Far-IR Detectors for Cosmic Dawn

Matt Bradford

January 3, 2017

- Far-IR Overview and Origins Space Telescope
- 3 Detector approaches with examples
- Outlook

Far-IR spectroscopy decodes cosmic history in galaxies

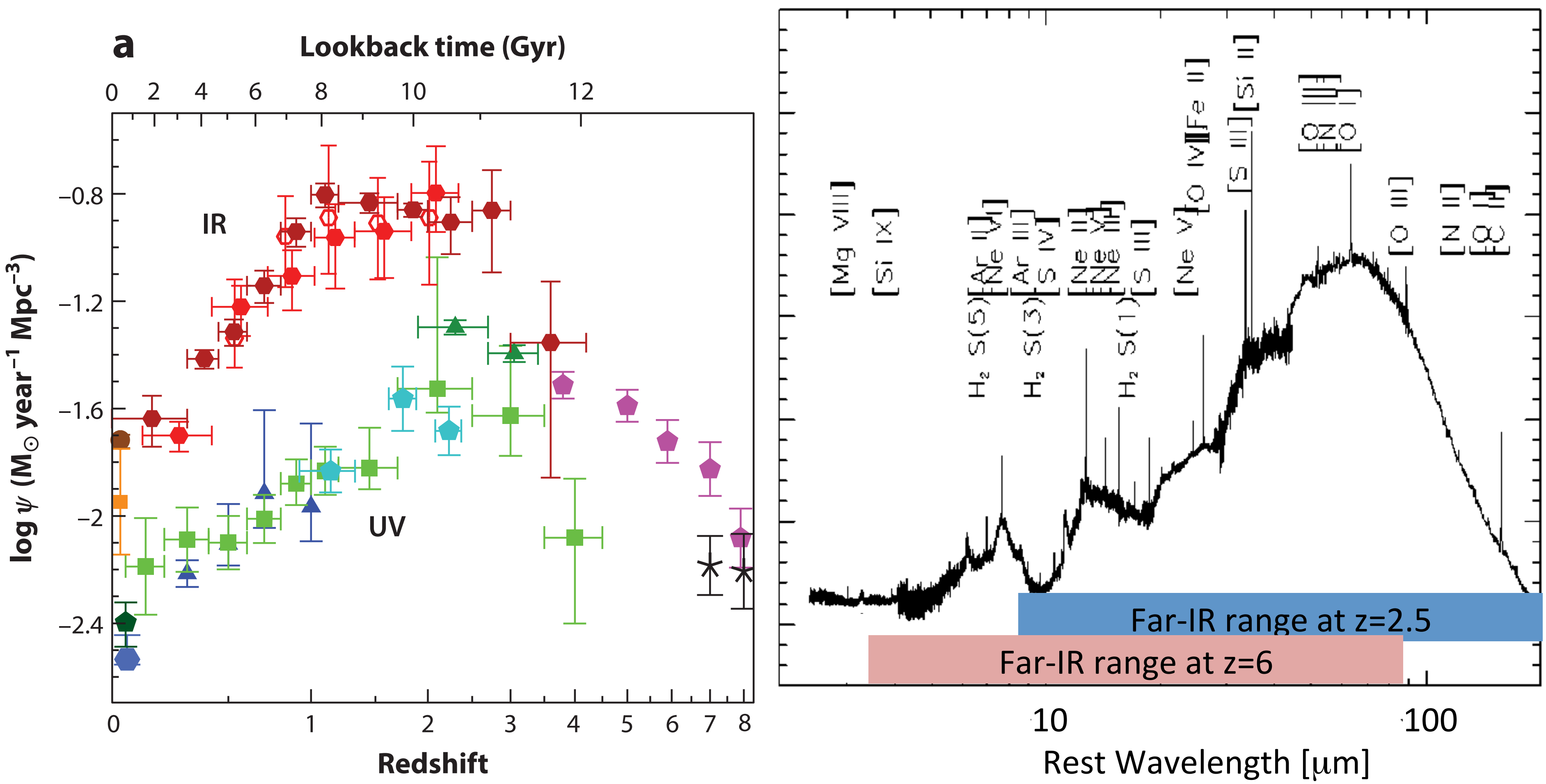
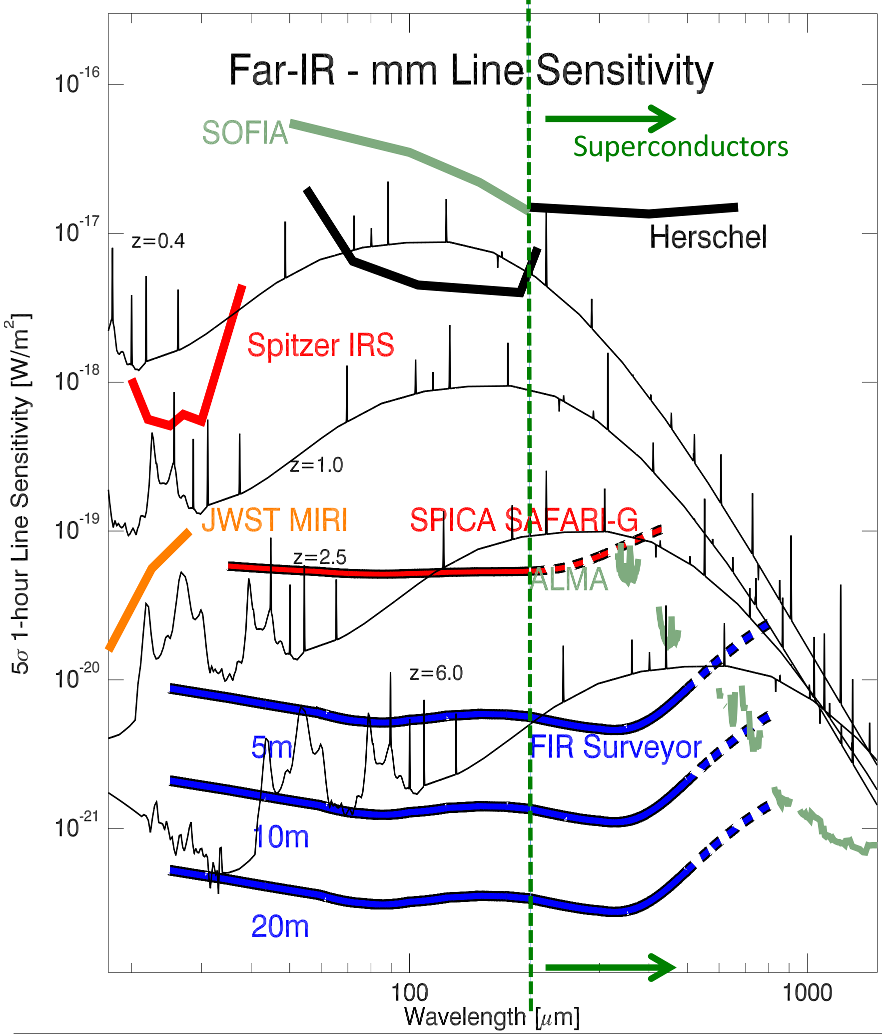
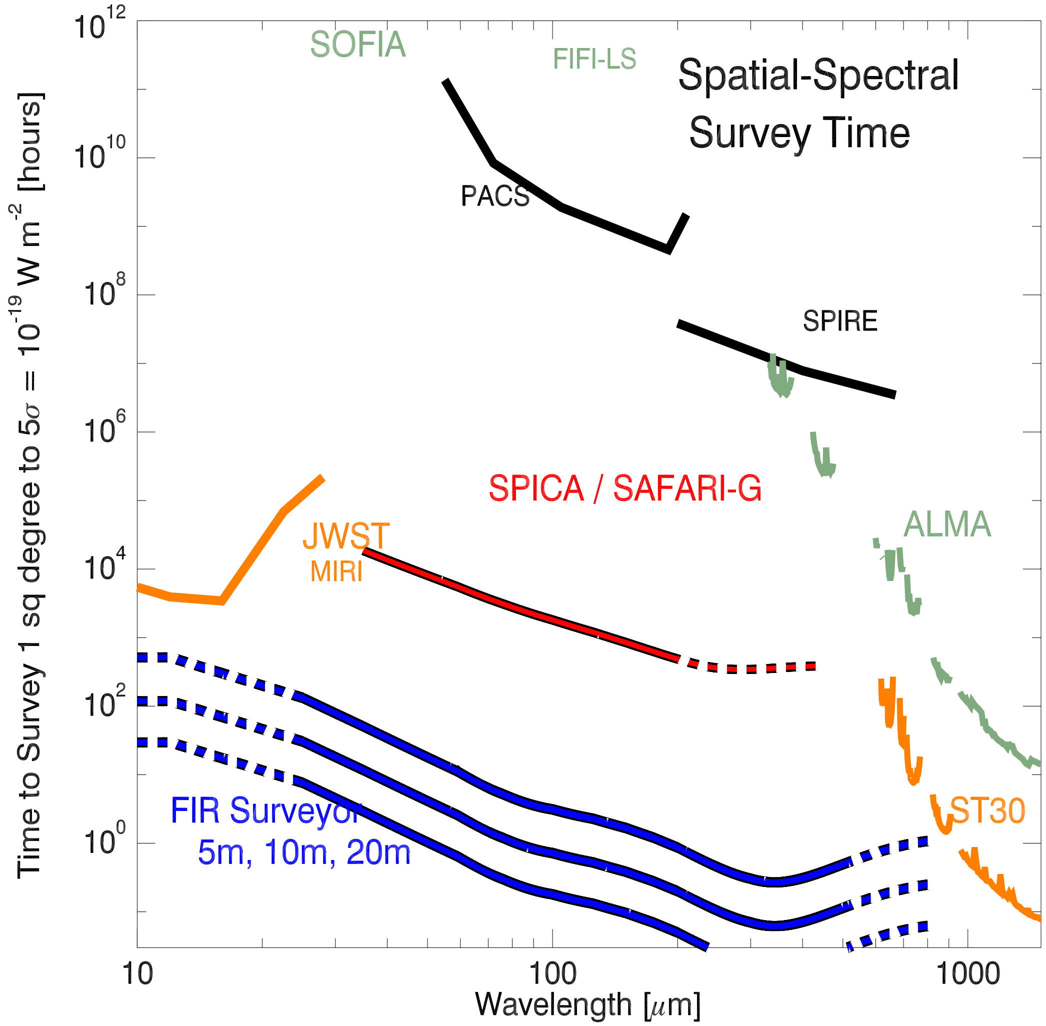


Figure 1: LEFT Cosmic star formation rate history as measured in the rest-frame ultraviolet, and far-infrared, reprinted from Madau & Dickinson, 2014 [44]. Red points are from Spitzer and Herschel, green and blue from rest-frame UV surveys. Purple points are from the Bouwens et al. [7, 6] based on deep Hubble fields using dropout selections. Right: Full-band spectrum of Circinus, a nearby galaxy with an active nucleus obscured by dust, obtained with the Infrared Space Observatory (ISO) [25, 50, 63]. This shows the range of ionized, atomic, and molecular gas cooling lines originating deep in the obscured core of the source. (Vertical axis is λF_λ, major ticks $5\times10^{-12}\,\mathrm{W\,m^{-2}}$.)

Spectral Surveys. Capabilities from mid-IR to millimeter.



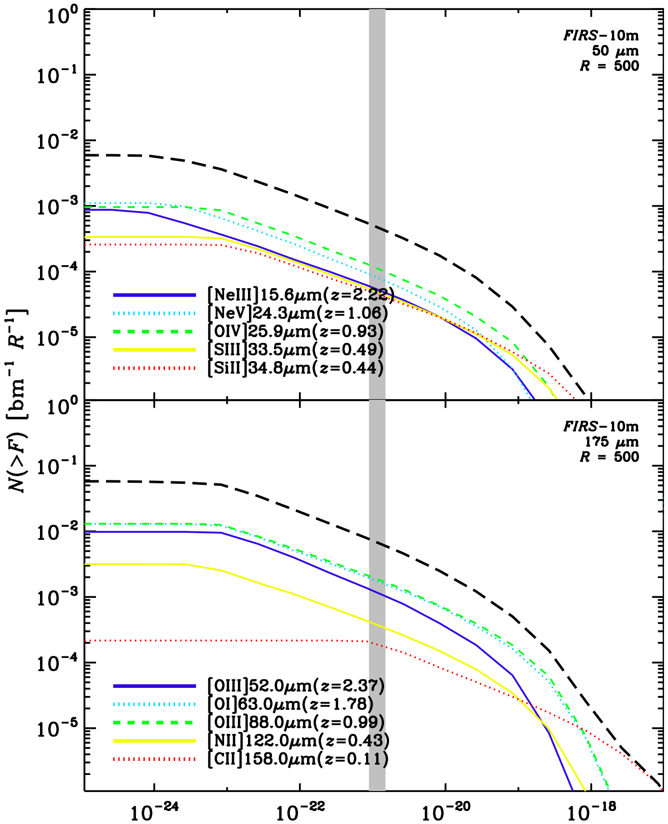


- Origins Space Telescope (OST) (and to some extent SPICA) can obtain spectra of galaxies in the Universe's first billion years as they are born, comparable to JWST and ALMA in sensitivity. Spectrometers assume 100 beams, R=500, essentially BG limited.

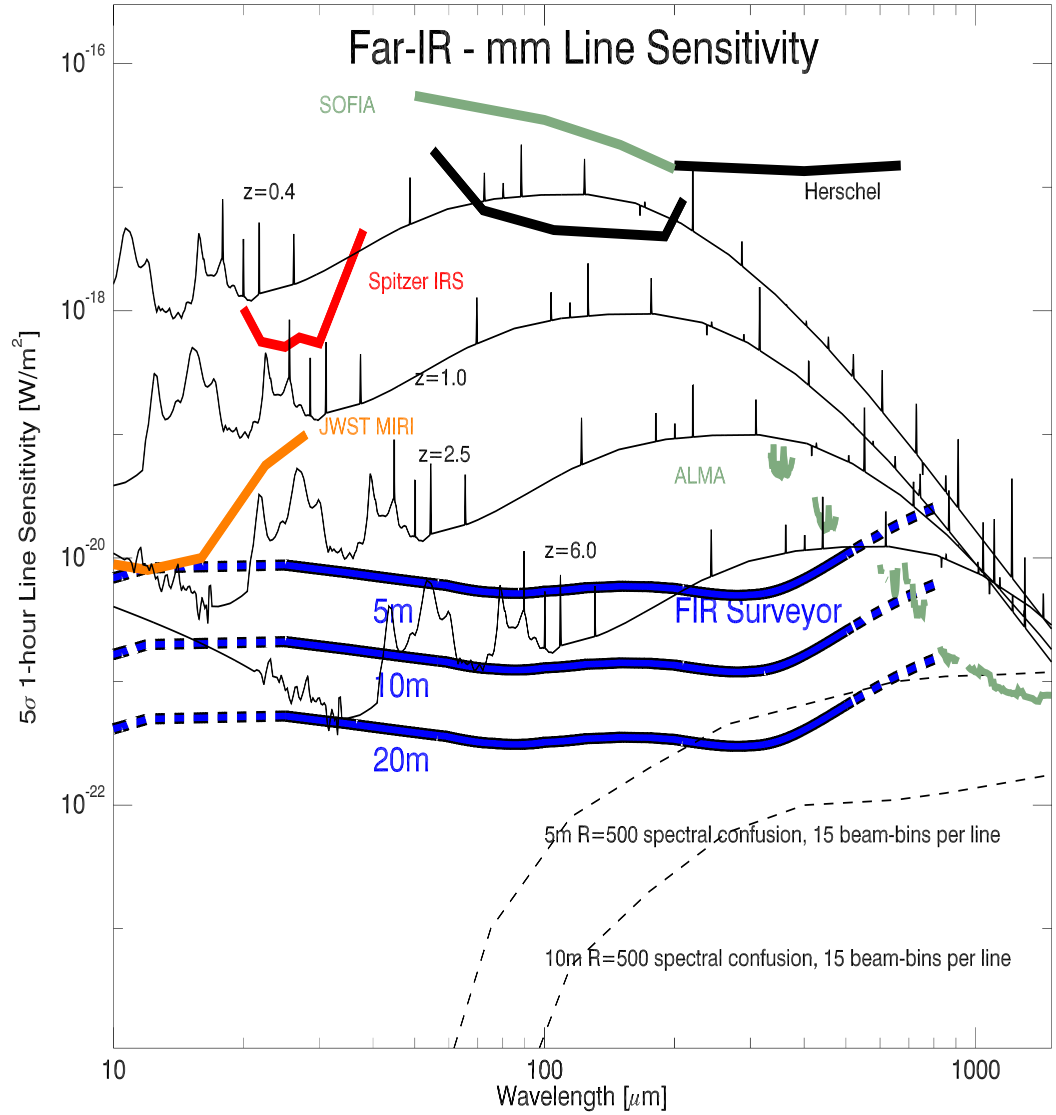
New web site: *origins.ipac.caltech.edu*

- SPICA currently proposed to Cosmic Visions M5 proposal. 2.5 meter aperture, SAFARI R=300 grating spectrometer with R=3000 etalon mode. Our proposal for MoO under preparation.
- **ST30 is CSST** – 30m ground-based telescope for the submm, assuming 100 element MOS.

Confusion for Spectroscopy: Not an issue



E. Murphy et al., in prep



`Line Counts' indicate that even with 5 or 10m telescope and R=500, confusion is not an issue except perhaps in very long integrations at the longest wavelengths.

Example 3-D spatial-spectral surveys

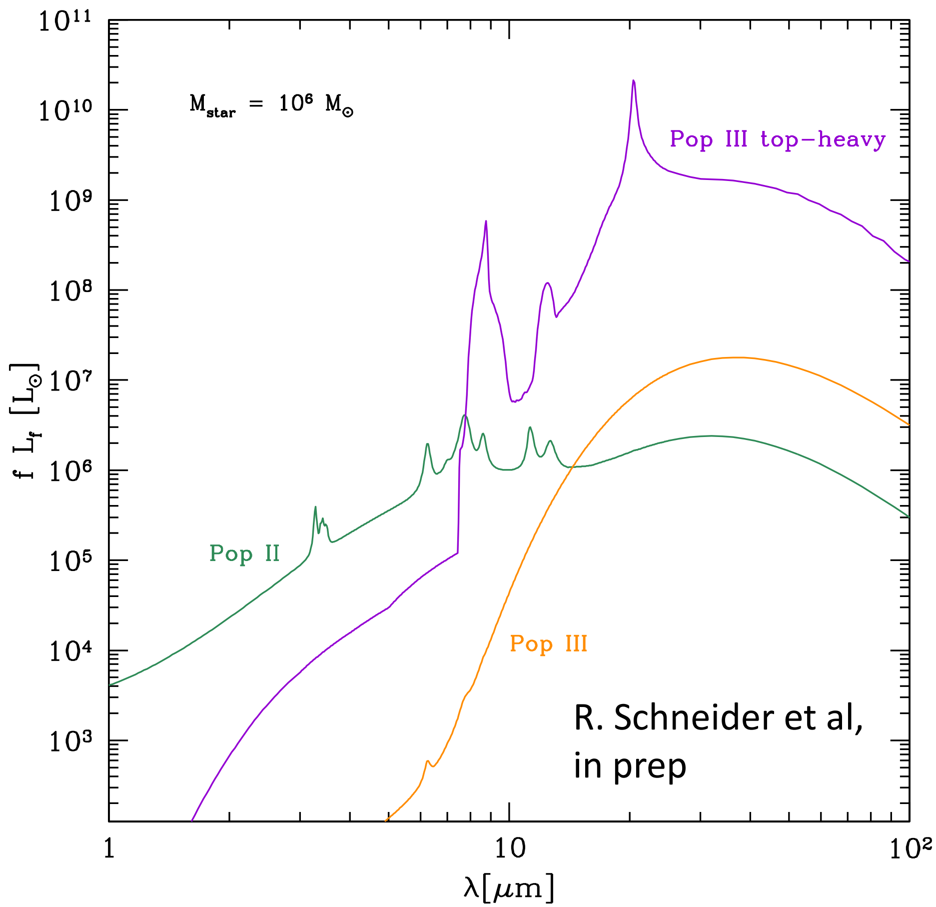
Table 3: Far-IR Surveyor Example 3000-hour Spectroscopic Surveys (on 10m)

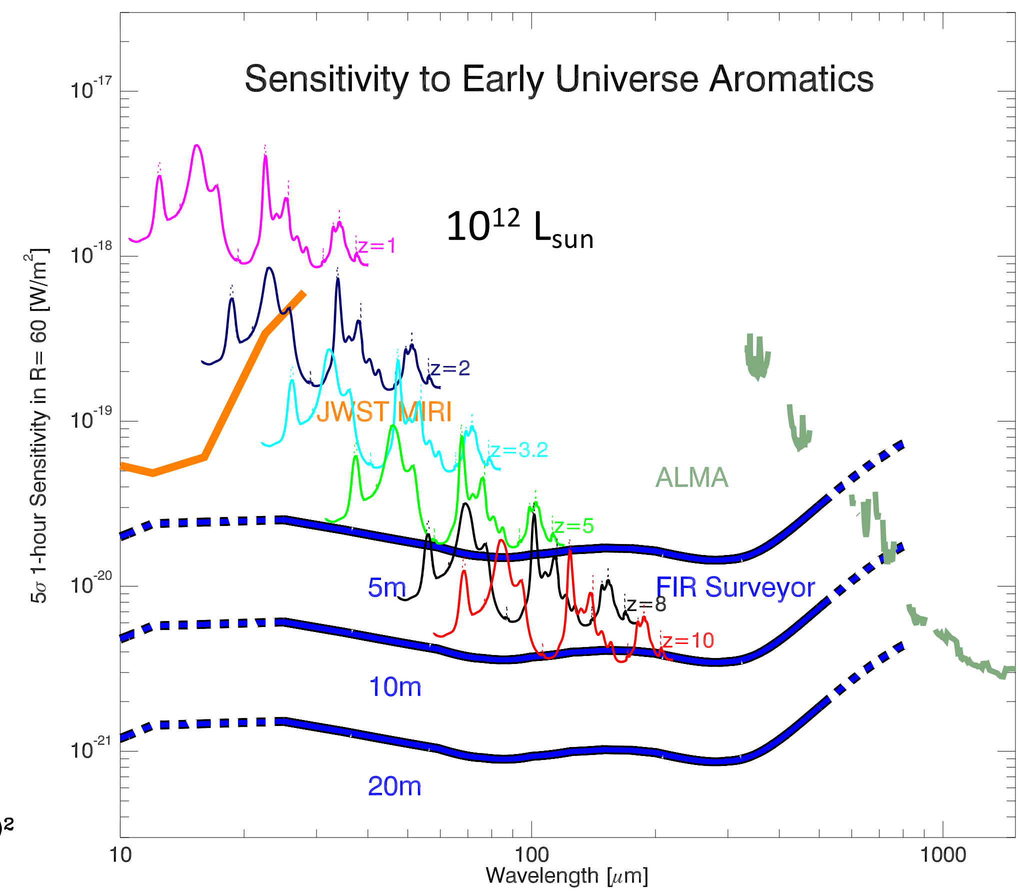
30 μm	50 μm	100 μm	200 μm	400 μm	approx. galaxy yield
LSS survey: 5000 square degrees – 5σ depths [W m^{-2}]					
6.1e-19	2.9e-19	1.21e-19	6.4e-20	3.8e-20	$\sim$1 billion
wide: 100 square degrees – 5 σ depths [W m^{-2}]					
8.6e-20	4.1e-20	1.7e-20	9.0e-21	5.4e-21	$\sim$60 million
deep: 3 square degrees – 5 σ depths [W m^{-2}]					
1.5e-20	7.1e-21	3.0e-21	1.6e-21	9.3e-22	$\sim$4 million
ultra-deep: 110 square arcminutes – 5 σ depths [W m^{-2}]					
1.5e-21	7.1e-22	3.0e-22	1.6e-22	9.3e-23	?

Numbers are for a 10-meter telescope, using R=500 sensitivities. Assumes that background is subtracted with no penalty. Depth scales as $1/D_{\rm tel}^2$. Instrument is assumed to be 100 beams in all bands. Survey yield is based on line count estimates at 200 microns, integrating over 1 octave of bandwidth (e.g. 140–280 μm) based on line counts from Murphy et al.

Staggering yield for the 5000 square degree survey!!
Galaxy yield is a lower limit, since only considers 1 band.

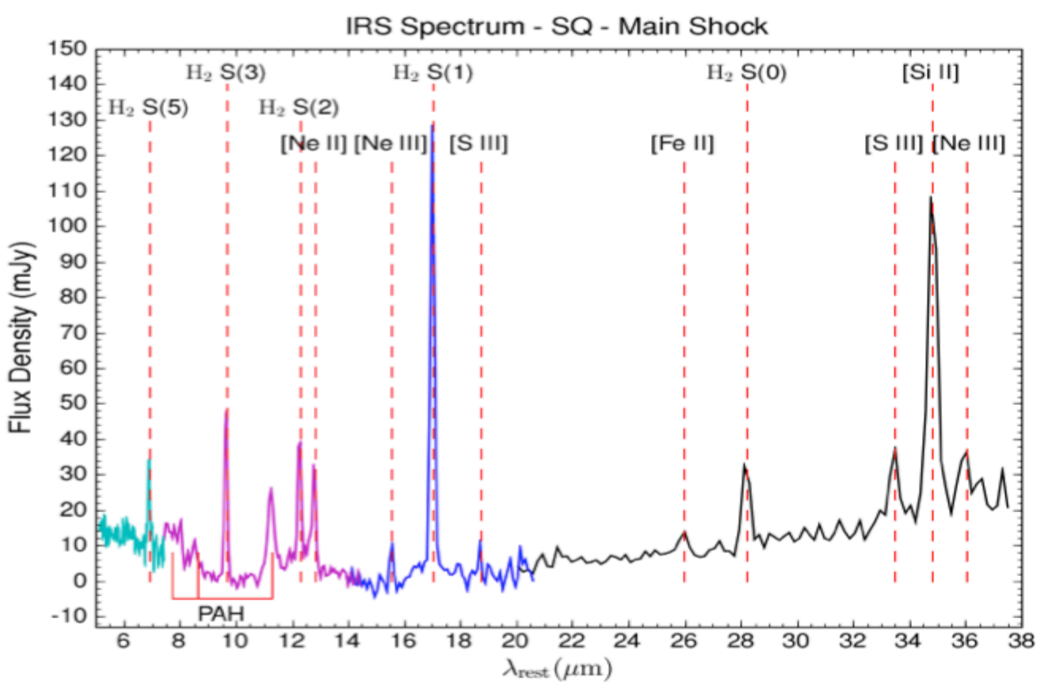
Far-IR Accesses First Dust

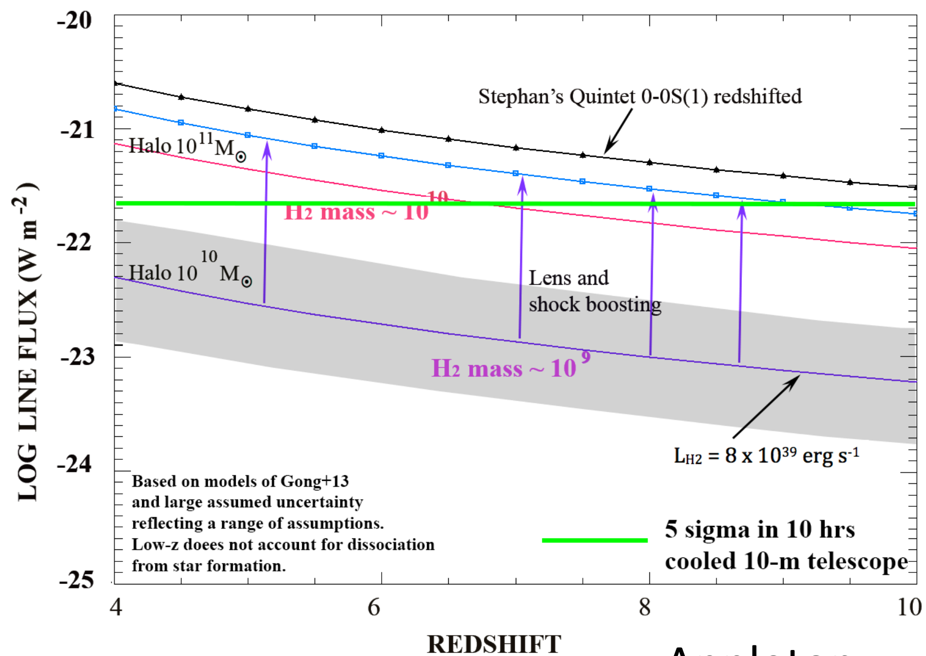




- Origin of large (10^8 M_{sun}) reservoirs of dust in z~5-7.5 galaxies & quasar hosts is not understood. (high mass supernovae, growth in ISM, AGB stars?)
- Rest-frame mid-IR dust features can distinguish this early dust buildup and the early generation of star formation

Primordial Molecular Hydrogen





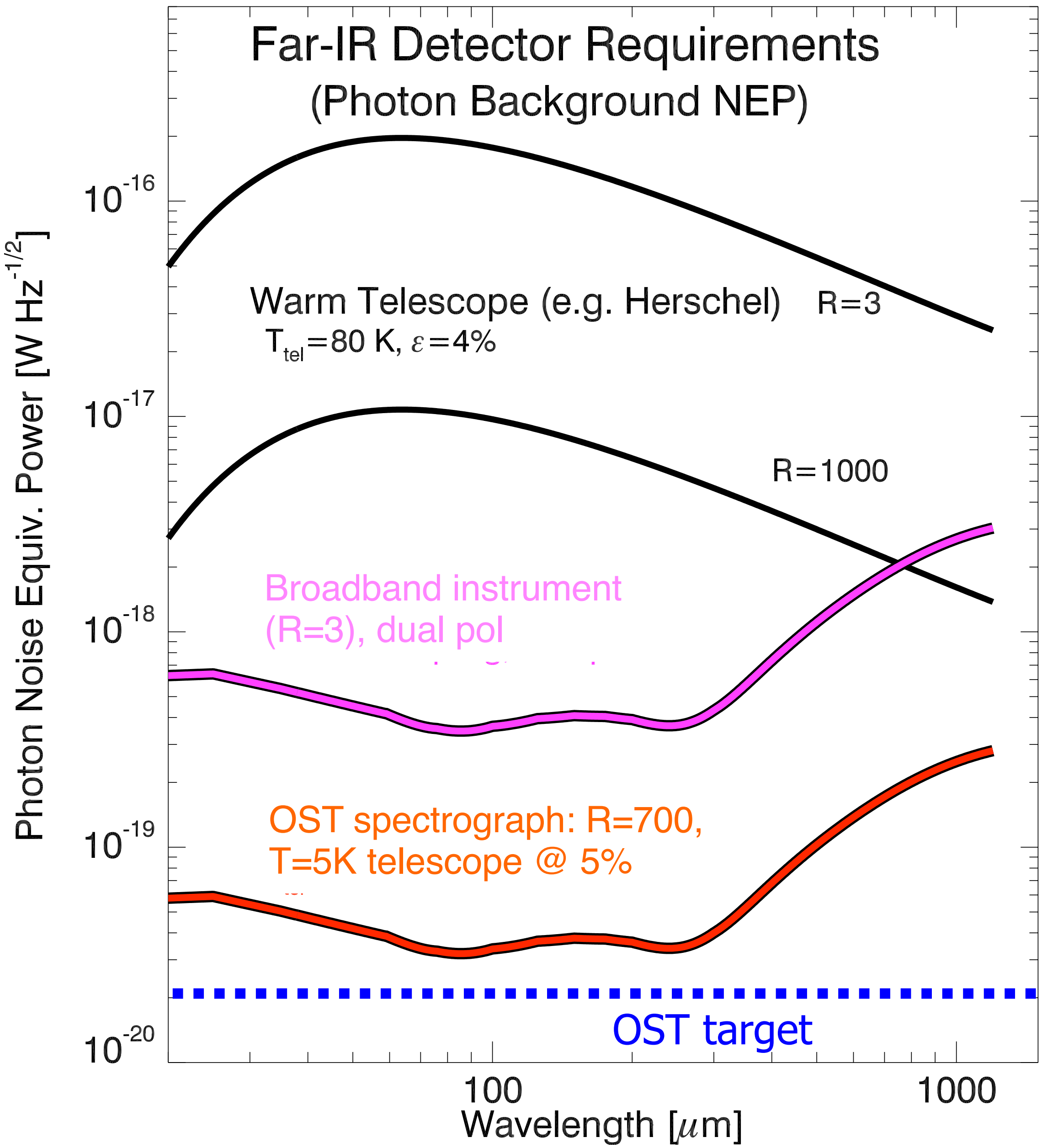
Appleton

- Quadrupole H_2 rotational transitions may be an important coolant enabling galaxy formation and growth in early dark matter halos, particularly if completely primordial (un-enriched).
- Local systems have shown that H_2 transitions measure mechanical energy dissipation as gas collapses in advance of star formation. Can dominate fine-structure line cooling even in moderately enriched systems.
- Sensitive far-IR spectrograph can detect 10^{10} M_{sun} halos if boosted either by lensing or shock heating. Densities is high enough to expect detections in a modest survey of cluster lenses.

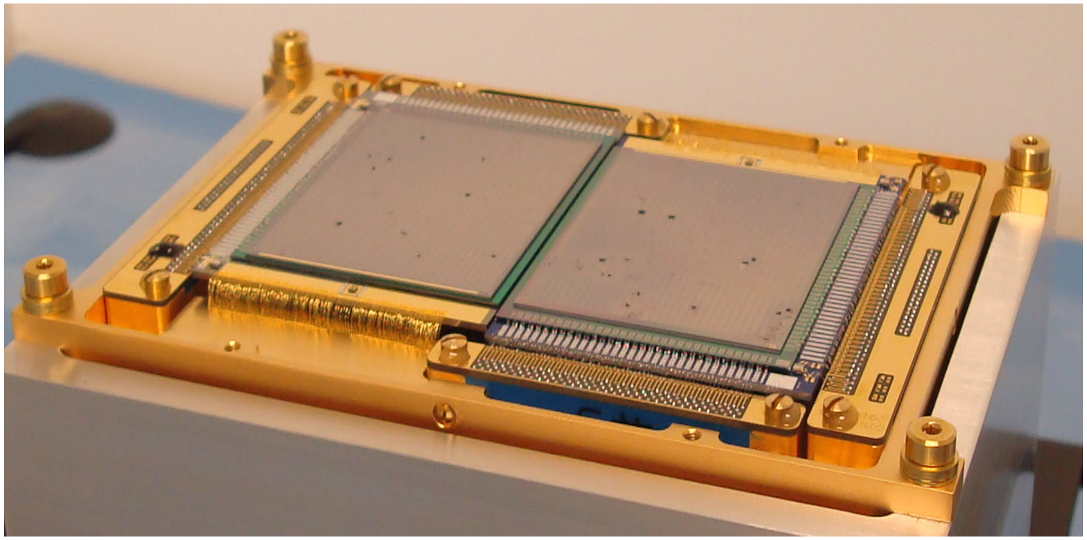
Far-IR Detector Requirements

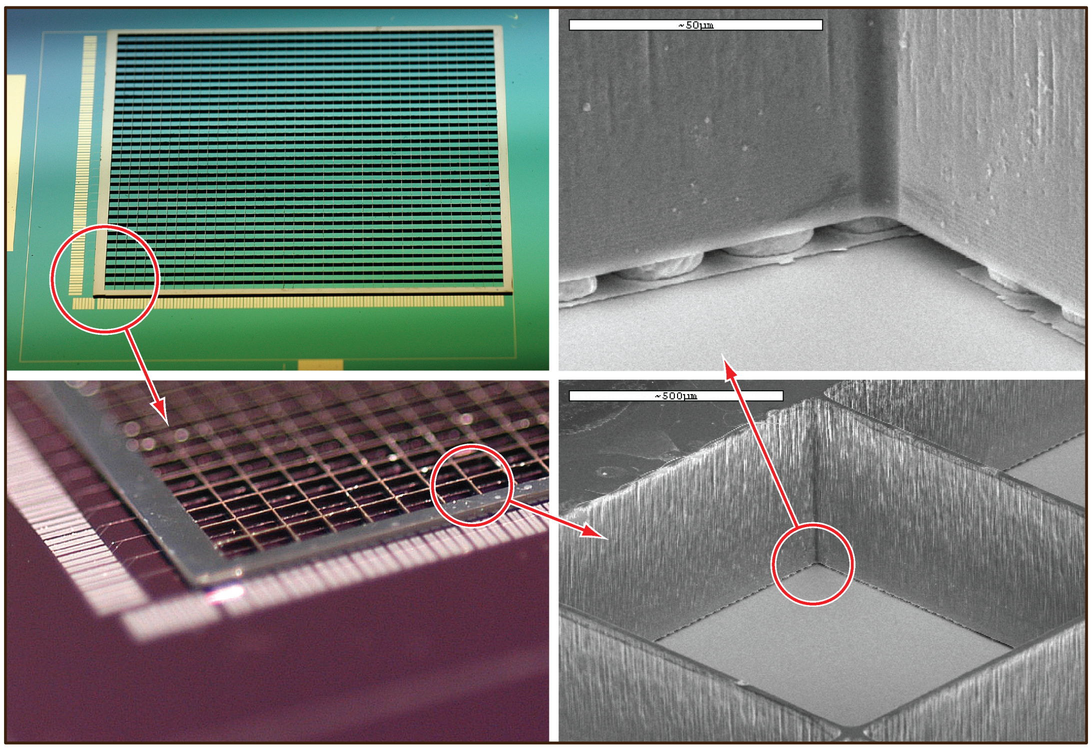
- Per-pixel sensitivity below 3×10^{-20} W $Hz^{-1/2}$ for spectroscopy
- Readout / system scheme enabling 10^5 to 10^6 total pixels in a large observatory.
- Ability couple efficiency across the full 30 microns to 1 mm spectral band.

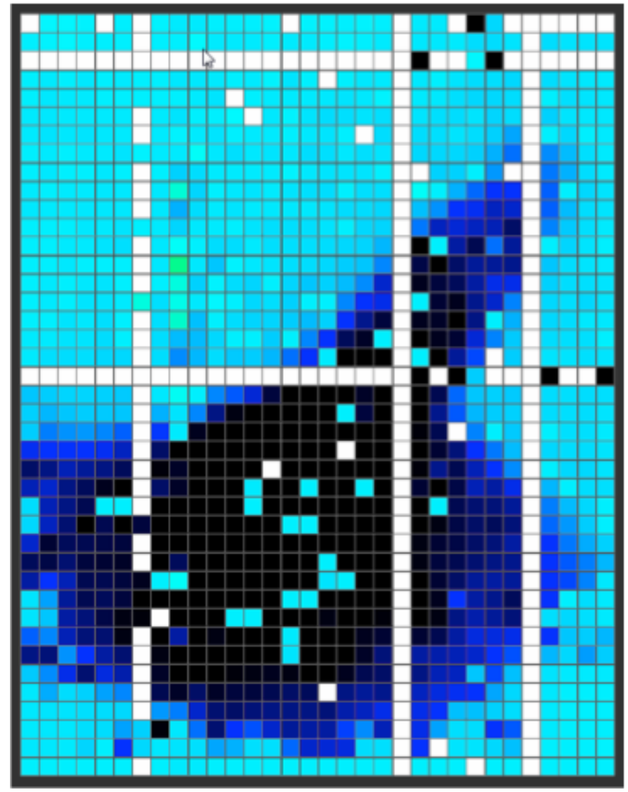
No other market for this technology -> NASA astrophysics + Euro & Japanese agencies must develop.



Transition-edge sensed (TES) bolometers





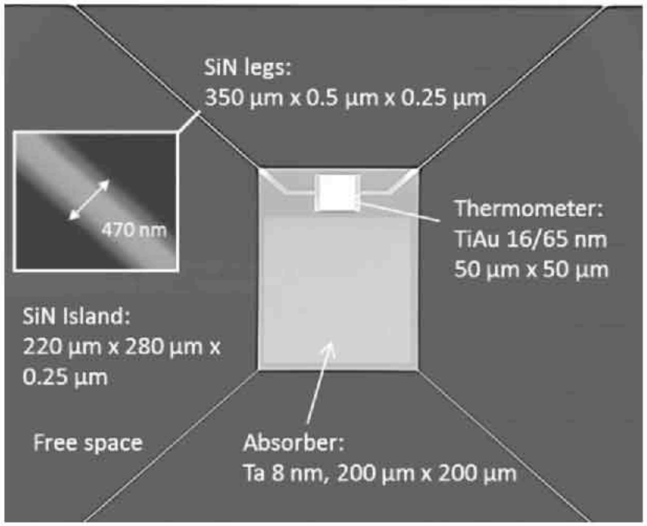


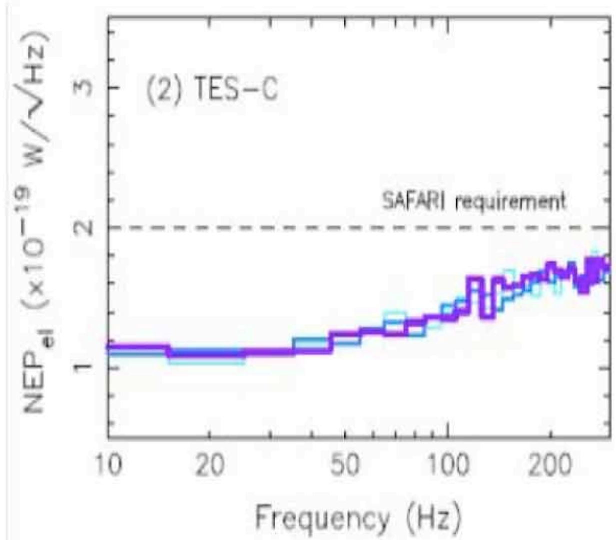
Goddard kilo-pixel array for Hawc-Pol on SOFIA.

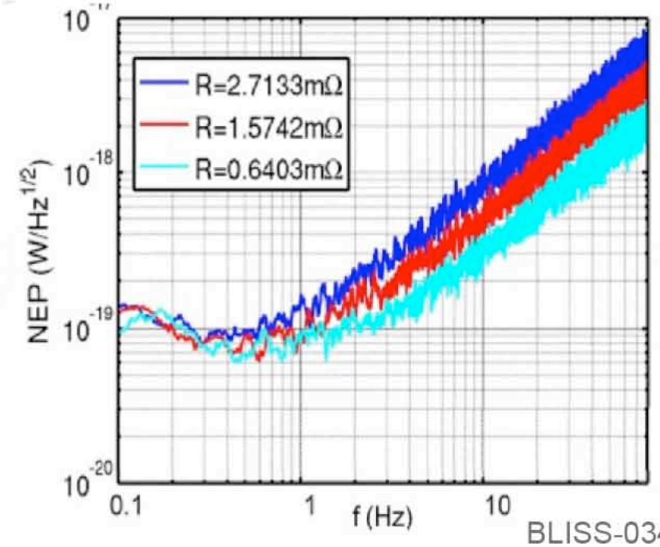
- 32 x 40 format with integrated bump-bonding to multiplexer.
- NEP ~ 8×10^{-17} W $Hz^{-1/2}$
- Time-domain multiplexer as per SCUBA-2, BICEP / Keck. Hard to scale to OST formats.

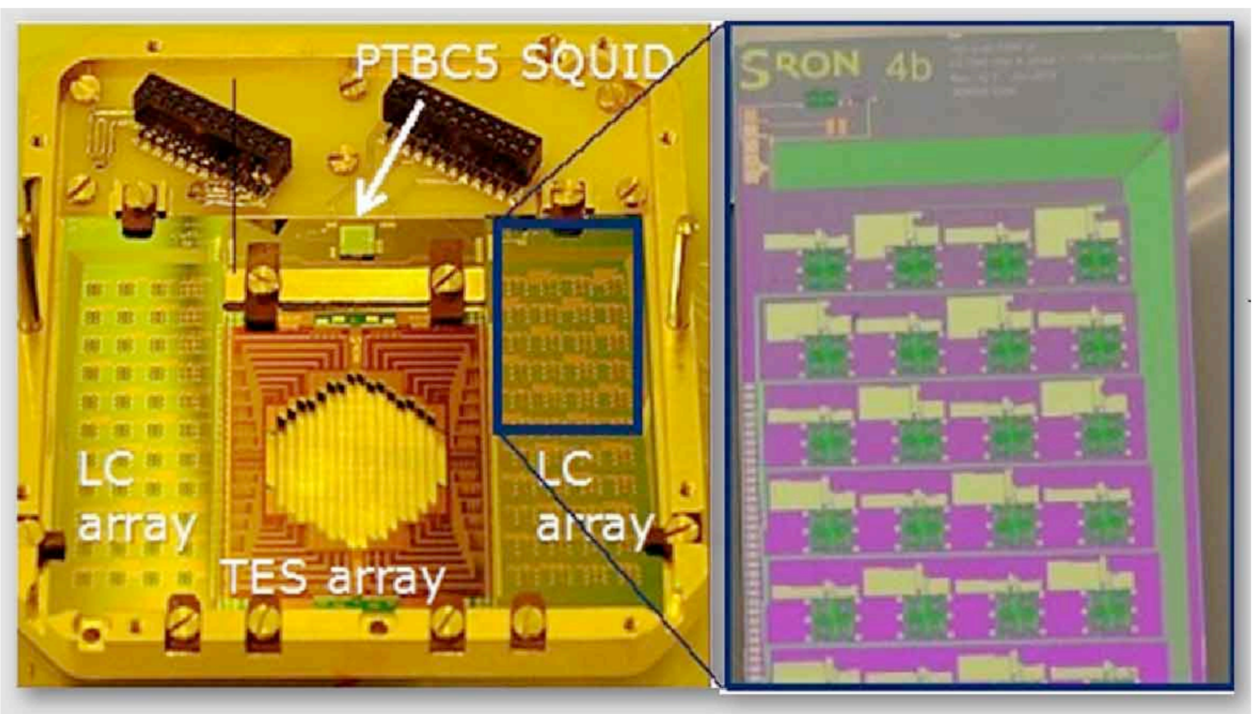
J. Staguhn et al. @ GSFC

Transition-edge sensed (TES) bolometers





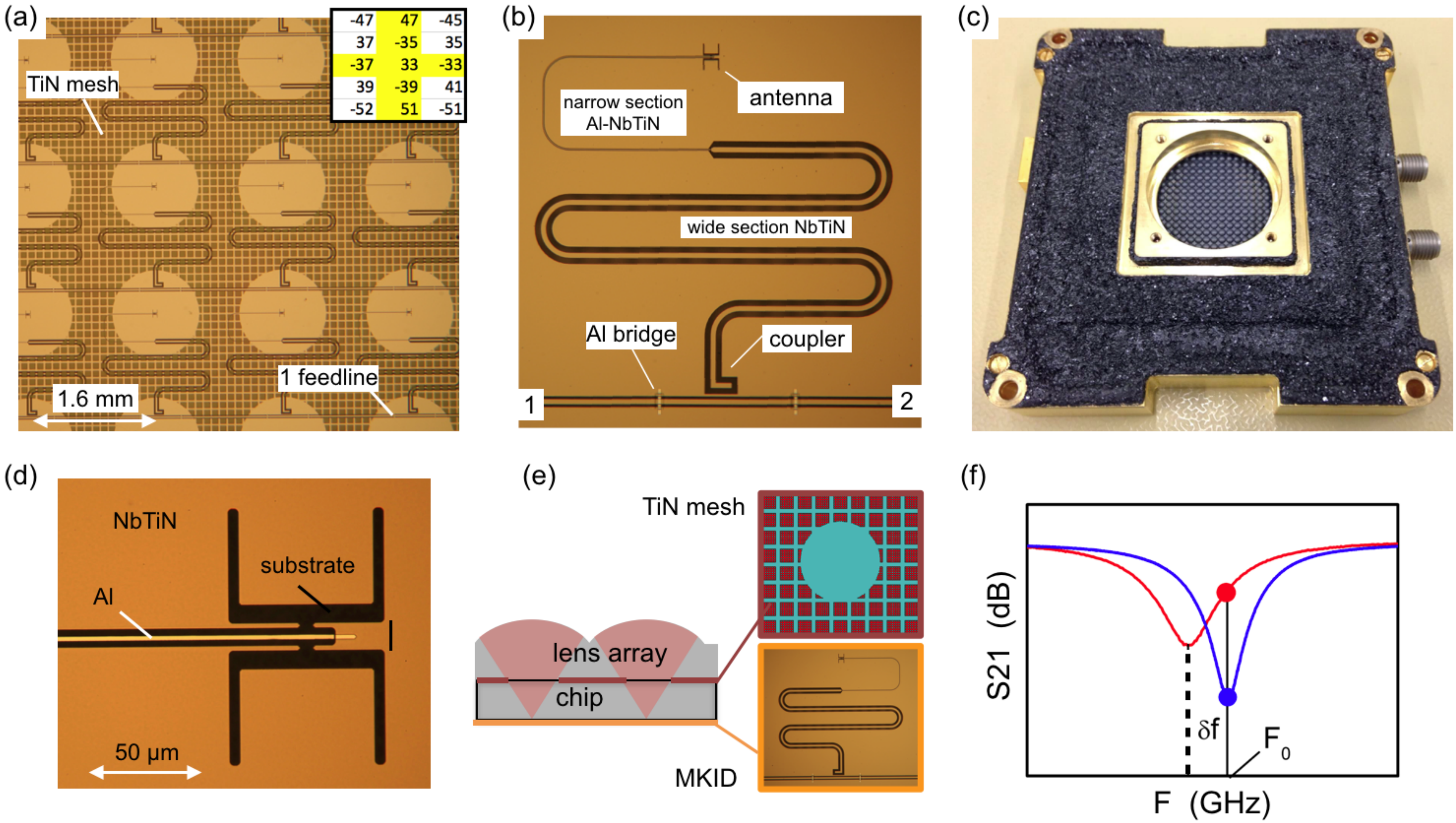




JPL and SRON developed TES bolometers for spectroscopy – long legs and 50-100 mK temperature.

- **NEP ~ 1×10^{-19} W $Hz^{-1/2}$**
- SRON RF frequency-domain MUX with 160-pixel circuit. Might approach OST format with careful thermal design for wiring.

Kinetic Inductance Detectors



J. Baselmans et al. 2016. ESA-funded SPACEKIDs program.

961 Pixel array, 350 microns, antenna coupled. ArXiv #1609.01952

Kinetic Inductance Detectors

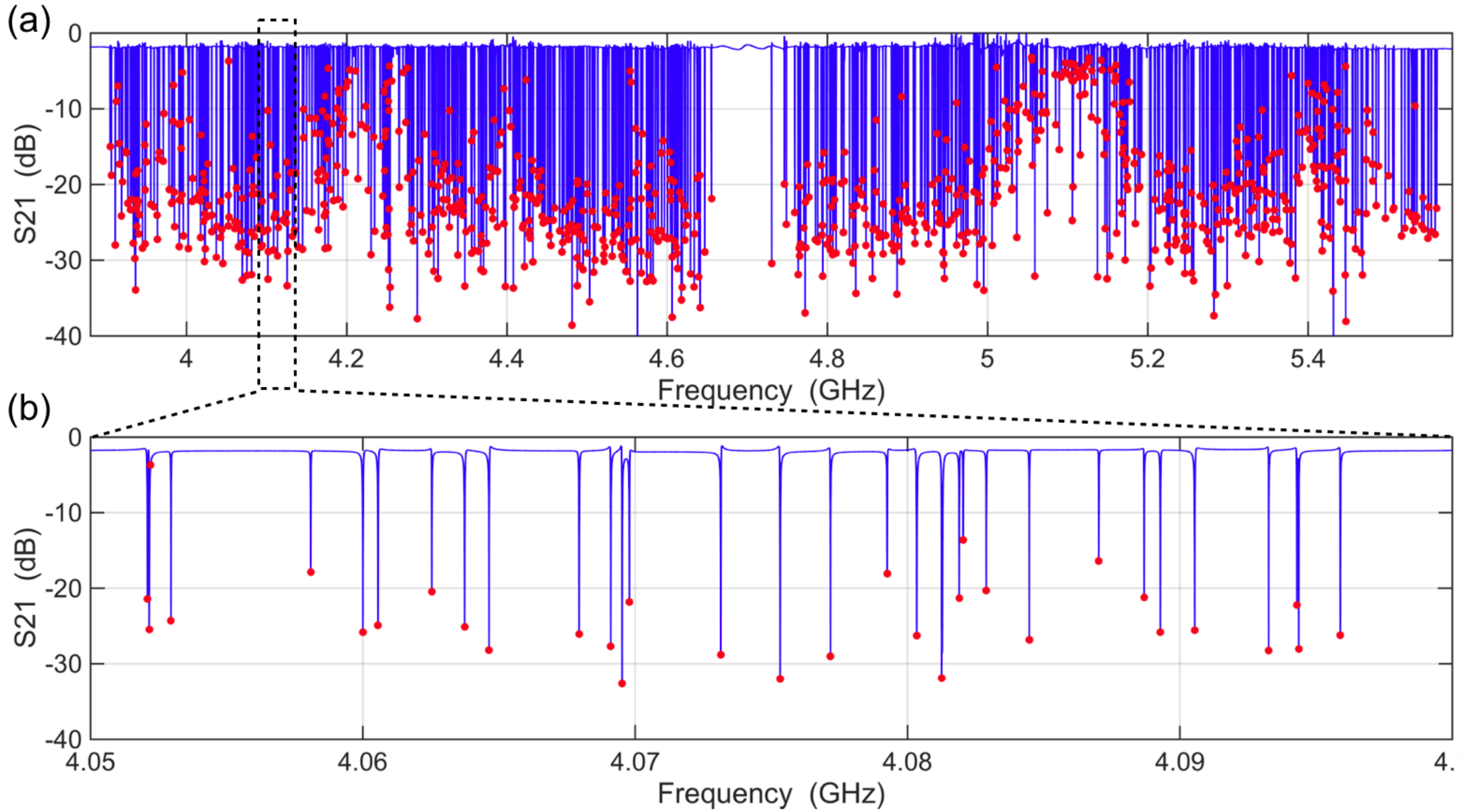
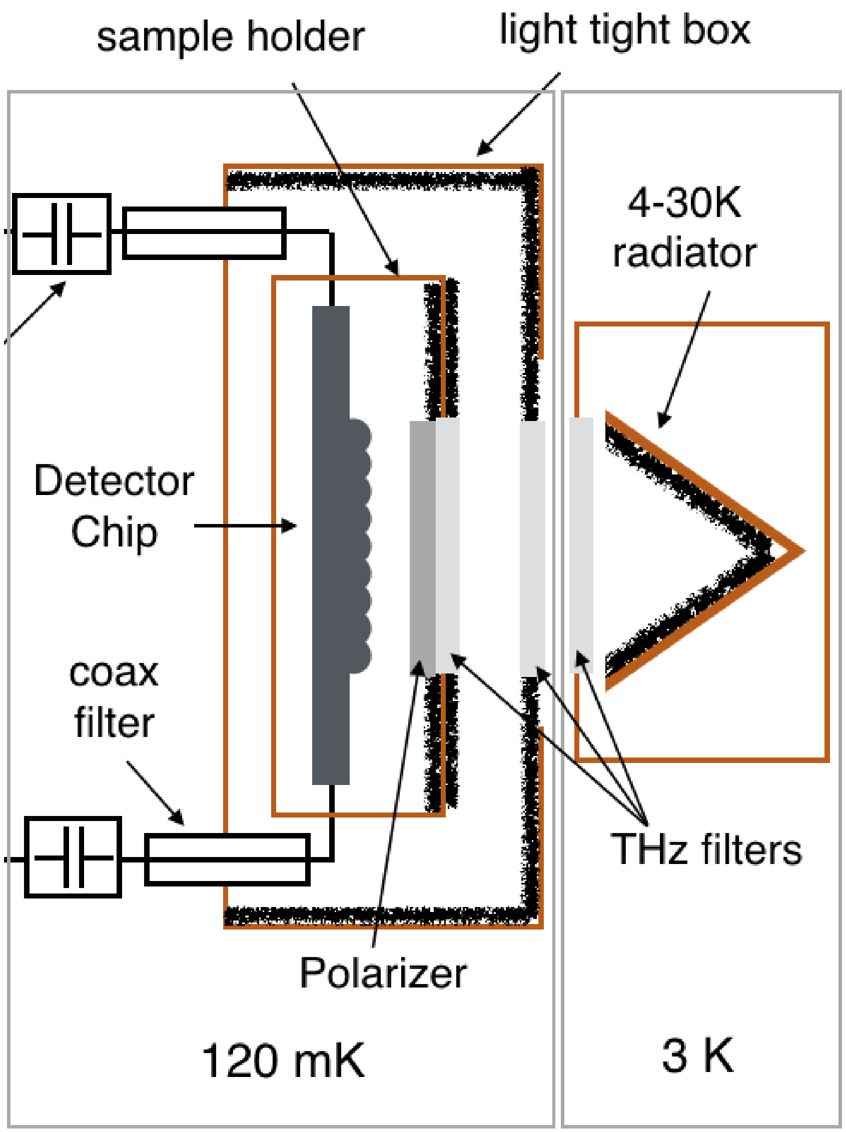


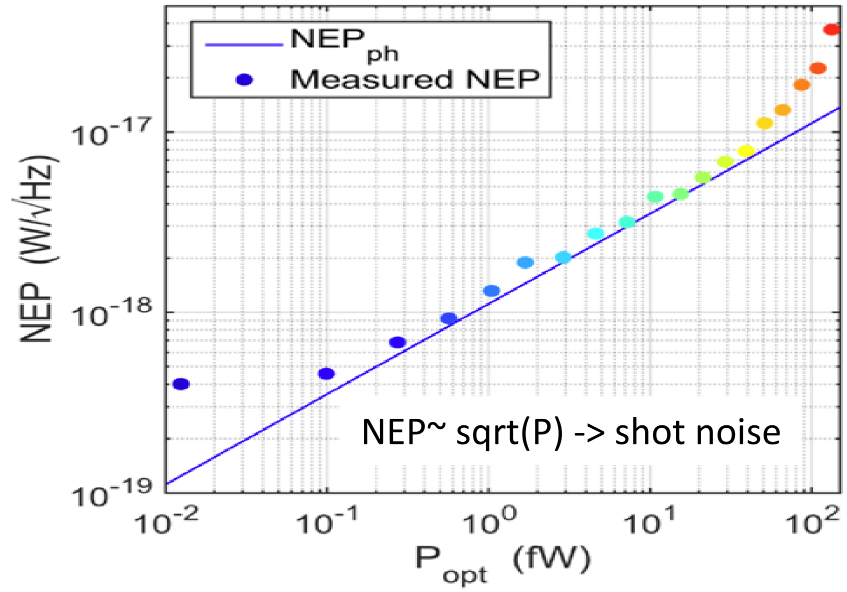
Fig. 3. (a) Frequency sweep of the array, with each dip corresponding to a different MKID pixel. (b) Zoom of a section of panel (a), showing the relative bandwidth of the resonators and the scatter in frequency of the resonators, mainly due to thickness variations in the NbTiN.

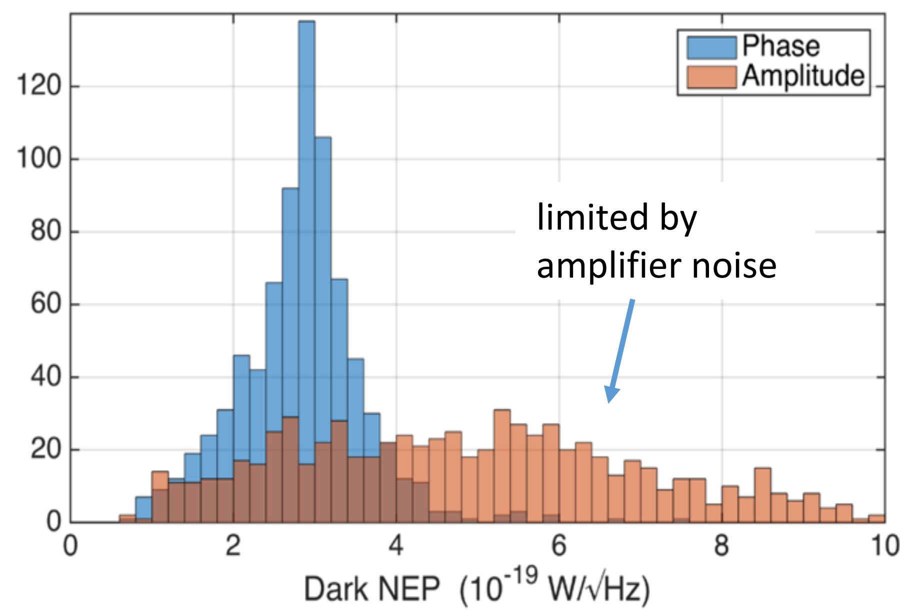
Baselmans et al., 2016

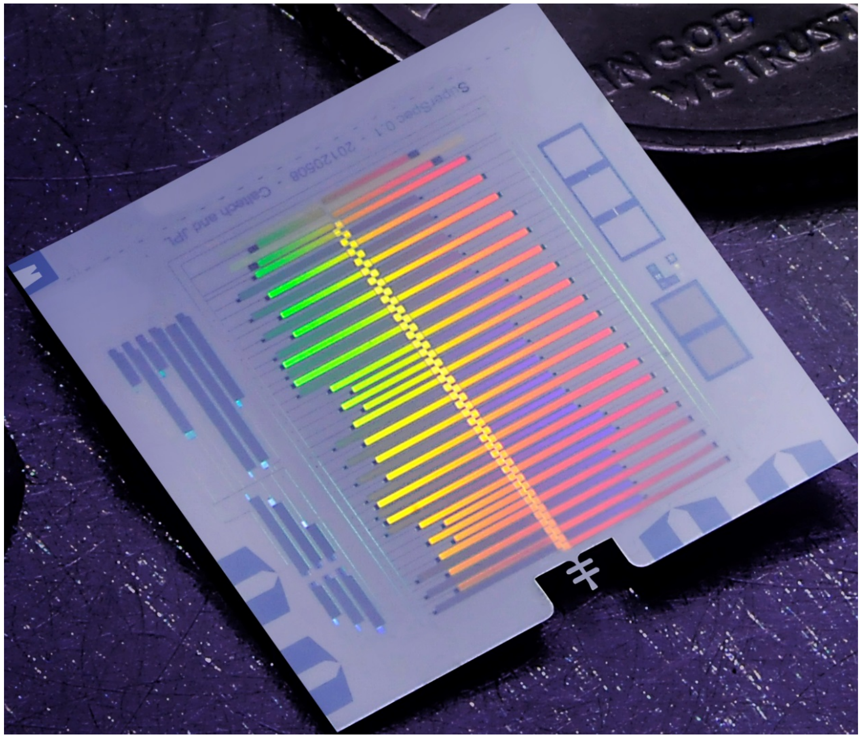
Kinetic Inductance Detectors



Baselmans et al., 2016

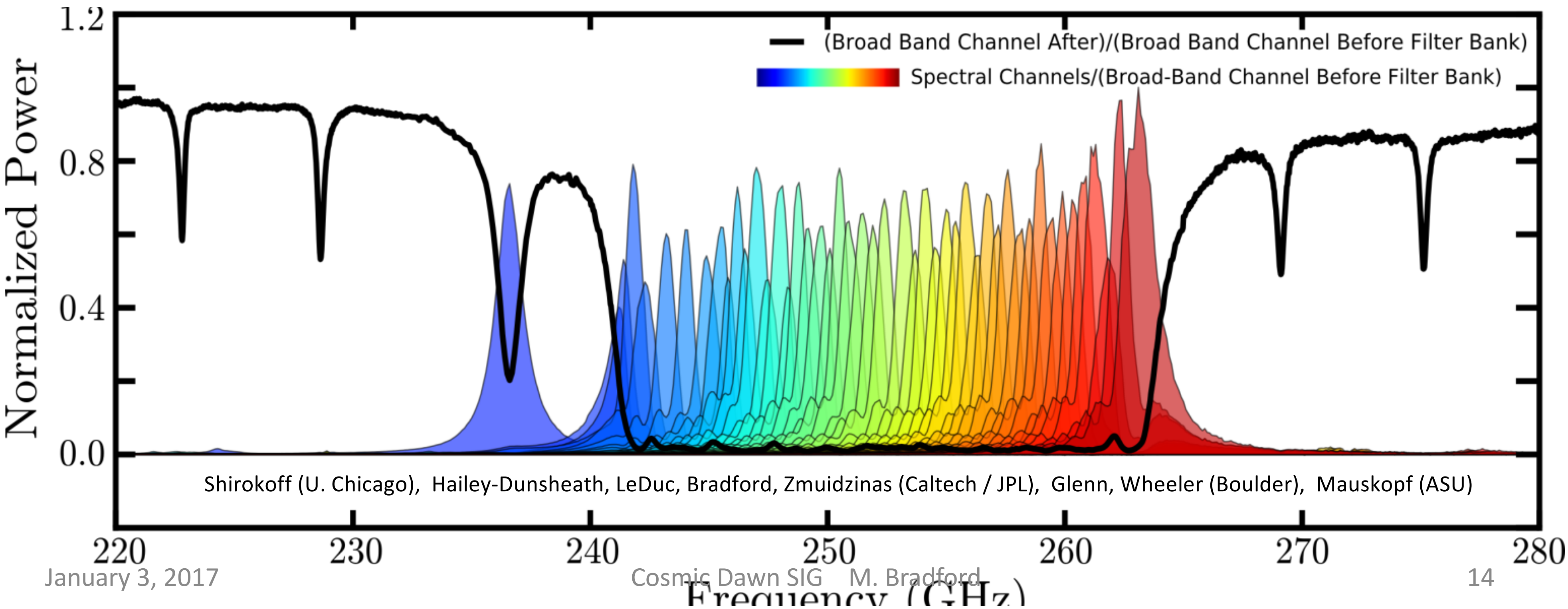






SuperSpec on-chip filterbank spectrometer

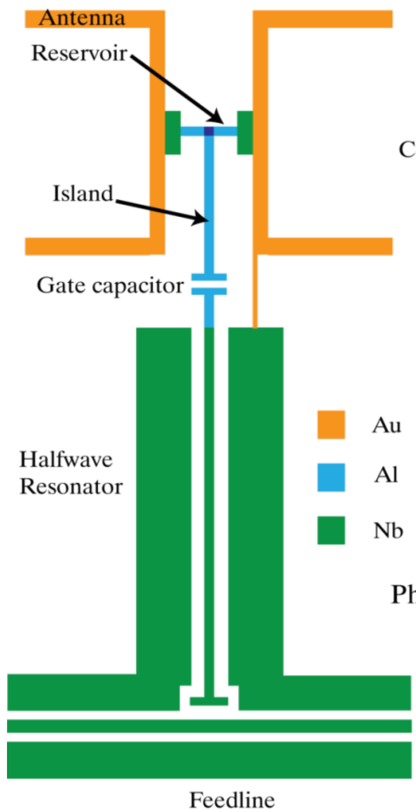
- Filterbank patterned in Nb / SiN / Nb microstrip.
- Integrated array of TiN KIDs. Reaching BG limit for mm-wave ground-based system.
- Full chip size on order 10 cm² for a single 200-channel spectrometer.
- Multi-object spectrometer on CSST / LMT can exceed ALMA's $N_{objects}$ x Bandwidth survey speed.
- Ideal for powerful future [CII] tomography instrument.

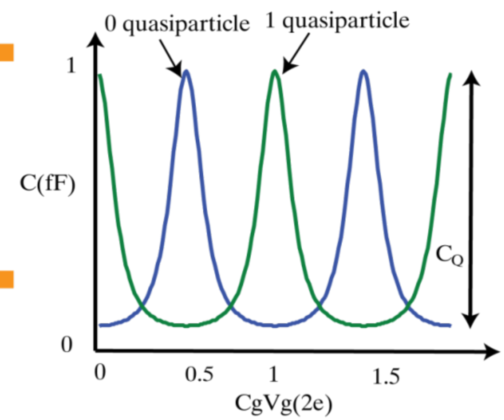


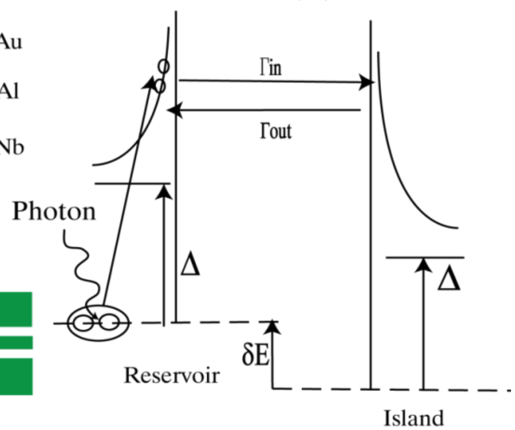
Shirokoff (U. Chicago), Hailey-Dunsheath, LeDuc, Bradford, Zmuidzinas (Caltech / JPL), Glenn, Wheeler (Boulder), Mauskopf (ASU)

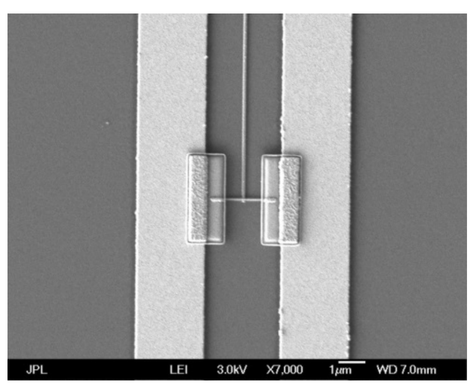
The Quantum Capacitance Detector (QCD)

Pierre Echternach et al @ JPL

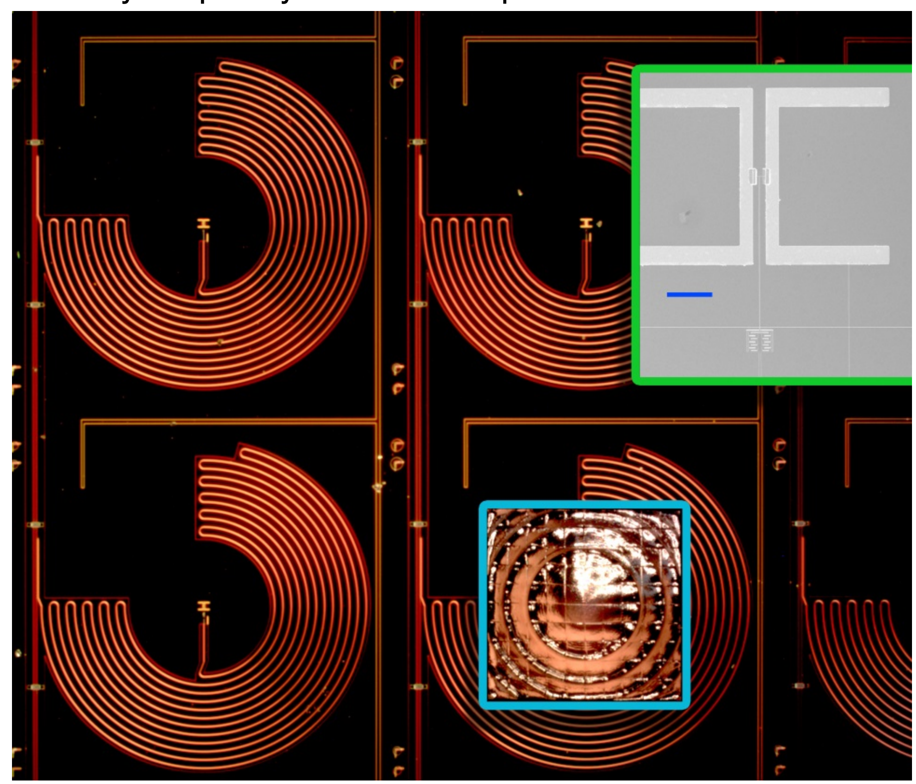






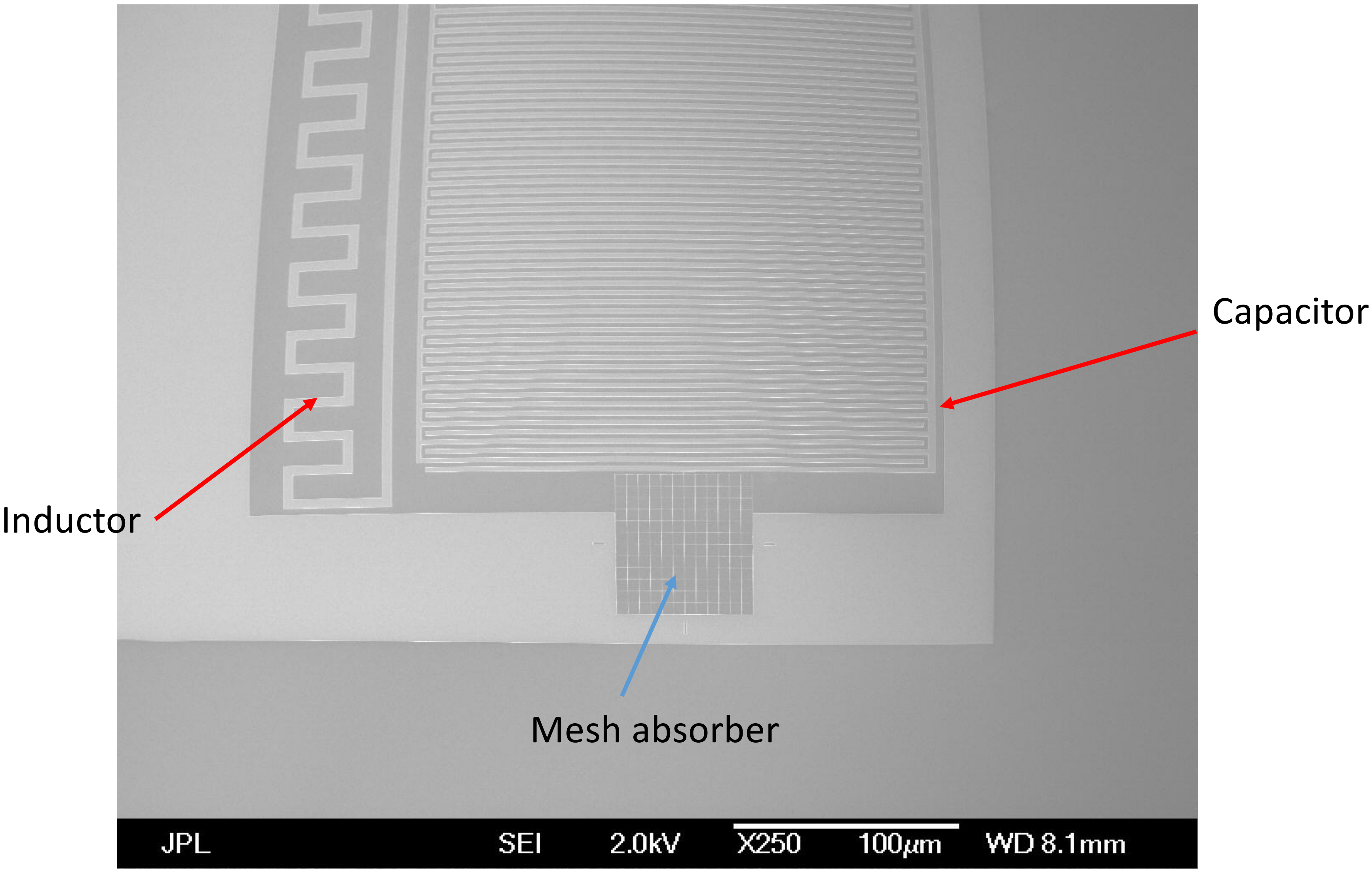


- Radiation coupled by an antenna breaks Cooper pairs in the reservoir (absorber) establishing a density of quasiparticles(QP) proportional to the optical signal.
- QP density in reservoir set by the ratio of tunneling rates onto and out of the island. The average QP occupation on the island ($0 < P_{odd} < 1$) is proportional to optical power.
- Bias at a peak, then average gate capacitance is a measure of optical power.
- Incorporate gate capacitor into a half-wave microwave resonator, changing C shifts readout frequency. Naturally frequency-domain multiplexed.



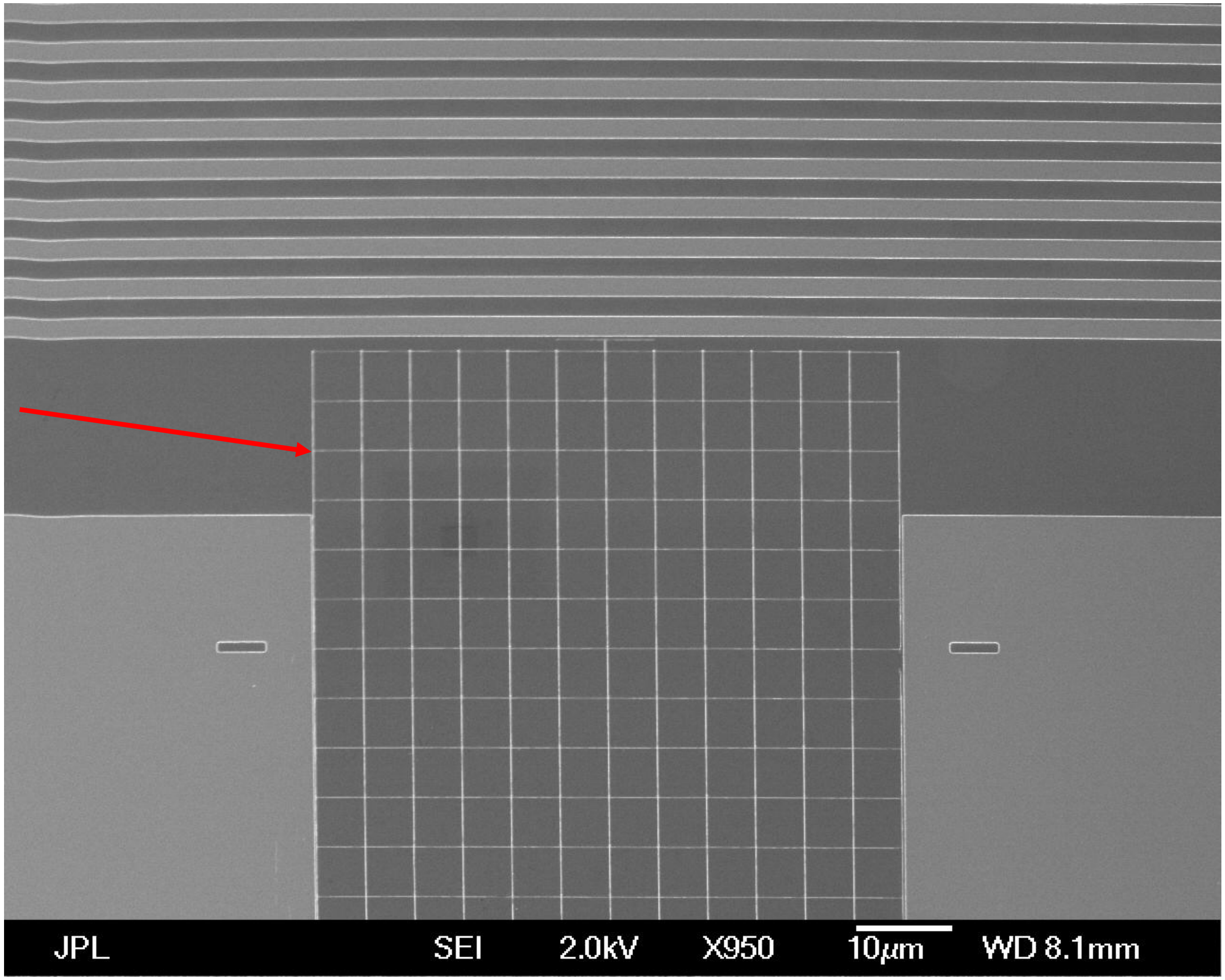
Lens-coupled mesh absorber

- Developing mesh absorber instead of antenna to better couple to general far-IR radiation.
- Lumped element resonator saves space and has better characteristics than CPW half wave resonator

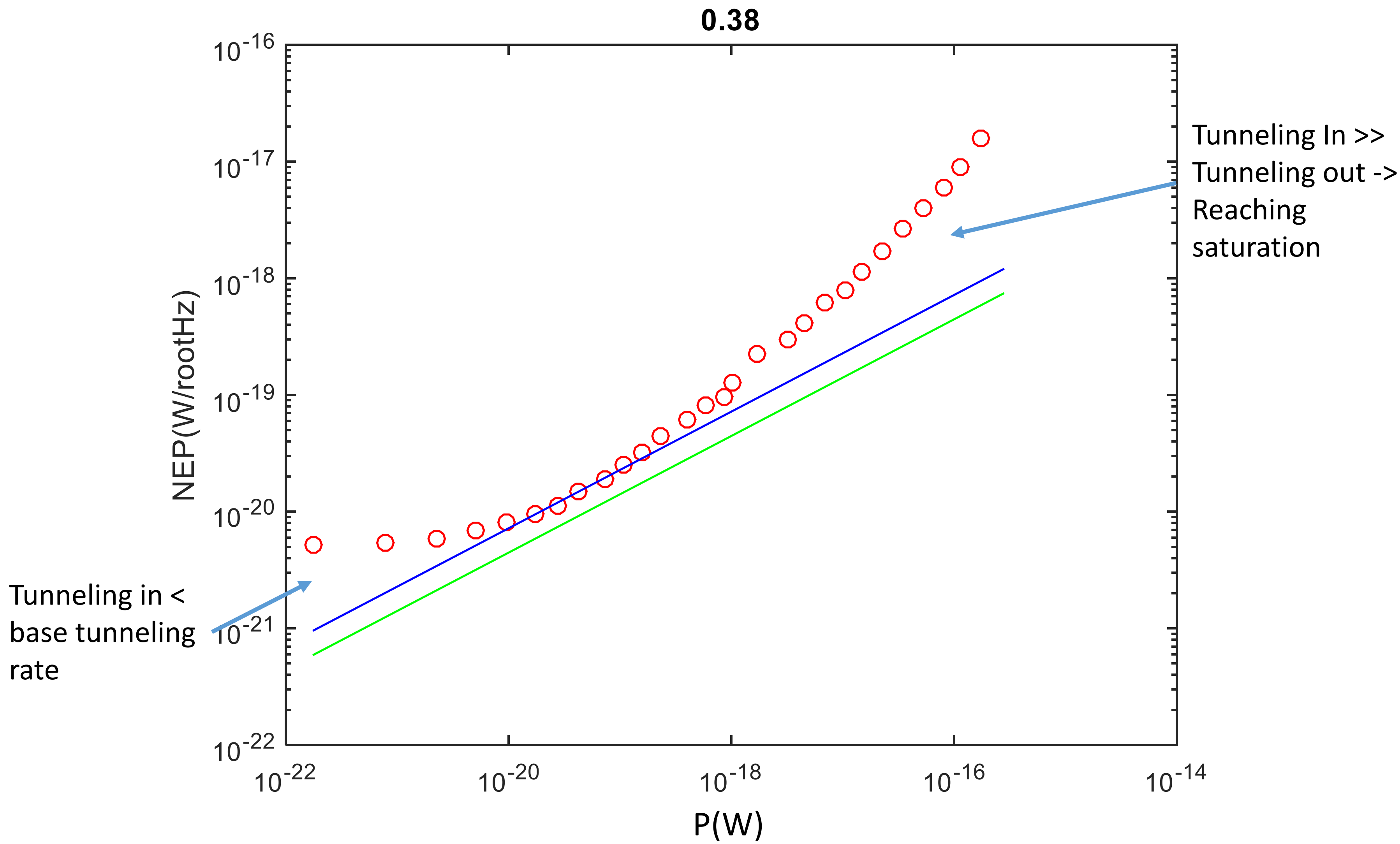


Lens coupled mesh absorber LEQCD

Mesh
absorber

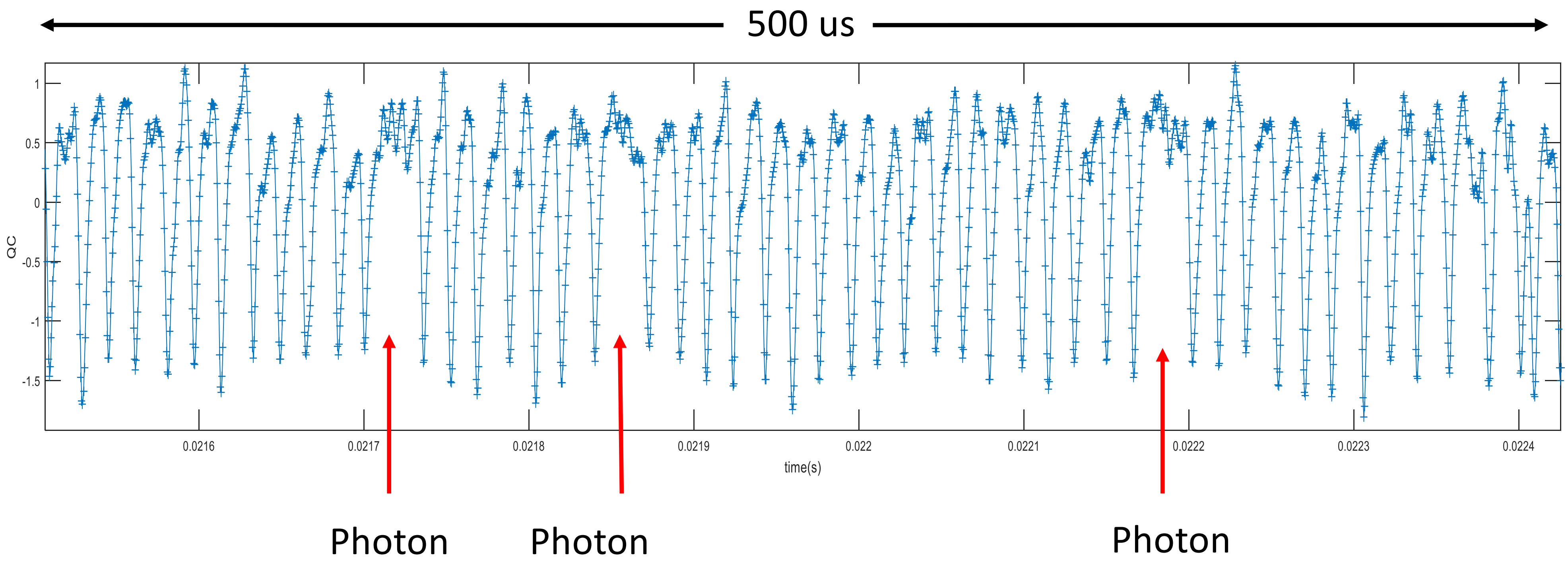


QCD – shot-noise-limited sensitivity meets OST requirement



- $P^{1/2}$ dependence implies photon noise limited performance.
- Efficiency extracted from ratio of measured NEP and photon shot noise NEP.
- Should be able to detect single photons.

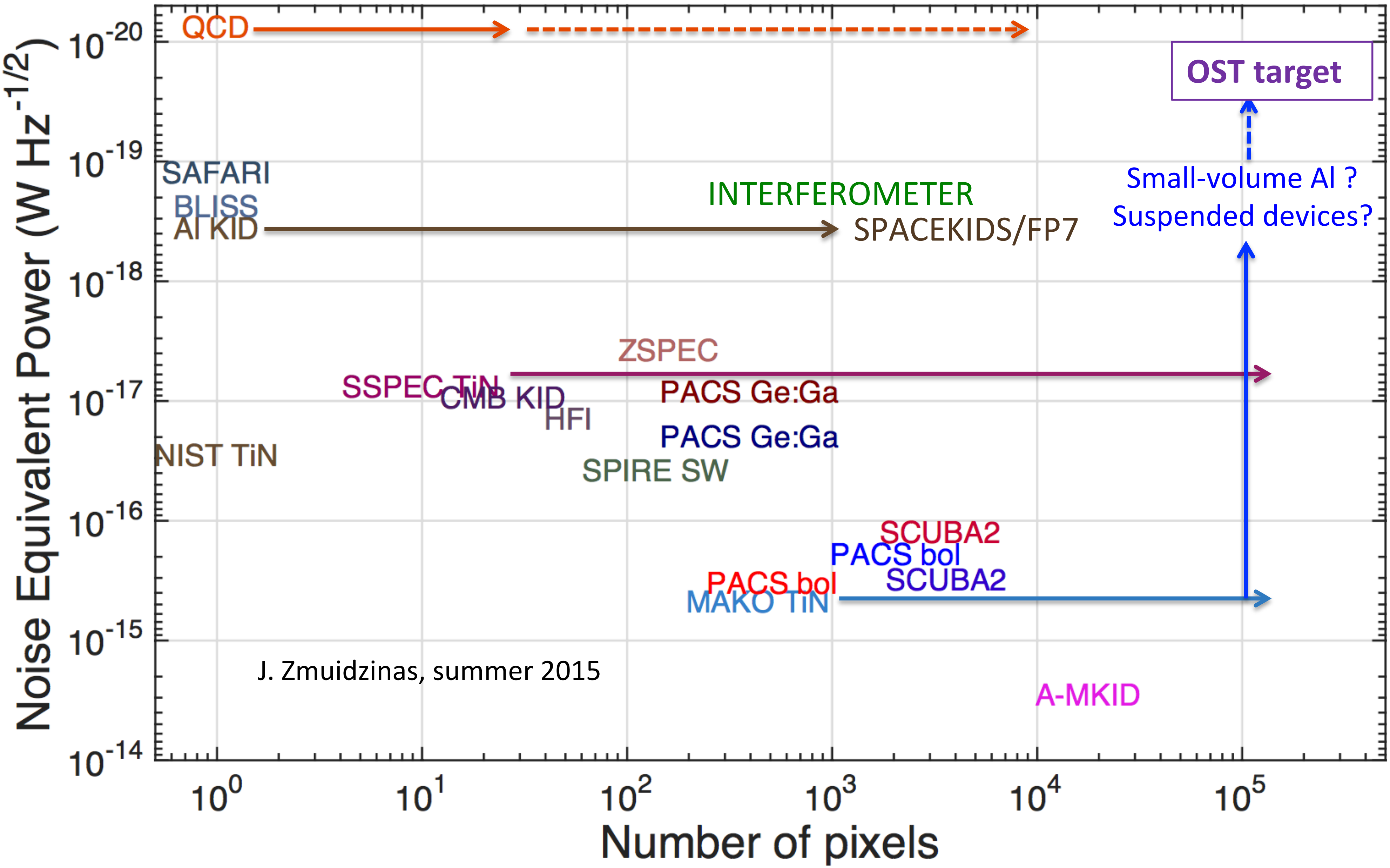
Fast sweep rate reveals single photon events – *counting far-IR photons*.

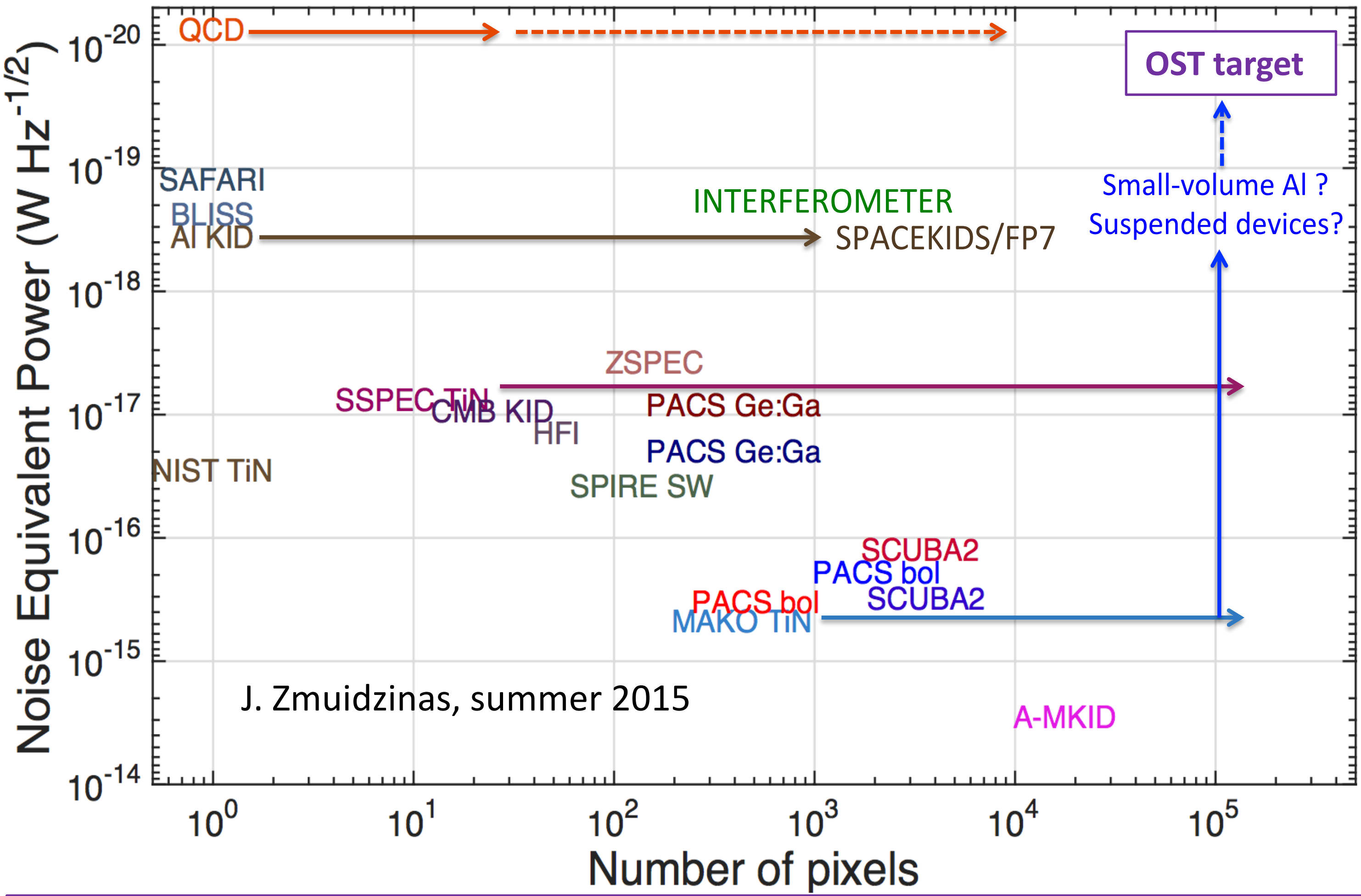


- Sweep rate ~ 22kHz spanning 4 Quantum Capacitance Peaks => effective sweep rate ~ 88kHz
- Should block background tunneling while still allowing tunneling due to single photon absorption
- Raw QC time trace should be absolutely periodic
- Gaps are due to high tunneling suppressing the Quantum Capacitance signal, due to photon absorption.

Photon counting not required for OST science, but does offer some system-level advantages: *1/f noise not an issue, * low NEP strictly speaking not required.

Current state of the art performance



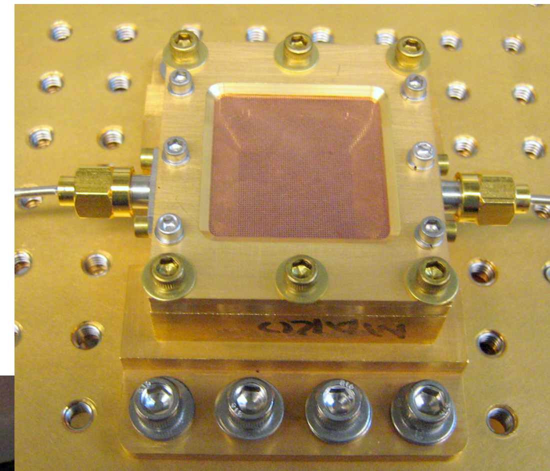


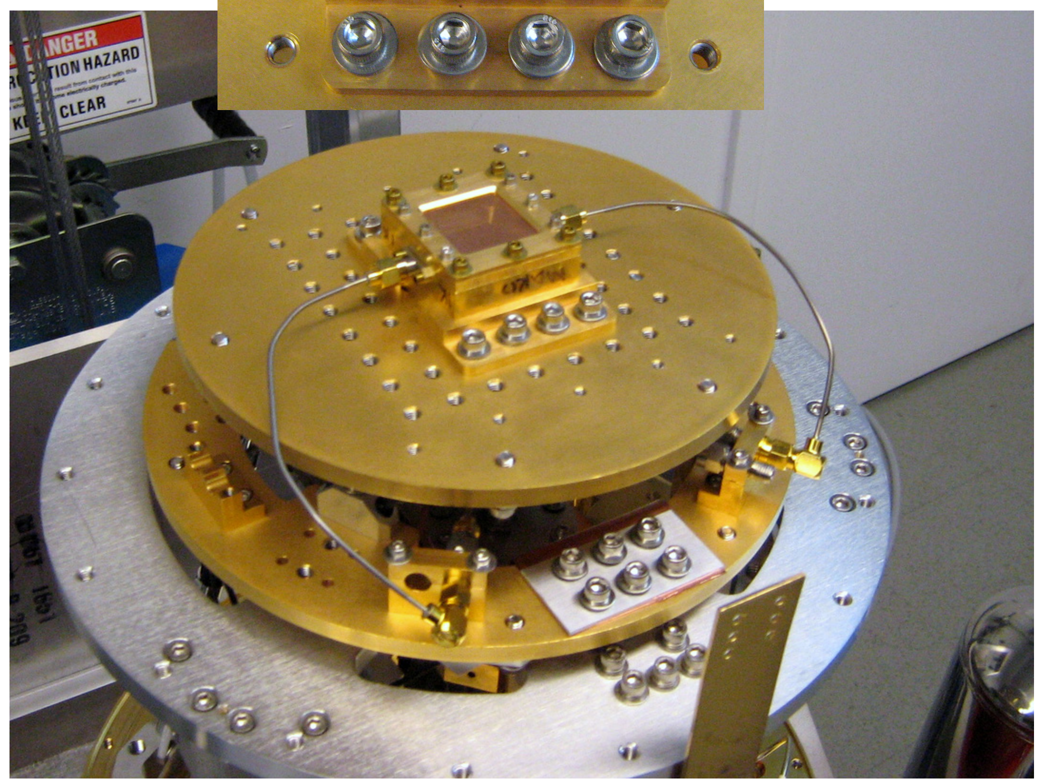
Outlook

- Far-IR detectors are unique and will not develop themselves.
- Sensitivity and format are the primary metrics.
- We have at least 3 promising technologies / approaches with proof of principle demonstrated in small 2-3 year APRA and SAT-type grants.
- **But sustained, directed development is required to reach sensitivity & format, and also maturity for OST and/or precursors / Probes.**
  - **E.g. cosmic ray susceptibility.**

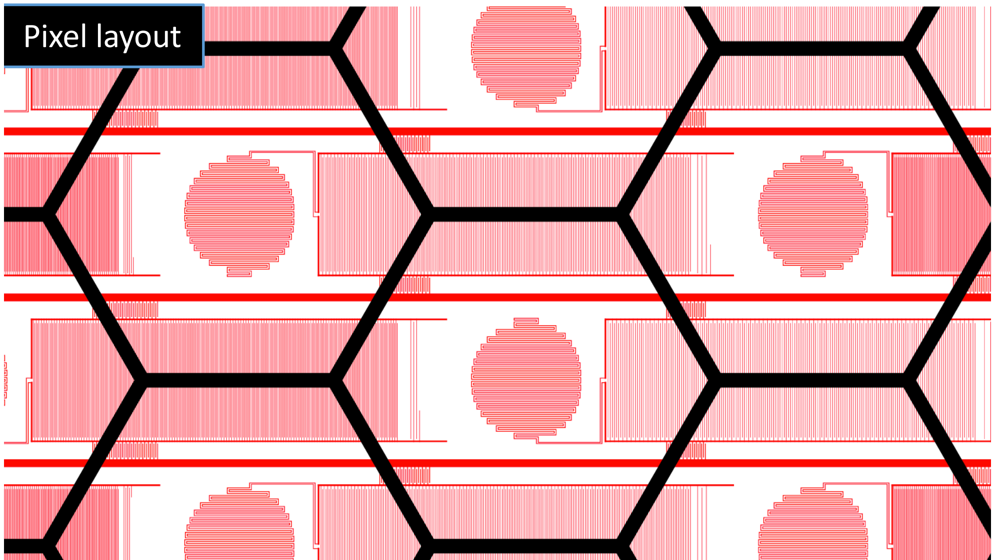
extras

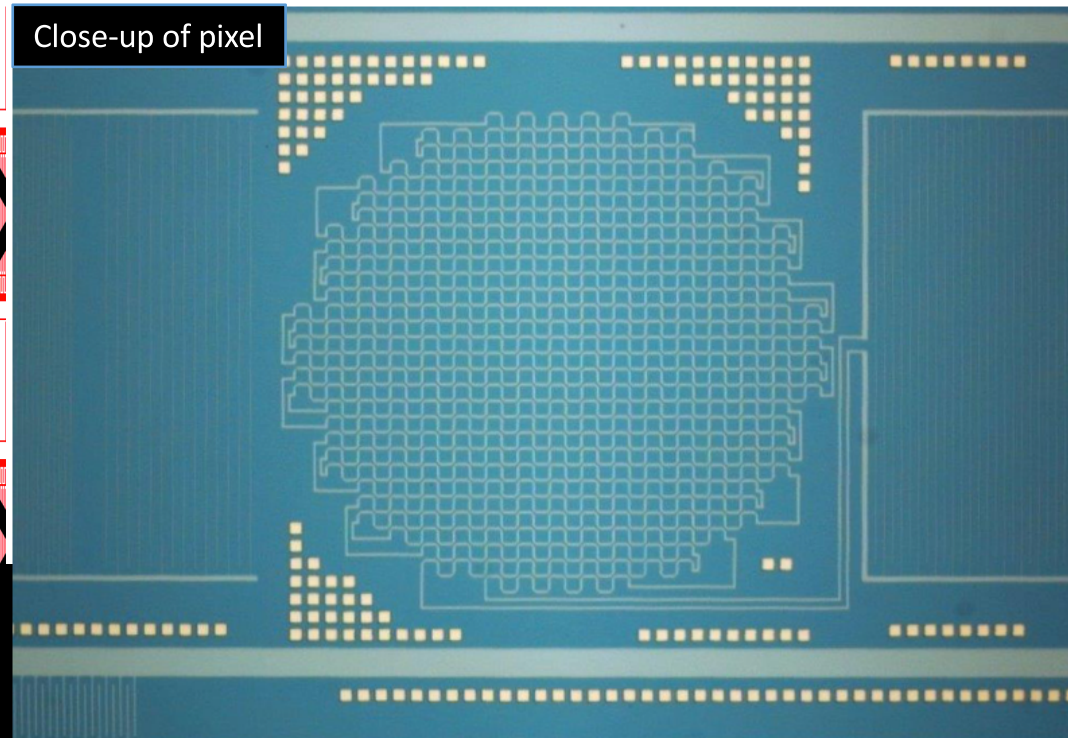
MAKO: a prototype camera

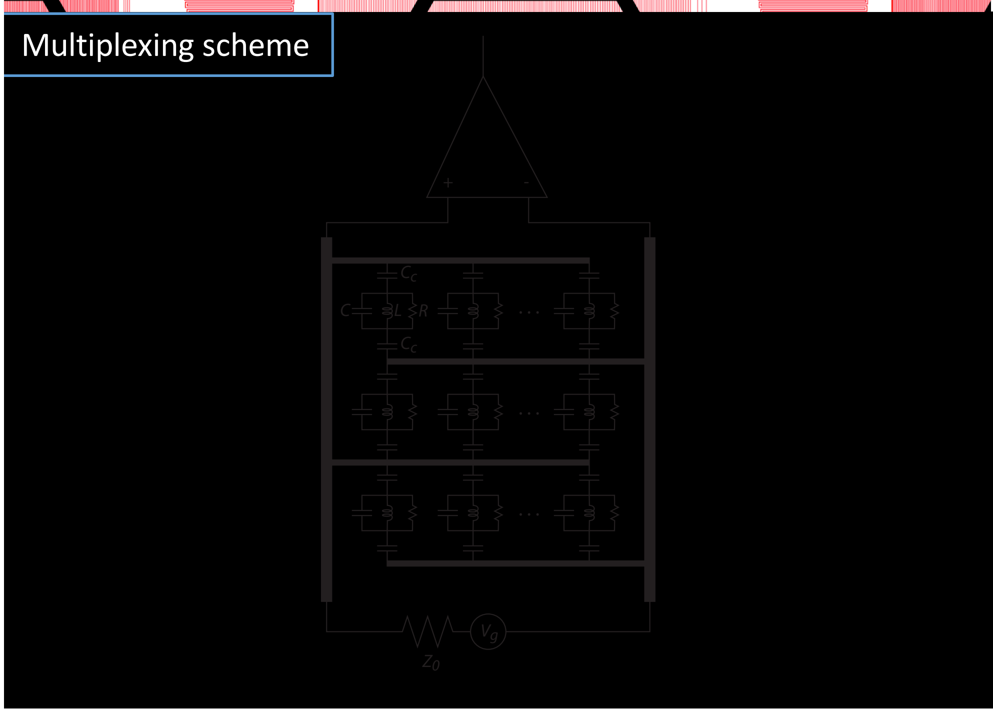




Some Details


Pixel layout

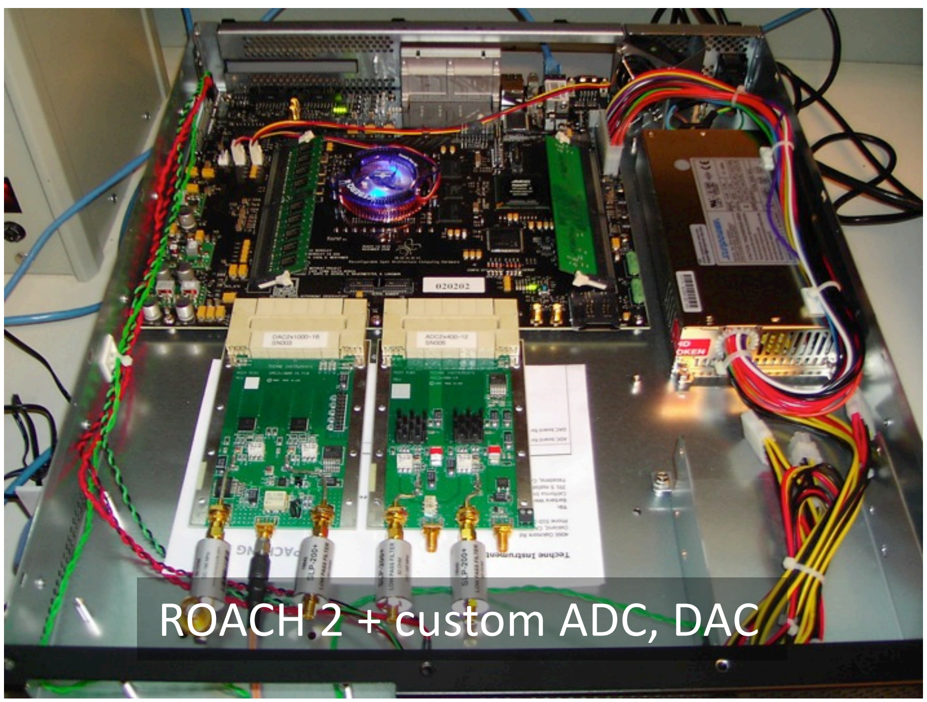

Close-up of pixel


Multiplexing scheme

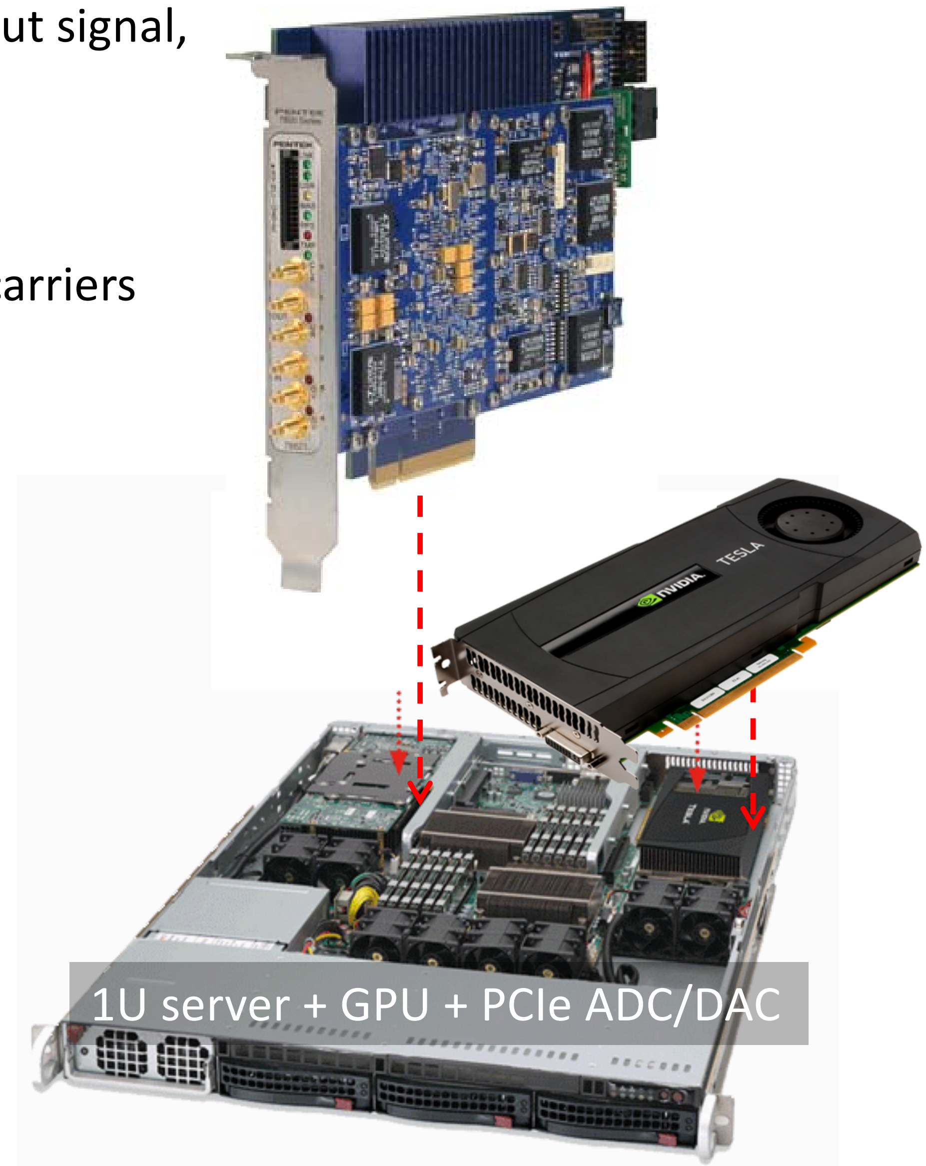

Silicon microlens array

Readout Electronics

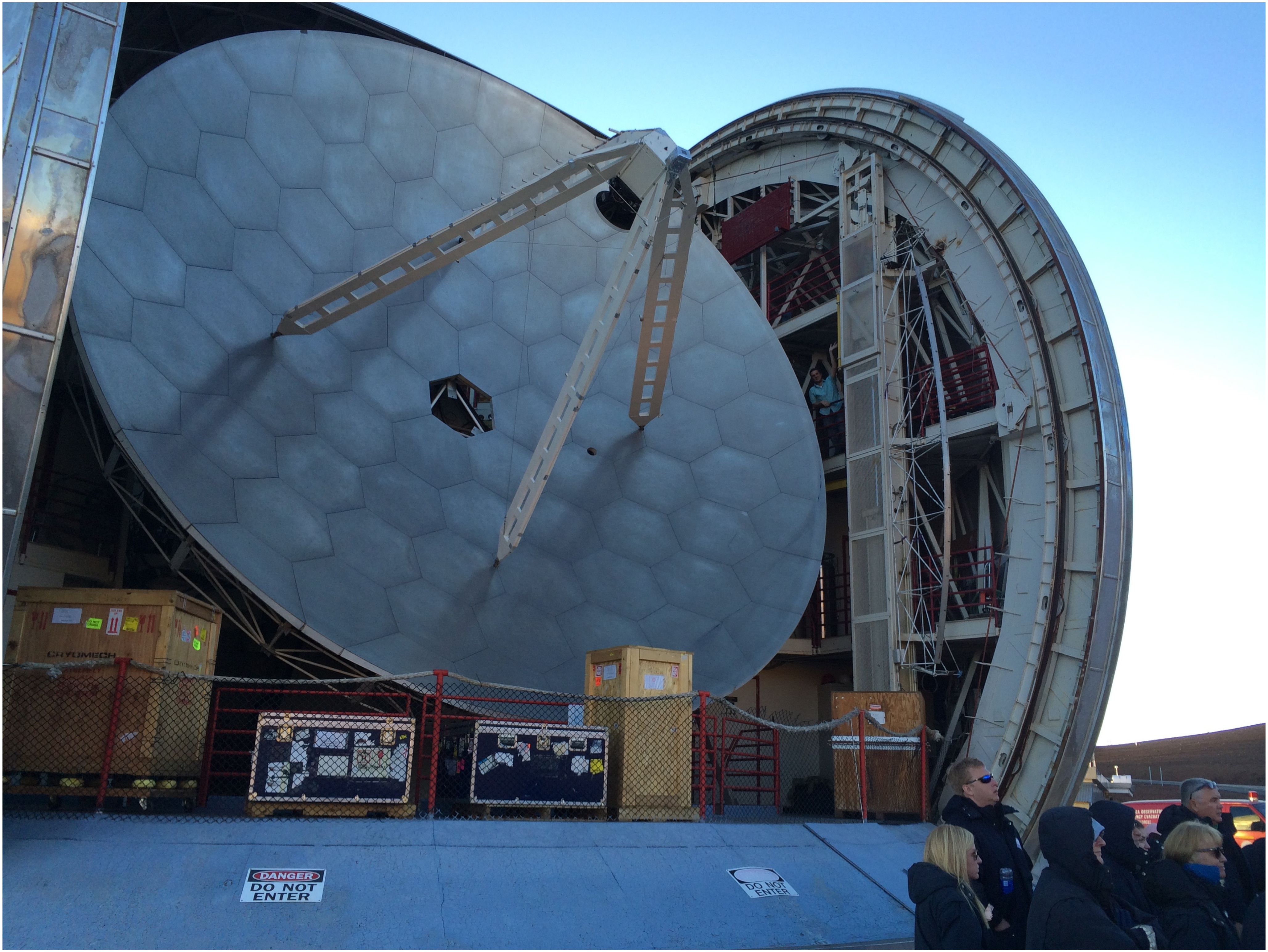
- Use fast DAC to generate multifrequency readout signal, send to cryostat
- Digitize returning signal (200-500 MSPS)
- Perform FFT in real time (FPGA/GPU)
- Select FFT channels corresponding to readout carriers
- Stream to disk



ROACH 2 + custom ADC, DAC



1U server + GPU + PCIe ADC/DAC


DANGER
DO NOT
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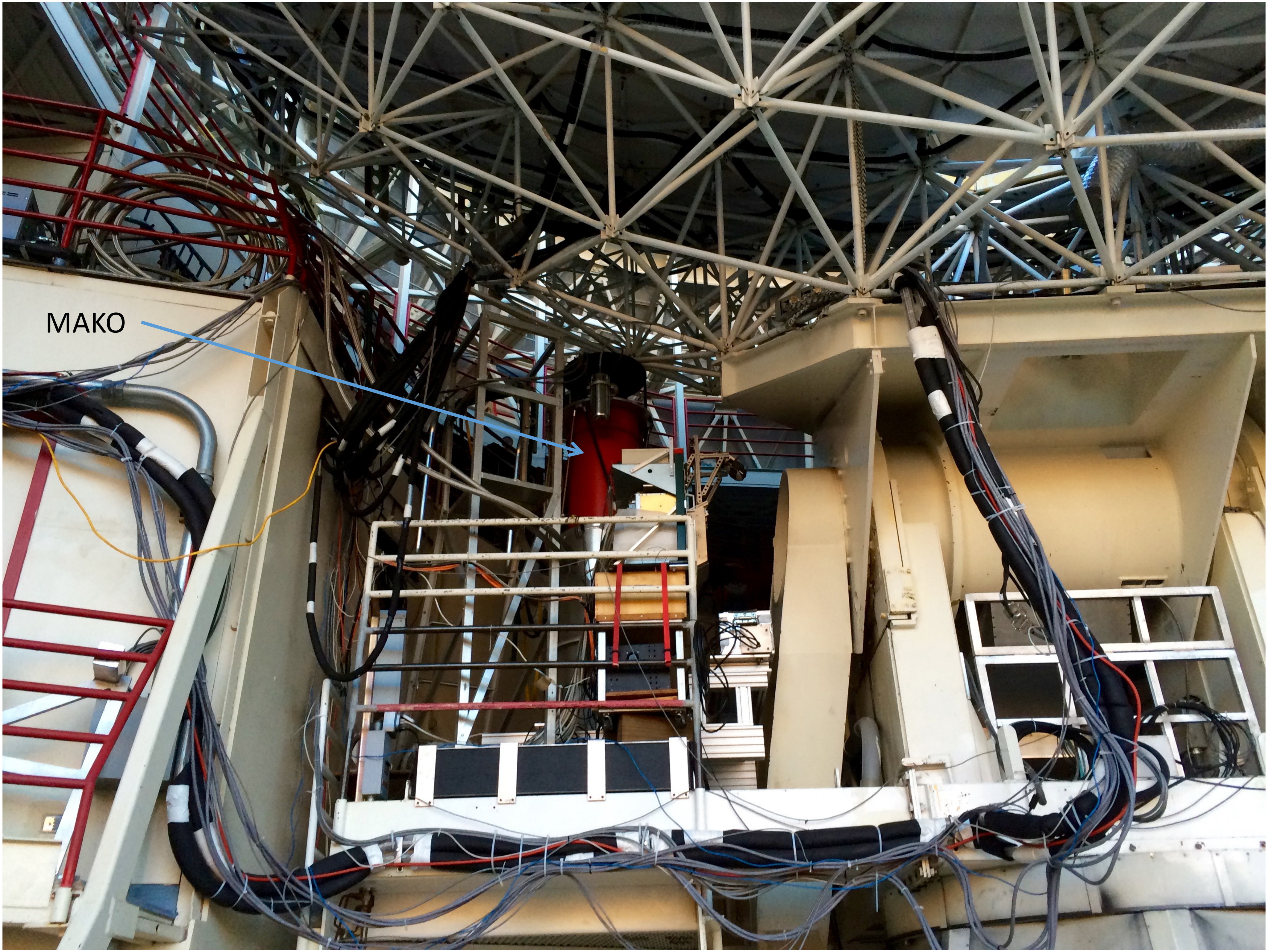
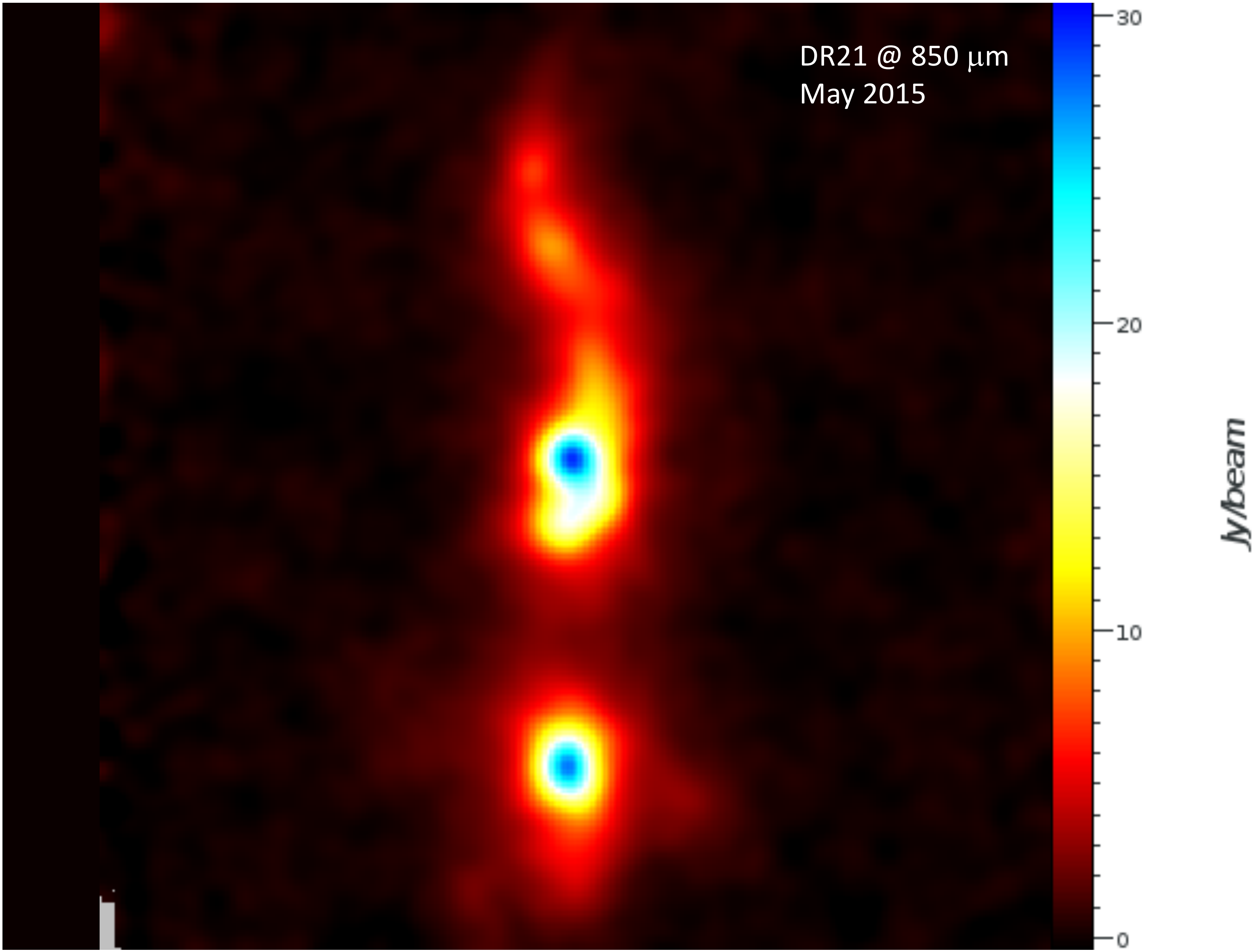
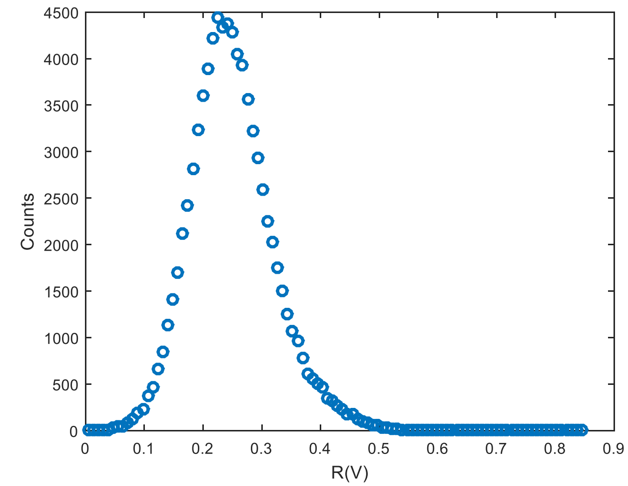

MAKO

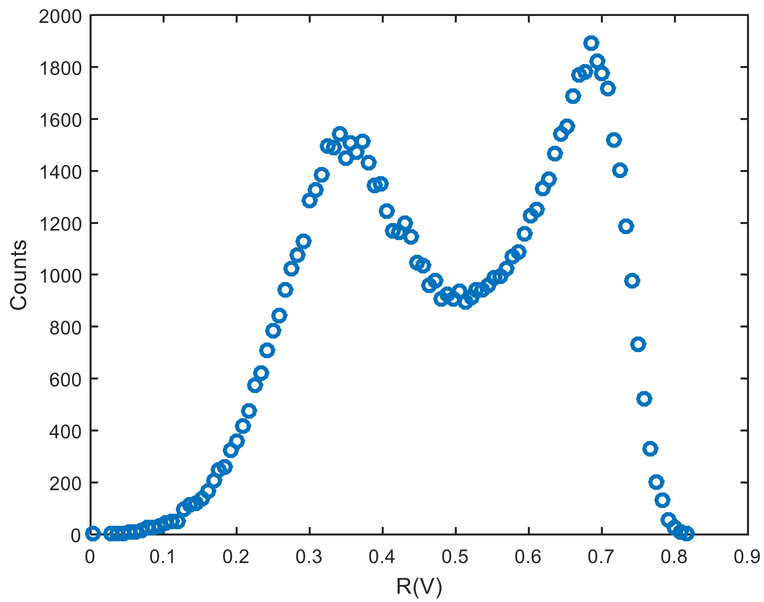

DR21 @ 850 μm
May 2015
30
20
10
0
Jy/beam

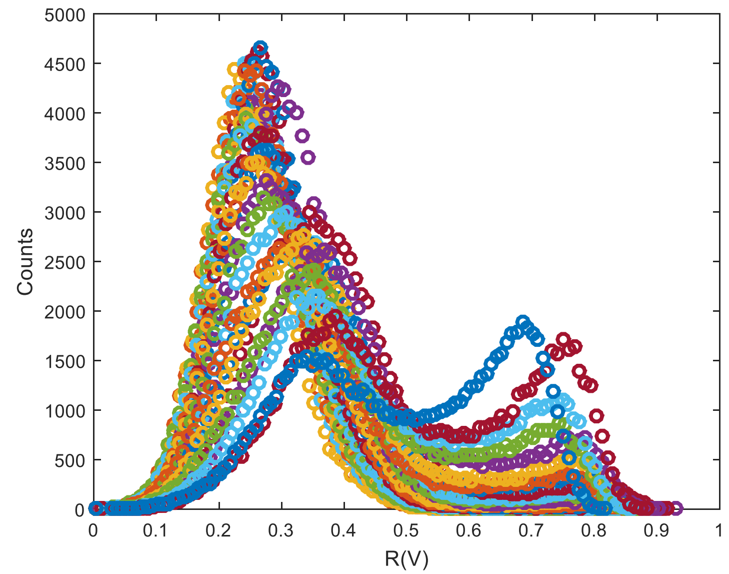
Histogram of response for various black body temperatures
For cold black body only peak around 0.25 exists
For hot black body peak around 0.6-0.7 is larger than peak at 0.25

Cold black body



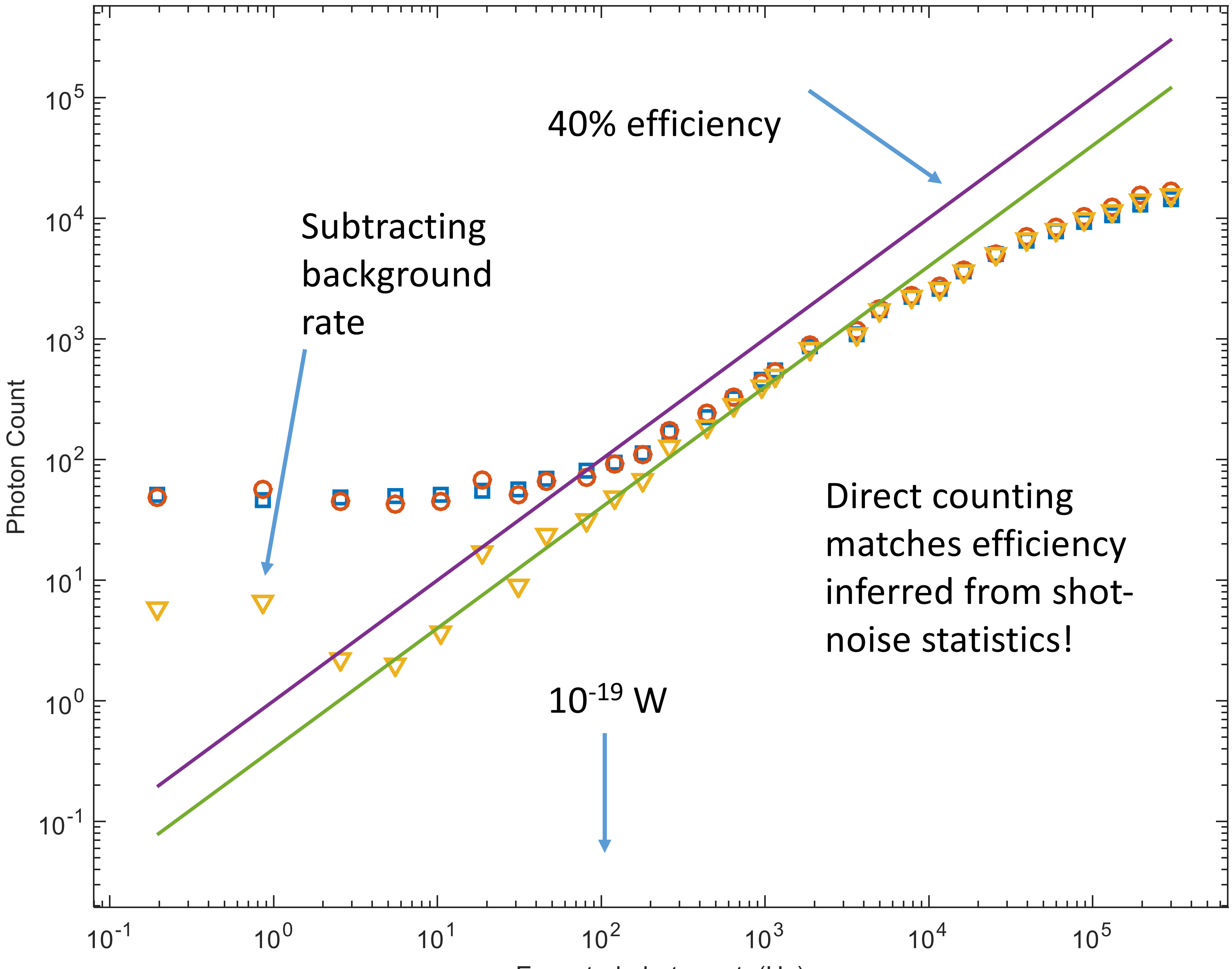
Hot black body





- Peaks get closer together at high black body temperatures due to filtering by the resonator of the high frequency stream
- Could lower resonator Q by stronger coupling at the expense of fewer channels

Counts of response between 0.6 and 0.9 versus number of expected photons



Efficiency rolls off when time intervals between photons become comparable to the time separation of two Quantum Capacitance Peaks