Millimeter-Wave Superconducting Spectrometers for Next-Generation Cosmology

Kirit S. Karkare (SLAC)
CPAD, 2023-11-09

HEP at the Cosmic Frontier

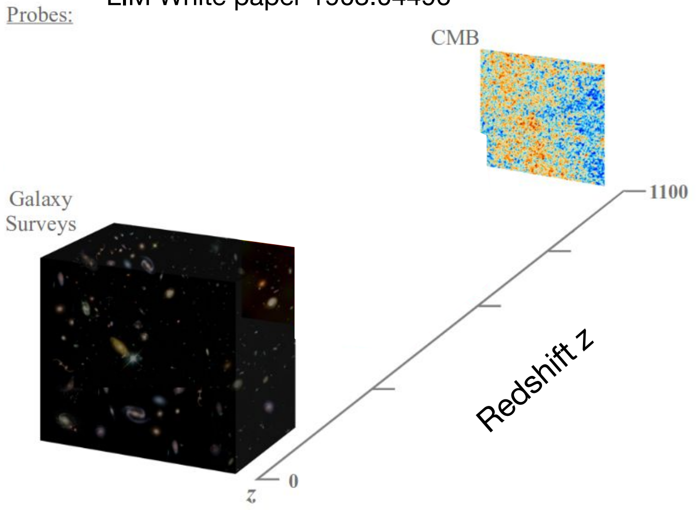
To make progress on key cosmic frontier science questions…

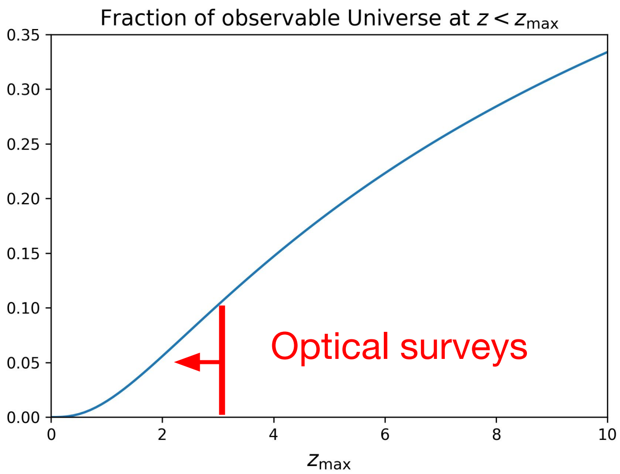
- Dark energy
- Inflation
- Light relativistic particles

…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!

LIM White paper 1903.04496





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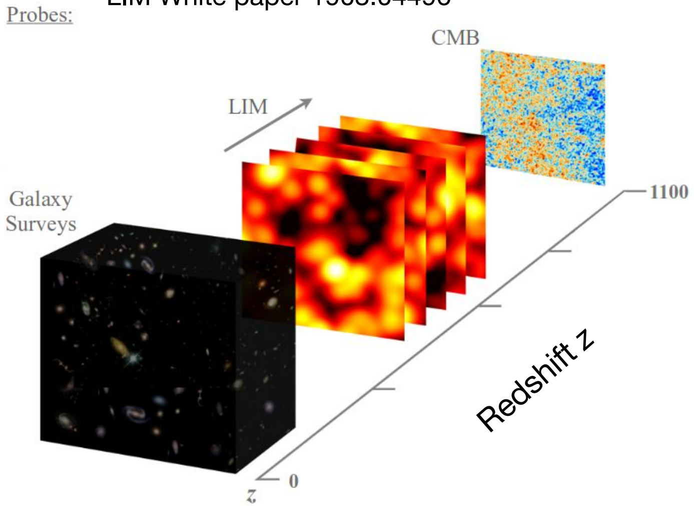
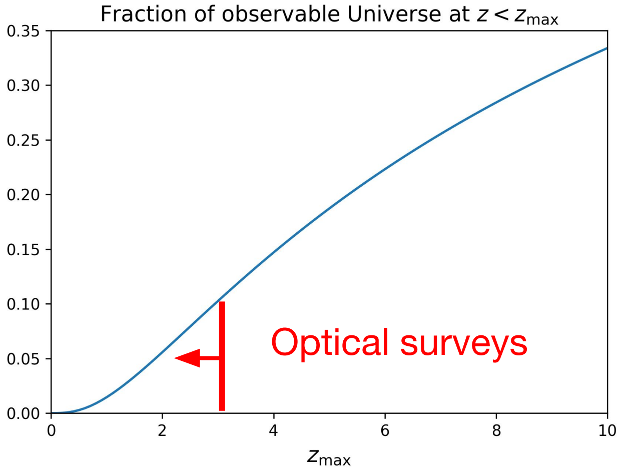
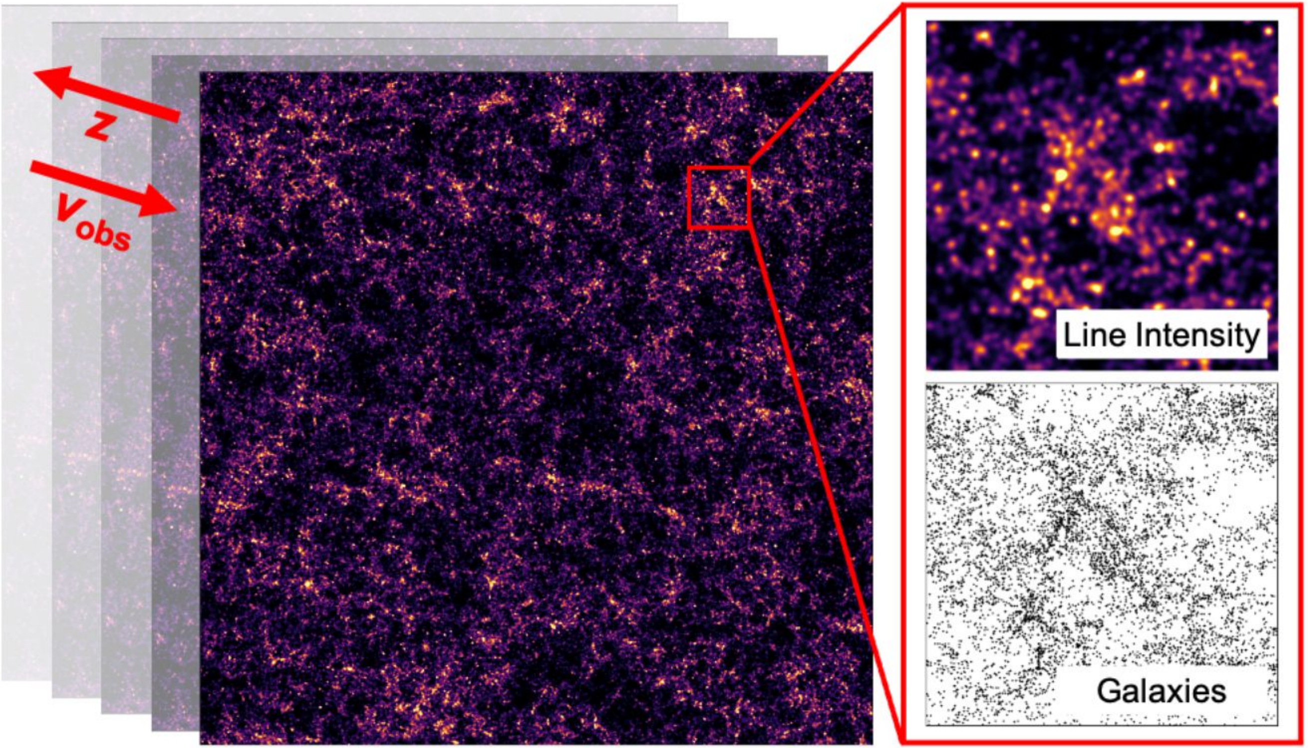




Line Intensity Mapping (LIM)

Karkare+ 2203.07258
Snowmass white paper



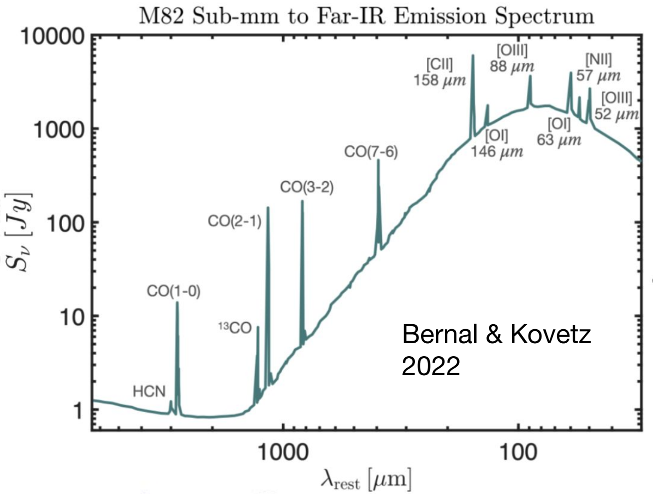
Integrate over individual sources while retaining large-scale cosmology.

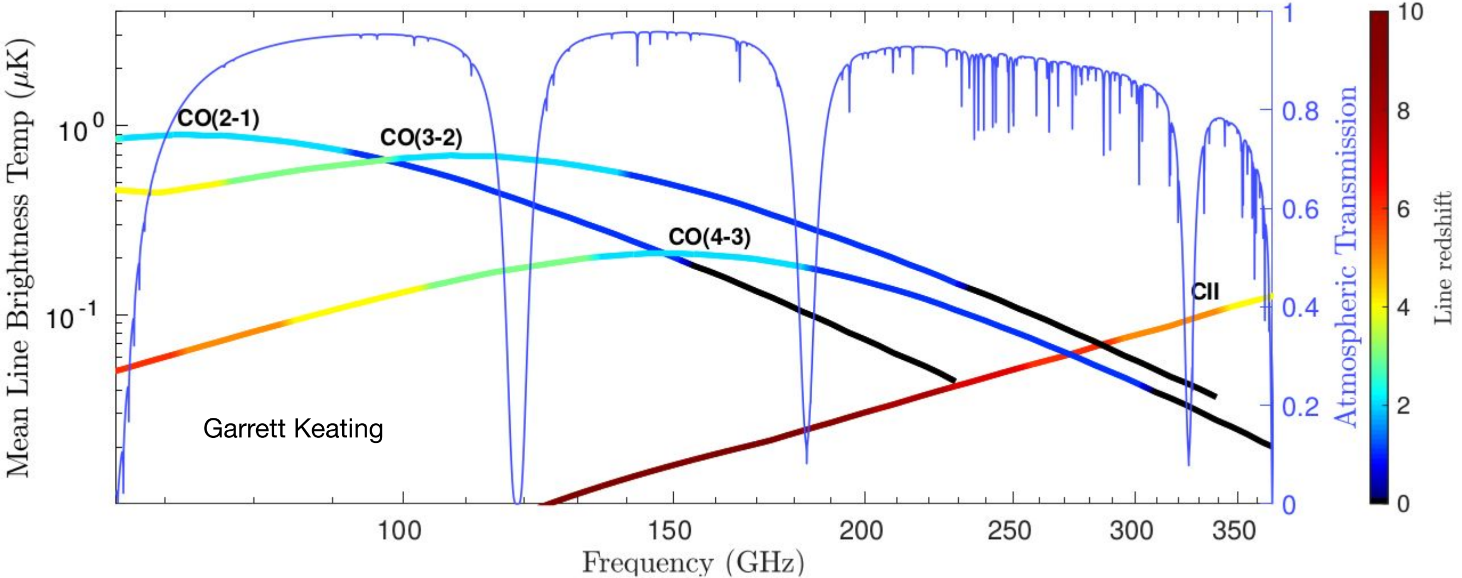
Much more efficient than object detection at high redshift.

Choose a spectral line – observed wavelength corresponds to distance.

Millimeter-Wave LIM

High-redshift galaxies have strong thermal dust emission (far-IR, ~100 μm), on top of which are strong emission lines such as the CO rotational ladder and [CII] ionized carbon.

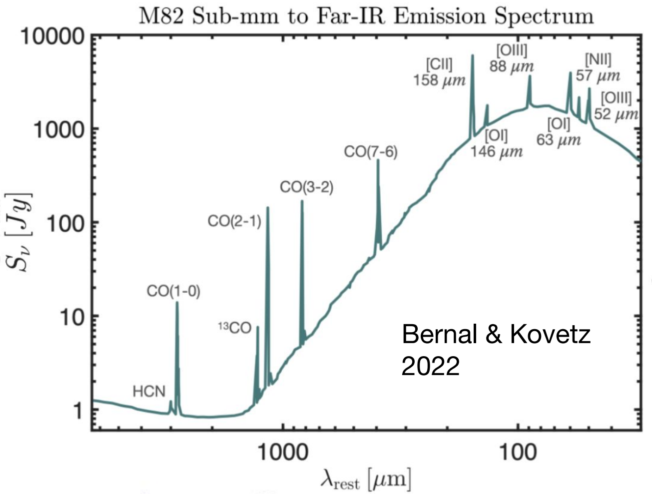


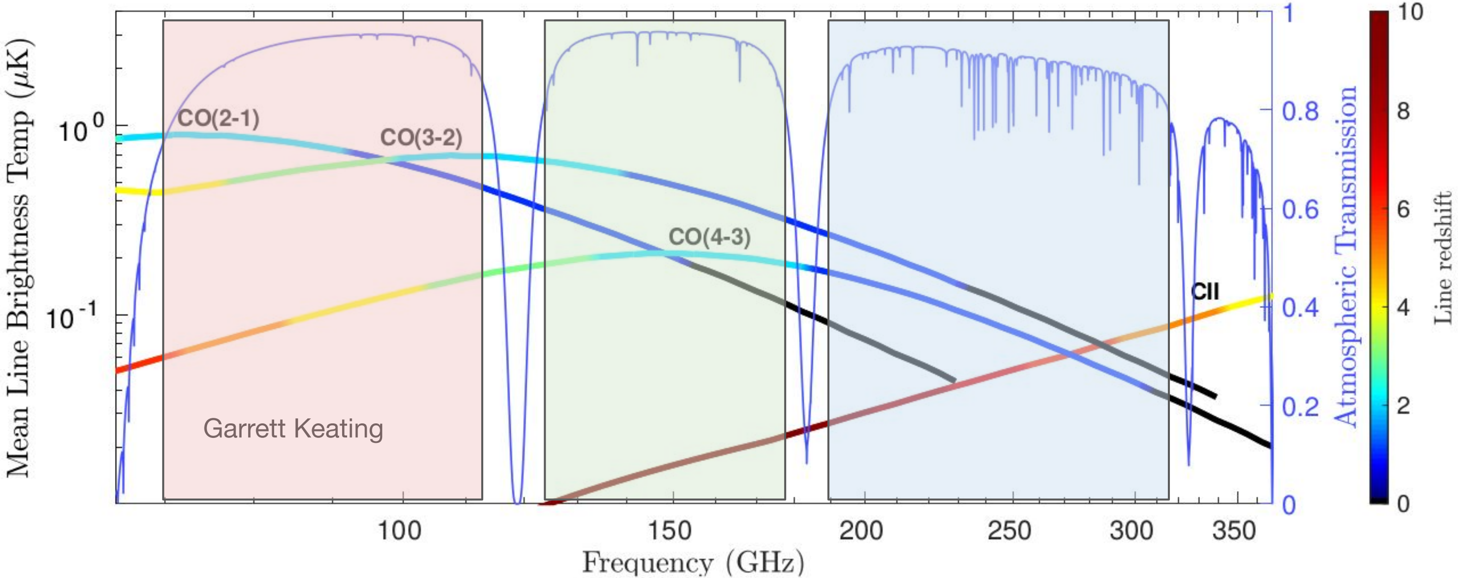


Those lines redshift to the mm-wave atmospheric windows, where they can be observed from the ground…

Millimeter-Wave LIM

High-redshift galaxies have strong thermal dust emission (far-IR, ~100 μm), on top of which are strong emission lines such as the CO rotational ladder and [CII] ionized carbon.

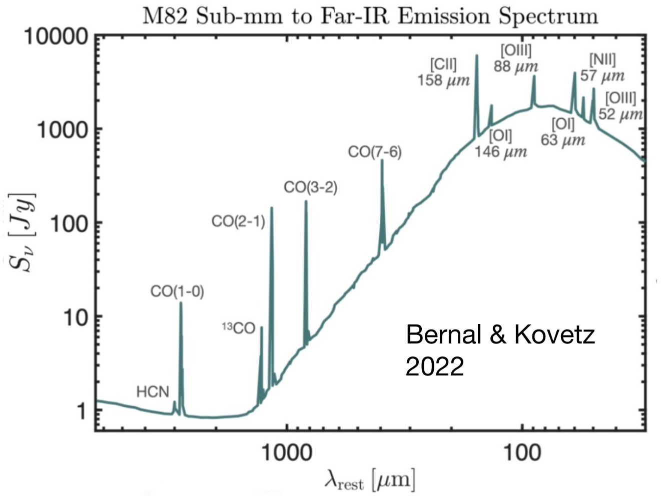


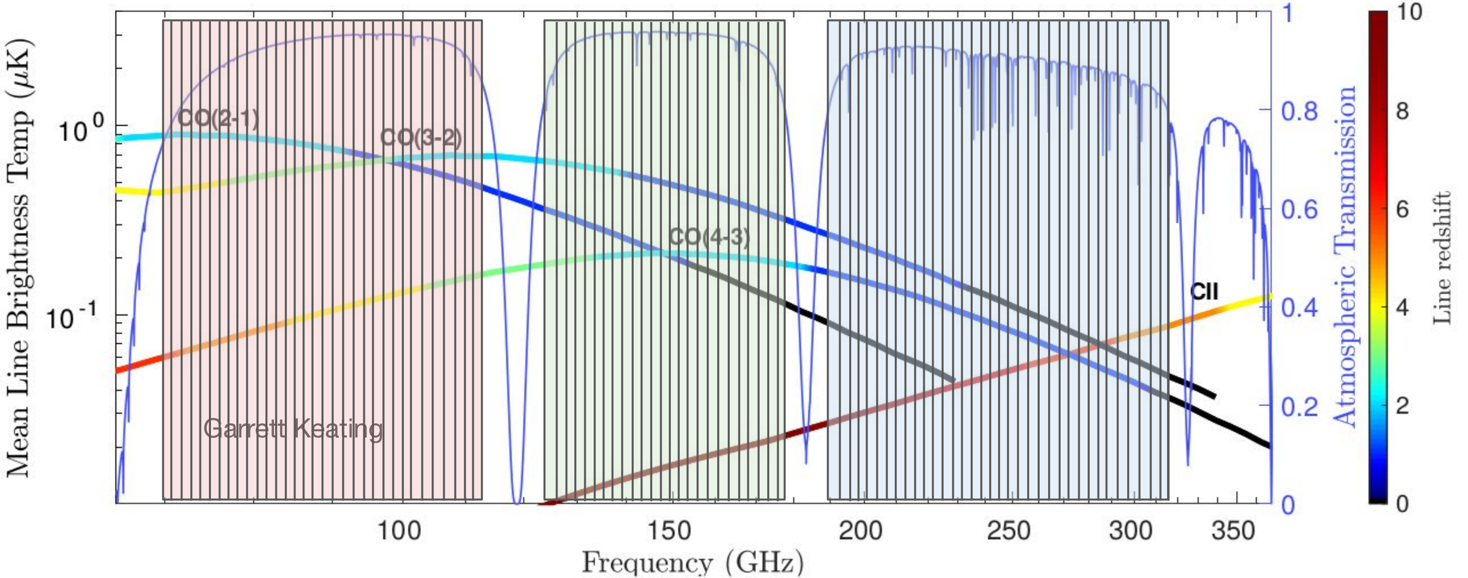


Those lines redshift to the mm-wave atmospheric windows, where they can be observed from the ground…exactly where CMB experiments are!

Millimeter-Wave LIM

High-redshift galaxies have strong thermal dust emission (far-IR, ~100 μm), on top of which are strong emission lines such as the CO rotational ladder and [CII] ionized carbon.



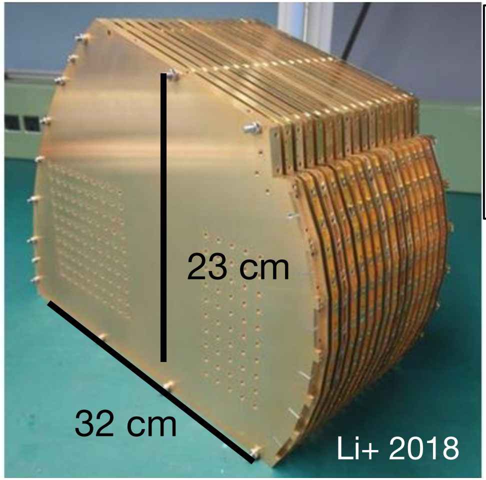


Those lines redshift to the mm-wave atmospheric windows, where they can be observed from the ground…exactly where CMB experiments are!

We need **mm-wave spectrometers.**

Key Enabling Technology: On-chip Spectroscopy

Contemporary mm-wave spectrometers (gratings, Fourier Transform, Fabry-Perot) are large - only ~10s can fit in a reasonable cryostat.

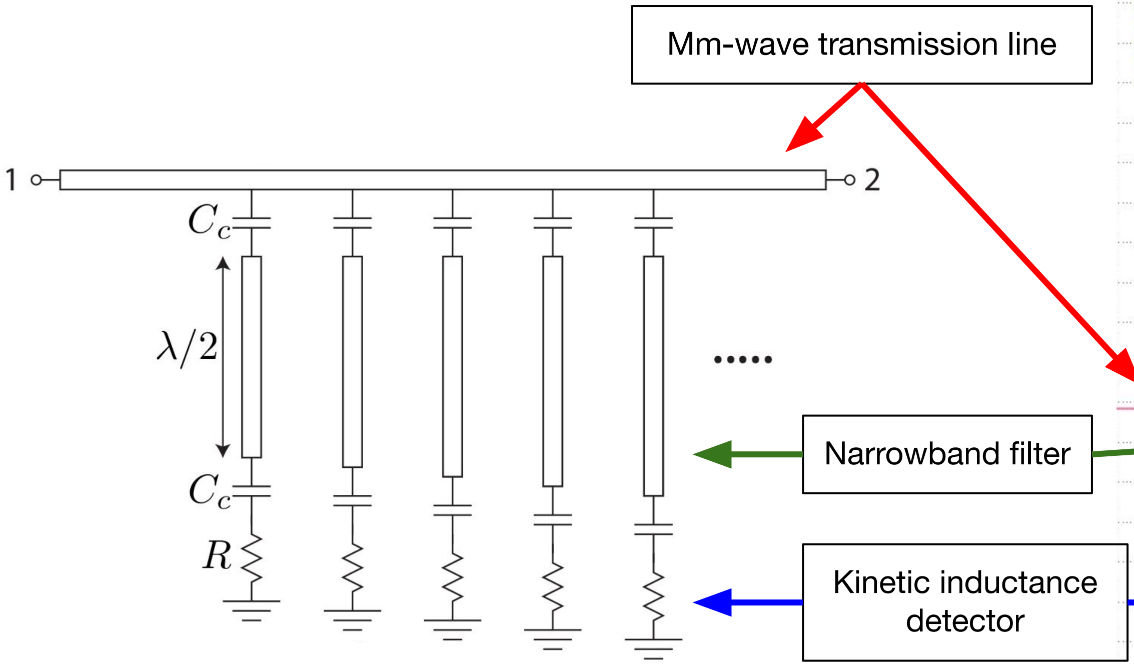


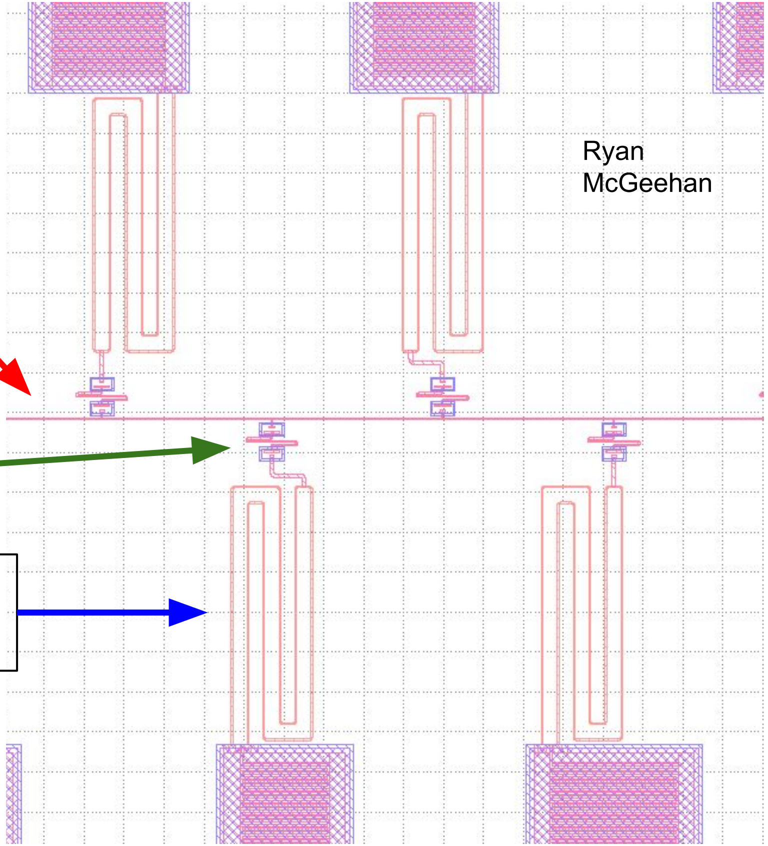
TIME grating:
32 x 23 x 1 cm
~ 736 cm^3

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

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

Filter-Bank Spectrometers Realized with Thin-Film Superconducting Circuits





Kovács & Zmuidzinas 2010

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

Student
Postdoc
co-PI

McGill
M. Adamic
M. Dobbs
M. Rouble

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K. S. Karkare
A. Saleem
C. Zhang

U. Arizona
D. Kim
D. Marrone

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

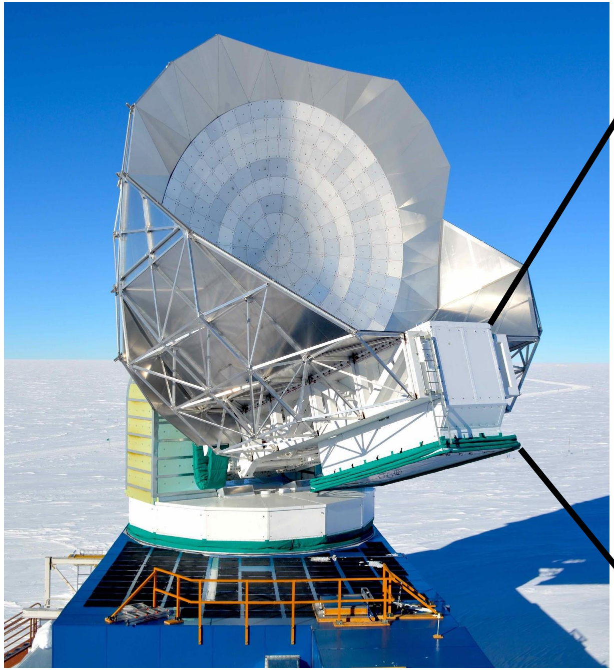
Deploy a LIM pathfinder to the South Pole Telescope during the austral summer season (Nov–Feb) while SPT-3G is not observing.

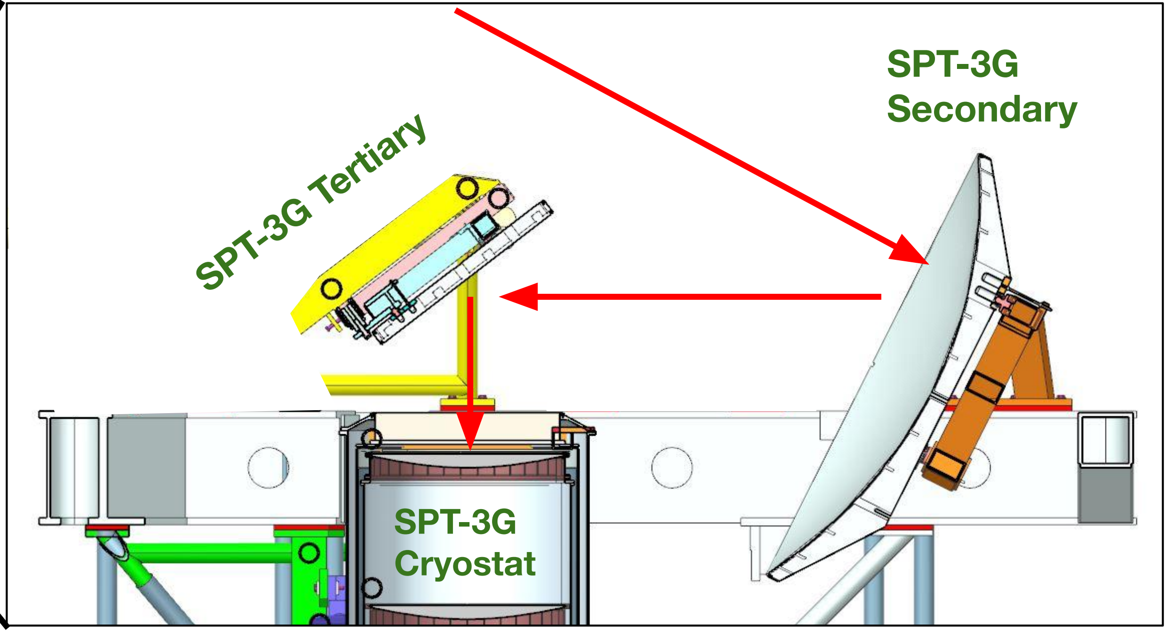
Demonstrate the enabling technology of on-chip spectrometers for the LIM measurement.

Fully funded by NSF and Fermilab in 2021.

See Adam Anderson's poster for more details!

The SPT Summertime Line Intensity Mapper (SPT-SLIM)

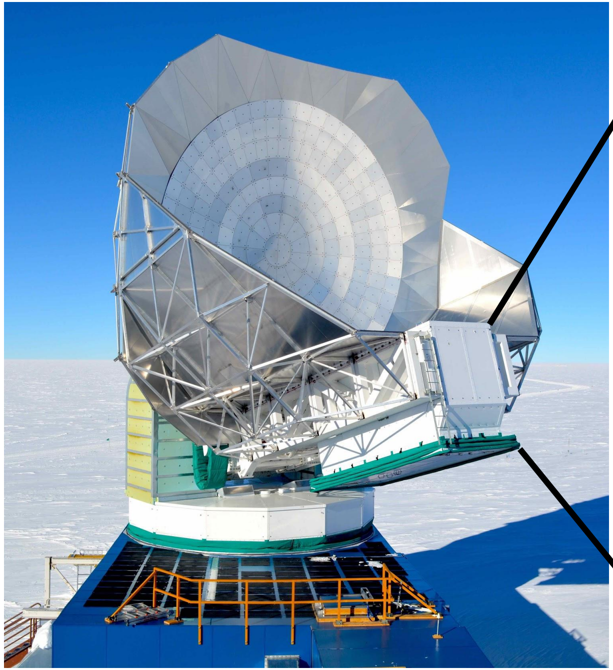


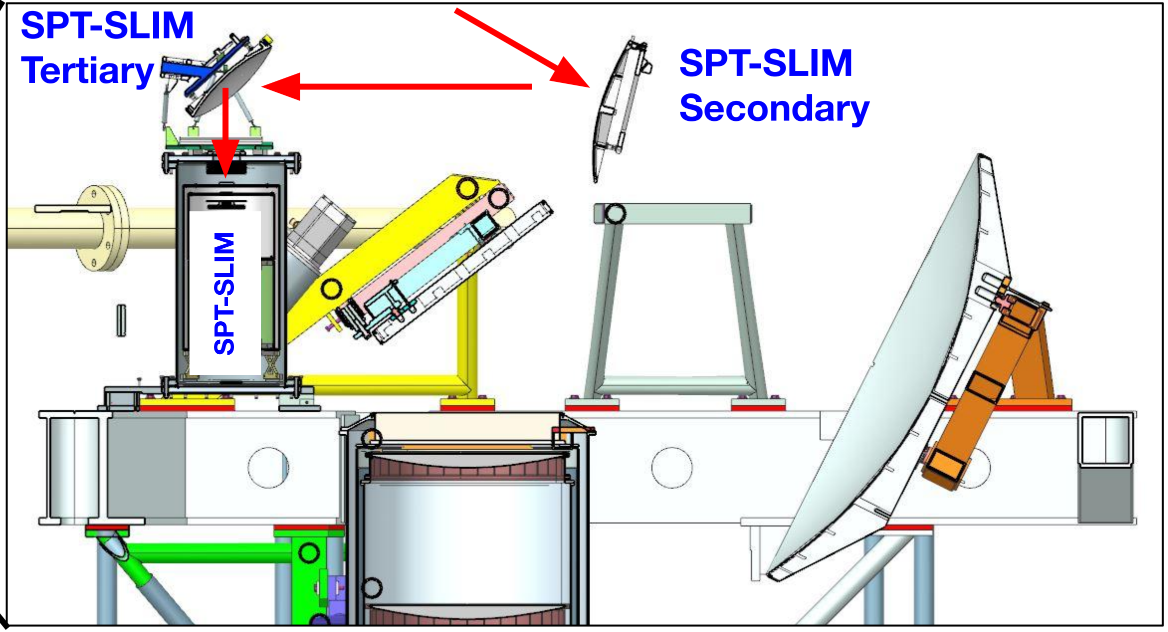


In normal operation, light from the primary is reflected into the receiver cabin, and then into the SPT-3G cryostat…

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!

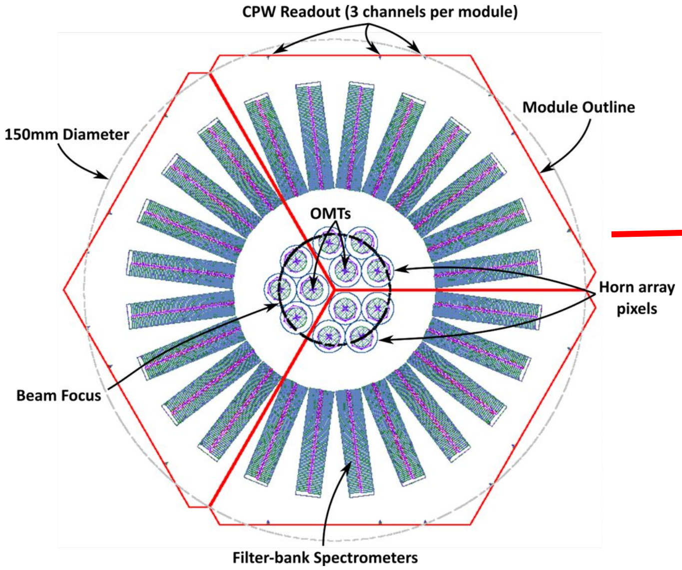
Karkare+ J. Low Temp. Phys.
2111.04631

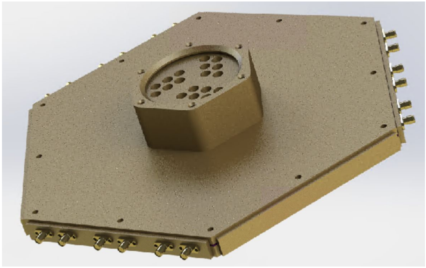
Don Mitchell

The SPT-SLIM Instrument

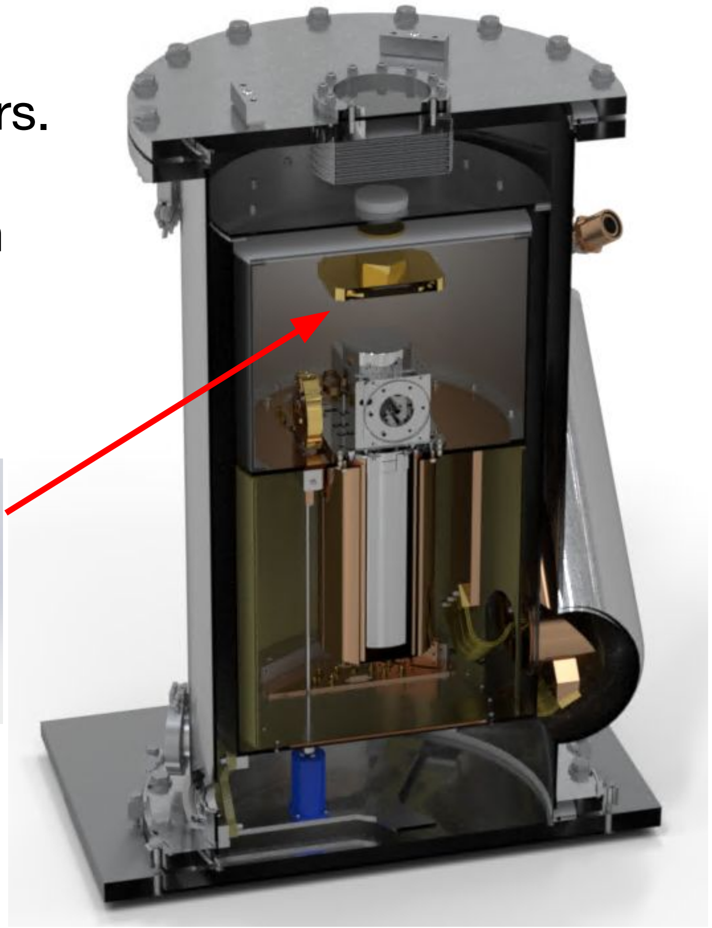
12 dual-pol pixels, each feeding two spectrometers.

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

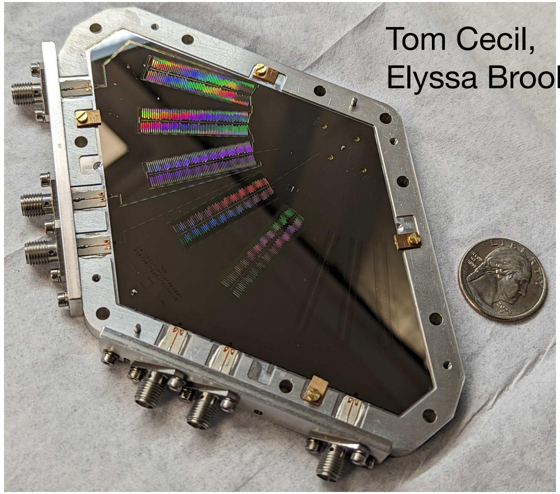




Pete Barry,
Gethin Robson

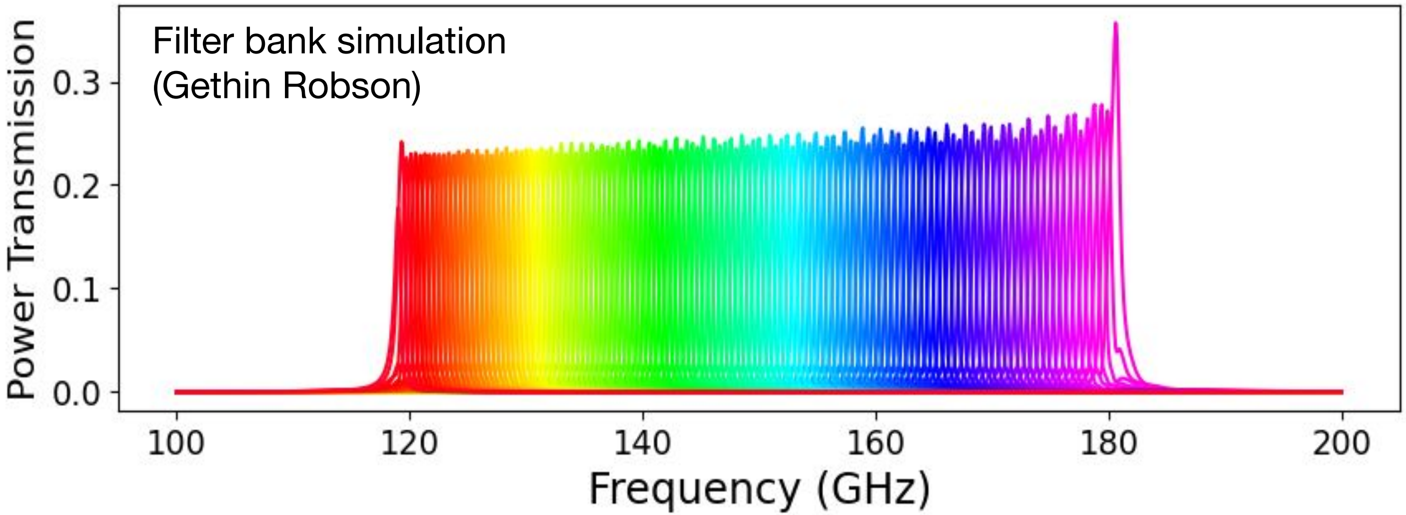


The SPT-SLIM Detectors



Each spectrometer covers 120–180 GHz with R~200 resolution.

Aluminum KIDs read out from 2-2.5 GHz.



Prototype optical arrays fabricated at ANL and UChicago now being tested!

See Tom Cecil's poster.

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

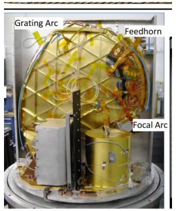
Effective number of modes ($\times 10^{-6}$) correlated with the initial conditions

Karkare+ 2203.07258
Snowmass white paper

How much sensitivity do we need?

	Spec-hrs	$\lesssim 10^5$
	Timescale	2023
	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



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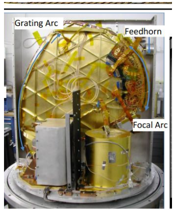
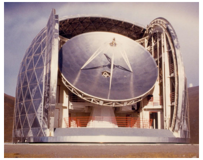
How much sensitivity do we need?

	Spec-hrs	$\lesssim 10^5$	10^6
	Timescale	2023	2026
	Example	TIME, SPT-SLIM	TIME-Ext
Neutrino masses	$\boldsymbol{\sigma}(M_\nu)$ [eV]		0.047
Dark energy	$\boldsymbol{\sigma}(w_0)$ incl. z>3		0.03
Inflation	Primordial FoM		0.1

Dedicated facilities





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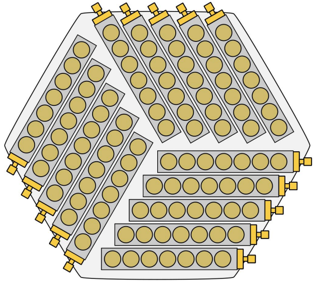
How much sensitivity do we need?



Spec-hrs	$\lesssim 10^5$	10^6	10^7
Timescale	2023	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

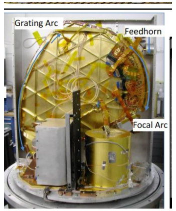
Neutrino masses

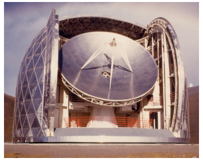
Dark energy

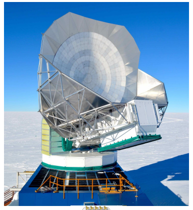
Inflation

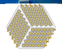
Focal plane with ~hundred spectrometers

DESI: FoM ~ 1









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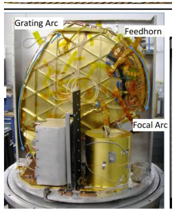
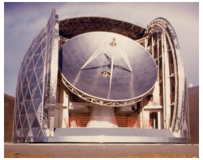
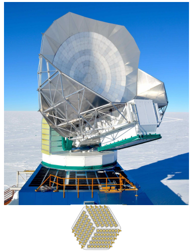
How much sensitivity do we need?

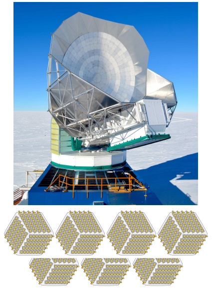
	Spec-hrs	$\lesssim 10^5$	10^6	10^7	10^8
	Timescale	2023	2026	2028	2031
	Example	TIME, SPT-SLIM	TIME-Ext	SPT-3G+ one tube	SPT-3G+ 7 tubes
Neutrino masses	$\sigma(M_\nu)$ [eV]		0.047	0.028	0.013
Dark energy	$\sigma(w_0)$ incl. $z>3$		0.03	0.013	0.005
Inflation	Primordial FoM		0.1	1	10

MegaMapper:
FoM ~ 10









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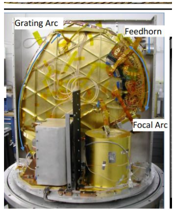
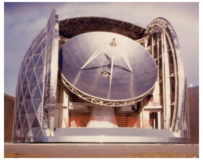
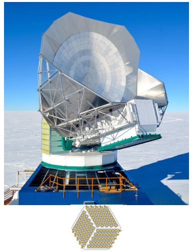
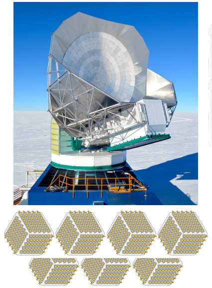
How much sensitivity do we need?

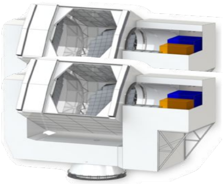
	Spec-hrs	$\lesssim 10^5$	10^6	10^7	10^8	10^9
	Timescale	2023	2026	2028	2031	2038
	Example	TIME, SPT-SLIM	TIME-Ext	SPT-3G+ one tube	SPT-3G+ 7 tubes	CMB-S4 85 tubes
Neutrino masses	$\sigma(M_\nu)$ [eV]		0.047	0.028	0.013	0.007
Dark energy	$\sigma(w_0)$ incl. $z>3$		0.03	0.013	0.005	0.003
Inflation	Primordial FoM		0.1	1	10	100











Karkare+ 2203.07258
Snowmass white paper

How do we get there?

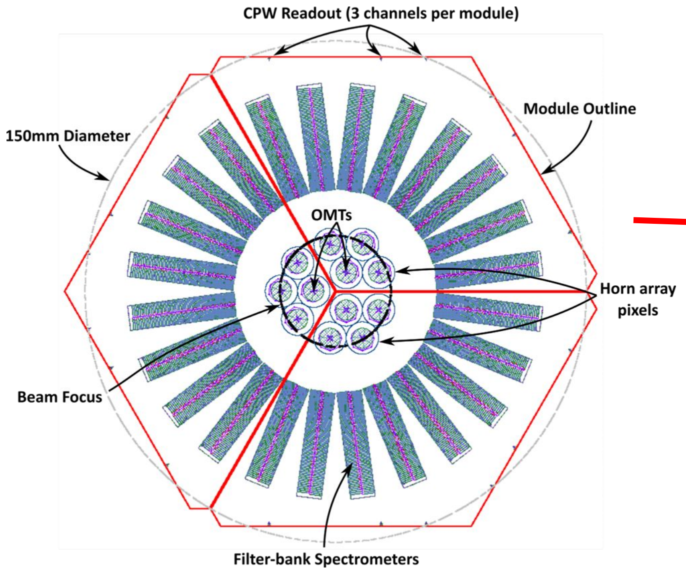
To achieve cosmological relevance*, we need surveys with >2 orders of magnitude improvement in sensitivity.

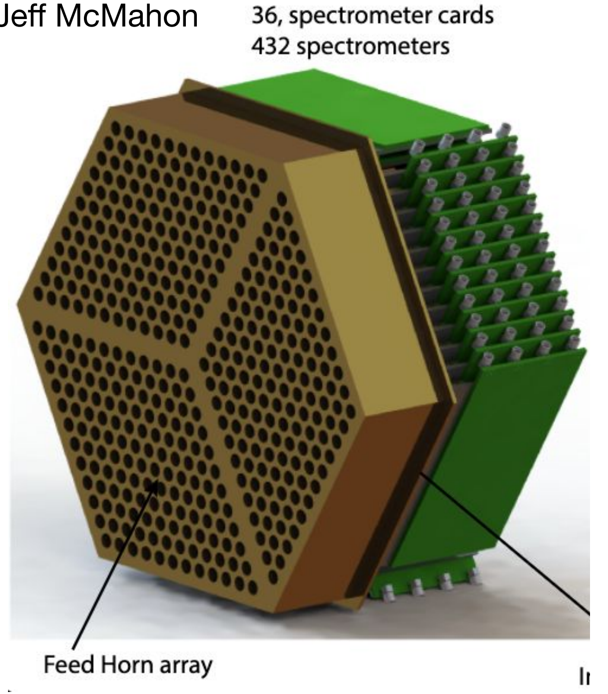
- Dedicated wide-field platforms at excellent sites and multi-year observations
- Detector arrays that are as sensitive as possible, with enough spectral resolution to extract all of the cosmological information
  - Presumably this means on-chip spectrometers…
- Readout to accommodate overwhelmingly-large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

*not true for astrophysical relevance

Detector Packing Density

Pete Barry
Jeff McMahon

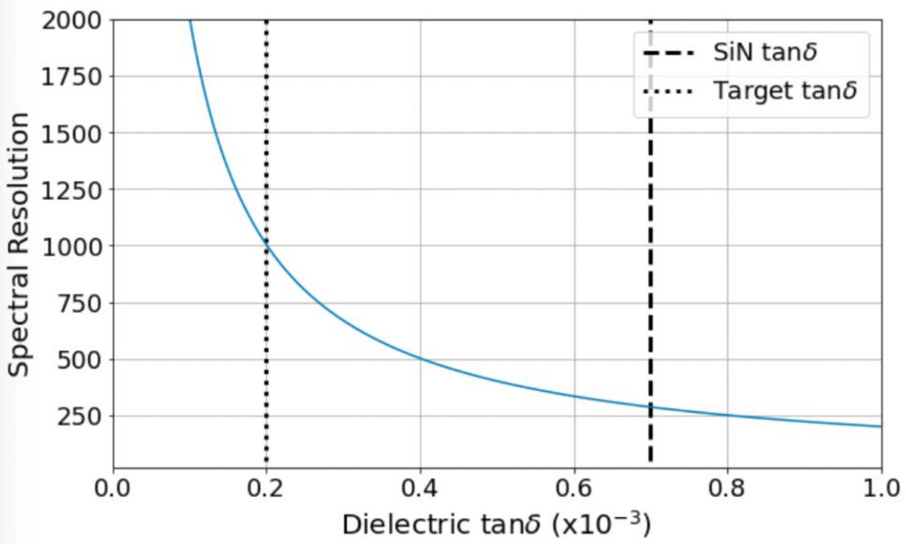


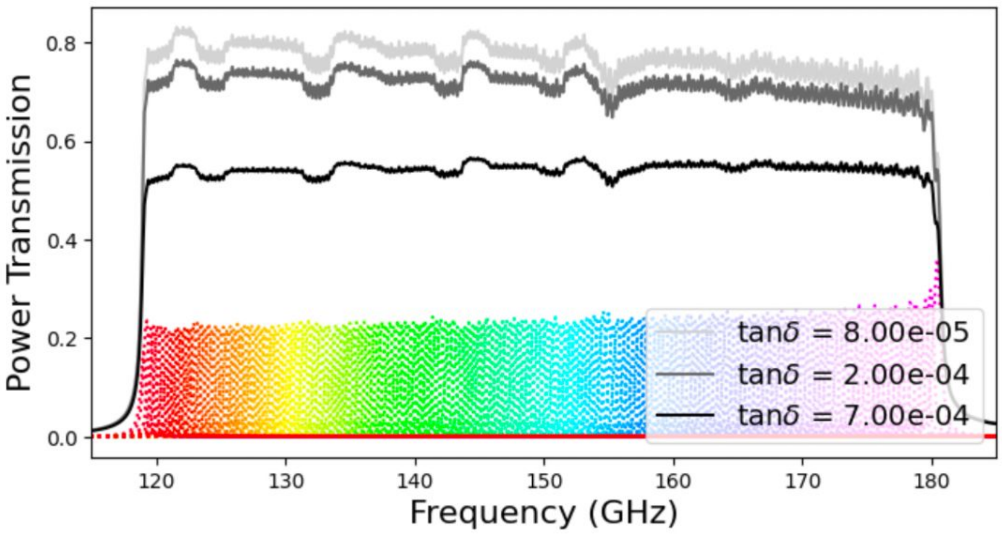


The filter bank takes up an area ~5x the size of the diffraction-limited spot. Can we move the spectrometer out of the focal plane to approach optimal sampling?

Spectral Resolution and Optical Efficiency

Gethin Robson





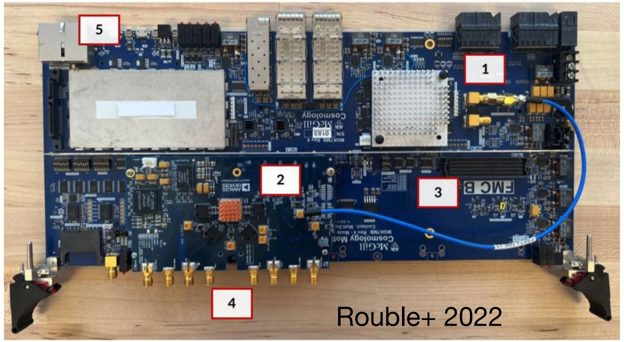
For microstrip implementation, loss in dielectric limits resolution and optical efficiency!
Promising low-loss candidates pursued by many groups - even a factor of 2-3 reduction in loss could improve filter-bank performance significantly.

High-Density Readout

We are probably forced into GHz frequency-domain multiplexing: 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

Can RFSoCs get us to O(10000)/line at ~$1/channel?

- How many coax and LNAs can reasonable cryostats accommodate cryogenically?
- Can we get the required Qs and frequency placement?

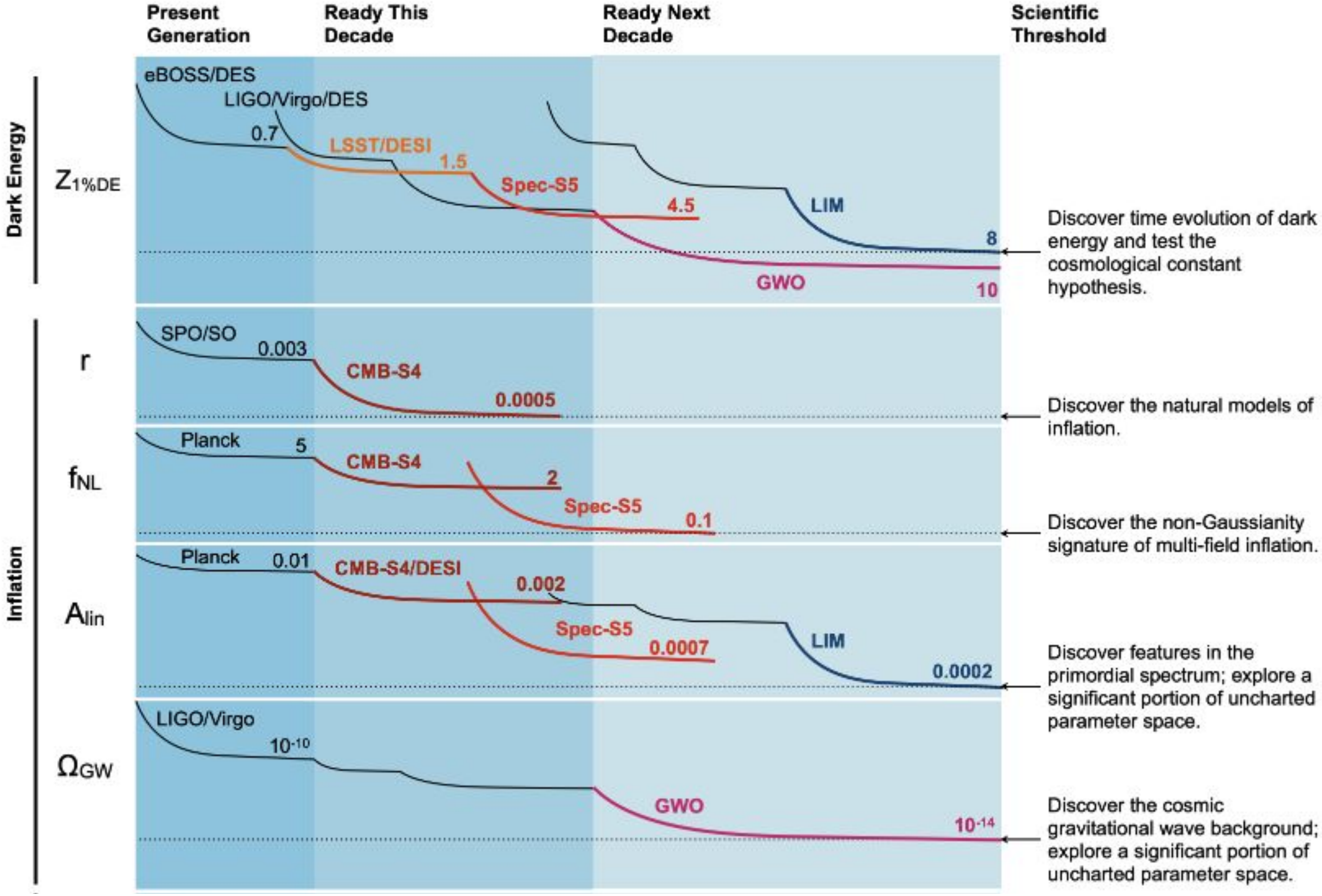
Conclusions

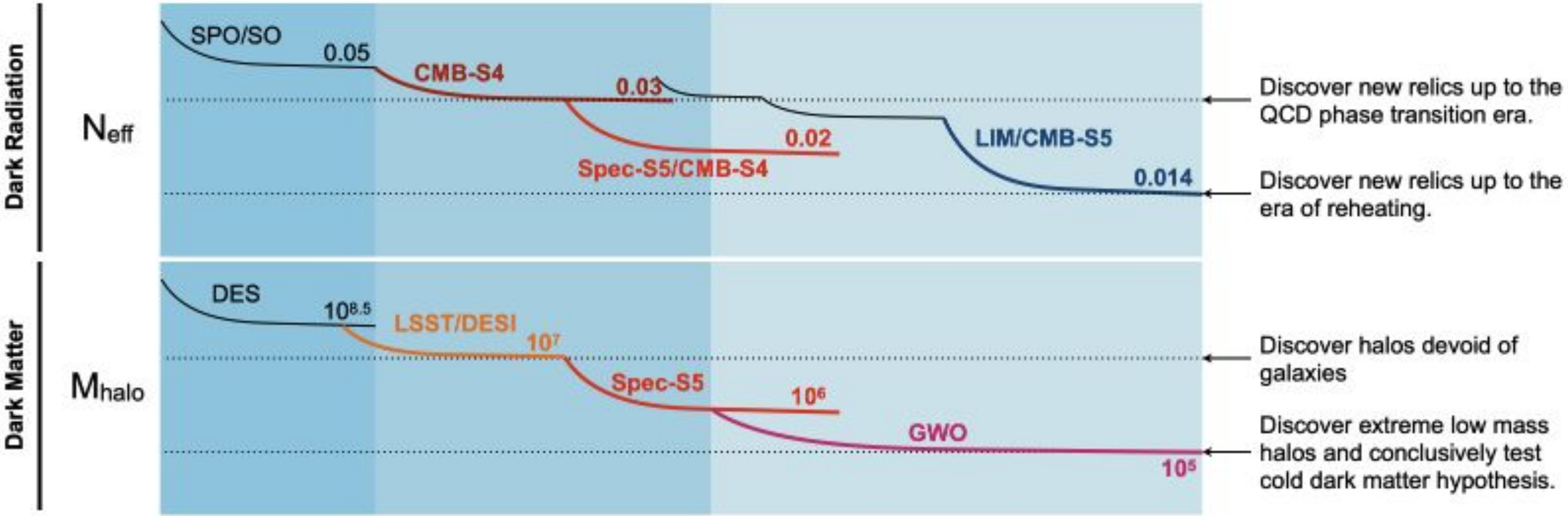
Millimeter-wave LIM is one of the only feasible ways to measure large-scale structure over extremely large volumes and redshifts - a unique observable for the cosmic frontier.

We're now demonstrating the enabling technology of compact on-chip spectrometers with SPT-SLIM and other projects, and there is a path to scaling up following the example of CMB experiments.

We can re-use CMB infrastructure to deploy at scale (e.g., SPT-3G+ and more!)

There is still a **lot of detector development needed**! Improving spectrometer design, superconducting materials, readout all feasible with ~few $M efforts.


Present Generation
Ready This Decade
Ready Next Decade
Scientific Threshold
Dark Energy
Z1%DE
eBOSS/DES
LIGO/Virgo/DES
0.7
LSST/DESI
1.5
Spec-S5
4.5
LIM
8
GWO
10
Discover time evolution of dark energy and test the cosmological constant hypothesis.
Inflation
r
SPO/SO
0.003
CMB-S4
0.0005
Discover the natural models of inflation.
fNL
Planck
5
CMB-S4
2
Spec-S5
0.1
Discover the non-Gaussianity signature of multi-field inflation.
Alin
Planck
0.01
CMB-S4/DESI
0.002
Spec-S5
0.0007
LIM
0.0002
Discover features in the primordial spectrum; explore a significant portion of uncharted parameter space.
ΩGW
LIGO/Virgo
10-10
GWO
10-14
Discover the cosmic gravitational wave background; explore a significant portion of uncharted parameter space.



Dark Radiation
Neff
SPO/SO
0.05
CMB-S4
0.03
0.02
Spec-S5/CMB-S4
LIM/CMB-S5
0.014
Discover new relics up to the QCD phase transition era.
Discover new relics up to the era of reheating.
Dark Matter
Mhalo
DES
10^8.5
LSST/DESI
10^7
Spec-S5
10^6
GWO
10^5
Discover halos devoid of galaxies
Discover extreme low mass halos and conclusively test cold dark matter hypothesis.