Far-IR Detectors

Jonas Zmuidzinas
Caltech & JPL

Photon noise

$$S_I = 2e\bar{I} = 2(e)^2\bar{\Gamma}_e$$

Spectral density of current (shot noise)
Campbell 1909; Schottky 1918

$$S_P = 2h\nu\bar{P} = 2\left(h\nu\right)^2\bar{\Gamma}_{h\nu}$$

Spectral density of optical power

$$S_P = 2h\nu\bar{P}\left(1+n\right)$$

Photon bunching

$$\mathrm{NEP}_\gamma^2 = S_P$$

NEP^2 = spectral density of optical power

$$\bar{P} = h\nu\bar{\Gamma}_{h\nu} = h\nu(2n\Delta\nu)$$

n = # photons / sec / Hz / mode

$$n(\nu,T) = \left[\exp(h\nu/kT)-1\right]^{-1}$$

occup. number for blackbody

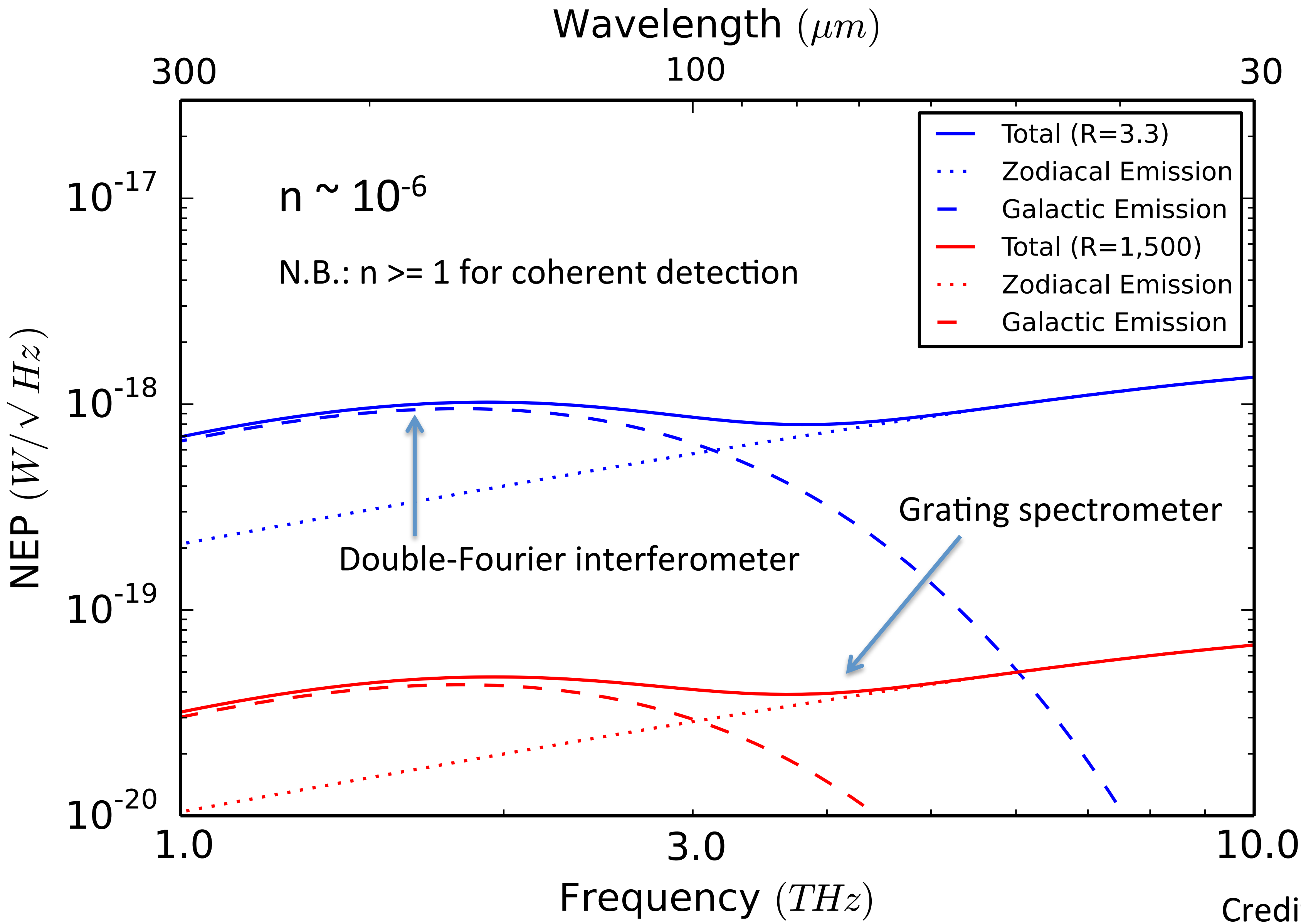
$$n = \tau_{\mathrm{cold}}\left(\epsilon_{\mathrm{optics}}n_{\mathrm{optics}} + n_{\mathrm{sky}}\right)$$

cold transmission

optics emissivity

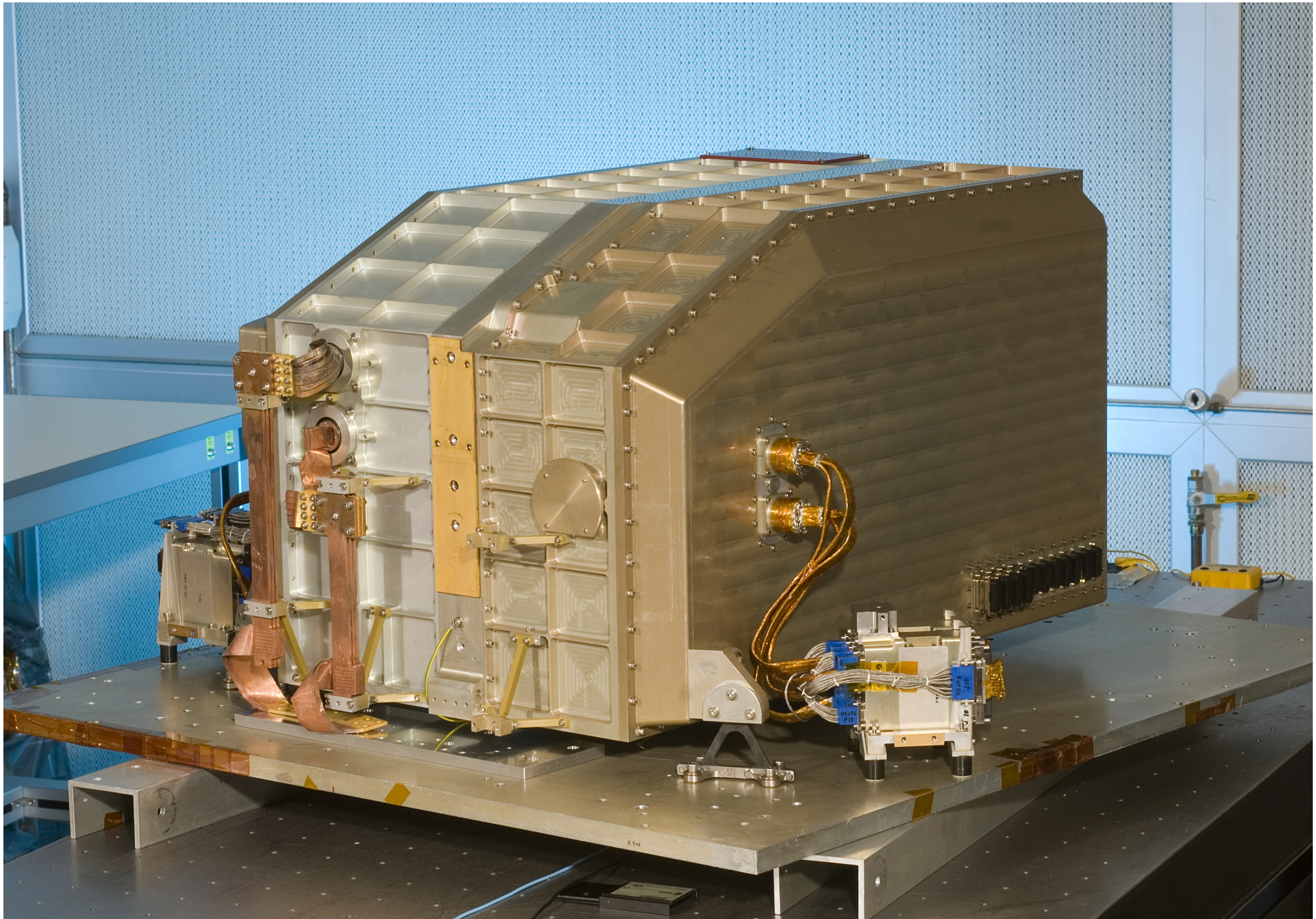
sky background

Sky background

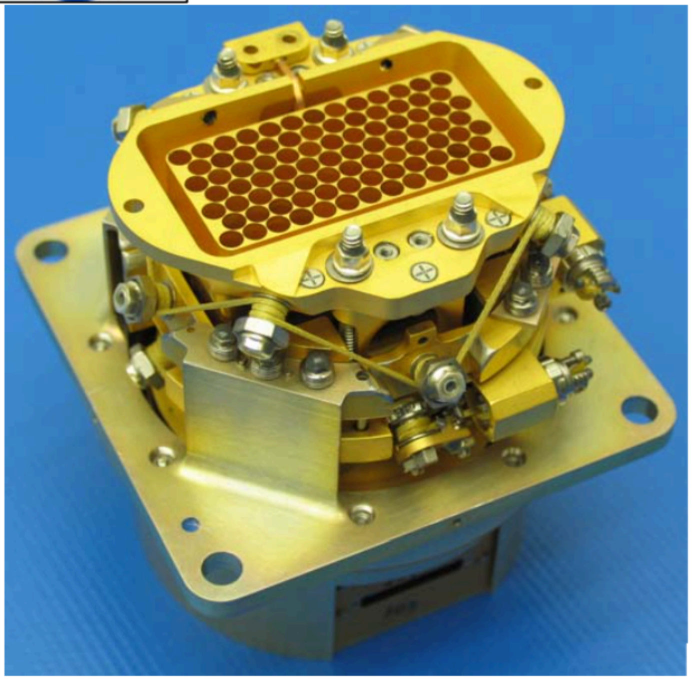


Credit: J. Glenn

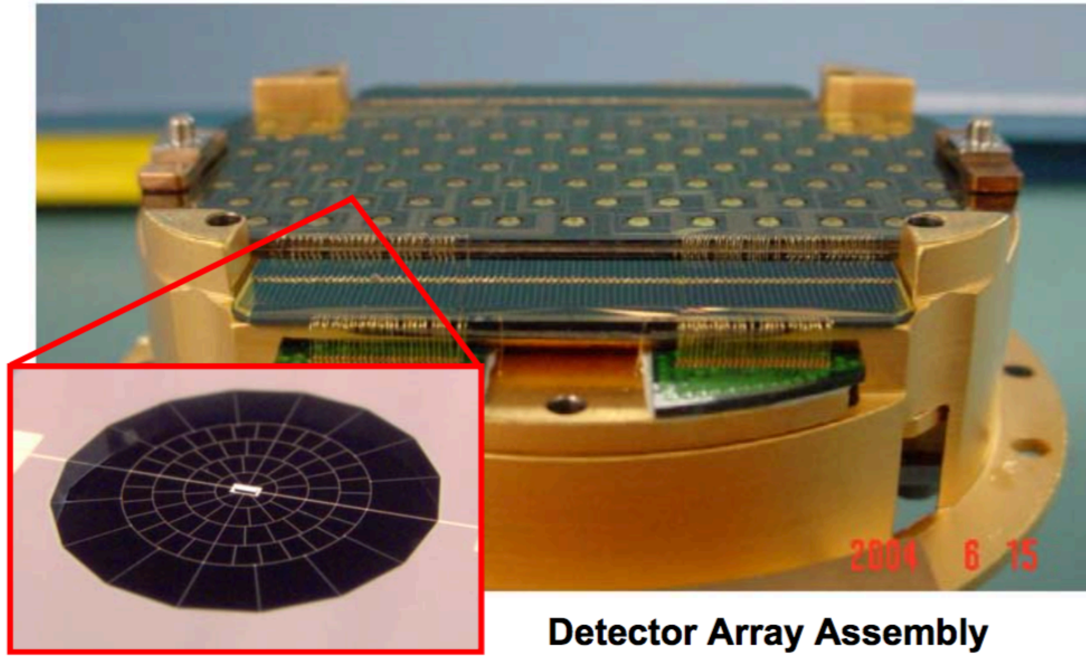
Herschel/SPIRE



SPIRE Bolometer Arrays

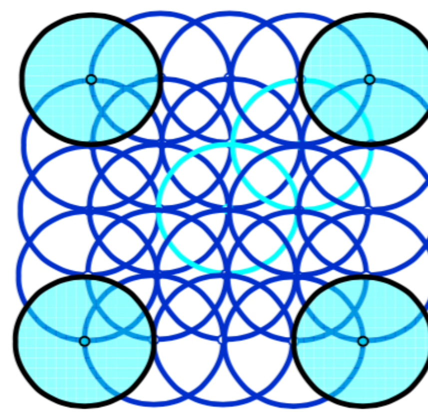


300 mK Assembly



Single ‘spiderweb’ bolometer

Detector Array Assembly



Sparse beams on sky

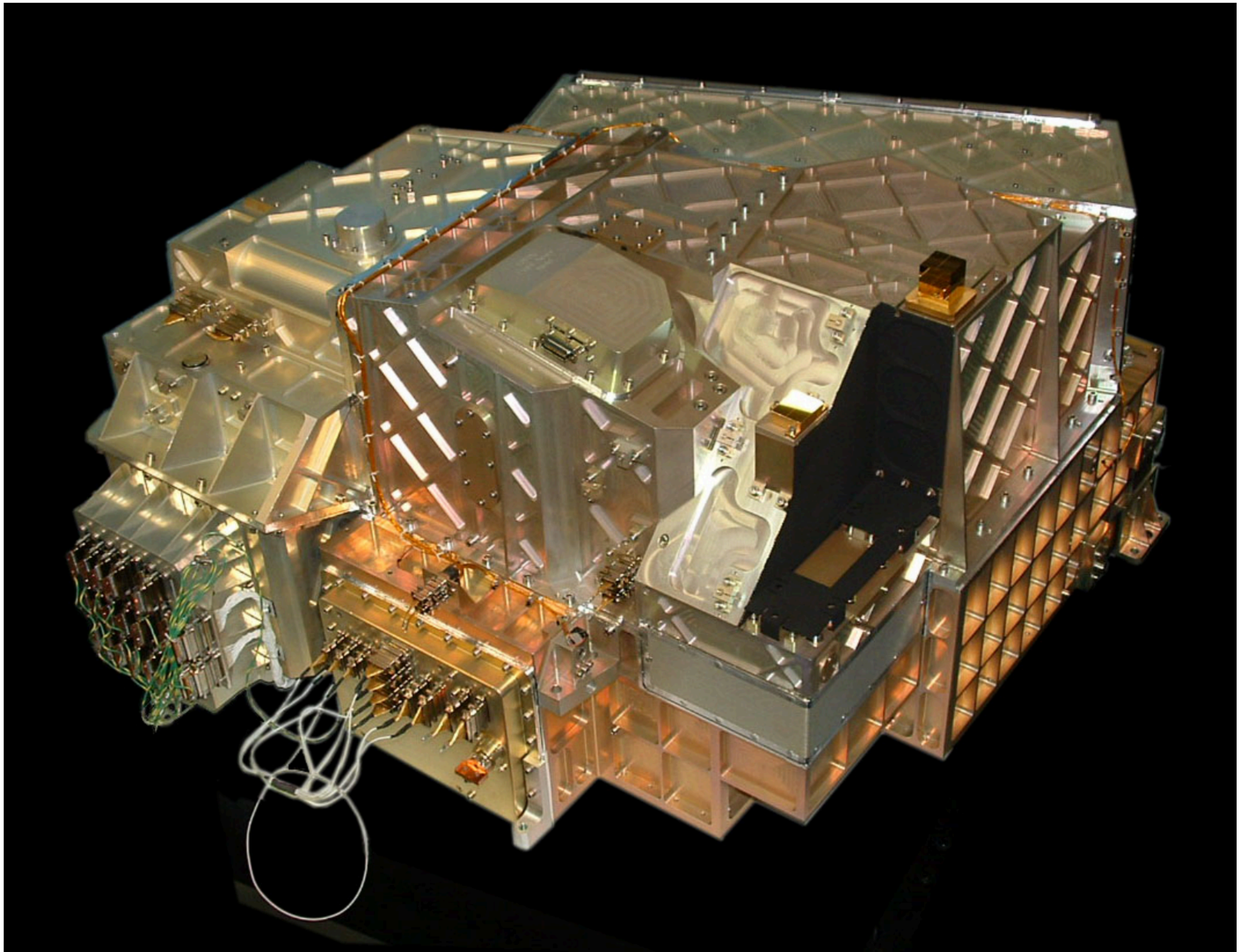
- NEPs designed to meet Herschel photon background
- Small format – 16:1 “feedhorn multiplexed”
- Low-frequency stability for drift-scanned observations

325 detectors in 5 arrays
NEP = 4e-17 W/√Hz (dark)
QE = 75 %
T_0 = 300 mK

Feedhorn-coupled

Credit: J. Bock

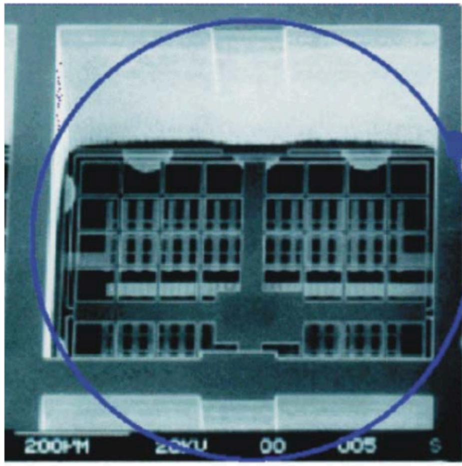
Herschel/PACS

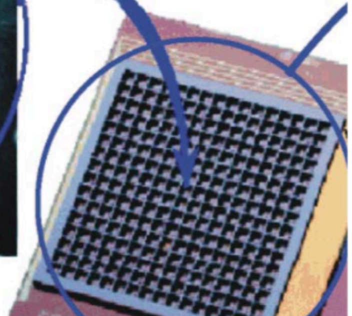


PACS Bolometer Arrays

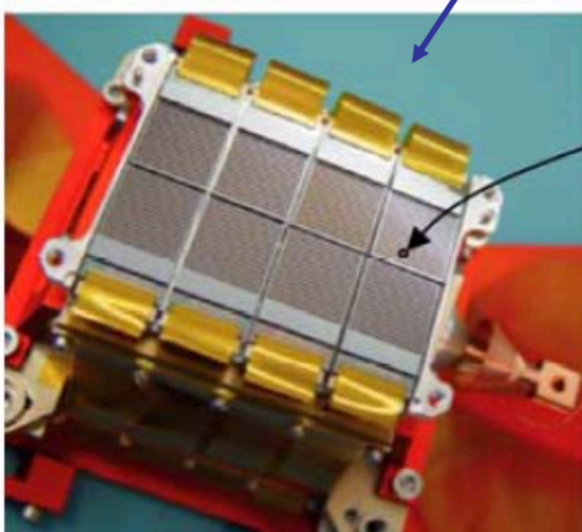
Absorber-coupled (no horns)

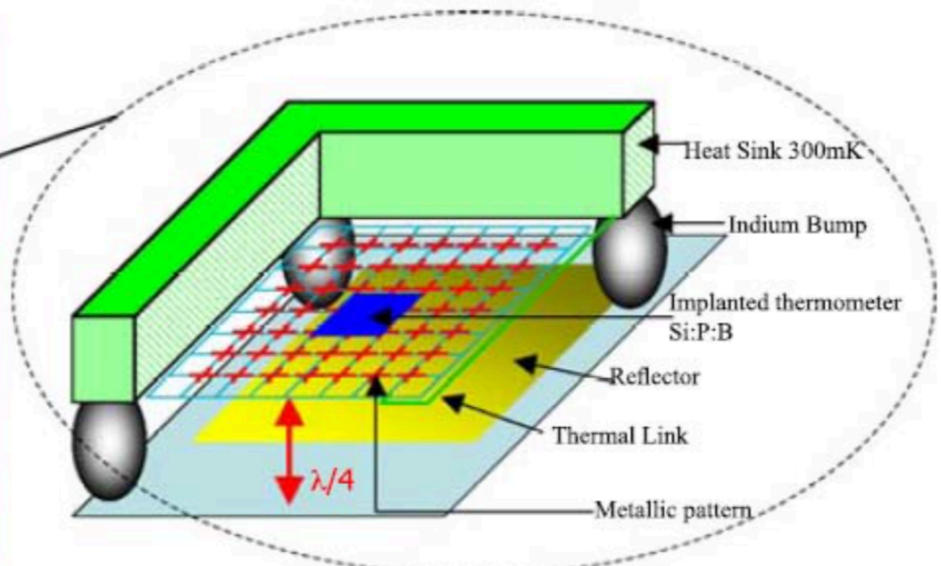
- Large format - CMOS multiplexed
- Close packing for Nyquist sampling
- Higher NEPs suited for Herschel background





2560 detectors in 2 arrays
NEP = 2e-16 W/√Hz (dark)
T_0 = 300 mK





Credit: J. Bock

The Herschel/PACS 2560 bolometers imaging camera

Nicolas Billot[a], Patrick Agnèse[b], Jean-Louis Augueres[a], Alain Béguin[b], André Bouère[a], Olivier Boulade[a], Christophe Cara[a], Christelle Cloué[a], Eric Doumayrou[a], Lionel Duband[c], Benoît Horeau[a], Isabelle Le Mer[a], Jean Le Pennec[a], Jérome Martignac[a], Koryo Okumura[a], Vincent Revéret[d], Marc Sauvage[a], François Simoens[b] and Laurent Vigroux[e]

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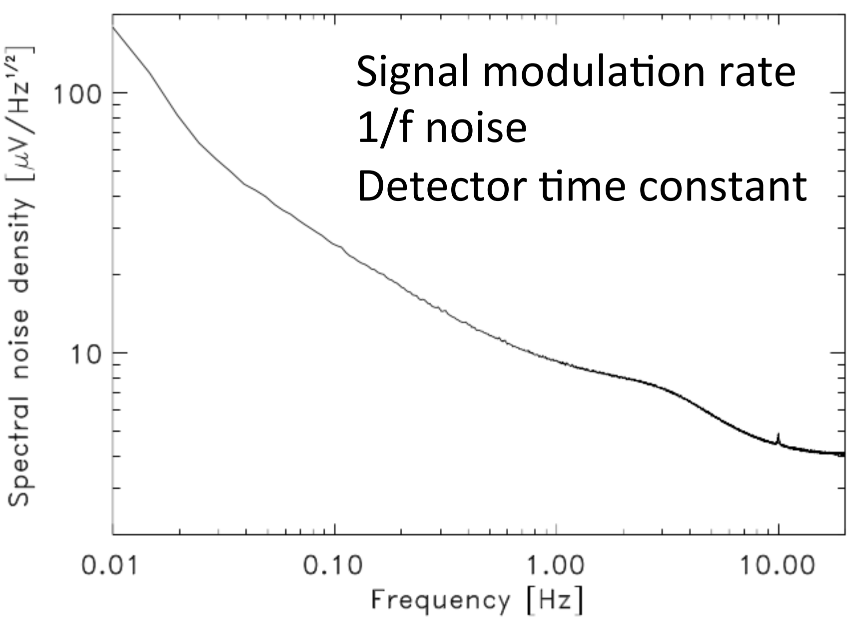
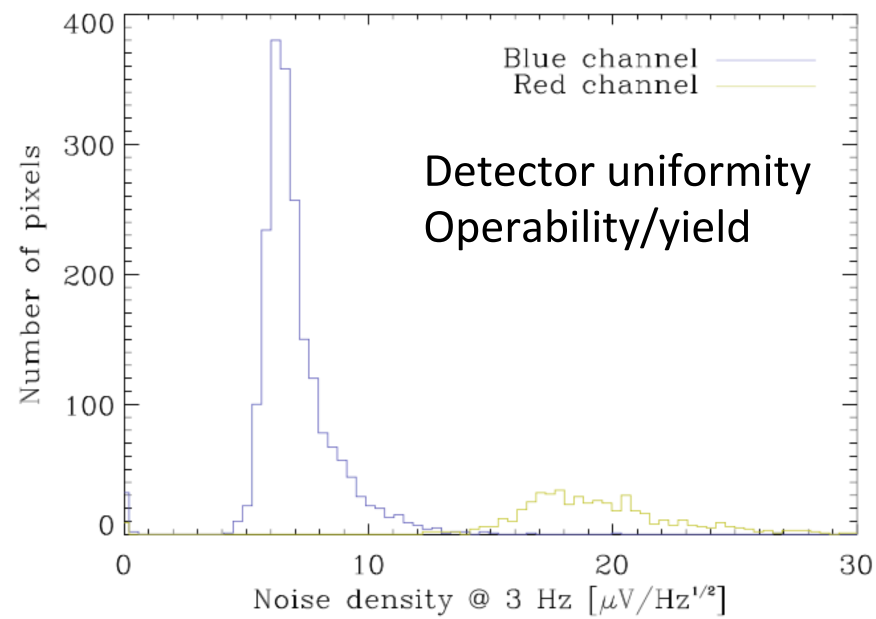
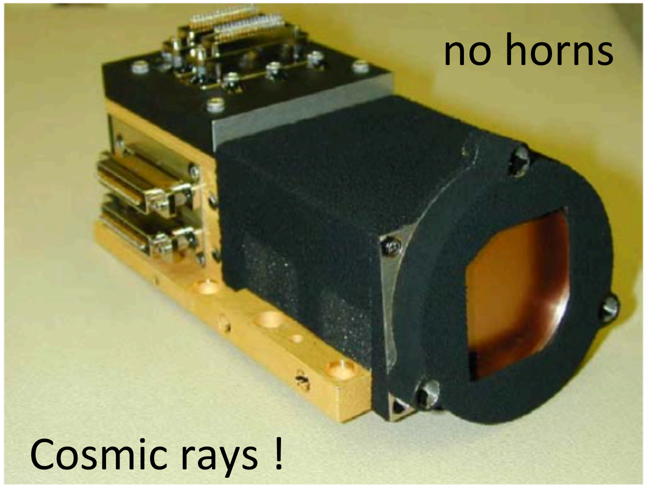
[d]European Southern Observatory, Vitacura, Casilla 19001 Santiago 19, CHILE;
[e]Institut d'Astrophysique de Paris, 75014 Paris, FRANCE



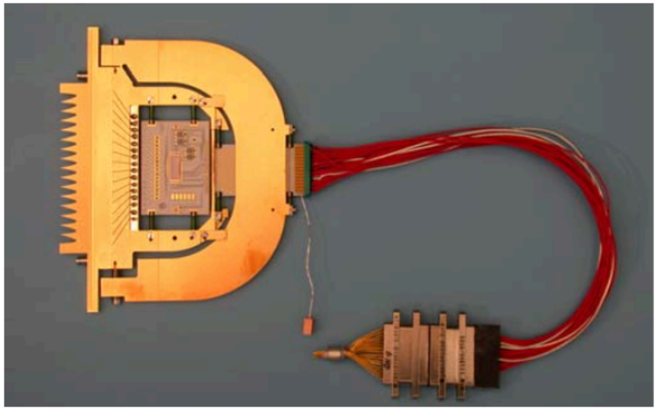


PACS Photoconductor Arrays

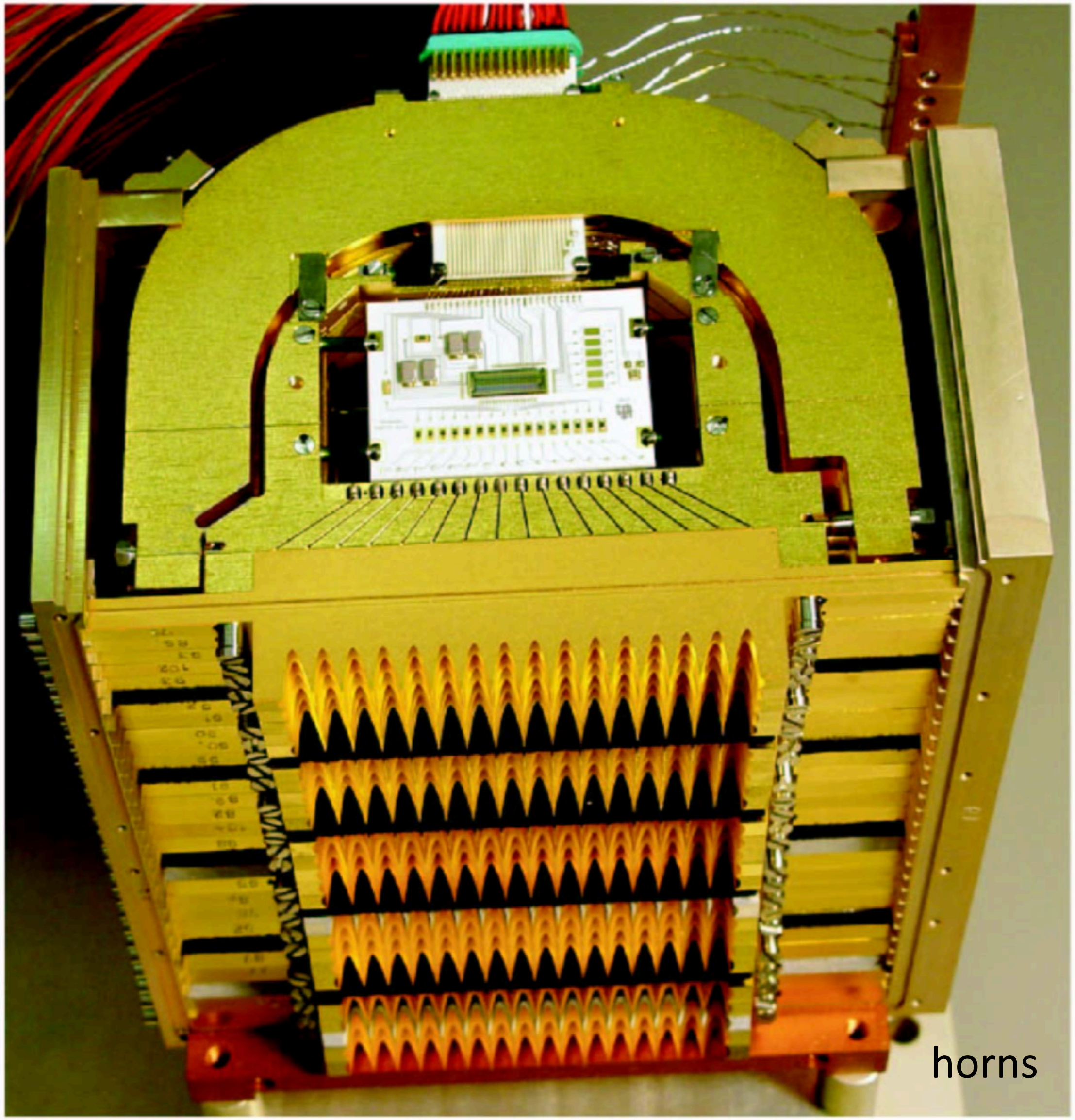
800 detectors in 2 arrays
NEP = 5e-18 W/√Hz (dark)
QE = 30 %
T_0 = 1.7 K



MIPS 32x32 Unstressed Ge:Ga

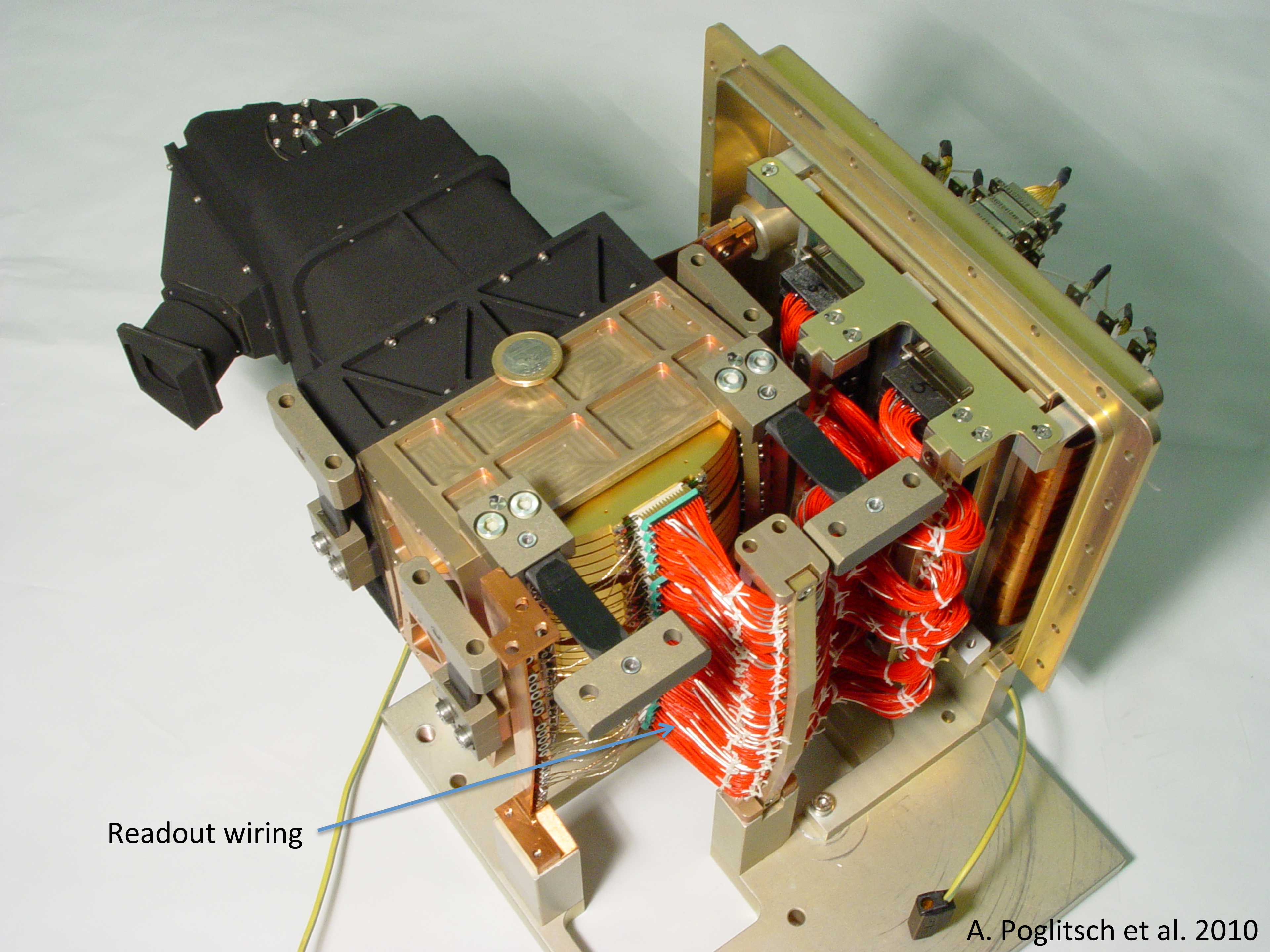


Ge:Ga Stress Block

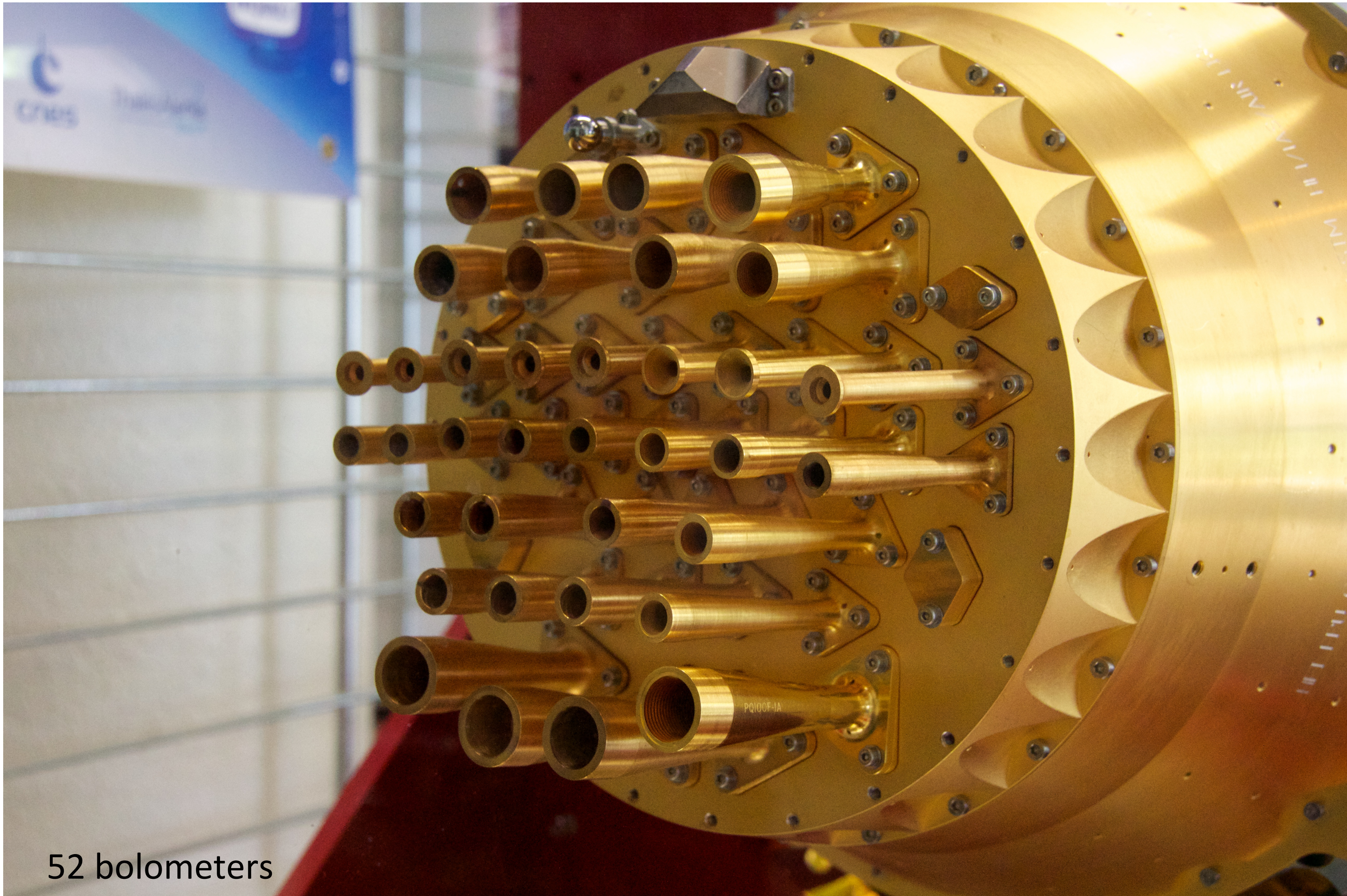


PACS Photoconductor Focal Plane Array

Credit: J. Bock

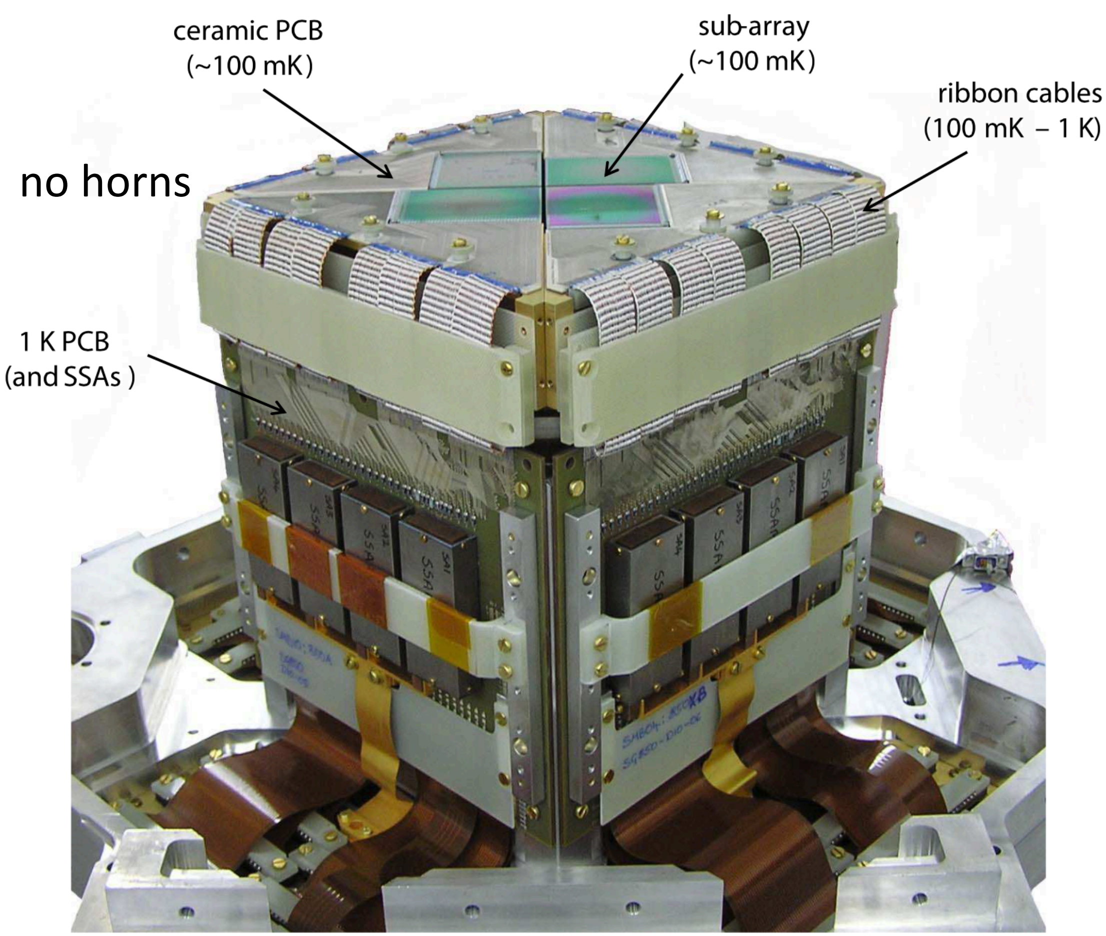

Readout wiring
A. Poglitsch et al. 2010

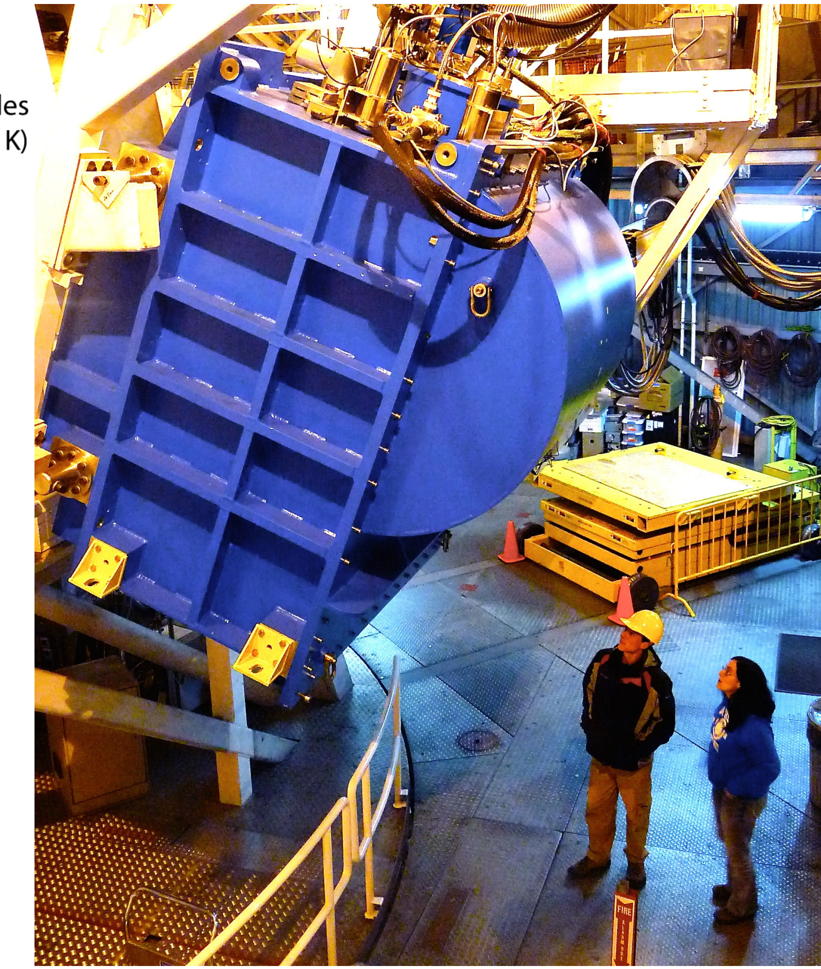
Planck/HFI



SCUBA 2

superconducting bolometers with multiplexed SQUID readout

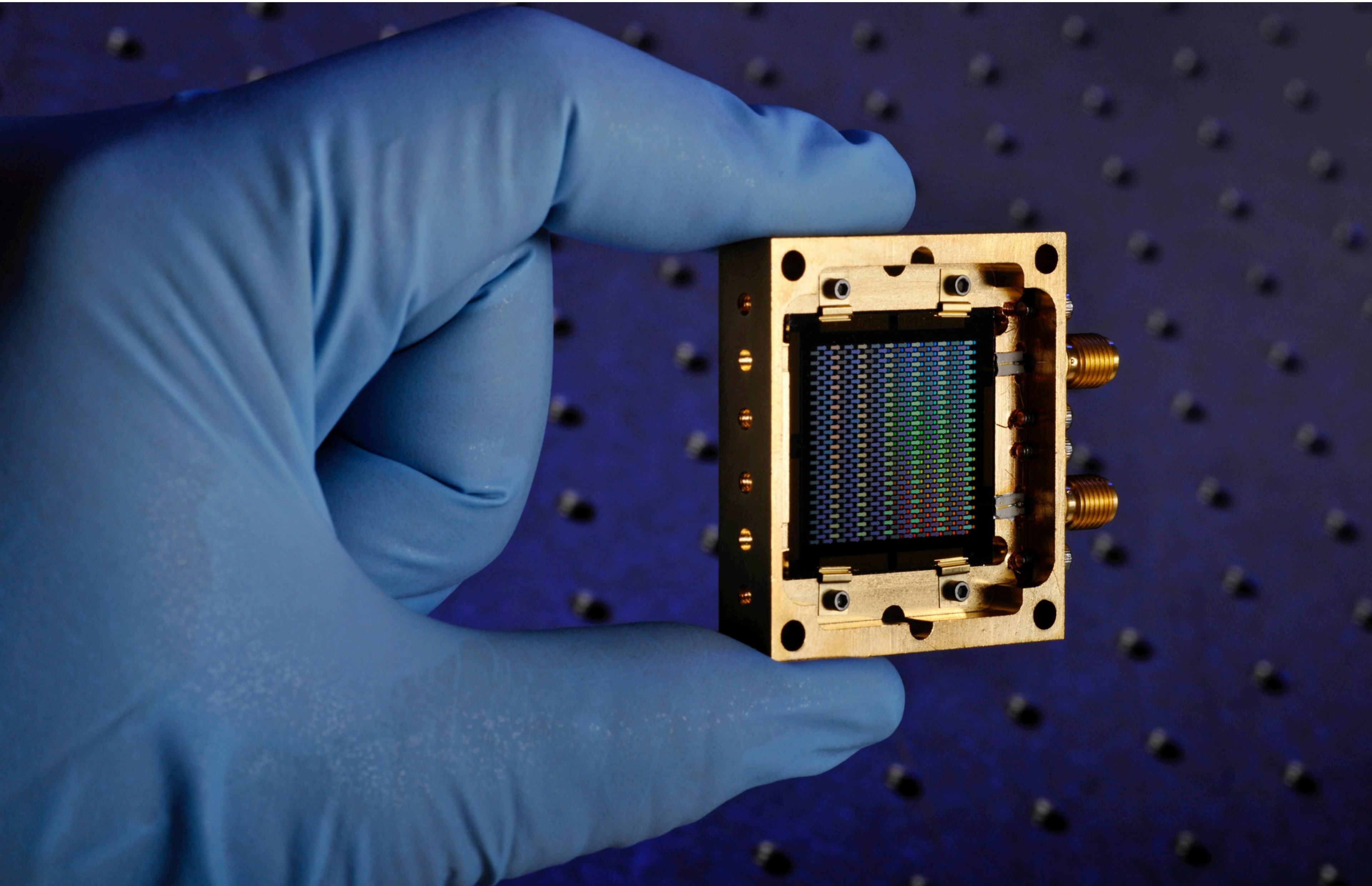




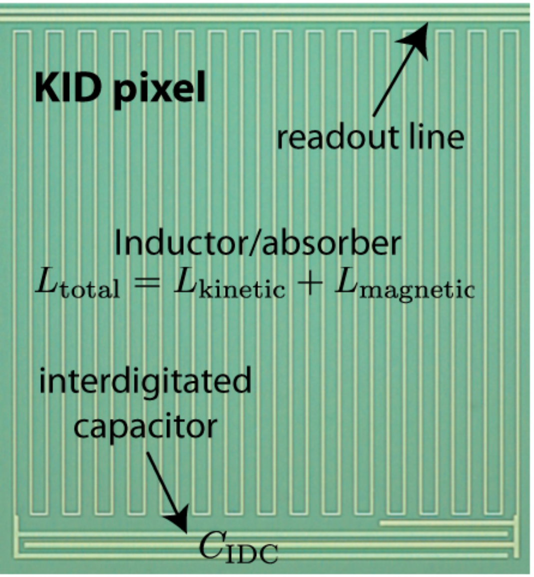
5120 pixels per band, 100 mK, TES/SQUID TDM
NEP ~ low 10^{-16} W $Hz^{-1/2}$

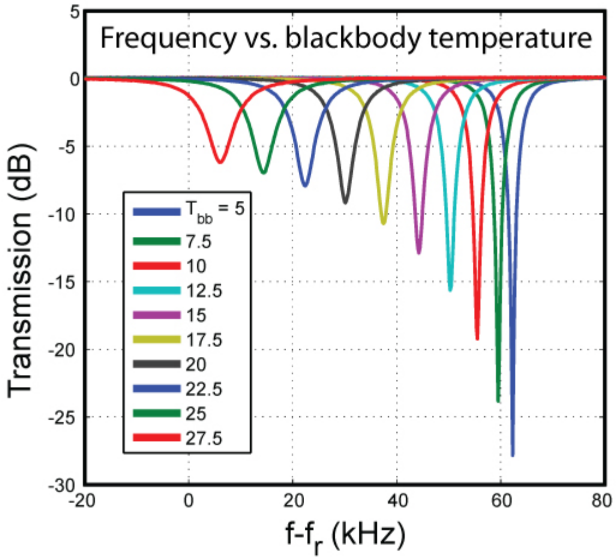
Holland et al. 2013

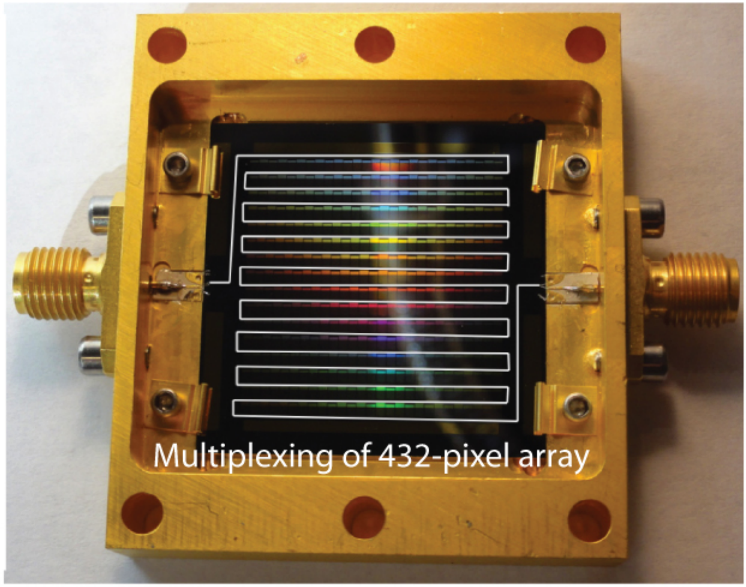
1999 – present: (M)KID
(Microwave) Kinetic Inductance Detectors

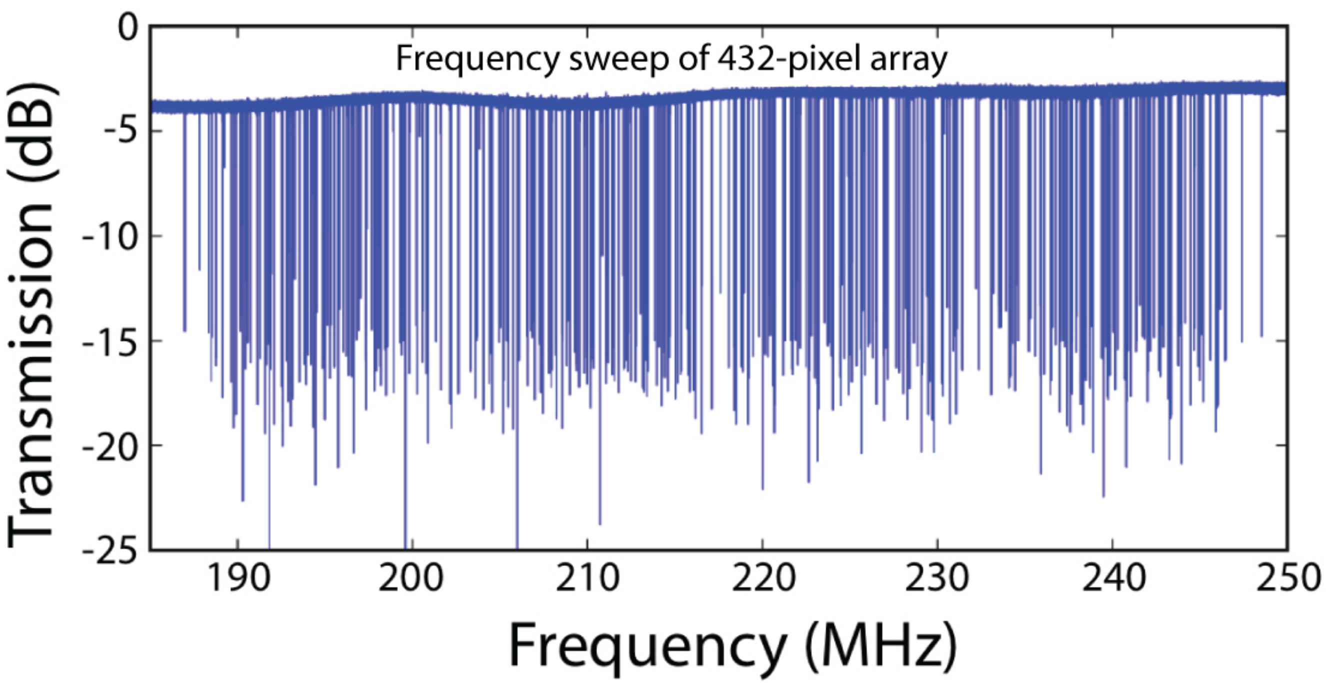


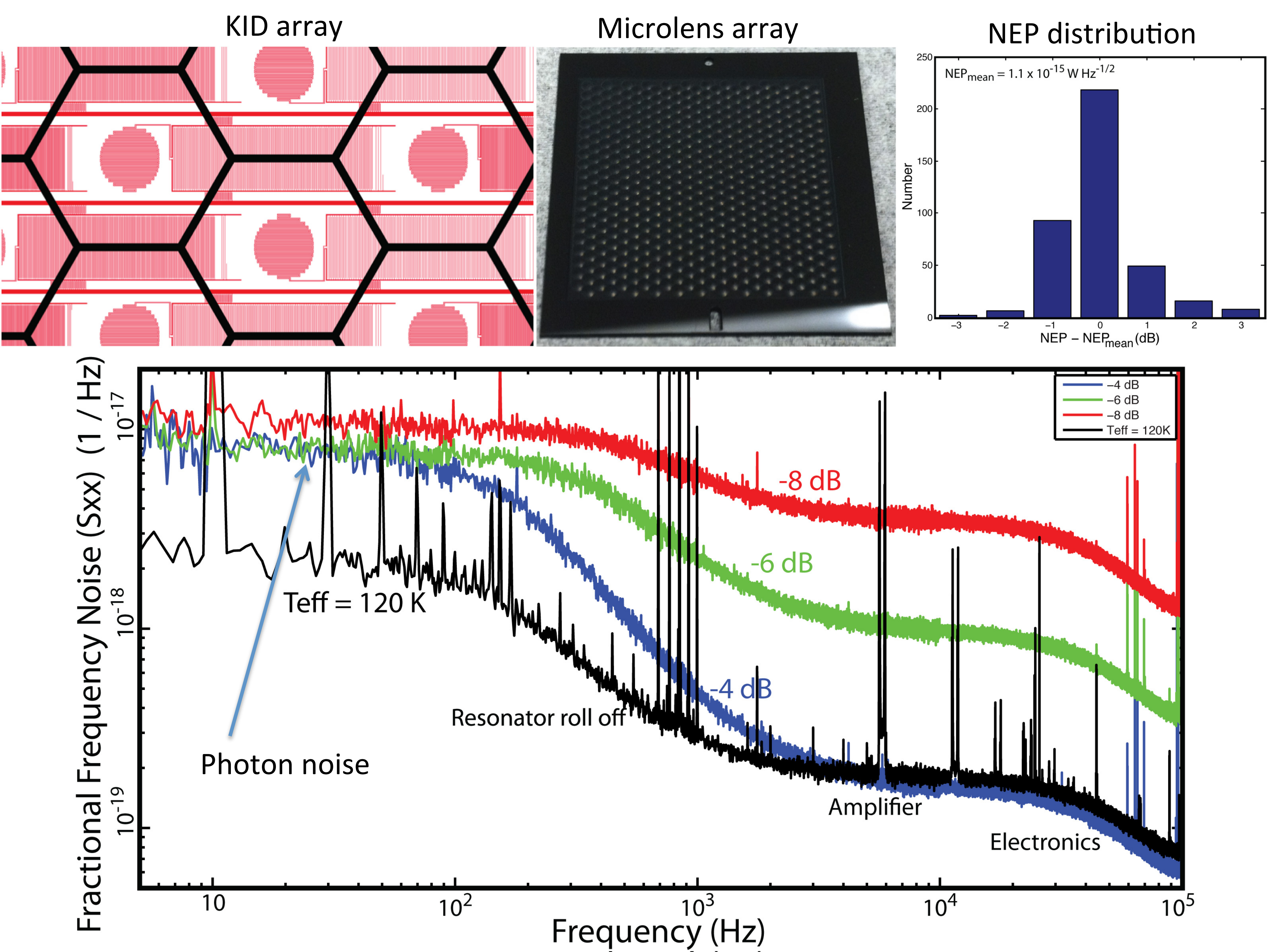
KIDS: basic concept











KID array
Microlens array
NEP distribution
NEPmean = 1.1 x 10-15 W Hz-1/2
Number
250
200
150
100
50
0
−3
−2
−1
0
1
2
3
NEP − NEPmean (dB)
−4 dB
−6 dB
−8 dB
Teff = 120K
-8 dB
-6 dB
-4 dB
Teff = 120 K
Photon noise
Resonator roll off
Amplifier
Electronics
Fractional Frequency Noise (Sxx) (1 / Hz)
10-17
10-18
10-19
10
10^2
10^3
10^4
10^5
Frequency (Hz)

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;
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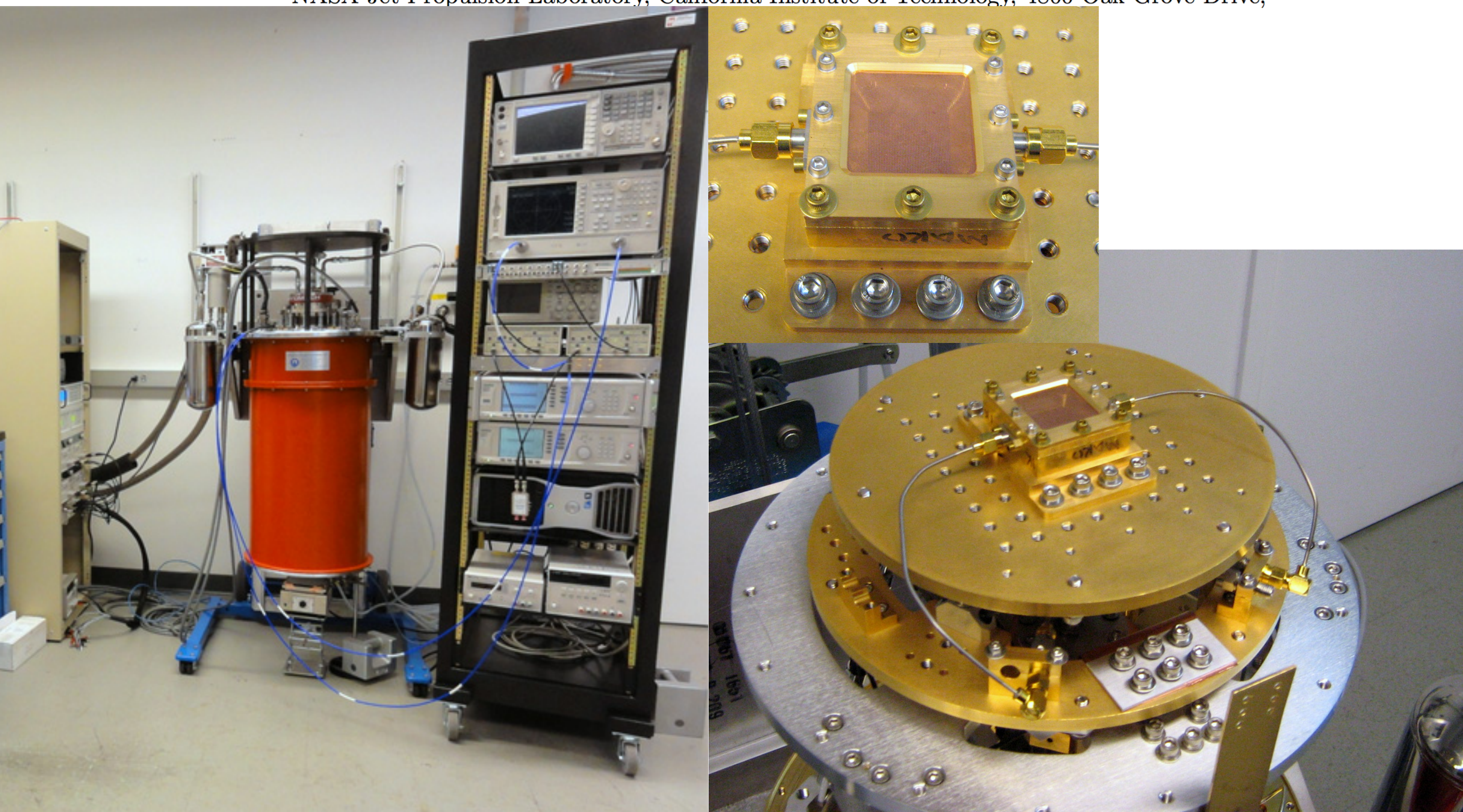
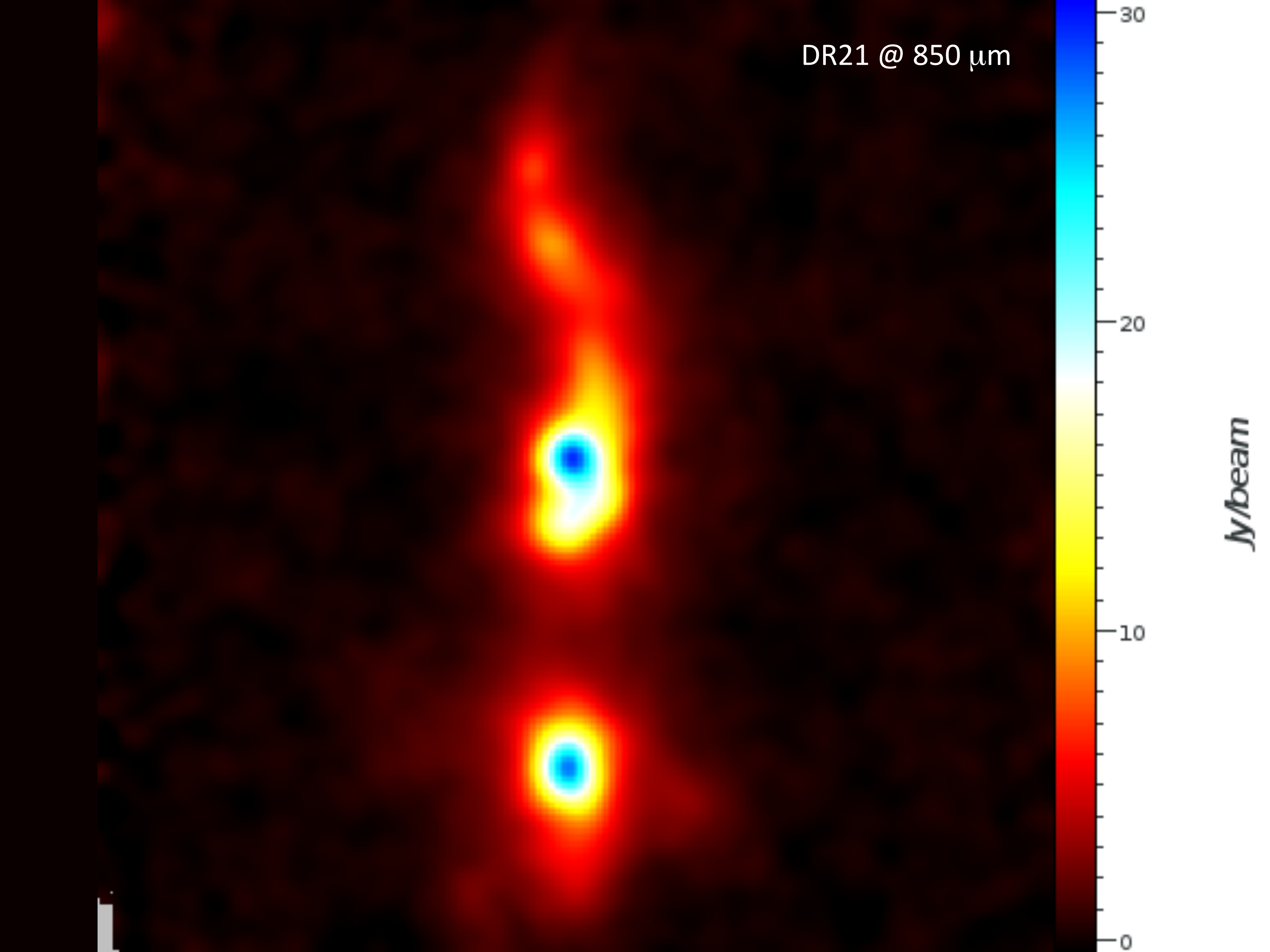



DANGER
DO NOT ENTER
DO NOT ENTER

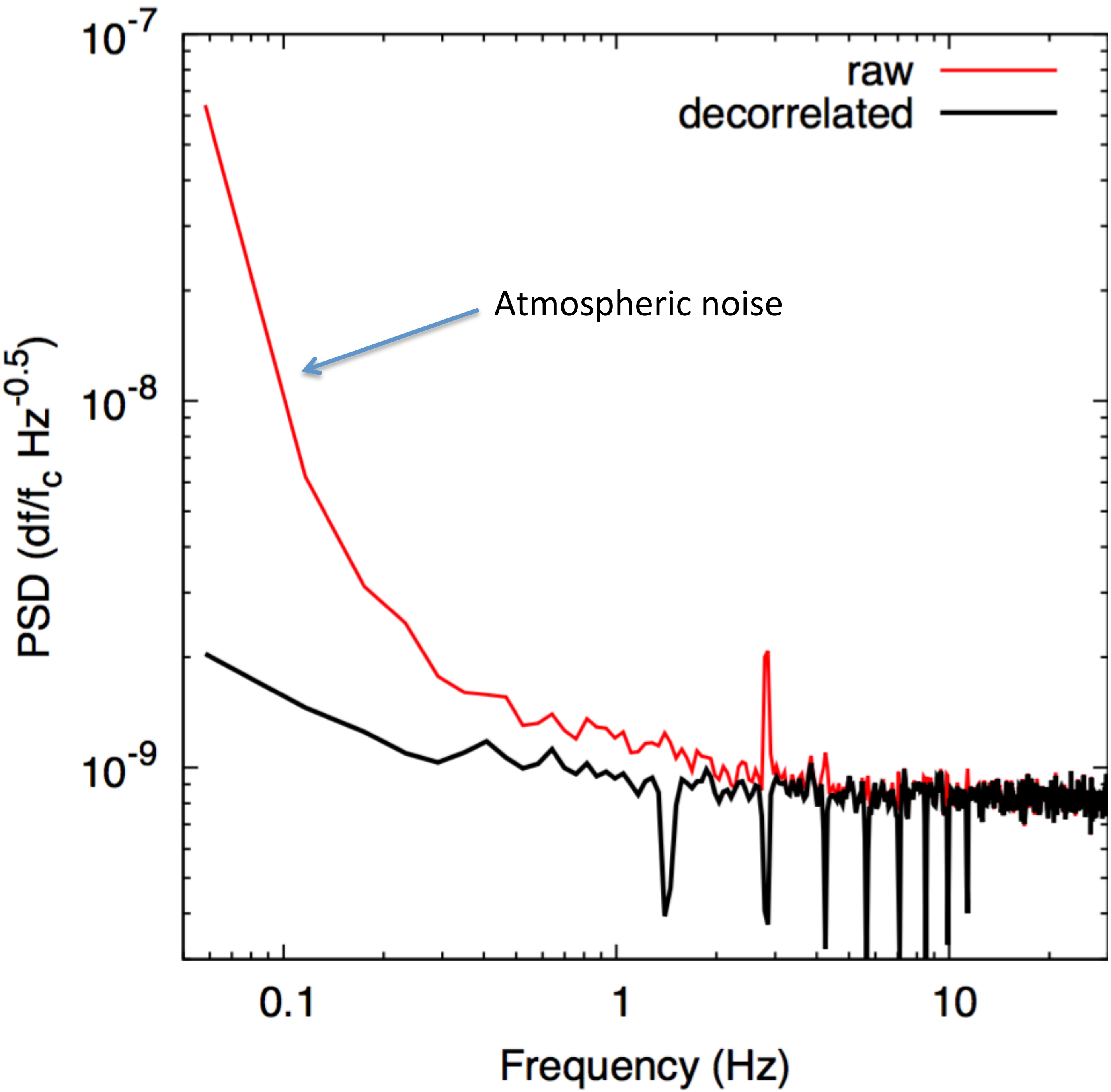

MAKO

MAKO – 484 TiN KIDs @ 350 μm

ZSPEC – 160 bolometers

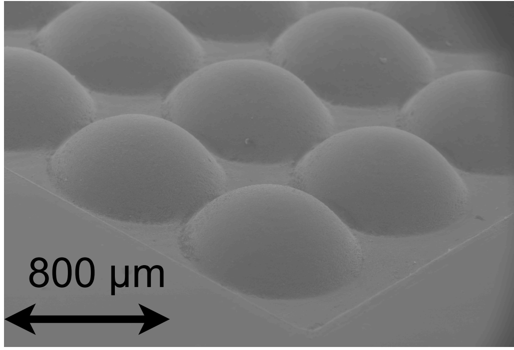

DR21 @ 850 μm
30
20
10
0
Jy/beam

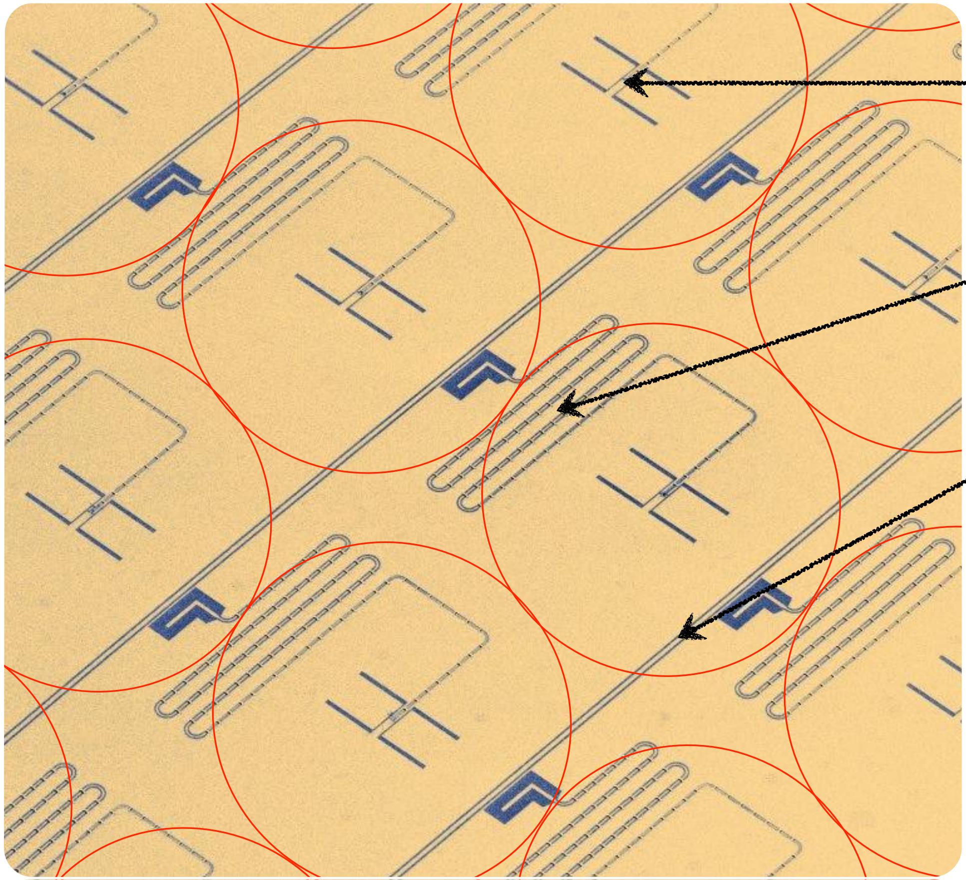
MAKO (2015 May)



KID imaging Array

Lens/antenna coupling
GHz readout

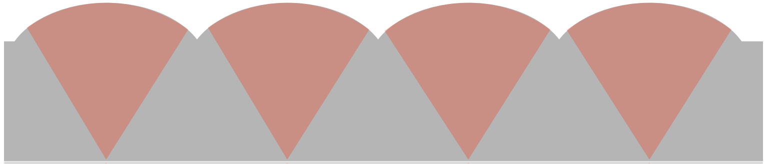




Identical antenna's

Resonators have different length
Different resonance frequencies

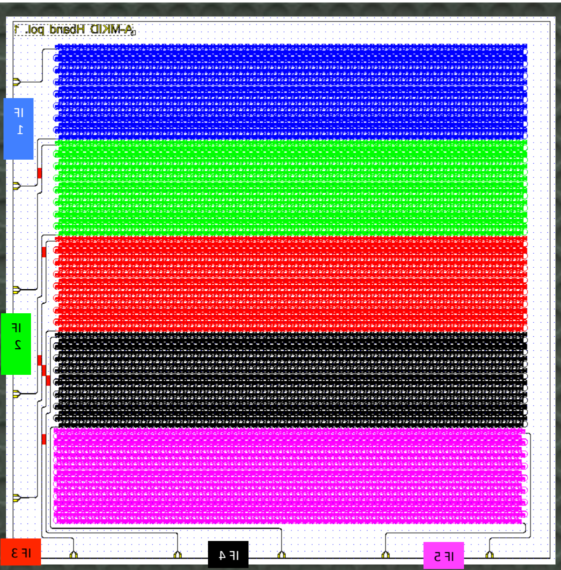
1 readout line connecting all pixels



Flies eye lens array, 1 lens/pixel

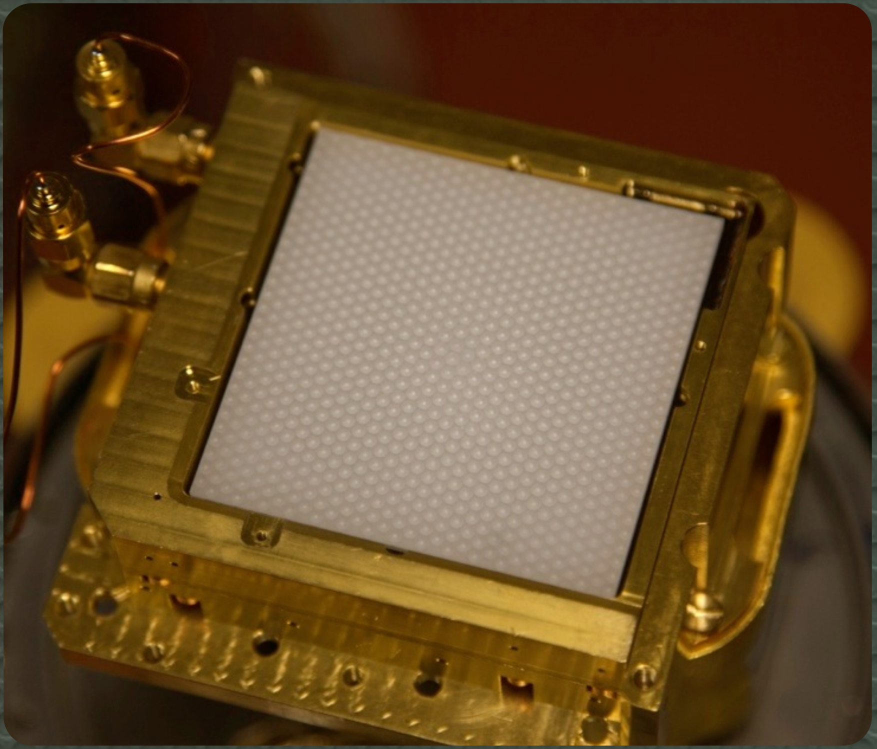
Arrays for A-MKID

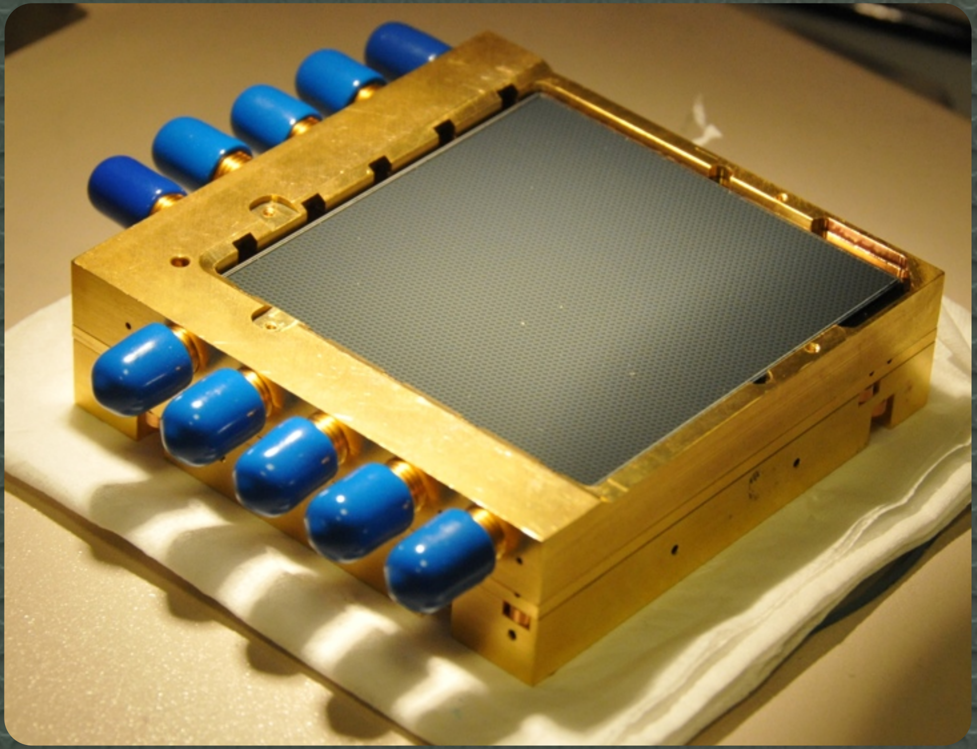
4 x 880 = 3520 pixels @ 350 GHz
4 x 5400 = 21600 pixels @ 850 GHz
Total = 25120 pixels



350 GHz
1 IF line
62.5 x 62.5 mm
880 pixels
Al_2O_3 lens array 2 mm

850 GHz
5 IF lines
62.5 x 62.5 mm
5400 pixels
Si lens array 0.8 mm





ceratec® Technical Ceramics BV

PHILIPS Philips Lighting Uden

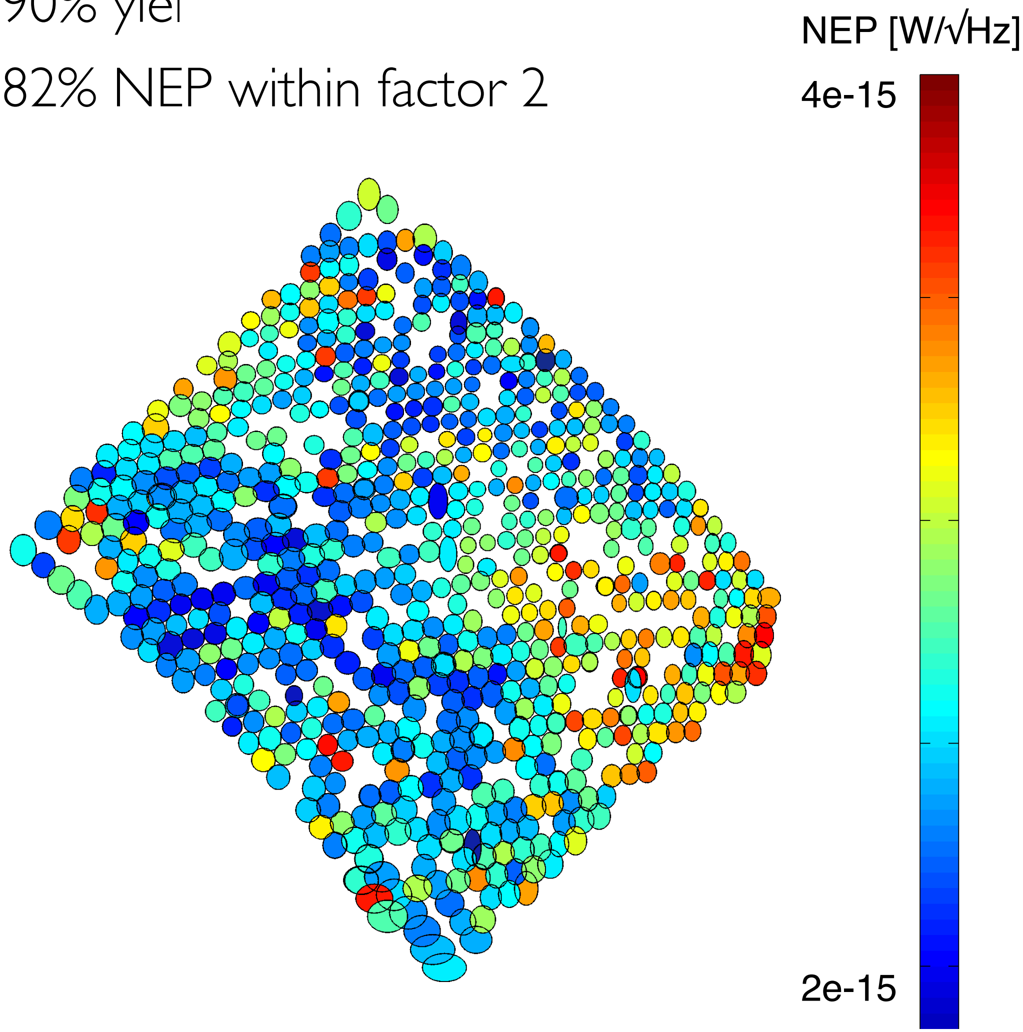
veldlaser laser micro machining materials

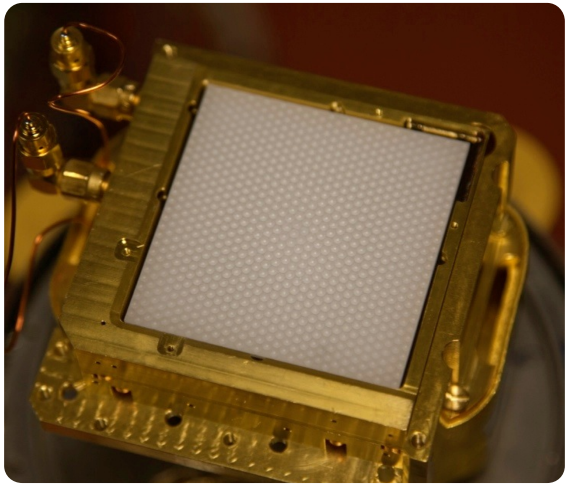
Credit: J. Baselmans, SRON

Array Performance 77K load

>90% yiel

~82% NEP within factor 2





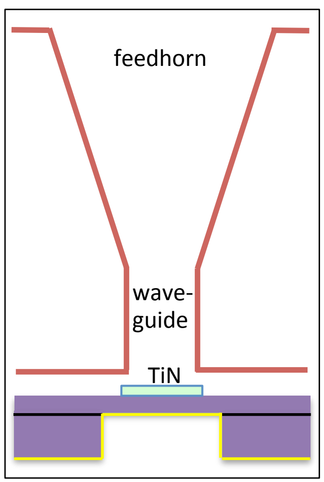
NIST
National Institute of Standards and Technology
U.S. Department of Commerce

Photon-noise limited sensitivity in MKIDs at 250 μm

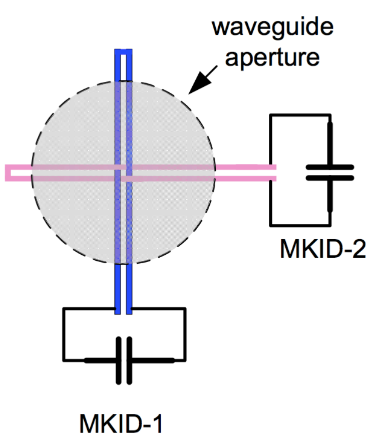
in development for BLAST-TNG, a balloon-borne polarimeter

detector development is a collaboration between NIST, UPENN, ASU and Stanford

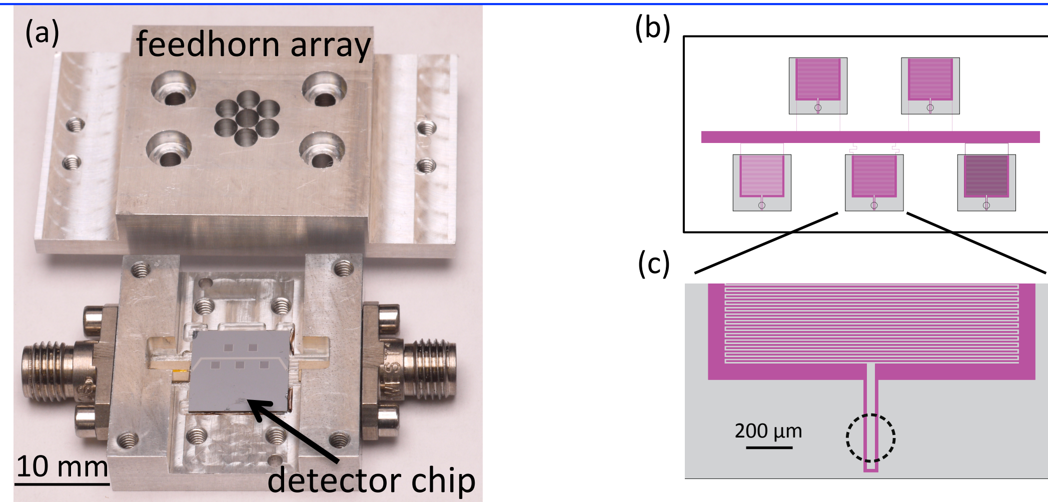
Feedhorn-coupled MKID concept



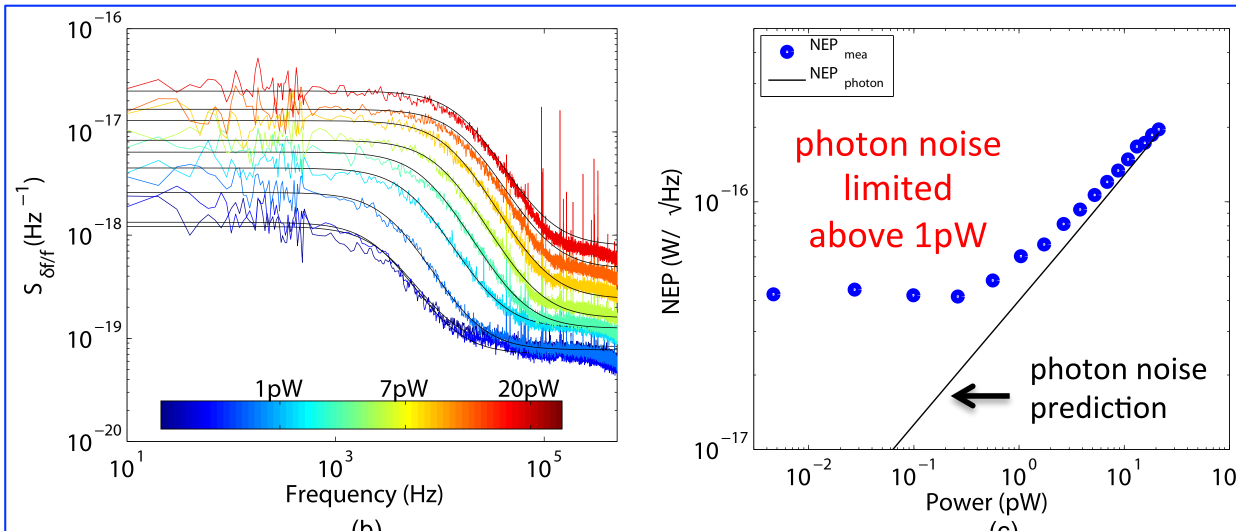
dual-polarization sensitivity within one spatial pixel



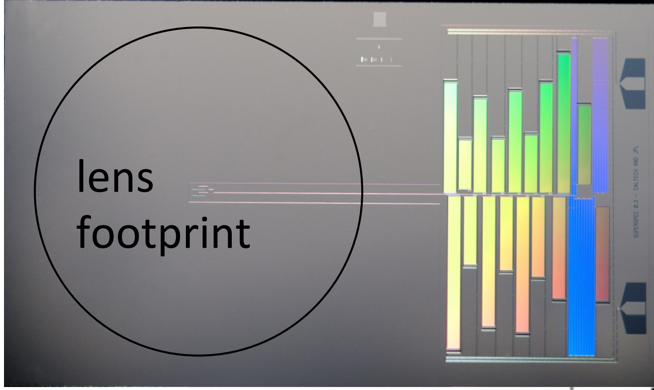
Experimental package   Hubmayr et al. 2014

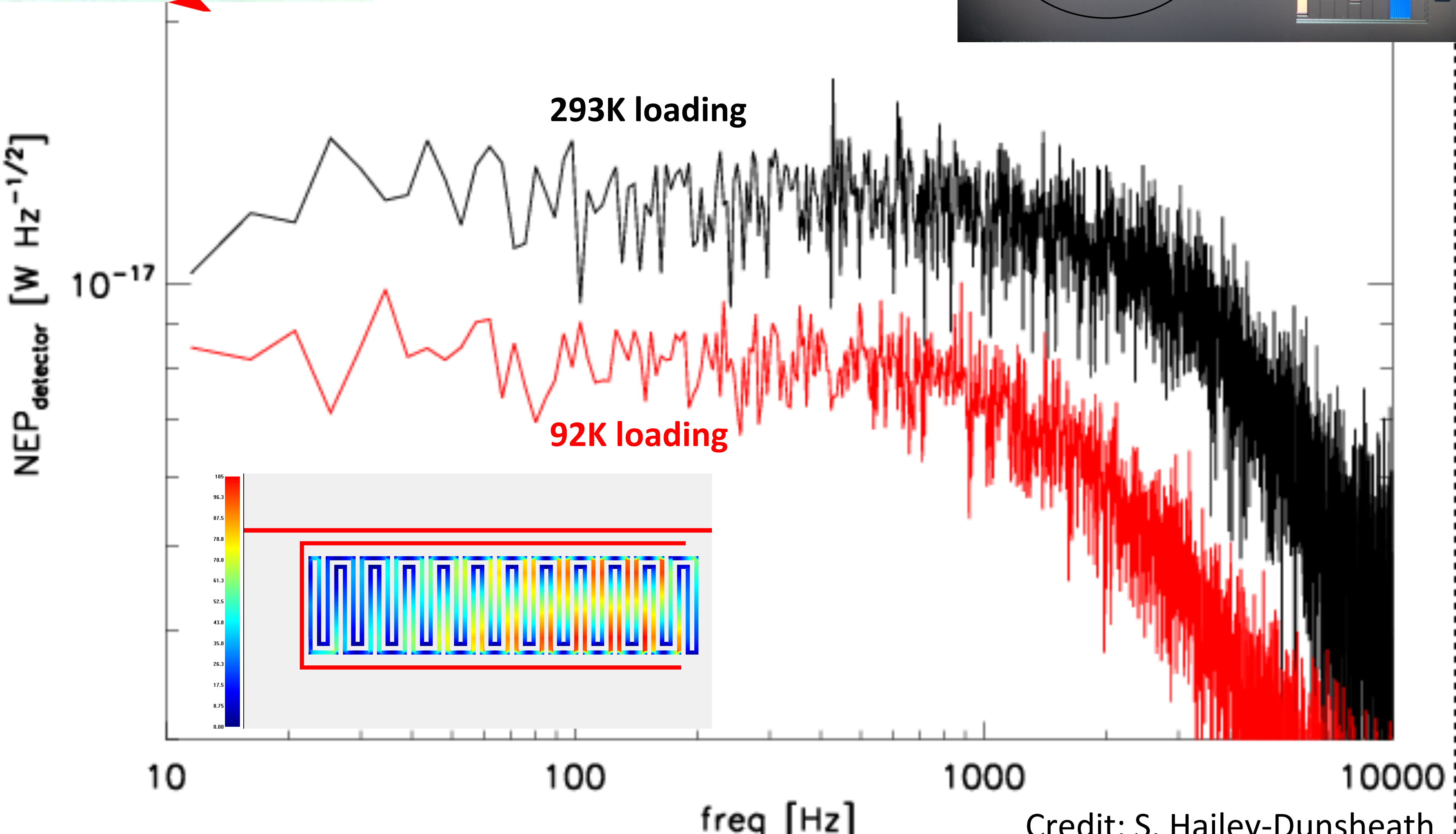


Sensitivity to variable temperature thermal load



Superspec





Credit: S. Hailey-Dunsheath

ARTICLE

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OPEN

Fluctuations in the electron system of a superconductor exposed to a photon flux

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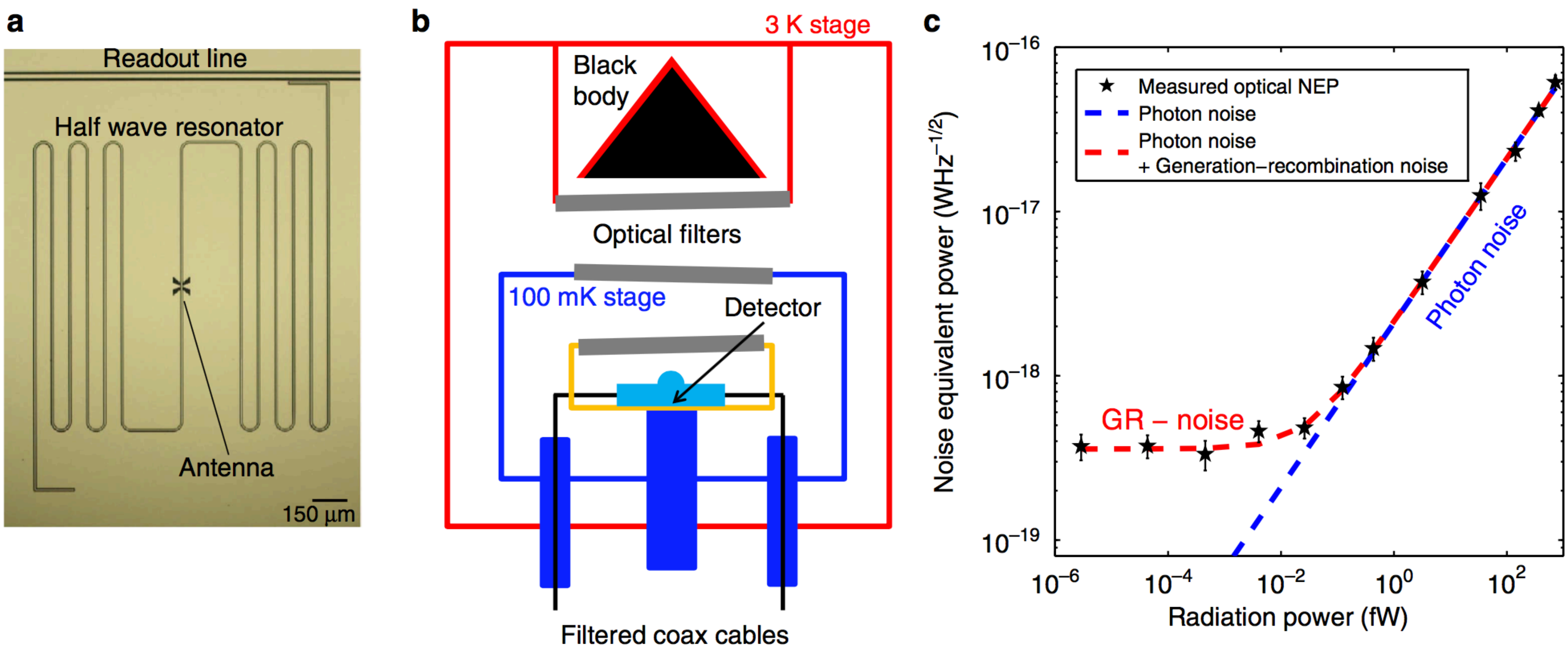
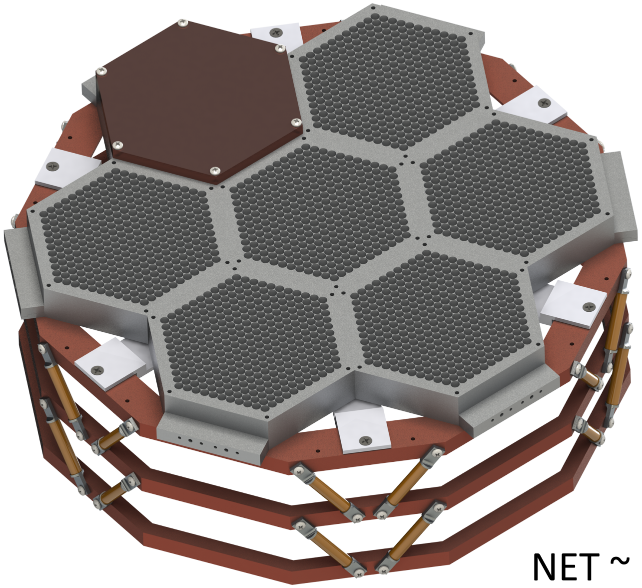
Delft/SRON



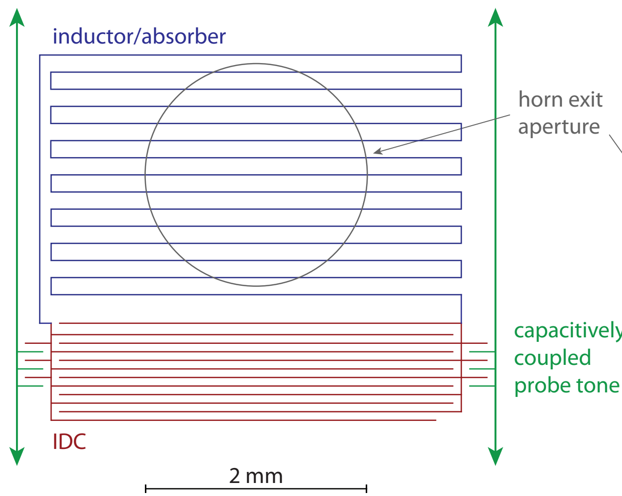
Horn-coupled KIDs for CMB polarization

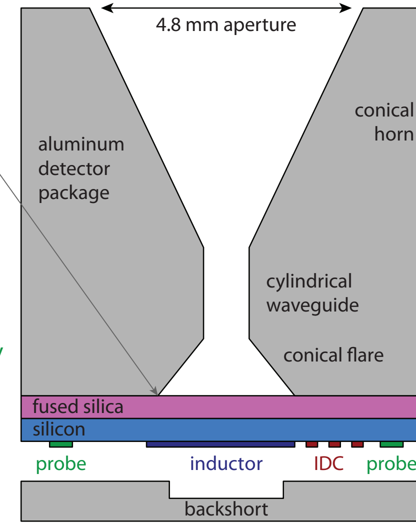
McKarrick et al., Rev. Sci. Instrum. 2015

seven modules = 2317 single-polarization detectors

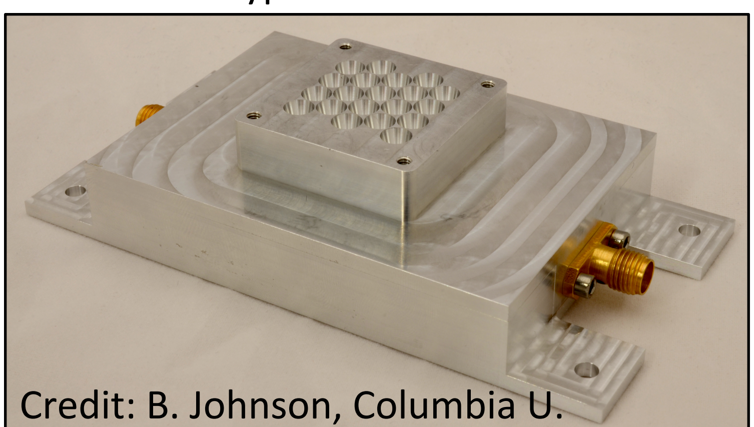


NET ~ 30 μK sec$^{1/2}$

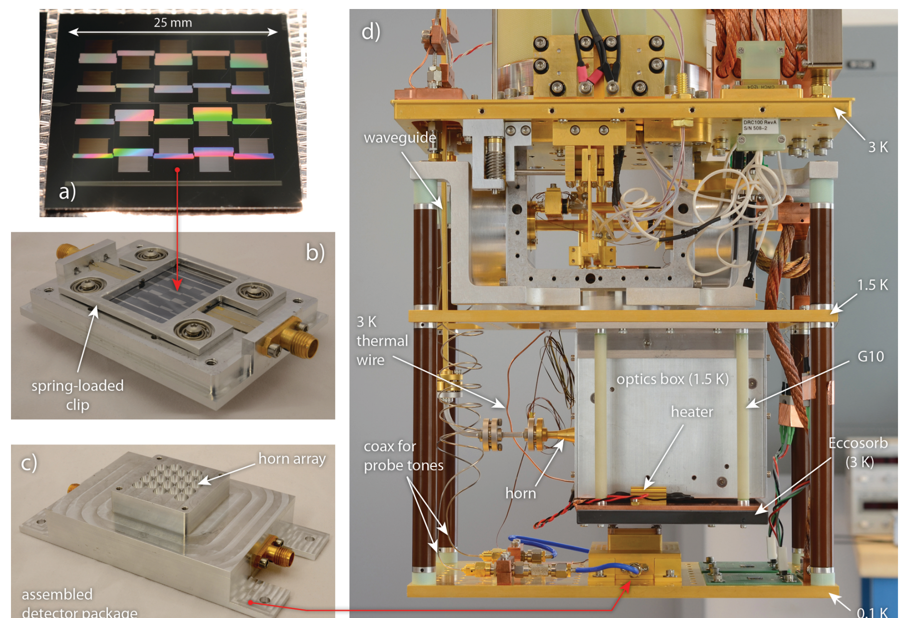




Prototype 150 GHz Module



Credit: B. Johnson, Columbia U.



Horn-Coupled, Commercially-Fabricated Aluminum Lumped-Element Kinetic Inductance Detectors for Millimeter Wavelengths

H. McCarrick,[1,a)] D. Flanigan,[1] G. Jones,[1] B. R. Johnson,[1] P. Ade,[2] D. Araujo,[1] K. Bradford,[3] R. Cantor,[4] G. Che,[3] P. Day,[5] S. Doyle,[2] H. Leduc,[5] M. Limon,[1] V. Luu,[1] P. Mauskopf,[6,2] A. Miller,[1] T. Mroczkowski,[7,b)] C. Tucker,[2] and J. Zmuidzinas[8,5]

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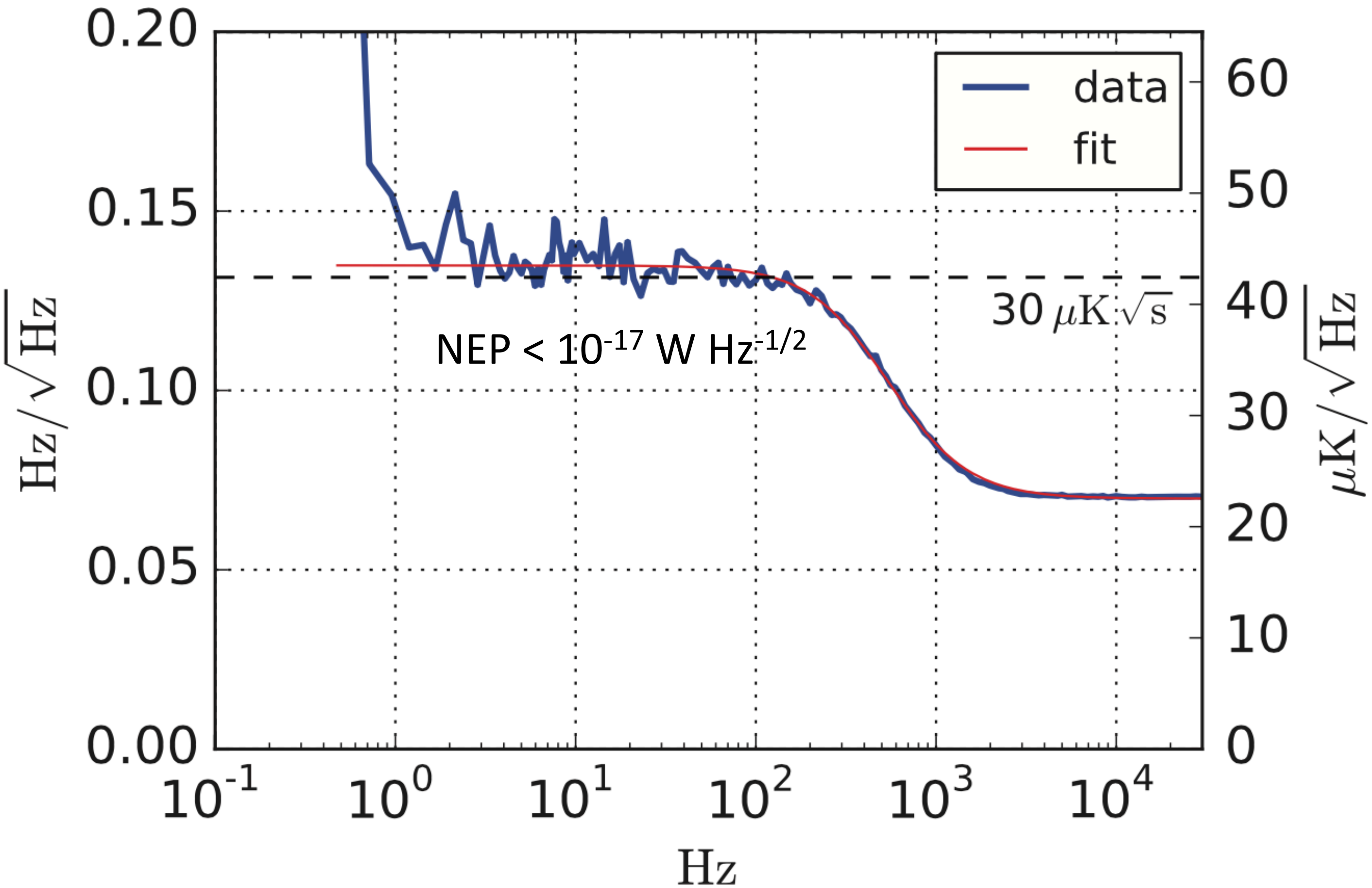
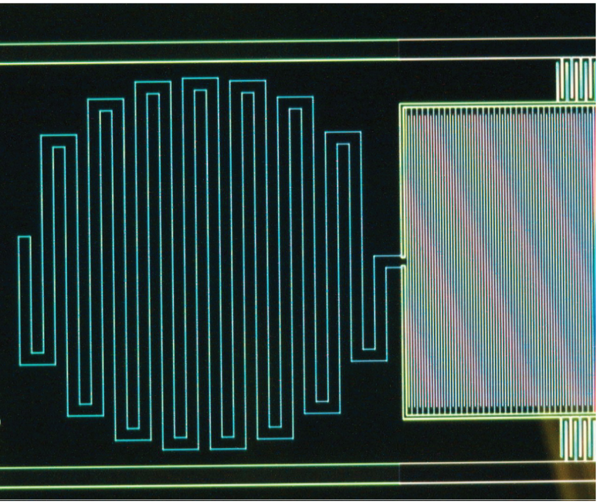
[7)] *Naval Research Laboratory, Washington, DC, 20375, USA*
[8)] *Department of Physics, Caltech, Pasadena, CA, 91125, USA*

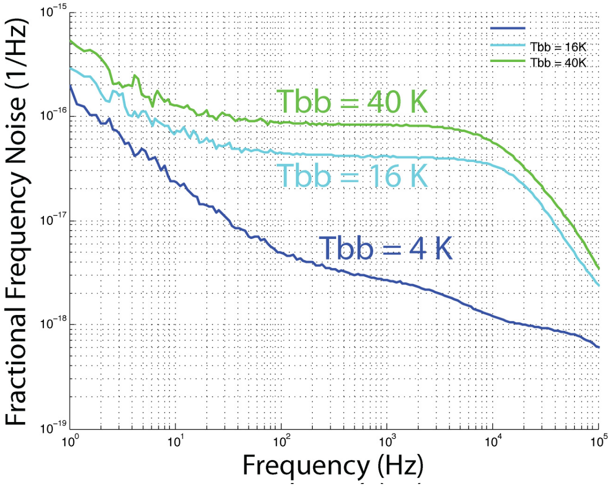
(Dated: 27 March 2015)

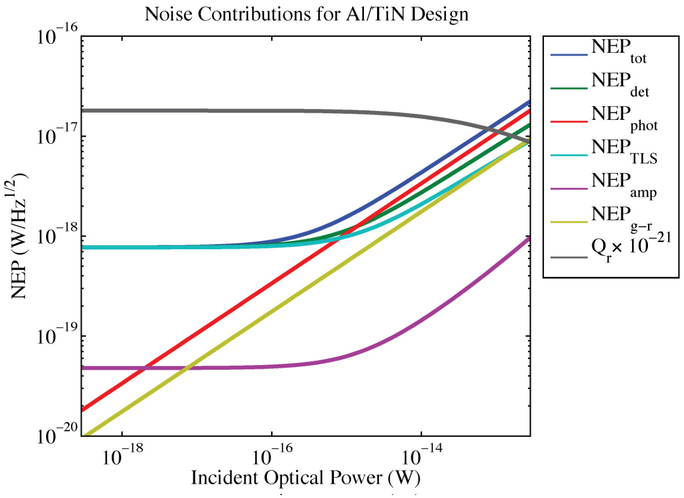


Small-volume AL KIDs

predictions





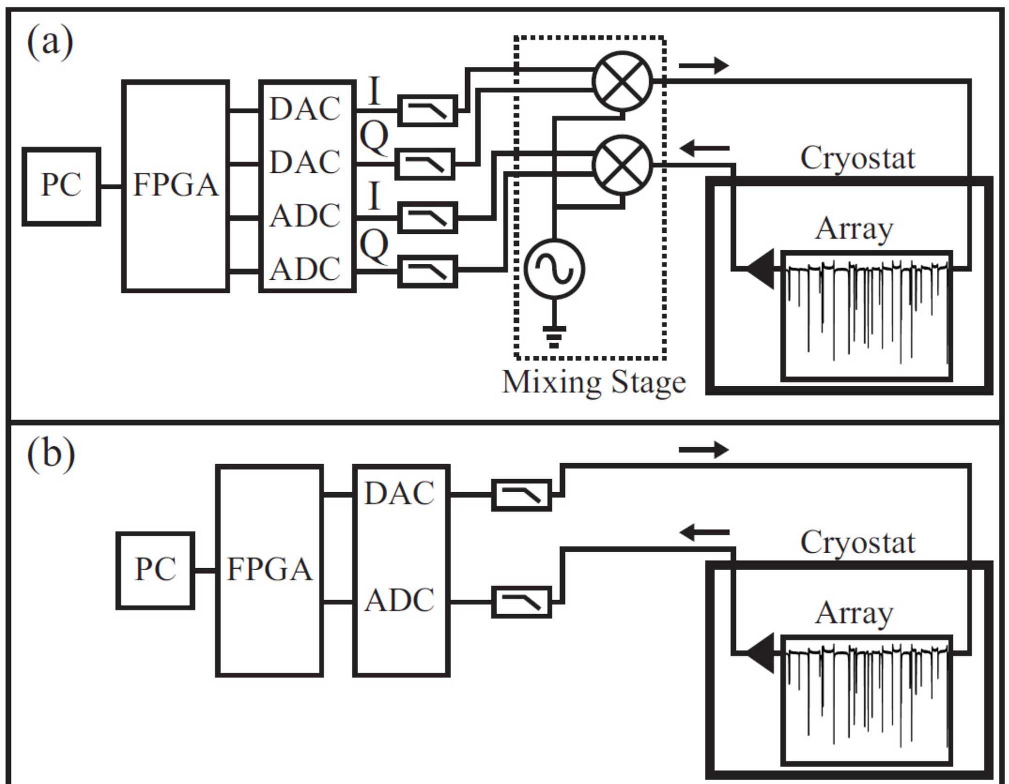


P. Day, B. H. Eom, H. G. Leduc, C. McKenney, C. Dowell, J. Zmudizinas

Multichannel Digital Readout

- FPGA implements digital channelizer for readout tone separation
- Microwave (GHz) readout requires up/down frequency conversion
- RF readout (< 500 MHz) allows ``direct drive'' with ADC/DAC
  - Reduces readout bandwidth, complexity, and cost

Microwave readout



A-MKID, etc

RF readout

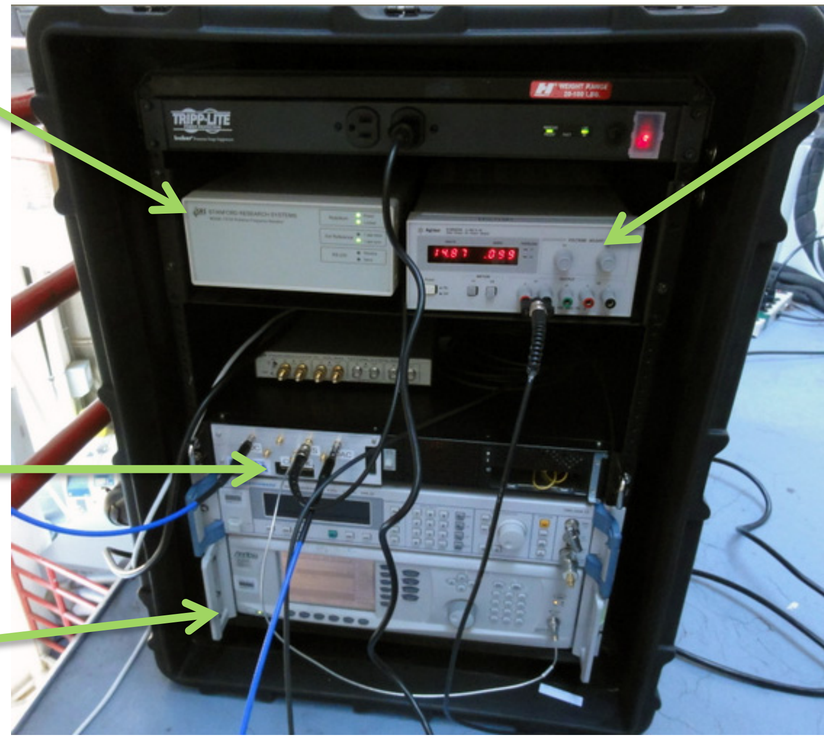
MAKO, SuperSpec, McKarrick et al

L. Swenson, LTD-15 2013

MAKO Readout Electronics

10 MHz rubidium standard & 1 PPS Signal
(from GPS antenna)

Amp
Bias

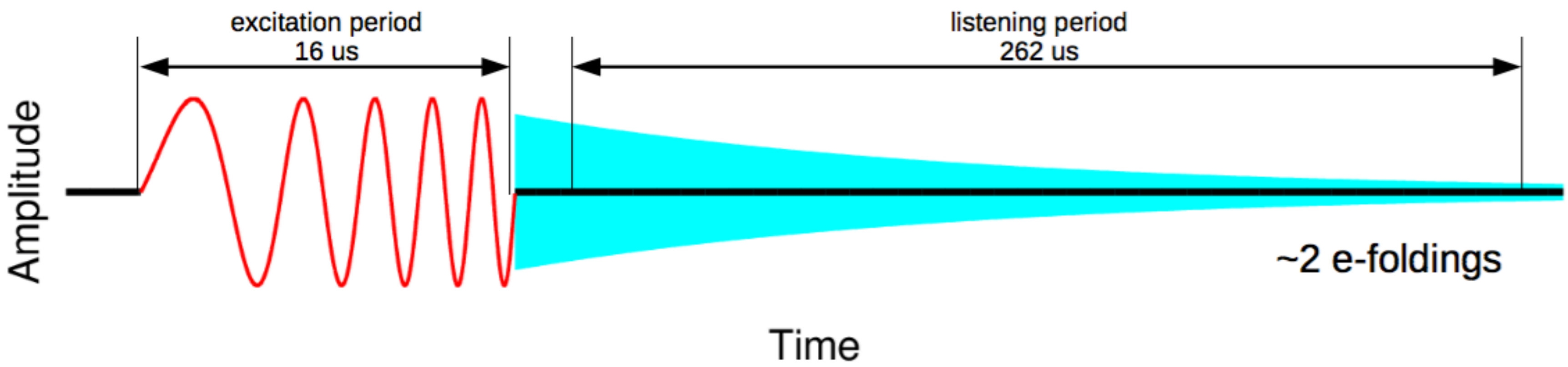


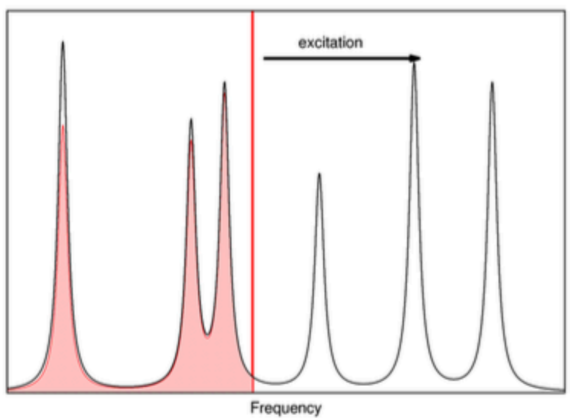
ROACH

Roach Clock
(500 MSPS)

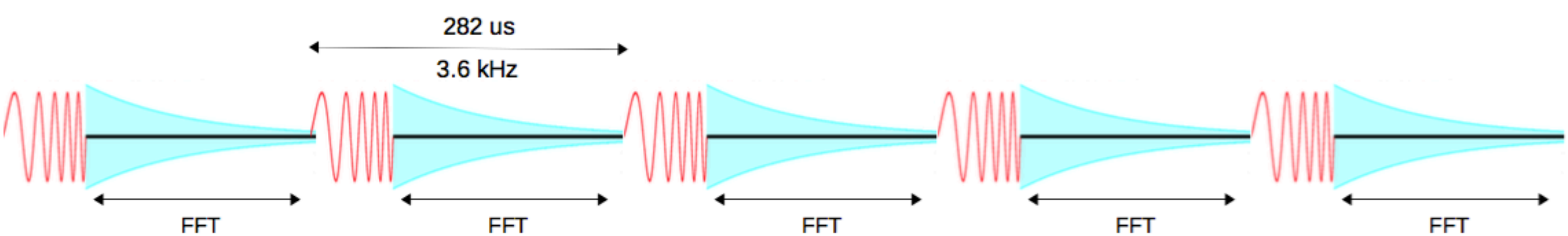
10 MHz standard, Clock, and Amp bias can be shared by multiple ROACH readouts
1 ROACH can handle 2 readout lines, up to 4000 detectors
MAKO/ROACH firmware developed by Ryan Monroe, CIT/JPL

Chirp 101





Requires FFTs at 200 – 250 MSPS (in ~2Q chunks)

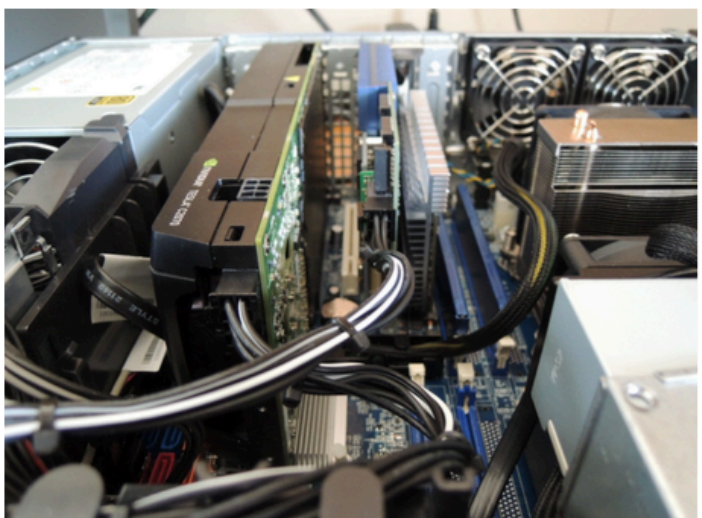


Components

GPU
$ **2K**
(80 W)

PC Host
$ **4K**
(~200 W)

Pentek board
$ **13K**
(18 W)

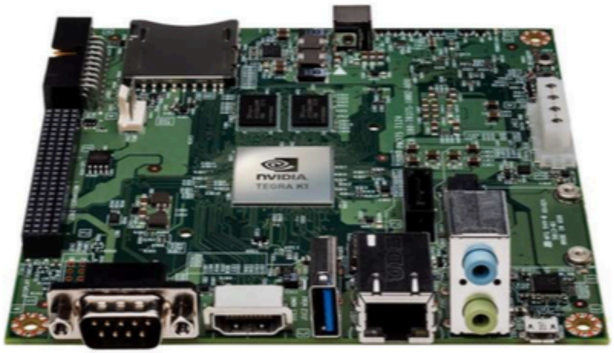


... 5000+ lines of code (C / CUDA)

$ 5 / channel	**$ 500k** for 10^5 channels
75 mW / channel	**7.5 kW** for 10^5 channels

Where next?

Make it (a lot) cheaper and less power hungry...



NVIDIA Tegra K1
(ARM Cortex A15 + 192 CUDA cores)
mini PCIe (x1)

$ 192

(~10 W)

+

?

How to get 250 MSPS
(2^{nd} Nyquist)
streamed to it?

FPGA

ADC interface
- or -
fibre optic interface

$ 0.10 / channel $ 10k for 10^5 channels

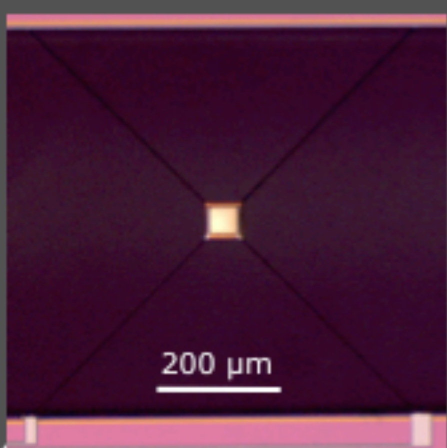
5 mW / channel 500 W for 10^5 channels

SAFARI: TiAu TES bolometers for S-band

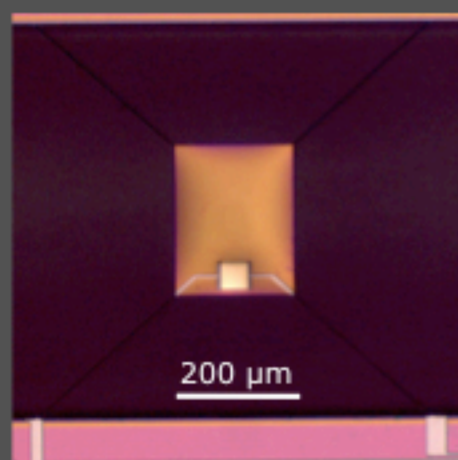
- Tc=110 mK
- SiN leg width ~0.5 µm
- SiN leg thickness 0.2 µm
- Pixel size: for S-band for SAFARI
- Fabricated with new DRIE process (in 2014)

- TES with three different designs:
  small island: lower G, no absorber
  large island: a bit higher G, no absorber
  large island +absorber: will see straylight ifany

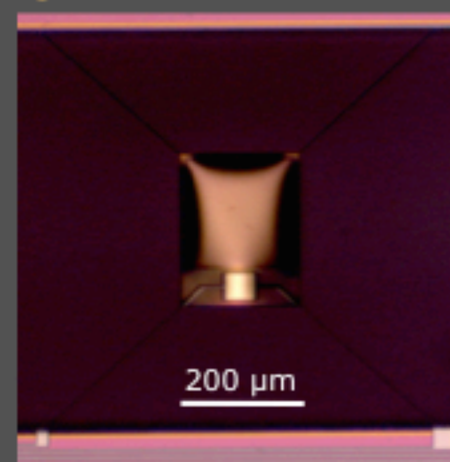
Small island



Large island

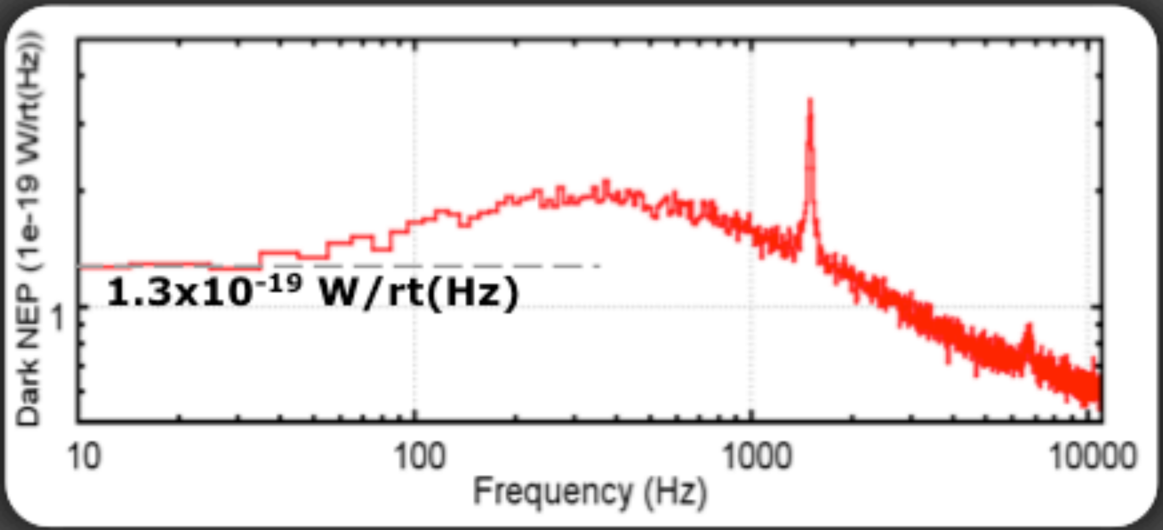


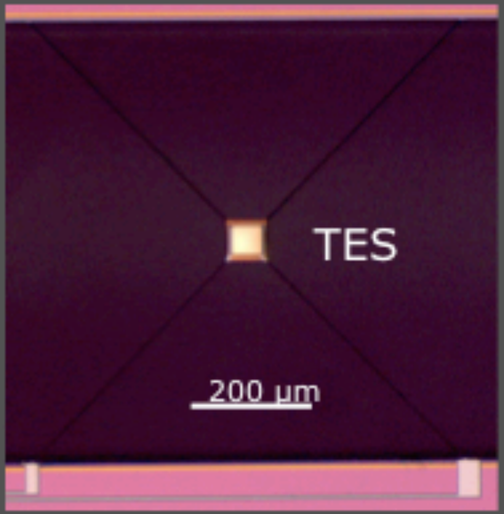
Large island + absorber



Credit: J. Gao

Lowest NEP measured





- NEP down to 1.3×10^{-19} W/rt(Hz) (electrical)
- Time constant = 200 µsec (0.2 msec)
- Saturation power = 1.2 fW (Tbath=50 mK)
- Small-island device
- Many more TES measured, give consistent results

Credits:
Measurements by Toyo and Pourya at SRON
Fabrication by Marcel Ridder

SRON

Credit: J. Gao

Multiplexed readout demonstration of a TES-based detector array in a resistance locked loop

Accepted for publication in IEEE Transactions on Applied Superconductivity, DOI 10.1109/TASC.2015.2393716

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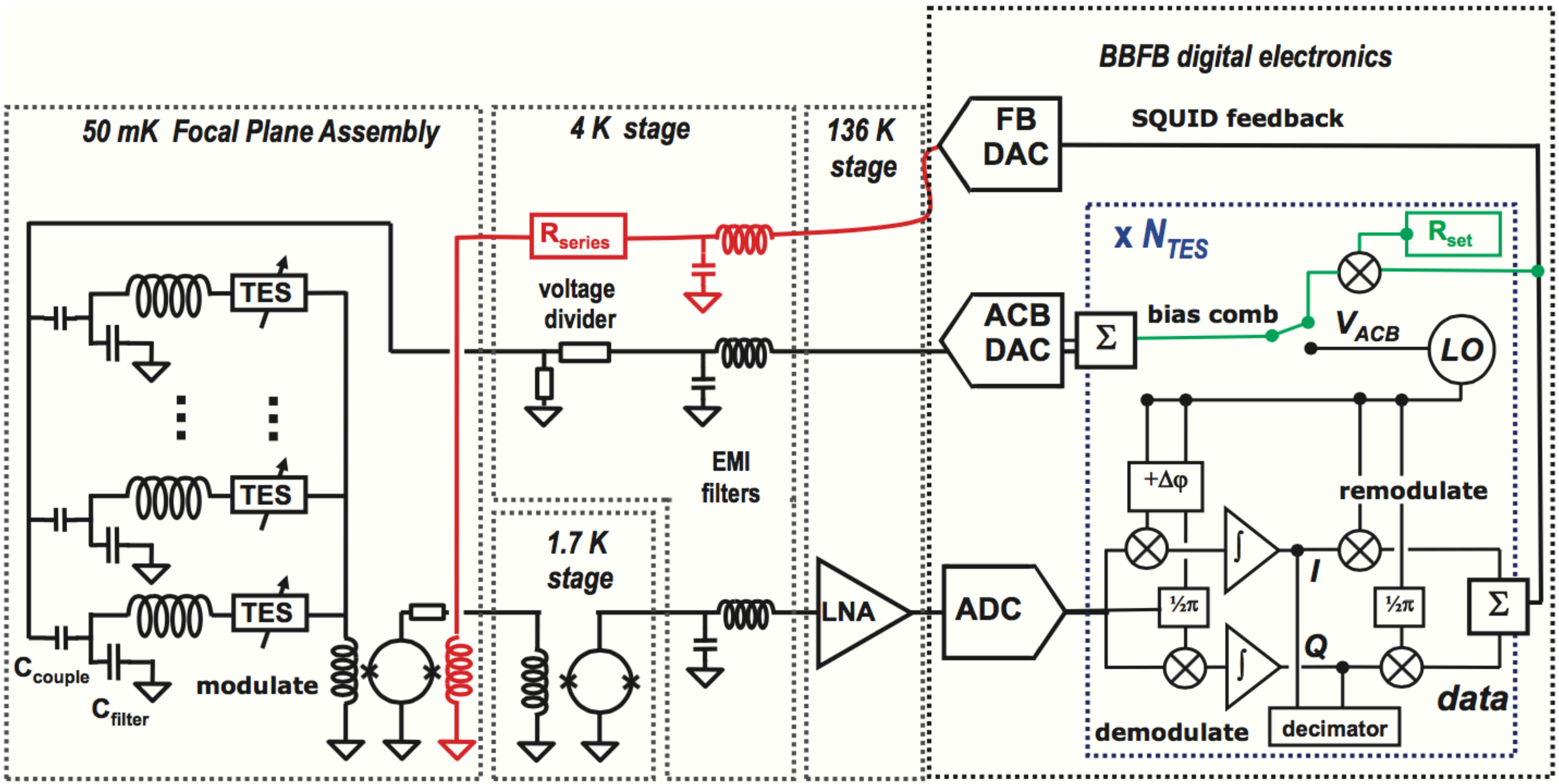
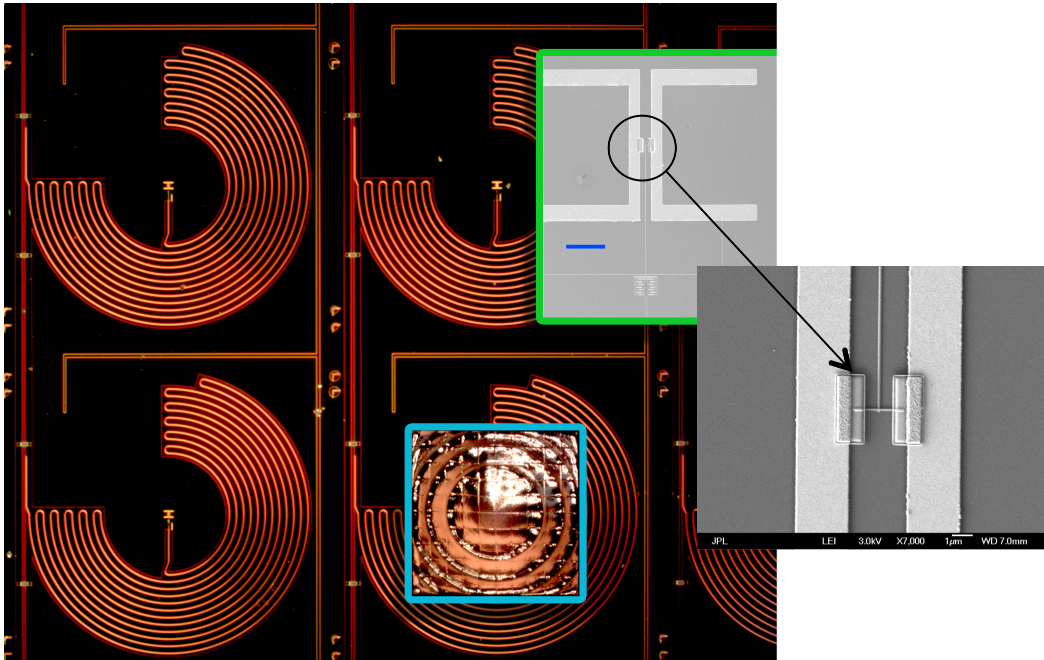
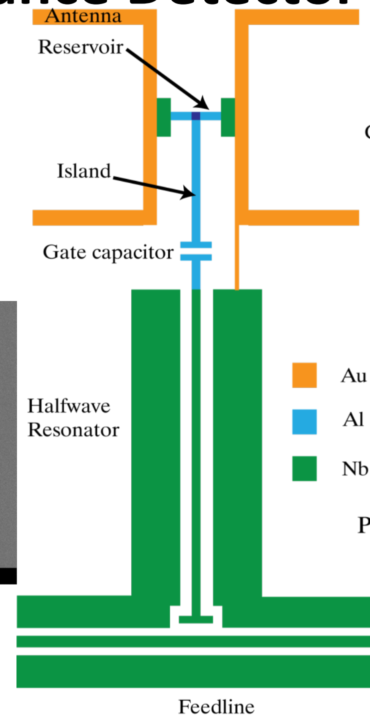
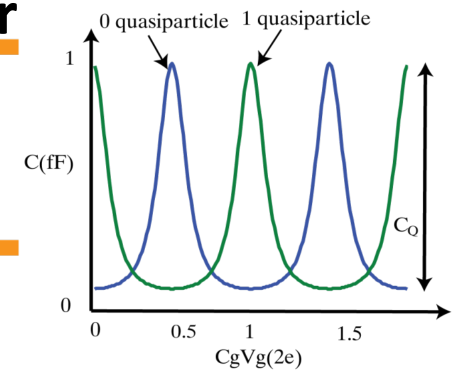


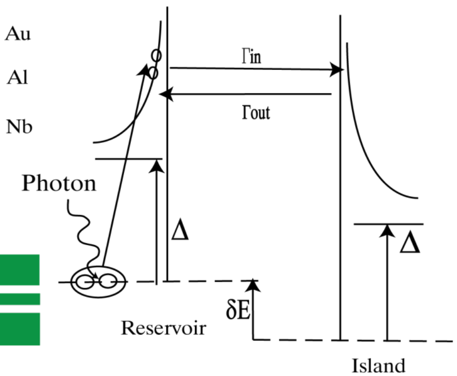
Fig. 1. Schematic diagram of the 8-pixel frequency domain multiplexed TES readout system. The resistance locked loop is integrated in the baseband feedback electronics as drawn on the right hand side. The envelope of the AC bias current is present in the I-channel. The AC bias voltage is equal to this measured current times the required set point resistance of the TES (R_{set}). With the switch the user can choose between voltage bias and RLL operation.

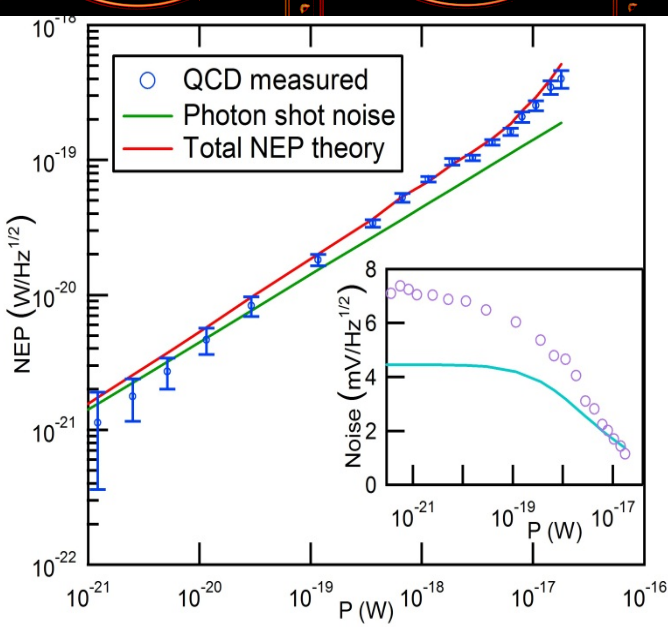
The Quantum Capacitance Detector

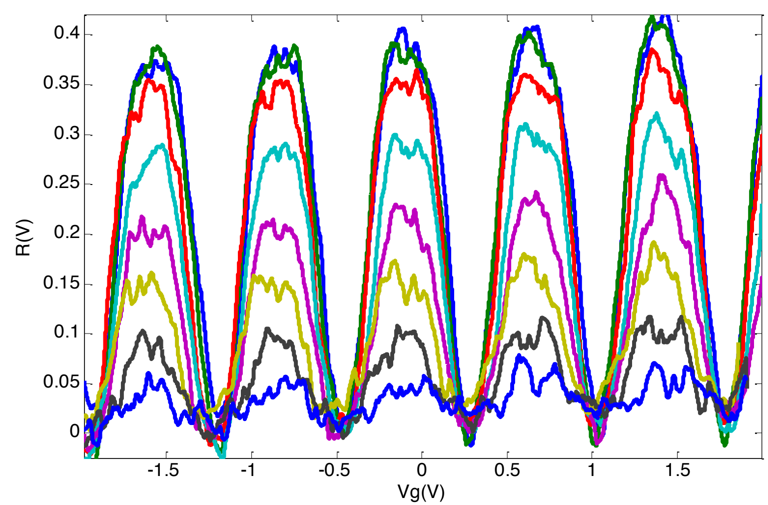






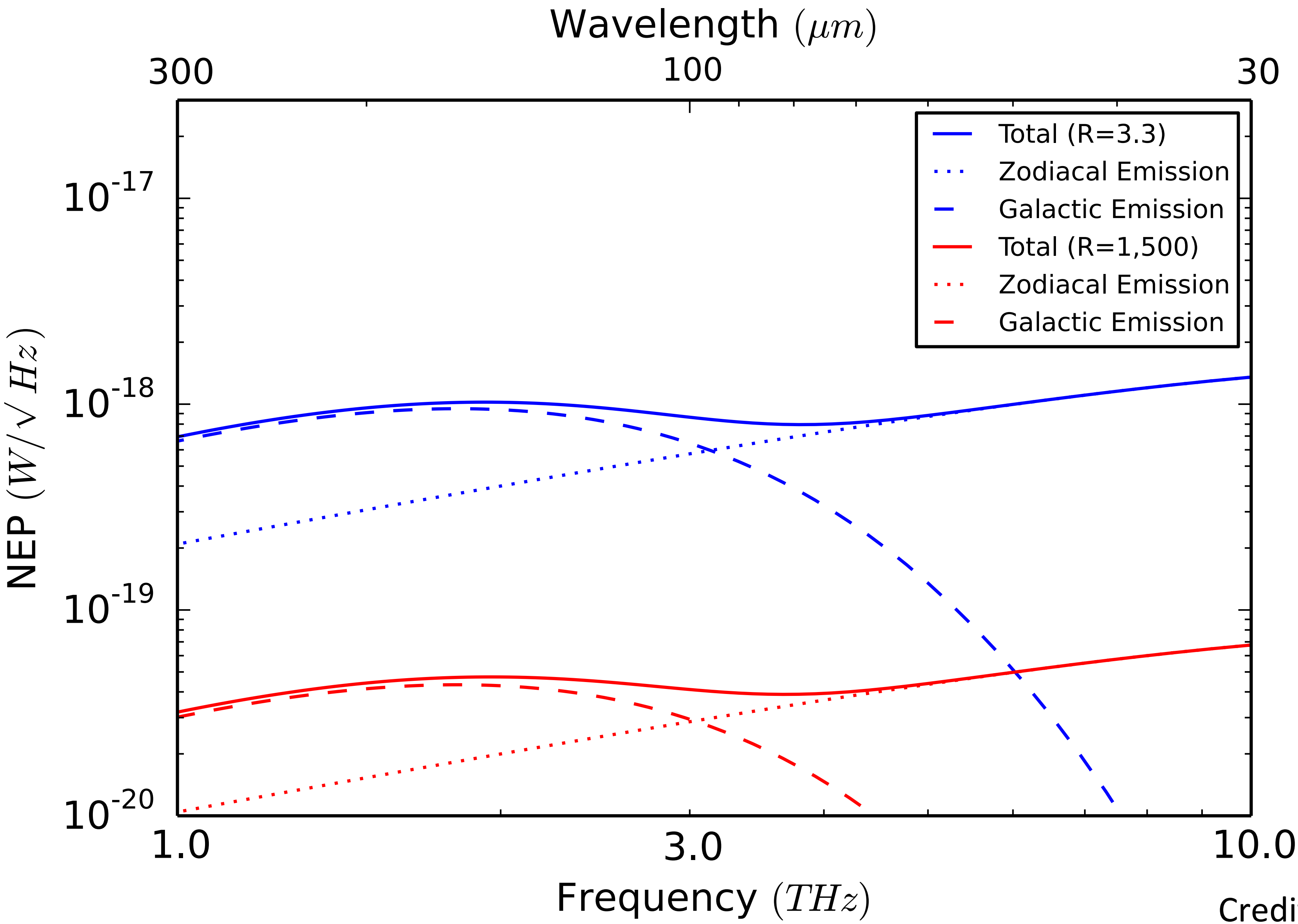






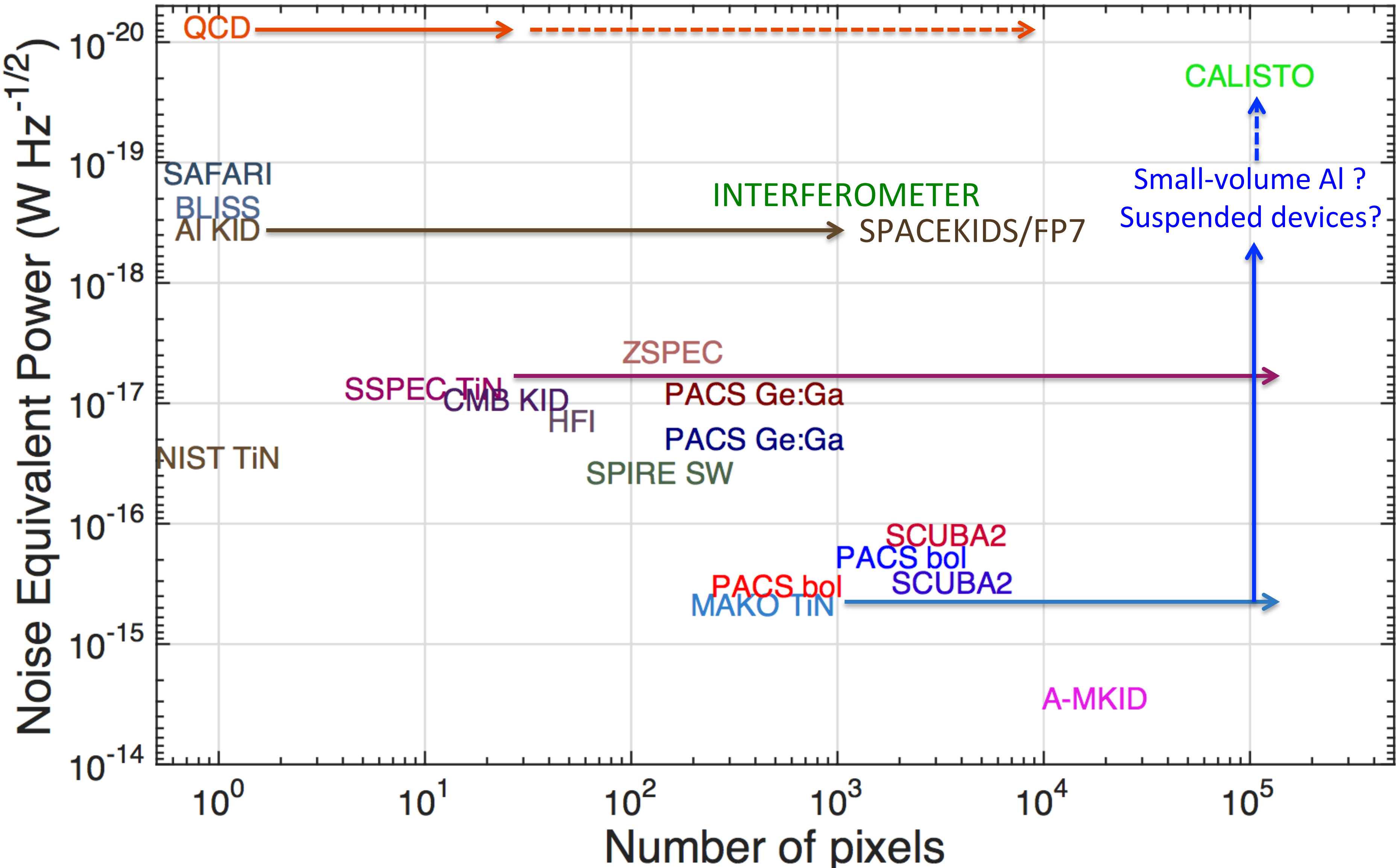
Credit: P. Echternach / JPL

Sky background



Credit: J. Glenn

The landscape in 2015



What will it take?

- Lower NEP
  - Reduce active volume
    - Antenna vs absorber coupling ?
  - Use suspended devices to slow down energy loss
    - Detector time constant ?
- Larger arrays
  - Simplify as much as possible
    - KIDs vs TES vs QCD ?
  - Reduce readout frequencies
    - Tradeoff vs active volume ?
- Lower power readout (e.g., ASIC spectrometer chip)
- Opportunities for full-system testing
- Significant commitment / investment
  - Current levels will not get us to CALISTO

A. Poglitsch, 2010

- With the PACS instrument, we have – for the first time – introduced large, filled focal plane arrays … in the far infrared. Without any prior demonstration, several major, technological developments have found their first application with PACS in space.
- The success of this path … should encourage our community to defend this more “pioneering” approach against trends towards an “industrial” (i.e., minimal-risk) approach, which will not allow us to take advantage of the latest, experimental developments, on which our scientific progress often depends.

END