A Microwave Kinetic Inductance Detector for the DAG Telescope

Tolga Güver[a,b], Benjamin A. Mazin[c], Kieran O'Brien[d], Burak Kay[e], Sinan Aliş[a,b], F. Korhan Yelkenci[a,b], Cahit Yeşilyaprak[f,g], Sinan K. Yerli[h], Ayşe Erol[e], and Onur Keskin[i]

[a]Department of Astronomy and Space Sciences, Faculty of Science, Istanbul University, Istanbul, Turkey
[b]Istanbul University Observatory Research and Application Center, Istanbul University, Istanbul, Turkey
[c]Department of Physics, University of California, Santa Barbara, CA 93106
[d]Department of Physics, University of Oxford, Denys Wilkinson Building, Keble Road, Oxford, OX1 3RH, UK
[e]Department of Physics, Faculty of Science, Istanbul University, Istanbul, Turkey
[f]Atatürk University, Science Faculty, Department of Astronomy and Astrophysics, Erzurum, Turkey.
[g]Atatürk University, Astrophysics Research and Application Center (ATASAM), Erzurum, Turkey
[h]Orta Doğu Teknik Üniversitesi (METU), Physics Department, Ankara, Turkey.
[i]FMV Işık University, Department of Mechanical Engineering, Istanbul, Turkey

ABSTRACT

We present the details of a proposed microwave kinetic inductance detector (MKID) for the DAG (Eastern Anatolia Observatory in Turkish) telescope, DAG-MKID. The observatory will have a modern 4m size telescope that is currently under construction. Current plan to obtain the first light with the telescope is late 2019. The proposed MKID based instrument will enable astronomers to simultaneously detect photons in the relatively wide wavelength range of 4000 - 13500 Å with a timing accuracy of μs and spectral resolution $R = \lambda/\Delta\lambda = 10 - 25$. With a planned field of view of approximately an arcminute, DAG-MKID will mostly be used for follow-up observations of transient or variable objects as well as a robust tool to measure photometric redshifts of a large number of galaxies or other extra-galactic objects.

Keywords: focal plane instrumentation, telescope, microwave kinetic inductance

1. DAG (EASTERN ANATOLIA OBSERVATORY IN TURKISH)

DAG is a Turkish state funded (Ministry of Development) project with a goal of establishing a 4m class observatory in Erzurum, Turkey (http://dag-tr.org/; see Figure 1). The project started in 2011. The telescope will be located at Karakaya hills at an altitude of 3170 m, making it one of the highest altitude telescopes in the world. DAG has a Ritchey-Chrétien configuration with two Nasmyth foci (no Cassegrain focus) and a 4m primary mirror. The focal length will be 56 m, which results in an f-ratio of 14 and an unvignetted field of view of 30 arcmin. The mirrors will be coated with Aluminum resulting in a high reflectivity in the 350 3000 nm. There will be active optics as well as GLAO (corrected field of view 5') in one of the Nasmyth foci (see poster AS16-9910-113 for details). Figure 1 shows the current design of the observatory building and the telescope.

Further author information: (Send correspondence to T.G.)
T.G.: E-mail: tolga.guver@istanbul.edu.tr, Telephone: +90 440 00 00 / 10284

High Energy, Optical, and Infrared Detectors for Astronomy VII, edited by Andrew D. Holland, James Beletic,
Proc. of SPIE Vol. 9915, 99152P · © 2016 SPIE · CCC code: 0277-786X/16/$18 · doi: 10.1117/12.2234281

Figure 1. *Architectural design of DAG observatory building and telescope. ©2016 Günarda & DAG. See AS16-9911-106 for other details of civil work.*

2. MICROWAVE KINETIC INDUCTANCE DETECTORS

A microwave kinetic inductance detector (MKID; see Figures 2 and 3) is a type of superconducting photon detector operating below 1 K and can be used in high-sensitivity astronomical observations in a broad wavelength range extending from 0.1 to 5 μm.[1] The operation of an MKID is based on the kinetic inductance effect.[2,3] Absorbed photons with an energy $h\nu > 2\Delta$, where Δ is the bandgap of the superconducting material,[4] in a cooled superconducting film breaks the Cooper pairs and creates quasi-particles, leading to a change in the surface impedance of the superconductor via the kinetic inductance process. This change can be measured using a superconducting inductor in a microwave resonant circuit. These circuits include lithographically produced coplanar-waveguide (CPW) resonators.[3,5] An MKID can be easily fabricated using lithographic techniques in the form of large arrays.

Although, superconducting materials have high surface impedance, as long as $T < T_c$, it is impossible to calculate the surface impedance via general solutions, where T_c is the critical temperature of the material being used.[6–8] Therefore, in order to calculate the surface impedance, numeric calculation methodology is inevitably needed.[6–8] Moreover, electromagnetic wave being absorbed on the material, by itself triggers a change in the surface impedance. As a result, this enables the calculation of the density of state (DOS) in a superconducting material. DOS not only explains the change of carrier density in the material but also is a key parameter in the selection of the material to be used in an MKID.

Titanium Nitride (TiN) has been used frequently as the absorbing material in MKIDs for optical astronomical applications. Currently, the best quality TiN thin film can be grown by Atomic Layer Deposition (ALD) method.[9] Nitrogen composition of TiN_x used in an MKID is less than 1.[1,10,11] Phase separation, which is occurs due to the electromagnetic wave being sent on the material, depends on the Nitrogen composition and begins at 800 mK, reaching its peak level at 110 mK. Lifetime of the quasi-particles in the material varies from 50 to 100 μs.[1] The fabrication of this material using orthodox lithography techniques is a difficult task because

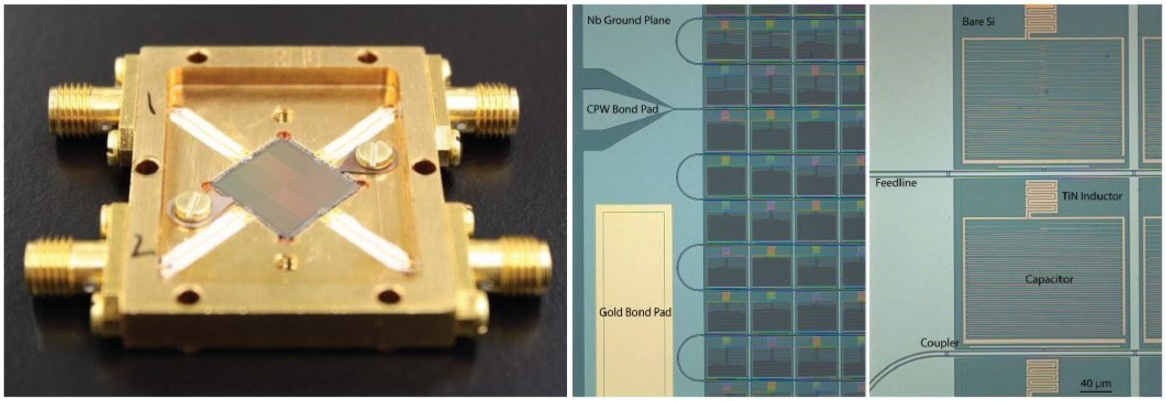

Figure 2. *Left: Photograph of a 2024 pixel MKID array namely ARCONS. Right: Microscope image of the same 2024 pixel MKID array, reprinted from Mazin et al. (2013).*[1]

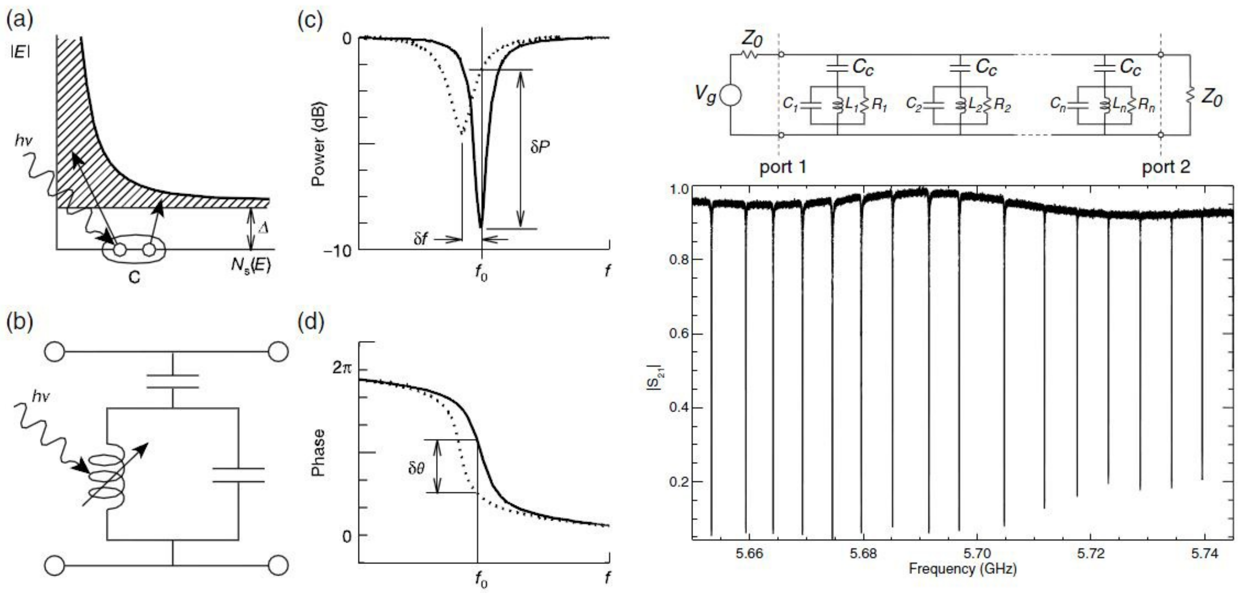

Figure 3. *Basic operation of an MKID, reprinted from Day et.al (2003).*[3] *Left: (a) An energy level diagram showing the number of states Ns(E) a superconductor with gap Δ. Photons with energy $h\nu$ are absorbed in a superconducting film, breaking Cooper pairs C, and producing a number of excitations called quasi-particles. (b) To sensitively measure these quasi-particles, the film is placed in a high frequency planar resonant circuit. In the right panels, the amplitude (c) and phase (d) response of a microwave excitation signal sent through the resonator as a function of frequency are shown. The change in the surface impedance of the film following a photon absorption event pushes the resonance to lower frequency and changes its amplitude. If the detector (resonator) is excited with a constant on-resonance microwave signal, the energy of the absorbed photon can be determined by measuring the degree of phase and amplitude shift. Right: Example of frequency domain multiplexing (FDM) of MKIDs showing many resonators being read out through a single transmission line.*

of high surface impedance of the material. It also has surface non-uniformity.[9–11] For a TiN material, due to structural defects and thermal-induced causes, DOS expansion can occur, which is undesirable and one of the major obstacles for material lithography. This is proportional with the material's growth condition parameter.

One of the most successful application of the TiN is the ARCONS,[1] the Array Camera for Optical to Near-IR Spectrophotometry. ARCONS is a 2024 pixel MKID array yielding a 20" × 20" when used at the Palomar 200 inch and Lick 120 inch telescopes. Within a relatively short 24 day observing run a number of scientific results have already been published.[1,12,13]

Table 1. MKID Test Device Properties[1,10,14]

Material	Critical Temperature T_c	Internal Quality Factor Q_i	Energy Resolution E/ΔE	Quasiparticle Lifetime τ_q	Optical Absorption
TiN	800 mK	$> 10^6$	8 - 10	50 - 100 μs	
PtSi	850-910 mK	150,000	8	20 μs	20-40

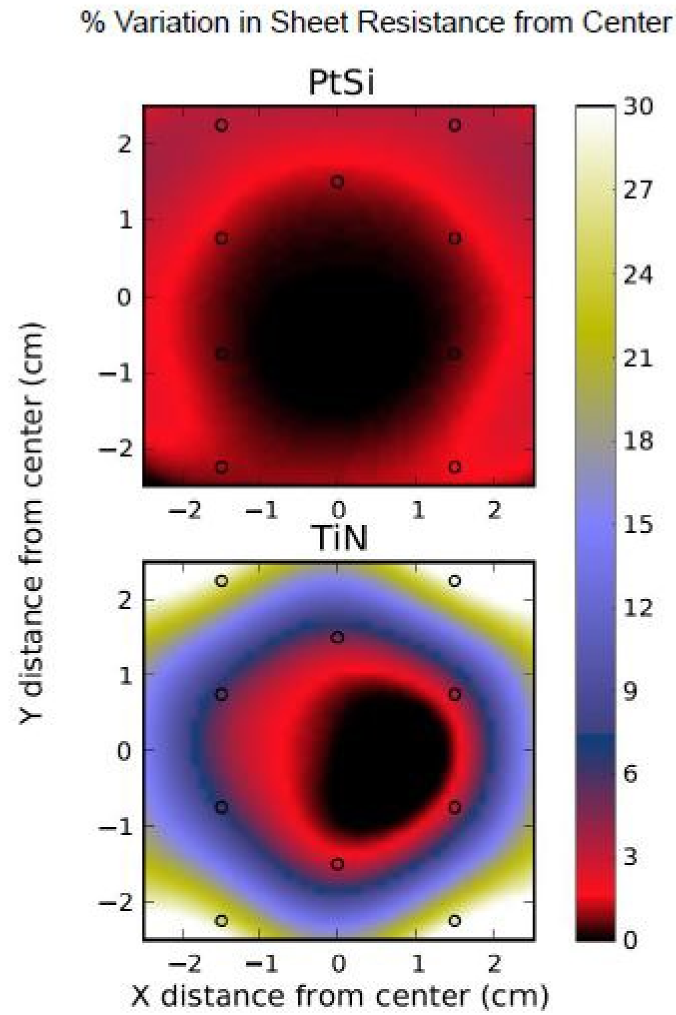

Figure 4. *4x4 cm uniformity of PtSi and TiN materials reprinted from Szypryt et al. 2016*[14]

To increase the operating temperature of MKIDs and improve their efficiency, an intense research programme is ongoing to discover novel superconducting materials. Recently, **Platinum Silicide (PtSi)** has been proposed[14] as an alternative to TiN with its superior properties over TiN as given in Table 1.

PtSi can be grown by Electron beam physical vapor deposition methods,[15] therefore it is possible to have a larger uniform area than that of TiN material, see Figure 4. Although nitrogen composition having less than 1 in TiN material reduces the critical temperature to the desired level, non-uniformity of the surface leads to a change in the structural characteristic of TiN material.[1,9–11] Furthermore, it is impacting the equivalence of pixel sensitivity.[14]

Due to its wider surface uniformity, it is expected that pixel sensitivity of the detector which is produced from PtSi material will be better than TiN based-detector, see Figure 4.

3. DAG-MKID

The proposed DAG-MKID will be an array of approximately 183×183 pixels sensitive to photons in the 400 nm - 1350 nm wavelength range with and effective spectral resolution of $R = \lambda/\Delta\lambda \approx 25$ and 10 in the 400 nm and J band, respectively. The instrument will provide a time resolution of $\sim 1\mu$s. DAG-MKID will be produced using PtSi. DAG-MKID will be one of the first MKID based instruments that will be used by the general astronomical community on site at all times. In order to allow astronomers to use the instrument as effectively as possible we will also establish a laboratory and service unit in Istanbul University. In this laboratory tests, calibrations and possible improvements of this instrument will be made. Also the whole data archive of the instrument will be kept. A pipeline software based on the existing software for ARCONS[16] for basic calibration and for the creation of final science products will be developed and maintained in the same laboratory.

4. SCIENCE CASES

We are in the era of a variety of currently planned or ongoing multi-wavelength surveys (PanSTARRS, SDSS, GAIA, LSST, WFIRST, e-ROSITA, Euclid, FERMI, etc.). Furthermore a large number of survey projects have already been progressing for several years and resulted in large databases full of treasures (i.e. SDSS, PanSTARSS, 2MASS, GAIA). Therefore, scientific rationale and drivers of the DAG telescope have been motivated by the obvious need of follow-up observations of all the newly discovered or to be discovered objects by these surveys. For this purpose, DAG Science Team is planning to position the observatory as a reliable and effective follow-up facility in addition to regular observing campaigns. The telescope will be observing in queue mode and will have a flexible observing programme. With such aims it is important to have a versatile instrument that allows for efficiently observing objects in a wide wavelength range.

If successfully installed DAG-MKID will play an important role in such a telescope because of its key capabilities:

- No read-out or dark noise enabling the observations of dim objects effectively.
- Ability to observe with very high time resolution.
- Ability to create spectral energy distributions (400 - 1350 nm) of all the detected sources in the field of view simultaneously without using any optical elements.

These key capabilities will allow the DAG-MKID to be effective especially in the following science cases:

- Search for electromagnetic counter-parts of gravitational wave signatures
- Follow-up of Gamma-Ray bursts and supernovae
- Monitoring observations of X-ray binaries, CVs, AGNs and other time variable objects
- Observations of nearby pulsars
- Transit observations of exoplanets
- Determining photometric redshifts of galaxies
- Detection of galaxy clusters up to z 1

Below we provide a few example cases:

4.1 Monitoring of Transient and Variable Objects

There is a small but vibrant and effective X-ray community in Turkey working mainly on sources showing temporal variability. Researchers located especially in Sabancı University, Istanbul University, Middle East Technical University, Istanbul Technical University, Adıyaman University and several other institutions, work on transient and persistent low mass X-ray binaries, gamma-ray bursts, active galactic nuclei, interacting binaries and other similar objects. Below we very briefly summarize these science cases.

4.2 Gamma-Ray Bursts

Gamma-ray bursts (GRBs) are intense flashes observed in the gamma-ray band. During the initial peak a GRB becomes the brightest object in the whole gamma-ray sky. A number of different monitoring telescopes today allow the detection of the GRBs at these early stages and provide their precise coordinates that allows for larger optical telescope to follow-up the afterglow and any other related emission in the optical/NIR regime. Although today we know that the long GRBs (the ones that last longer that 2 s) are the result of a massive start directly to a black hole. The details of the resulting jet emission are not known very well. Furthermore, although mostly attributed to the mergers of compact objects, the progenitors of short gamma-ray bursts ($T_{90} < 2$ s) and their relation with the gravitational wave sources are still not very well known.[17]

As mentioned above, DAG will be a queue based observatory, with an emphasize on time critical observations and will have flexible scheduling. These properties already make this observatory and exciting site for time domain astronomy related projects. DAG-MKID together with these policies will make DAG a unique observatory. Specifically, DAG-MKID will allow for simultaneous observation of the afterglow (or the prompt emission) in the whole optical and part of the near-IR band with high time resolution.

4.3 Compact Objects

Compact objects (white dwarfs, neutron stars and black holes) especially in binary systems are expected be one of the main targets for the proposed DAG-MKID. Specifically high time resolution observations of X-ray binaries during outbursts can provide unique clues on the jet formation and its evolution.[18,19] In nearby binary systems it has even been possible to measure directly the orbital expansion in an AM CVn system.[12]

Isolated and especially nearby neutron stars will also provide a very good target for DAG-MKID. Strader et al.[13] took advantage of the ARCONS detector and observed an optical enhancement from the Crab Pulsar.

4.4 Determining Photometric Redshifts

Photometric redshift is a very powerful tool to study the large-scale structures in the universe. As classical spectroscopy is time consuming and highly demanded mode for observing, it is difficult to obtain redshifts for large number of objects. The technique was introduced by Baum[20,21] and have been used in all imaging surveys extensively. Especially, since 2000 when SDSS became operational. Determining photometric redshifts rely on obtaining multi-band photometry (e.g. fluxes) of interested objects. Thus, producing a spectral energy distribution becomes possible which is used to constrain object's redshift. In this respect having photometric measurements in many filters becomes crucial to improve the accuracy of photometric redshifts.[22]

DAG-MKID will enable to determine photometric redshifts as it can measure multi-wavelength fluxes with very low background noise. Moreover, it can measure fluxes simultaneously within the wavelength range which is not the case for current imaging surveys. This feature will obviously decrease the time spent for each object and will enable to undertake larger projects with the DAG telescope. Given the size of the array and the focal ratio, expected field-of-view will be around 1 arcmin. This FOV is not very large but substantial for observing individual objects and galaxy clusters with $z \geq 0.1$.

4.5 Detecting Galaxy Clusters

Photometric redshifts will be obtained with DAG-MKID can be used to detect galaxy clusters.[23] Wavelength range of the instrument will help to detect clusters around $z \sim 1$ as Y and J bands in the near-infrared will be covered. Several studies have shown the importance of using near-infrared fluxes due to the shift of the spectral energy distribution of galaxies towards longer wavelengths with increasing redshift.[24–26] For detecting clusters with $z \geq 0.8$ it is almost crucial to use near-infrared fluxes.[24] DAG-MKID can be used to detect clusters especially in the redshift range of $0.8 \geq z \geq 1.2$ in a similar fashion with Euclid mission. The instrument can also be used to confirm galaxy clusters detected in X-rays. Specifically, a synergy between eRosita and ART-XC onboard SRG satellite is strongly desired and expected.

5. CONCLUSIONS

With its 4m aperture and high technology new design, DAG will allow astronomers in Turkey and all around the world a unique opportunity in a number of different science cases. DAG-MKID is aimed at putting this to another level with a state-of-the-art instrument that allows the simultaneous detection of photons in the whole optical and near-IR (up to J band) wavelength range with high time resolution. With these characteristics DAG-MKID is expected to especially be used in follow-up observations of transient and variable objects as well as transit observations and photometric redshift estimations. The use of MKID based instruments in the optical band is very new and is expected to open up an array of new scientific opportunities. Engaging in this developing technology at its early stages also gives Turkish astronomers, physicists and engineers a chance to be involved with the technology, make use of all the opportunities that it provides and help improving the current state of the art of this technology.

ACKNOWLEDGMENTS

Authors would like to thank Republic of Turkey, Ministry of Development; Istanbul University, Istanbul/Turkey (Project No: 2016K121370); Atatürk University, Erzurum/Turkey (Project No: 2011K120230, 2016K121140); Orta Dou Teknik Üniversitesi, Ankara/Turkey (Project No: 2016K121380); FMV Işık University, Mechanical Engineering Department, Istanbul/Turkey; Istanbul University Observatory Research and Application Center (IUGUAM), Istanbul/Turkey; FMV Ik University, Center of Optomechatronics Application and Research (OPAM), Istanbul/Turkey for their support through out the DAG project.

REFERENCES

[1] Mazin, B. A. et al., "Arcons: A 2024 pixel optical through near-ir cryogenic imaging spectrophotometer," *Publications of the Astronomical Society of the Pacific* **125**, 1348–1361 (2013).

[2] Mattis, D. C. and Bardeen, J., "Theory of the anomalous skin effect in normal and superconducting metals," *Physical Review* **111**(2), 412–417 (1958).

[3] Day, P. K. and othes, "A broadband superconducting detector suitable for use in large arrays," *Nature* **425**, 817–821 (2003).

[4] Mazin, B. A., O'Brien, K., McHugh, S., Bumble, B., Moore, D., Golwala, S., and Zmuidzinas, J., "ARCHONS: a highly multiplexed superconducting optical to near-IR camera," *Groundbased and Airborne Instrumentation for Astronomy III Edited by I. McLean* **7735**(285), 773518–773518–10 (2010).

[5] Mazin, B. A., "Microwave Kinetic Inductance Detectors Ph.D. thesis," (2004).

[6] Gao, J. et al., "Experimental evidence for a surface distribution of two-level systems in superconducting lithographed microwave resonators," *Applied Physics Letters* **92**, 1–3 (2008).

[7] Gao, J., "The Physics of Superconducting Microwave Resonators Thesis by," *CIT PhD thesis* , 1–141 (2008).

[8] Zmuidzinas, J., "Superconducting microresonators: Physics and applications," *Annual Review of Condensed Matter Physics* **3**(1), 169–214 (2012).

[9] Vissers, M. R., Gao, J., Sandberg, M., Duff, S. M., Wisbey, D. S., Irwin, K. D., and Pappas, D. P., "Proximity-coupled Ti/TiN multilayers for use in kinetic inductance detectors," *Applied Physics Letters* **102**(23), 1–10 (2013).

[10] Gao, J., Vissers, M. R., Sandberg, M. O., Da Silva, F. C. S., Nam, S. W., Pappas, D. P., Wisbey, D. S., Langman, E. C., Meeker, S. R., Mazin, B. A., Leduc, H. G., Zmuidzinas, J., and Irwin, K. D., "A titanium-nitride near-infrared kinetic inductance photon-counting detector and its anomalous electrodynamics," *Applied Physics Letters* **101**(14) (2012).

[11] Diener, P., Yates, S. J. C., Lankwarden, Y. J. Y., Baselmans, J. J. A., and Leduc, H. G., "Design and testing of kinetic inductance detectors made of titanium nitride," *Journal of Low Temperature Physics* **167**(3-4), 305–310 (2012).

[12] Szypryt, P., Duggan, G. E., Mazin, B. A., Meeker, S. R., Strader, M. J., van Eyken, J. C., Marsden, D., O'Brien, K., Walter, A. B., Ulbricht, G., Prince, T. A., Stoughton, C., and Bumble, B., "Direct detection of SDSS J0926+3624 orbital expansion with ARCONS," *MNRAS* **439**, 2765–2770 (Apr. 2014).

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

[14] Szypryt, P. et al., "Platinum Silicide MKIDs for UVOIR Astronomy," *16th International Workshop on Low Temperature Detectors* (2016).

[15] Szypryt, P., Mazin, B. A., Bumble, B., Leduc, H. G., and Baker, L., "Ultraviolet , Optical , and Near-IR Microwave Kinetic Inductance Detector Materials Developments," **25**(3), 3–6 (2015).

[16] van Eyken, J. C., Strader, M. J., Walter, A. B., Meeker, S. R., Szypryt, P., Stoughton, C., O'Brien, K., Marsden, D., Rice, N. K., Lin, Y., and Mazin, B. A., "The ARCONS Pipeline: Data Reduction for MKID Arrays," *ApJS* **219**, 14 (July 2015).

[17] Berger, E., "Short-Duration Gamma-Ray Bursts," *ARA&A* **52**, 43–105 (Aug. 2014).

[18] Kalemci, E., Dinçer, T., Tomsick, J. A., Buxton, M. M., Bailyn, C. D., and Chun, Y. Y., "Complete Multiwavelength Evolution of Galactic Black Hole Transients during Outburst Decay. I. Conditions for "Compact" Jet Formation," *ApJ* **779**, 95 (Dec. 2013).

[19] Chun, Y. Y., Dinçer, T., Kalemci, E., Güver, T., Tomsick, J. A., Buxton, M. M., Brocksopp, C., Corbel, S., and Cabrera-Lavers, A., "Multiwavelength Observations of the Black Hole Transient XTE J1752-223 during Its 2010 Outburst Decay," *ApJ* **770**, 10 (June 2013).

[20] Baum, W. A., "Photoelectric determinations of redshifts beyond 0.2c," *Astronomical Journal* **62**, 6 (1957).

[21] Baum, W. A., "Photoelectric Magnitudes and Red-Shifts," *IAU Symposium* **15**, 390 (1962).

[22] Ilbert, O. et al., "Cosmos Photometric Redshifts with 30-Bands for 2-deg^2," *The Astrophysical Journal* **690**, 1236–1249 (2009).

[23] Durret, F. et al., "Galaxy cluster searches based on photometric redshifts in the four CFHTLS Wide fields," *Astronomy & Astrophysics* **535**, A65 (2011).

[24] Willis, J. P. et al., "Distant galaxy clusters in the XMM Large Scale Structure survey," *Montly Notices of the Royal Astronomical Society* **430**, 134–156 (2013).

[25] Santos, J. S. et al., "Dust-obscured star formation in the outskirts of XMMU J2235.3-2557, a massive galaxy cluster at z = 1.4," *Montly Notices of the Royal Astronomical Society* **433**, 1287–1299 (2013).

[26] Pierini, D. et al., "First simultaneous optical/near-infrared imaging of an X-ray selected, high-redshift cluster of galaxies with GROND. The galaxy population of XMMU J0338.7 + 0030 at z = 1.1," *Astronomy & Astrophysics* **540**, A45 (2012).