Large-Format, Transmission-Line-Coupled Kinetic Inductance Detector Arrays for HEP at Millimeter Wavelengths

Tom Cecil

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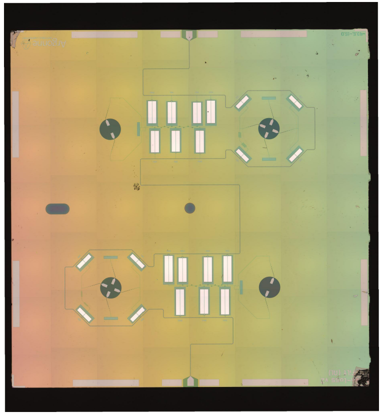

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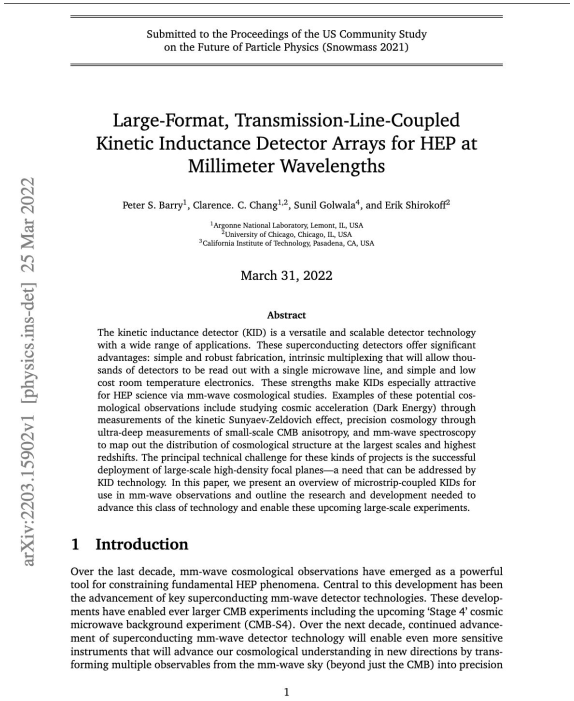
Outline

For full white paper: https://arxiv.org/abs/2203.15902

- Introduction
- Science Opportunities
- Technical Requirements
- Enabling Technologies
- Future Developments



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Large-Format, Transmission-Line-Coupled Kinetic Inductance Detector Arrays for HEP at Millimeter Wavelengths

Peter S. Barry[1], Clarence. C. Chang[1,2], Sunil Golwala[4], and Erik Shirokoff[2]

[1]Argonne National Laboratory, Lemont, IL, USA
[2]University of Chicago, Chicago, IL, USA
[3]California Institute of Technology, Pasadena, CA, USA

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Abstract

The kinetic inductance detector (KID) is a versatile and scalable detector technology with a wide range of applications. These superconducting detectors offer significant advantages: simple and robust fabrication, intrinsic multiplexing that will allow thousands of detectors to be read out with a single microwave line, and simple and low cost room temperature electronics. These strengths make KIDs especially attractive for HEP science via mm-wave cosmological studies. Examples of these potential cosmological observations include studying cosmic acceleration (Dark Energy) through measurements of the kinetic Sunyaev-Zeldovich effect, precision cosmology through ultra-deep measurements of small-scale CMB anisotropy, and mm-wave spectroscopy to map out the distribution of cosmological structure at the largest scales and highest redshifts. The principal technical challenge for these kinds of projects is the successful deployment of large-scale high-density focal planes—a need that can be addressed by KID technology. In this paper, we present an overview of microstrip-coupled KIDs for use in mm-wave observations and outline the research and development needed to advance this class of technology and enable these upcoming large-scale experiments.

1 Introduction

Over the last decade, mm-wave cosmological observations have emerged as a powerful tool for constraining fundamental HEP phenomena. Central to this development has been the advancement of key superconducting mm-wave detector technologies. These developments have enabled ever larger CMB experiments including the upcoming 'Stage 4' cosmic microwave background experiment (CMB-S4). Over the next decade, continued advancement of superconducting mm-wave detector technology will enable even more sensitive instruments that will advance our cosmological understanding in new directions by transforming multiple observables from the mm-wave sky (beyond just the CMB) into precision

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Mm-wave cosmological observations

- Powerful tool for constraining fundamental HEP phenomena
  - CMB temperature / polarization to search for signs of inflation
  - Kinetic Sunyaev-Zeldovich (kSZ) effect being used to constrain galaxy and cluster peculiar velocities
- Advances in superconducting mm-wave detector technology has been key to enabling science
  - Sensors have achieved background limited noise performance
  - Array size scaled from ~ 10^2 to ~ 10^4
- Realizing the full potential of mm-wave observations will required focal plane arrays of ~ 10^6 - 10^7 detectors

Science Opportunities

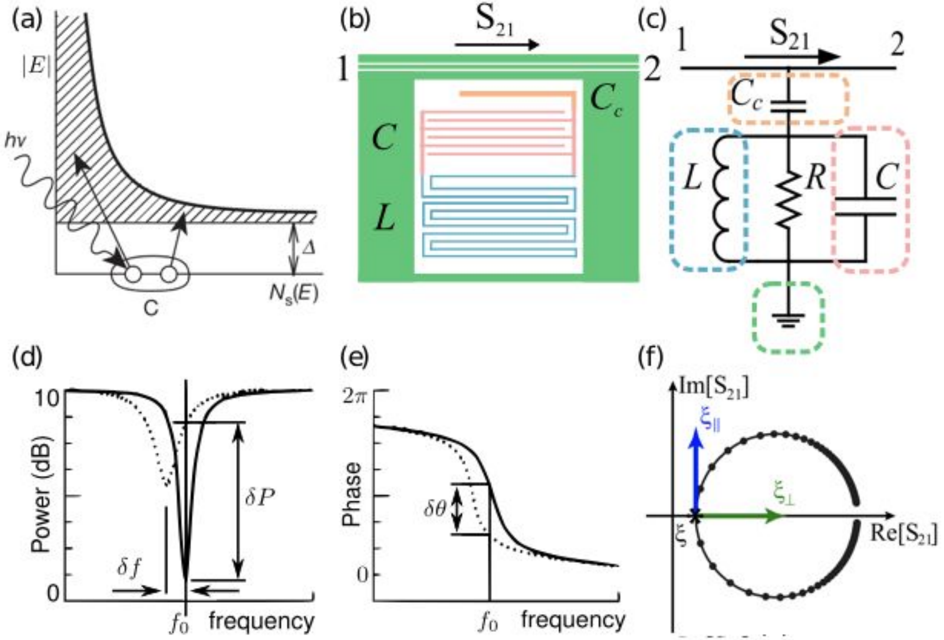
- Peculiar velocities via the kinetic Sunyaev-Zeldovich Effect (kSZ)
  - New method for constraining the dark energy equation of state and test for modification of GR
  - Complementary to other techniques and bands (e.g. X-ray temperature information)
- BAO and RSD via mm-wave Integral-Field Spectroscopy
  - Flux of dusty/molecular/atomic components of galaxies is roughly redshift independent at mm-wave -> mm-wave sky is dense with sources
  - Line intensity mapping extended to mm-wavelengths -> access to cosmological modes beyond the redshift reach of traditional optical / IR galaxy surveys (z = ~ 0.5 - 10)
  - Snowmass White paper: 2203.07258
- Dark Matter Science from Small-Scale CMB Polarization with CMB-HD
  - Use gravitational lensing to distinguish pure cold dark matter models
  - Test or rule out new light thermal particles at > 95% confidence level
  - Probe for axion dark matter in the ueV to meV mass range
  - Snowmass White paper: 2203.05728

Technical Requirements

- Imaging and Polarimetry Surveys
  - Detector arrays of ~ 10^6 - 10^7
  - Spectral coverage from ~ 30 GHz to 420 GHz
- Spectroscopic Surveys
  - Detector arrays of ~ 10^7 - 10^9
  - Increased detector density
- Improved multiplexing schemes
  - Current technology has reached limit of ~ 10^3 detectors per 150mm wafer

Enabling technologies - Kinetic Inductance Detectors

- Essentially a superconducting resonator
- Advantages
  - Inherently multiplexable
  - Simplified fabrication
  - Readout electronics share development with quantum computers



Direct Absorbing KIDs

- KIDs serves as photon absorber, sensors, and readout
- Can be as simple as a single metal layer (often a few layers)
- Optical bandpass defined by waveguides, filters, etc. to limit detectors to single observing band
- To date, only facility-grade KID instruments (NIKA-2, MUSCAT, TolTec)

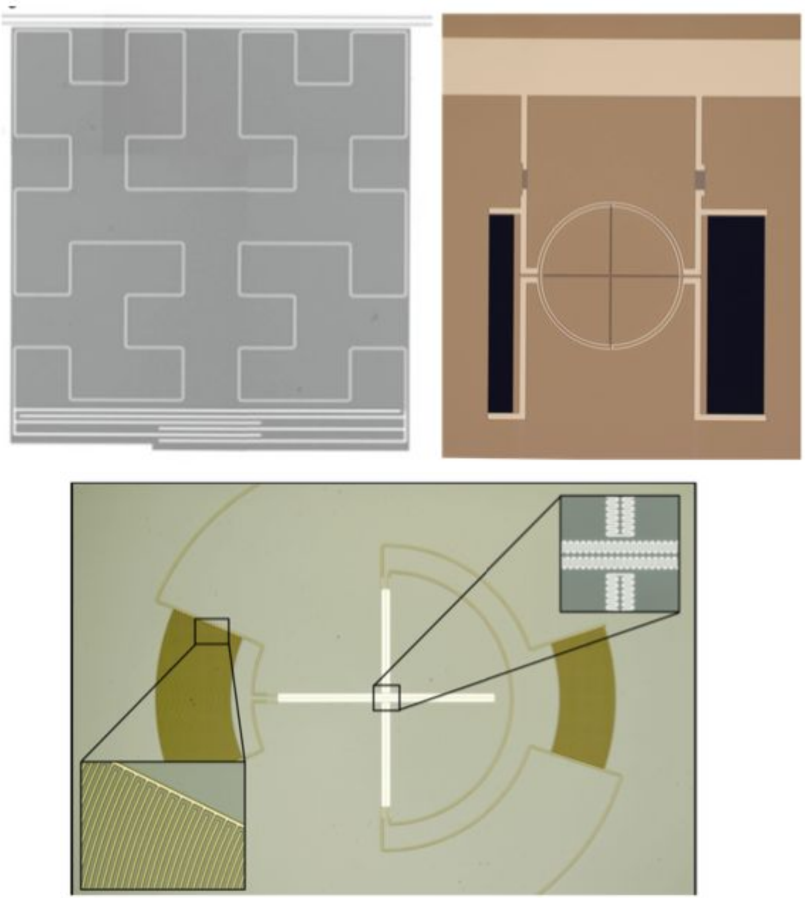


Figure 2: Examples of direct absorbing lumped-element KID architectures. ***Left****) dual-polarisation Hilbert fractal Al absorber used by NIKA2 [46],* ***middle****) a polarimetric detector design made up of two single-polarisation detectors using TiN developed at NIST for Toltec [47], and* ***right****) Al for the SPT-4 instrument [48].*

Microstrip-coupled KID

- Separate absorber and sensing functions
- Allows for multi-chroic pixels
- Benefits from recent advances in superconducting electronics and low-loss transmission lines

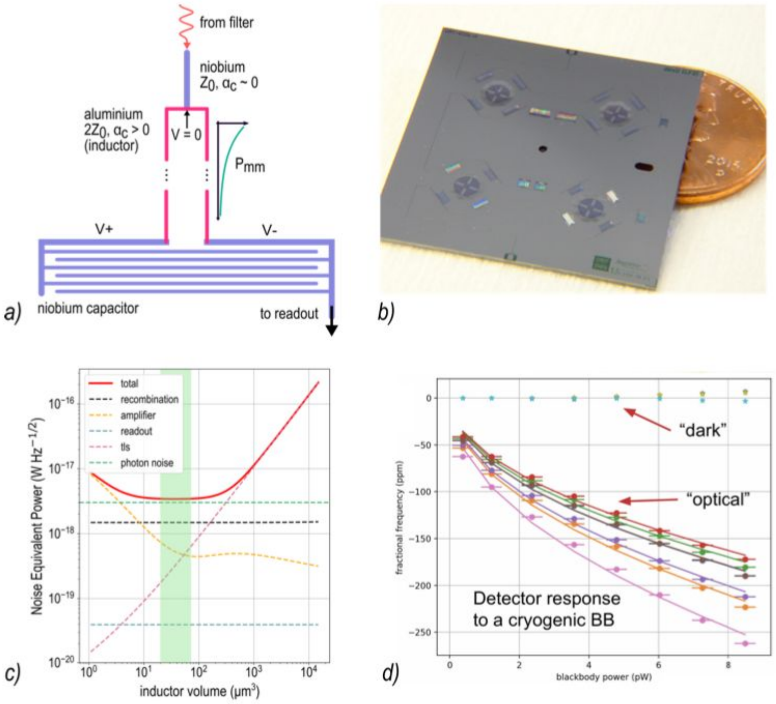


Figure 5: a) Schematic of the principle of operation of a mc-leKID. See text for details. b) Photograph of a prototype mc-leKID device, c) Predicted performance of the mc-leKID as a function of inductor geometry. d) preliminary measurement of optical response characterized with a cryogenic blackbody source as a function of load temperature.

Thermal KIDs

- Couple radiation via bolometric design
- Allows independent optimization of resonator geometry and optical coupling
  - Resonator does not need to electrically connect to optical circuitry
- Electro-thermal feedback to improve stability and increase dynamic range

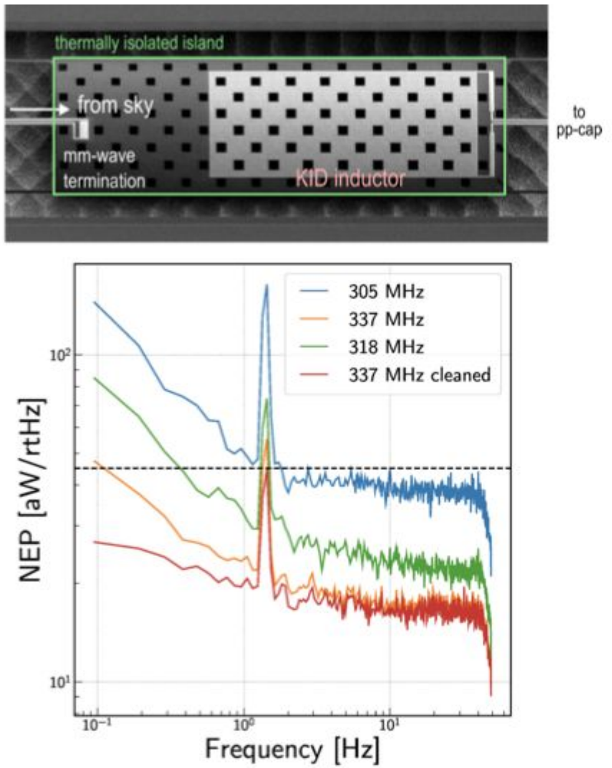


Figure 6: mm-wave TKIDs fabricated at JPL. Figure adapted from [59, 60]

On-chip Spectroscopy

- Filterbank architecture extends multi-band imaging
- Each pixel is coupled to ~ 100 - 1000 detectors
- Fully on-chip spectrometers provides pathway to focal planes with ~ 100s pixels and ~ 10^5 detectors -> KID based readout

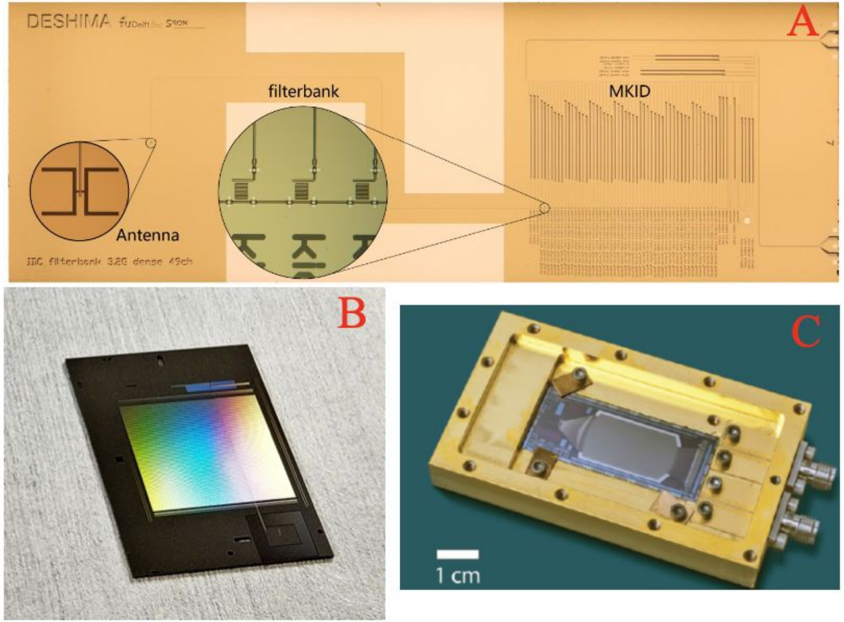


Figure 7: Examples of state of the art on-chip, KID-based spectrometers: (A)DESHIMA (B) SuperSpec (C) Micro-Spec. (see text for references)

Future Developments

- Single Pixel Optimization
    - Fundamental sensitivity has been shown to be comparable to TES
    - On-going work at low optical loading as expected at lower frequencies
    - Materials development needed for detection at frequencies below ~ 90 GHz
- Scaling and Cost reduction
    - Readout is a major cost factor - need to bring down cost/KID
    - Long term goal of ~ $1/KID (1-2 orders of magnitude reduction from current experiments)
- Integrated performance
    - Facility level instruments are significant investment requiring demonstrated performance
    - Deployment of small-scale systems is needed to validate performance models for full end-to-end performance

Summary

- Mm-wave observations are a powerful tool for constraining many fundamental HEP phenomenon
- Strong heritage in detector technology development via CMB experiments
    - Advanced from ~100 detectors to ~ 500,000 detectors
- Future experiments will require larger detector counts, new detector technology
- Kinetic Inductance Detectors (KIDs) offer advantages for increasing detector count and density
    - Single pixel lab tests are encouraging
    - Small-scale field tests necessary to validate performance