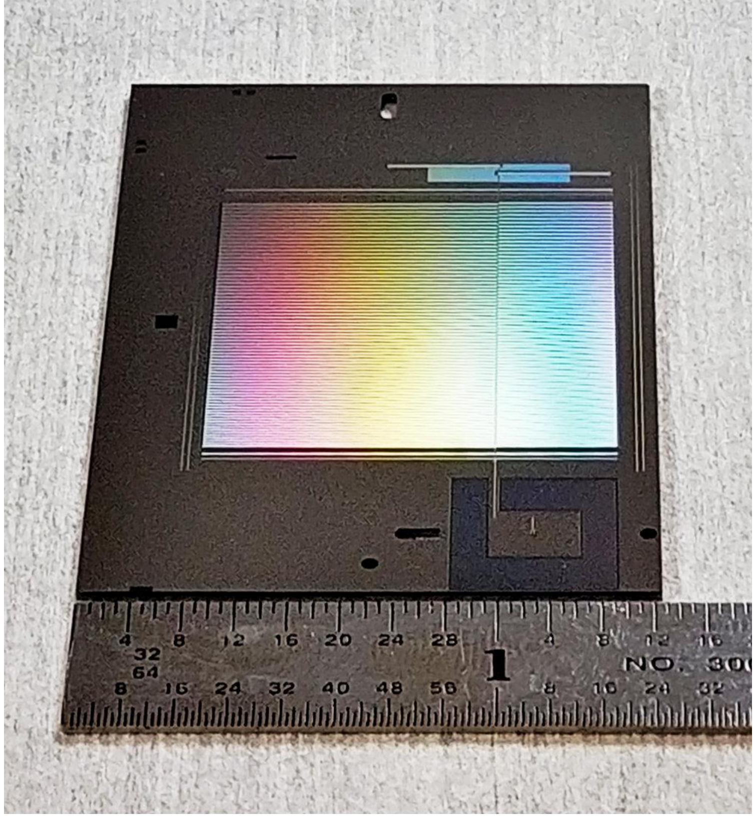
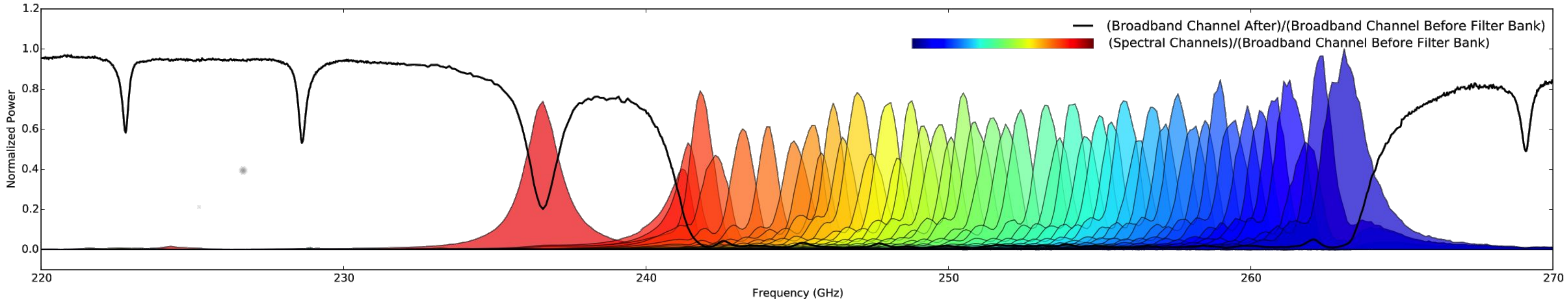
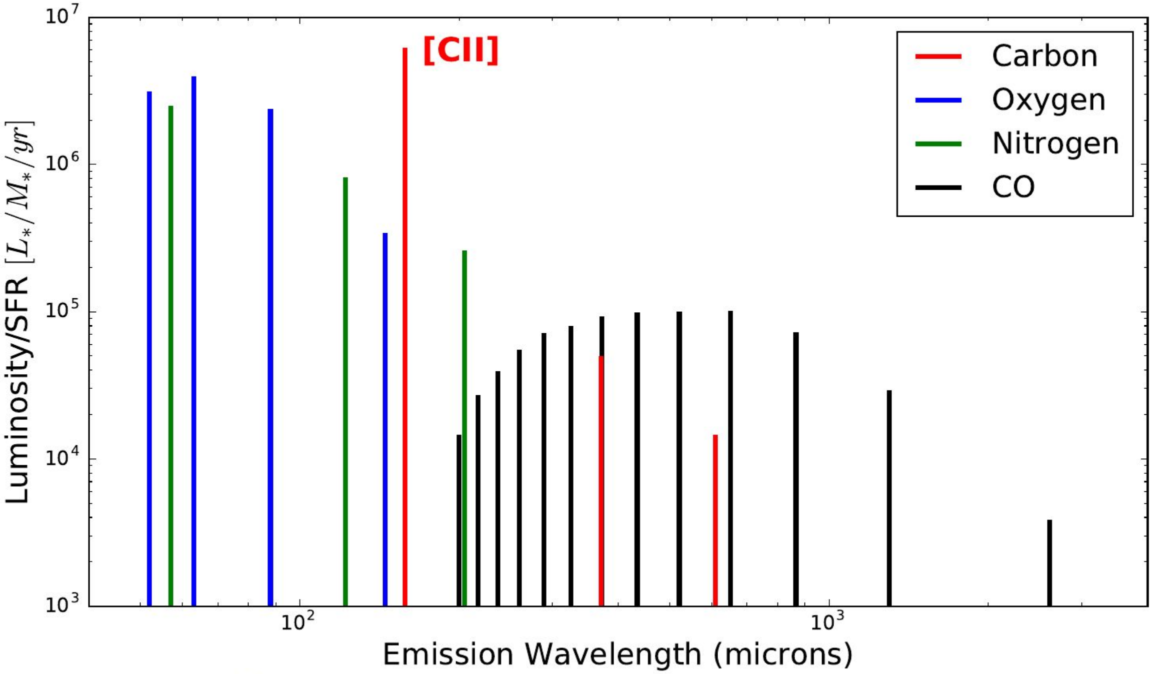
Next-Gen mm-wave Intensity Mapping with On-Chip Spectroscopy



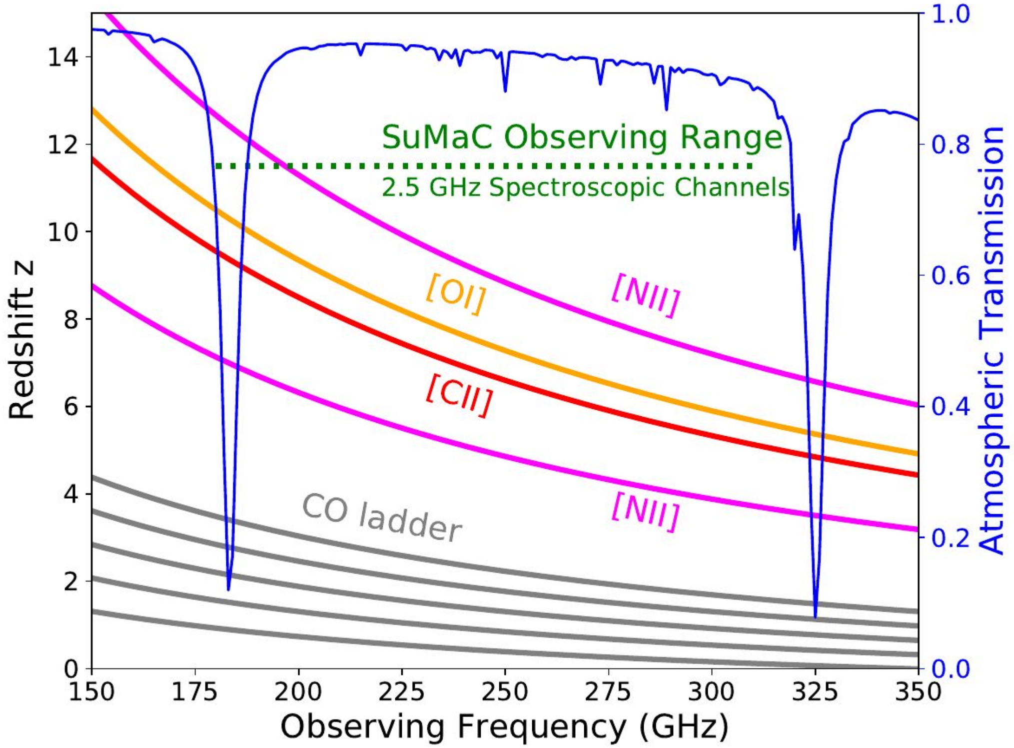


Kirit Karkare
Grainger/KICP Fellow, University of Chicago
CCA Intensity Mapping Workshop, 2019-02-21

Potential targets for mm-wave line intensity mapping



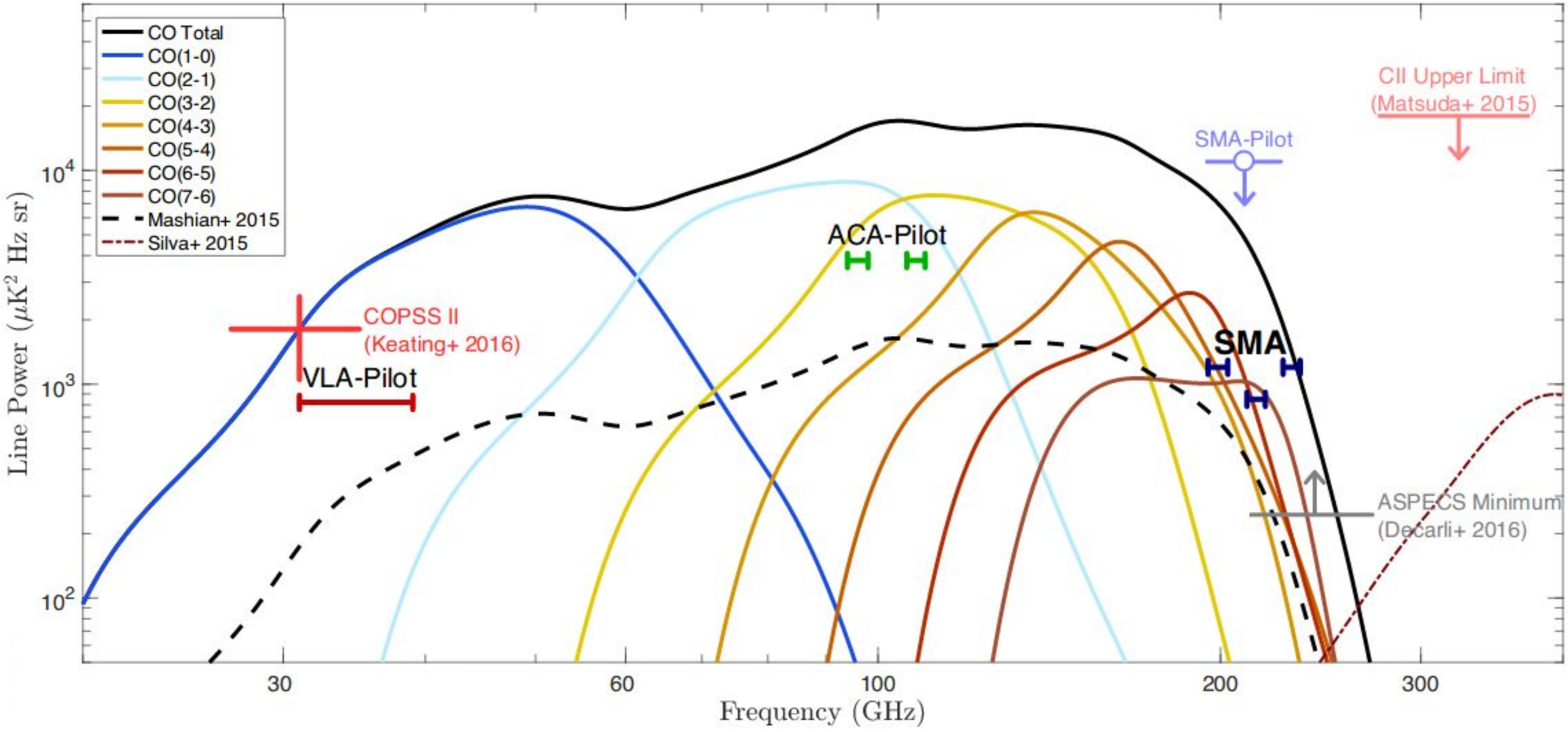
FIR line luminosities (nearby galaxies) adapted from Visbal and Loeb 2010



The 200-300 GHz atmospheric window enables access to multiple lines at a number of redshifts

Current Technology: Coherent/Interferometric

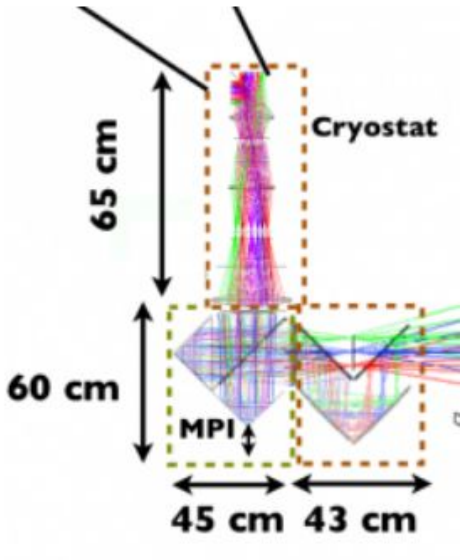
VLA, ALMA, SMA, etc...e.g. mmIME, ASPECS



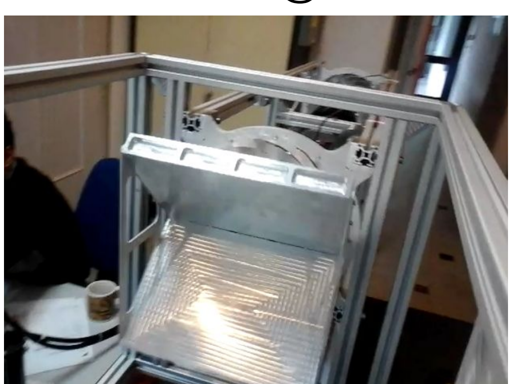
Karto Keating

Current Technology: Bolometers Behind Something

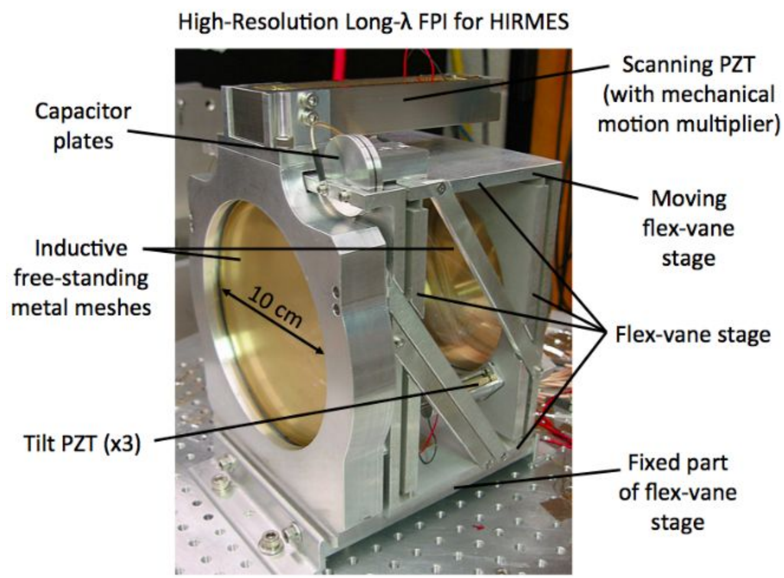
Fourier Transform Spectrometer (CONCERTO) neel.cnrs.fr

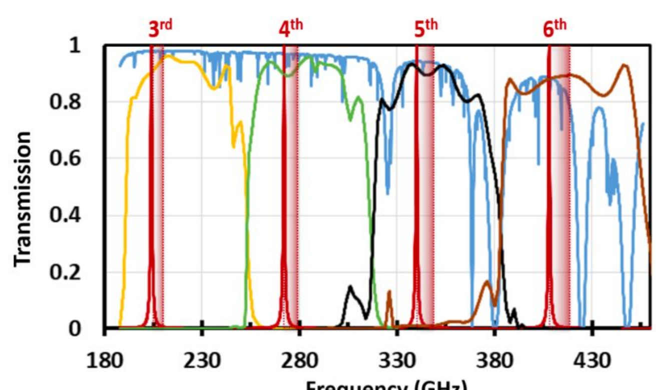


Mirror moves @ 5 Hz

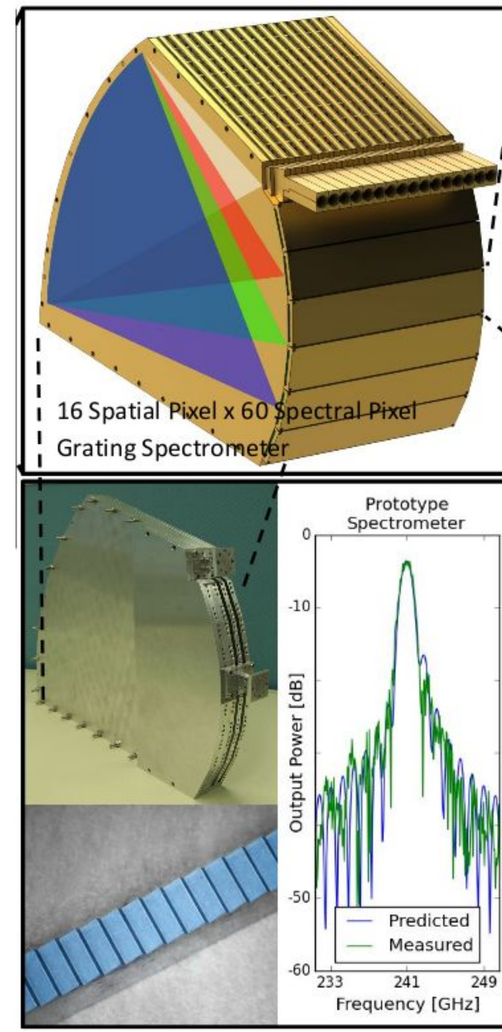


Fabry-Perot (CCAT-p) 1807.00058

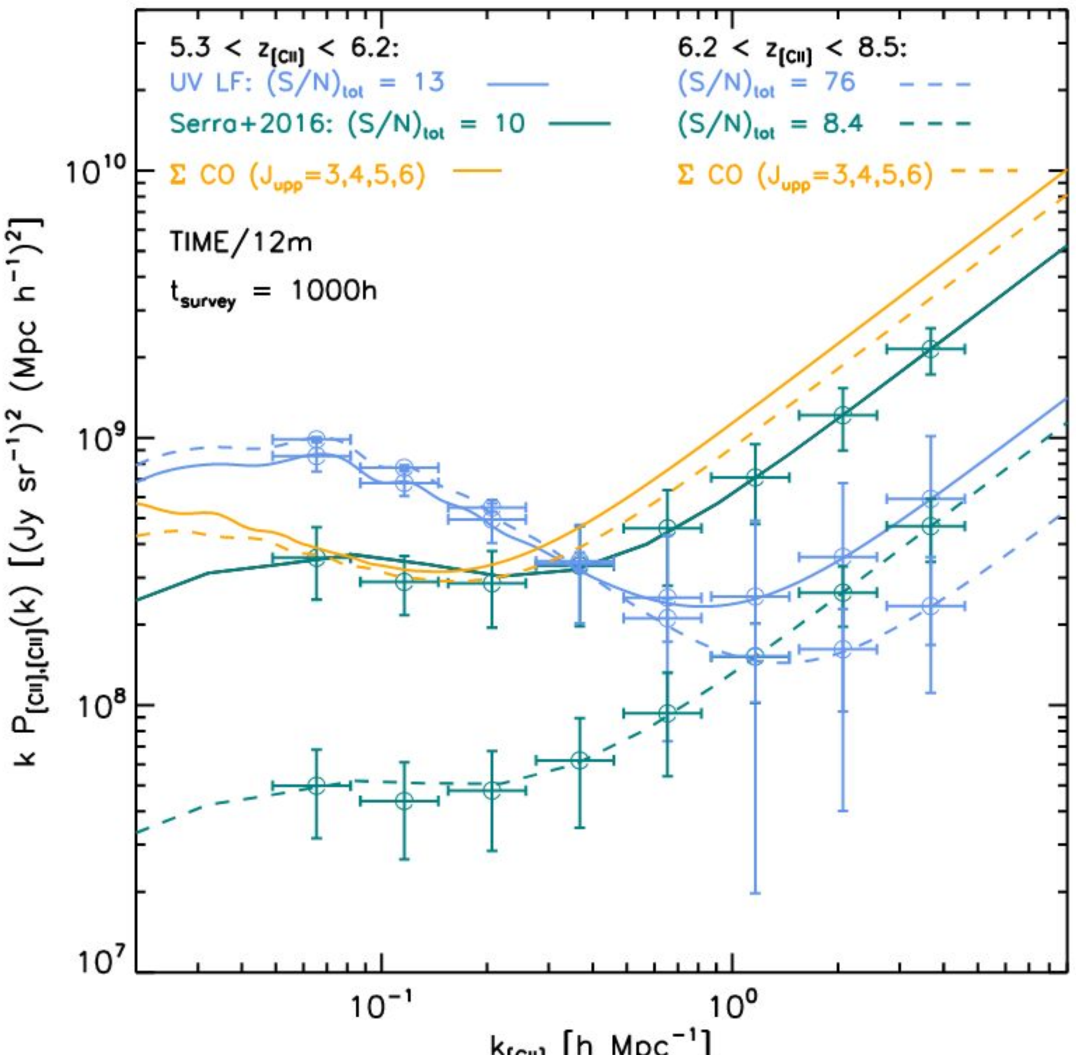




Grating Spectrometer (TIME) Abby Crites



TIME Sensitivity



32x R~100 spectrometers
183-326 GHz

300 nights at APA

Abby Crites

...but we need more!

Lidz & Taylor 2016 (interloper lines):

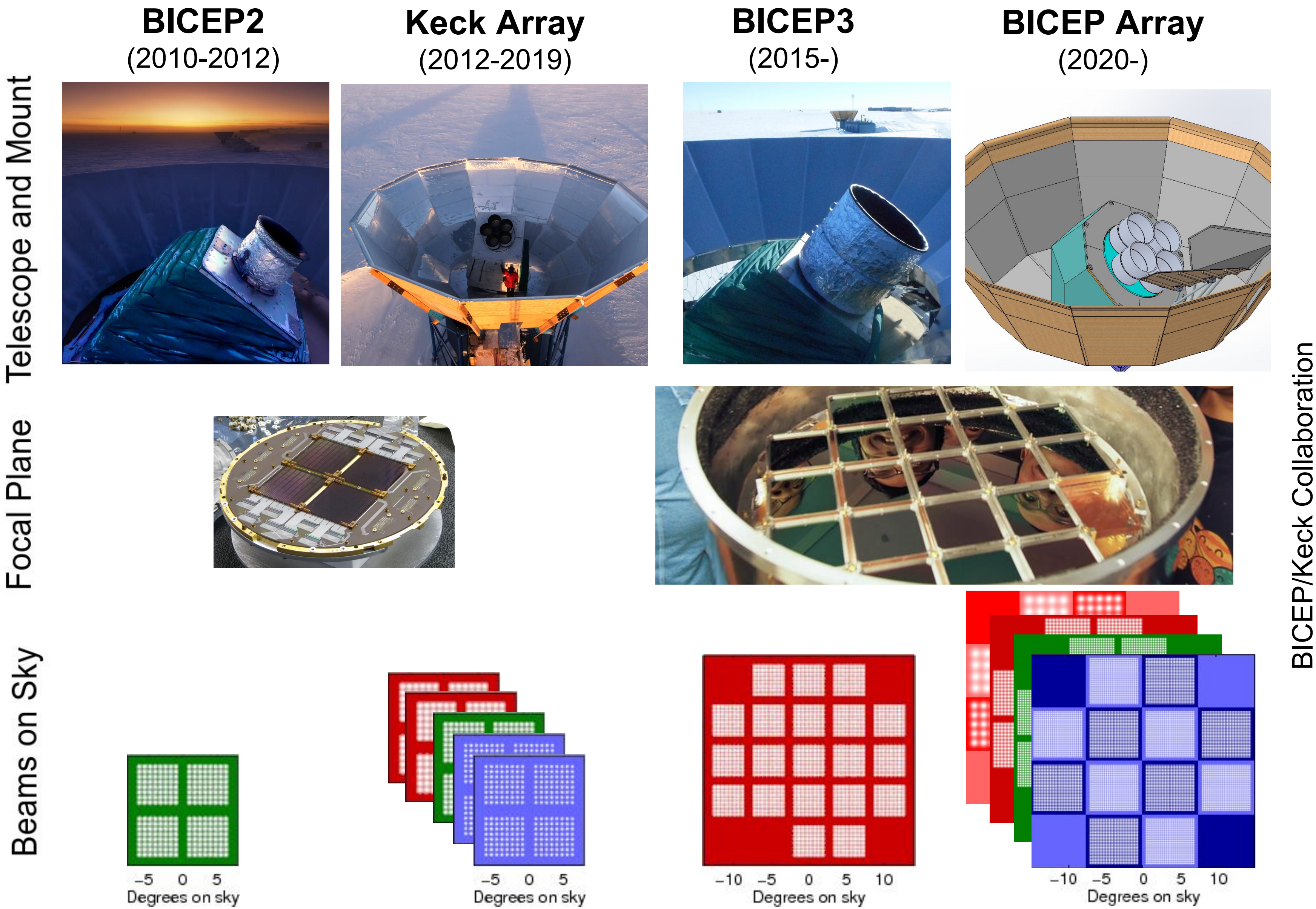
“Since we find that even this sensitivity is insufficient for our purposes, we consider a still more sensitive experiment with (σ2NVpix)/tobs= 4.3 ×107Jy2str−2(Mpc/h)3.This value represents our fiducial noise level in what follows. We caution that the noise power here is approximately twenty times smaller than in the Stage-II experiment considered by Silva et al. (2015)...Rapid progress in detector development may also help to increase sensitivity beyond what is assumed here, e.g. it may be possible to increase the number of spatial pixels, Nsp.”

A “TIME-like” experiment with 64 spectrometers, 2000 hrs at a good site
(i.e. several times more sensitive than TIME)

Mm-wave detectors are now background-limited, so scaling up detector count is the way to improve sensitivity.

COLD (~100-300 mK) components and multiple receivers will benefit from detector/focal plane/optical simplicity, i.e. no moving parts!

See e.g. CMB



BICEP2
(2010-2012)
Keck Array
(2012-2019)
BICEP3
(2015-)
BICEP Array
(2020-)
Telescope and Mount
Focal Plane
Beams on Sky
BICEP/Keck Collaboration
−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

The SuperSpec Team

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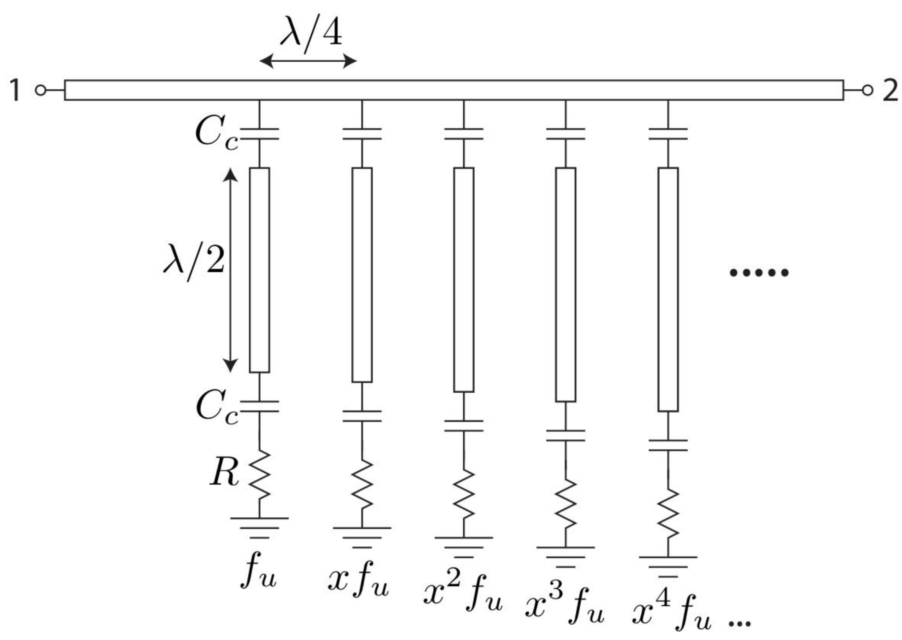
The SuperSpec Concept

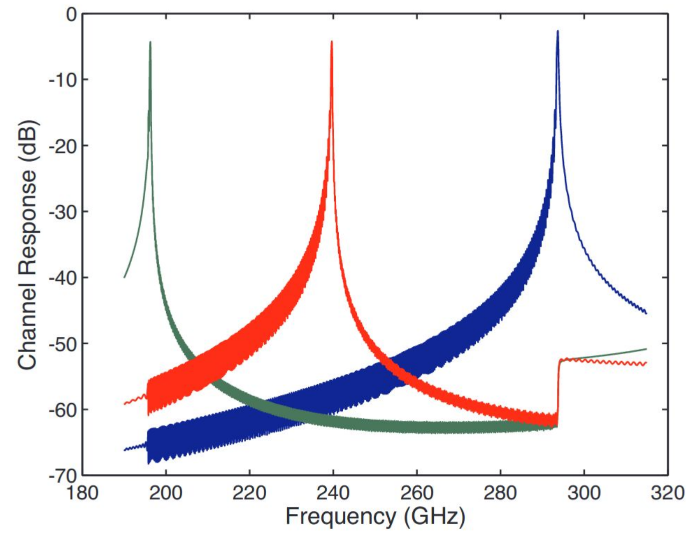
A general filter-bank (cochlear) spectrometer

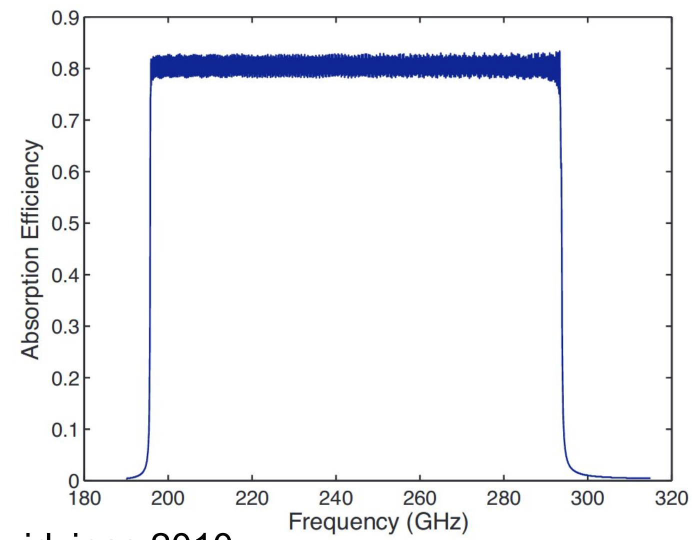
Incoming radiation sorted by narrowband filters

Each channel couples to a power detector

Channel width/spacing independently adjustable



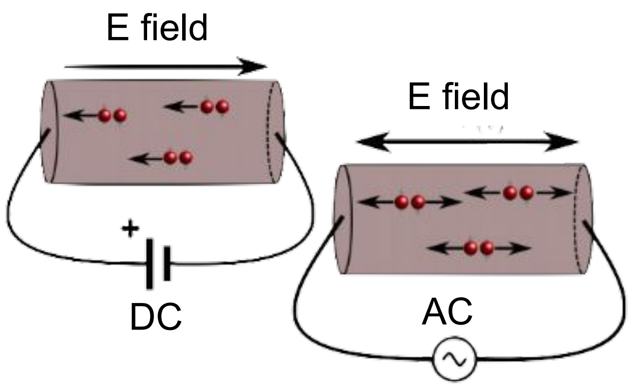




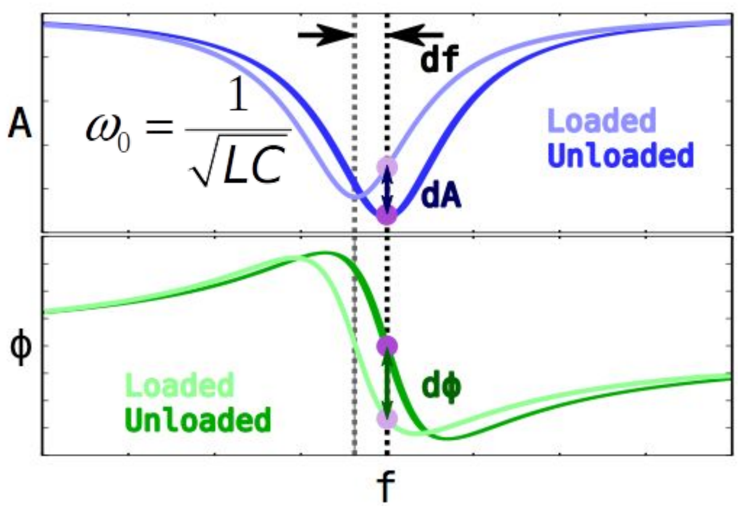
Kovacs and Zmuidzinas 2010

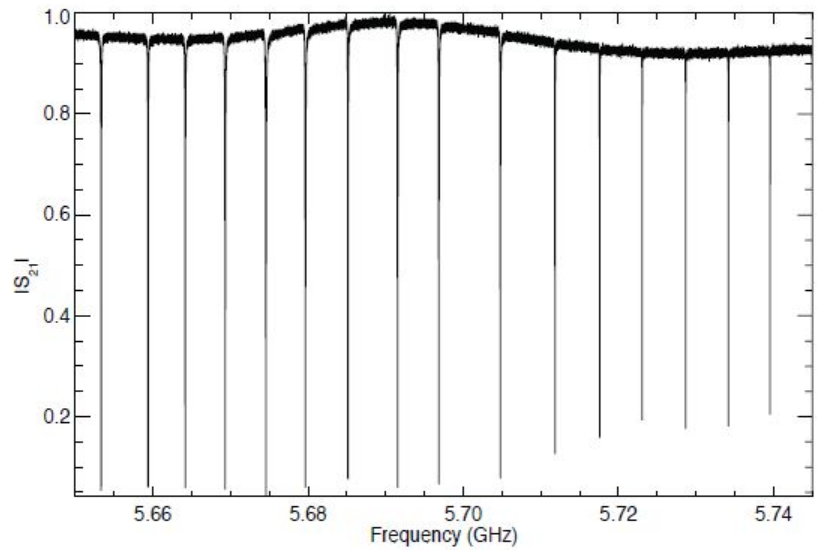
Aside on Kinetic Inductance Detectors

Superconductors have zero DC resistance (shorts through Cooper pairs)...
But have nonzero AC reactance due to mass of electrons -> “kinetic” inductance



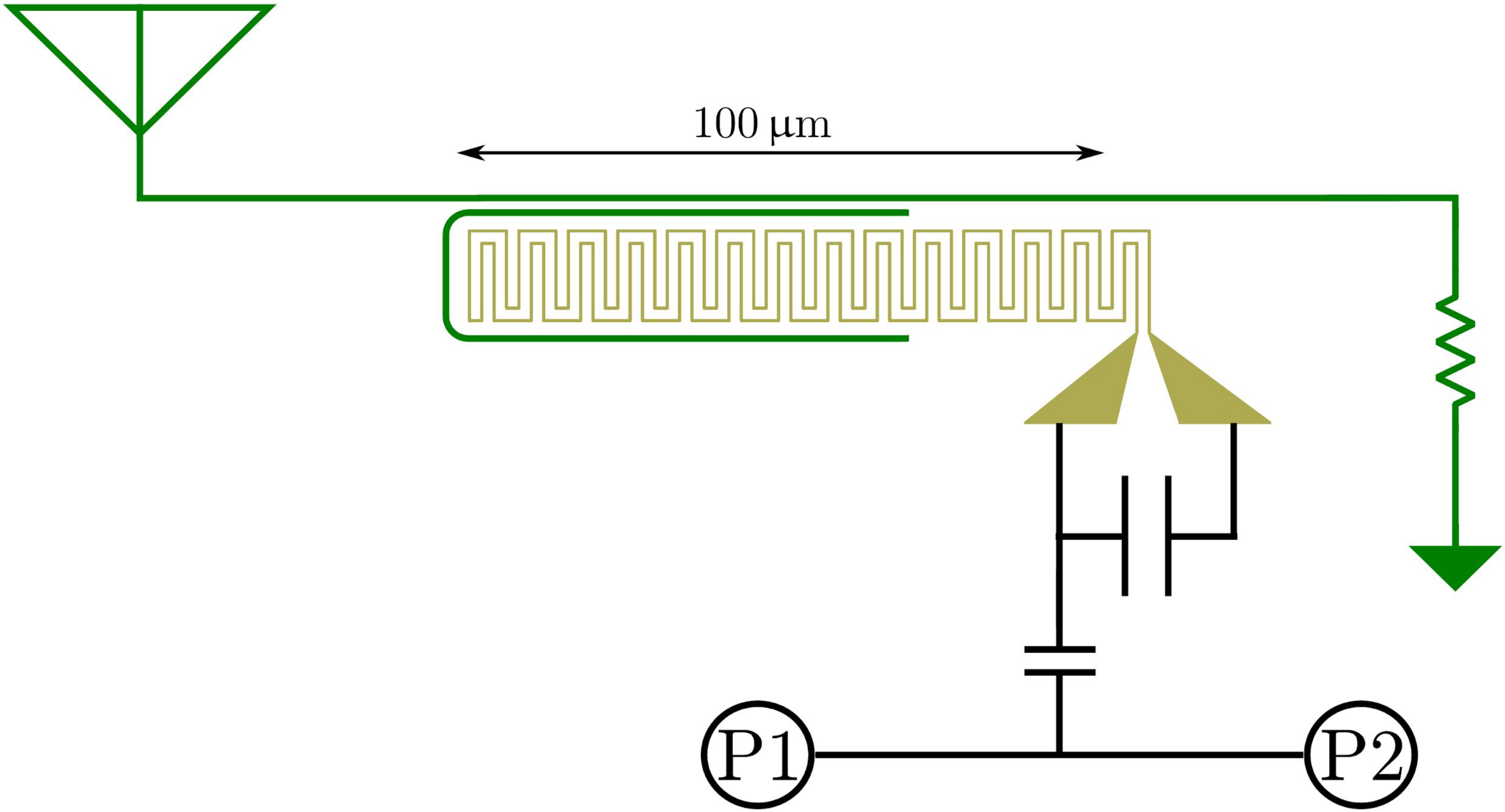
Incident photons of the right energy break Cooper pairs and change the kinetic inductance
-> resonant frequency of a microwave resonator...

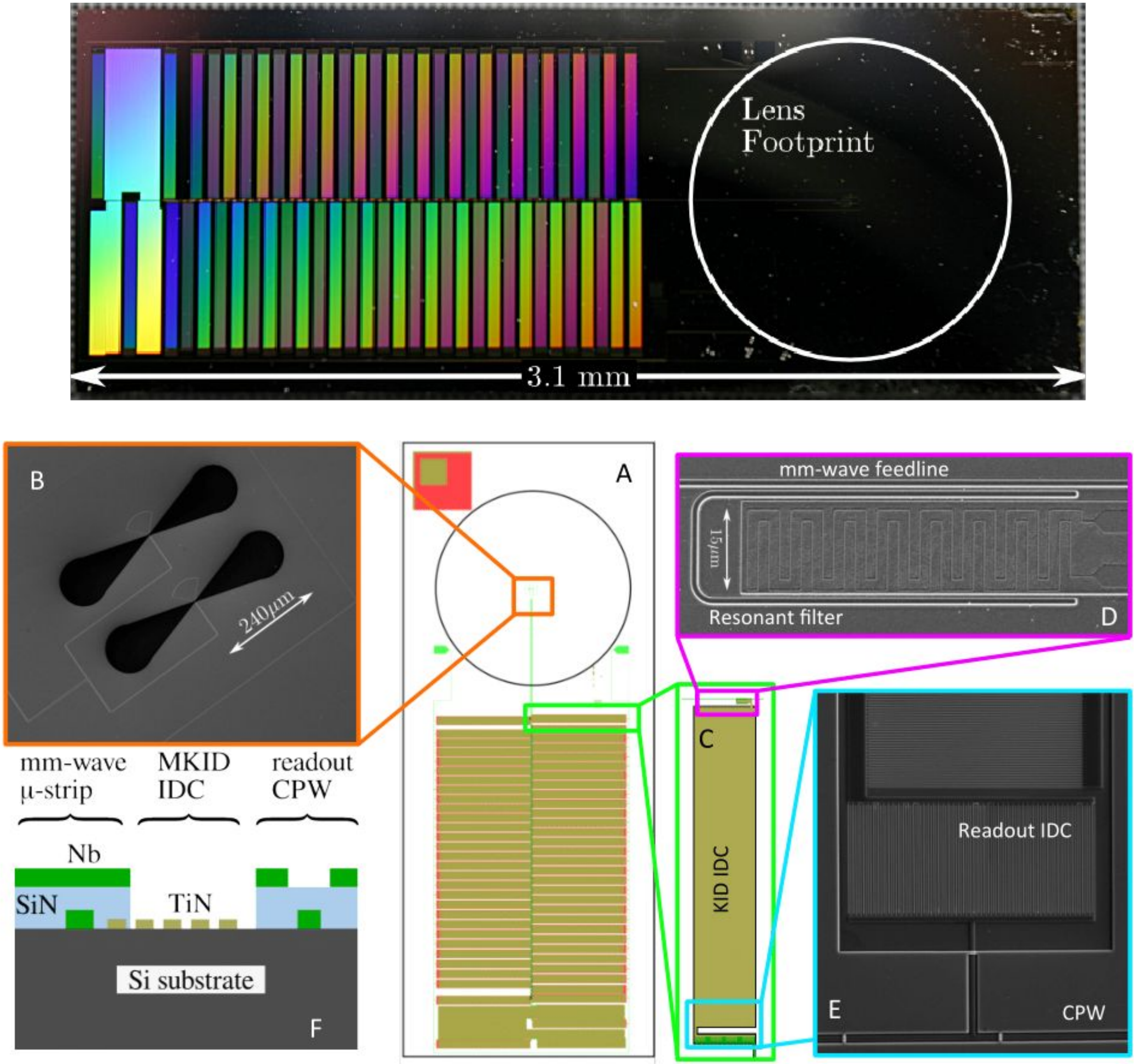




...many of which can be read out with a “comb” of tones on a single microwave line, each probing a detector with a unique resonant frequency

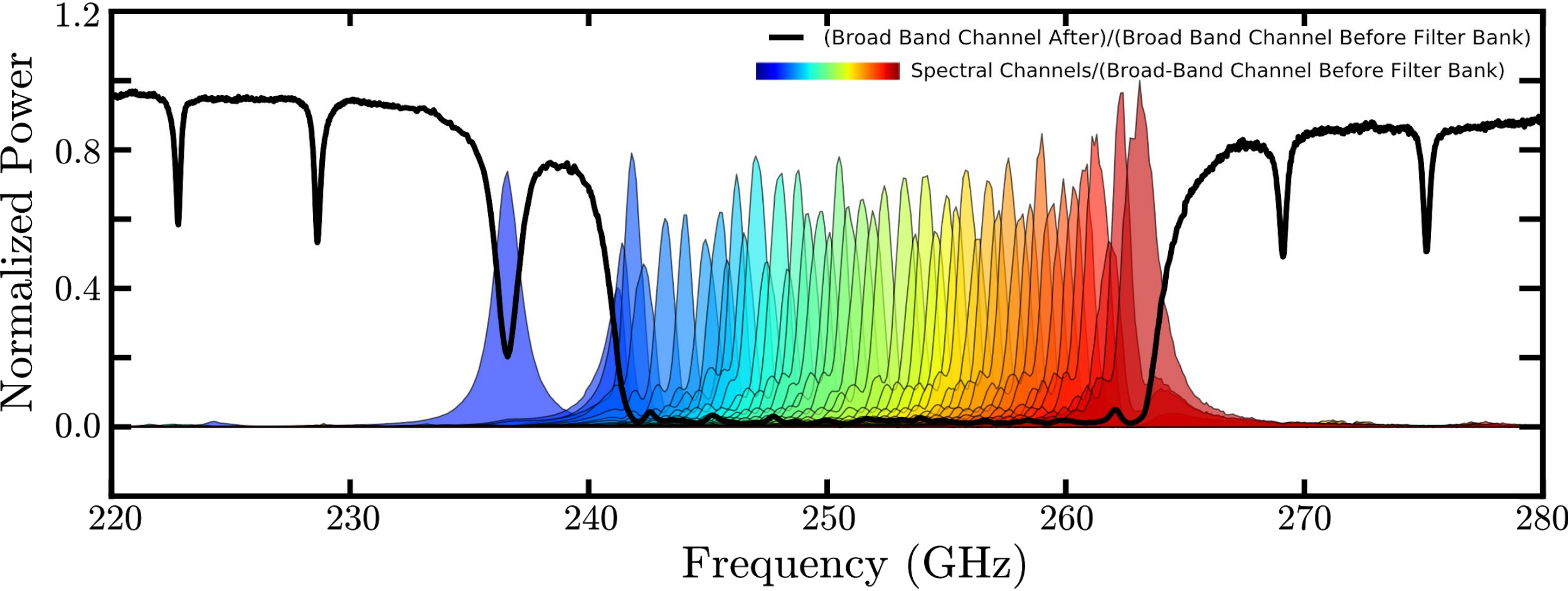
SuperSpec with MKIDs





Lens
Footprint
3.1 mm
B
240μm
A
mm-wave feedline
15μm
Resonant filter
D
C
KID IDC
Readout IDC
E
CPW
mm-wave
μ-strip
MKID
IDC
readout
CPW
Nb
SiN
TiN
Si substrate
F

Measured Spectra

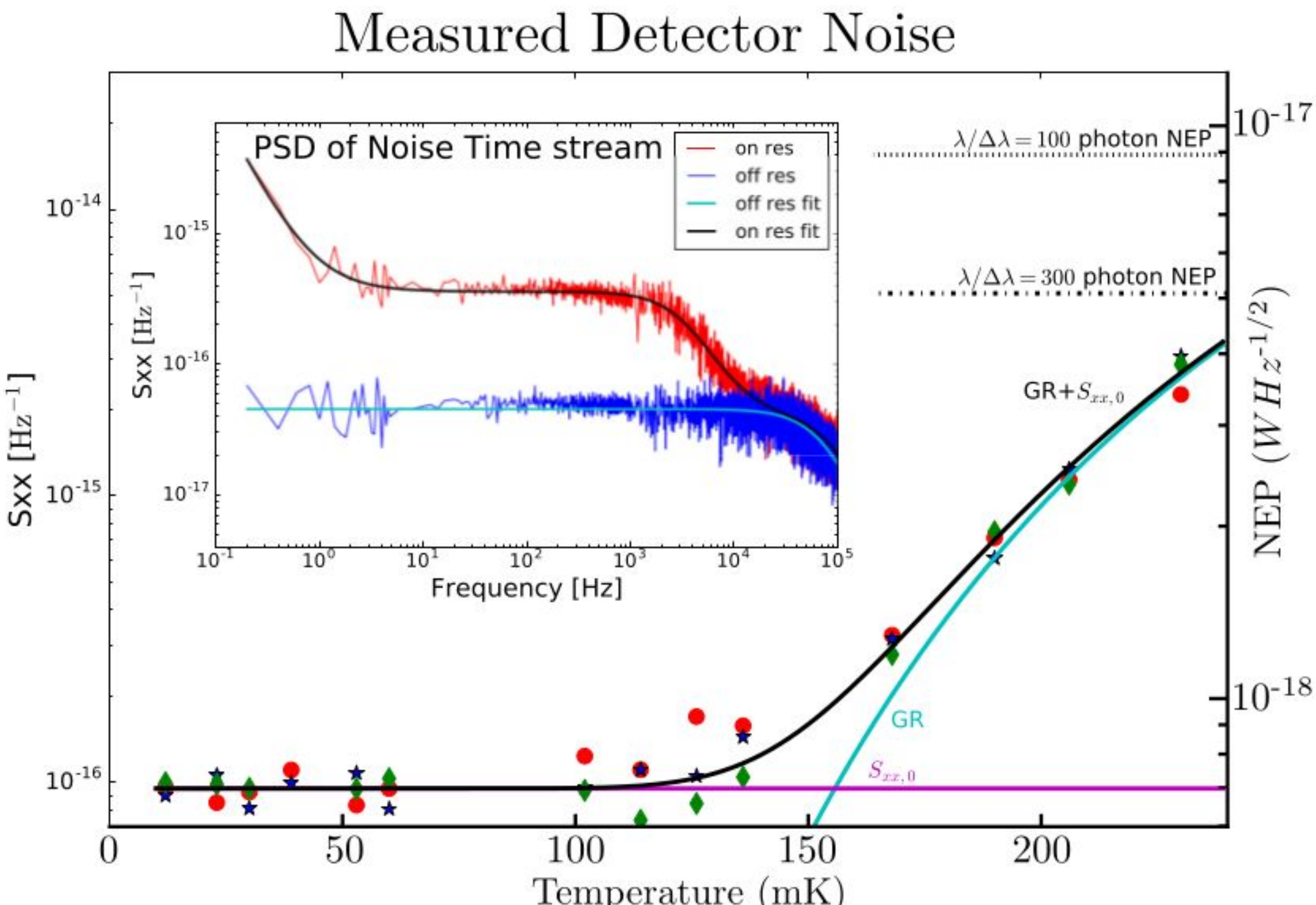


Wheeler et al. 2016

...can also move band around and tune the channel spacing

Funded! NASA APRA 2019-2022
R~1000 @ 300 GHz, R~300 @ 1 THz
Other lines possible, e.g. [OIII]

Noise Low Enough for Ground-Based Observations



McGeehan et al. 2018

2019 Deployment to Large Millimeter Telescope

3 dual-pol ~300 channel spatial pixels, covering 195-310 GHz, R~300

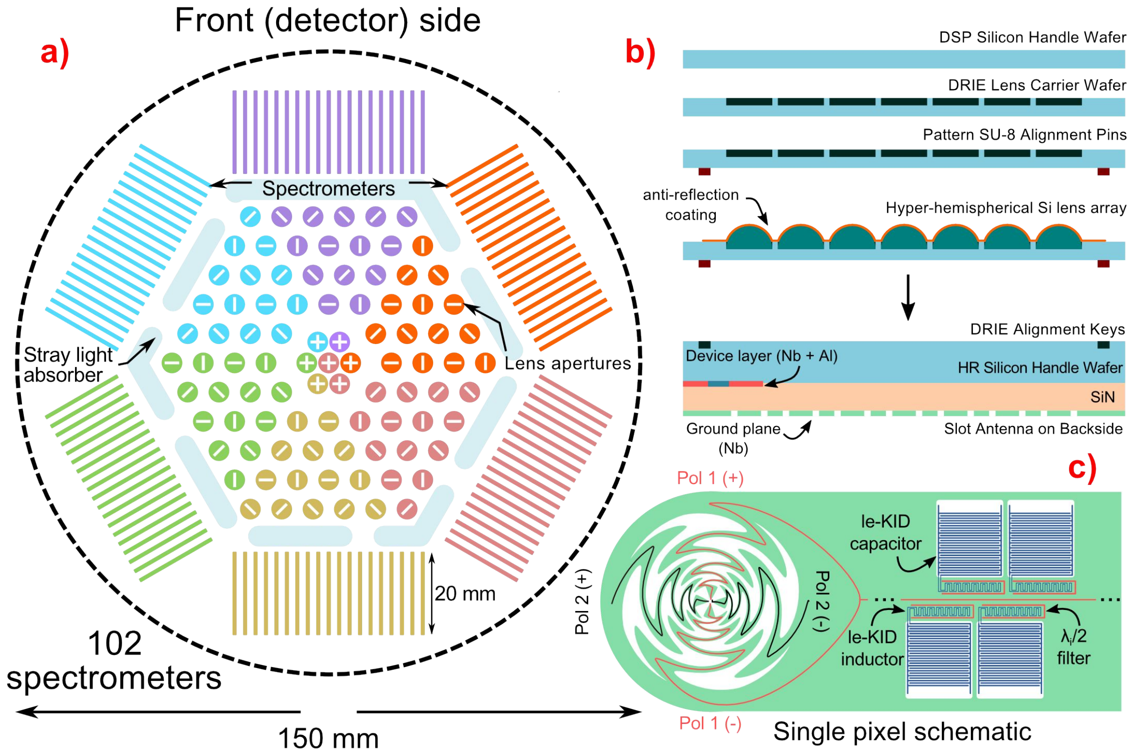
Targeted high-z galaxy [CII] observations, as followup to mm-wave camera surveys:
10 sigma in ~20m for ULIRG at z=5

Pending AAG to support observations.

@ LMT:
Engineering run in spring 2019
Competed science observations in late 2019

SuMaC (SuperSpec-Muscat Collaboration)

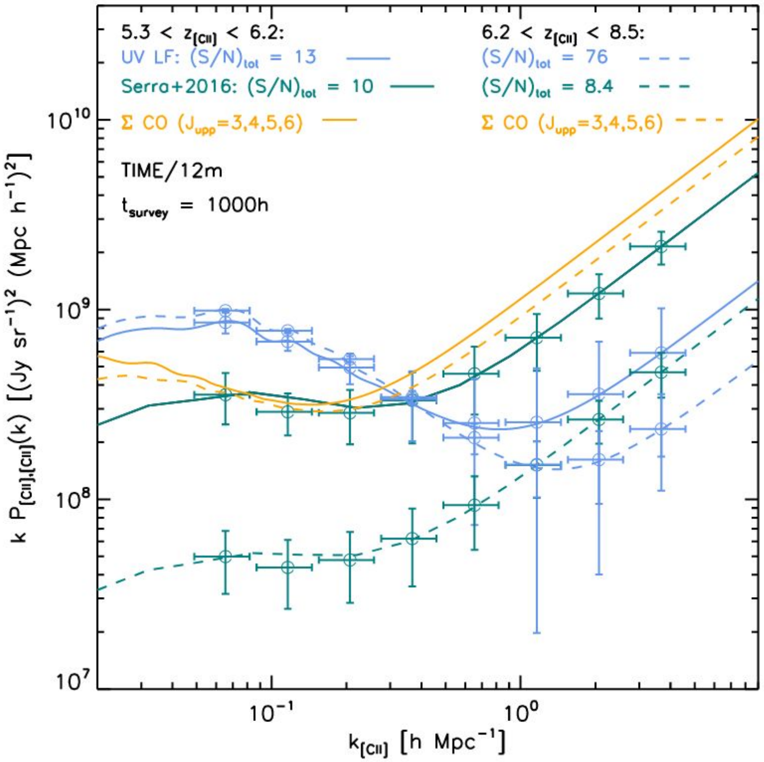
- Pending NSF ATI
- Install in MUSCAT (Cardiff / INAOE) cryostat a U. Chicago spectrometer focal plane
- Nominally 100 pixels at R~100, with a 4 arcmin FOV
- Science goals:
  - High-ell [CII] intensity mapping to measure total SFR level in the shot-noise regime
  - Pointed follow-up of individual SMGs for redshift and gas properties.
  - Mapping and identifying candidate protocluster members.
  - High spatial resolution maps of SZ null and amplitude for sub-cluster structure.



Pete Barry

Future IM Instruments

Mass-producing ~100-pixel wafers should be doable in ~4 years...consider a “drop-in” TIME replacement with 3x spectrometer count and simpler optics



Considering SPT-spec: new focal plane with ~several hundred spectrometers after SPT-3G is done in ~2023

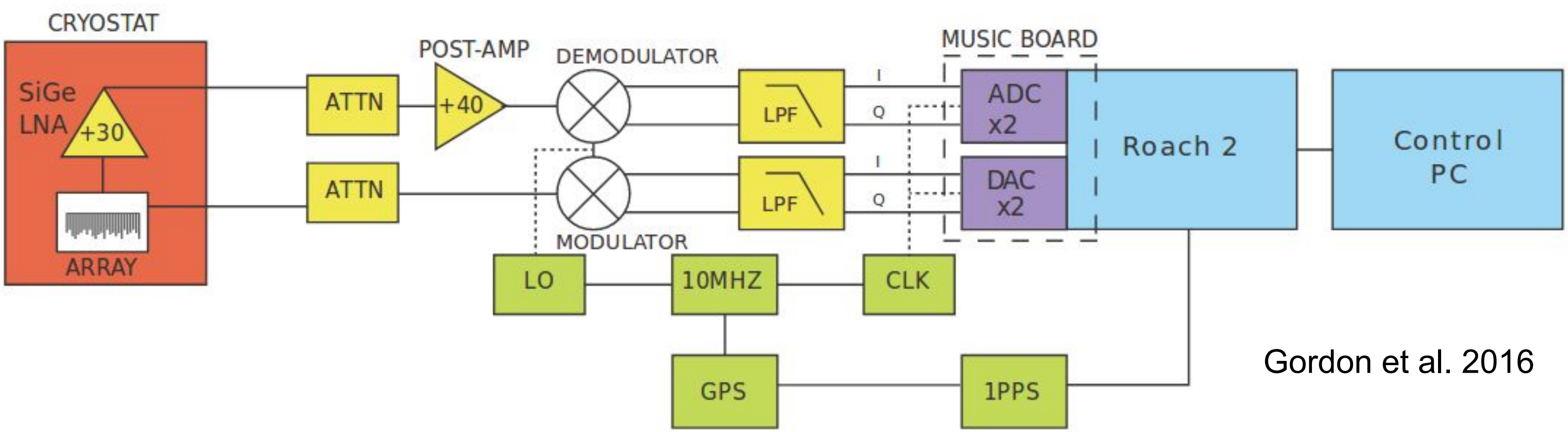
Challenges

Just like CMB, getting the fab right takes time

Easy enough to print out 100s of spatial pixels, but this means 10^4 detectors or more (see CMB-S4 readout challenge!)

“Off-the-shelf” solution: ROACH readout (~$20/detector)

Other solutions: warm part of uMUX, RF-SOC, GPUs, etc (down to ~$few/detector)



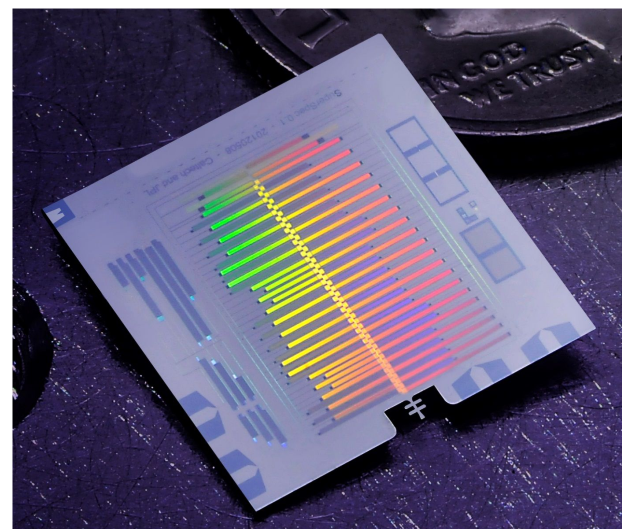
Gordon et al. 2016

Summary

Mm-wave IM will need a significant sensitivity boost to probe EoR (...and to eventually be competitive for cosmology!)

While current technology should work, gratings/FPI/FTS are not expandable by the orders of magnitude necessary for next-gen experiments

SuperSpec offers an elegant solution: easily-multiplexed on-chip spectroscopy that is similar to CMB focal planes



SuperSpec will demonstrate a several-pixel spectrometer on sky this year

Working on scaling up to filled wafers in the next few years

Large-scale readout is the most pressing technical challenge (...but CMB-S4 is on it!)