Microwave Kinetic Inductance Detectors

Ben Mazin, April 2018

The UVOIR MKID Team:

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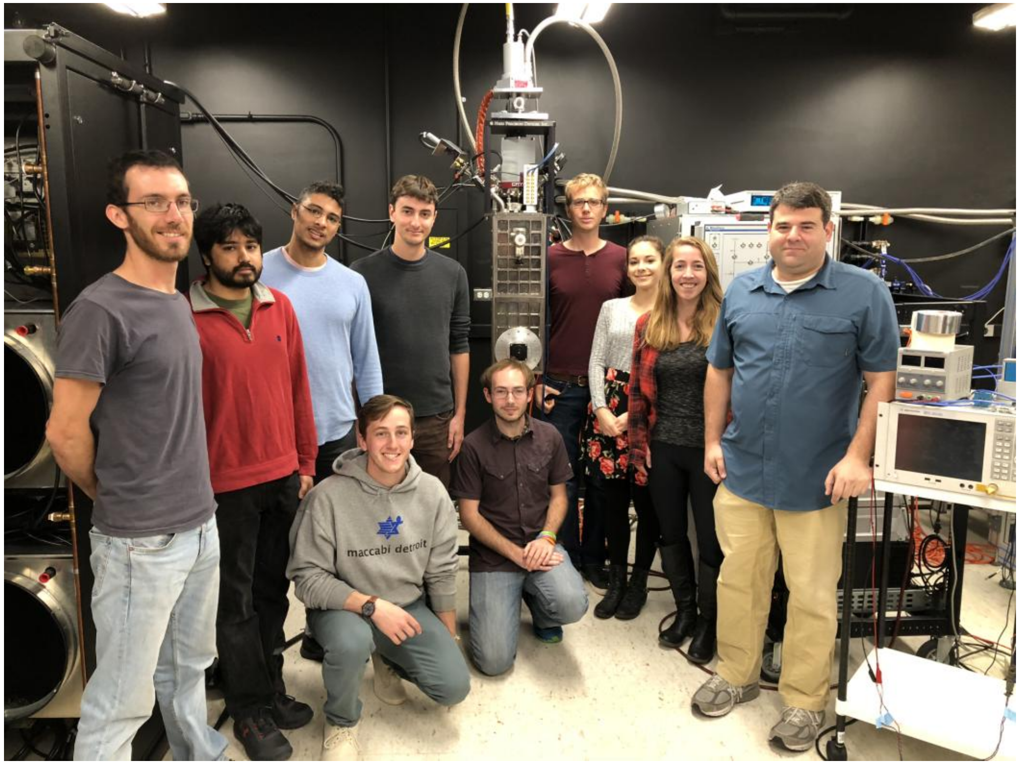
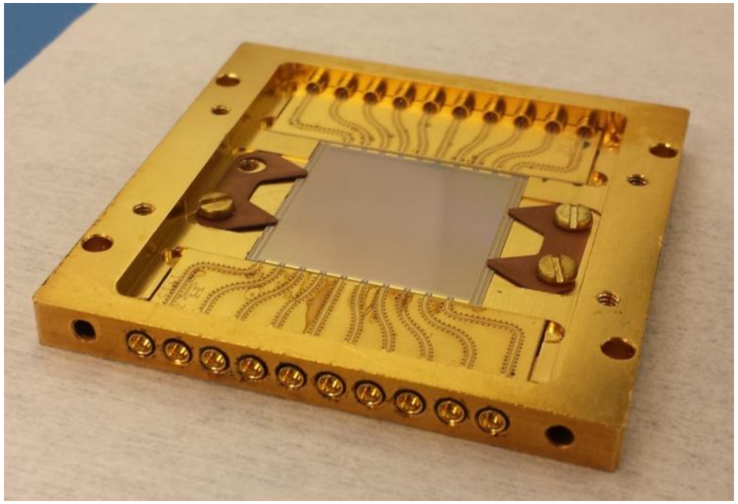
Subaru: Olivier Guyon, Julian Lozi
Caltech: Dimitri Mawet, Nem J.
JPL/IPAC: Seth Meeker, Bruce Bumble, Gautam Vashisht, Mike Bottom
Oxford: Kieran O'Brien, Rupert Dodkins
Fermilab: Gustavo Cancelo, Juan Estrada
NIST: Paul Szypryt



Mazin Lab
All of the wavelengths
All of the times
mazinlab.org

Take Aways

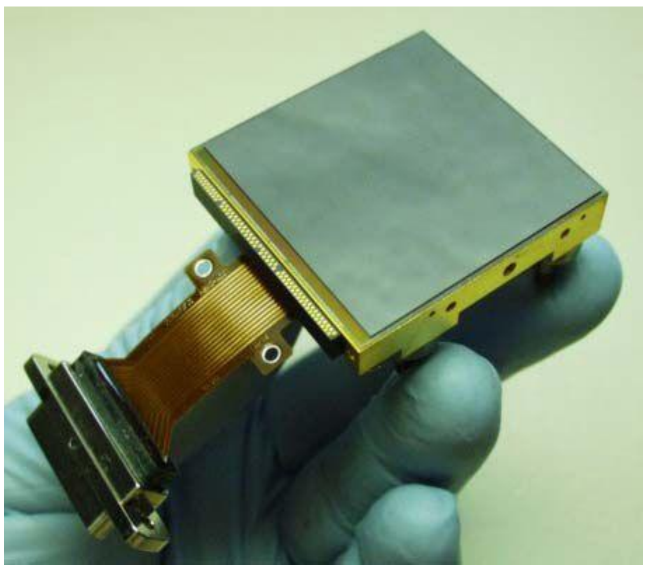
- We've built a superconducting optical/near-IR detector array that can count individual photons and determine their energy without filters or gratings
- On a pixel for pixel basis, these are **the most powerful UVOIR detectors in the world**
- We're going to use these detectors to revolutionize astronomy by taking spectra of EVERYTHING, but especially extrasolar planets
- We also make X-ray detectors using the same technology



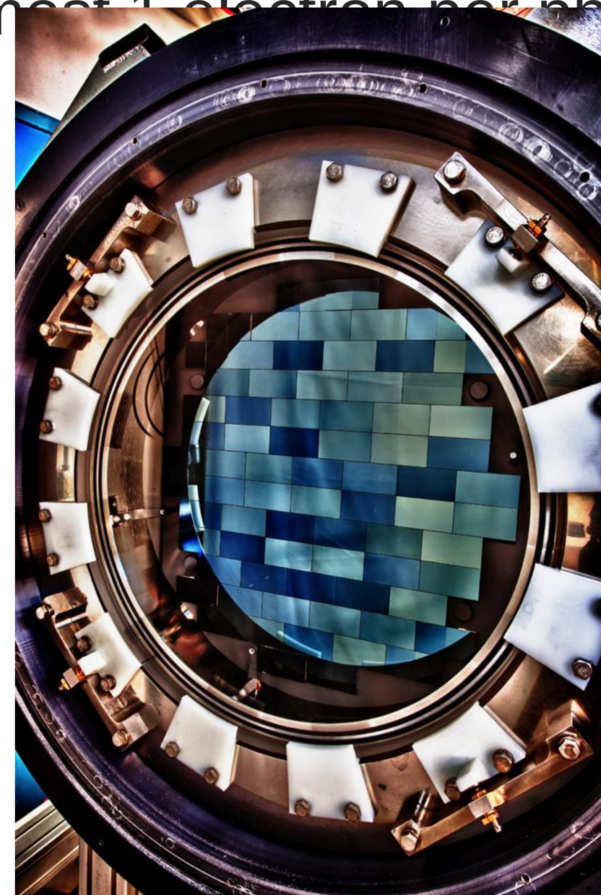
Day *et al.*, Nature, 2003
Mazin *et al.*, Optics Express 2012
Mazin *et al.*, PASP 2013
Szypryt *et al.,* Optics Express 2017

Semiconductor Detectors

- Astronomers typically use CCDs and CMOS detectors in the optical/near-IR range to convert photons into electrical signals
- Photoelectric effect means at most 1 electron per photon



Hawaii2rg HgCdTe Array



DECam CCD Mosaic

Superconductors

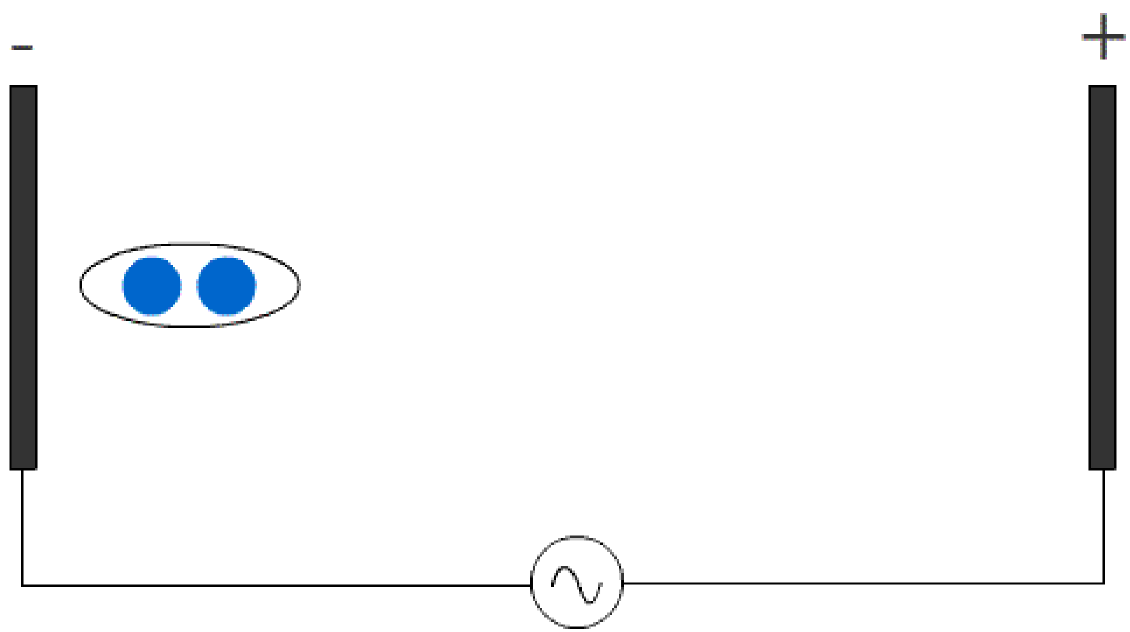
- A superconductor is a material where all DC resistance disappears at a “critical temperature”. 9 K for Nb, 1.2 K for Al, 0.9 for our PtSi
- This is caused by electrons pairing up to form “Cooper Pairs”
  - Nobel Prize to BCS in 1972

John Bardeen   Leon Neil Cooper   John Robert Schrieffer

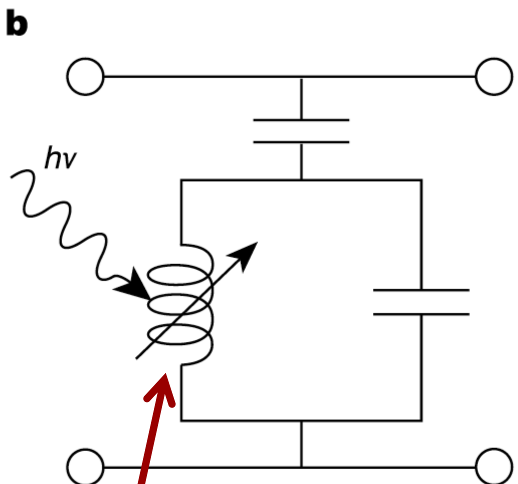
- Like a semiconductor, there is a “gap” in a superconductor, but it is 1000-10000x lower than in Si
- So instead of one electron per photon in a semiconductor, you get ~5000 electrons per photon in a superconductor – much easier to measure (no noise and energy determination)! We call these excitations quasiparticles.
- However, superconductors don’t support electric fields (perfect conductors!) so CCD tricks of shuffling charge around don’t work
- Excitations are short lived, lifetimes of ~20-50 microseconds

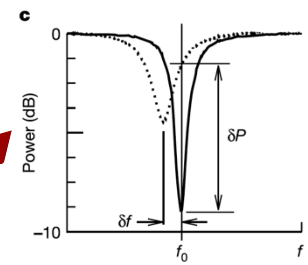
Kinetic Inductance Effect

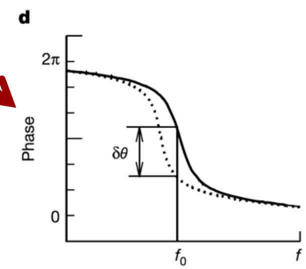
Kinetic Inductance = extra inductance from stored kinetic energy in Cooper Pairs



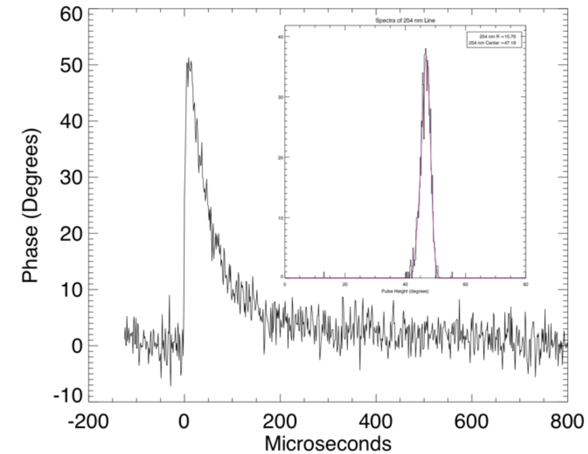
MKID Equivalent Circuit

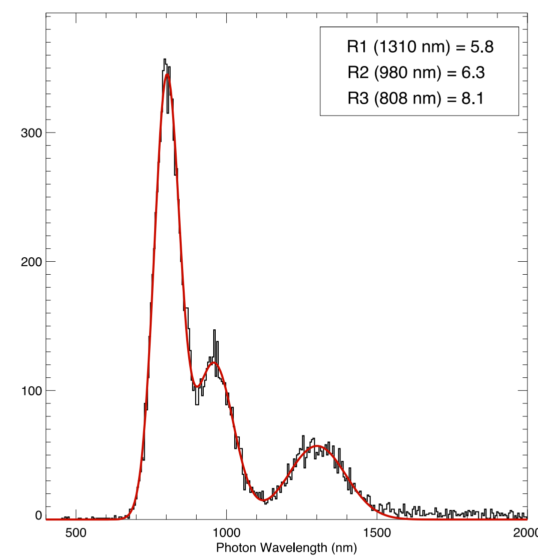




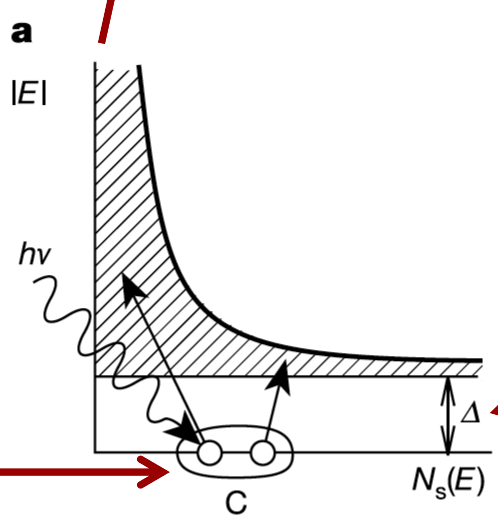


Typical Single Photon Event





Inductor is a Superconductor!



Cooper Pair

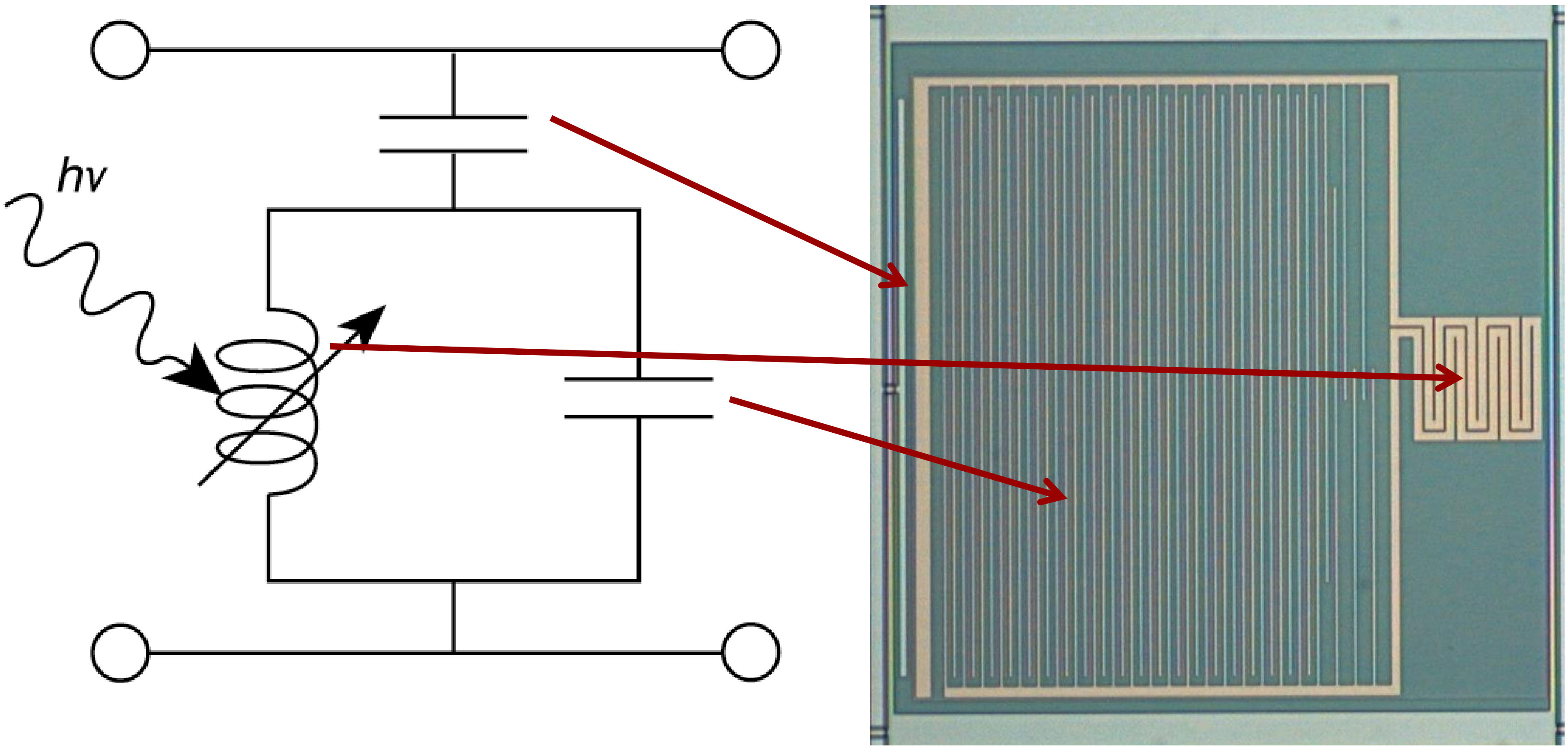
Energy Gap

Silicon – 1.10000 eV
PtSi or TiN – **0.00013** eV

Energy resolution:

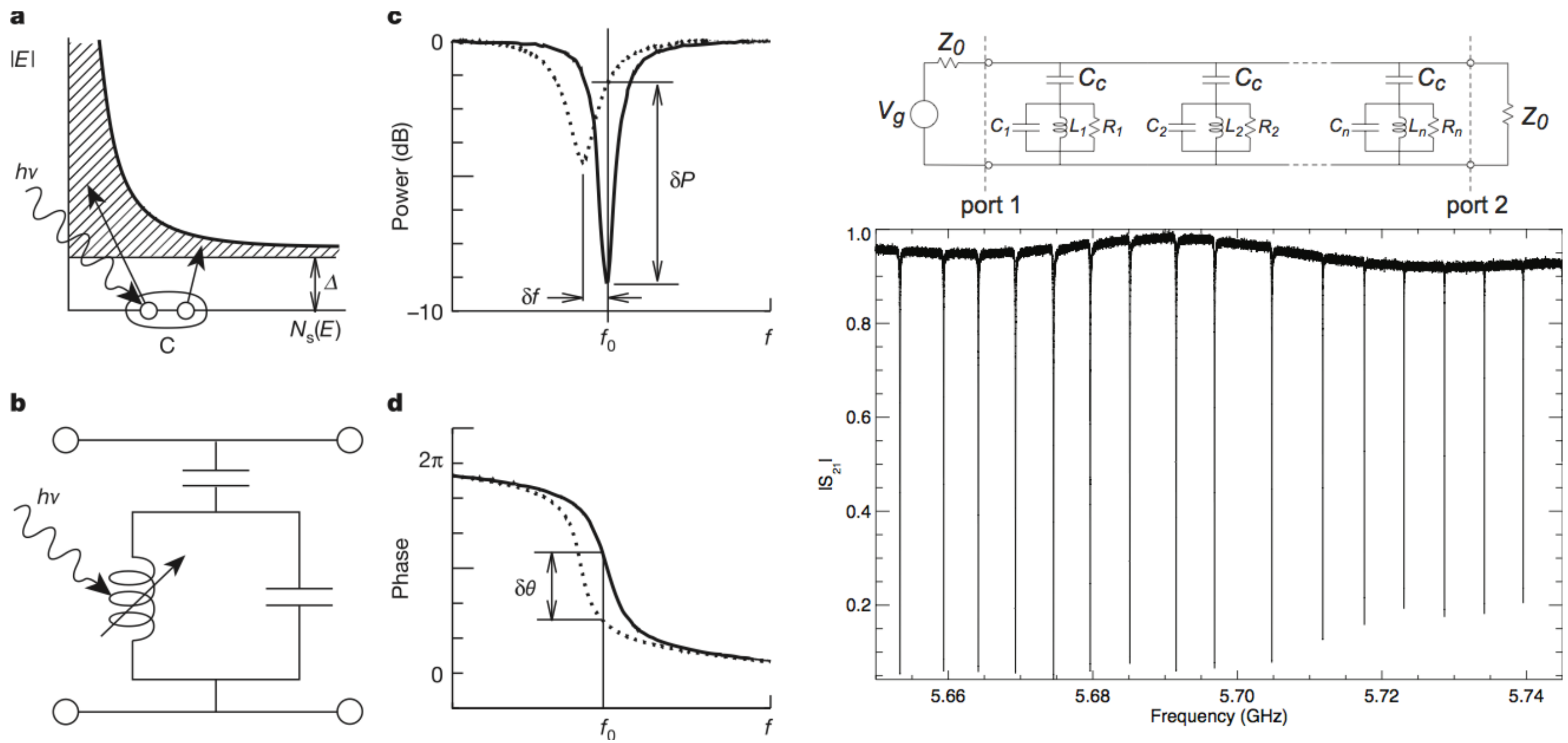
$$R = \frac{1}{2.355}\sqrt{\frac{\eta h\nu}{F\Delta}}$$

What is a Kinetic Inductance Detector ?



We use a square microlens array to improve effective fill factor to ~92%

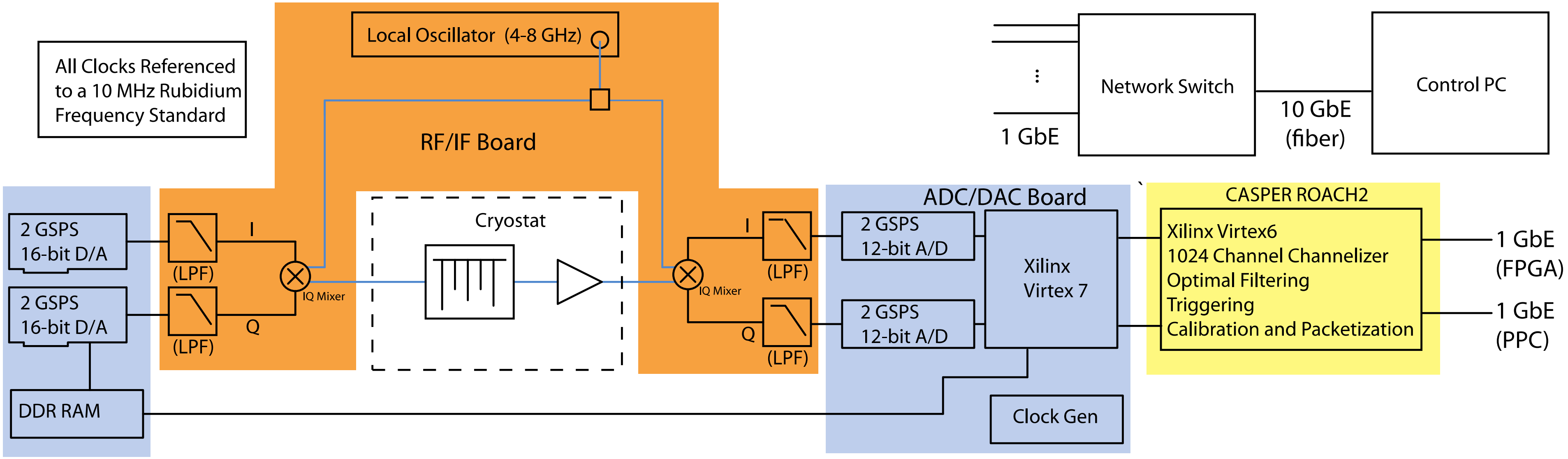
Frequency Domain Multiplexing



- Each resonator (pixel) has a unique resonant frequency in the GHz range
- A comb of sine waves is generated and sent through the device
- Thousands of resonators can be read out on a single microwave transmission line (FDM)

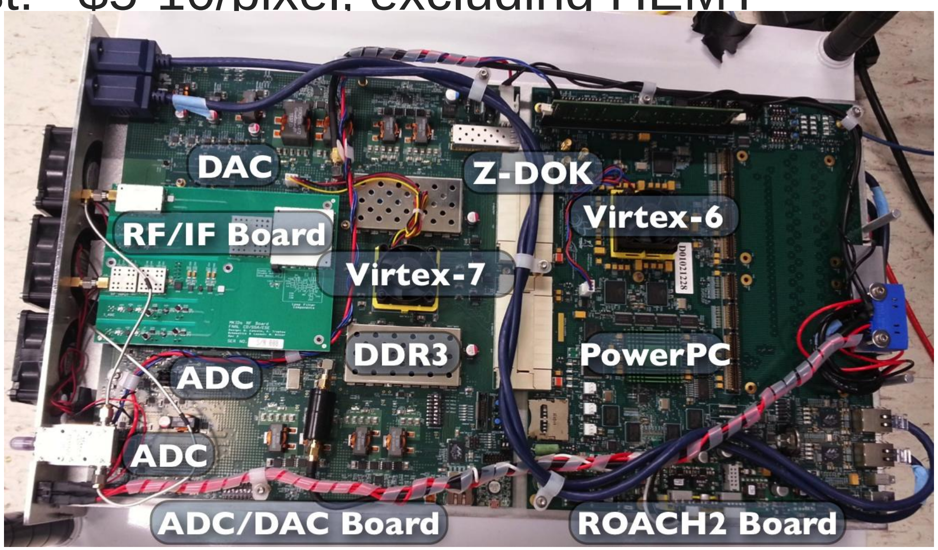
Digital MKID Readout

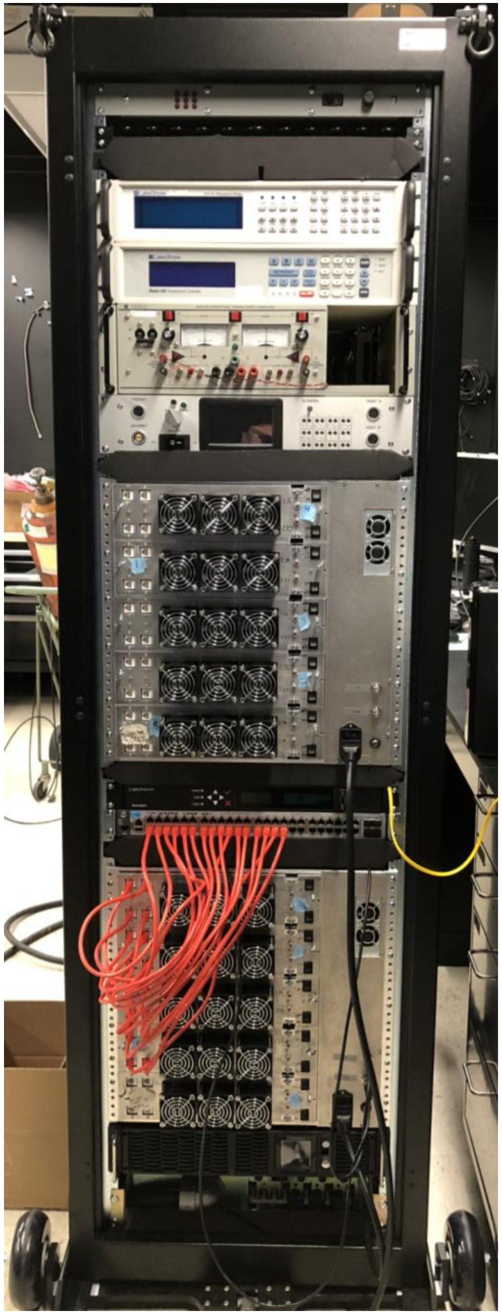
- Software Defined Radio (SDR) Overview
  - Leverages massive industry investment in ADCs/FPGAs
  - Generate frequency comb and upconvert to frequency of interest
  - Pass through MKID and amplify
  - Downconvert and Digitize
  - “Channelize” signals in a powerful FPGA
  - Process pulses (optical/UV/X-ray) or just output time stream (submm)



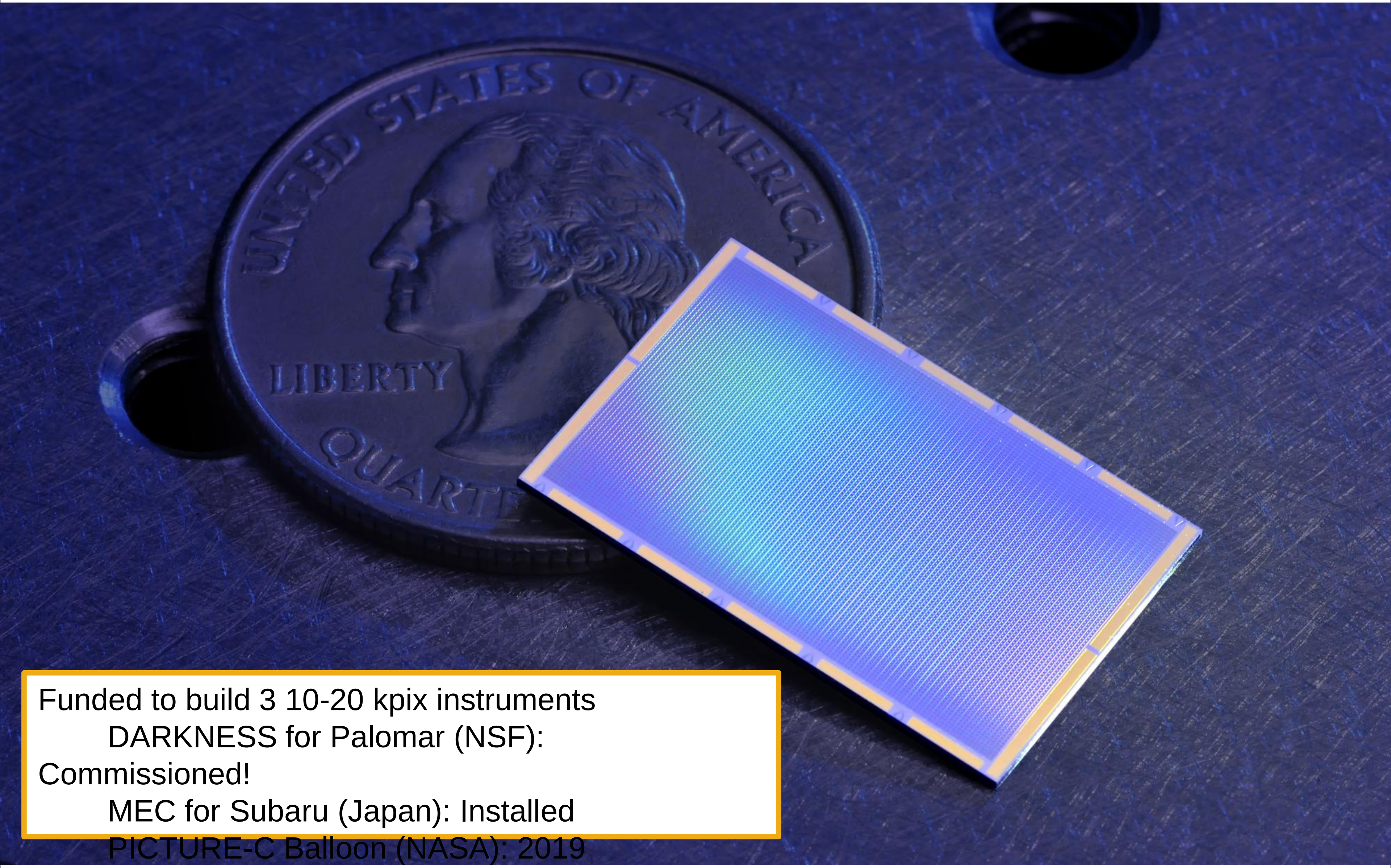
Gen 2 Readout

- Designed in collaboration with **Fermilab**
- Based on Casper ROACH2 (Virtex 6)
- Uses dual 2 GSPS 12 bit ADC
- Reads out 1024 pixels in 2 GHz
- 2 boards per feedline in 4-8.5 GHz band
  - scalable to 30+ kpix
- Air to Water/Glycol heat exchangers
- Cost: ~$5-10/pixel, excluding HEMT and





10 kpix DARKNESS Array

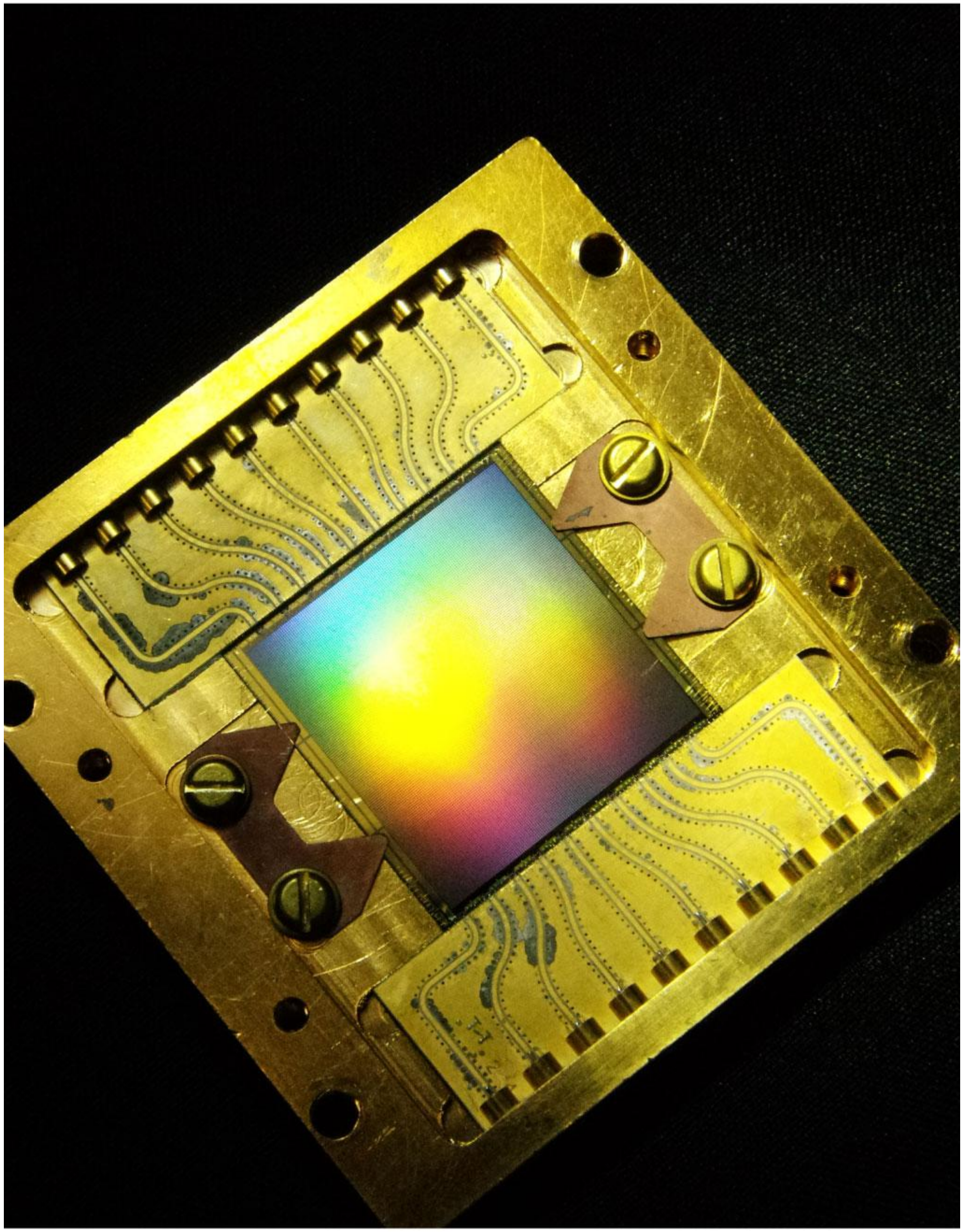


Funded to build 3 10-20 kpix instruments

- DARKNESS for Palomar (NSF): Commissioned!
- MEC for Subaru (Japan): Installed
- PICTURE-C Balloon (NASA): 2019

MEC Array

- New 20 kpix PtSi MKID array for Subaru SCExAO-MEC
  - 140x146 pixels, 150 micron pixel pitch, 22x22 mm imaging area

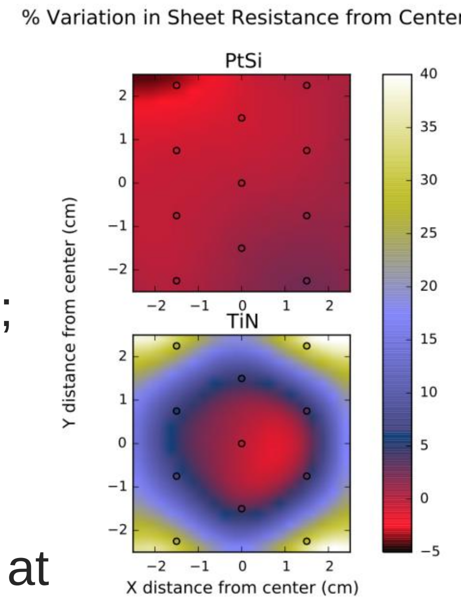


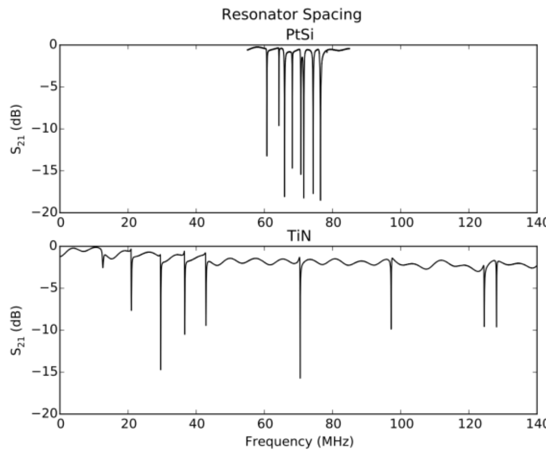
Array fabricated at UCSB by P. Szypryt and G. Coiffard.

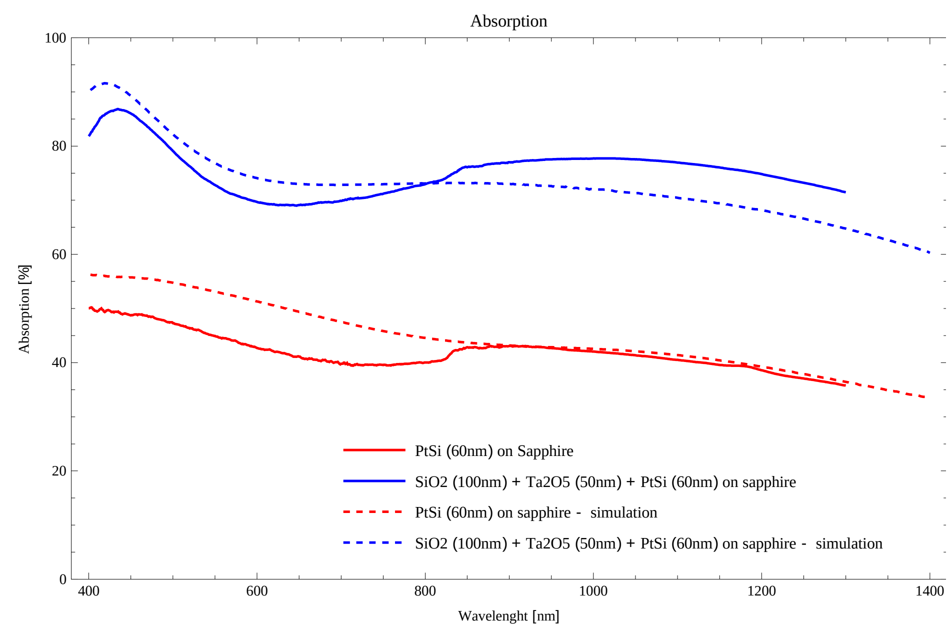
Szypryt et al. 2017, Optics Express

Outstanding Issues

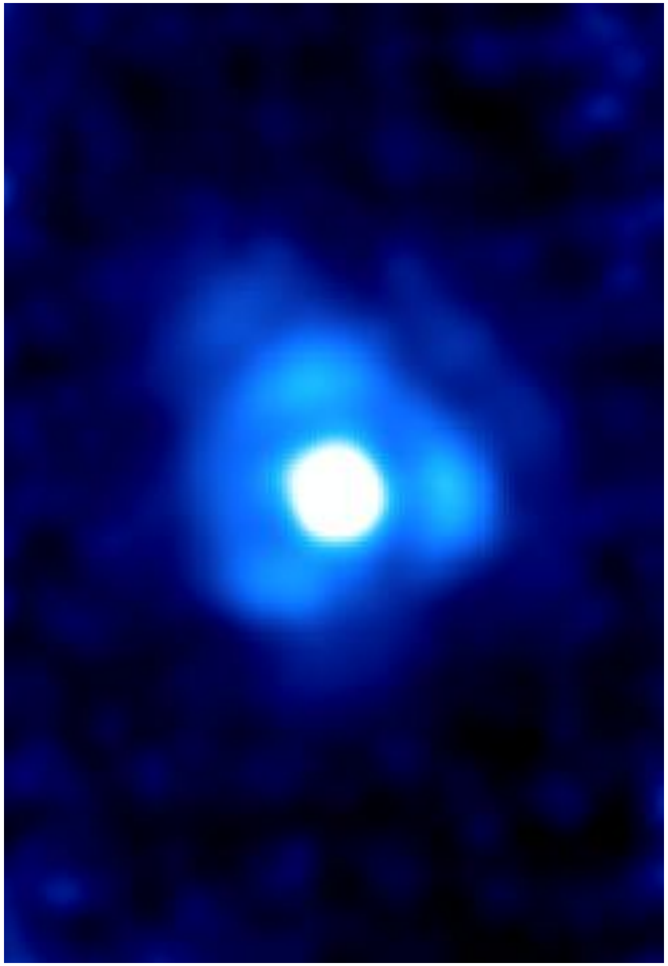
- Three main issues need improvement:
  - **Pixel Yield**
    - ✓ 75% in ARCONS
    - DARKNESS/MEC: Req. 85%; 95% goal
  - **Spectral Resolution**
    - ✓ R=8 at 400 nm in ARCONS
    - DARKNESS/MEC: Req. R=8 at 1000 nm; R=15 goal
  - **Quantum Efficiency**
    - ✓ ARCONS TiN: 40% at 400 nm, 15% at 1000 nm
    - DARKNESS/MEC PtSi: Req. 15% at 1000 nm; >25% goal
  - Attempting to increase R now as it has the biggest impacts on the exoplanet science we want to do

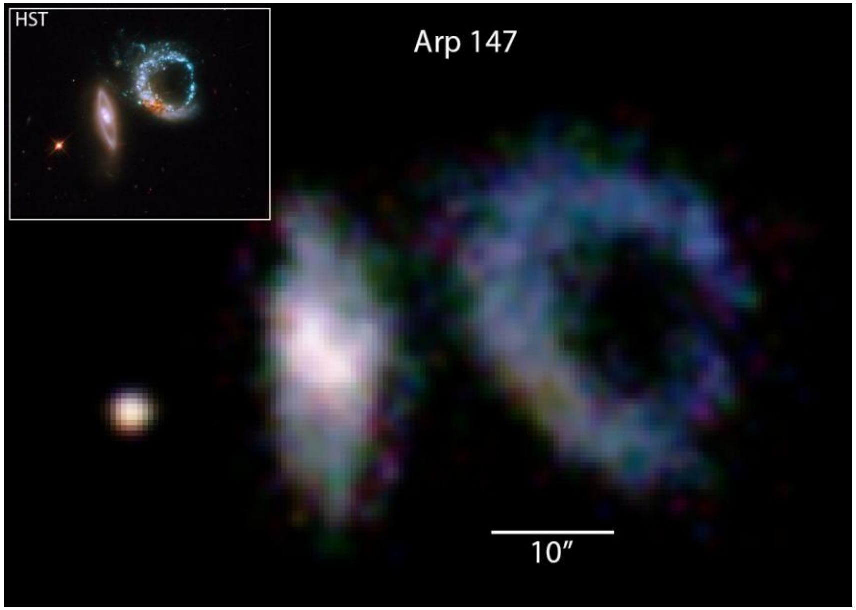


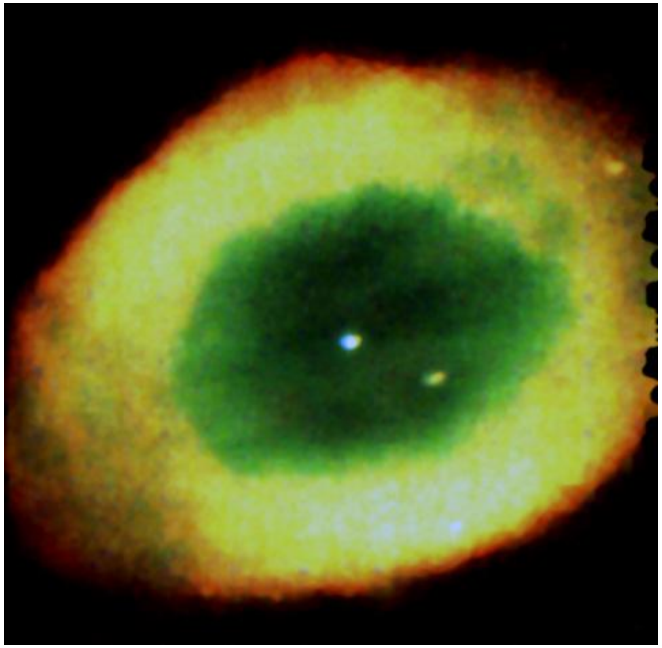




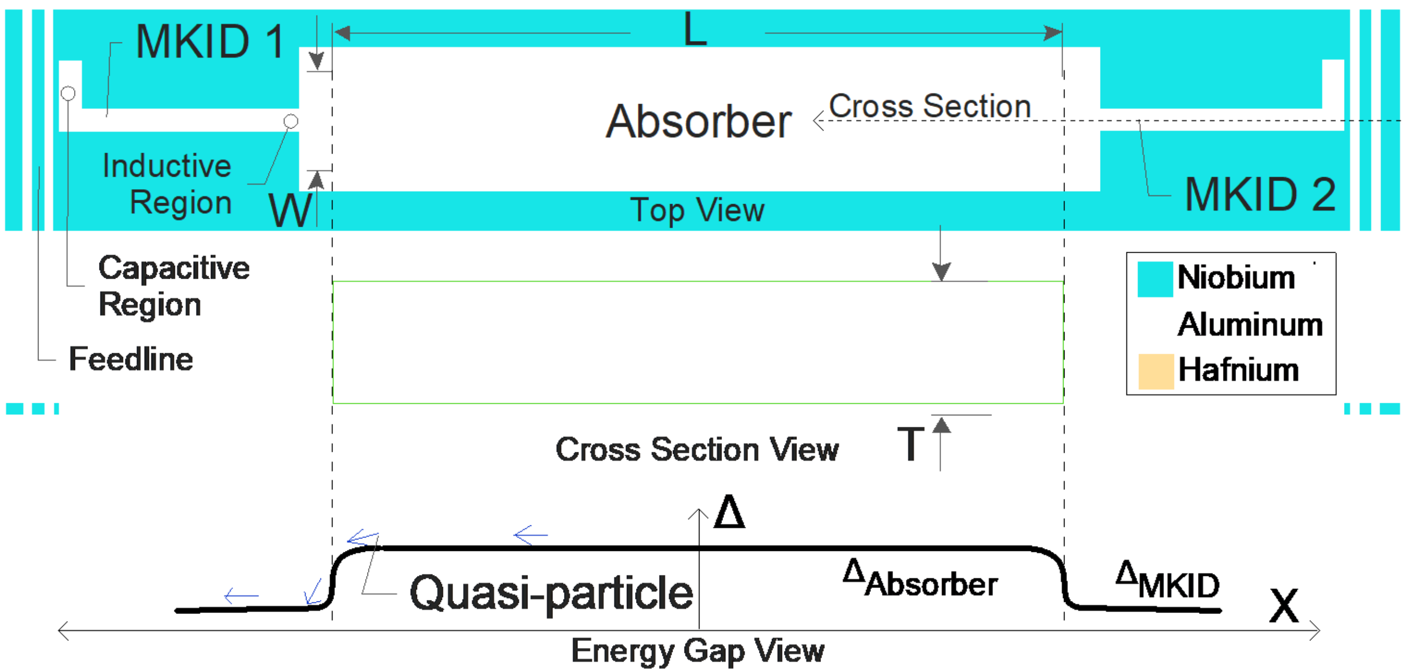
Images from ARCONS and DARKNESS







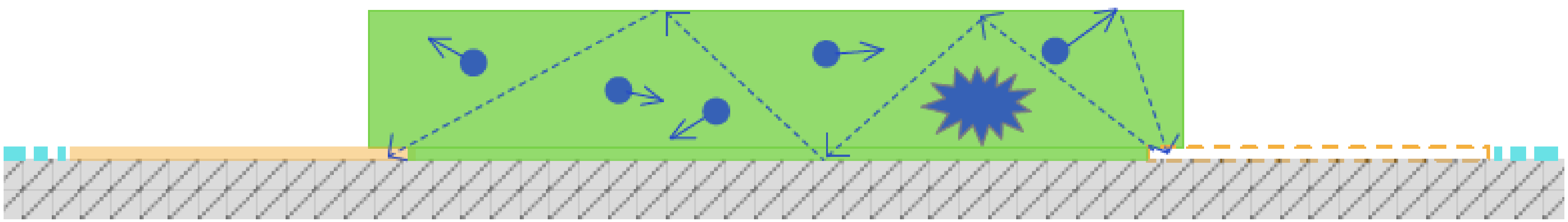
MKID Strip Detector Concept



Absorber Dimensions: 2000 μm x 200 μm x 5 μm :: L x W x T

Slides courtesy Miguel Daal 

Why Use a Strip Detector?



Using two or more MKIDs to collect quasi-particles

- allows for larger absorber
- increases energy collection efficiency
- enables position sensitivity

Experience with Strip Detectors

APPLIED PHYSICS LETTERS 89, 222507 (2006)

Position sensitive x-ray spectrophotometer using microwave kinetic inductance detectors

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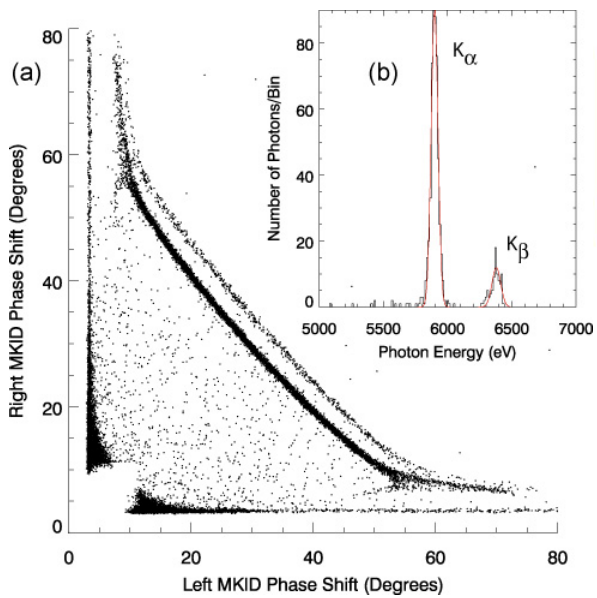
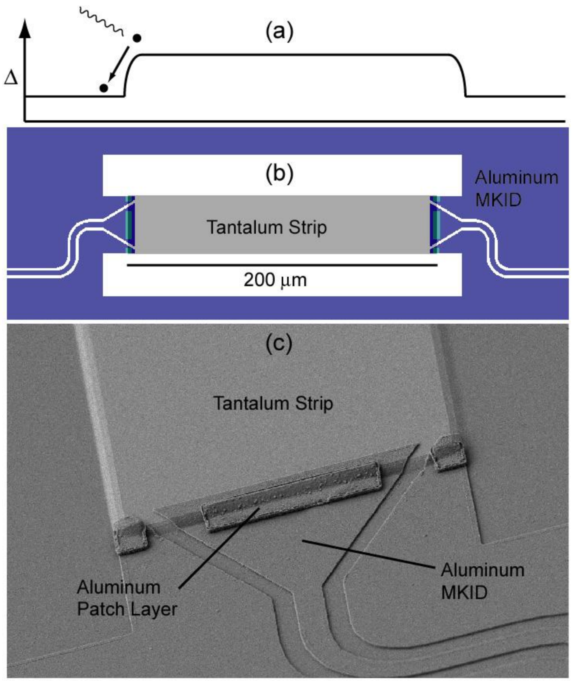
Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, MS 169-506, Pasadena, California 91109-8099

Megan E. Eckart, Sunil Golwala, Jonas Zmuidzinas, and Fiona A. Harrison
Physics Department, California Institute of Technology, 1200 E. California Blvd., Pasadena, California 91125

Data From:

- 200 nm thick Al
- 600 nm thick Ta
- ^{55}Fe source
- δE = 62 eV at 5.9 keV





Why Use an Aluminum Absorber?

- Long quasi-particle lifetime
  - ~ 3 msec (J. Baselmans et al, *AIP Conf. Proc.*, 2009.)
- Long diffusion length
  - ~ 2 mm (M. Loidl, et al. *NIMA*, Jun. 2001.)
- Easy to obtain in high purity
- Dark matter event rate ∝ normal conductivity, σ_1
  - Rate (Y. Hochberg et al, PR D, 2017):
  - 5□$_{eff}$ = effective kinetic mixing parameter (coupling to normal matter)

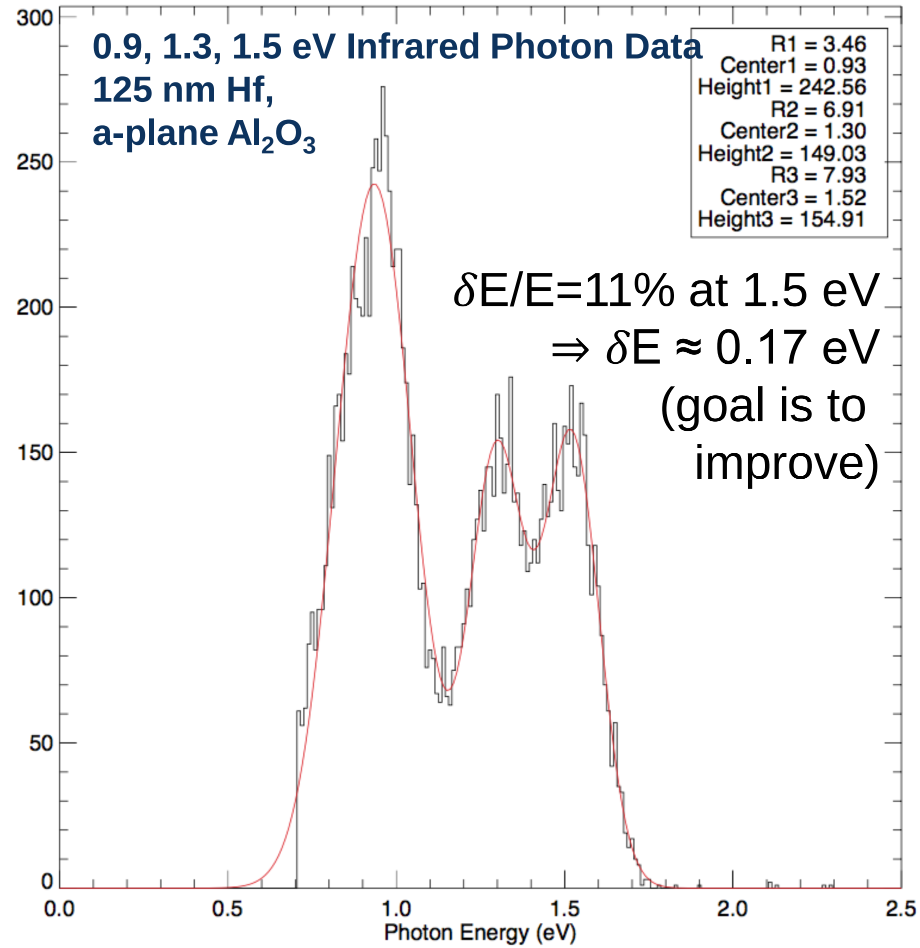
$$R = \frac{1}{\rho_{\text{absorber}}} \frac{\rho_{\text{DM}}}{m_{\text{A}'}} \kappa_{\text{eff}}^2 \sigma_1$$

Why Use Hafnium Resonators?

- Generally want low T_c materials because
  - Higher sensitivity (Smaller Tc, $\Delta \approx 1.72\ T_c k_B$)
  - Finer Energy Resolution

$$\frac{\delta E}{E} = 2.355 \sqrt{\frac{F_{\text{Fano}} \Delta}{\eta E_{\text{DM}}}}$$

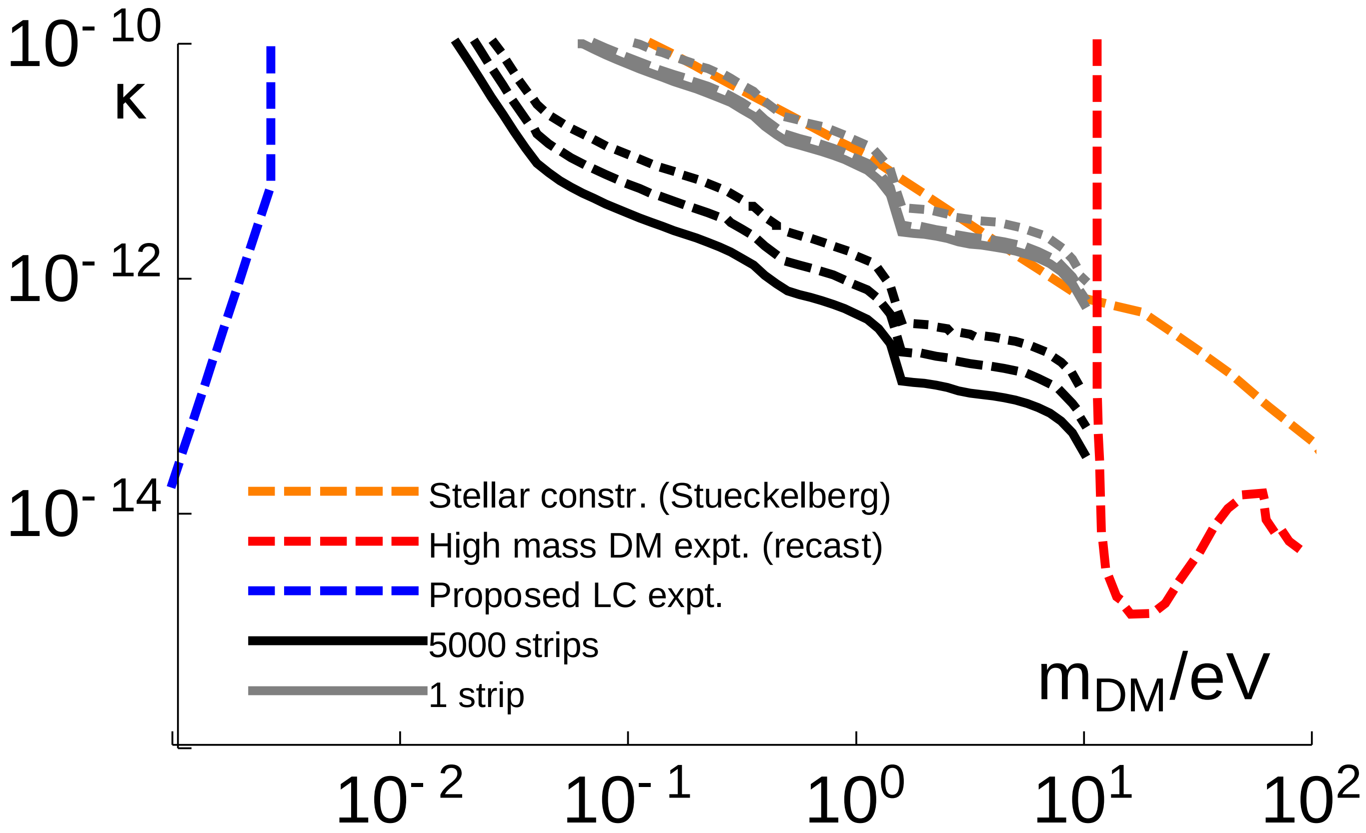
- Hafnium happens to work:
  - Produces high Q resonators (~ 500K)
  - Elemental material (easy to deposit & good uniformity)
  - Film Tc ≈ 450 mK @ 125 nm thickness ⇒ High L_{kin} ~ 20 pH/□
  - High normal state resistivity ⟹ high L
  - measured τ_{qp} ~ 30 μsec



δE/E=11% at 1.5 eV
⇒ δE ≈ 0.17 eV
(goal is to improve)

Estimated Dark Photon Sensitivity

- Proposing 5000 MKID Strip Detectors = 10,000 MKIDs = 10 mm³ Al = 2 x 4” wafers
- 6 months
- 1, 10, 100 Background events



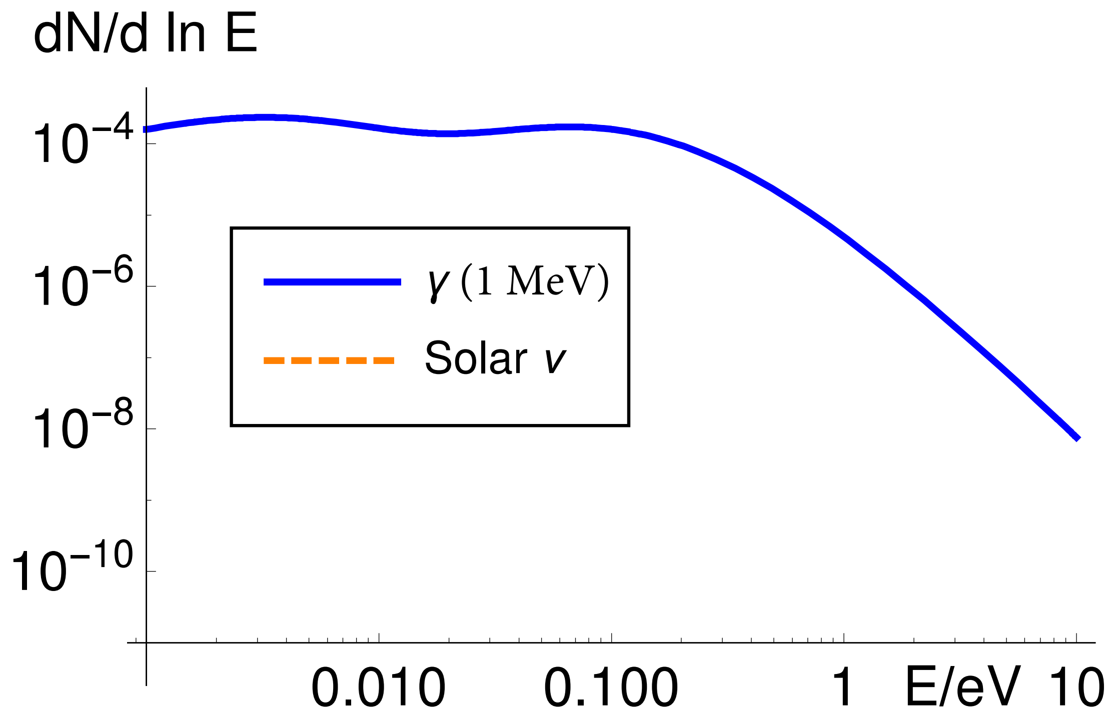
All questions on this should go to Dave Sutherland and Nathaniel Craig!

Backgrounds

We are estimating backgrounds from:

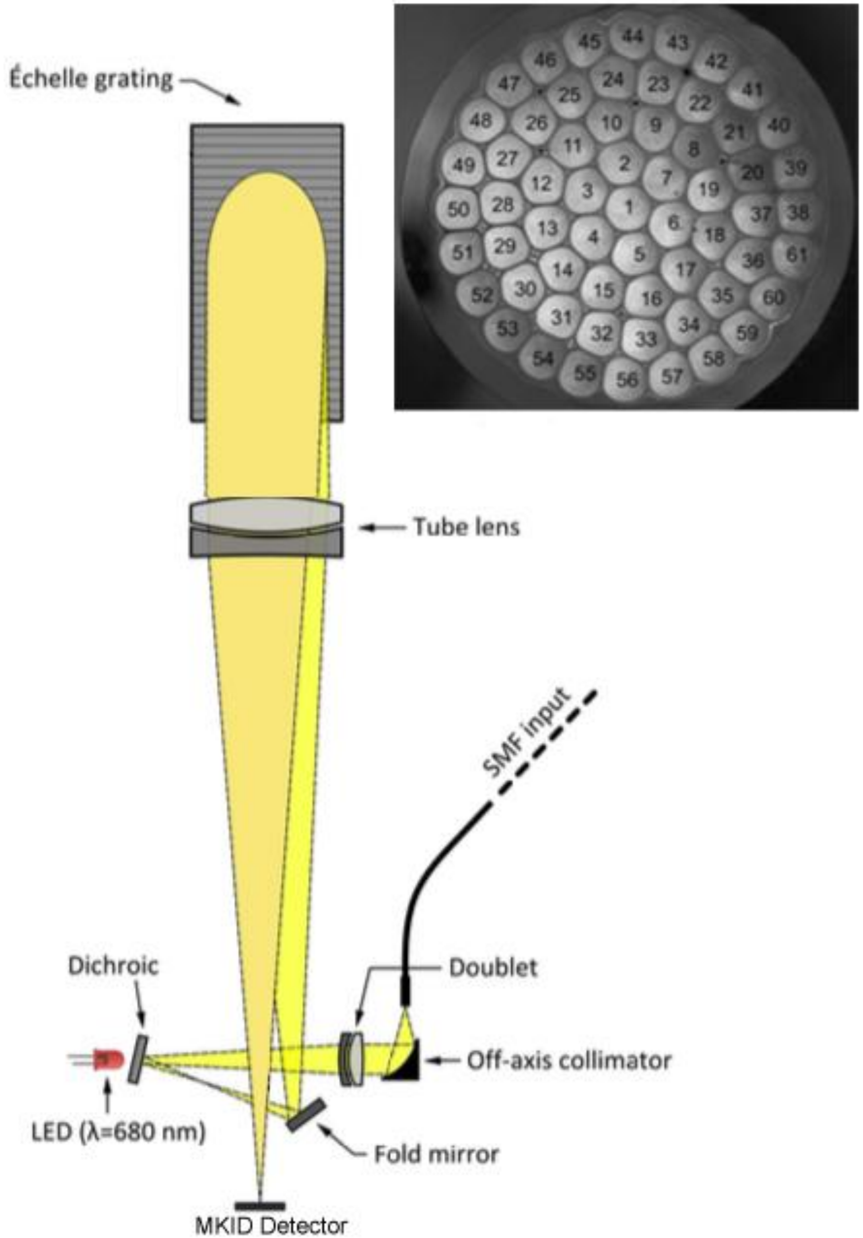
- Radioactivity
- Cosmic Rays (expt above ground)
- Coherent Photon Scattering off Atoms
- Stray Light
- Vibrations
- [pp – Neutrinos]

…Pulse shape/timing/energy spectrum discrimination



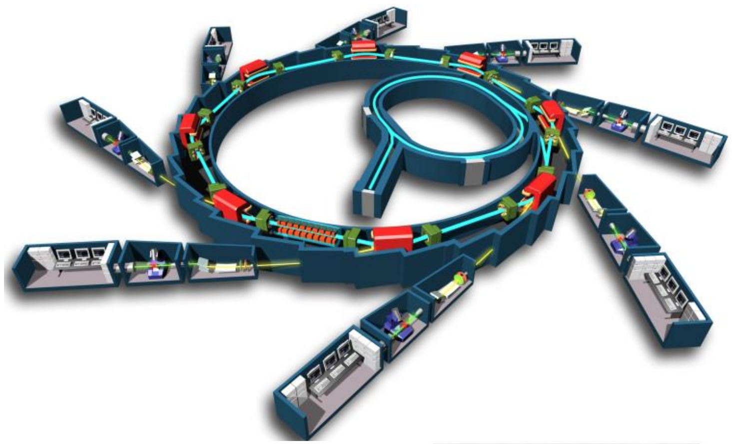
MKID-based HRMOS

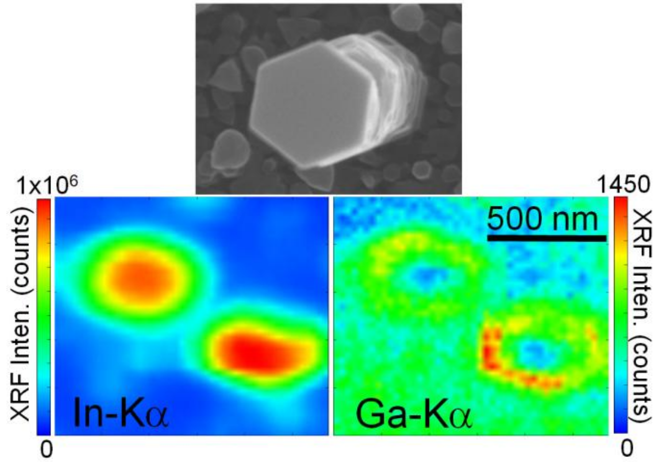
- We can use MKIDs to sort the orders coming off an Echelle
  - No read or dark noise even into the near-IR
    - Huge benefits for faint objects!
  - No cross disperser
    - Compact, high throughput
  - Long linear arrays of MKIDs are pretty easy
    - Making 5 x 2048 arrays with 20 µm pixel pitch now!
  - Can make a R>20k multiobject spectrograph
    - 100+ simultaneous fibers?
    - Looking at this for “High Dispersion Coronography”
    - Earth analogues from TMT?

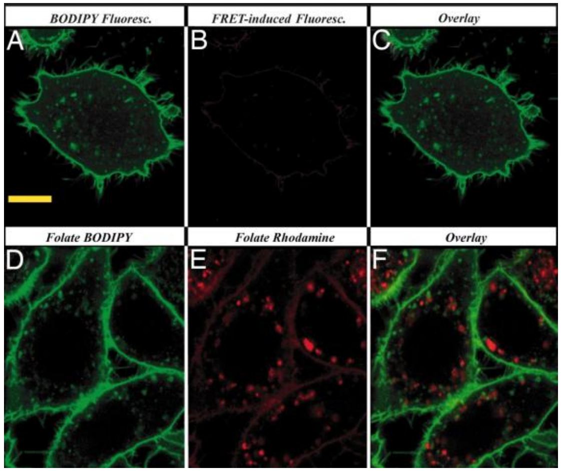


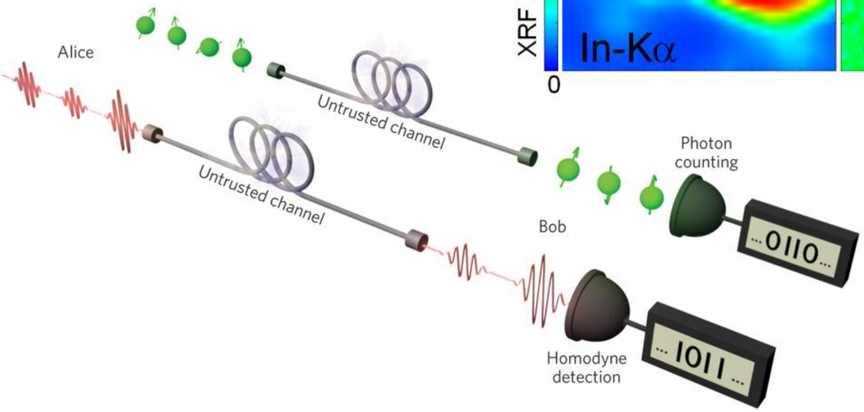
Other Applications

- There are a significant number of other potential applications:
  - Satellite-based reconnaissance
  - X-ray beam line studies
  - Semiconductor process debugging (XRF)
  - Laser communications
  - Quantum Key Distribution
  - Biological Imaging (FRET, etc.)
  - Fundamental Physics/Dark Matter
    - Light Scalar Dark Matter!

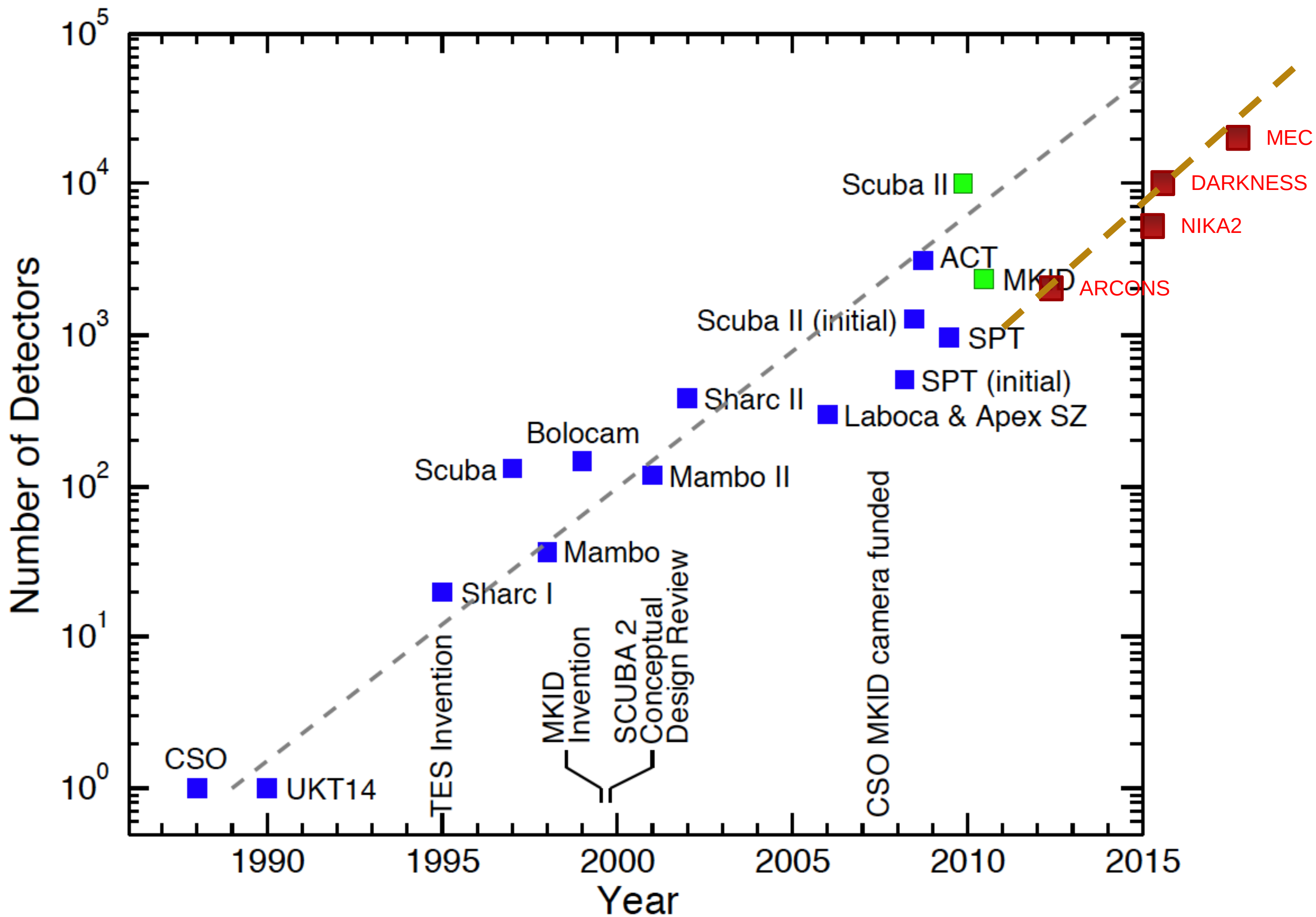








MKID Scaling



Original plot from J. Zmuidzinas