

Cosmology with Millimeter-Wave On-Chip Spectrometers: SPT-SLIM and the Path to Large-Format Focal Planes



Kirit S. Karkare (Boston University)
CPAD, 2026-10-21

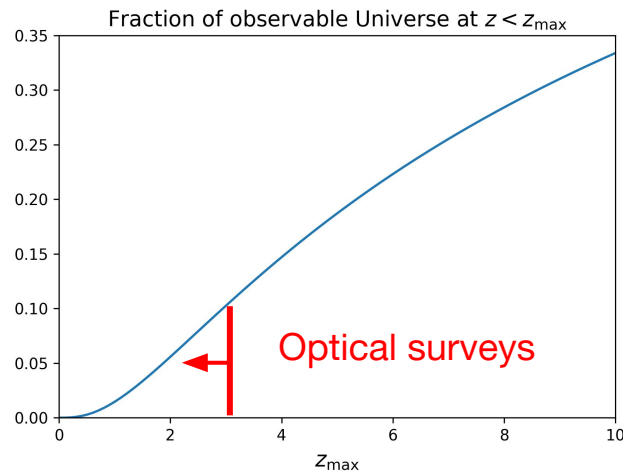
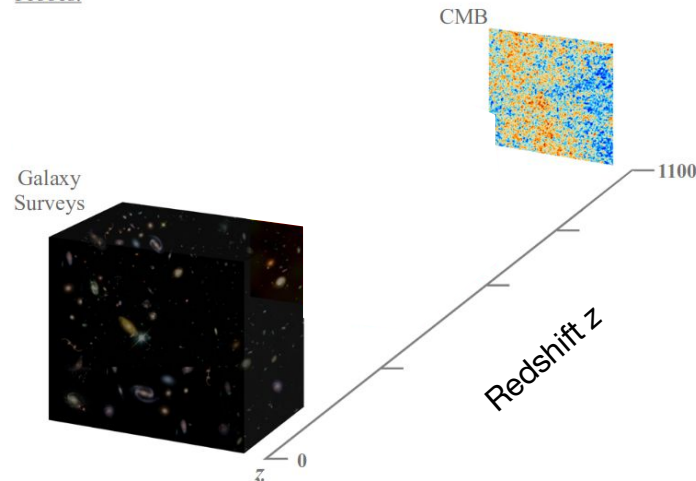
HEP at the Cosmic Frontier

To make progress on key cosmic frontier science questions...

- Dark energy
- Inflation
- Light relativistic particles

...we need cosmic surveys over **larger volumes** (better statistics) and **higher redshift** (break degeneracies).

But our standard probes leave a huge fraction of the universe unmeasured!



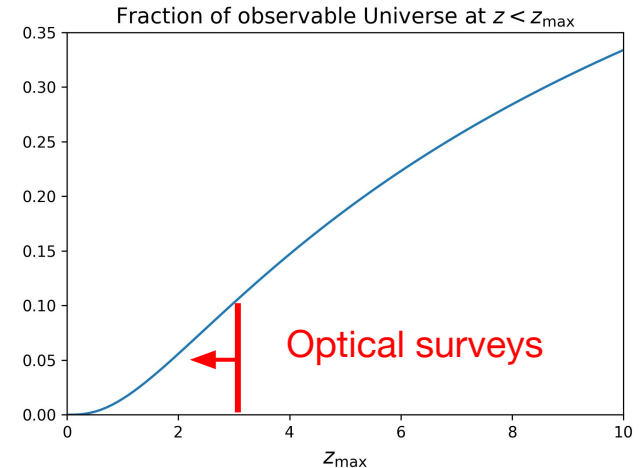
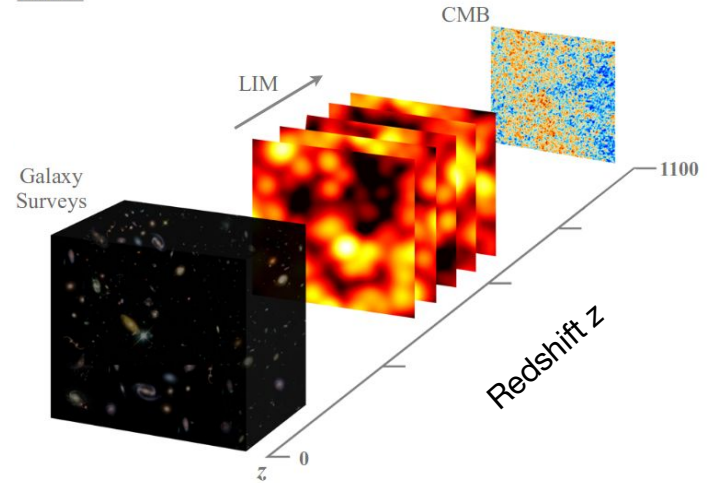
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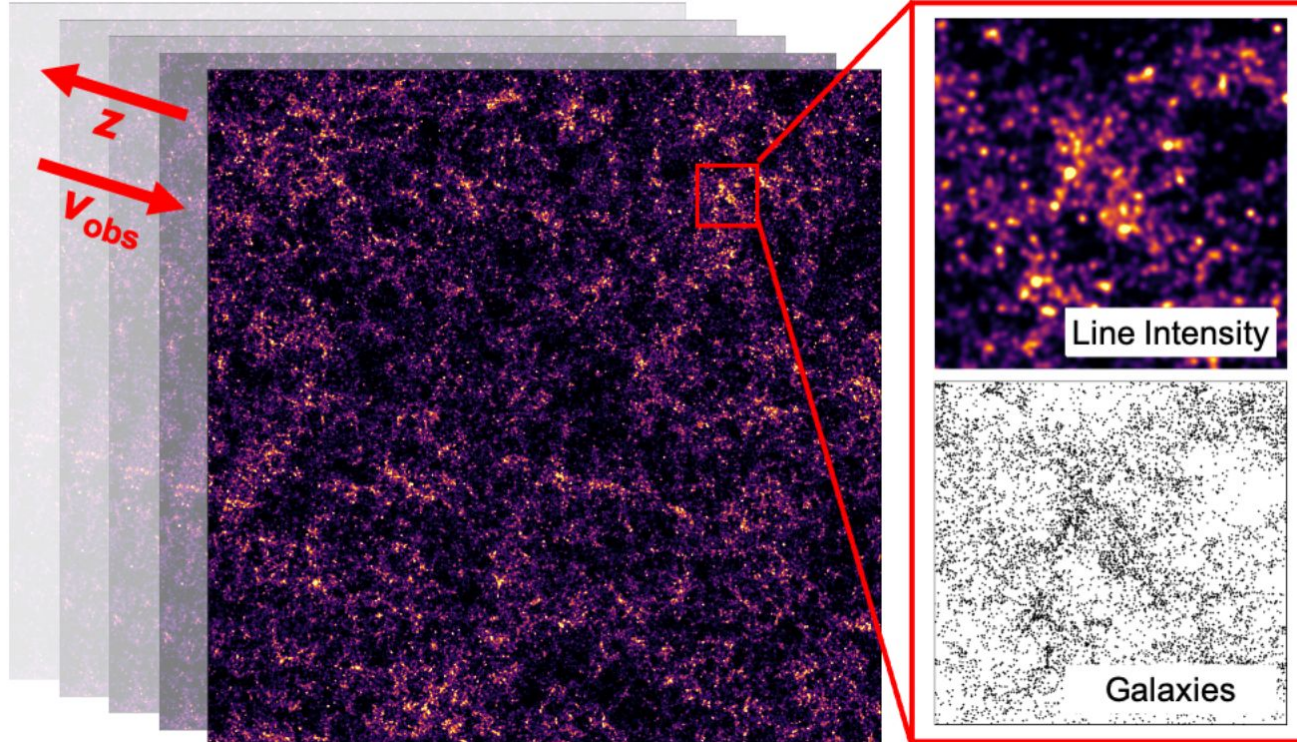
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Line Intensity Mapping (LIM)



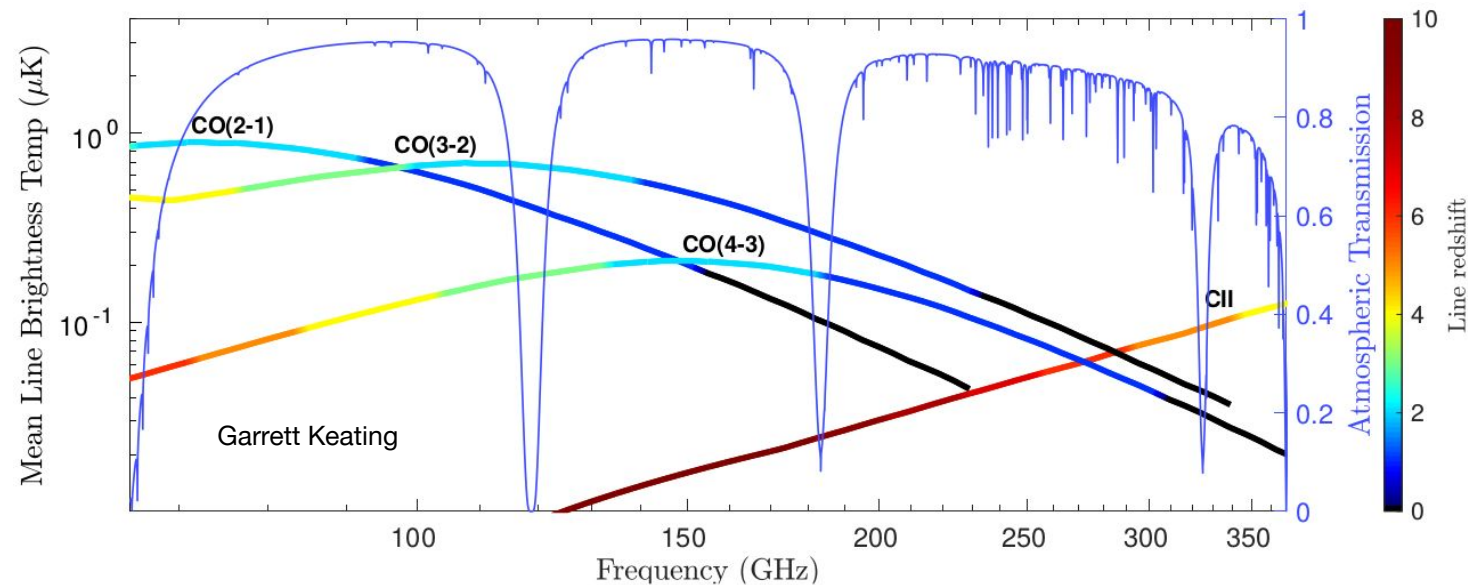
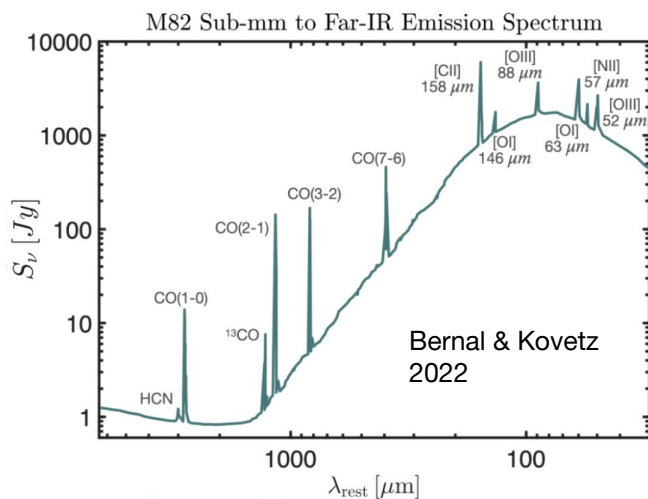
Integrate over individual sources while retaining large-scale cosmology.

Much more efficient than object detection at high redshift.

Choose a spectral line – observed wavelength corresponds to distance.

Millimeter-Wave LIM

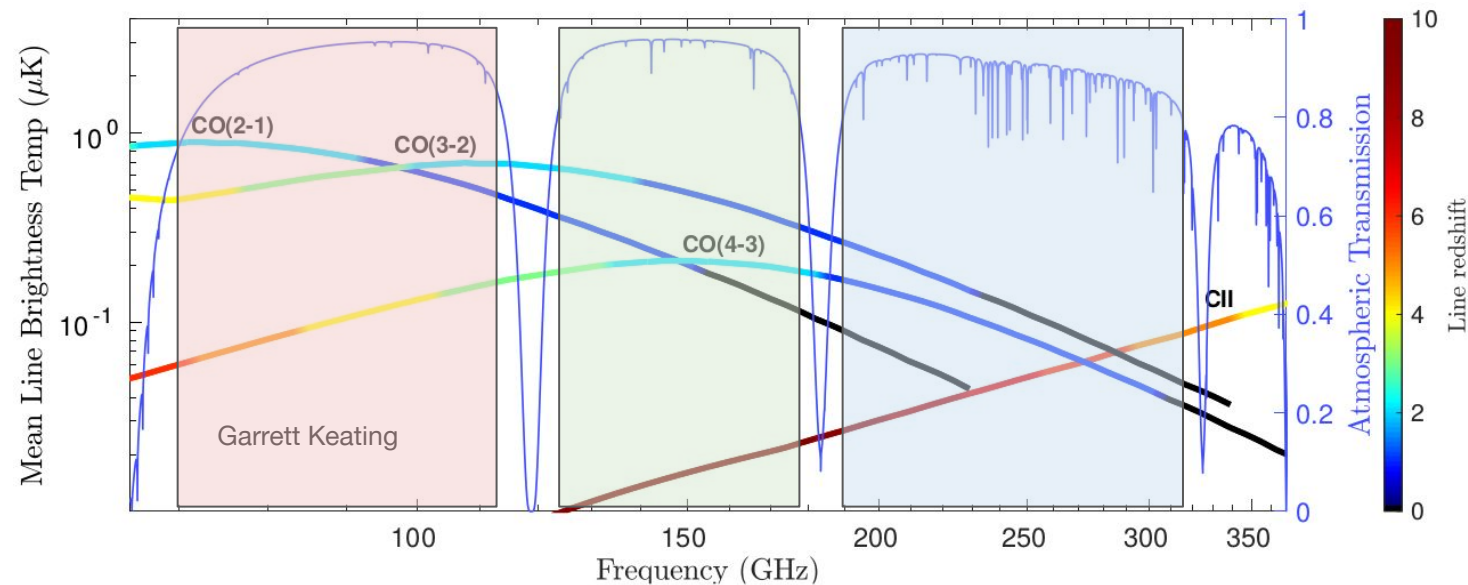
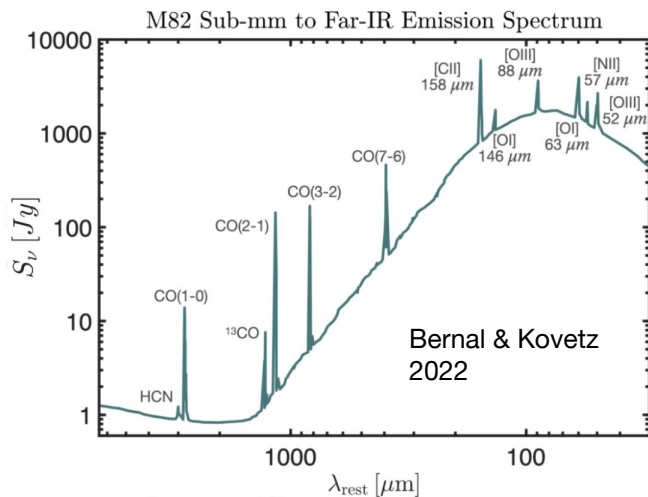
High-redshift galaxies have strong thermal dust emission (far-IR, $\sim 100\ \mu\text{m}$), on top of which are strong emission lines: the **CO** rotational ladder and **[CII]** ionized carbon.



They redshift to mm-wave atmospheric windows, where they can be observed from the ground...

Millimeter-Wave LIM

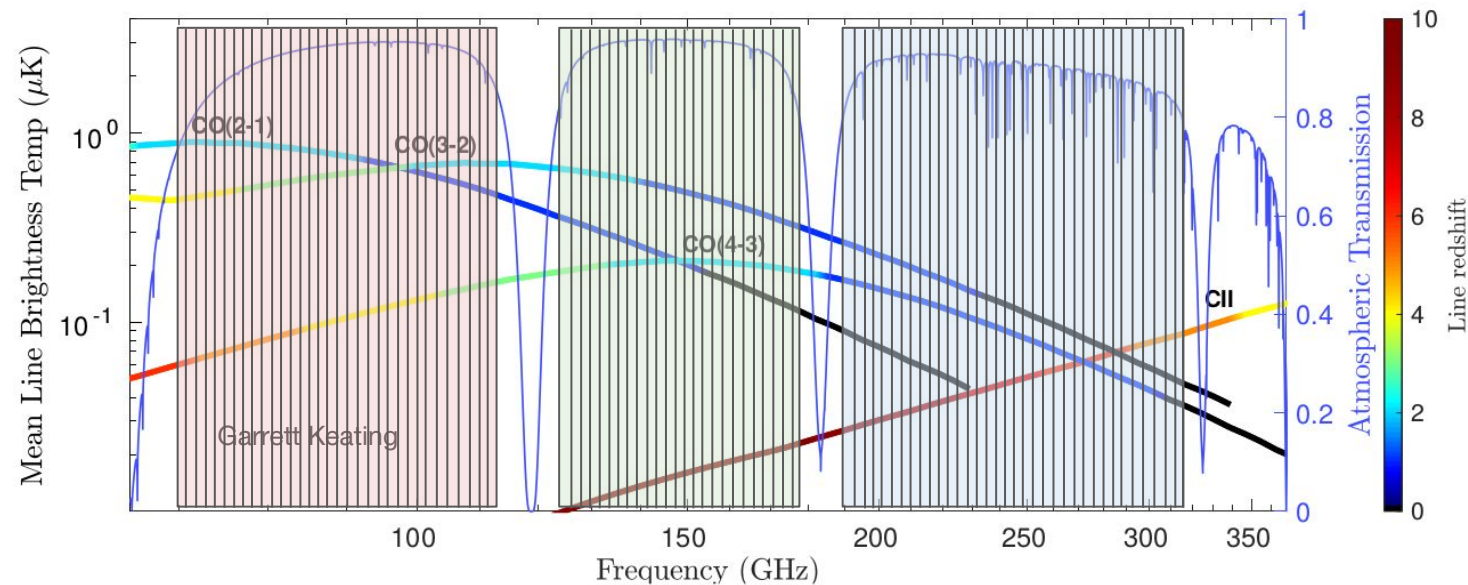
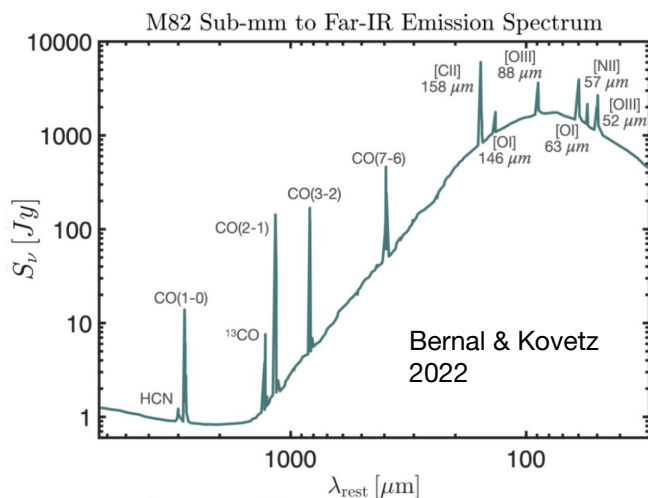
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Millimeter-Wave LIM

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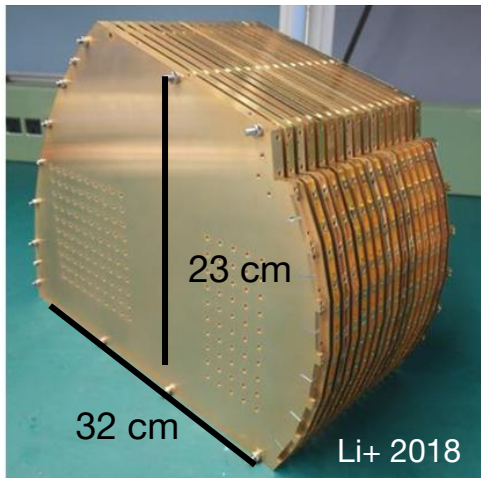


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We need **mm-wave spectrometers**.

On-Chip Filter-Bank Spectrometers

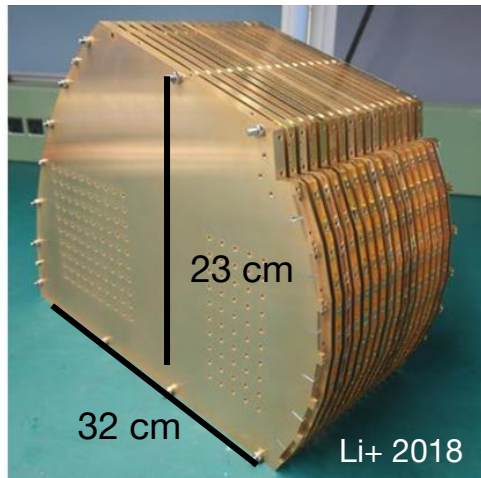
Existing mm-wave spectrometers are relatively large and hard to scale up...



TIME grating:
32 x 23 x 1 cm
~ **736 cm³**

On-Chip Filter-Bank Spectrometers

Existing mm-wave spectrometers are relatively large and hard to scale up...



TIME grating:
32 x 23 x 1 cm
~ **736 cm³**

SuperSpec:
3.6 x 5.7 x 0.05 cm
~ **1 cm³**



By printing the spectrometer on a silicon wafer, we can efficiently deploy the hundreds of pixels we need to do cosmology. To accommodate the large detector counts (hundreds X equivalent CMB receivers), use **kinetic inductance detectors**.⁹

The SPT Shirokoff Line Intensity Mapper (SPT-SLIM)

Argonne

T. Cecil
C. Chang
M. Lisovenko
V. Yefremenko
C. Yu

Boston U.

K. S. Karkare
A. Lapuente
A. Reda
S. Savorgnano

Caltech

K. Dibert

Cardiff

P. Barry
C. Benson
G. Robson

CfA

G. Keating

Fermilab

A. Anderson
B. Benson
M. Young

McGill/t.O

M. Adamic
M. Dobbs
J. Montgomery
M. Rouble
G. Smecher

U. Arizona

D. Kim
H. Taylor
D. Marrone

U. Chicago

A. Bapat
J. Carlstrom
K. Fichman
T. Natoli
A. Mangu

A. Rahlin
J. Zebrowski

Argonne
NATIONAL LABORATORY



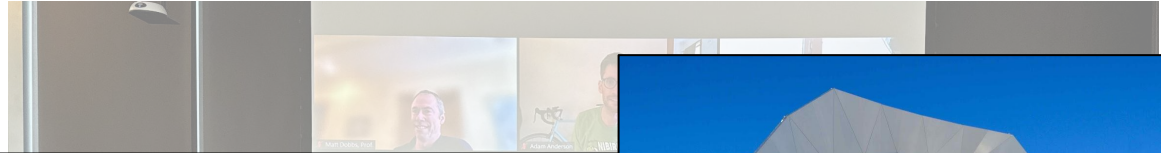
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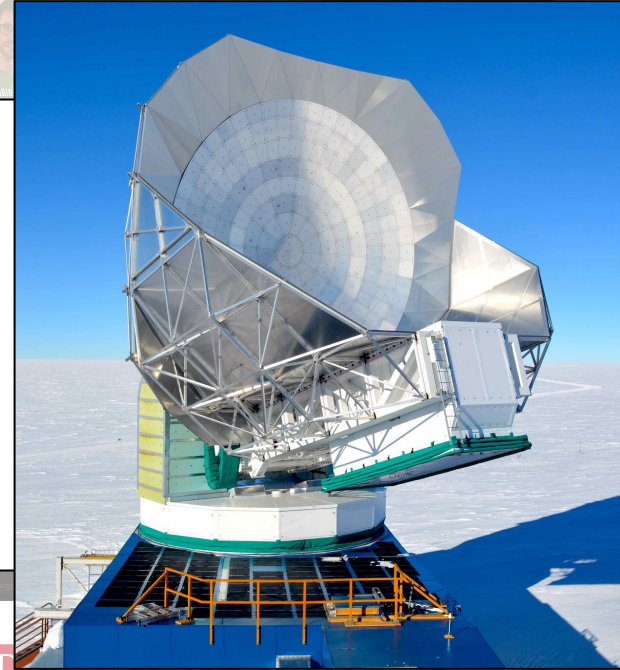
Fermilab

A. Anderson
B. Benson
M. Young



A Technology Demonstrator:

- Show that can we use on-chip spectrometers for mm-wave LIM...
- ...by deploying the first multi-pixel on-chip mm-wave spectrometer to the **10-m South Pole Telescope**
- Funded by NSF ATI and Fermilab LDRD in 2021.



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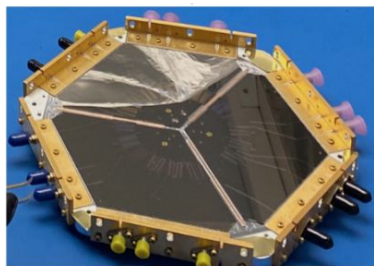


The SPT-SLIM Spectrometers

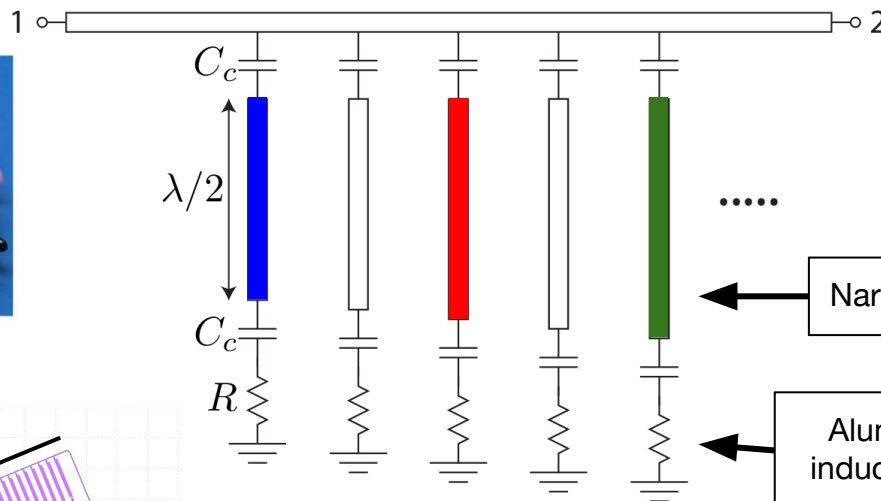
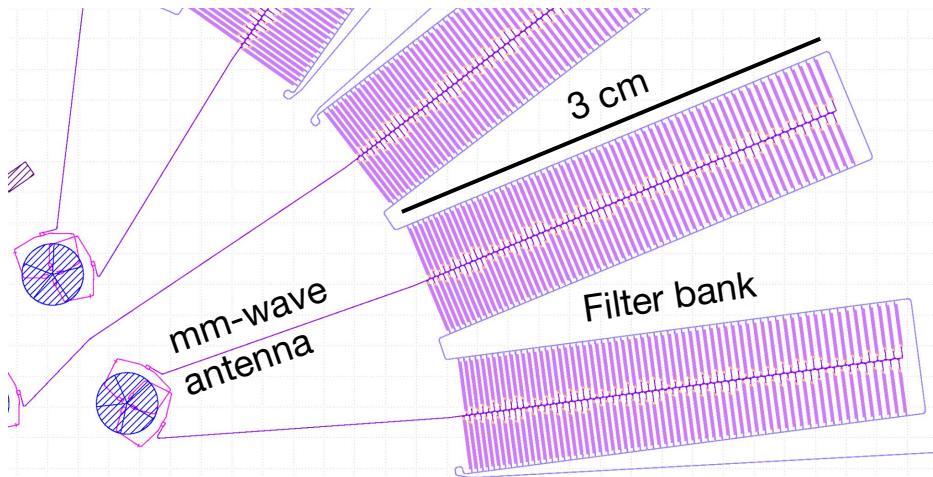
**On-chip mm-wave
integral field unit:**

9 dual-pol pixels,
 $R \sim 100$,
110-170 GHz

Fabricated at ANL -
see Tom Cecil's talk



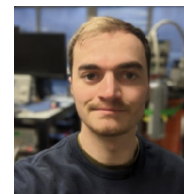
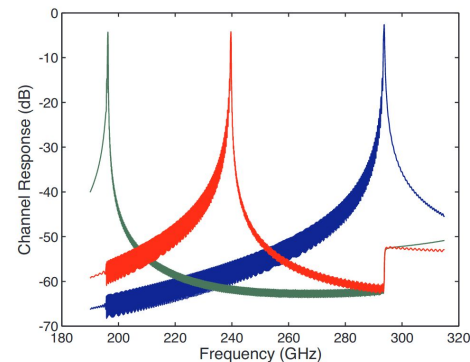
180 mm



Mm-wave transmission line

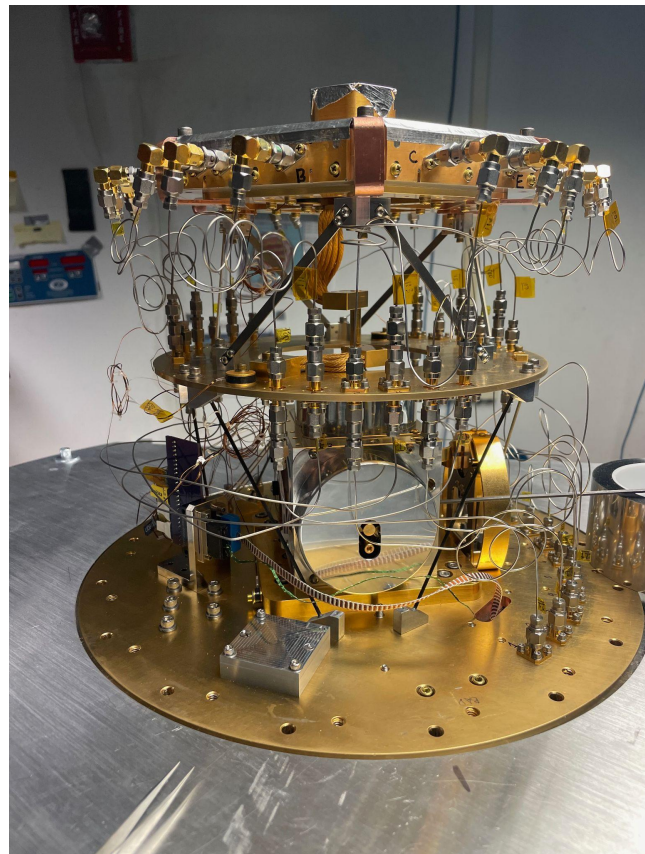
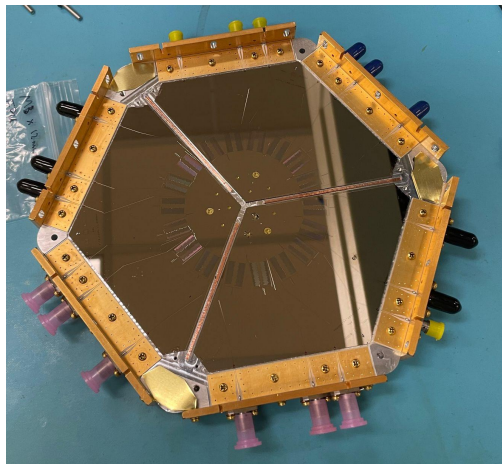
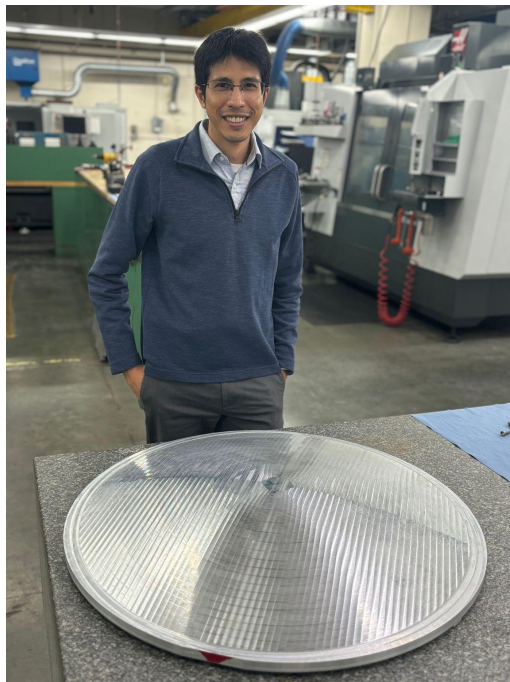
Kovács &
Zmuidzinas
2010

Aluminum Kinetic
inductance detector



Gethin Robson, Elyssa Brooks

SPT-SLIM Coming Together in 2024

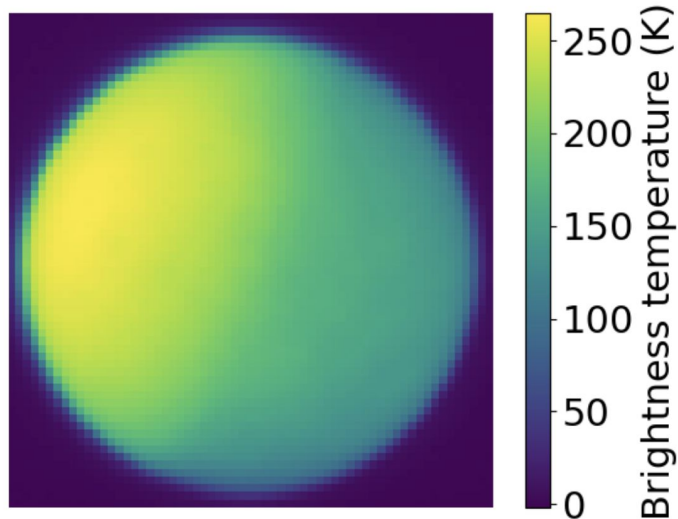


January 2025

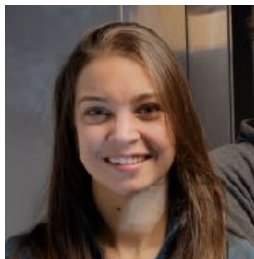


< 2 weeks on sky for commissioning and preliminary source observations

First-Light Images



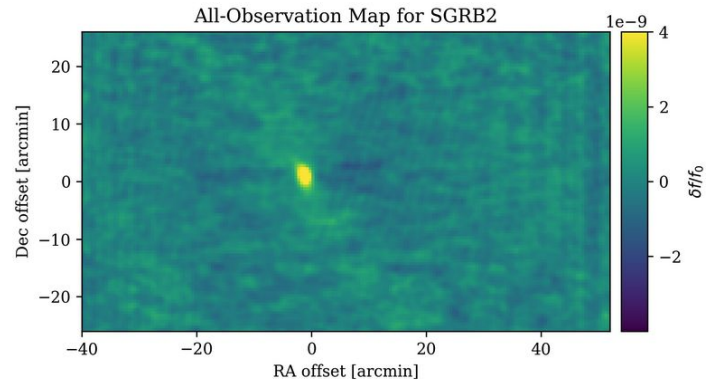
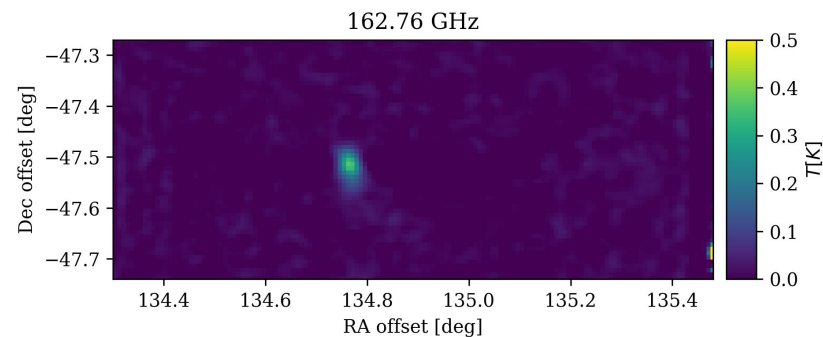
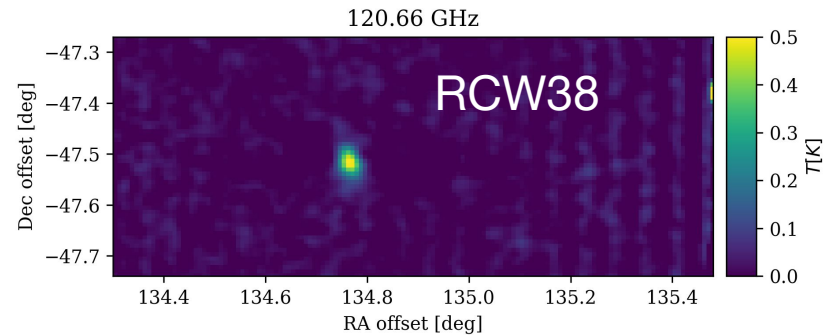
Karia Dibert



Jessica Zebrowski

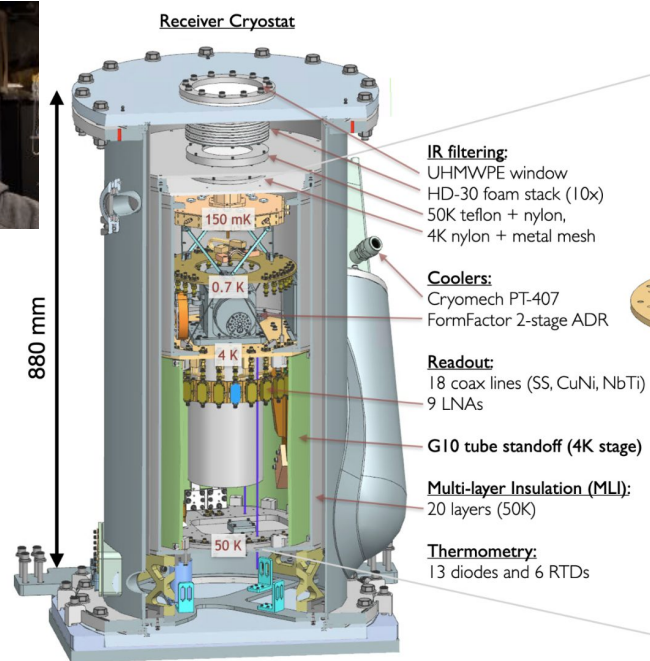
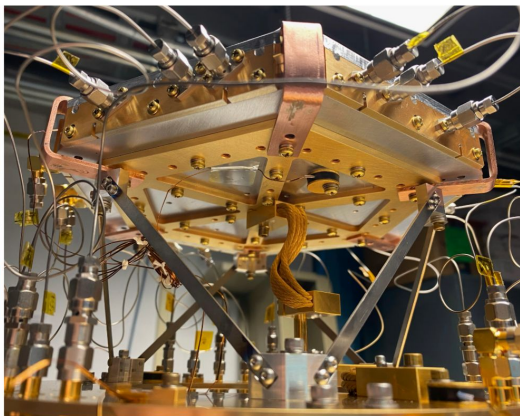
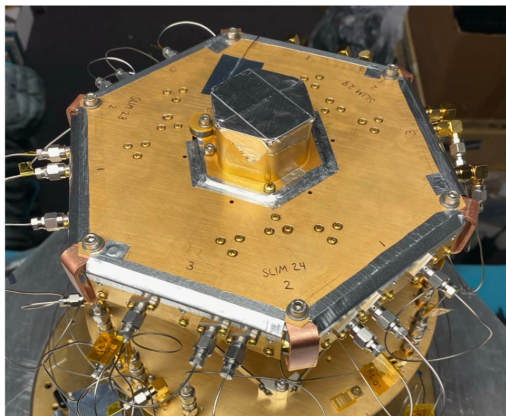
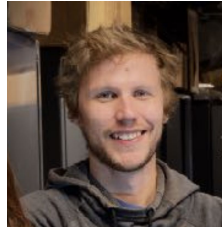


Alex Lapuente



Paper 1: Cryostat

Matt Young
arxiv:2510.14219

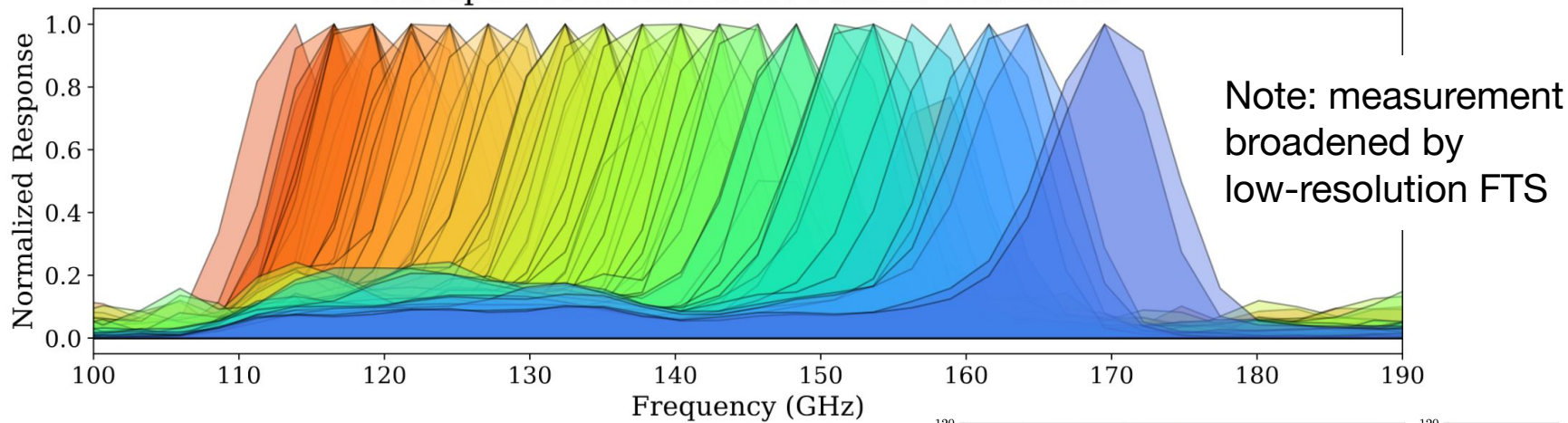


Stage	Modeled load					Measured load
	Conductive	Wiring	Radiative	Optical	Total	Total
50K	2.65 W	0.13 W	11.5 W	0.25 W	14.5 W	15 W
4K	101 mW	136 mW	7 mW	321 mW	113 mW	110 mW
GGG	9.33 μ W	5.30 μ W	0.21 μ W	0 μ W	14.8 μ W	17.0 μ W
FAA	0.93 μ W	0.28 μ W	0.42 μ W	0.01 μ W	1.62 μ W	2.20 μ W

Paper 2: Spectrometers

arxiv:2509.02245

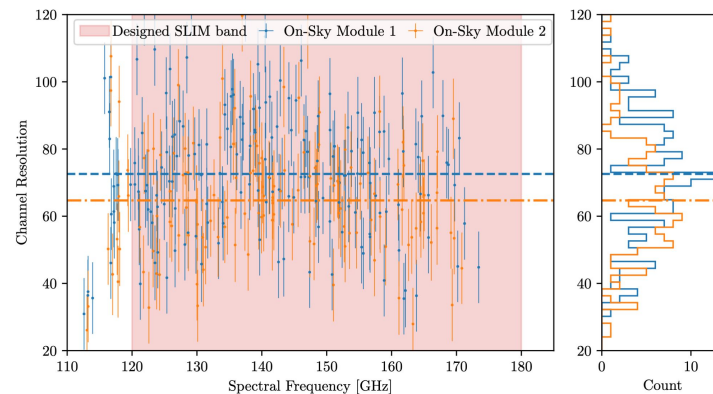
Bandpasses From Direct Fourier Transform



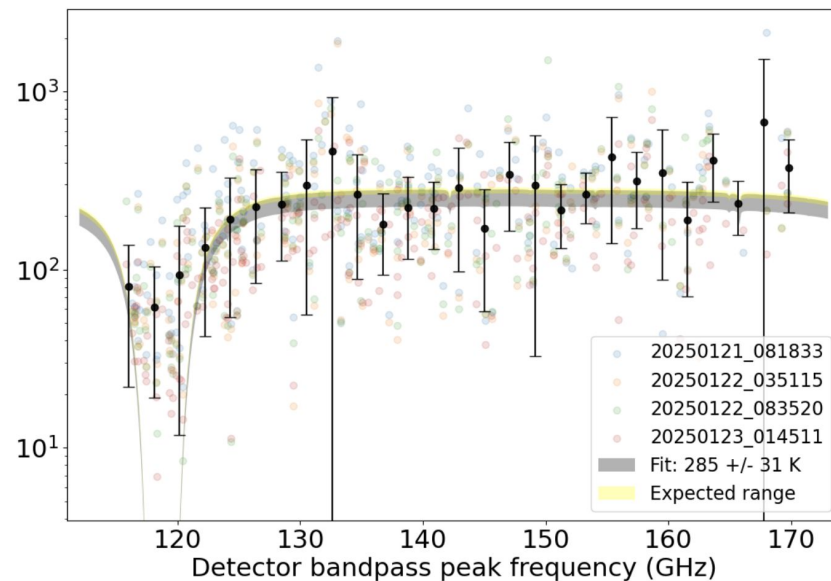
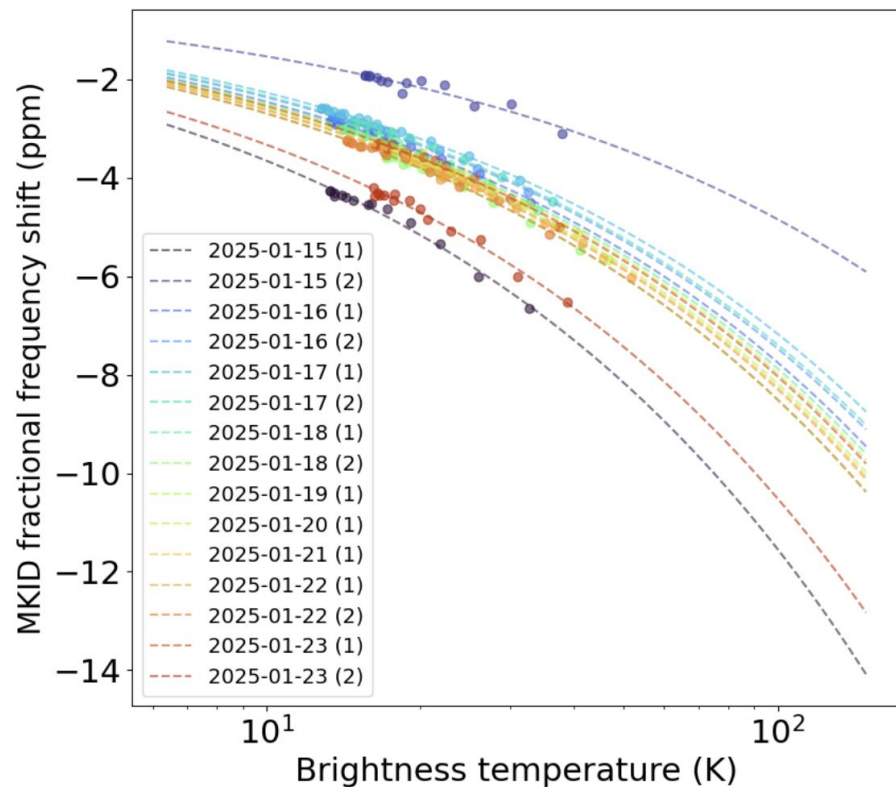
Typical spectral resolution $R \sim 70$



Kyra Fichman
Chris Benson



Paper 3: Atmospheric Calibration



Karia Dibert
arxiv:2510.14220



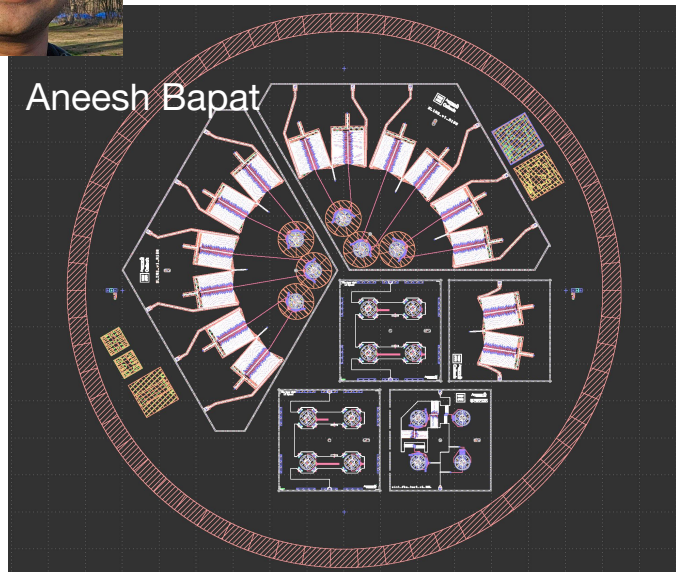
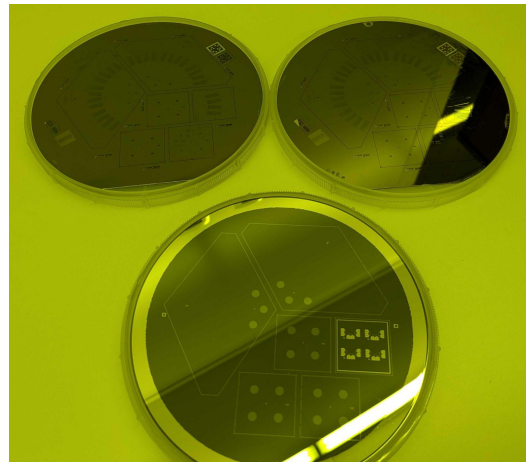
What's Next?

With SPT-SLIM we've demonstrated

- *The first astronomical observations with a multi-pixel on-chip mm-wave spectrometer!*
- New in-lab and on-sky calibration techniques relevant for LIM
- A working cryostat at the SPT that is ready for future observations.

Now preparing for 2027 with new detectors:

- More compact layout increases fab throughput/efficiency
- 30 nm Al process (previous baseline, but descope to 50 nm) → higher responsivity



What's Next?

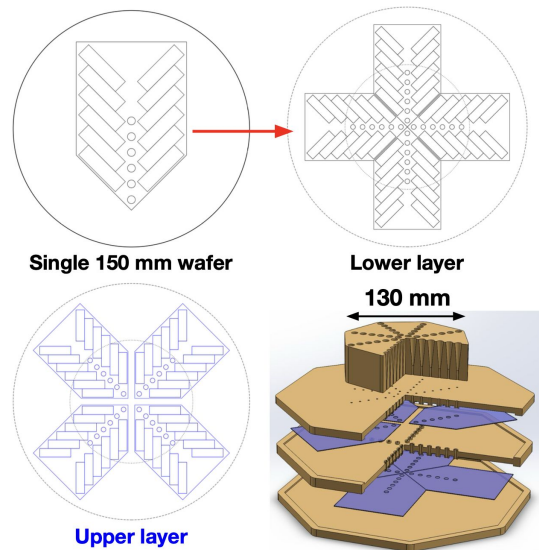
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Next round just funded by NSF ATI:

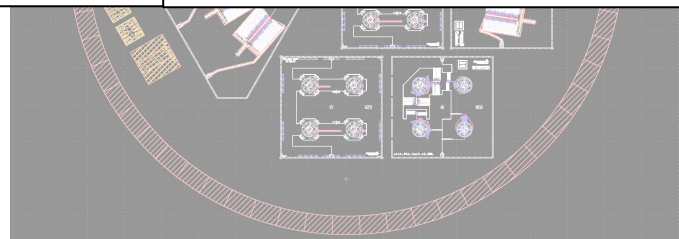
**COLIMATE: COsmology Line Intensity Mapping
with Advanced Technology Experiment
(PI Karkare, co-PIs Chang, Anderson)**

Scale up SPT-SLIM: large-format IFU (48 spectrometers) with improved efficiency and spectral resolution. Will be the first mm-LIM focal plane sensitive enough for cosmology!



throughput/efficiency

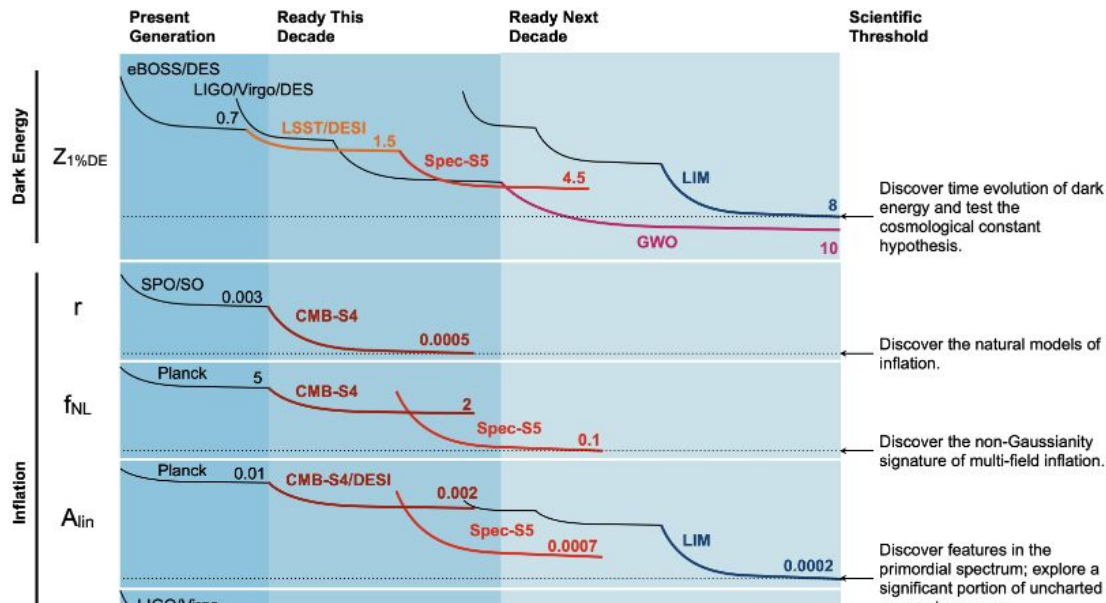
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What's Next?

High-redshift cosmology demands more.

- We are at 10s of spectrometers - **we need hundreds.**

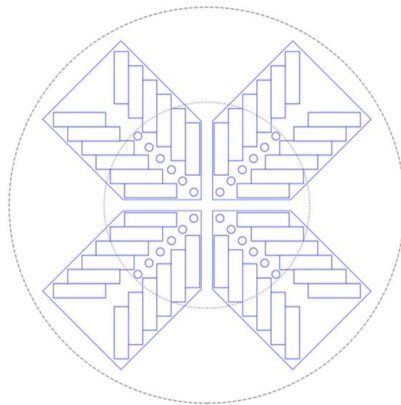


Snowmass 2021 white paper calculating LIM sensitivity needed to surpass galaxy surveys with high-z data

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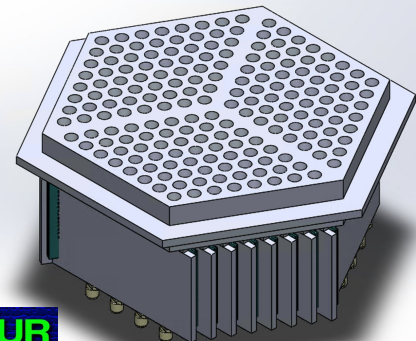
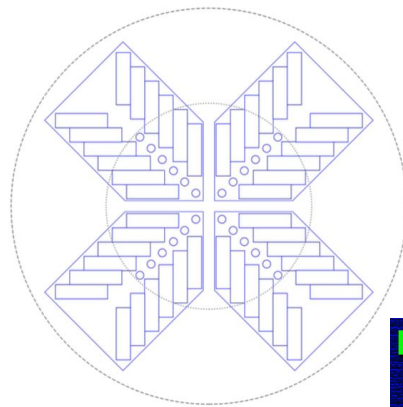
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- The planar architecture shown here is possibly scalable to the levels needed (COLIMATE), but R&D in more creative architectures could be game-changing.



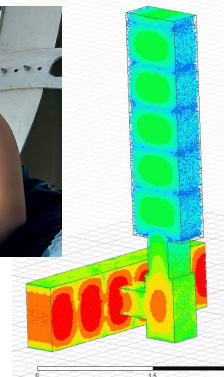
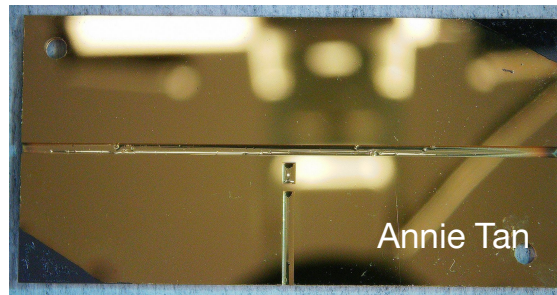
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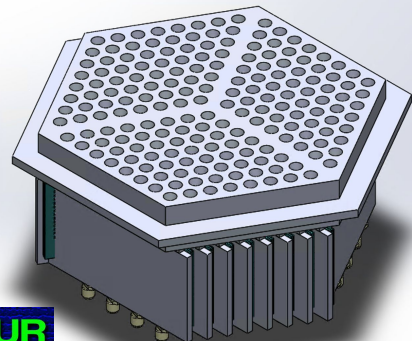
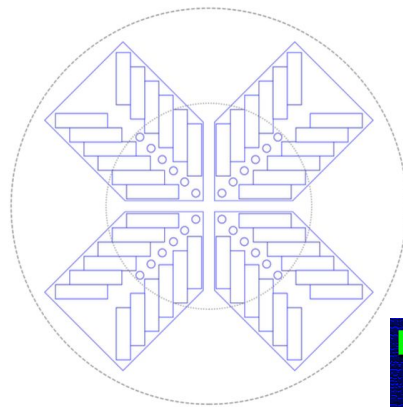
Waveguide spectrometers and similar architectures could move the spectrometers out of the focal plane



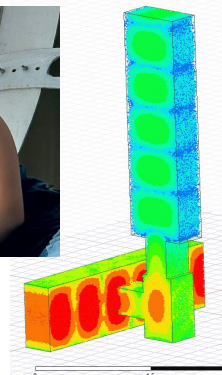
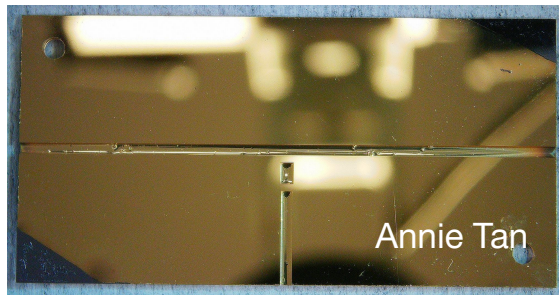
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We're working hard on the detector R&D. Stay tuned!