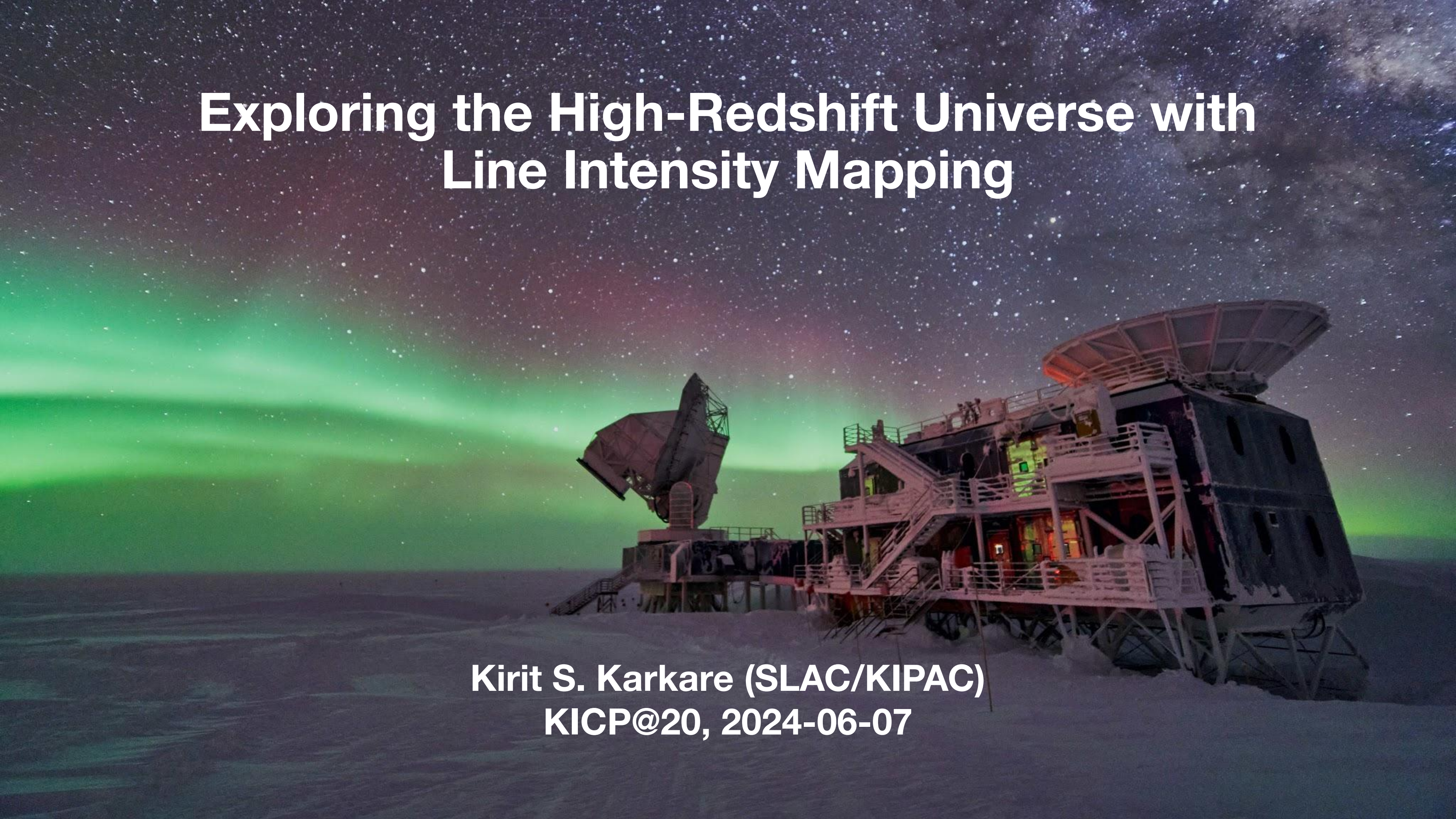
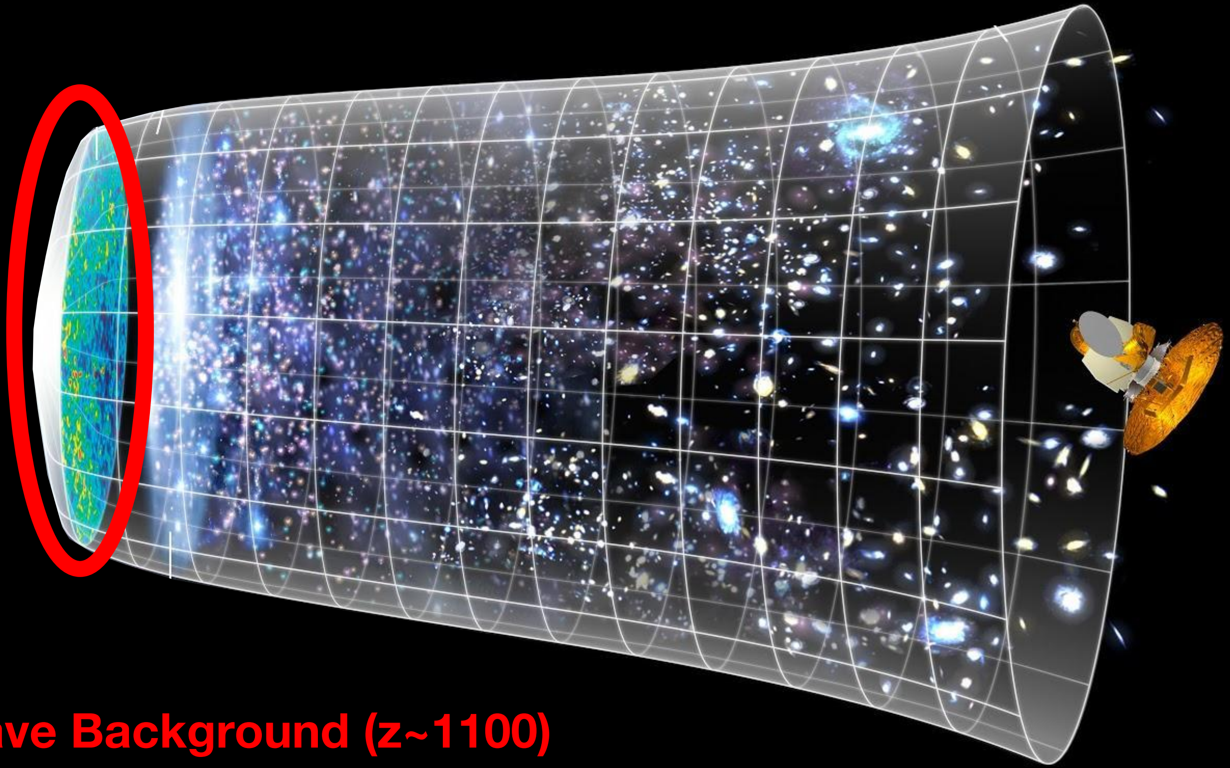
Exploring the High-Redshift Universe with Line Intensity Mapping



Kirit S. Karkare (SLAC/KIPAC)
KICP@20, 2024-06-07

Observational Probes

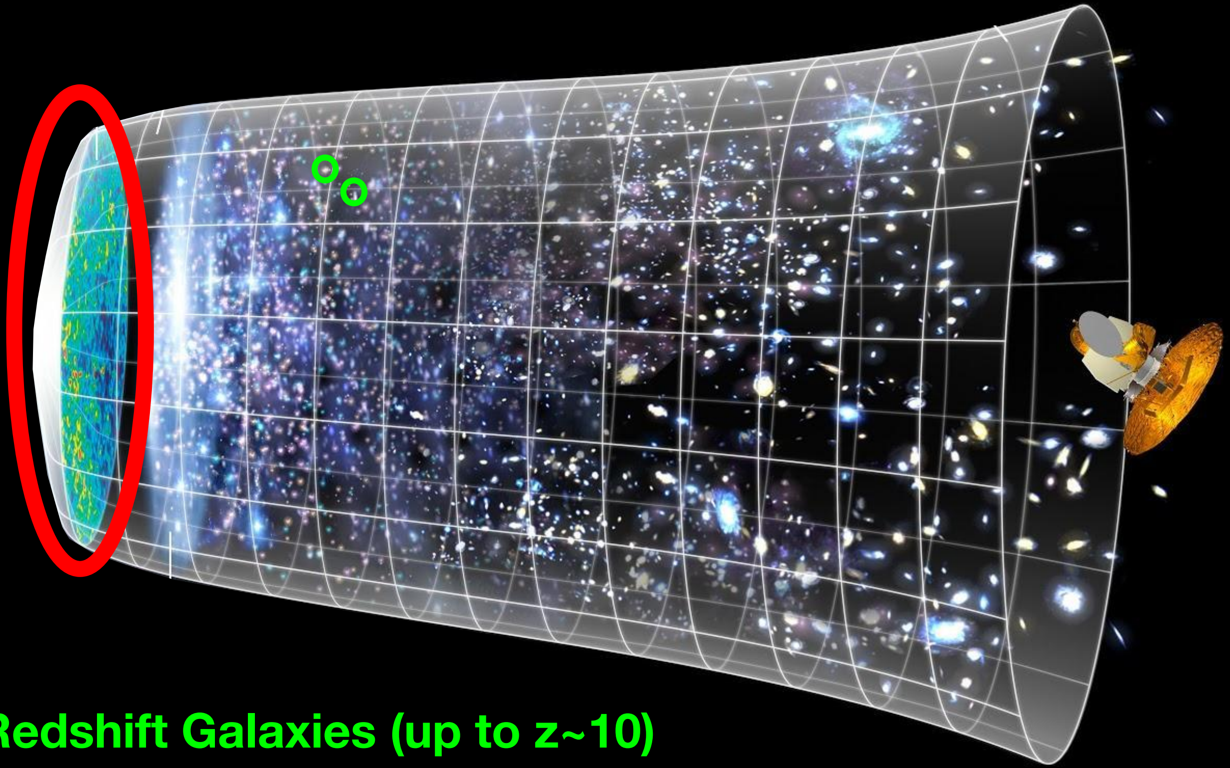


Cosmic Microwave Background (z~1100)

Initial conditions

NASA/WMAP
Science Team

Observational Probes

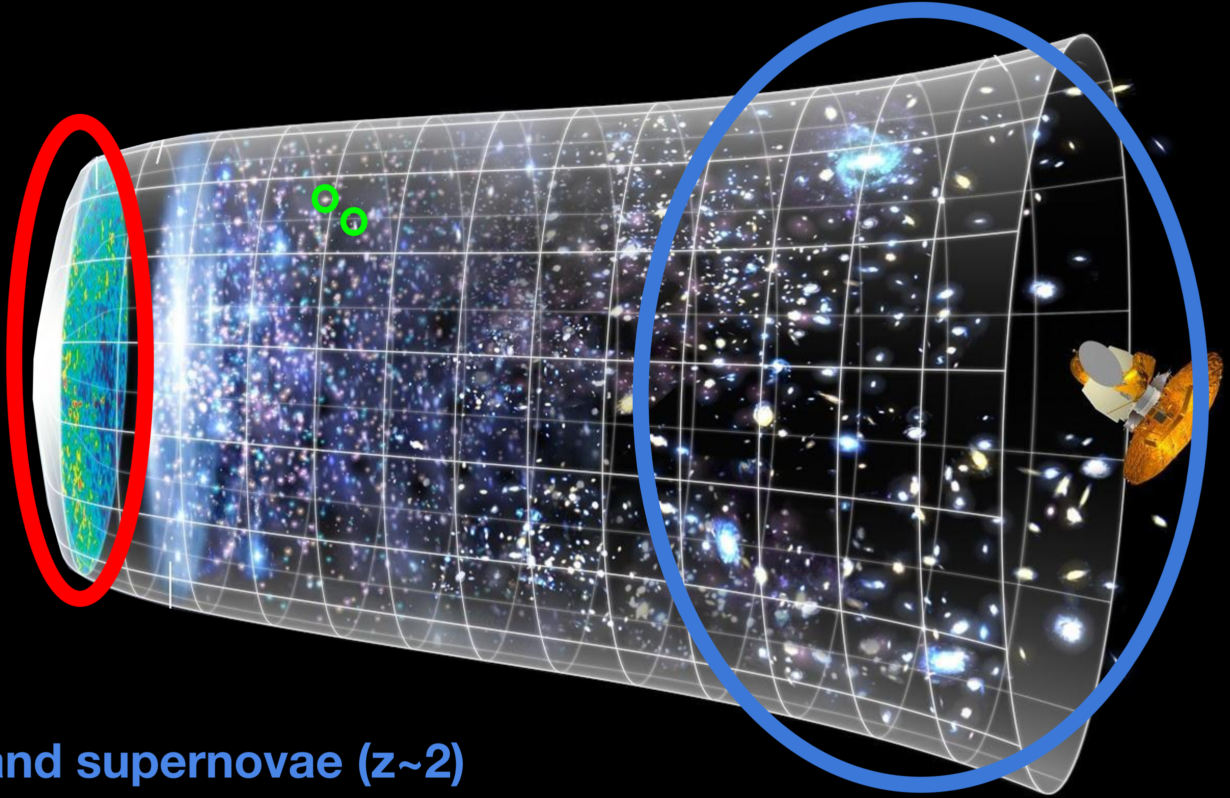


Individual High-Redshift Galaxies (up to z~10)

Bright, massive objects

NASA/WMAP
Science Team

Observational Probes

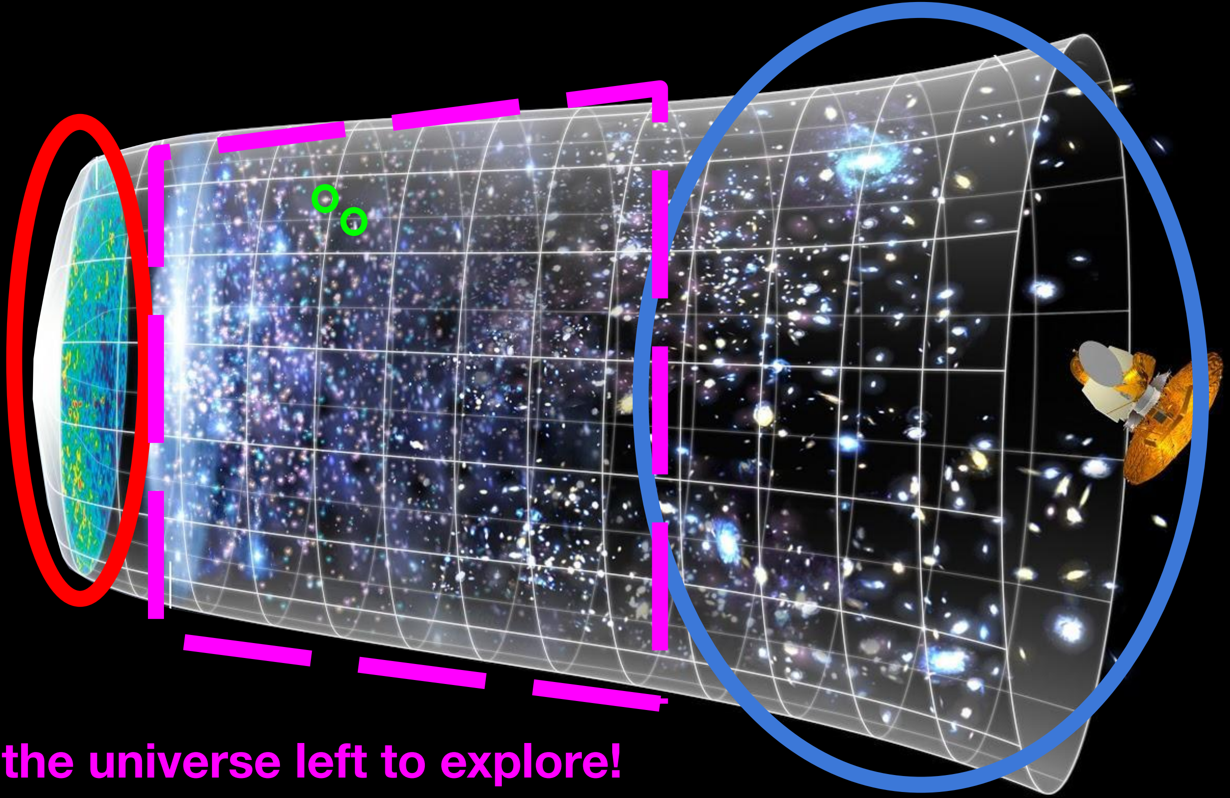


Galaxy surveys and supernovae (z~2)

Late-time large-scale structure, Hubble rate

NASA/WMAP
Science Team

Observational Probes

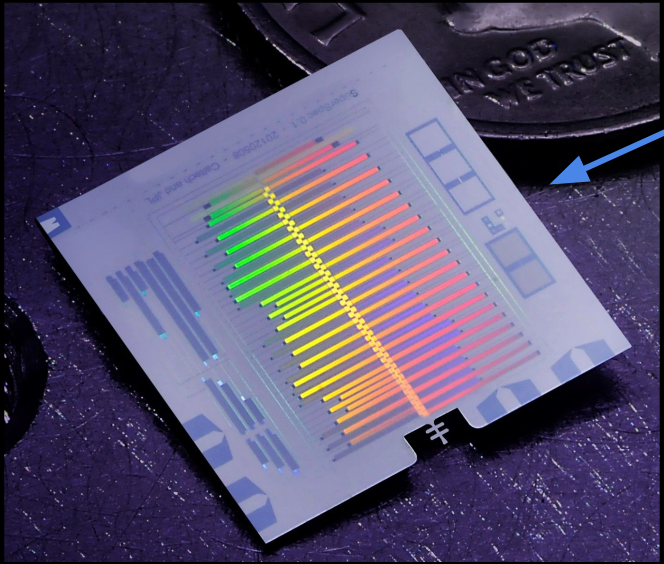


Huge fraction of the universe left to explore!

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?**

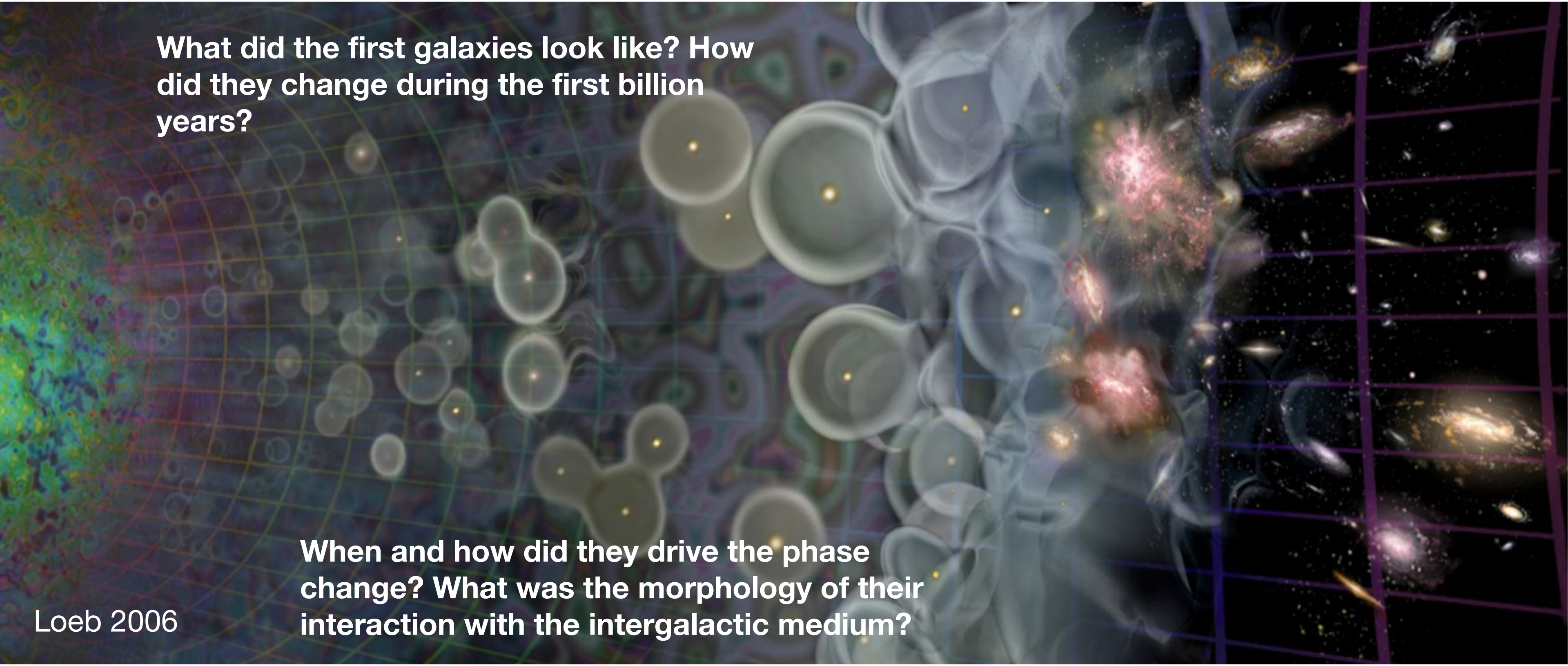


KICP is playing a major role in developing the technology (on-chip superconducting millimeter-wave spectrometers)

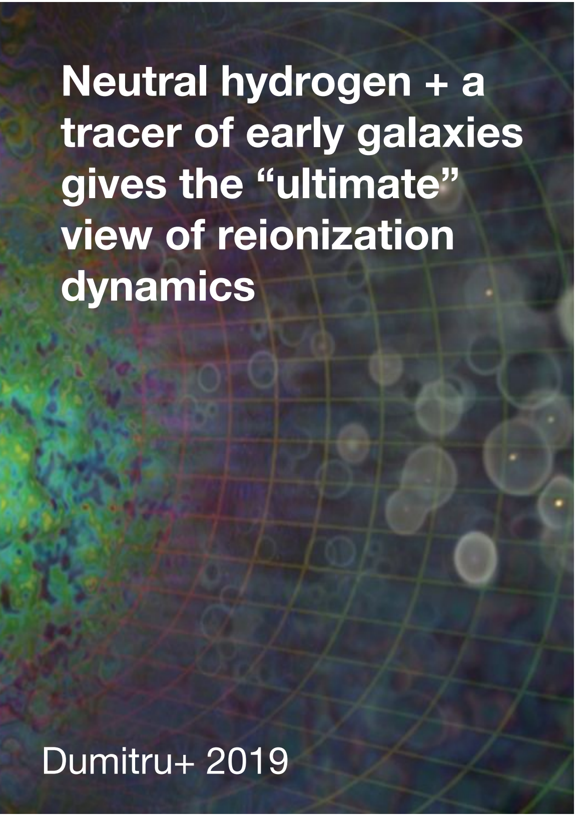
and the observational technique of line intensity mapping with a series of experiments (SuperSpec, SPT-SLIM, SPT-3G+, …)

to efficiently detect the *complete population* of faint, high-redshift galaxies over the full sky.

The Epoch of Reionization

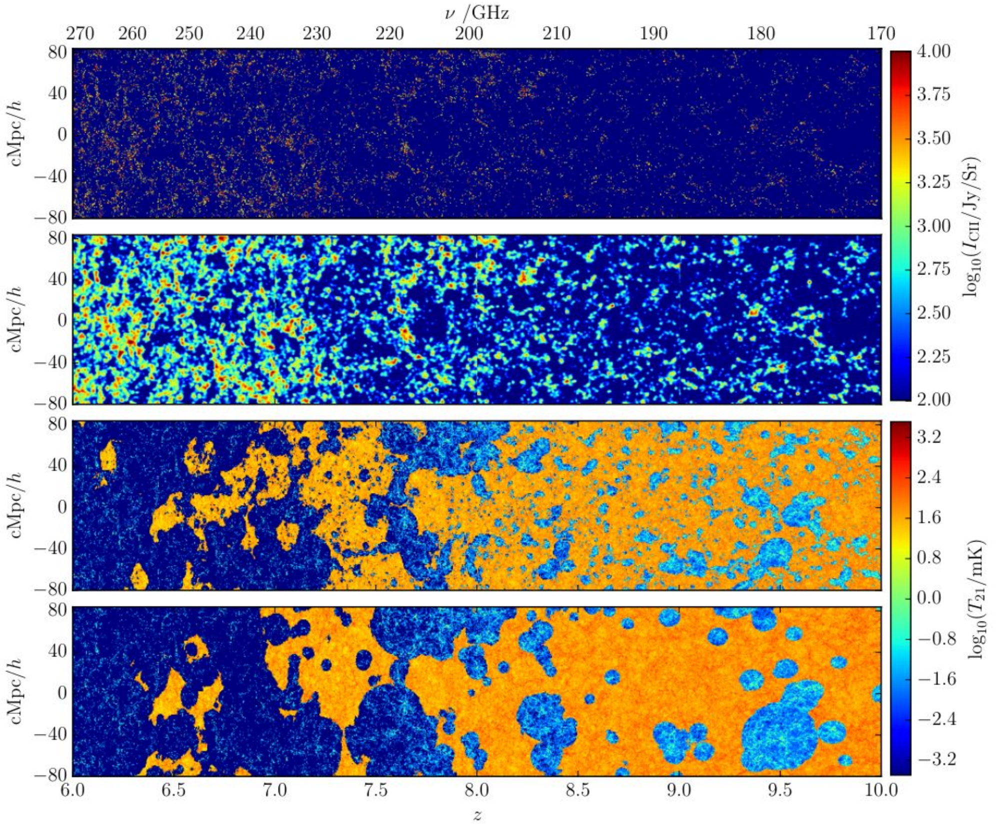


The Epoch of Reionization



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

Dumitru+ 2019

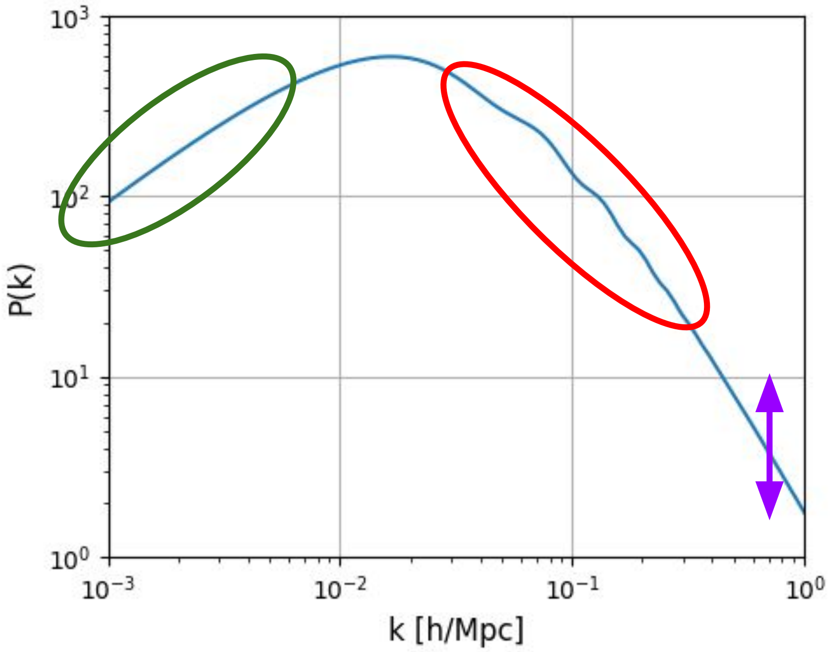


Large-Scale Structure Constrains Our Cosmological Model

Primordial non-Gaussianity
Did inflation involve multiple fields?

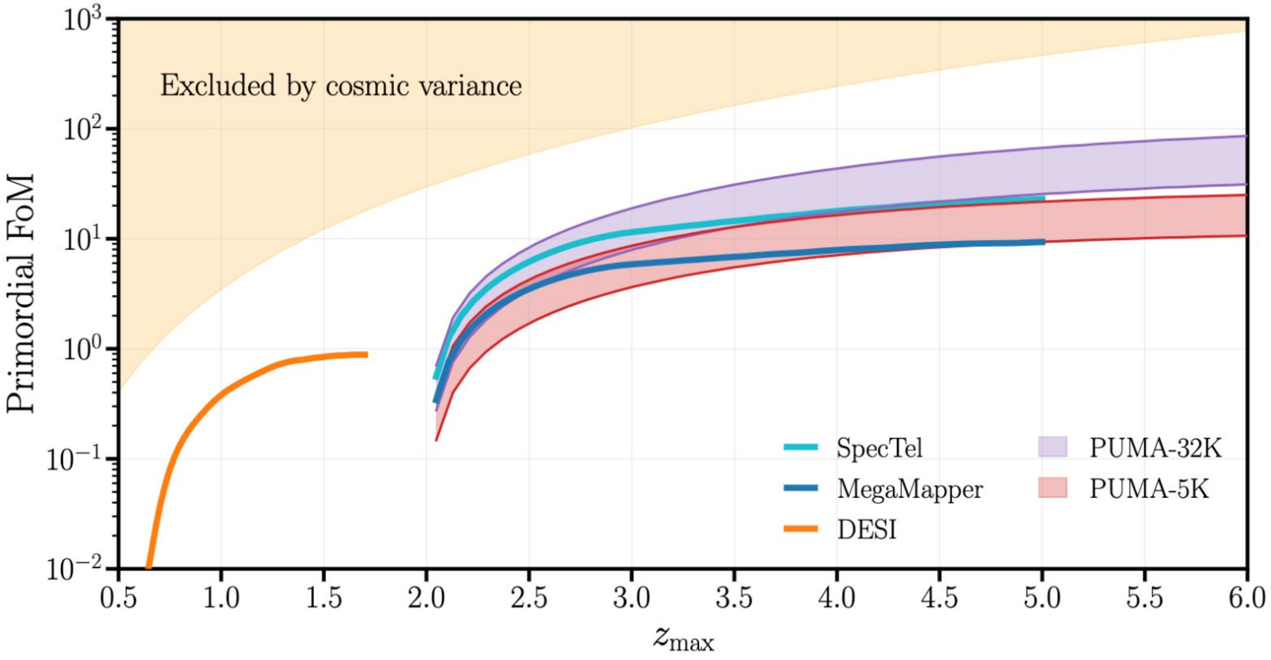
Expansion History
Is the dark energy equation of state (w=-1) constant?

Growth of Structure
Does the neutrino have a normal or inverted hierarchy?



Why High Redshift?

More volume, better statistics.

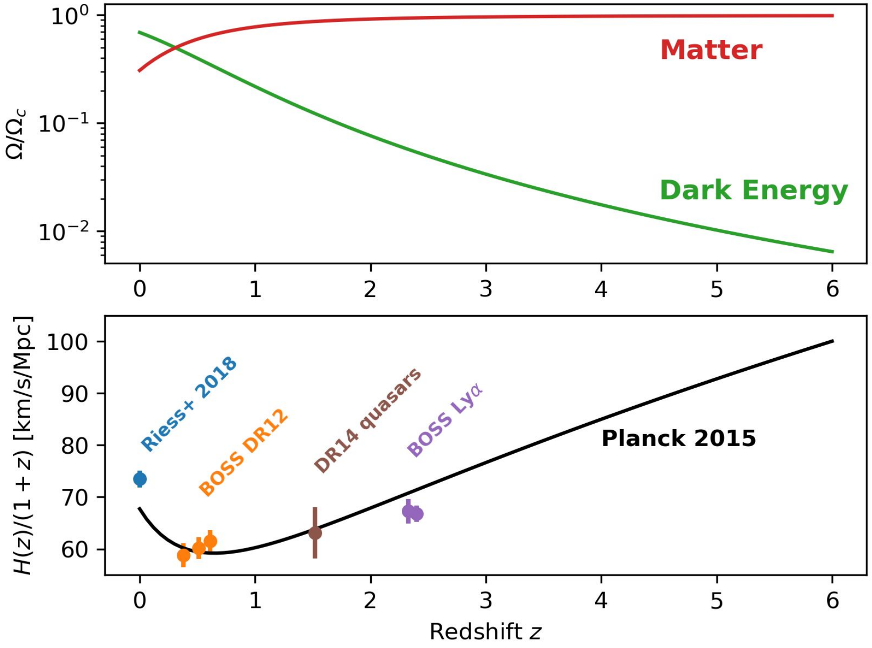


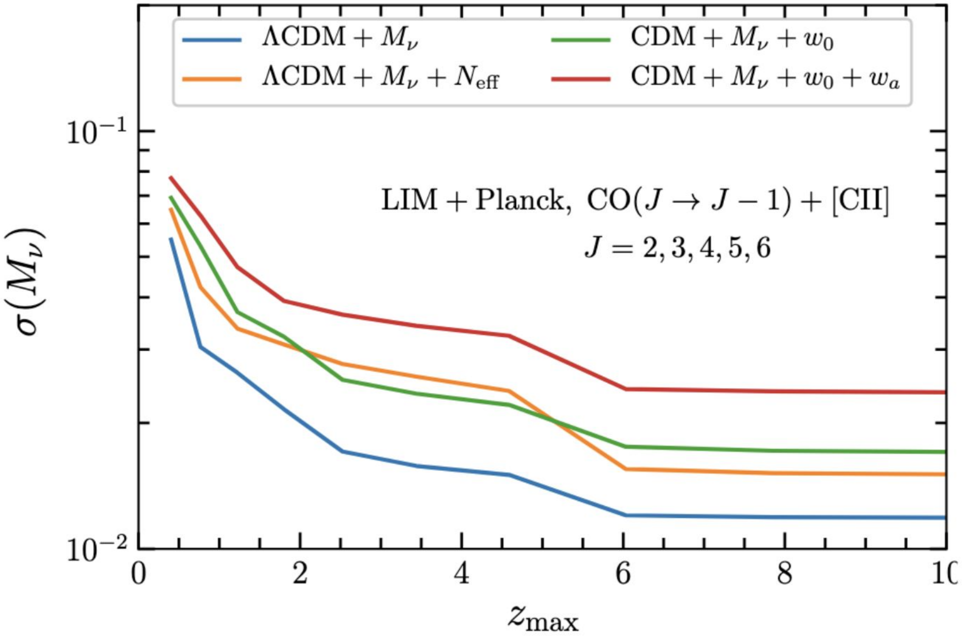
Ferraro+
Snowmass
white paper

“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

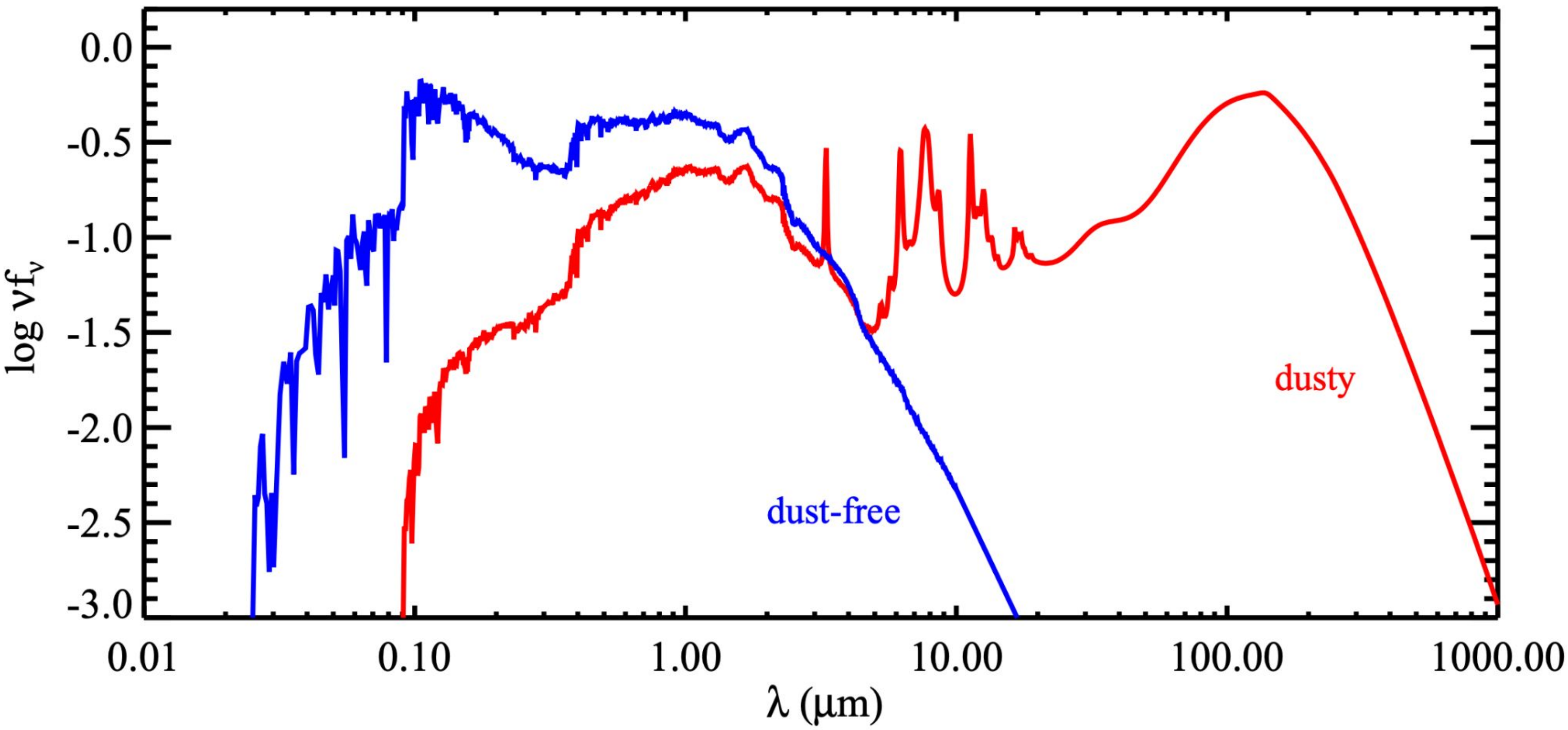
Getting to High Redshift

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**

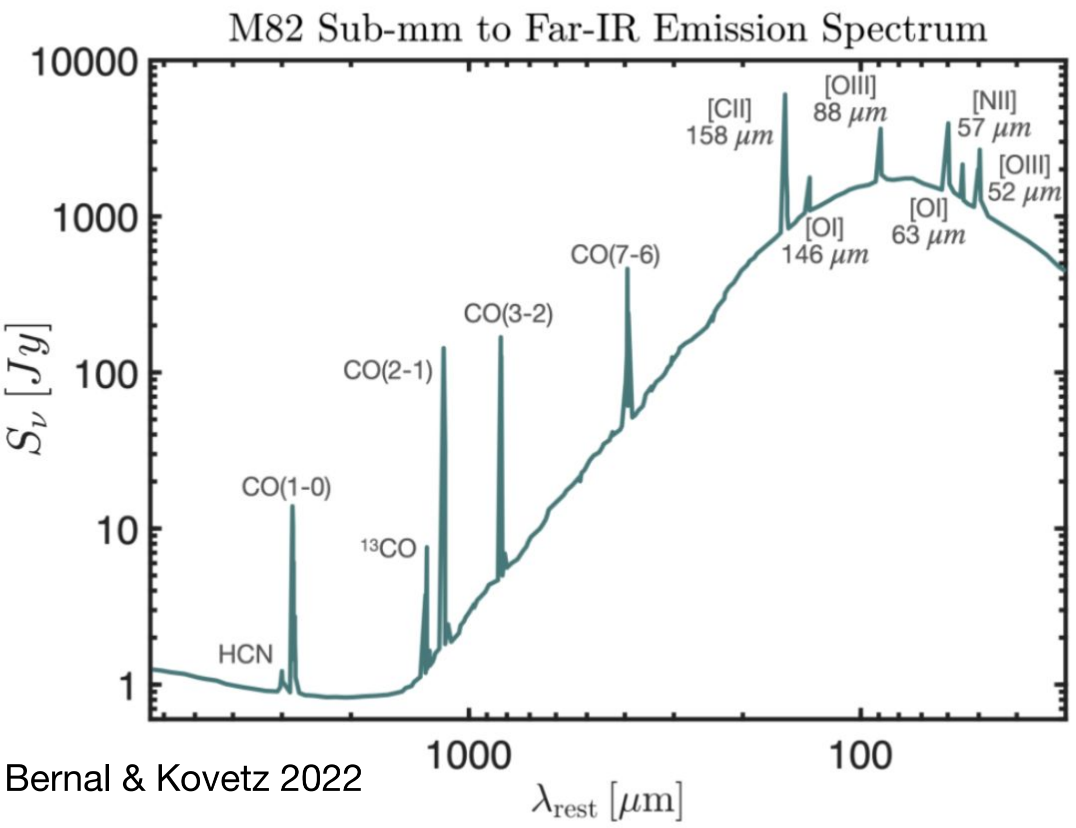
Far-IR is Important!

Conroy ARA&A 2013

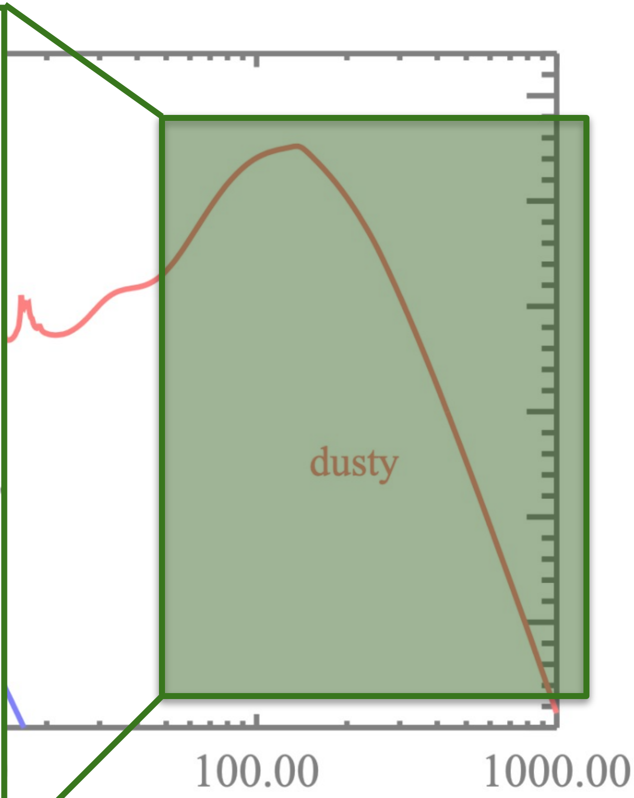


Far-IR is Important!

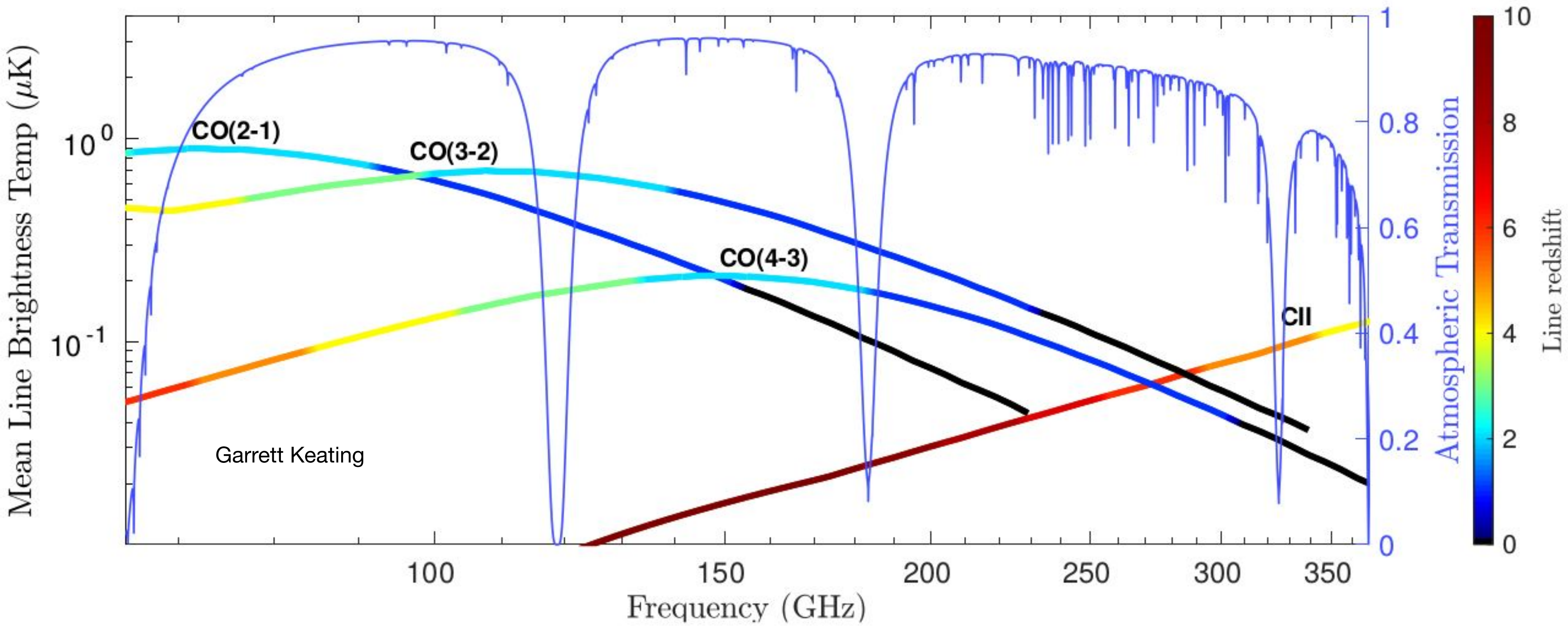
Conroy ARA&A 2013



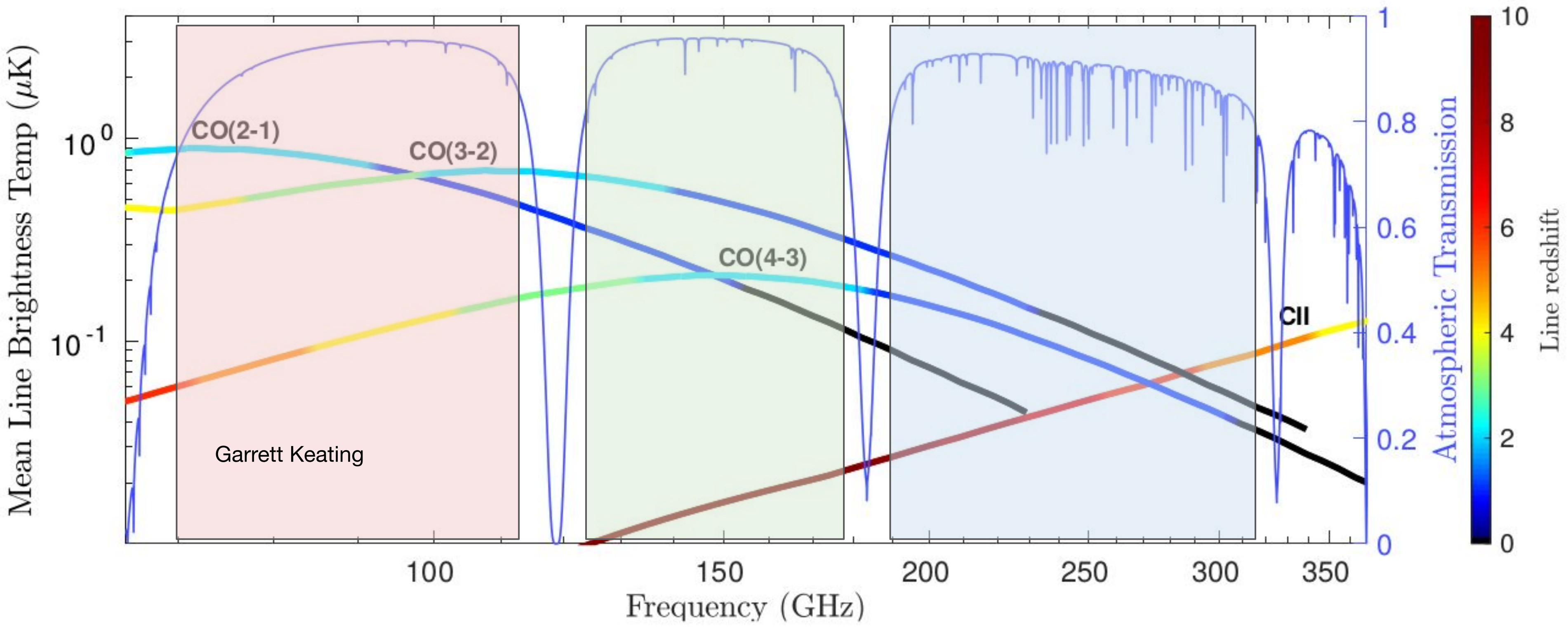
Bernal & Kovetz 2022



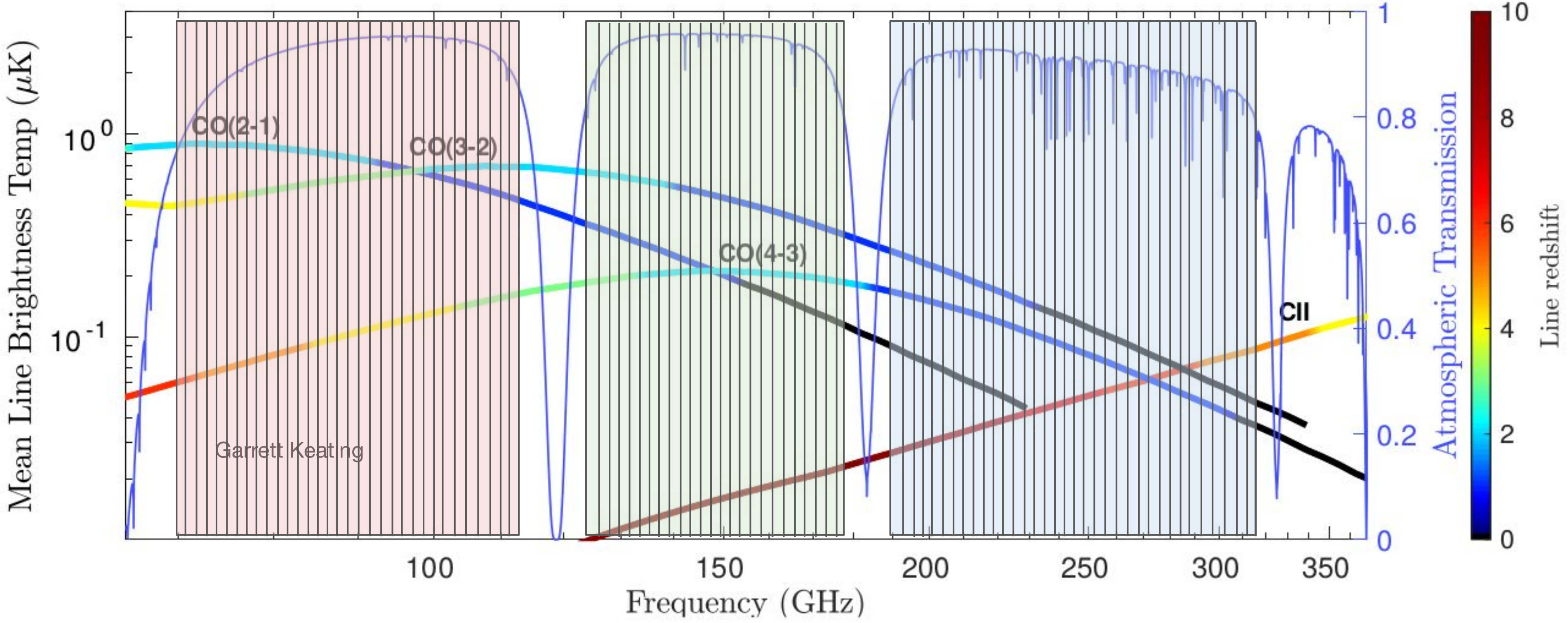
Wide Redshift Coverage in the Millimeter Range



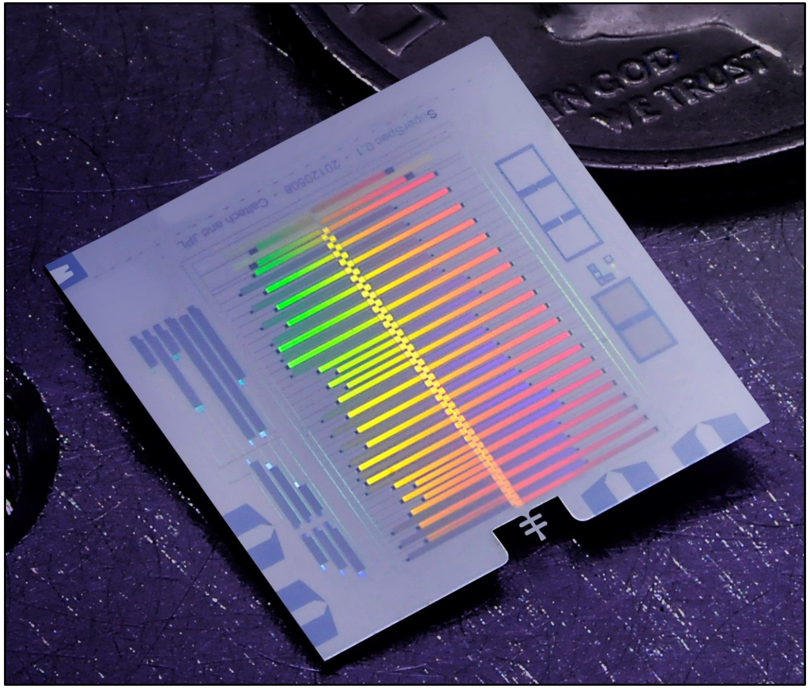
Wide Redshift Coverage in the Millimeter Range



Wide Redshift Coverage in the Millimeter Range



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

SLAC/KIPAC
K. S. Karkare

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

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

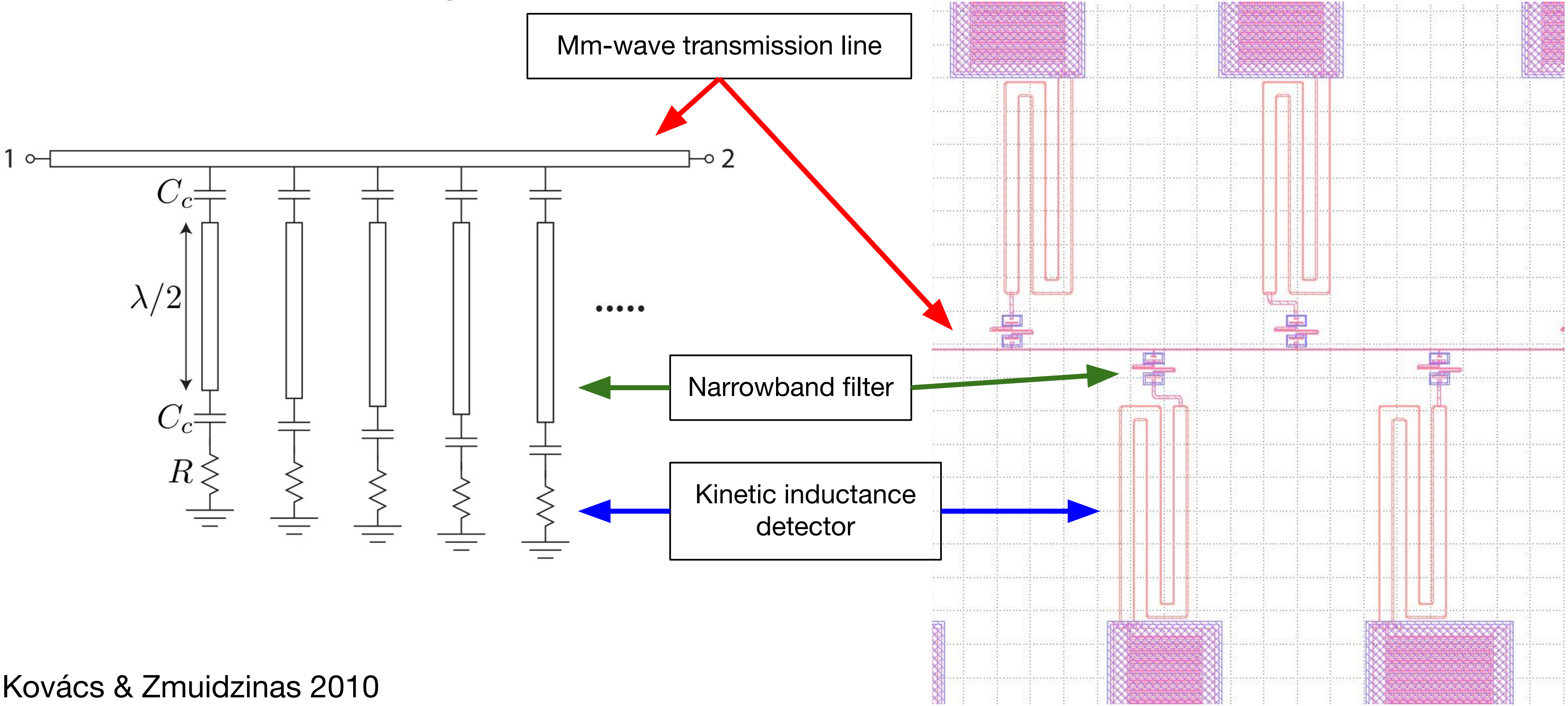
Arizona State University
K. Massingill
P. Mauskopf

Cardiff University
P. Barry
S. Doyle
C. Tucker

UC Santa Barbara
J. Redford

Dalhousie University
S. Chapman

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

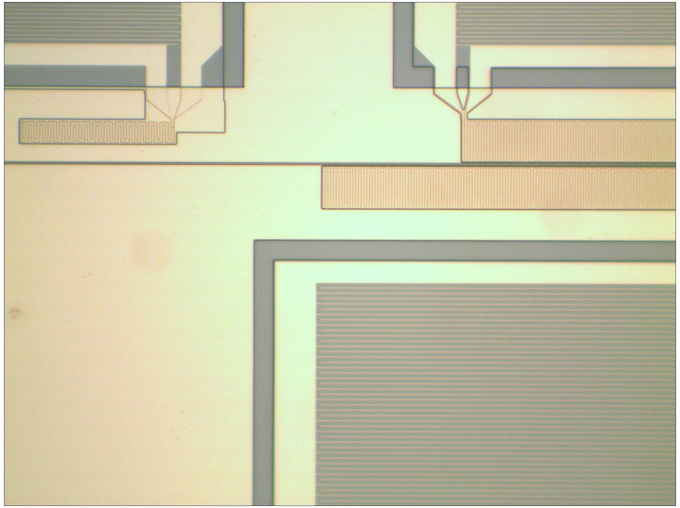


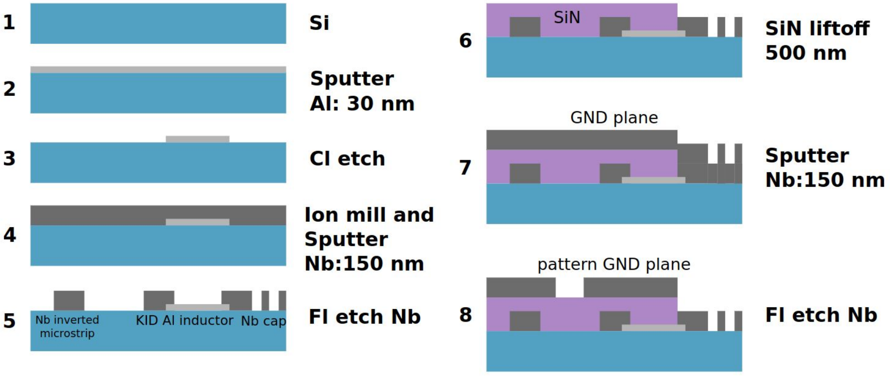
Kovács & Zmuidzinas 2010

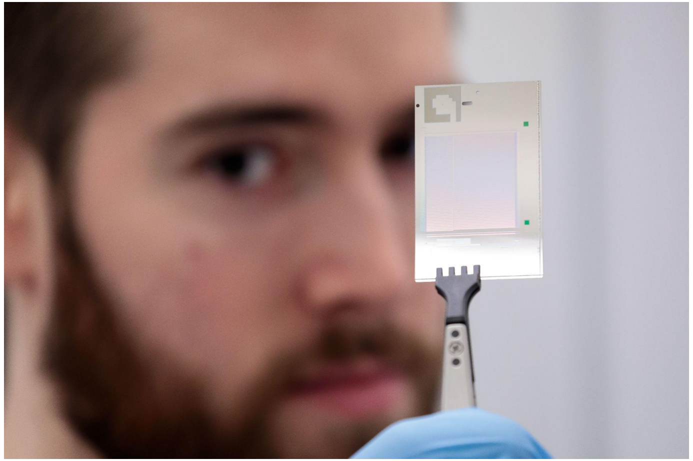
Detector Fabrication

UChicago Pritzker Nanofabrication Facility

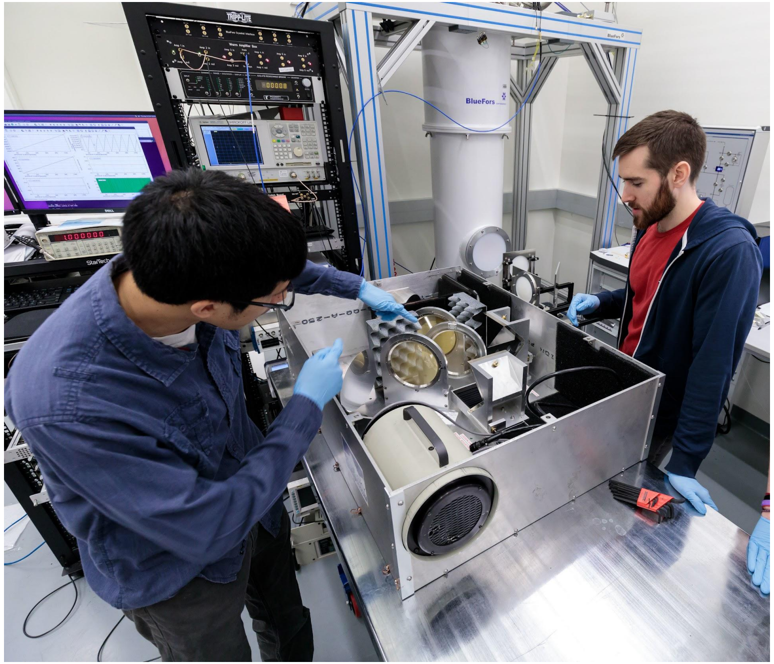
Ryan McGeehan, UChicago Ph.D. 2023 SuperSpec design and fabrication

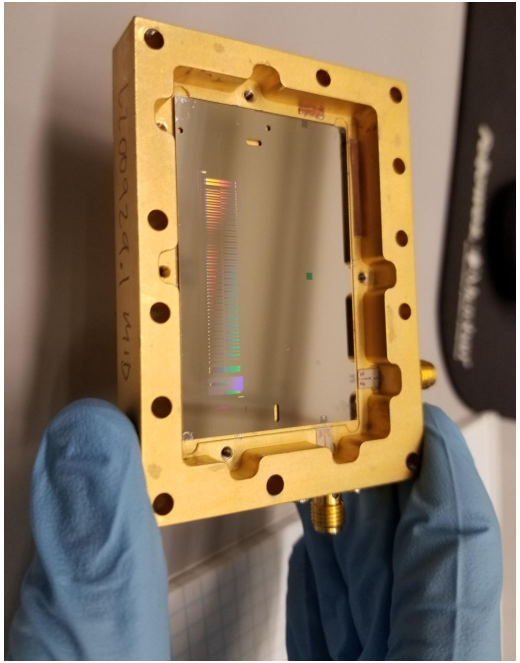


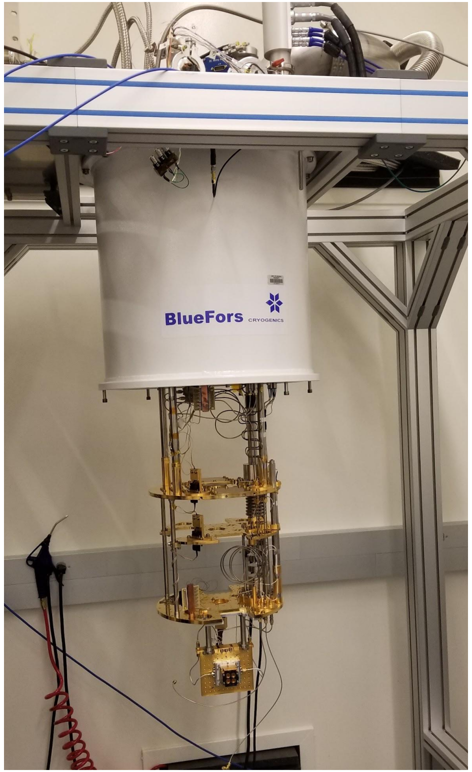




Device Characterization

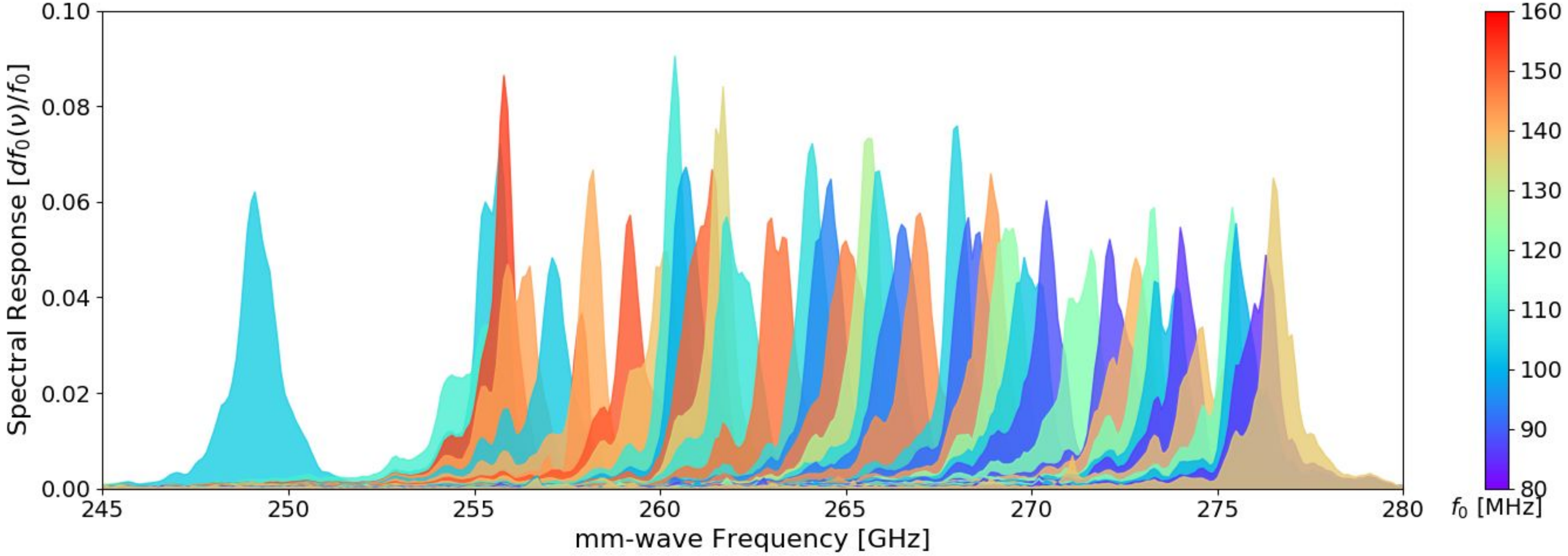






The Spectrometer Works!

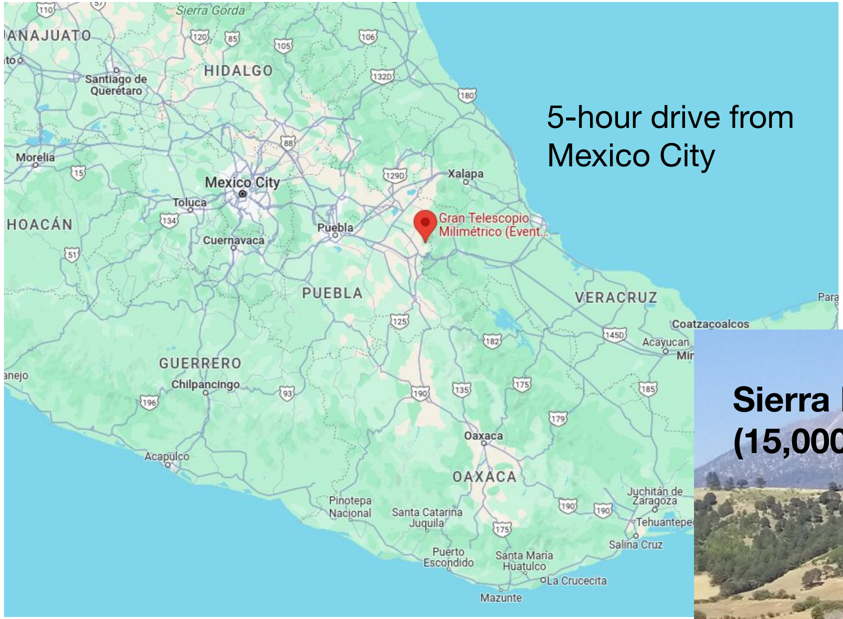
Karkare+ J. Low Temp. Phys.
2002.04542



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 50-meter **Large Millimeter Telescope** in Mexico – an ideal facility for pointed observations of high-z galaxies.



On-Sky Demonstration

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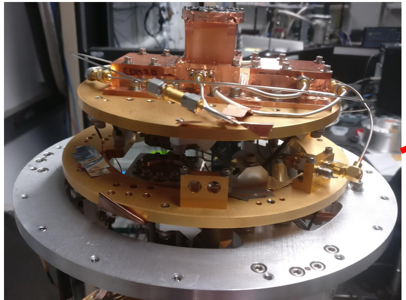
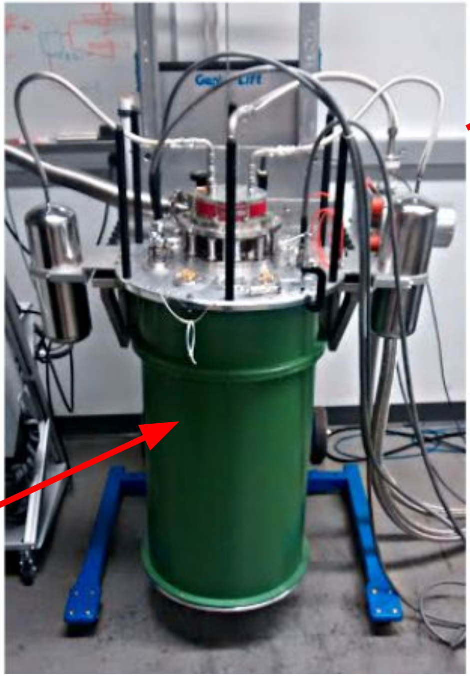
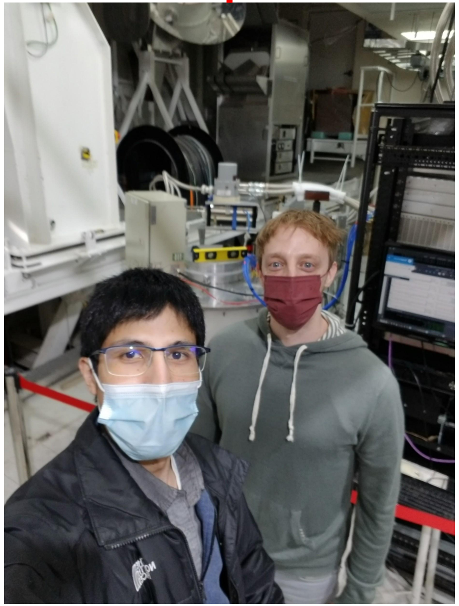
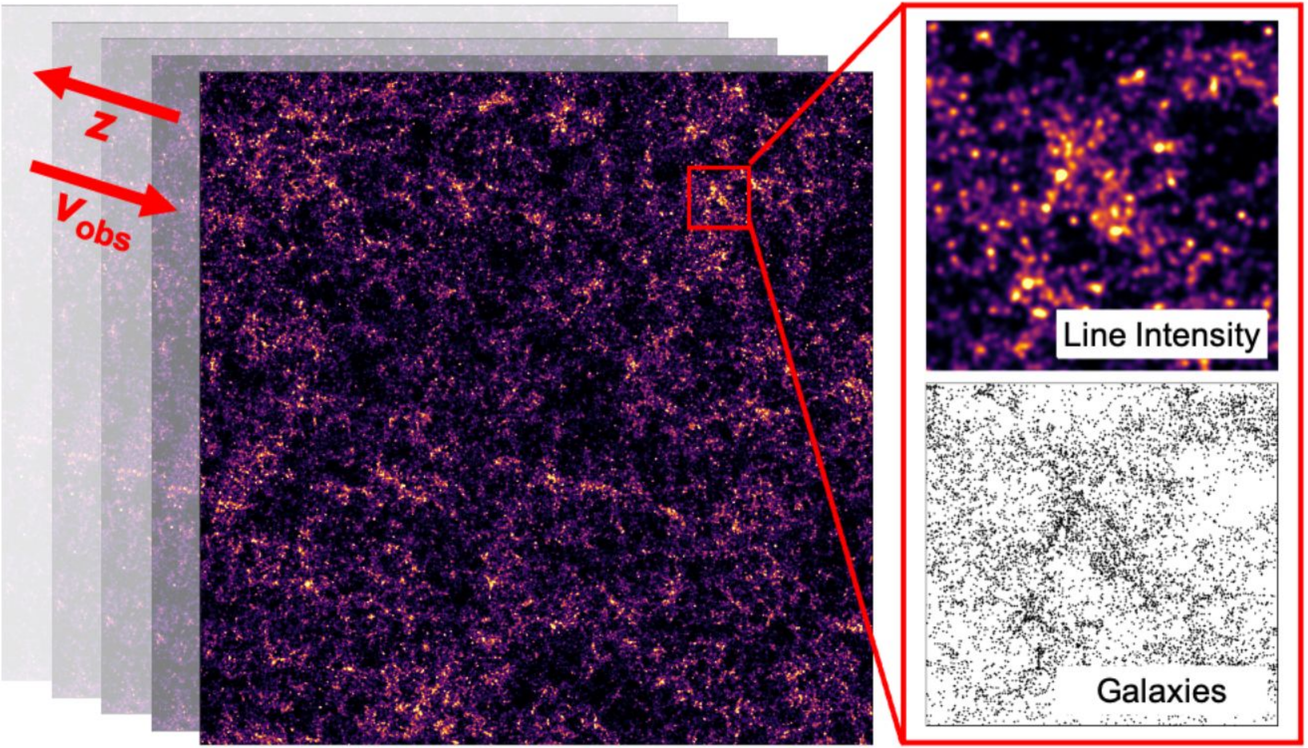






Line Intensity Mapping (LIM)

Karkare+ 2203.07258
mm-wave LIM white paper



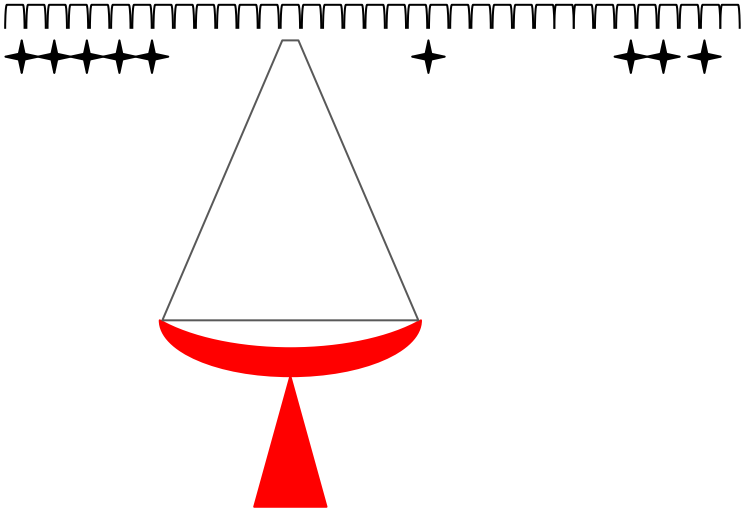
Integrate over individual sources while retaining large-scale cosmology.

Spectroscopic observations provide redshifts.

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

Galaxy Detection vs LIM

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

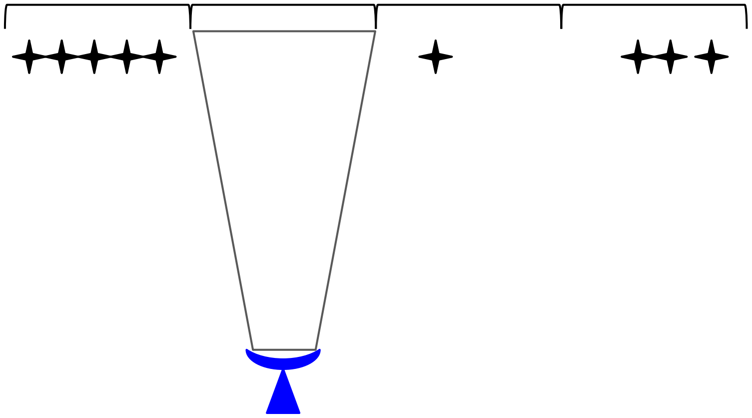


An object is **detected** when it reaches some threshold (maybe 5σ).

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

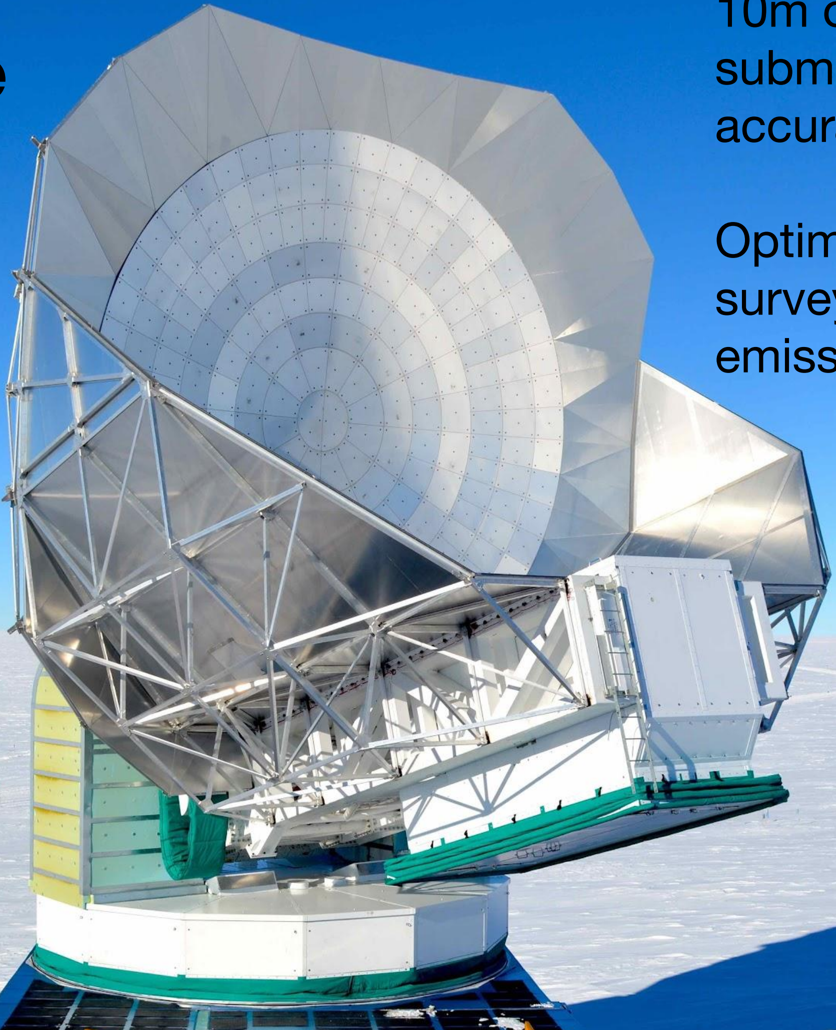
Galaxy detection is optimal in the high SNR regime, while intensity mapping is optimal in the low SNR regime (e.g., high redshifts).

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!)

The SPT Summertime Line Intensity Mapper (SPT-SLIM)

Argonne
T. Cecil
C. Chang
Z. Pan
C. Yu

Cardiff
P. Barry
C. Benson
G. Robson

CfA
G. Keating

Fermilab
A. Anderson
B. Benson
M. Young

Student
Postdoc
co-PI

McGill
M. Adamic
M. Dobbs
M. Rouble

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

U. Arizona
D. Kim
D. Marrone

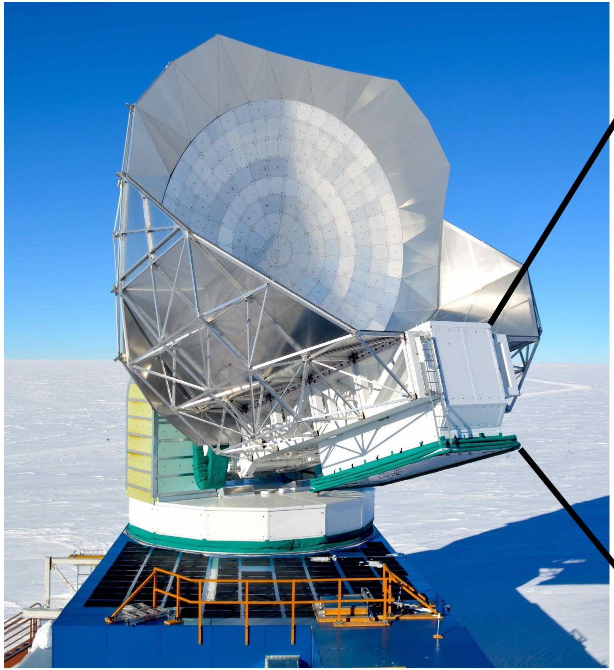
U. Chicago
E. Brooks
J. Carlstrom
K. Dibert
K. Fichman
T. Natoli
A. Rahlin
J. Zebrowski

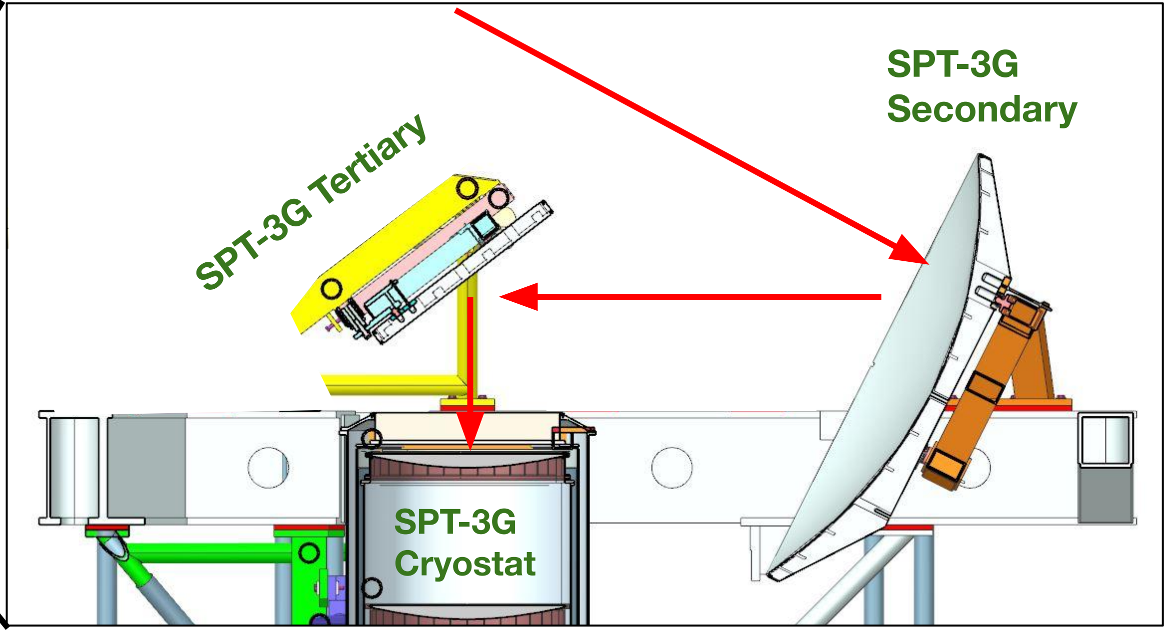
Deploy a LIM pathfinder to the South Pole Telescope during the austral summer season (Nov–Feb) while SPT-3G is not observing.

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

Fully funded by NSF and Fermilab in 2021.

The SPT Summertime Line Intensity Mapper (SPT-SLIM)

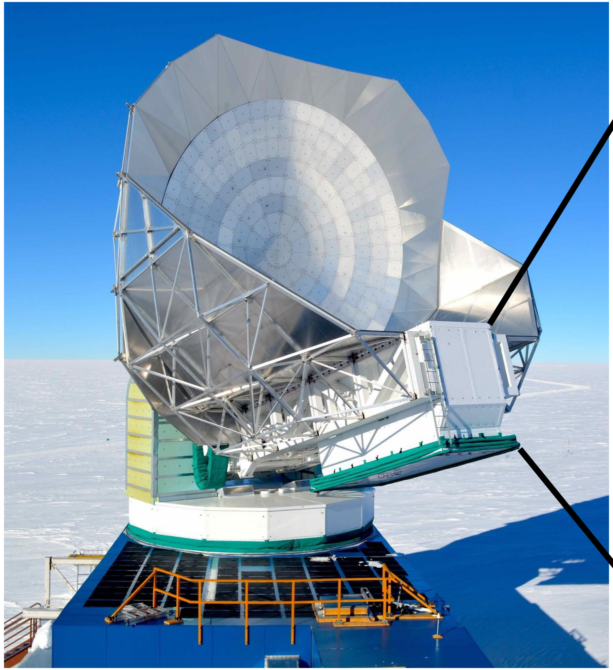


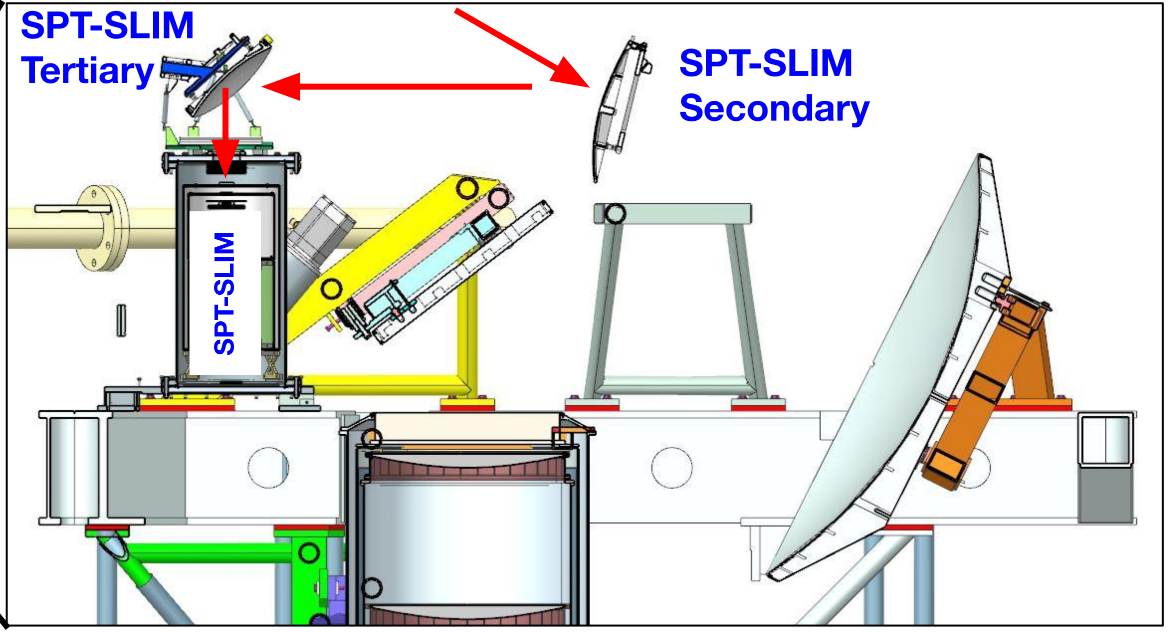


In normal operation, light from the primary is reflected into the receiver cabin, and then into the SPT-3G cryostat…

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

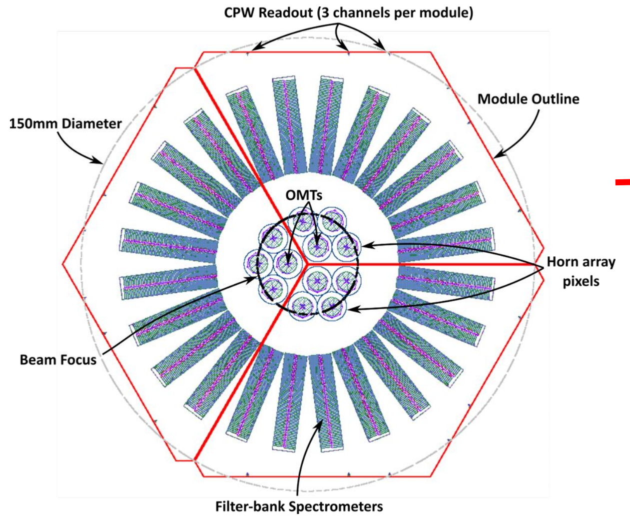
Verifying the Fit (with the help of wecutfoam.com)

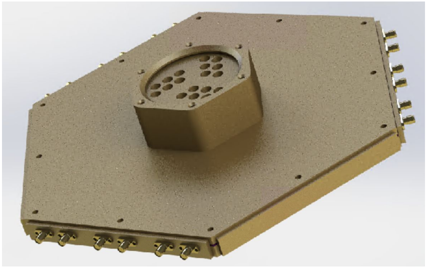
The SPT-SLIM Instrument

Don Mitchell

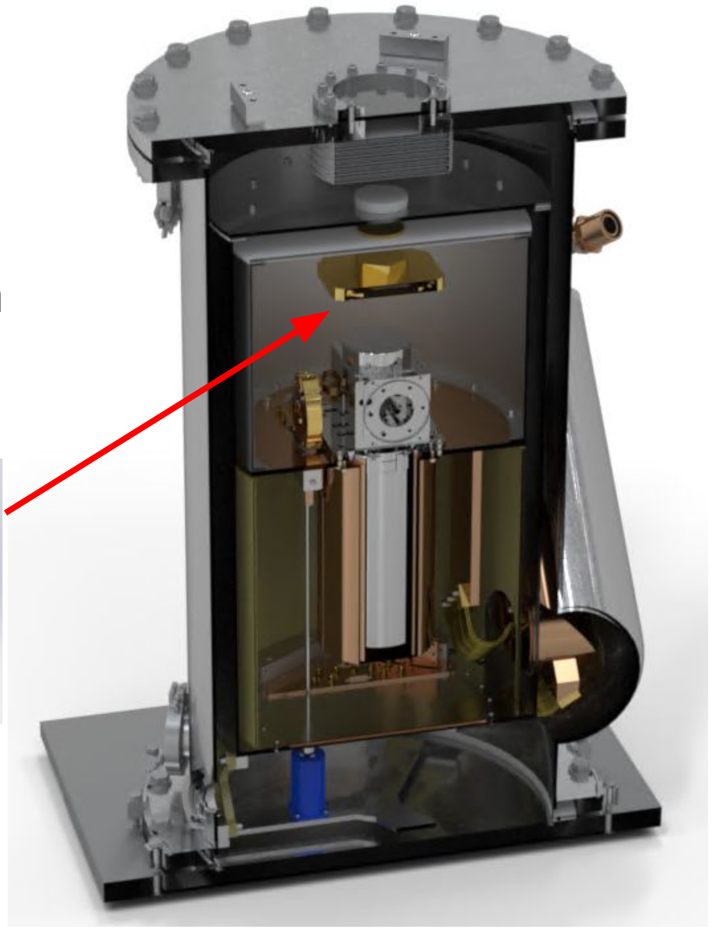
The first mm-wave integral field unit (IFU):
12 spatial-spectral pixels.

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





Pete Barry,
Gethin Robson



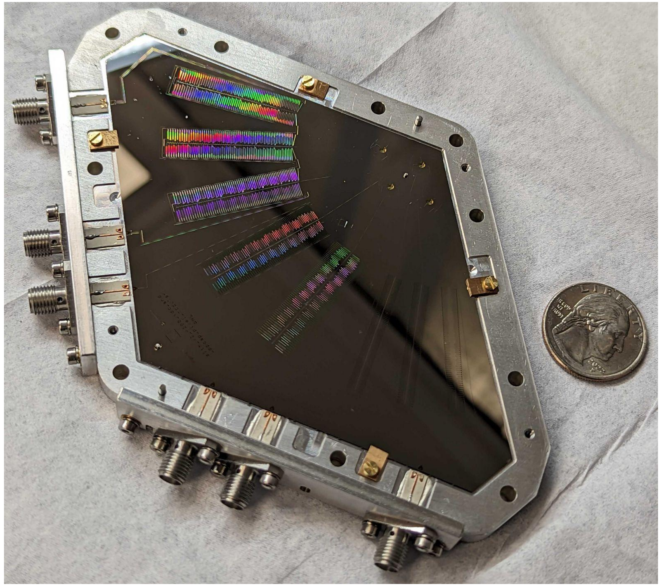
The SPT-SLIM Instrument

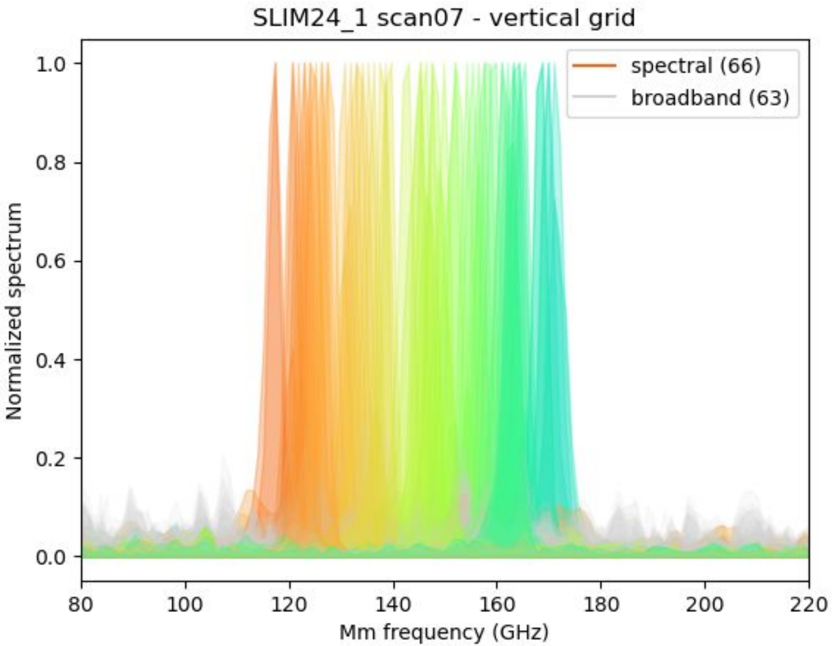
The SPT-SLIM Detectors



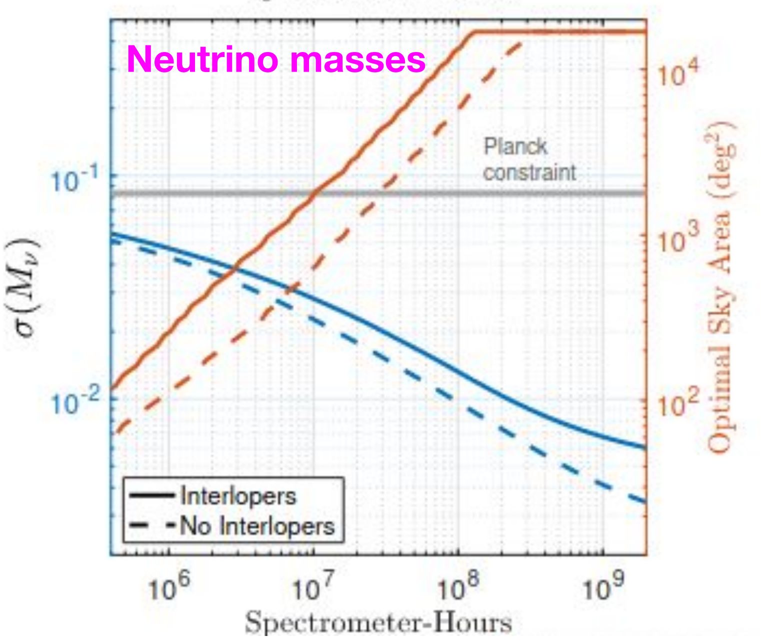
Each spectrometer covers 120–180 GHz with R~200 resolution targeting CO(2-1), (3-2), (4-3) from 0.5 < z < 2.5.

Elyssa Brooks,
Karia Dibert,
Kyra Fichman





LIM Cosmology



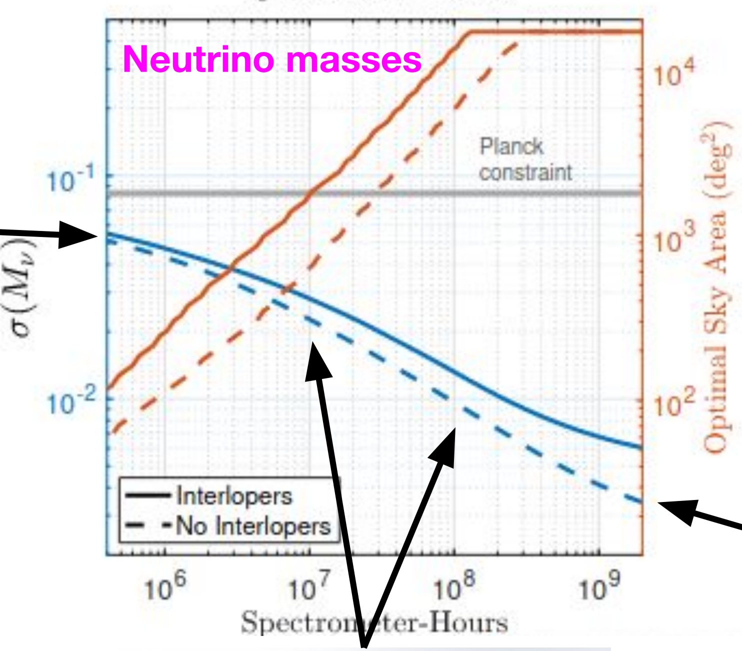
Karkare+ 2203.07258
Snowmass white paper

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

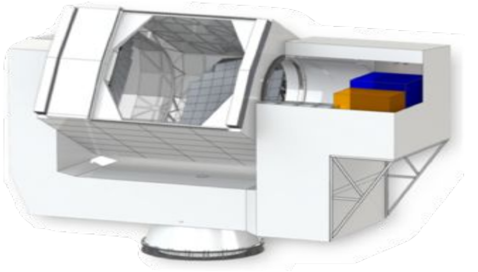
Reionization astrophysics possible with ~1.

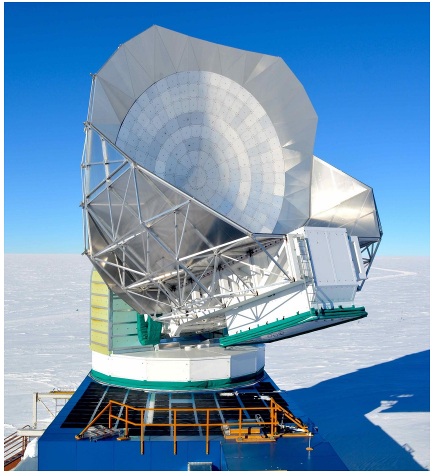
LIM Cosmology

SPT-SLIM
pathfinder
2025

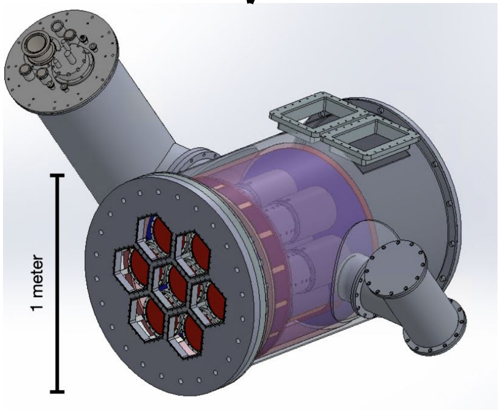


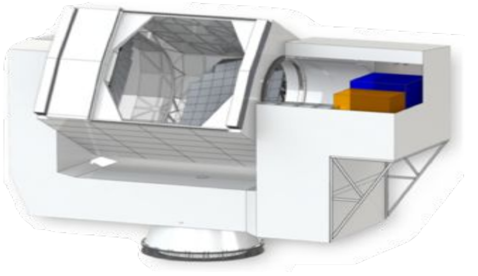
Karkare+ 2203.07258
Snowmass white paper





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





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

Community Support for LIM is Growing

December 2023: the P5 report endorses LIM 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).

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!