Research statement:

Numerous scientific disciplines are based on detecting and characterizing single photons or particles. From photographic plates over CCDs to transition edge sensors, every technological step in detector development has so far resulted in substantial scientific progress and often even enabled completely new fields. But particle and light detectors are still not perfect yet: State of the art instrumentation for astronomy, particle physics or material science more and more often not only demands as big a detector array as possible, but also considerable single pixel energy resolution, high readout speeds or vanishing dark counts. CCD arrays can scale up to multi-megapixels but are intrinsically limited by (among others) big semiconductor band gaps, low energy resolution and slow readout speeds. Novel low temperature detectors have to operate at temperatures below 100 mK but in exchange have significant advantages like single photon sensitivity, single pixel energy resolution, extreme time resolution or vanishing read noise. But the first generation of low temperature detectors (superconducting tunnel junctions (STJs), transition edge sensors (TESs) and magnetic micro-calorimeters (MMCs)) have one major drawback: They all require multiple electrical connections per pixel between the low temperature stage and room temperature, and as cooling power at mK temperatures is seriously restricted, this limits the possible number of pixels severely. Even with impressively complex and challenging multiplexing schemes these detectors still lack a feasible way to scale up to more than a few kilopixels.

The latest development in low temperature detectors are **M**icrowave **K**inetic **I**nductance **D**etectors (**MKID**s). I have participated in the development of single photon detecting MKIDs since 2012 and during my time at UCSB, we were able to field the first MKID camera at any wavelength to produce published astronomical results[1]. Every single MKID pixel in an array can not only count single photons or particles but also detects their individual energies and their arrival times with very high resolution (1 µS or better) and without dark counts. But most importantly, MKIDs offer a reliable and feasible, in-built multiplexing scheme as several thousand pixels can be read out over just 2 connections to room temperature. This unique and crucial advantage enables MKID scalability up to megapixel arrays and makes MKIDs tremendously attractive not only for many next generation astronomical instruments but also for multiple applications in material science and particle physics.

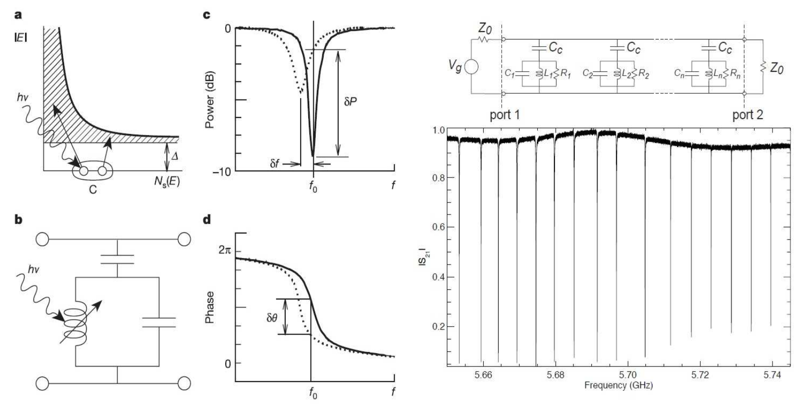

Fig. 1: MKID operation principle[2].

The expression 'kinetic inductance' describes that, caused by a final charge carrier mass, it takes time and energy to reverse the direction of motion of charge carriers and thus current always trails behind an AC voltage. As the size of this additional inductance in a given circuit depends on charge carrier density and velocity, it is low for normal metals but high for superconductors or at high frequencies. MKIDs utilize this effect for photon or particle detection: A superconductor is patterned into an LC resonant circuit with a well-defined resonant frequency. Any particle with an energy of more than twice the superconductor band gap that hits this resonator will reduce the charge carrier density by breaking Cooper pairs and thus will increase the kinetic inductance (fig. 1a). This higher inductance reduces the resonant frequency ($f_r \sim 1/\sqrt{LC}$, fig. 1b). As MKID resonators are coupled to a microwave (4-8 Ghz) feedline (that's why they are called, somehow misleading, 'Microwave' kinetic inductance detectors), the shift in resonance frequency caused by photon absorption shifts both the amplitude of the transmitted feedline signal (fig. 1c) as well as its phase response (fig. 1d) to lower frequencies. Since especially the phase shift can be measured fast and very precisely, every single photon produces its own signal pulse, the pulse height determined by the photon energy, allowing single pixel energy resolution. With a band gap of most suitable superconductors between 10^{-4} and 10^{-5} eV, MKIDs are much more sensitive compared to semiconducting detectors (Si has a band gap of 1.1 eV) and can also be operated as micro-calorimeters. Even though MKIDs have to operate around 100 mK, as every pixel has its own, lithographically defined resonant frequency, it is possible to couple and monitor thousands of them to a single feedline (fig 1, right), requiring just two lines to room temperature. This built-in multiplexibility makes MKIDs unique among low temperature detectors and presents a simple and feasible way to kilo- or even megapixel MKID arrays.

A variation of the basic MKID principle is the Thermal Kinetic Inductance Detector, or TKID (fig. 2). As the sensitive part of the resonator, the inductor is located on a free floating Si_3N_4 membrane, the amount of broken Cooper pairs depends on the membrane's temperature rise after photon absorption. Thus, the measured signal height is given by the photon energy and the membrane's heat capacity. The two basic advantages of TKIDs are that the photon or particle absorber can be varied (material, thickness, …) freely without changing the detector characteristics too much, allowing flexibility and good X-ray or particle stopping power. Also, due to the free floating membrane, loss of high energy phonons to the substrate is minimized, significantly increasing energy resolution. (Fig. 2 shows one of our early prototypes, an optimized detector would have a mushroom shaped absorber to increase the pixel fill factor.) We already demonstrated[3] first TKID prototypes with an energy resolution of 75 eV at 6 keV, still clearly suffering from saturation effects. Preliminary calculations show that at least 10 eV at 6 keV are possible just from eliminating the saturation and that, as the fundamental limits are comparable, TKIDs should be able to resolve less than 2 eV at 6 keV like TESs can.

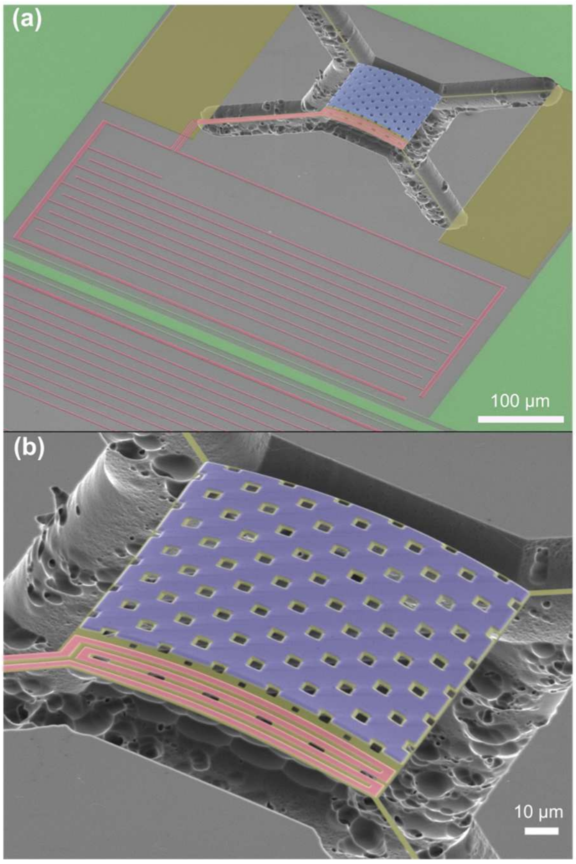

Fig. 2: SEM of one of our Thermal Kinetic Inductance Detectors (TKIDs): The superconductor has been colored red, a Ta absorber blue, yellow is Si_3N_4 and green a Nb ground plane and feedline. In a TKID, the resonator's inductor is located on a free floating Si_3N_4 membrane that is covered by an X-ray absorber. A TKID operates as micro-calorimeter as the measured shift in resonance phase is caused by a temperature increase of the membrane.

One of the most captivating features of MKIDs is their impressively broad field of possible applications. Many experiments in several disciplines of fundamental and applied physics urgently require or at least profit a lot from bigger detector arrays and are therefore prime candidates for MKIDs. As MKIDs are also very flexible and can be optimized to detect light (or particles) from microwave energies up to at least MeV, they are very attractive in even more fields. In particle physics for example, in order to increase their sensitivity, cryogenic rare event searches have to significantly scale up their test masses. This often requires thousands of bolometers, and MKIDs offer a way to do that while still reducing complexity of readout, detector fabrication and experimental setup compared to competing solutions[4]. MKIDs are proposed to be used as bolometers for direct neutrino mass measurements or direct dark matter detection[5] and are also considered to enhance background rejection in the search for the neutrinoless double beta decay by using them as easily multiplexible high time resolution photon detectors[6].

Some of the most exciting applications for MKIDs and TKIDs lie in observational astronomy. At UCSB we have already demonstrated MKID arrays covering a broad wavelength range[7] and capable of high sensitivity in the infrared[8]. MKID array sizes are basically limited by readout cost (currently 5 – 10 US-$ per pixel but dropping rapidly with the evolution of microelectronics), and even smaller MKID arrays offer single photon counting, single pixel energy resolution for integral field spectroscopy[9,10] and μS resolution time domain observations[1]. But the field profiting most from MKID's unique capabilities is high contrast imaging of exoplanets: First generation high-contrast imagers (so called coronagraphs) deliver impressive results but in order to observe planets in the habitable zones of their host star bigger telescopes and significantly higher contrast ratios (and thus better detectors) are required. The high time resolution of MKIDs in combination with their energy resolution and vanishing read noise allows novel and much more efficient ways to reduce background in high contrast imaging and promises to increase coronagraphic contrast ratios by up to two orders of magnitude[8]. The group of Ben Mazin at UCSB is already developing MKID arrays for high contrast imaging for Palomar Observatory and the Subaru telescope, but coronagraphs are part of the planned instrumentation package of many existent and almost all new telescopes to be built in the next decade, and with further detector development, MKIDs will be the perfect detector technology for them. For the first time in human history we have a feasible way to search for life outside our own solar system. This makes the direct imaging of exoplanets (and the development of optimized detectors for it) immensely fascinating.

As X-ray and higher energy astrophysics requires specialized detectors that are able to stop high energy photons we started to develop TKIDs. Earlier instruments for X-ray astronomy used CCD arrays, but as these have reached their fundamental energy resolution, low temperature detectors have already replaced them in state-of-the-art instrumentation, even though they suffer from the above mentioned limitation in pixel number and also require complex and error prone low temperature readout electronics. TKIDs are an attractive option for high energy astronomy as they are comparably simple, have almost all their readout at room temperature and, most importantly, can reach big array sizes even with severely limited cooling power. Bigger detector arrays not only provide larger fields of view but also higher mapping speeds and thus enhance the science return of both small and large missions significantly. As TKIDs have no dark counts they also offer high sensitivity for point sources and their impressive time resolution could for example allow to resolve pulse profiles of X-ray pulsars. The next step for TKIDs is to increase their energy resolution to TES levels while demonstrating the same array sizes (> 20.000) that have already been shown for MKIDs. Considering the impressive potential of high energy resolution X-ray observations demonstrated by JAXA's Hitomi satellite (also called ASTRO-H), the planned X-ray telescope Athena and several more proposals to NASA for next generation X-ray observatories, the scientific interest in astronomical observations at high energies is immense. As novel detector capabilities are the best way to increase mission performance and returns without increasing cost, TKIDs could become a very attractive or even dominant option among available detectors for future X-ray telescopes.

Another example for the many fascinating MKID / TKID applications is X-ray microanalysis with synchrotron beam lines. TKID arrays can cover a large part of the detection area of dispersive X-ray spectrometers, not only significantly speeding up the X-ray spectroscopy itself but also allowing spatial scanning or the examination of delicate samples that would otherwise be destroyed by prolonged irradiation. Additionally, compared with conventional solid state detectors used in synchrotron light sources, TKIDs reach the same count rate with much higher energy resolution, resolving difficult X-ray fluorescence lines that often occur in environmental and biological samples where large varieties of elements are present. As less line overlapping due to higher energy resolution also results in lower signal background, TKIDs could significantly enhance the sensitivity for dilute or delicate samples. Just a moderate enhancement over their demonstrated capabilities is necessary to allow TKIDs to open a wide field of novel and intriguing applications for synchrotron science.

We have already demonstrated optical MKID arrays with 10.000 pixels[8] as well as TKIDs for X-ray detection[3]. The research I am proposing is to build on this expertize and continue improving basic TKID & MKID performance, mainly in the areas of energy resolution, pixel number and quantum efficiency. Different superconductors[11] with higher homogeneity or lower critical temperatures are a very promising route to follow, but reducing noise with different substrates or novel amplifiers is also attractive. Adapting the bolometric detection principle of TKIDs for lower energies could also increase energy resolution as it prevents the loss of high energy phonons to the substrate. For higher energy photons or particles, TKIDs mainly require further development effort to eliminate obvious shortcomings of their first generation prototypes like saturation and non-optimized thermal designs. Their energy resolution could be improved significantly by a variation of readout scheme or general sample geometry. And in order to increase their pixel fill factor, mushroom shaped absorbers or different geometries have to be implemented. In many fields, low temperature detectors are the future, and MKIDs and TKIDs are the most promising low temperature technology proposed so far.

I believe scientific research in general profits tremendously from collaborations, especially between different but neighboring fields. As I intend to emphasis demonstrating the highly multidisciplinary character of TKIDS and MKIDS, my goal is to seek collaborations for possible instrumentation in as many and as diverse scientific applications as feasible. Detector development lends itself to interdisciplinary collaboration, and to explore the multiple ways MKIDs and TKIDs can contribute to the scientific progress is one of their many fascinating aspects.

1: M.J. Strader, M.D. Johnson, B.A. Mazin, G.V. Spiro Jaeger, C.R. Gwinn, S.R. Meeker, P. Szypryt, J.C. van Eyken, D. Marsden, K. O'Brien, A.B. Walter, G. Ulbricht, C. Stoughton, B. Bumble: *Excess Optical Enhancement Observed with ARCONS for Early Crab Giant Pulses.* ApJL **779**, L12 (2013)

2: Day, P.K., LeDuc, H.G., Mazin, B.A., Vayonakis, A., Zmuidzinas, J.: *A broadband superconducting detector suitable for use in large arrays.* Nature, **425**, 817–821 (2003)

3: G. Ulbricht, B.A. Mazin, P. Szypryt, A.B. Walter, C. Bockstiegel, and B. Bumble: *Highly multiplexible thermal kinetic inductance detectors for X-ray imaging spectroscopy.* APL, **106**, 251103 (2015)

4: D. C. Moore, *PhD thesis*, Caltech (2012)

5: A. Nucciotti: *The Use of Low Temperature Detectors for Direct Measurements of the Mass of the Electron Neutrino*. Adv. High En. Phys. **2016**, 9153024 (2016)

S. Golwala, J. Gao, D. Moore, B. Mazin, M. Eckart, B. Bumble, P. Day, H. G. LeDuc, J. Zmuidzinas: *A WIMP Dark Matter Detector Using MKIDs.* J. Low. Temp. Phys. **151**:550-556 (2008)

6: L. Cardani, I. Colantoni, A. Cruciani, S. Di Domizio, M. Vignati, F. Bellini, N. Casali, M. G. Castellano, A. Coppolecchia, C. Cosmelli and C. Tomei: *Energy resolution and efficiency of phonon-mediated kinetic inductance detectors for light detection.,* APL, **107**, 093508 (2015)

7: Mazin, B.A., Meeker, S.R., Strader, M.J., Bumble, B., O'Brien, K., Szypryt, P., Marsden, D., van Eyken, J.C., Duggan, G.E., Ulbricht, G., Walter, A.B., Stoughton, C., and Johnson, M.: *ARCONS: A 2024 Pixel Optical through Near-IR Cryogenic Imaging spectrophotometer* PASP, **123**, 933 (2013)

8: Meeker, S.R., Mazin, B.A., Jensen-Clem, R., Walter, A.B., Szypryt, P., Strader, M.J., and Bockstiegel, C.: *Design and Development Status of MKID Integral Field Spectrographs for High Contrast Imaging.* Proc. AO4ELT 4 (2015)

9: Marsden, D., Mazin, B.A., O'Brien, K., Hirata, C.: *Giga-z: A 100,000 Object Superconducting Spectrophotometer for LSST Follow-up.* ApJS, **208**, 8 (2013)

10: K. O'Brien, N. Thatte, B. Mazin: *KIDSpec: an MKID based medium resolution integral field spectrograph*, Proceedings of the SPIE, **9147**, 91470G (2014)

11: Szypryt, P., Mazin, B.A., Ulbricht, G., Bumble, B., Meeker, S.R., Bockstiegel, C., Walter, A.B.: *High Quality Factor Platinum Silicide Microwave Kinetic Inductance Detectors.* APL, **109**, 151102 (2016)