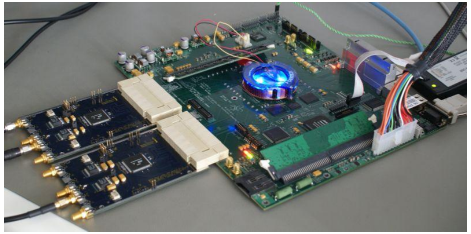
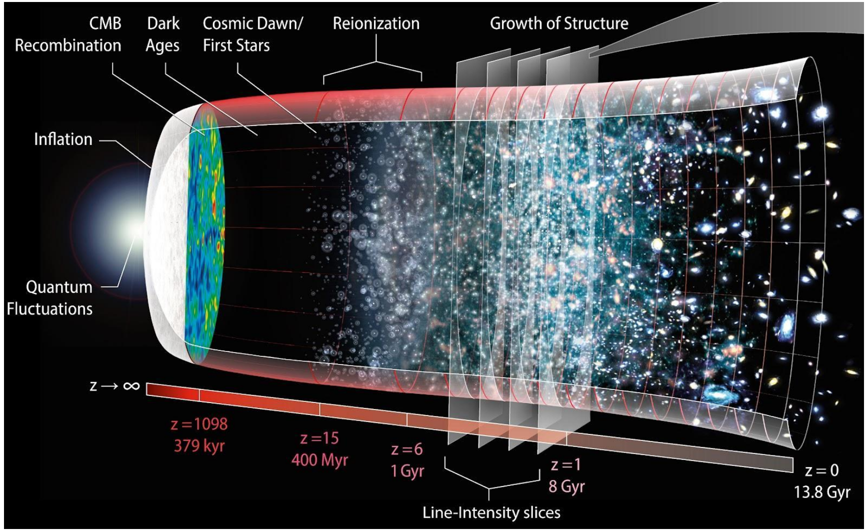
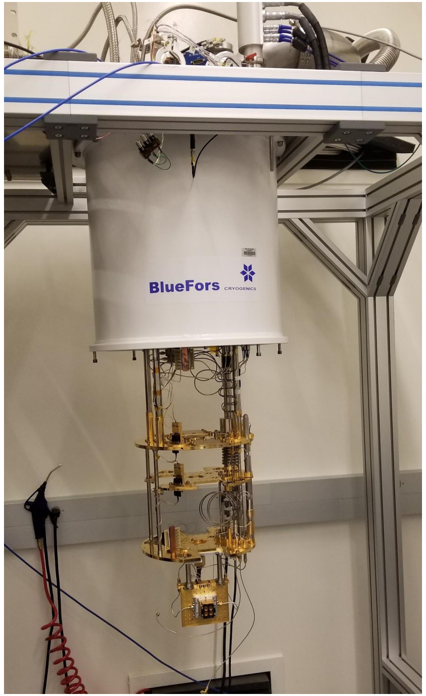
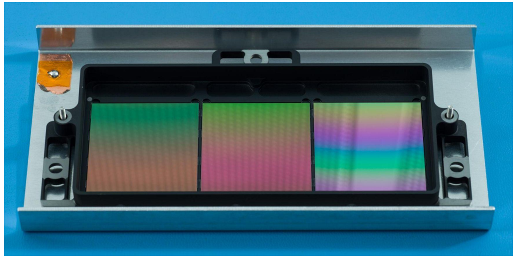


Current and Future Technologies for LIM







Kirit S. Karkare

LIM25, Annecy, 2025-06-06

BOSTON UNIVERSITY

A Reminder

We are attempting a measurement *unlike most in astrophysics*. We want to detect

- Extremely low surface brightness, extended emission…

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- …while minimizing systematics from the instrument and astrophysics.

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(this is **not** object-oriented astronomy)

A Reminder

We are attempting a measurement *unlike most in astrophysics*. We want to detect

- Extremely low surface brightness, extended emission…
- …over a wide range of angular scales…
- …over a wide range of wavelengths…
- …over (eventually) large areas of sky…
- …while minimizing systematics from the instrument and astrophysics.

All of this requires **bespoke instruments**, and in many cases dedicated technology development.

Technology initially weighted towards improving **sensitivity**, then transitions to understanding/characterizing **systematics**.

Overly-generalized summary

Wavelength	**Observational Status**	**Limited by?**
21cm	Signal at low z	Systematics control
cm (CO)	Hints of a signal?	Sensitivity
mm (CO, [CII])	Hints of a signal?	Sensitivity
Optical (Lyα, Hα)	Analysis underway	Platform, sensitivity?

Technological needs differ based on stage of experiment/what is needed!

Overly-generalized summary

Build a better experiment

Wavelength	**Observational Status**	**Limited by?**
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Build a bigger experiment

Analyze the experiment

Technological needs differ based on stage of experiment/what is needed!

Low-frequency radio (HIRAX, CHIME, LOFAR, PAPER, HERA, MWA, Tianlai…)

A reminder about radio frequency receivers:

The electric field on the sky is sampled by the antenna. The receiver system then needs to amplify the weak signal while adding minimal noise, digitize, and perform cross-correlations (for interferometers).

For low enough frequencies, the sky is so bright that room-temperature amplifiers add negligible noise!

The signal can be directly digitized without mixing.

Liu+ 2203.07864

Low-frequency radio (HIRAX, CHIME, LOFAR, PAPER, HERA, MWA, Tianlai…)

Instruments conceived as buildable with mostly off-the-shelf parts: low-frequency electronics are cheap, antennas easy to duplicate.

Liu+ 2203.07864

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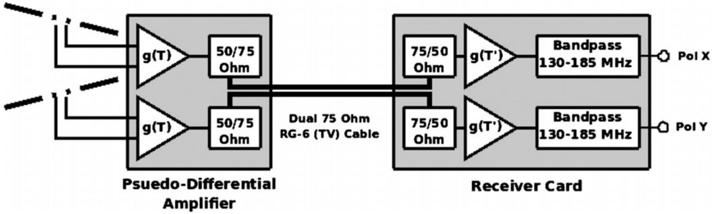
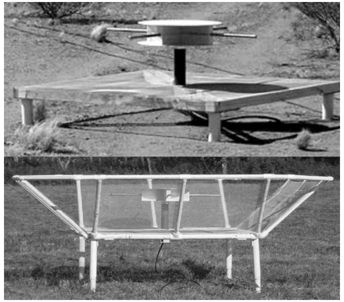


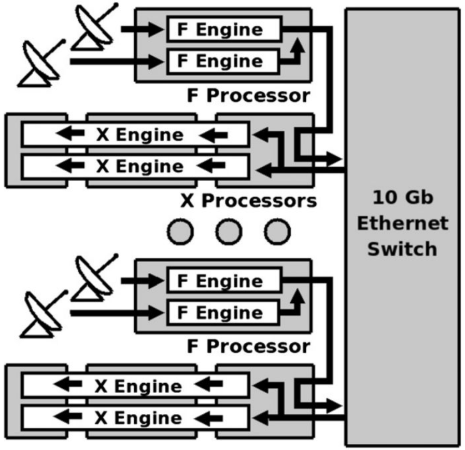


Parsons+ 2010

Low-frequency radio (HIRAX, CHIME, LOFAR, PAPER, HERA, MWA, Tianlai…)

Liu+ 2203.07864

Development of **digital signal processing** and correlators drove much of the initial growth as we moved from pathfinders to large-N interferometers.



Parsons+ 2010

Low-frequency radio (HIRAX, CHIME, LOFAR, PAPER, HERA, MWA, Tianlai…)

Liu+ 2203.07864

The **sensitivity** is there…but major challenges in systematics control, e.g. frequency dependence in instrument response - beam or gain variations.

How can we improve the hardware to minimize systematics?

E.g., CHIME: beam needs to be measured to 0.1%, time dependent gain to 1%.

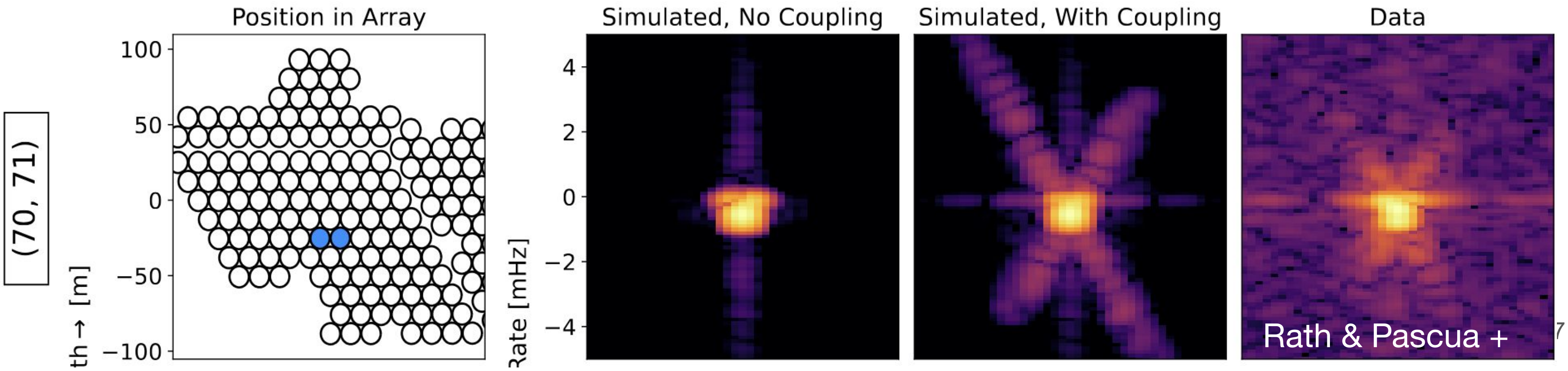
Improved Antennas

Composite dishes with sub-mm surface accuracy should improve ability to calibrate and model the beam pattern - much more uniform.

Image: Brian Hoff

Improved Antennas

Reduce crosstalk/mutual coupling with improved optical design (“deep-dish,” f/0.21).



Analog Design

Wide, uniform bandwidth (300-1500 MHz for CHORD!)

Well-controlled polarization response

Bandpass shape can limit foreground removal - additional RF circuitry could flatten bandpasses

More generally: redundant baselines set requirements on array element uniformity…especially important for FFT beamformers.

Early Digitization and Signal Processing

Analog components are susceptible to gain variation (e.g. from temperature changes). Digitizing directly at the dish focus makes the signal more resilient against time-variable changes in the signal chain.

There has been great progress on amplifiers with required noise temps and low-cost digitizers. However:

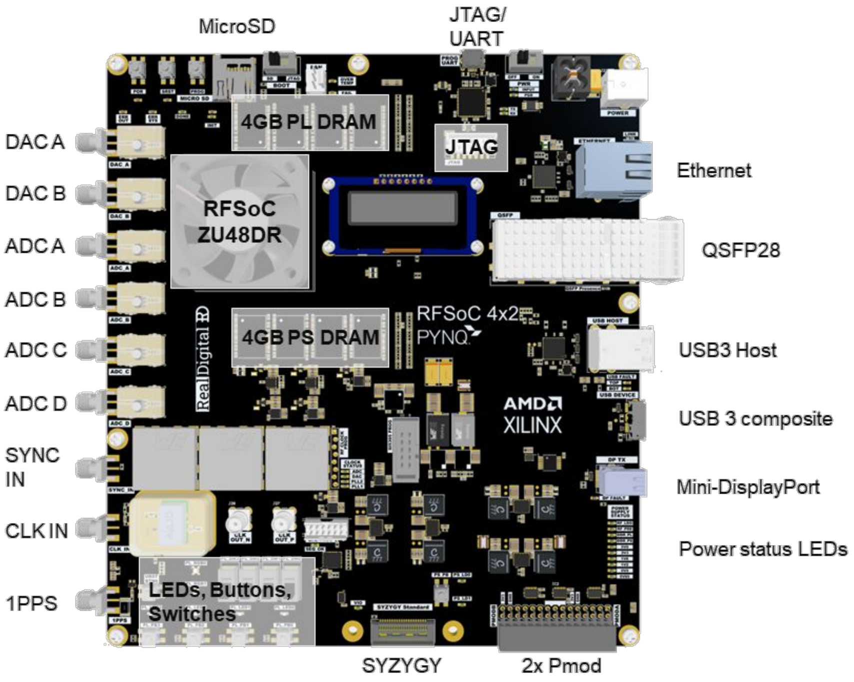
- RFI from digitization in field (-100 dBm vs 0 dBm)
- Increased cost
- Needs carefully-designed amplifiers and thermal regulation at focus (~1 deg)
- Clocks driving ADC need to be synchronized to sub-ps precision

Early Digitization and Signal Processing

Over the past decade, RF Systems-on-a-Chip (RFSoCs) have been introduced with multiple, high-rate ADCs and DACs embedded with fast programmable logic, memory, and quad-core ARM processors.

Can replace much of the older analog circuitry!

Also useful for mm-wave readout…



Zynq Ultrascale+ RFSoC Gen 3 ZU48DR

Computing

Liu+ 2203.07864

Experiment	Data rate [GB/s]	Year	Note	Ref.
VLA	0.3	2013	Resident Shared Risk Observing mode	[152]
ALMA	1.8	2021	Overall	[153]
LHC	25	2018	Average rate, all 4 experiments after triggering	[154]
LSST	6.4	2022	Peak rate	[155]
LCLS	10	2009	CXI instrument	[156]
LCLS-II	320	2027	High frame-rate scattering detector	[157]
XFEL	13	2017	2D area detector	[158]
SKA1	8,500	2022	Overall	[159]
CHIME	13,000	2017	Input to F-engine	[160]
PUMA	**655,000**	2030	**Input to F-engine**	[161]

Cm-wave (COPSS, COMAP, AIM-CO)

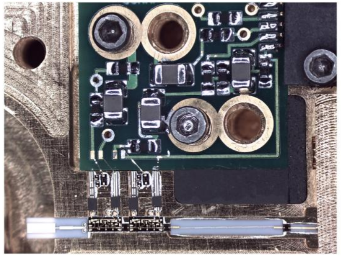
Unlike 21cm, sky brightness is low enough that we want cryogenic receivers → different instrumental challenges!

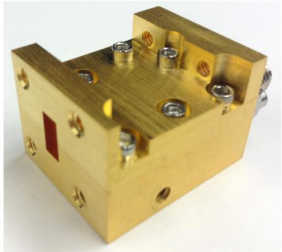
- Cooling to 4K is straightforward with Gifford-McMahon or Pulse Tube technology

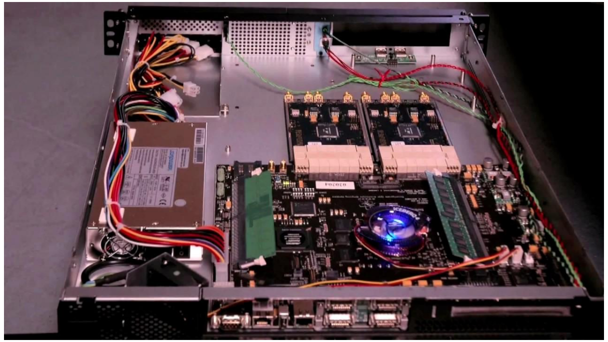
(luckily, wavelength shrinks enough that multiple detectors can be packed in a receiver and on a telescope - “radio cameras”)

Generally moving from interferometry to direct imaging since angular resolution is sufficient for LIM with 10-m class dishes.

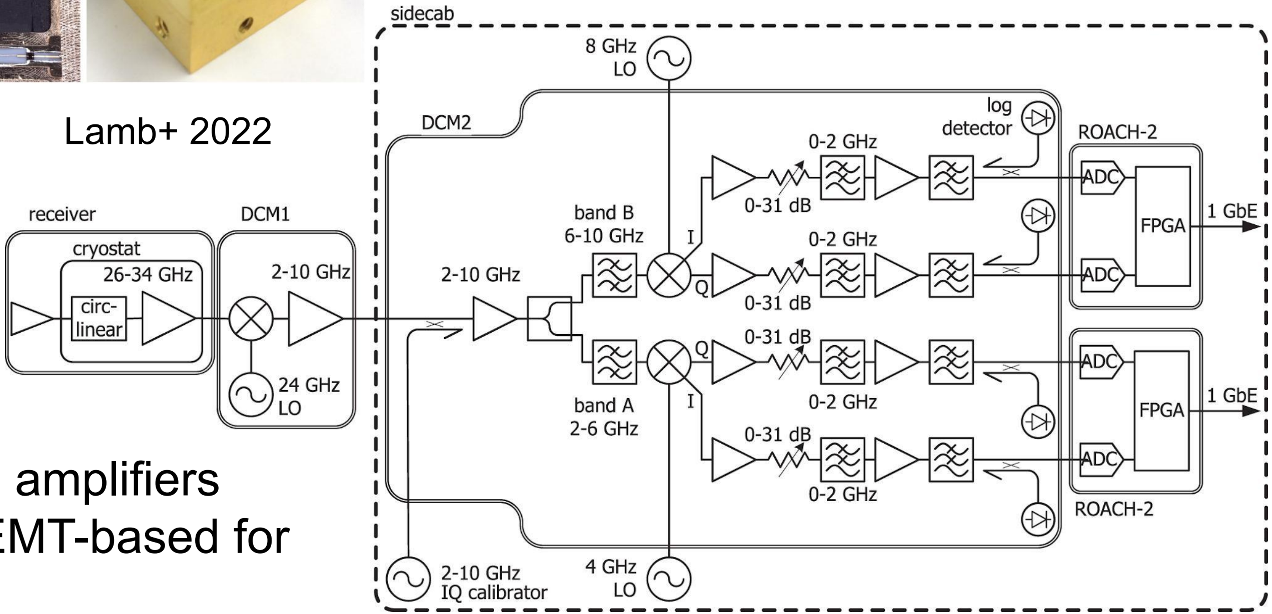
Cm-wave: Enabling Technology







Lamb+ 2022



Low-noise amplifiers (MMIC HEMT-based for COMAP)

“Cheap” signal processing (ROACH2…x 38)

Cm-wave: Improving Sensitivity in the Receiver

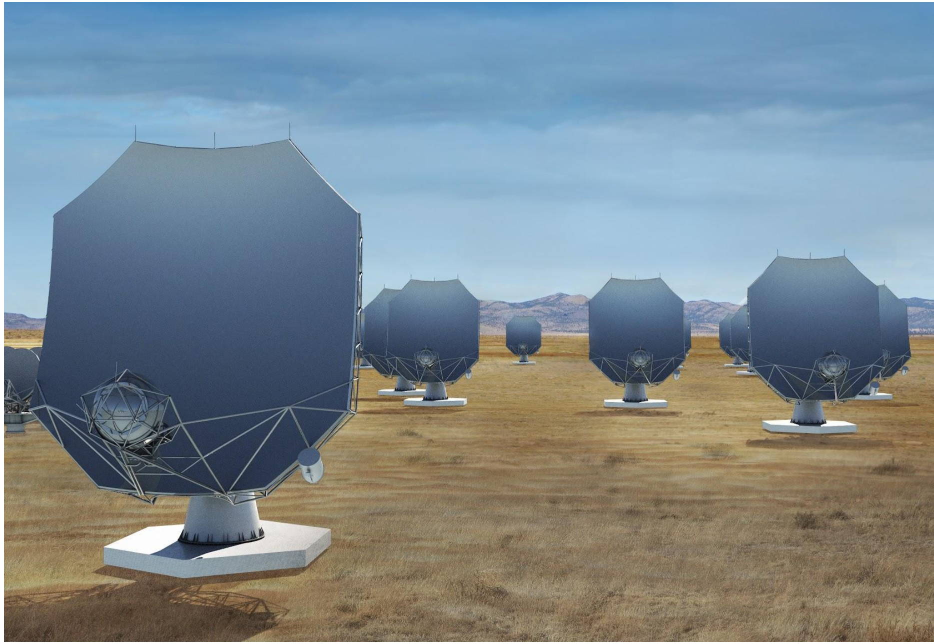
Unlike with other wavelengths, there doesn’t seem to be a single, obvious technical advance that will make next-generation experiments much more sensitive…but steady improvements are possible:

- HEMT amplifiers closer to the quantum limit (Tsys from 44 → 34 K?)
- Quantum-limited amplifiers using other technologies, e.g., traveling wave parametric amplifiers (synergies with mm-wave detectors)
- Signal processing with RFSoCs would improve bandwidth/sensitivity, simplify receiver design, and access larger line-of-sight scales.

Cm-wave: Improving Sensitivity by Scaling Up

It's difficult to pack more cm-wave detectors on a COMAP-style dish with good optical performance, so we need to deploy more antennas!

Similarly, new, larger antennas will need to be built for lower frequencies targeting CO during reionization (e.g., ngVLA 18m).



NRAO

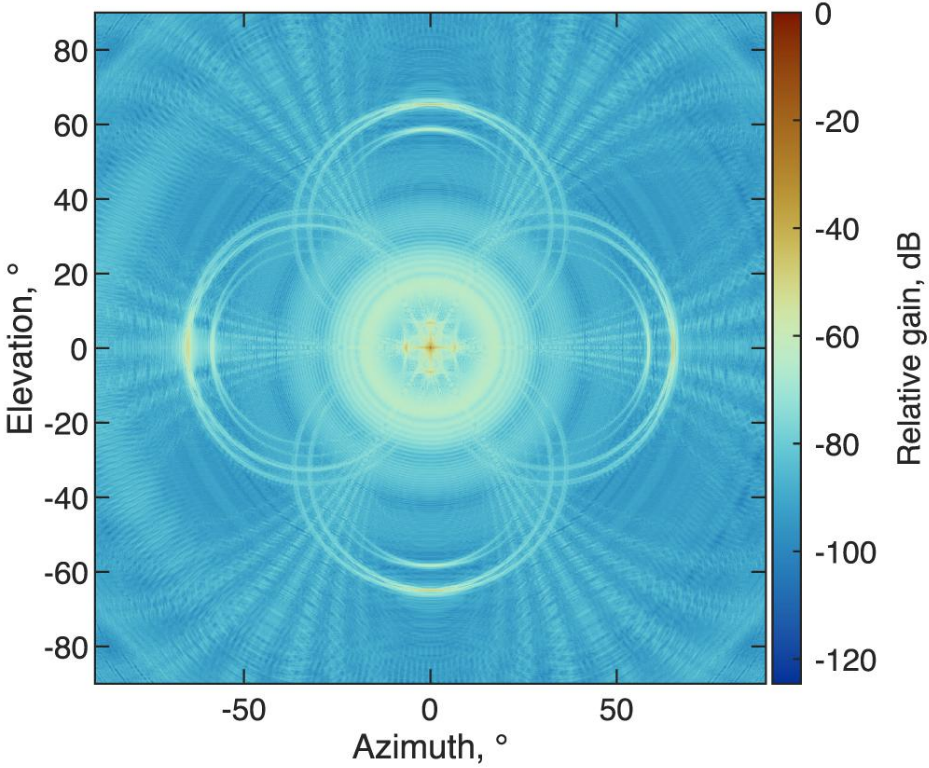
Cm-wave: Systematics

On-axis optics with feed legs can induce substantial systematics!

Sidelobes intercept the ground and can contaminate the map.

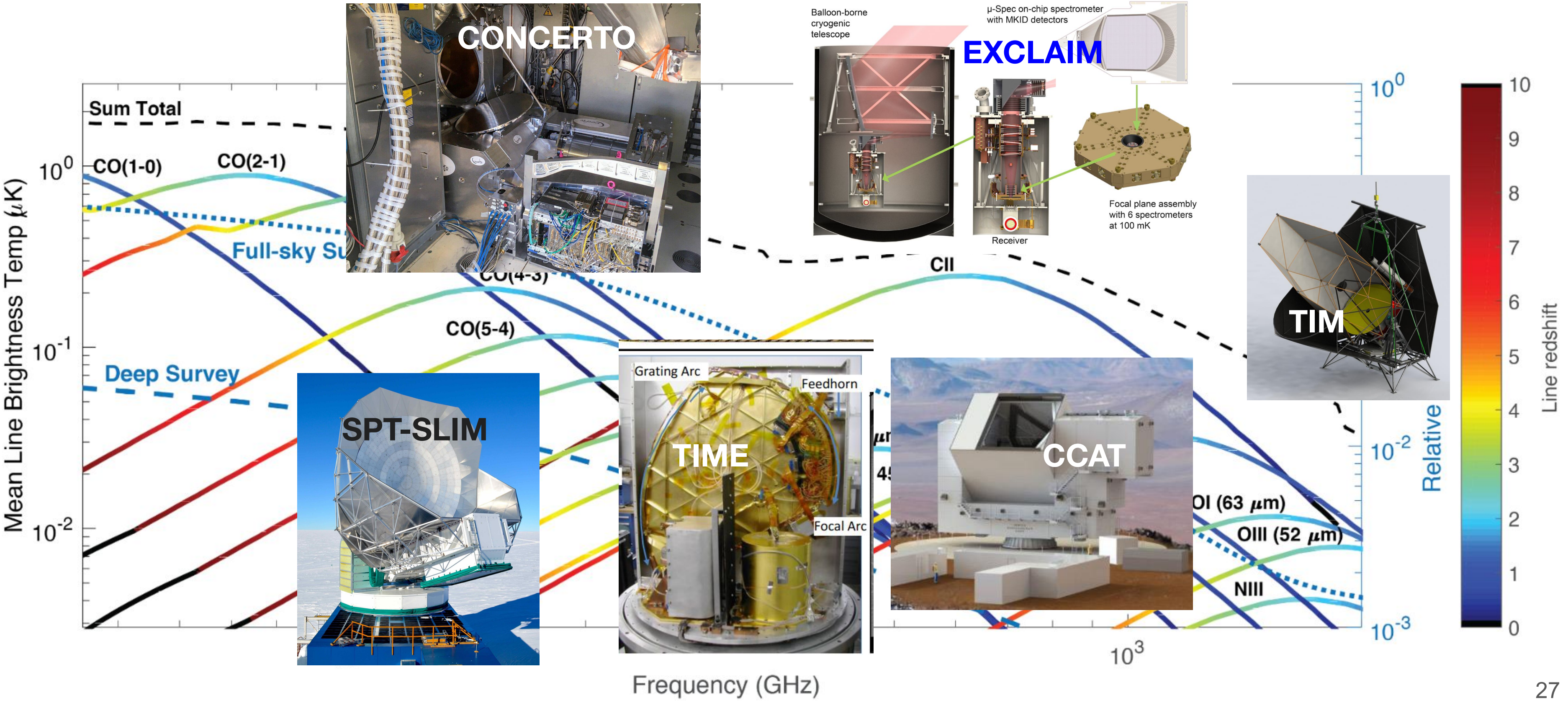
Reflections can set up standing waves.

One solution: **Off-axis, unobstructed dishes.**



Lamb+ 2022

Mm-wave : current instruments

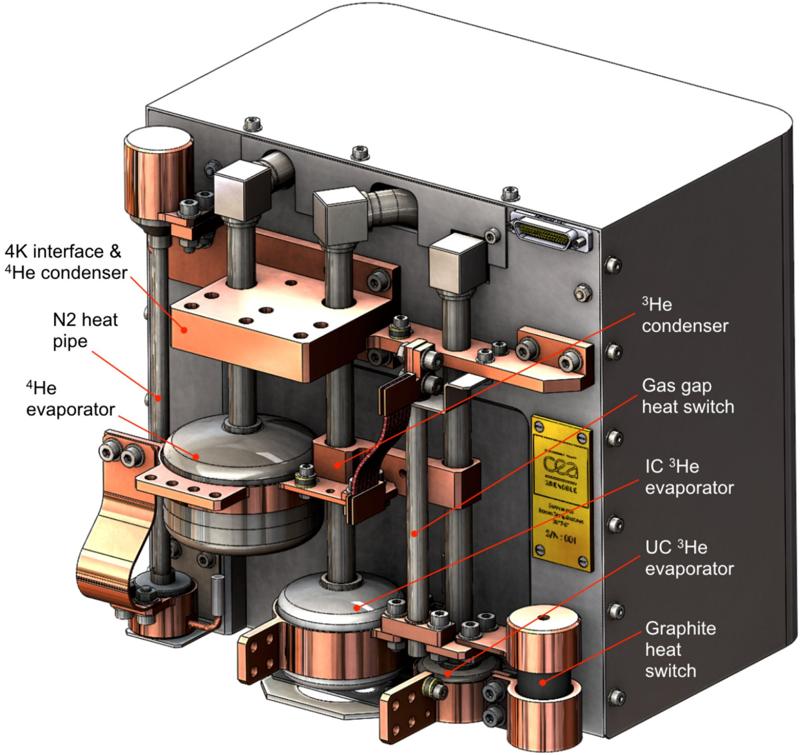


Mm-wave: New Challenges

Moving from cm to mm, the primary difference is that amplifiers become less attractive above ~100 GHz - incoherent detectors avoid paying the “quantum tax” for preserving amplitude and phase.

Sensitive mm-wave detectors typically operate at 100-30(mK, requiring more involved cryogenic infrastructure backed by a GM or Pulse Tube.

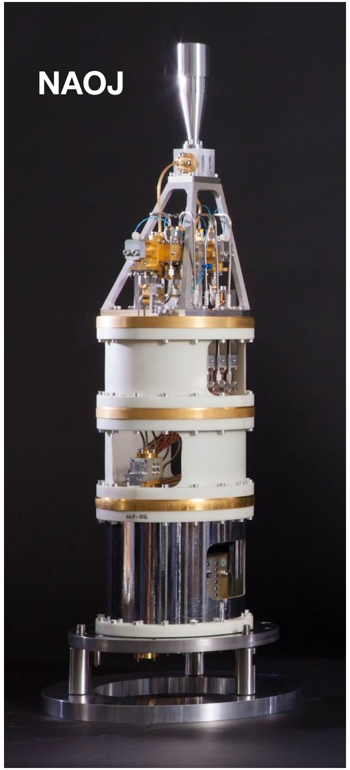
- **Helium sorption refrigerator:** pump on condensed He4/He3, cooling the liquid to ~220 mK
- **Adiabatic demagnetization refrigerator:** decrease B field around a salt pill (molecules with large magnetic moments) to extract heat from environment.
- **Helium dilution refrigerator:** at low temperatures, He3/4 separates into 2 phases. Pumping on He3 causes more atoms to cross the phase barrier, removing heat from the environment. Provides the most cooling power!

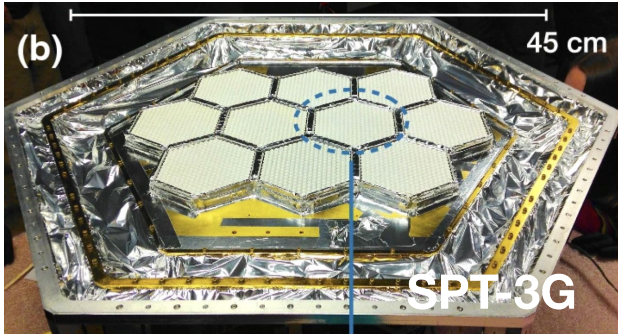


He4-He3-He3 sorption fridge, Duband (CEA Grenoble)

The (recent) State of the Art

Technology	Example	Pro	Con
Heterodyne	ALMA	High spectral resolution Preserves phase	Limited bandwidth Quantum tax Packing density
Bolometers	Almost all CMB experiments	Sensitivity Large arrays	Low spectral resolution Sub-Kelvin required





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A “shovel-ready” approach: take sensitive, broadband “CMB-style” detectors and add spectroscopy.

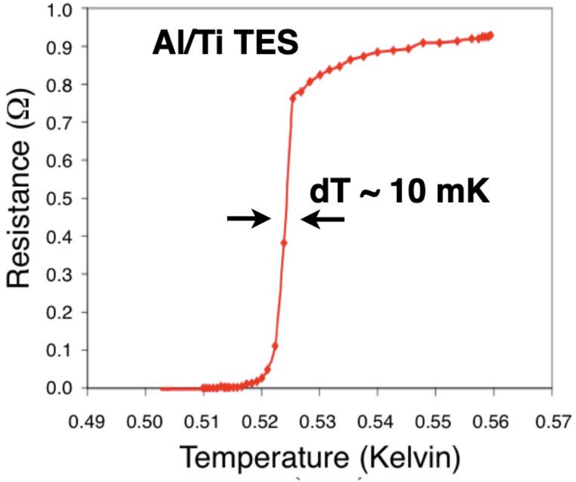
Two flavors of detectors: TES bolometers and MKIDs.
Both flavors routinely made to be “photon noise dominated”

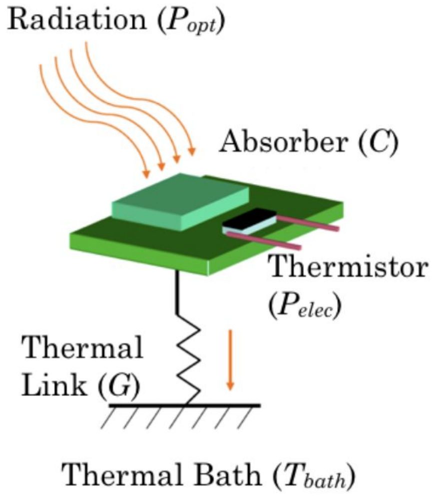
Transition Edge Sensor Bolometers

Consider cooling a superconductor, but holding it on the very narrow superconducting transition. By monitoring its resistance, we have a very sensitive thermometer.

Now place that thermometer on a thermally-isolated island, on which mm-wave radiation is deposited and absorbed. There is a weak thermal link to a bath where heat can flow out.

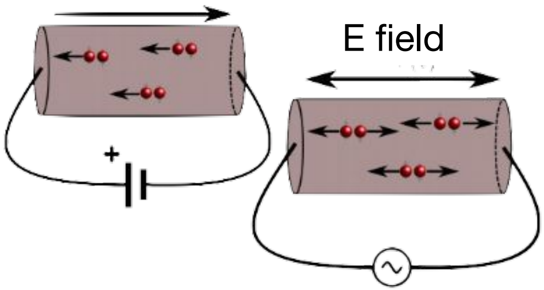
By holding the detector at constant voltage, negative electrothermal feedback keeps total power on the bolometer constant!





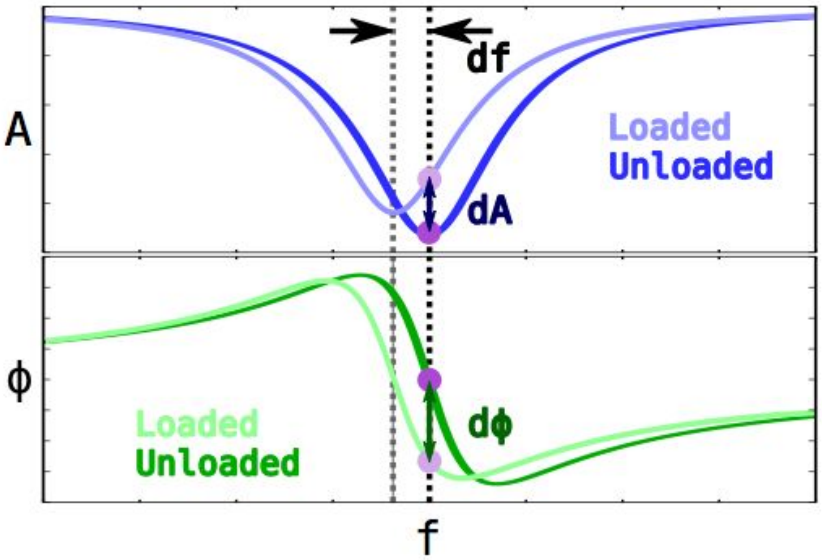
Kinetic Inductance Detectors (KIDs)

Superconductors have zero DC resistance, but nonzero AC reactance (“kinetic inductance”).



Photons of the right energy break the superconducting Cooper pairs, changing the kinetic inductance.

We can form an LC resonator whose resonant frequency changes with photon load!



$$\omega_0 = \frac{1}{\sqrt{LC}}$$

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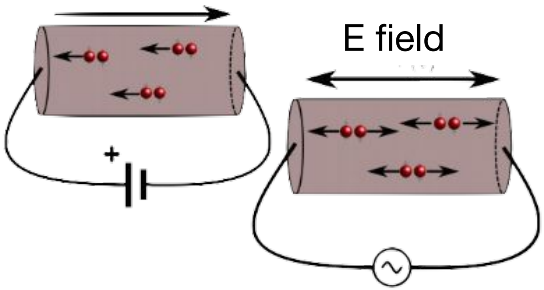

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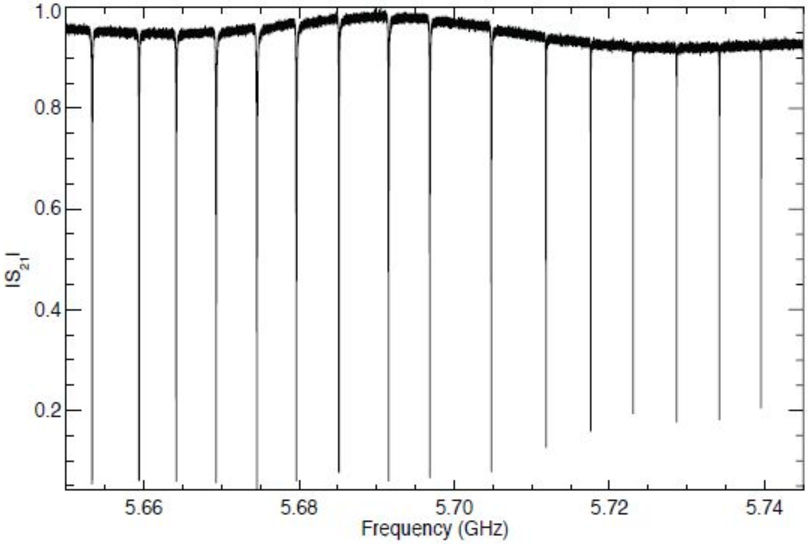
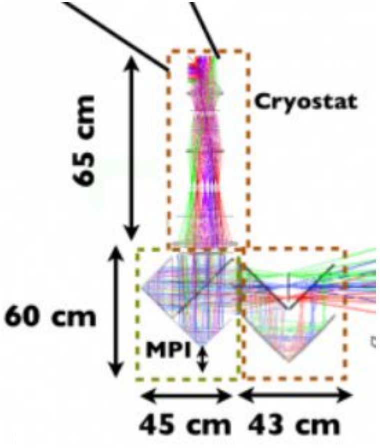
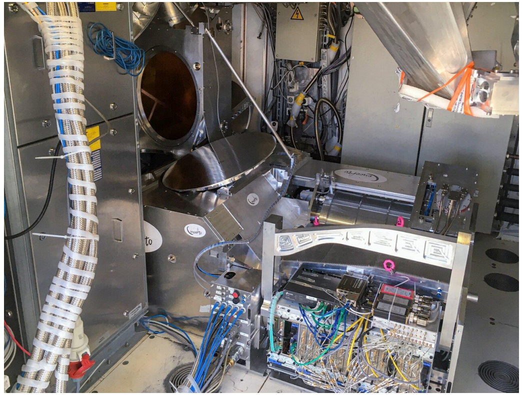


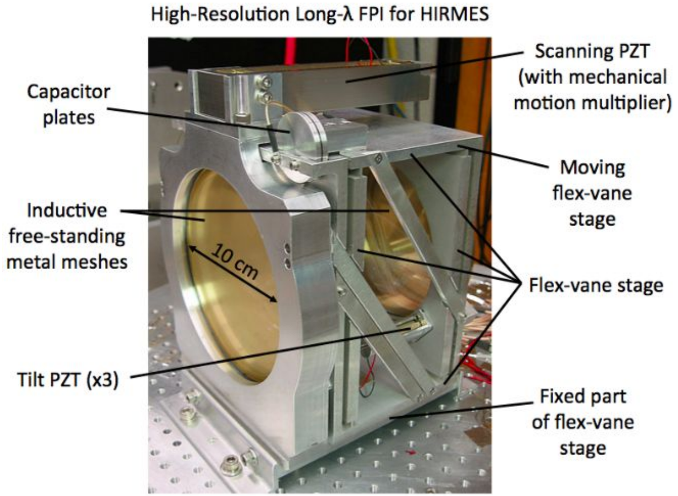
Each detector is assigned a unique resonant frequency, enabling readout of thousands on a single microwave line.

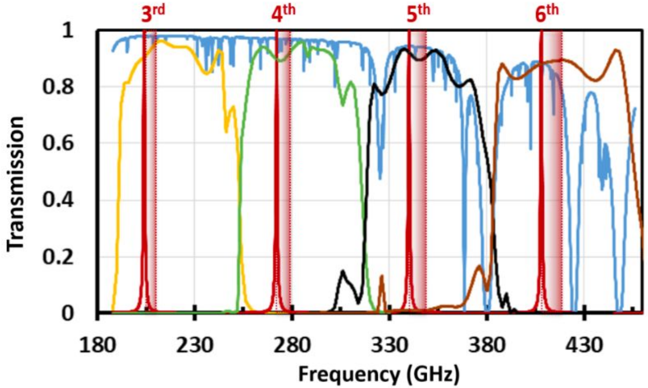
Fourier Transform Spectrometer (CONCERTO) neel.cnrs.fr



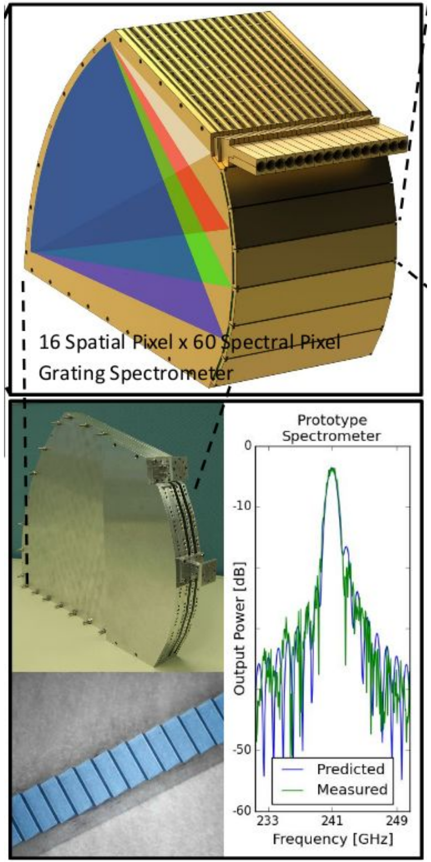


Fabry-Perot (CCAT-p) 1807.00058

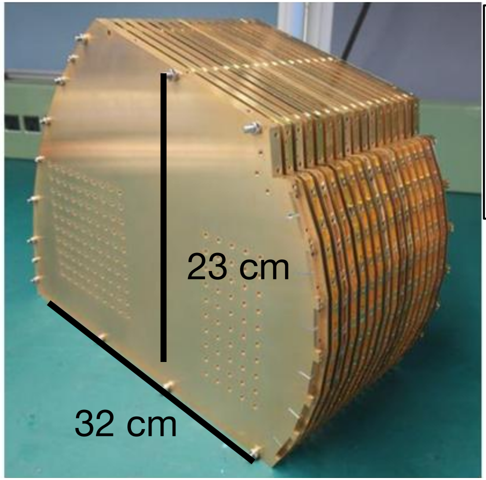




Grating Spectrometer (TIME) Abby Crites



On-Chip Spectroscopy Can Shrink the Volume

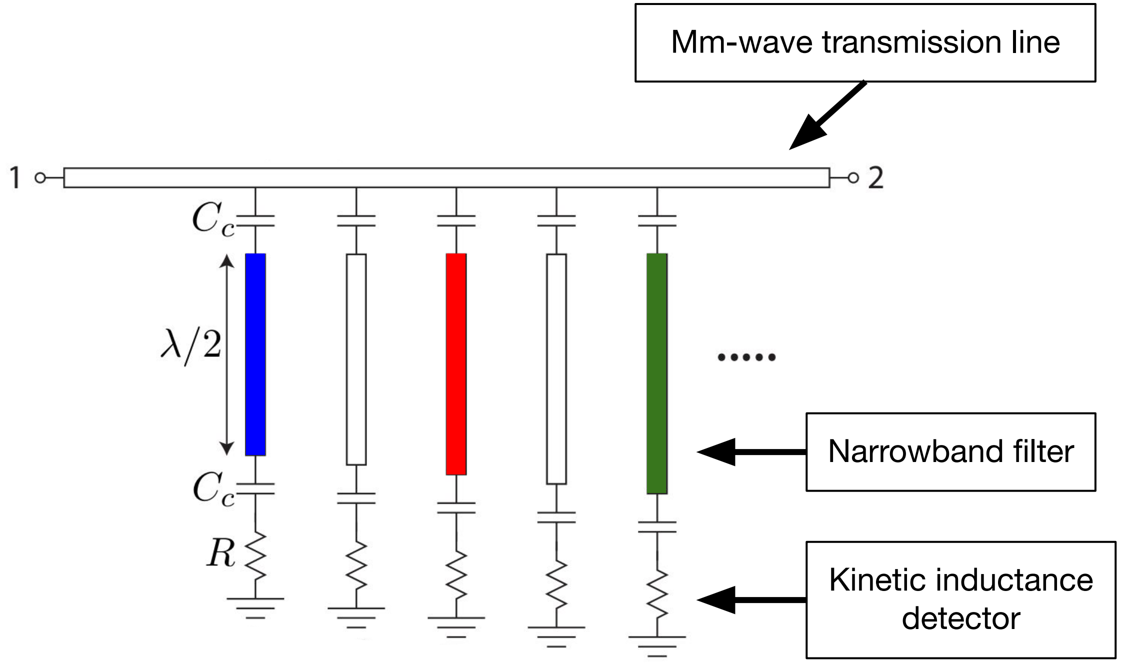


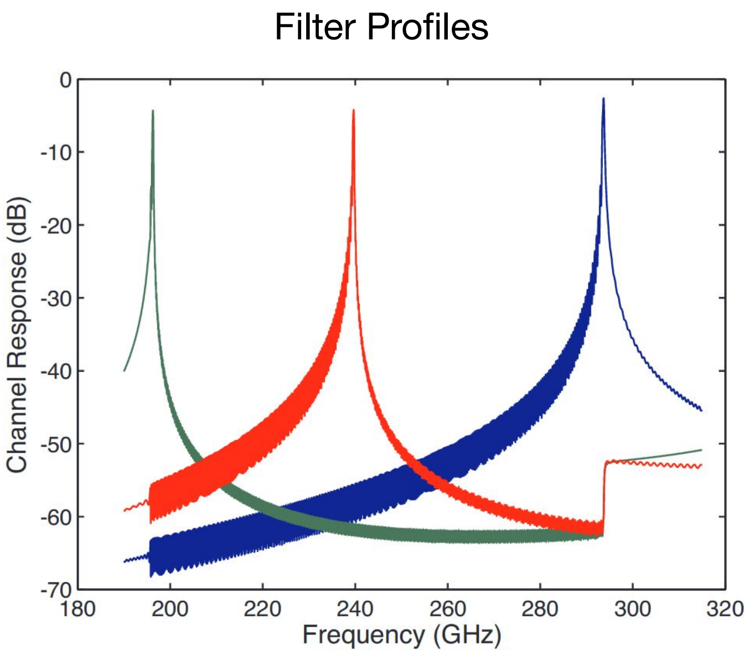
Diffraction grating:
32 x 23 x 1 cm
~ 736 cm^3

On-chip version:
3.6 x 5.7 x 0.05 cm
~ 1 cm^3

Looking forward, our primary goal is to maximize sensitivity.
Leverage CMB community development of large-format lithographed thin-film superconducting detector arrays.

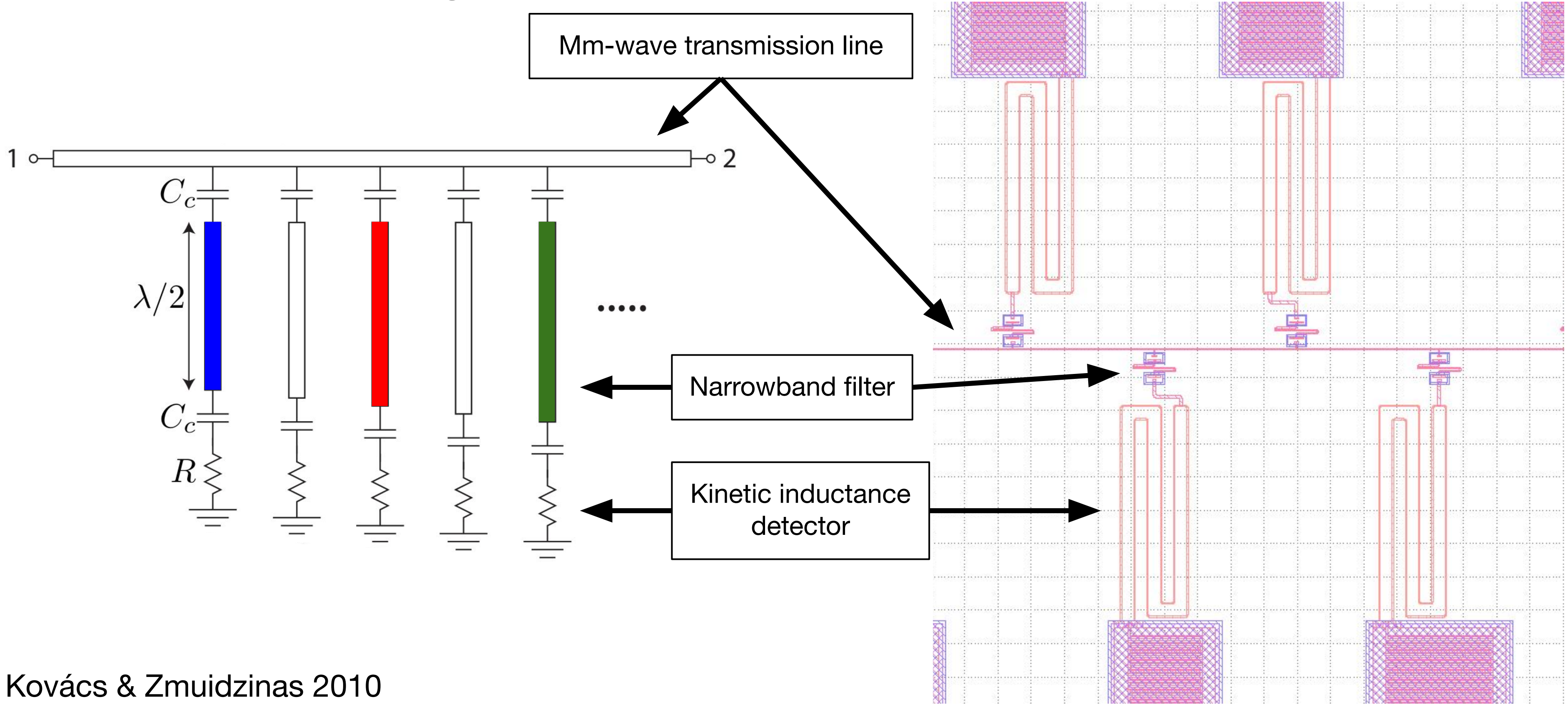
A Filter-Bank Spectrometer





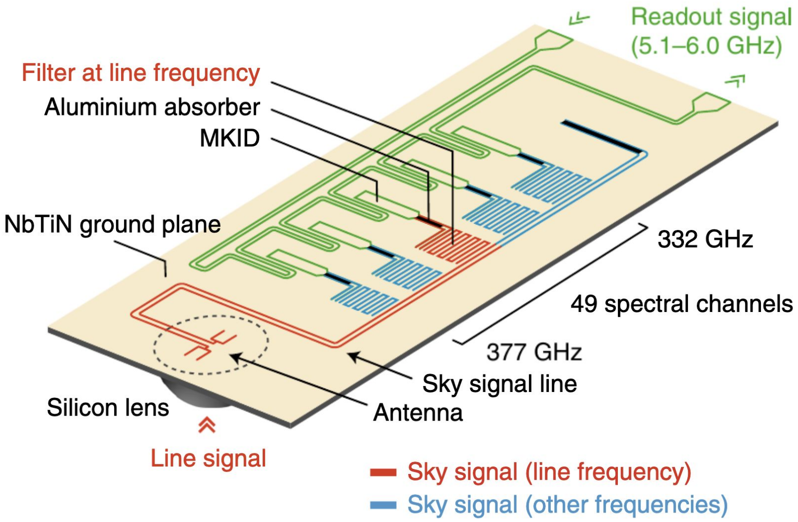
Kovács & Zmuidzinas 2010

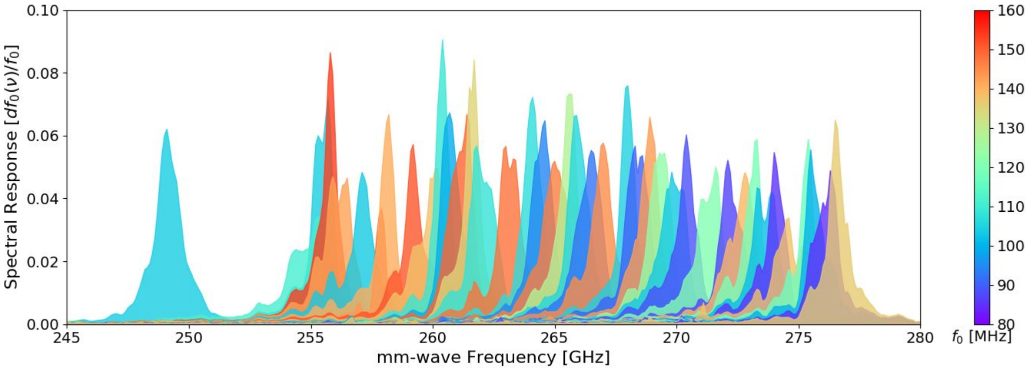
A Filter-Bank Spectrometer Realized with Thin-Film Superconducting Circuits



Kovács & Zmuidzinas 2010

Parallel Development!

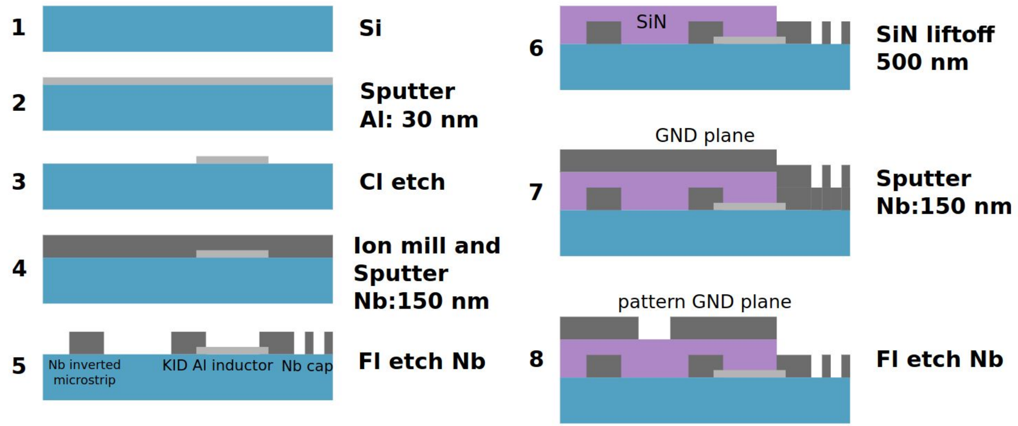


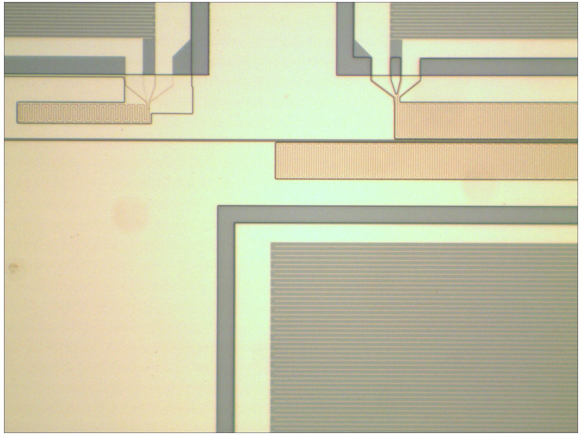


DESHIMA
Endo+ 2019

SuperSpec
Shirokoff+ 2014, Karkare+ 2020

Detector Fabrication

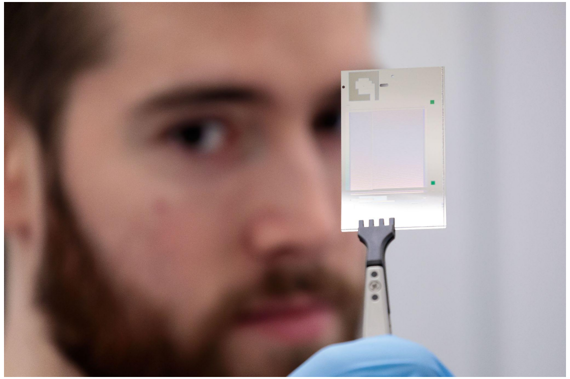




Use superconducting thin films:
Niobium, Aluminum, Titanium Nitride…

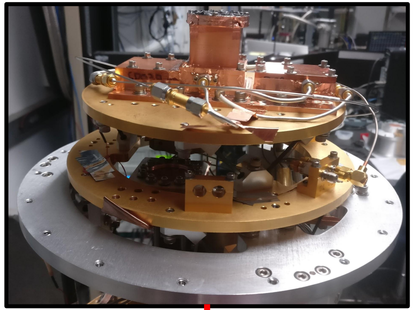
JPL Microdevices Laboratory and
UChicago Pritzker Nanofabrication Facility

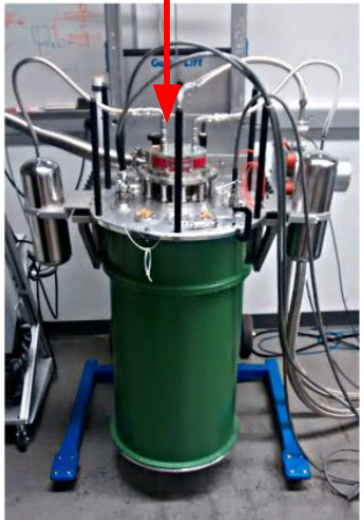
Ryan
McGeehan

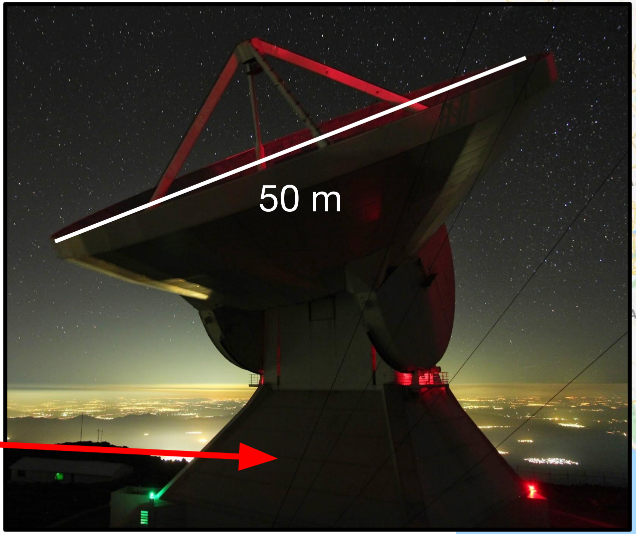


SuperSpec @ LMT

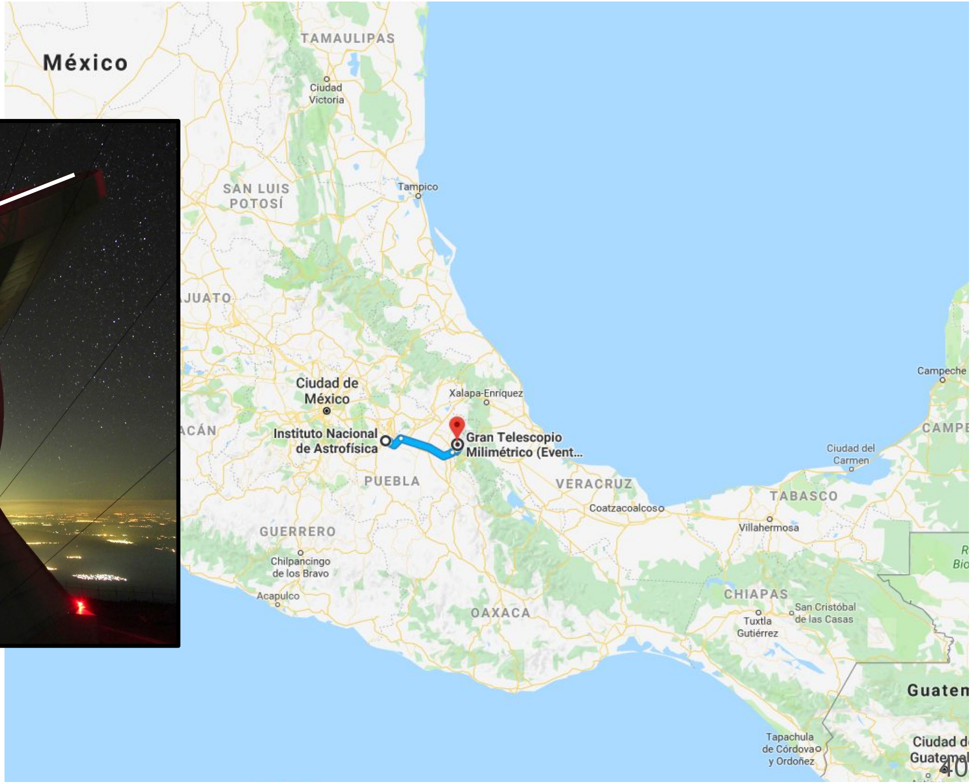
We are finally deploying a 6-spectrometer receiver to the Large Millimeter Telescope in Mexico – an ideal facility for pointed observations of high-z galaxies.







lmtgtm.org



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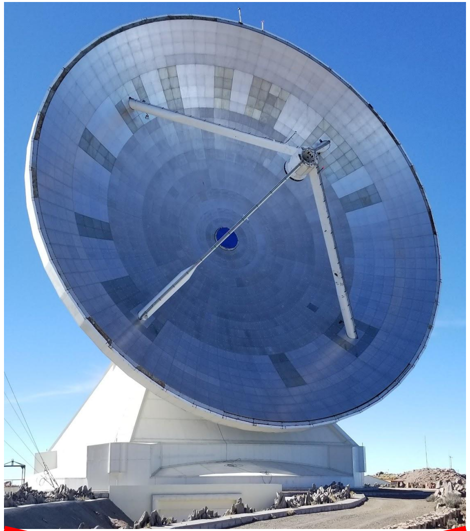
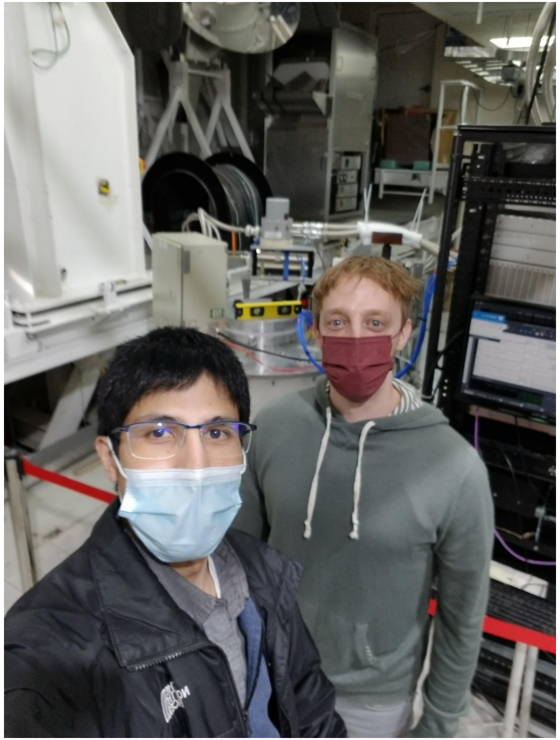
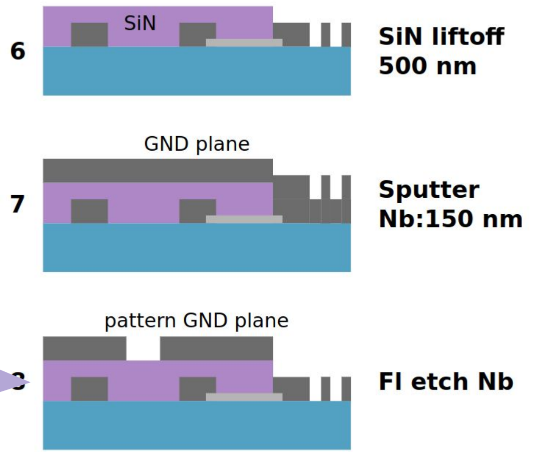


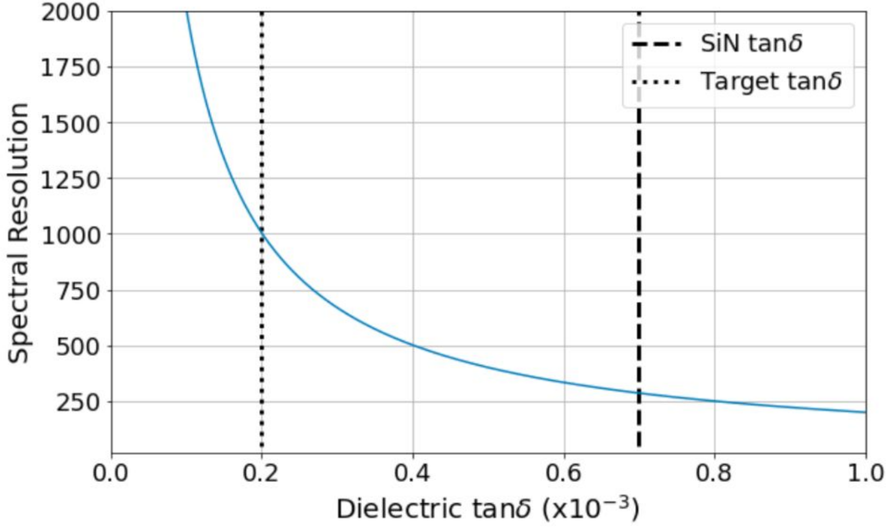


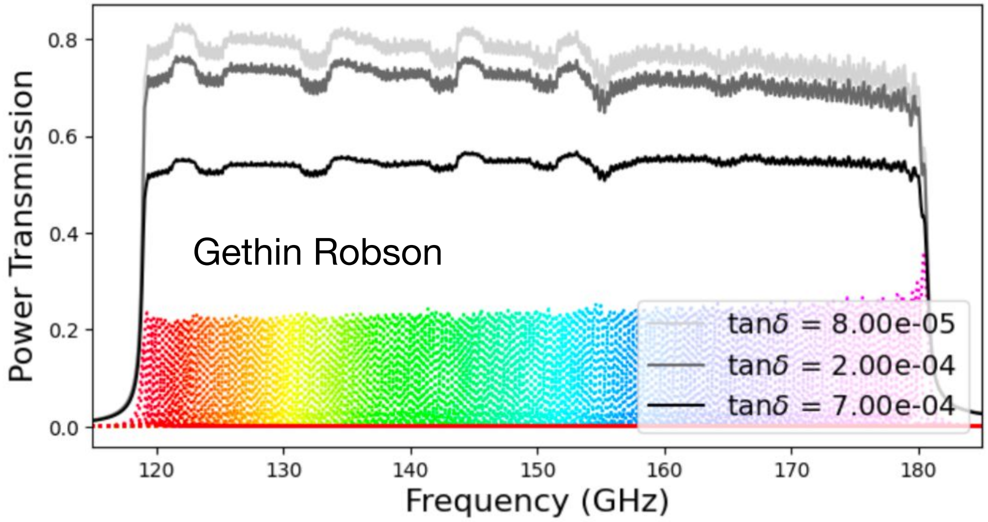
Improving the Spectrometer Itself

Most on-chip prototypes have ~10% optical efficiency.
Achieved spectral resolution ranges from 50 - 500.

One avenue: reduce loss in microstrip dielectric.





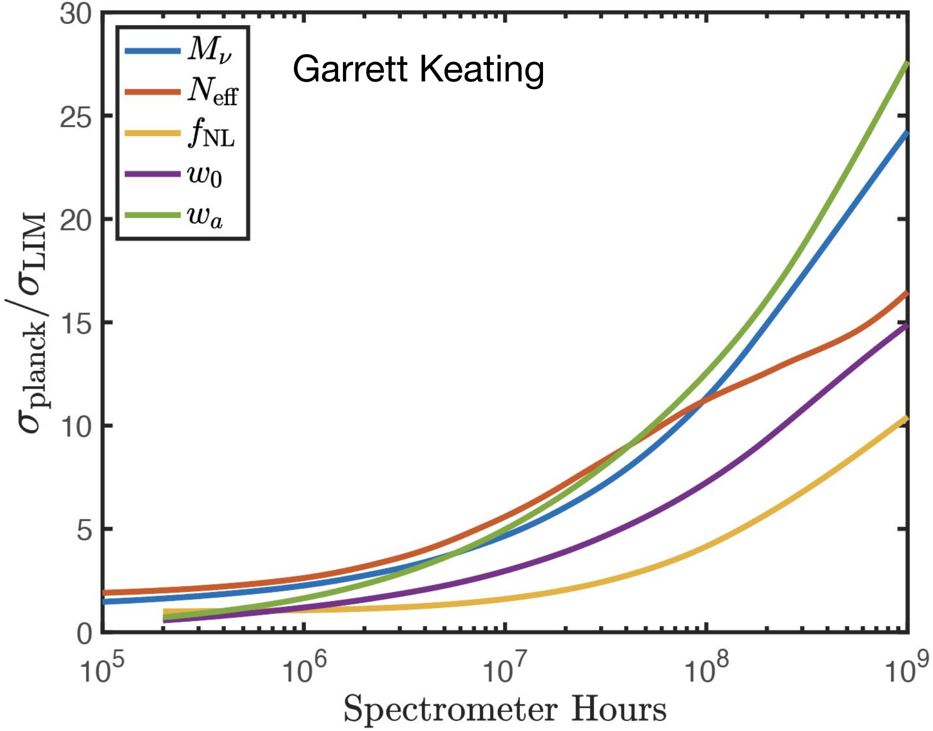


What Do We Need for Cosmology?

Spec-hrs	$\lesssim 10^5$	10^6	10^7	10^8	10^9
Timescale	2025	2027	2029	2033	2040
Example	TIME, SPT-SLIM	TIME-Ext	SPT-3G+ one tube	SPT-3G+ 7 tubes	CMB-S4 85 tubes
$\boldsymbol{\sigma}(M_\nu)$ [eV]		0.047	0.028	0.013	0.007
$\boldsymbol{\sigma}(w_0)$ incl. z>3		0.03	0.013	0.005	0.003
Primordial FoM		0.1	1	10	100

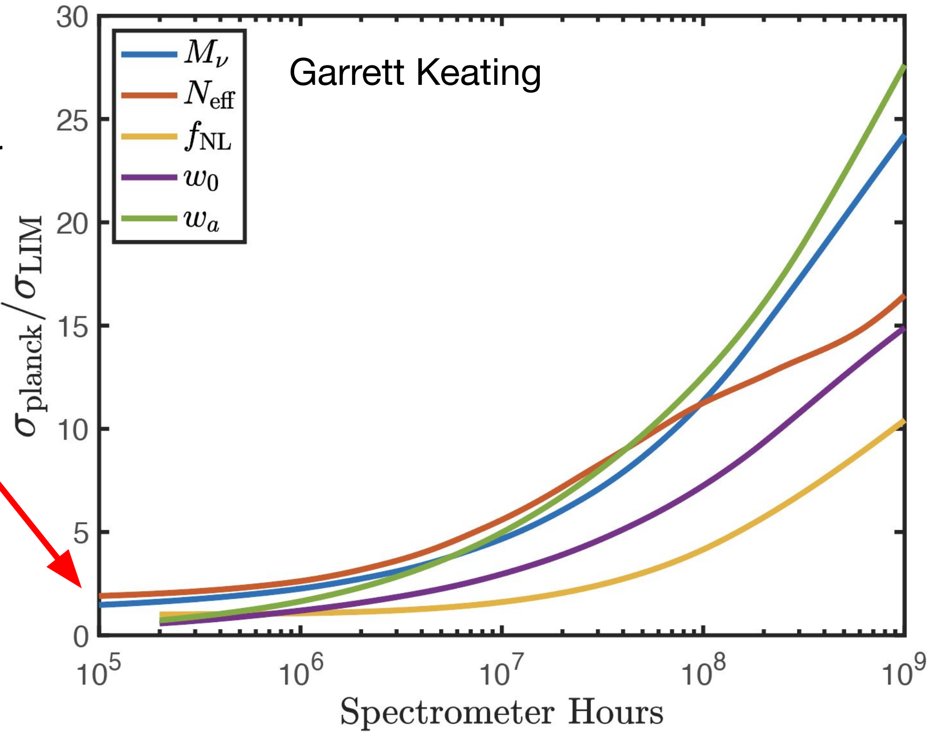
Karkare, Moradinezhad Dizgah, Keating, Breysse, Chung
2203.07258 Snowmass white paper

What Do We Need for Cosmology?



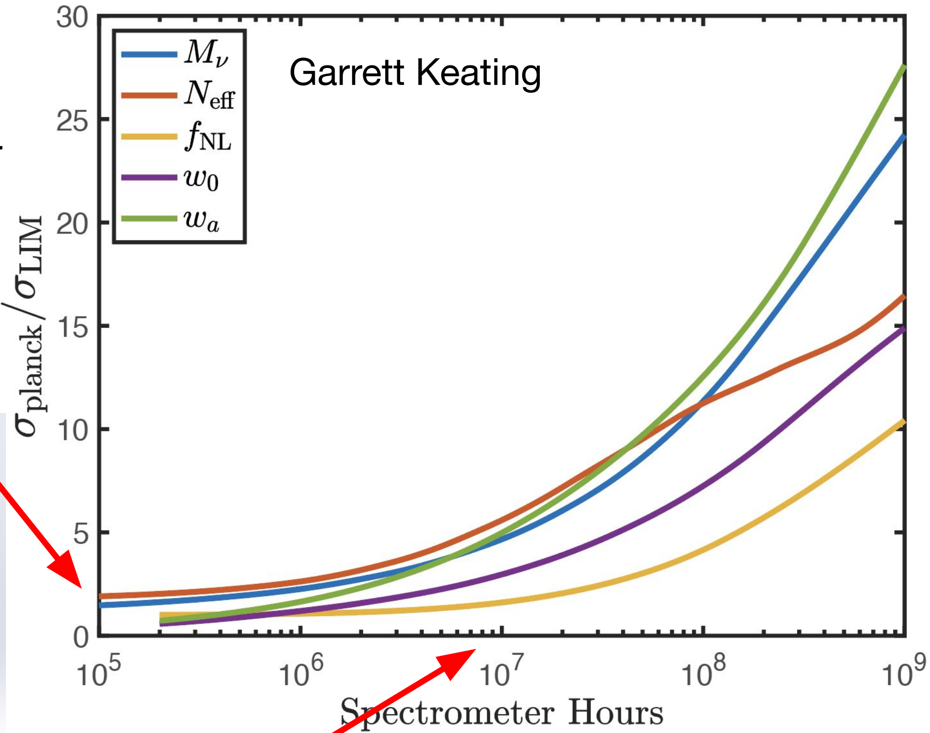
What Do We Need for Cosmology?

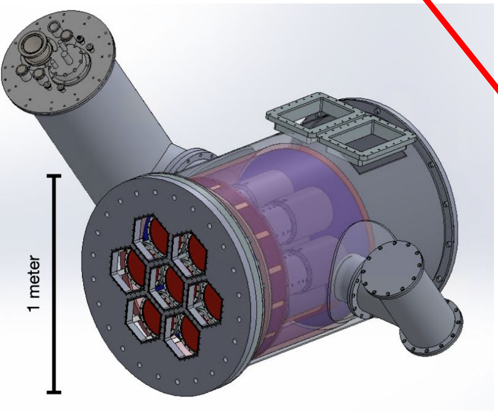
SPT-SLIM
pathfinder
2025



What Do We Need for Cosmology?

SPT-SLIM
pathfinder
2025

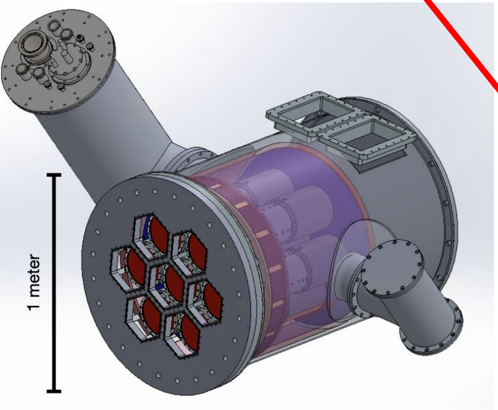


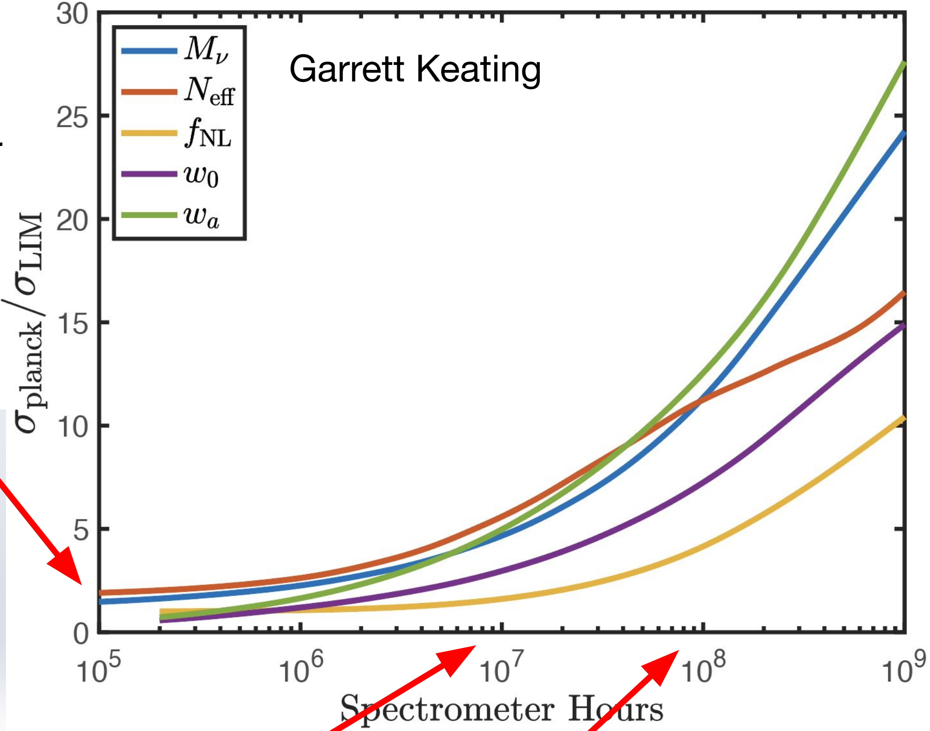


SPT-3G+
2029 (1 tube)

What Do We Need for Cosmology?

SPT-SLIM
pathfinder
2025

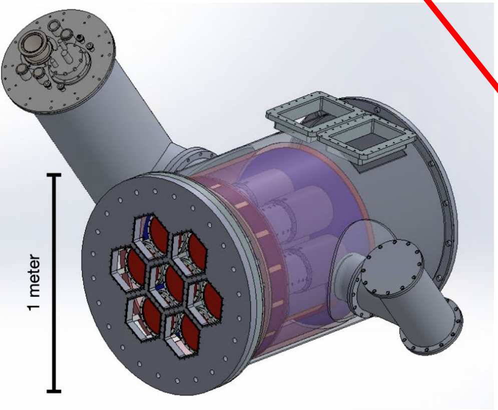


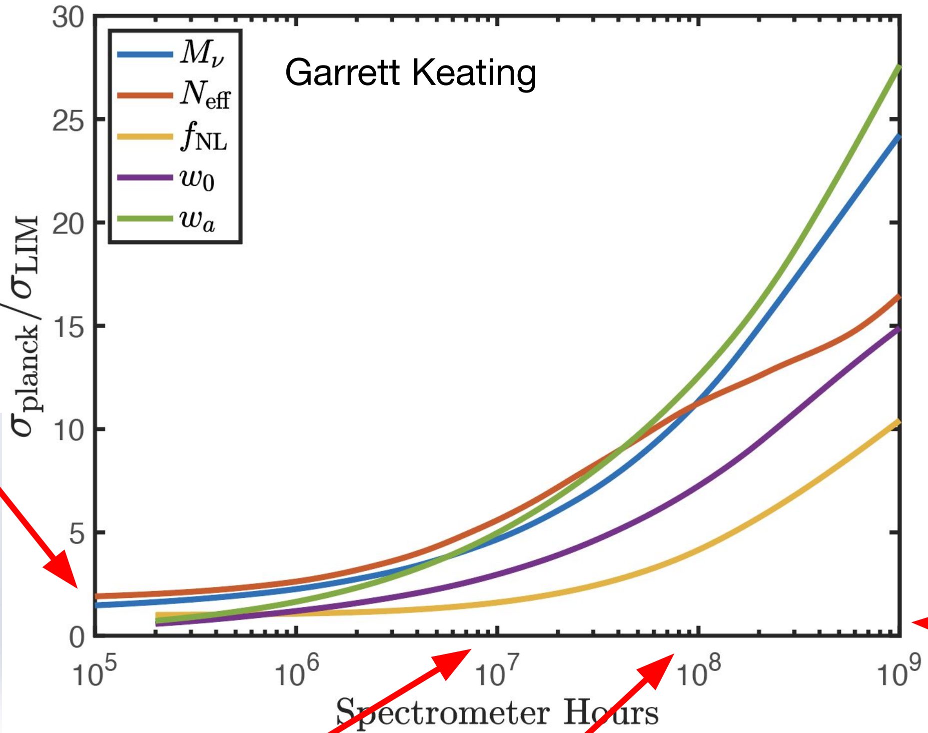


SPT-3G+
2029 (1 tube), **2034** (7 tubes)

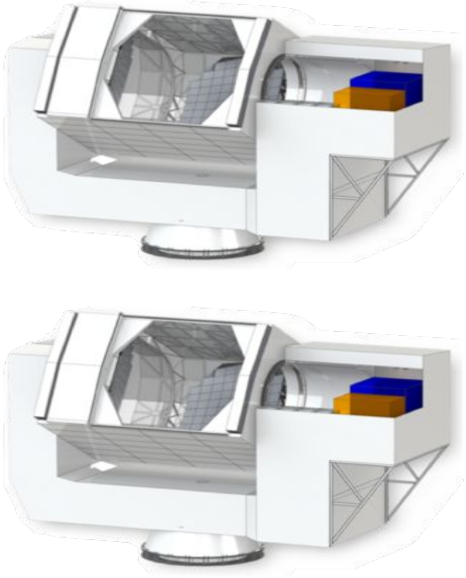
What Do We Need for Cosmology?

SPT-SLIM pathfinder
2025



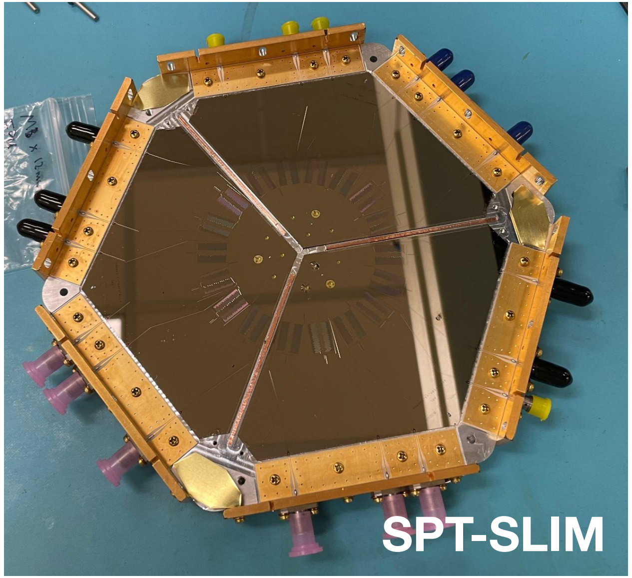


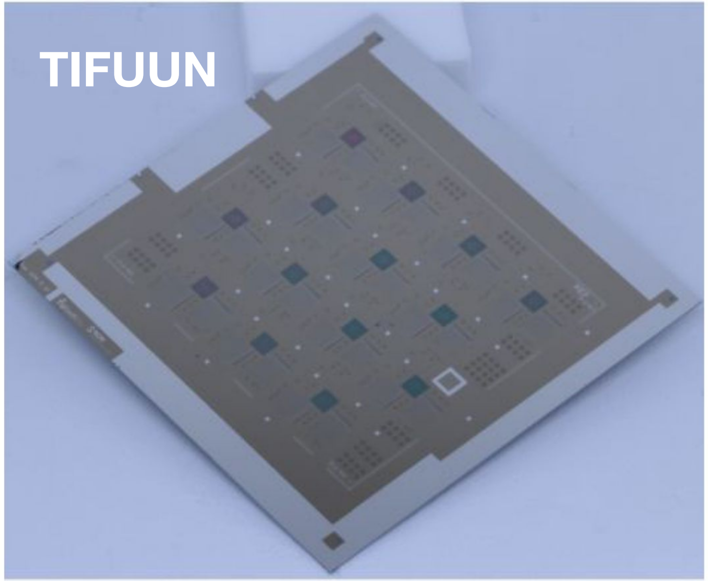
SPT-3G+
2029 (1 tube), **2034** (7 tubes)



CMB-S4 with spectrometers
2040 (85 tubes)

Multi-Pixel Spectrometers



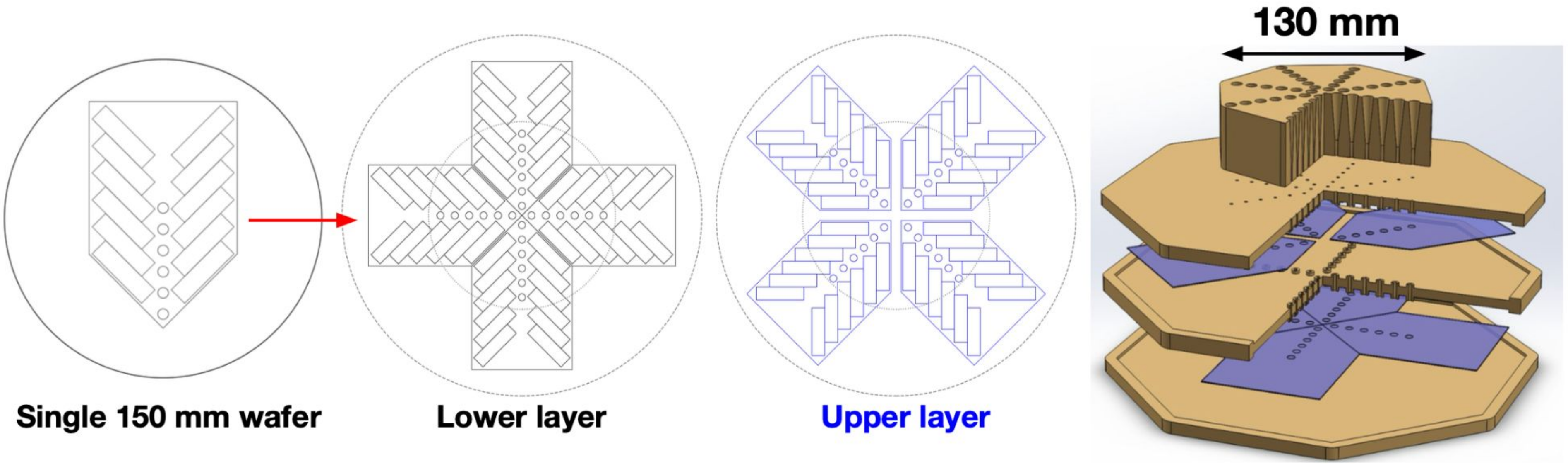


14-spaxel x 2-pol
IFU demonstrator
(K. Karatsu et al.)

In principle, it is straightforward to print multiple pixels on a wafer and assemble several wafers into a large-format focal plane.

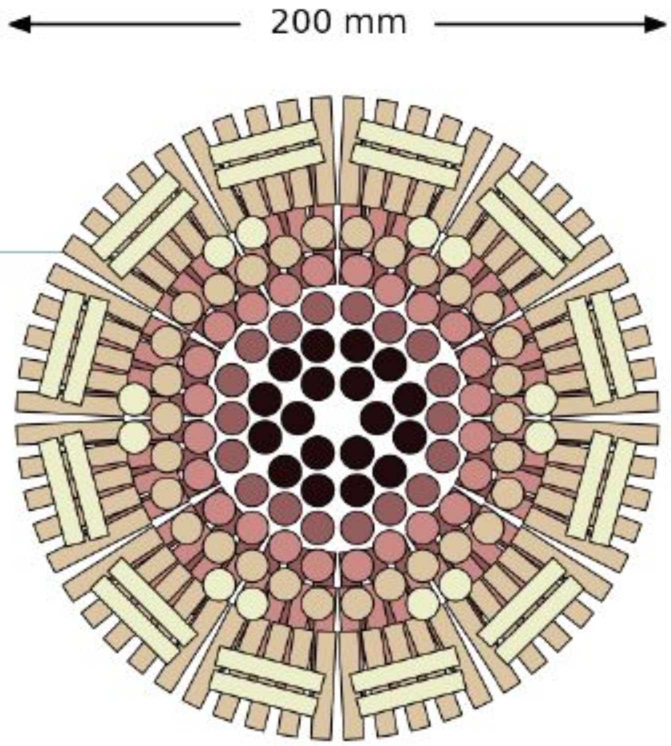
Cheng Zhang

An “Easy” Approach

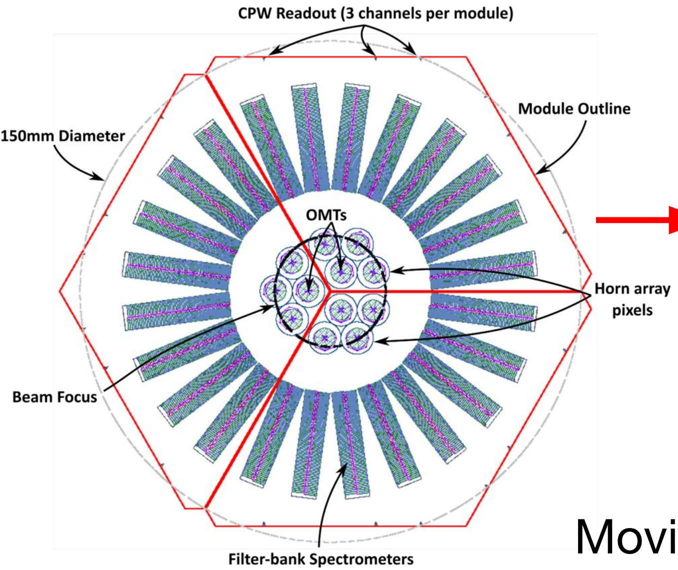


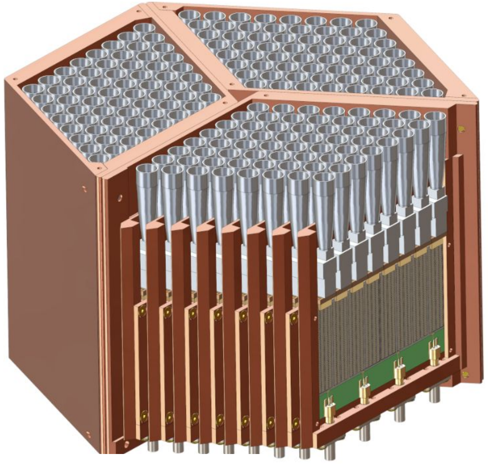
Cheng Zhang

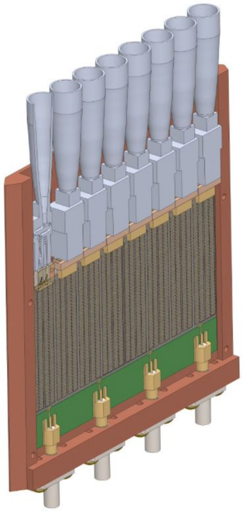
Slightly more complicated…



The Harder Approach







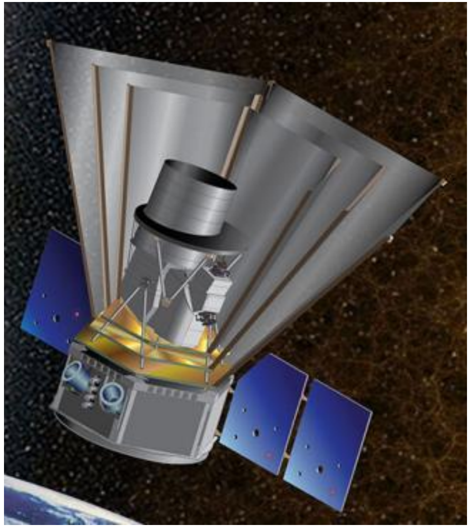
Moving detectors *off the focal plane* is the most elegant way to hit our sensitivity target with a reasonable number of receivers.

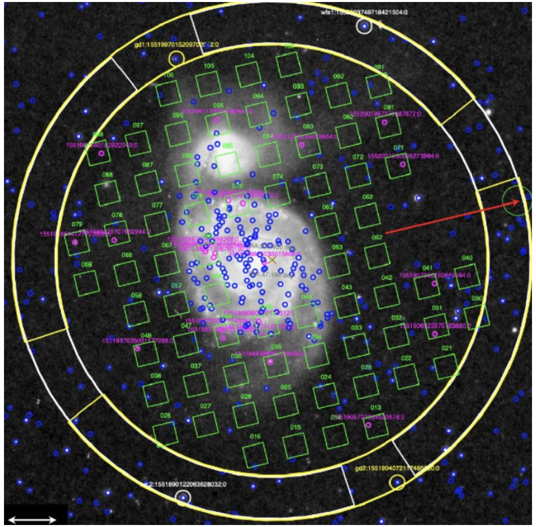
Jessica Zebrowski, Austin Stover

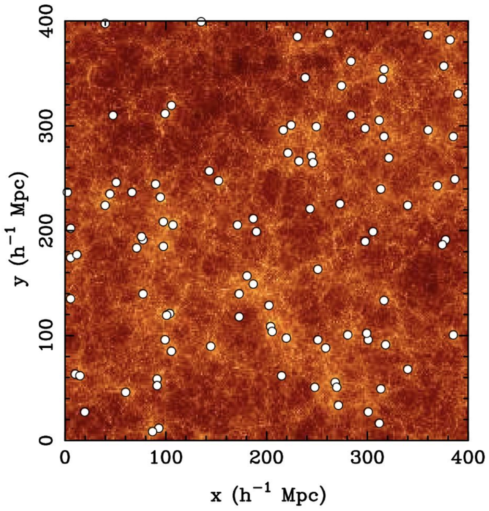
Optical/NIR: A Much Broader Landscape

On Wednesday we heard from SPHEREx and HETDEX, and there have been Lyα LIM results from from quasar sight lines.

Note that these are *not* dedicated LIM experiments!







Croft+ 1806.06050

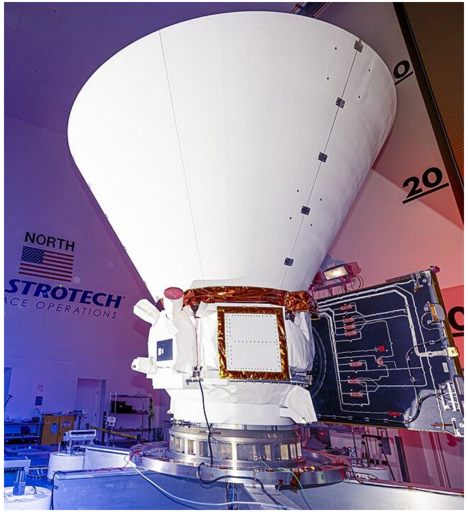
SPHEREx: Linear Variable Filter

One direction of the filter corresponds to wavelength, so the telescope must be scanned to build up a full spectral image.

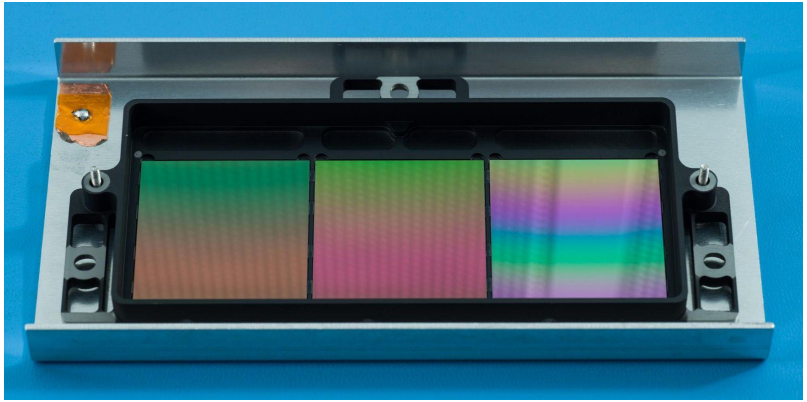
R ~ 35-120, varying from 0.5-5 um.

Life is very different in OIR: detectors are effectively off-the-shelf components!

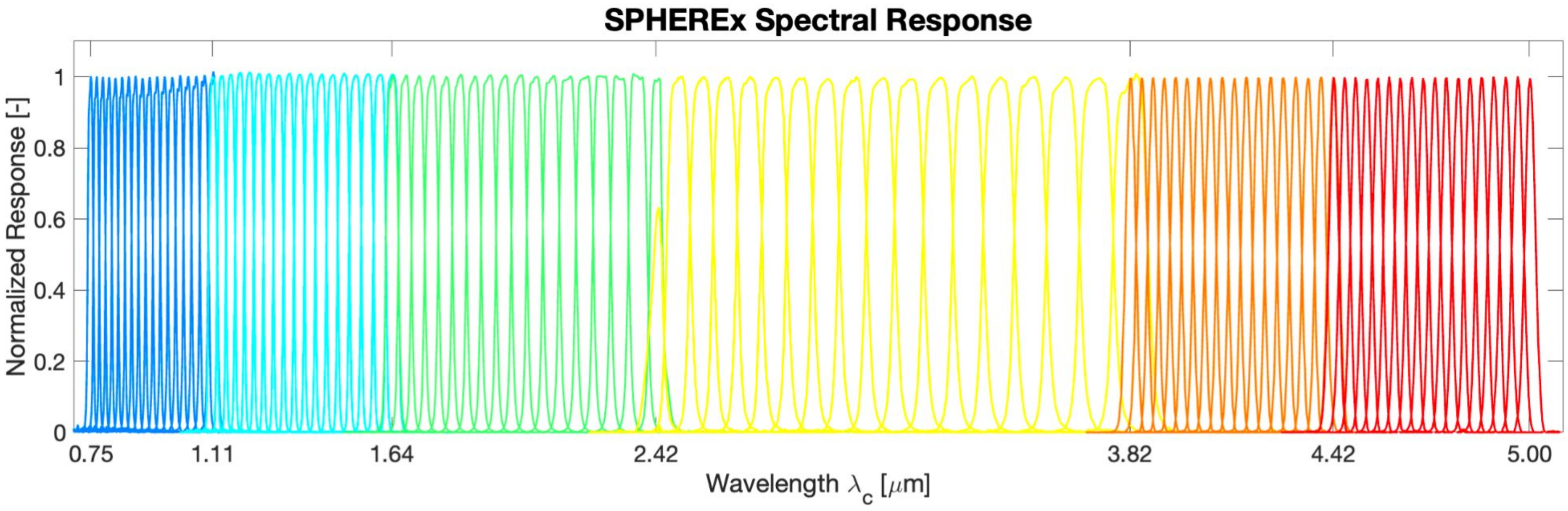
(However, still need to characterize PSF, sidelobes, etc.)



NASA



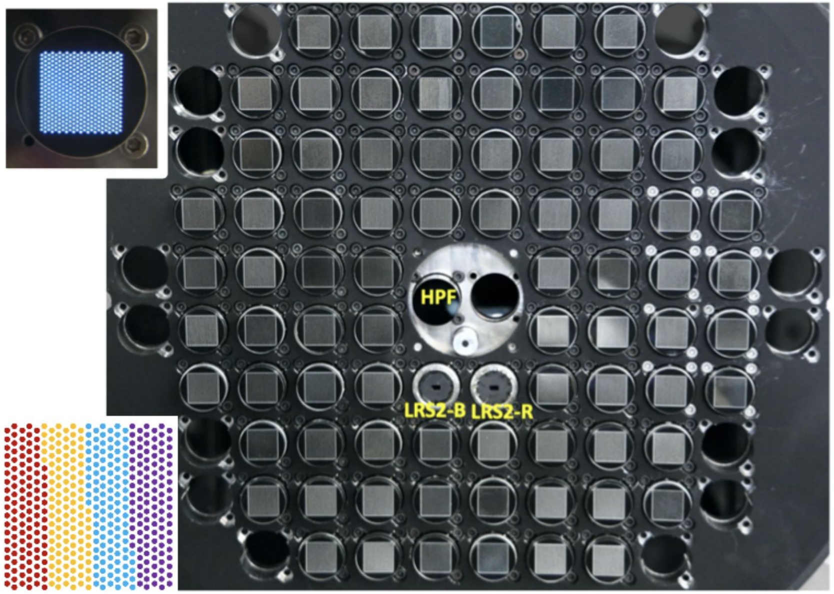
SPHEREx: Linear Variable Filter



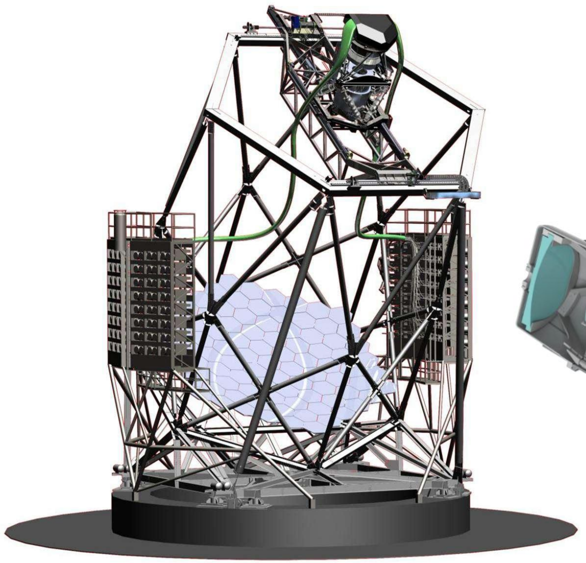
Hui+ 2024

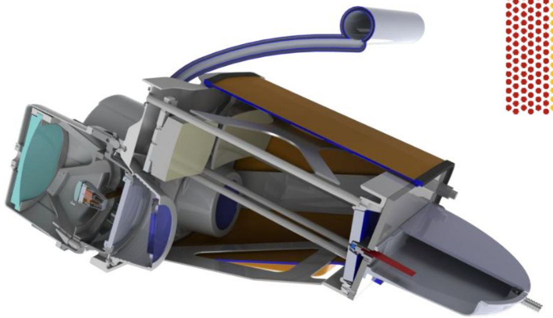
Hill+ 2021

HETDEX: “Blind” IFU Survey



156 identical optical spectrographs,
fed by 35,000 fibers in 78 IFUs.





Fill-factor of ⅓, requires dithering

350-500 nm, R~800

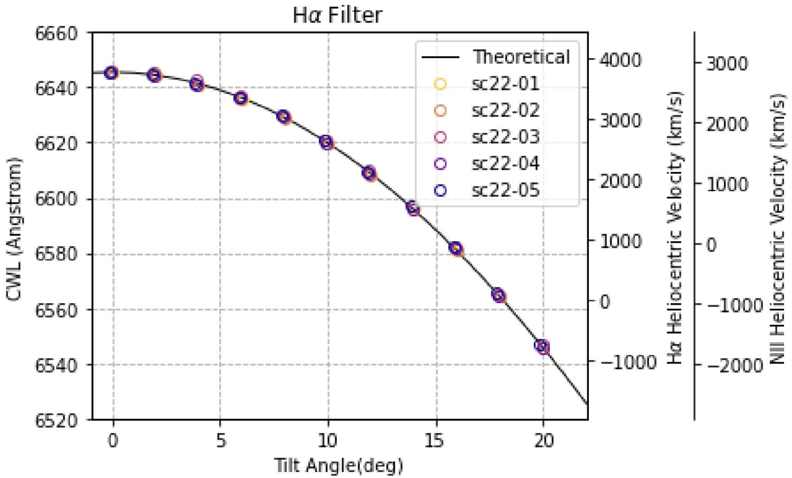
Dragonfly

Telephoto lenses and relatively small individual apertures (equivalent to 1 m, f/0.4). “Low” spatial resolution of 6”

Optimized for low surface brightness observations: ultra-diffuse galaxies on large angular scales

Control of scattered light and improved anti-reflection coatings

Spectral line capability added recently. Tilting narrowband filters shifts the central wavelength.



Chen+ 2022

Future Optical LIM

Optical LIM has not been the *primary* observing mode of any experiment.

Is there a case for one?

What would a dedicated experiment look like?

- What lines/wavelengths would be targeted?
- Does it need to be in space?
- What resolution/bandwidth?
- Could fast scan modulation help with varying sky conditions? What about detectors with high time and moderate energy resolution?

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).

Conclusions

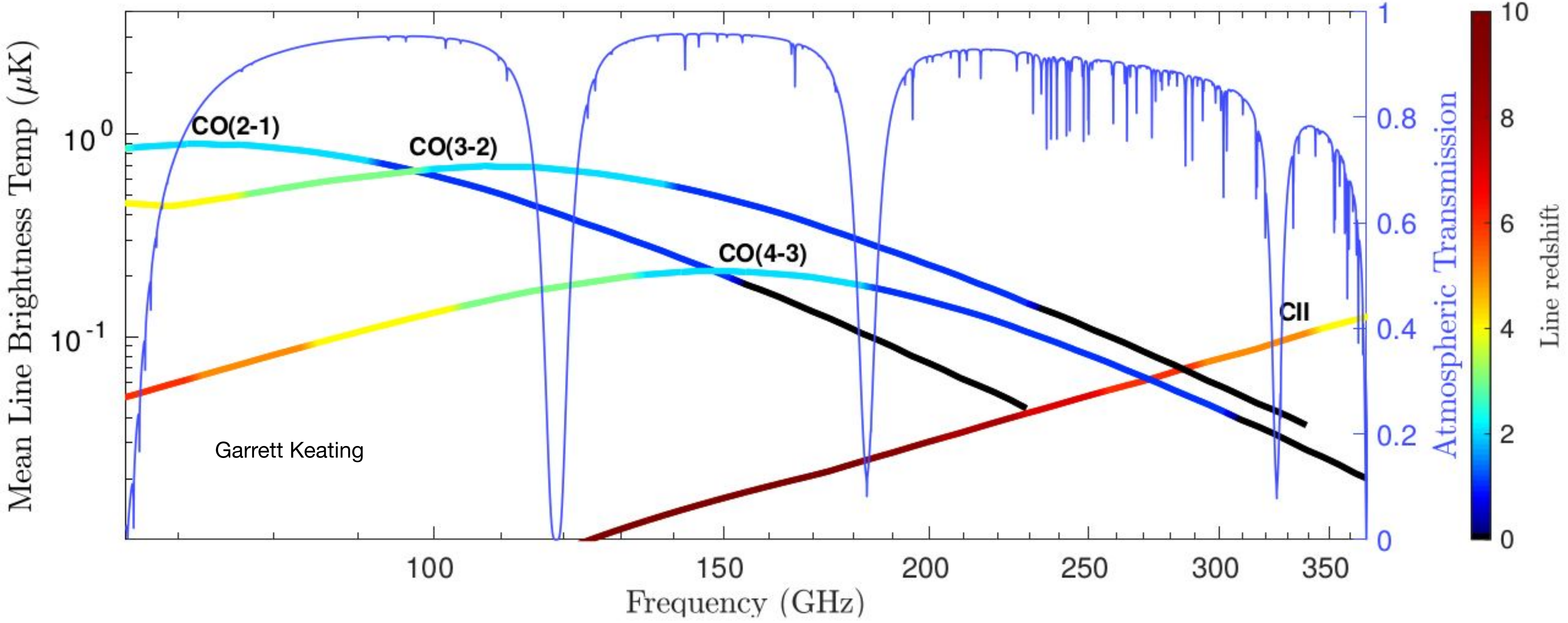
The technology we use is deeply intertwined with the science we want to do.

- I would encourage all theorists to touch the instrument (or at least raw data) at least once :)

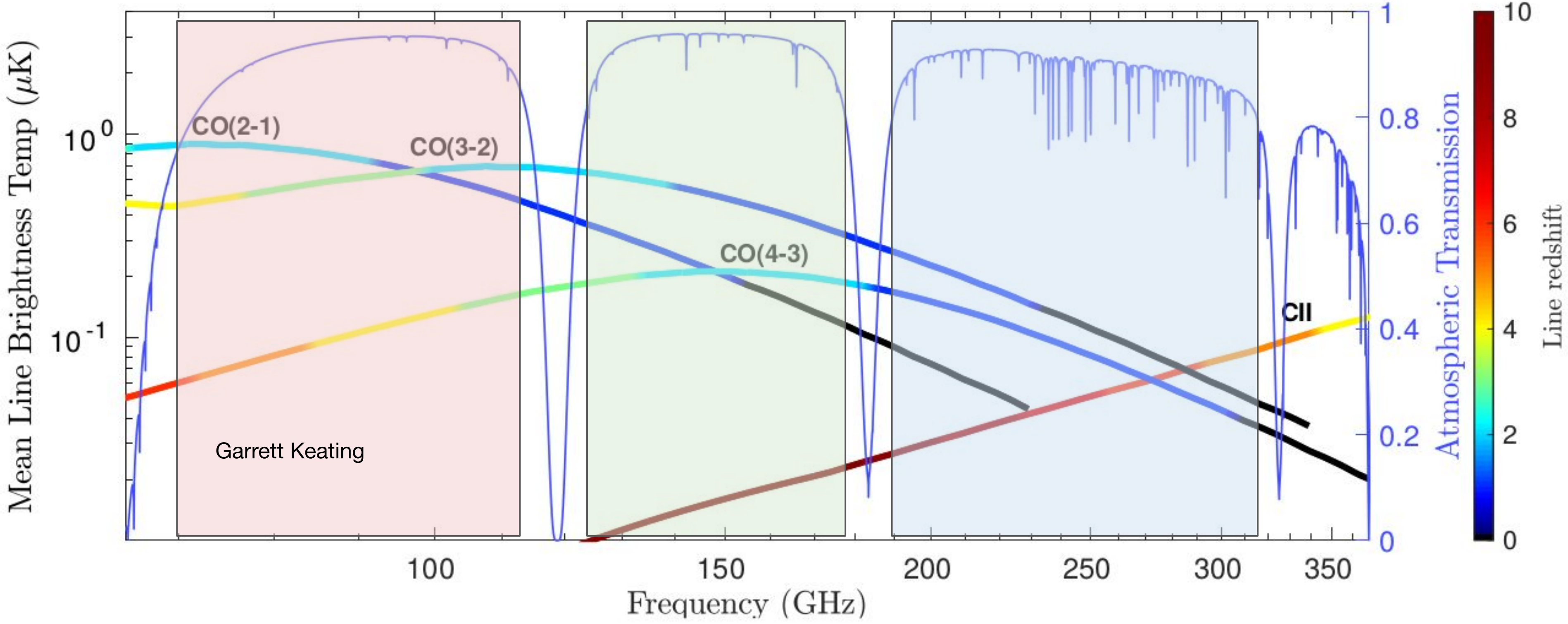
While instruments should be built with systematics control in mind, in practice it is difficult to predict which will be important or limit the measurement. But, several common themes emerge:

- Building an instrument that is **inherently stable** (temporally, spatially, spectrally) is critical! Calibration is important but it can't compensate for everything.
- It's common to need to iterate, often over many years, to improve the technology to the point where it can deliver science. *No substitute for being in the field*.
- We are starting to need **dedicated platforms** to enable multi-year surveys and tinkering/upgrades on a regular basis.
- On a practical level, many projects are taking advantage of improvements in signal processing (driven by commercial communications applications). Pay attention to new tech!

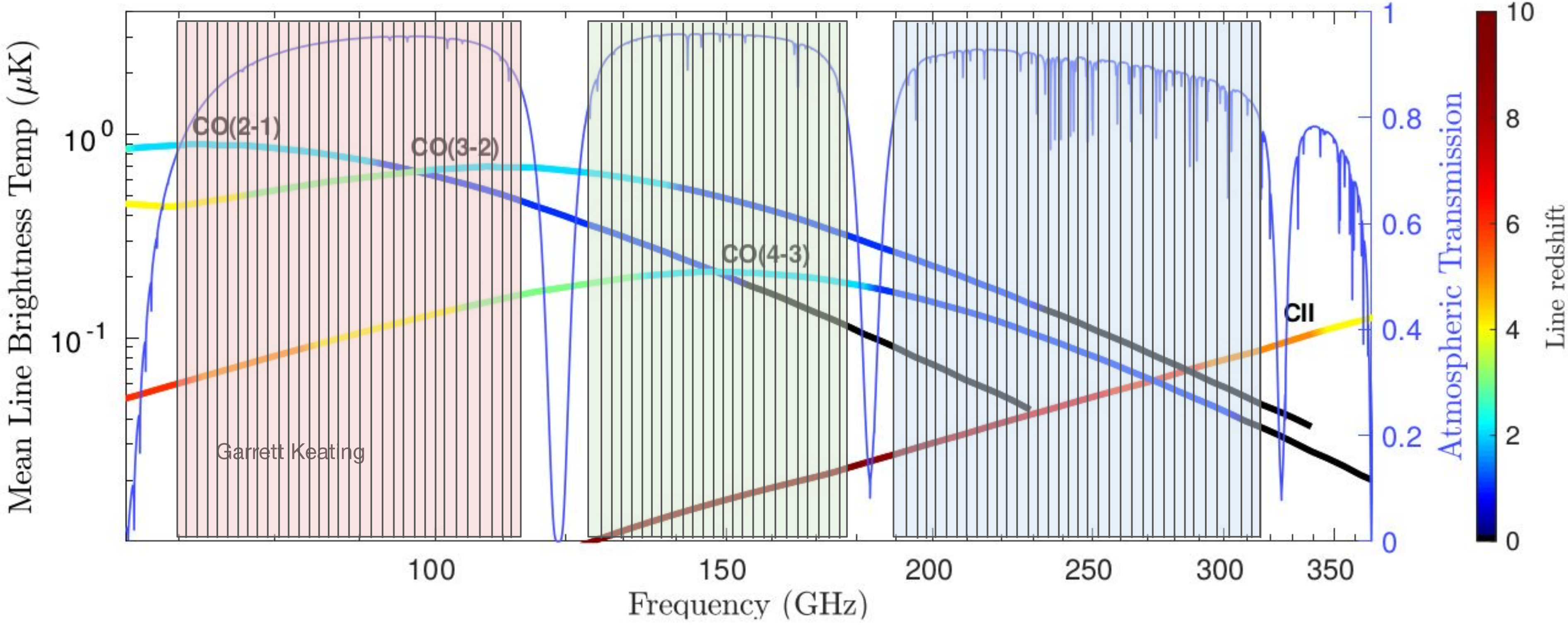
Wide Redshift Coverage in the Millimeter Range



Wide Redshift Coverage in the Millimeter Range

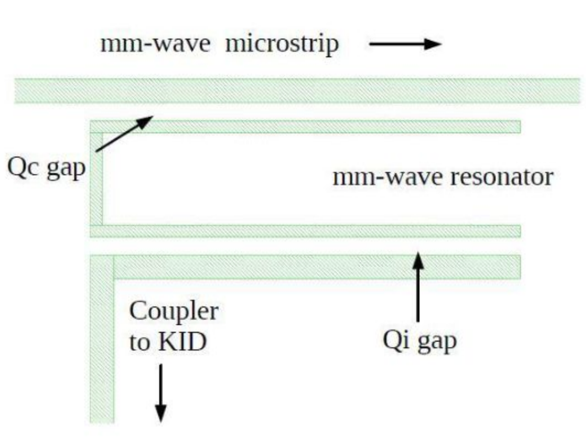


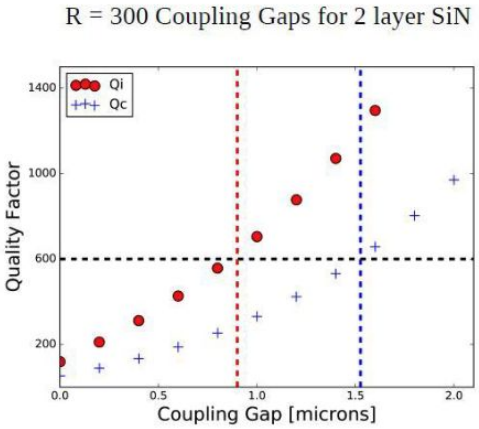
Wide Redshift Coverage in the Millimeter Range



Designing the Filter Bank

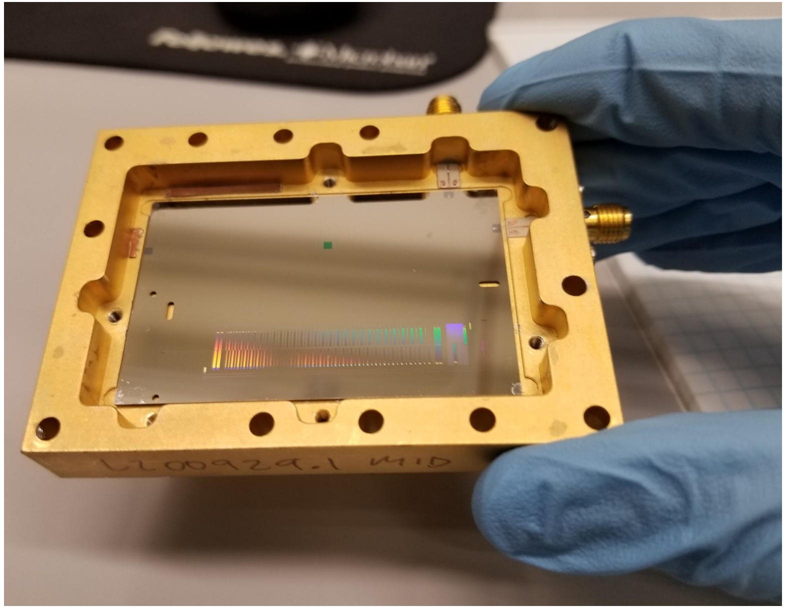
Requirements	Degrees of Freedom
● KID must absorb photons at the right frequency, remain a high-Q resonator ● Noise/responsivity ● Spectral resolution	● KID material (superconducting gap, resistivity, quasiparticle lifetime) ● Detector geometry ● Coupling to feedline



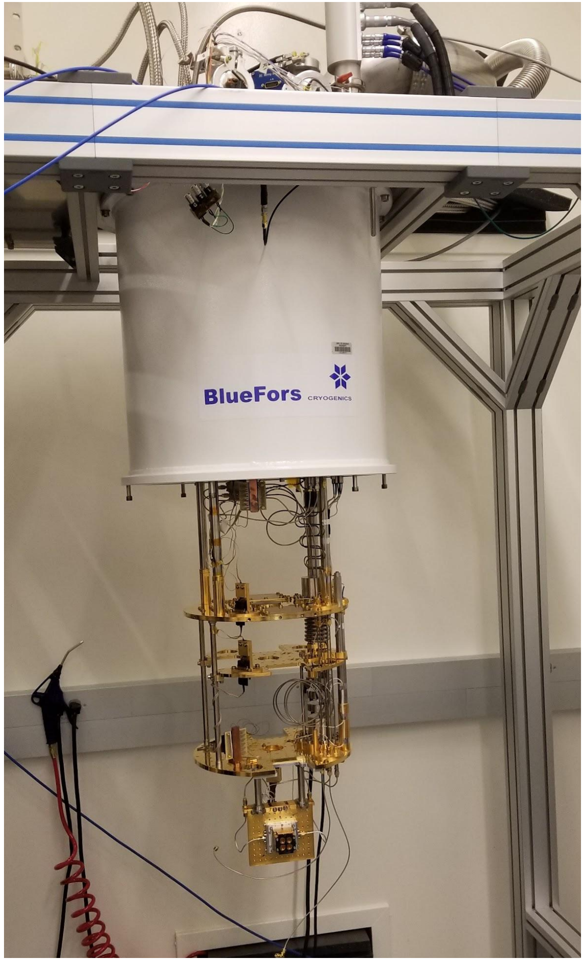


Ryan McGeehan,
UChicago Ph.D. 2023
Spectrometer design

Device Characterization

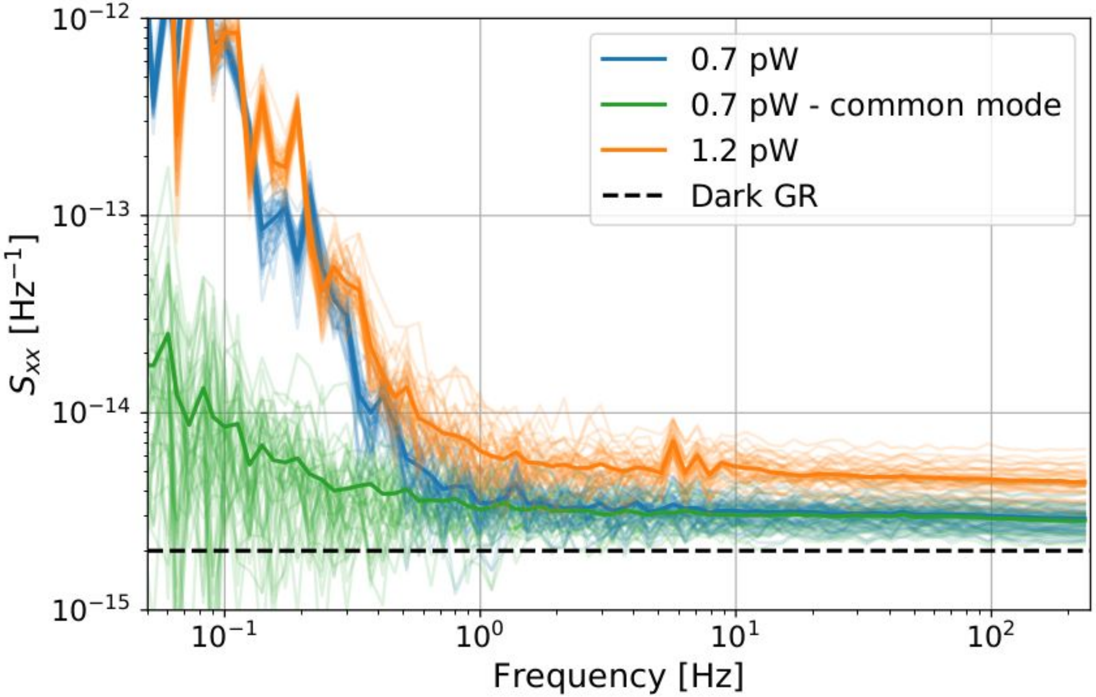


Test devices in a helium dilution refrigerator
(~100 mK required for optimal operation)

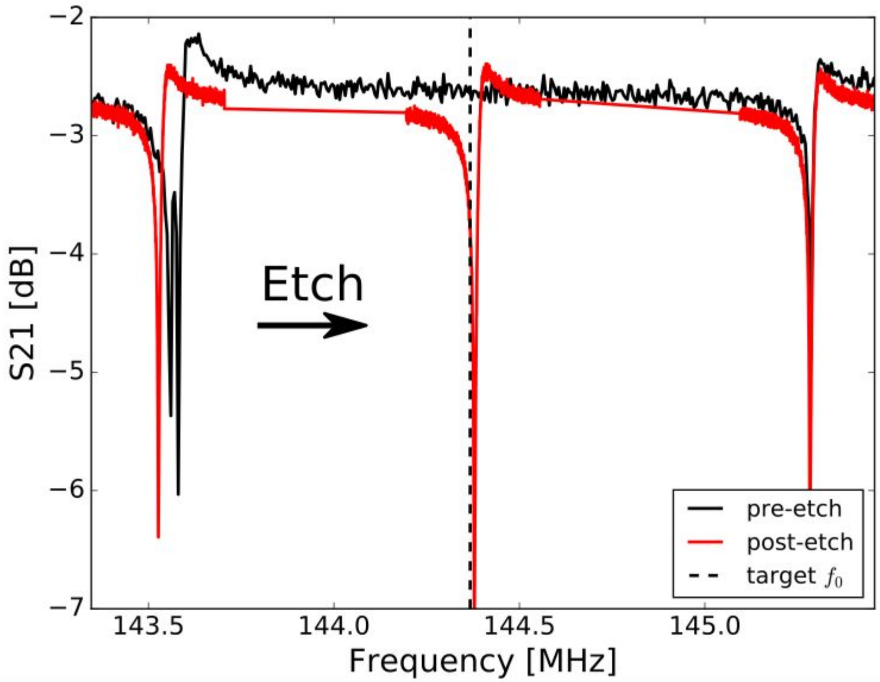


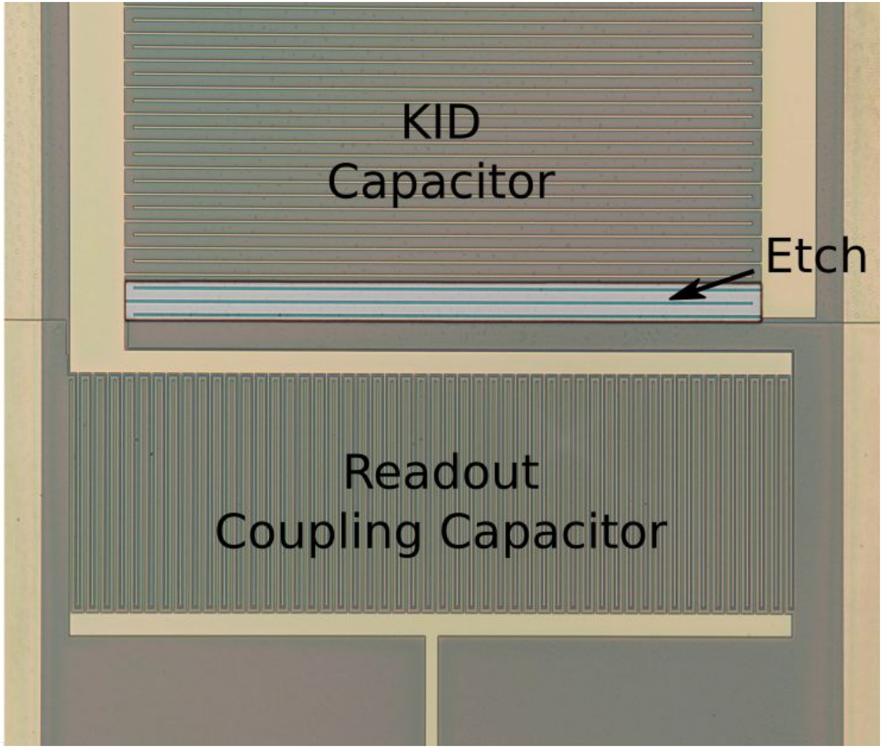
The Spectrometer Works!

Karkare+ J. Low Temp. Phys.
2002.04542

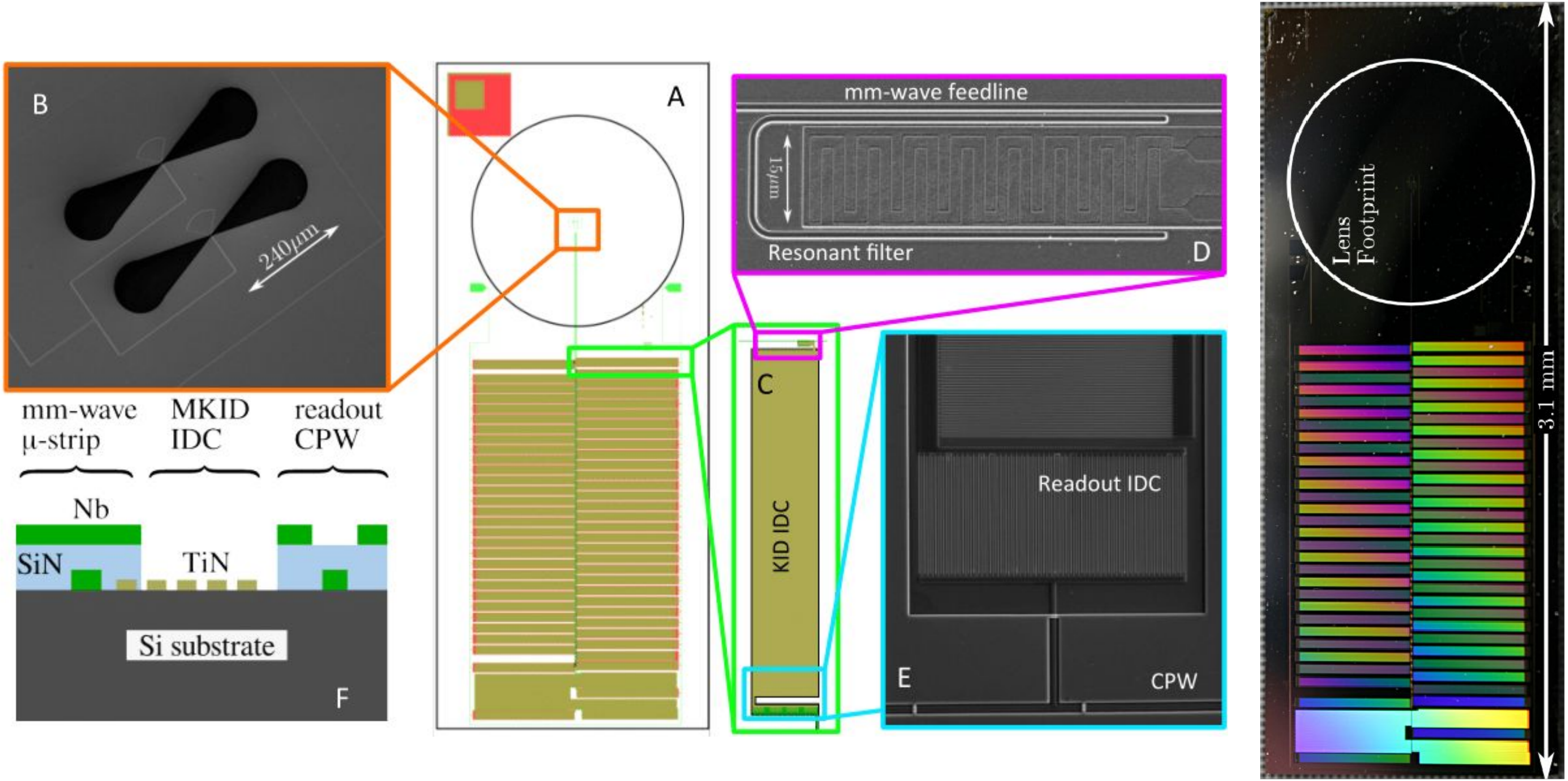


Noise levels are low enough for observations at ground-based observatories (i.e., *photon noise dominated)*.





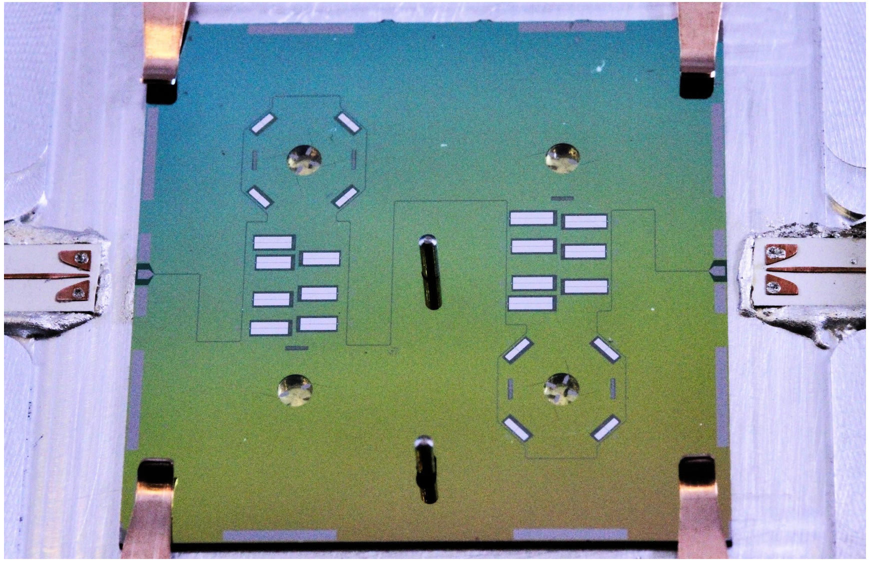
McGeehan et al. 2018



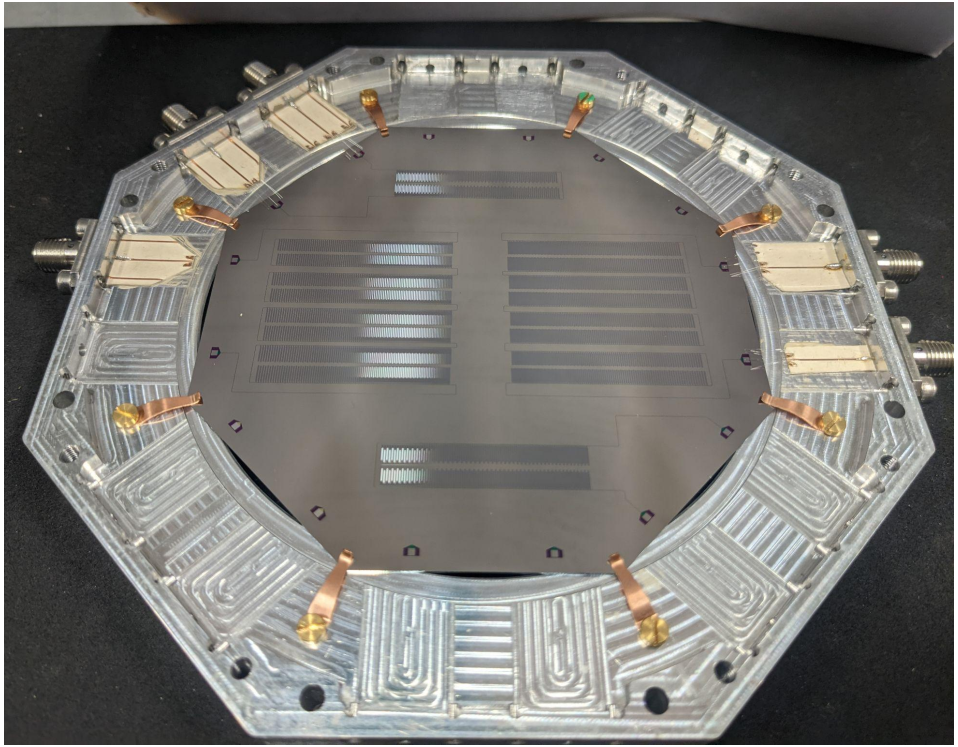
Karkare+ 2020

Detector Development

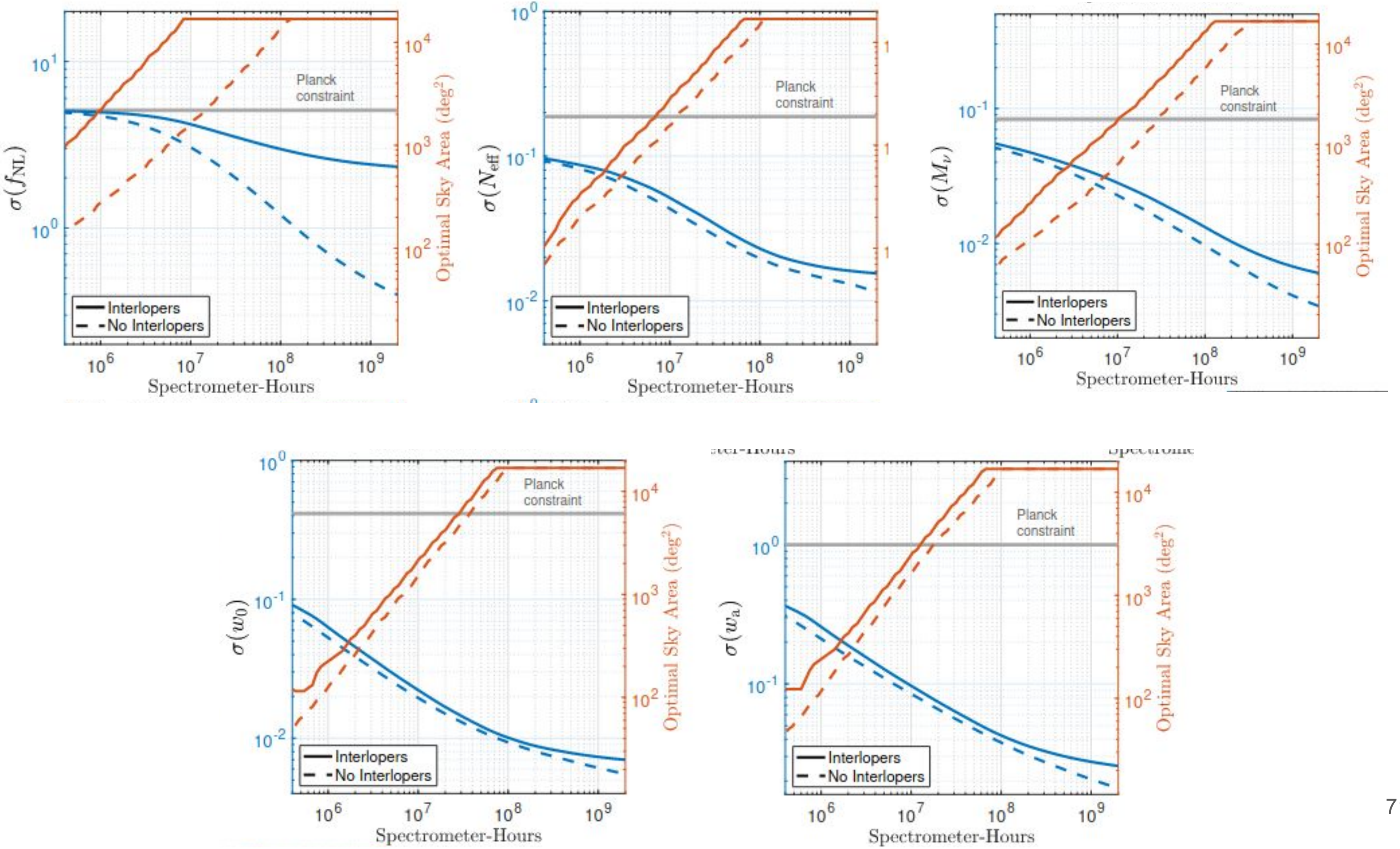
Elyssa Brooks



Orthomode transducer-coupled spectrometer test chip



Multiplexing test chip: 800 kinetic inductance detectors on a readout line



$\sigma(f_{\rm NL})$
$\sigma(N_{\rm eff})$
$\sigma(M_\nu)$
$\sigma(w_0)$
$\sigma(w_{\rm a})$
Optimal Sky Area (deg^2)
Spectrometer-Hours
Planck constraint
Interlopers
No Interlopers