Snowmass2021 - Letter of Interest

Microstrip-Coupled Kinetic Inductance Detectors for Cosmological Surveys

Topical Group(s): (check all that apply by copying/pasting ☐/☑)

☐ (CF1) Dark Matter: Particle Like
☐ (CF2) Dark Matter: Wavelike
☐ (CF3) Dark Matter: Cosmic Probes
☑ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☑ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
☐ (CF7) Cosmic Probes of Fundamental Physics
☑ (Other) *[Please specify frontier/topical group]*

IF1: Quantum Sensors

IF2: Photon Detectors

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Abstract:
The HEP community has recognized in the last decade the value of mm-wave cosmological observations for constraining fundamental HEP phenomena, motivating CMB-S4. The mm-wave sky has substantial additional potential, though. The kinetic Sunyaev-Zeldovich (kSZ) effect is already being used to constrain galaxy and cluster peculiar velocities, which can probe cosmic acceleration and test for deviations from GR. Integral-field spectroscopy at mm wavelengths is an emerging technology that may provide an important complement to O/IR multi-object spectroscopy for measuring BAO and RSD via large-scale structure. Realization of the future potential of mm-wave cosmology will require focal plane arrays of detectors with O(10^6-10^7) detectors that reach fundamental noise limits from 90 to 420 GHz and have flexibility in their optical coupling, being capable of multiband imaging for the SZ effect and integral-field spectroscopy. Microstrip-coupled detectors offer the largest toolkit for optical coupling by being amenable to many coherent optical reception architectures and spectral selection and even spectroscopy. Simultaneously, kinetic inductance detectors are a massively multiplexable detector technology that can reach fundamental sensitivity limits. This LOI discusses progress toward a flexible, microstrip-coupled architecture for KIDs, enabling these important mm-wave cosmological probes of HEP.

Scientific Motivation and Technical Requirements:

v_{pec} via the kinetic Sunyaev-Zeldovich Effect: Observation of the kSZ effect is a new, competitive method to measure the cosmological velocity field to constrain the dark energy equation-of-state and test for modifications of GR. kSZ measurements directly probe the peculiar velocities (v_{pec}) of large objects, while the other method of using velocity measurements, redshift-space distortions (RSD), indirectly probes v_{pec} with smaller objects[1]. RSD and kSZ measurements have different systematics, and so they can complement each via cross-checks, breaking of parameter degeneracies, and reduction of uncertainties. One developed method for measuring the small kSZ v_{pec} signal in the presence of noise and the spectrally degenerate CMB primary anisotropy, demonstrated by ACT[2], SPT[3], and *Planck*[4], uses correlations between mm-wave maps and O/IR galaxy spectroscopic surveys to statistically detect the pairwise relative velocity between concentrations of mass. Another approach to kSZ v_{pec}, measuring *individual* cluster peculiar velocities with high precision, could have substantial potential for cosmology. A survey of 30000 galaxy clusters with σ_v=200 km/s would yield a Dark Energy Task Force figure-of-merit (FoM) of 170[5]. Combining with Stage IV surveys such as DESI (RSD; FoM 700) and LSST (weak lensing; FoM 800) would improve their FoMs by a factor of two[6]. The same survey would yield a constraint on the cosmological growth index γ of $\sigma_\gamma = 0.02$[7], sufficient to distinguish modified gravity models such as DGP[8] from GR ($\gamma_{\mathrm{DGP}} - \gamma_{\mathrm{GR}} = 0.13$) and complementing comparably precise measurements by LSST, DESI, WFIRST, and Euclid.

To do so requires X-ray temperature information and mm-wave measurements in multiple spectral bands, isolating the kSZ from other, much larger signals: the thermal SZ effect, radio and dusty galaxies, and CMB primary anisotropy. To date, this has been done for fast-moving galaxy cluster substructures with a 10m telescope[9,10], pointing to future potential for cluster peculiar velocities. The required combination of sensitivity, angular resolution, and spectral information necessitates a large (≥ 30m) mm-wave telescope with a focal plane array covering 6 spectral bands from 90 to 420 GHz. The tens of $M cost of such a large telescope warrants full use of its focal plane, motivating the development of focal plane arrays providing this wide spectral coverage for each spatial pixel. The factor of 4 range in diffraction spot size necessitates preserving the wave nature of the incoming light after optical reception (by, e.g., feedhorns or antennas) so it can be coherently summed in a way to match this varying spot size. The favored tool for this coherent combination is superconducting microstripline. The technology must scale to O(10^6) detectors (# of angular resolution elements in 6 spectral bands for a 1° FoV 30m telescope) and must enable spectral bandpass definition.

BAO and RSD via Mm-wave Integral-Field Spectroscopy: Another incipient technique at mm wavelengths for cosmological measurements is integral field, moderate-resolution spectroscopy. This approach combines two features of the mm-wave sky: due to the canceling effects of redshift and the $\nu^{2+\beta}$ behavior of a dusty greybody spectrum, the flux of the dusty/molecular/atomic component of galaxies is roughly redshift-independent at mm wavelengths; and, therefore, the mm-wave sky is dense in sources at even the angular resolution of 30m telescope, 10" at 300 GHz. Thus, with the FoV for a 30m telescope at these wavelengths filled with spectrometers, a galaxy will occupy each spatial pixel, and each may be detectable in CO or [CII] spectral line emission. Using these lines to extend baryon acoustic oscillation (BAO) and RSD measurements over an enormous range of redshift, $z \approx 0.5$-10, could be transformational for probing the expansion and cosmological growth function history.

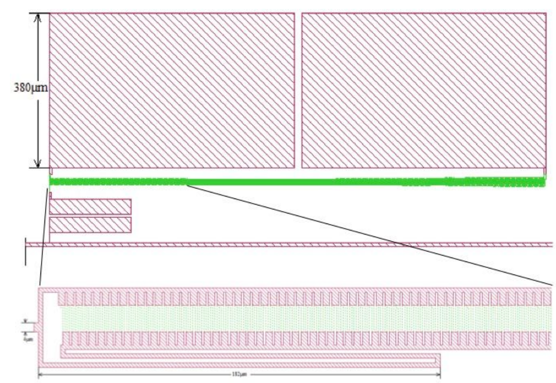
To determine redshifts requires a resolving power $R = \lambda/\Delta\lambda \approx 300$-1000. The only conceivable approach to provide spectroscopy *for each spatial pixel* uses superconducting microstripline coupled arrays of mm-wave resonators that transmit narrow spectral bands to individual detectors[11], along with the aforementioned concept for matching to the diffraction spot size. Filling the FoV of a 30m telescope at this R for 90-420 GHz would thus require O(10^7) detectors.

Technical Approach: Microstrip-Coupled Kinetic Inductance Detectors

Microstrip Coupling: Superconducting microstripline provides two key capabilities for the above applications on large mm-wave telescopes: a way to tailor the beam to the diffraction spot size over a large frequency range, 90-420 GHz, and a way to provide R = 300-1000 spectroscopy for every spatial pixel. Banks of spectral bandpass filters can provide the needed $R \approx 3$-4 for kSZ.

Kinetic Inductance Detectors: KIDs[12,13] are superconducting LC resonators. When mm-wave power breaks Cooper pairs, the resonant frequency f_r and quality factor (Q_i) change, modifying the phase and amplitude of a probe signal at f_r. KIDs are intrinsically multiplexable: because $Q_i > 10^5$ well below the superconducting transition temperature for attractive materials (e.g., Al, AlMn, TiN_x), a single readout line and 4 K low-noise amplifier suffices for ~$10^{3\text{-}4}$ KIDs. This kind of RF-multiplexed readout is the only conceivable way to handle the $10^{6\text{-}7}$ detector counts specified above.

KIDs and TESs: The leading mm-wave technology is currently transition-edge sensors (TESs)[14,15]. At the same operating temperature, TES and KID fundamental sensitivity limits differ by <5-10%. A key advantage of KIDs is their *intrinsic* RF multiplexability. TESs can be RF multiplexed, but at the cost of much greater focal plane complexity. Another is the fact that the isolation from the thermal bath needed to see an optical signal is provided by the KID material itself while TESs generally require isolating thermal legs, adding fabrication complexity.



Device Architecture: The figure at right shows an example of the microstripline-coupled KID architecture being developed. Nb superconducting microstripline (a ground plane, a thin dielectric (~1 µm), and top layer supporting the EM wave) enters from the left. (Bandpass filter banks would precede this; for spectroscopy, see below.) A flexible coupling structure dissipates the mm-wave power in the meandered inductor of the KID (green, TiNx or Al). An important feature of the coupler is that it largely decouples absorption efficiency from the KID geometry, providing much greater design flexibility than prior architectures. The inductor is connected to large Nb metal pads that form parallel-plate capacitors (PPC) with the ground plane using the same dielectric layer as the microstripline. KIDs are typically designed to have acceptable noise due to defect two-level system (TLS)-driven dielectric constant fluctuations by using interdigitated capacitors, whose electric field lives predominantly in the low defect-density crystalline substrate, but such IDCs act like (poor) antennas, creating a spurious light path into the KID. Grounded PPCs are inherently insensitive to such stray light: the floating electrodes sit only 1 µm away from a ground plane, which enforces a zero-electric-field condition for mm-wave light incident from vacuum, and the underlying ground plane blocks light leaked into the substrate by the optical reception element. The KIDs may additionally be isolated on islands with substrate-photon-blocking legs, though such a complicating measure would only be implemented if necessary. Spectroscopic applications can incorporate the spectral band definition in the mm-wave coupler by using a half-wave resonant structure more weakly coupled to the incoming microstripline.

Sensitivity Expectations: A full optimization of KID design for both TiNx and Al KID inductors results in KIDs that suffer <10% degradation relative to fundamental noise limits and <30% degradation relative to photon background-limited performance at 50 mK operating temperature. (The degradation would be smaller for lower operating temperature and is common to KIDs and TESs.) This results in a sensitivity of, e.g., 250 $\mu K_{CMB}\sqrt{s}$ at 150 GHz for R=3, appropriate for kSZ.

Current Status: Yield >95% has been obtained and devices are being characterized dark and with a cryogenic blackbody. A white paper to be submitted in Spring, 2021 will present sensitivities.

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