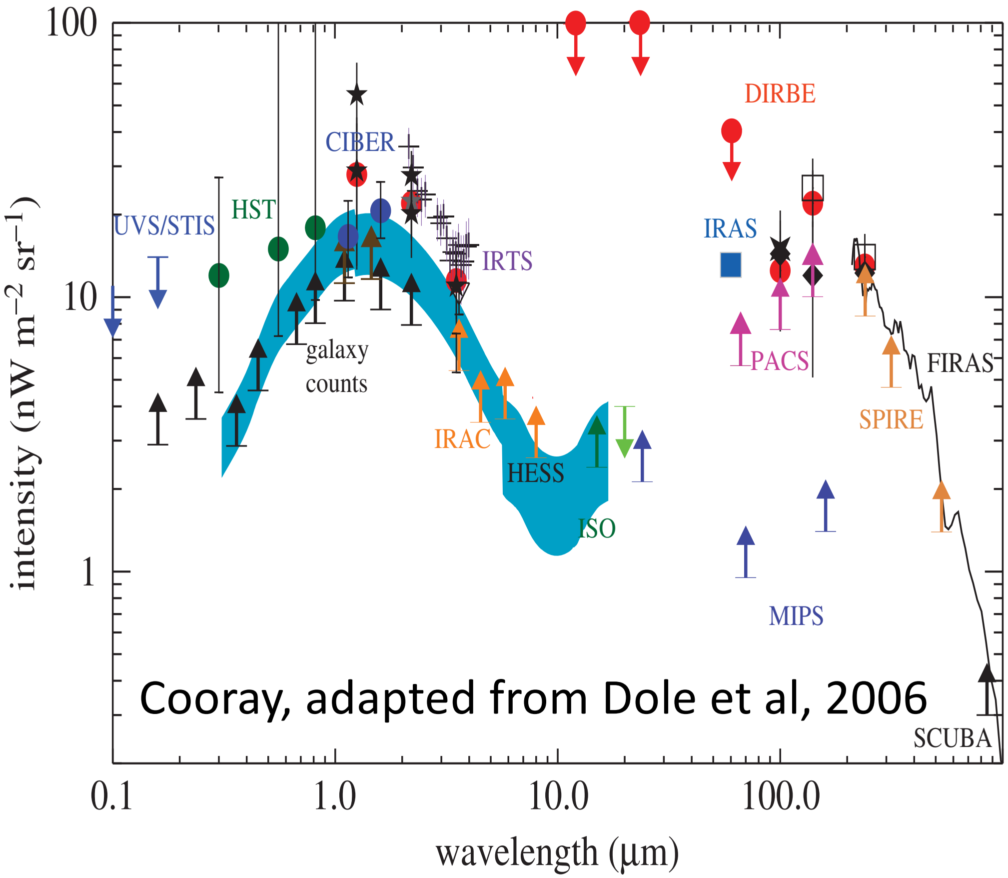
Far-IR Technology: Review and Update

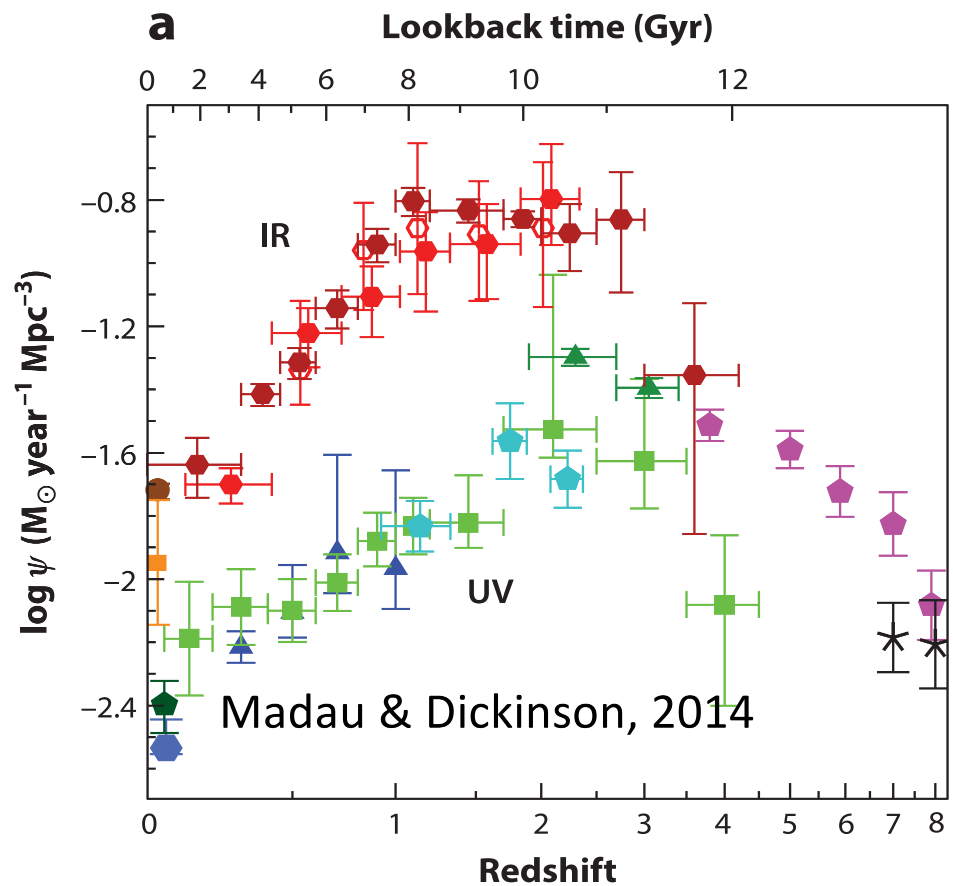
Matt Bradford

9 January 2018

- Why far-IR? Scientific opportunities from space, including SPICA.
- Far-IR detector system requirements.
- Detectors system approaches and examples.
- Outlook

Why Far-Infrared?

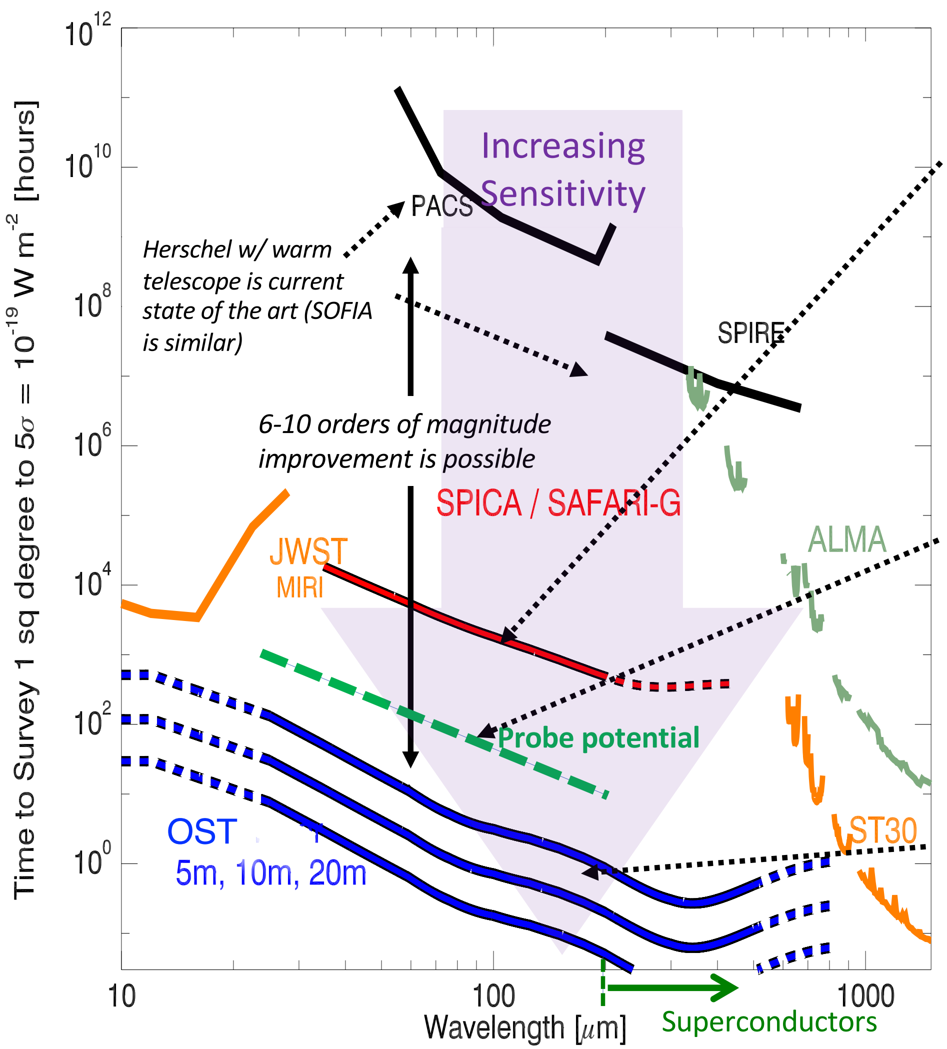




- ~Half of the remnant electromagnetic light from stars and galaxies is in the far-IR.
  - Far-IR background is a cosmological background, not a low-redshift phenomenon.
- Most of energy from star formation and accretion activity emerges in the far-IR.
  - Young stars and accreting black holes are obscured by their very fuel.
- Mechanisms driving these transformative processes, and the results are inaccessible in the optical / NIR.
- Reionization epoch in particular – vital historically but leaves little in backgrounds.

Far-infrared is a Scientific Frontier

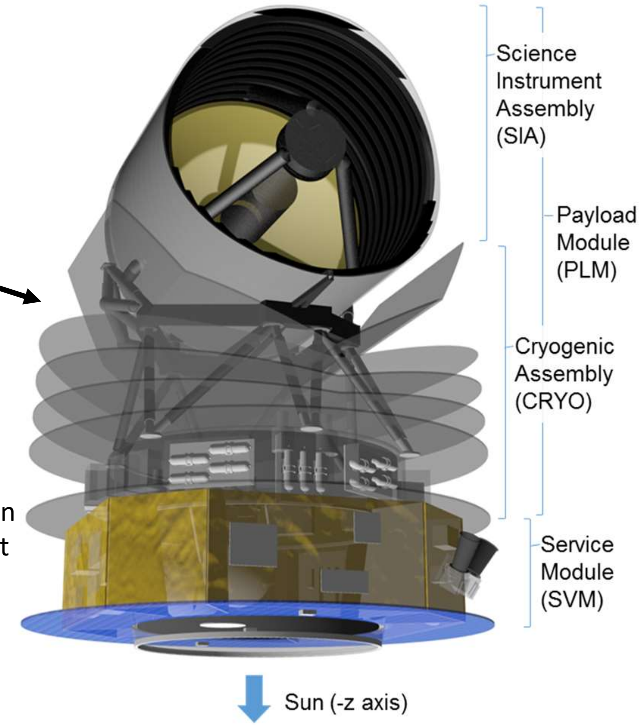
Time required for new spectroscopic discoveries in the far-IR (lower is faster)



JWST | **Far-IR**, a NASA frontier | **Ground (e.g. ALMA)**

- **SPICA**

Proposed ESA / JAXA 2.5m cooled observatory w/ potential JPL provision of far-IR detectors. Launch in 2030. Need to build and demonstrate bolometer arrays to win MoO competition in 2018 / 2019.

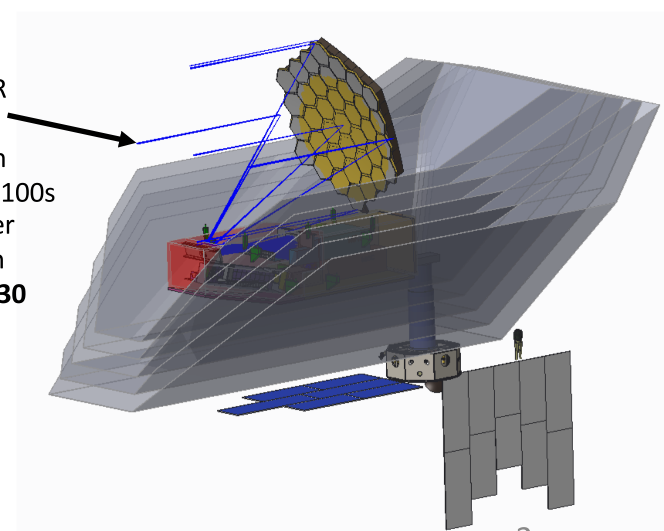


- **FIR Probe**

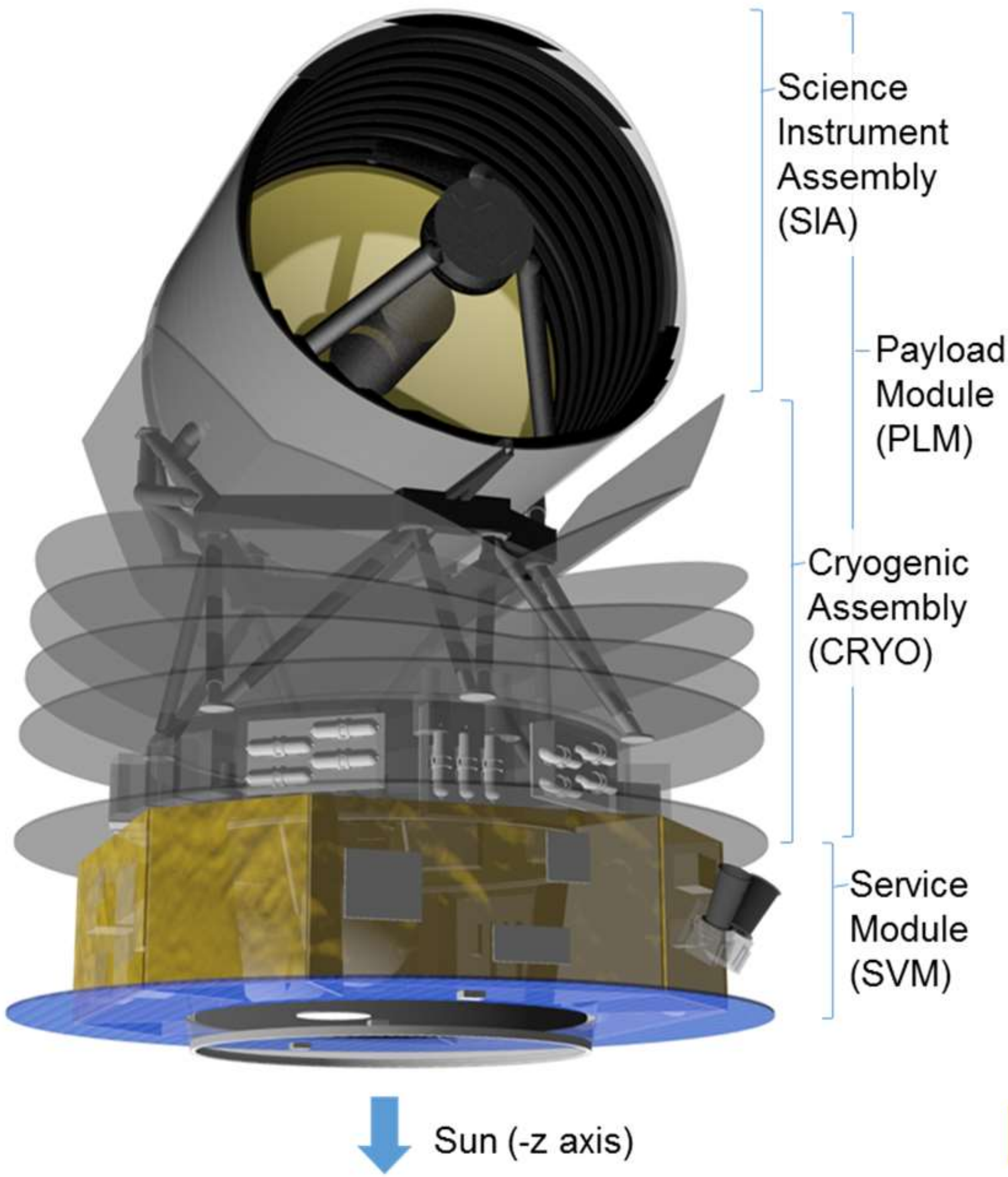
Under study @ JPL for submission to Decadal. Similar to SPICA, but potentially more capable with advanced JPL detectors & readouts (KIDs, QCDs) which will feature in Decadal submission. **Jason Glenn presentation 2:09 PM, session 121.**

- **OST**

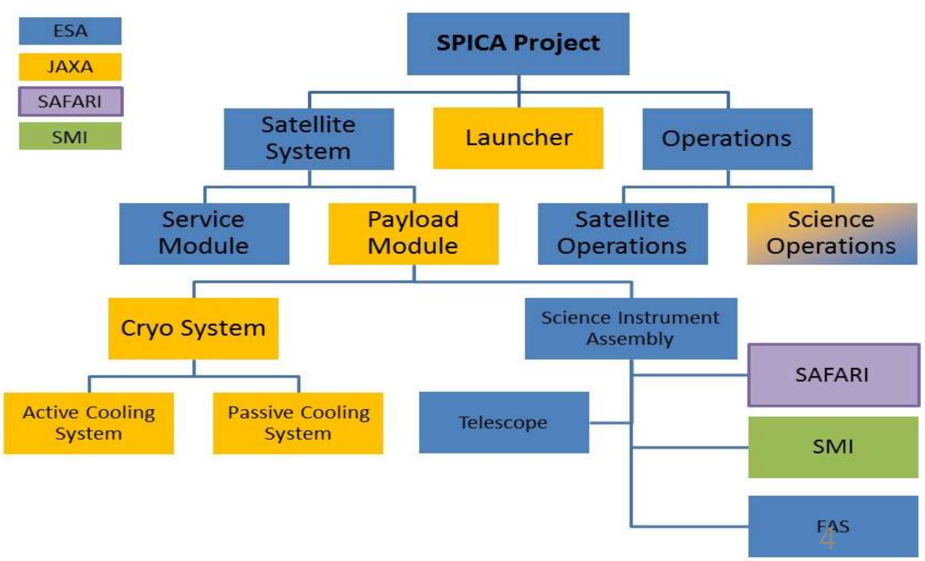
Origins Space Telescope -- Far-IR flagship under study for NASA submission to 2020 Decadal (9m version shown). Cooled to 4 K, 100s of kilo-pixels. 2nd concept under design now. Start 2020s, launch 2030s. **Poster session Thurs 5:30**



SPICA



- ESA / JAXA collaboration, ~2029 launch.
    - **Pending candidacy with ESA Cosmic Visions M5 opportunity (550 Meuro).**
    - **JAXA commitment in place.**
- 2.5 meter telescope actively cooled to below 8 K.
    - Sumitomo closed cycle 4.5K, 1.7K coolers
    - Planck-like thermal design.
- **European-led SAFARI far-IR spectrometer**
    - **Grating system like BLISS but with high-res mode.**
    - **Proposed US contribution here.**
- Wide-field mid-IR instrument which complements JWST (JAXA).



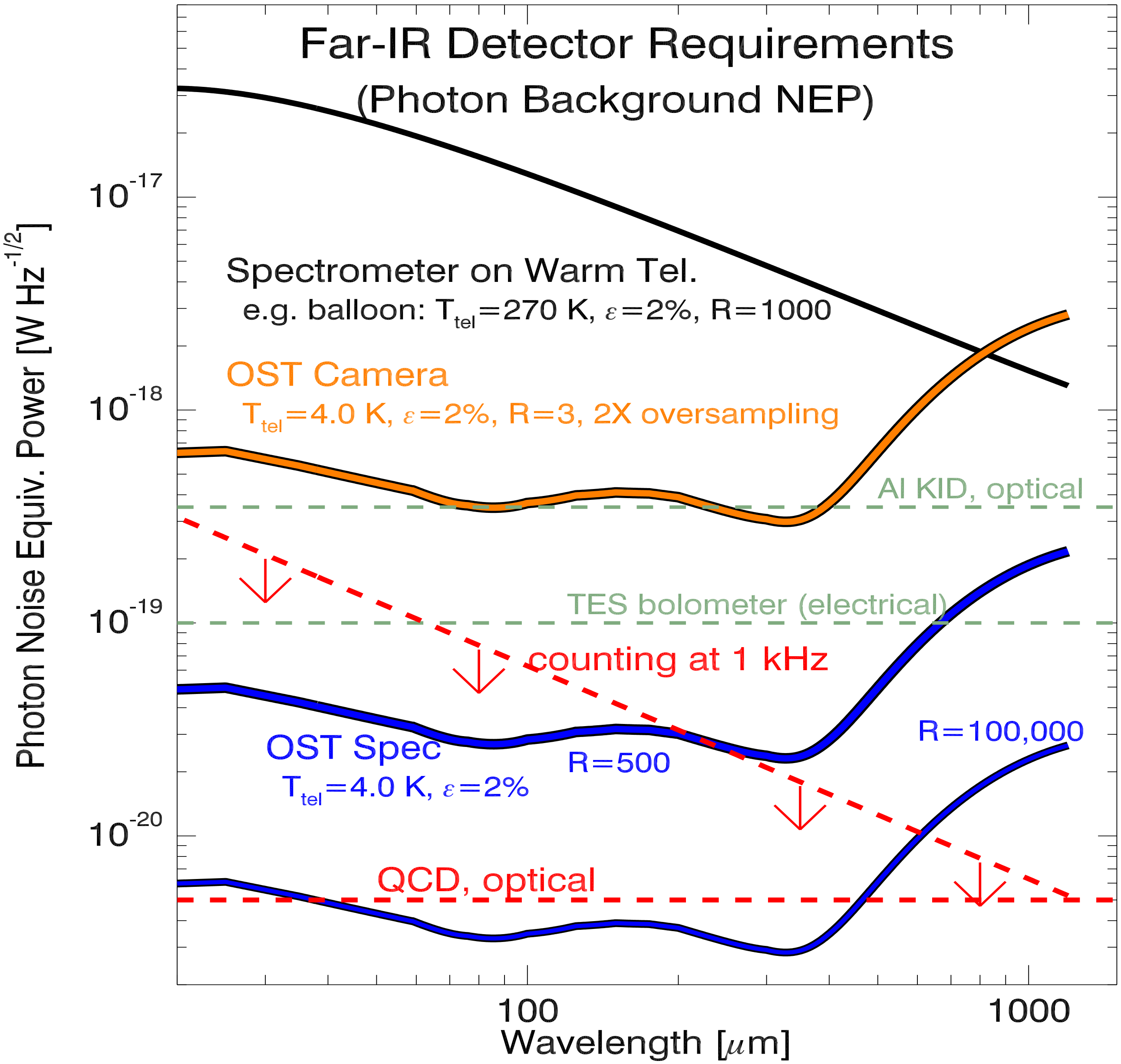
Far-IR Detectors for Space-Borne Astrophysics

Essential, and must be built by scientists

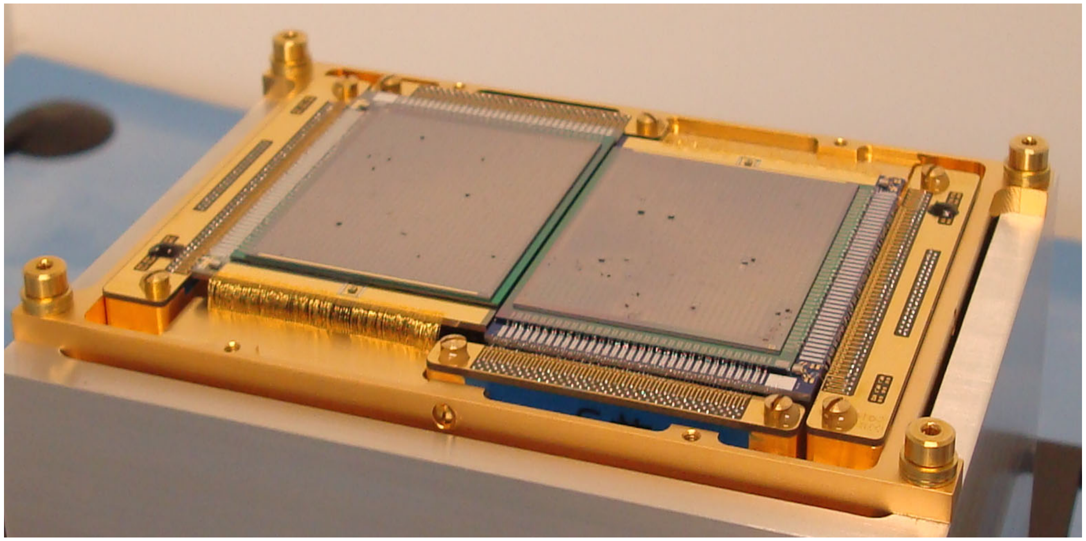
Long-term far-IR detector Requirements

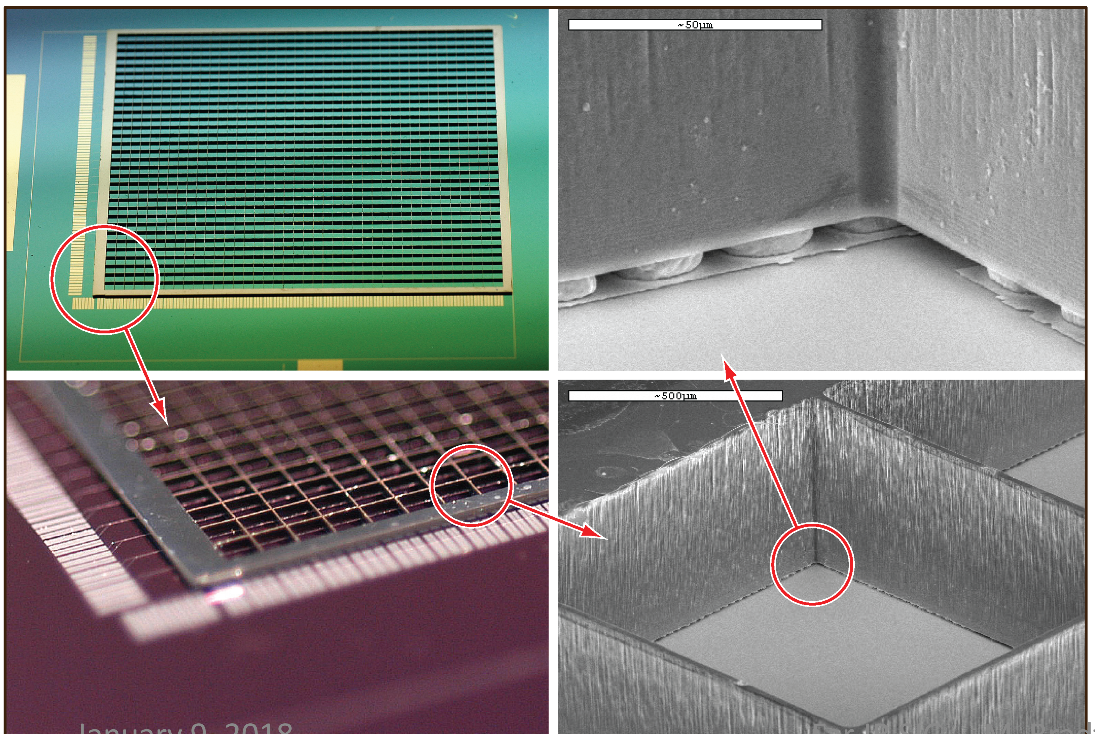
- Per-pixel sensitivity below 3×10^{-20} W Hz$^{-1/2}$ for spectroscopy (targeting 1×10^{-19} for this work).
- Readout / system scheme enabling 10^5 to 10^6 total pixels in a large observatory.
- Ability couple efficiency across the full 30 microns to 1 mm spectral band.

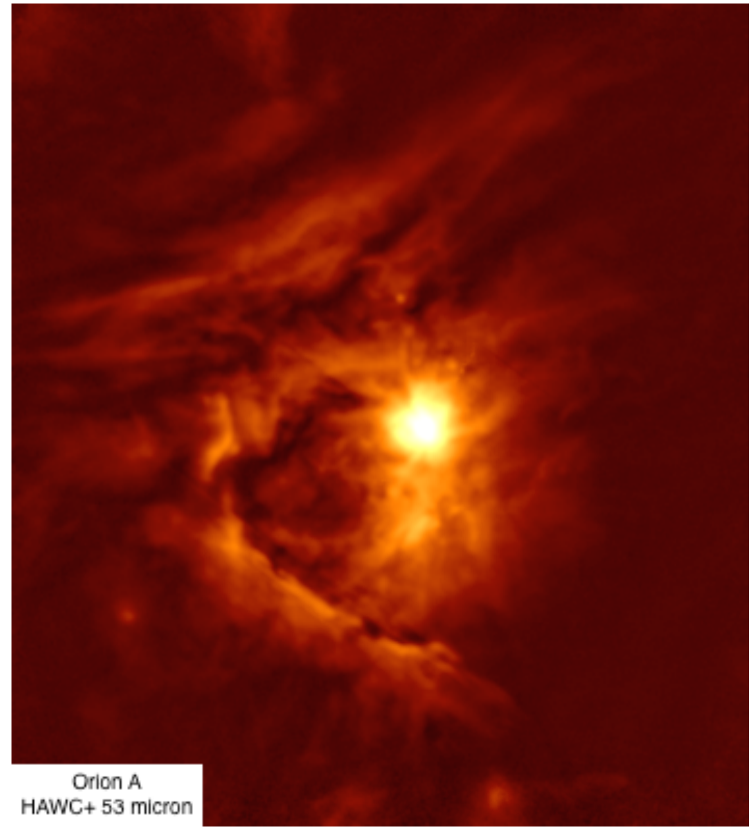
No other market for this technology -> NASA astrophysics must support development.



Transition-edge sensed (TES) bolometers





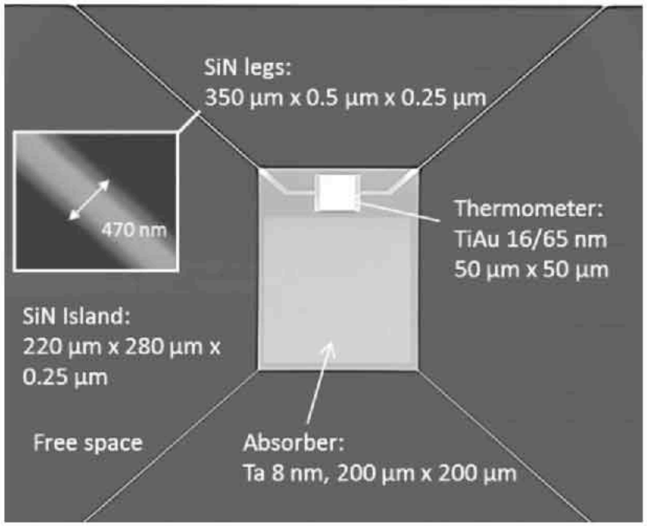


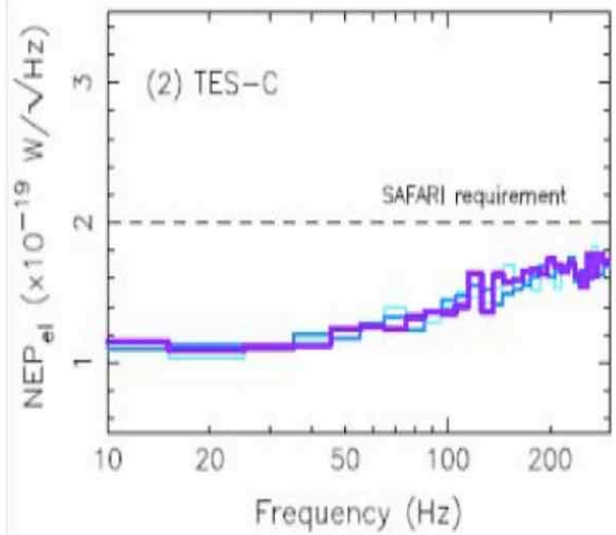
Goddard kilo-pixel array for Hawc+ on SOFIA.

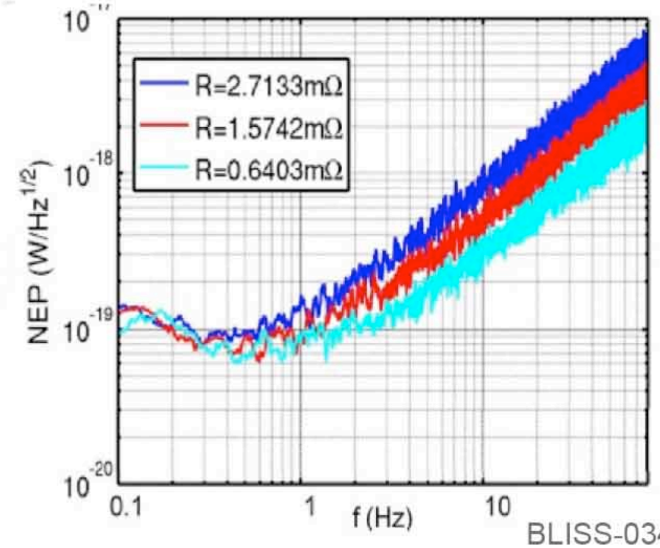
- 32 x 40 format with integrated bump-bonding to multiplexer.
- NEP ~ 8×10^{-17} W $Hz^{-1/2}$
- Time-domain multiplexer as per SCUBA-2, BICEP / Keck. Hard to scale to OST formats.

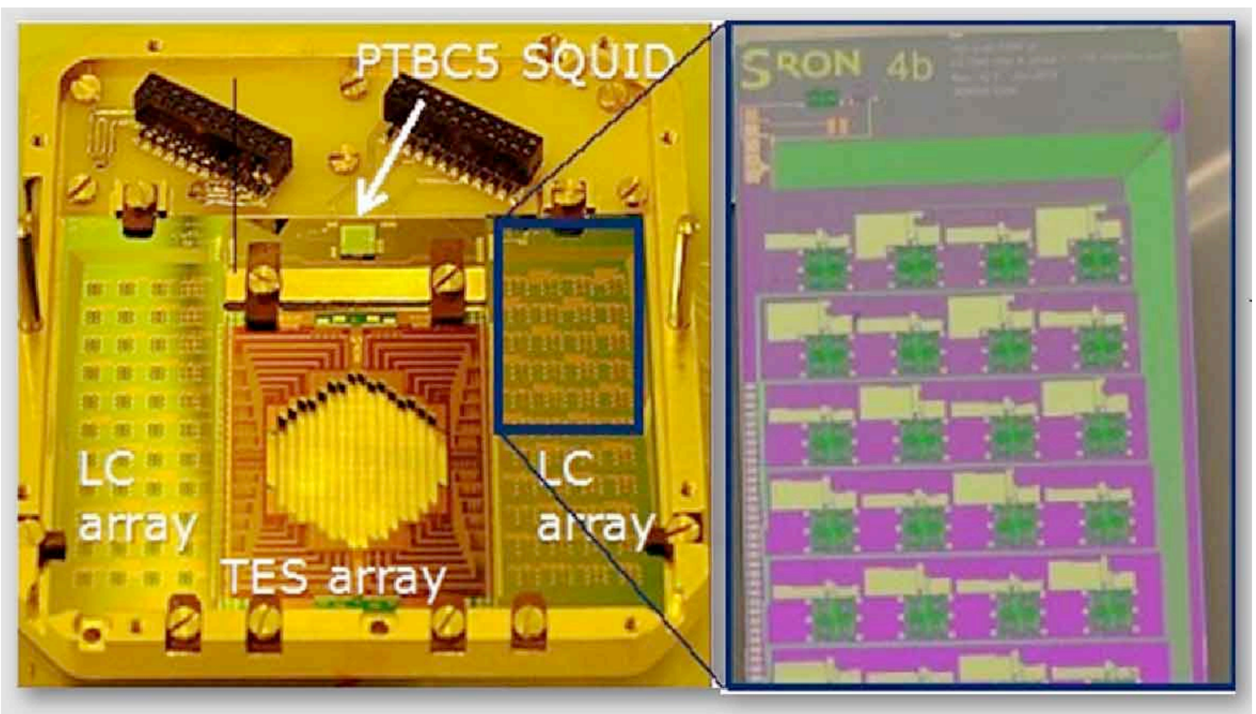
J. Staguhn et al. @ GSFC

Transition-edge sensed (TES) bolometers







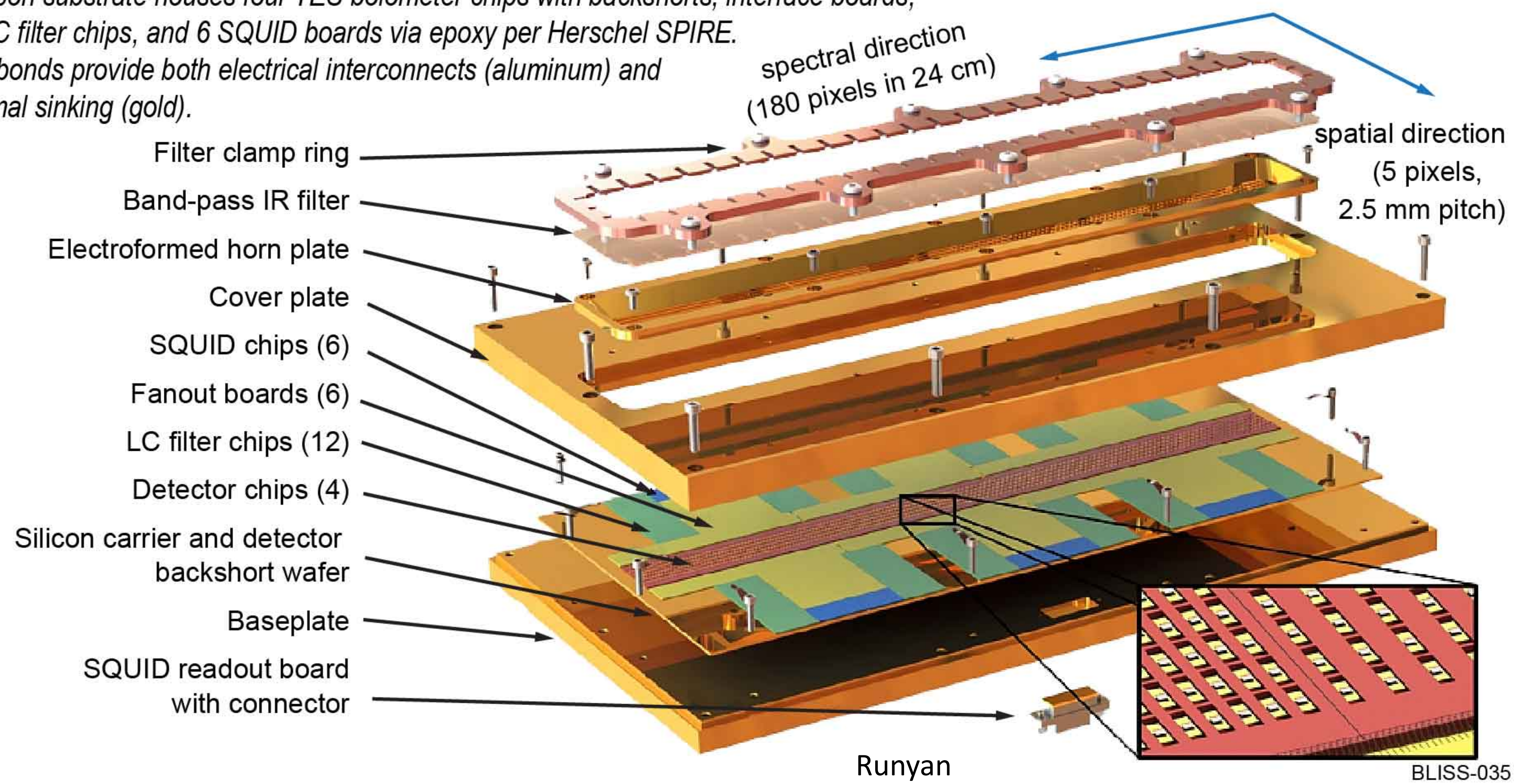


JPL and SRON developed TES bolometers for spectroscopy – long legs and 50-100 mK temperature.

- **NEP ~ $1x10^{-19}$ W $Hz^{-1/2}$**
- SRON RF frequency-domain MUX with 160-pixel circuit. Might approach OST format with careful thermal design for wiring.

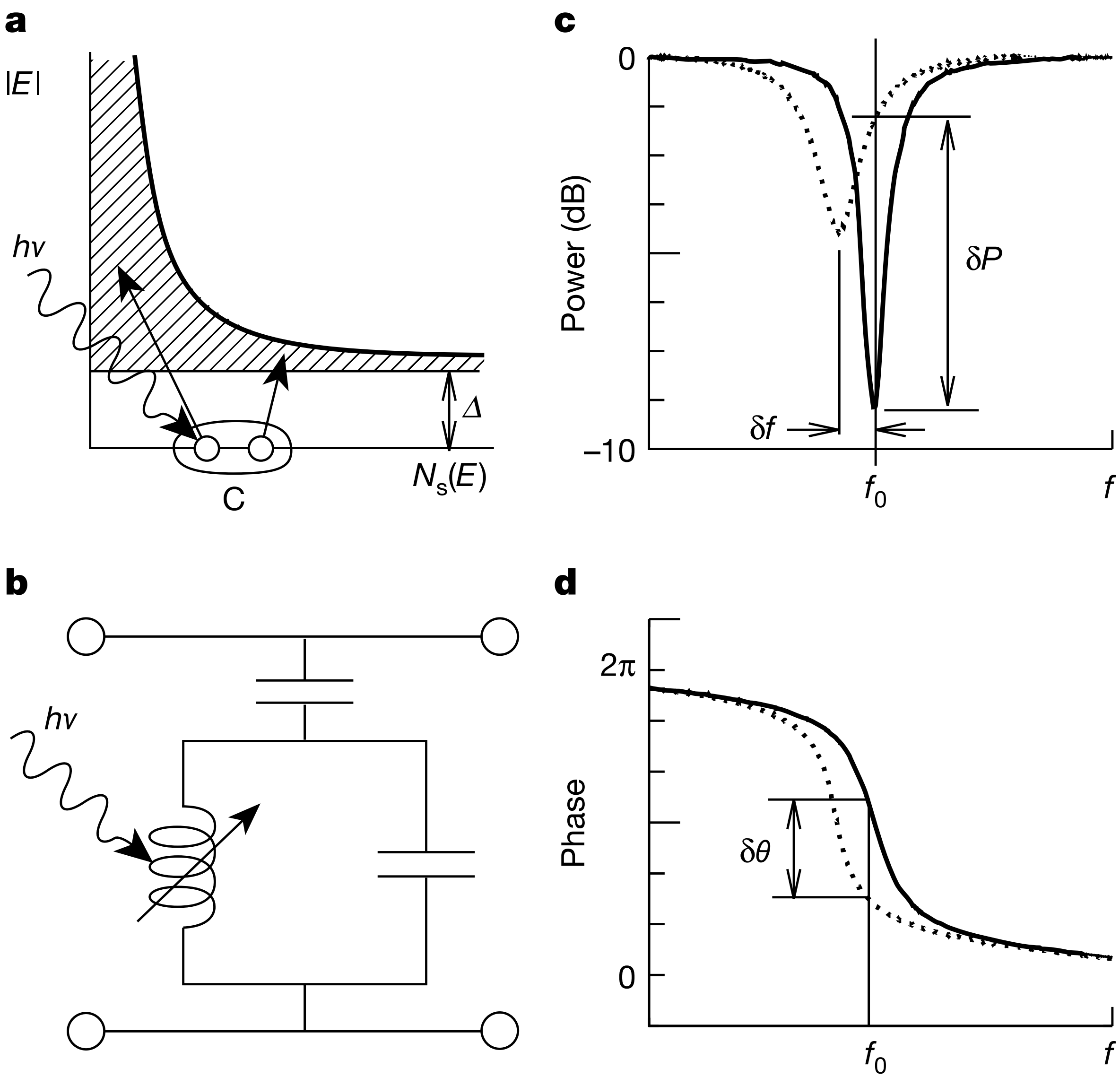
BLISS Focal Plane Array Concept

A silicon substrate houses four TES bolometer chips with backshorts, interface boards, 12 LC filter chips, and 6 SQUID boards via epoxy per Herschel SPIRE. Wirebonds provide both electrical interconnects (aluminum) and thermal sinking (gold).



5 x 180 pixel TES bolometer array, 1e-19 NEP design, 2e-19 requirement, use SRON freq. domain MUX.

Resonator Multiplexing: Kinetic Inductance Detectors



Day, Zmuidzinas & LeDuc 2003

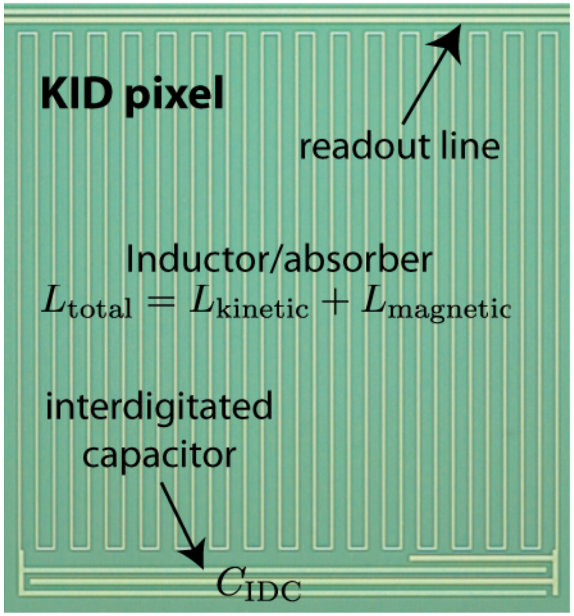
Superconducting high Q resonator

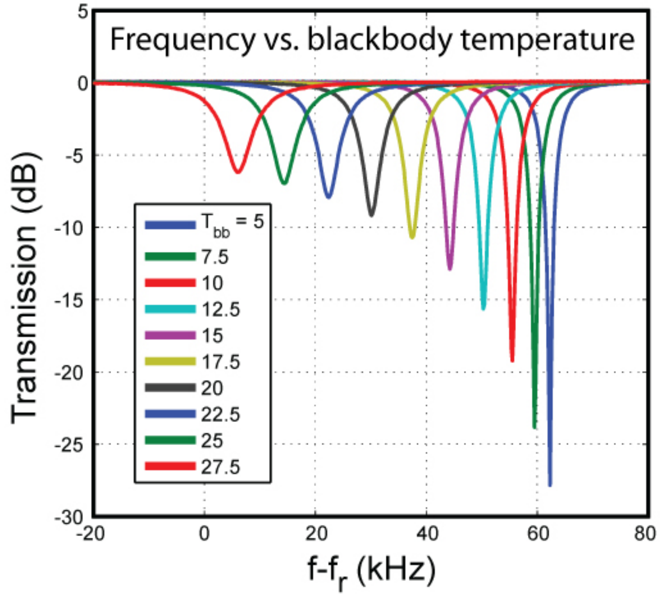
Photons break superconducting Cooper Pairs, creating free electrons which change the impedance of the resonator.

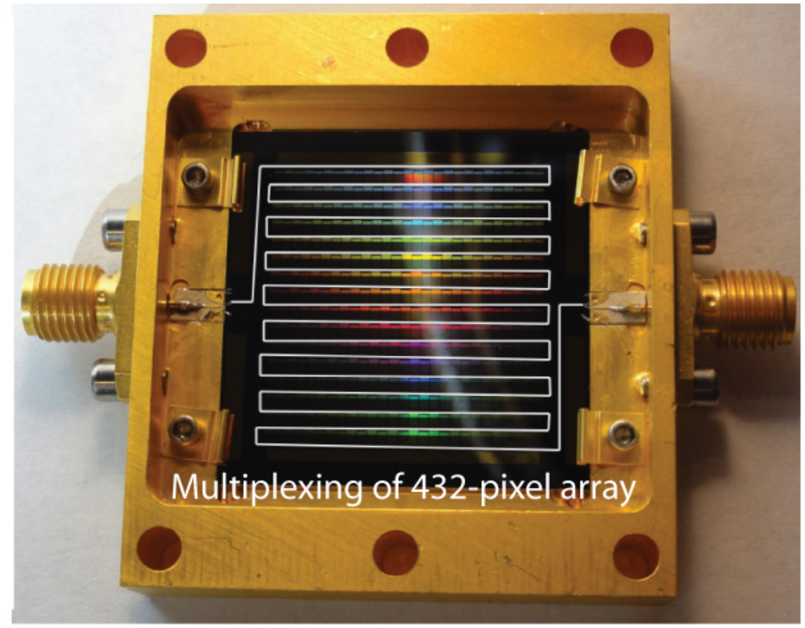
Frequency shift is measured via phase shift in RF / microwave probe tone.

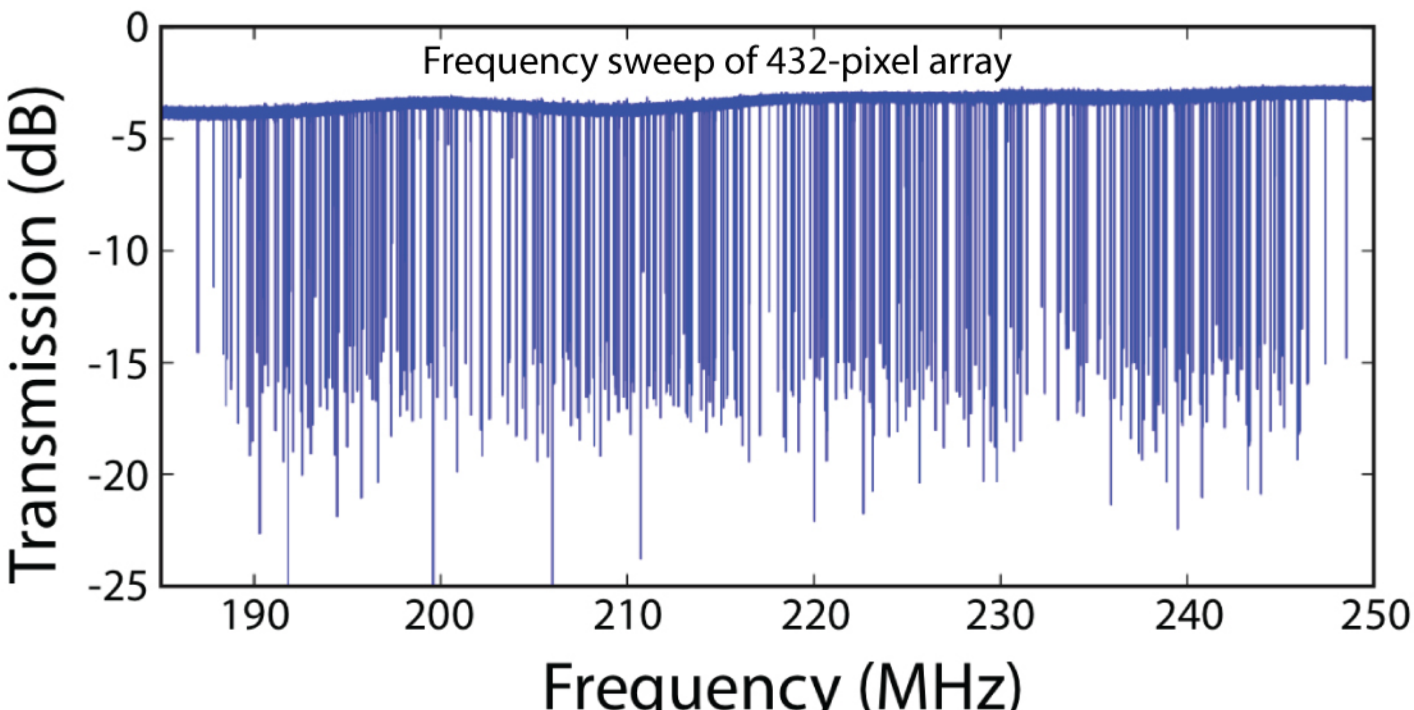
Hundreds can be read out on a single line

Resonator Multiplexing: Kinetic Inductance Detectors





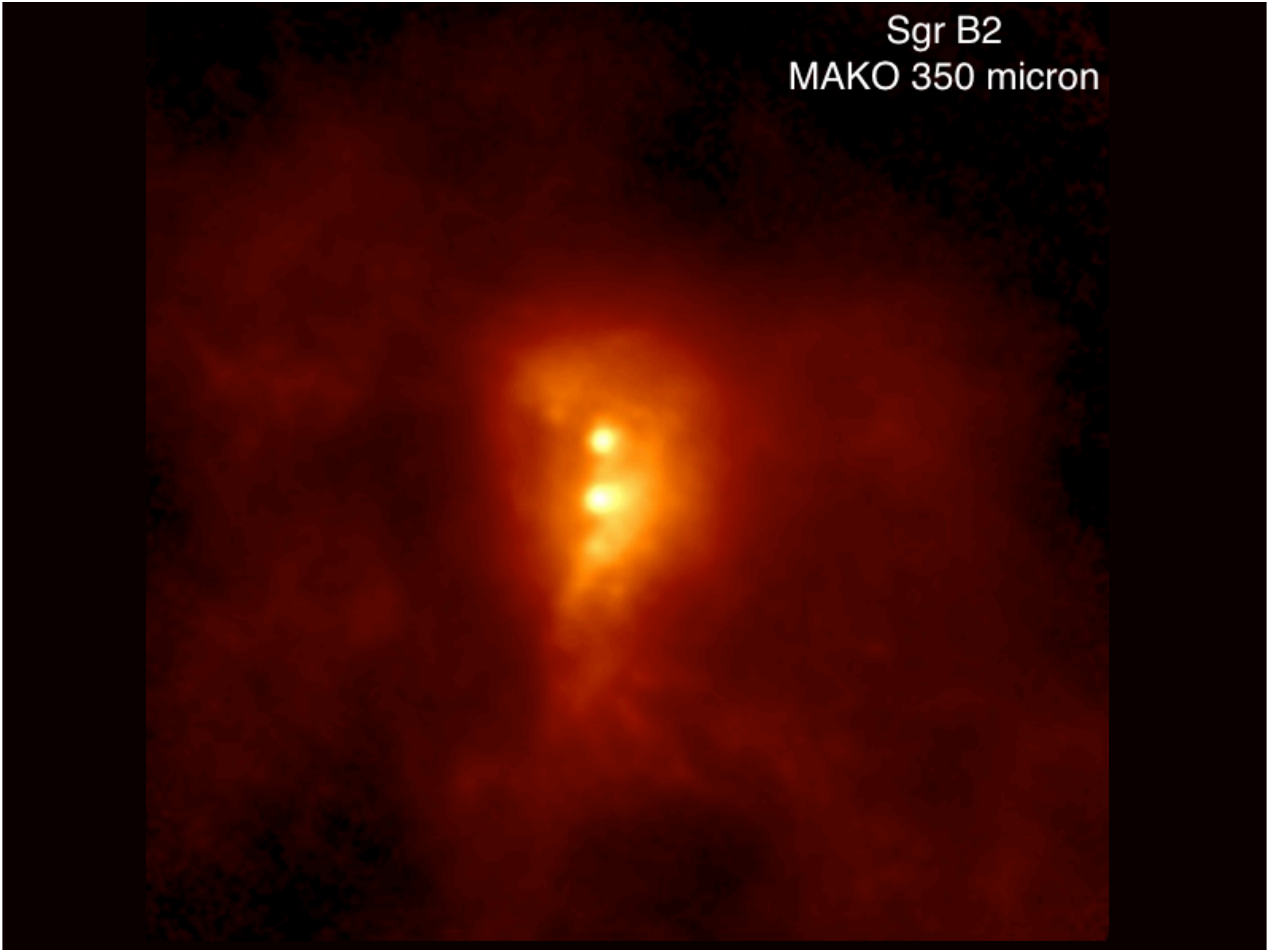




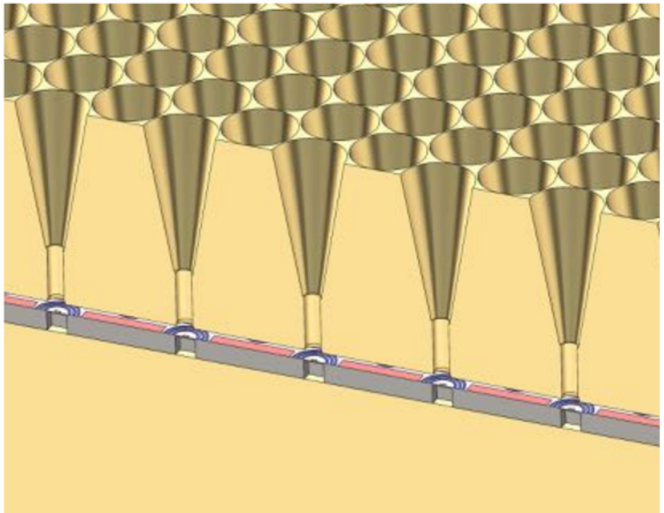
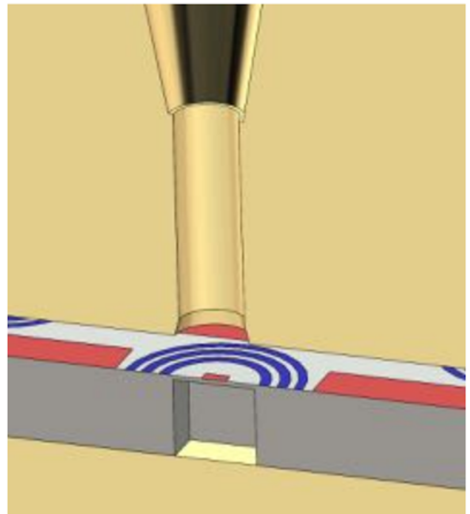
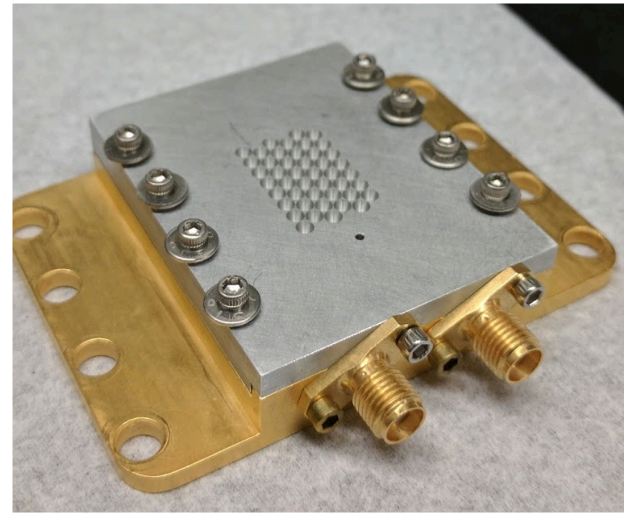
MAKO 350 micron camera

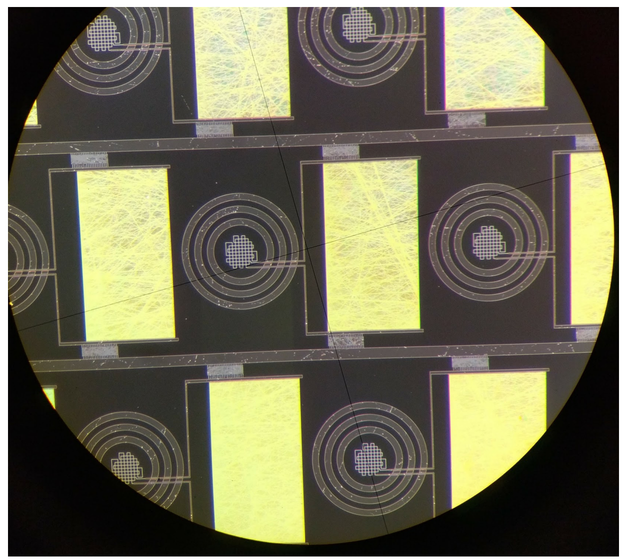
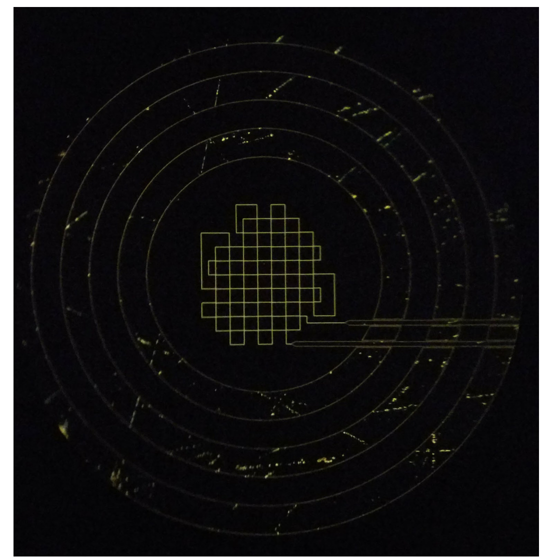
NEP ~ 10^{-16} W/sqrt(Hz)

J. Zmuidzinas


Sgr B2
MAKO 350 micron

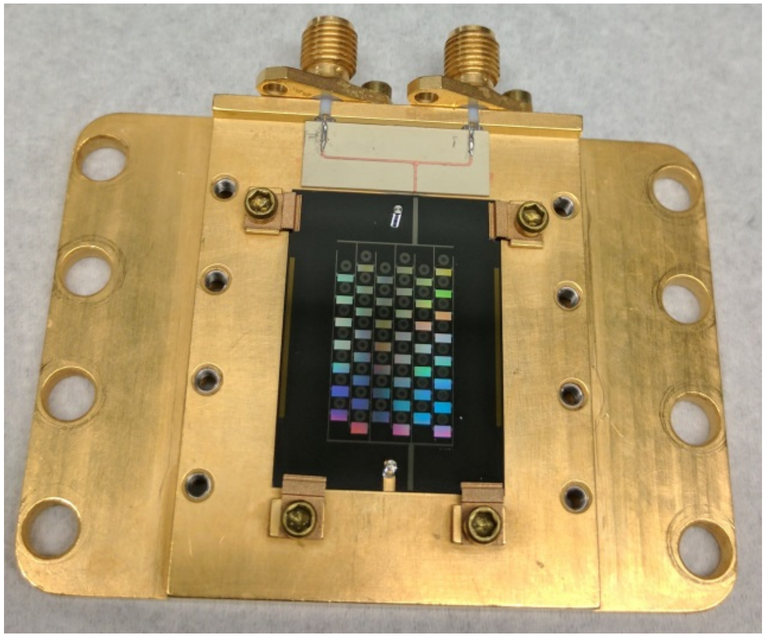
Direct Absorbing Aluminum KID

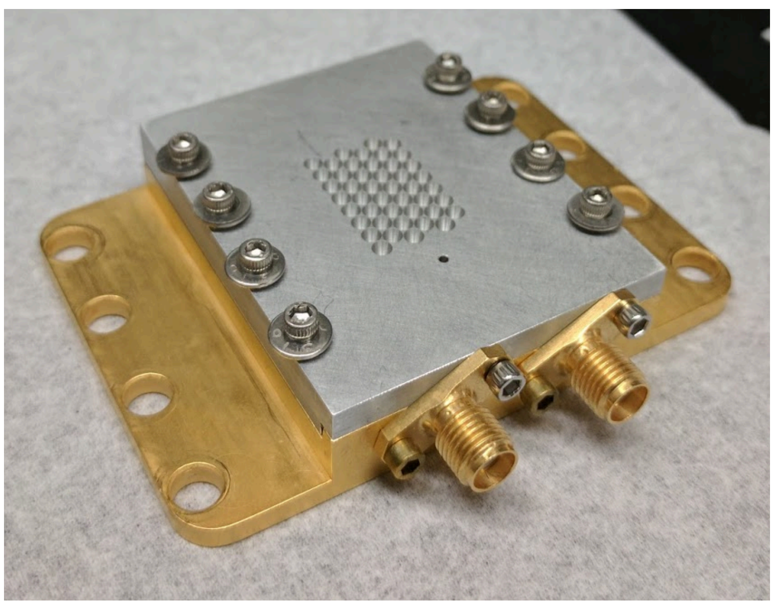




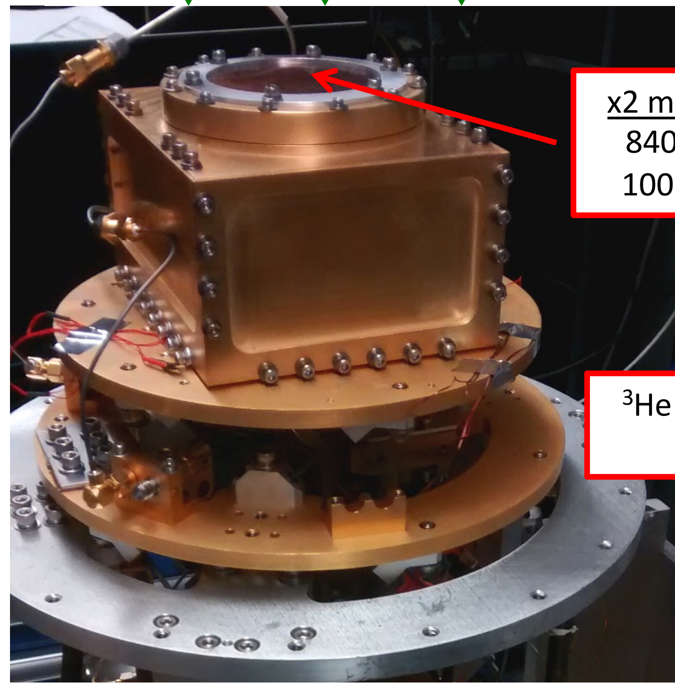



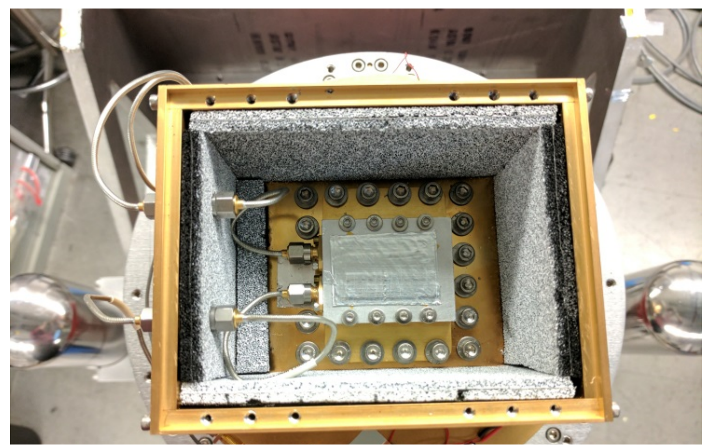
Single-layer 40 nm aluminum. Dual-pol meandered inductor. (McKinney & Reck design, LeDuc fab). Backshort for 850 GHz via SOI. ~100 MHz readout frequencies

Detector Package / Testbed



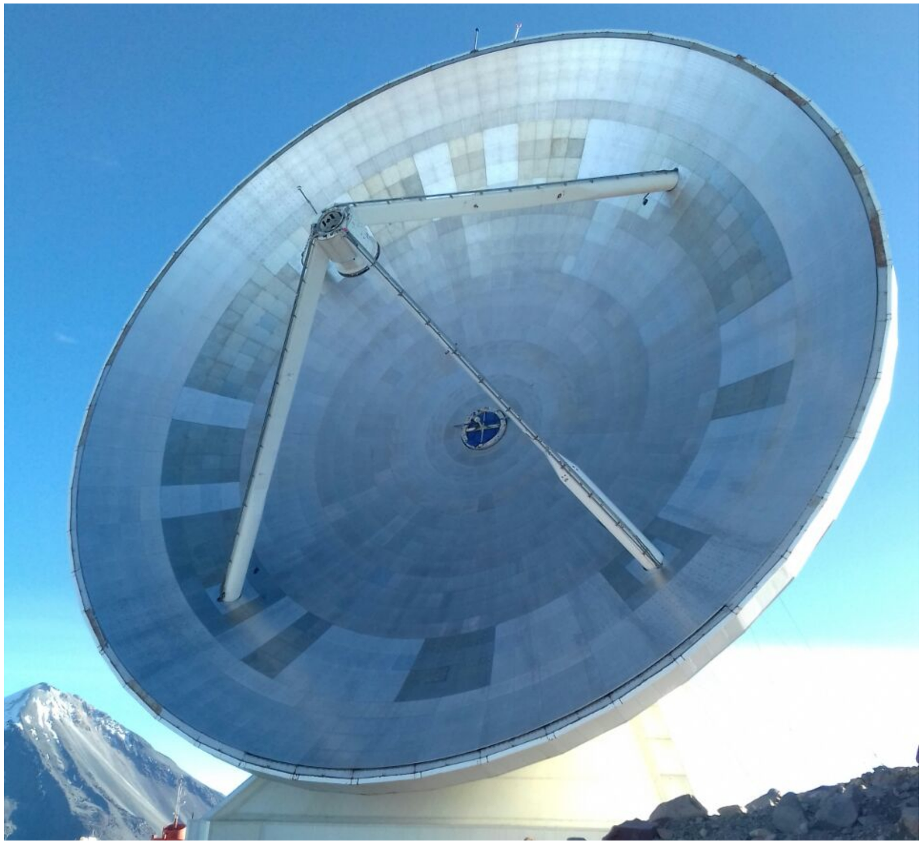




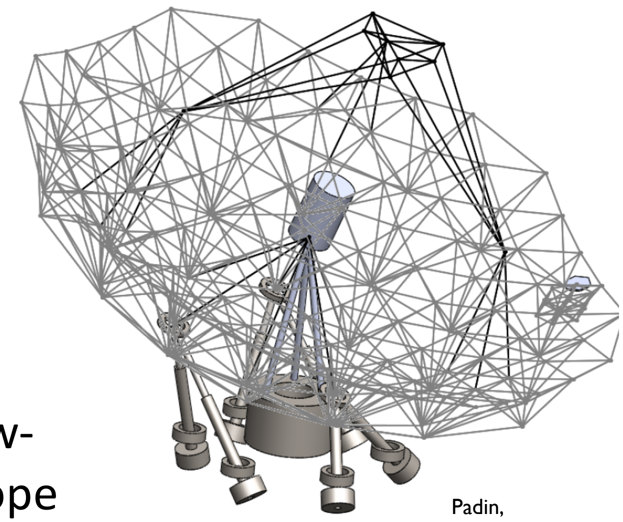


Hailey-Dunsheath et al, JLTP, in press

Ground-Based Science in the Age of ALMA



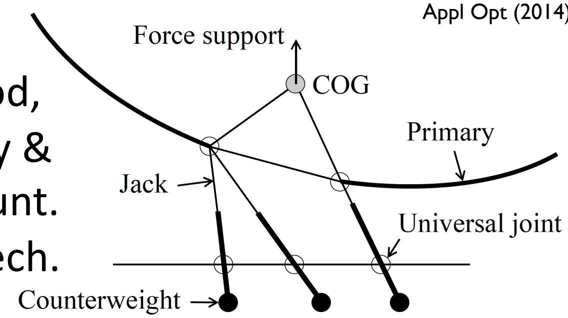
LMT / GTM on Cerro Negra, Mexico. Now fitted at 50 m!



CSST concept: low-cost 30-m telescope for Atacama.

Supported by hexapod, not traditional (heavy & expensive) Az/El mount.

Golwala lead @ Caltech.

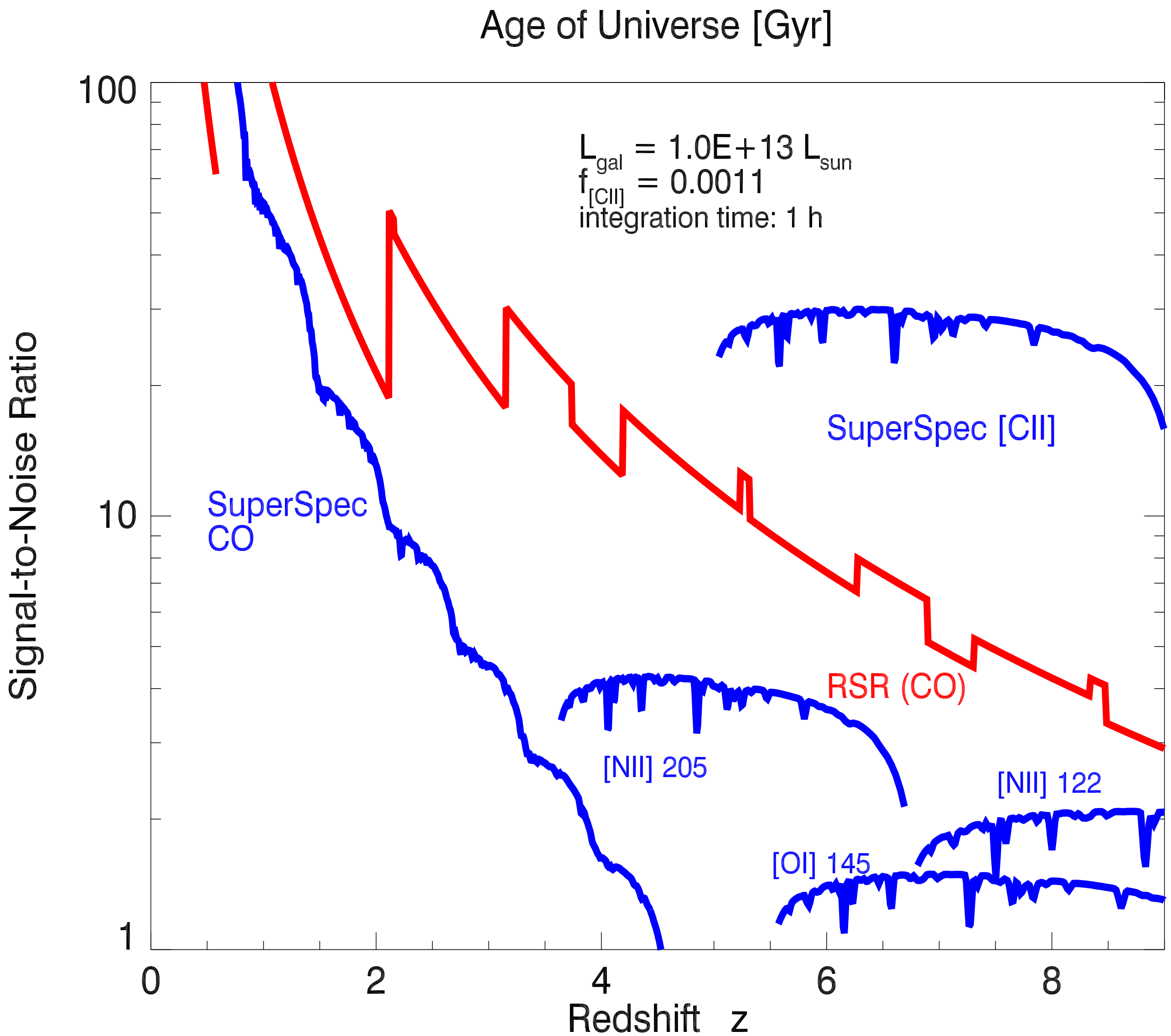


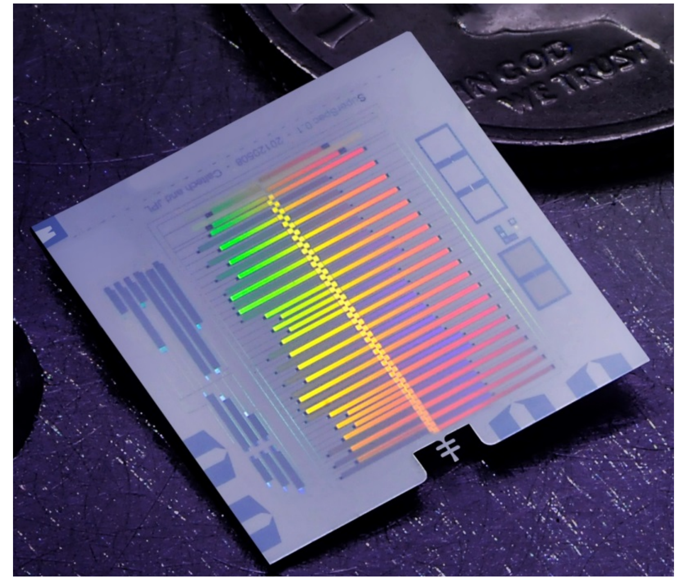
ALMA very sensitive but not well-suited to:

1. Surveys of many (meaning thousands) of galaxies, particularly when redshifts are not known. This can be addressed with a multi-object spectrometer (MOS) using a number of wideband backends with steered feeds on a large telescope.
2. Detection of diffuse glow from unresolved sources, e.g. from the Epoch of Reionization. This can be addressed through tomography with an camera composed of many wideband spectrometer 'pixels.'

Both require a compact, array-able wideband direct-detection spectrometer.

Ground-Based Science in the Age of ALMA





- Superspec on-chip spectrometer: 300 channels covering 1 mm window. Few square cm in size.
- Tomography for CII & CO
- Multi-object spectrometer which can be faster than ALMS for galaxy spectral surveys.
- First step is demonstration on Large Millimeter Telescope (LMT) in late 2018.

Wheeler et al., JLTP
McGeehan et al, JLTP

Far-IR Detectors for Space-Borne Astrophysics

Essential, and must be built by scientists

Long-term far-IR detector Requirements

- Per-pixel sensitivity below 3×10^{-20} W Hz$^{-1/2}$ for spectroscopy (targeting 1×10^{-19} for this work).
- Readout / system scheme enabling 10^5 to 10^6 total pixels in a large observatory.
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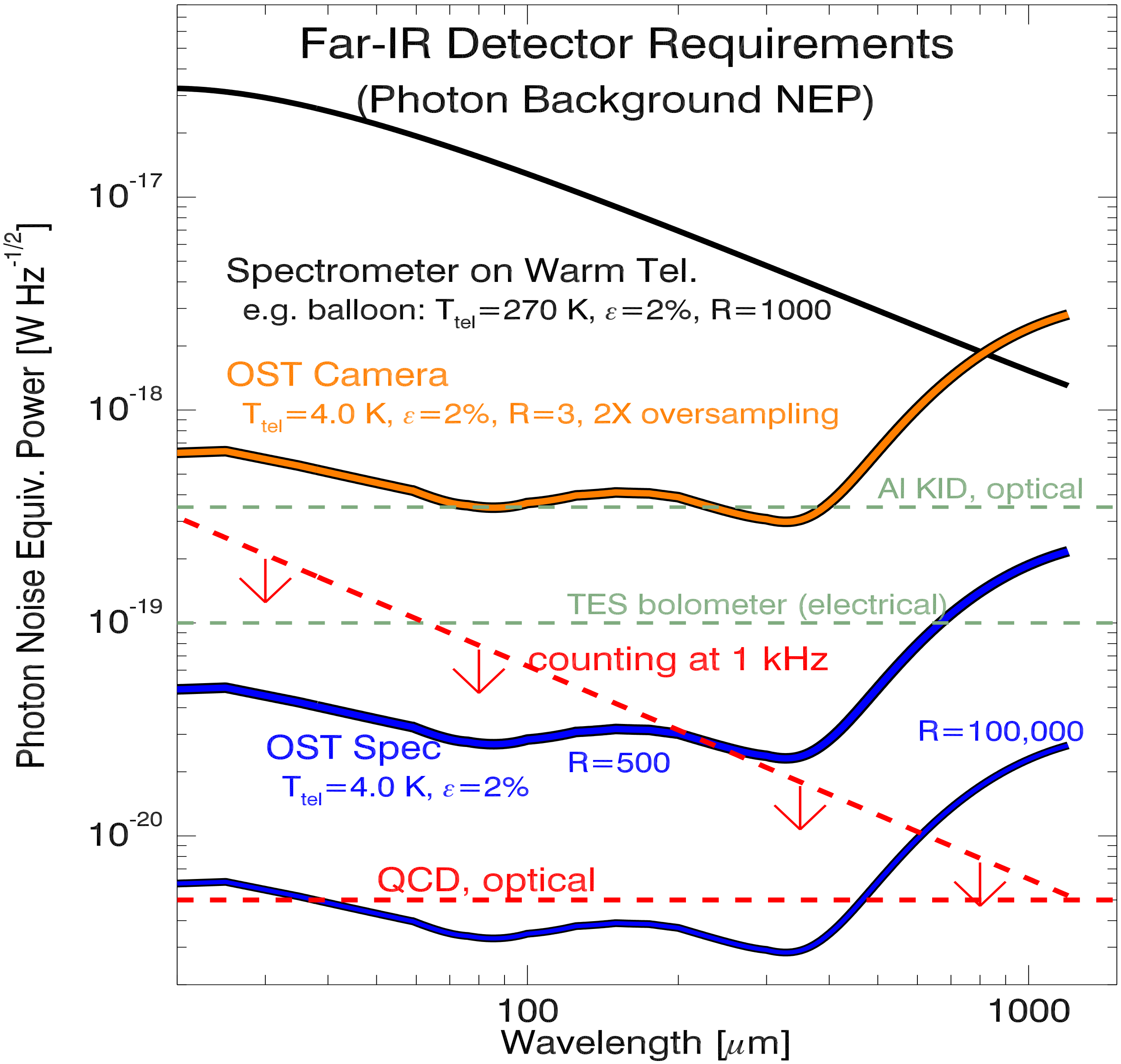
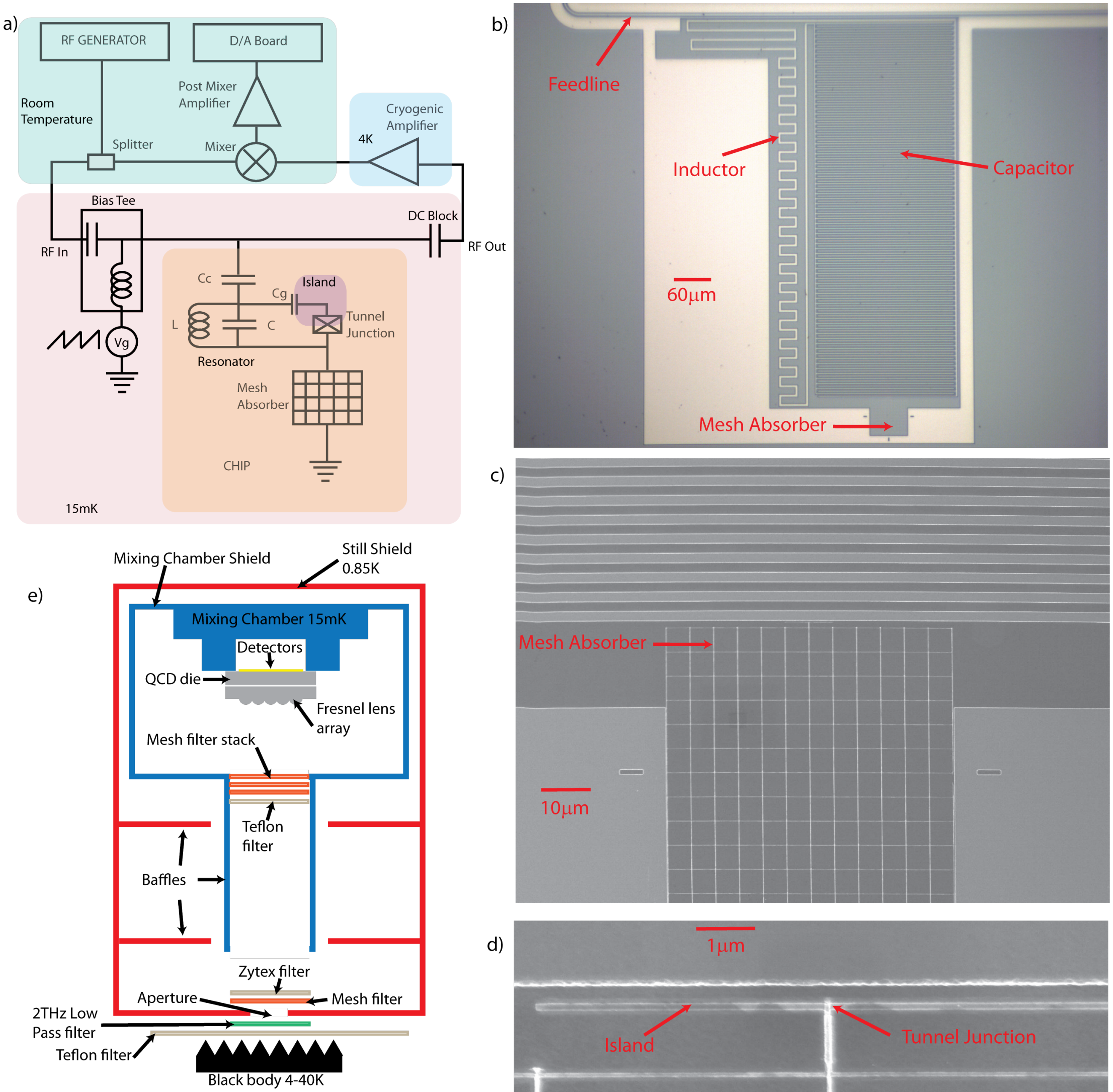
No other market for this technology -> NASA astrophysics + Euro & Japanese agencies must develop.



Quantum Capacitance Detector (QCD)

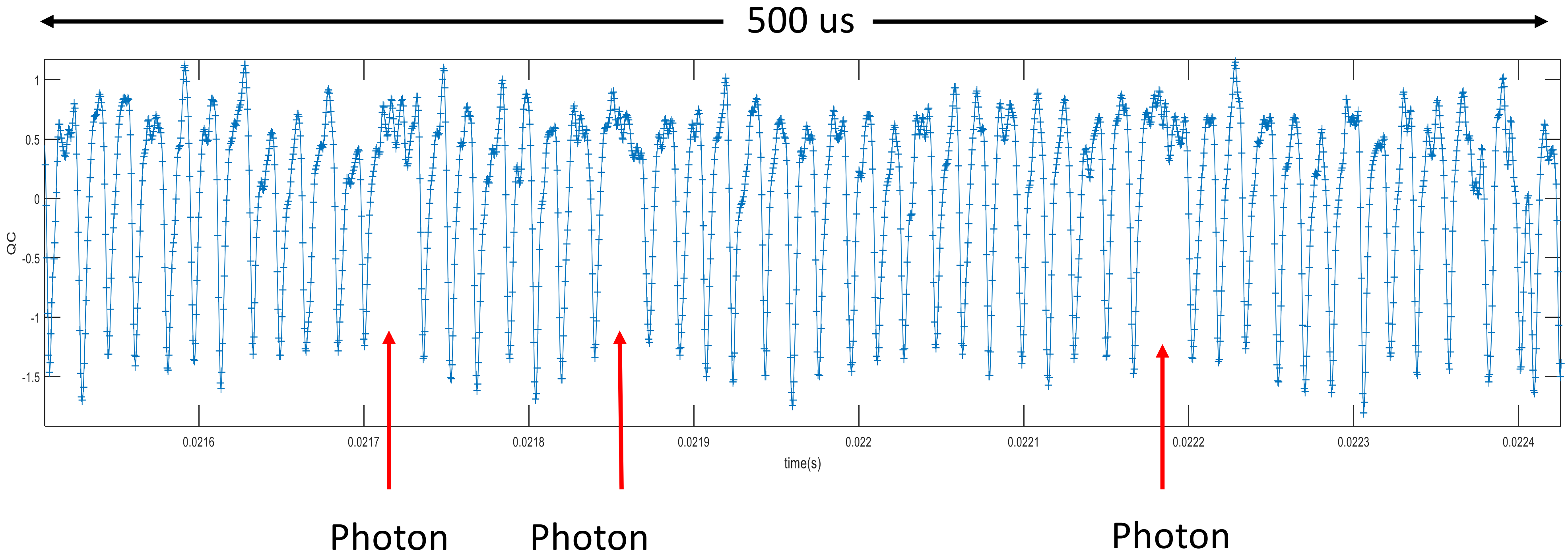
update on 200-micron devices



- Aluminum mesh absorber which is impedance matched to free space (like typical far-IR KIDs),
- But has a small volume: 1.6 microns^3. 60 microns extent (about lambda in silicon).
- (Illuminated through silicon micro-lens)
- Resonators operate around 3 GHz, each is ~700 x 300 microns in size: 0.2 mm^2, but not optimized
- Area scales as f^-2, so to push down to ~1 GHz requires 1.9 mm^2, but expect can do ~2x better with more efficiency design.

- Pierre Echternach et al.

Counting Far-IR Photons with the QCD

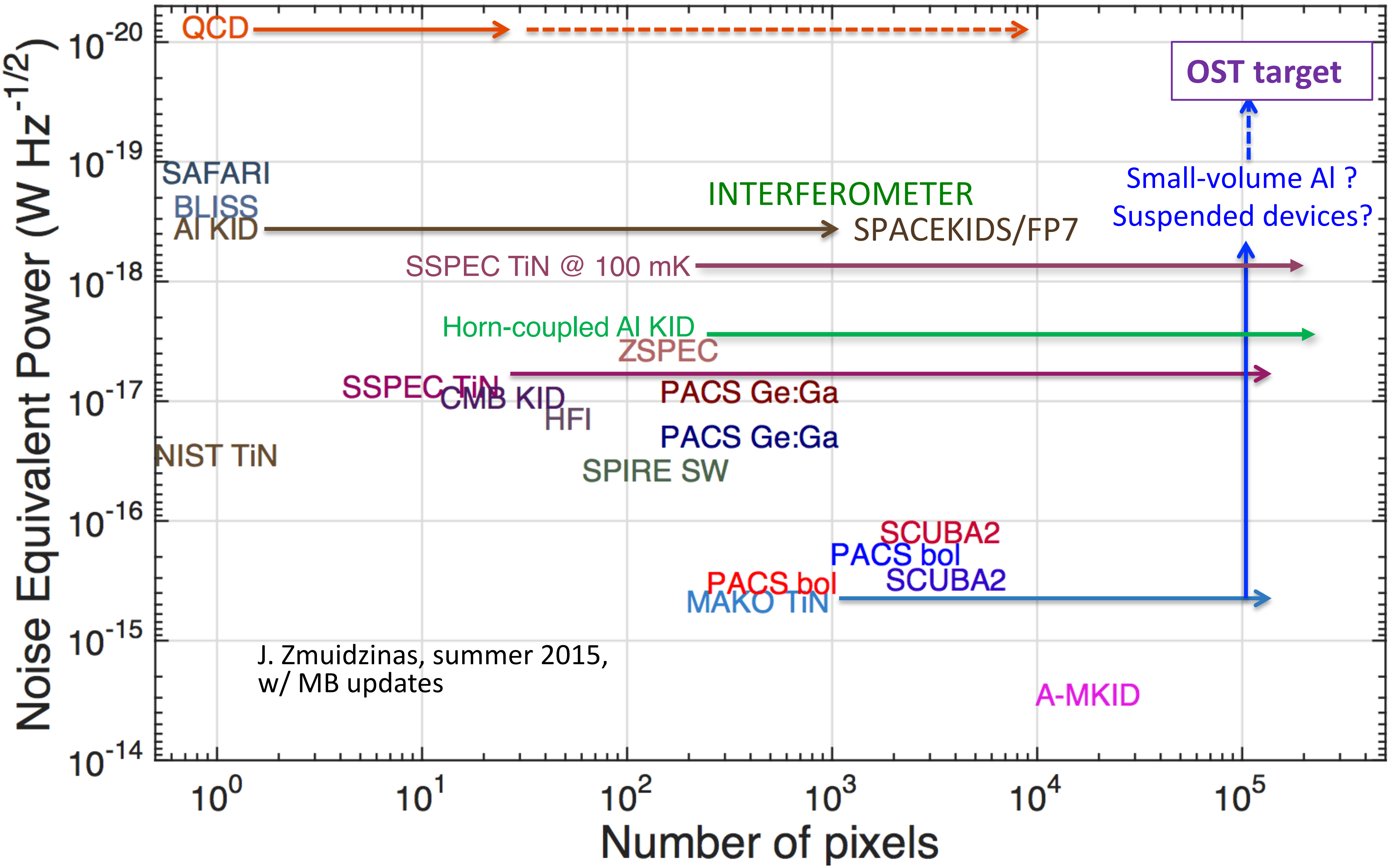


- Sweep rate ~ 22kHz spanning 4 Quantum Capacitance Peaks => effective sweep rate ~ 88kHz
- Should block background tunneling while still allowing tunneling due to single photon absorption
- Raw QC time trace should be absolutely periodic
- Gaps are due to high tunneling suppressing the Quantum Capacitance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

Echternach et al., Nature Astronomy 2, 90-97 Nov 2017

Far-IR Detectors: Current State of the Art



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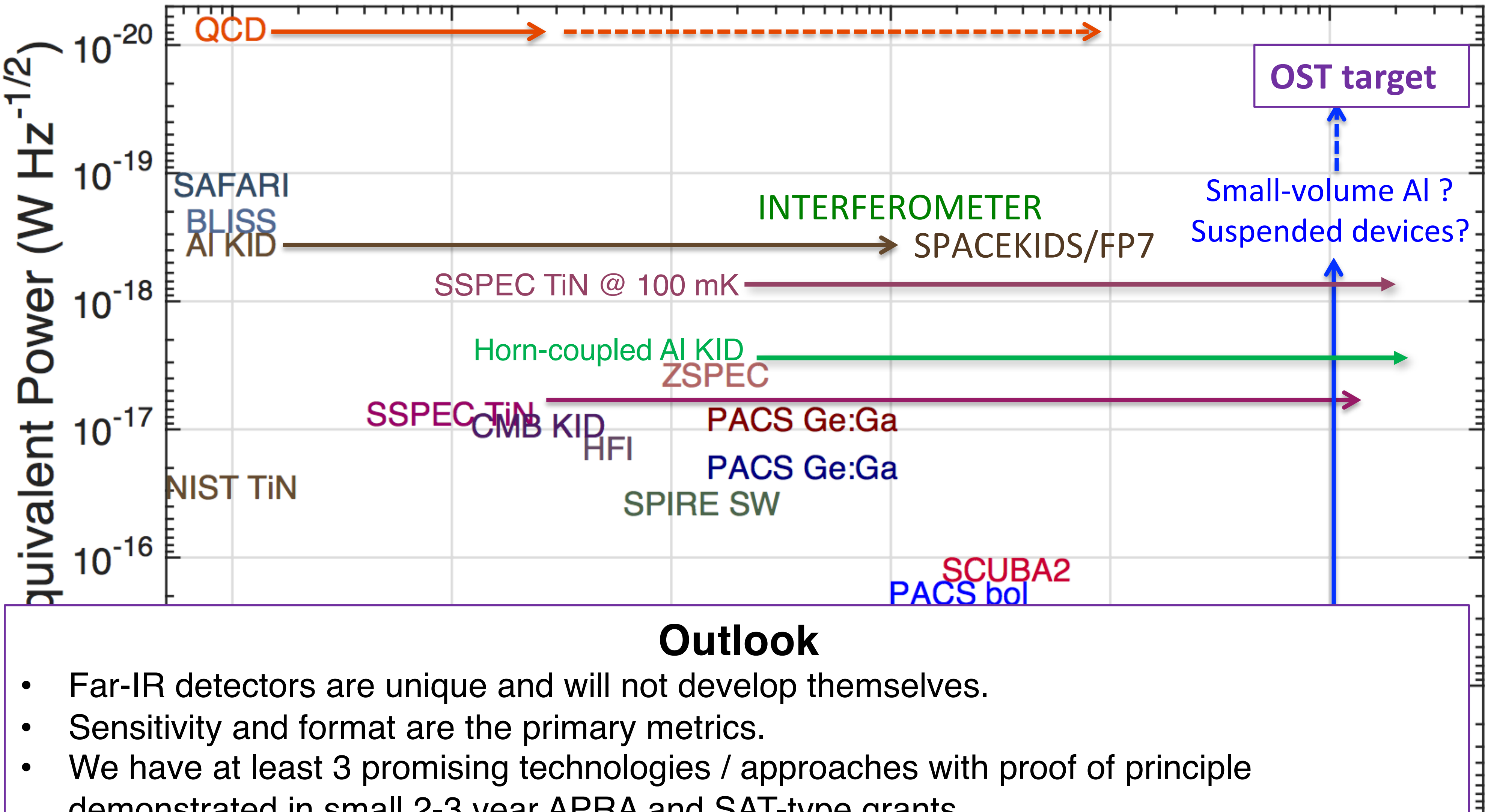

Outlook

- 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.
- **Sustained, directed development is required to reach sensitivity & format, and also maturity for OST and/or precursors / Probes.**
  - **E.g. cosmic ray susceptibility.**

Thank you