Title: Microwave Kinetic Inductance Detectors for Exoplanets and Light Dark Matter

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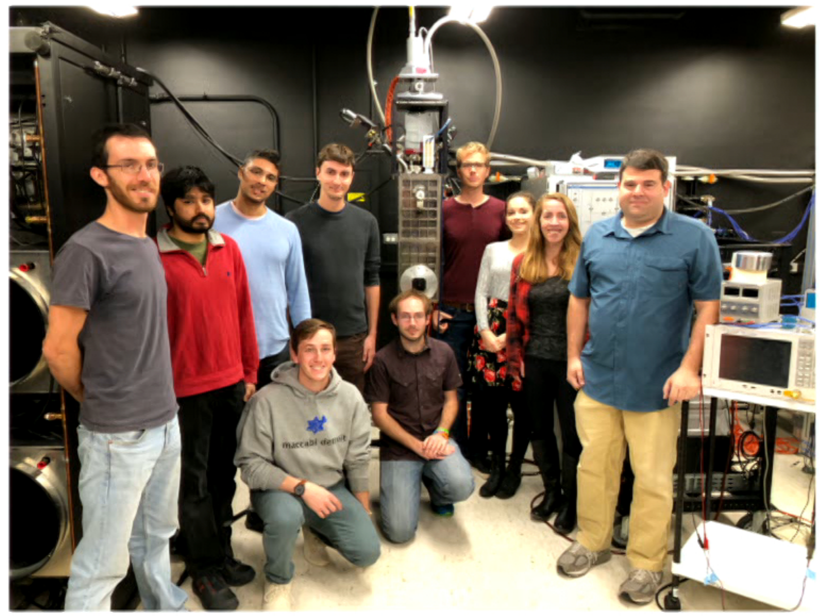
Abstract: <p><span style="font-size:10.5pt;font-family:"Arial",sans-serif;
mso-fareast-font-family:"Times New Roman";mso-ansi-language:EN-US;mso-fareast-language:
EN-US;mso-bidi-language:AR-SA">Microwave Kinetic Inductance Detectors, or MKIDs, are superconducting detector arrays that can measure the energy and arrival time of individual optical through near-IR photons without read noise or dark counts. I will discuss our recent work and results from the first two MKID Integral Field Spectrographs (IFSs) for high contrast imaging, DARKNESS/SDC at the Palomar 200" and MEC/SCExAO on Subaru. I will then look at the future of MKIDs and their potential on 30-m class telescopes like the TMT, and explore a fascinating new application in the detection of light scalar dark matter. </p>

Microwave Kinetic Inductance Detectors for Exoplanets and Dark Matter

Ben Mazin, April 2018

The UVOIR MKID Team:

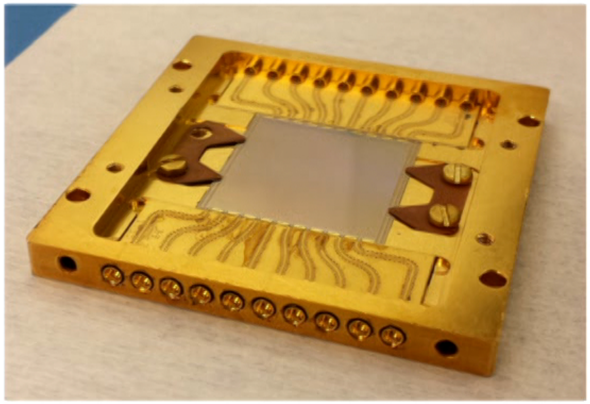
UCSB: Ben Mazin, Alex Walter, Clint Bocksteigel, Neelay Fruitwala, Isabel Liparito, Nicholas Zobrist, Gregoire Coiffard, Miguel Daal, Sarah Steiger, Noah Swimmer
Subaru: Olivier Guyon, Julian Lozi
Caltech: Dimitri Mawet, Nem J.
JPL/IPAC: Seth Meeker, Bruce Bumble, Gautam Vashisht, Mike Bottom
Oxford: Kieran O'Brien, Rupert Dodkins
Fermilab: Gustavo Cancelo, Juan Estrada
NIST: Paul Szypryt



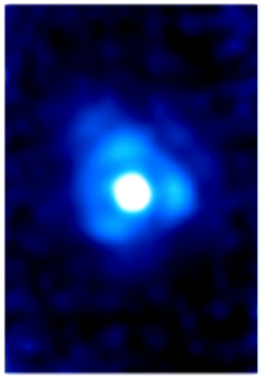
Mazin Lab
All of the wavelengths
All of the times
mazinlab.org

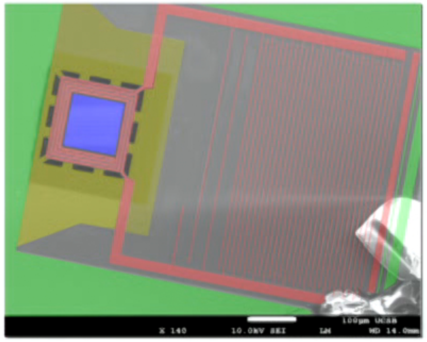
Take Aways

- We've built superconducting optical/near-IR detector arrays 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, starting with extrasolar planets
- We also make X-ray detectors using the same technology (Ulbricht et. al 2015)



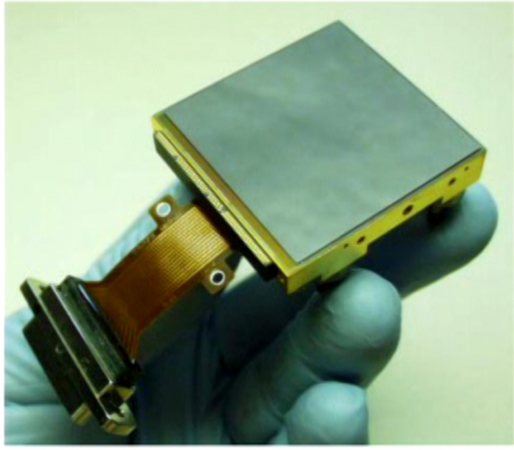
Day *et al.*, Nature, 2003
Mazin *et al.*, Optics Express 2012
Mazin *et al.*, PASP 2013
Szypryt *et al.*, Optics Express 2017
Meeker *et al.*, PASP, 2018



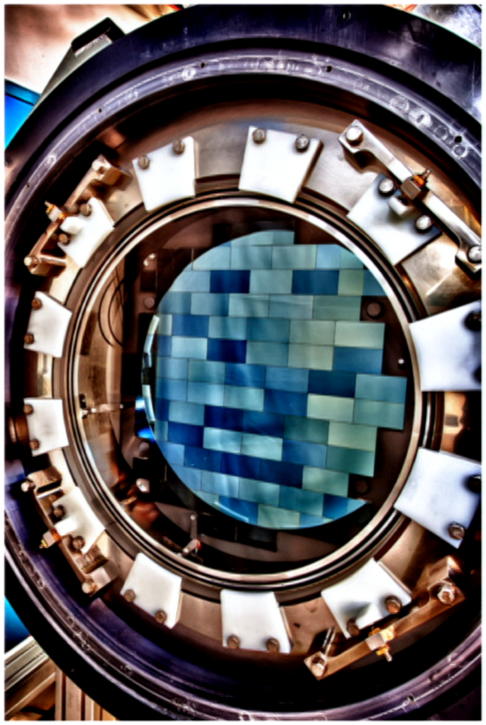


Semiconductor Detectors

- 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

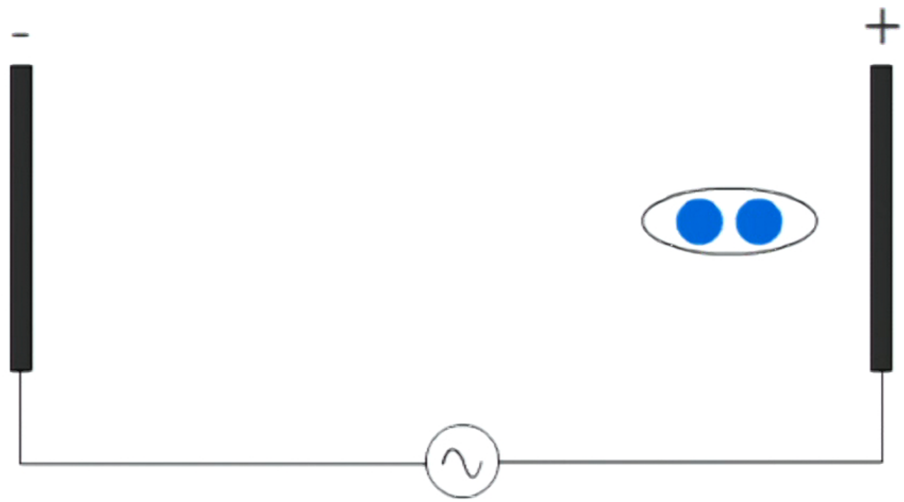
- A superconductor is a material where all DC resistance disappears at a "critical temperature". 9 K for Nb, 1.2 K for Al, 0.9 for our PtSi
- This is caused by electrons pairing up to form "Cooper Pairs"
  - Nobel Prize to BCS in 1972

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

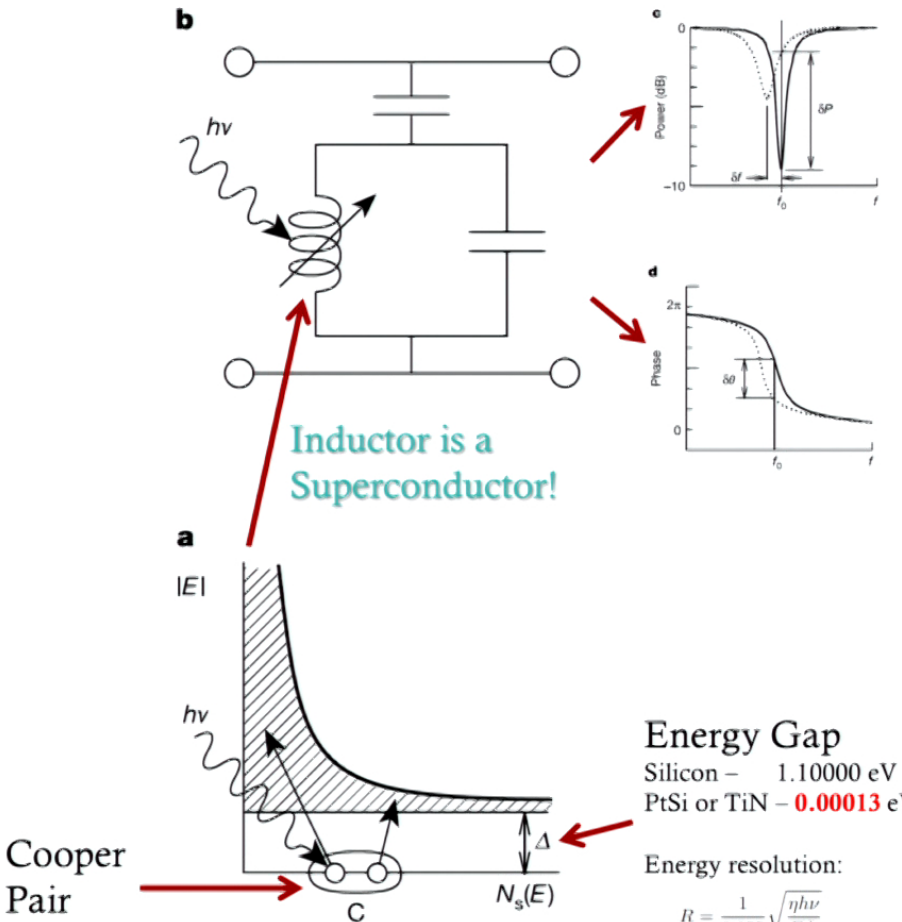
Kinetic Inductance Effect

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



MKIDs

MKID Equivalent Circuit



Energy Gap

Silicon – 1.10000 eV

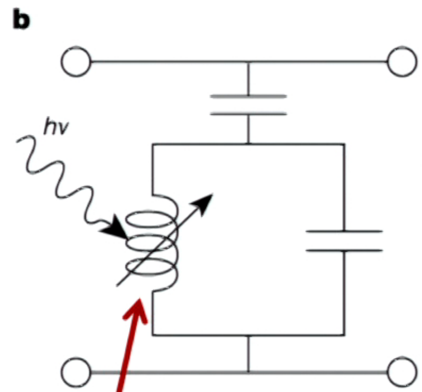
PtSi or TiN – **0.00013** eV

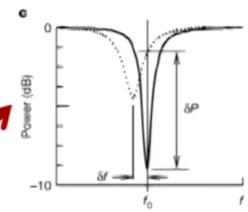
Energy resolution:

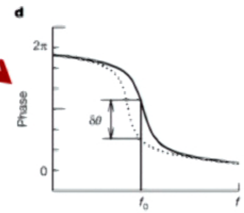
$$R = \frac{1}{2.355}\sqrt{\frac{\eta h\nu}{F\Delta}}$$

MKIDs

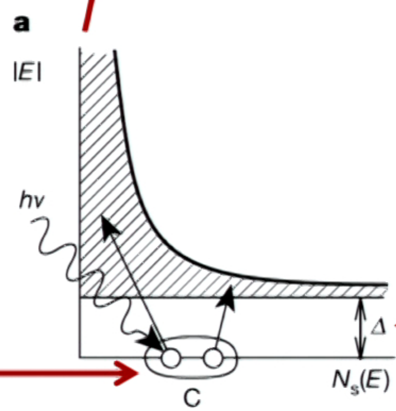
MKID Equivalent Circuit





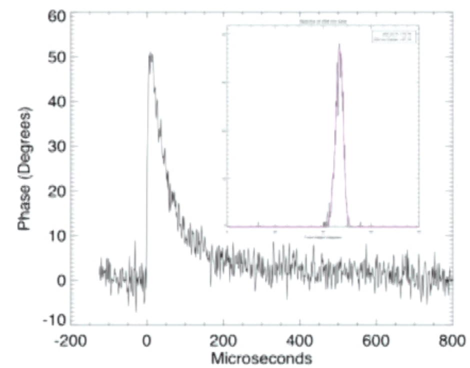


Inductor is a Superconductor!



Cooper Pair

Typical Single Photon Event



Energy Gap

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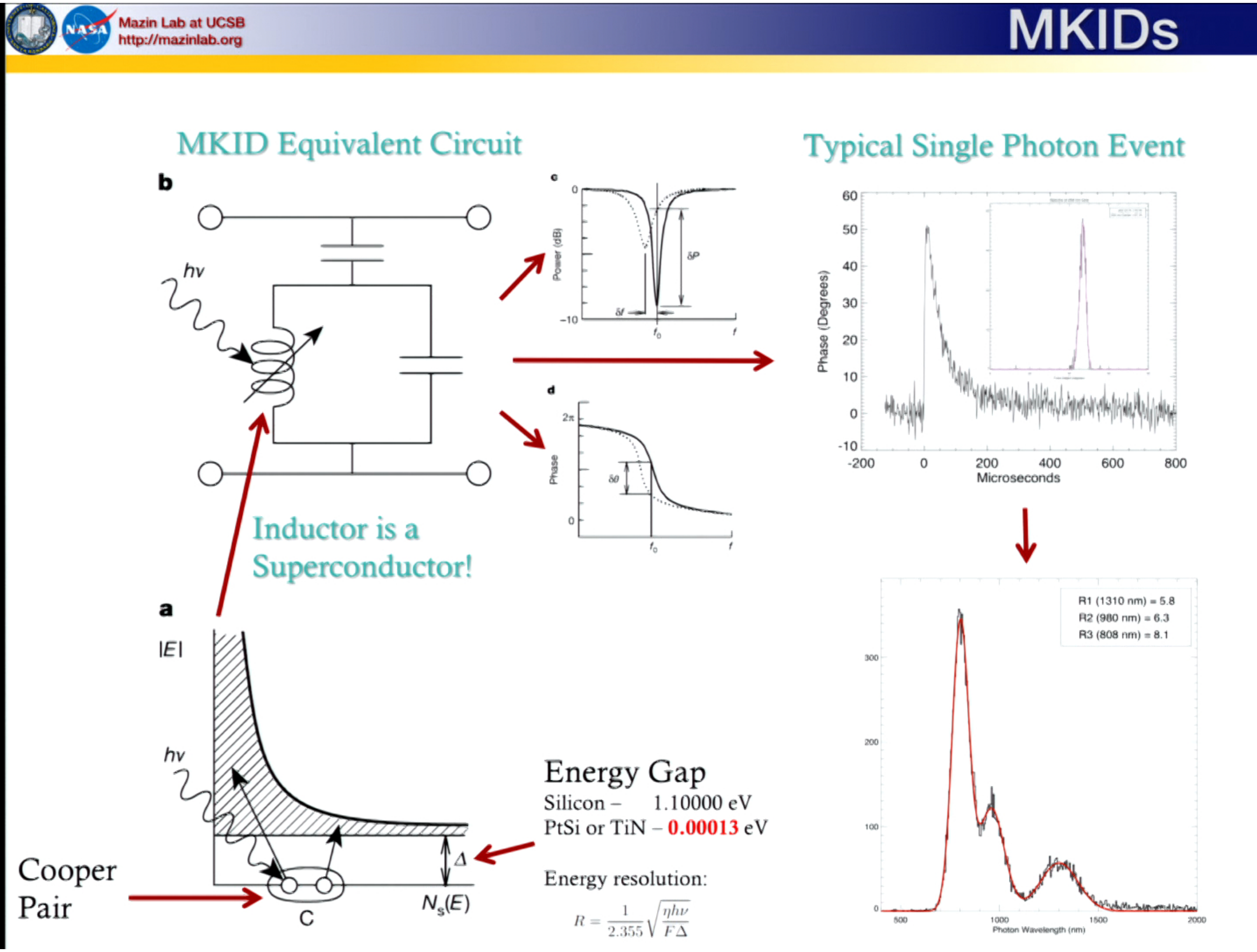
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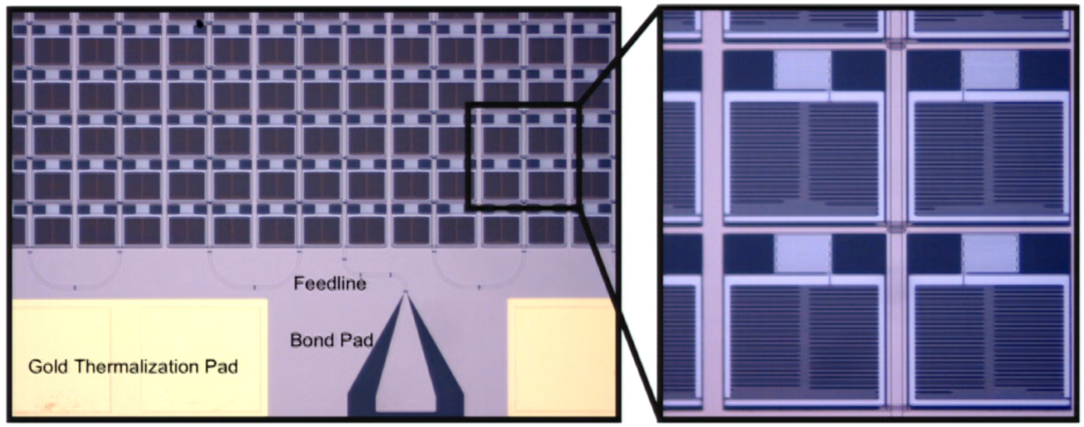
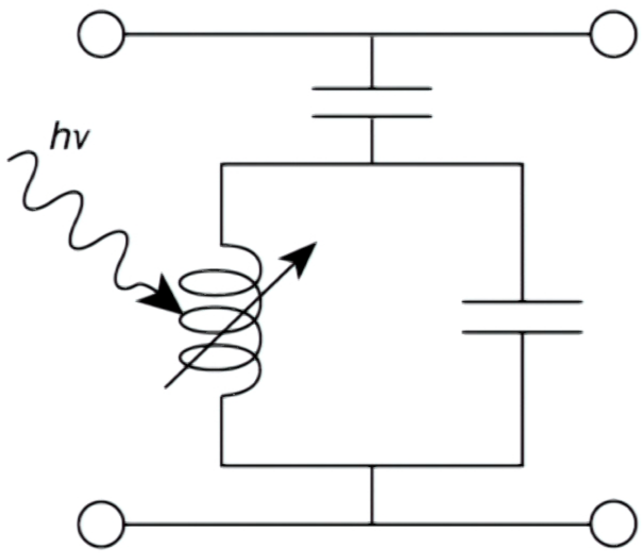
MKIDs
MKID Equivalent Circuit
Typical Single Photon Event
b
hν
c
Power (dB)
δP
δf
f_0
d
2π
Phase
δθ
Inductor is a
Superconductor!
Phase (Degrees)
Microseconds
R1 (1310 nm) = 5.8
R2 (980 nm) = 6.3
R3 (808 nm) = 8.1
Photon Wavelength (nm)
a
|E|
Δ
$N_s(E)$
C
Cooper
Pair
Energy Gap
Silicon – 1.10000 eV
PtSi or TiN – 0.00013 eV
Energy resolution:
$R = \frac{1}{2.355}\sqrt{\frac{\eta h\nu}{F\Delta}}$

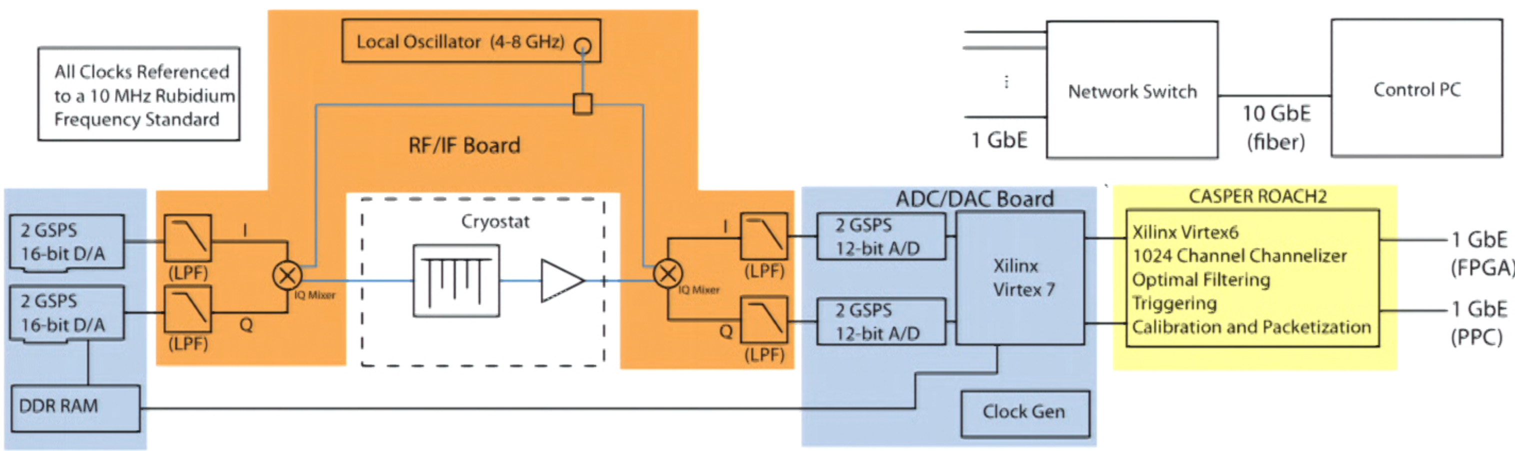
What is a Kinetic Inductance Detector ?





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)



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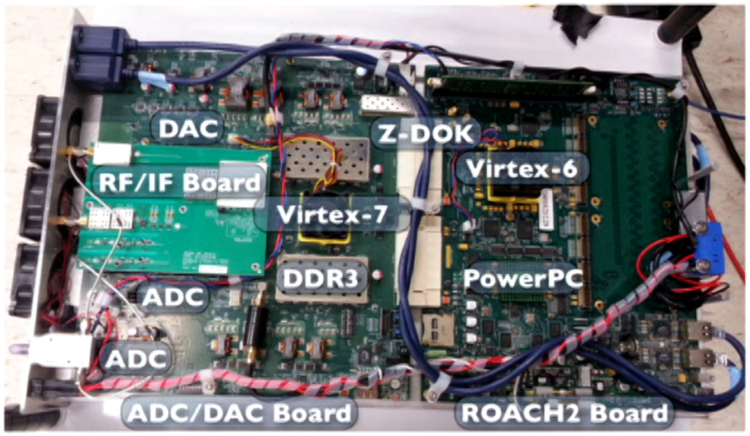
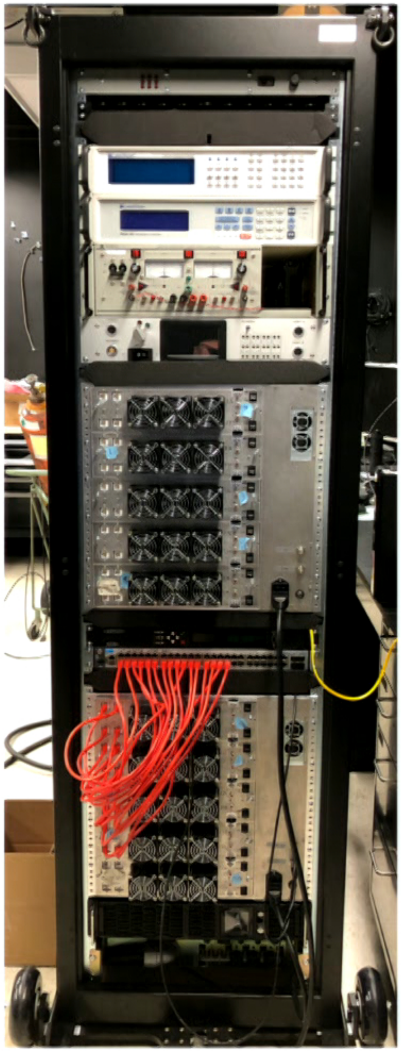
Gen 2 Readout

- 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 FPGAs





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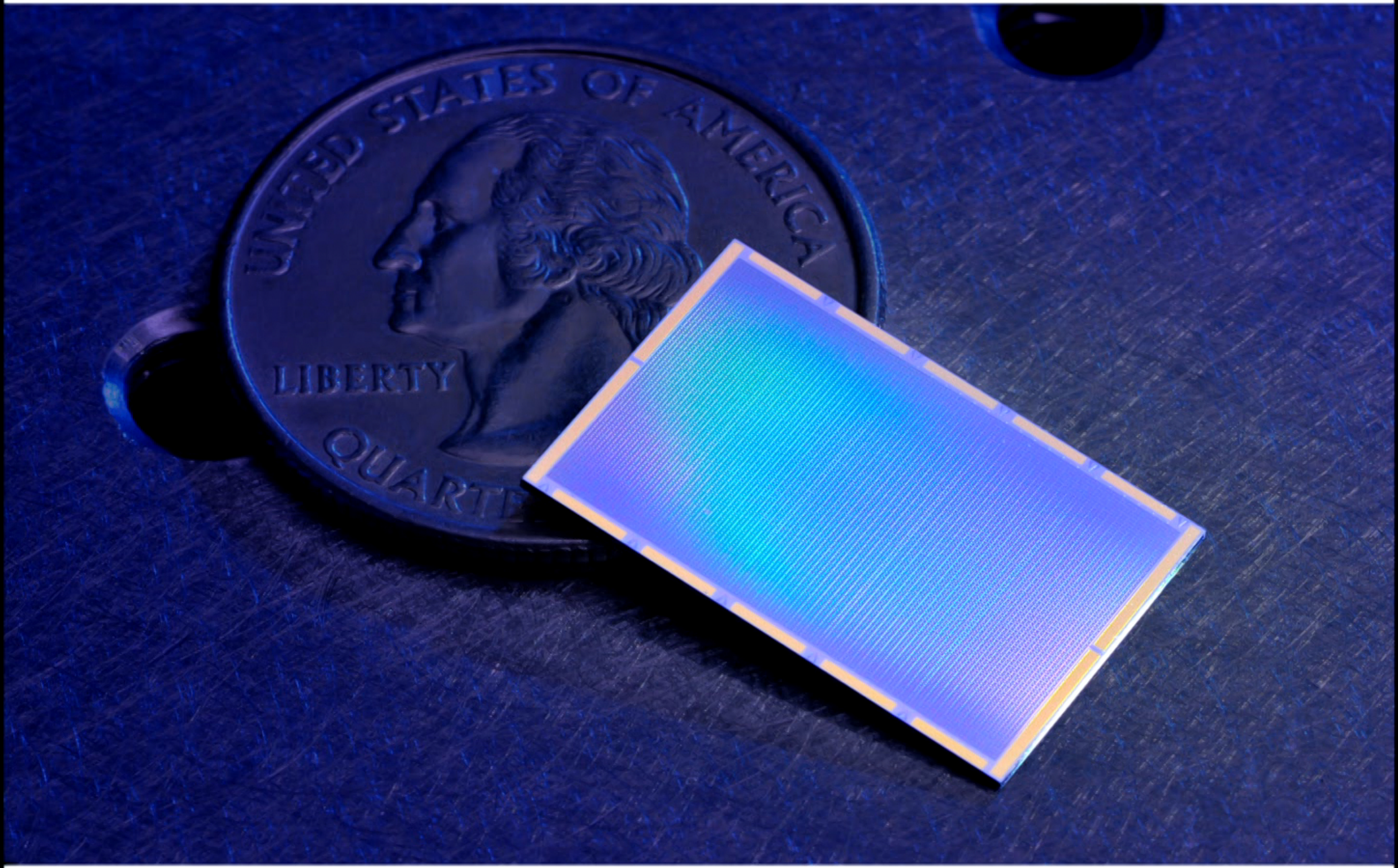
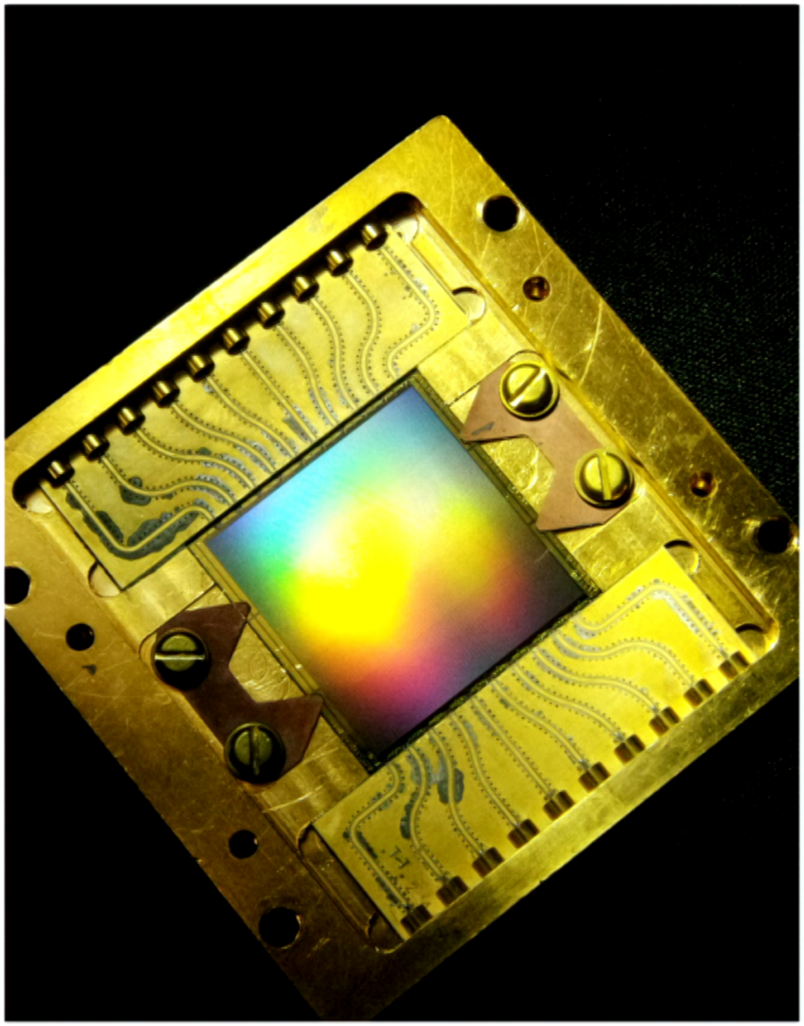
10 kpix DARKNESS Array



MEC Array

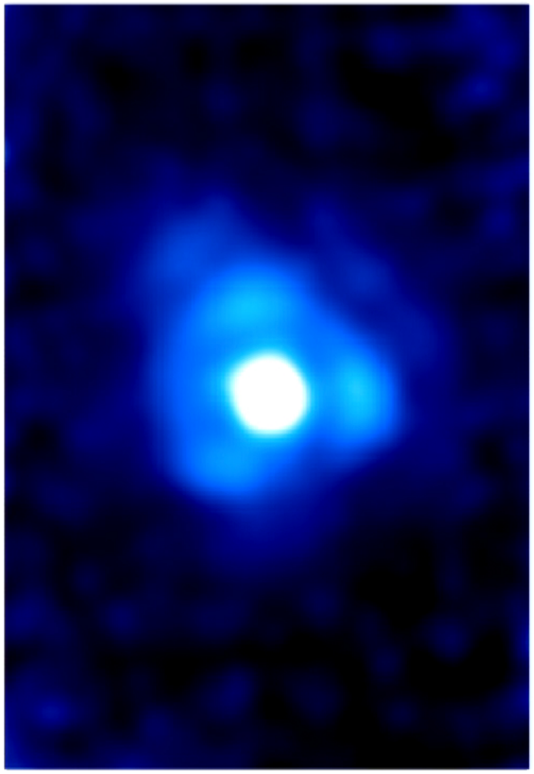
- New 20 kpix PtSi MKID array for Subaru SCExAO-MEC
  - 140x146 pixels, 150 micron pixel pitch, 22x22 mm imaging area

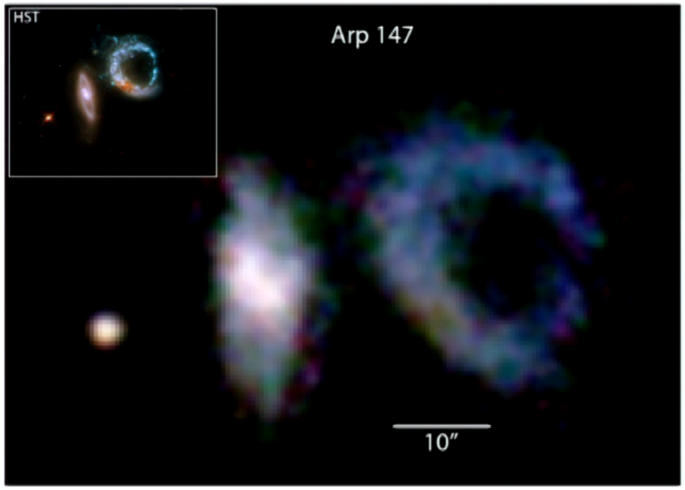


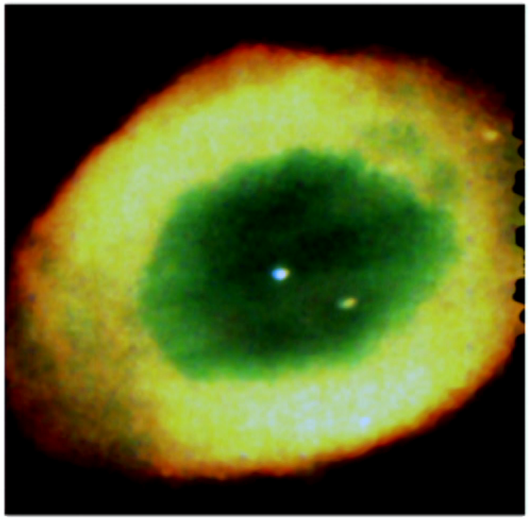
Array fabricated at UCSB by P. Szypryt and G. Coiffard.

Szypryt et al. 2017, Optics Express

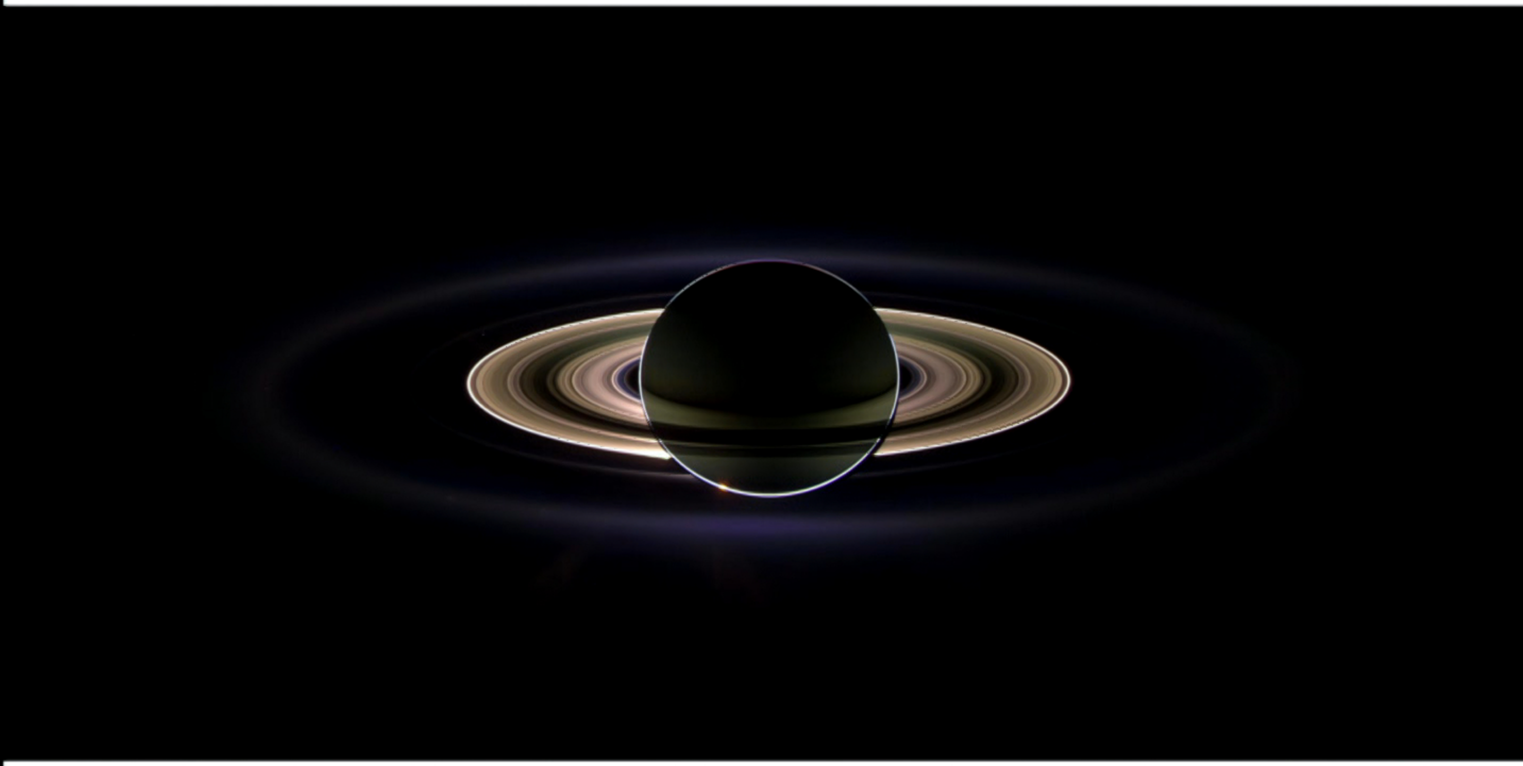
Images from ARCONS and DARKNESS







Exoplanets



- Our best estimate is that 5-25% of stars (and maybe every M dwarf?) have an ~Earth radius planet in their habitable zone!
- Most likely one around the nearest star – Proxima Centauri b
- How can we find and characterize these planets?
  - Huge potential payoff: Atmospheres out of chemical equilibrium → **Life**

Methods of Exoplanet Detection

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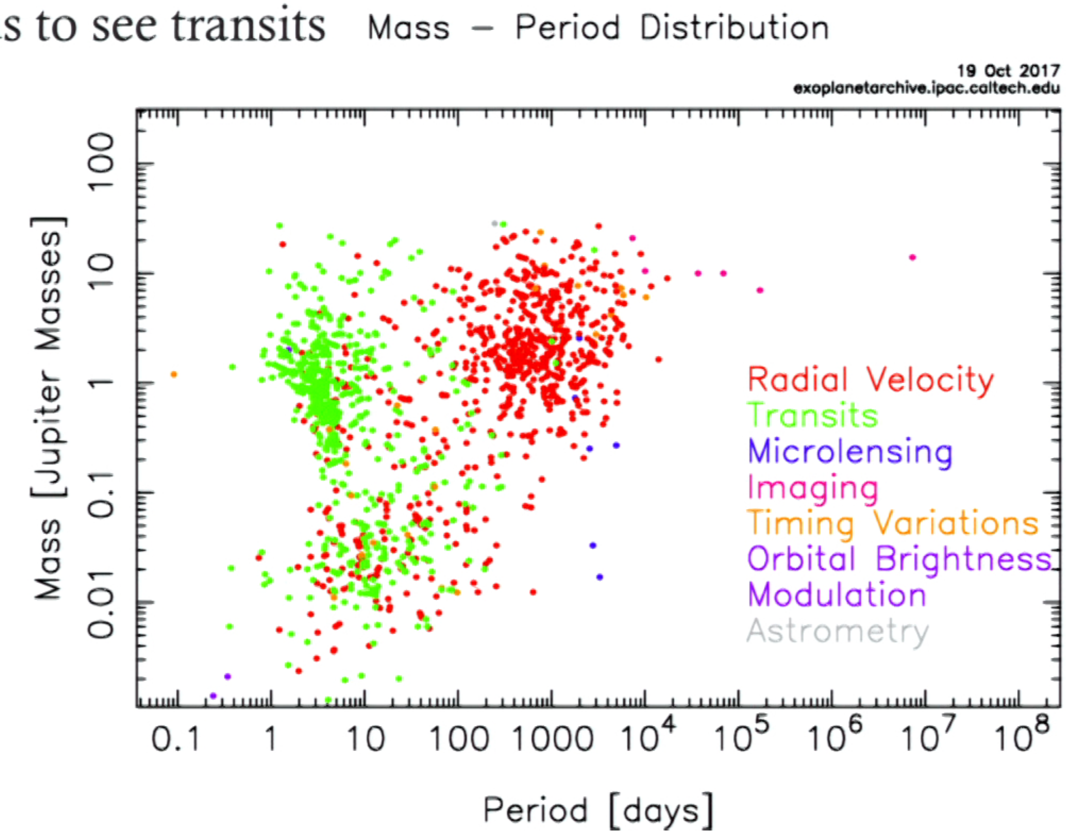
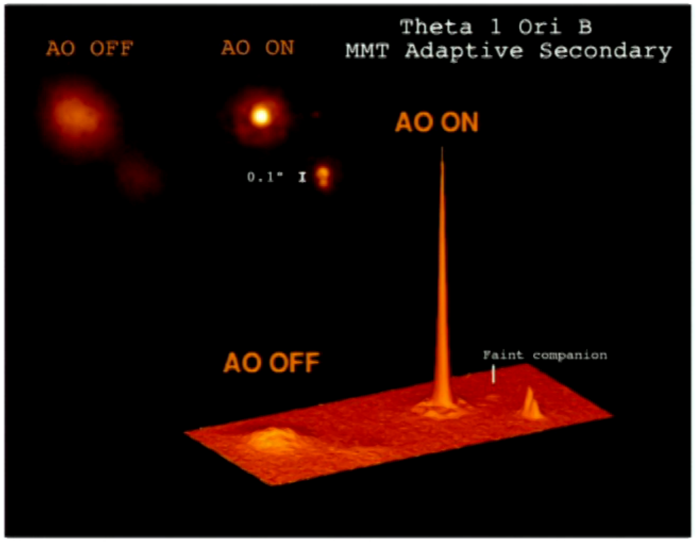
- **Radial Velocity:** Good for massive planets around well behaved stars with lots of sharp features in their spectrum
- **Transit:** Good for only the 1% of stars that are aligned correctly for us to see transits



Step 1: Adaptive Optics

- The atmosphere messes up incoming starlight
  - Twinkling stars!
  - Good for kids rhymes, bad for astronomy
- Fix it with (lots and lots of) technology!



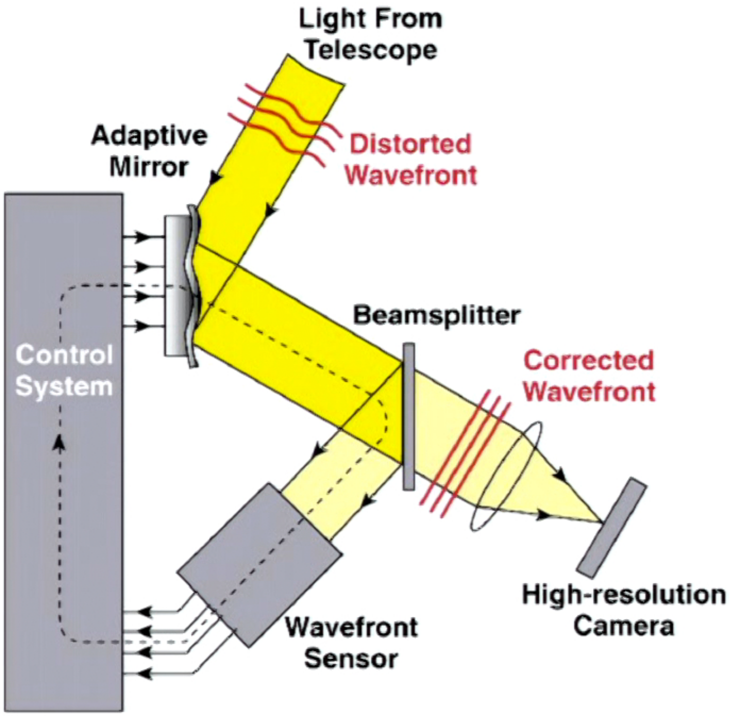
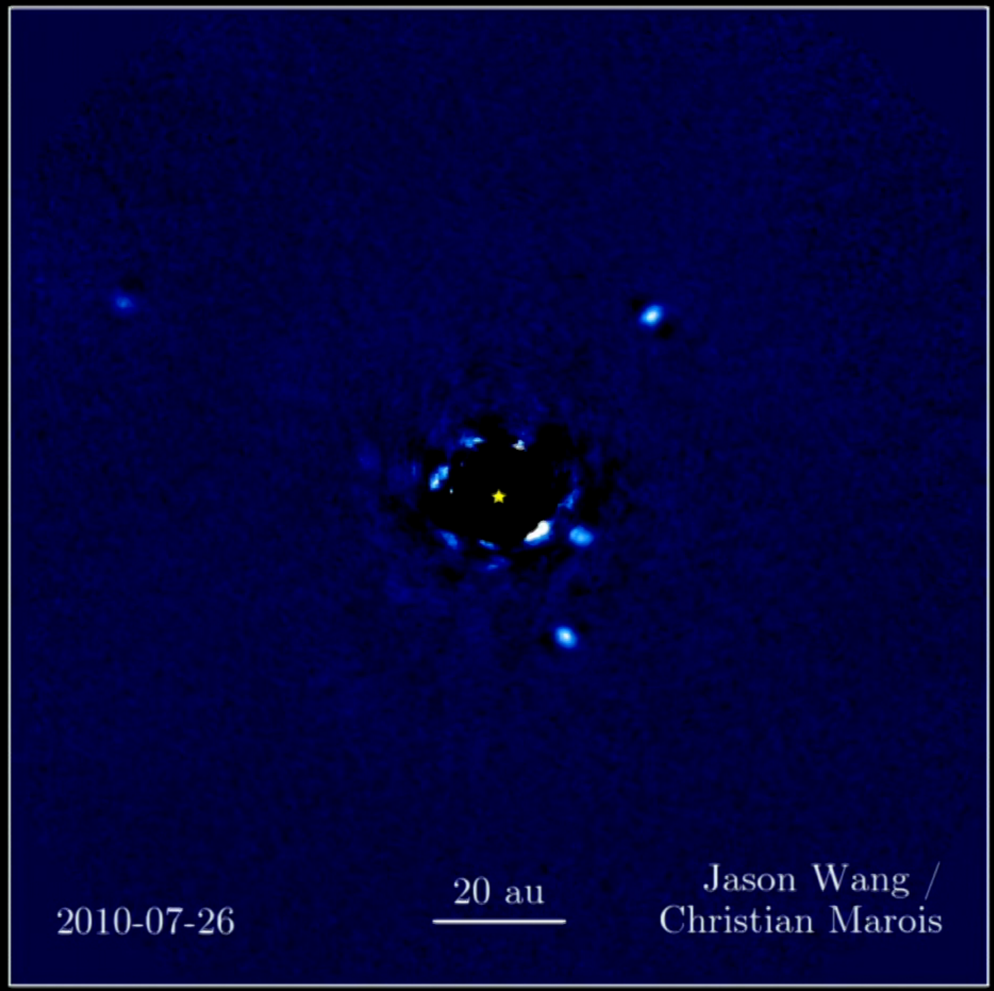
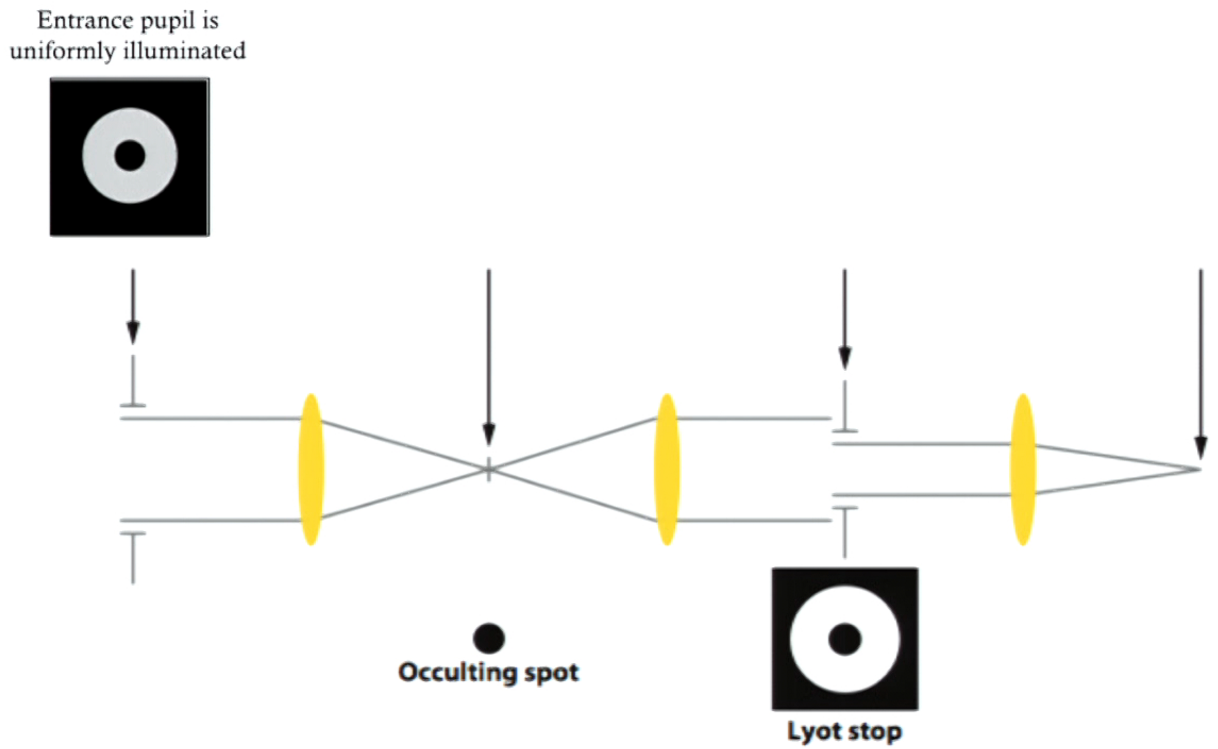


Image Credit: Above: Clare Max, CfAO
Left: Laird Close, UoA

HR8799



Step 2: Coronagraphy



Adapted From Oppenheimer & Hinkley (2009), which adapted it from Sivaramakrishnan et al. (2001)

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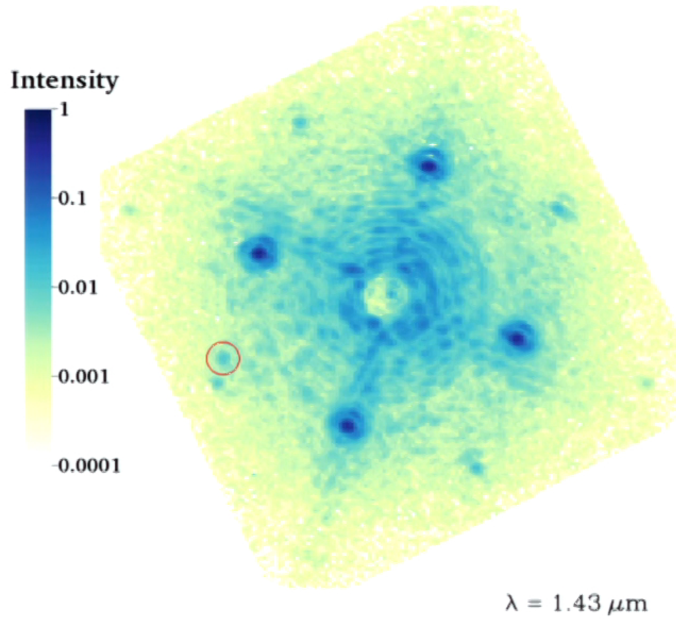
Step 3: Detection

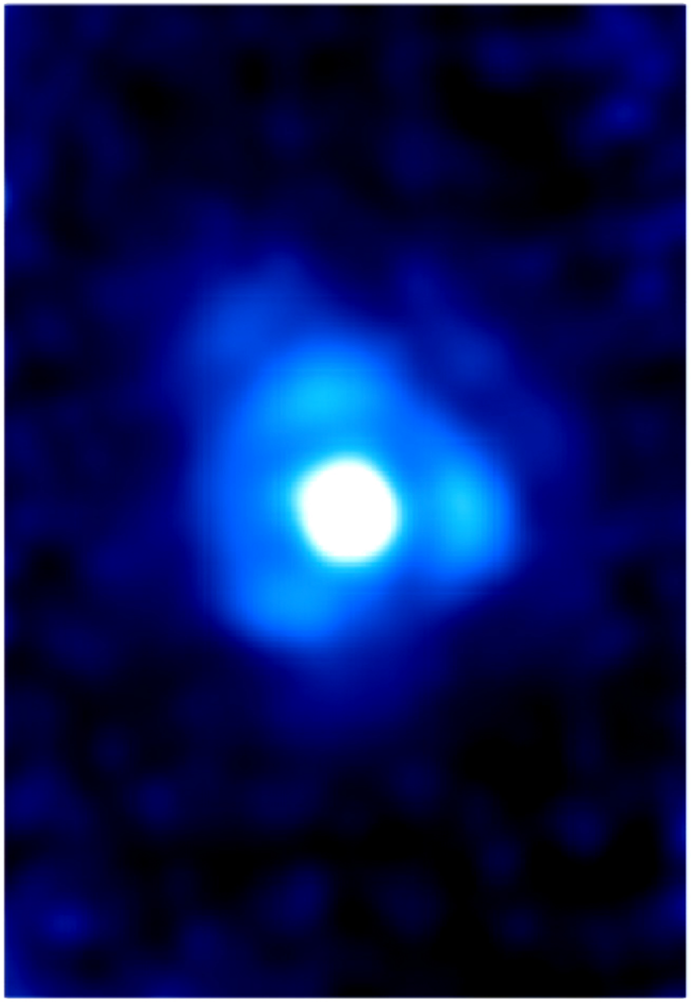
- Coronagraphs are limited by speckles from scattered and diffracted light
  - Speckles are *coherent* and *chromatic* and have a variety of lifetimes
    - Quasi-static: many minutes
    - Atmospheric: <1 second
  - Energy-resolving focal planes increase sensitivity by a factor of up to **10-100**
    - **Spectral Differential Imaging**
    - **Temporal Speckle Statistics**
    - **Active Speckle Nulling**
    - Removes requirement of a separate spectrograph
    - Gives the spectra of all planets in the dark box



- Data on brown dwarf HD1160B from Tim Brandt and CHARIS/SCExAO

It works!

- Diffraction limited star in J-band with DARKNESS



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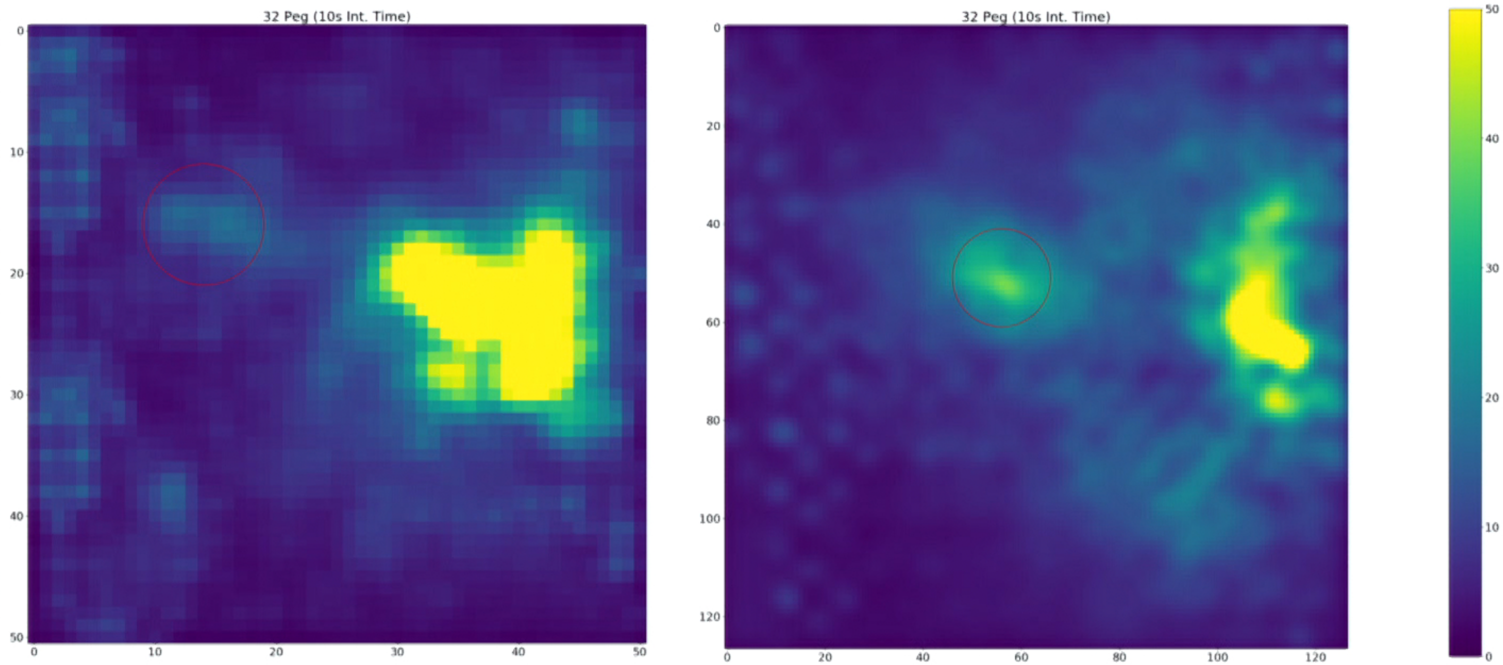
32 Peg



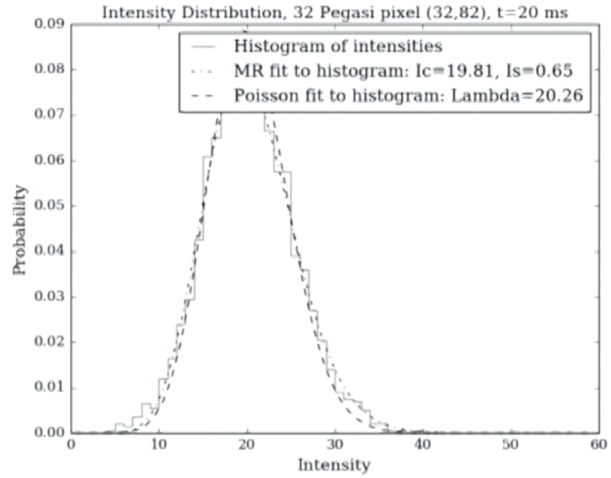
Coronagraph OUT

Coronagraph IN

Reduction by Isabel Lipartito 

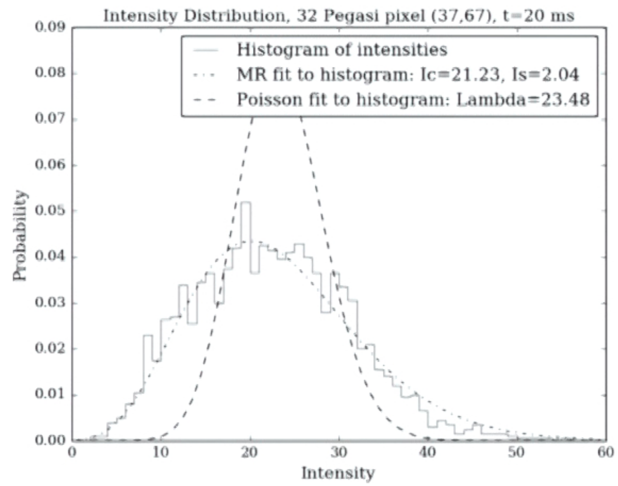
Histogram
location
A (companion)

Mean intensity
~20 photons /
20 ms



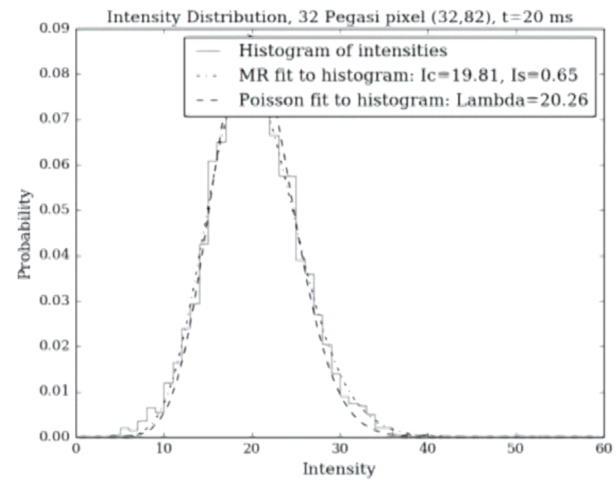
Histogram
location
B (satellite
speckle)

Mean intensity
~23 photons /
20 ms



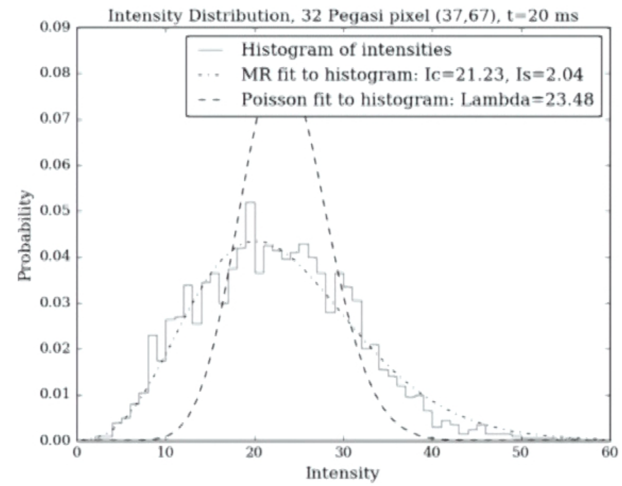
Histogram location A (companion)

Mean intensity ~20 photons / 20 ms



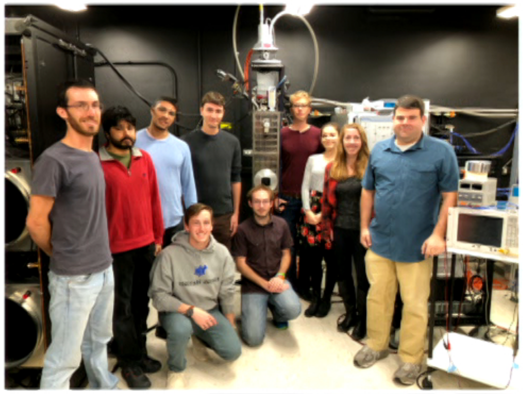
Histogram location B (satellite speckle)

Mean intensity ~23 photons / 20 ms



MEC

- MEC is a 20 kpix version of DARKNESS for Subaru SCExAO
  - 20 kpix MKID IFU
  - SCExAO at Subaru Observatory
    - PIAA/Vector Coronagraph
  - Observe cold gas giants in reflected light?

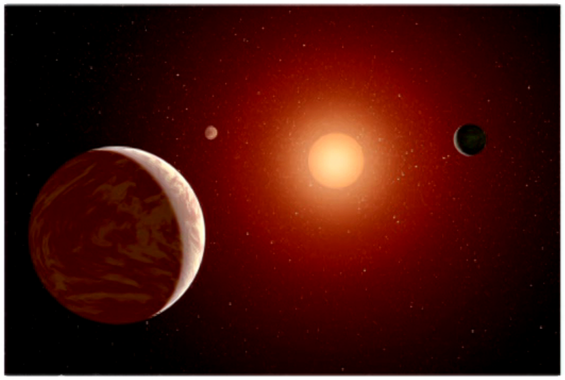


MEC is the thesis project of Alex Walter

Large Apertures are Vital for Direct Imaging of Exoplanets

- GPI/SPHERE/SCExAO/P1640 show planets are rare past 10 AU
- Going inside 10 AU pushes us to large aperture and short wavelengths for a small inner working angle (IWA)
  - $2\lambda/D$ for TMT at 1.3 micron = 10 mas!
  - 0.1 AU at 10 pc
    - M star habitable zones at 10^{-8} contrast ratios
    - 275 M stars within 10 pc
      - TRAPPIST-1 – lots of rocky planets!
    - 22 G stars within 10 pc
  - 1 AU at 100 pc
    - Gas Giants at high spectral resolution
  - 4.5 AU at 450 pc (Orion)
    - Planet formation

TMT Telescope
Image Credit: TMT



M star habitable zone
Image Credit: NASA/JPL-Caltech

MKID Strip Detector Concept

Mazin Lab at UCSB
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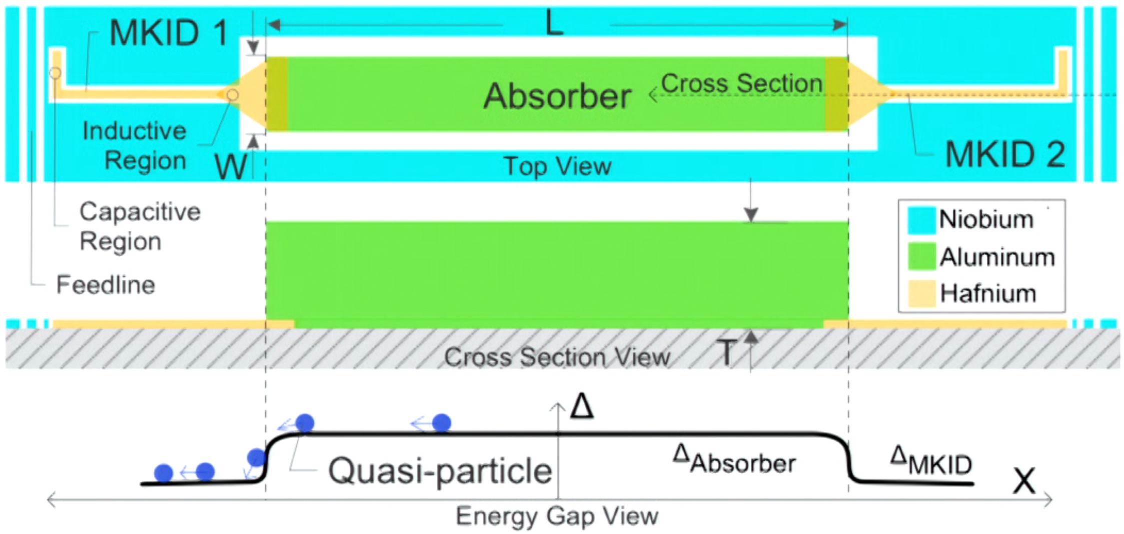
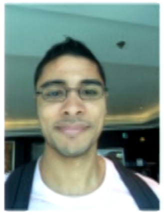


Absorber Dimensions: 2000 μm x 200 μm x 5 μm :: L x W x T

Slides courtesy Miguel Daal
DM Calculations by Dave Sutherland
and Nathaniel Craig



Experience with Strip Detectors

APPLIED PHYSICS LETTERS **89**, 222507 (2006)

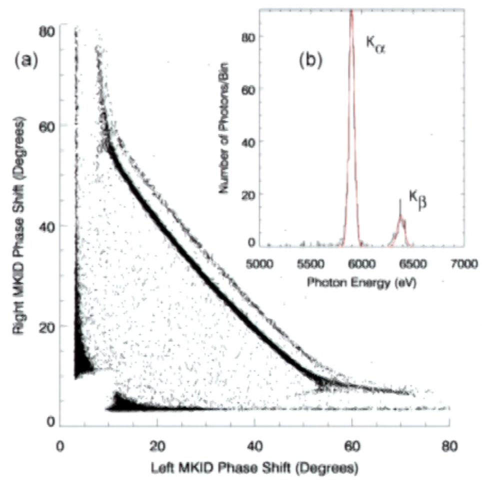
Position sensitive x-ray spectrophotometer using microwave kinetic inductance detectors

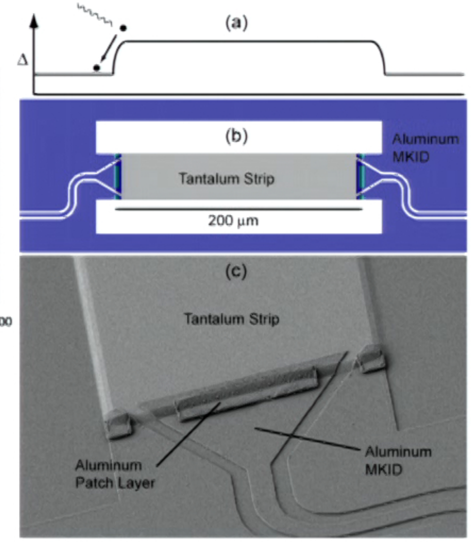
Benjamin A. Mazin,[a] Bruce Bumble, and Peter K. Day
Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, MS 169-506, Pasadena, California 91109-8099

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):
  - κ_{eff} = effective kinetic mixing parameter (coupling to normal matter)

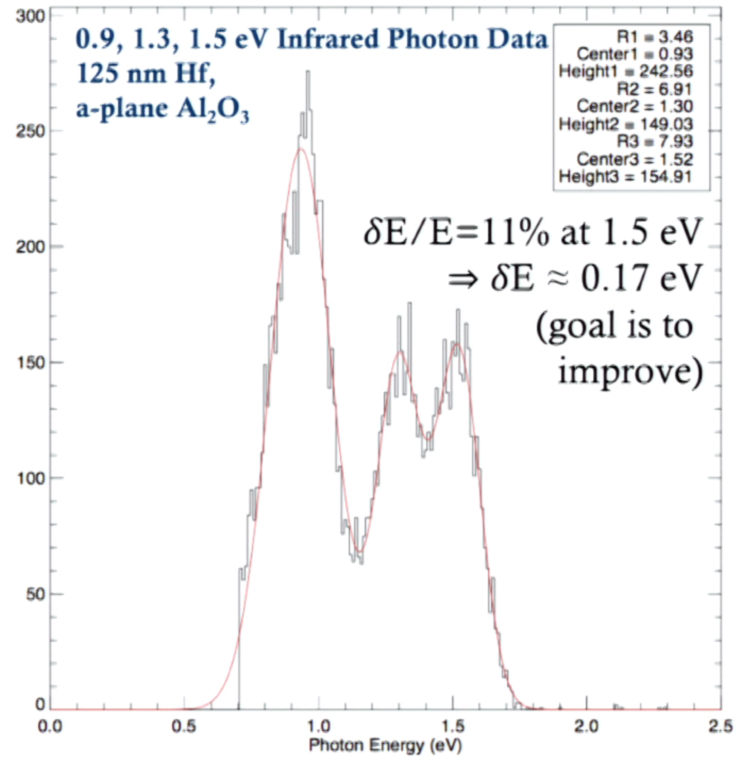
$$R = \frac{1}{\rho_{\text{absorber}}} \frac{\rho_{\text{DM}}}{m_{\text{A}'}} \kappa_{\text{eff}}^2 \sigma_1$$

Hafnium Resonators

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

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

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

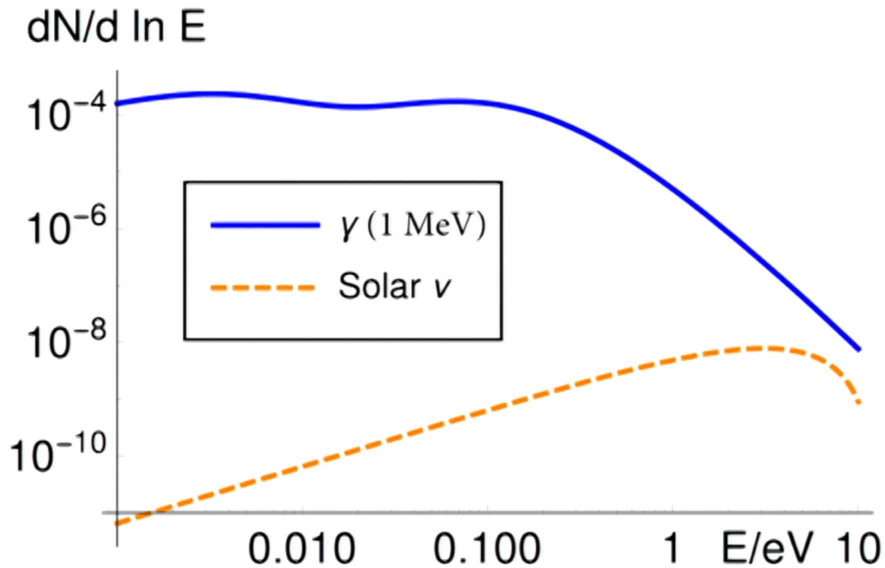


Backgrounds

We are estimating backgrounds from:

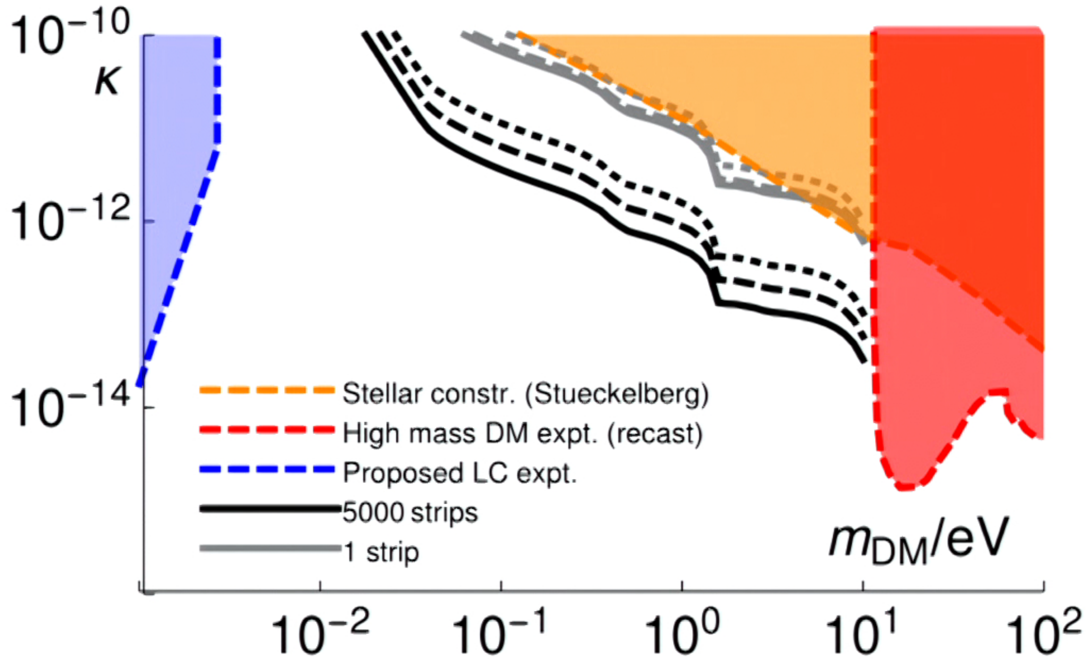
- Radioactivity
- Cosmic Rays (expt above ground)
- Coherent Photon Scattering off Atoms
- Stray Light
- Vibrations
- [pp – Neutrinos]

…Pulse shape/timing/energy spectrum discrimination



Estimated Dark Photon Sensitivity

- Proposing 5000 MKID Strip Detectors
  = 10,000 MKIDs
  = 10 mm^3 Al
  = 2 x 4" wafers
- 6 months
- 1, 10, 100 Background events



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

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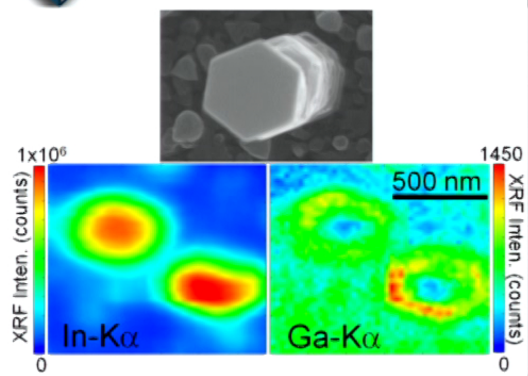
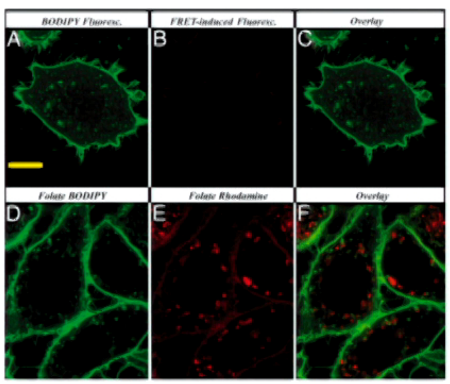
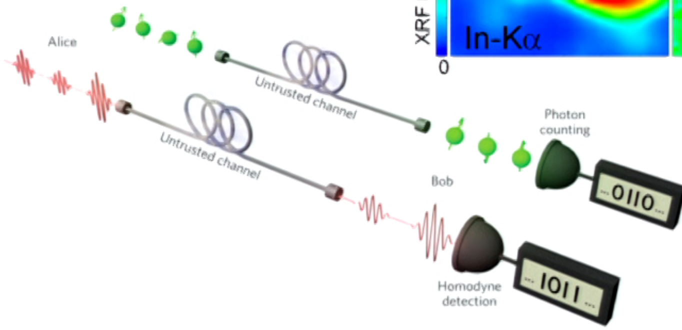
Other Applications

- 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!







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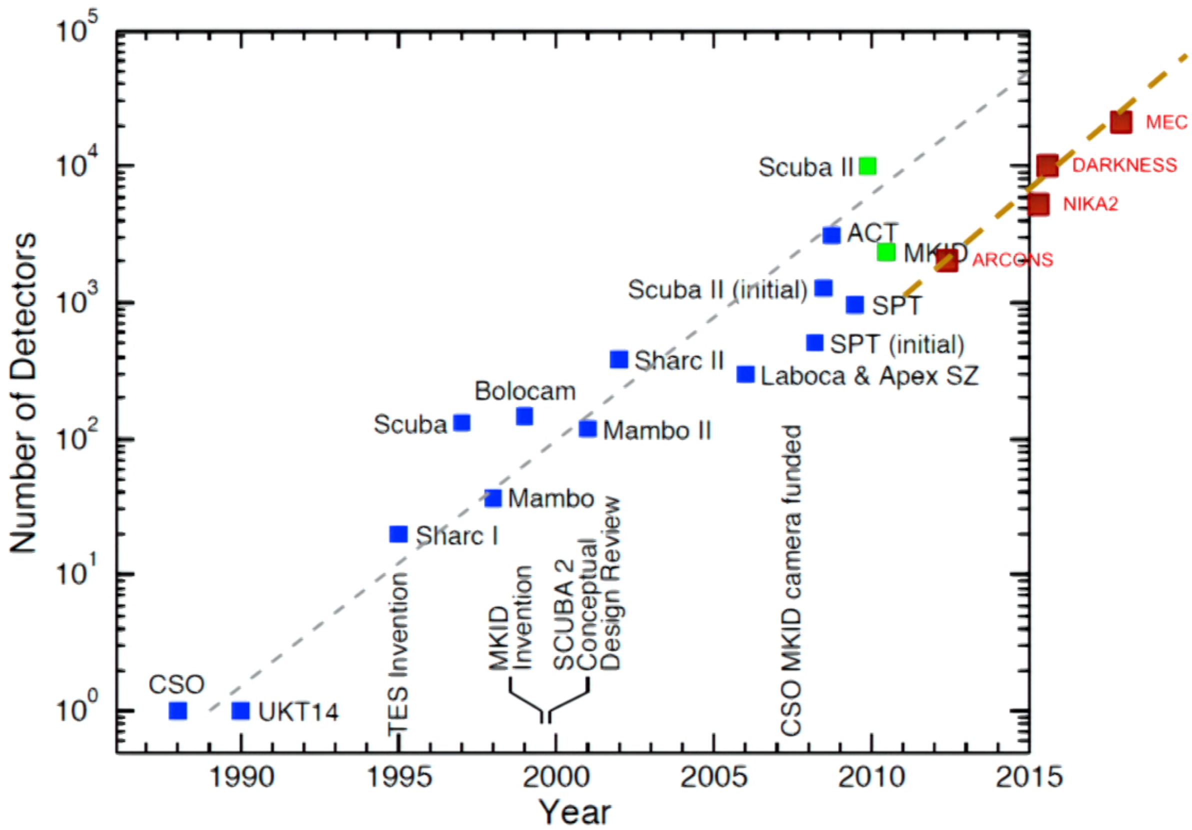
MKID Scaling



Original plot from J. Zmuidzinas