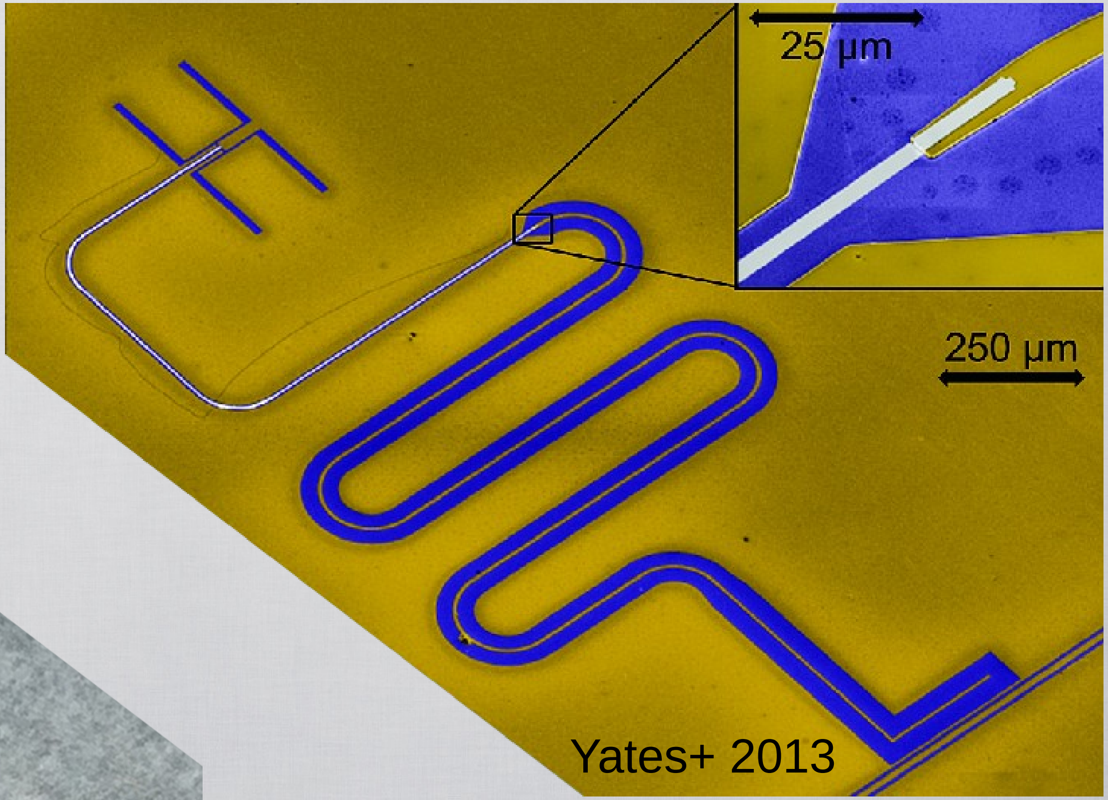
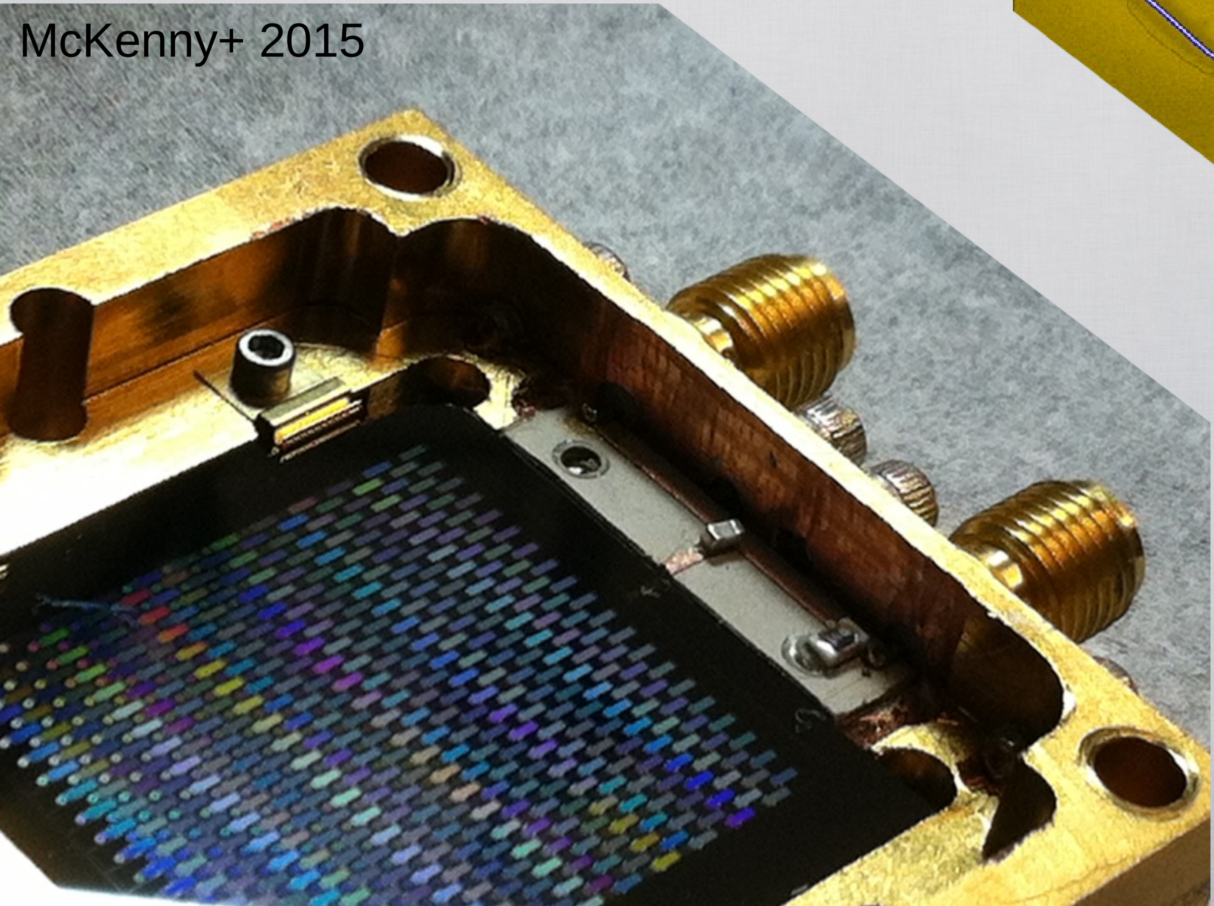
Technology for next-generation submm and far-IR instruments

Erik Shirokoff

University of Chicago



Yates+ 2013



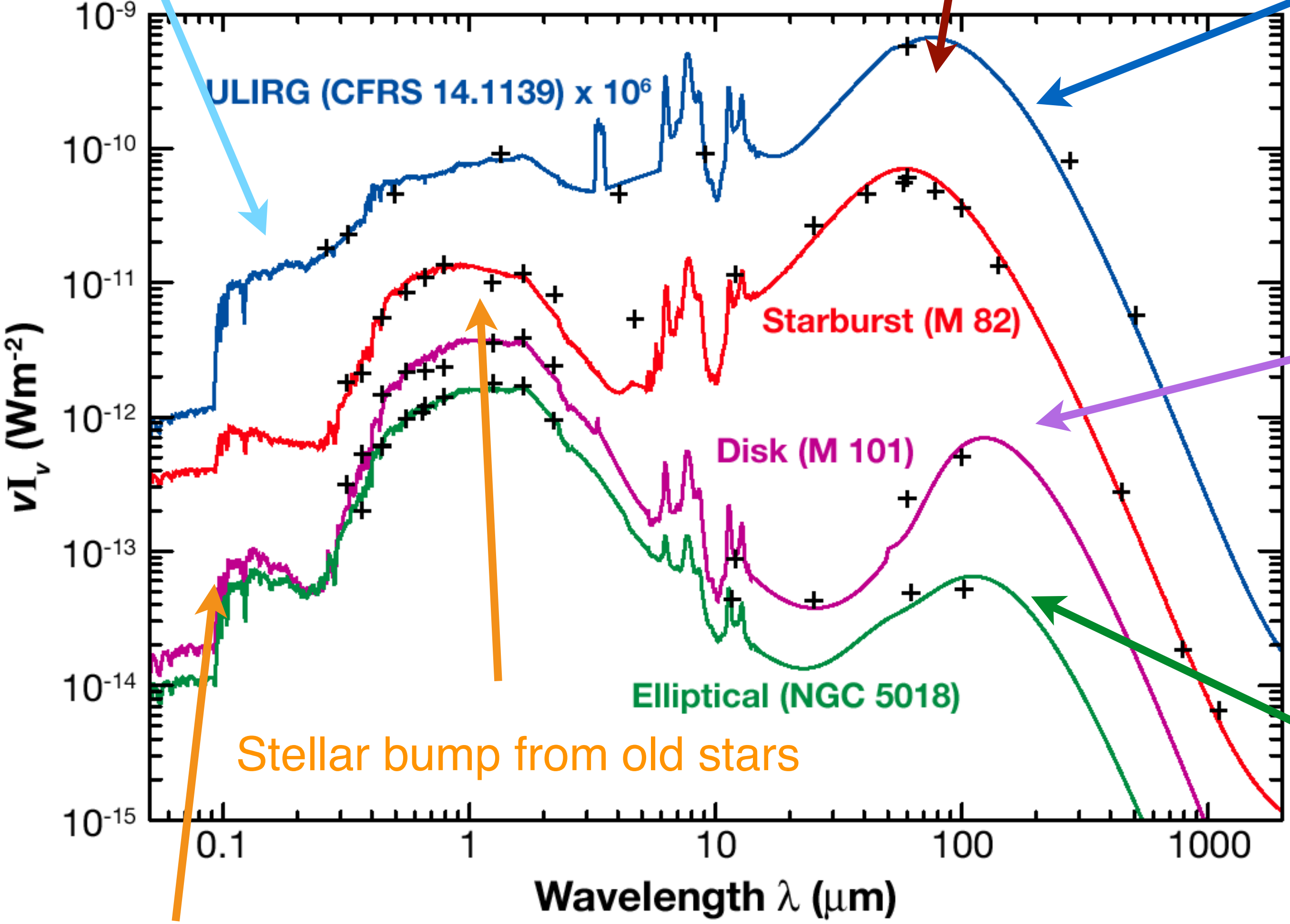
McKenny+ 2015

8 January, 2019

Spectral Energy Densities of Galaxies

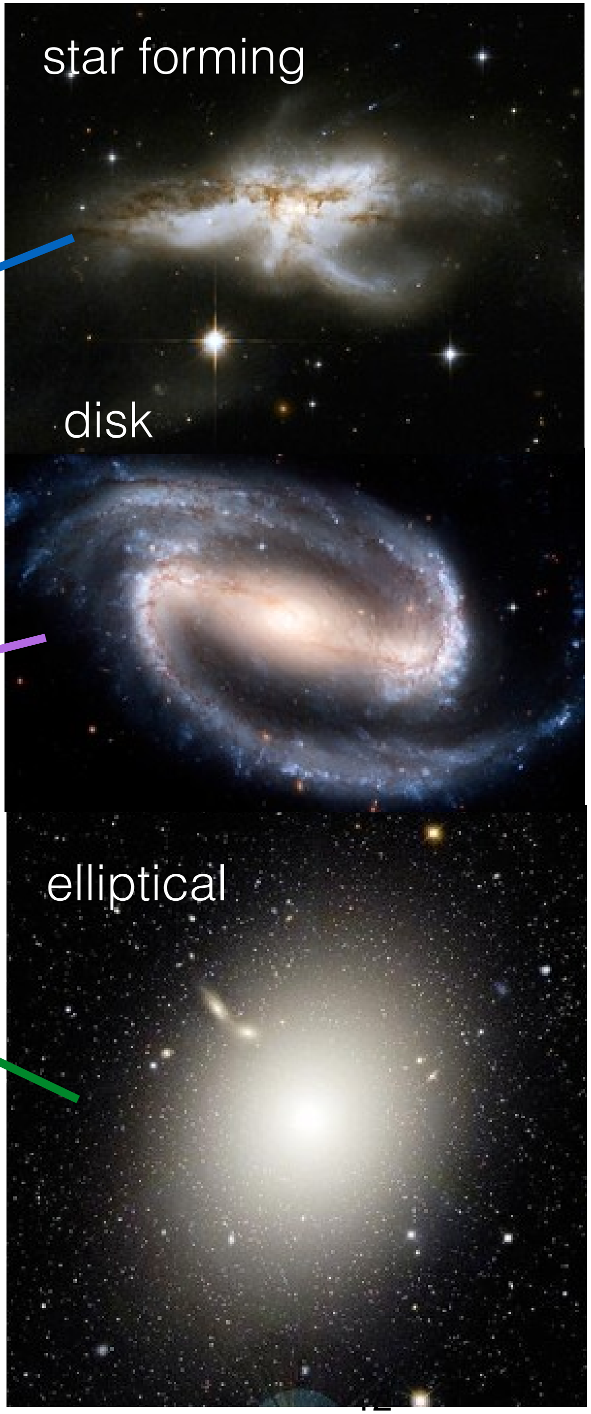
UV radiation absorbed by dust

Dust re-emits in the FIR



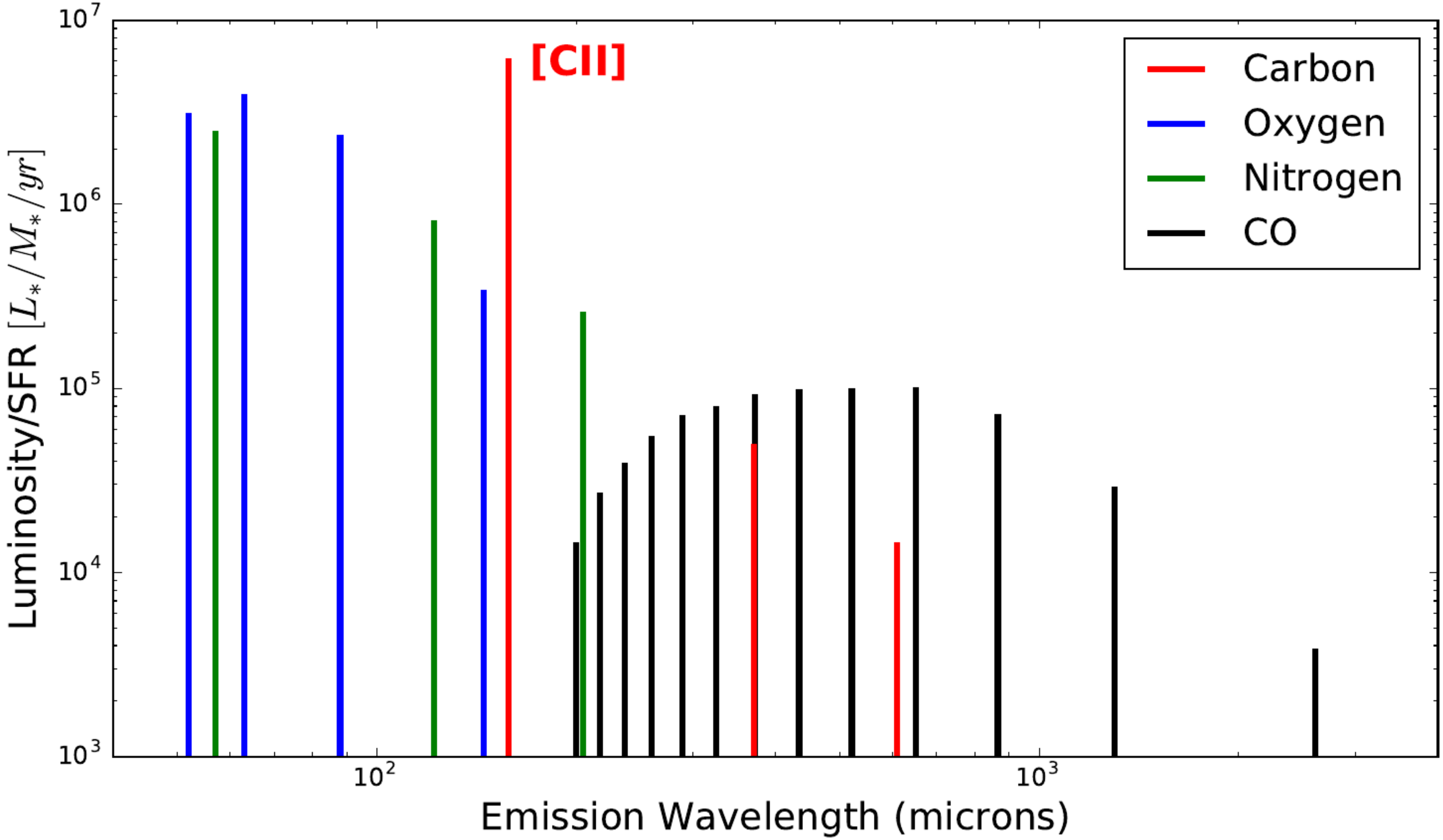
Stellar bump from old stars

UV from young, hot stars



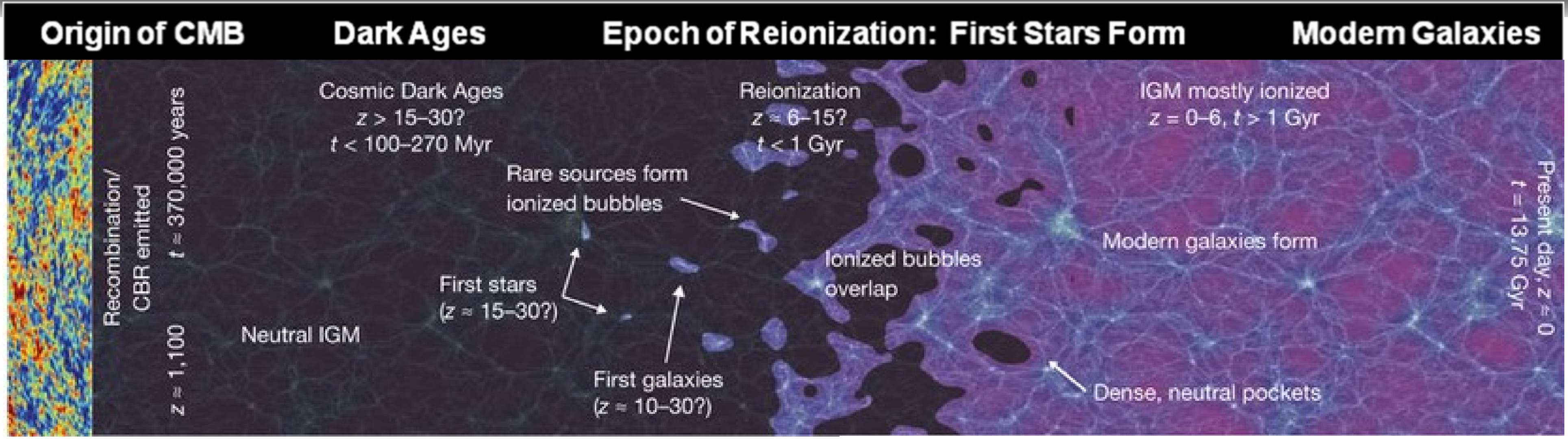
Lagach+2005, based on Galliano 2007, adapted by J. Viera

There are bright atomic and molecular lines at submm wavelengths

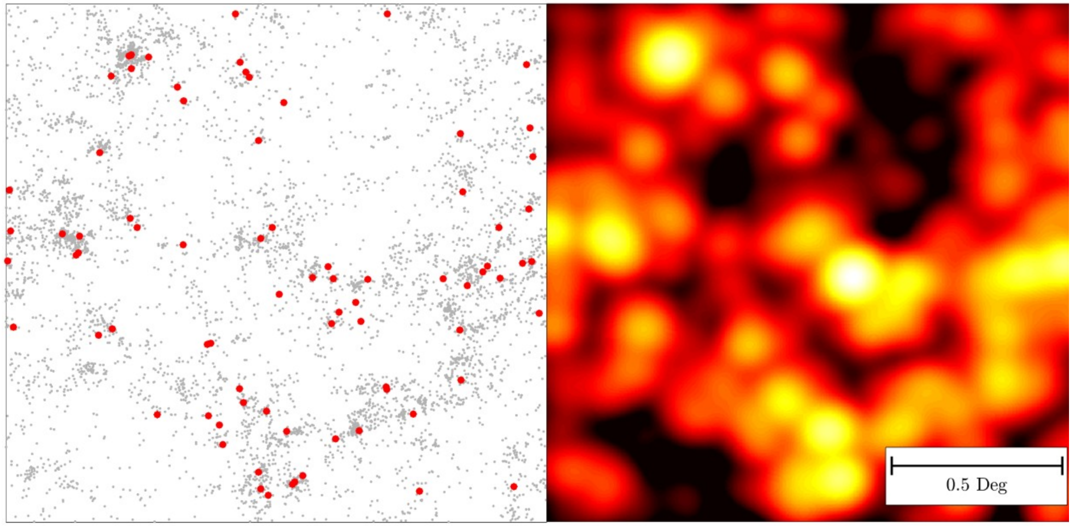


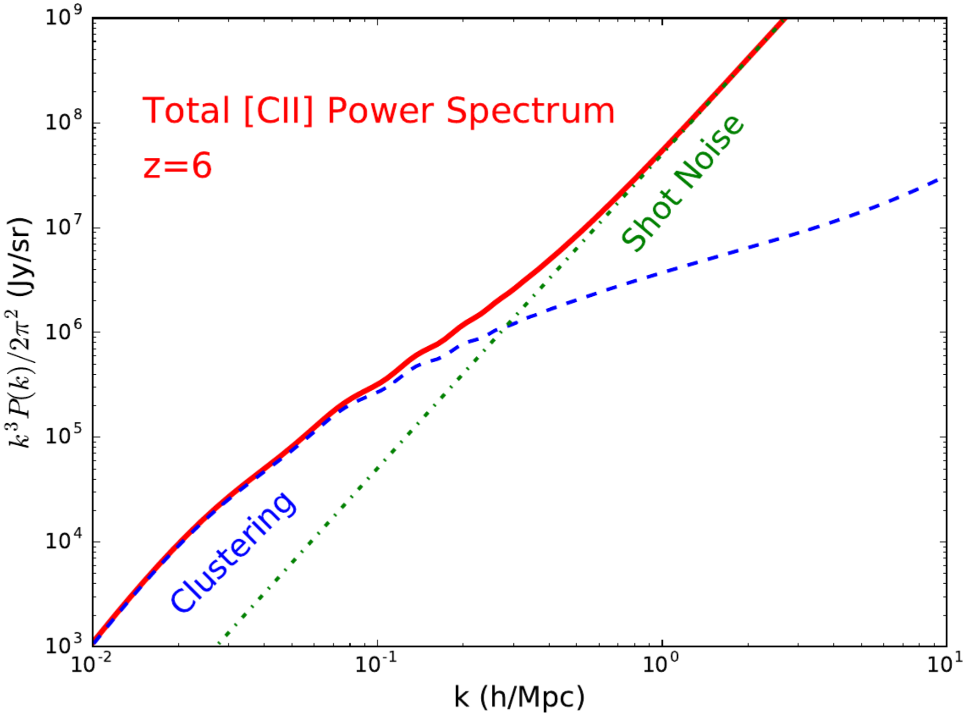
FIR line luminosities (nearby galaxies) adapted from Visbal and Loeb 2010. Figure by K. Karkare

Intensity mapping: total star formation rate, clustering, and the epoch of reionization



Dunlop & McLure





Submmm suvey science and tomography requires many very sensitive pixels.

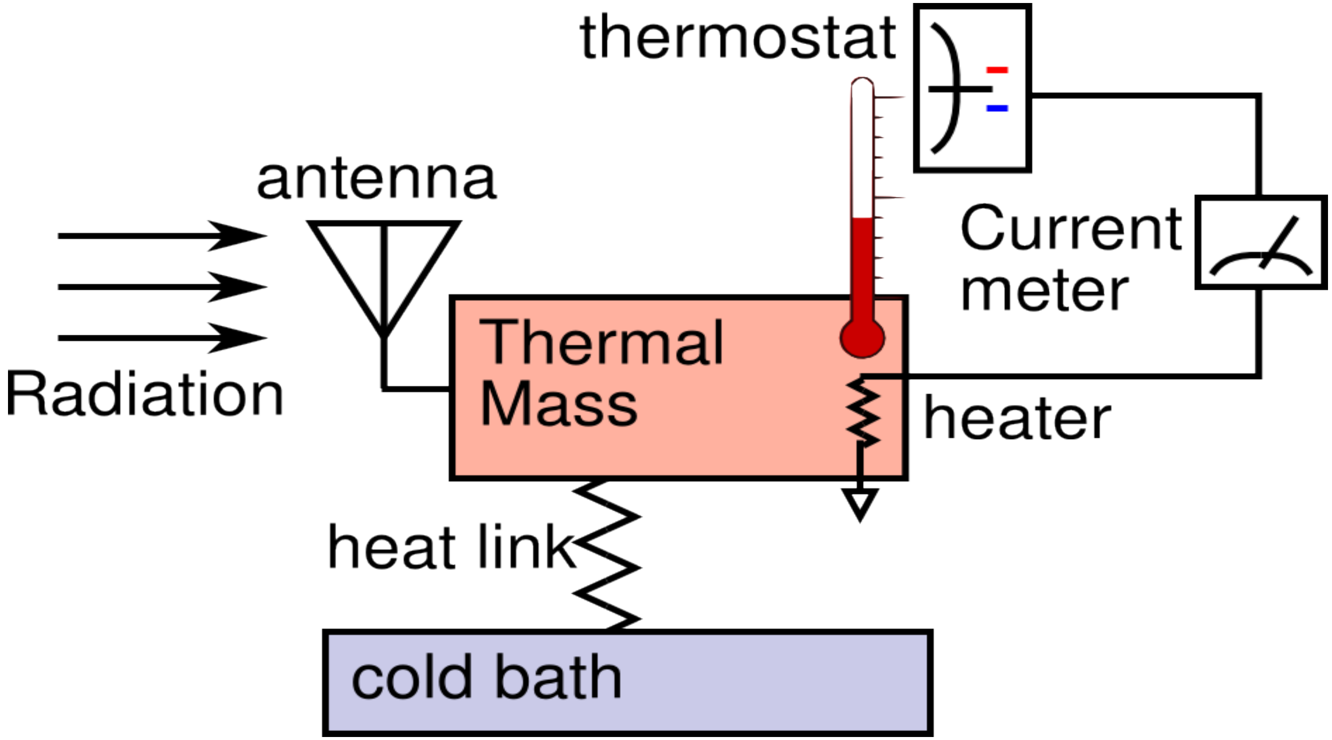
New developments in sub-K incoherent detecors:

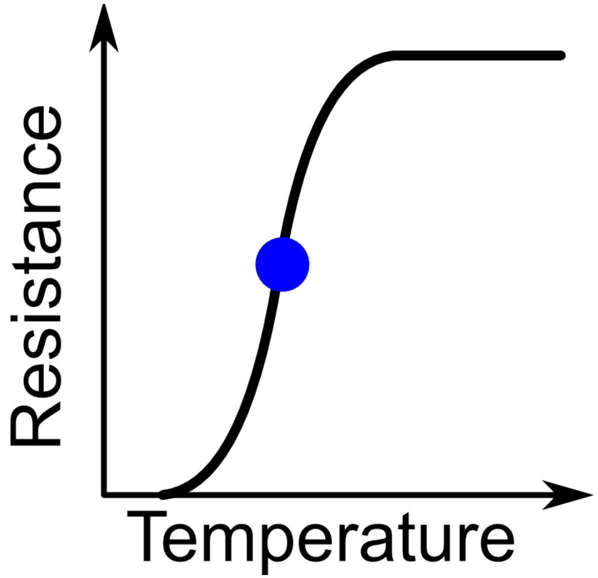
- Bolometers and multiplexing
- Kinetic inductance detectors
- On-chip submm archetecture

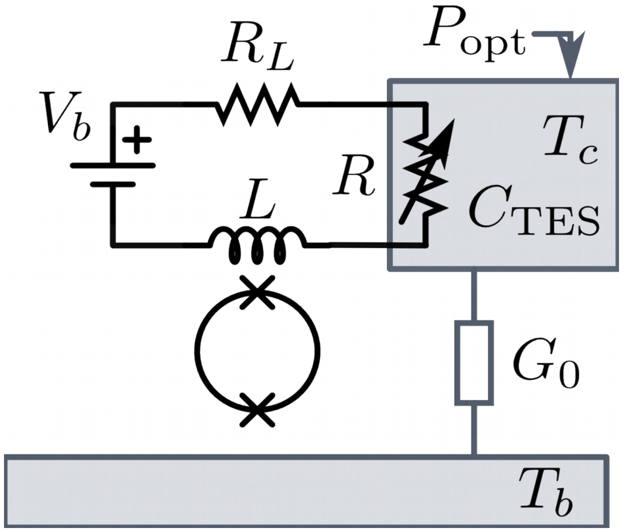
Note there are many exciting new things I'm skipping today:

- Coherent receivers
- Semiconductor devices
- Fourier Transform spectroscopic instruments

Bolometers: measure how much heat is deposited in a thermally-isolated material.





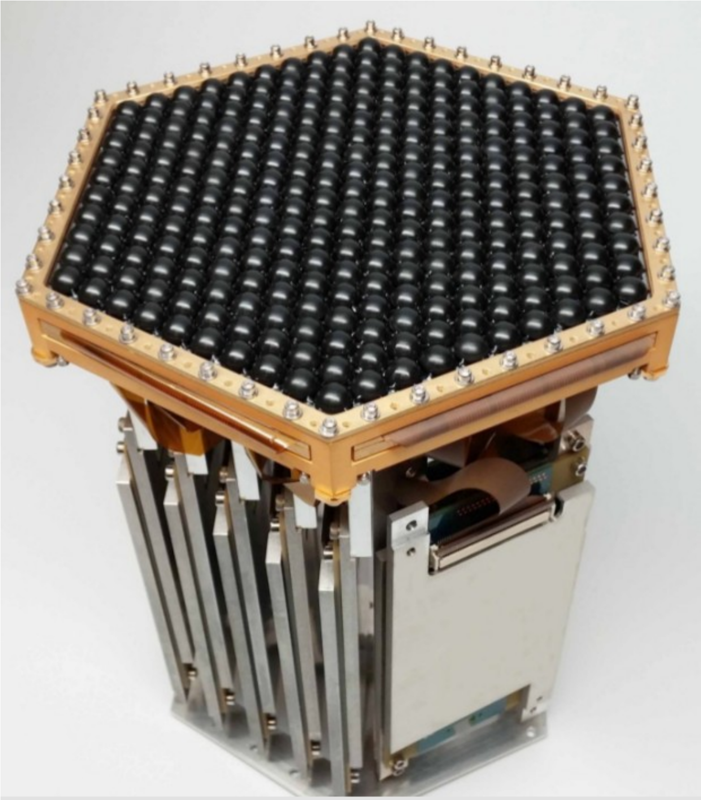


New readout schemes allow for much denser readout multiplexing of TES devices.

- Microwave frequency domain mux:
  - AC bias TESes at tens to hundreds of MHz
- Microwave mux:
  - The DC current through a resonator-coupled SQUID change the phase of a microwave tone
  - Currently planned for the Simons Observatory.

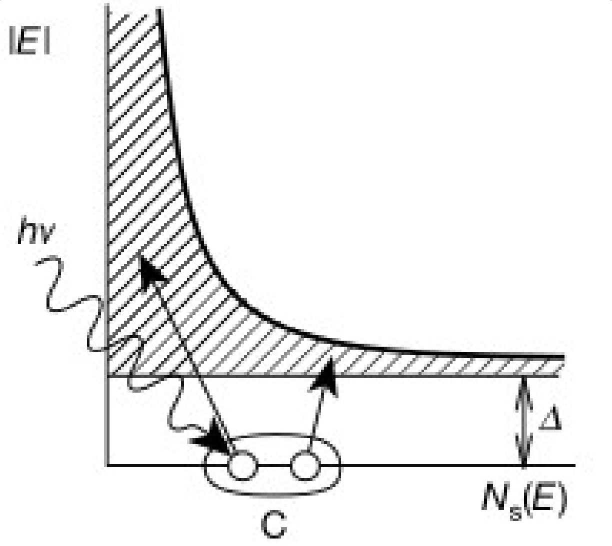
SPT-3G fielded 16000 pol-sensitive, 3-color detectors.

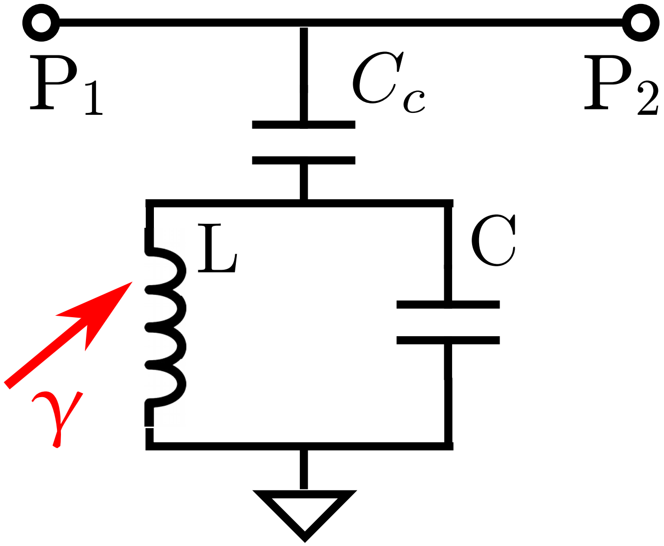
CMB-S4 plans to field half a million!

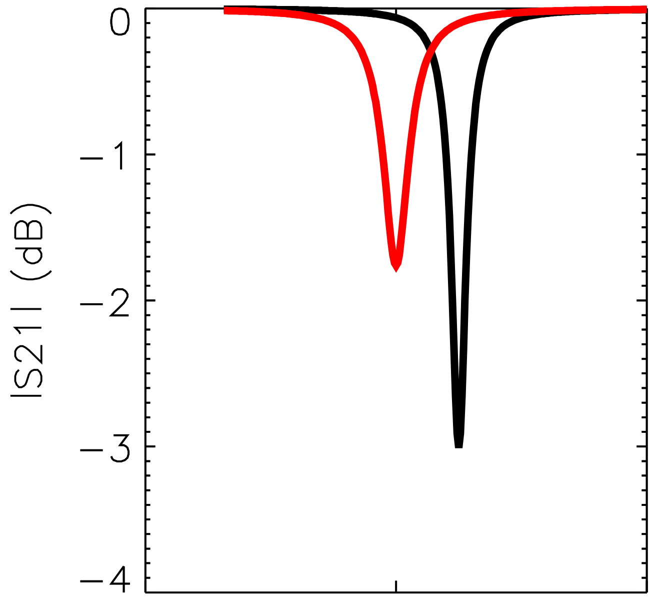


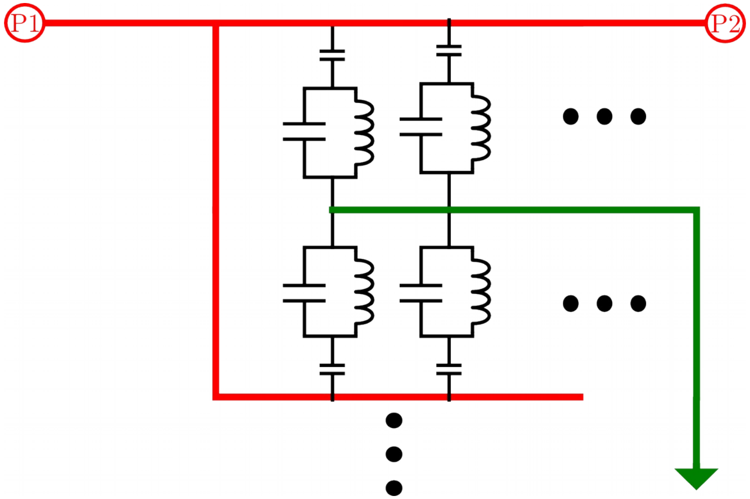
PolarBear-2 module

The kinetic inductance detector: photon absorption breaks Cooper pairs, causes a frequency shift in a microwave resonator.



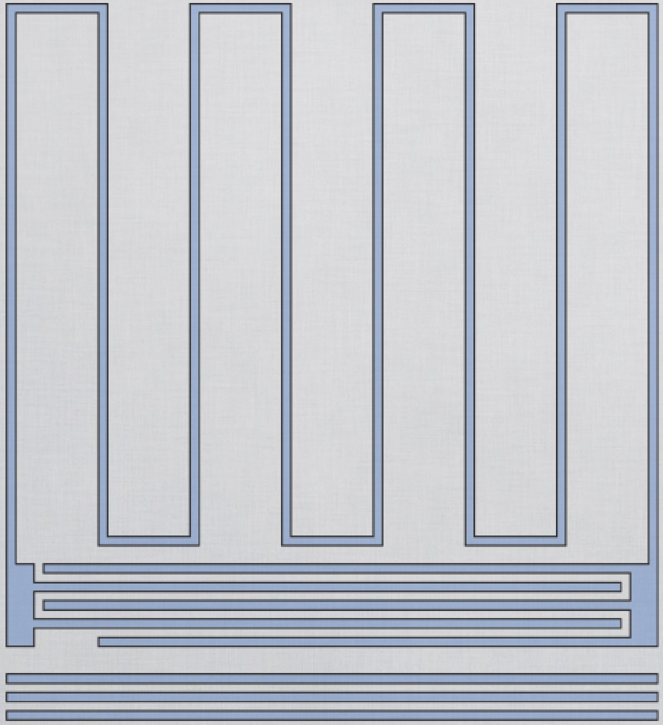


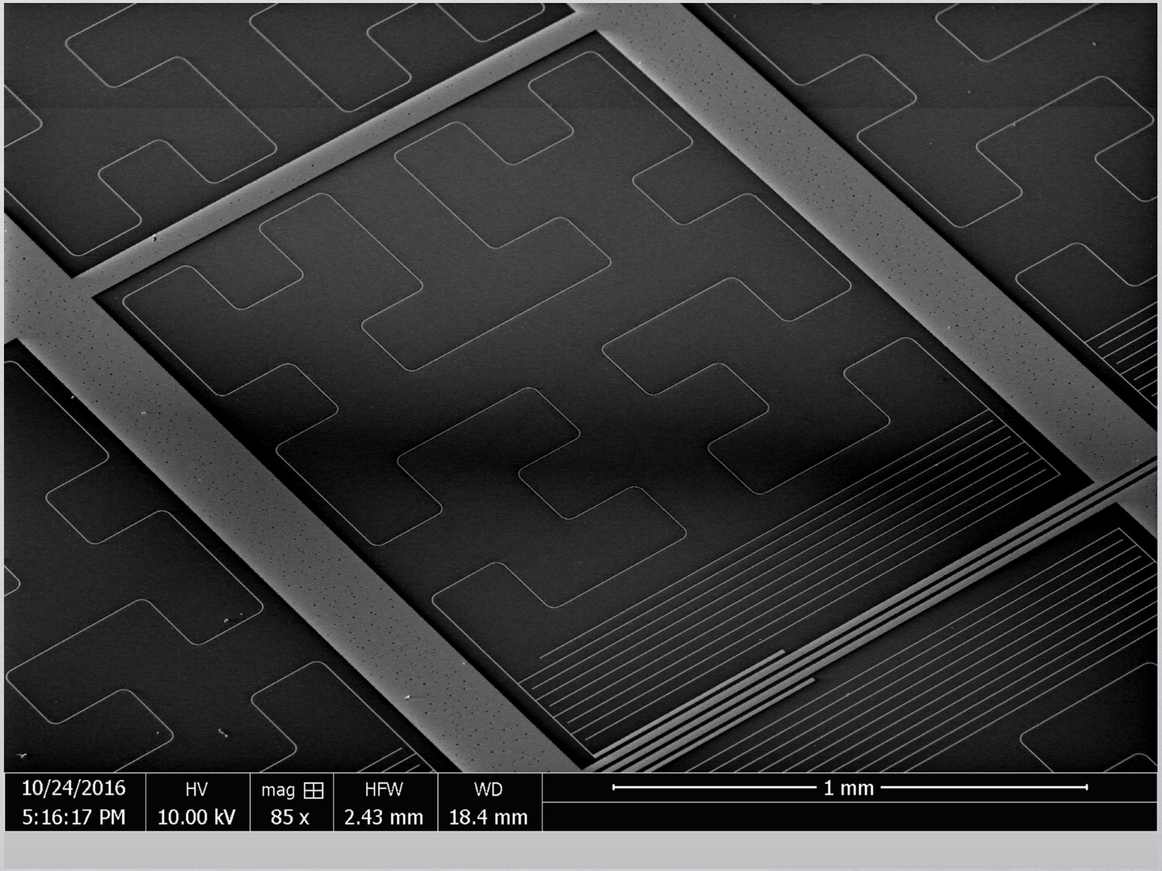




Some figures: Zmuidzinas group

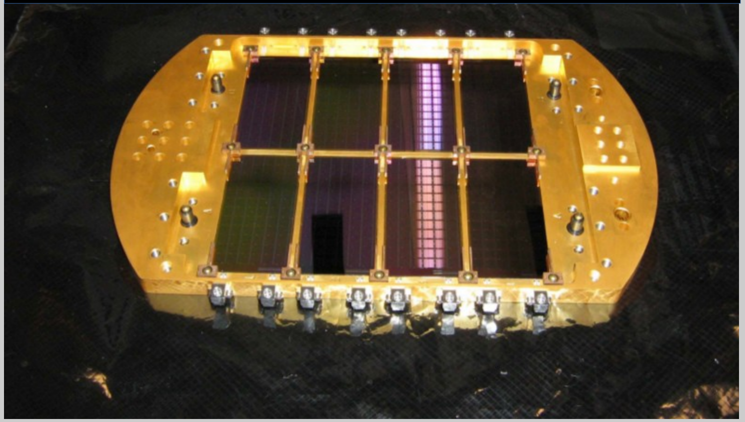
Direct-absorbing lumped-element KID (LeKID): inter-digitated capacitor and meandered inductor



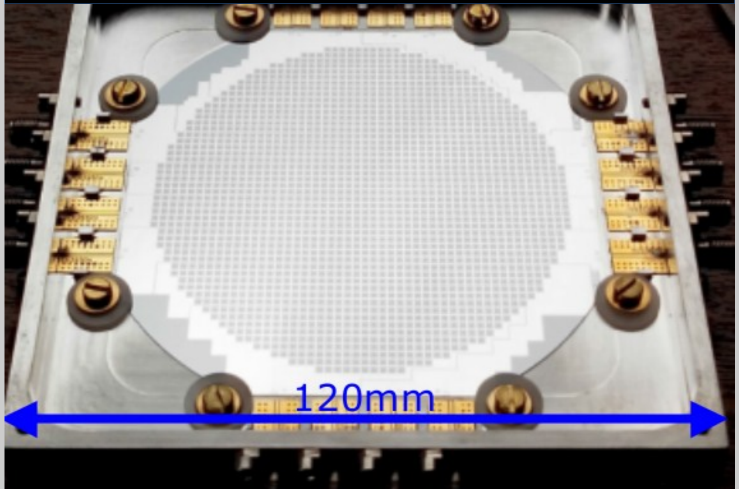


On-sky cameras exist, and many more are coming next year!

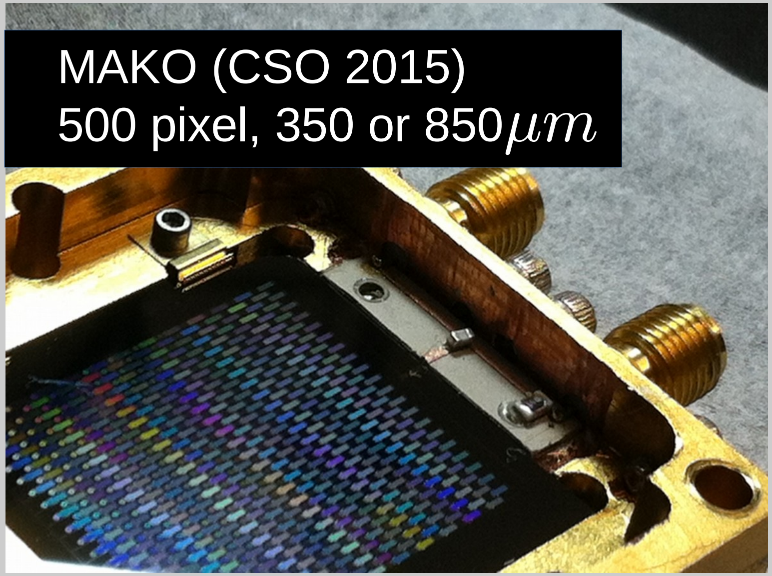
MUSIC: CSO 2012-2015
576 4-color pixels, 2mm-850μm

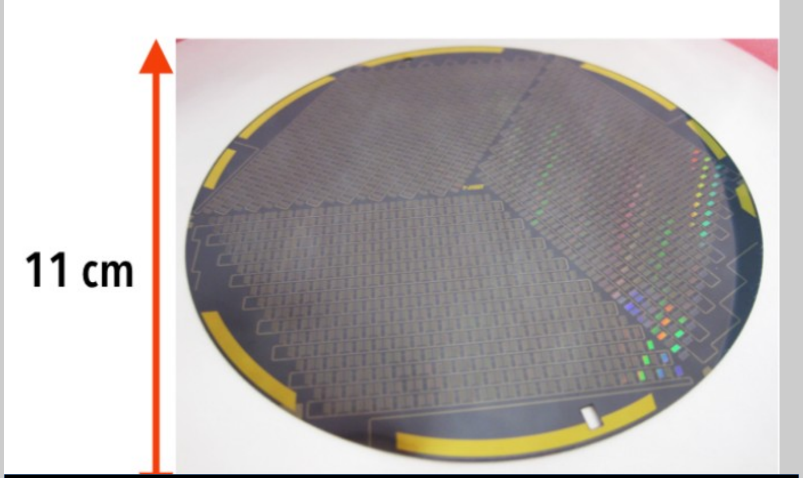


NIKA / NIKA2 (IRAM 2011-pres.)
300/5000 1.25 and 2mm pixel



MAKO (CSO 2015)
500 pixel, 350 or 850μm

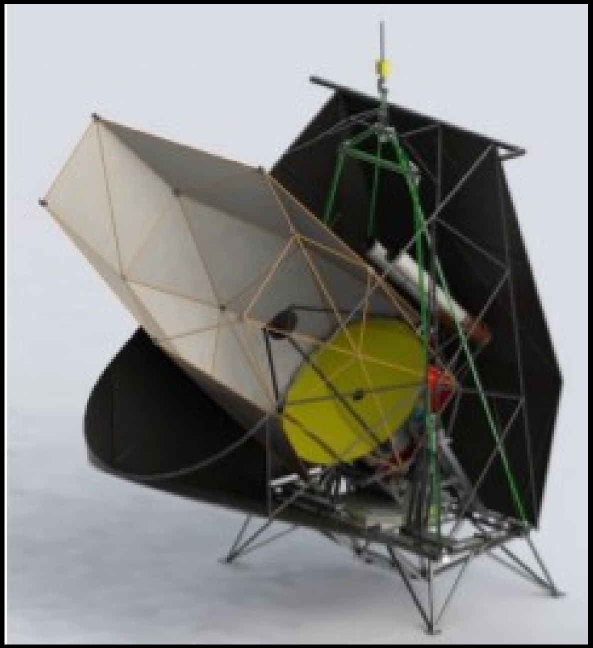


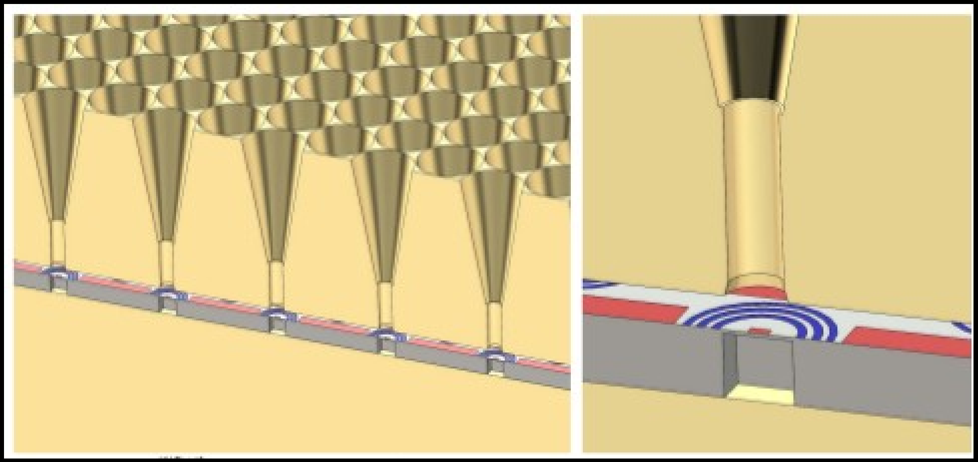


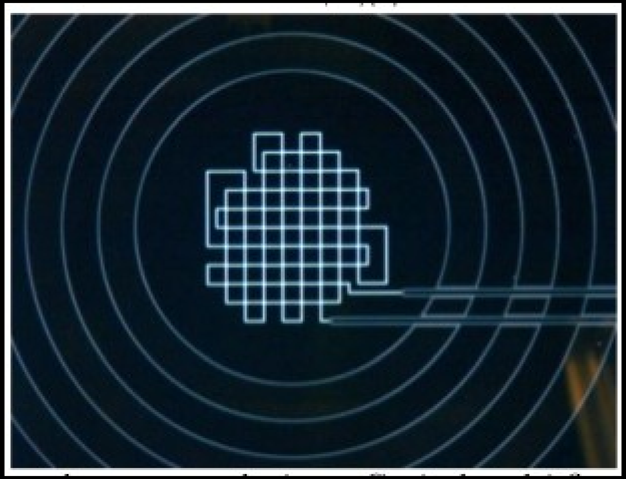
BLAST TNG (Antarctic balloon)
3300 detectors 250, 350, 500μm

STARFIRE: the Spectroscopic Terahertz Airborne Receiver for Far-InfraRed Exploration

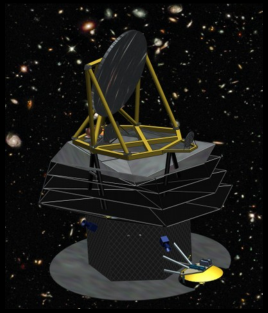
- Baloon, based on BLAST gondola
- IFU grating spectrometer
- 240 to 420 micron
- Direct-absorber KID detectors





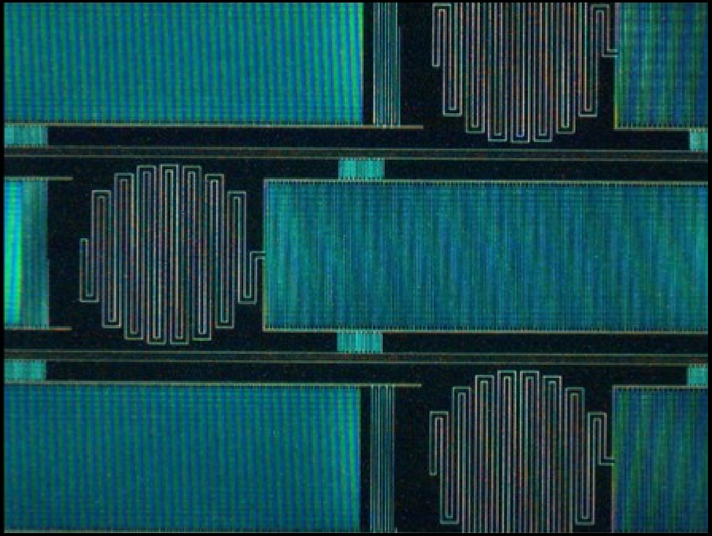


Galaxy Evolution Probe KIDs

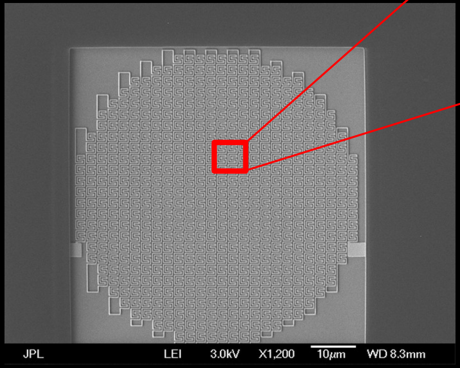


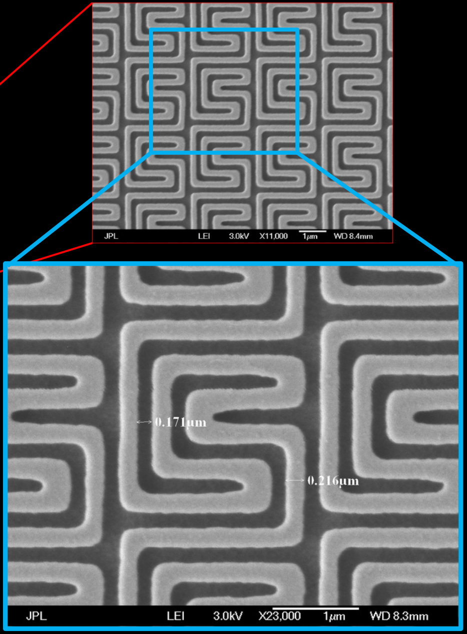
- 50,000 KIDs split evenly between imager and spectrometer
- Why baseline KIDs?
  - Simple architecture, simple cryogenic readout, one focal plane technology for all wavelengths.

100 - 400 µm: MAKO type LEKID



10 - 95 µm: Unit cell of mid-IR KID absorber.

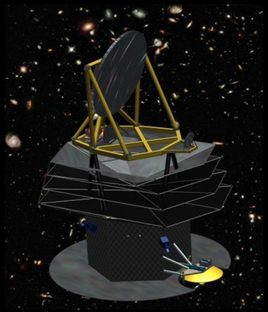




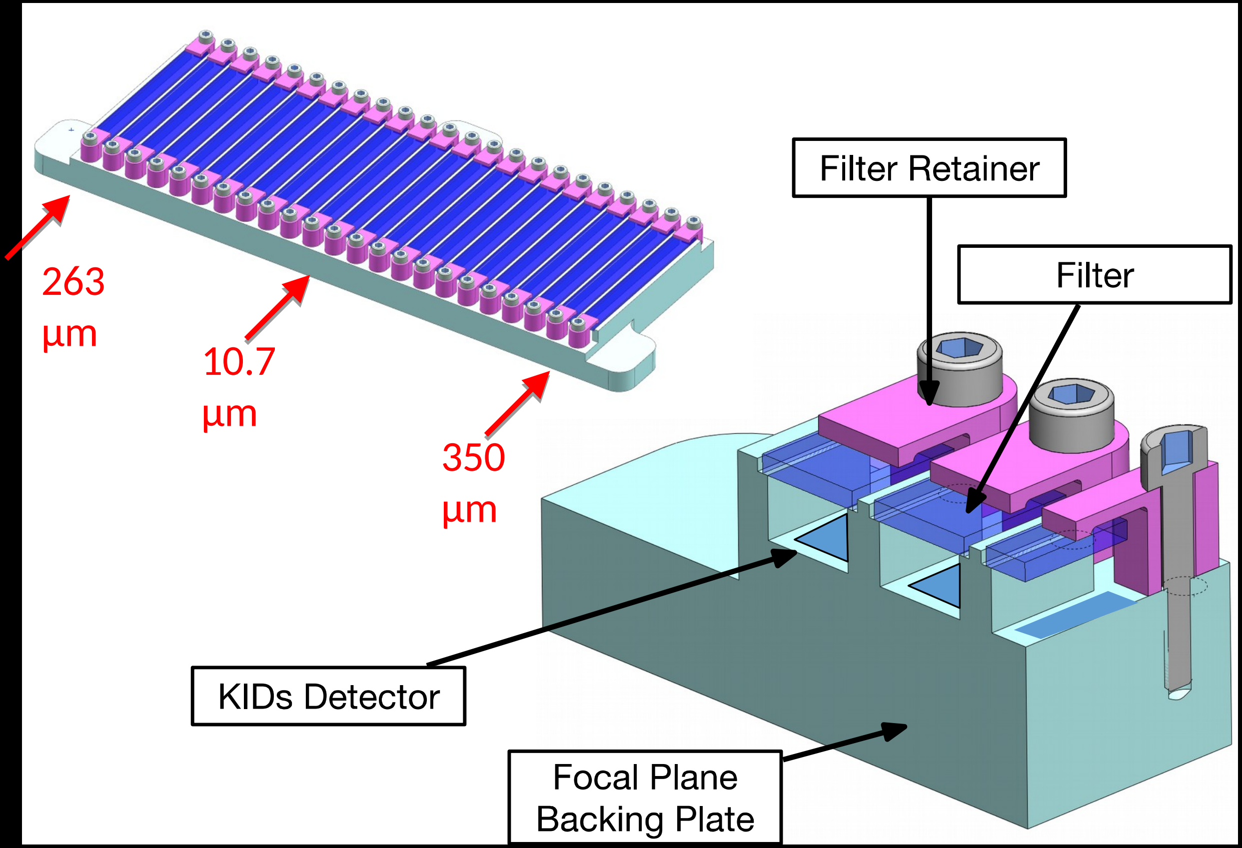
Day, LeDuc, Fyhrie, Glenn, Perido, Zmuidzinas

Technology development plan: MIR KIDs (10 – 100 µm), readout

GEP-I Focal Plane (KIDs)



Continuous scanning for full spectral coverage



Spectral Resolution

10-95 µm:

$R = \lambda/\Delta\lambda = 8$

95-400 µm:

$R = \lambda/\Delta\lambda = 3.5$

FoV and Sampling

$0.5° \times 0.1°$

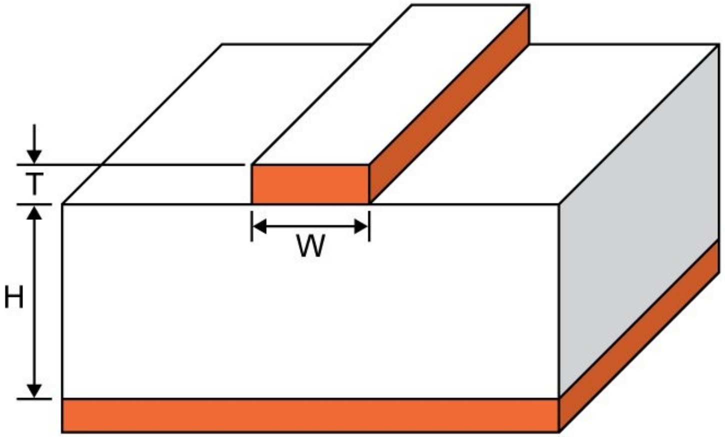
$\lambda < 70$ µm:

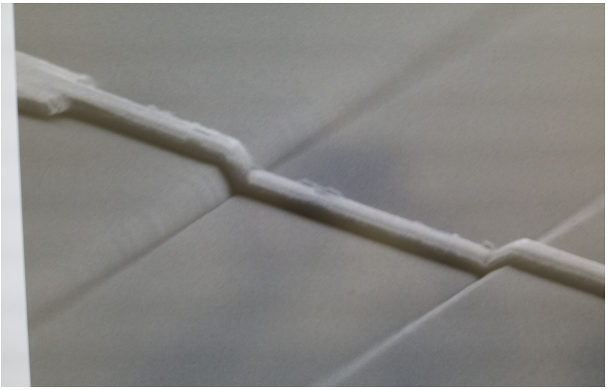
3.43” pixels

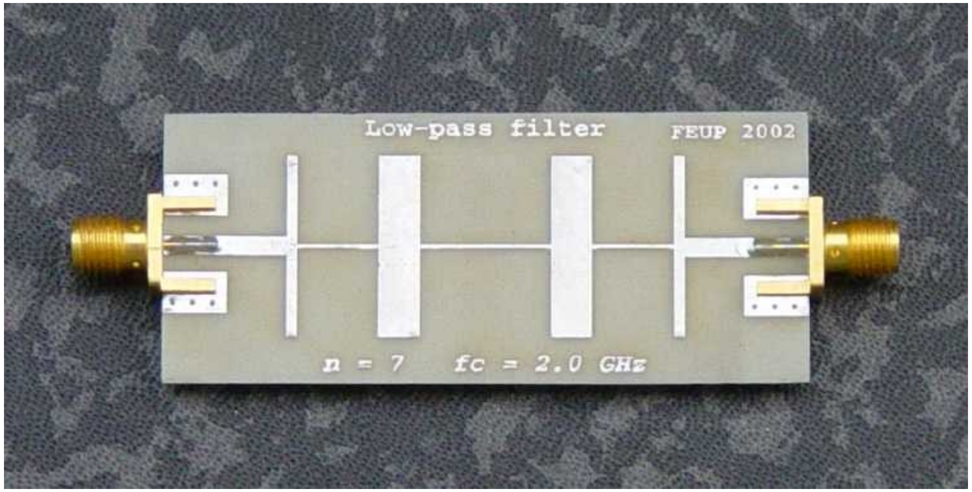
$\lambda > 70$ µm:

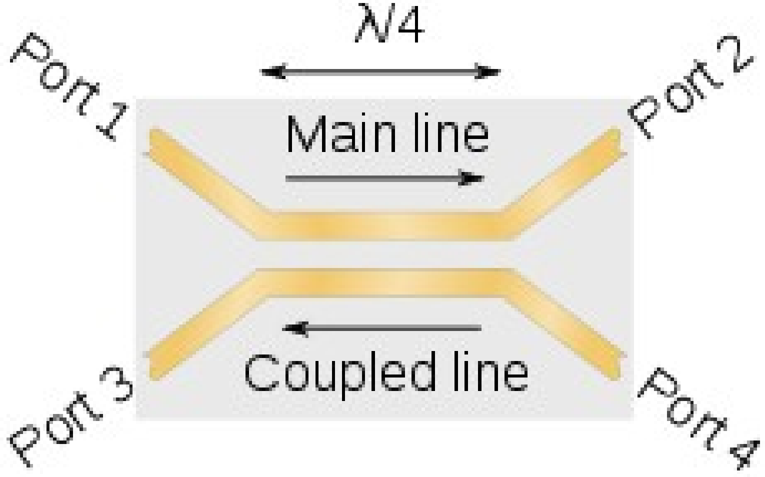
Nyquist

Tools: microwave transmission lines for submm-wavelength on-chip features



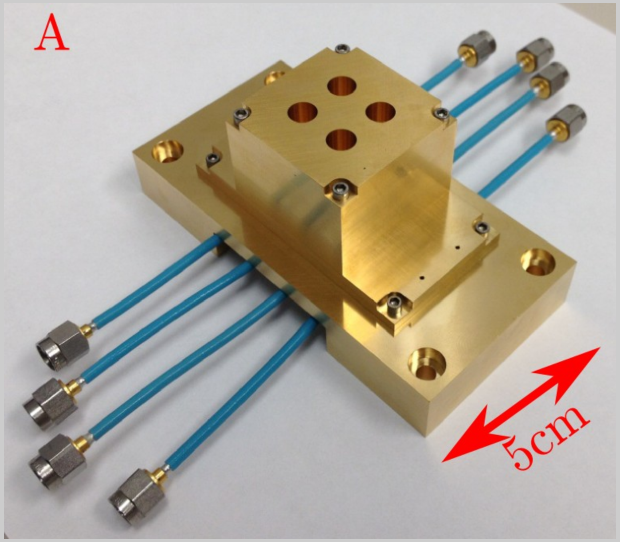


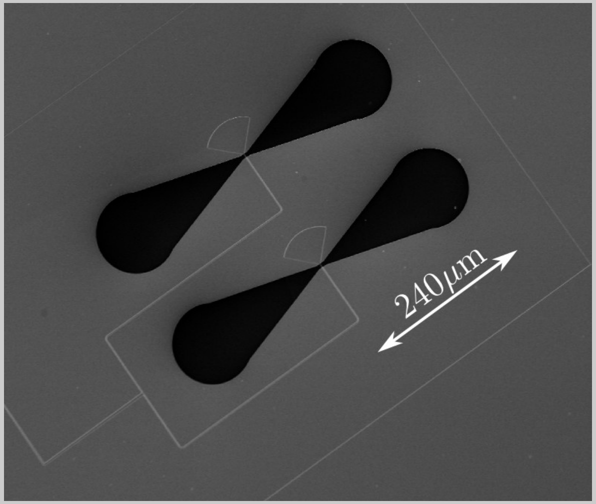


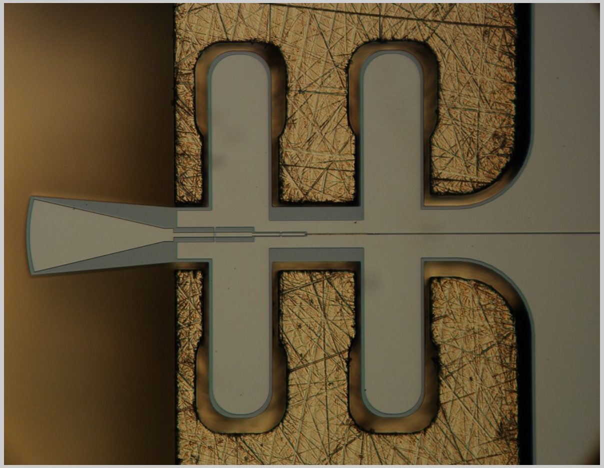


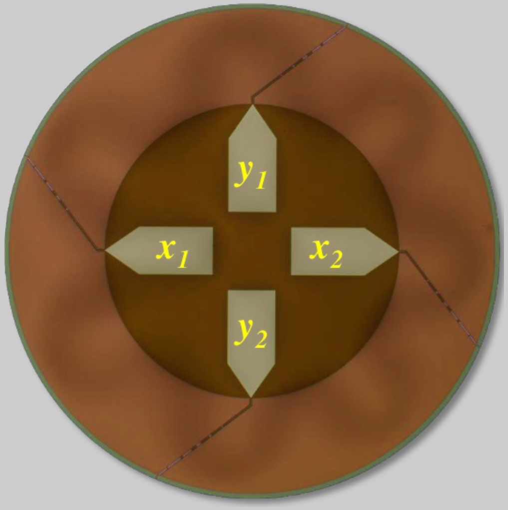
Images: H. Miranda; spinningspark@wikipedia

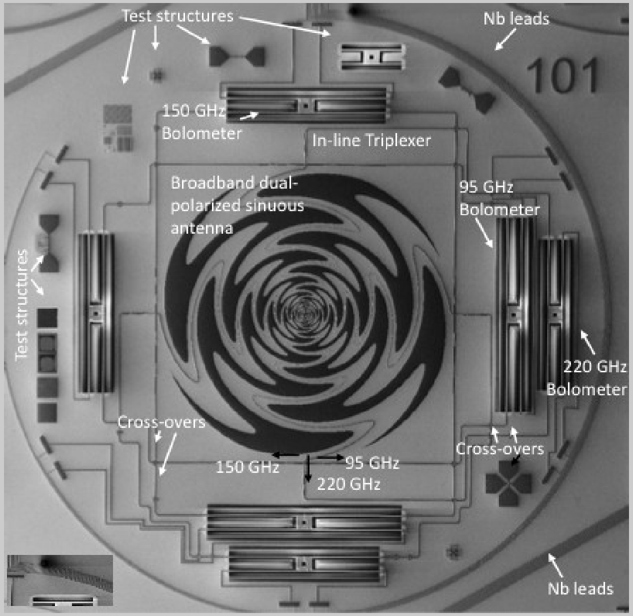
Tools: antennas and horns





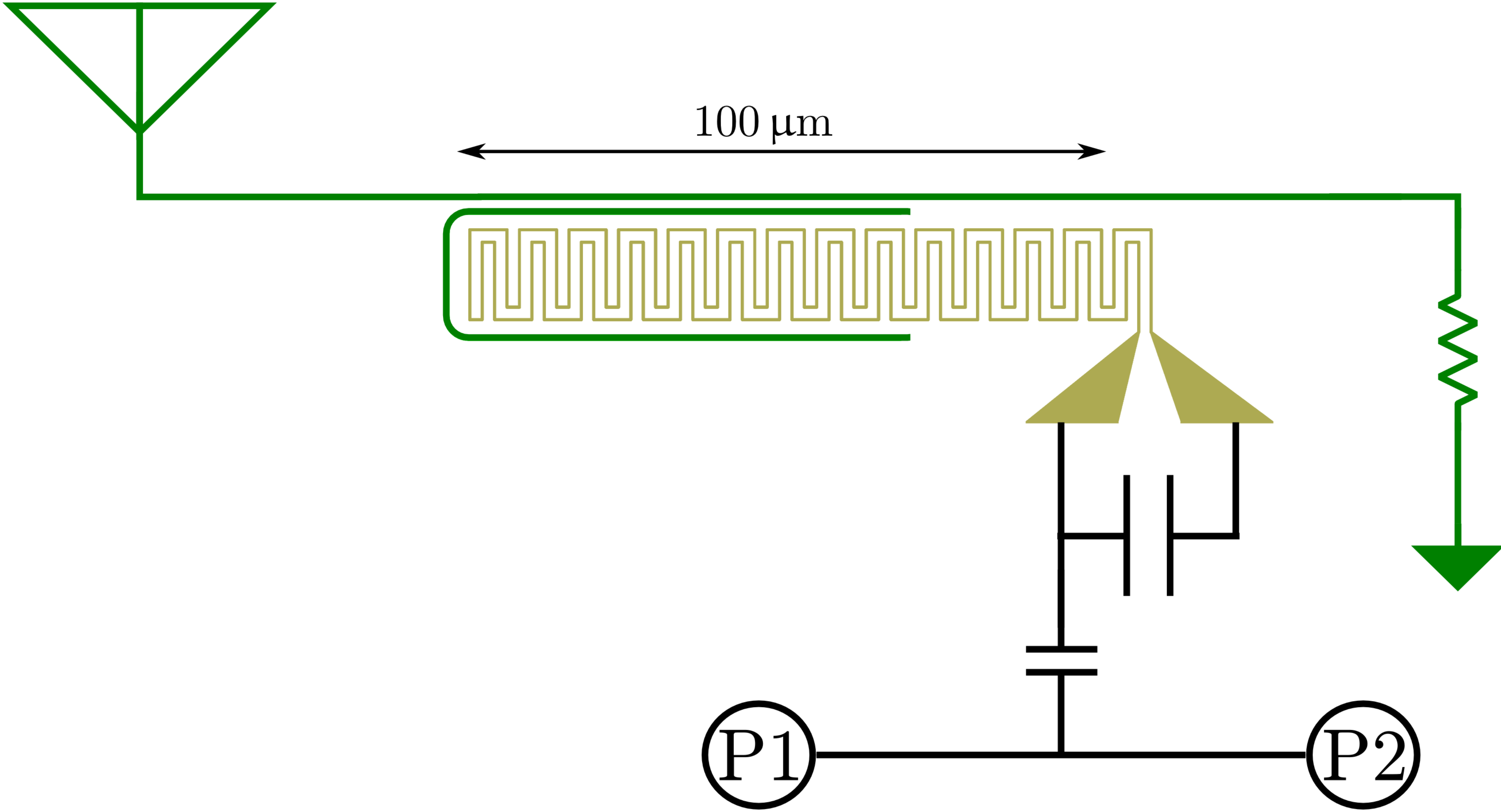




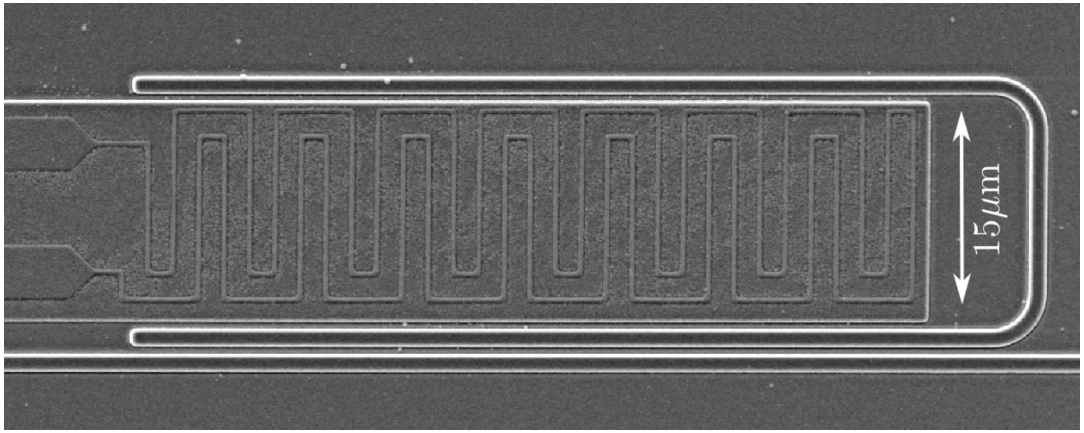


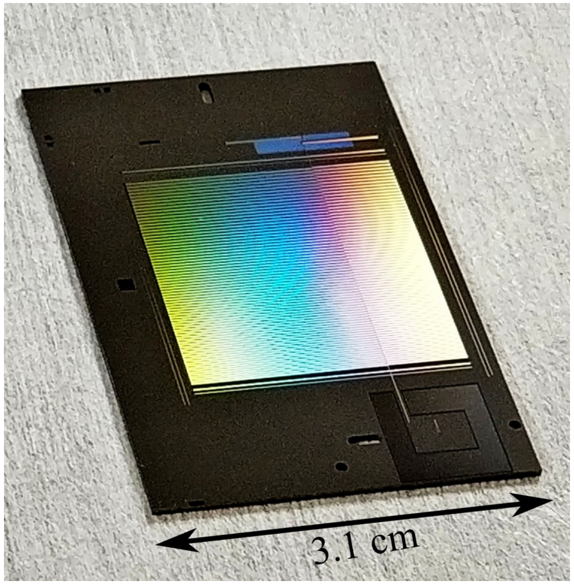
Some images: Advanced ACTPOL; SPT-3G

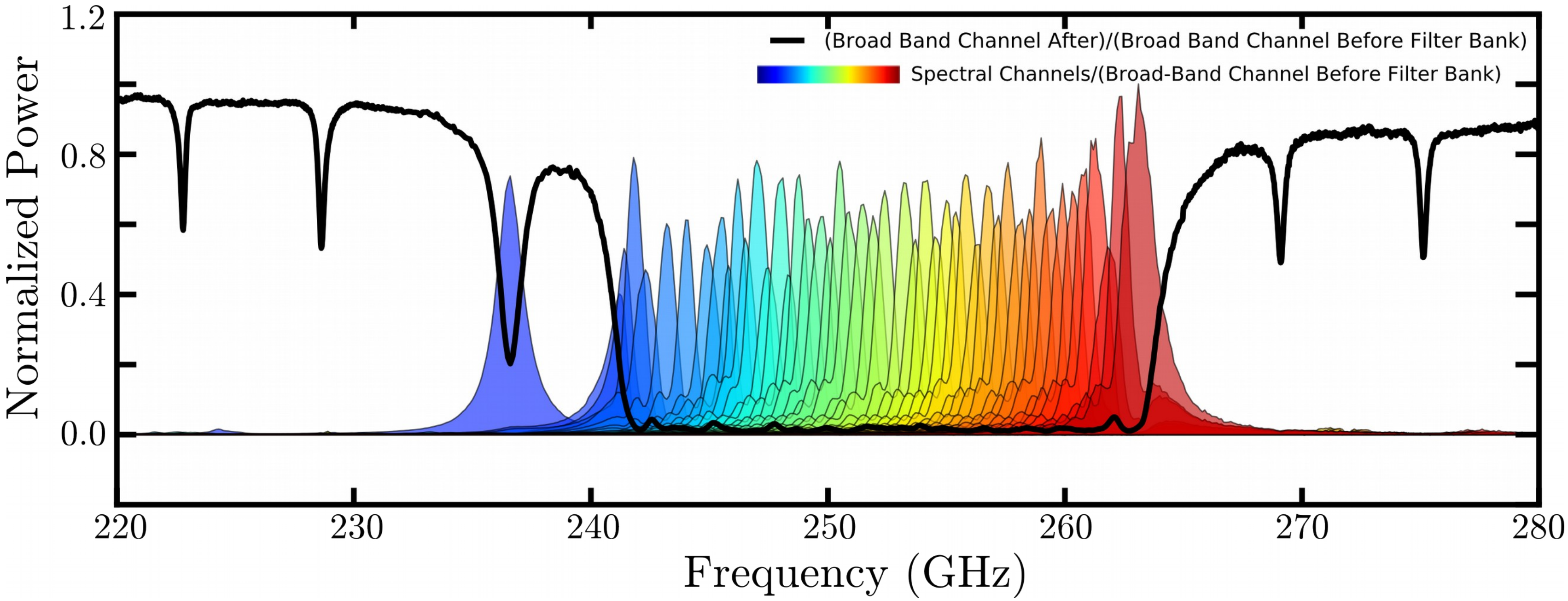
SuperSpec: on-chip spectroscopy using microstrip resonator filters



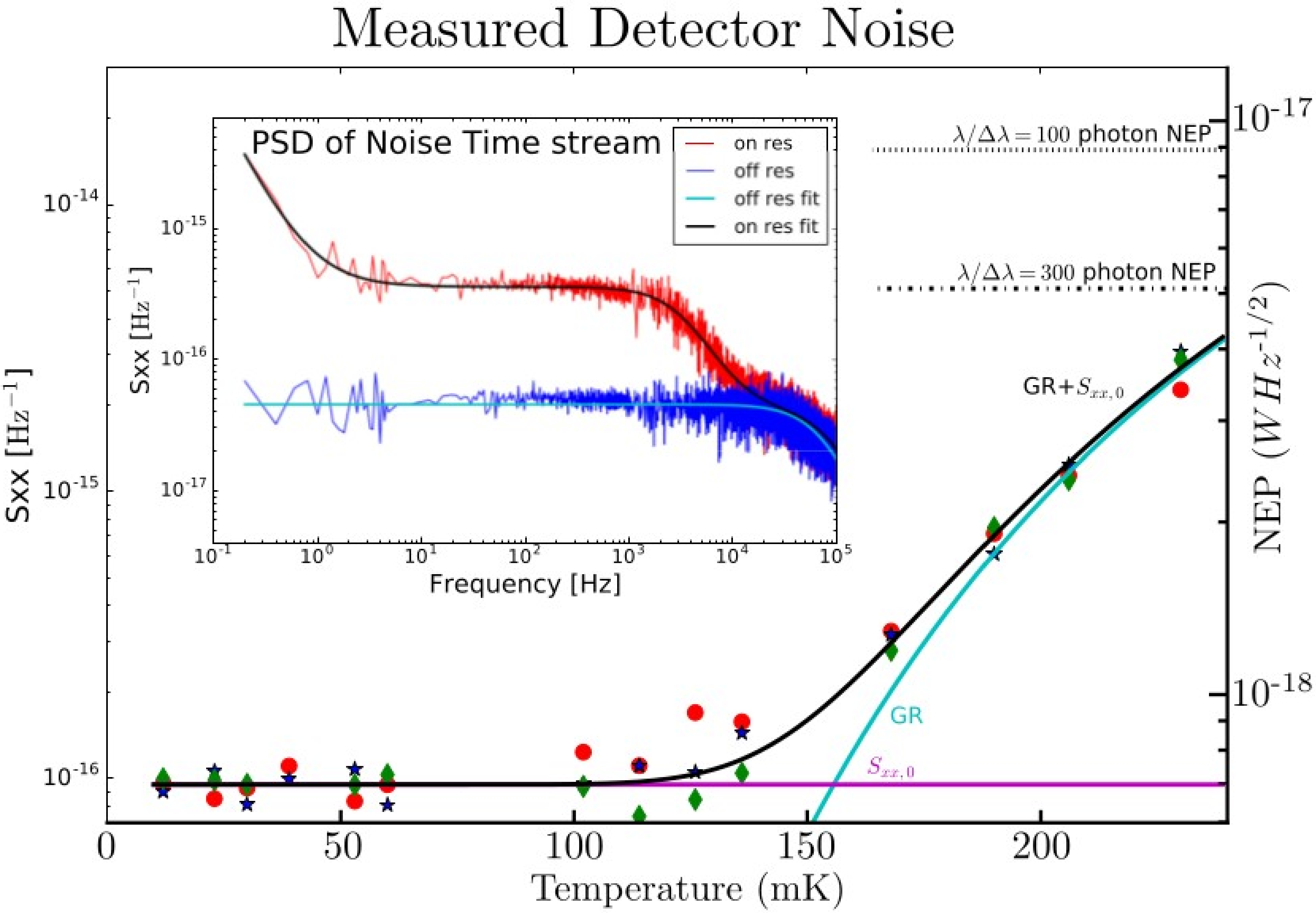
SuperSpec: an on-chip, R=300 spectrometer covering the 1 mm atmospheric band







Measured NEPs meet requirements for ground-based spectroscopy and submm/mm cameras.


Measured Detector Noise

PSD of Noise Time stream

Next steps for on-chip band definition: improving R

- How high can we go in resolving power?
  - Current devices are limited by dielectric loss in the material used for the microstrip.

$$1/R = 1/Q_c + 1/Q_i + 1/Q_{\mathrm{loss}}$$

$$Q_{\mathrm{loss}} = 1/\tan\delta$$

Efficient operation requires $R \lesssim Q_{\mathrm{loss}}/3$

Currently $Q_{\mathrm{loss}} \sim 1400$ for silicon nitride.
This limits R to a few hundred.

Lower loss materials exist:
amorphous sputtered Si, crystal Si

Currently working to: deliver R=1000, explore R~3000

Next steps for on-chip band definition: higher frequencies

- How HIGH can we go in frequency?
  - Superconducting transmission lines stop working below

$$\nu_{\rm max} < 72\,{\rm GHz}\,\frac{T_c}{1.0K}$$

Candidates:

Nb: 8-9 K, 600 GHz (500 microns)
NbN: ~14 K, 1.0 THz (300 microns)
NbTiN: ~16 K, 1.2 THz (250 microns)
Metamaterial dielectric “waveguide” could go even higher.

Currently working on:
Nb 850 and 650 micron devices
NbTiN or NbN at 350 and 250 microns

Next steps for everything: More sensitive detectors

- Several groups have measured NEPs of $\mathrm{few}\times 10^{-19}\mathrm{W}/\mathrm{Hz}^{-1/2}$
- This is great for most sub-orbital applications.
- Work is ongoing to explore lower noise limits needed for cold space cameras, narrow suborbital bands
- This is technology-agnostic: similar detectors can be used behind a grating spectrograph, a horn array, or an antenna.

Conclusions

- Very large arrays of submm detectors will enable new classes of instruments.

- Kinetic inductance detectors have many useful properties and are now a mature technology.