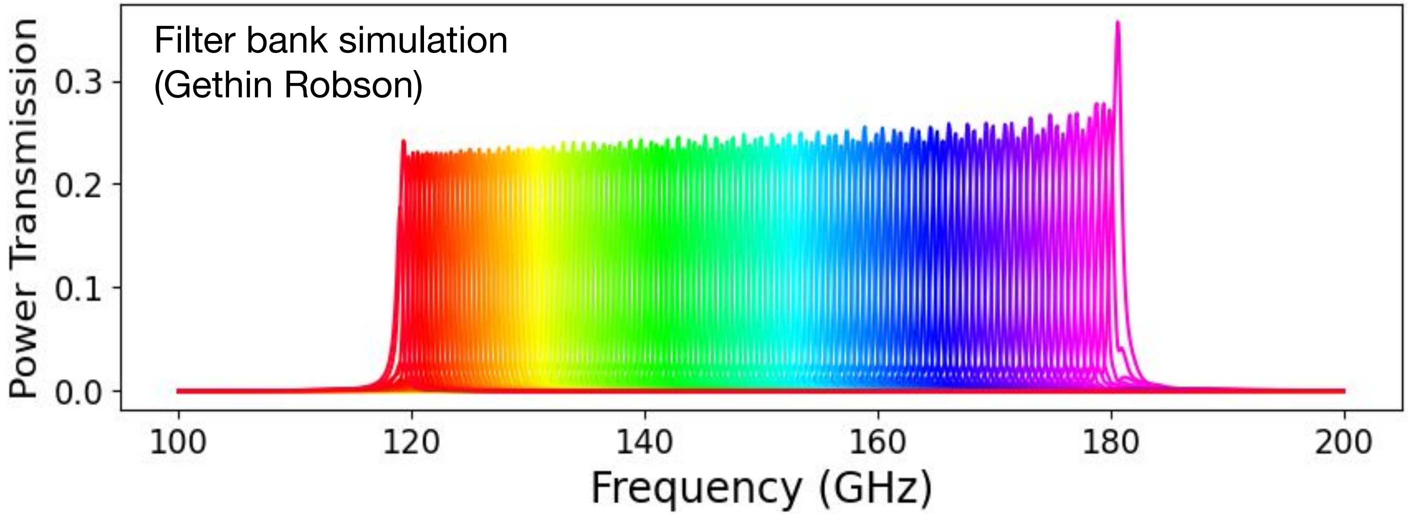


The SPT-SLIM Instrument

The SPT-SLIM Detectors

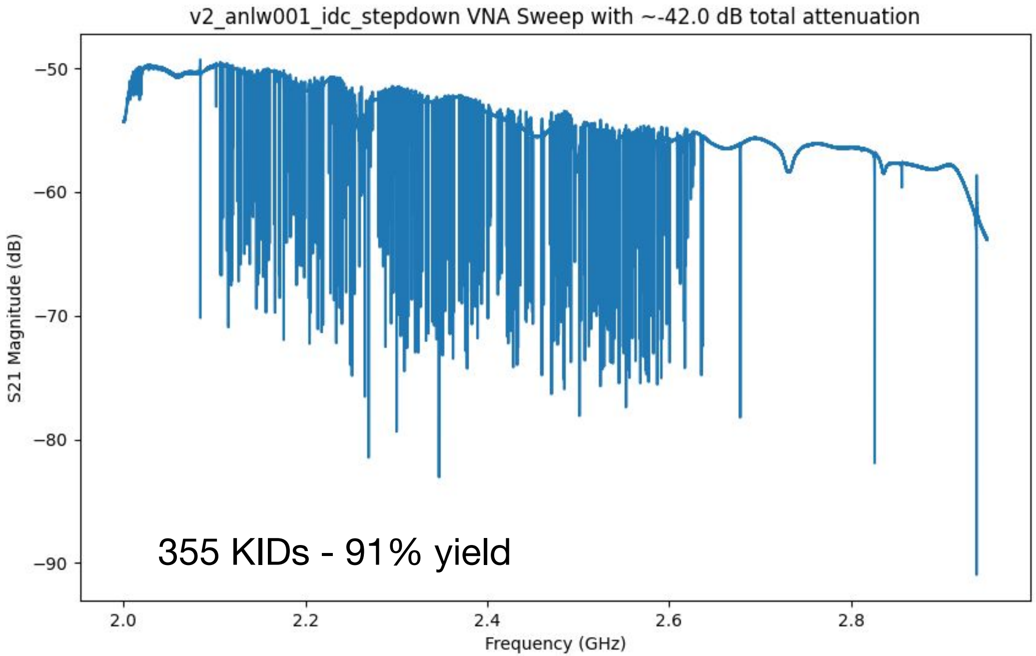
Each spectrometer covers 120–180 GHz with R~200 resolution - targeting CO(2-1), (3-2), (4-3) from 0.5 < z < 25.

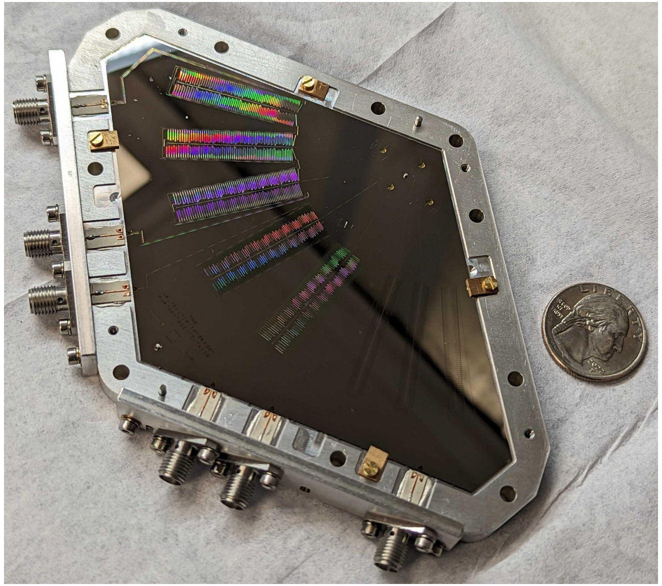
Aluminum KIDs read out from 2-2.5 GHz.



The SPT-SLIM Detectors

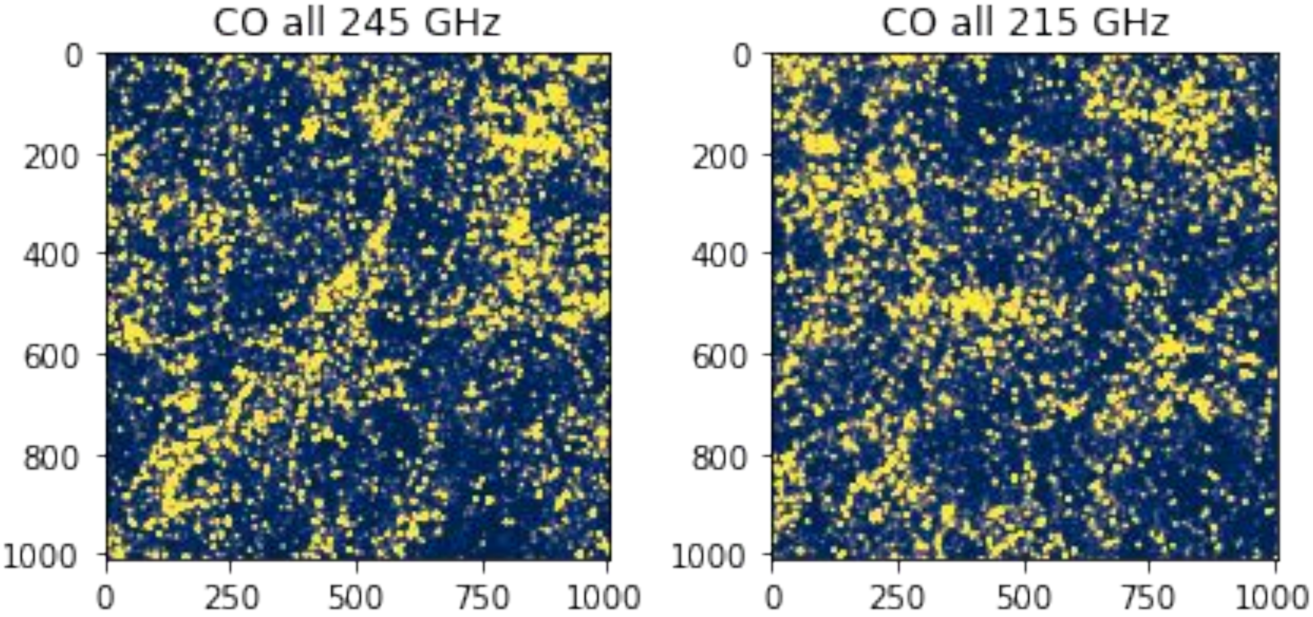
Elyssa Brooks,
UChicago Ph.D. student





Optical arrays fabricated at ANL and UChicago now being tested!

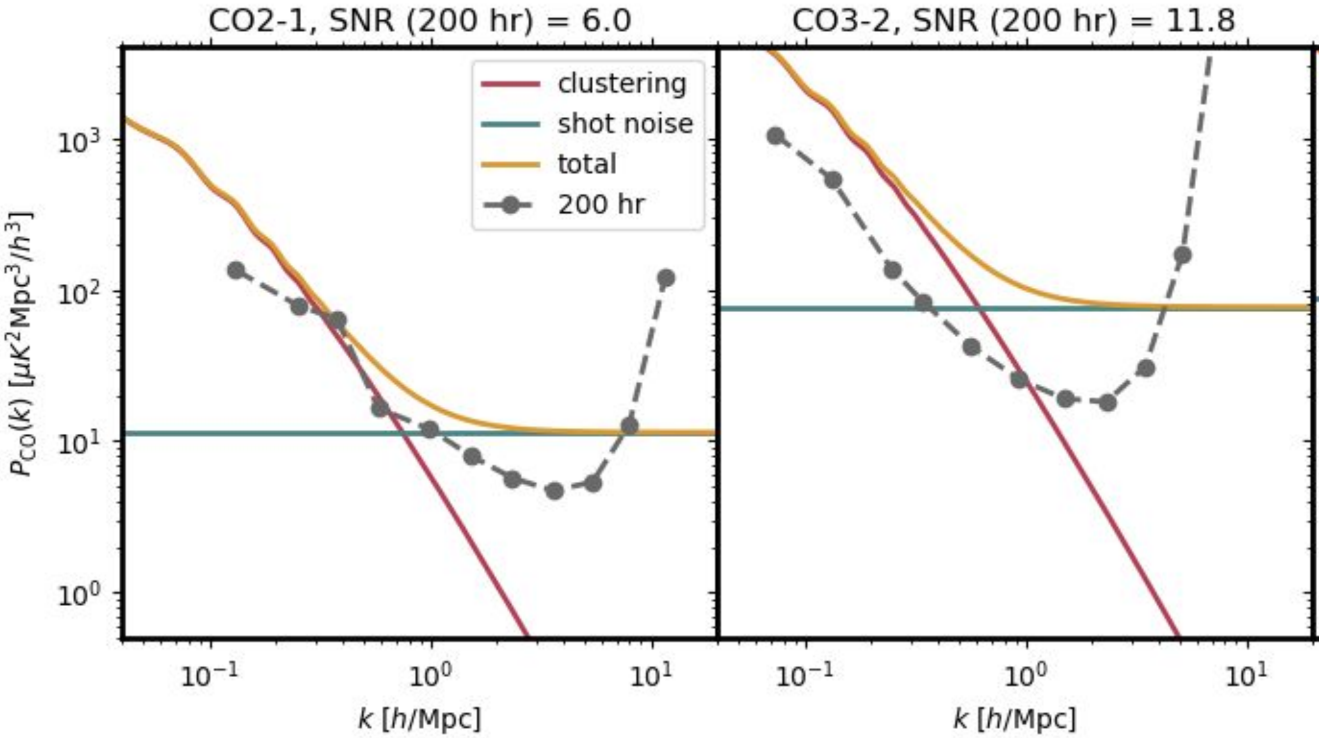
Simulated Maps and Sensitivity

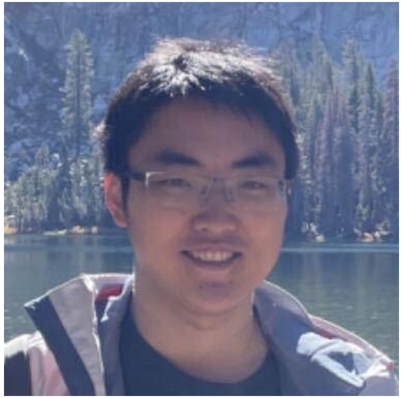


CO Line maps for mock observations

Cheng Zhang
Porat Fellow

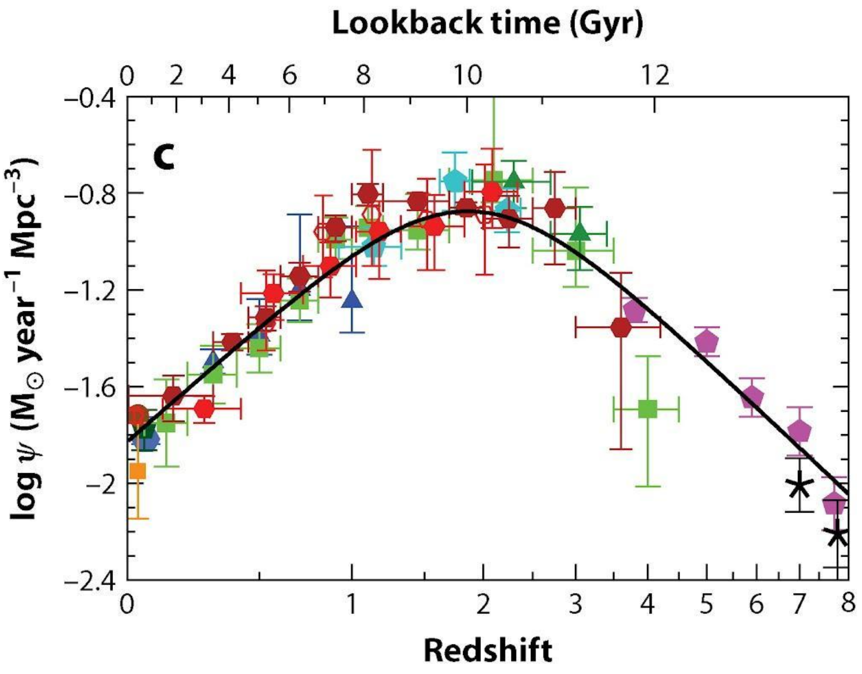
Simulated Maps and Sensitivity



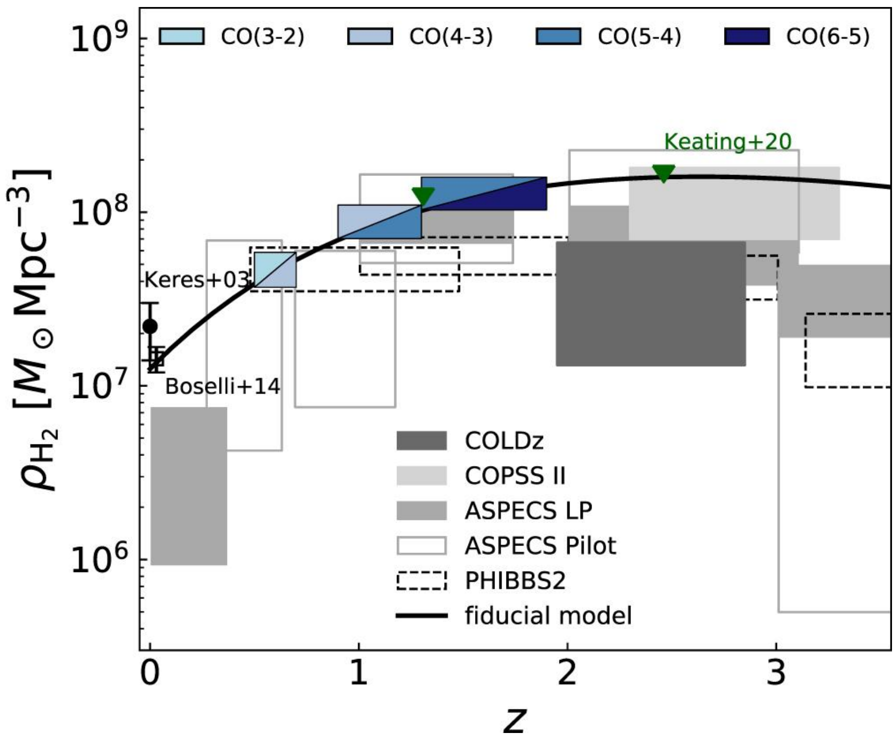


Zhuoqi Zhang
Stanford Ph.D. student

Cosmic Star Formation History



Madau & Dickinson 2014



Sun+ 2020

Part 2 Recap: SPT-SLIM

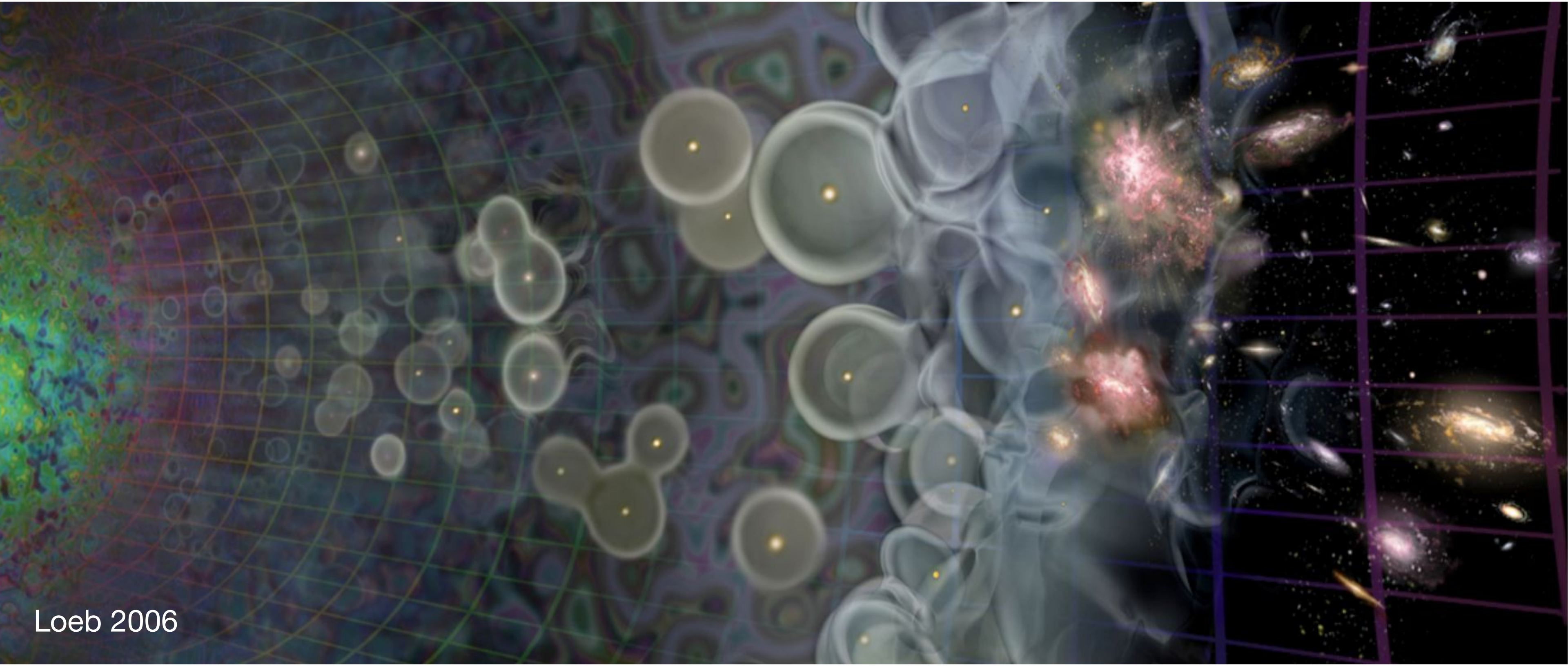
LIM detects the aggregate emission from faint, unresolved galaxies in 3D, enabling efficient surveys of large volumes and high redshifts.

This is a quickly-evolving field! Several mm-wave LIM experiments are coming online now. With SPT-SLIM, we're demonstrating that on-chip spectrometers can be used for this measurement…

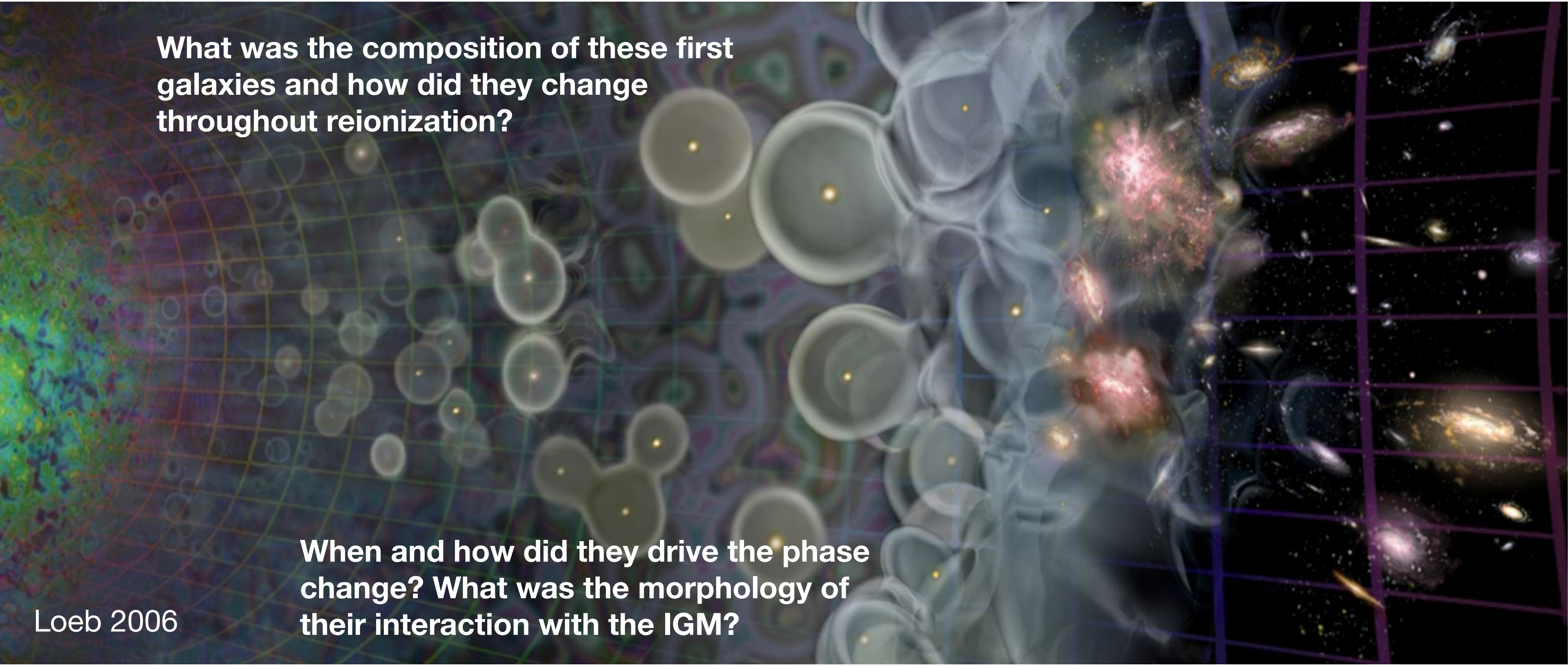
…but these are all still relatively small-volume surveys.

What science can we do with ultra large-volume surveys?

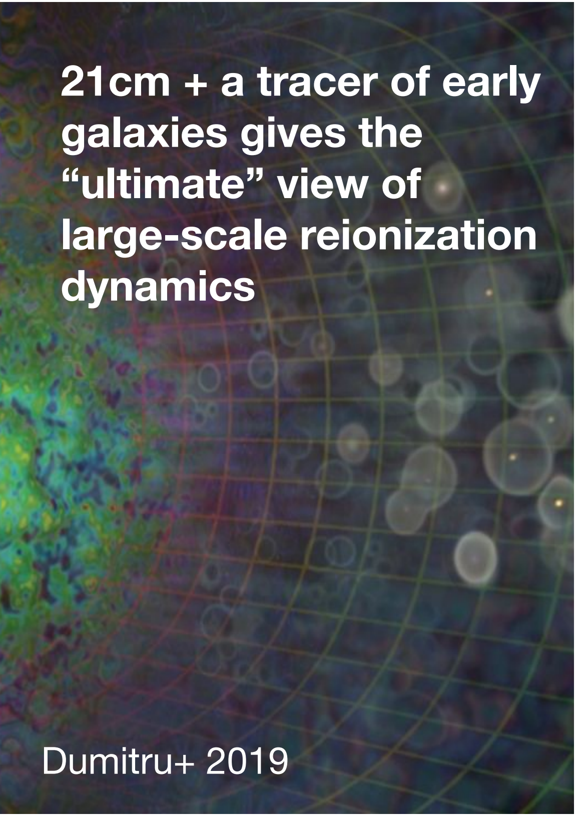
The Epoch of Reionization



The Epoch of Reionization

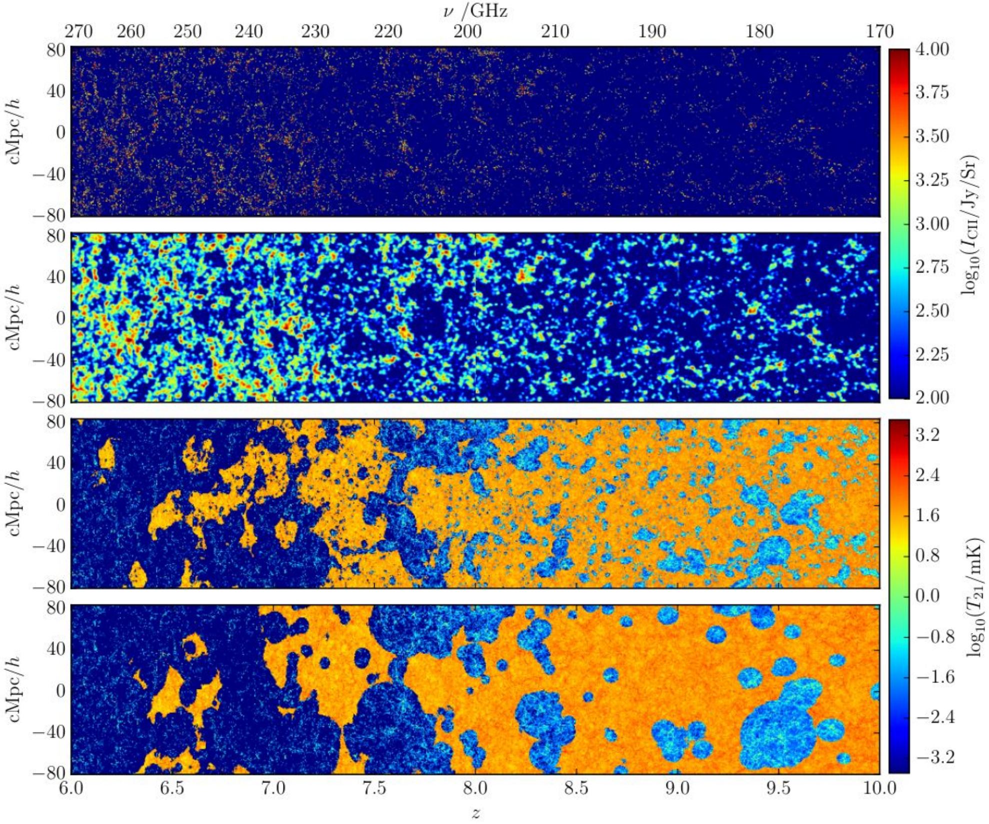


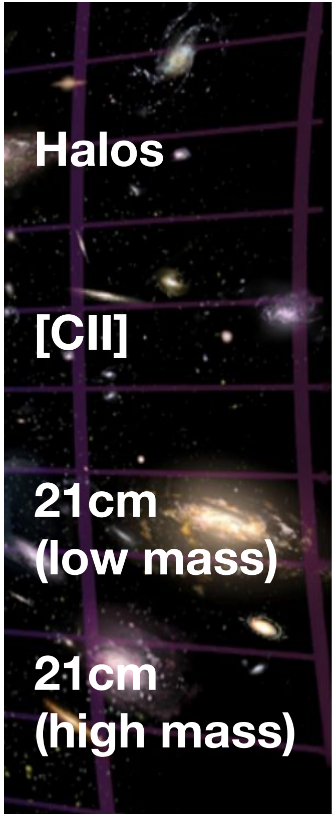
The Epoch of Reionization



21cm + a tracer of early galaxies gives the “ultimate” view of large-scale reionization dynamics

Dumitru+ 2019

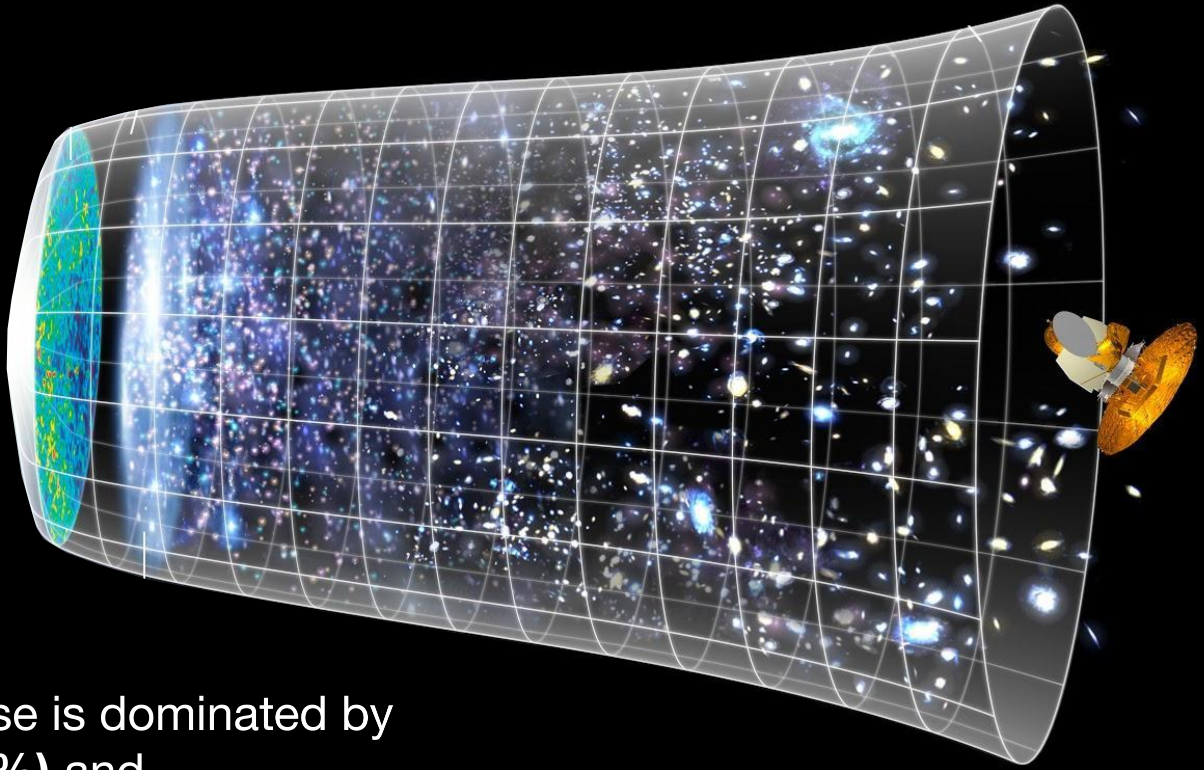




The “Standard Model” of Cosmology

Planck 2018 + ext
1807.06209

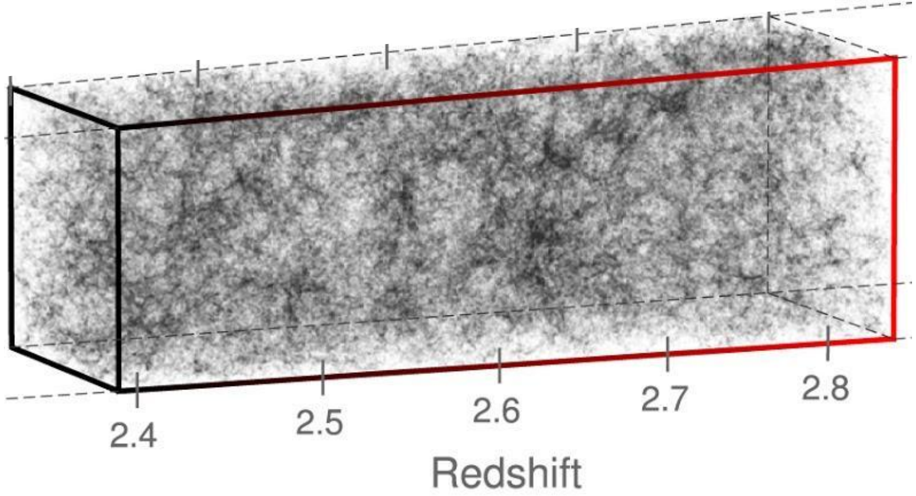
$\Omega_b h^2$	0.02242 ± 0.00014
$\Omega_c h^2$	0.11933 ± 0.00091
$100\theta_{MC}$ . .	1.04101 ± 0.00029
τ	0.0561 ± 0.0071
$\ln(10^{10} A_s)$.	3.047 ± 0.014
n_s	0.9665 ± 0.0038

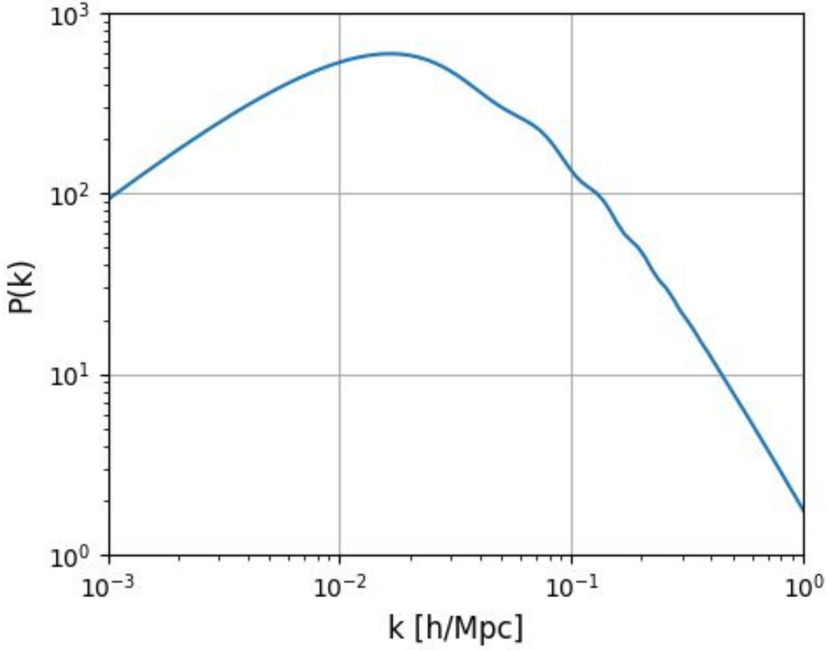


ΛCDM: the Universe is dominated by
Dark Energy (~70%) and
Cold Dark Matter (~25%), with initial conditions set by **inflation**

NASA/WMAP
Science Team

Large-Scale Structure Constrains Our Cosmological Model





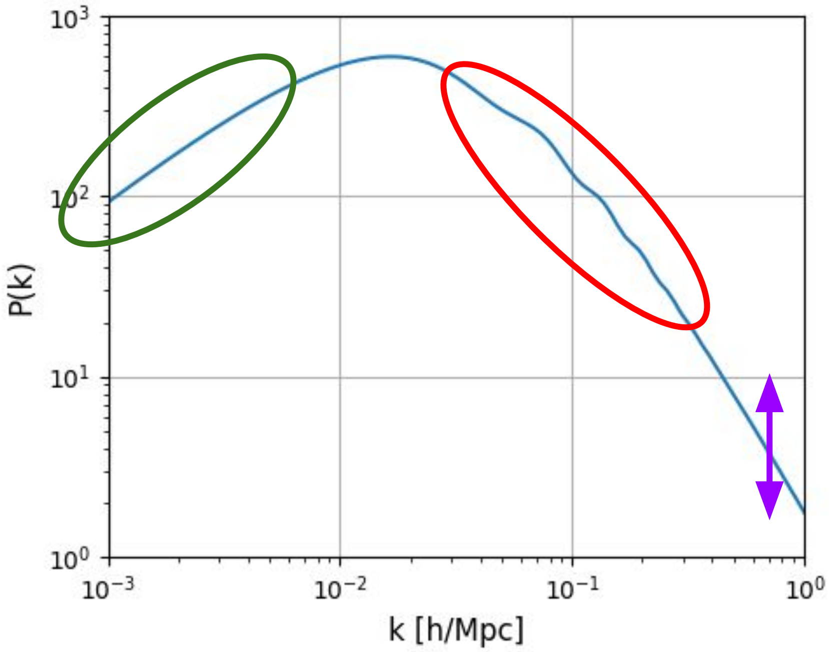
Li+ 2015

Large-Scale Structure Constrains Our Cosmological Model

Primordial non-Gaussianity
(multi-field inflation)

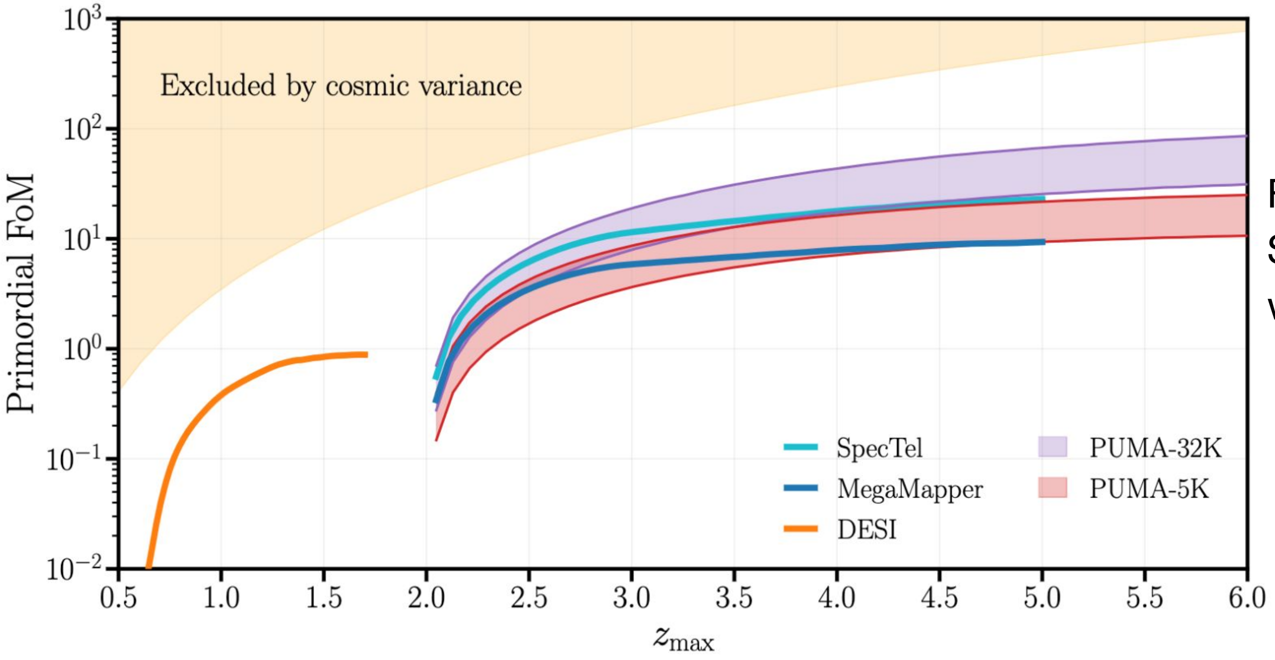
Expansion history
(dark energy/modified gravity)

Massive neutrinos



Why High Redshift?

More volume, better statistics.

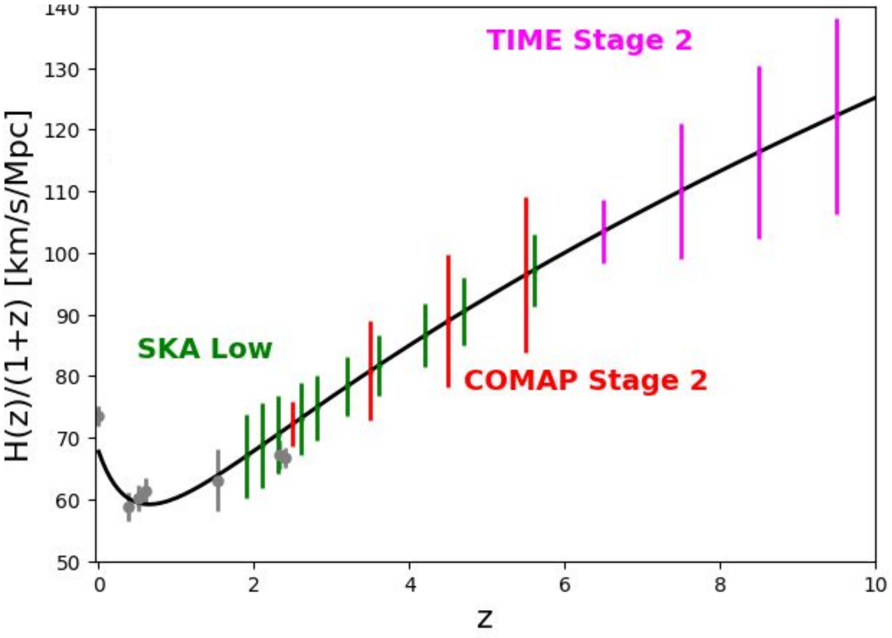


Ferraro+ Snowmass white paper

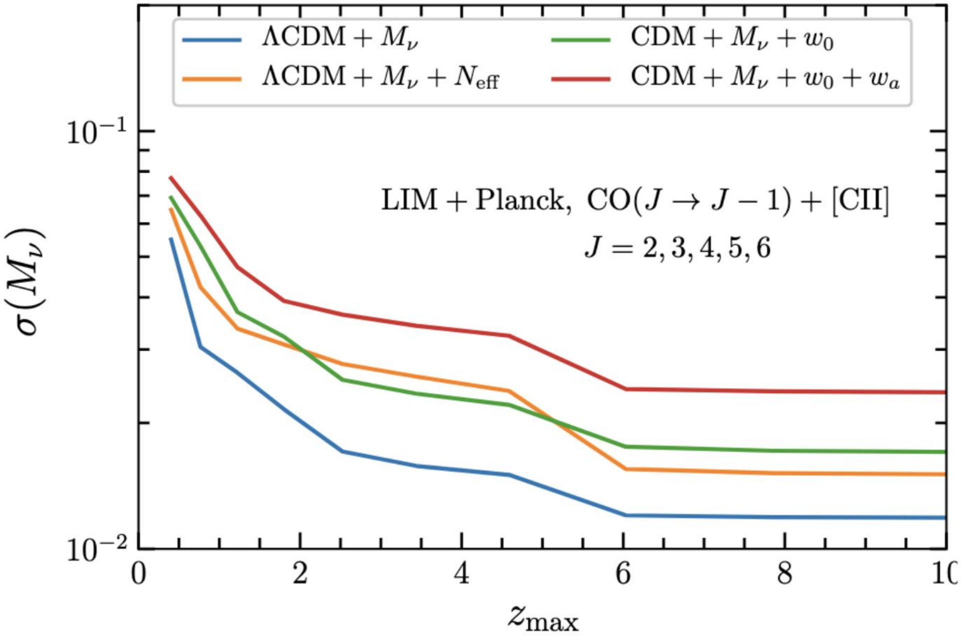
Effective number of modes ($\times 10^{-6}$) correlated with the initial conditions

Why High Redshift?

Wide redshift coverage probes different epochs and alleviates parameter degeneracies.



Karkare & Bird,
PRD 1806.09625



Moradinezhad Dizgah, Keating, Karkare et al.
ApJ 2110.00014

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.

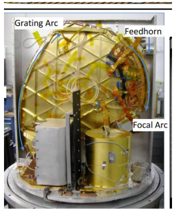
Karkare+ 2203.07258
Snowmass white paper

How much sensitivity do we need?

	Spec-hrs	$\lesssim 10^5$
	Timescale	2024
	Example	TIME, SPT-SLIM
Neutrino masses	$\boldsymbol{\sigma}(M_\nu)$ [eV]	
Dark energy	$\boldsymbol{\sigma}(w_0)$ 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	2024	2026
Example	TIME, SPT-SLIM	TIME-Ext
$\sigma(M_\nu)$ [eV]		0.047
$\sigma(w_0)$ incl. $z>3$		0.03
Primordial FoM		0.1

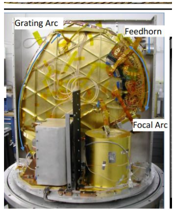
Neutrino masses

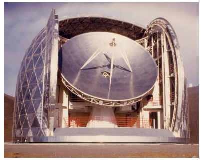
Dark energy

Inflation

Pathfinder instruments at dedicated facilities.

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

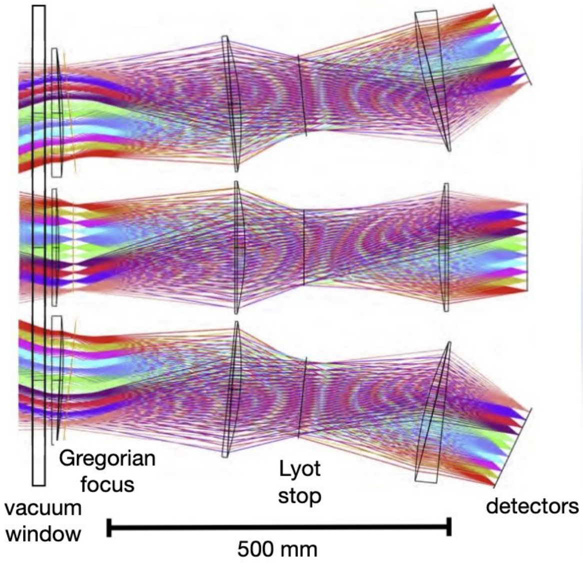


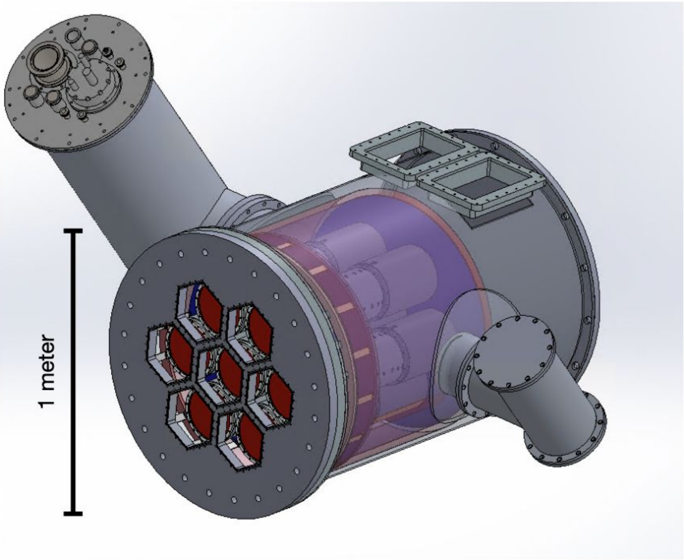


Karkare+ 2203.07258
Snowmass white paper

SPT-3G+, a high-throughput receiver

Anderson+ 2022



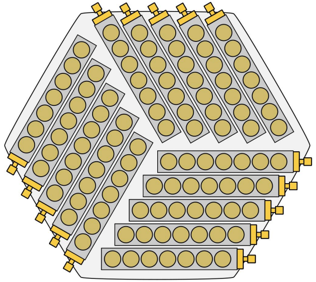


Plan to deploy in ~2027 with high-frequency detectors for kSZ measurements.

Will replace with spectrometers as they become available.

7 modular optics tubes. Dilution refrigerator in Bill's lab!

How much sensitivity do we need?



Neutrino masses

Dark energy

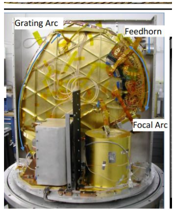
Inflation

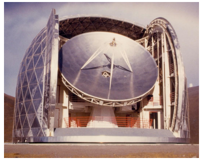
Spec-hrs	$\lesssim 10^5$	10^6	10^7
Timescale	2024	2026	2028
Example	TIME, SPT-SLIM	TIME-Ext	SPT-3G+ one tube
$\sigma(M_\nu)$ [eV]		0.047	0.028
$\sigma(w_0)$ incl. z>3		0.03	0.013
Primordial FoM		0.1	1

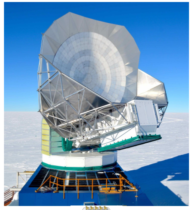
Focal plane with ~hundred spectrometers

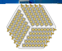
Starting to compete with galaxy surveys, but including high redshifts. **Constrain dynamical DE models.**

DESI: FoM ~ 1









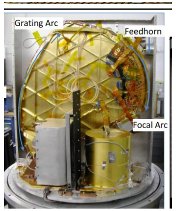
Karkare+ 2203.07258
Snowmass white paper

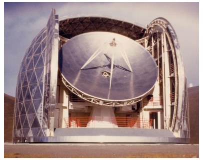
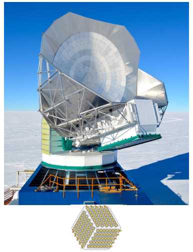
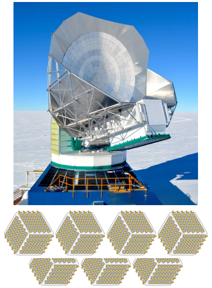
How much sensitivity do we need?

	Spec-hrs	$\lesssim 10^5$	10^6	10^7	10^8
	Timescale	2024	2026	2028	2032
	Example	TIME, SPT-SLIM	TIME-Ext	SPT-3G+ one tube	SPT-3G+ 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



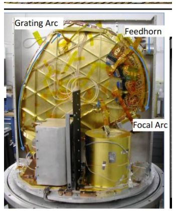




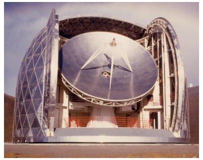
Karkare+ 2203.07258
Snowmass white paper

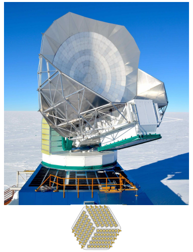
How much sensitivity do we need?

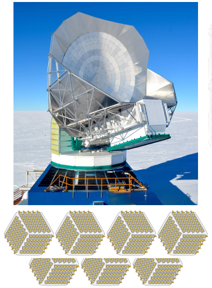
Well beyond DESI/LSST!

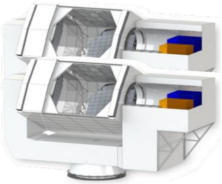
	Spec-hrs	$\lesssim 10^5$	10^6	10^7	10^8	10^9
	Timescale	2024	2026	2028	2032	2038
	Example	TIME, SPT-SLIM	TIME-Ext	SPT-3G+ one tube	SPT-3G+ 7 tubes	CMB-S4 85 tubes
Neutrino masses	$\sigma(M_\nu)$ [eV]		0.047	0.028	0.013	0.007
Dark energy	$\sigma(w_0)$ incl. $z>3$		0.03	0.013	0.005	0.003
Inflation	Primordial FoM		0.1	1	10	100











Karkare+ 2203.07258
Snowmass white paper

Community Support for LIM is Growing

December 2023: the P5 report endorses LIM (at all wavelengths) as a promising new direction for particle physics!

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.

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).

How do we get there?

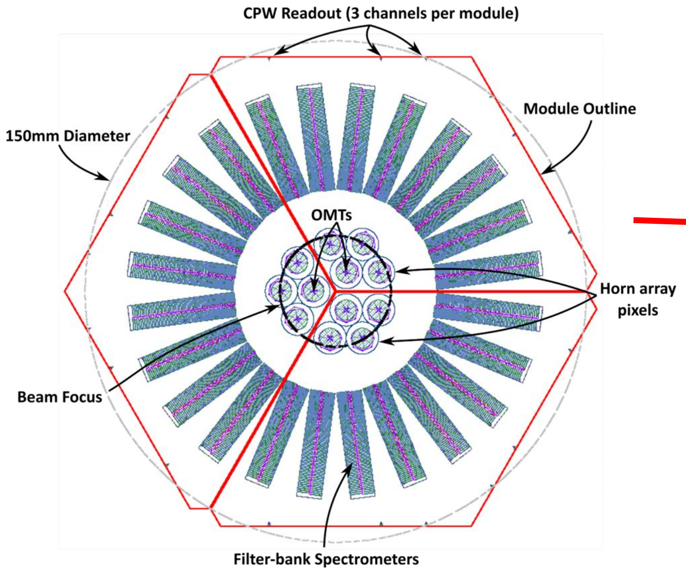
To achieve cosmological relevance*, we need surveys with >2 orders of magnitude improvement in sensitivity.

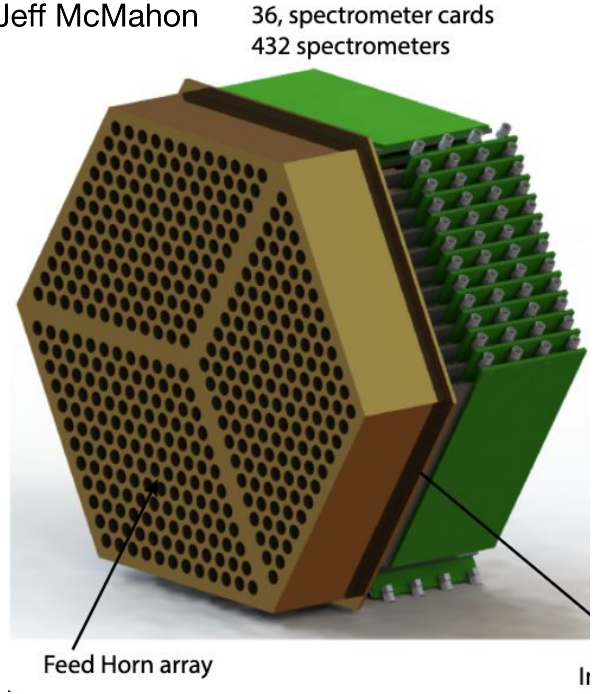
- Dedicated wide-field platforms at excellent sites and multi-year observations
- Detector arrays that are as sensitive as possible, with enough spectral resolution to extract all of the cosmological information
- Readout to accommodate overwhelmingly-large detector counts

*not true for astrophysical relevance

Detector Packing Density

Pete Barry
Jeff McMahon

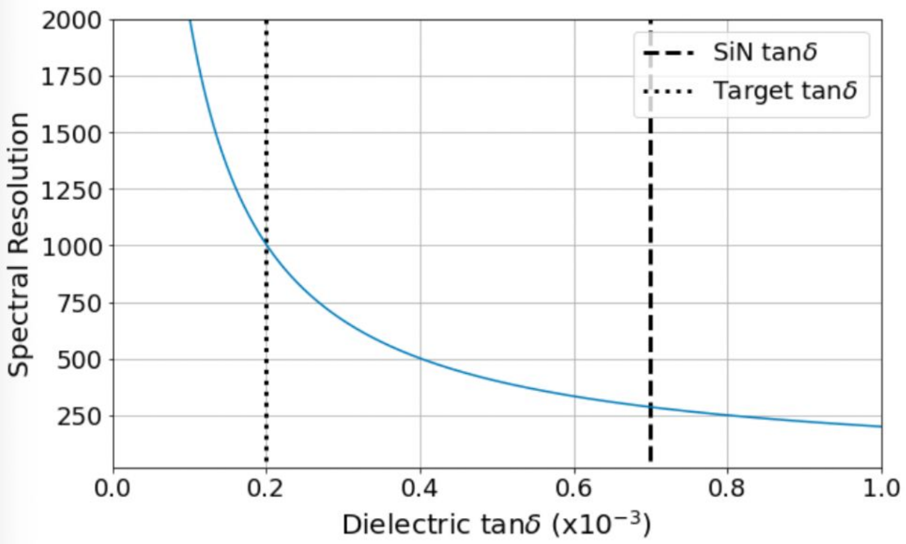


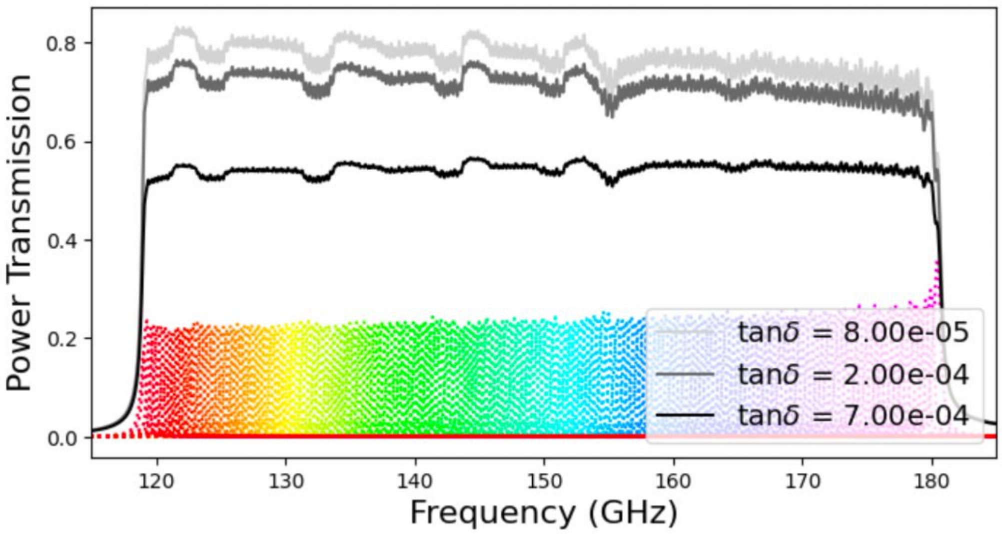


The filter bank takes up an area ~5x the size of the diffraction-limited spot. Can we move the spectrometer out of the focal plane to approach optimal sampling?

Spectral Resolution and Optical Efficiency

Gethin Robson



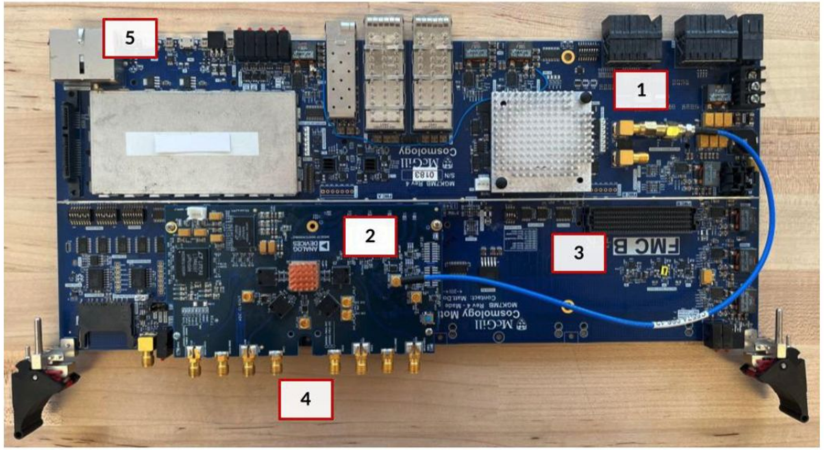


For microstrip implementation, loss in dielectric limits resolution and optical efficiency! Promising low-loss candidates pursued by many groups - even a factor of 2-3 reduction in loss could improve filter-bank performance significantly.

High-Density Readout

A 1000-spectrometer, R=300 array has similar detector count to CMB-S4!

Current gen: ROACH, SMuRF, RF-ICE, etc. O(1000) channels/line



Rouble+ 2022

RF System-on-a-Chip systems can hopefully get us to O(10000)/line at ~$1/channel

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.

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.