Energy sensitive detectors for wavefront sensing

or…
Kinetic Inductance Detectors (KIDs) for wavefront sensing

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Durham, UCSB, SRON, JPL

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Detectors for astronomy

	Sensitivity	Noise	Time resolution	Energy resolution	Array size	Cost/unit
Eyes	Poor	Good	msec	Poor	Good	Free
Photographic plates	Fair	Poor	minutes	none	Good	Moderate
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STJ	Fair	Excellent	μsec	Fair	Poor	High
TES	Fair	Excellent	μsec	Fair	Poor	High
KID	Fair	Excellent	μsec	Fair	Fair	Moderate

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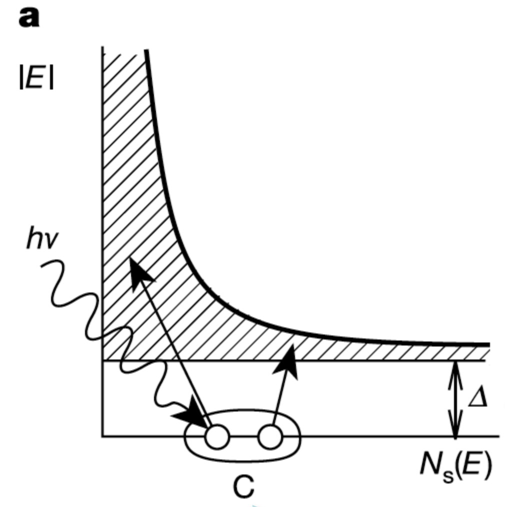
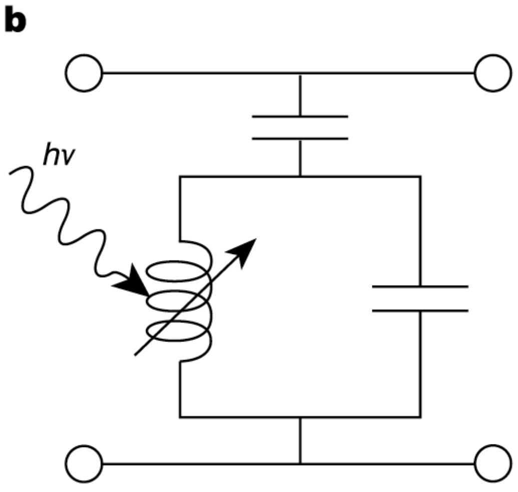
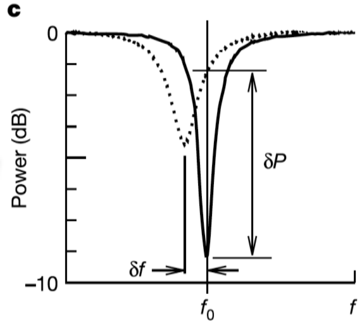
Kinetic Inductance Detectors

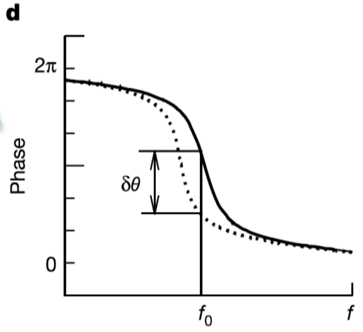
MKID Equivalent Circuit

Inductor is a Superconductor!









Cooper Pair

Energy Gap

Silicon –	1.10000 eV
Aluminum –	0.00018 eV
PtSi -	0.00007 eV

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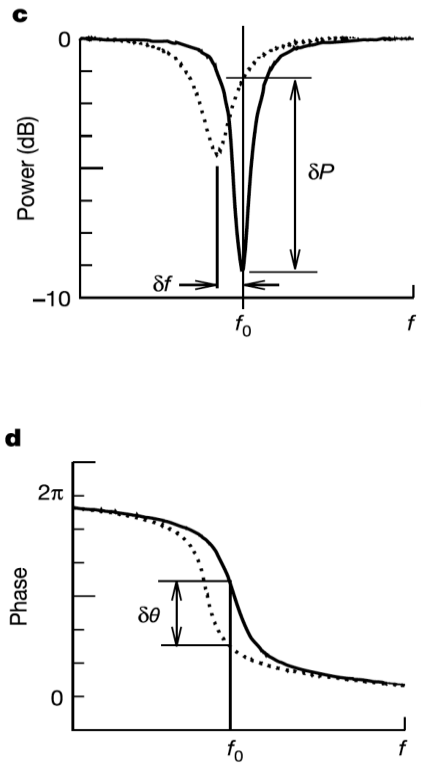
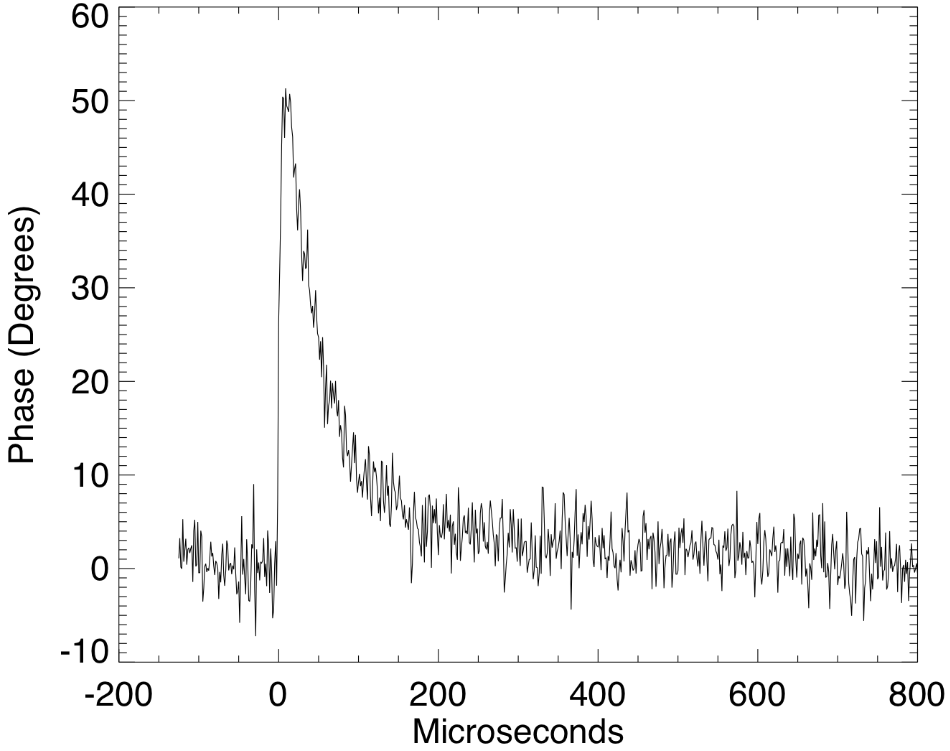
Phase-shift of probe signal



Typical Single Photon Event



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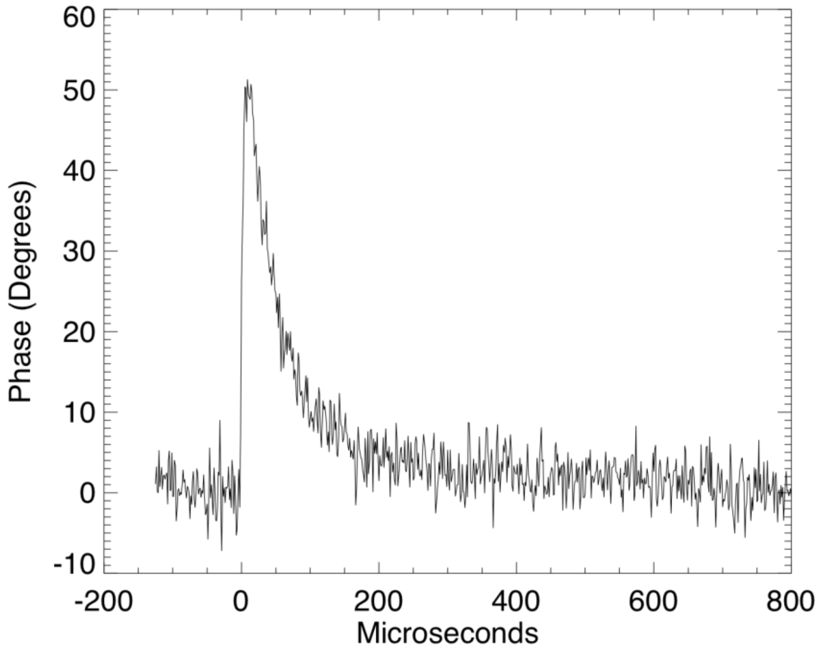
Energy resolving detector

Energy Gap

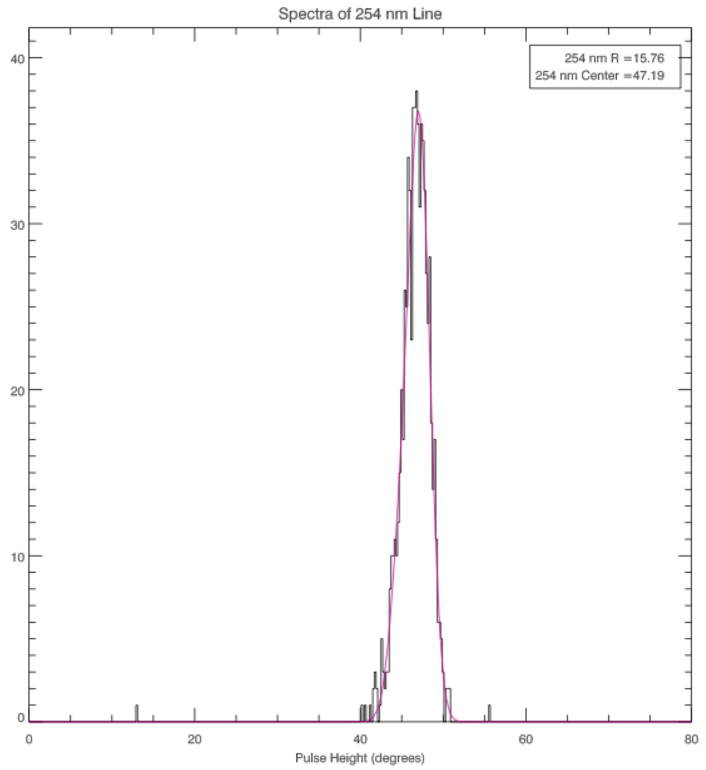
Silicon – 1.10000 eV
Aluminum – 0.00018 eV
PtSi - 0.00007 eV

$$R_{max} = \frac{1}{2.355}\sqrt{\frac{\eta h\nu}{F\Delta}}$$



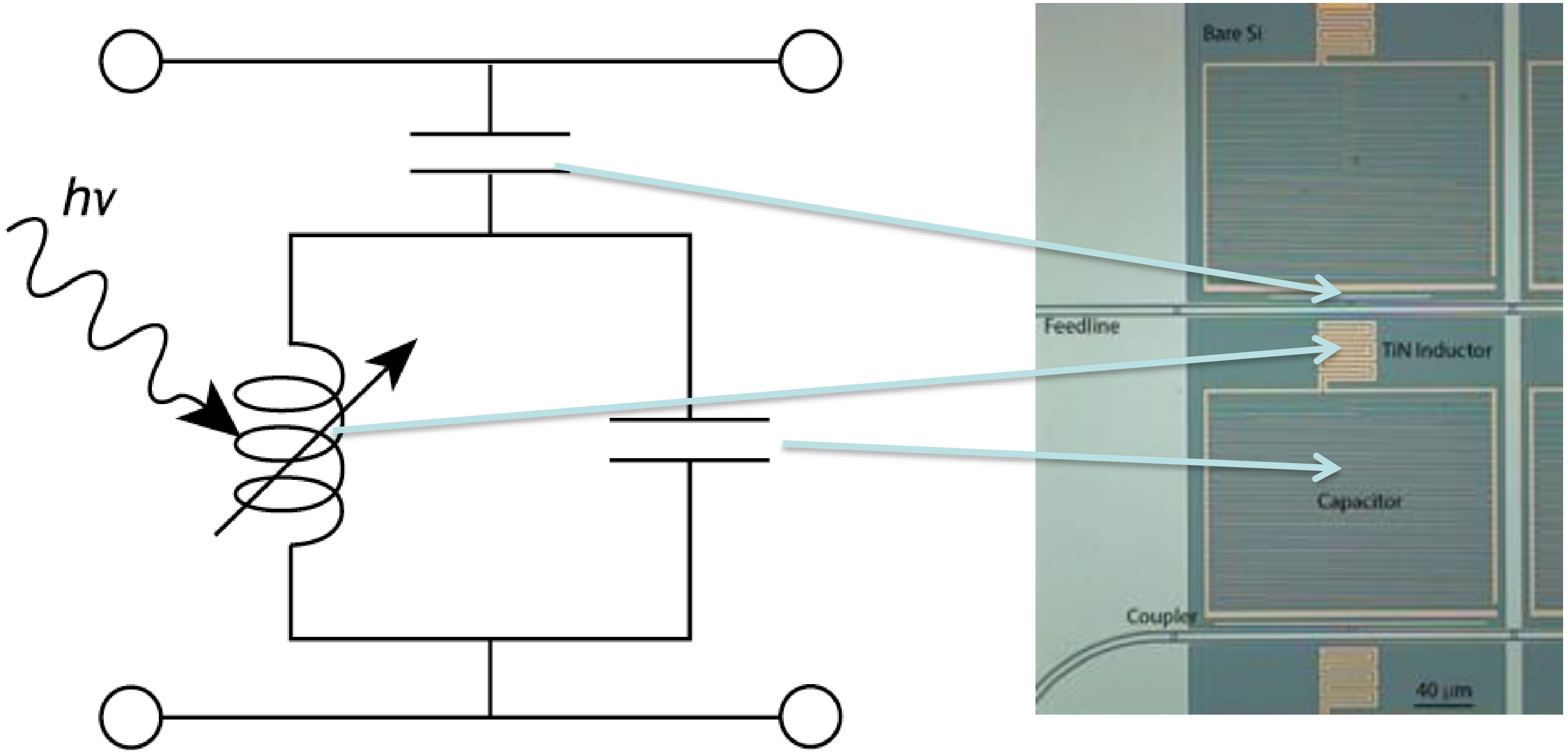
hν= 3.1eV (400nm), R <~ 150 for η=0.57, F = 0.2

Distribution of Photon Events

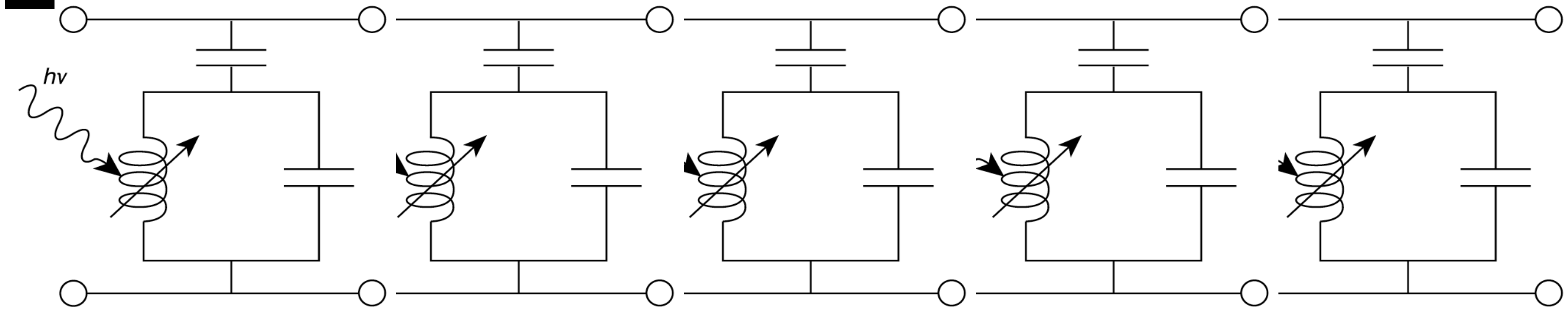


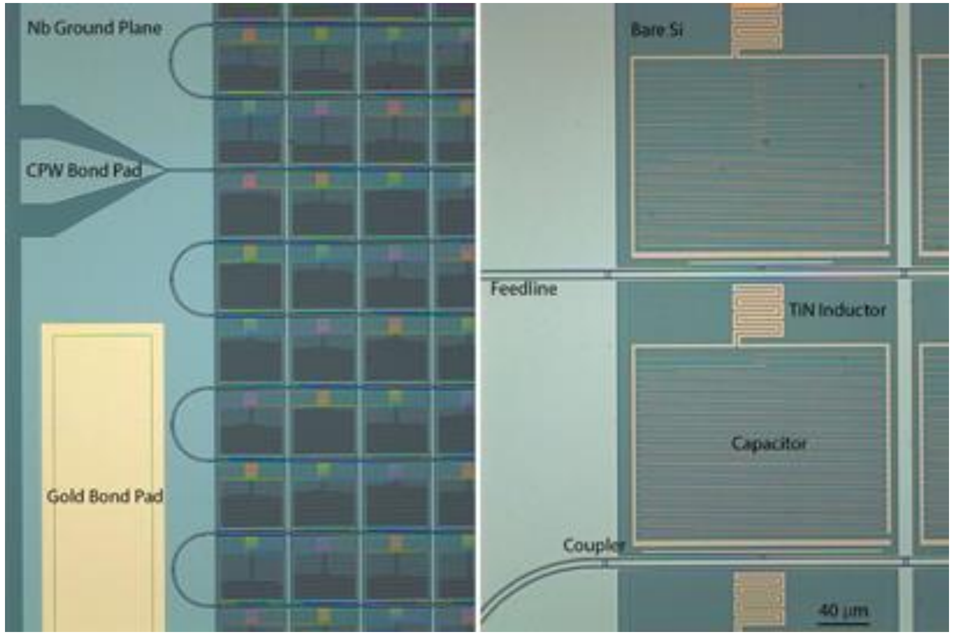
$$R_{meas} = \frac{\mathrm{E}}{FWHM(\mathrm{E})}$$

Lumped element pixels



Arrays of MKIDs

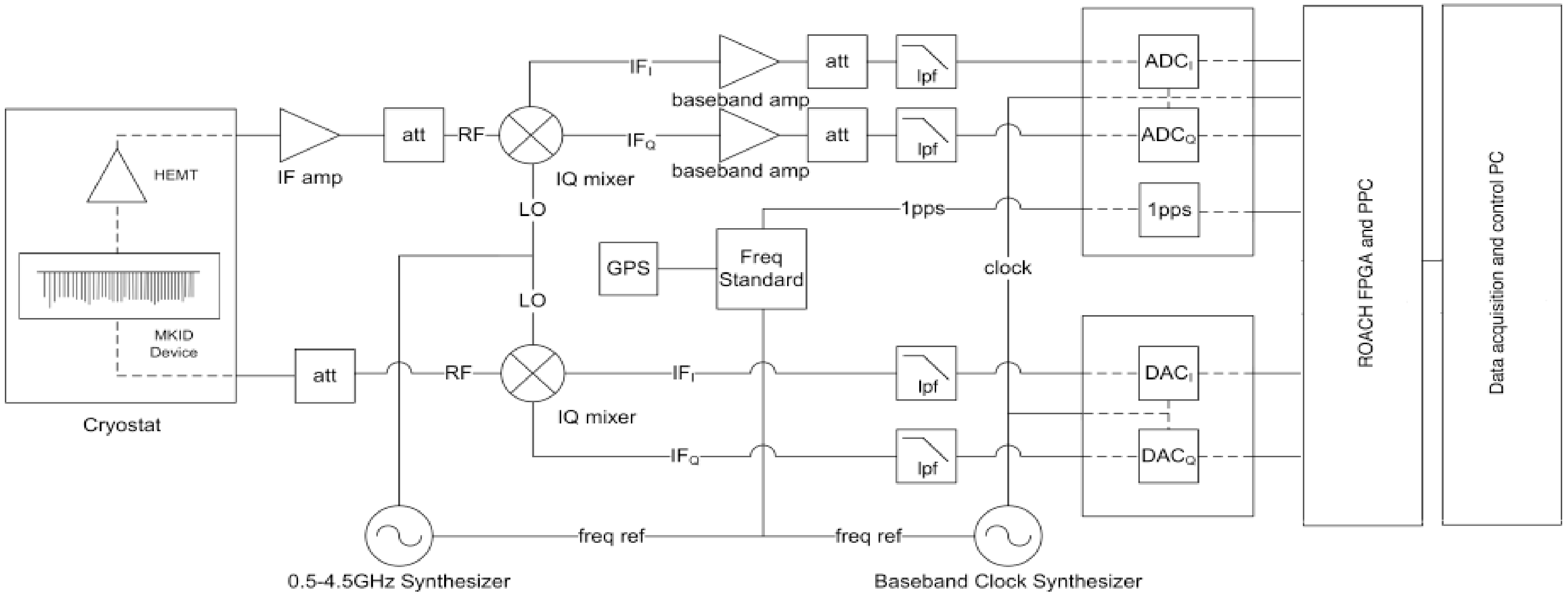




Digital MKID Readout

Software Defined Radio (SDR) Overview

- Leverages massive industry investment in ADCs/FPGAs
- Generate frequency comb and up-convert to frequency of interest
- Pass through MKID and amplify
- Down-convert and Digitize
- “Channelize” signals in a powerful FPGA
- Process pulses (optical/UV/X-ray) or just output time stream (sub-mm)

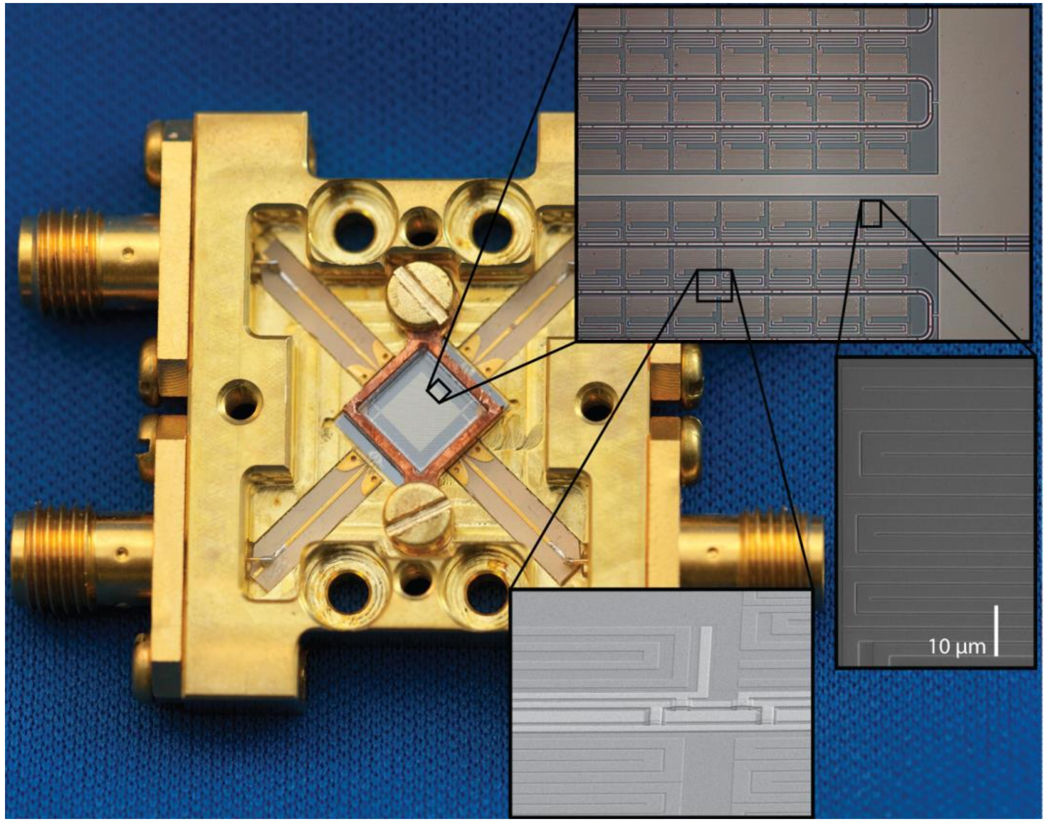


Gen-3 read-out

- Uses latest Xilinx RF system-on-chip (RFSoC) hardware that combines FPGA and ADC/DACs
  - ZCU111
    - ZYNQ ULTRASCALE+ FPGA
    - 8x 14-bit 6.5GSPS DAC
    - 8x12-bit 4GSPS ADC
  - Development driven by telecoms industry
- Firmware similar architecture to Gen-1 & 2
- Developed single-feedline hardware for mixing to 4-8GHz with UKRI-funding, now have hardware for 10,000 pixel array
- Investigating firmware architectures to read-out multiple feedlines on a single board, reducing cost/pixel further
  - ROACH Based readout cost ~$50/pixel used in ARCONS
  - RFSoC system being deployed now is ~$6/pixel

The first science array (2011)

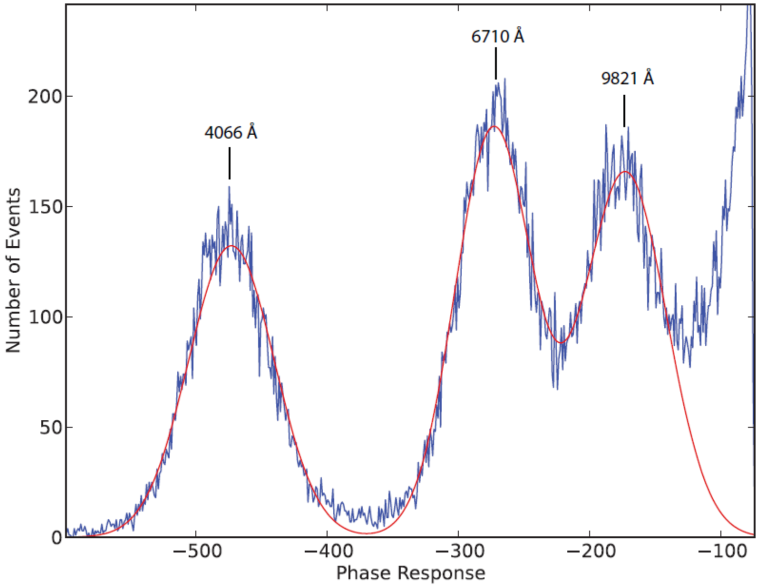
- 1024 pixel array (15x larger than any previous STJ/TES array)
- 2 feedlines with 512 resonators/feedline
- Designed to have 2MHz spacing between resonators
- Resonators close in frequency are far apart in space
- 839 resonators found in wide sweep (82%)
- 669 pixels accessible by read-out (4x512MHz)
- 65% of total array



Mazin, et al. PASP, 123, 933

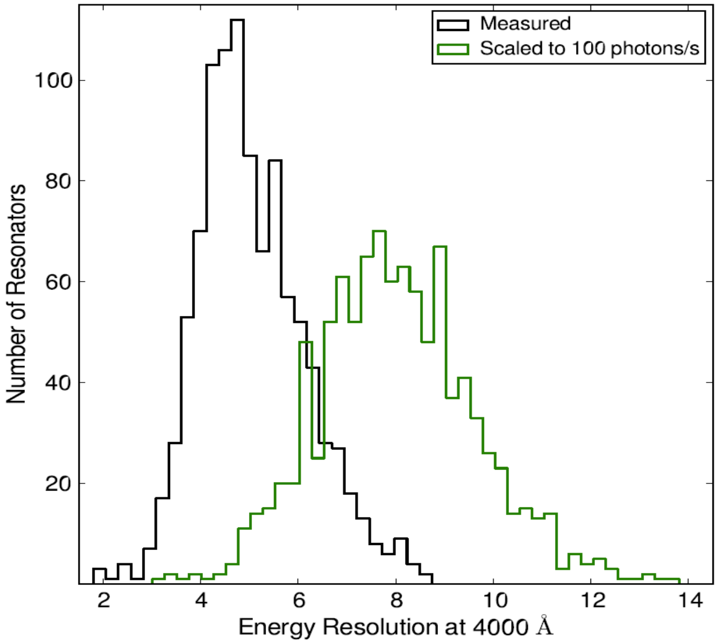
Spectral response

Currently far from 'Fano' limit.



Typical histogram of pulse heights from calibration source

Histogram of resolution of individual resonators (pixels)



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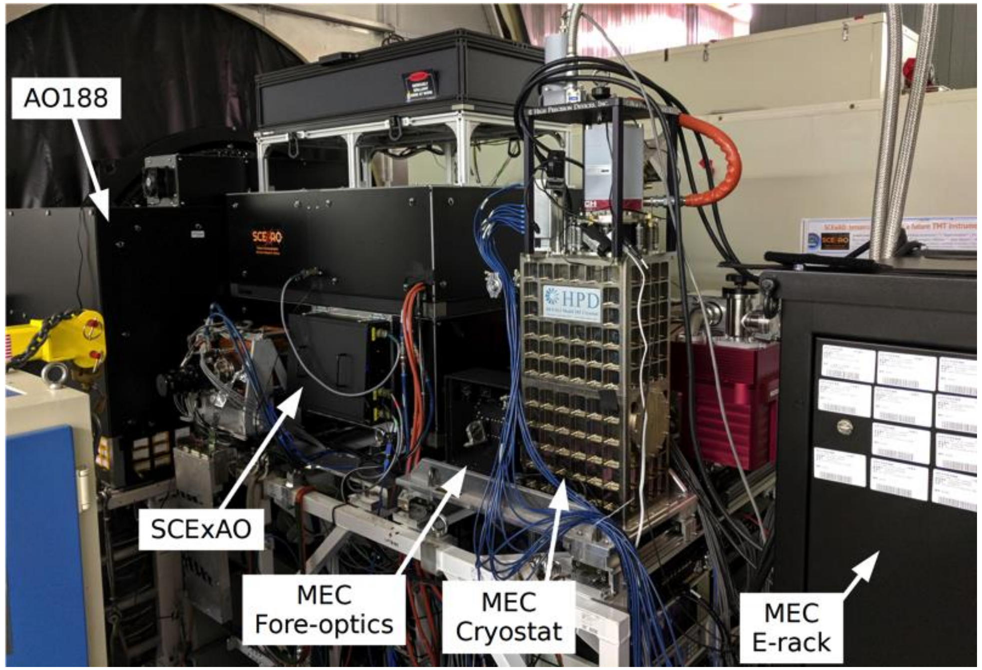
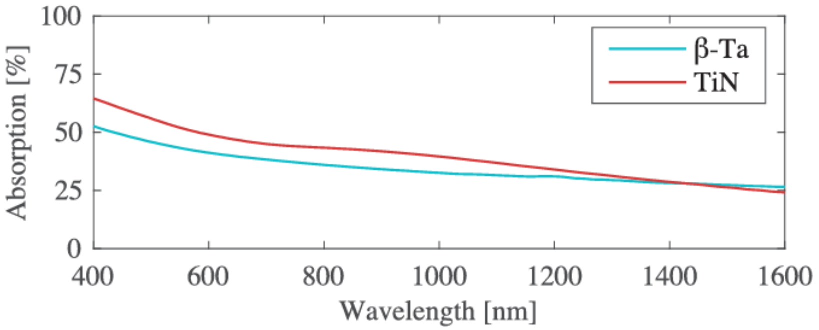
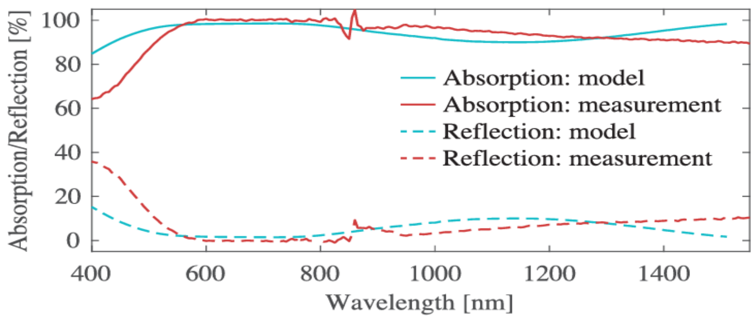
MEC at SCExAO

- Ben Mazin at UCSB
- Walter et al., 2020 PASP 132 125005
- Focal plane IFS at y-band to J-band
- 20,000 pixel MKID array
- Stochastic Speckle Discrimination (SSD) using the photon arrival times
- First instrument in regular use with MKIDs

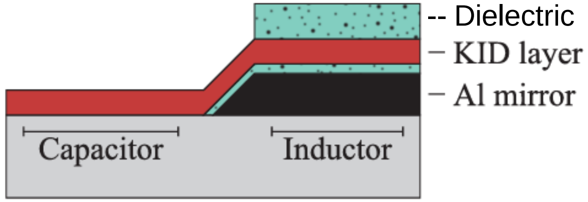


Quantum Efficiency



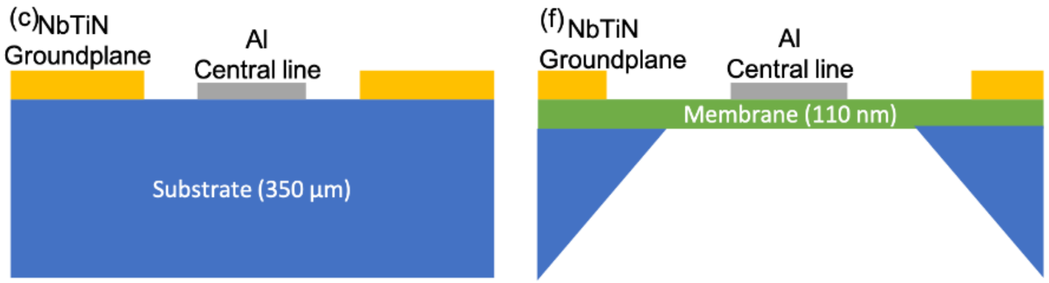


- Metals with natural absorption of 30-50%
- Simple model
  - 85 nm SiOx
  - 60 nm TiN (KID inductor)
  - 23 nm SiOx
  - 100 nm thick Al (mirror)
- Needs to be demonstrated in a large array
- Can be further improved with more complex dielectric stacks



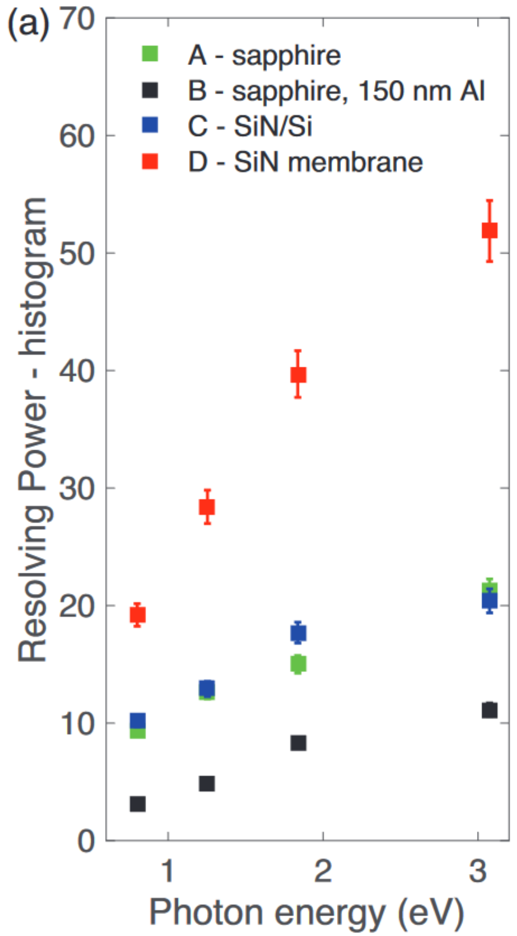
Kouwenhoven, et al. JLTP, 2022

Energy resolution - I

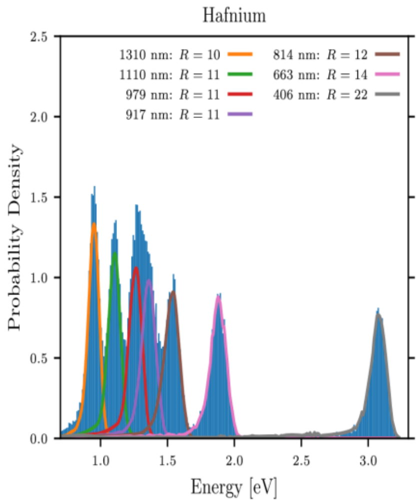


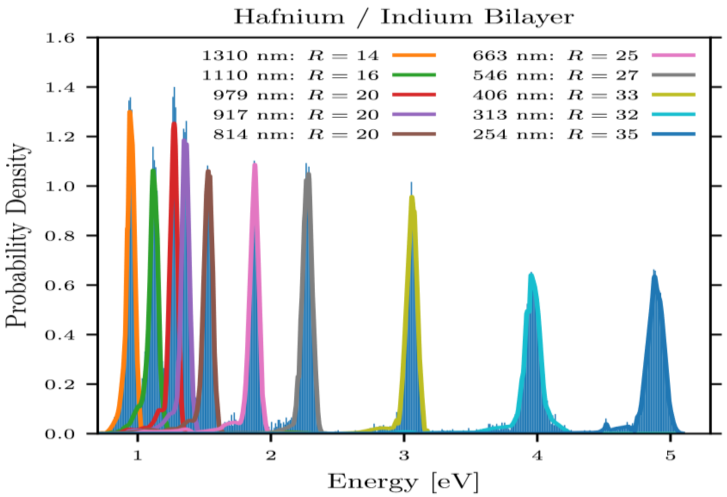
Pieter de Visser et al, PhyRevApp, 16, 034

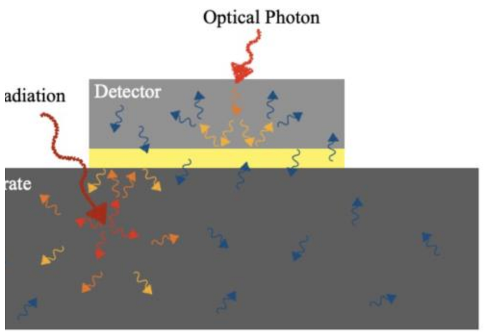
- SRON group
- NbTiN-Al Hybrid MKID
- Suspended on SiN membrane
- Phonons take longer to be lost to substrate, so can break more cooper pairs
- Single pixel device (at the moment)
- Energy resolution of ~50 at 400nm



Energy resolution - II







Nick Zobrist et al., Physical Review Letters, Volume 129, 017701

- UCSB-team
- Indium (yellow) beneath Hafnium (light grey) MKID
- Different phonon states means they are reflected either back into detector (optical photons) or back into substrate (cosmic rays)
- Easier to manufacture, especially large arrays
- Energy resolution: R=33 from R=22 at 406nm
  R=25 from R=14 at 663nm

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KID (next 5 years?)	Excellent	Excellent	μsec	Good	Good	Fair

Instrument concepts

Classification of transients	Accretion onto compact objects	Dark matter/energy	Exoplanets	Wave-front sensing
High throughput, low spectral resolution Integral Field Spectroscopy	High time resolution and high spectral resolution single-object spectroscopy	Highly multiplexed, low spectral resolution spectroscopy	Photon-counting IFS for coronographic planet finder	High speed, low latency, zero read-noise detector
ARCONS/ KRAKENS	KIDSPEC	Mega-Z / Giga-z	‘Darkness’ MEC	Ultra-fast WFS
Mazin, et al. PASP, 123, 933 Mazin, et al. SPIE, 107020H	O’Brien, JLTP, 199, 537	Marsden, et al., ApJS, 208, 8	Meeker, et al. PASP, 130, 65 Walter, et al. PASP 132, 125	Magniez, et al., in prep

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Summary

MKIDs for optical/IR astronomy have been successfully demonstrated on sky

Challenges remain in increasing uniformity and responsivity of arrays

Their unique scalability amongst energy sensitive detectors makes them an excellent candidate for future instrumentation

MKIDs are not just for 'science' focal planes

- broad passband (0.3-2.5µm in astronomy)
- Photon counting
- Read-noise free
- Large arrays (20,000 pixels/spaxels; 400,000 voxels)

The perfect detector for a wide range of applications where every photon counts

The next step towards the 'Ultimate Detector'?

Join the MKID revolution!