MKIDs for Exoplanet Direct Imaging

Ben Mazin, August 2016

The UVOIR MKID Team:

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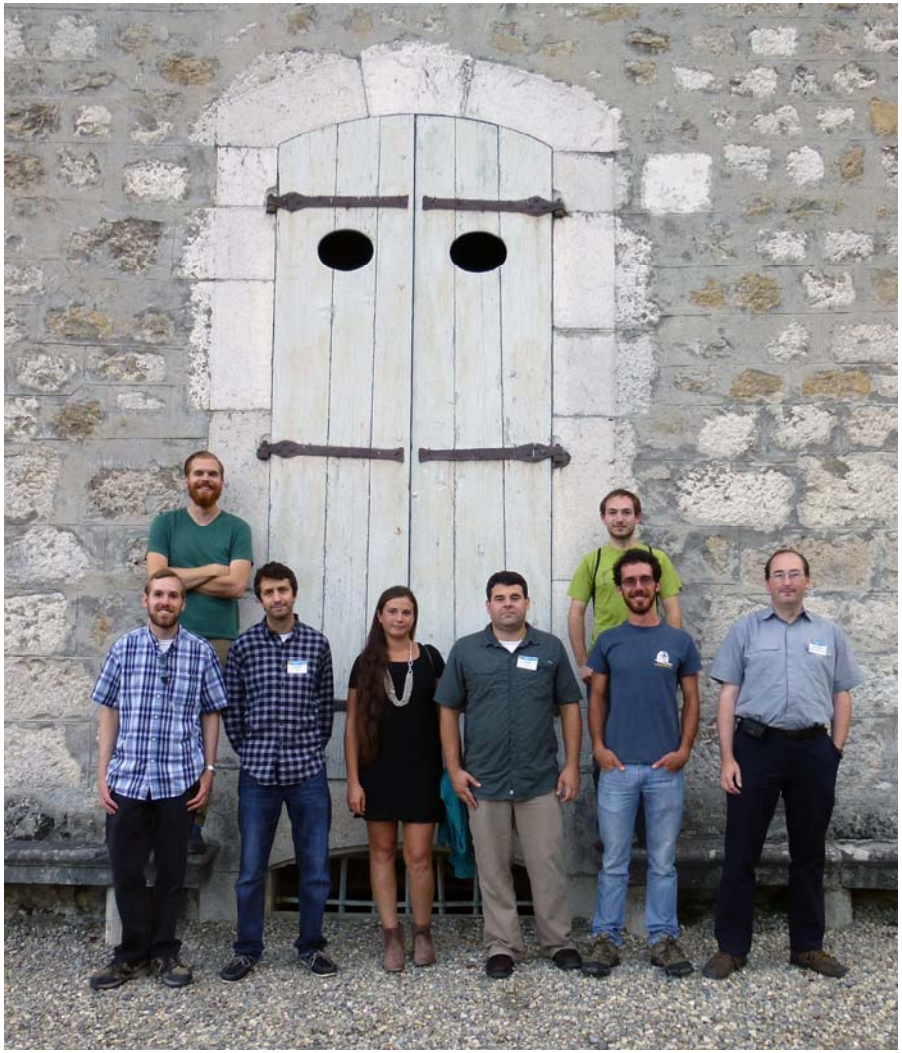
JPL/IPAC: Bruce Bumble, Julian van Eyken

Oxford: Kieran O'Brien, Rupert Dodkins

Fermilab: Chris Stoughton, Juan Estrada, Gustavo Cancelo



MazinLab.org @

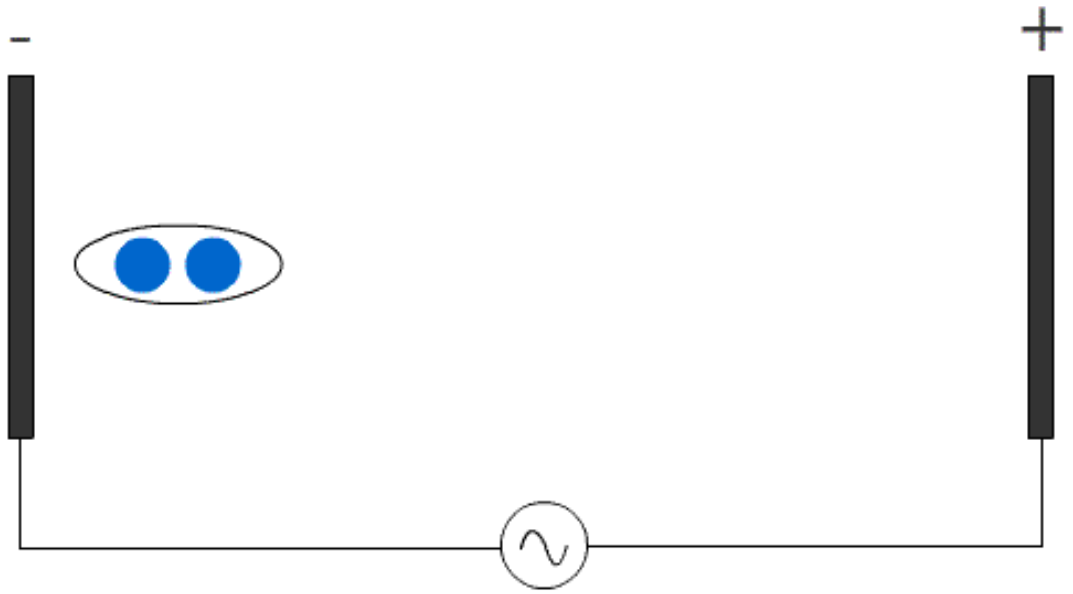
Superconductors

- A superconductor is a material where all DC resistance disappears at a "critical temperature". 9 K for Nb, 1.2 K for Al, 0.8 for our TiN
- This is caused by electrons pairing up to form "Cooper Pairs"
  - Nobel Prize to BCS in 1972

- 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 ~50 microseconds

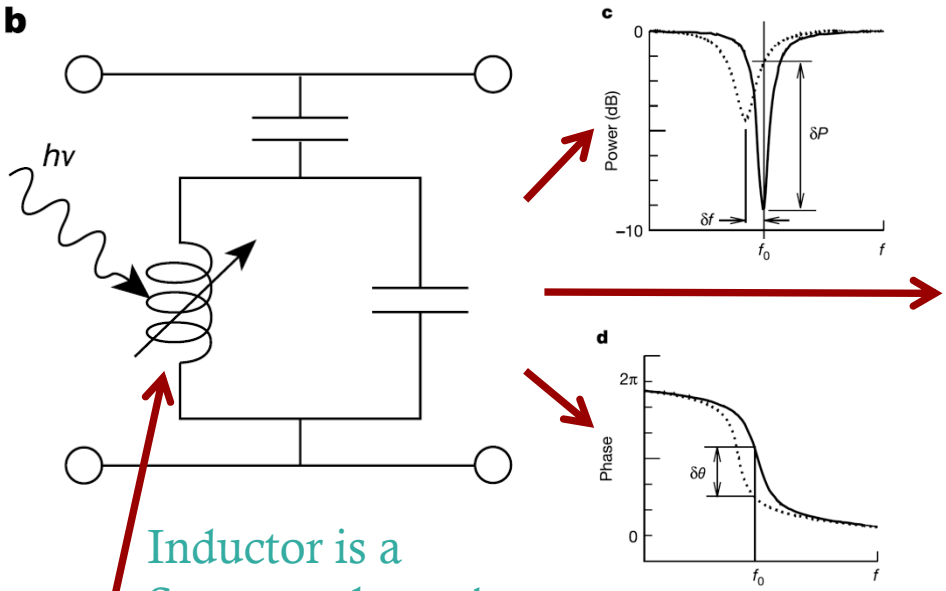
Kinetic Inductance Effect

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

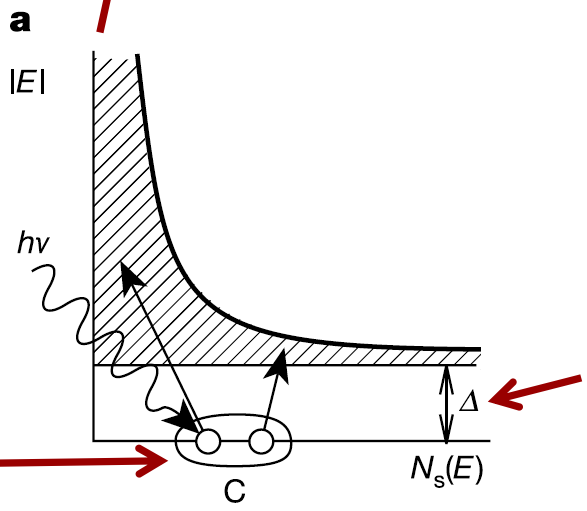


MKIDs

MKID Equivalent Circuit



Inductor is a Superconductor!



Coope
r Pair

C

Energy Gap

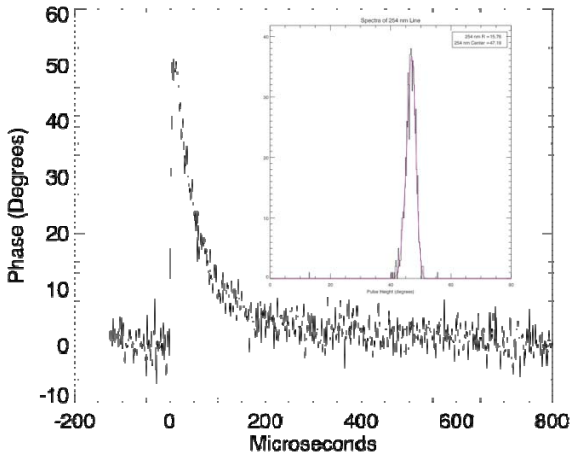
Silicon – 1.10000 eV

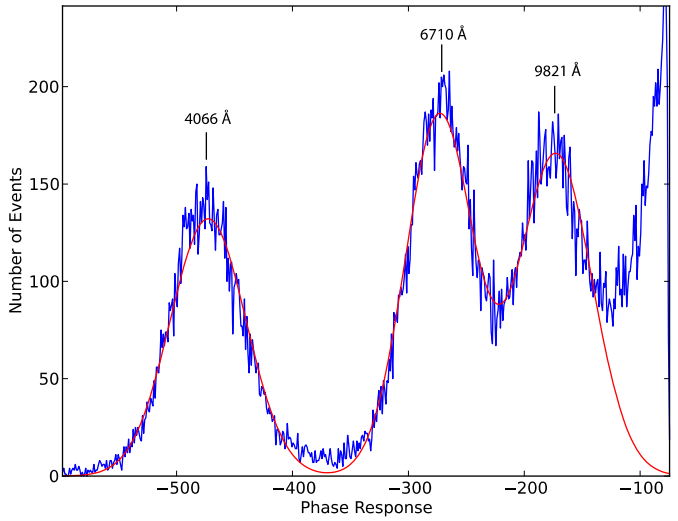
Aluminum – 0.00018 eV

Energy resolution:

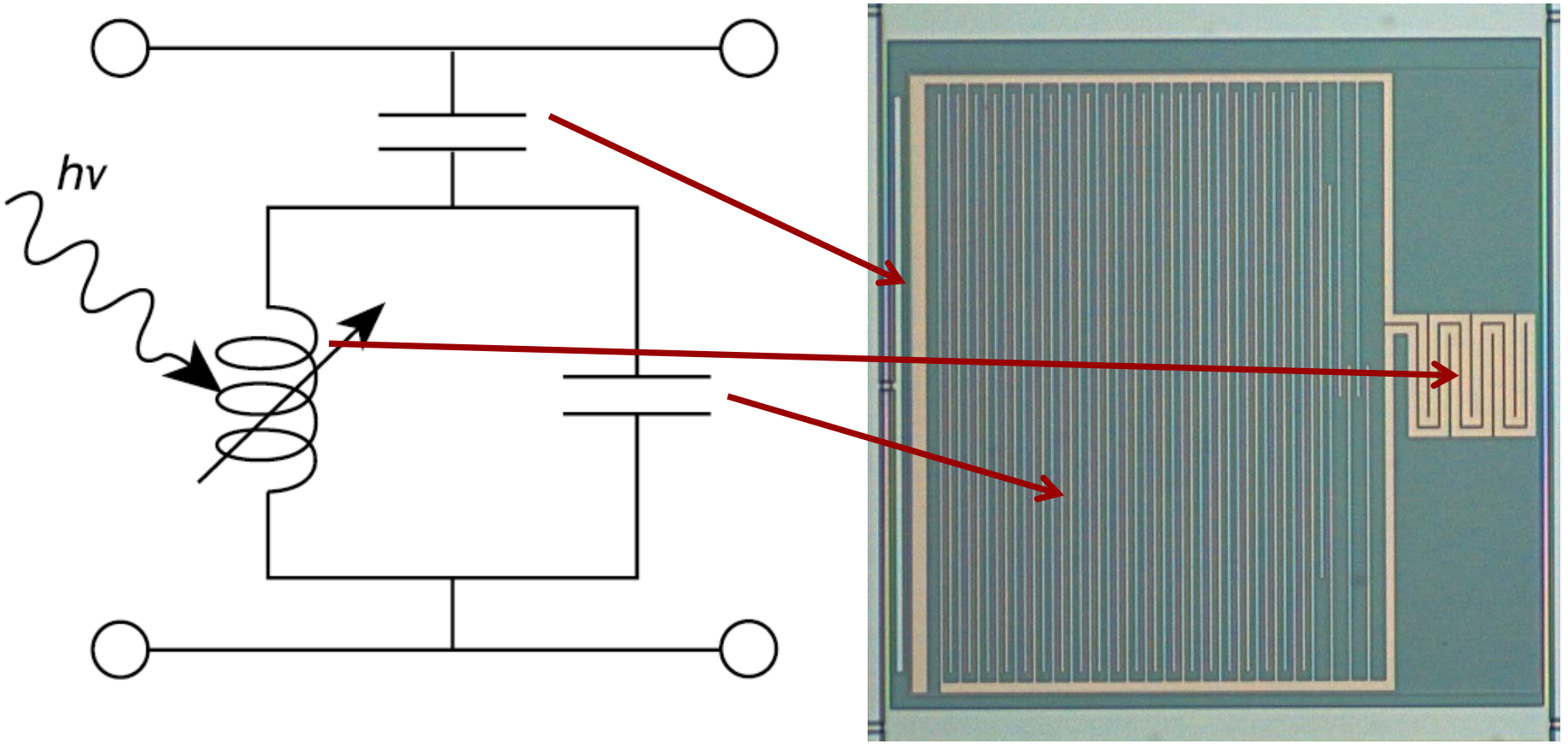
$$R = \frac{1}{2.355}\sqrt{\frac{\eta h\nu}{F\Delta}}$$

Typical Single Photon Event



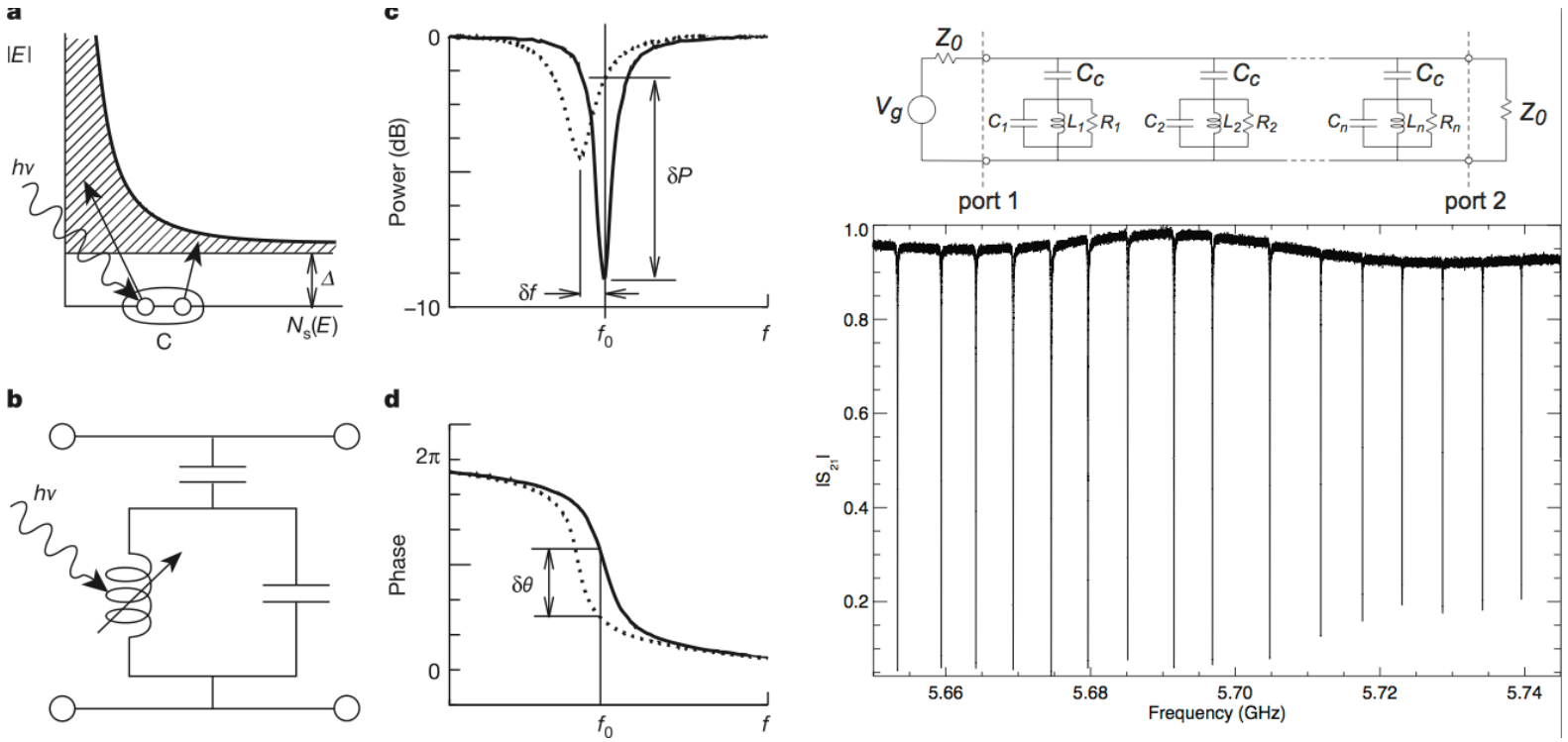


What is a Kinetic Inductance Detector ?



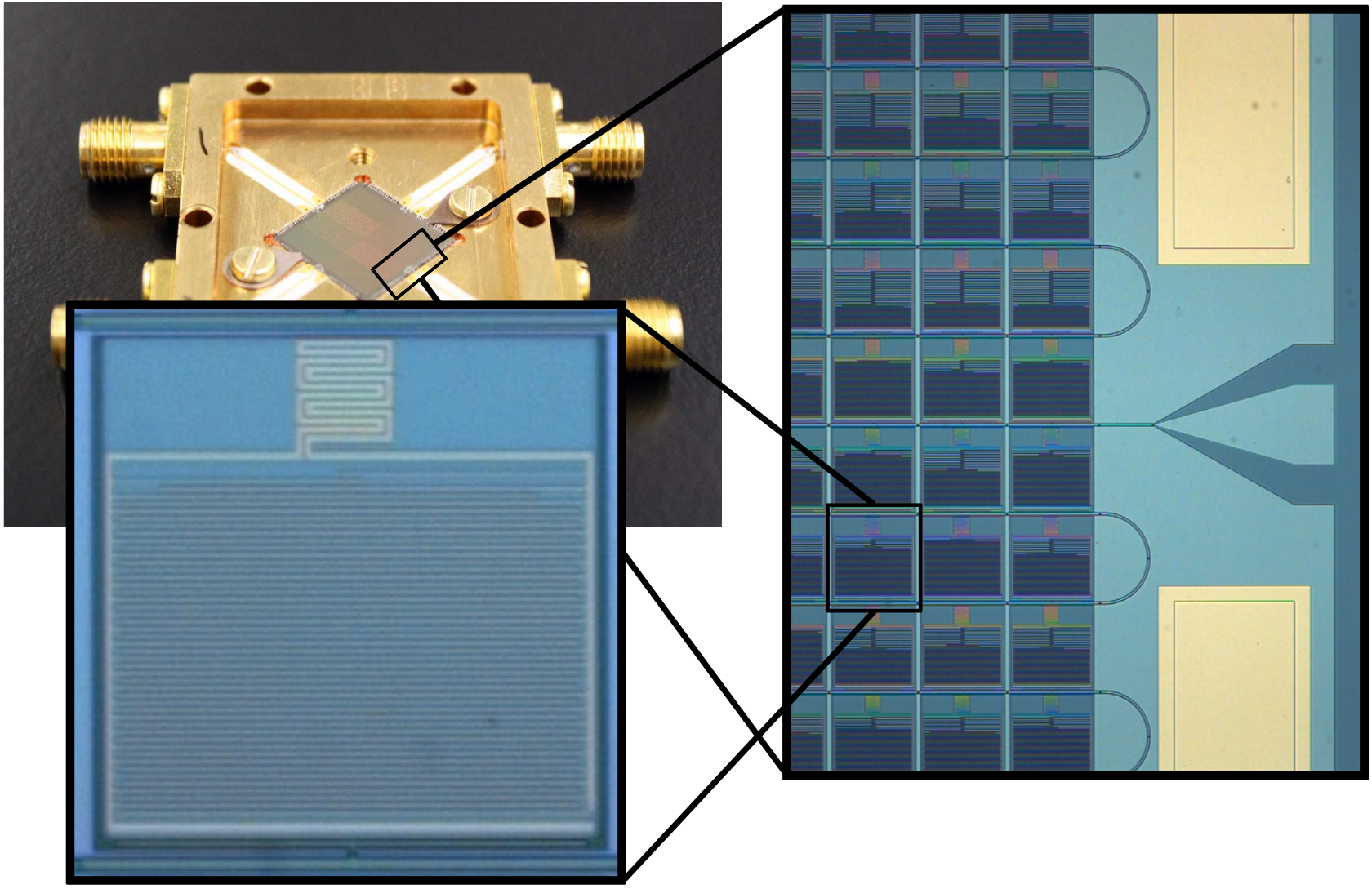
We use a square microlens array to improve effective fill factor to ~92%

Frequency Domain Multiplexing



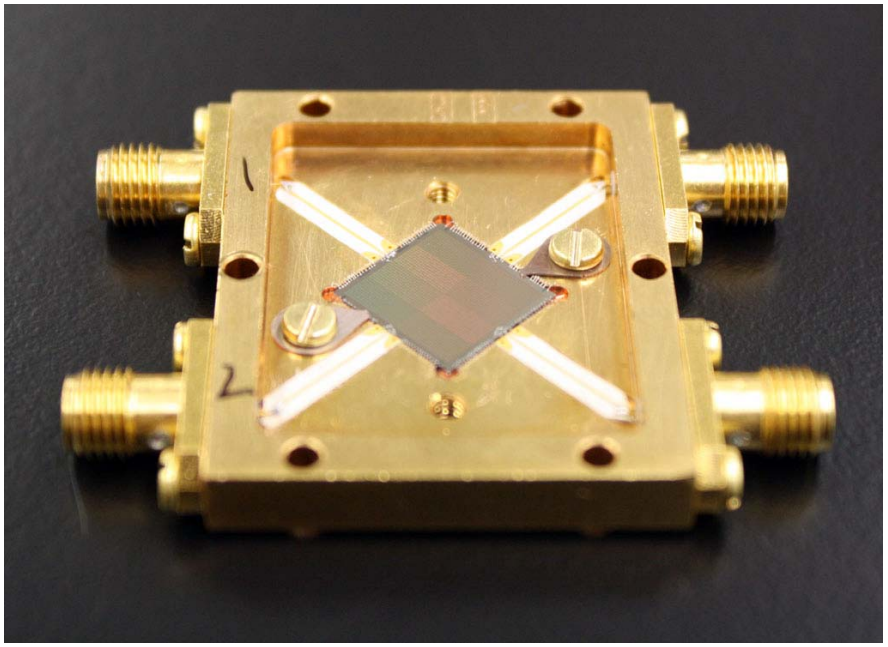
- Each resonator (pixel) has a unique resonant frequency in the GHz range
- A comb of sine waves is generated and sent through the device
- Thousands of resonators can be read out on a single microwave transmission line (FDM)

UVOIR MKIDs



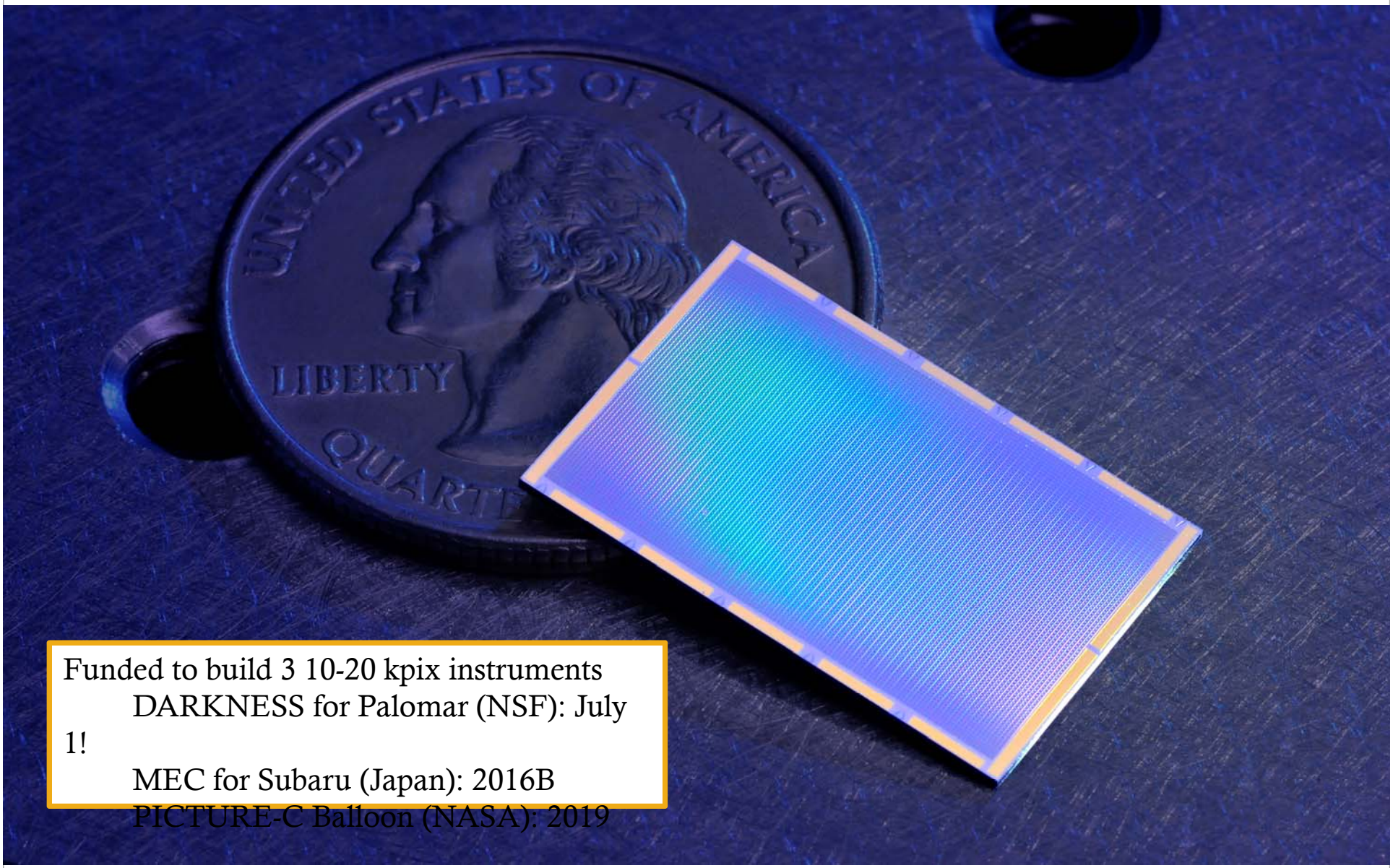
UVOIR MKIDs

- ARCONS MKID Array
- 2024 (44x46) pixel array
- 222 micron pixel pitch
- 2 feedlines
- 2 MHz resonator spacing
- ~92% resonator yield
- ~70% "good" pixel yield
  - Frequency collisions dominate yield!
  - More uniform TiN (multilayer, ALD, new materials) should significantly improve yield
- 110 mK operating temp.



Mazin et al. 2012, Optics Express, 20, 2

10 kpix DARKNESS Array

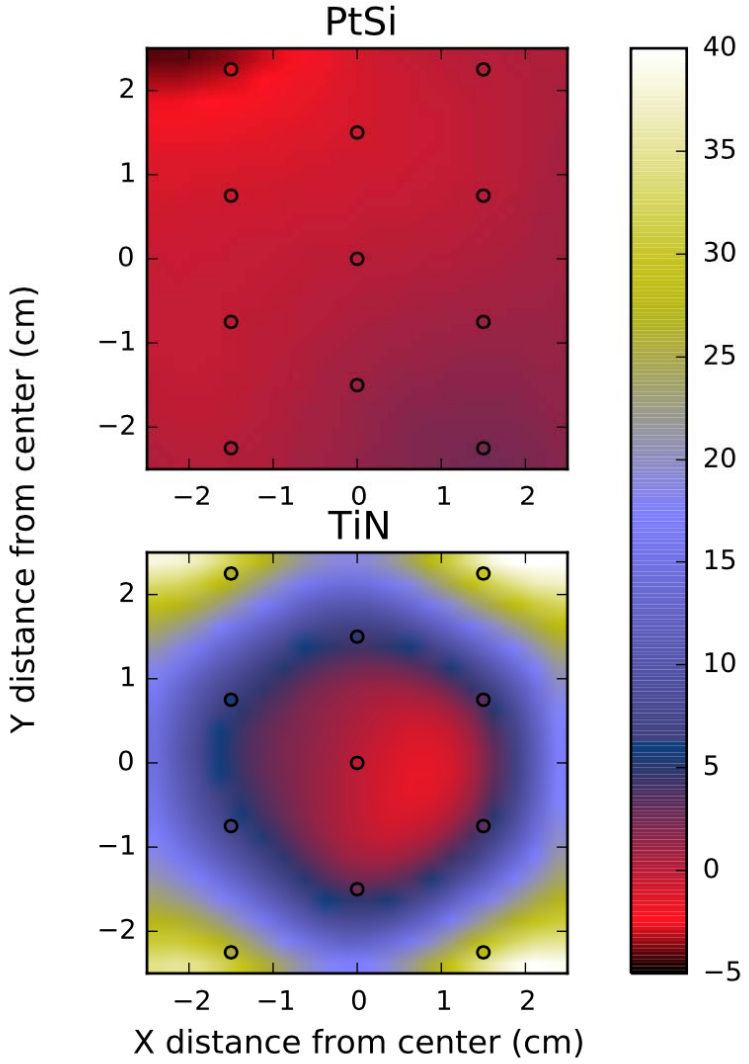


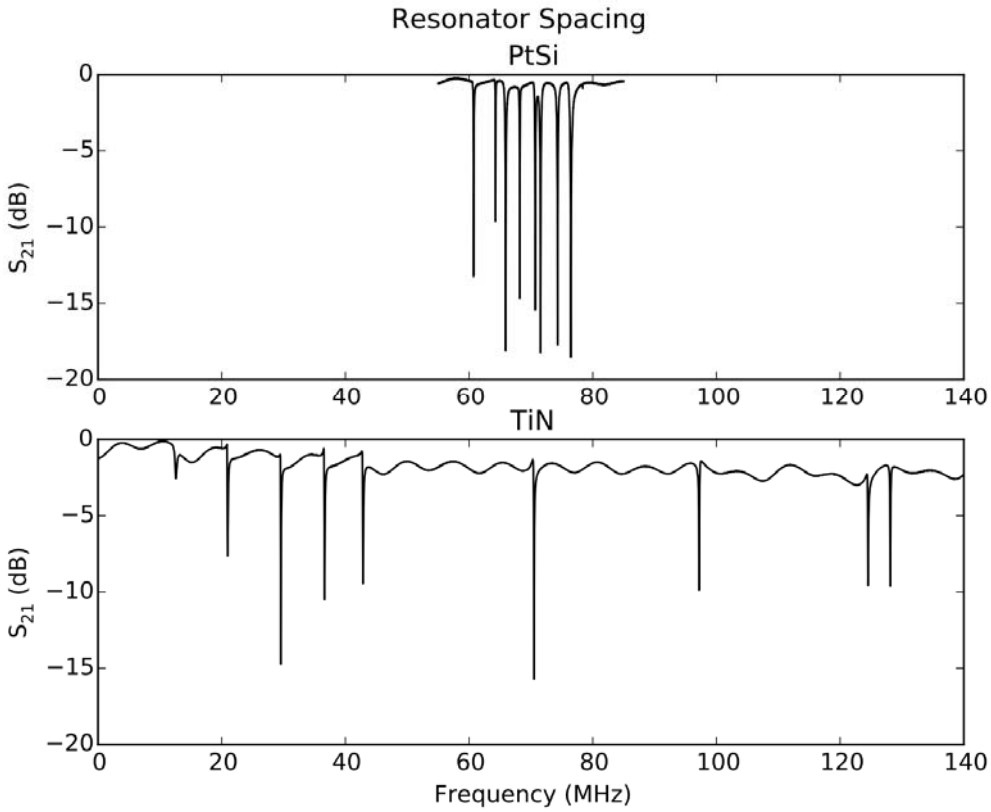
Funded to build 3 10-20 kpix instruments

- DARKNESS for Palomar (NSF): July 1!
- MEC for Subaru (Japan): 2016B
- PICTURE-C Balloon (NASA): 2019

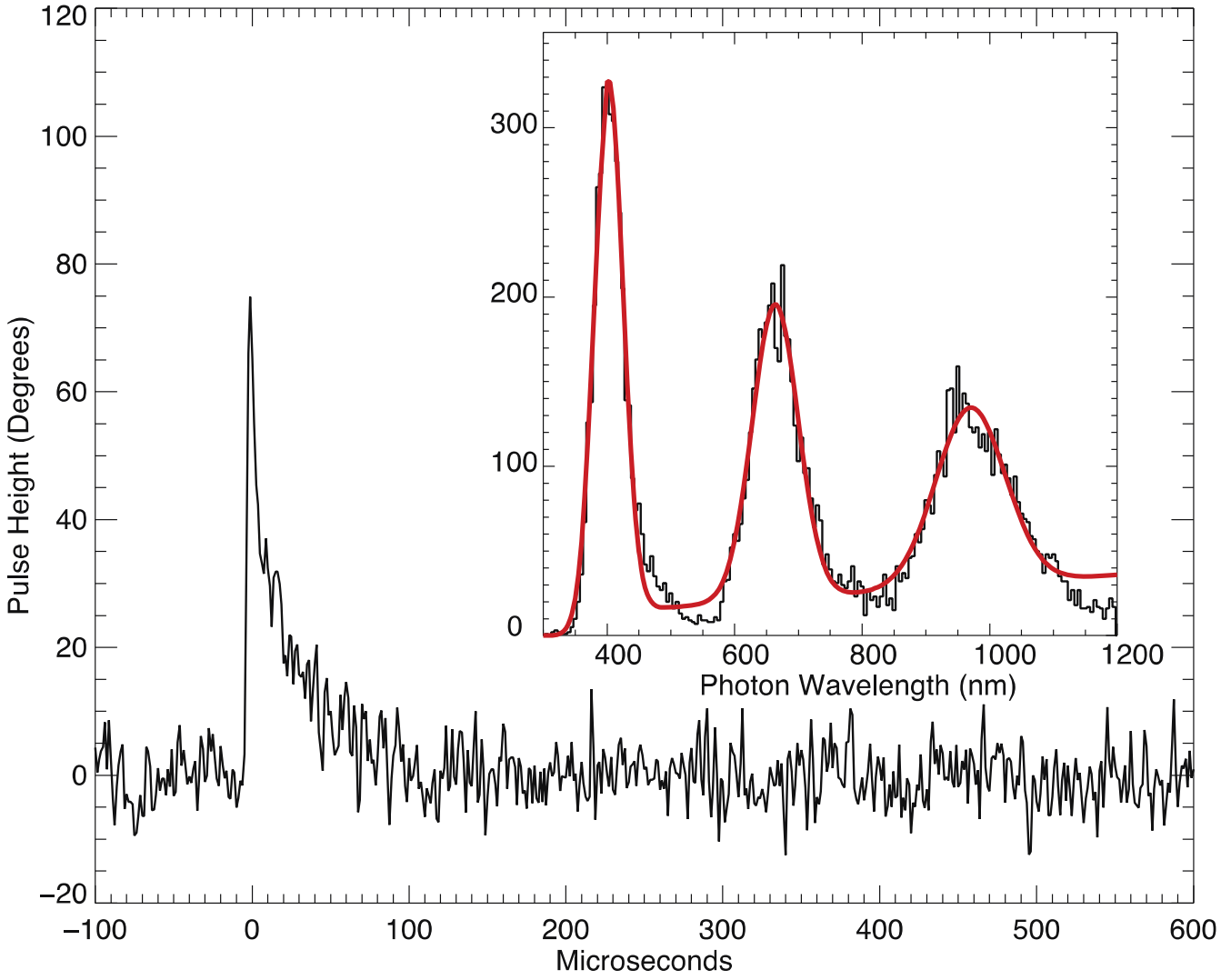
PtSi

% Variation in Sheet Resistance from Center





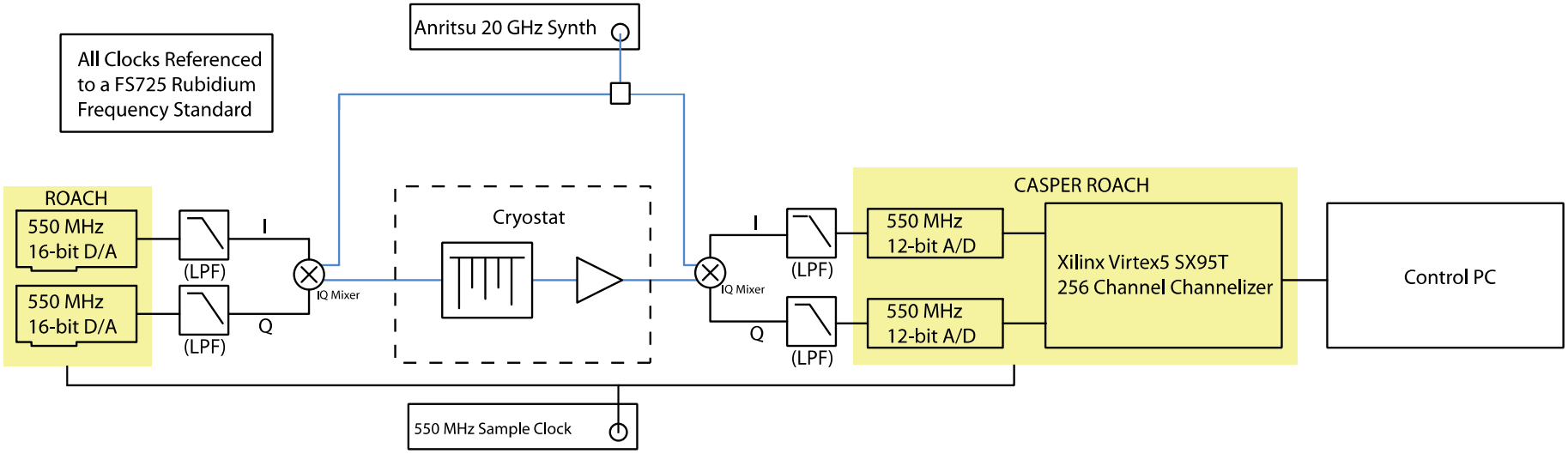
PtSi



R=8 at 1 micron

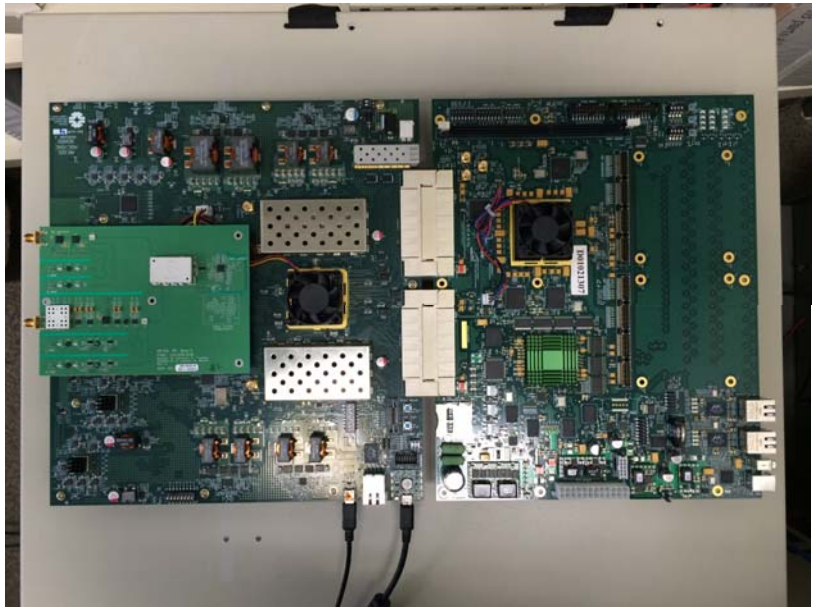
Digital MKID Readout

- 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)

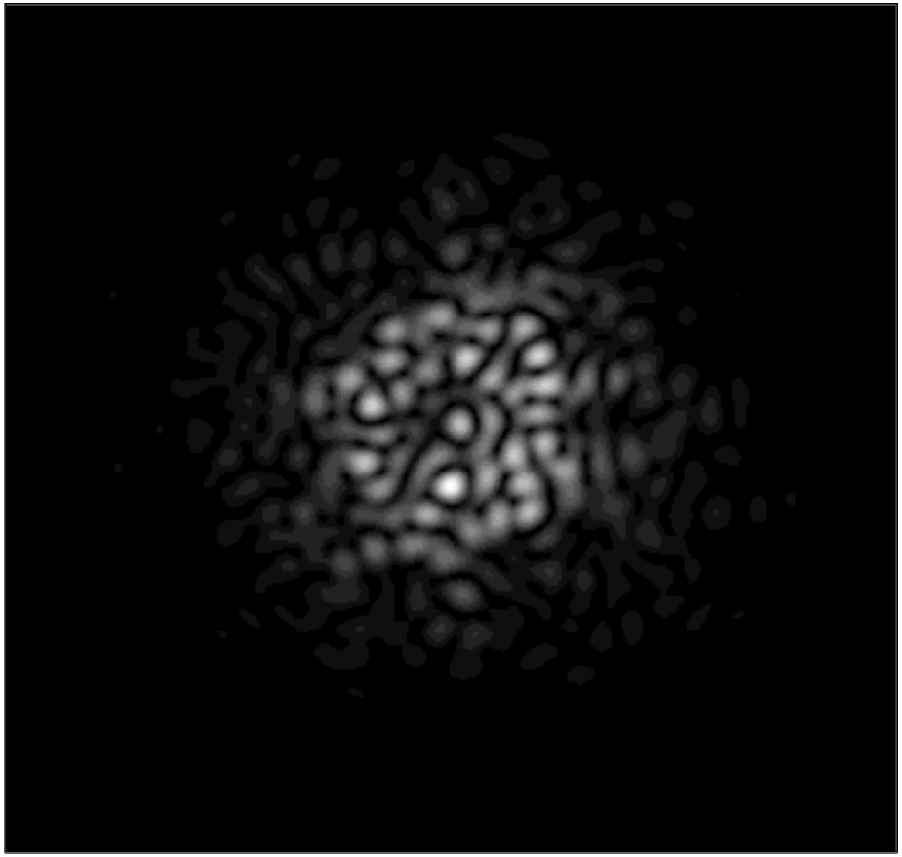


Gen 2 Readout

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



Killing Speckles



Correcting speckles optimally requires:
Speed! (kHz frame rates)
Focal plane correction to reduce NCPA
Energy resolution

Detector Wish List:

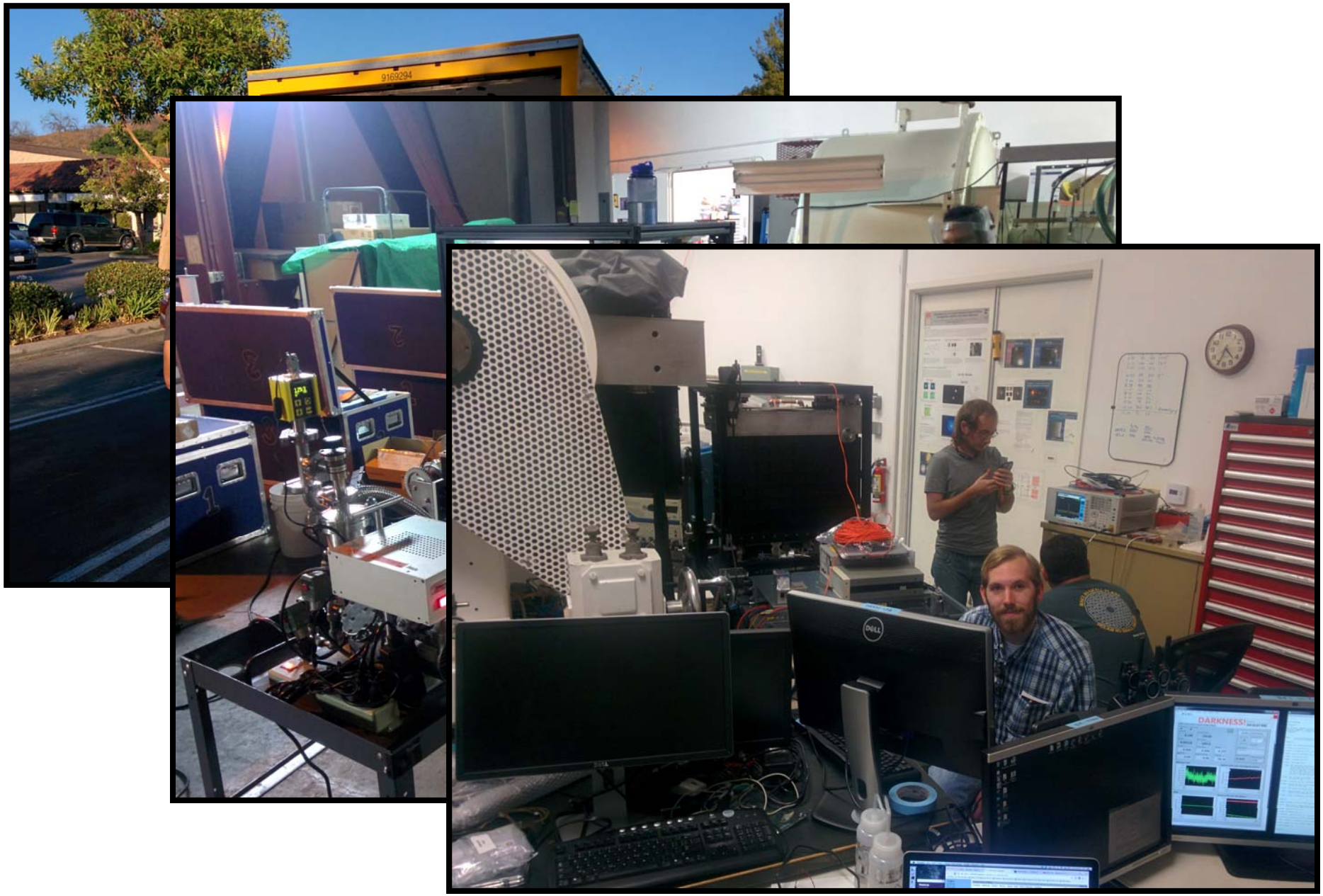
Energy Resolution

Photon-counting/Arbitrarily Short exposures

Fast (Instantaneous) Readout

Zero dark current or read-noise

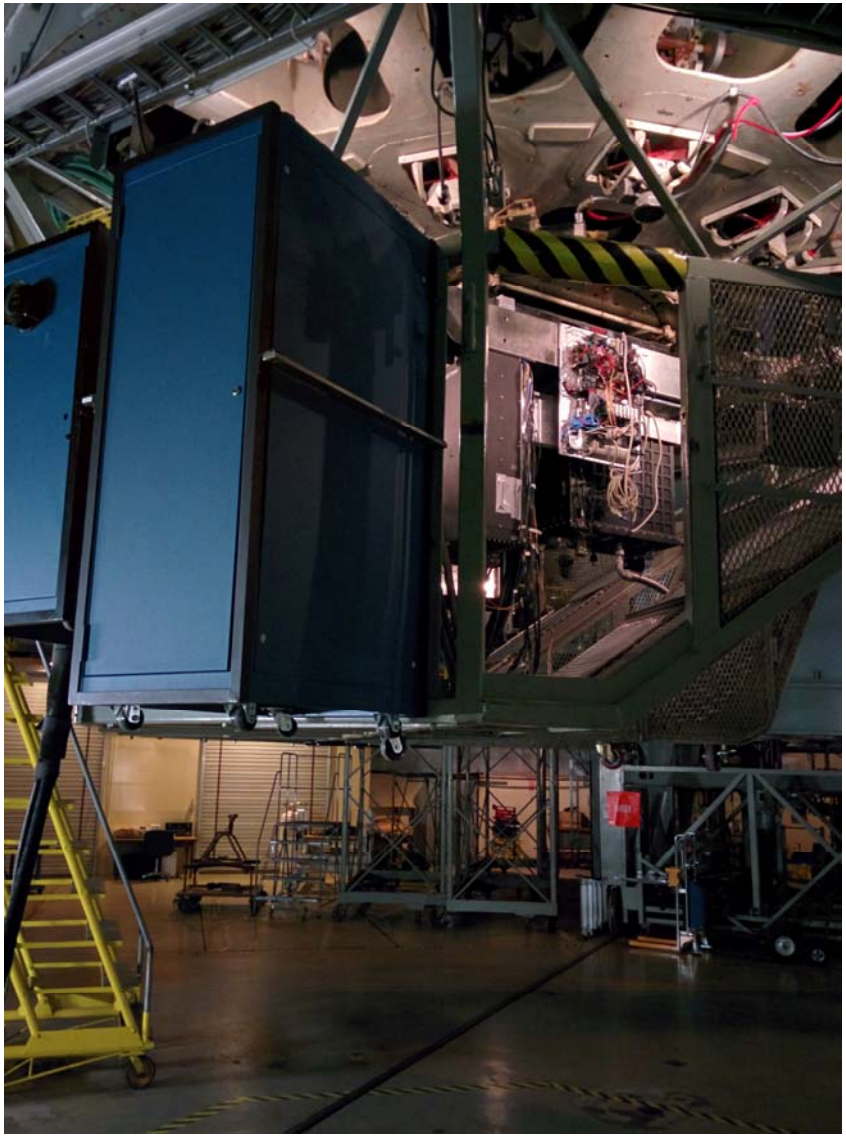
DARKNESS goes to Palomar

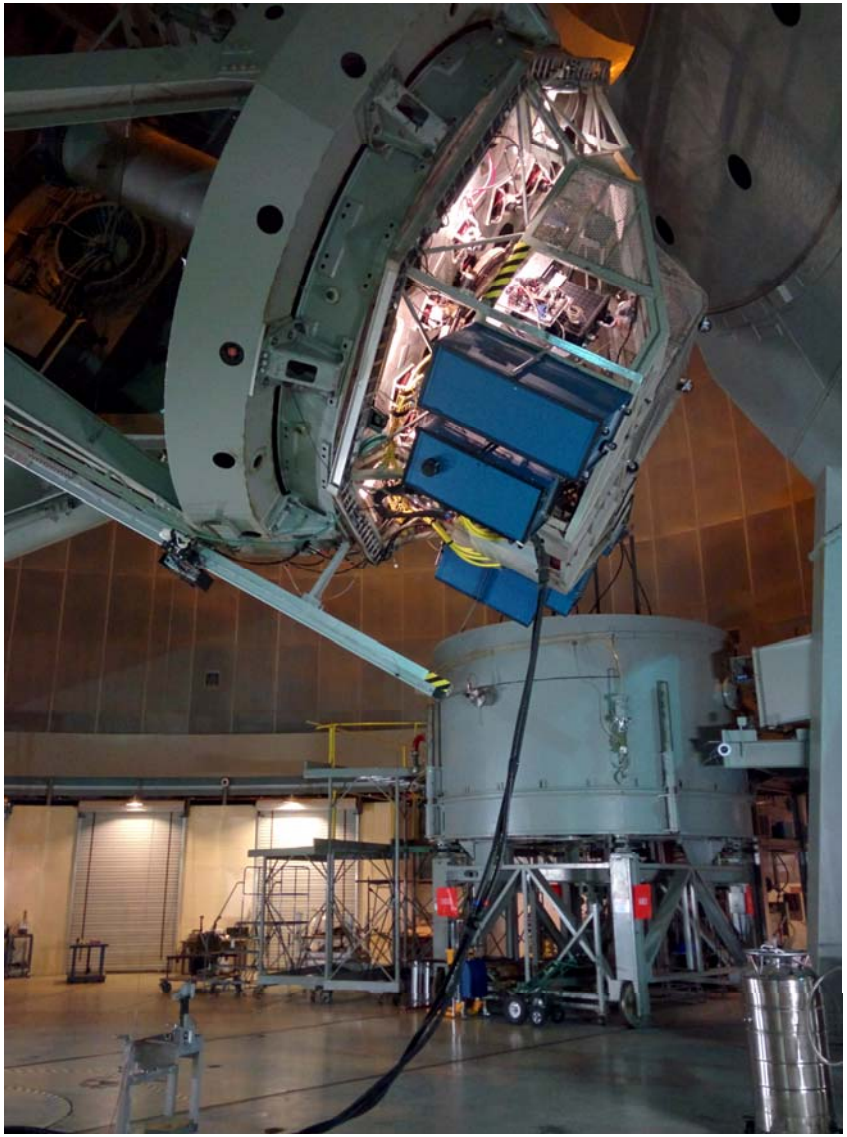


DARKNESS at Palomar

DARKNESS Commissioning, July 2016

On-sky, July 23 2016

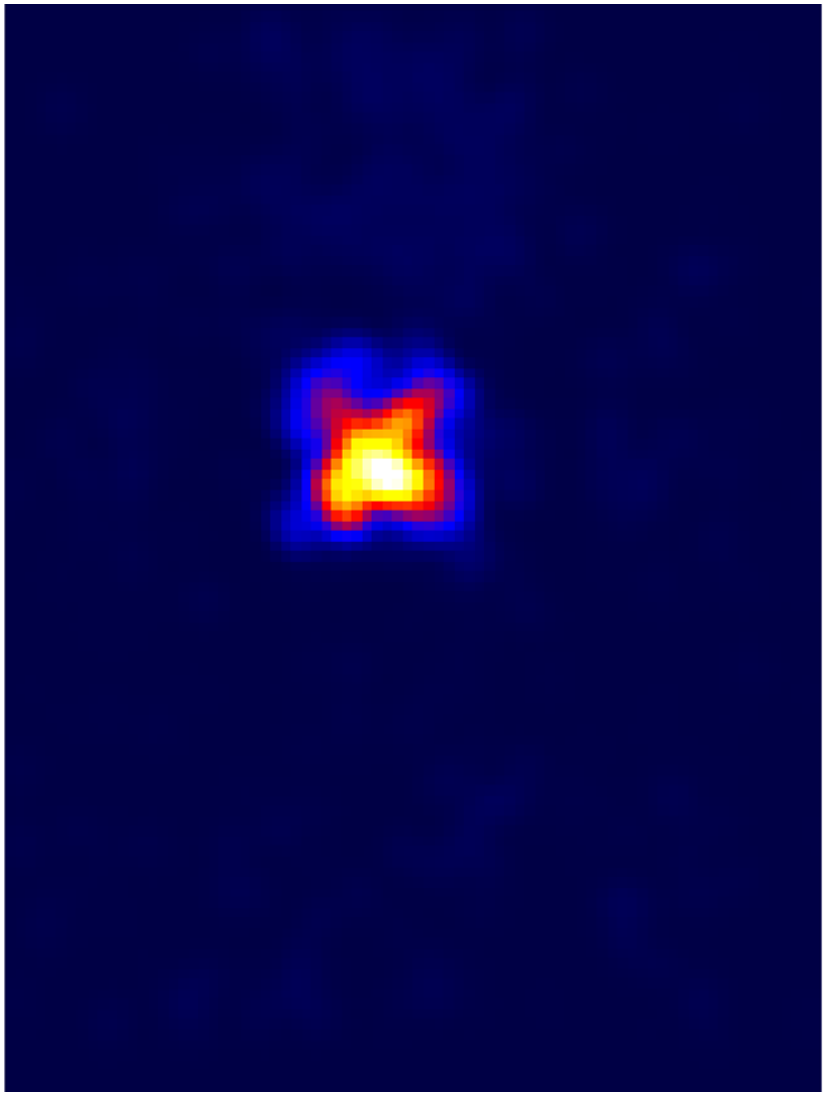




First light, July 24 2016

Party

First light: SAO 65485



MEC

- MEC is a 20 kpix version of DARKNESS for Subaru SCExAO
  - **M**KID **E**xoplanet **C**amera
    - MKID IFU
    - SCExAO at Subaru Observatory
      - PIAA/Vector Coronagraph
    - Observe cold gas giants in reflected light ~2017
    - We have T-shirts

ELTs

- This work is a warm-up for planet searches on ELTs
- Inner working angle of ELTs enables an entirely new regime
  - M dwarf habitable zones! (G and K dwarf habitable zones probably require a space mission)

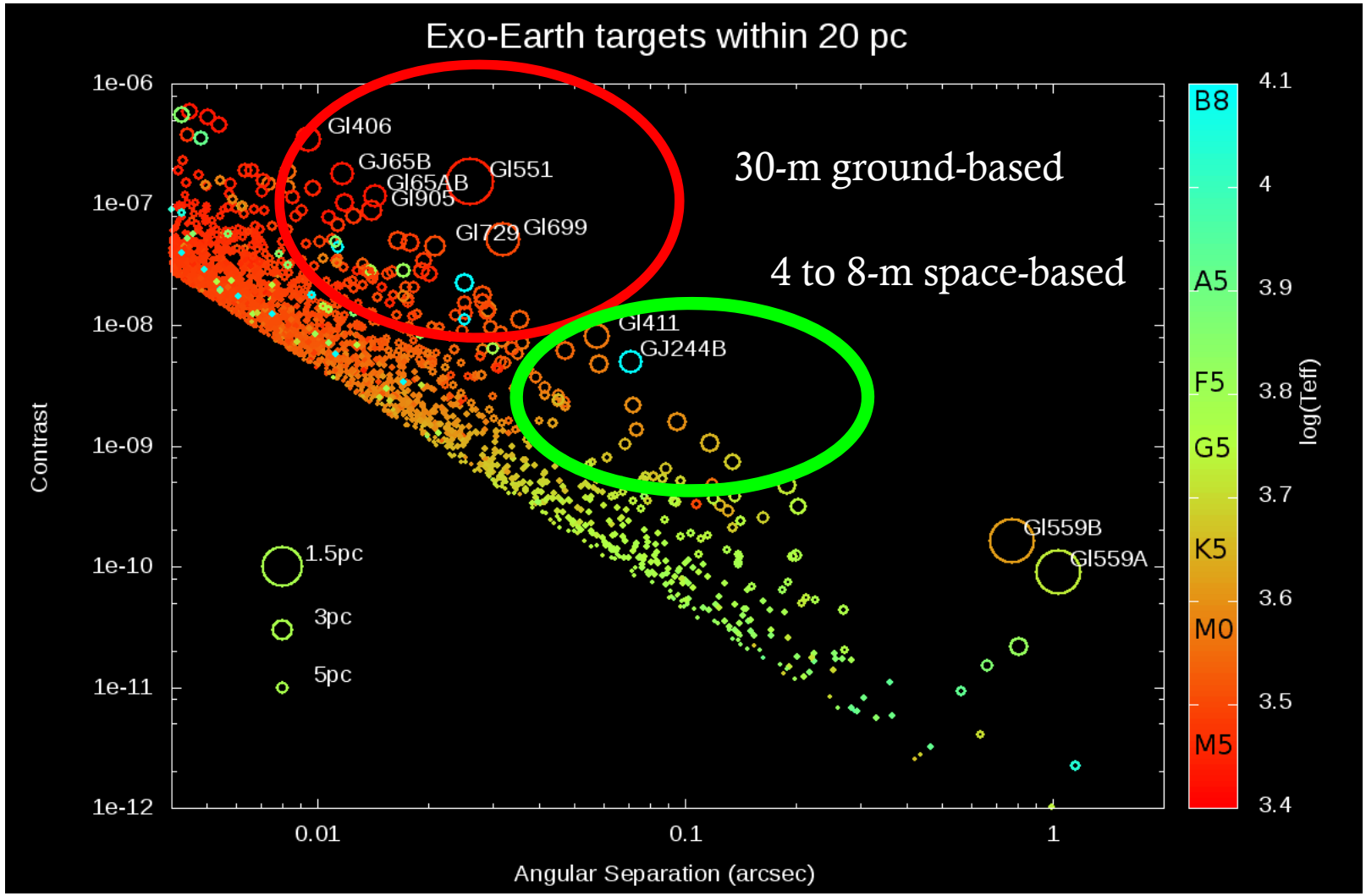
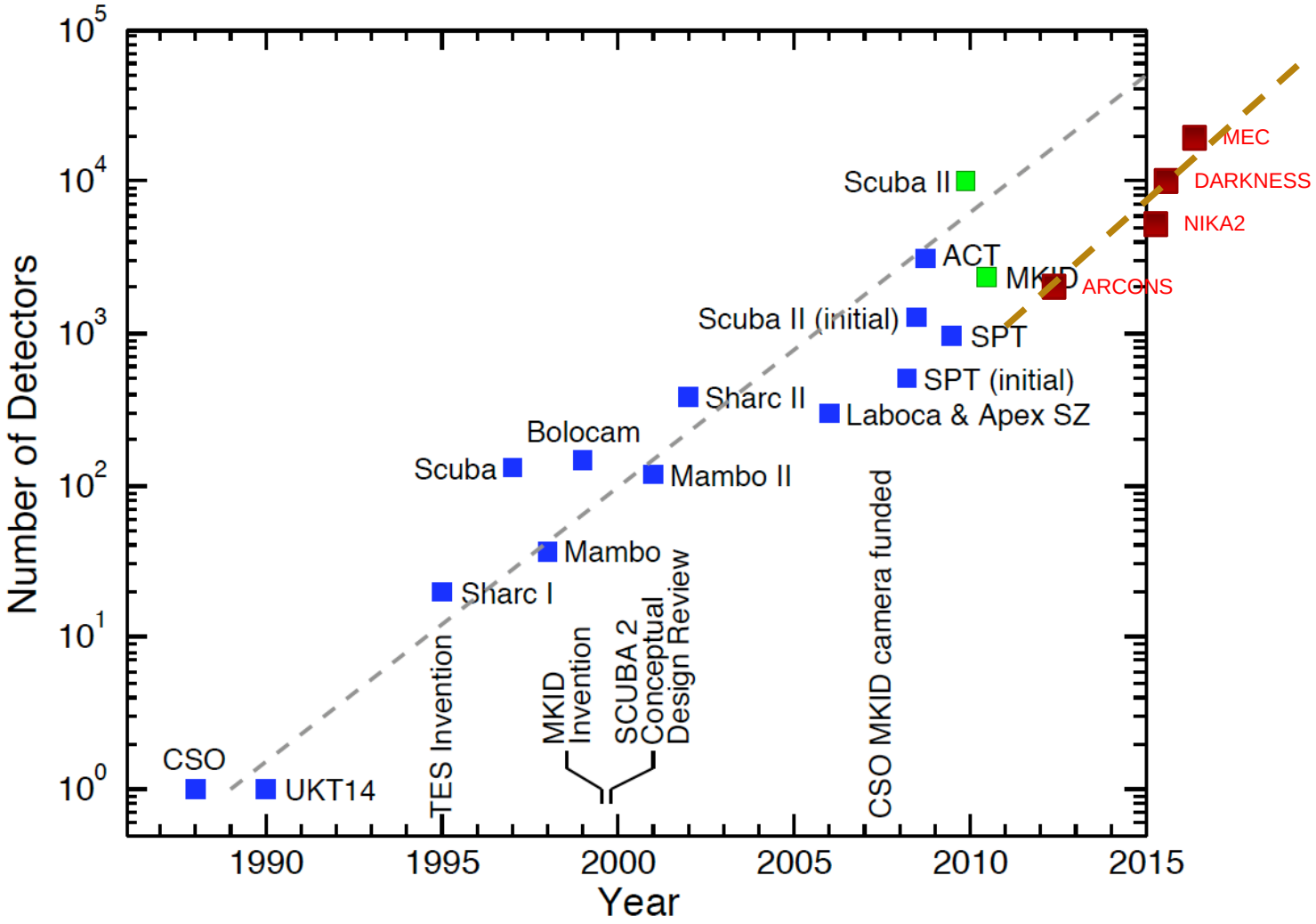


Figure from O. Guyon

MKID Scaling

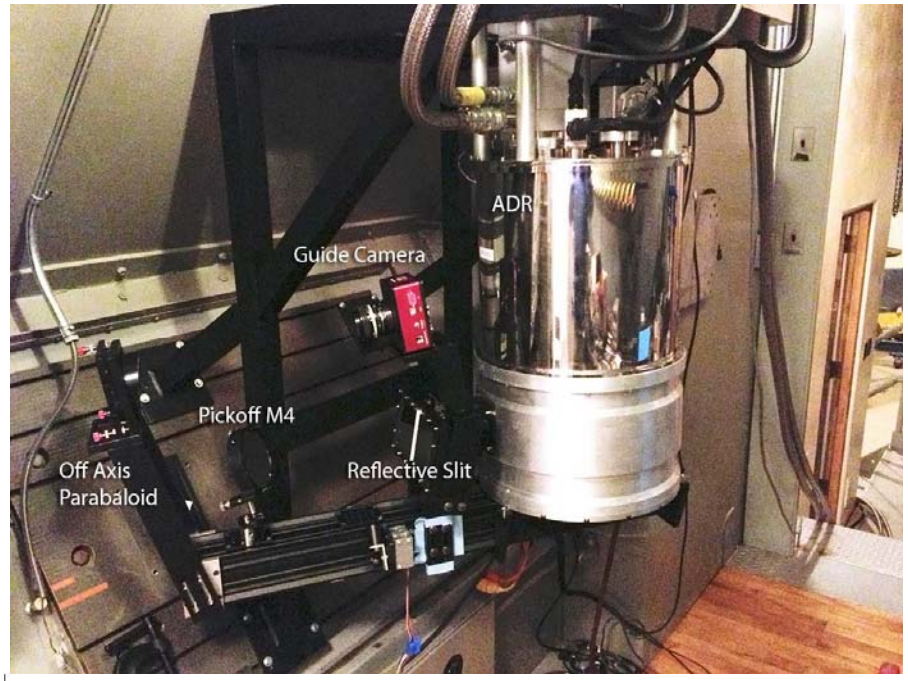


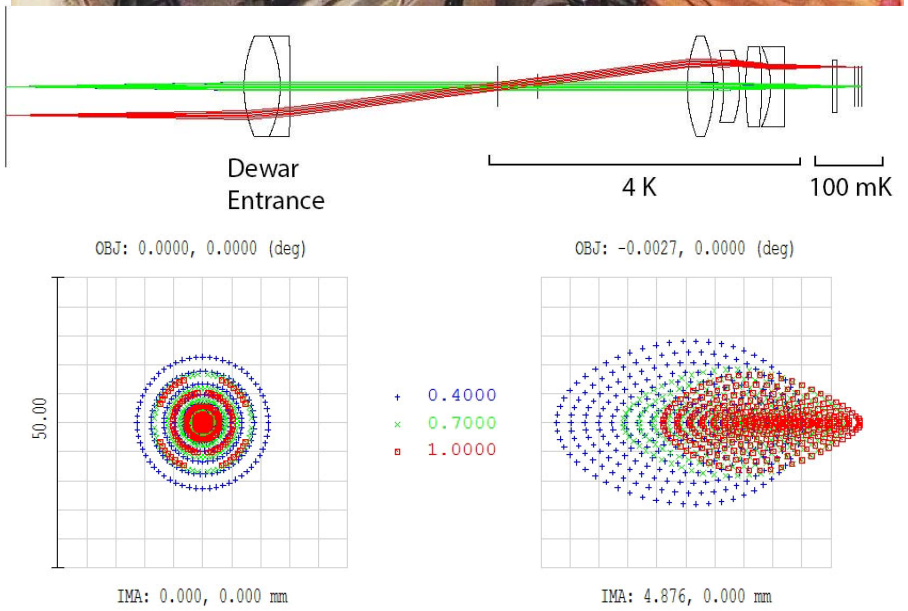
Original plot from J. Zmuidzinas

Proven at the Telescope with ARCONS

- Array Camera for Optical to Near-IR Spectrophotometery (ARCONS)
- First Light: July 28, 2011, Palomar 200” Coudé
- Now 35 observing nights (Palomar+Lick)
- Lens coupled 2024 (44x46) pixel array in cryogen-free ADR
- 0.4” pixels yields 20”x20” FOV
- 380 nm to 1150 nm simultaneous bandwidth with maximum count rate of ~2000 cts/pixel/sec
- Energy resolution R~8 at 400 nm

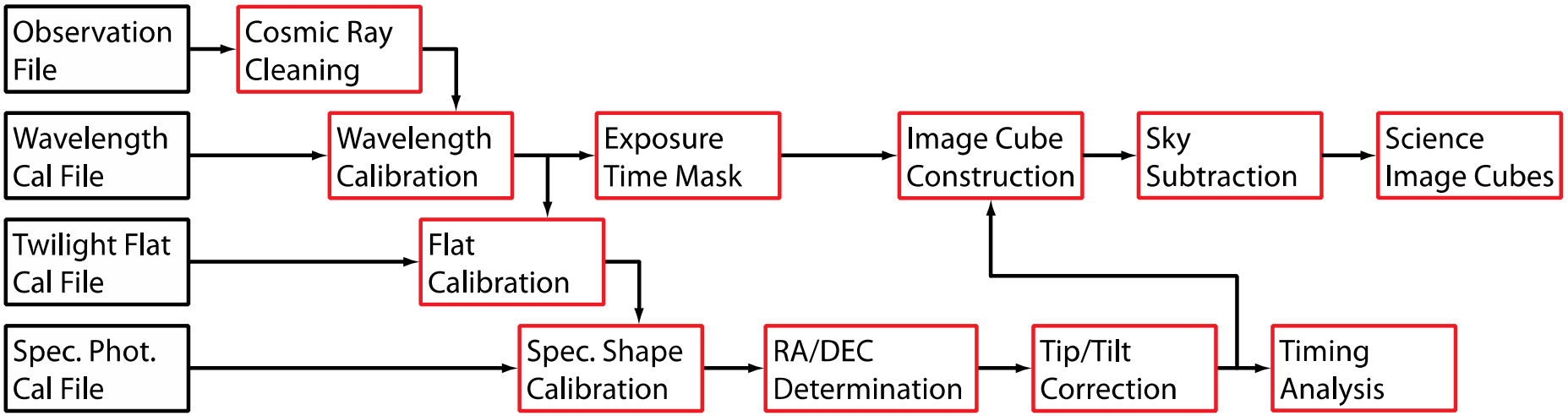
Mazin et al. 2013, PASP

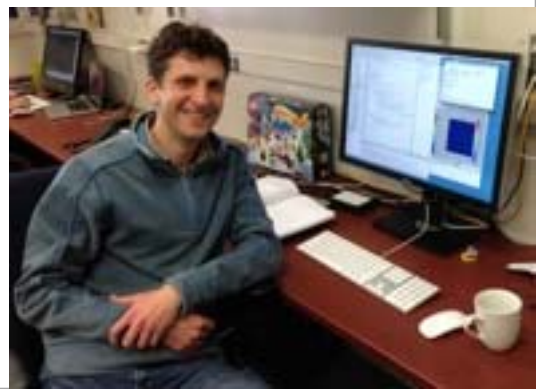




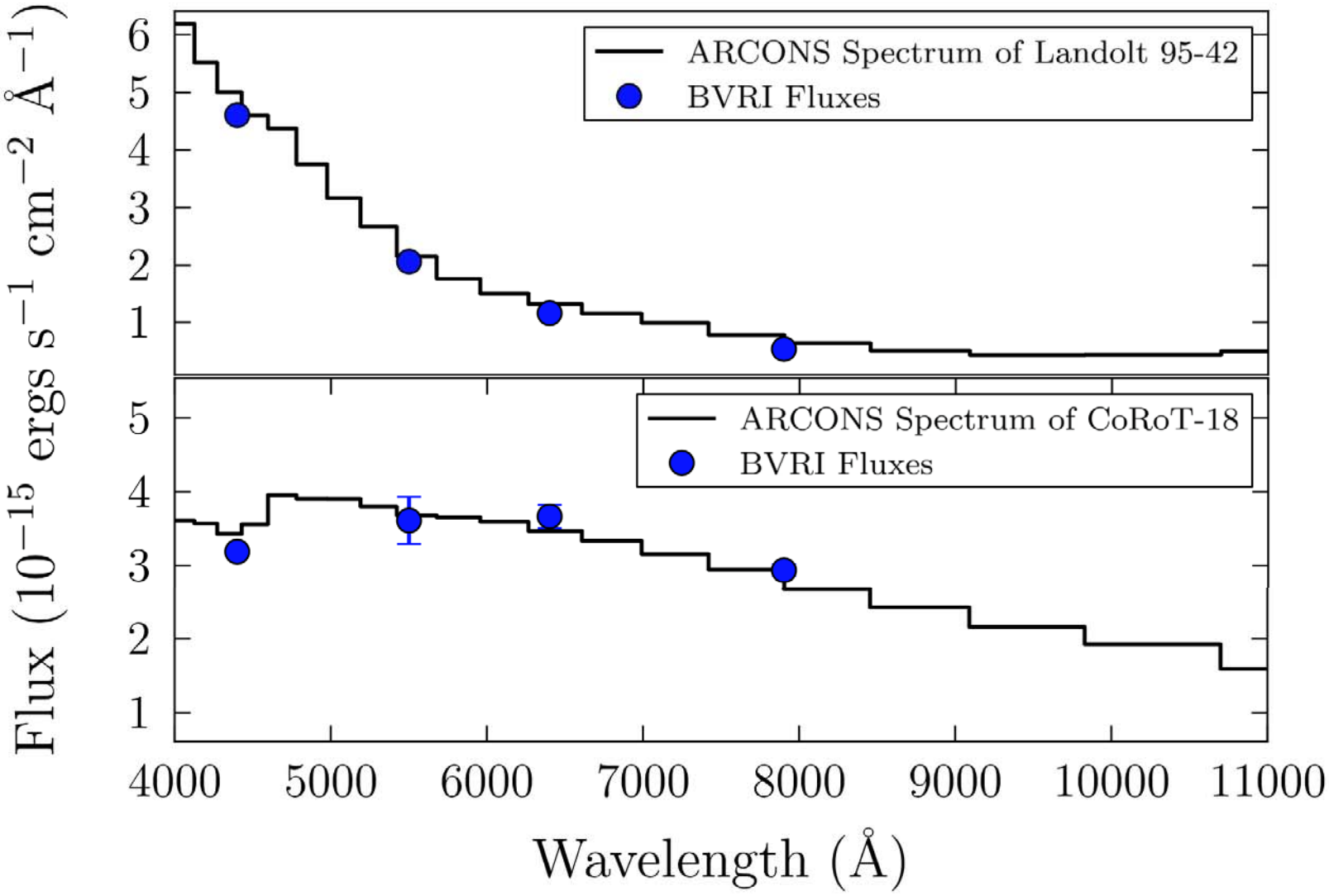
Data Pipeline

- Man man-years already invested, many more to go…
- Complex!
- Data format is HDF5, with each photon stored as a 64-bit packet
- van Eyken et al., ApJS 219, 14 (2015)
- Open source, available at github.com/bmazin/ARCONS-pipeline



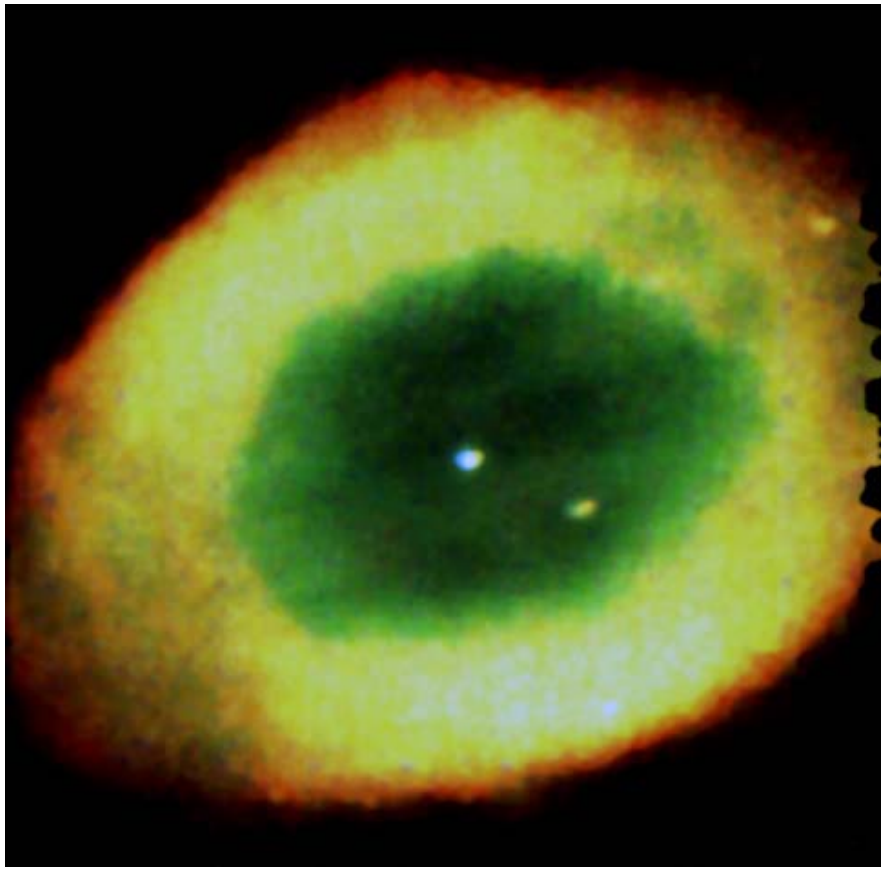


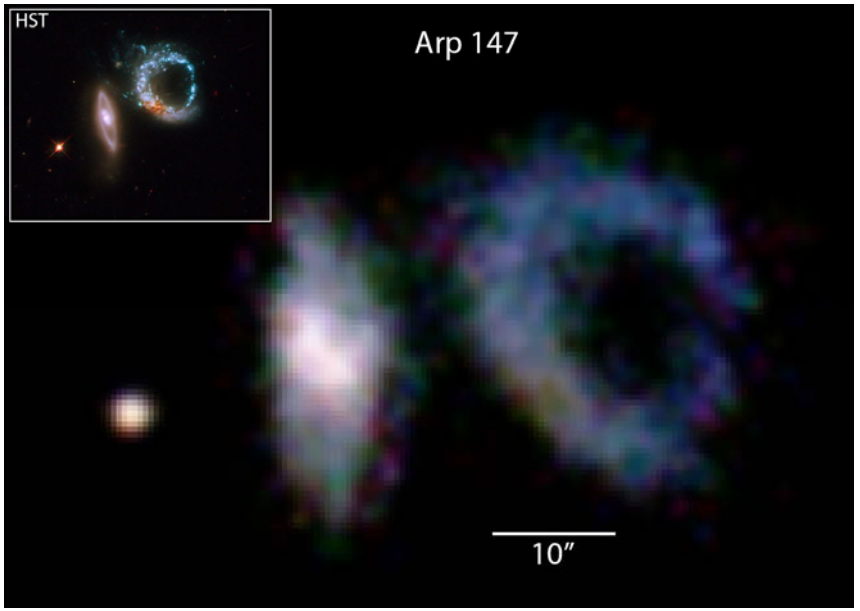
Flux Calibrated Spectra

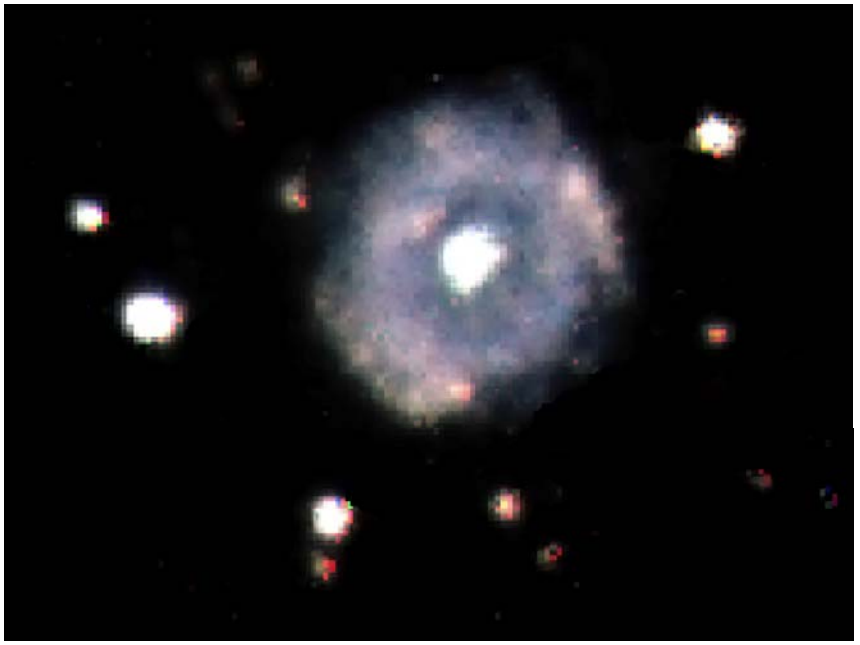


- Spectra of standard stars match pre-existing photometry

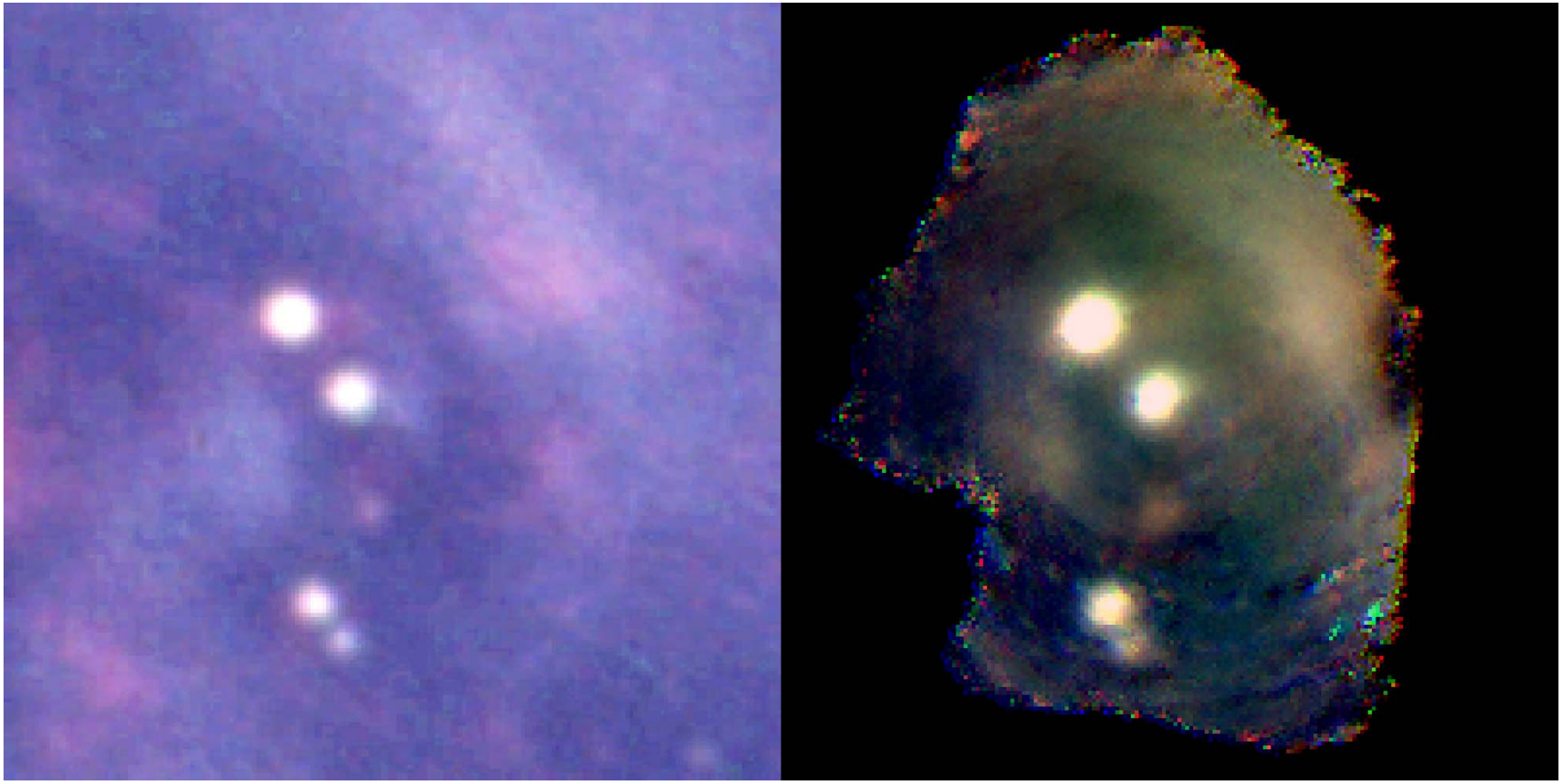
Images from ARCONS



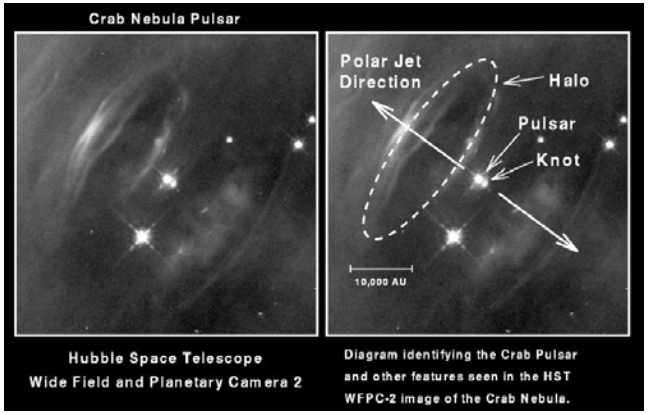




Crab with ARCONS vs. HST



- Left: Kitt Peak 4-m image, Right: ARCONS at Palomar
- 2 hours of Crab data processed through the full imaging pipeline
- Still have work to do!

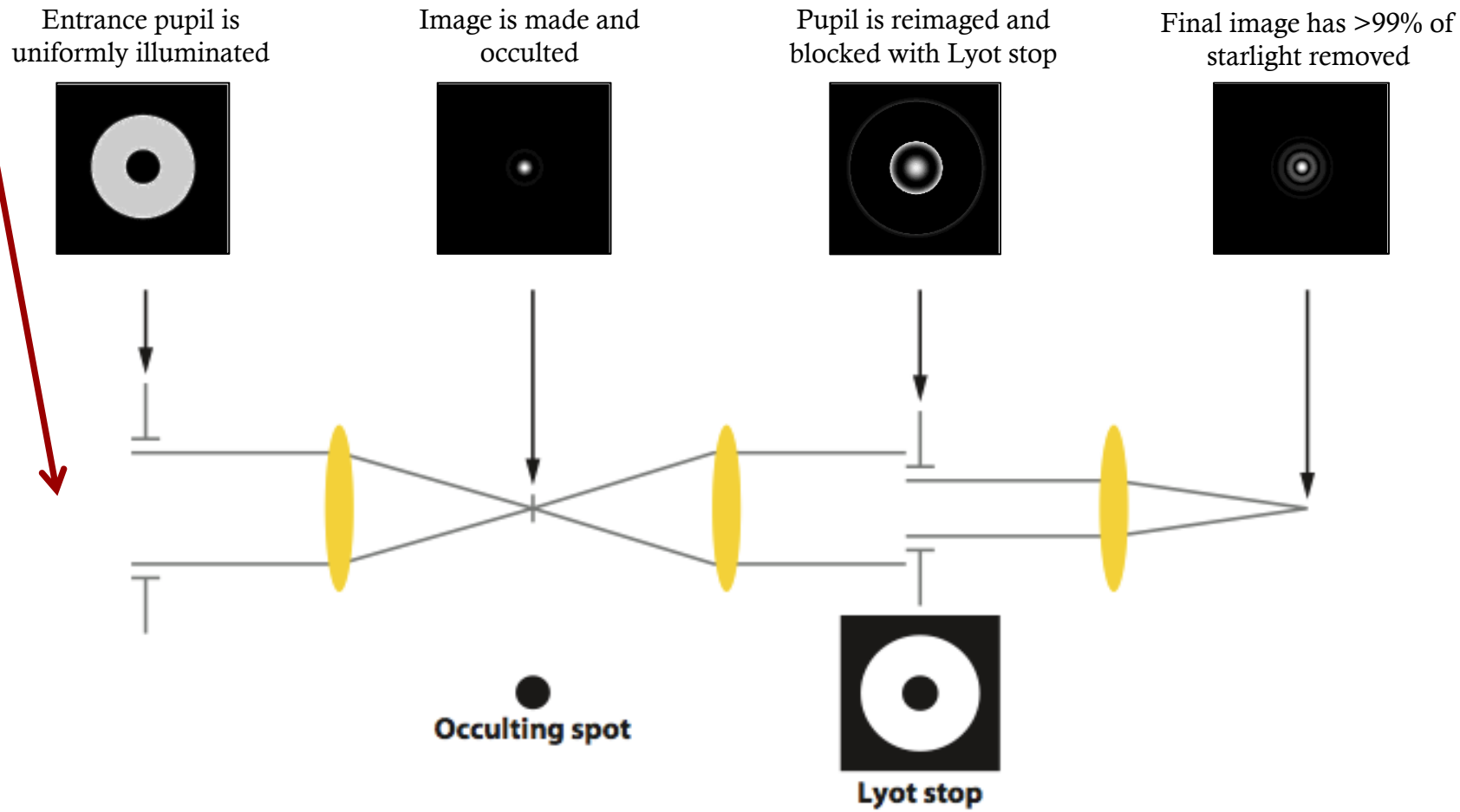


Crab Pulsar

- Made on the mountain during our Palomar run!

Coronagraphy

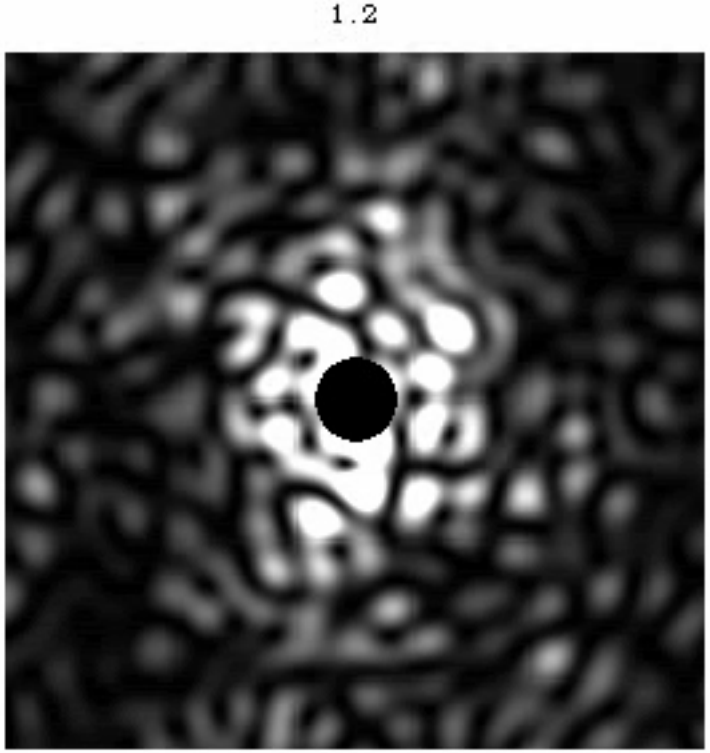
Adaptive Optics cleans up PSF!
ExAO – Stehl 50-90% needed!



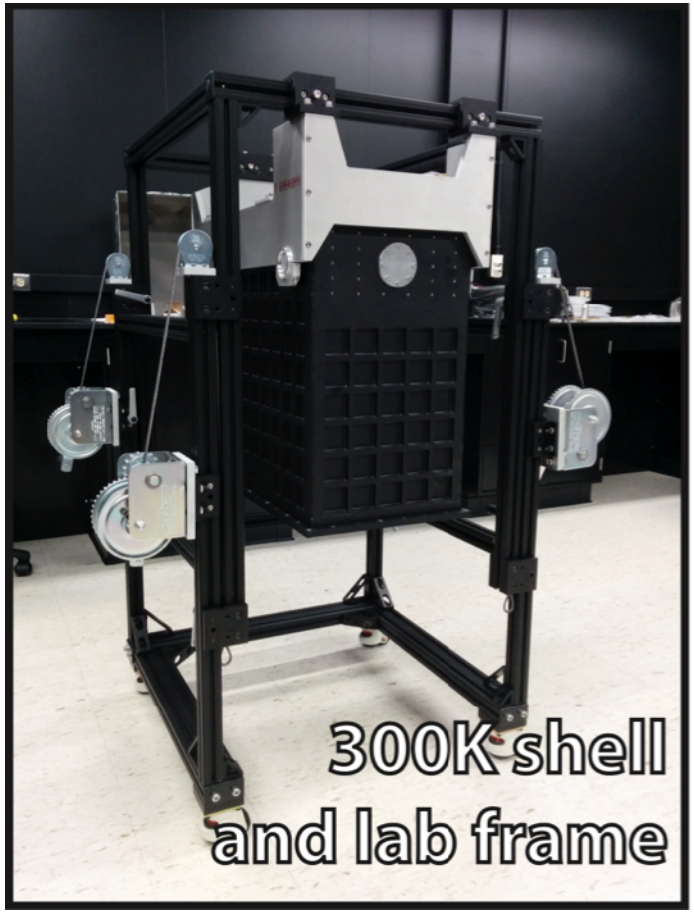
Adapted From Oppenheimer & Hinkley (2009), which adapted it from Sivaramakrishnan et al. (2001)

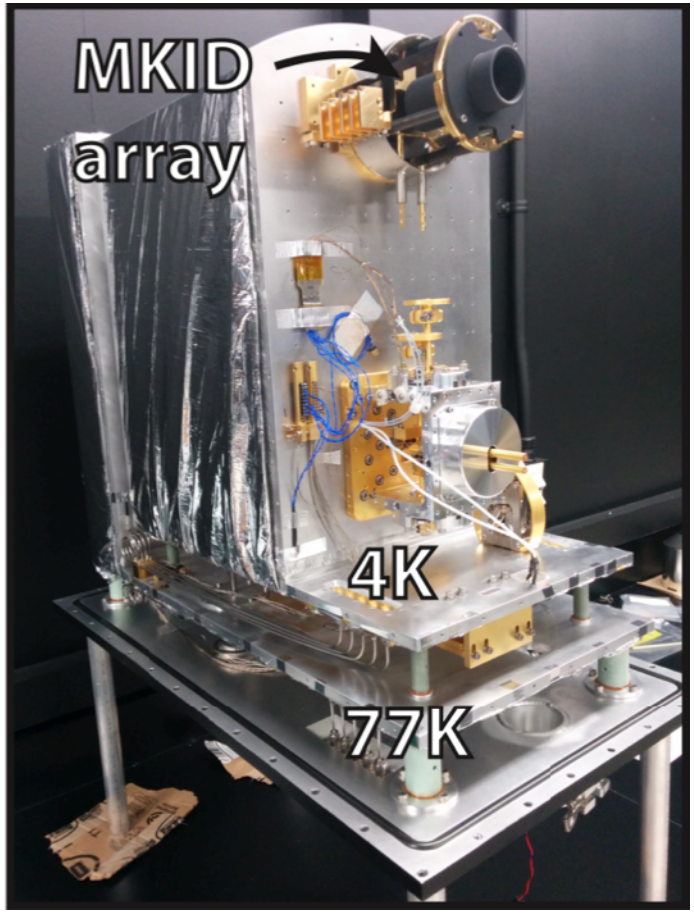
IFU for Planet Finding

- Coronagraphs are limited by speckles from scattered and diffracted light
  - Speckles are **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 (SDI)**
    - **Temporal Speckle Statistics**
    - **Active Speckle Nulling**
    - Removes requirement of a separate spectrograph
    - Gives the spectra of all planets in the dark box



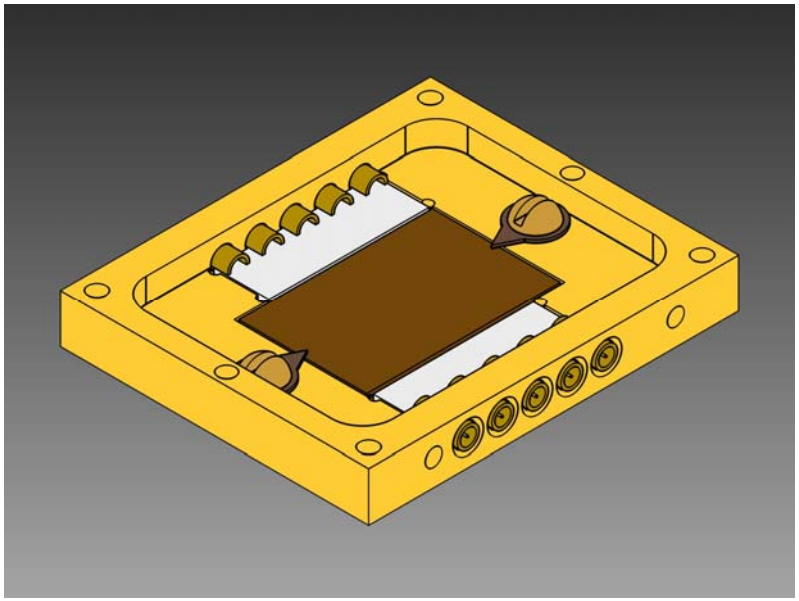
- Simulation from S. Remi and R. Oppenheimer

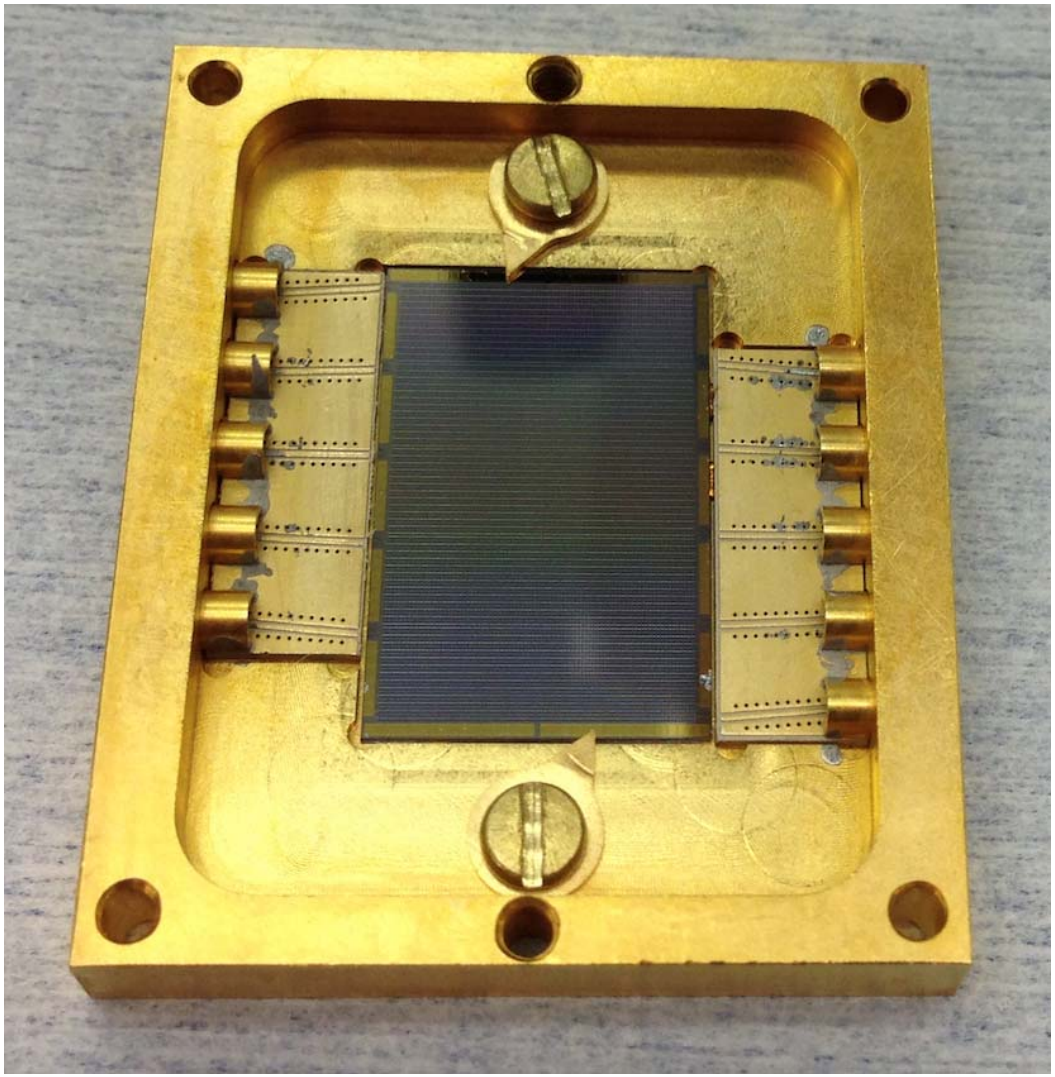

300K shell
and lab frame


MKID
array
4K
77K

New Device Box

- Moving to *TINY* G3PO connectors (this box ix 1.25” x 1.5” x 0.2”)





Quantum Efficiency

- We need to improve QE for some applications