National Aeronautics and Space Administration

Early Stage Technology Workshop

Astrophysics and Heliophysics

March 3-4, 2015

Microwave Kinetic Inductance Detectors for UVOIR Astrophysics

March 3, 2015 UCSB Department of Physics

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TECHNOLOGY DRIVES EXPLORATION

Non-Proprietary

Research Team

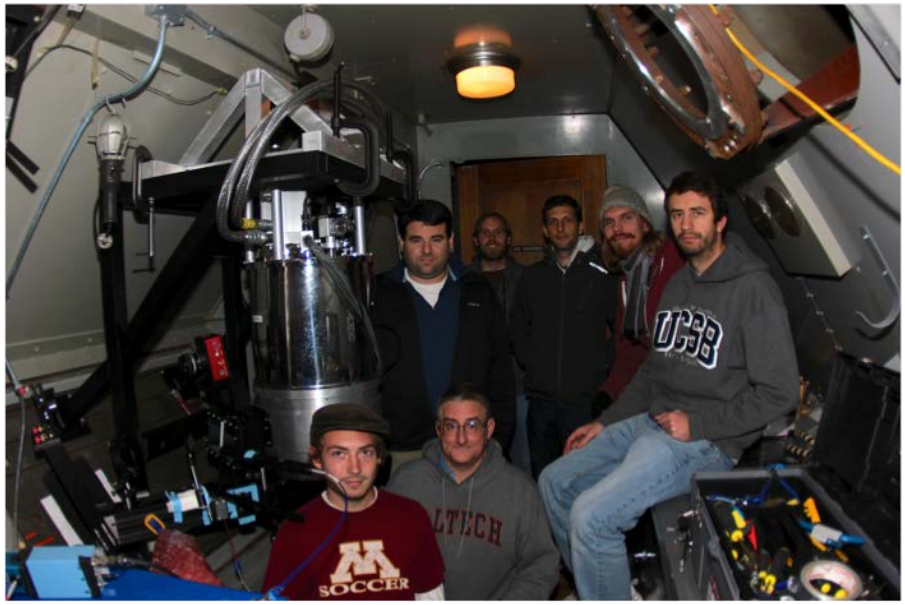
The Optical/UV MKID Team:

UCSB: Ben Mazin (P.I.) Seth Meeker, Matt Strader, Paul Szypryt, Gerhard Ulbricht, Alex Walter, Clint Bockstiegel, Giulia Collura

JPL/IPAC: Bruce Bumble, Julian van Eyken

Oxford: Kieran O'Brien, Rupert Dodkins

Fermilab: Chris Stoughton, Juan Estrada, Gustavo Cancelo

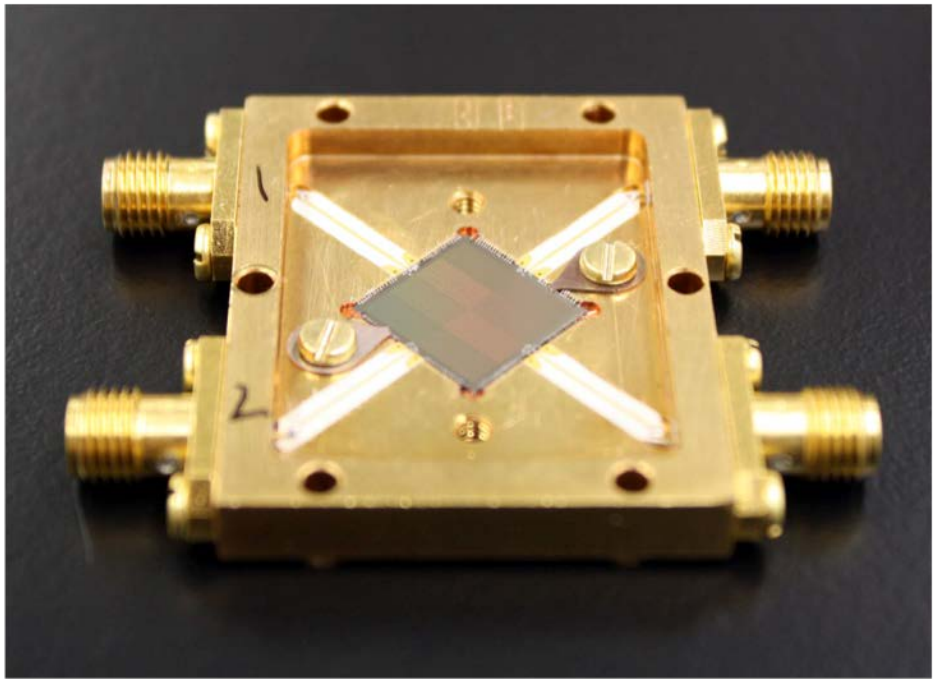


Overview of Technology

Microwave Kinetic Inductance Detectors (MKIDs)

NASA funded detectors for astronomy at many wavelengths, X-ray through Submillimeter.

- Superconducting technology with operating temperatures below 1 Kelvin
- Single-photon counting at optical and X-ray wavelengths with microsecond time resolution
- Energy resolving
- No read-noise or dark current
- Scalable to large arrays
- Simple cosmic ray rejection

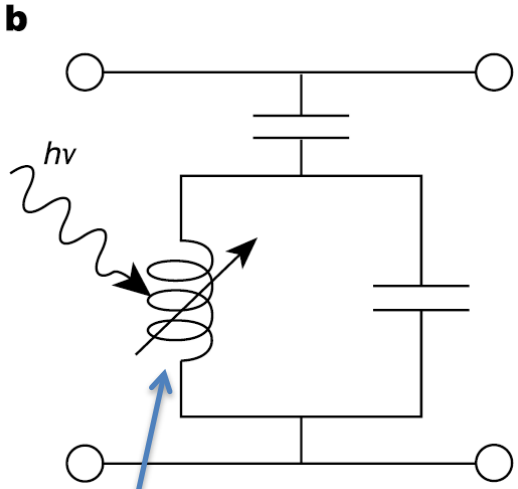


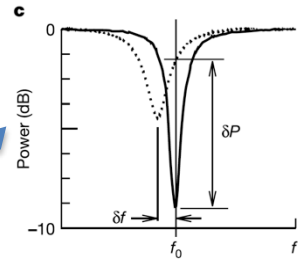
Mazin et al. 2012, Optics Express, 20, 2

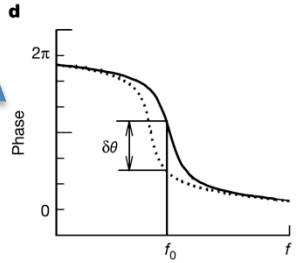
Pixel for pixel, the most capable UVOIR detector available.

UVOIR MKIDs

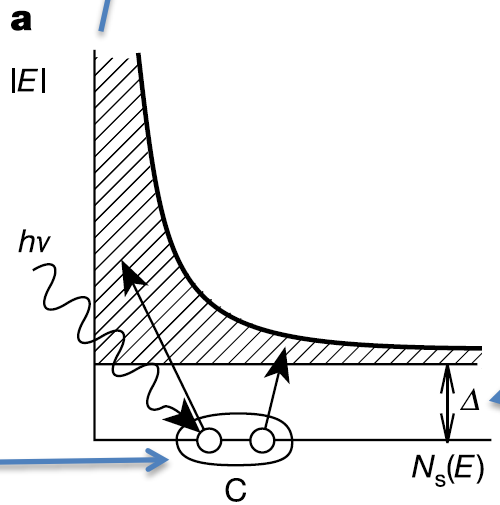
MKID Equivalent Circuit







Inductor is a Superconductor!



Cooper Pair

Energy Gap

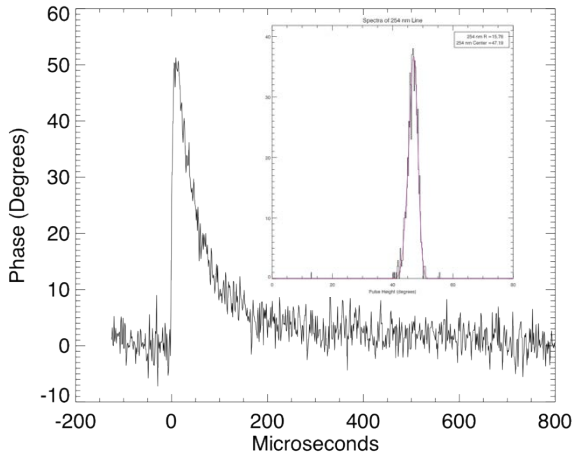
Silicon – 1.10000 eV

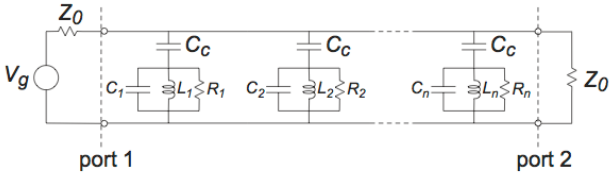
Aluminum – 0.00018 eV

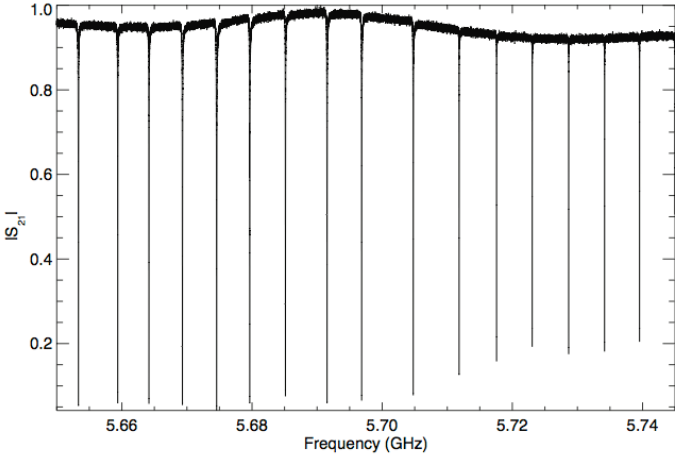
Energy resolution:

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

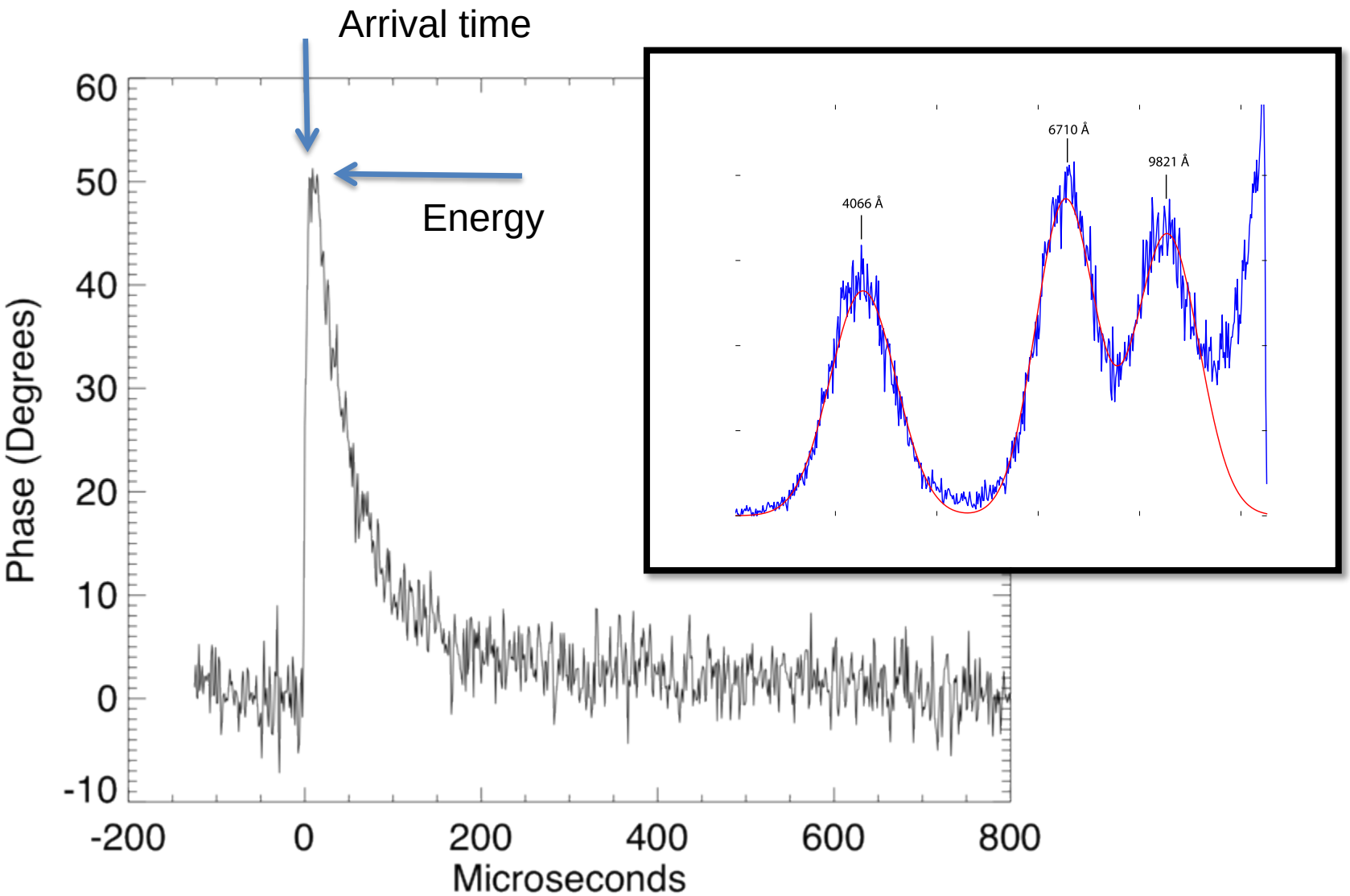
Typical Single Photon Event



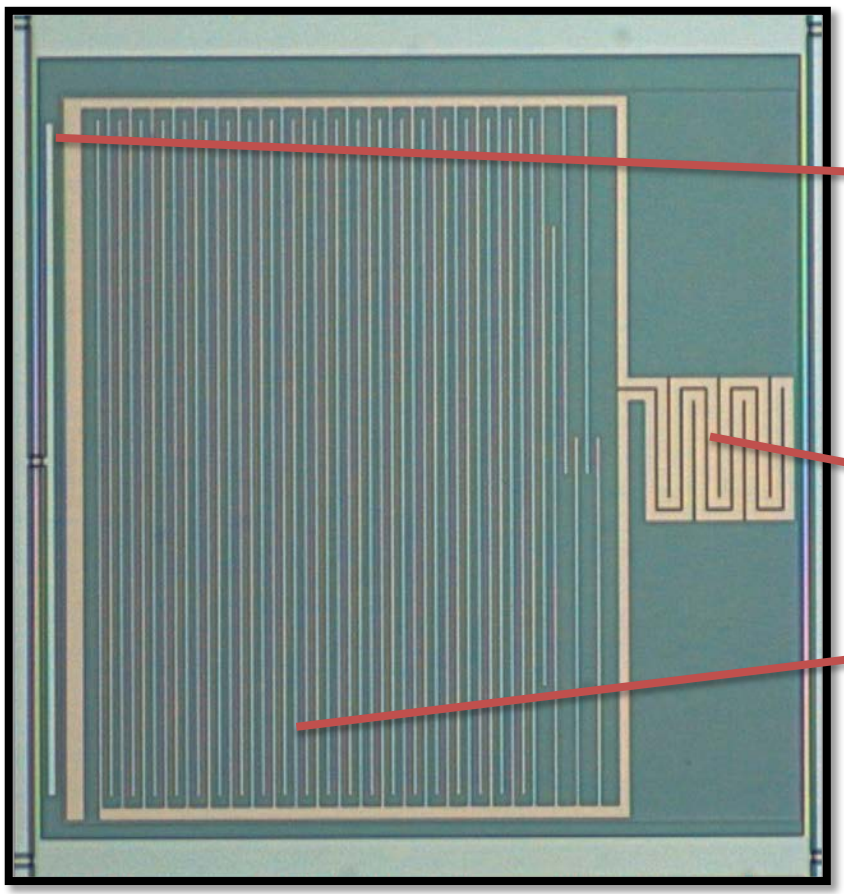




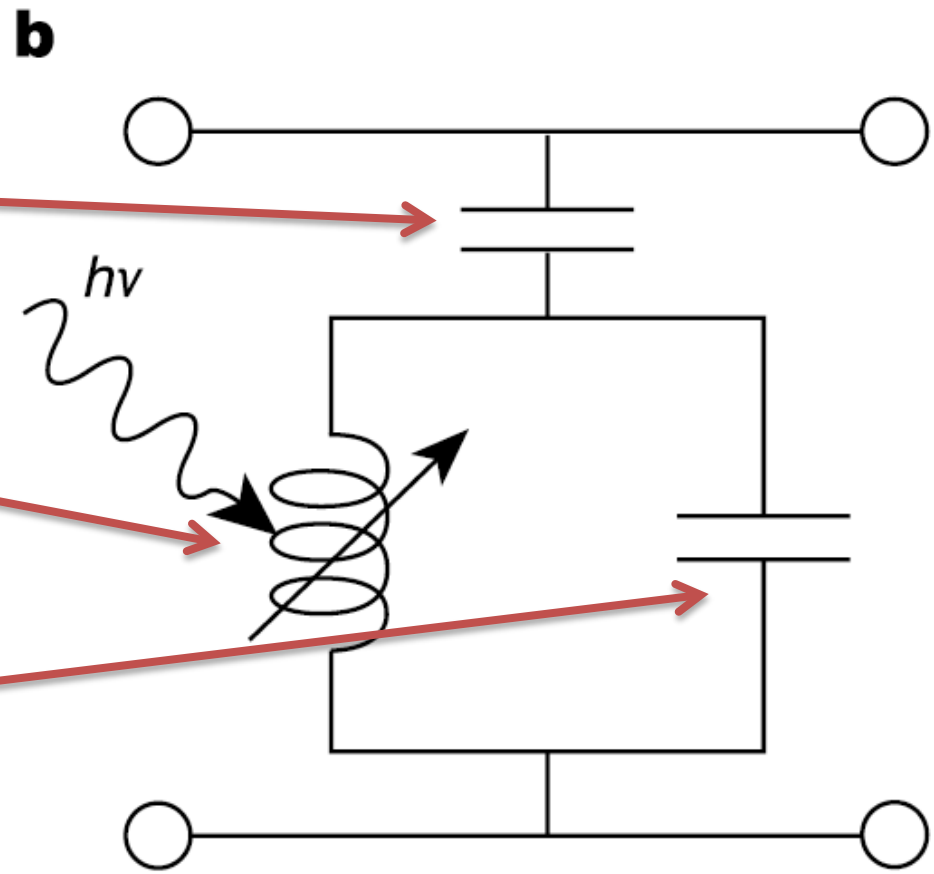
Photon Detection



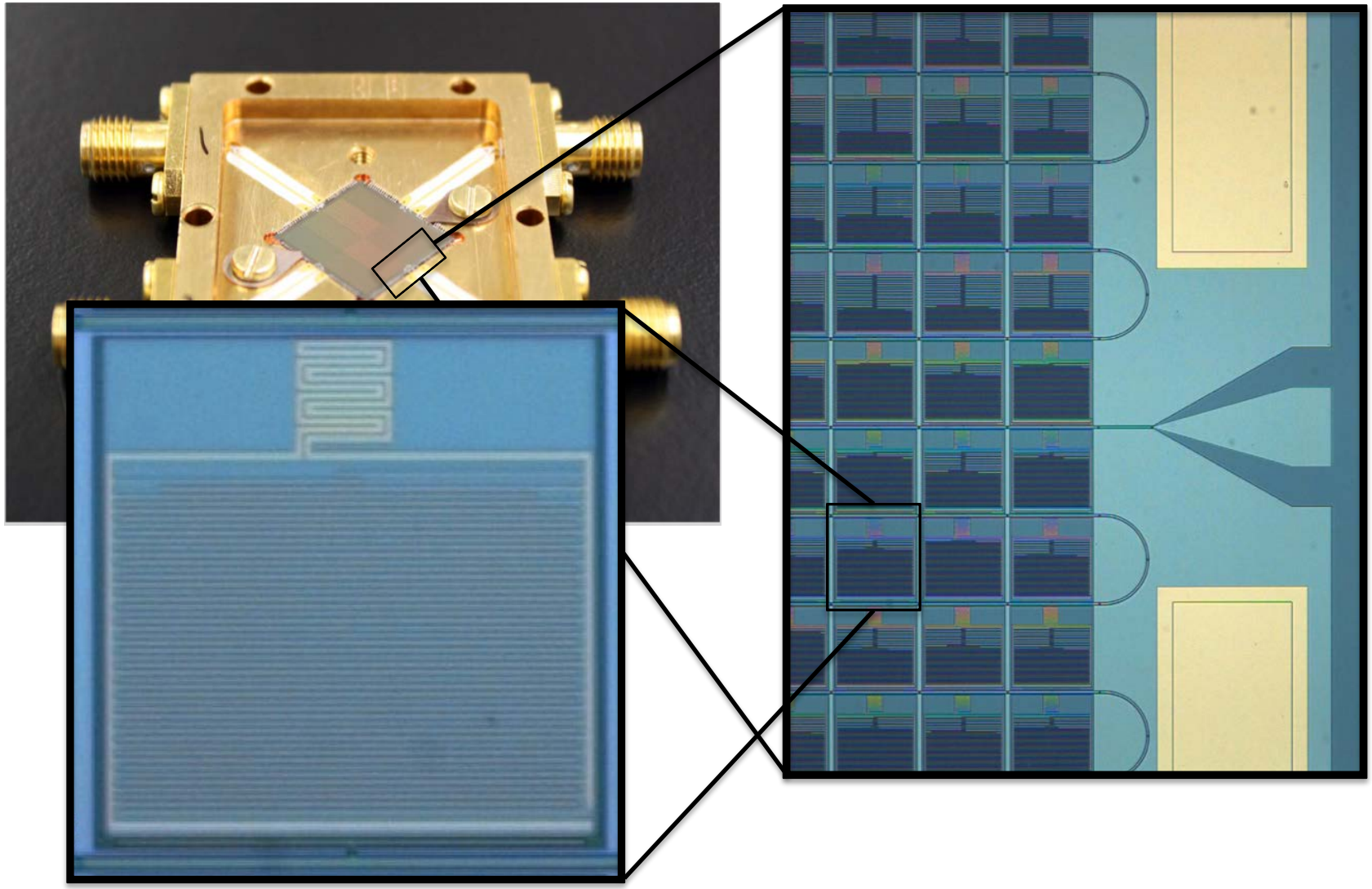
Basic MKID Anatomy



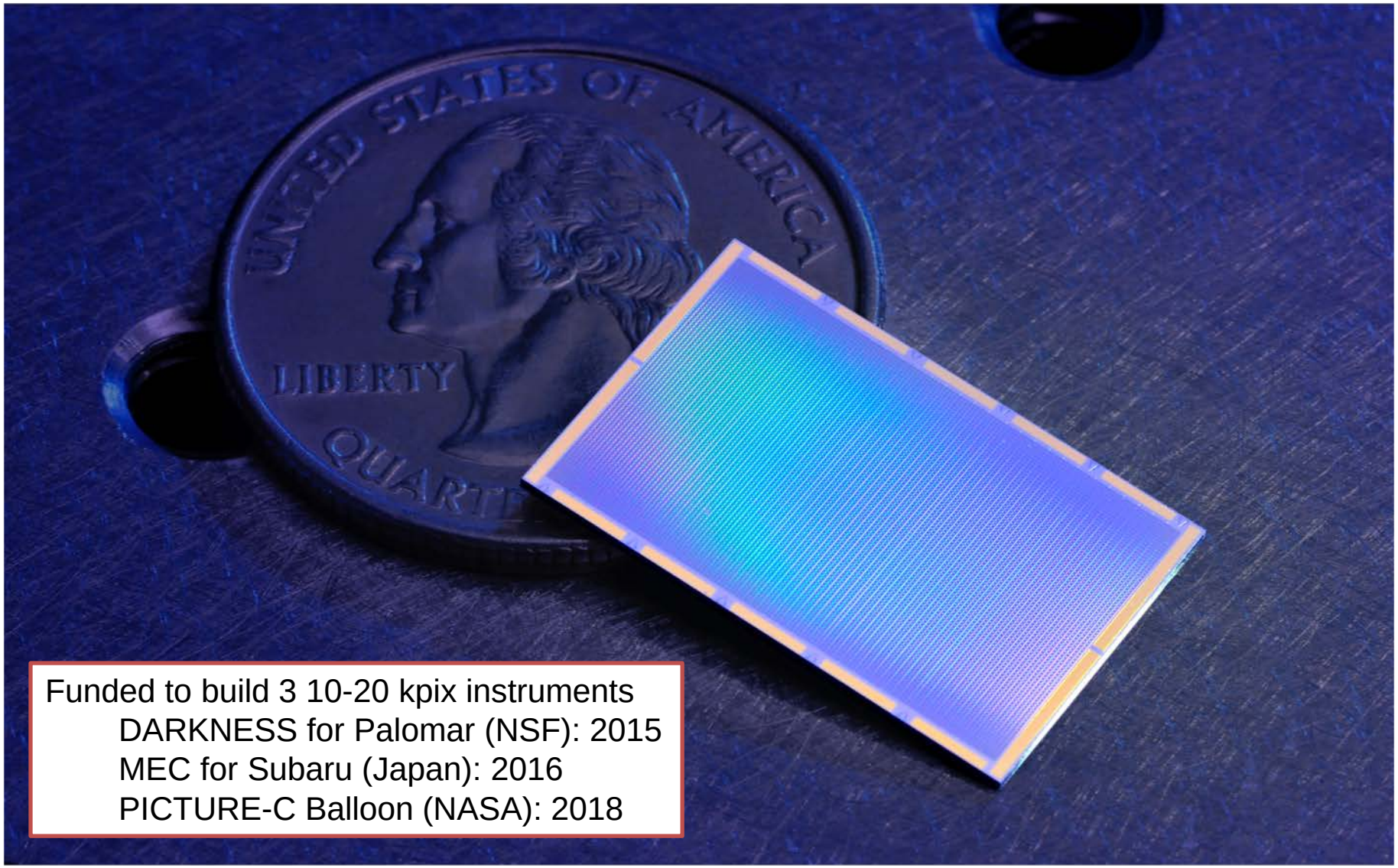
200 microns



2024 Pixel Array (2012)

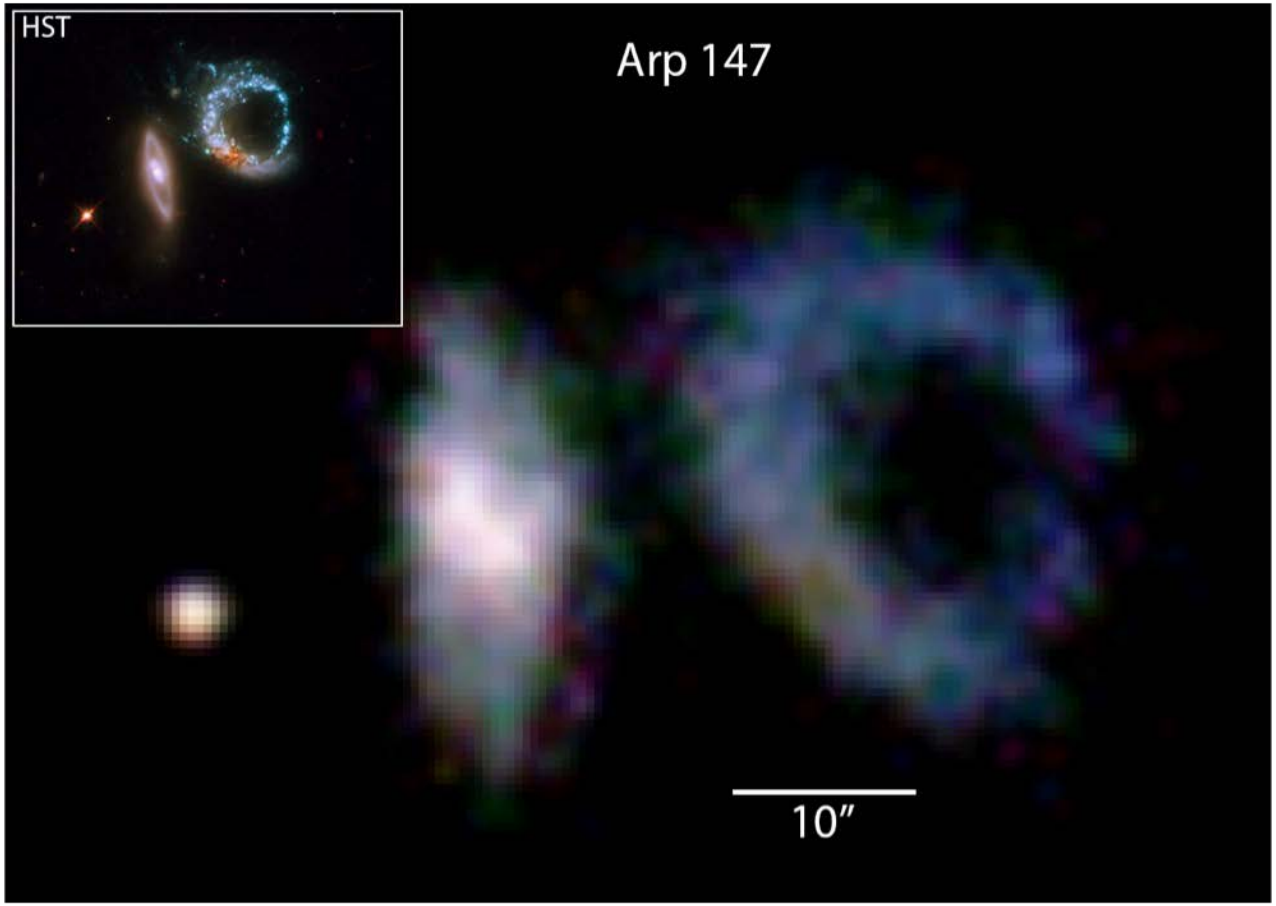


10,000 Pixel Array (2014)



Funded to build 3 10-20 kpix instruments
- DARKNESS for Palomar (NSF): 2015
- MEC for Subaru (Japan): 2016
- PICTURE-C Balloon (NASA): 2018

Arp 147 Mosaic



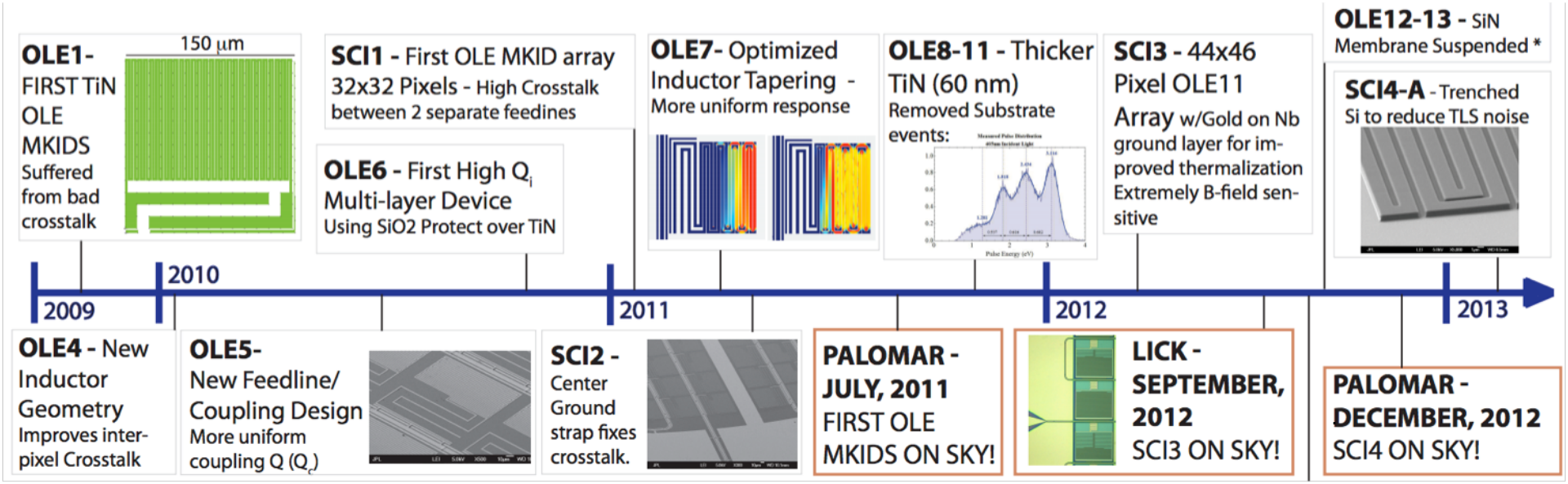
- Mosaic of Arp 147 taken at the Palomar 200” in December 2012 with ARCONS
- 36 pointings on 6” x 6” grid, 1 minute obs. time/pointing
- Colors generated from MKID wavelength information!

Overview of Progress

In the three year ROSES APRA period (2011-2014) we've:

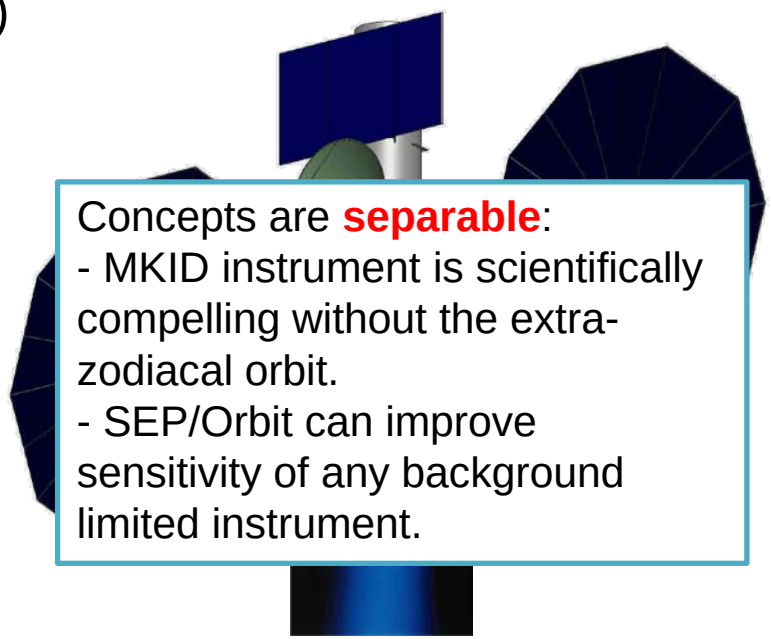
- Developed working single pixel UVOIR MKIDs
- Integrated these pixels into 2024 pixel arrays
- Fielded these arrays for 34 nights at the Palomar 200" and Lick 120"
- Published several detector and instrument papers (Optics Express, PASP, Proc. of SPIE)
- Published the first two MKID astrophysics papers at any wavelength

Current TRL Level: **3-4**



Faint Object Explorer (FOE) Concept

- Selected "SALSO" Concept
- Use new NASA-developed technologies to deliver an observing speed up to **500x greater than HST**
  - UVOIR Microwave Kinetic Inductance Detectors (MKIDs), 0.2-1.8 micron
    - Photon counting, energy resolving arrays (like an X-ray microcalorimeter)
    - No read noise, no dark current, excellent **cosmic ray rejection**
    - R=E/ΔE=50 ➔ 50x observing speed increase compared to multiple filters
  - Extra-zodiacal orbit achieved with Solar Electric Propulsion (SEP)
    - Orbit developed for EZE concept
    - 10-150x lower sky background power
    - SEP demonstrated on DAWN Mission
    - SEP vital to many NASA objectives



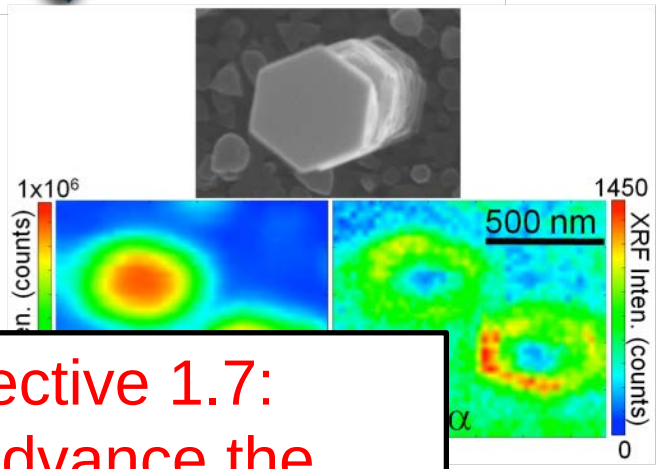
Concepts are **separable**:
- MKID instrument is scientifically compelling without the extra-zodiacal orbit.
- SEP/Orbit can improve sensitivity of any background limited instrument.

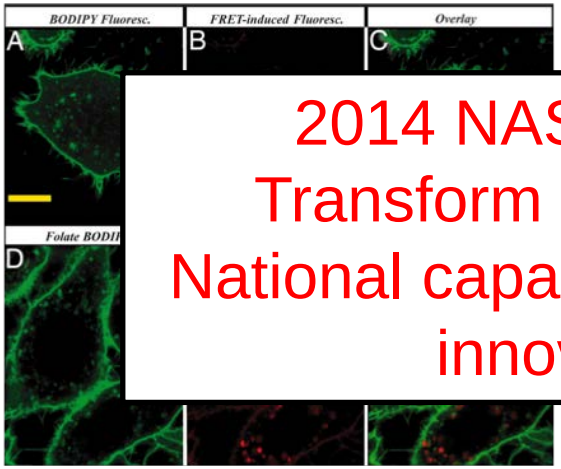
FOE is Crosscutting

- **FOE advances HEOMD and SMD "pull technologies" for in-space propulsion while providing scientific return**
- **FOE provides a near-term focal point to achieve consolidation of separate OCT and SMD SEP technology development efforts as recommended by the NRC review of NASA technology development roadmaps**
- **The SEP technology utilized by FOE is a key step toward realization of:**
  - Higher power systems required by NEA and Mars human exploration objectives
  - High priority planetary science technology recommended by the Planetary Decadal Survey
  - Astrophysics Decadal Survey technology priorities such as New Worlds Observer
- **The FOE system can set both SMD Planetary and Astrophysics science divisions on a new cost effective path of discovery by providing enabling propulsion technology for:**
  - Strategic and community proposed planetary science missions
  - Cost effective access to dark sky orbits for high performance UVOIR astronomy
    - Key advance needed ahead of planning for the Flagship successor to the JWST
    - Enables unprecedented science performance for future Explorer- and Probe-class missions to increase SMD portfolio diversity and resiliency to downward budget pressure
- **SEP propulsion for FOE can be realized with current TRL 5/6 technologies, such as NEXT and Ultra-Flex, to yield a flight-proven system that is scalable to high power levels needed to achieve broad Agency exploration objectives**

Other Applications

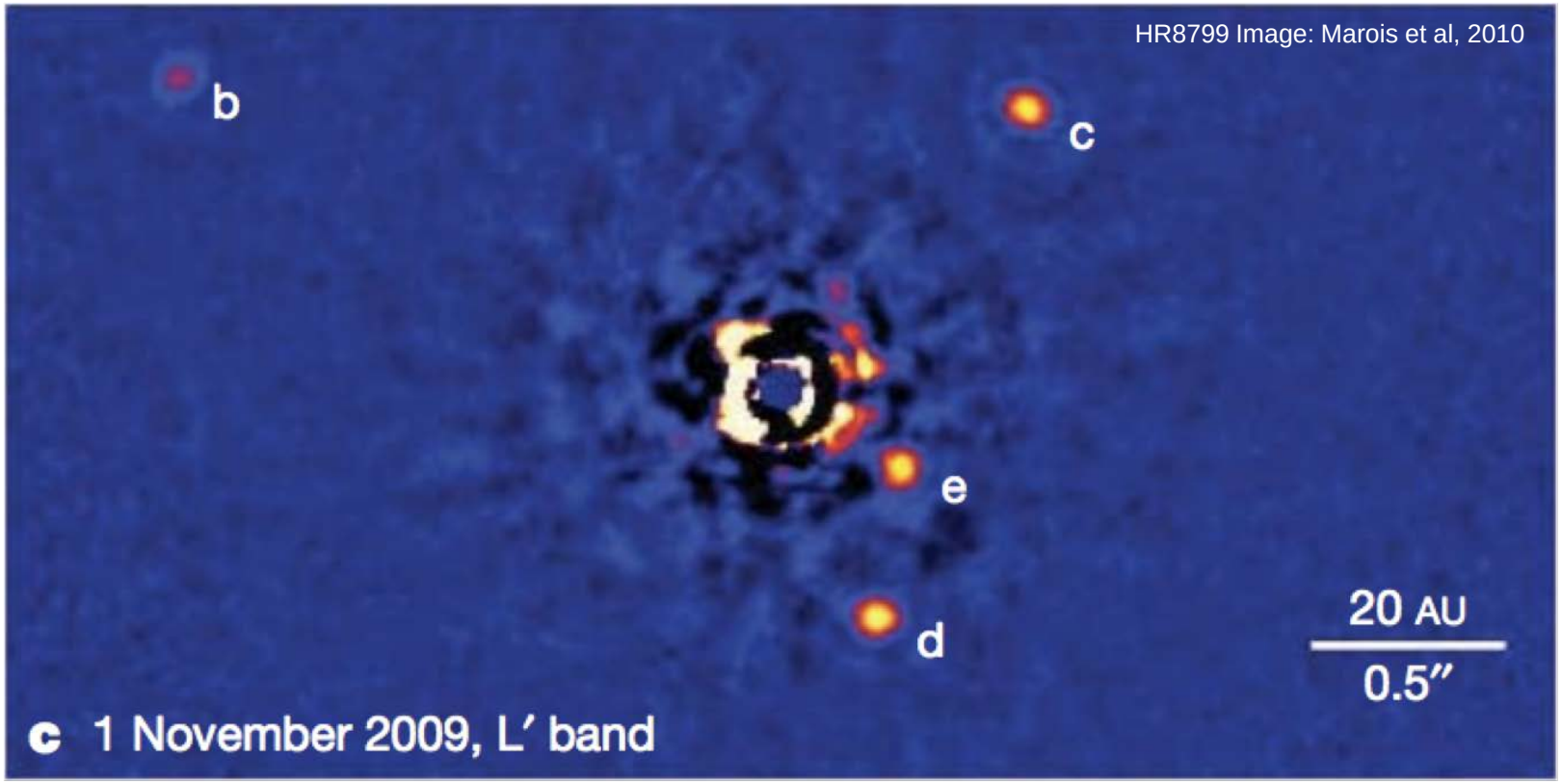
- There are a significant number of other potential applications:
  - Satellite-based Reconnaissance
  - X-ray beam line studies
  - Semiconductor process debugging (XRF)
  - Laser communications
  - Quantum Key Distribution
  - Biological Imaging (FRET, etc.)





2014 NASA Strategic Plan Objective 1.7: Transform NASA missions and advance the National capabilities by maturing crosscutting and innovative space technologies.

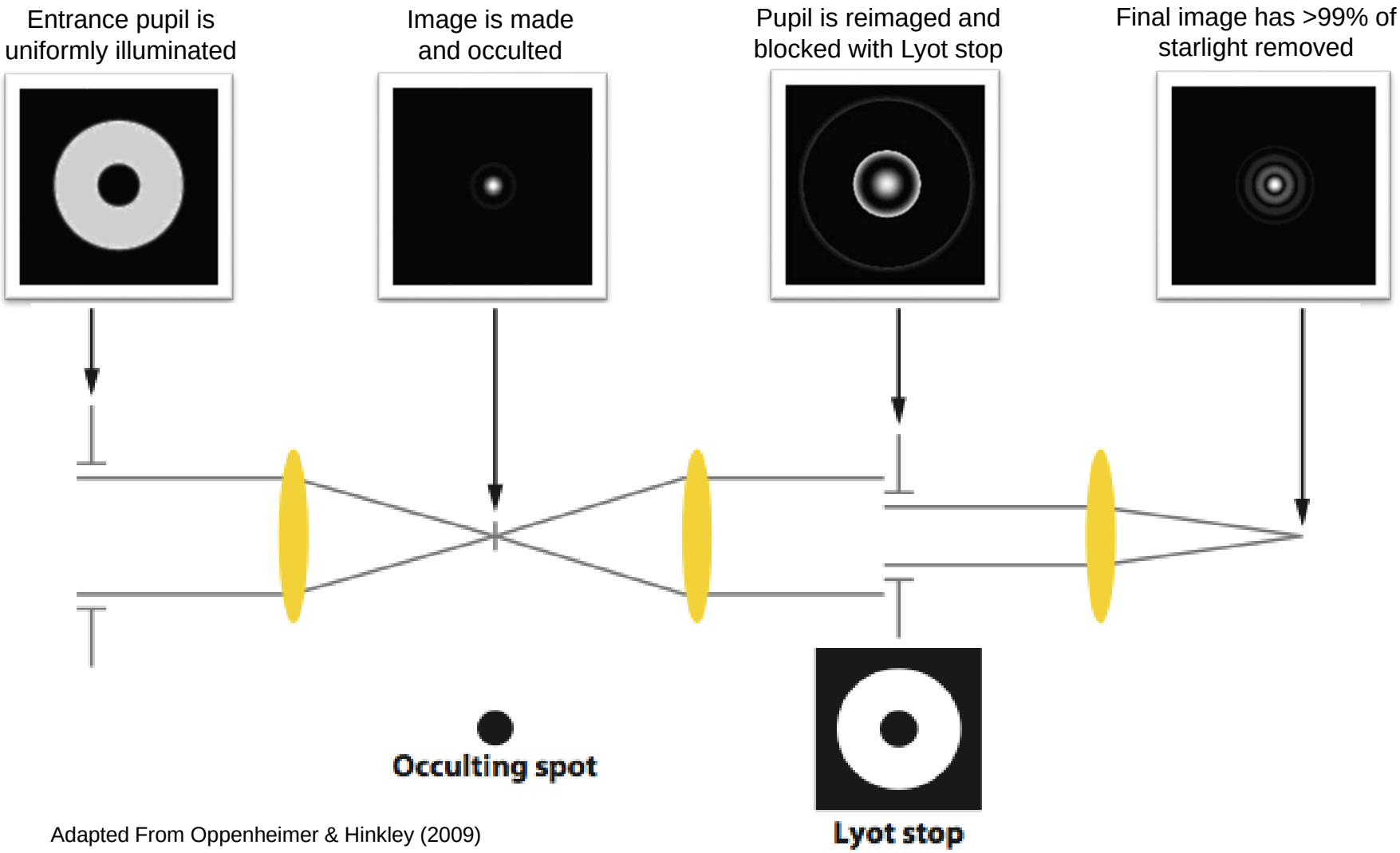
MKIDs for Exoplanet Science



NASA 2013 Astrophysics Long Term Roadmap, page 88:

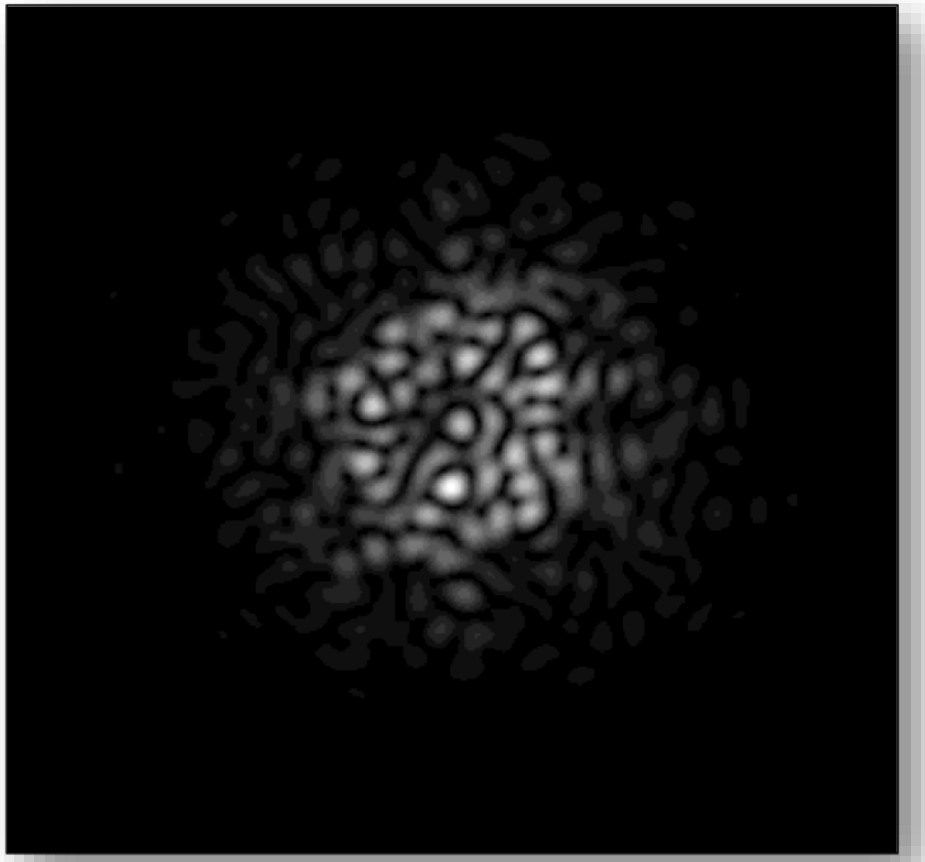
Advances in detector technologies can have a major impact on the performance and scientific reach of the telescope... Direct imaging of exoplanets would greatly benefit from low-noise photon-counting detectors. Energy-resolving detector arrays such as the microwave kinetic inductance detectors (MKIDs) would be a ***game-changing capability****, considerably simplifying the instruments' optical design and allowing a significant gain in scientific return: they could allow simultaneous spectroscopic imaging of exoplanets and wavefront control for a high-contrast imaging coronagraphic instrument, and could enable multi-object spectroscopy to a scale not possible with conventional detectors.*

Coronagraph Basics



Adapted From Oppenheimer & Hinkley (2009)

Speckles



Wavefront errors result in a residual "speckle" pattern, which is **chromatic**, and **quasistatic**.

The most problematic speckles have coherence times ~1s; too slow to average away, but too fast to control with most detectors.

Correcting these speckles requires:

Energy Resolution

Photon-counting

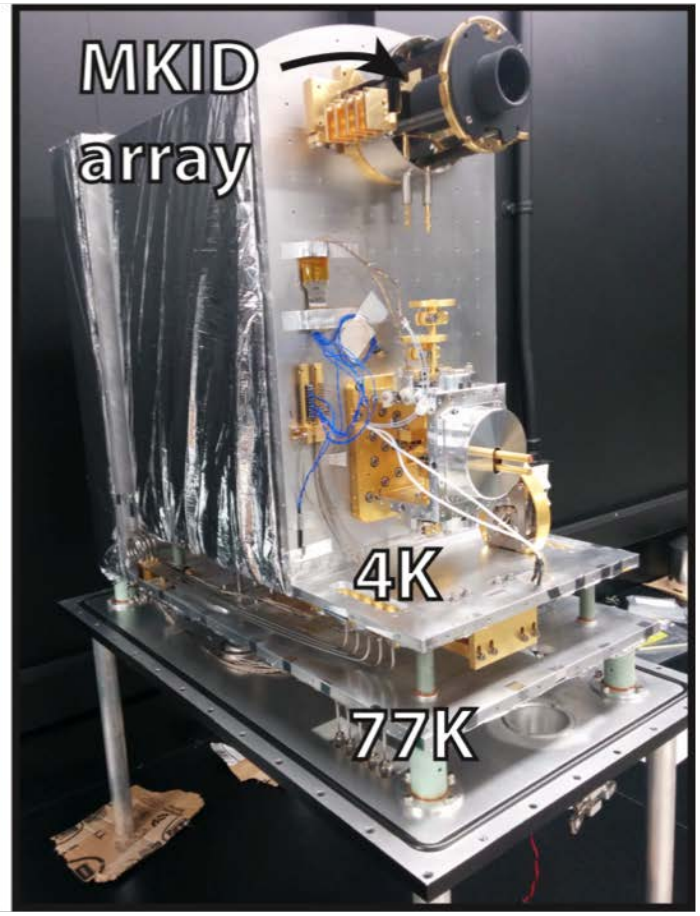
Zero dark current or read-noise

DARKNESS

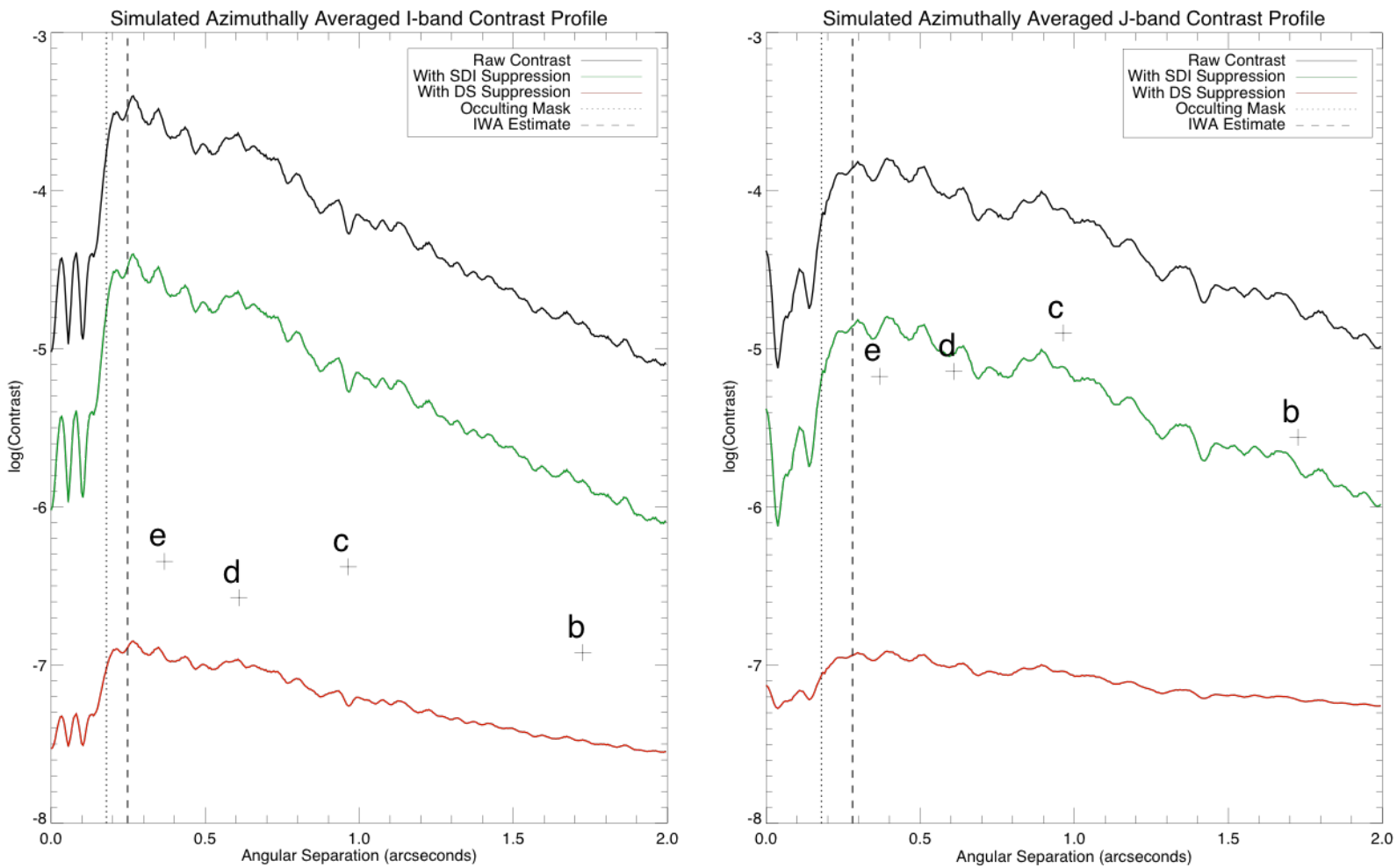
•10,000 pixel Exoplanet imaging camera for integration with Palomar Coronagraphs

• Operating wavelength range of 0.7 to 1.4 microns

•LHe cooled dewar designed as drop-in replacement for current Palomar IR imager (PHARO)

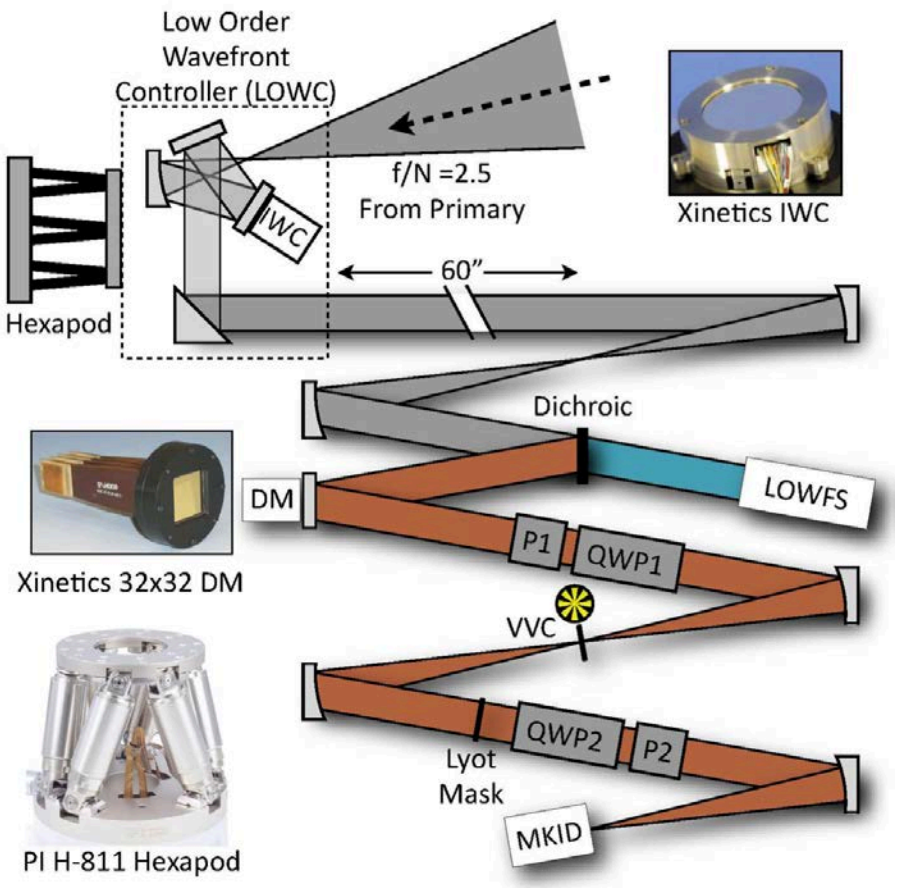


DARKNESS Performance



DARKNESS will improve J-band contrast by a factor of 100 (!)

Advancing MKID TRL with PICTURE-C



NASA funded balloon based coronagraph + MKID camera. Flight scheduled for 2019

Science objectives: image exoplanets and exozodiacal disks

Technology objectives: **demonstrate flight capability of Coronagraph and MKIDs**

The Search for Other Earths

- Objective 1.5: Ascertain the content, origin, and evolution of the solar system and the potential for life elsewhere.
- Objective 1.6: Discover how the universe works, explore how it began and evolved, and search for life on planets around other stars.

MKIDs could be an **enabling** technology for finding and characterizing Earth-like planets around nearby stars

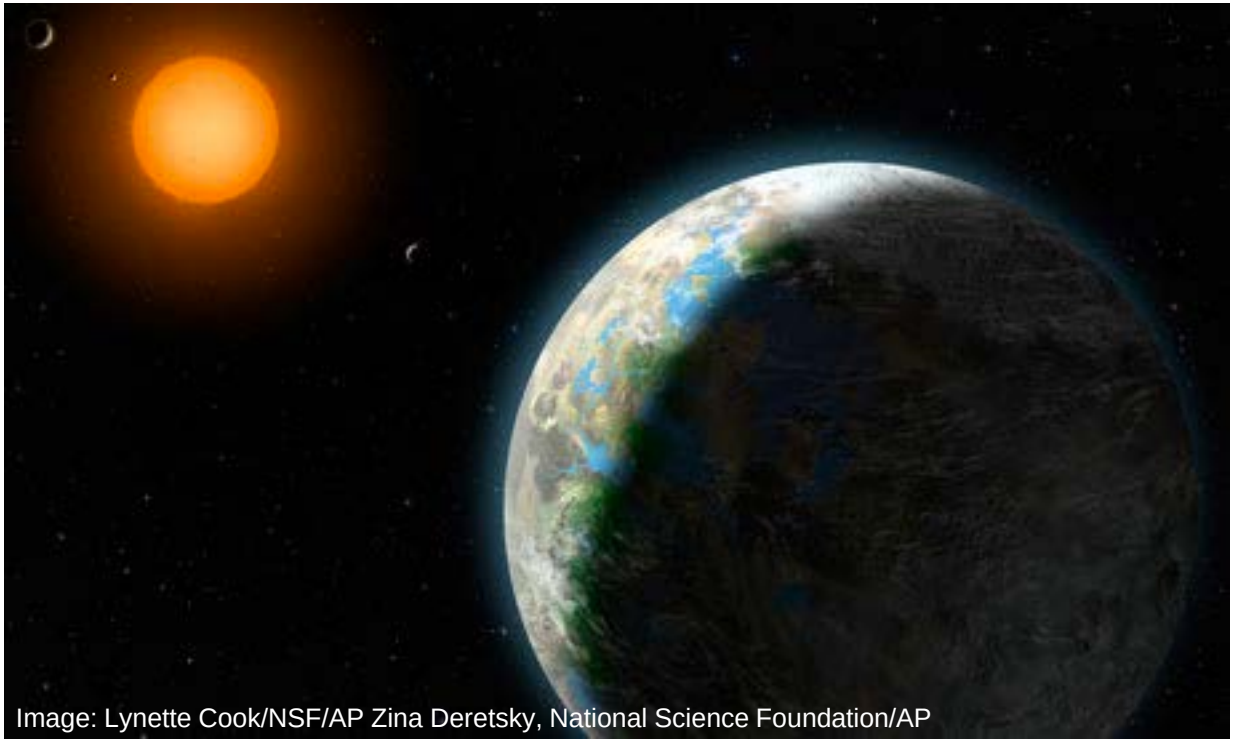


Image: Lynette Cook/NSF/AP Zina Deretsky, National Science Foundation/AP

Current Development Status of Technology

- The technology is functional and being used for science
- Three new MKID instruments (including a NASA Stratospheric Balloon) are currently under construction
- Significant funding is needed to improve the array quality, size, and usability
  - Exact numbers depend on the application!
  - 20 kpix planet finders for the ground ready now for ~$1M each
- This technology is currently by far the most capable UVOIR detector on Earth
- For applications where the $150k added costs of the cryogenics is not critical (on the ground, more in space!), MKIDs enable massive performance improvements
- Synergy for space cryogenics with X-ray and Far-IR

Contacts

- Contact Information:
  - bmazin@physics.ucsb.edu
  - 805-893-3344
  - web.physics.ucsb.edu/~bmazin/
- References
  - Mazin, B.A., et al. A superconducting focal plane array for ultraviolet, optical, and near-infrared astrophysics. Optics Express, 20, 2., 1503-1511, 2012.
  - Mazin, B.A., et. al. ARCONS: A 2024 Pixel Optical through Near-IR Cryogenic Imaging Spectrophotometer. PASP, 123, 933, 2013.

Summary of Key Points

- Core technical competencies & expertise
  - We are the undisputed world leaders in photon counting MKIDs
  - We design, fabricate, and build MKID arrays and instruments and use them for Astronomy
- Manufacturing & facility capabilities
  - We use the excellent fabrication facilities at JPL (through Co-I B. Bumble) to make our arrays
  - We make SiN membrane suspended X-ray MKIDs at UCSB
  - We have MKID testbeds capable of reading out thousands of MKIDs at once and doing a full suite of optical tests

Back-up charts

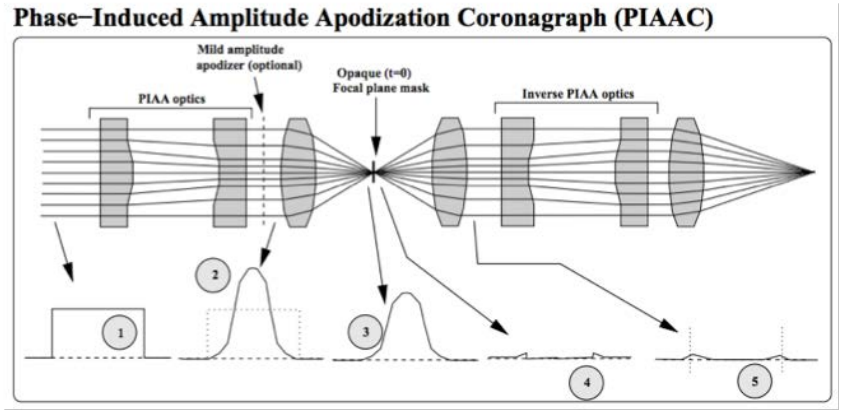
MEC+SCExAO

- The Subaru Coronagraphic Extreme AO Project

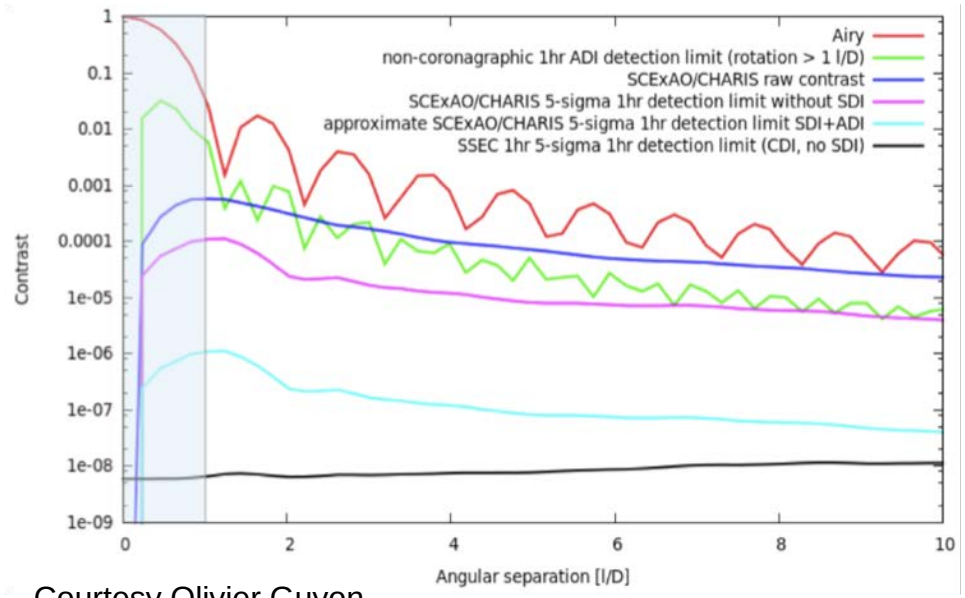
- PIAA Coronagraph:
  - Lossless apodization
  - 1 λ/D Inner Working Angle

- High frame rate imaging for integrated speckle nulling

- MKID Exoplanet Camera (MEC) will provide ~kHz focal plane feedback to control the fastest coherent speckles

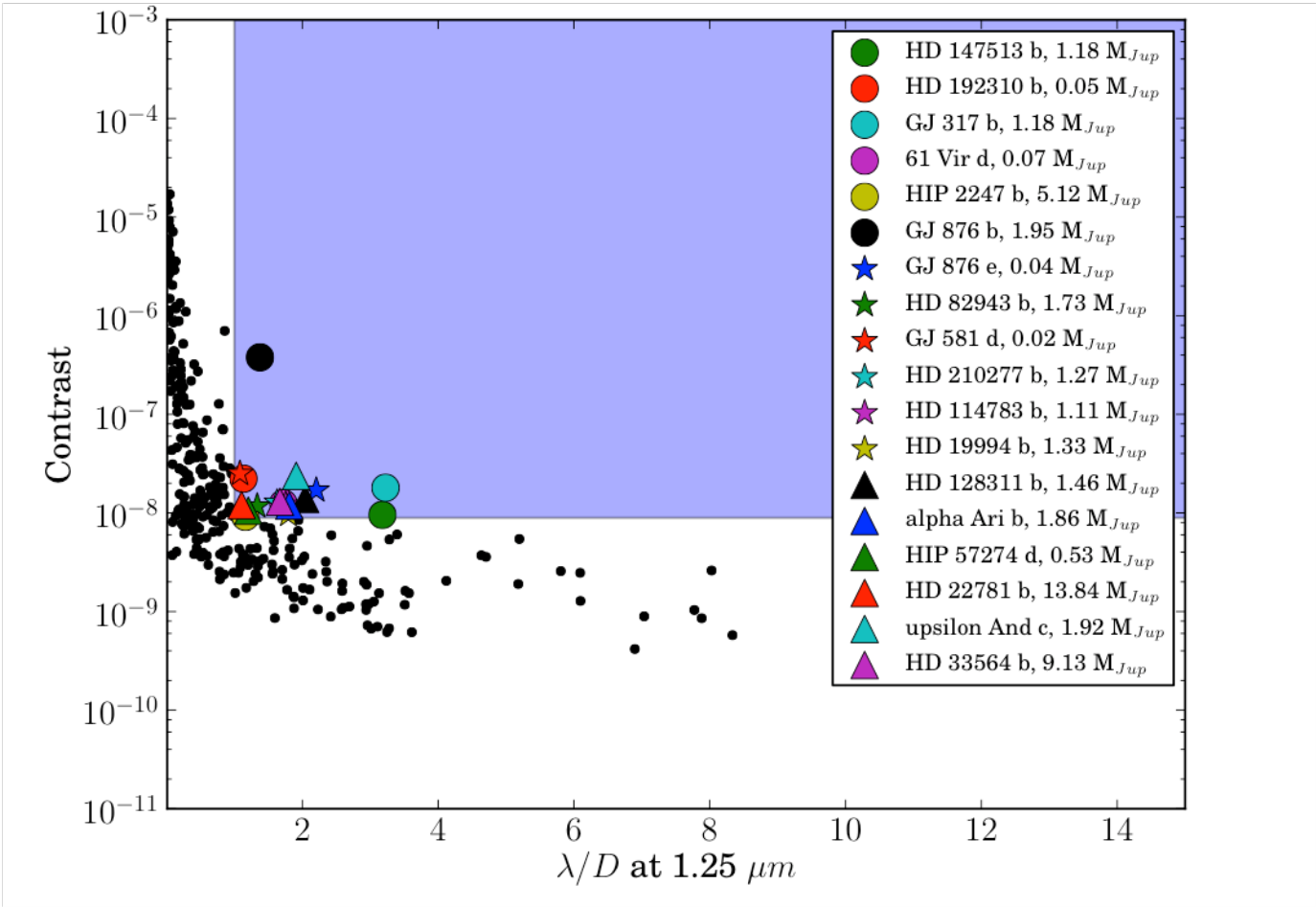


Guyon et al 2006



Courtesy Olivier Guyon

Directly Imaging RV Planets with MEC



MEC + SCExAO will achieve the first direct imaging of known radial velocity planets in reflected light