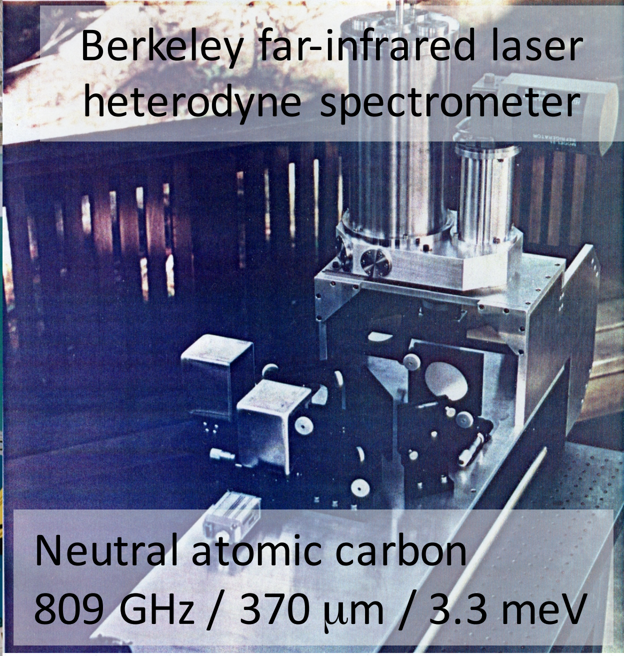
Millimeter wavelength spectrometers

(0.01 – 3 mm, or 0.4 – 120 meV)

Jonas Zmuidzinas

Caltech



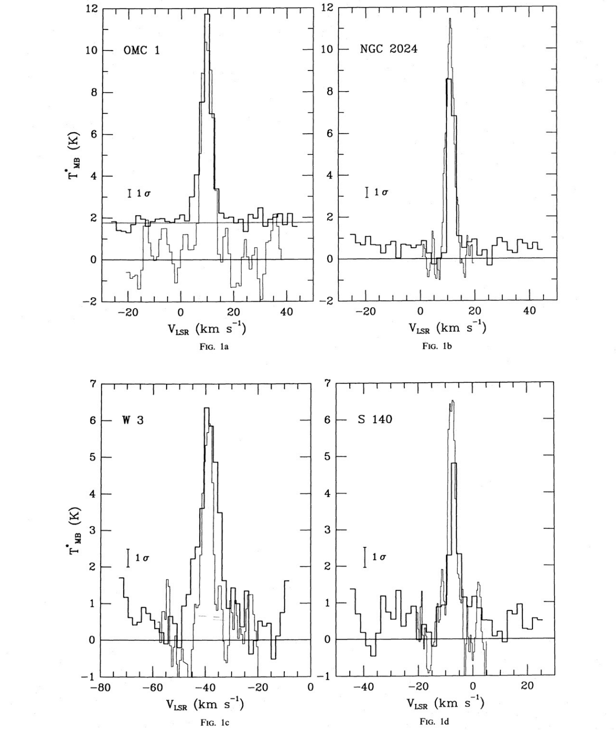
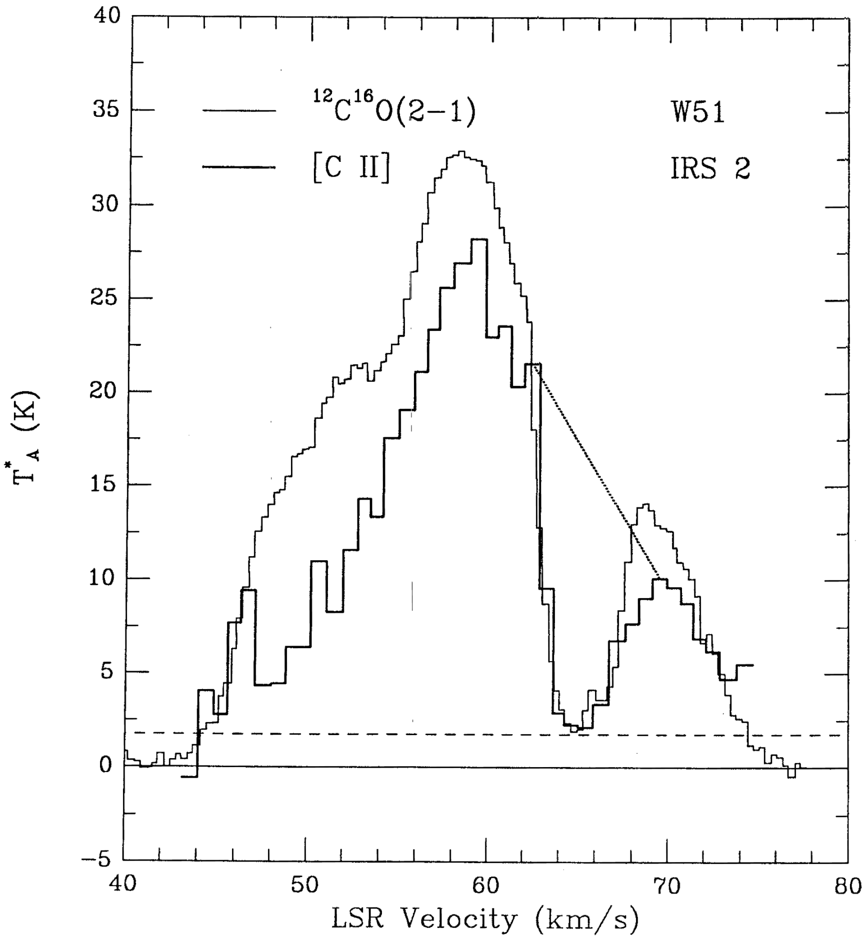
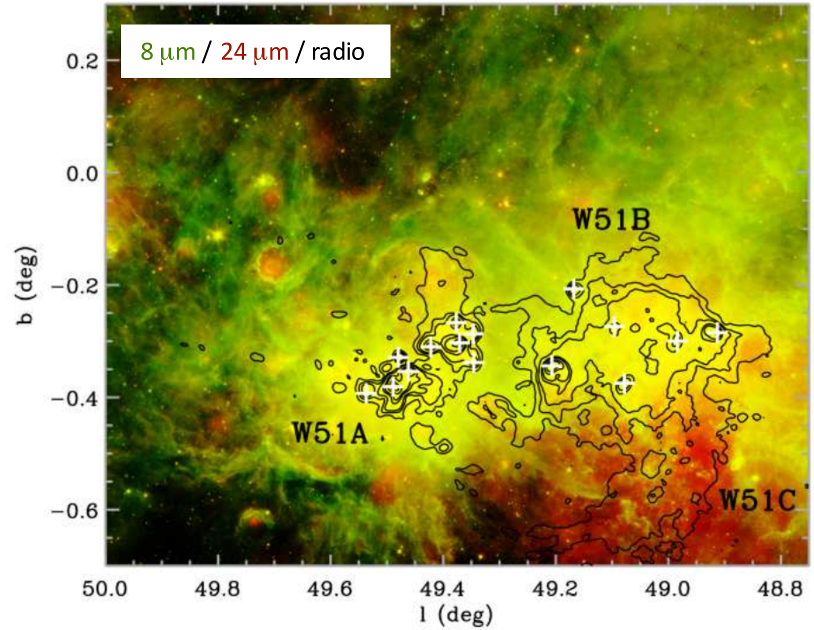


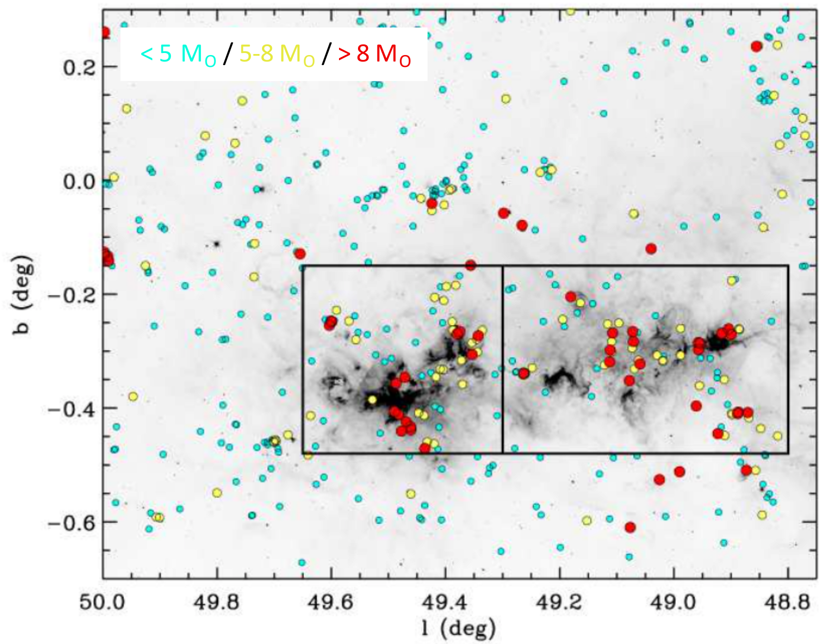
Fig. 1.—809 GHz [C I] $^3P_2$–$^3P_1$ emission (*heavy line*) observed toward (*a*) OMC 1, integration time of 60 minutes; (*b*) NGC 2024, integration time of 32 minute (*c*) W3, integration time of 32 minutes; and (*d*) S140, integration time of 26 minutes. The $^3P_1$–$^3P_0$ data (*light line*) of Phillips and Huggins (1981) are also shown. Th 2–1 data were obtained in 1986 September. The dotted line in (*a*) shows the expected 370 μm continuum emission in a 90″ beam (Keene, Hildebrand, and Whitcom 1982) corrected for the dewar window transmission in each sideband. Statistical uncertainties of 1 σ are shown for the $^3P_2$–$^3P_1$ data only.

1986: C^+ in W51

1900 GHz / 158 μm / 7.9 meV







Kang et al. 2009

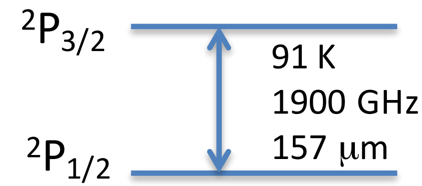
C^+ is an efficient coolant of interstellar gas

Dalgarno & Rudge, ApJ 1964

The cooling mechanism is the excitation of low-lying levels of C^+ and Si^+ in spin-flip collisions with hydrogen atoms:

$$C^+(2p\ ^2P_{1/2}) + H \rightarrow C^+(2p\ ^2P_{3/2}) + H\ ,$$

$$Si^+(3p\ ^2P_{1/2}) + H \rightarrow Si^+(3p\ ^2P_{3/2}) + H\ .$$

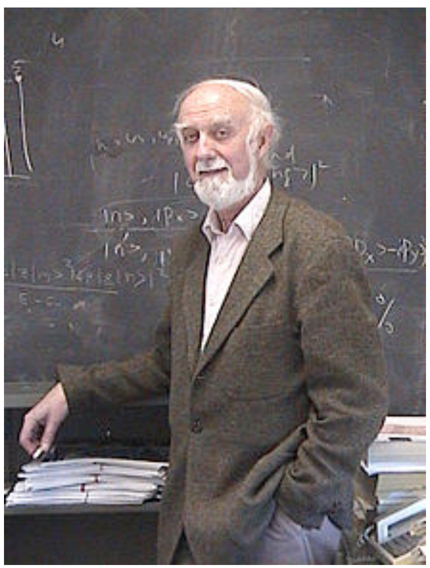


By a straightforward generalization of the theory used by Dalgarno (1961), it may be shown that the cross-section for these processes has the form

$$Q = \frac{2\pi}{3k^2} \sum_{l=0}^{\infty} (2l+1) \sin^2(\eta_l^t - \eta_l^s)\ ,$$

A. Dalgarno
M. R. H. Rudge

March 30, 1964
Department of Applied Mathematics
The Queen's University of Belfast
Northern Ireland



A. Dalgarno (1928-2015)
2013 Benjamin Franklin Medal

Z	Element	Mass fraction in parts per million	
1	Hydrogen	739,000	71 × mass of oxygen (red bar)
2	Helium	240,000	23 × mass of oxygen (red bar)
8	Oxygen	10,400	
6	Carbon	4,600	
10	Neon	1,340	
26	Iron	1,090	
7	Nitrogen	960	
14	Silicon	650	
12	Magnesium	580	
16	Sulfur	440	

Galaxies are *predicted* to be bright in C^+

THE ASTROPHYSICAL JOURNAL, Vol. 155, February 1969

FINE-STRUCTURE TRANSITIONS AND THE BACKGROUND MICROWAVE RADIATION*

VAHÉ PETROSIAN AND JOHN N. BAHCALL†
California Institute of Technology, Pasadena

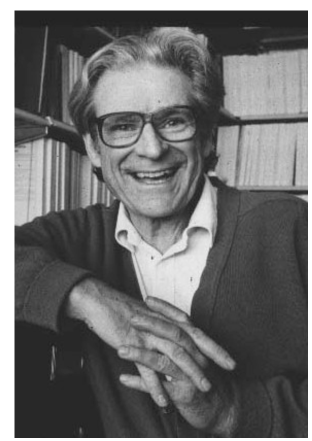
AND

E. E. SALPETER‡
Cornell University, Ithaca, New York

Received December 16, 1968

V. Petrosian

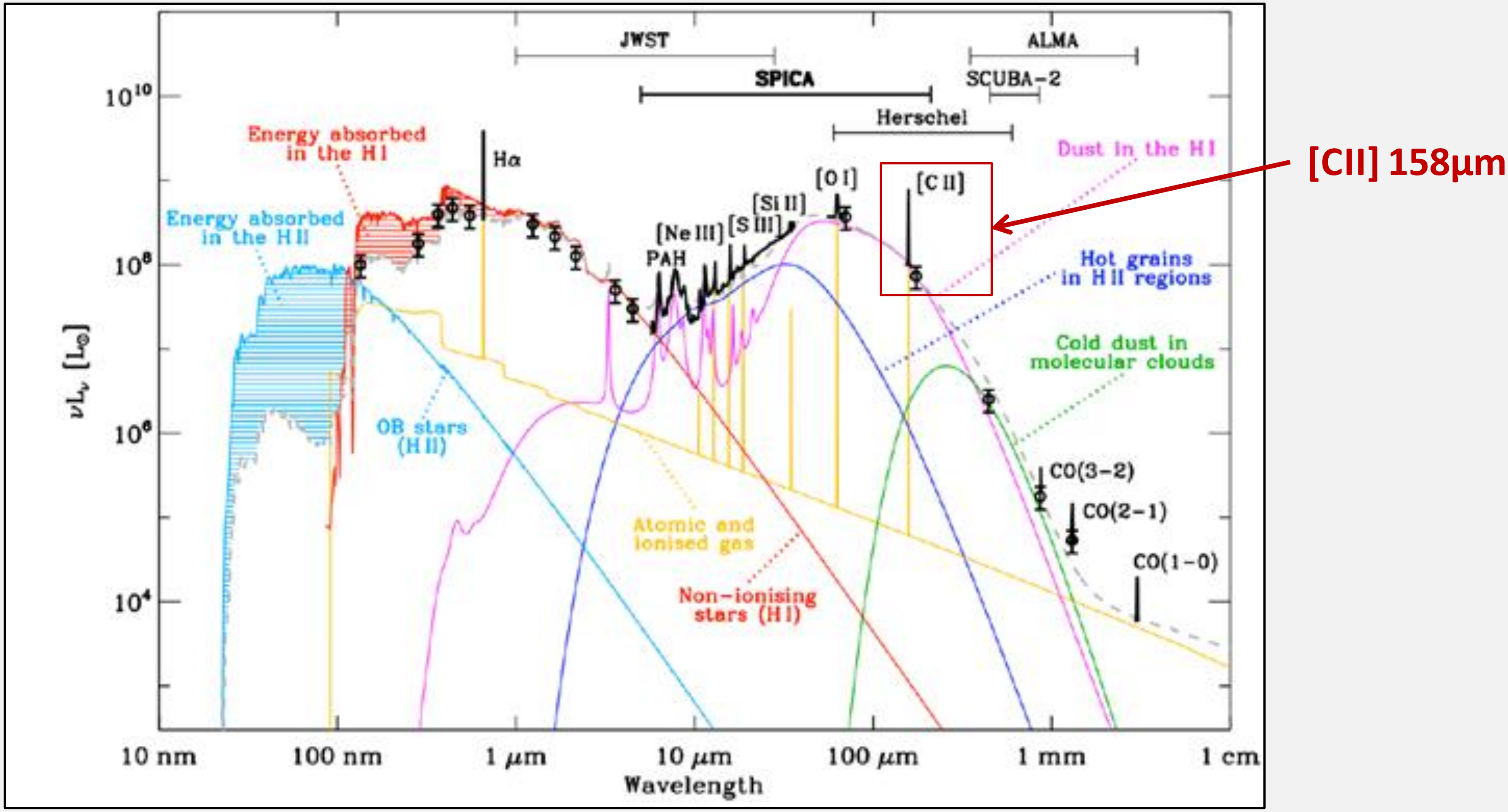
J. Bahcall



E. Salpeter

Panchromatic SED of a Galaxy

- Dust grains absorb stellar UV/optical, radiate thermally in IR, heat neutral gas

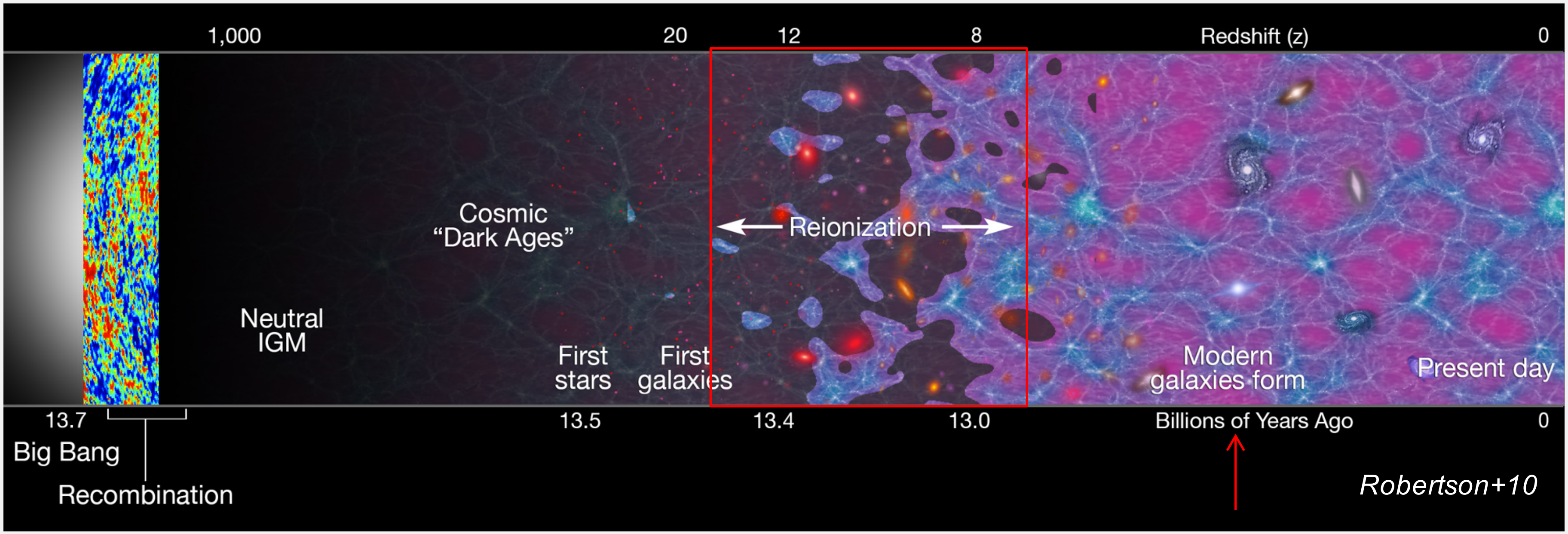


Tóth, Zahorecz, Kiss 2013
Credit: S. Hailey-Dunsheath

Cosmic Reionization

Cosmological Redshift
- scale factor $a = \frac{1}{1+z}$ photon wavelength $\lambda \propto \frac{1}{1+z}$

$z = 0$
$t = 13.7\ Gyr$

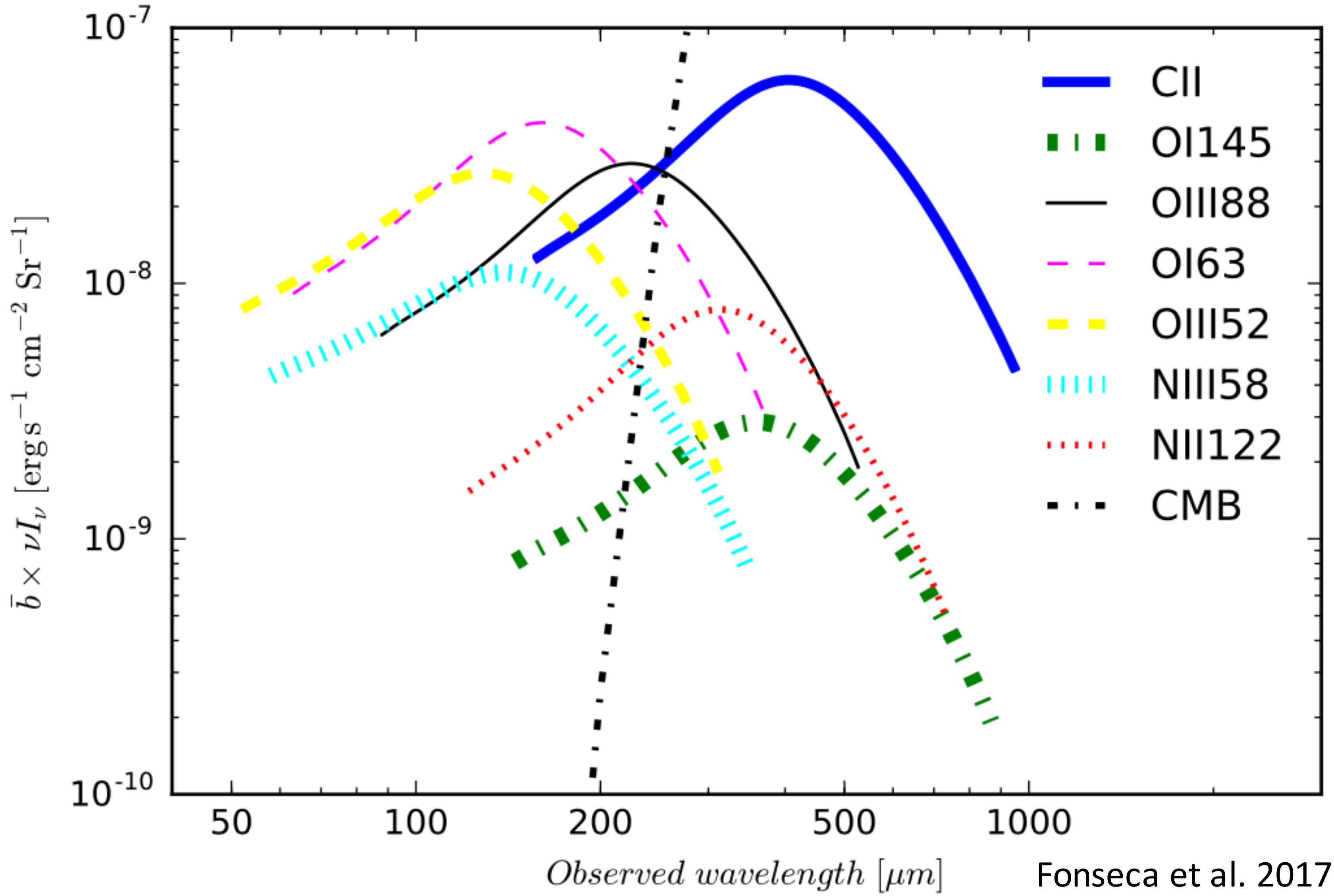


$z \approx 1100$
$t \approx 370{,}000\ yr$
Recombination

$z \approx 6 - 15$
$t < 1\ Gyr$
Epoch of Reionization

$z \approx 1 - 3$
$t \approx 2 - 6\ Gyr$
Epoch of Galaxy Assembly

Model Predictions for Intensity Mapping, z=0-5

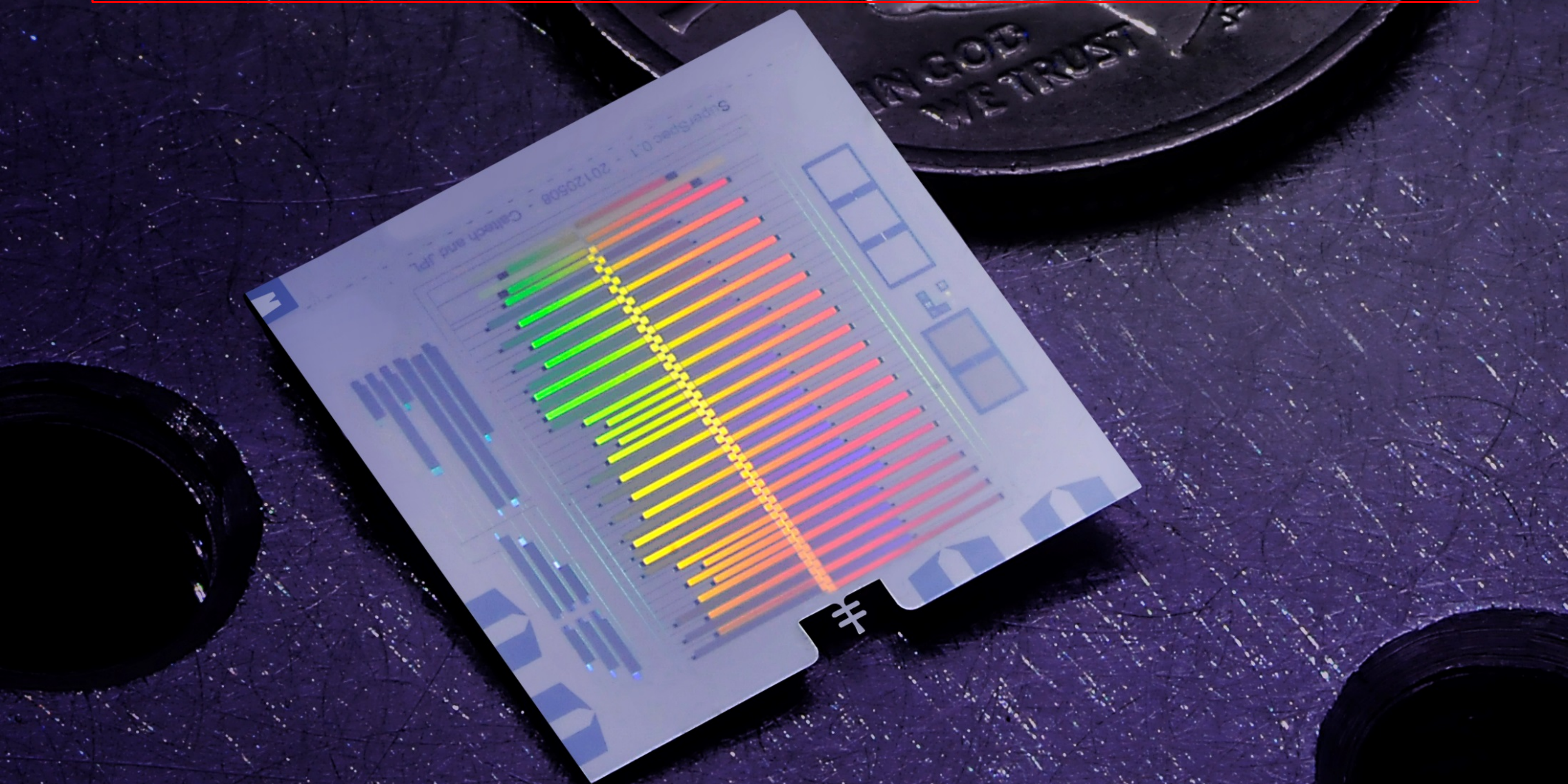


Fonseca et al. 2017

Progress on SuperSpec: A Broadband, On-Chip Millimeter-Wave Spectrometer

Steve Hailey-Dunsheath, Caltech

November 3, 2016



The SuperSpec Team

Caltech/JPL

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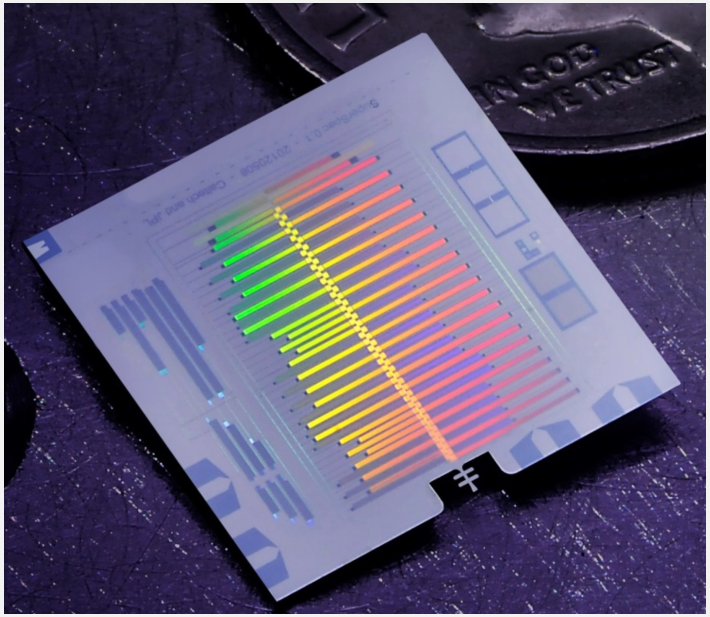
J. Wheeler

Dalhousie University

S. Chapman
C. Ross

Introduction + Overview

- SuperSpec is an on-chip spectrometer we are developing for moderate resolution, large bandwidth, (sub)millimeter astronomy
- A single chip integrates
  - antenna
  - moderate resolution (R ~ 100 – 500) filterbank with large BW (δν/ν ~ 0.6)
  - associated detectors (KIDs)
- Each chip is ~10 cm^2 in size
- Facilitate construction of multi-object survey spectrometers
- Scientific Motivation: galaxy spectral surveys and line intensity mapping
- **Prototype filterbank covering 20% of the 200 – 300 GHz range**



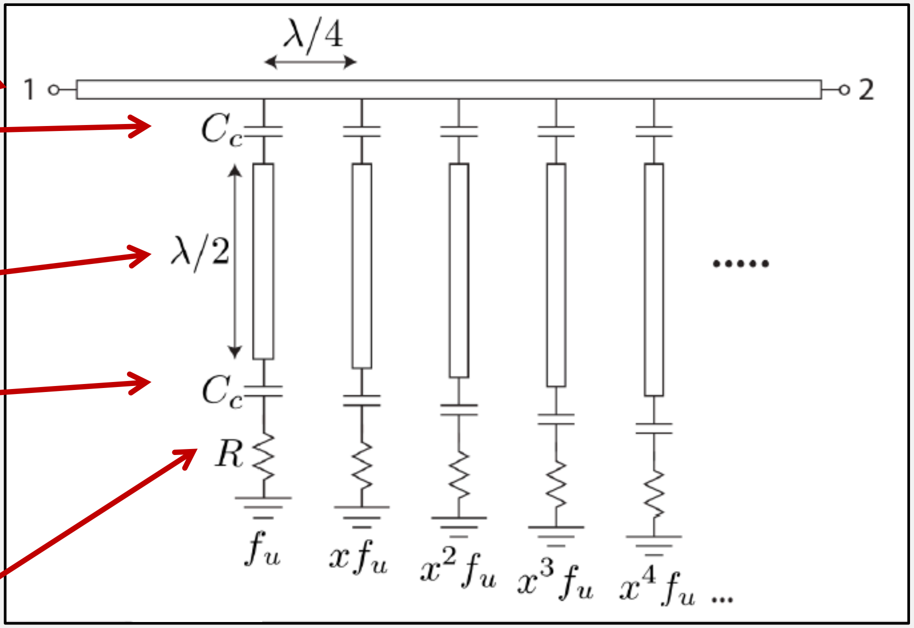
Microwave Circuit Model

Input from antenna

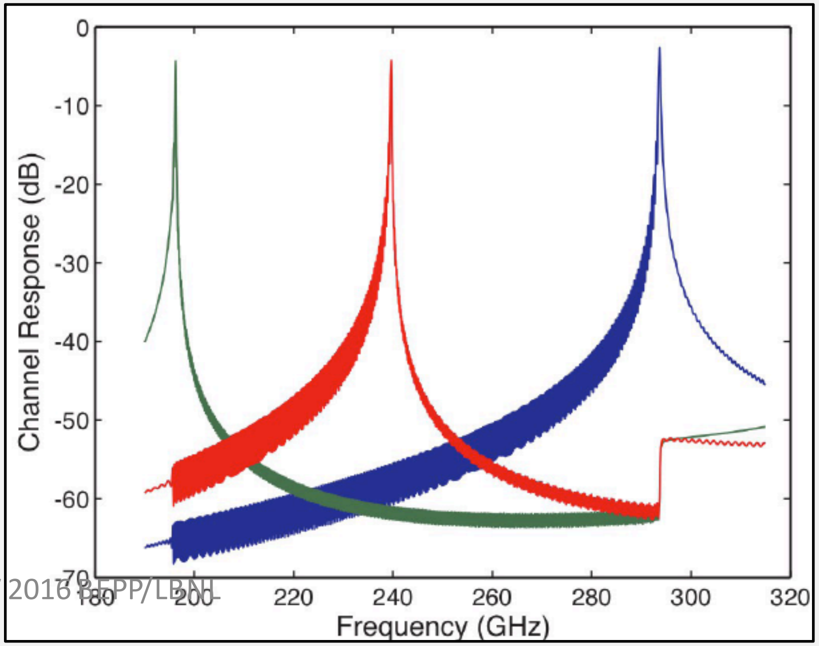
half-wave resonator

coupling capacitors

total power detector

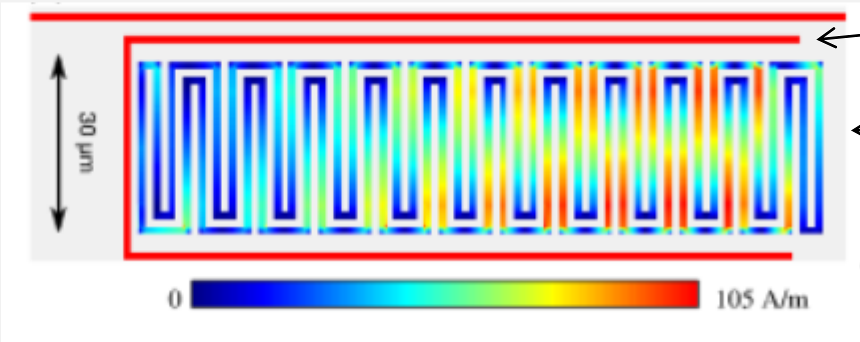


spectral response



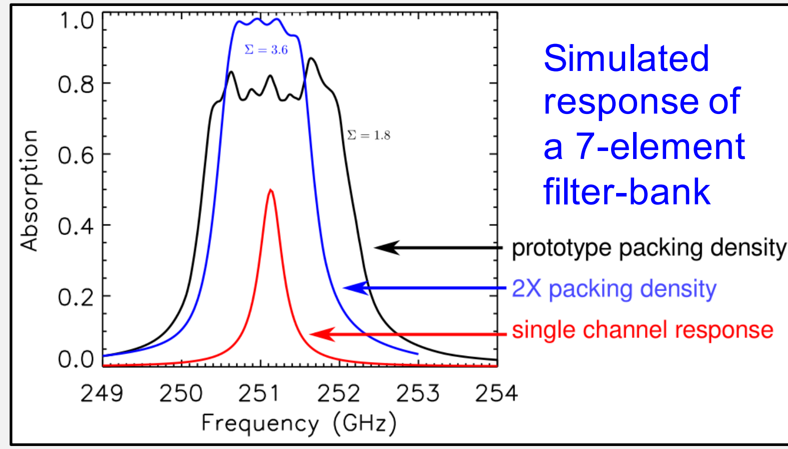
Kovacs and Zmuidzinas 2010, internal memo

Optical Coupling and Filterbank Architecture

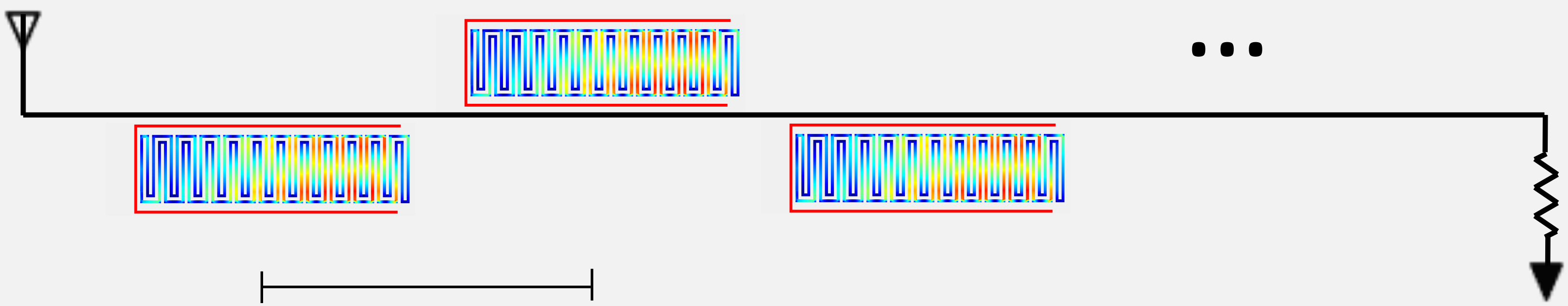


$$\frac{1}{R} = \frac{1}{Q_c} + \frac{1}{Q_i}$$

$$Q_c = Q_i \rightarrow \eta = 50\%$$

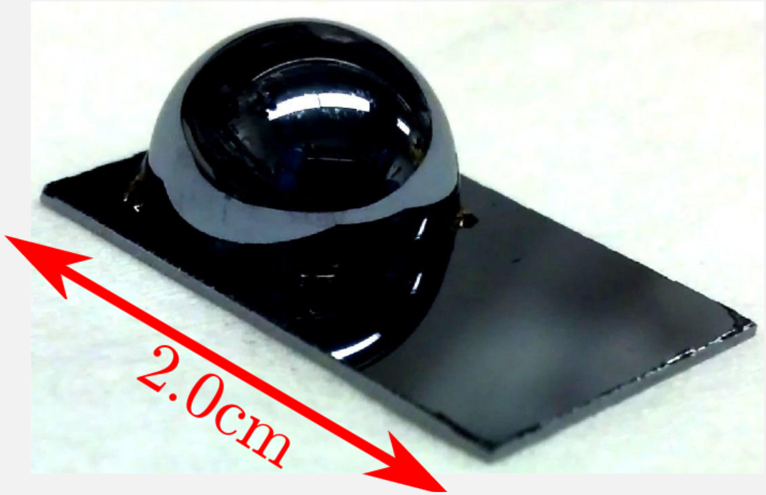


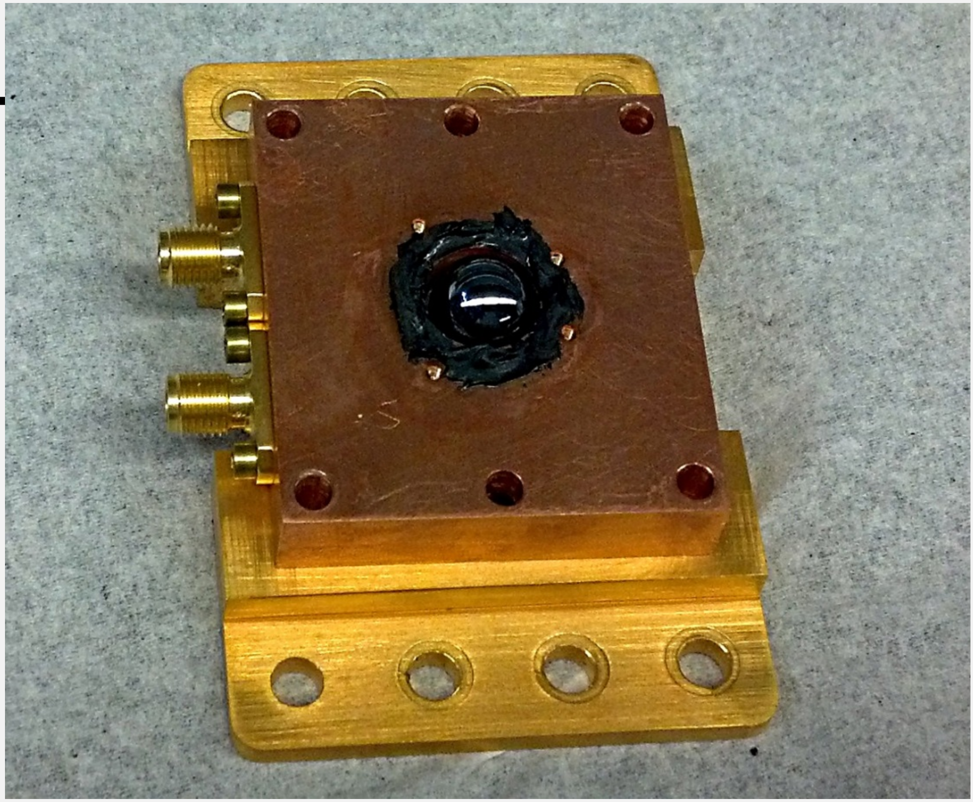
Monotonically decreasing in frequency

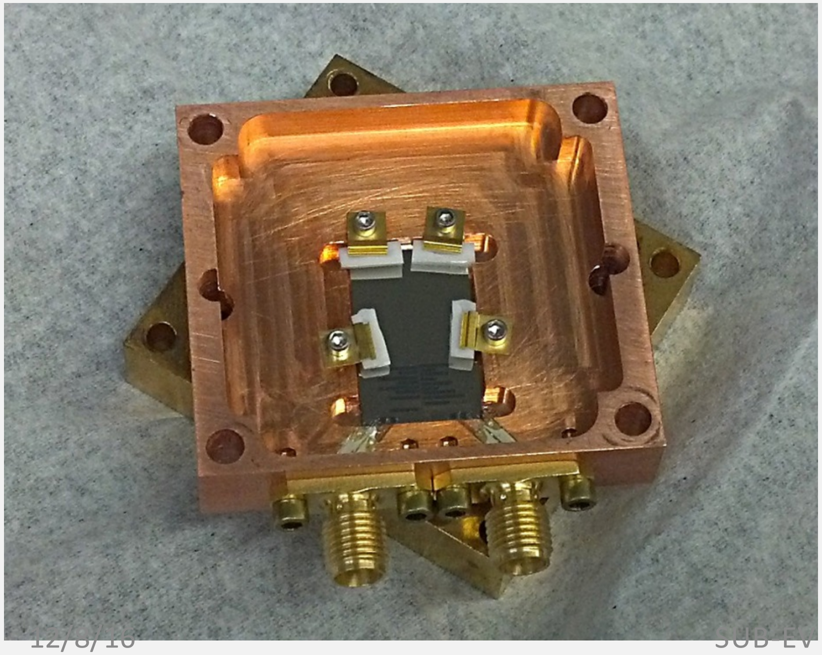


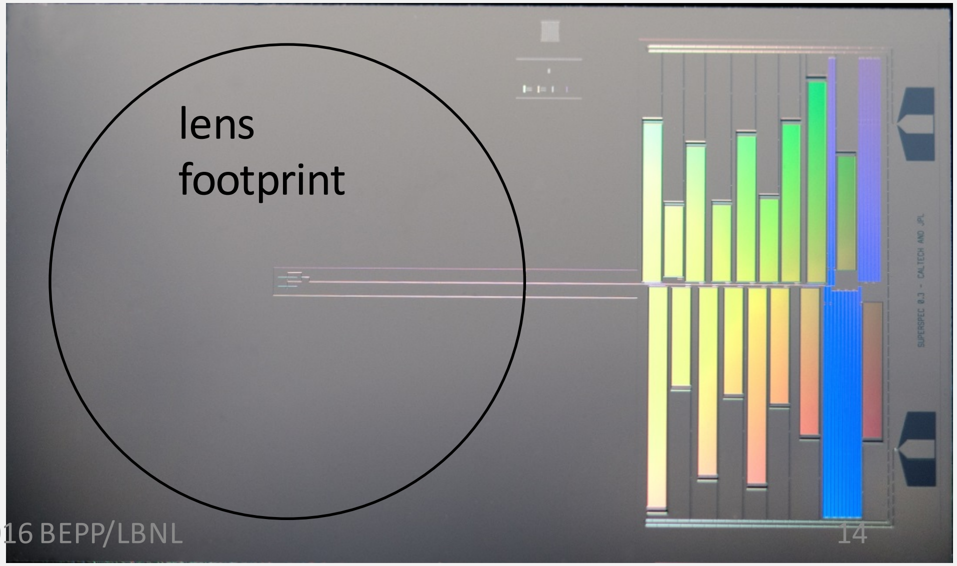
λ/4 or 3λ/4 spacing

Die Packaging

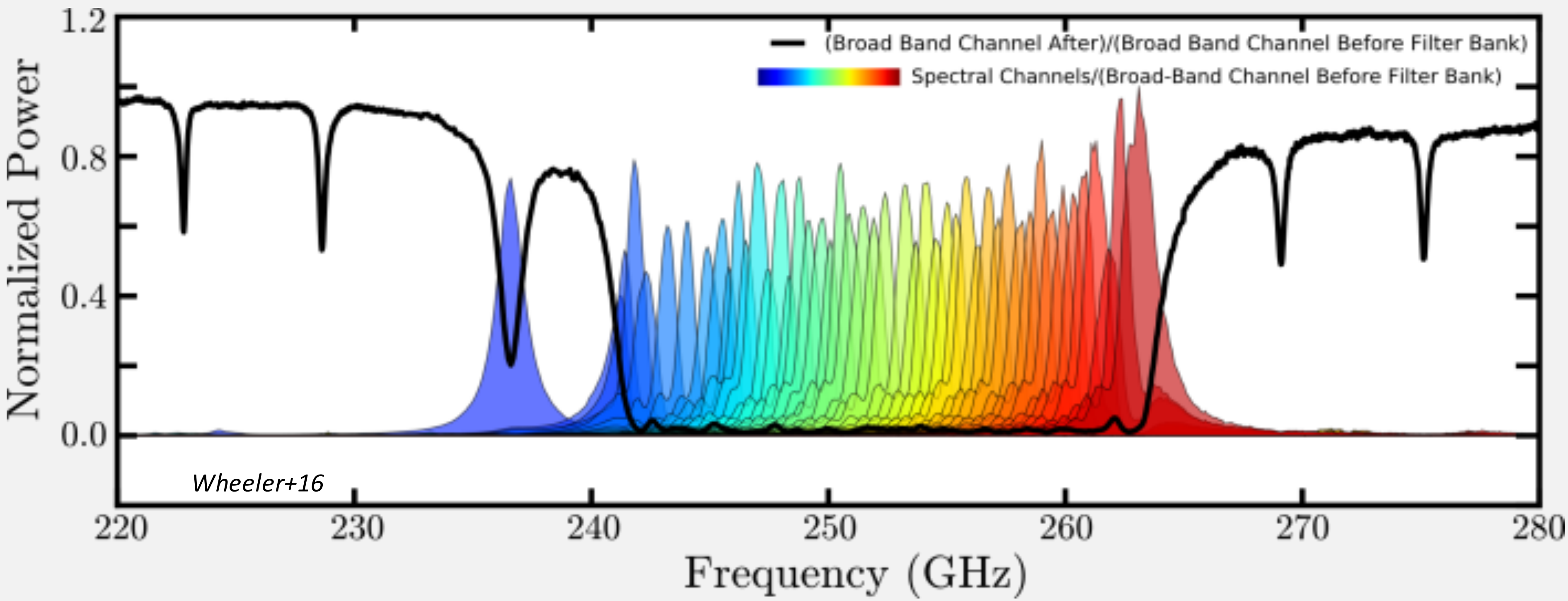








50 Channel Log-Spaced Filterbank



100% yield (on 2 dies)

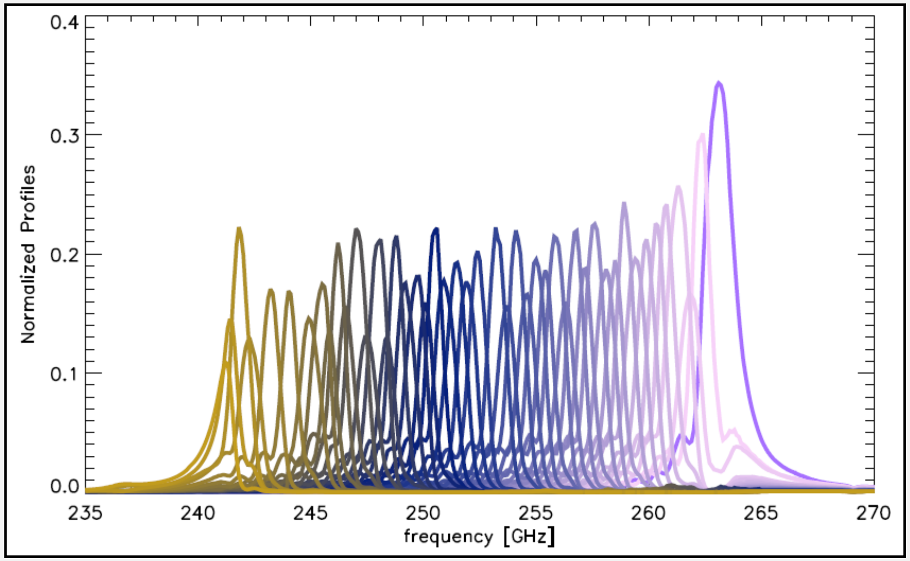
$T_c = 1.8\,\mathrm{K}$, (designed for 1.2)

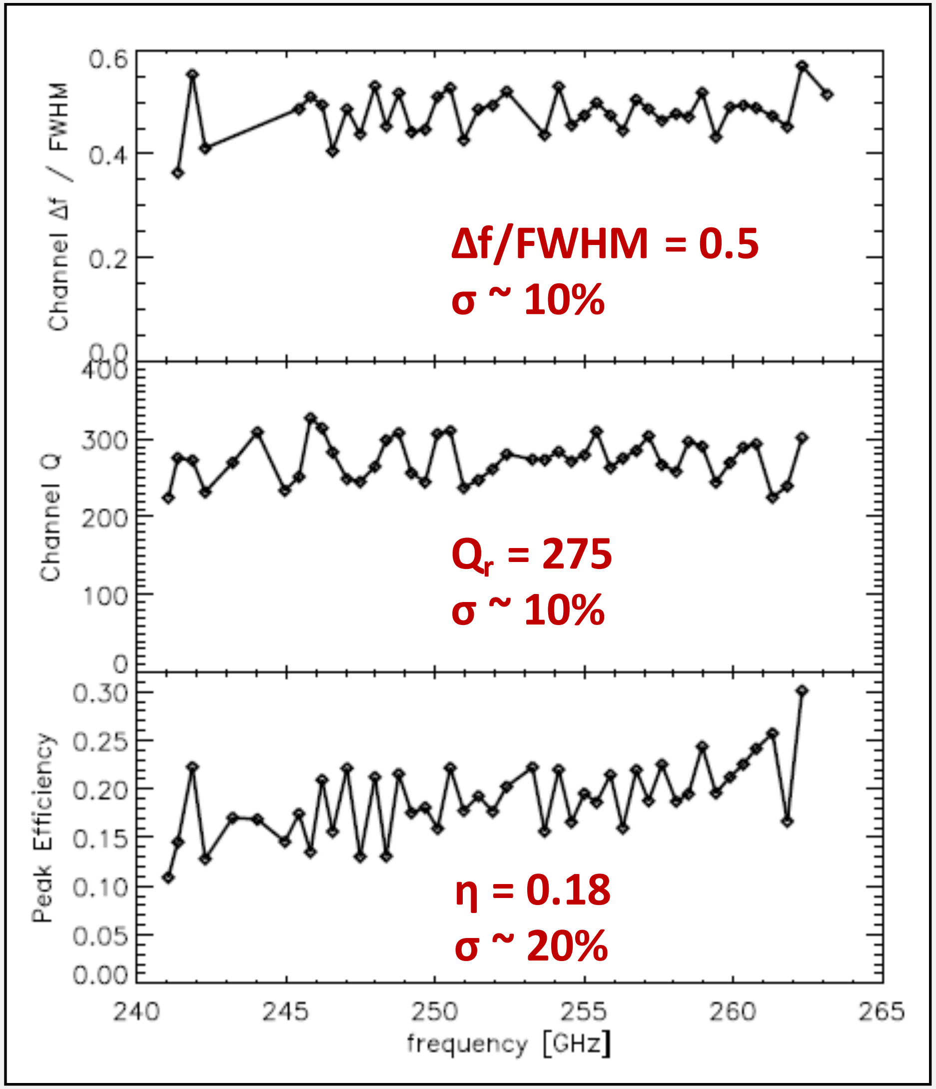
$\mathrm{NEP} \approx 1.5 \times 10^{-17} \mathrm{W}/\sqrt{\mathrm{Hz}}$

- Qloss = 1100
- Qi = 620 (designed for 800)
- Qc = 420 (designed for 462)
- Qr = 200 (designed for 293)
- peak coupling = 0.24

Normalized Profiles

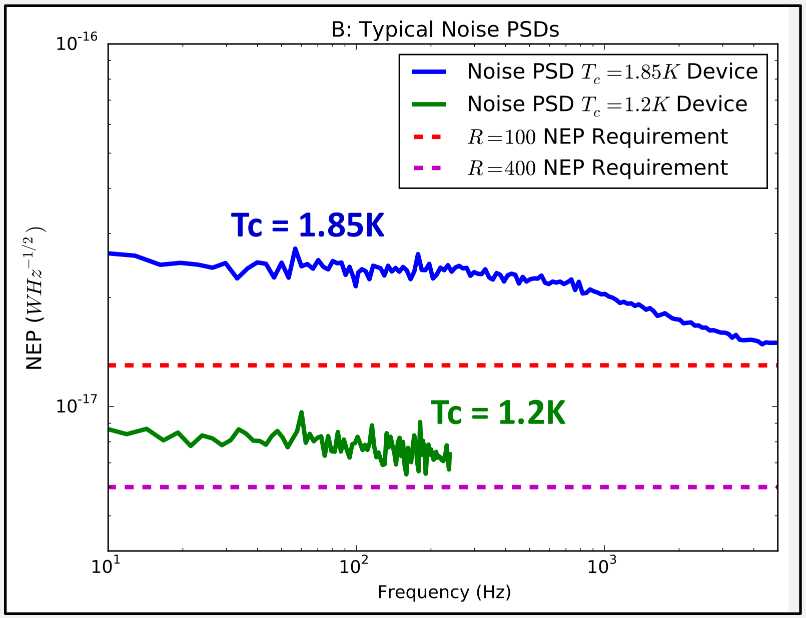
uniform sensitivity across the full band

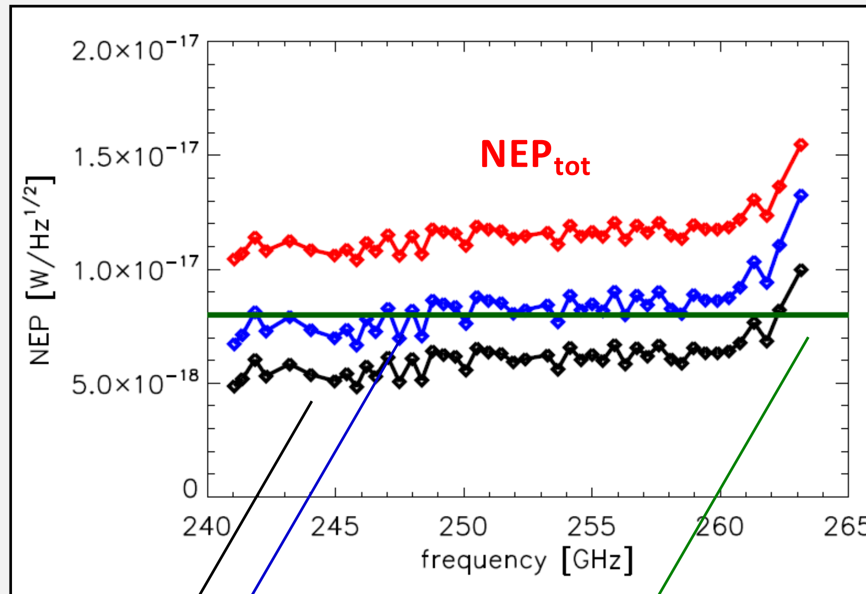




Noise Budget

- Construct noise budget using current spectrometer efficiency, best detector NEP (achieved for T_c = 1.2K).
- Total NEP is x2 higher than fundamental photon limit.





NEP_γ (ε_{warm} = 15%, T_{warm} = 260 K)

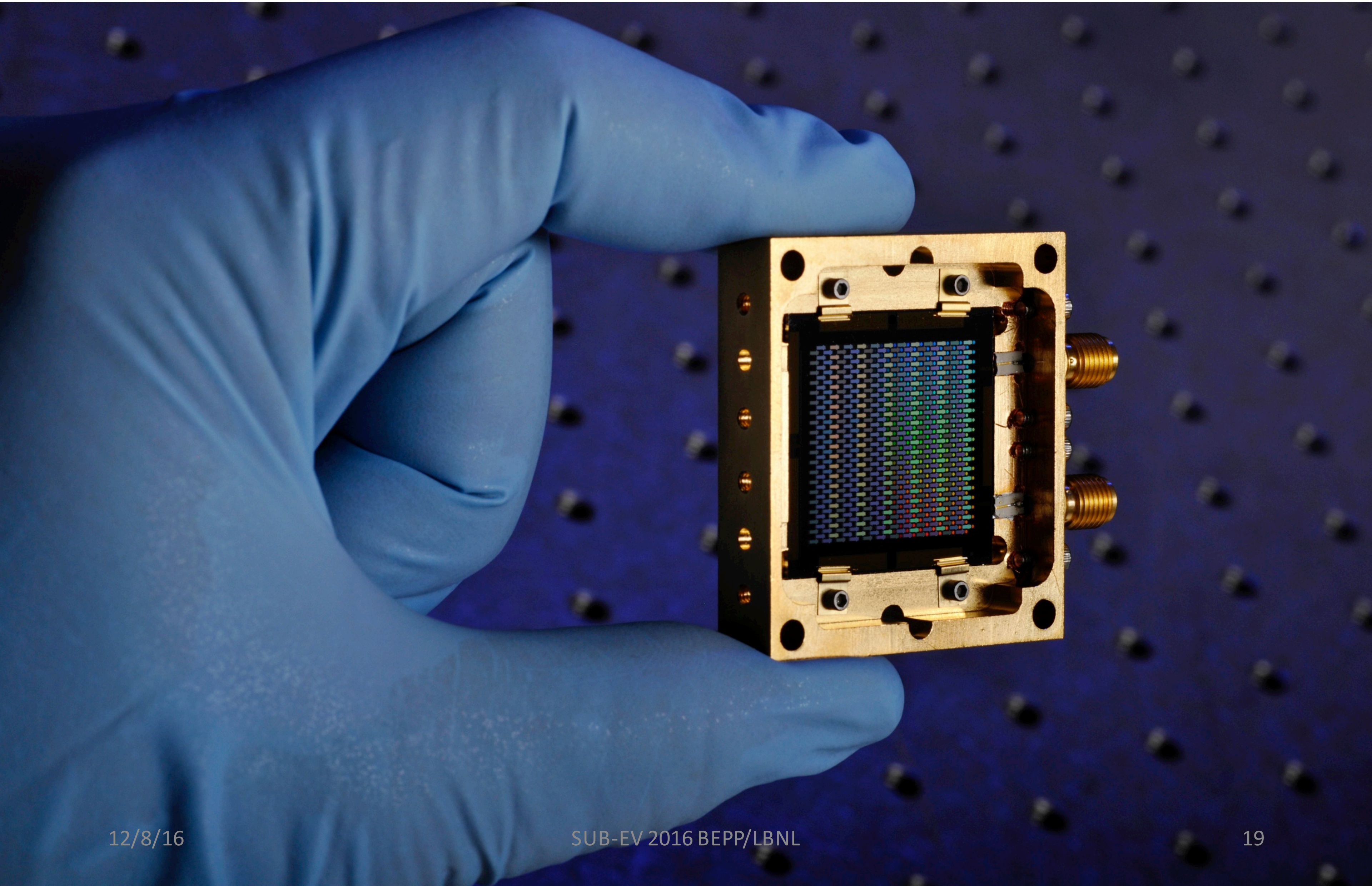
$NEP_\gamma + NEP_{rec}$

NEP_{det}

Summary

- Prototype 50-channel filter bank very close to meeting requirements for ground-based instruments
- Future goals:
  - Design and test full-band filter bank
  - Demonstrate single spectrometer on ground-based telescope
  - Develop imaging array spectrometers

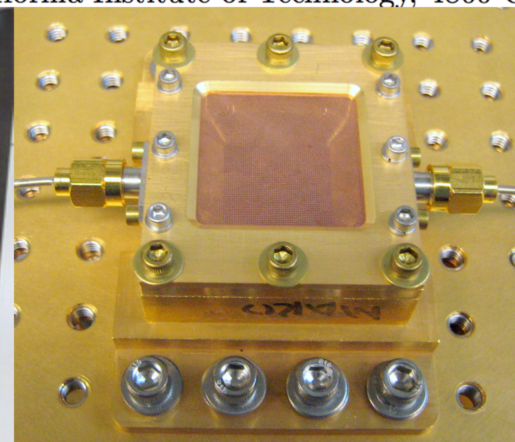
(Microwave) Kinetic Inductance Detectors
1999 - present

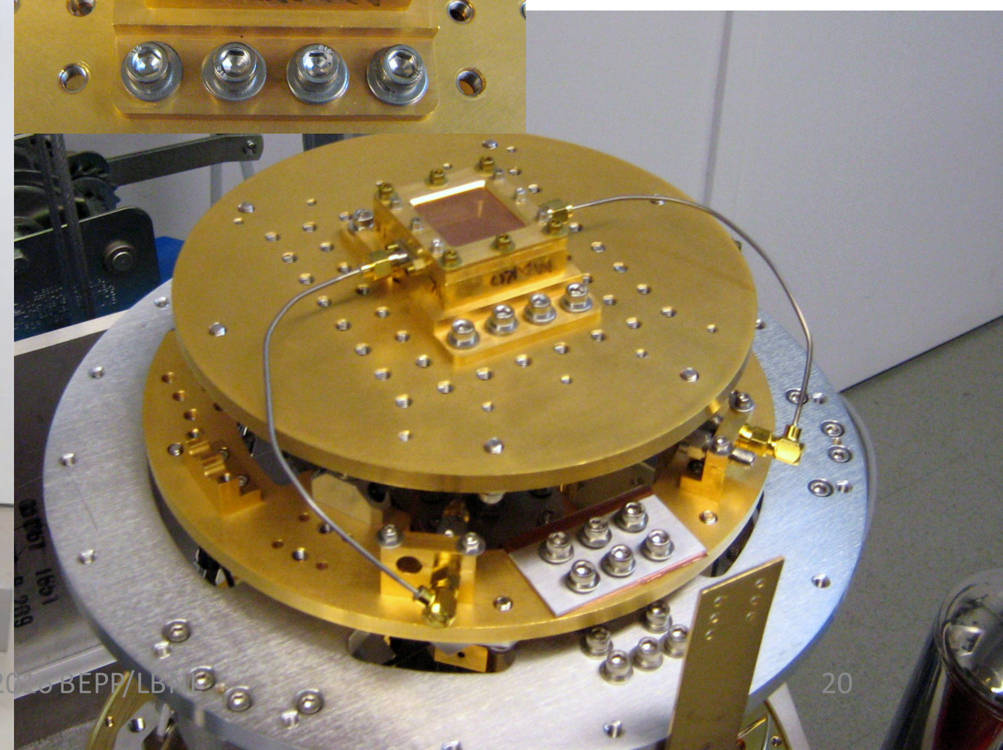


MAKO: A pathfinder instrument for on-sky demonstration of low-cost 350 micron imaging arrays

Loren J. Swenson[a,b], Peter K. Day[b], Charles D. Dowell[b], Byeong H. Eom[a], Matthew I. Hollister[a,b], Robert Jarnot[b], Attila Kovács[a], Henry G. Leduc[b], Christopher M. McKenney[a], Ryan Monroe[b], Tony Mroczkowski[a,b], Hien T. Nguyen[b], and Jonas Zmuidzinas[a,b]

[a]California Institute of Technology, 1200 East California Blvd, Pasadena, California, United States;
[b]NASA Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive,

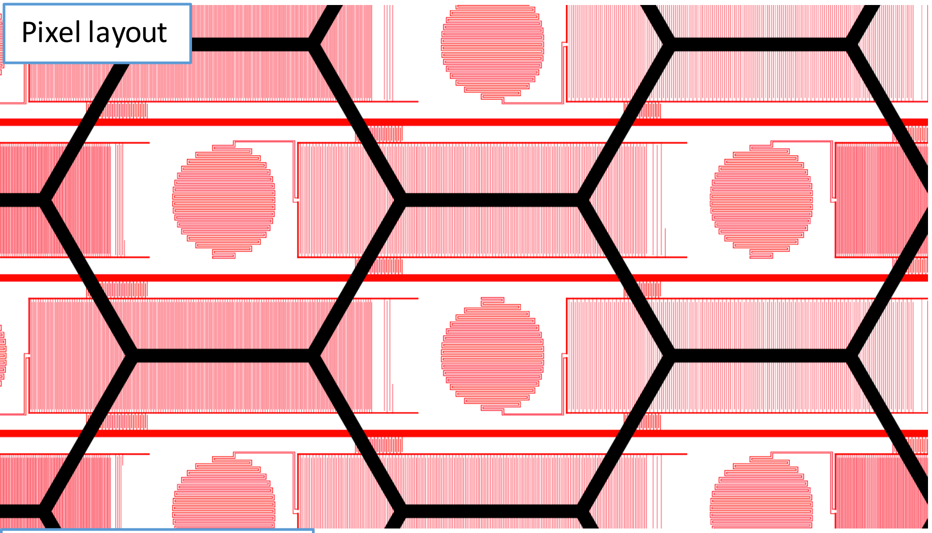




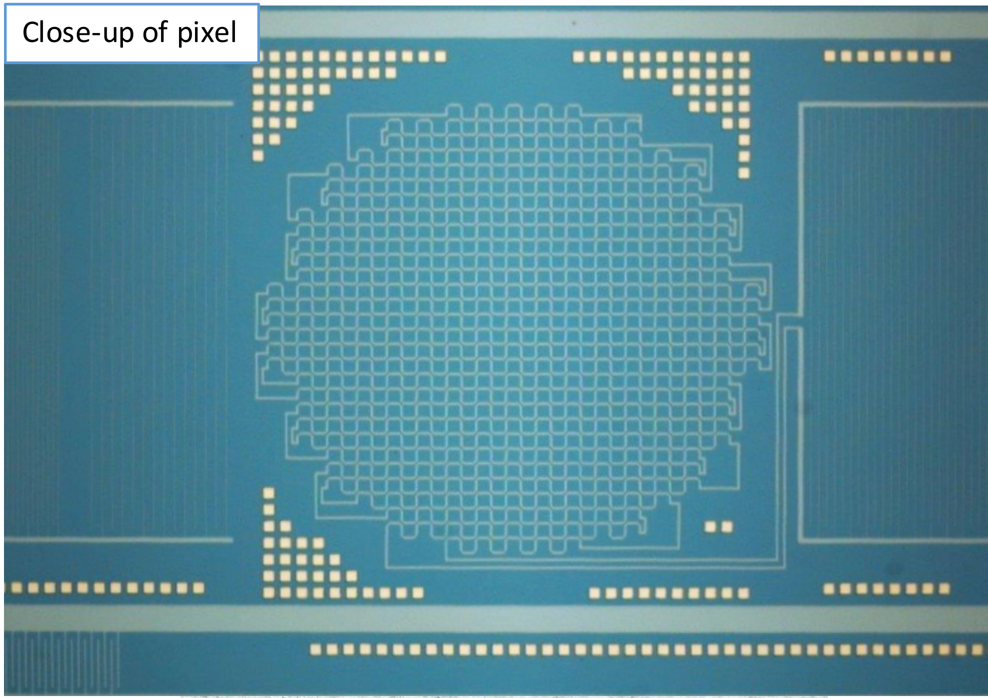
CSO Deployment, May 2015

Some Details

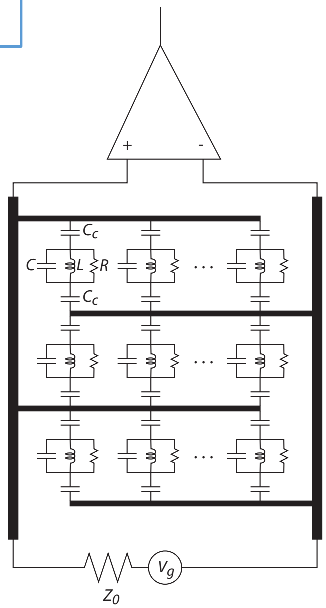
Pixel layout



Close-up of pixel



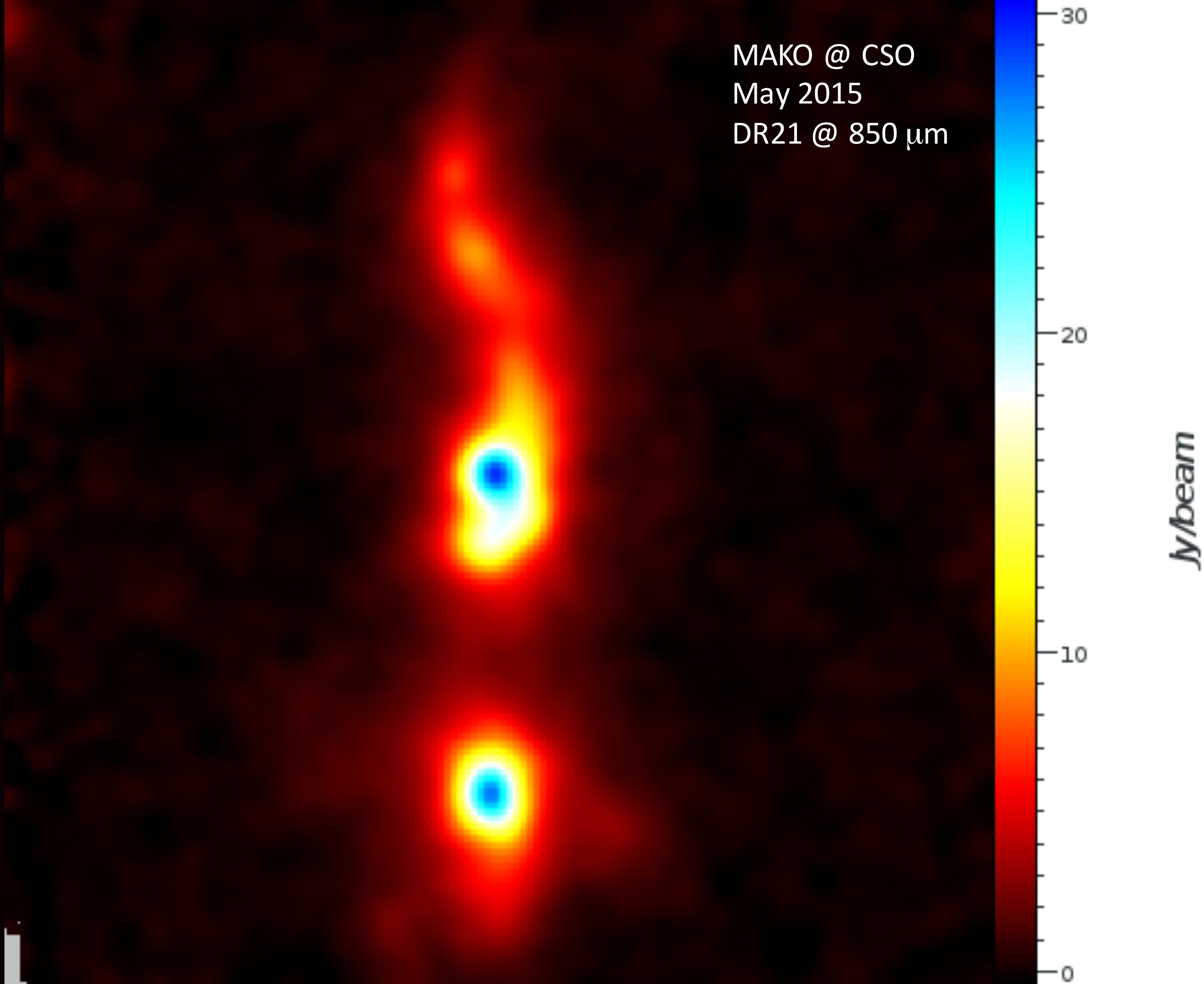
Multiplexing scheme



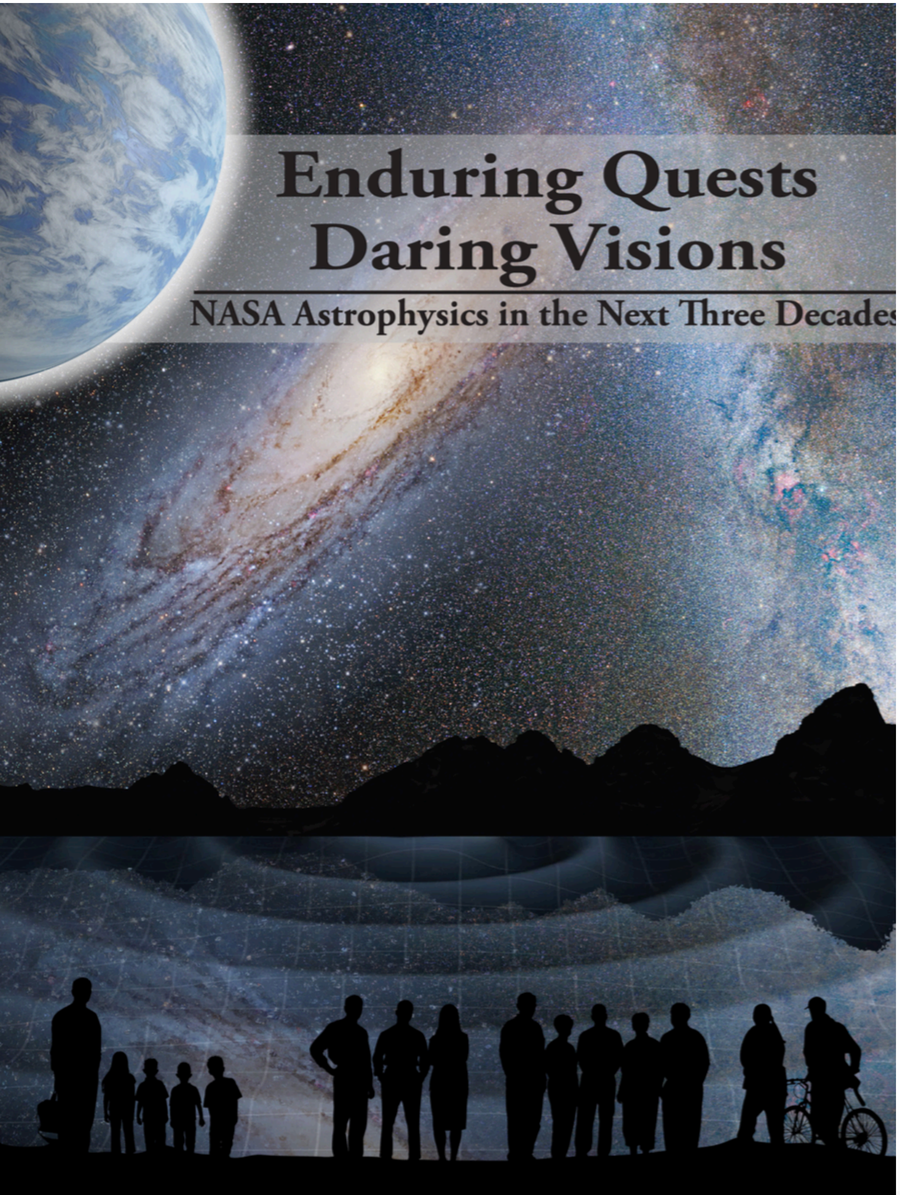
Silicon microlens array

MAKO – 484 TiN KIDs @ 350 μm
2 coax cables for readout

ZSPEC – 160 Ge bolometers @ 1.3 mm
Note large box for detector preamps


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

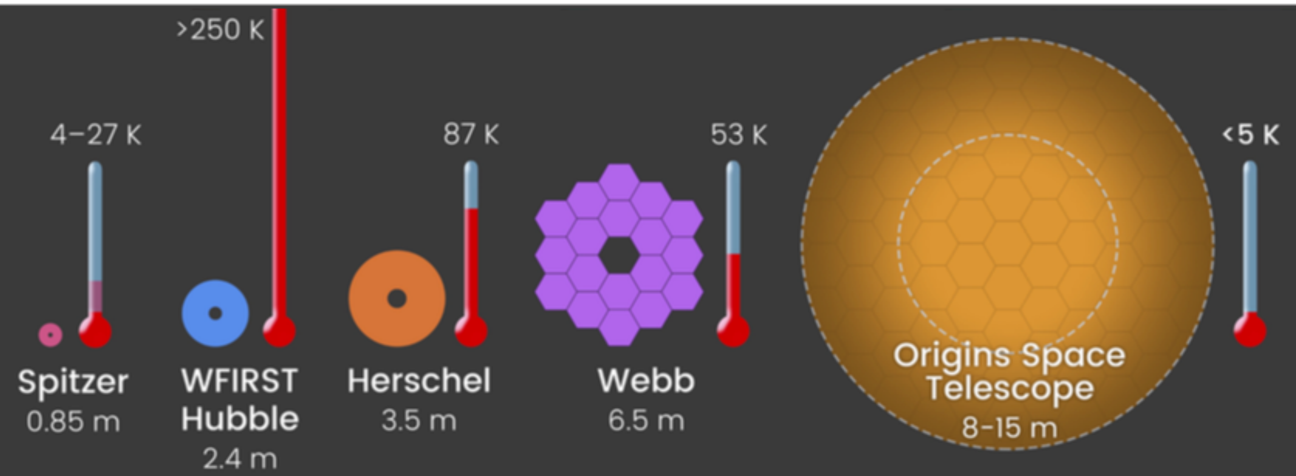
NASA Astrophysics 30-year Roadmap (2013)



ORIGINS Space Telescope | Capabilities & Characteristics

Origins is planned to be a large aperture, actively-cooled telescope covering a wide span of the mid- to far-infrared spectrum. Its spectrographs will enable 3D surveys of the sky that will discover and characterize the most distant galaxies, exoplanets and the outer reaches of our Solar System. The Science and Technology Definition Team would like to hear your science questions and goals for this mission.

Contact us at: *firsurveyor_info@lists.ipac.caltech.edu*



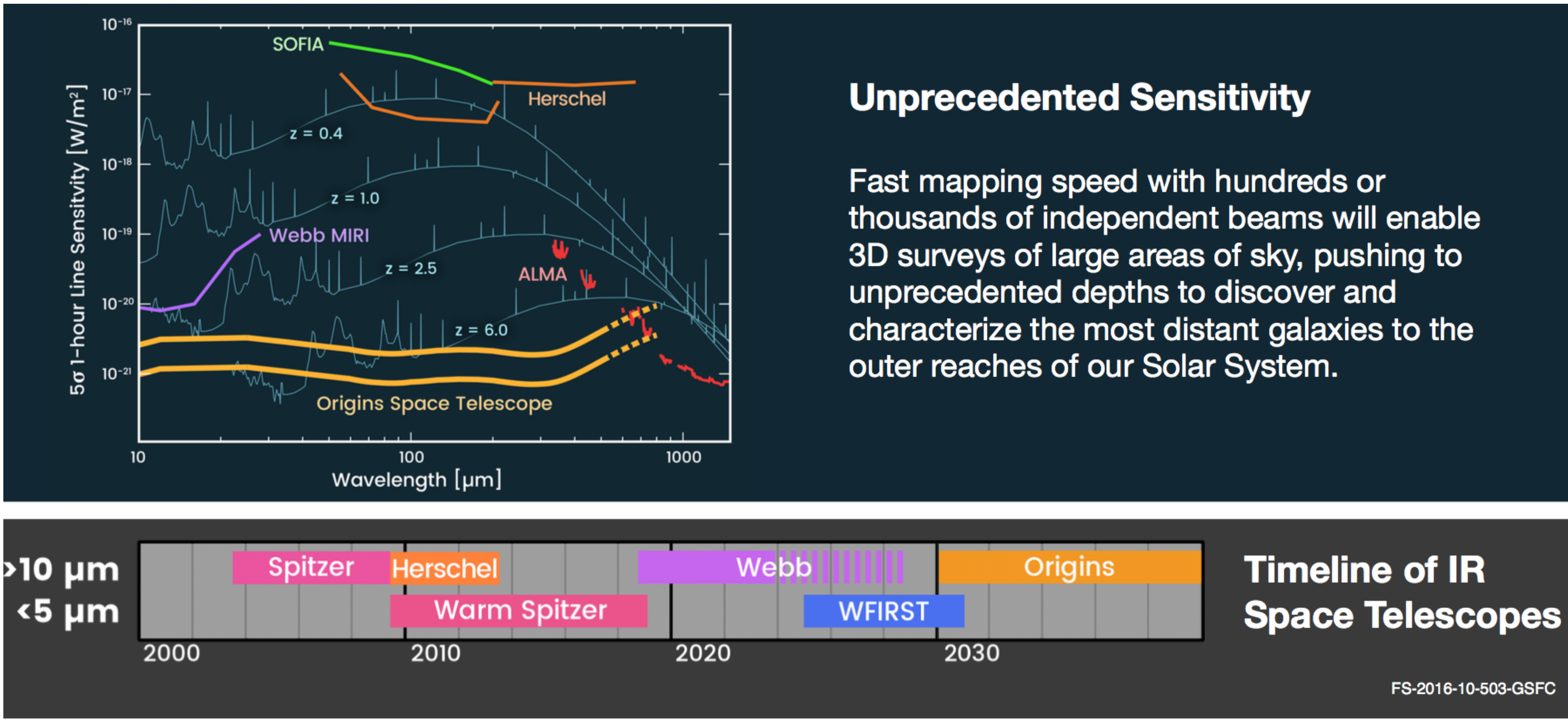
Actively-Cooled Large Aperture

Will attain sensitivities 100–1000x greater than any previous far-infrared telescope

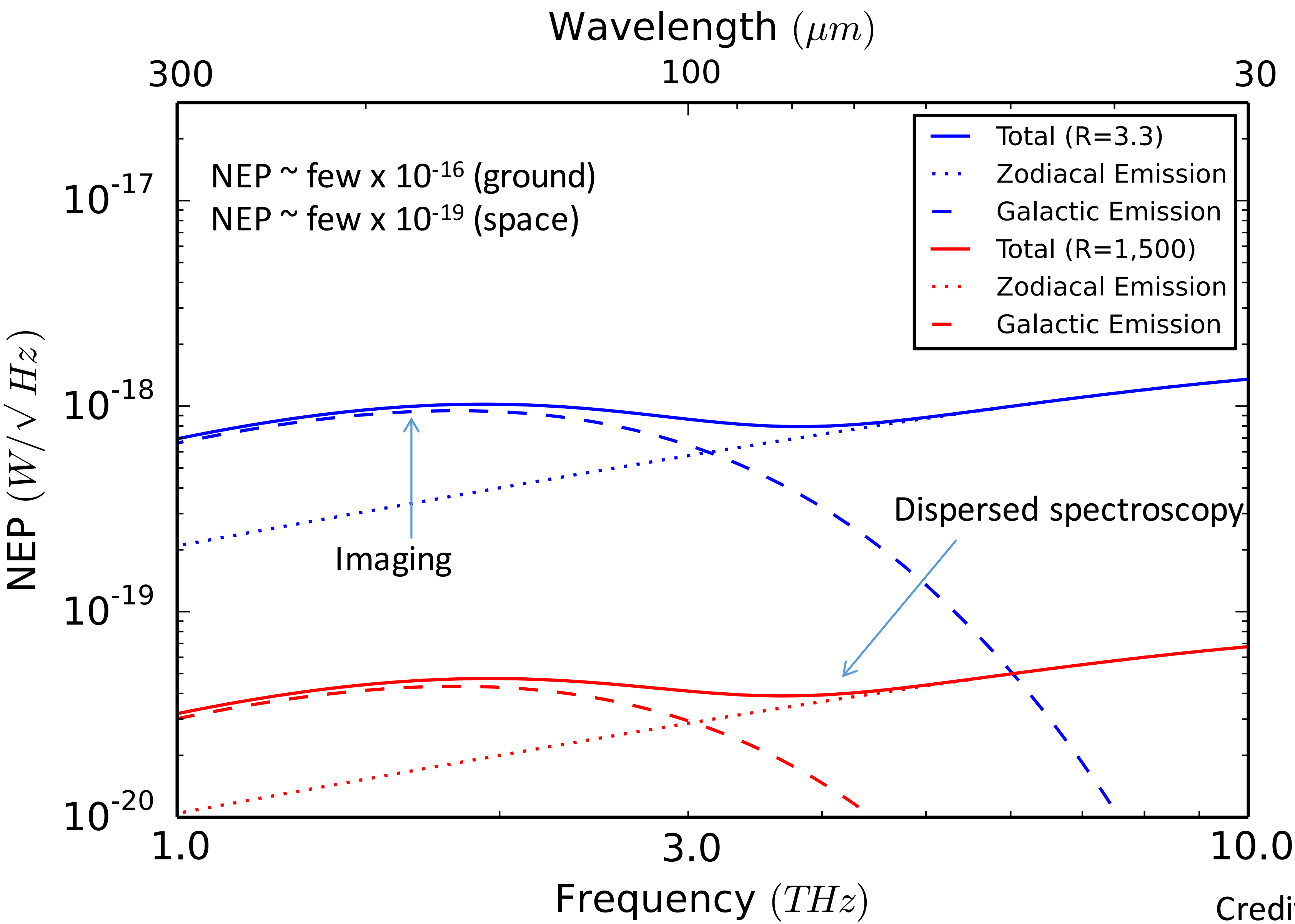
Potential Wavelength Coverage from 10 μm–1 mm

Enables observations of biosignatures in the atmospheres of transiting Earth-like planets, mid- and far-infrared diagnostic lines in galaxies out to redshifts of 10, and characterization of water from the Solar System to the ISM.

Spectroscopy with OST

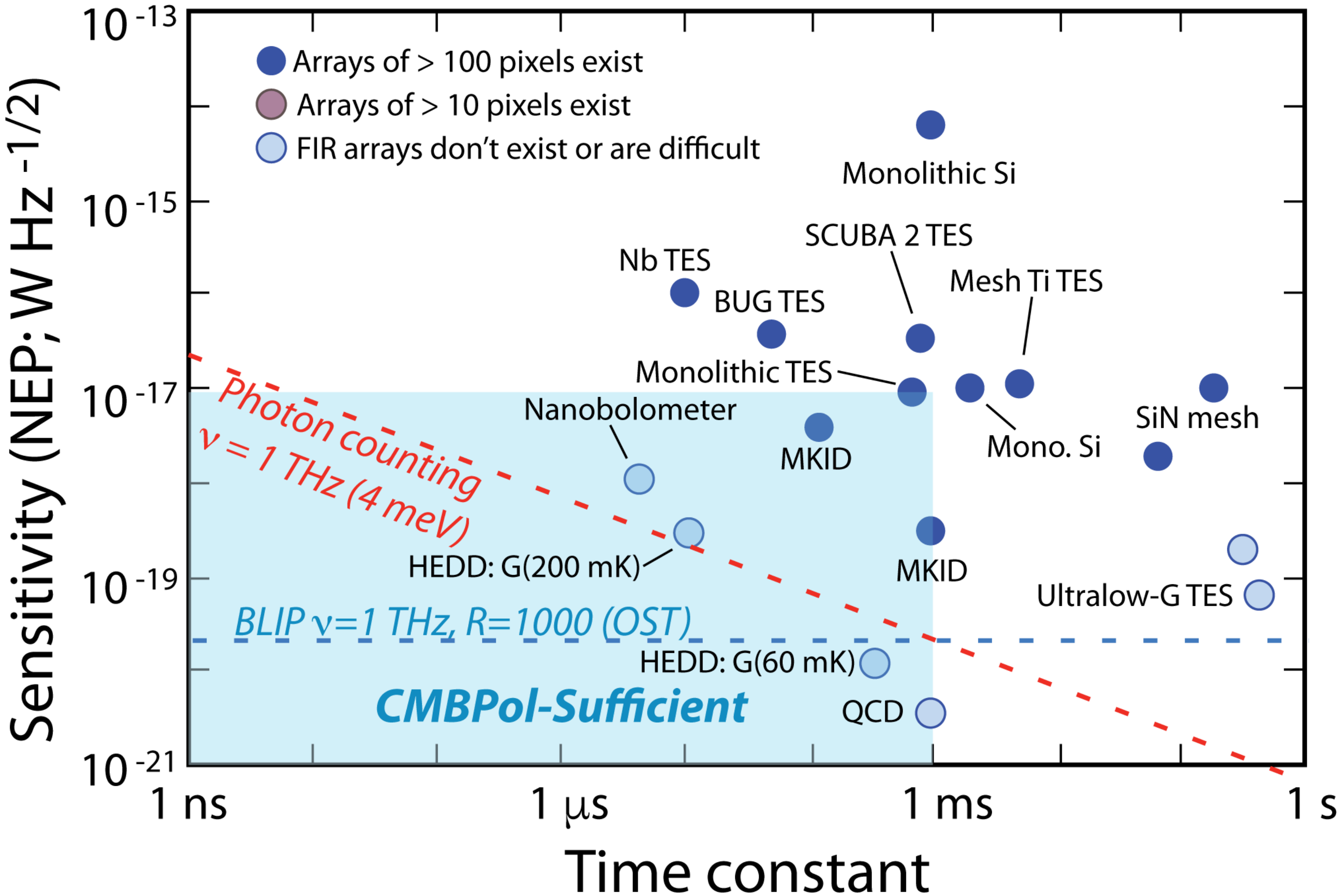


Backgrounds for Cold Space Telescope



Credit: J. Glenn

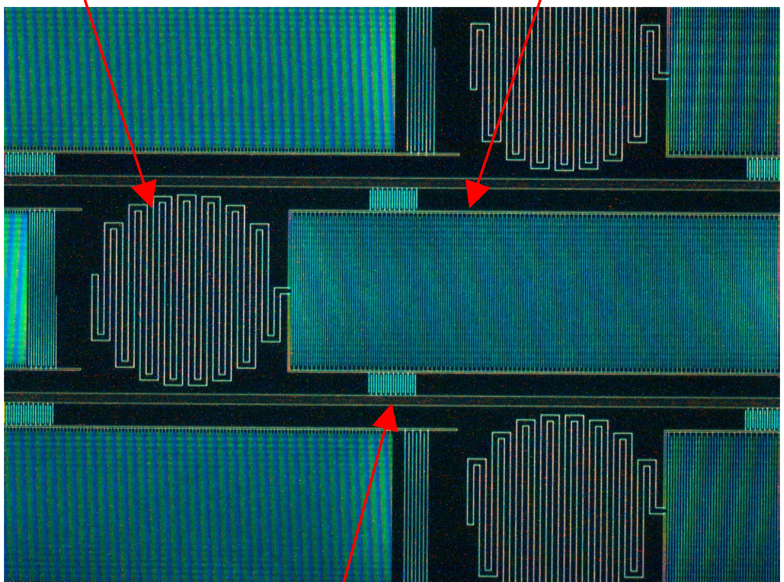
The Benford-Cleland plot



Small-volume absorber-coupled KIDs

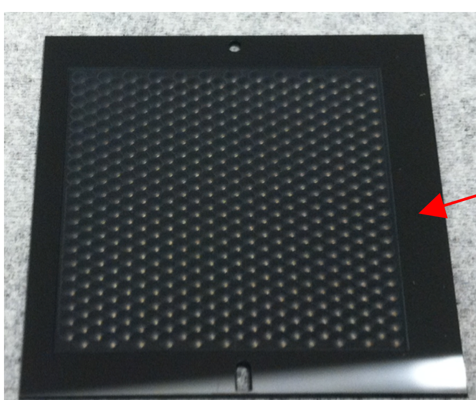
Meandered Inductor

Interdigitated Capacitor



Coupling Capacitor

Detector pitch: 1 mm



Microlens Array

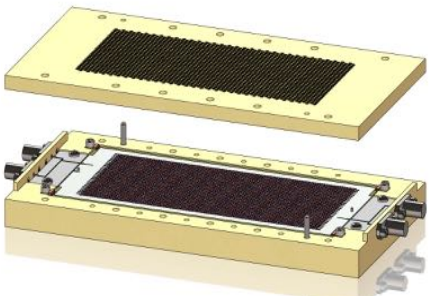
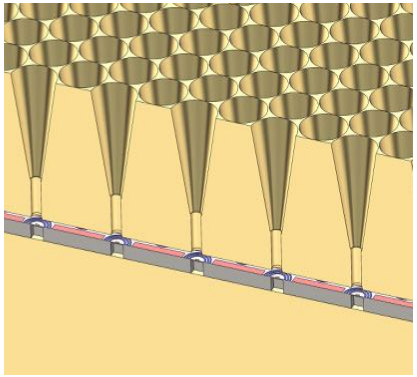
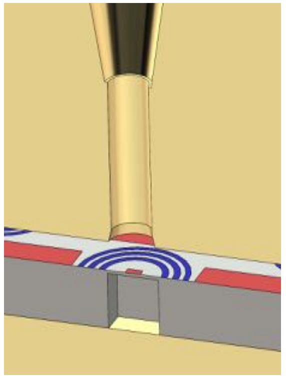
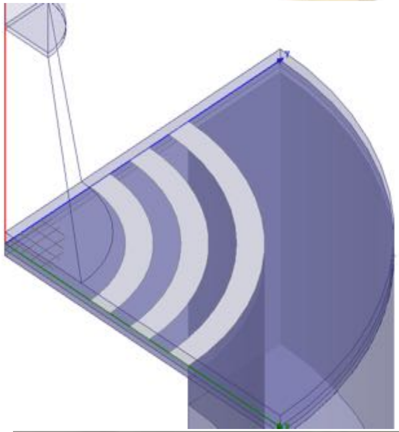
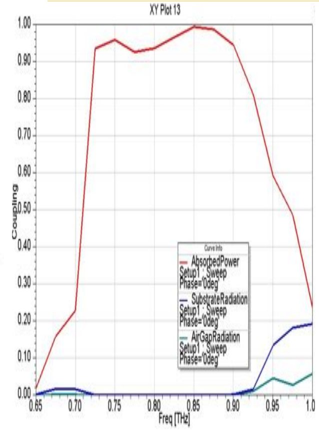
Why this architecture?

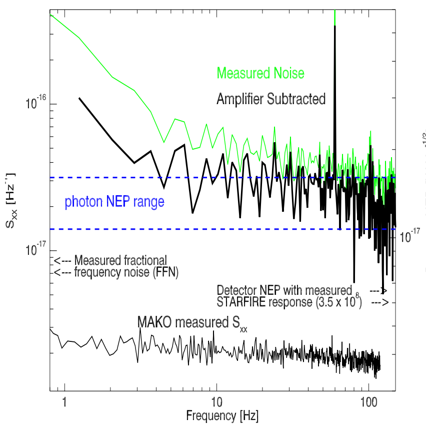
- Low volume inductors
  - ✧ Width: 150 nm
  - ✧ Thickness: 20 nm
  - ✧ Al: low resistivity ➔ Good optical absorption with a low absorber volume
  - ✧ Lens coupling ➔ Minimize inductor area, allow for IDCs
- Low f_0: few x 100 MHz
- τ_{qp} ~ 1 ms for Al
- **Challenge:** High yield?

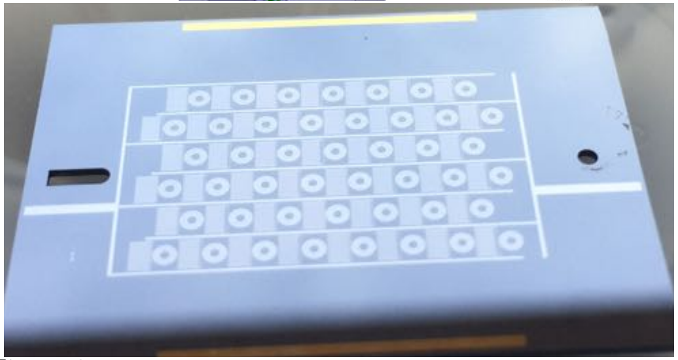
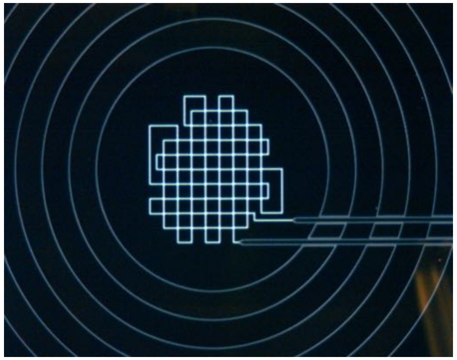
JPL / CIT / U. Colorado
J. Glenn+ SPIE 2016

Follow-on project: ICarIS

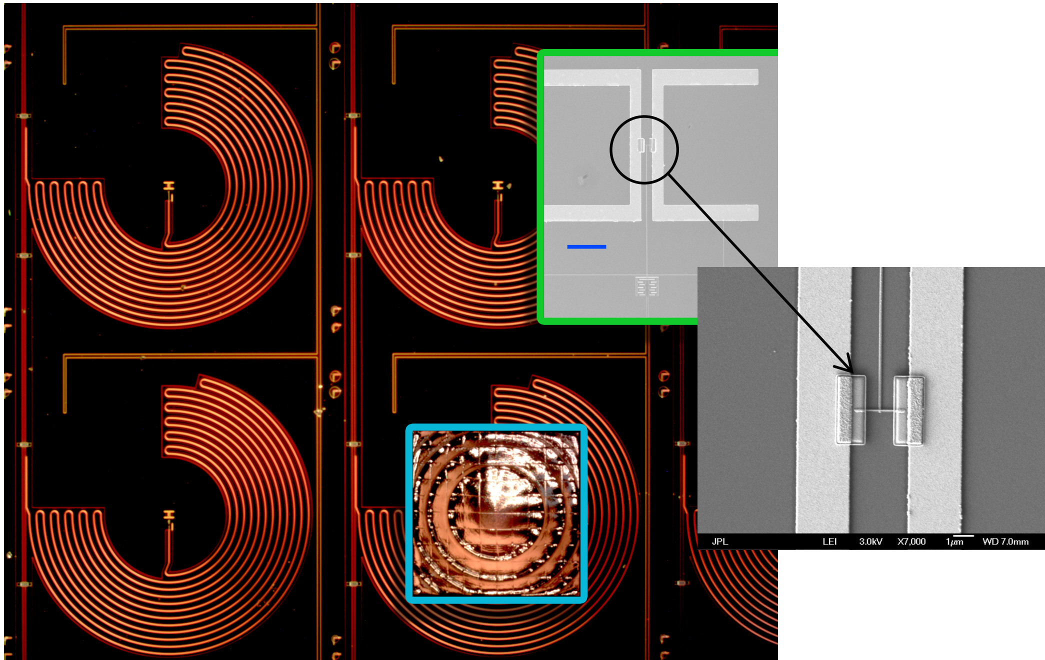
- Balloon payload, proposed to NASA
- C^{+} at 240-420 μm
  - z = 0.5-1.5
- U. Penn: Aguirre, Devlin (integration, gondola)
- JPL/CIT: Bradford, Hailey-Dunsheath (detectors - low-volume Al KIDs)
- U. Arizona: Marrone (telescope)
- Illinois: Vieira (optics)
- Chicago: Shirokoff (detector testing)
- ASU: Groppi, Mauskopf (readouts, machining)

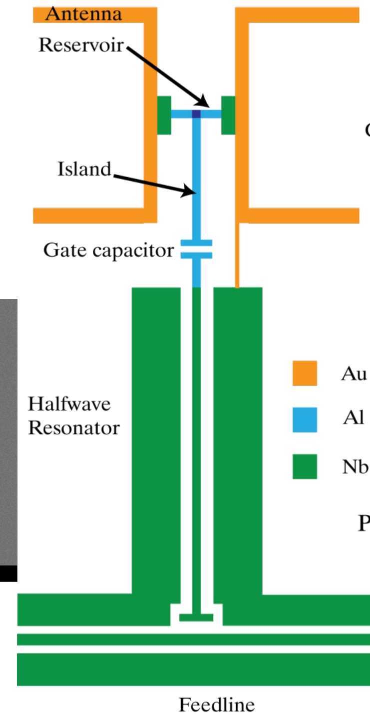






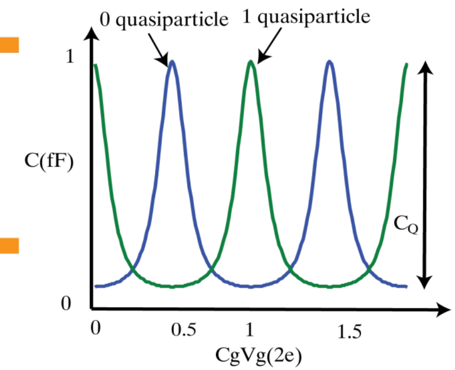


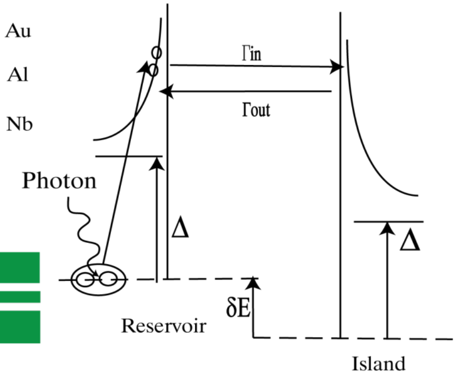



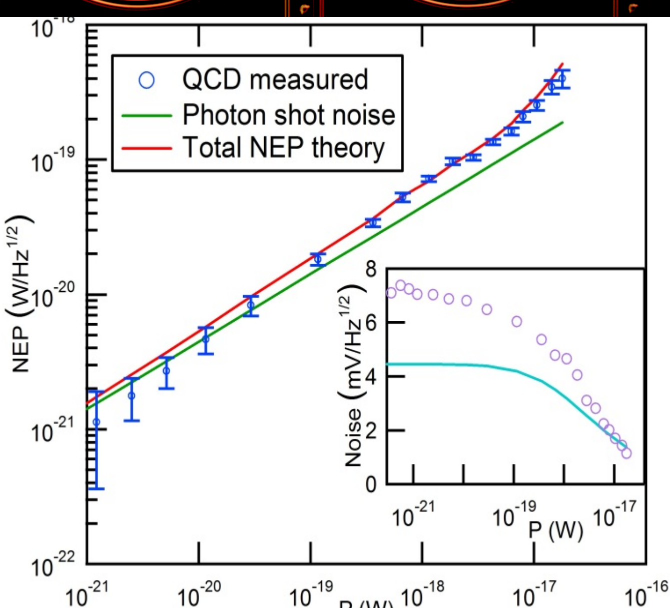
The Quantum Capacitance Detector

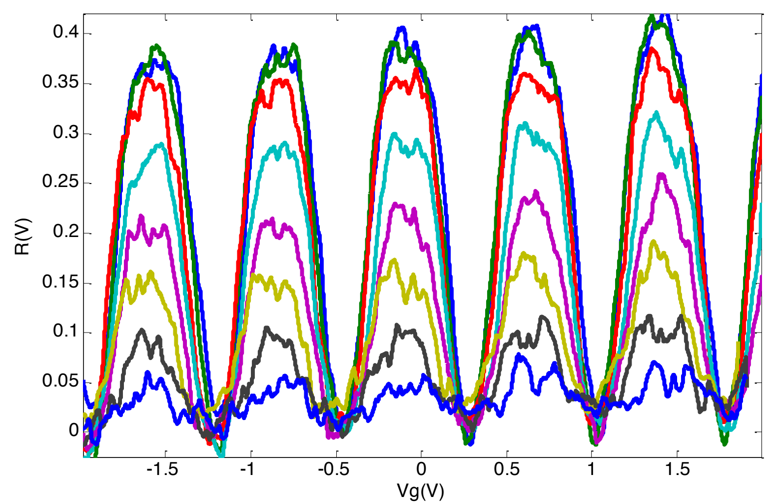






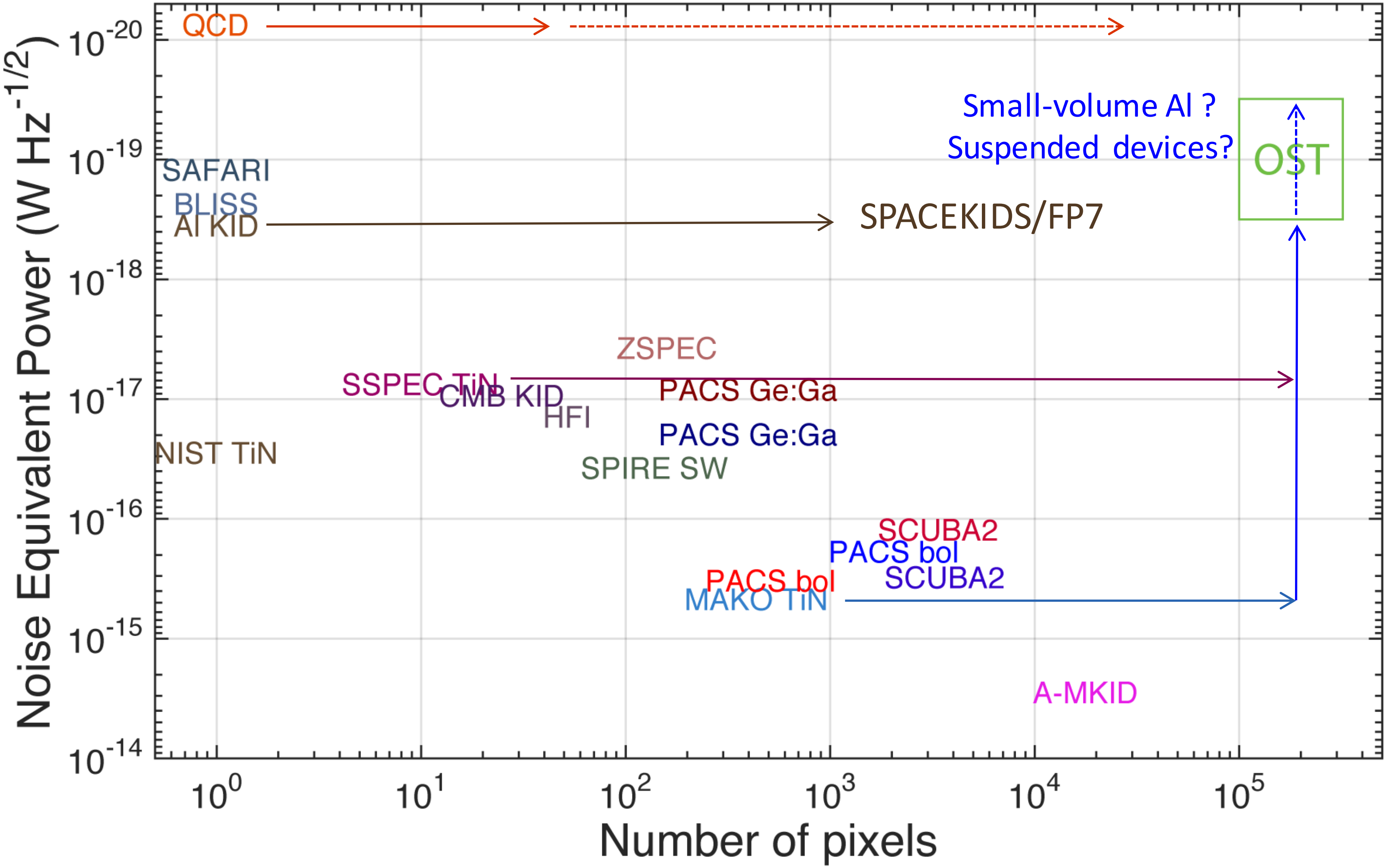






Credit: P. Echternach / JPL

OST’s #1 Technology Challenge

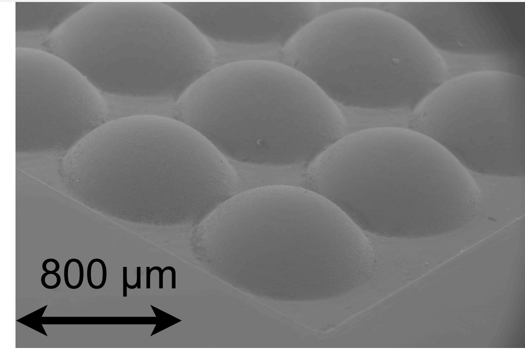


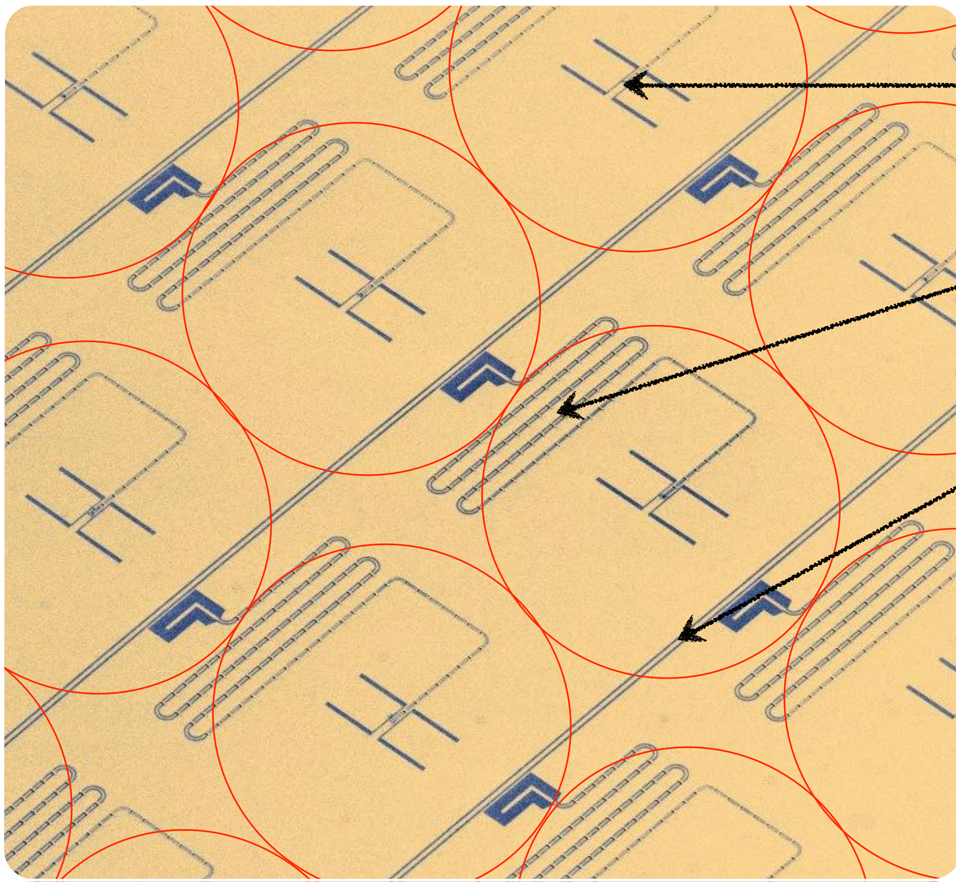
Summary

- Full-system demonstrations of KID instruments (MAKO, NIKA2, A-MKID, ARCONS…)
- Mm-wave chip spectrometers nearing fruition
- Future cold far-IR space telescopes will require detectors with energy resolution in the meV range, scalable to arrays with > 10^5 pixels

KID imaging Array

Lens/antenna coupling
GHz readout



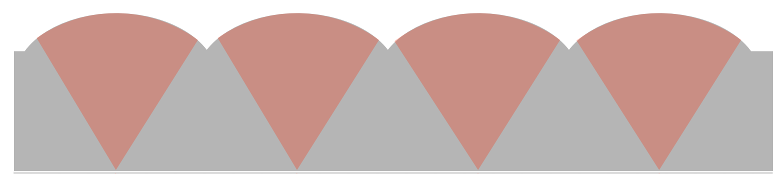


Identical antenna's

Resonators have different length
Different resonance frequencies

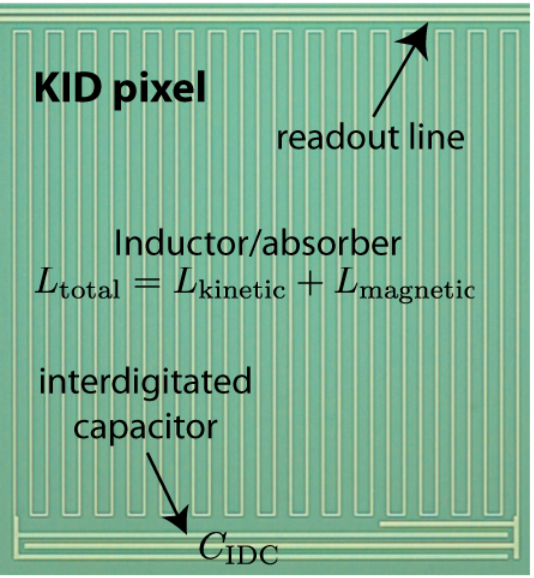
1 readout line connecting all pixels

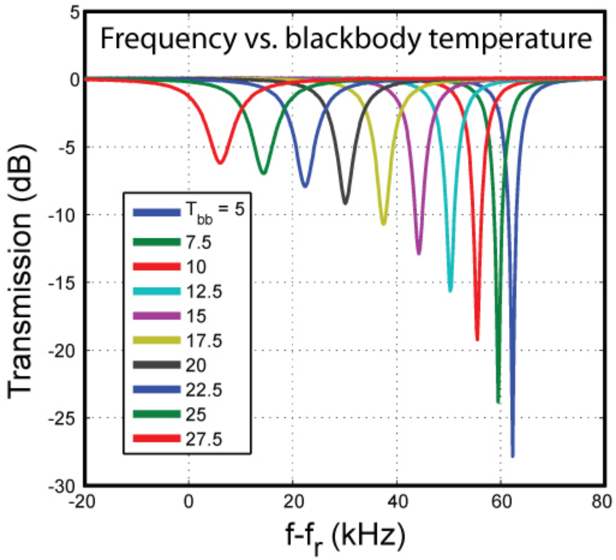
Credit: J. Baselmans, SRON

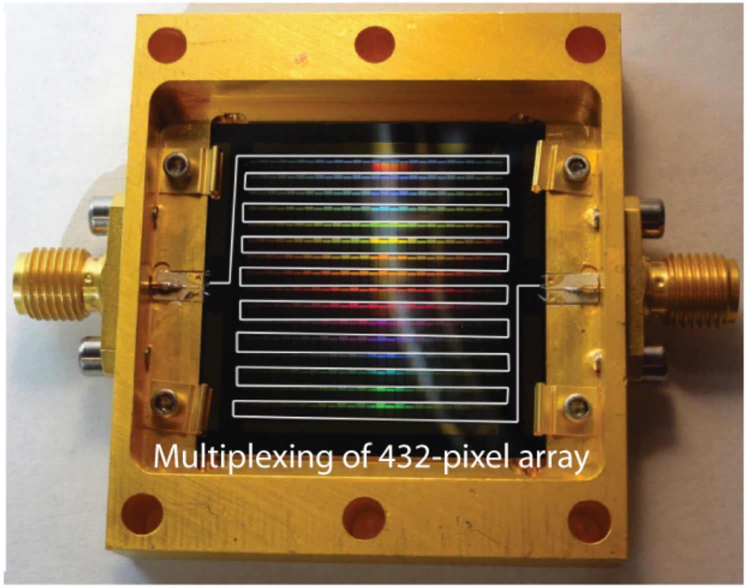


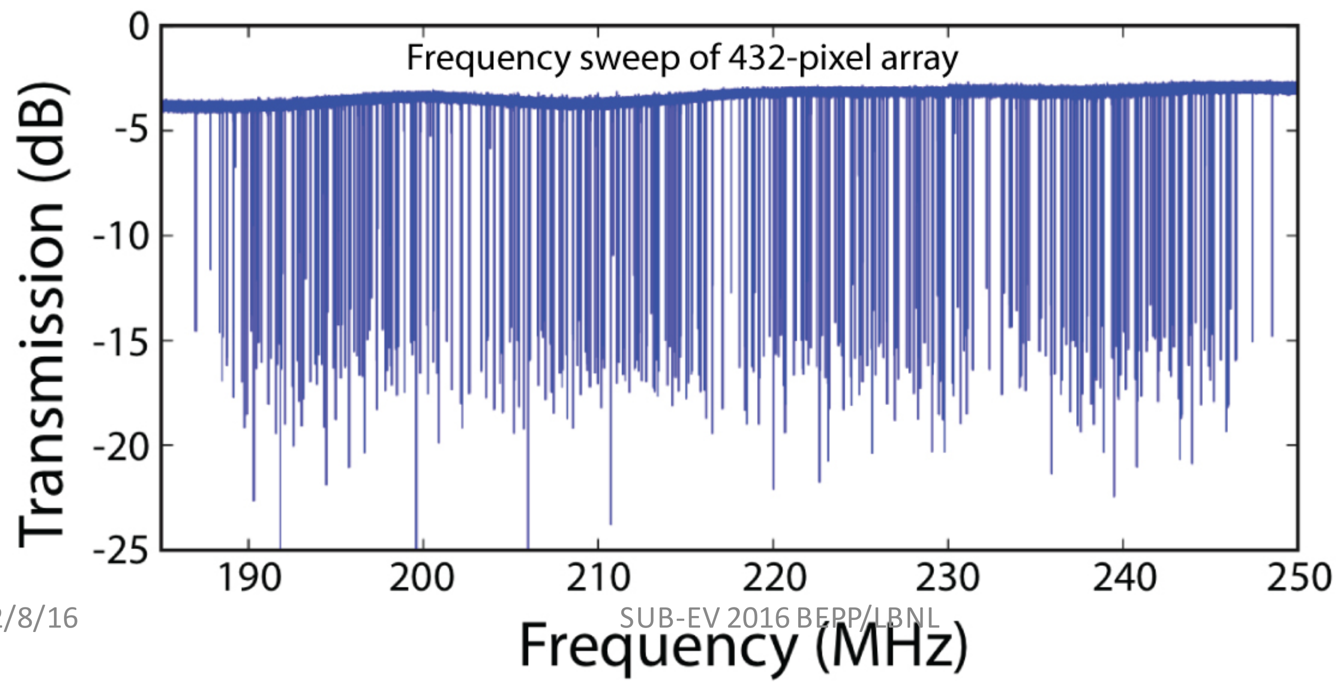
Flies eye lens array, 1 lens/pixel

KIDS: basic concept









Readout:

Fast (500 MSPS) DAC + ADC

Real-time FFT using FPGA or GPU


MAKO

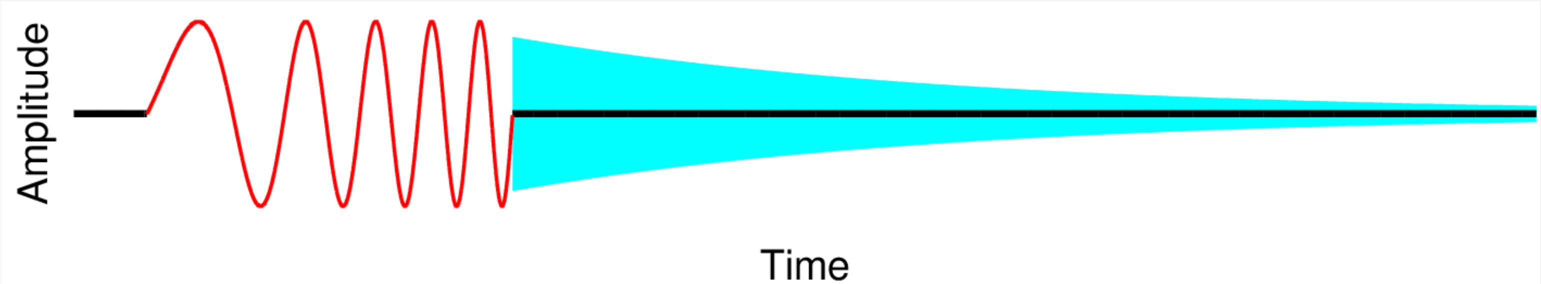
KIDs – Current Status

- Fundamentals of KIDs are well demonstrated and well understood
  - Reaching photon noise limit
  - NEP ~ few 10^{-19} W/Hz$^{1/2}$ (SPACEKIDS)
- A very active area of research
  - Activities at ~2 dozen groups/institutions
- Large KID instruments are on the way
  - 1-25 kpixels (NIKA2, A-MKID, BLAST-TNG, DARKNESS/MEC; + proposals)
  - Enabled by very large multiplexing factors (vs. TES bolometers)
  - Readout electronics now available
- Connections to interesting physics problems (not all solved yet)
  - Quasiparticle recombination dynamics
  - Quasiparticle generation/recombination noise
  - Nonequilibrium superconductivity
  - TLS noise in amorphous materials (→ TLS interactions)
- Several spinoffs
  - Resonators + qubits: cQED (Schoelkopf/Yale)
  - Kinetic inductance paramps
  - Kinetic inductance magnetometers
  - Kinetic inductance bolometers (e.g., YBCO)

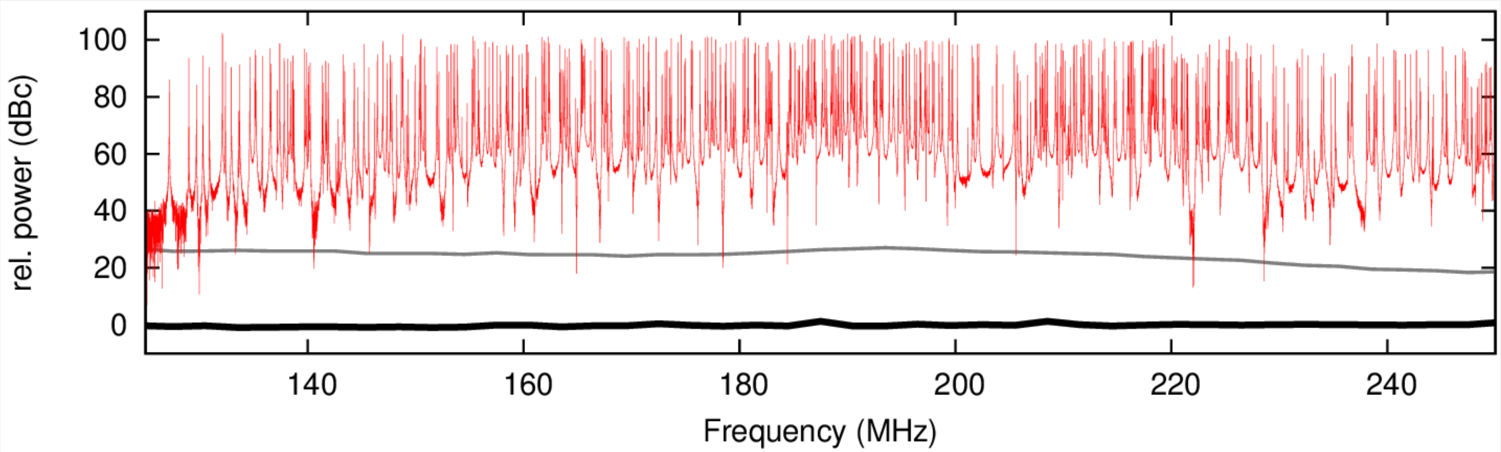
GPU Readout

Chirp pulse excites KID resonators

Resonator ring-down digitized with 500 MSPS ADC
3.6 kHz pulse repetition rate

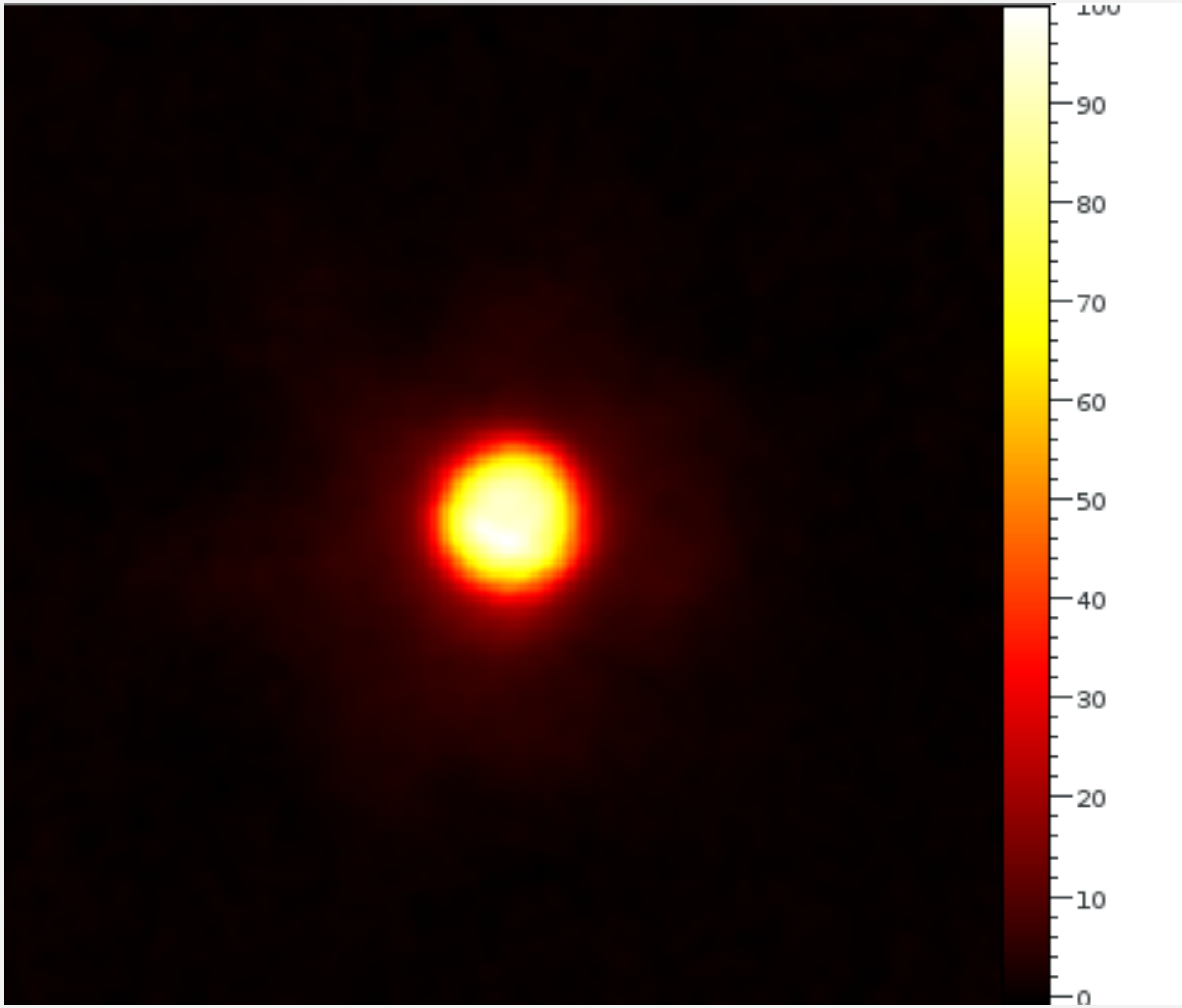


ADC data streamed via PCIe bus to GPU, which performs FFT
Find peaks and measure resonance frequencies of all KID resonators



No need to locate resonances beforehand
Insensitive to frequency shifts due to changes in atmospheric loading
Special tricks: fast GPU centroiding algorithm, handling resonator nonlinearity

On-sky Testing of Chirp Readout



Jupiter @ 350 μm
May 29, 2015
(in poor weather)