Kinetic Inductance technologies for submillimeter single-photon detection and quantum-limited amplification for spectroscopy in space

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**GSFC**:

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<u>Caltech/JPL:</u> Nikita Klimovich Peter Day Jonas Zmuidzinas



## The Kinetic Inductance Detector (KID)



## KID multiplexing and readout is a big advantage



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



## Increased sensitivity of future far-IR space telescopes



Origins Space Telescope Mission Concept Study - final report https://asd.gsfc.nasa.gov/firs/docs/OriginsVolume1MissionCo nceptStudyReport 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<sub>3</sub>) 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<sup>-20</sup> W/Hz<sup>1/2</sup> or photon-counting
- Large format arrays of ~ 10<sup>4</sup>-10<sup>6</sup> 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)</li>

#### **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 (2017)

## 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<sup>1/2</sup> dependence)

O.Noroozian (PI), Photon-counting KIDs for the Origins Space Telescope, NASA ROSES APRA (2017)



## 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

![](_page_10_Picture_8.jpeg)

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

![](_page_11_Figure_1.jpeg)

#### Credit: Thomas Stevenson, GSFC

- Dark counts are only caused by white amplifier noise at a rate of 5 Hz. This corresponds to NEP = 1-2 x 10<sup>-21</sup> 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.  $\sqrt{}$
- Recombination time and ring time are fast compared to photon arrival rate. Pulses decay with tau ~ 1.7 ms.  $\checkmark$
- 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 =  $0.05 \ \mu m^3$ , 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 (2017)

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

![](_page_12_Picture_1.jpeg)

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).

![](_page_12_Figure_3.jpeg)

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 $\mu$ -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

븕 -17

-18

19 -20

-21

y [cm]

-0.5

![](_page_13_Picture_4.jpeg)

## Optical measurement of µ-Spec channels

![](_page_14_Picture_1.jpeg)

## Measurement of a prototype $\mu$ -Spec designed for R = 64

![](_page_15_Figure_1.jpeg)

### **Demonstrated results:**

- Sharp line profile of (sinx/x)<sup>2</sup> (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 <u>phonons</u> below energy gap (unlike TESs)

![](_page_16_Figure_3.jpeg)

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

## A cryogenic black-body calibrator source with straylight shielding for testing space worthy KIDs

Filtered coax cables

![](_page_17_Picture_1.jpeg)

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).

# 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<sup>-21</sup> 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.

![](_page_18_Figure_5.jpeg)

#### J. Connors (formerly GSFC NPP postdoc)

## Blackbody calibrator design

- Graphite loaded epoxy coating forms a non-magnetic lossy absorber
- Optimized cone angle, absorber thickness, and thermal time constant
- 15 deg half angle chosen for BB to have < -35dB reflection at 850GHz (using multiple light ray bounces)
- Thermal time constant estimated at ~5min at 4K with copper wire defining G to 800mK bath

![](_page_19_Picture_5.jpeg)

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![](_page_19_Picture_6.jpeg)

![](_page_19_Figure_7.jpeg)

![](_page_19_Figure_8.jpeg)

J. Connors (formerly GSFC NPP postdoc)

## Blackbody calibrator being assembled at GSFC

![](_page_20_Picture_1.jpeg)

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

nature physics

- 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 ( $\sim 10 \mu W$ )
- In-band ripples (recently reduced)
- Relatively long line length of 2.5 cm (used to be 1 meter!)

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

PUBLISHED ONLINE: 8 JULY 2012 | DOI: 10.1038/NPHYS23

6 5

Freq. (GHz)

Byeong Ho Eom<sup>1</sup>, Peter K. Day<sup>2</sup>\*, Henry G. LeDuc<sup>2</sup> and Jonas Zmuidzinas<sup>1,2</sup>

![](_page_21_Figure_19.jpeg)

N. Klimovich and P. Day, Caltech

Freq. (GHz)

-5

## First demo of application of TWKIPs for KID readout

#### Wide-band parametric amplifier readout and resolution of optical microwave kinetic inductance detectors Nicholas Zobrist,<sup>1,a</sup> <sup>(1)</sup> Byeong Ho Eom,<sup>2</sup> Peter Day,<sup>2</sup>

Nicholas Zobrist<sup>1,a)</sup> <sup>(1)</sup> Byeong Ho Eom<sup>2</sup>, Peter Day<sup>2</sup>, Benjamin A. Mazin<sup>1,b)</sup> <sup>(1)</sup> Seth R. Meeker<sup>2</sup>, Bruce Bumble<sup>2</sup>, Henry G. LeDuc<sup>2</sup>, Grégoire Coiffard<sup>1</sup>, Paul Szypryt<sup>3</sup>, <sup>(1)</sup> Neelay Fruitwala<sup>1</sup>, Isabel Lipartito<sup>1</sup>, and Clint Bockstiegel<sup>1</sup>

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.

![](_page_22_Figure_8.jpeg)

### 808 nm photons

![](_page_22_Figure_10.jpeg)

AI	$A_{\mathrm{I}}$		$A_{\mathrm{H}}$	$A_{ m sys}$
$0.71\substack{+0.03+0.2\\-0.03-0.01}$	$0.59\substack{+0.\\-0.0}$	$2^{+0.2}_{-0.07}$ ]	$19.5_{-0.1-2}^{+0.1+2}$	$2.13\substack{+0.01+0.8\\-0.01-0.1}$
		Resolving Power $(E/\Delta E)$		
Energy (eV)		Measure	ed	Expected
1.53 (808 nm)		$5.8 \rightarrow 8.$	.9	$9.5 \rightarrow 23$
1.35 (920 nm)		$7.4 \rightarrow 9.$	.4	10  ightarrow 24
1.27 (980 nm)		$7.5 \rightarrow 9.5$	.6	$11 \rightarrow 25$
1.11 (1120 nm)		$6.6 \rightarrow 9.6$	.6	$9.3 \rightarrow 24$
0.946 (1310 nm)		6.0  ightarrow 9.	.2	$8.7 \rightarrow 23$

# 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!)

![](_page_23_Figure_4.jpeg)

- 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", ALMA final study report, 2013

## 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<sup>5</sup> 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

D. C. Moore,<sup>1,a)</sup> S. R. Golwala,<sup>1</sup> B. Bumble,<sup>2</sup> B. Cornell,<sup>1</sup> P. K. Day,<sup>2</sup> H. G. LeDuc,<sup>2</sup> and J. Zmuidzinas<sup>1,2</sup>

![](_page_25_Figure_4.jpeg)

![](_page_25_Figure_5.jpeg)

 Position reconstructed from partial signals across different KIDs and improved energy resolution from combining signals from many KIDs.

![](_page_25_Figure_7.jpeg)

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.

![](_page_25_Figure_9.jpeg)

FIG. 3. Observed spectrum from an <sup>129</sup>I source. The reconstructed energy

The End Thank you!

## <u>Funded by NASA in 2019</u>: Measuring the cosmological evolution of gas and galaxies with the EXperiment for Cryogenic Large-aperture Intensity Mapping (EXCLAIM)

- A high-altitude balloon spectrometer designed to measure the redshifted emission from CO and C[II] lines over cosmic time to deepen our understanding of star formation. (PI: E. Switzer)
- Intensity Mapping: Rather than detect individual galaxies, EXCLAIM will measure the statistics of brightness fluctuations of redshifted, cumulative line emission.
- All-cryogenic telescope with 1.5 K mirror coupled to six (6) μ-Spec chips each with resolution R=500.
- EXCLAIM will use significant heritage equipment including the gondola, cryostat, electronics, and software from the PIPER balloon mission. Commissioning planed for 2021.
- Detectors will be microstrip aluminum KIDs similar to the photon counting detector design.
- The project leverages the design, materials development, results, lessons learned, testing infrastructure, and same team for the KID project as well as the μ-Spec project.

	"Laboratory" MKID	R=256 balloon MKID	R=512 balloon MKID
Optical Frequency	~ 500 GHz	~ 500 GHz	~ 500 GHz
Power loading	1 nW – 20 pW	30 fW	50 aW
Thickness	100 nm	20 nm	10 nm
Q <sub>int</sub> under loading	20k – 137k	300k	800k
Detector NEP (W/Hz <sup>1/2</sup> )	1.5x10 <sup>-15</sup> – 5.5x10 <sup>-17</sup>	8x10 <sup>-18</sup>	3.5x10 <sup>-19</sup>
BLIP NEP	9x10 <sup>-16</sup> - 4x10 <sup>-</sup> <sup>17</sup>	5x10 <sup>-18</sup>	2x10 <sup>-19</sup>

![](_page_27_Figure_8.jpeg)

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7
-
R
Hz

#### Table 1: EXCLAIM Spectrometer