A review of next-generation superconducting kinetic inductance technologies for single-photon detection and spectroscopy in the far-infrared and submillimeter range

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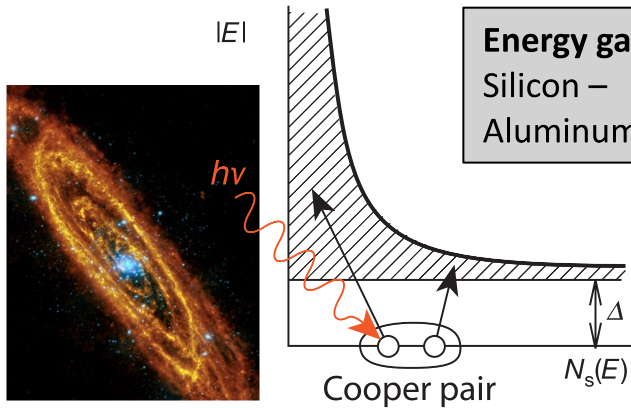
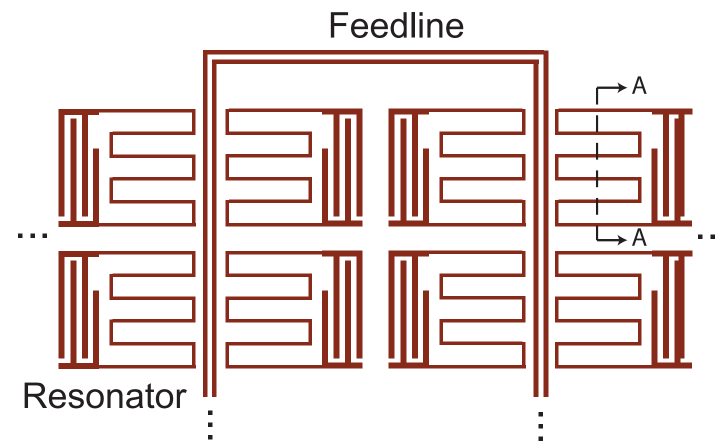
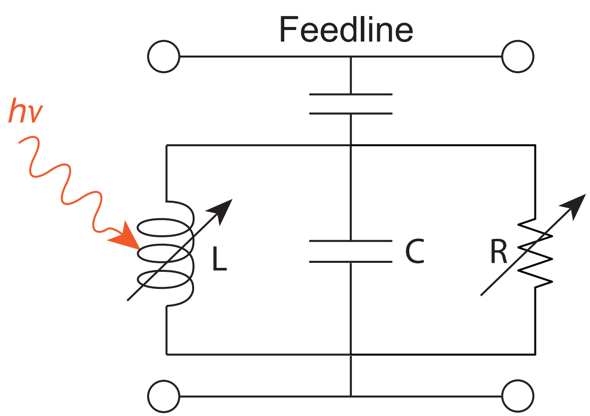
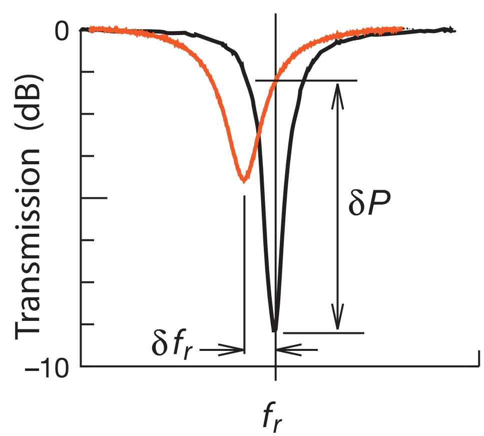
The Kinetic Inductance Detector (KID)

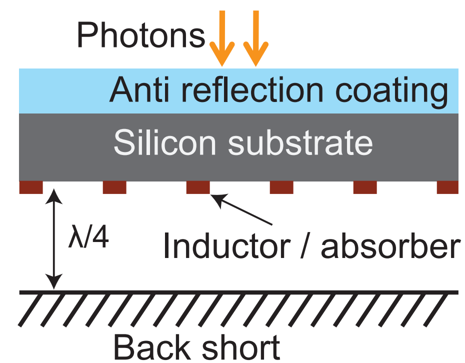


Energy gap:
Silicon – 1.10000 eV
Aluminum – 0.00018 eV





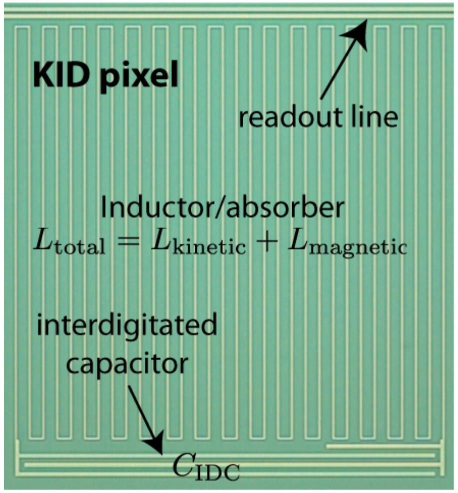


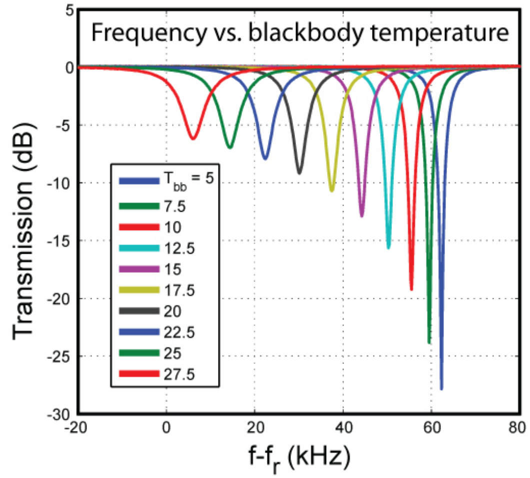


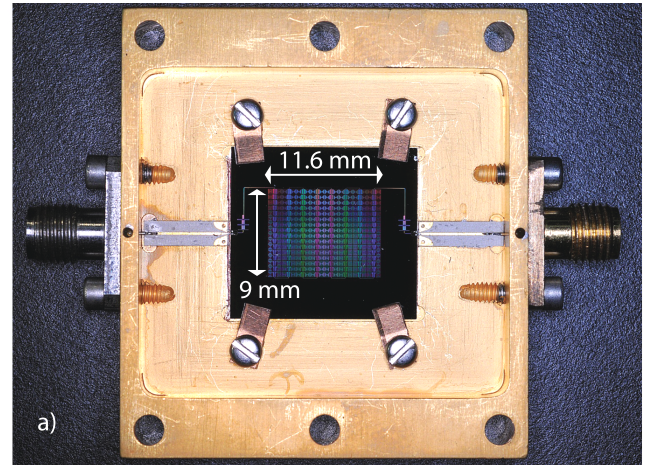
In superconductor: $L = L_m + L_{ki}(n_{qp}(h\nu))$

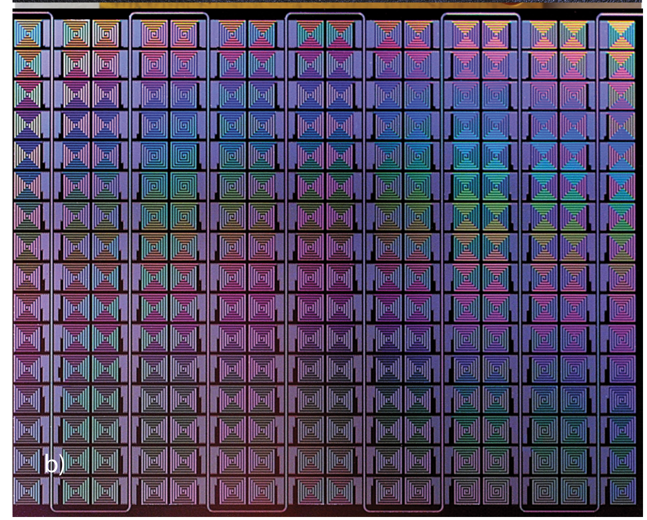
P. Day et al, *Nature* 425, 2003 (JPL, Caltech)
O. Noroozian, PhD thesis, 2012 (Caltech)

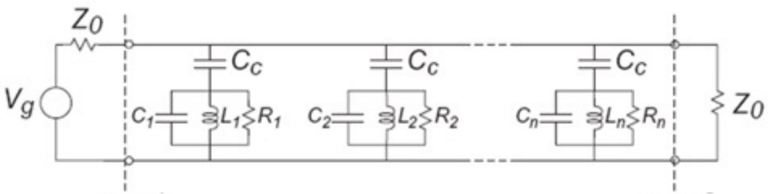
KID multiplexing and readout is a big advantage

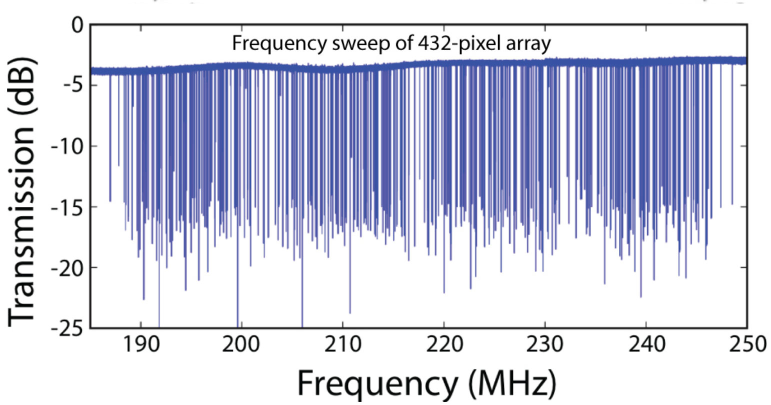


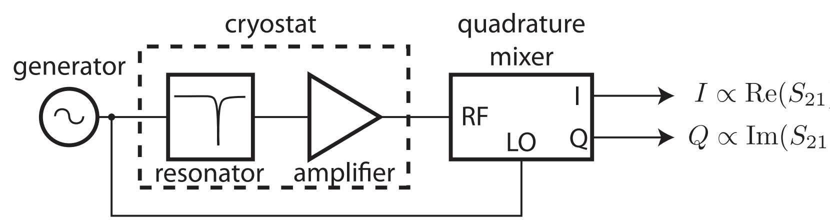






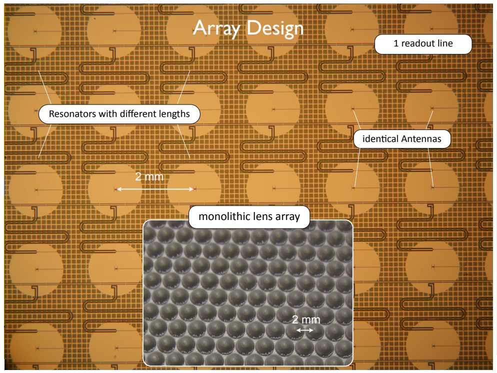


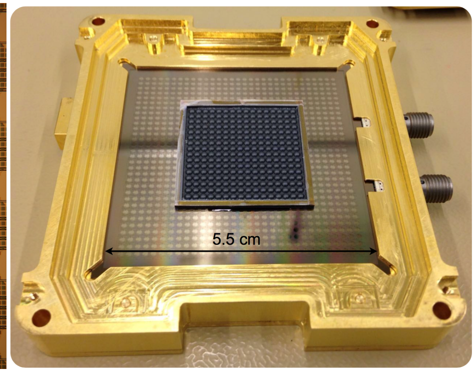


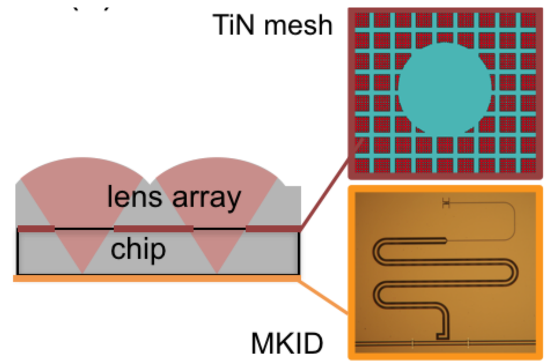


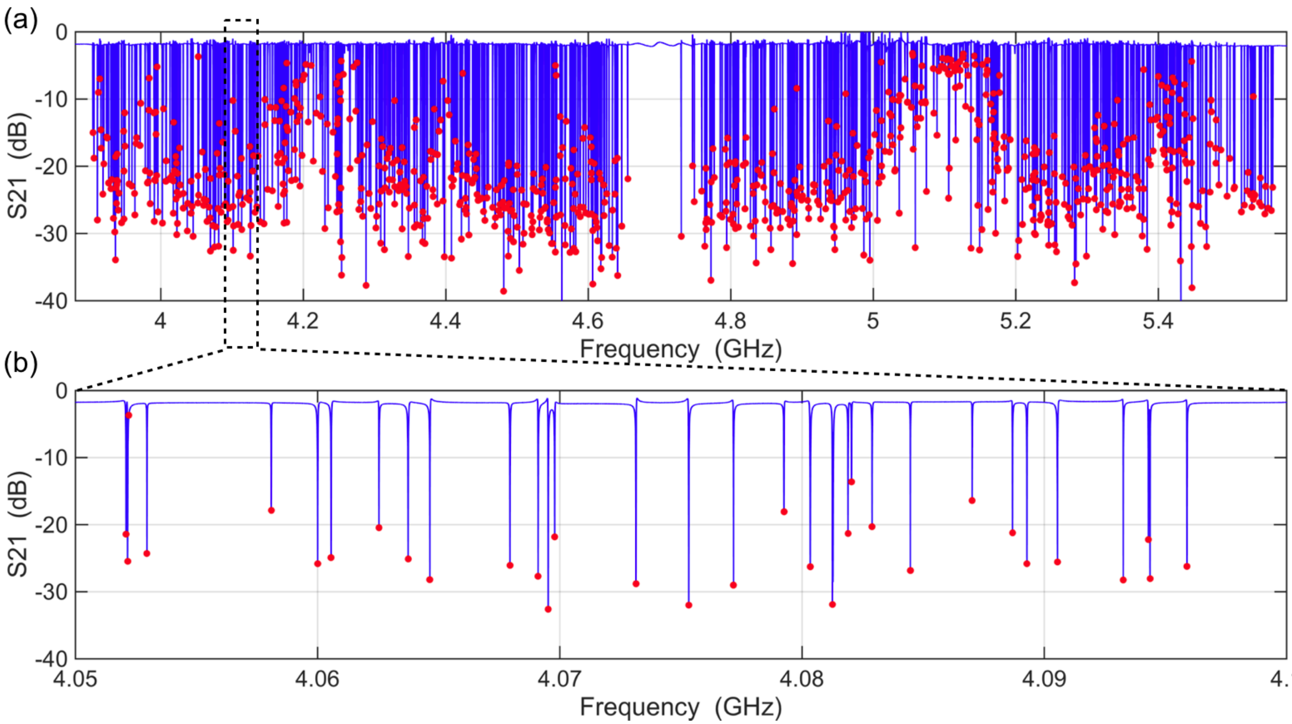
O. Noroozian et al., IEEE MTT **60** (2012)
L. Swenson et al., Proc. SPIE 8452, (2012)

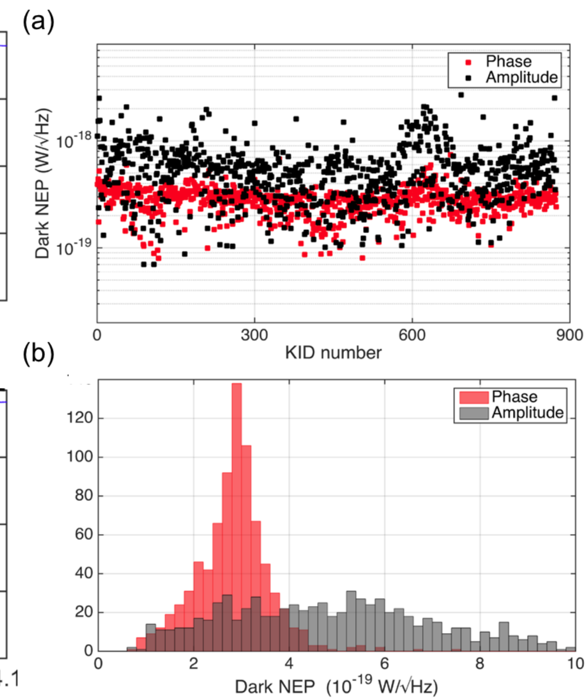
Multiplexed Readout of ~1000/GHz KIDs at SRON for the European 'Space KIDs' project





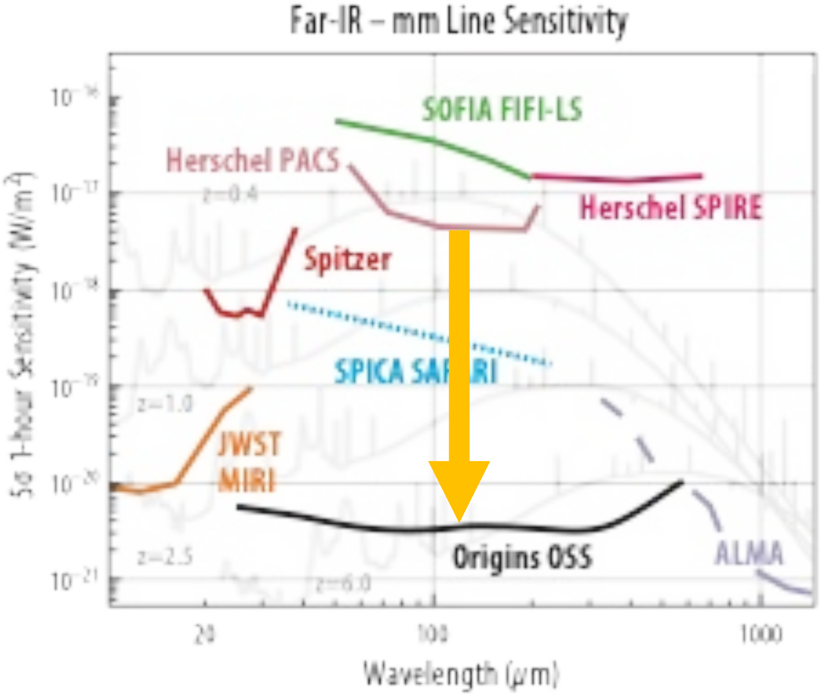






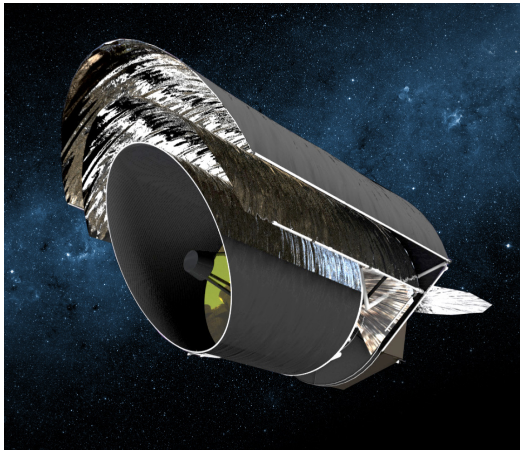
J. Baselmans et al., A&A 601, A89 (2017)

Increased sensitivity of future far-IR space telescopes



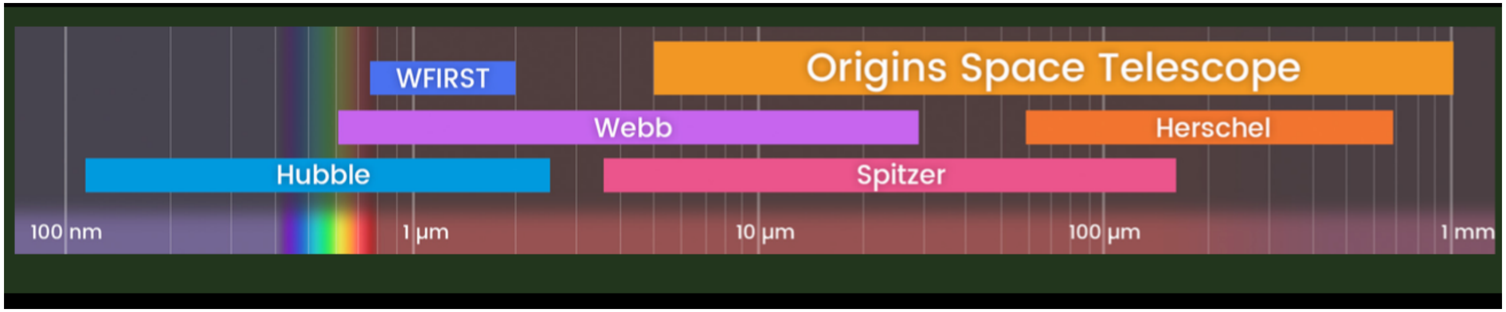
Origins Space Telescope Mission Concept Study - final report
https://asd.gsfc.nasa.gov/firs/docs/OriginsVolume1MissionConceptStudyReport_11Oct2019.pdf

NASA's Origins Space Telescope (OST)

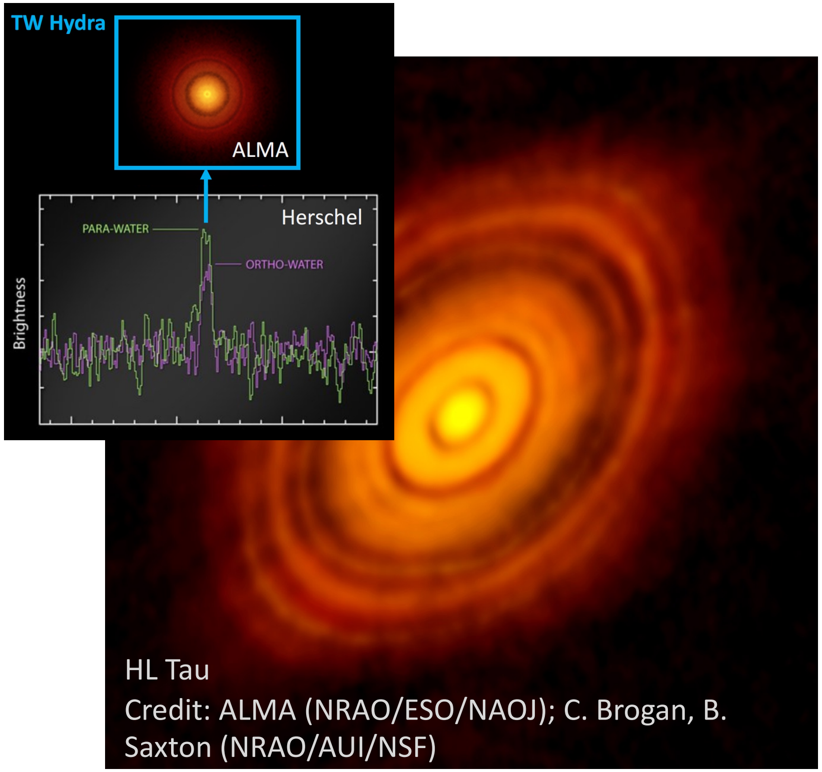


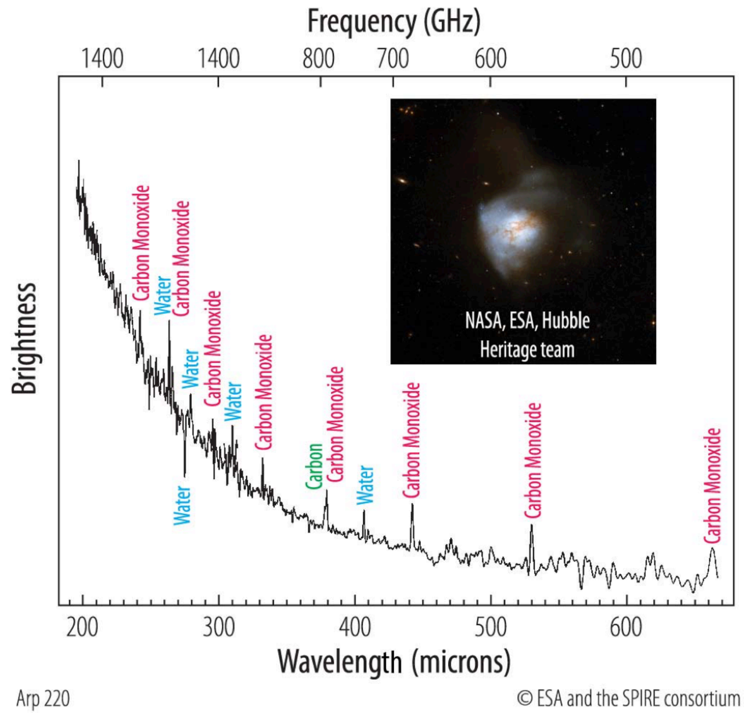
OST vs Herschel:

Massive gain in sensitivity from:
a) colder 4K telescope optics
b) larger aperture



Two science case studies enabled with ultrasensitive detectors on the Origins Space Telescope





- Protoplanetary disk evolution and search for life
- Formation of habitable planets

Technique: Mapping water, ice and molecular lines from key volatiles (e.g. NH_3) in protoplanetary disks

- Evolution of galaxies over cosmic time
- Growth of structure in the universe

Technique: Observing fine structure lines of high-z galaxies

Challenges for future submm/far-IR space detectors

Requirements:

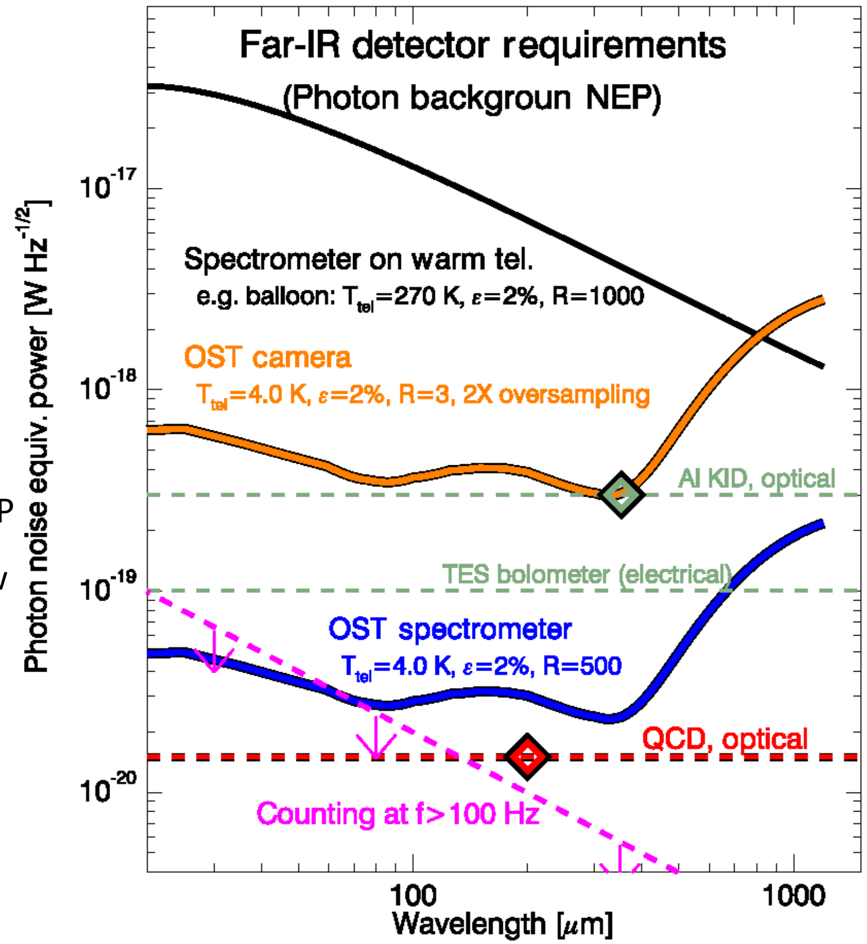
- Very low NEP of ~ 10^{-20} W/Hz$^{1/2}$ ***or*** <u>photon-counting</u>
- Large format arrays of ~ 10^4-10^6 pixels

Photon counting vs total power detection:

- Photon counting is not sensitive to 1/f drifts in telescope electronics, temperature, etc.
- No need to measure a calibrator (2x) and no need to subtract 1/f noise from signal (another 2x) → ~ 4x increase in observation speed
- Performance limited by "dark counts" rather than classical NEP
- Dark counts can fundamentally be close to zero for KIDs at low temperature (<100 mK)

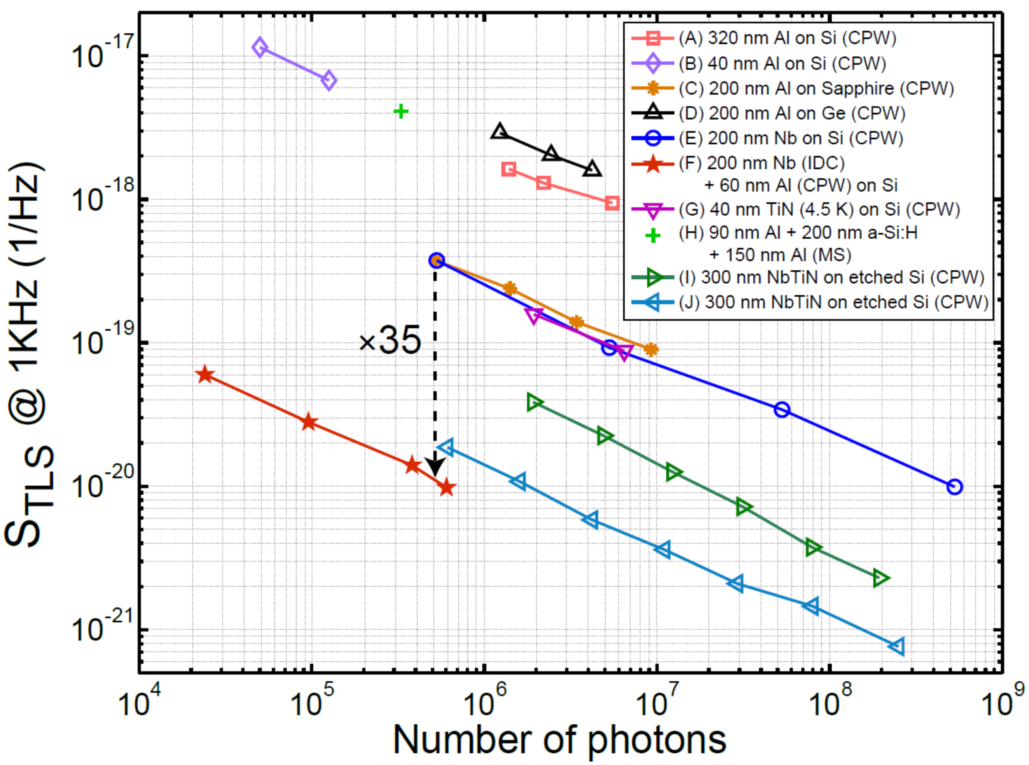
Challenges for KIDs:

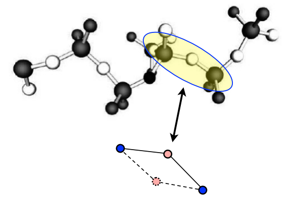
- >10x improvement in KID state of the art noise still needed
- Development of "cleaner" nano-fab techniques for ultra-pure thin films and substrates is crucial
- Extremely dark test environments for device characterization

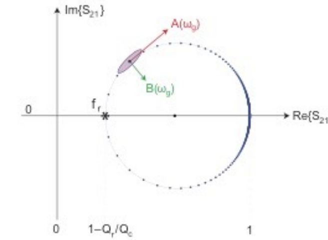


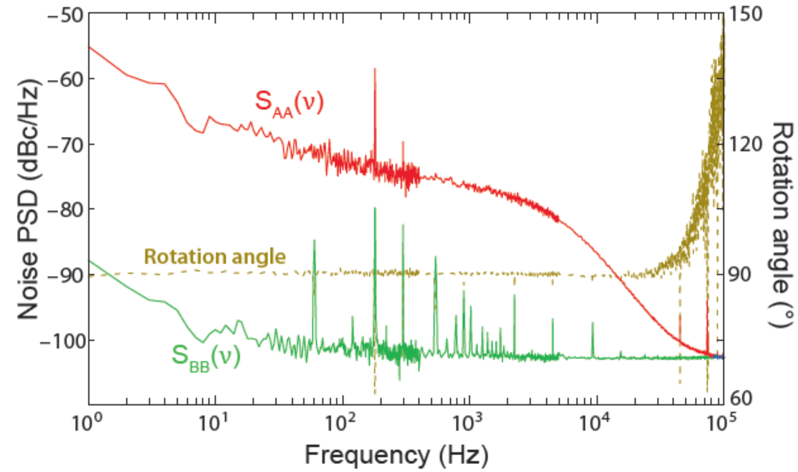
D. Farrah et al., arXiv:1709.02389
Review: Far-Infrared Instrumentation and Technology Development for the Next Decade

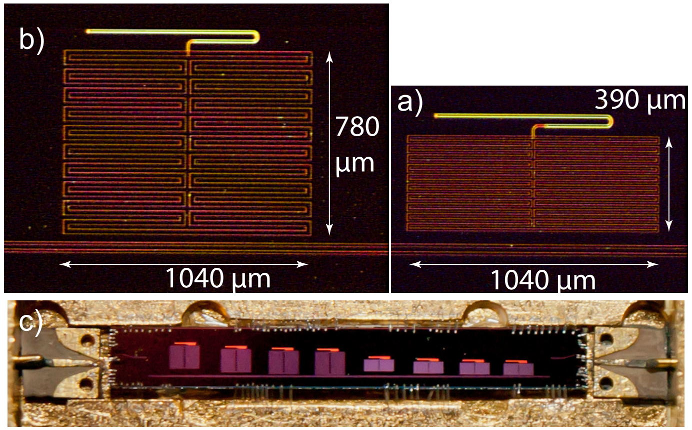
Reduced frequency noise in modern MKID resonators











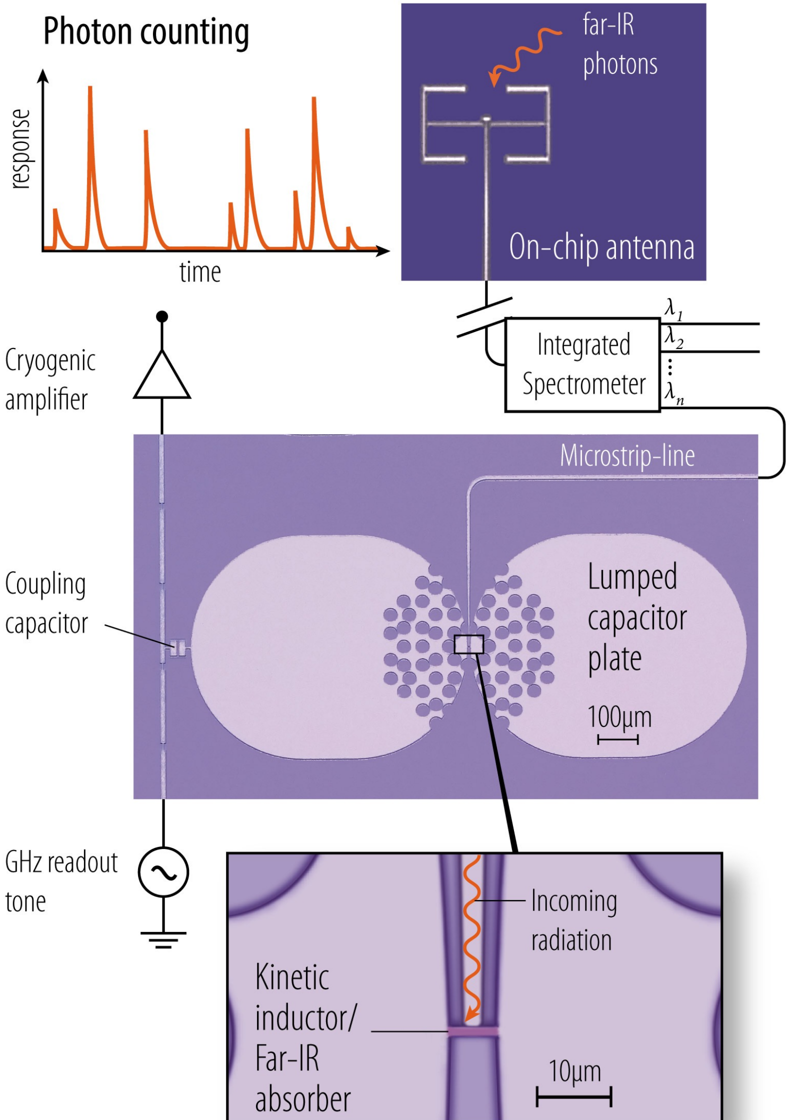
- Amorphous oxides/defects/dielectrics on resonator surfaces and interfaces contain “two-level system” defect states that tunnel randomly and create fluctuations in the dielectric constant. → Frequency noise

- Frequency noise originates mainly in capacitive parts (E-field areas)

- A **parallel-plate capacitor** with crystalline dielectric and clean interfaces will have significantly reduced TLS noise -> Microstrip-based resonators made using SOI wafer technology are a good candidate

O. Noroozian et al., *AIP conf. proc.* **1185**, 148, 2009
https://doi.org/10.1063/1.3292302
J. Zmuidzinas, *Annu. Rev. Condens. Matter Phys.*, **3**, 169, 2012
O. Noroozian, PhD thesis, 2012 (Caltech)

A single-photon counting KID design for submm/far-IR space spectroscopy



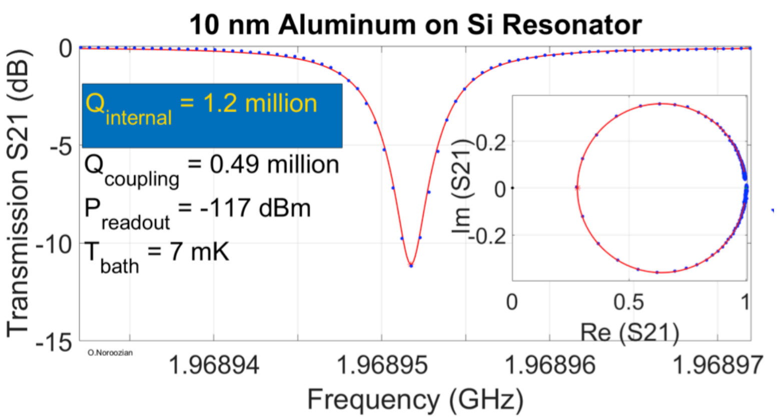
- Assuming spectrometer in space with R = 1000, background photon rate is expected $10^2 – 10^4$ photons/sec, so suitable for photon counting

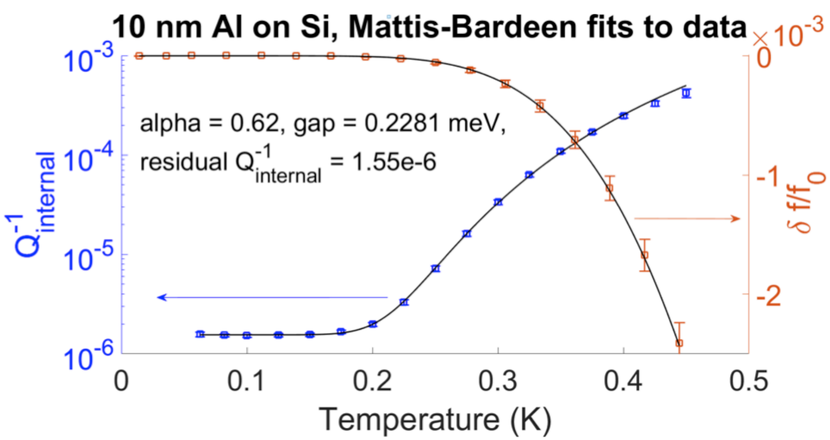
Our KID design and benefits:

- **Ultra-small volume** aluminum kinetic inductor for increased response to single photons
- **SOI wafer** (currently **0.45 µm** Si substrate)
- **Parallel-plate capacitor** on single-crystal Si for integration with spectrometer (µ-Spec) and reduced TLS frequency noise
- Choke filter for confinement of submm radiation inside sensitive inductor
- **All-microstripline** elements and no cuts in ground plane -> Immunity to stray radiation

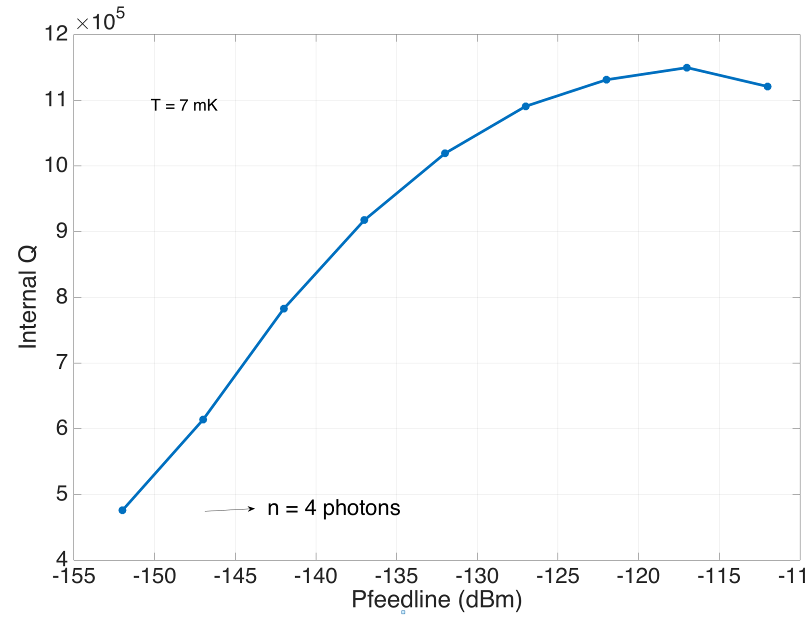
O.Noroozian (PI), Photon-counting KIDs for the Origins Space Telescope, NASA ROSES APRA

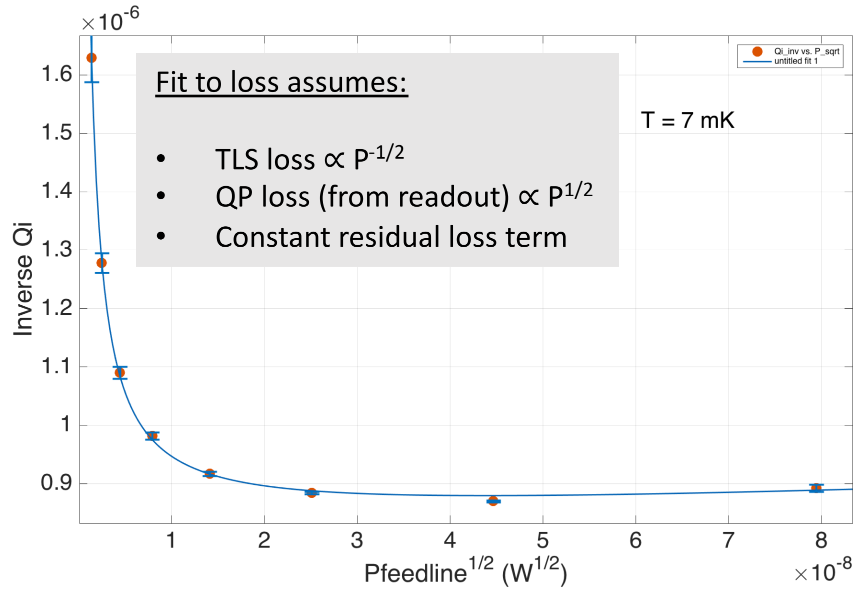
Thin aluminum films for ultrasensitive KID resonators





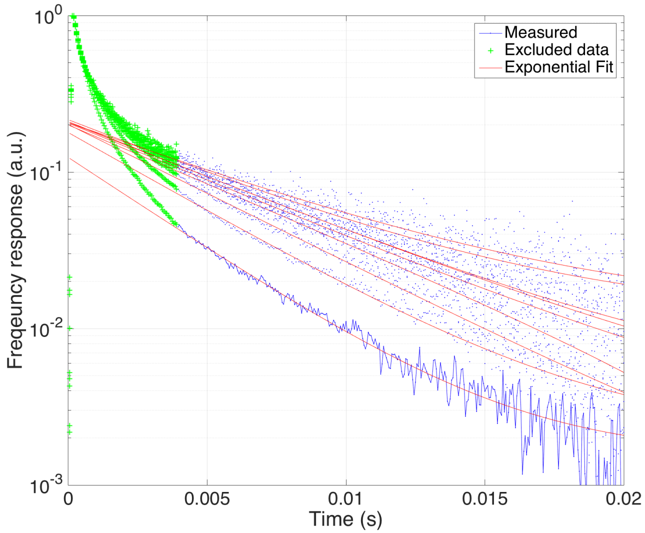
- Well-behaved material, follows BCS theory
- Reliable fabrication processes developed at GSFC
- High intrinsic material quality: Qi ~ 400,000 at n = 1 microwave readout photons
- Qi is limited by dielectric loss at low power (follows $P^{1/2}$ dependence)

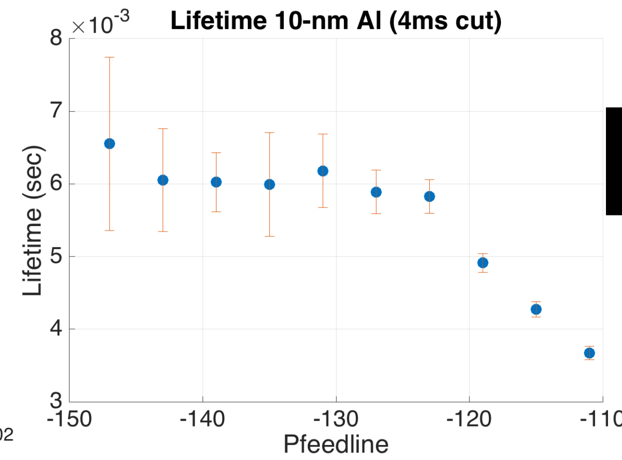


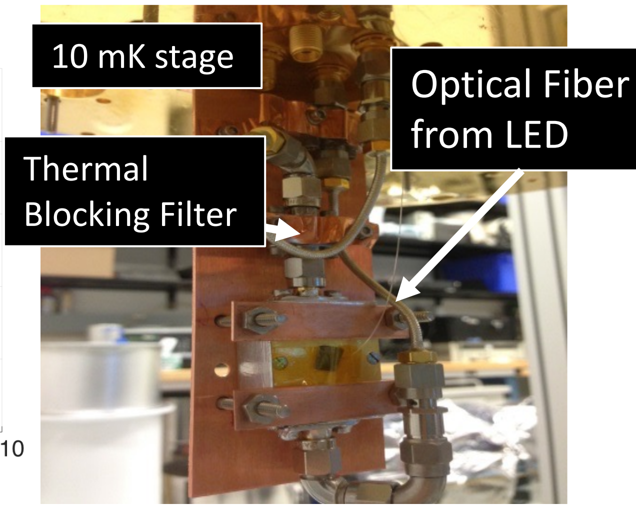


O.Noroozian (PI), Photon-counting KIDs for the Origins Space Telescope, NASA ROSES APRA

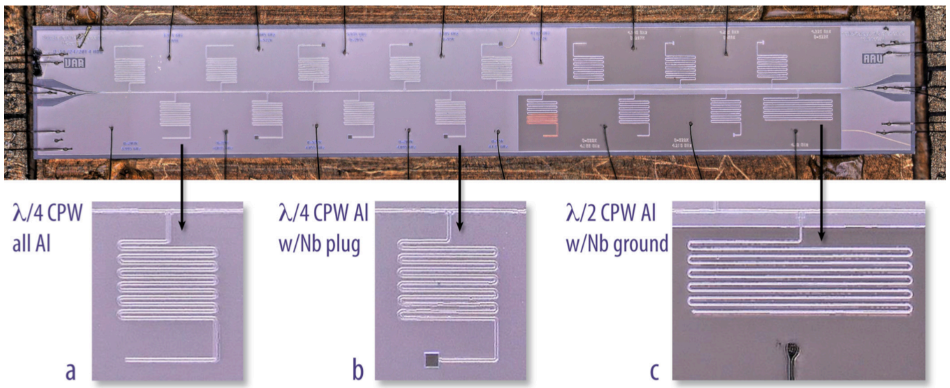
Very long quasi-particle lifetimes in Al





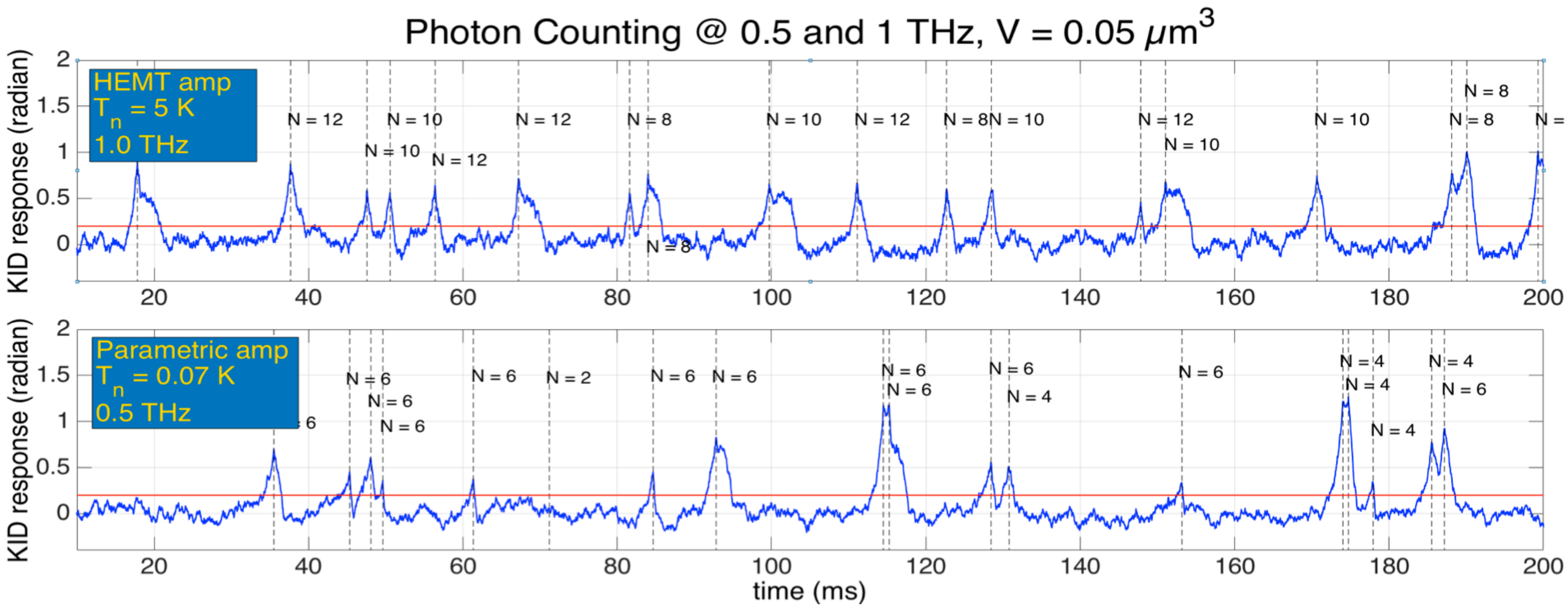


- Measured using fiber-coupled 660 nm LED pulsing at 7mK
- **Dark intrinsic Lifetime is very long > 6ms**
- Measurement limited by noise at tail end of pulse
- "Lifetime" keeps increasing over time as expected for very dark background
- On-set of decrease is caused by readout power QP generation
- Consistent with data from SRON



O.Noroozian (PI), Photon-counting KIDs for the Origins Space Telescope, NASA ROSES APRA

Simulation of photon counting at 0.5 -1.0 THz with a 10-nm aluminum KID on SOI



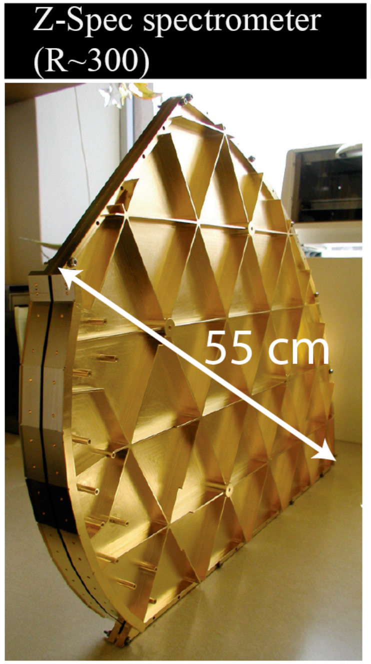
- Dark counts are only caused by white amplifier noise at a rate of 5 Hz. This corresponds to **NEP = 1-2 x 10^{-21} W/rt Hz in the 0.5-1 THz range** .
- Integrated over the signal bandwidth, TLS noise is sub-dominant to amplifier white noise, because internal Q is low during pulse. ✓
- Recombination time and ring time are fast compared to photon arrival rate. Pulses decay with tau ~ 1.7 ms. ✓
- **Counting photons with > 95% efficiency!**

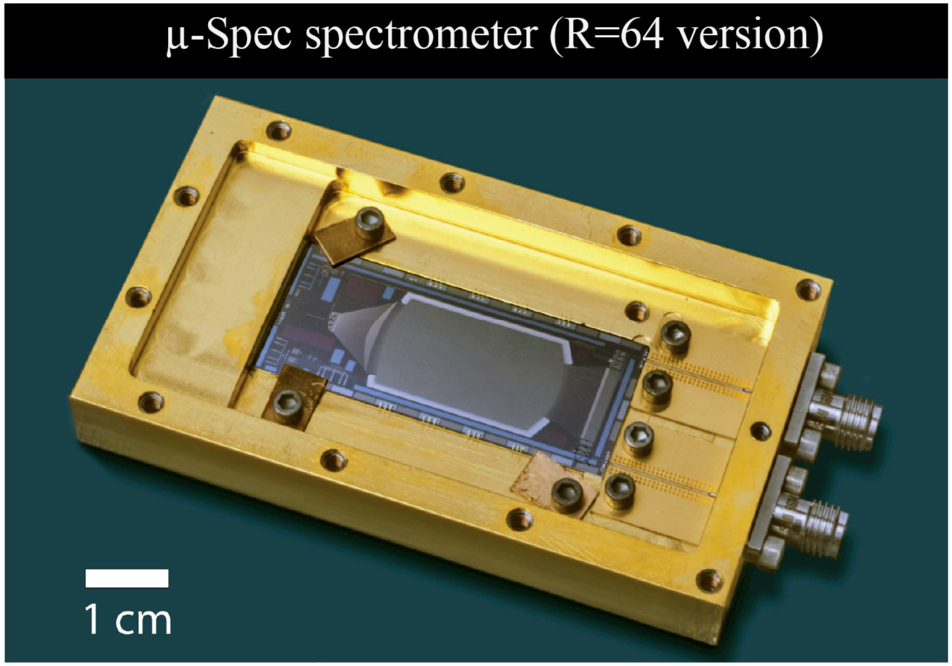
Assumptions:

photon rate = 100/s, spectrometer resolution = 1000, optical coupling efficiency = 25%, 4K telescope (conditions for high-Z galaxy case)
detector volume = 0.05 μm^3, bath temperature = 100 mK, readout power = -137 and -156 dBm
Material properties take from our films measured at GSFC.

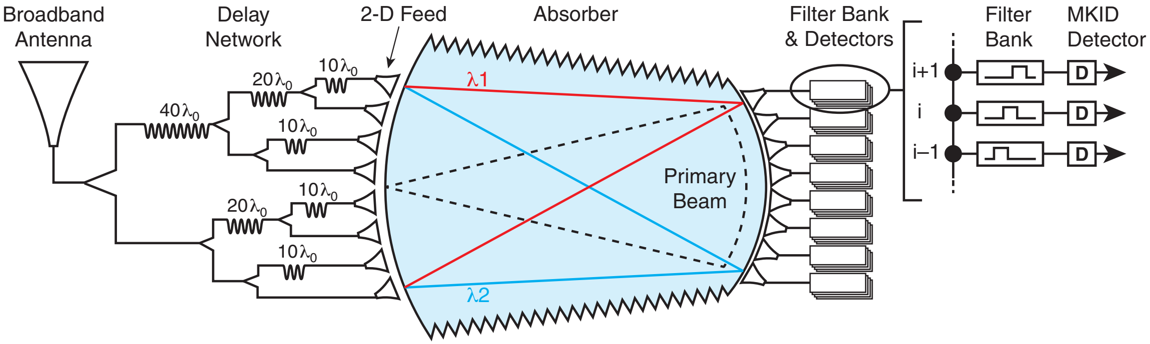
O.Noroozian (PI), Photon-counting KIDs for the Origins Space Telescope, NASA ROSES APRA

µ-Spec: an integrated spectrometer for submm/THz space spectroscopy (NASA GSFC)





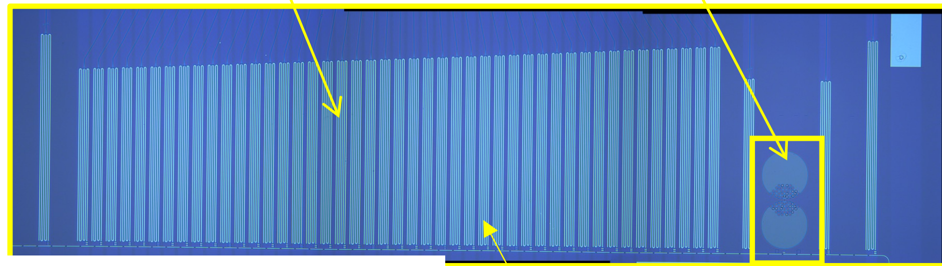
Orders of magnitude reduction in the mass and volume of our spectrometer are achieved by using ***superconducting microstrip transmission lines*** with ***low-loss single-crystal silicon dielectric*** substrates (0.45 µm thick).

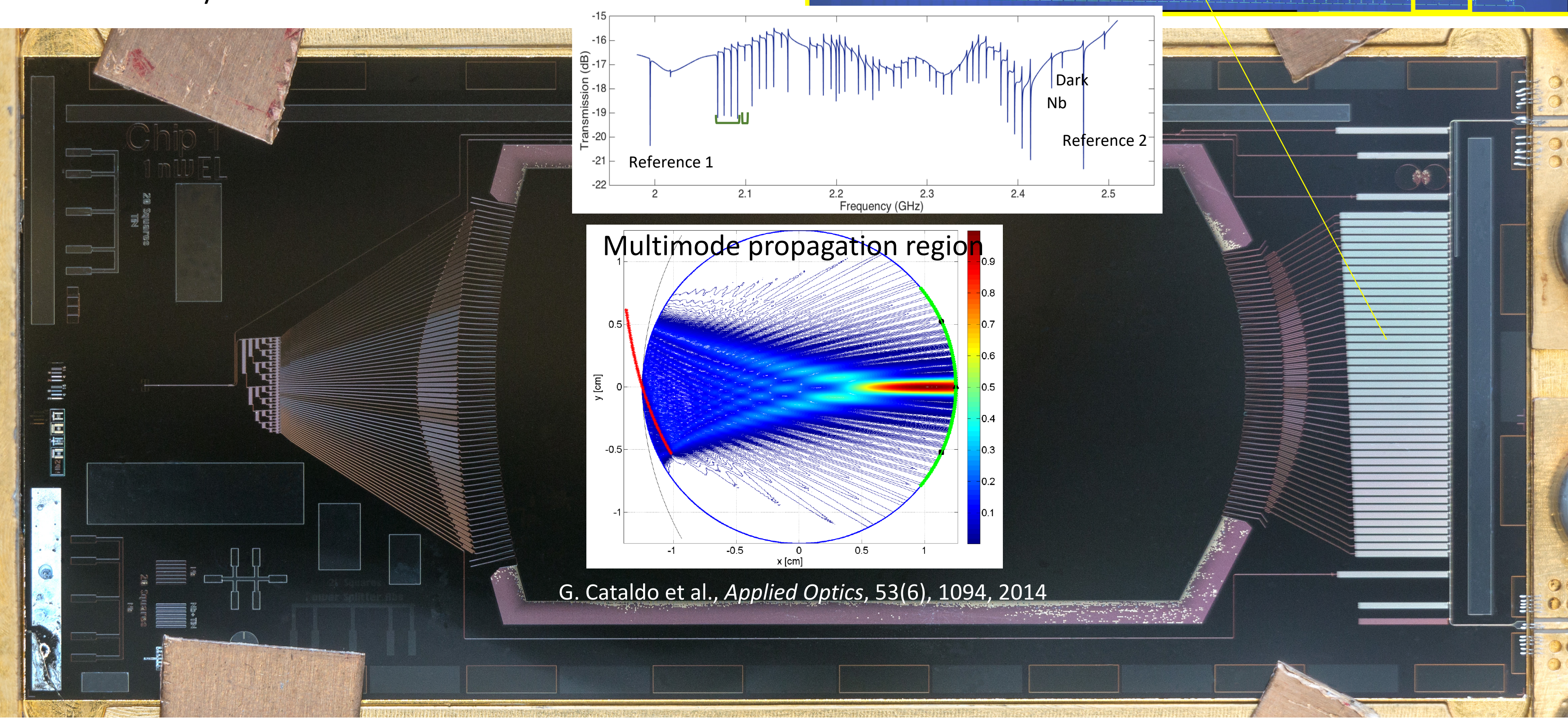


O. Noroozian et al.," 26th ISSTT conference, 2015: https://www.nrao.edu/meetings/isstt/papers/2015/2015000018.pdf
E. Barrentine et al., SPIE Proc. **9914**, 2016: https://doi.org/10.1117/12.2234462

A 400-600 GHz prototype µ-Spec chip with an R=64

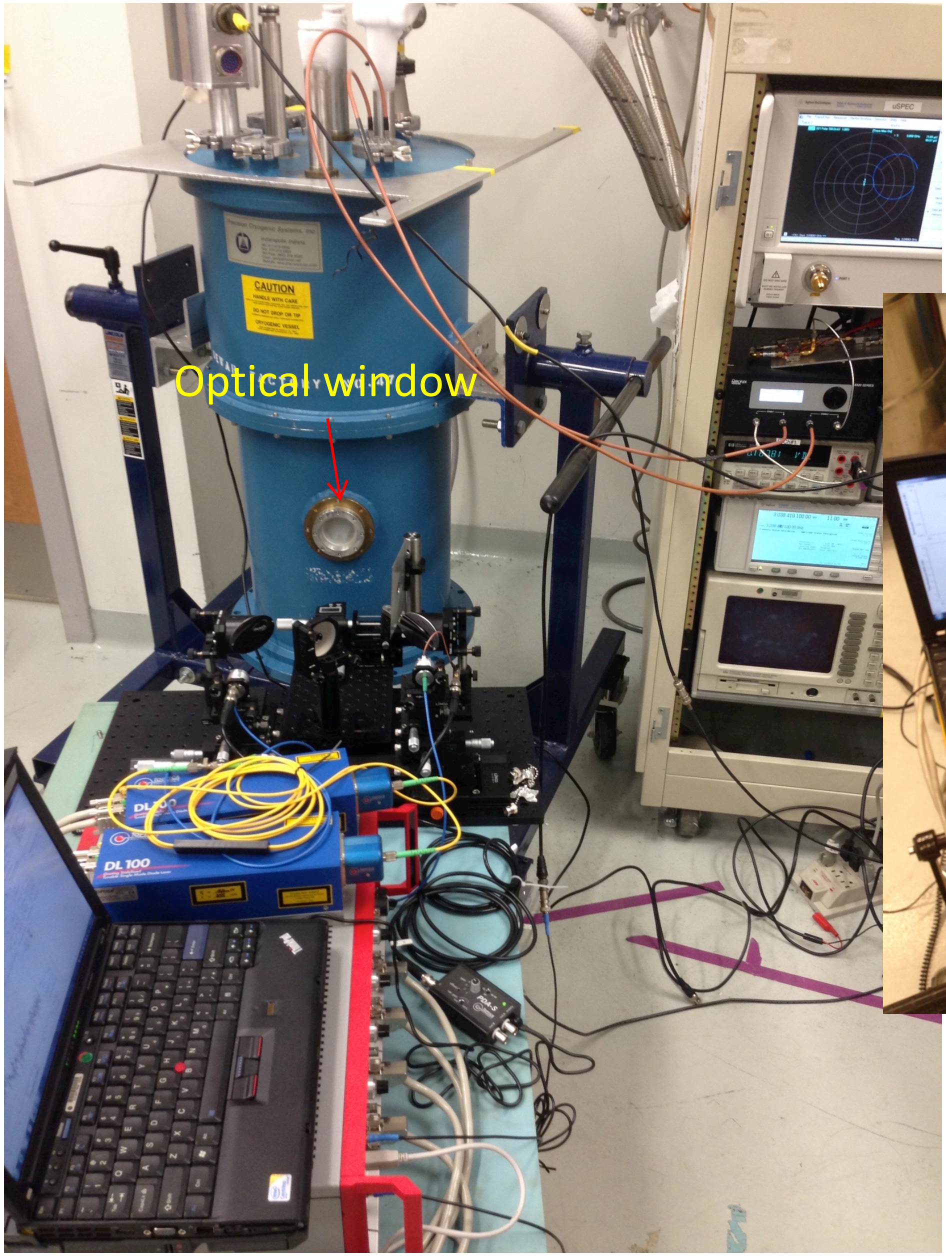
- µ-Spec is an analog of a grating spectrometer that uses an artificial grating (Rowland spectrometer).
- Phase delays in a tree of superconducting transmission lines are used to produce constructive and destructive interference in propagating waves, which focus light on diffraction-limited spots on a 2.5-D focal plane
- Photons go through order-sorting filters first and are then detected by ultra-sensitive KIDs



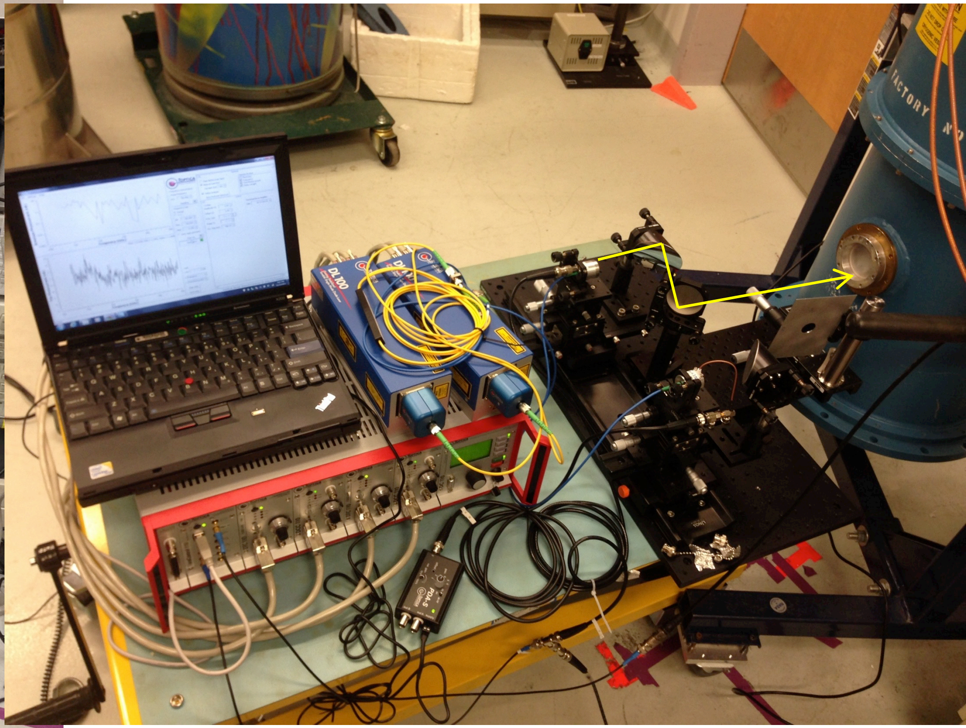


G. Cataldo et al., *Applied Optics*, 53(6), 1094, 2014

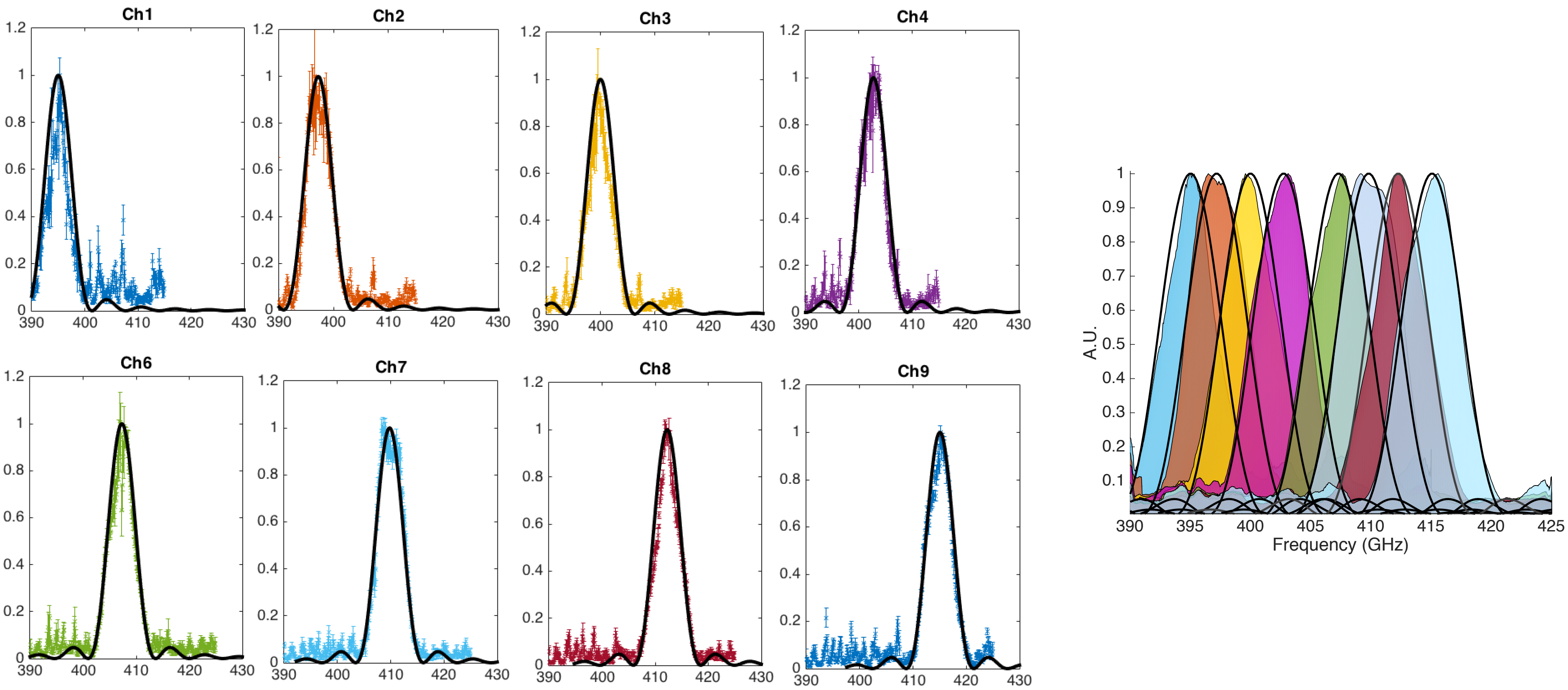
Optical measurement of µ-Spec channels



Tunable photomixer submillimeter source
100 GHz – 2 THz, chopped at 7.6 KHz



Measurement of a prototype μ-Spec designed for R = 64

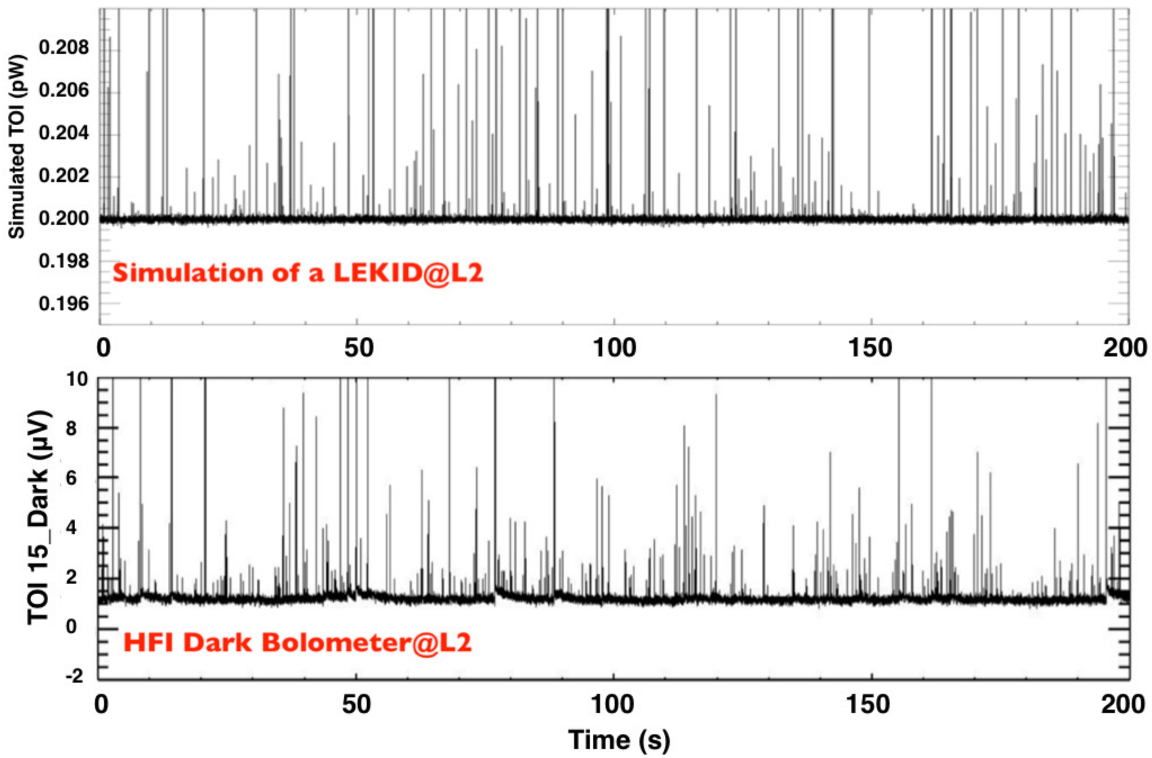


<u>Demonstrated results:</u>

- Sharp line profile of $(\sin x/x)^2$ (as opposed to Lorentzian in filterbank-based spectrometers)
- Resolution of R=64 achieved as designed
- Absolute frequency position within ±1 GHz as designed.

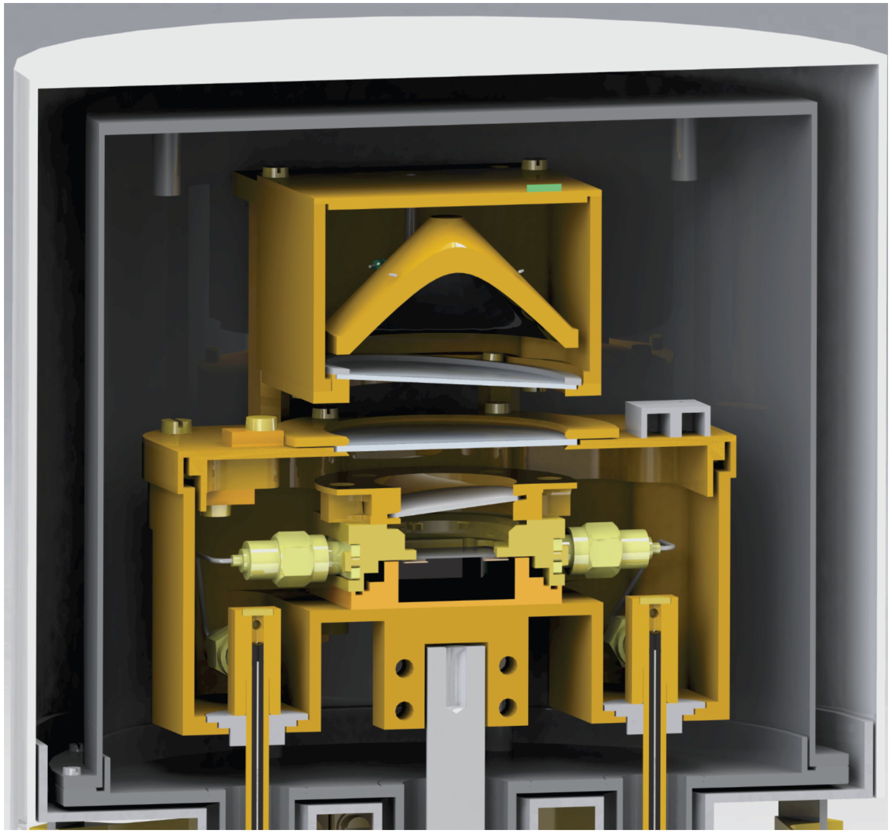
Insensitivity to cosmic radiation important in space

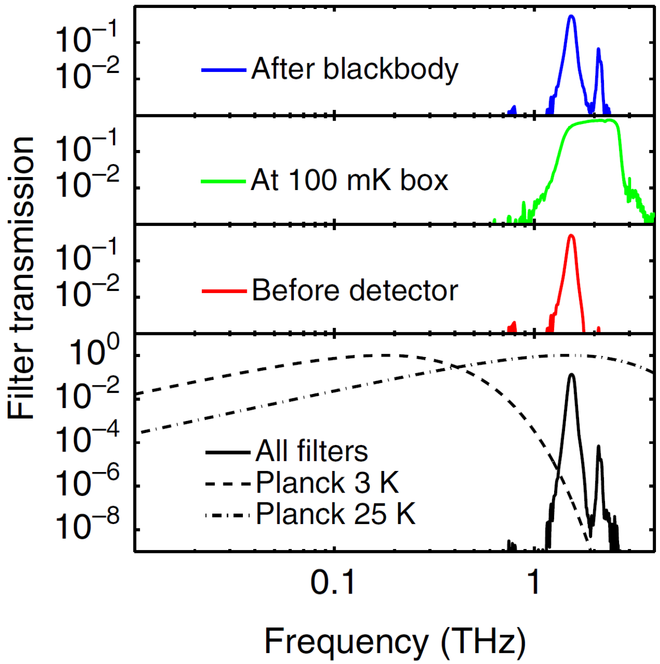
- Planck spacecraft bolometers were very sensitive to cosmic rays and lost significant observation time and data
- KIDs are more immune (better than bolometers) because:
  fast response time + insensitive to phonons below energy gap (unlike TESs)



A. Catalano, A&A 592, A26 (2016)

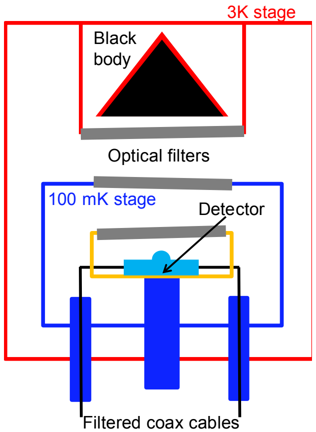
A cryogenic black-body calibrator source with stray-light shielding for testing space worthy KIDs





PJ. De Visser, PhD thesis, 2014 (TuDelft)

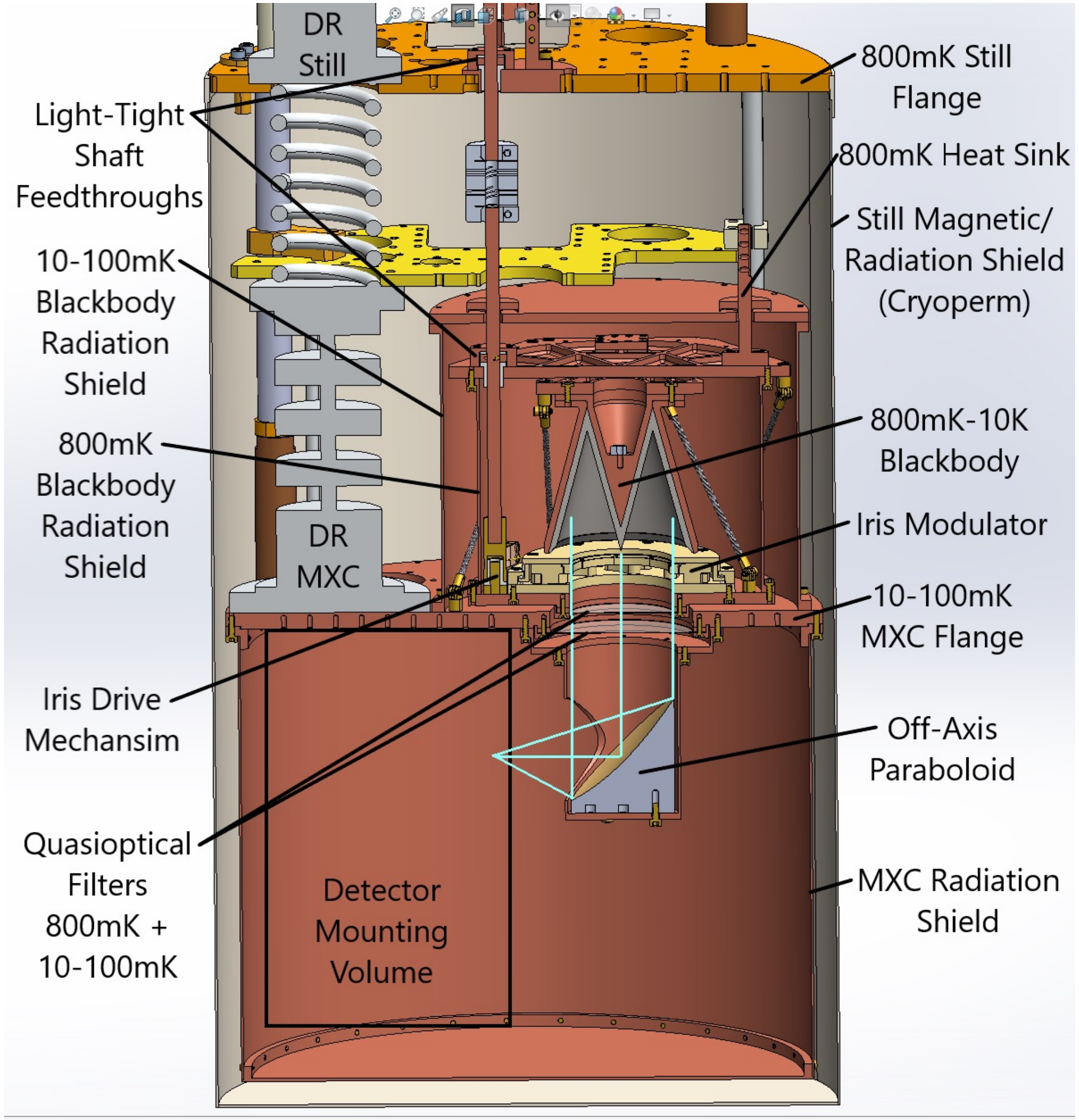
Using above design and concept as a starting point, we are currently implementing a shielded ultra-dark blackbody source at GSFC (see next slide).



Calibrated down to 10^{-21} W

GSFC design for an ultra-dark testbed with BB calibrator for KID spectrometer testing

- Photon-counting aluminum KIDs at 100mK need to see a background incident power of ~10^{-21} W at f > 90GHz
  → Need ~137dB attenuation from 3.2K and ~110dB from 800mK blackbody radiation from shields
- Primary issues are minimizing radiation leaks to high precision, filtering feedthroughs for DC and microwave lines
- Need a fast, temperature-swept, integrated blackbody to introduce known amounts of optical power to detector for characterization.
- Challenge: A combination of residual resonator TLS frequency noise, slow BB temperature control, drifts, and very low microwave read power create potential problems with long-duration noise/NEP measurements. → Solution is a manually controlled iris at <100mK. Modulator provides stable background when iris closed. Currently implementing this at GSFC.



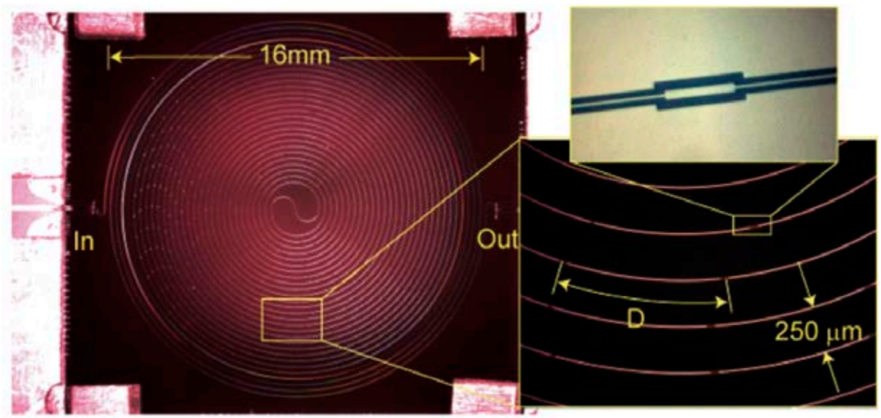
O.Noroozian (PI), Photon-counting KIDs for the Origins Space Telescope, NASA ROSES APRA

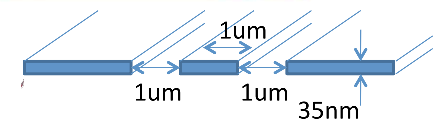
Kinetic Inductance Traveling-wave Parametric Amplifiers (TWKIP) for readout of KIDs

nature physics | ARTICLES
PUBLISHED ONLINE: 8 JULY 2012 | DOI: 10.1038/NPHYS2356

A wideband, low-noise superconducting amplifier with high dynamic range

Byeong Ho Eom[1], Peter K. Day[2]*, Henry G. LeDuc[2] and Jonas Zmuidzinas[1,2]





- Invented in 2012 at Caltech/JPL
- Kerr medium made of ultra low-loss and high kinetic inductance NbTiN film
- $\delta L_{kin} \propto I^2$
- Uses transmission-line architecture

The good:

- Quantum-limited noise
- Octave or more bandwidth
- High input dynamic range (-50 to -40 dBm)
- Very low dissipation
- Can operate at temperature of ~< 3 K
- Integration with superconducting electronics
- Can read out large array of detectors

The not-so-good:

- High pump power (~10 μW)
- In-band ripples (recently reduced)
- Relatively long line length of 2.5 cm (used to be 1 meter!)

First demo of application of TWKIPs for KID readout

Wide-band parametric amplifier readout and resolution of optical microwave kinetic inductance detectors

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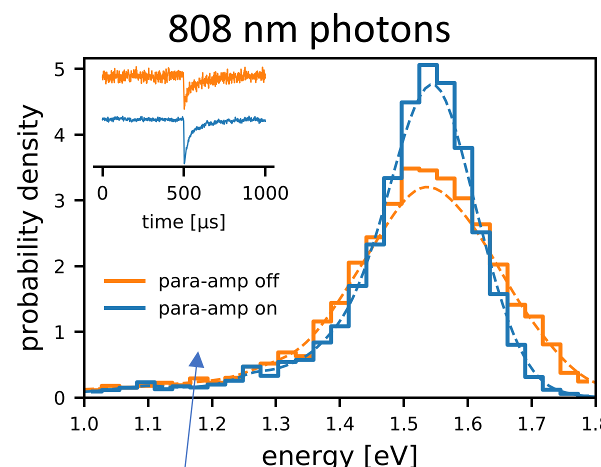
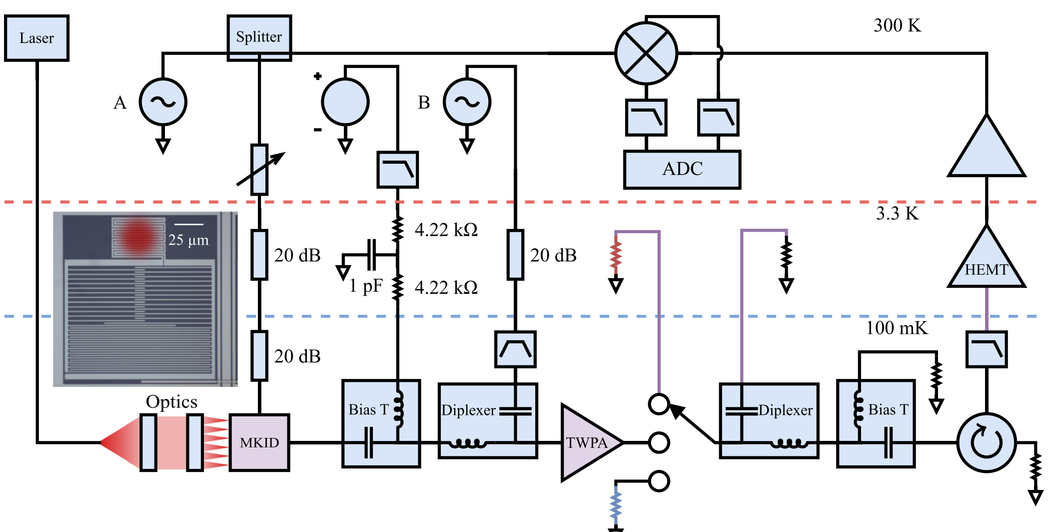
Appl. Phys. Lett. **115**, 042601 (2019)



- Application in exoplanet imaging coronographs: Single-photon energy-resolving optical MKID arrays serve as multi-band wavefront sensors in adaptive optics for high-speed star-light speckle suppression.
- Example: MEC (MKID Exoplanet Camera): ~ 20,000 PtSi MKIDs (800-1300 nm)
- Energy resolution (measured with paramp) R ~ 10
- R is currently limited by MKID design (current non-uniformity in absorber, TLS noise) and hot phonon escape to substrate. Could be improved to ~ 25.

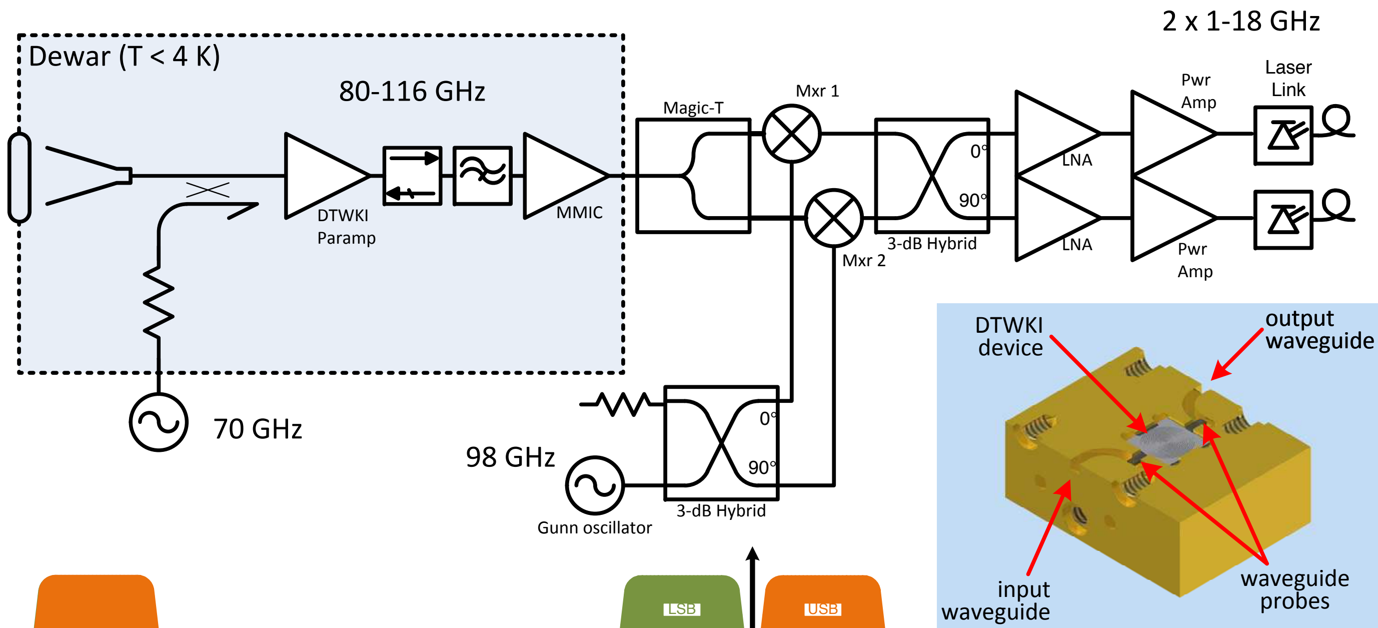


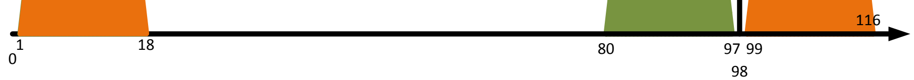
A_I	A_P	A_H	A_{sys}
$0.71^{+0.03+0.2}_{-0.03-0.01}$	$0.59^{+0.02+0.2}_{-0.02-0.07}$	$19.5^{+0.1+2}_{-0.1-2}$	$2.13^{+0.01+0.8}_{-0.01-0.1}$

	Resolving Power $(E/\Delta E)$	
Energy (eV)	Measured	Expected
1.53 (808 nm)	5.8 → 8.9	9.5 → 23
1.35 (920 nm)	7.4 → 9.4	10 → 24
1.27 (980 nm)	7.5 → 9.6	11 → 25
1.11 (1120 nm)	6.6 → 9.6	9.3 → 24
0.946 (1310 nm)	6.0 → 9.2	8.7 → 23

Millimeter-wave TWKIP amplifiers for astronomical receiver front-ends

- TWKIPs can in principle be designed to operate at frequencies up to 1 THz.
- Paramps could be used as front-end amplifiers before down-converting mixing elements
- This would obviate the need for SIS mixers altogether, would allow quantum-limited performance for full system, and increase the instantaneous bandwidth and observation speed of receiver systems by many times. **(e.g. for ALMA band 3 receivers → 8x increase in telescope observation speed!)**





- O. Noroozian, "Superconducting paramps: the next big thing in (Sub)millimeter-wave receivers", National Committee of URSI National Radio Science Meeting, 2018.
- D. Woody, "Development of ultra-wideband quantum limited amplifiers for millimeter and submillimeter receiver frontends" https://science.nrao.edu/facilities/alma/alma-develop-old-022217/Ultrawideband3amplifierstudyfinalreport2013MAY22.pdf

Many applications of TWKIP amplifiers

- Application for space-based detector readout. e.g. for the Origins Space Telescope to read out arrays of photon-counting spectrometers
- Replacing high power consuming HEMT amplifiers with TWKIPs for reducing SWaP in space platforms.
- Sensitive current sensors for multiplexed readout of large TES detector arrays for astronomical telescopes (e.g. CMB-S4 needs ~ 10^5 TESs)
- X-ray/Gamma-ray spectrometers for fast/real-time materials analysis in industry or national security.
- Deep-space communication – e.g. IF amplifiers for DSN
- Space debris tracking using radar

Application of KIDs for dark matter detection

APPLIED PHYSICS LETTERS **100**, 232601 (2012)

Position and energy-resolved particle detection using phonon-mediated microwave kinetic inductance detectors

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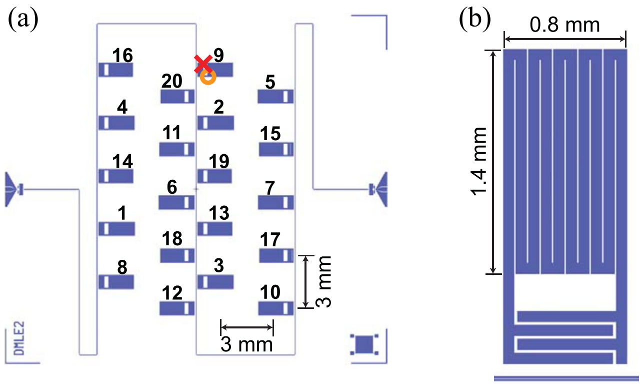

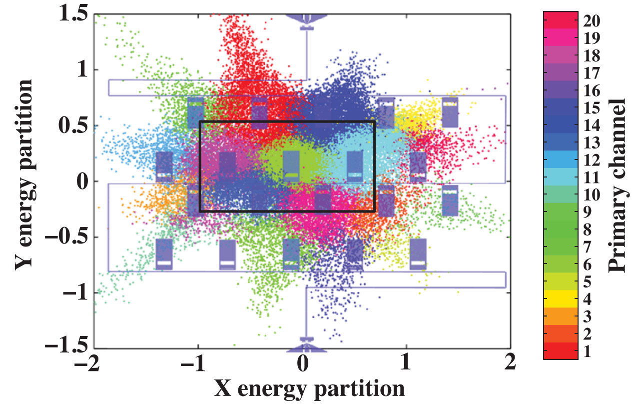

FIG. 4. Reconstruction of the interaction location from the energy partition. The coloring denotes the primary channel for each pulse. The black lines indicate the selection of events interacting in the center of the substrate. For comparison, the device geometry from Fig. 1 is overlaid.

- Energy and position of a rare dark matter particle interaction with the silicon substrate demonstrated with < 1mm accuracy and 0.55 eV at 30 keV resolution.
- Position reconstructed from partial signals across different KIDs and improved energy resolution from combining signals from many KIDs.

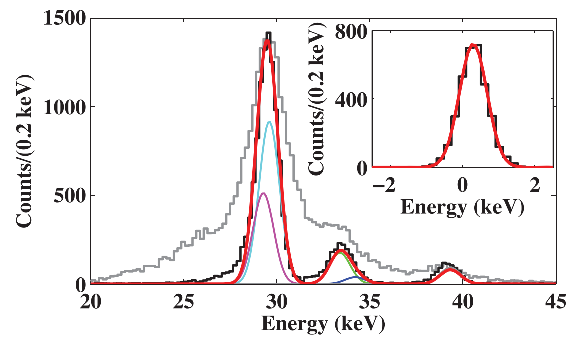

FIG. 3. Observed spectrum from an ^{129}I source. The reconstructed energy

The End

Thank you!