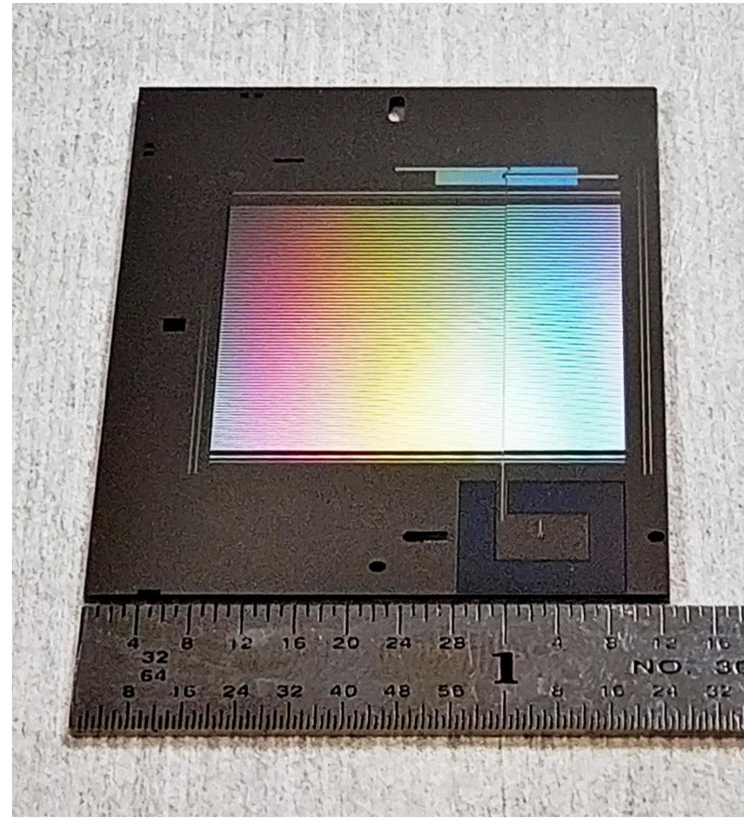
# Millimeter-Wave Line Intensity Mapping



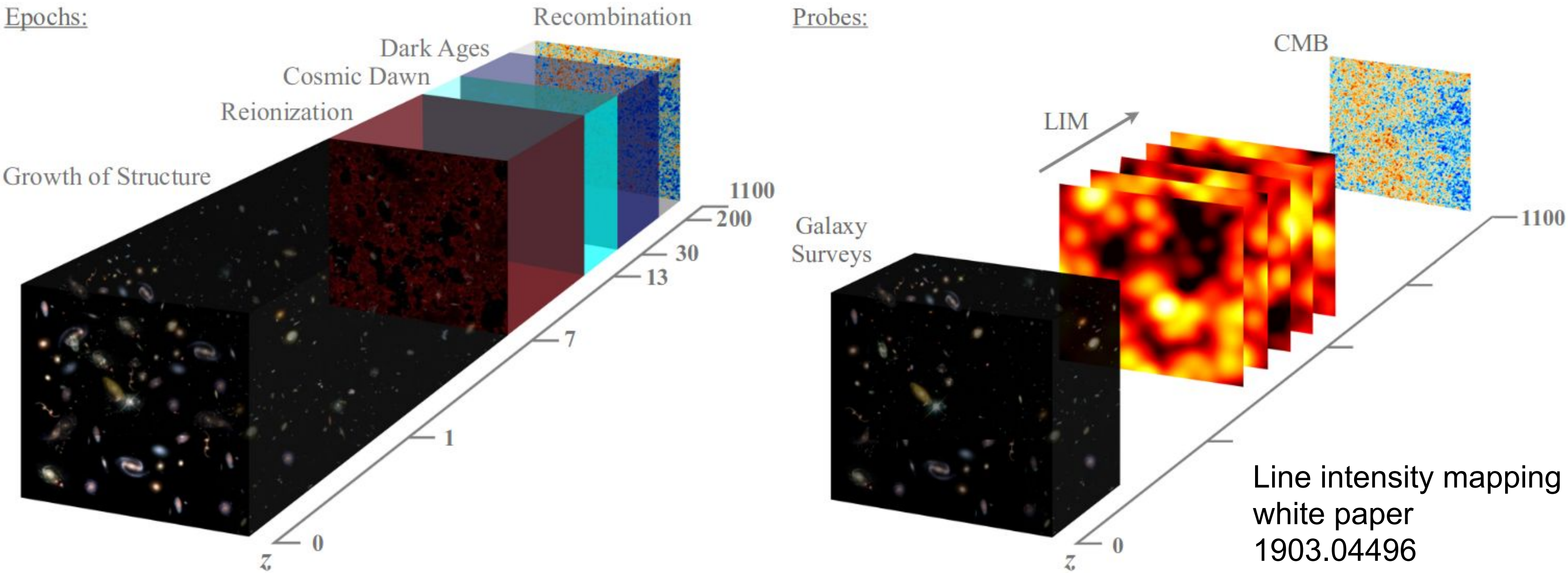


Kirit S. Karkare, University of Chicago



Snowmass 2021 CF4 Meeting, 2020-09-23

# Large-Scale Structure Observables




Line intensity mapping white paper 1903.04496

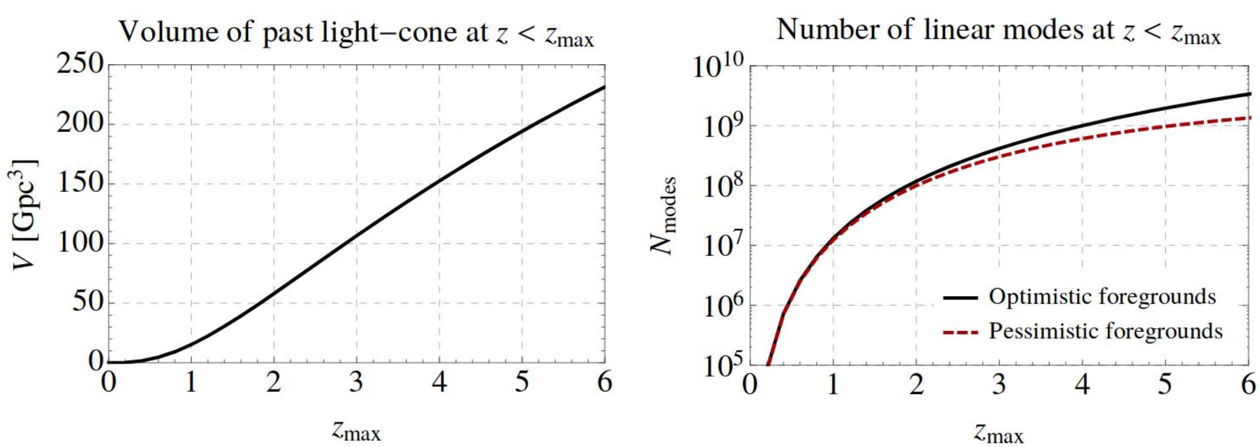
Line Intensity Mapping (LIM) can enable high-z measurements at lower cost and with different systematics than next-gen galaxy surveys.

# Why measure LSS at z > 2?

From Martin White's July 29 talk:

- Wide z range leads to rotated degeneracy directions
- Larger volume: more than 3x as many linear modes from 2 < z < 6 than z < 2
- More linearity and correlation with initial conditions
- High-precision theory

...and we want *spectroscopic information* where possible.

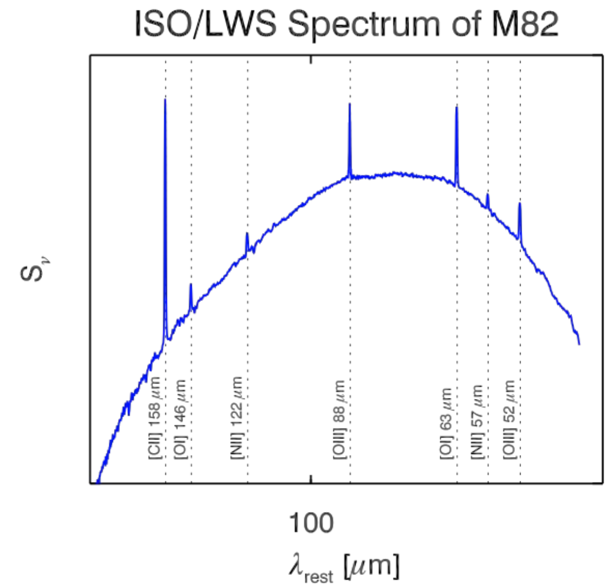


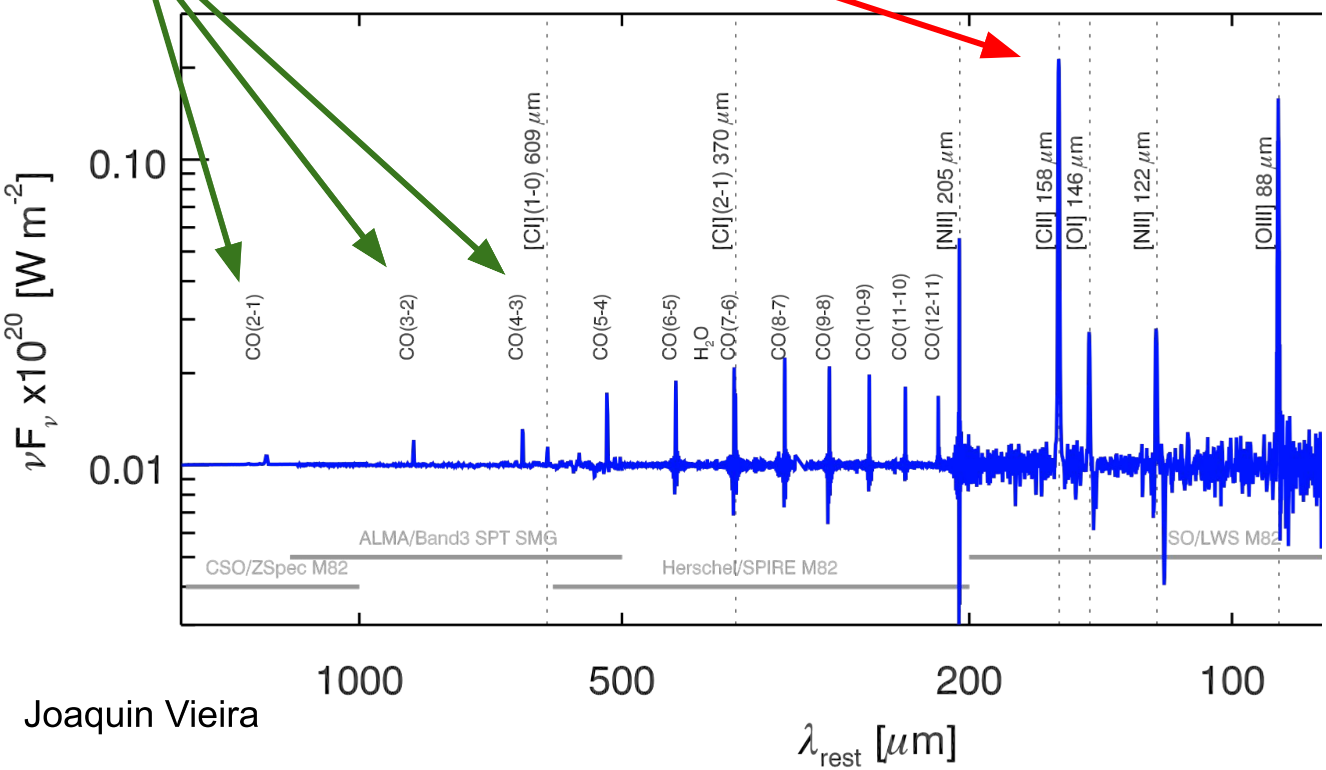

HI Stage 2 White paper
1810.09572

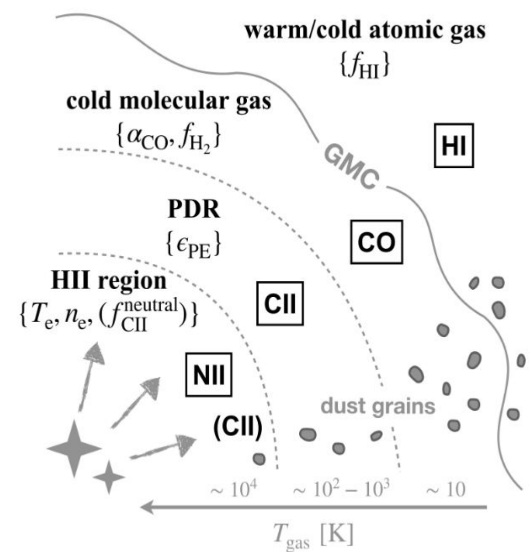
# Our focus: LIM at mm wavelengths

Far-IR lines excited by absorbed stellar radiation, emitted on top of the dust continuum. Known to exist at high redshift (ALMA), good tracers of star formation.

In particular: detectable from the ground at mm-wave CO (distinct ladder structure), [CII] (very bright)



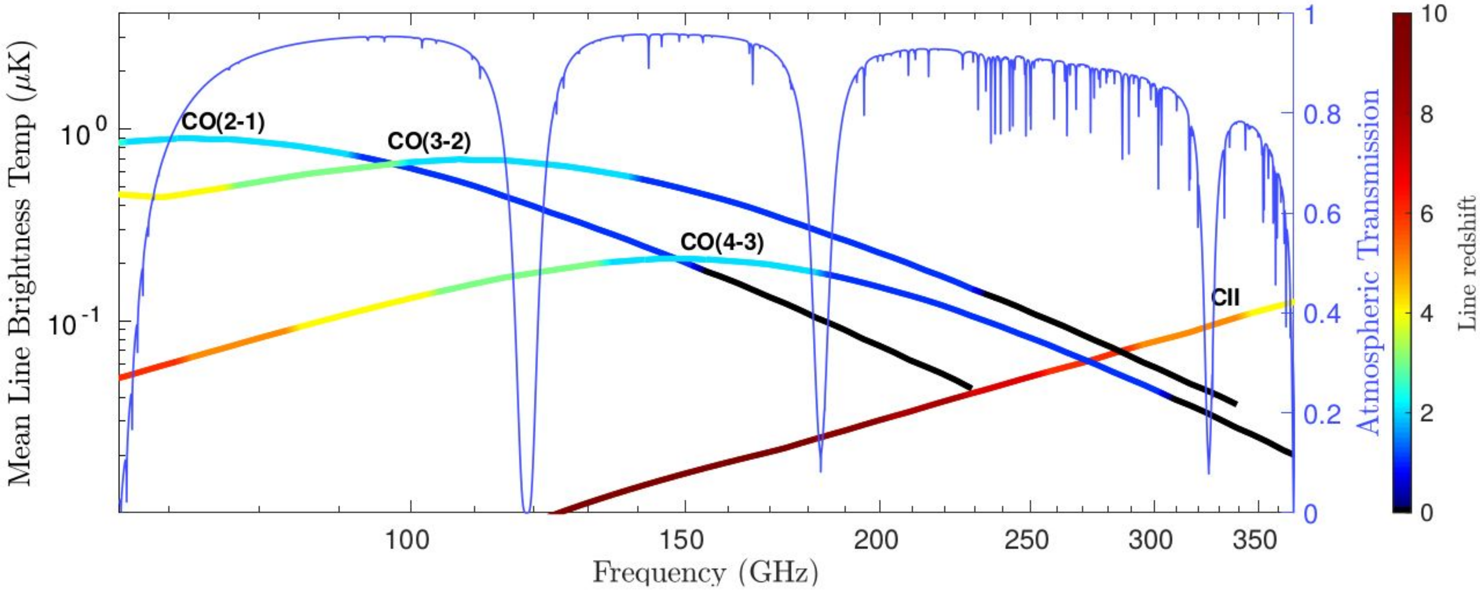




Sun+ 2019
1907.02999

Joaquin Vieira

# Our focus: LIM at mm wavelengths

A single instrument, covering standard ground-based CMB frequencies (80-300 GHz) could detect [CII] and CO over the entire range of 0 < z < 10!




Karto Keating

The major needed technical advance is to add spectroscopy to existing CMB-style large-format, background-limited mm-wave detector arrays.

# Science Case Summary

See e.g. PUMA Basic Science Drivers (1907.12559)

- Physics of Dark Energy
  - Characterize expansion history in the pre-acceleration era
  - Characterize structure growth in the pre-acceleration era
- Physics of Inflation
  - Constrain or detect primordial non-Gaussianity
  - Constrain or detect features in the primordial power spectrum
- Secondary cosmology
  - Broadband power spectrum: N_eff, etc
  - Weak lensing, matter field reconstruction at many redshifts
- Astrophysics
  - Star/galaxy formation at large scales - faint end of luminosity function
  - Epoch of Reionization dynamics
  - DSFG redshift followup

Most mm-wave LIM work has been in signal modeling, but we now need more comprehensive cosmology projections to bring up to 21cm maturity.

# Mm-wave in the LIM ecosystem

Advantages

- CMB Heritage
  - Leverage evolution in CMB detector fabrication and scaling up large-format focal planes
  - Precision beam, spectral calibration techniques already developed
  - Cryogenic systems extremely stable
  - Scan strategy optimized for *deep* observations of degree-arcminute scale structure
- Continuum Galaxy-to-signal ratio smaller than for HI

Challenges

- Line confusion
- Unlikely to access beyond EoR
- Less well-developed, both experimentally and theoretically

**Accessible Scales**

Radial:

- Spectrometer resolution R~300 (now), up to R~1000 with some effort
- In a ground-based receiver (80-300 GHz):
  - [CII]: $5 < z < 9$
  - CO(4-3): $0.5 < z < 4.8$
  - CO(3-2) $0.1 < z < 3.3$
  - CO(2-1) $0 < z < 1.9$
  - Atmospheric lines break up some ranges

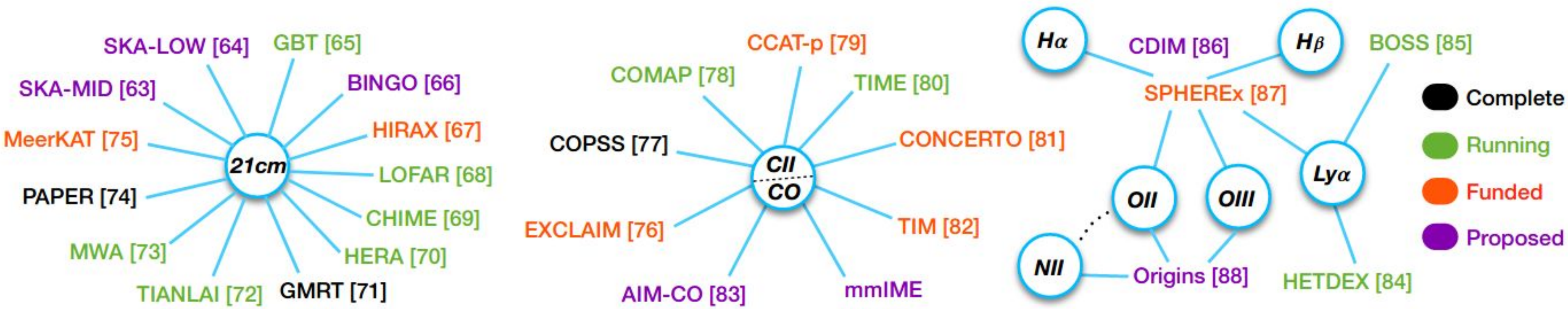
Angular (CMB heritage):

- Arcminute resolution on 10-m class dish, 0.25 deg using a BICEP-style refractor
- Continuous, CMB-style scanning to access low ell. Unclear how low we can go due to atmosphere (spinner?), but spectroscopy may help

# State of the Field https://arxiv.org/abs/1903.04496

Preliminary mm-wave detections:

- CO 1-0 @ z~2.5 (SZA, ~2 sigma, https://arxiv.org/abs/1605.03971)
- [CII] @ z~2.6 (Planck X CMass, ~2 sigma, https://arxiv.org/abs/1904.01180)
- CO @ 100 GHz (several lines, mmIME, https://arxiv.org/abs/2008.08087)




Uncertainties on signal strengths are now factors of ~a few.

Both COMAP (CO 1-0) and TIME ([CII]) expect first detections of clustering by 2022. Not sensitive enough to do serious cosmology!

# How do we make progress?

4 LOIs submitted:

- Cosmology with mm-wave LIM   CF LOI 242
- Primordial non-Gaussianity with mm-wave LIM   CF LOI 245
- Synergies between mm-wave LIM and other probes   CF LOI 248
- Mm-wave LIM facilities   CF LOI 246

# How do we make progress?  Analysis/Projections/Synergies

4 LOIs submitted:

- Cosmology with mm-wave LIM   CF LOI 242
- Primordial non-Gaussianity with mm-wave LIM   CF LOI 245
- Synergies between mm-wave LIM and other probes   CF LOI 248
- Mm-wave LIM facilities   CF LOI 246

- Develop line separation techniques (internal + external datasets)
- General cosmology projections
- Understand improvement when cross-correlating with optical surveys, 21cm, CMB
  - More tracers of the same structure with different biases, CV cancellation
  - Calibrating nuisance parameters e.g. line/galaxy bias
  - Robust control of uncorrelated systematics and foregrounds
- Higher-order statistics

# How do we make progress?  Technical

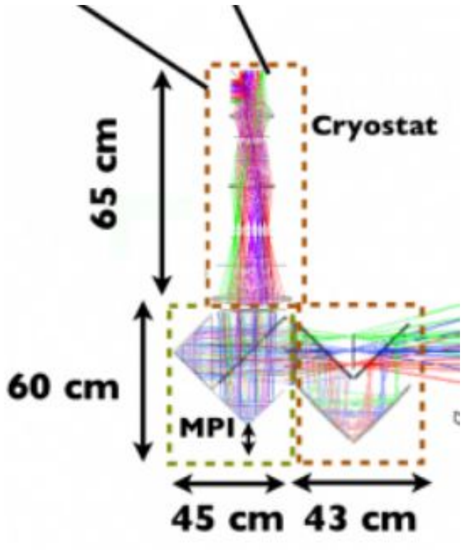
4 LOIs submitted:

- Cosmology with mm-wave LIM   CF LOI 242
- Primordial non-Gaussianity with mm-wave LIM   CF LOI 245
- Synergies between mm-wave LIM and other probes   CF LOI 248
- Mm-wave LIM facilities   CF LOI 246

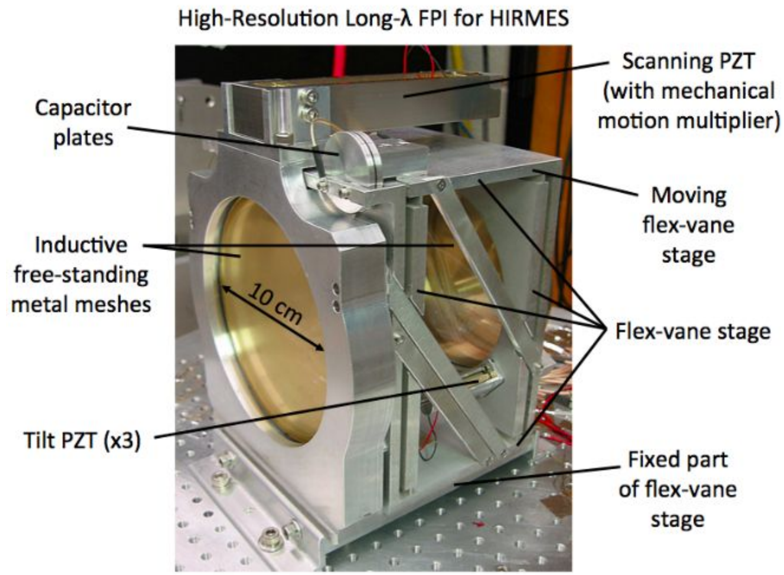
- Leverage significant investment in CMB detector technology to significantly increase mm-wave detector count by fabricating *filled, spectroscopic mm-wave IFUs*
- Readout development (detector count much higher than comparable CMB experiments) from CMB-S4
- Understand how to operate spectroscopic arrays in the field

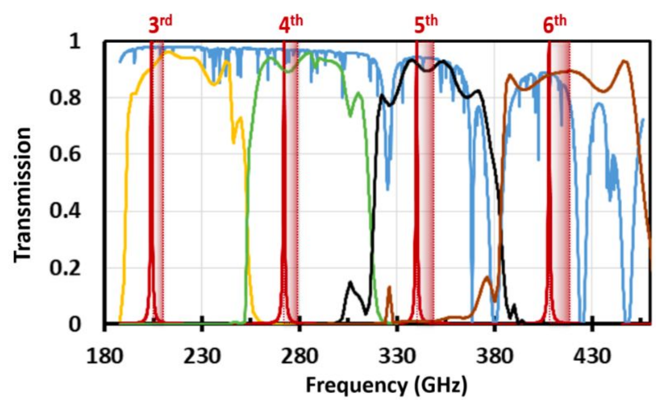
# “Shovel-ready” mm-wave spectrometers

Fourier Transform Spectrometer (CONCERTO) neel.cnrs.fr

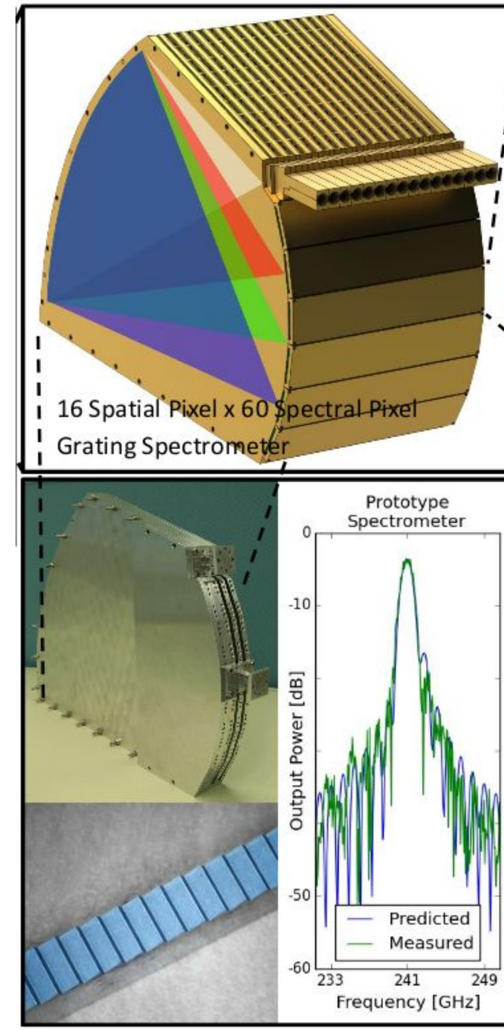



Fabry-Perot (CCAT-p) 1807.00058

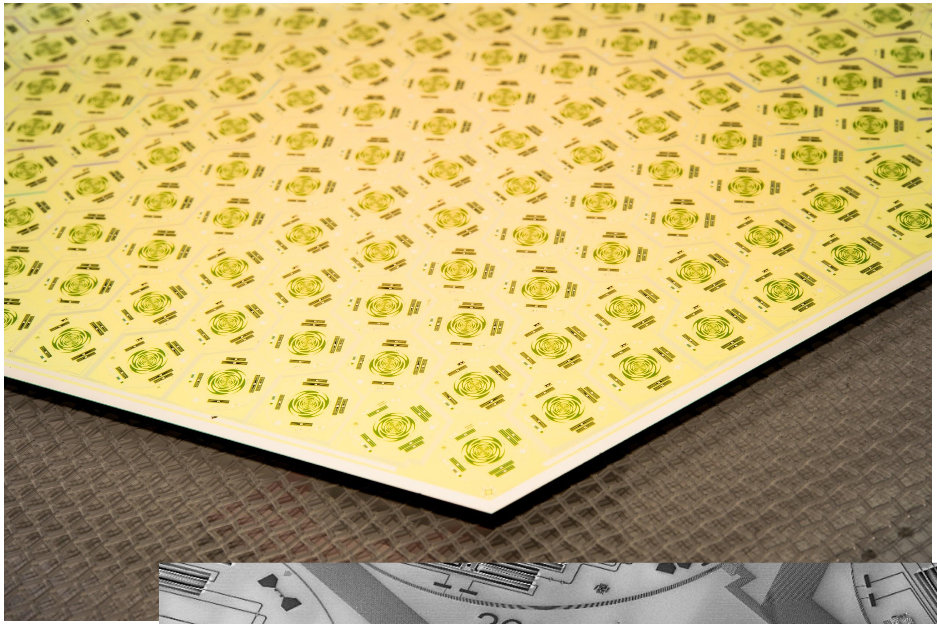


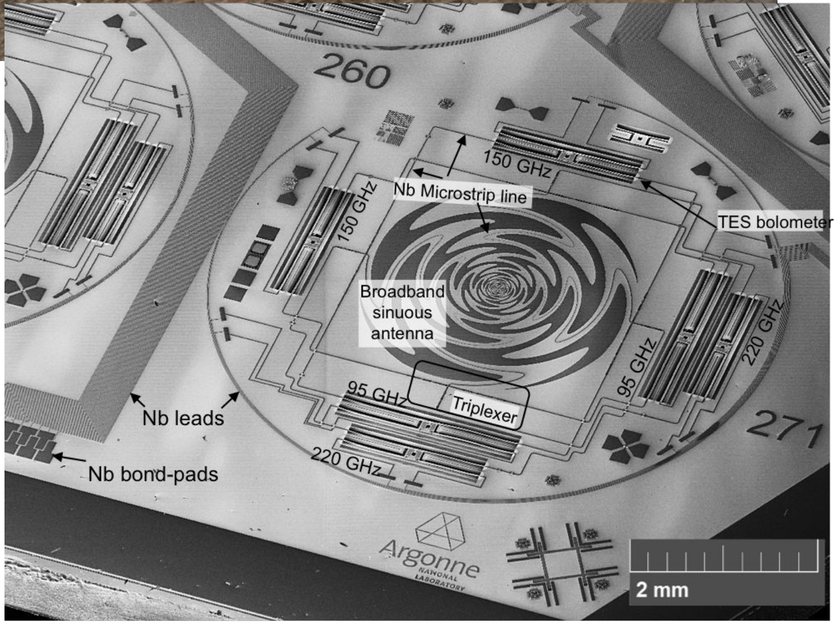



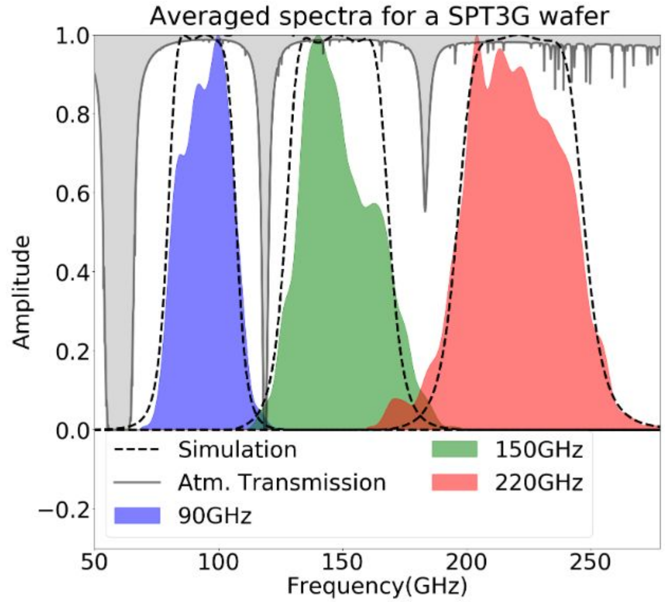

Grating Spectrometer (TIME) Abby Crites



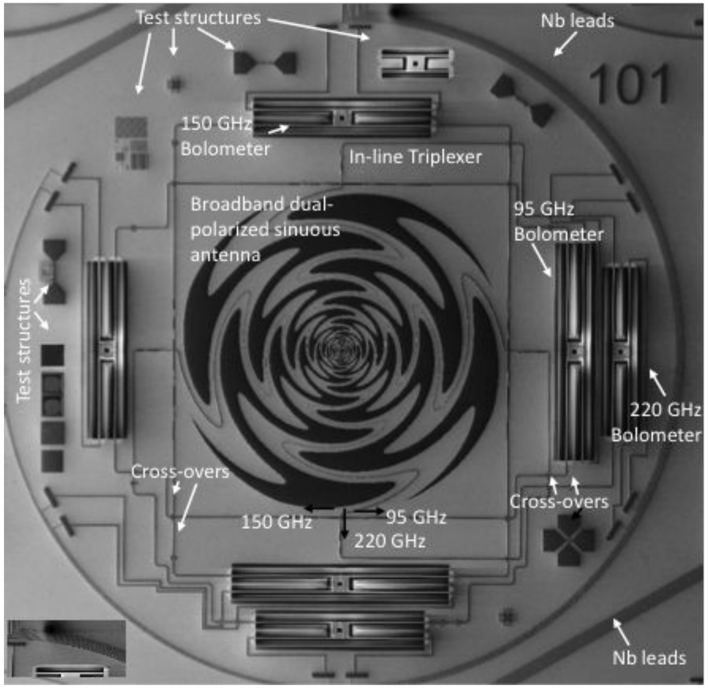
# Where we want to be: SPT-3G






Pan+ 2018




Clarence Chang

# The SuperSpec Team

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J. Glenn

J. Wheeler

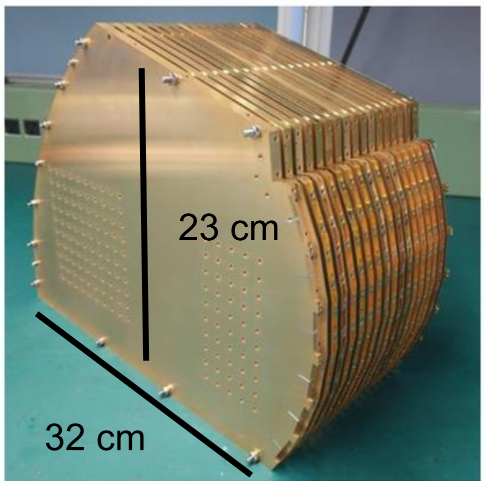
INAOE Puebla

David Hughes

# The SuperSpec On-chip mm-wave Spectrometer

Take favorable aspects of a grating spectrometer (wide bandwidth, high sensitivity) and put it on a silicon wafer.

Li+ 2018




Compare one spectrometer:

TIME grating, R~200:
32 x 23 x 1 cm **~ 736 cm$^3$**

SuperSpec, R~300:
3.6 x 5.7 x 0.05 cm **~ 1 cm$^3$**

Eventually could approach CMB efficiency with filled focal planes, i.e. hundreds of spectrometers on a single 6” chip.

Suitable for filled focal planes (LIM) or steered multi-object spectrographs.

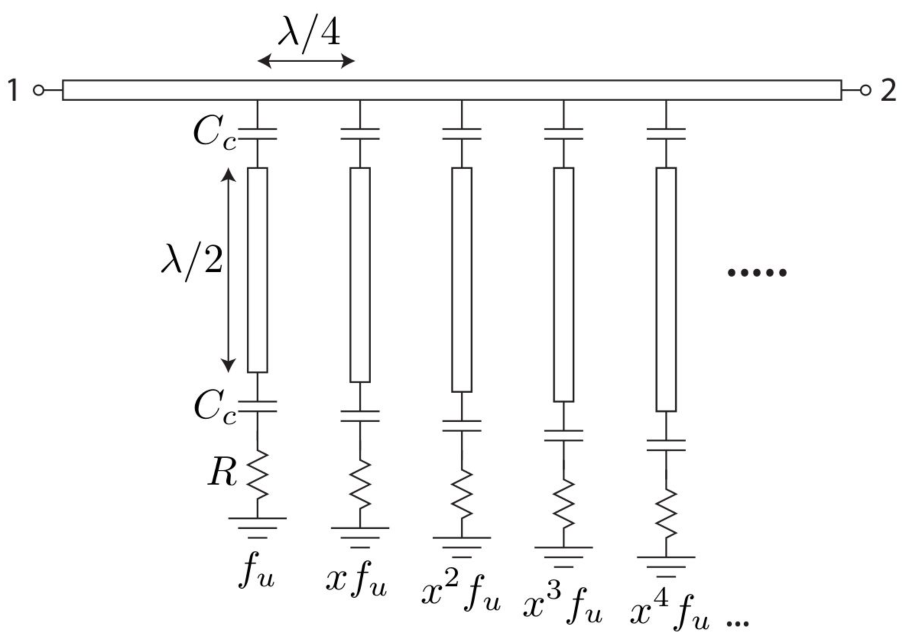
# The SuperSpec Concept

A general filter-bank (cochlear) spectrometer printed on a silicon wafer

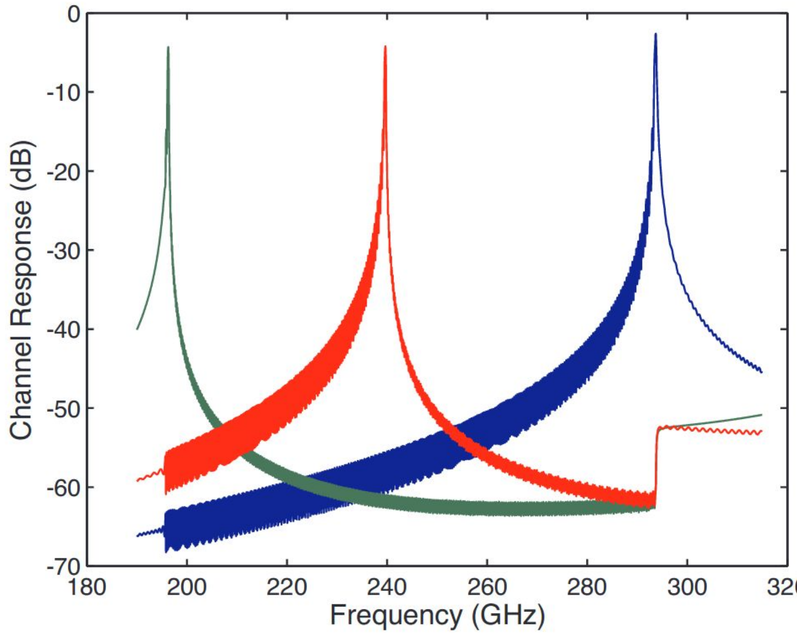
Incoming broadband radiation sorted by narrowband λ/2 filters

Each channel couples to a separate power detector

Channel width/spacing independently adjustable via feature geometry

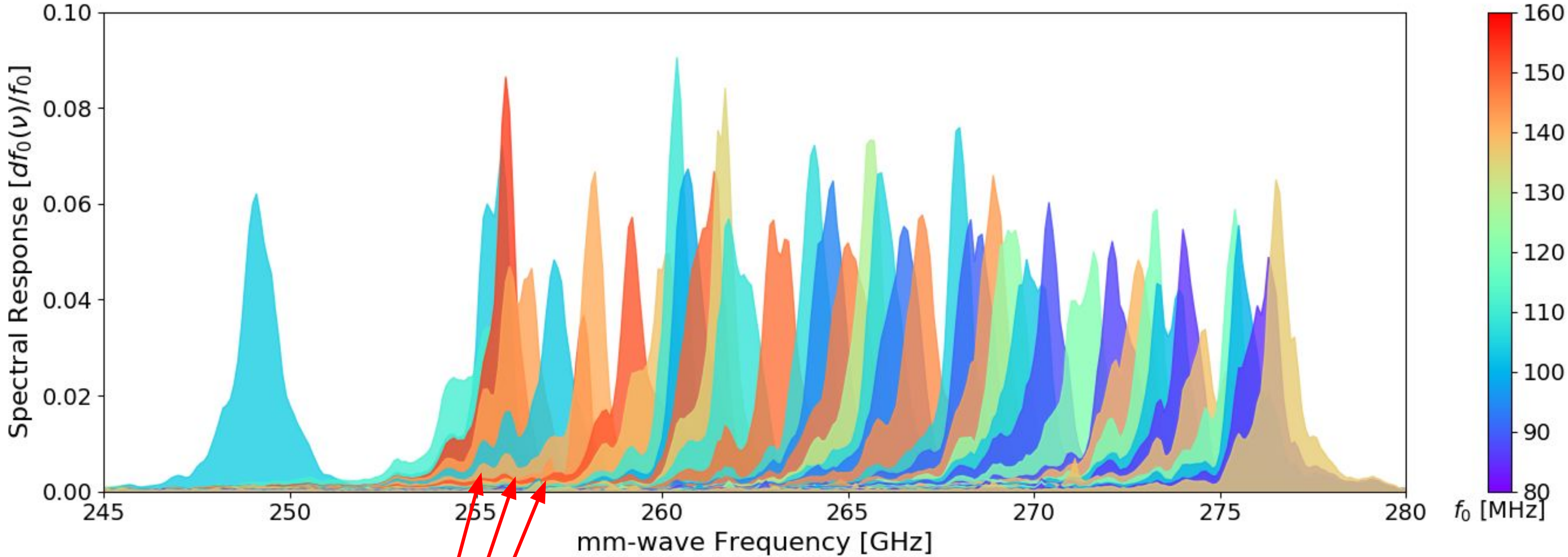


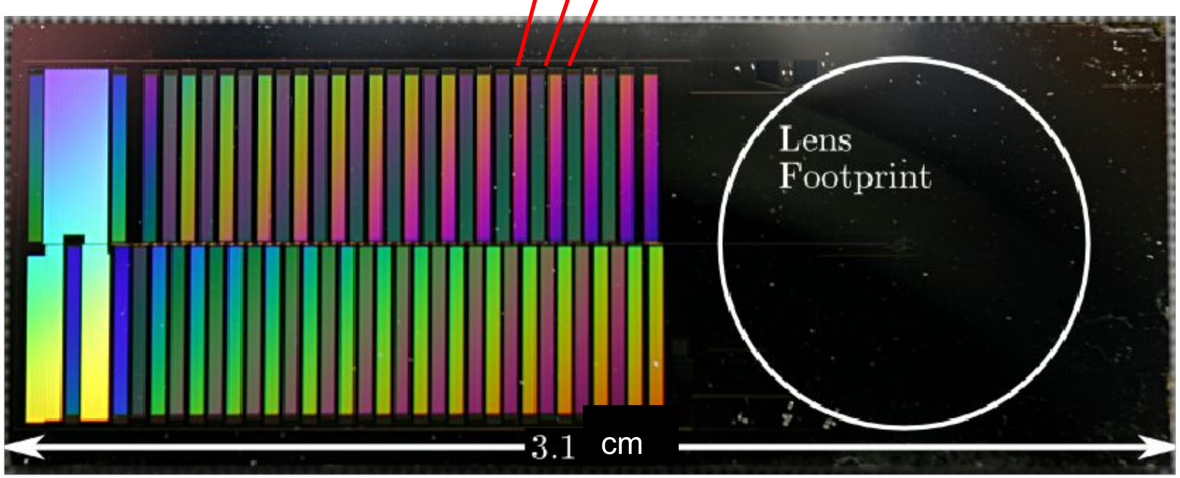

Kovacs and Zmuidzinas 2010



# Spectral Profiles

Karkare+ J. Low Temp Phys.
arXiv: 2020.04542




Photon noise dominated for ground-based observations.

**Ready to demonstrate on sky!**

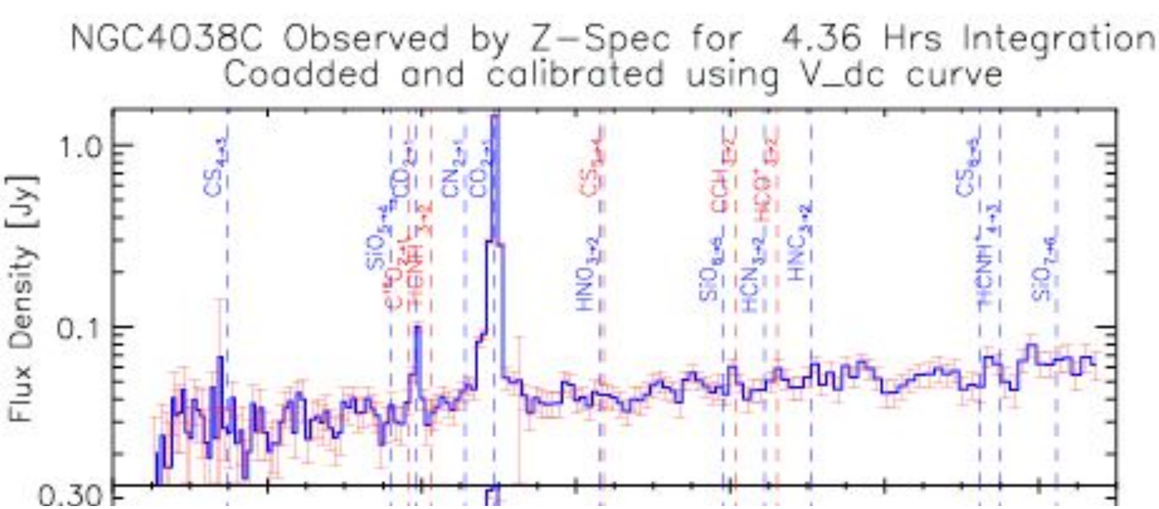

Large Millimeter
Telescope
James Lowenthal/UMass

# SuperSpec @ LMT

**Pre-COVID Status**: Ready to ship instrument to LMT in Spring 2020 for a Summer observing run - we should be on the mountain *right now!*

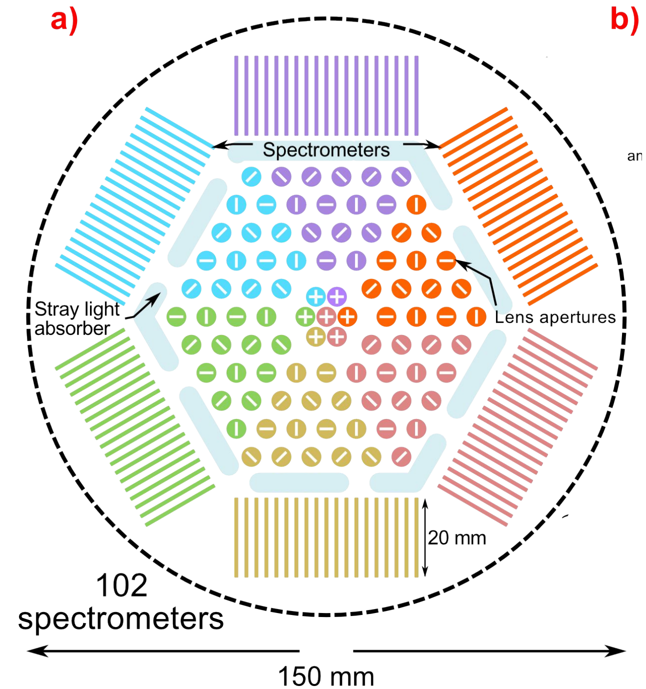
**Goals:**

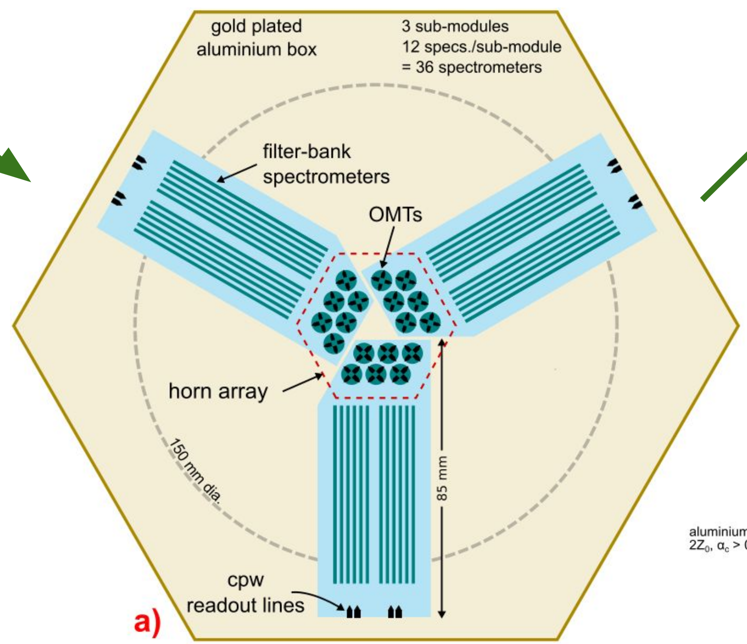
1. Demonstrate that SuperSpec can produce a spectrum of individual high-redshift galaxies
2. Understand noise performance to feed back into detector development
3. Develop on-sky calibration routines for spectroscopic MKIDs



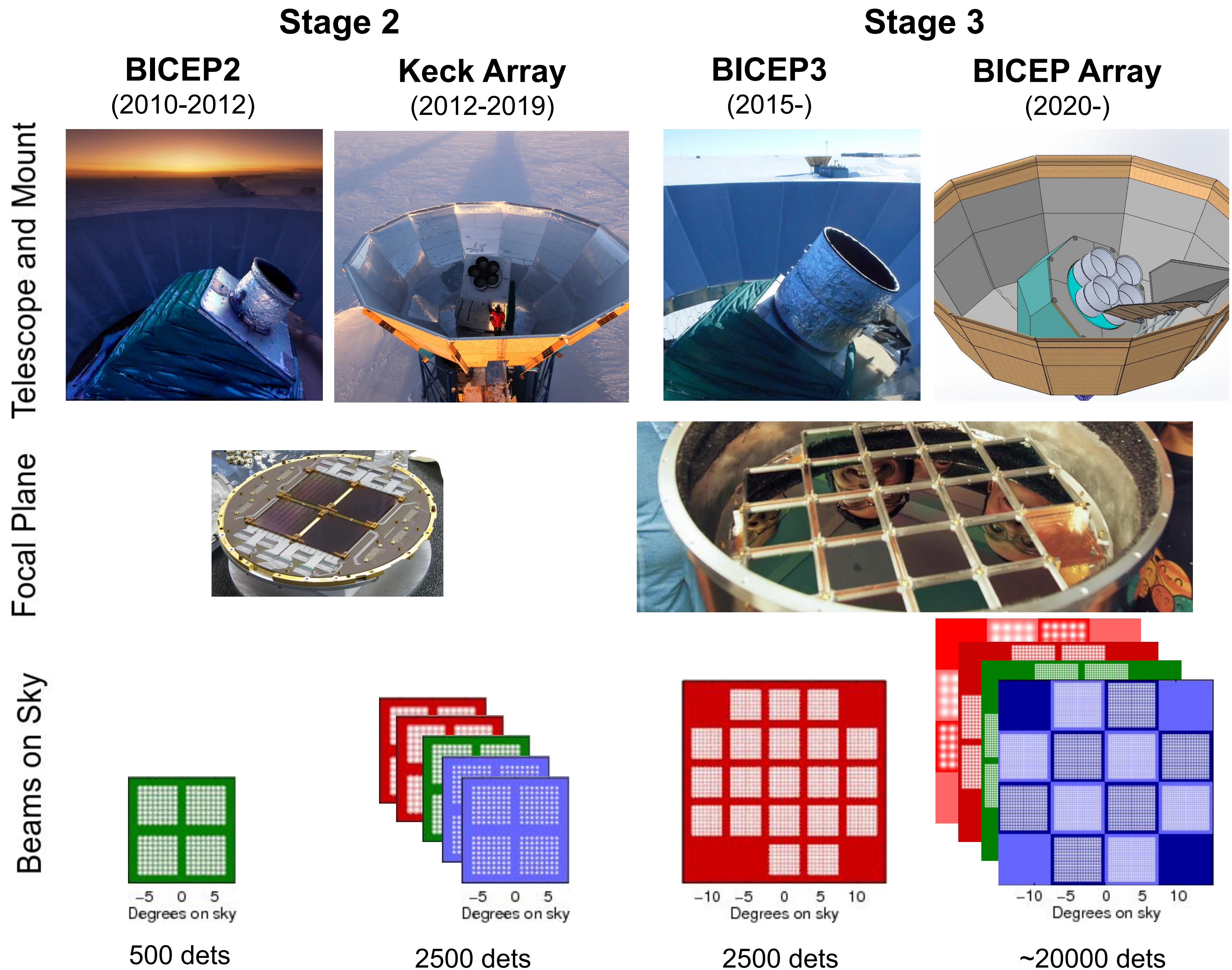

Jason Glenn
Matt Bradford

# Scaling Up Focal Planes




Pete Barry

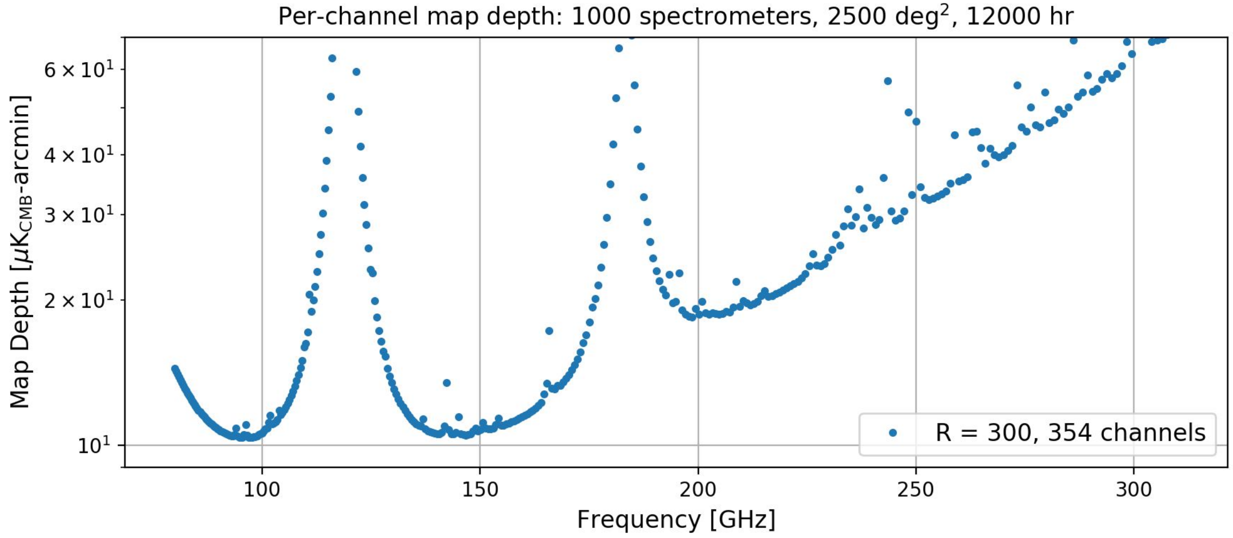

Stage 2
Stage 3
BICEP2
(2010-2012)
Keck Array
(2012-2019)
BICEP3
(2015-)
BICEP Array
(2020-)
Telescope and Mount
Focal Plane
Beams on Sky
−5 0 5
Degrees on sky
−5 0 5
Degrees on sky
−10 −5 0 5 10
Degrees on sky
−10 −5 0 5 10
Degrees on sky
500 dets
2500 dets
2500 dets
~20000 dets

# Next-Generation LIM Surveys

| Stage | Time | Spec. Count | Example | Science Threshold |
|---|---|---|---|---|
| Detection | Now | 10–50 | TIME[9], CONCERTO[10], CCAT-p[11] | Clustering power spectrum |
| Small-scale | 2-4 yr | 100–500 | SPT-like, 1 tube × 400 spec.<br>BICEP-like, 400 spec. | $\sigma(\alpha_{\mathrm{BAO}}) < 0.01$ at $z \sim 3$<br>$\sigma(f_{\mathrm{NL}}^{\mathrm{loc}}) < 3$ |
| Large-scale | 4-8 yr | 1000–5000<br>10000–50000 | Filled SPT/ACT, 7 tubes × 400 spec.<br>SO/CMB-S4 LAT, 85 tubes × 400 spec. | $\sigma(\Sigma m_\nu) < 0.036$ (+ Planck)<br>$\sigma(N_{\mathrm{eff}}) < 0.07$ (+ Planck) |

Table 2: Stages of future mm-wave LIM experiments. Note that "Small-scale" and "Large-scale" refer to spectrometer count and not angular scales. "Time" indicates rough time to start of operations given sufficient investment. The science thresholds are approximate and conservative—they are single-tracer, ignore cross-correlations, and only consider up to $k_{\mathrm{max}} = 0.2$ (smaller scales are accessible with the anticipated angular and spectral resolution).

mm-wave LIM Facilities LOI




Map depths for a "Large-scale" experiment, observing from South Pole.

Each dot is a separate R=300 frequency channel

# Summary

Millimeter-wave LIM detects early star-forming galaxies through their far-IR emission lines, and is a promising probe of cosmology beyond the reach of traditional galaxy surveys…

...but current mm-wave spectrometers are large and hard to scale up.

On-chip spectrometers will enable filled focal planes with orders of magnitude more detectors than current instruments.  In the context of Snowmass, SuperSpec is bringing the technical readiness level to CMB-scale instruments.

First demonstration of a R~300, 6-spectrometer receiver covering 200-300 GHz at the Millimeter Telescope is imminent!

Lots of work to do on projections/cross-correlations.