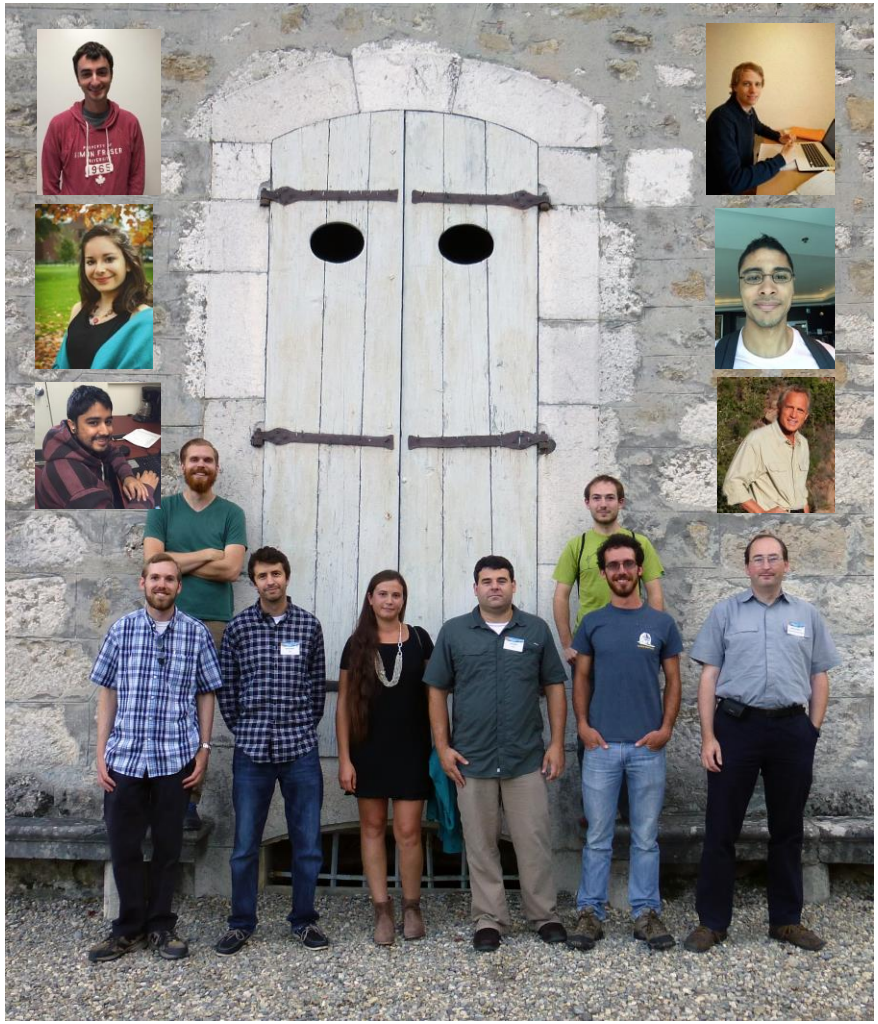
Microwave Kinetic Inductance Detectors for High Contrast Imaging with DARKNESS and MEC

Ben Mazin, June 2017

The UVOIR MKID Team:

UCSB: Ben Mazin, Seth Meeker, Paul Szypryt, Gerhard Ulbricht, Alex Walter, Clint Bocksteigel, Giulia Collura, Neelay Fruitwala, Isabel Liparito, Nicholas Zobrist, Gregoire Coiffard, Miguel Daal, James Massie
JPL/IPAC: Bruce Bumble, Julian van Eyken
Oxford: Kieran O'Brien, Rupert Dodkins
Fermilab: Juan Estrada, Gustavo Cancelo, Chris Stoughton



Mazin Lab
UNIVERSITY OF CALIFORNIA SANTA BARBARA
All of the wavelengths
All of the times
mazinlab.org

UCSB JPL UNIVERSITY OF OXFORD

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 PtSi
- This is caused by electrons pairing up to form "Cooper Pairs"
  - Nobel Prize to BCS in 1972


John Bardeen

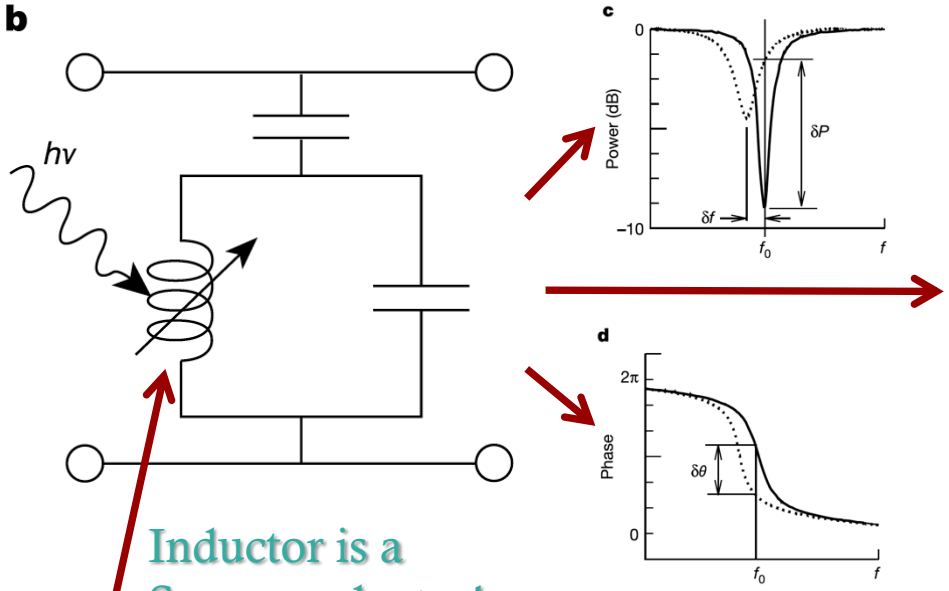

Leon Neil Cooper


John Robert Schrieffer

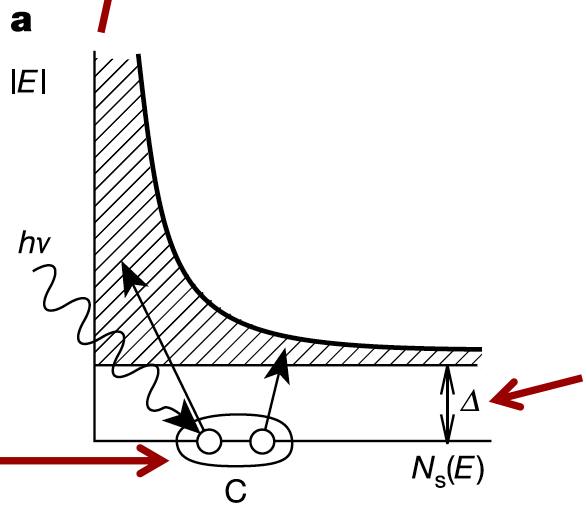
- Like a semiconductor, there is a "gap" in a superconductor, but it is 1000-10000x lower than the gap in Si
- Instead of one electron per photon in a semiconductor, we get ~5000 electrons per photon in a superconductor – much easier to measure (no noise and energy determination)! We call these excitations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

MKIDs

MKID Equivalent Circuit



Inductor is a Superconductor!



Cooper Pair

Energy Gap

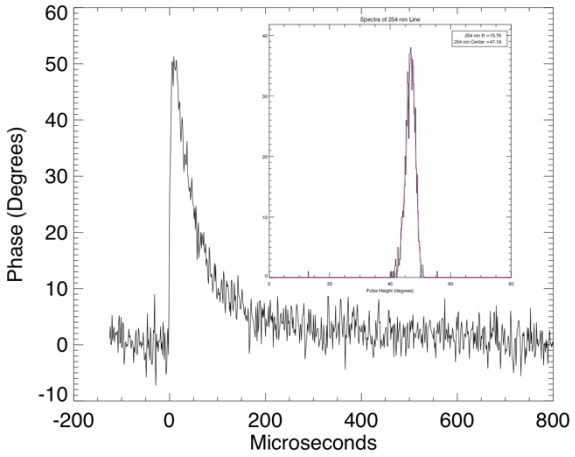
Silicon – 1.10000 eV

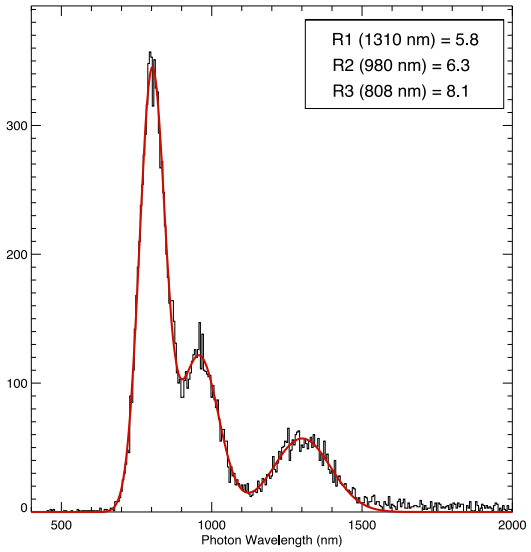
PtSi or TiN – **0.00013** eV

Energy resolution:

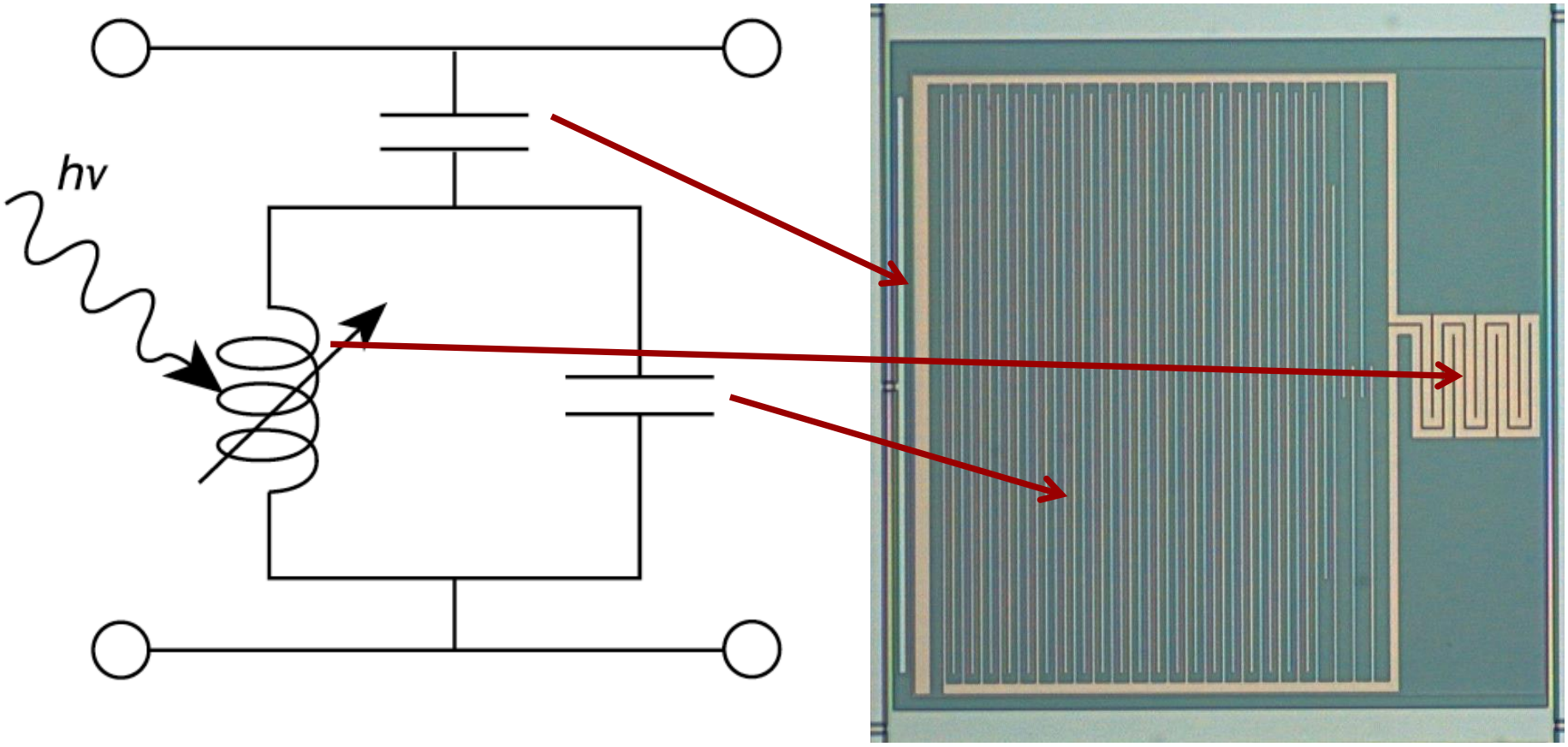
$$R = \frac{1}{2.355}\sqrt{\frac{\eta h\nu}{F\Delta}}$$

Typical Single Photon Event



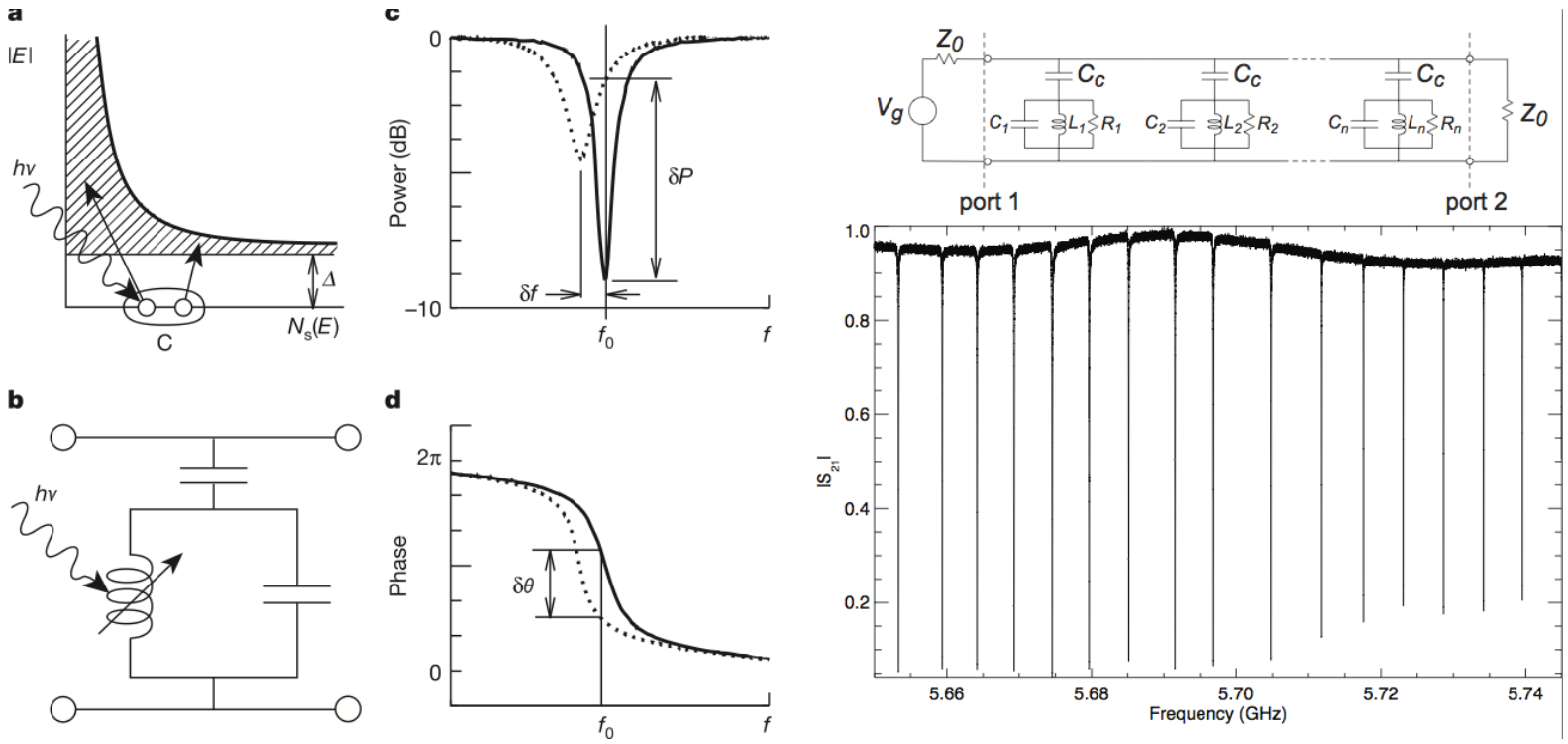


What is a Kinetic Inductance Detector?



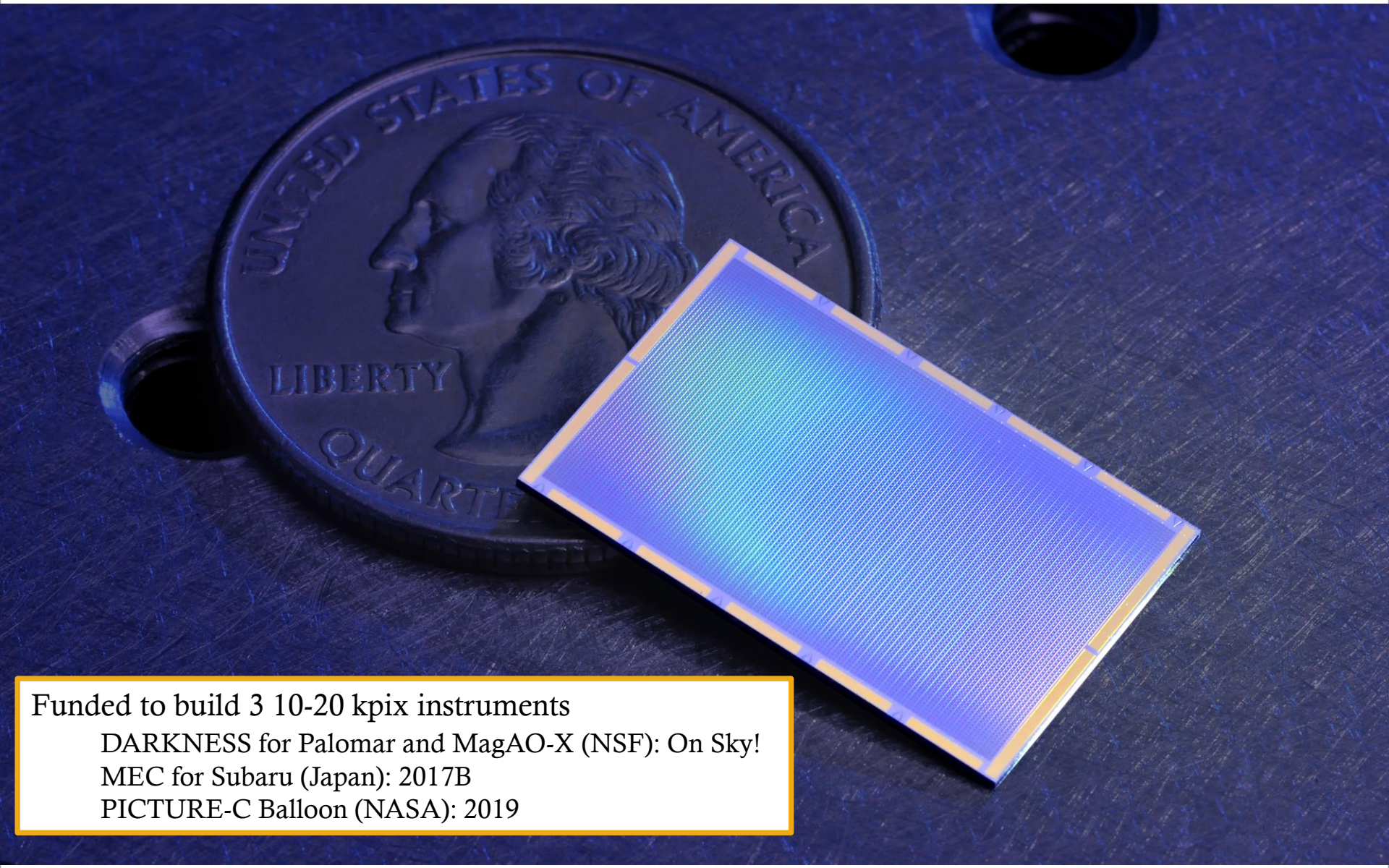
We use a square microlens array to improve effective fill factor to ~92%

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)

10 kpix DARKNESS Array

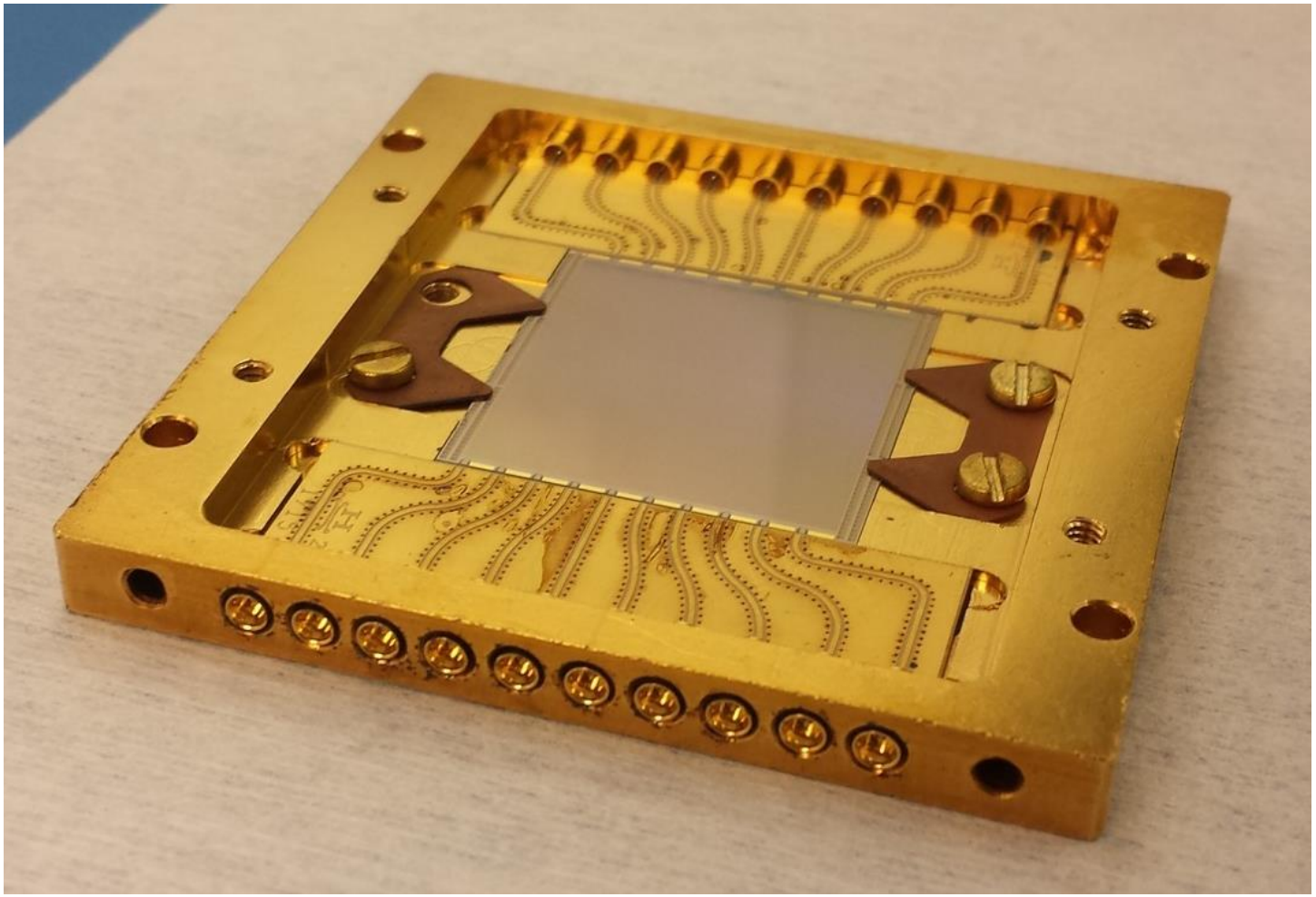


Funded to build 3 10-20 kpix instruments

- DARKNESS for Palomar and MagAO-X (NSF): On Sky!
- MEC for Subaru (Japan): 2017B
- PICTURE-C Balloon (NASA): 2019

MEC Array

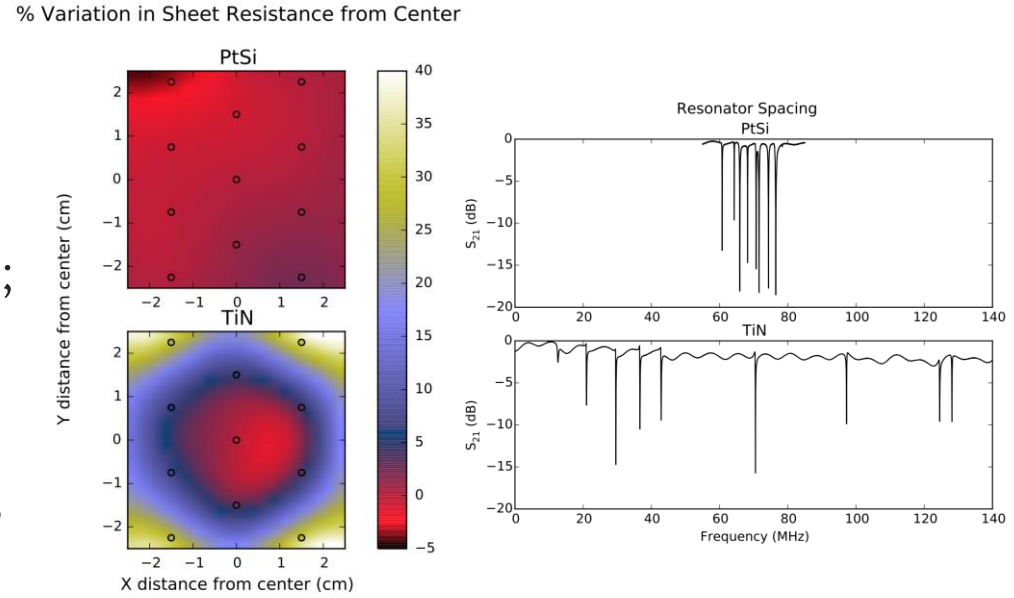
- New 20 kpix PtSi MKID array for Subaru SCExAO-MEC
  - 140x146 pixels, 150 micron pixel pitch, 22x22 mm imaging area

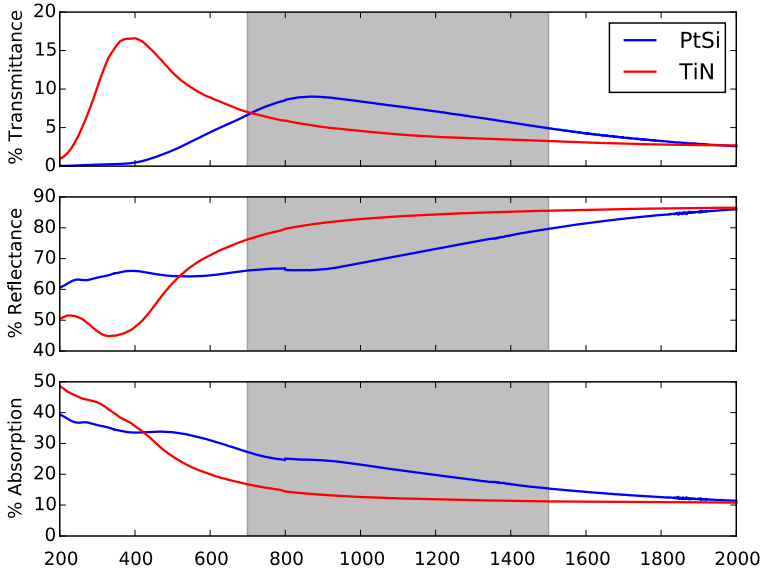


Array fabricated at UCSB by P. Szypryt and G. Coffard

Outstanding Issues

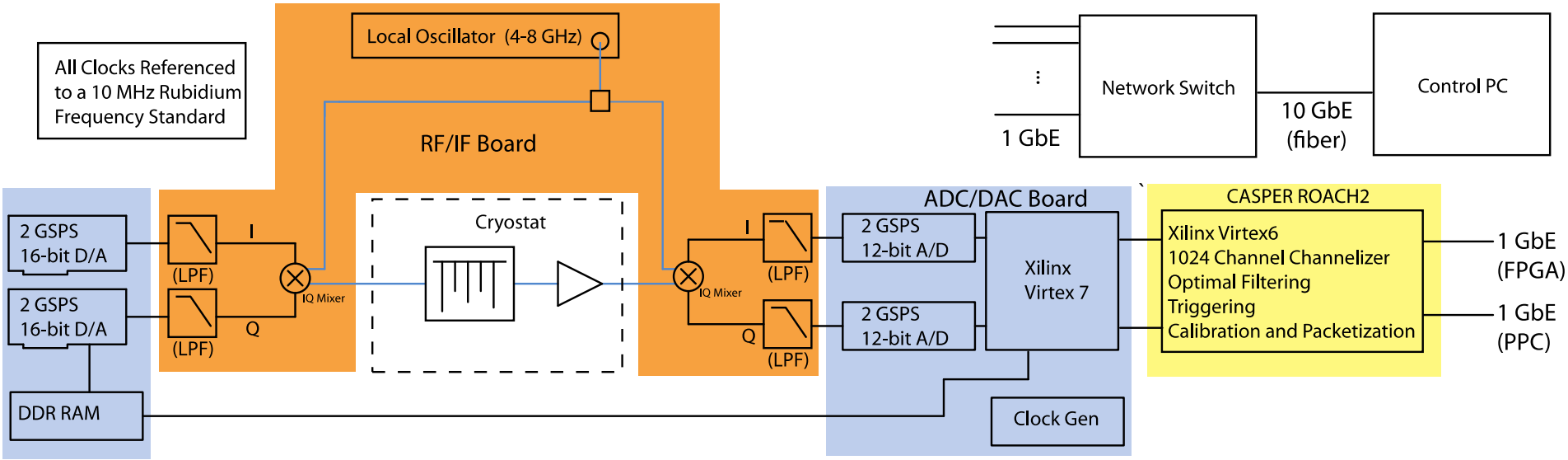
- Three main issues need improvement:
  - **Pixel Yield**
    - 75% in ARCONS
    - DARKNESS/MEC: Req. 85%; 95% goal
  - **Spectral Resolution**
    - R=8 at 400 nm in ARCONS
    - DARKNESS/MEC: Req. R=8 at 1000 nm; R=15 goal
  - **Quantum Efficiency**
    - ARCONS TiN: 40% at 400 nm, 15% at 1000 nm
    - DARKNESS/MEC PtSi: Req. 15% at 1000 nm; >25% goal
  - Attempting to improve yield and R first as they are the biggest impacts on the science we want to do
    - Exoplanet High Contrast Imaging from the ground is far from photon shot noise limited at the moment!





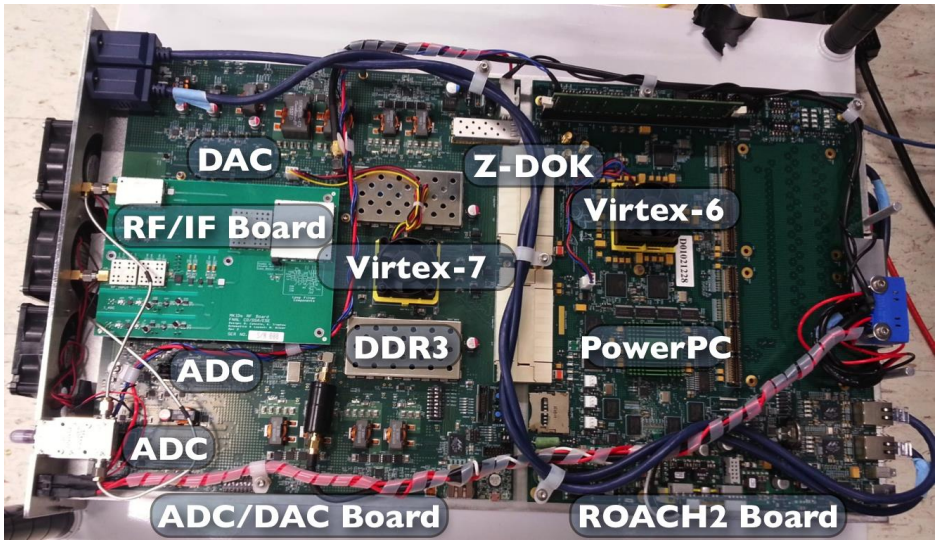
Digital MKID Readout

- 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)



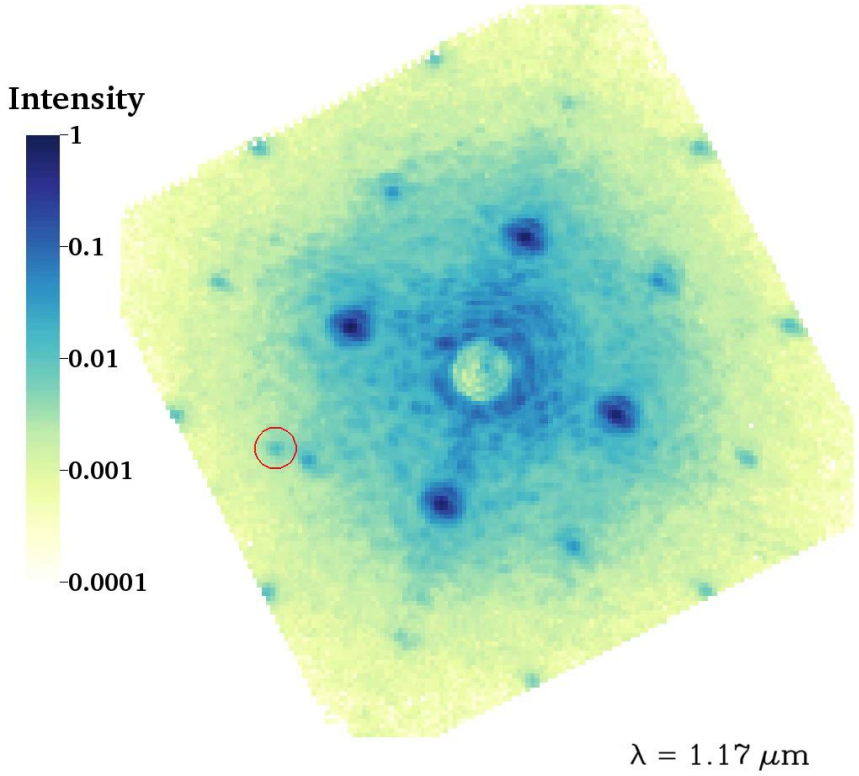
Gen 2 Readout

- 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 FPGAs



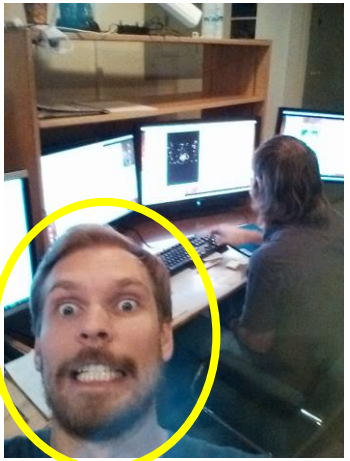
IFU for Planet Finding

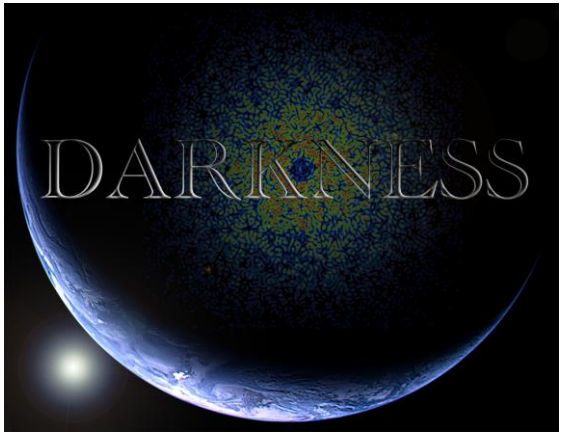
- Coronagraphs are limited by speckles from scattered and diffracted light
  - Speckles are *coherent* and chromatic and have a variety of lifetimes
    - Quasi-static: many minutes
    - Atmospheric: <1 second
  - Energy-resolving focal planes increase sensitivity by a factor of up to 10-**100 (!)**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

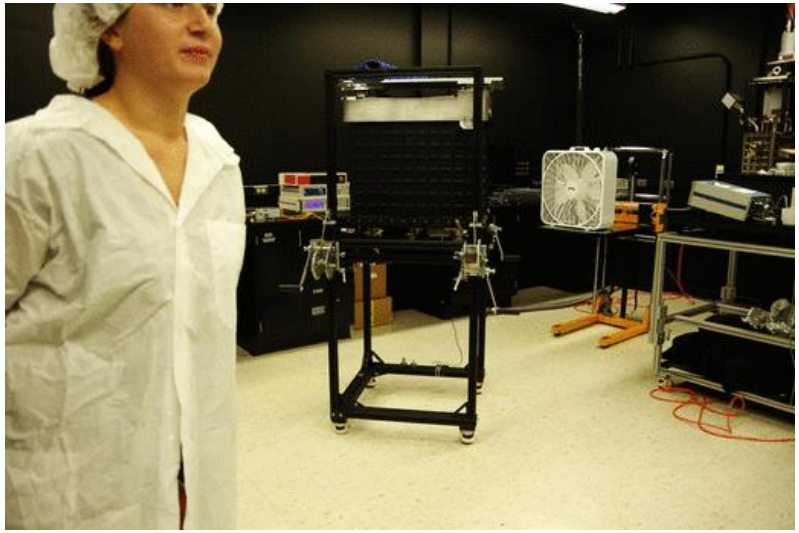


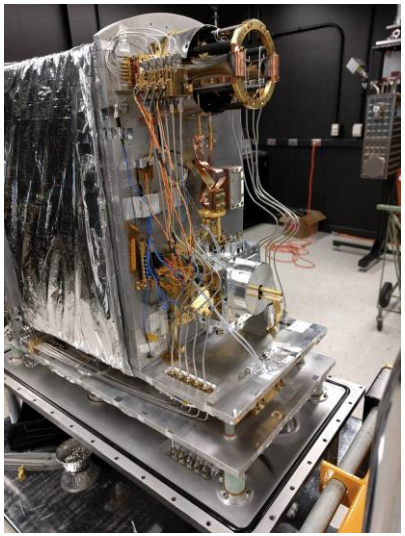
- Data on brown dwarf HD1160B from Tim Brandt and CHARIS/SCExAO

DARKNESS





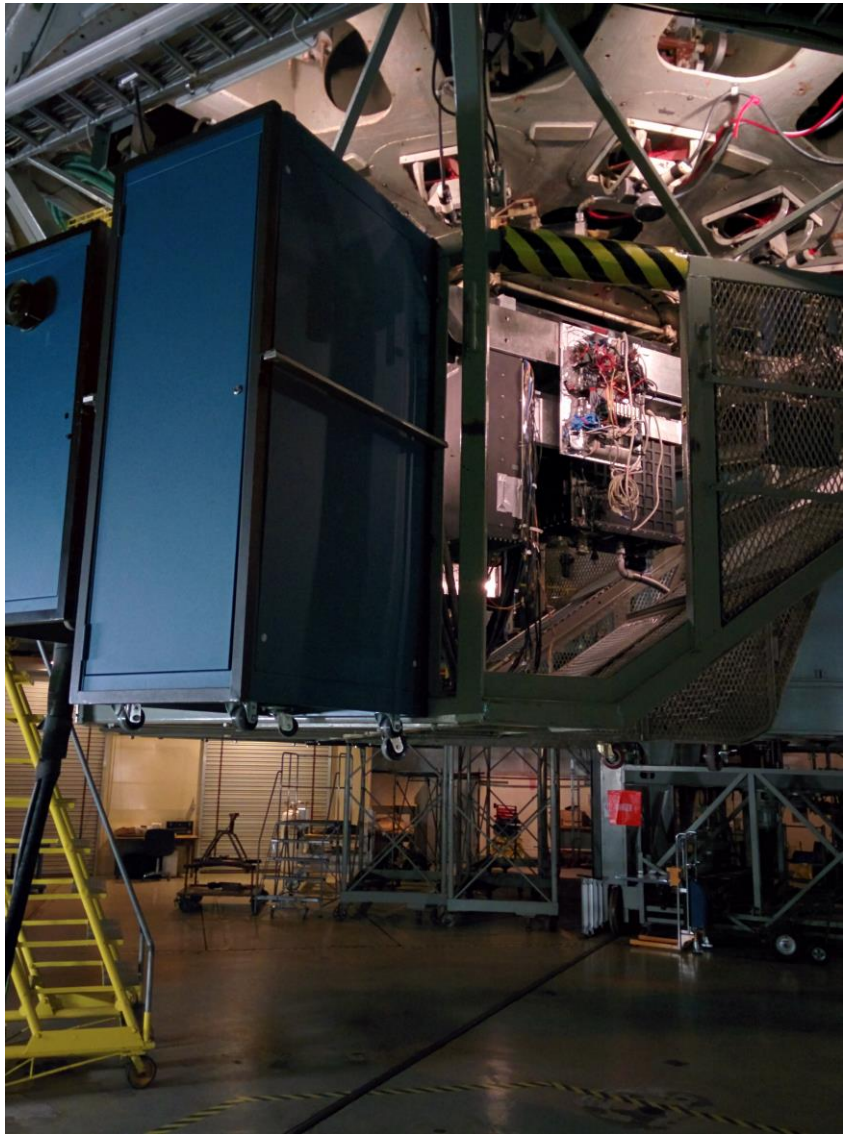


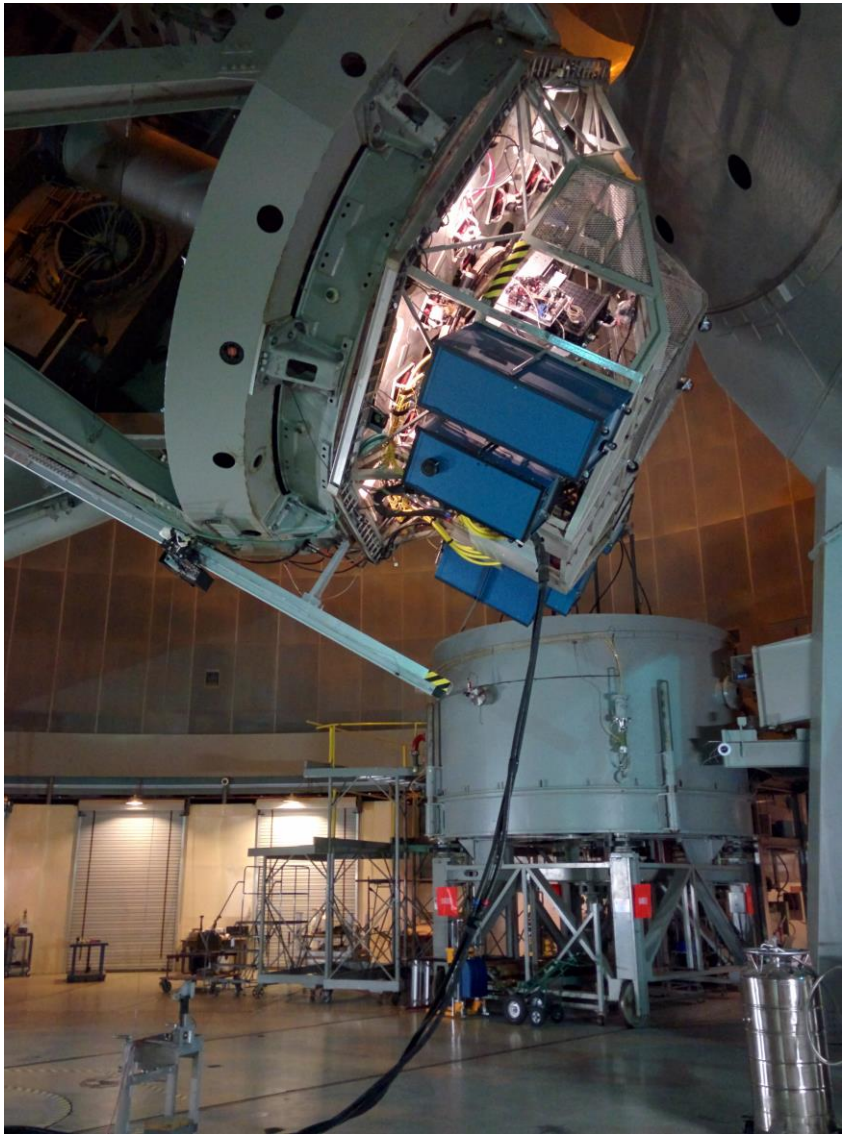


DARKNESS is the thesis project of Seth Meeker

DARKNESS Commissioning, July 2016

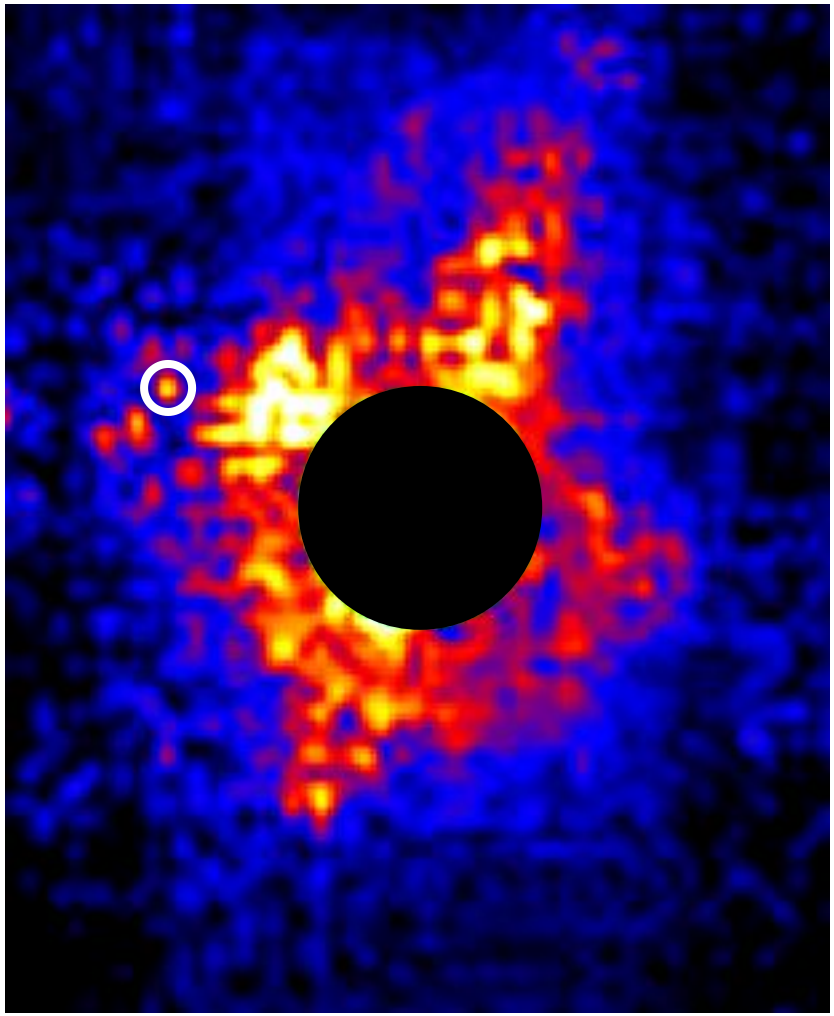
DARKNESS Commissioning, July 2016

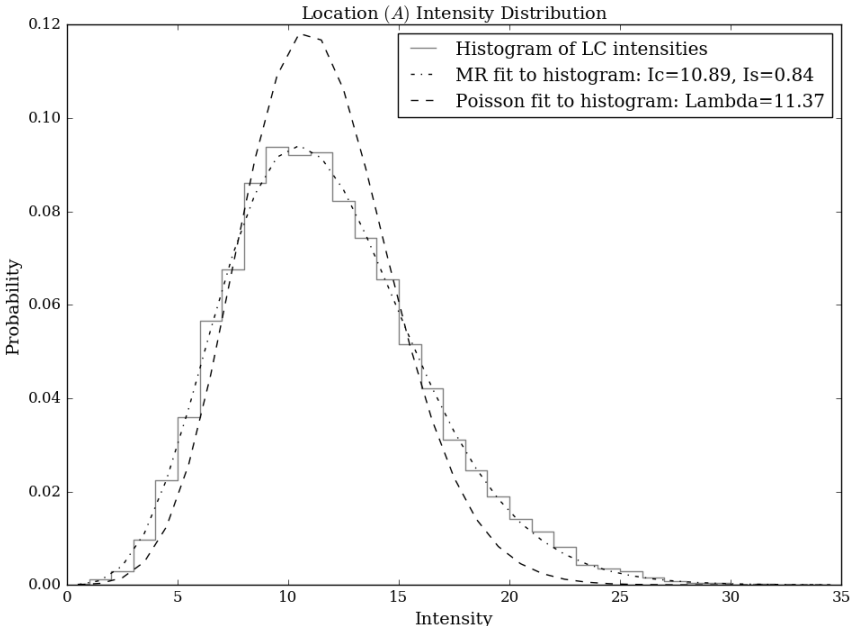


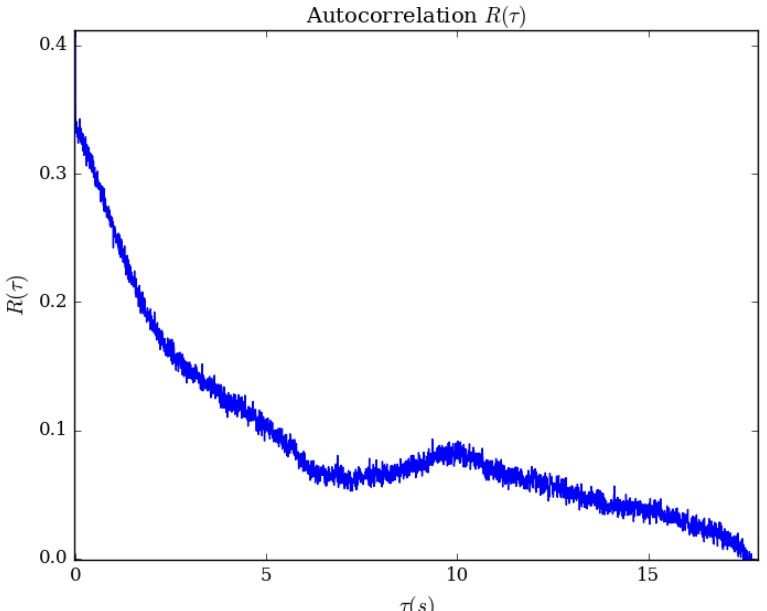


Party

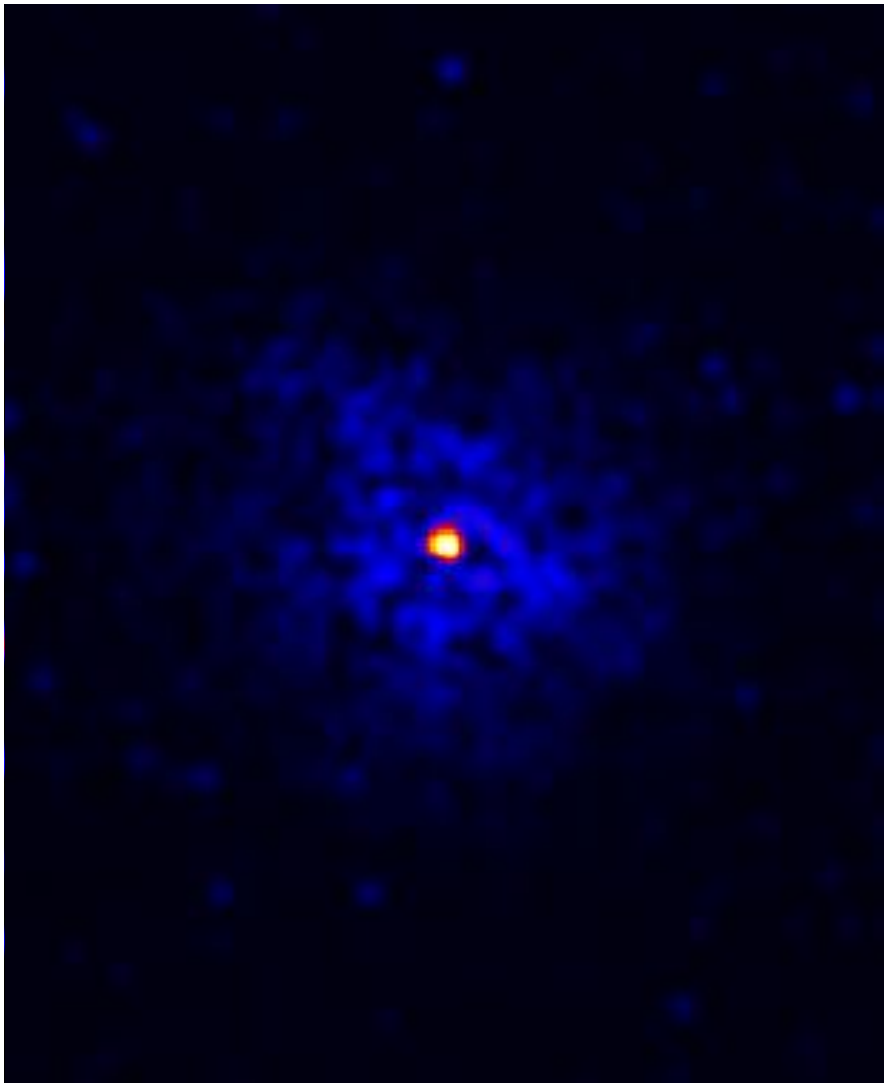
Internal White Light Source



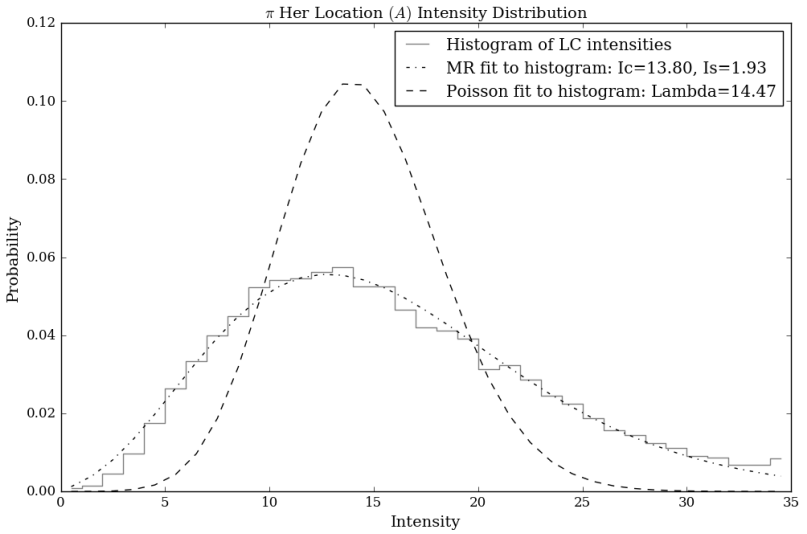




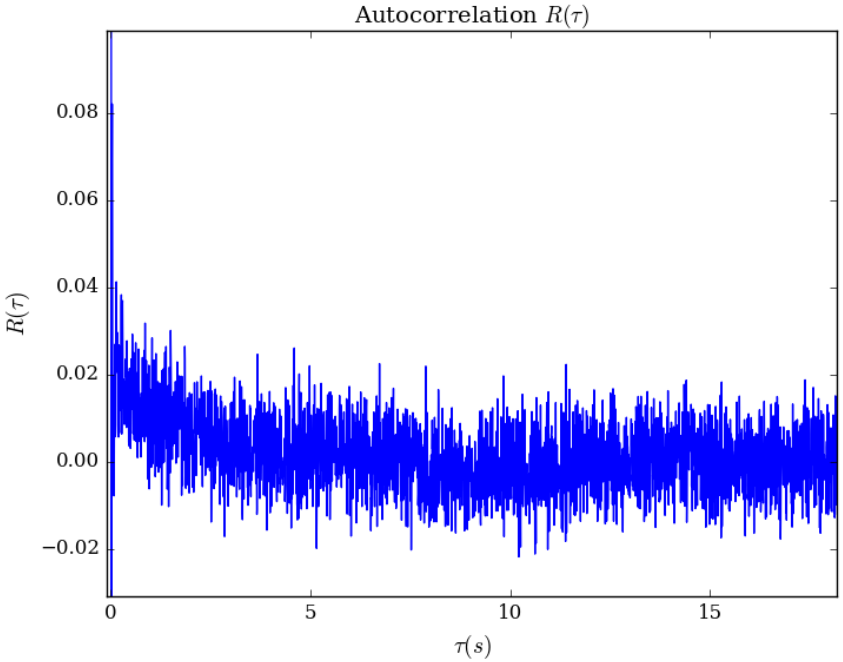
First On Sky Results: Pi Her in J-band



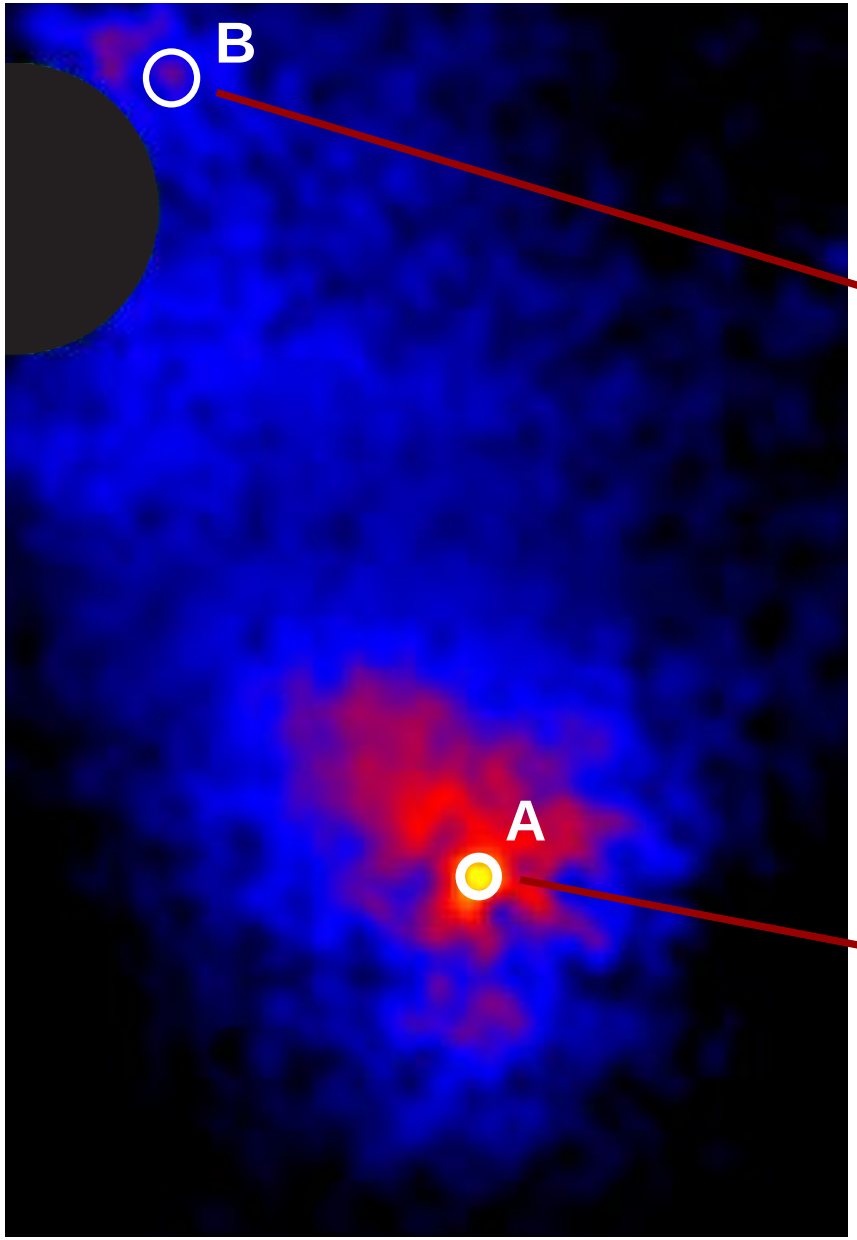
Mask Diam 6.6 λ/d

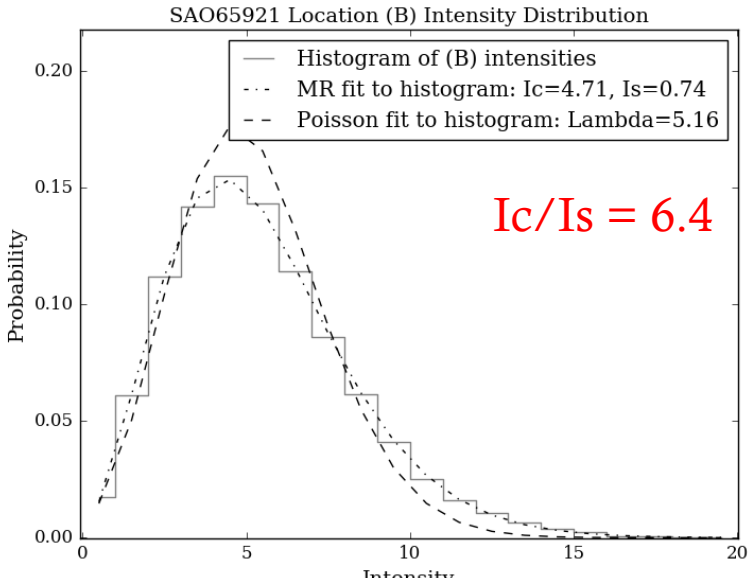


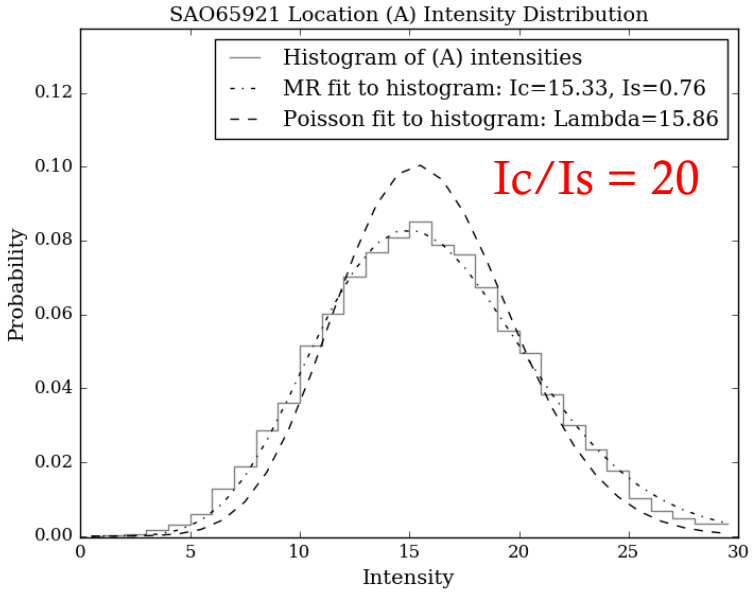
No read noise, 5 ms effective exposure time



SAO 65921

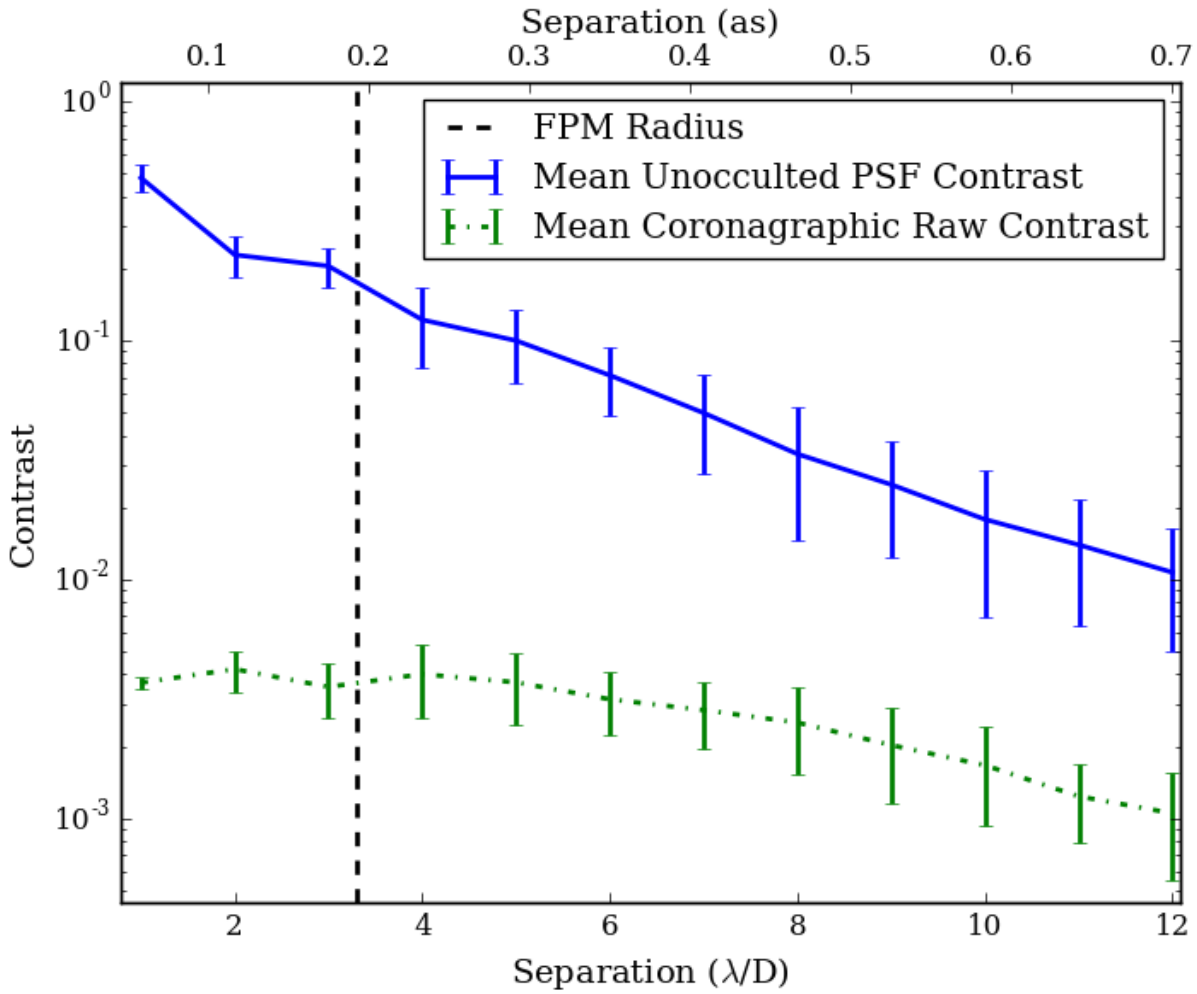

B
A


SAO65921 Location (B) Intensity Distribution
Histogram of (B) intensities
MR fit to histogram: Ic=4.71, Is=0.74
Poisson fit to histogram: Lambda=5.16
Ic/Is = 6.4
Probability
0.00
0.05
0.10
0.15
0.20
0
5
10
15
20

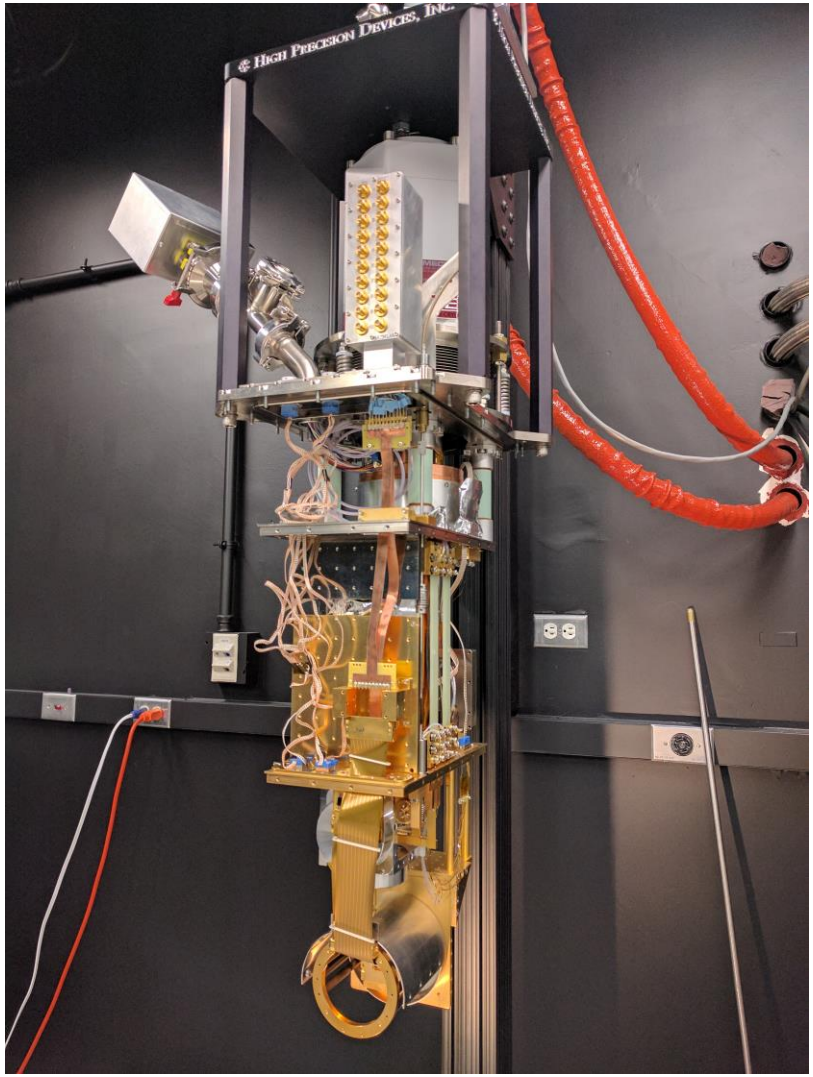

SAO65921 Location (A) Intensity Distribution
Histogram of (A) intensities
MR fit to histogram: Ic=15.33, Is=0.76
Poisson fit to histogram: Lambda=15.86
Ic/Is = 20
Probability
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0
5
10
15
20
25
30
Intensity

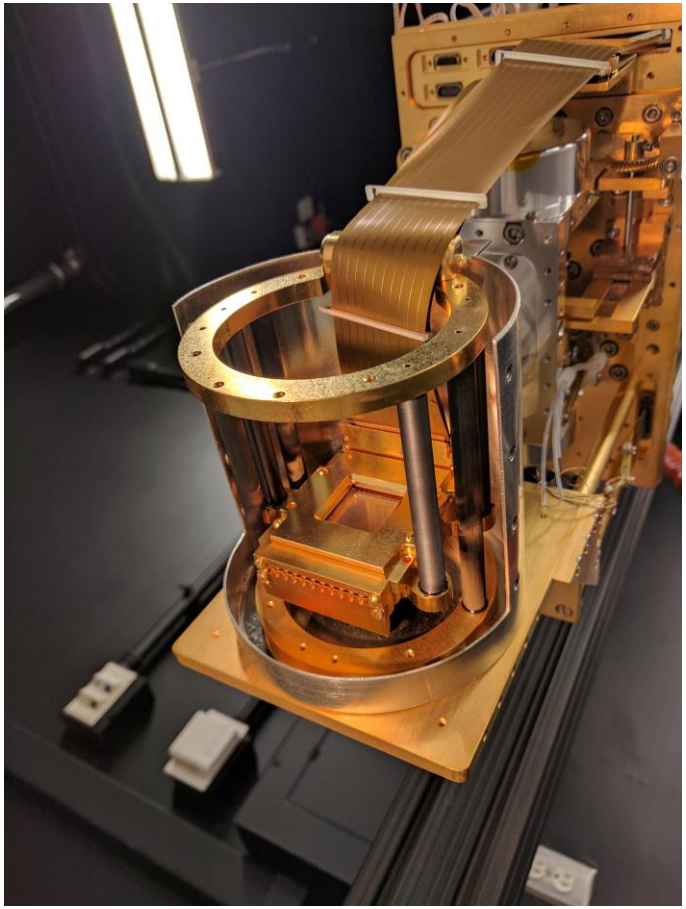
DARKNESS J-Band Raw Contrast

- Very preliminary RAW contrast w/Lyot Coronagraph
  - Charge 2 J-Band Vortex and P3K upgrades (higher Strehl) coming soon!



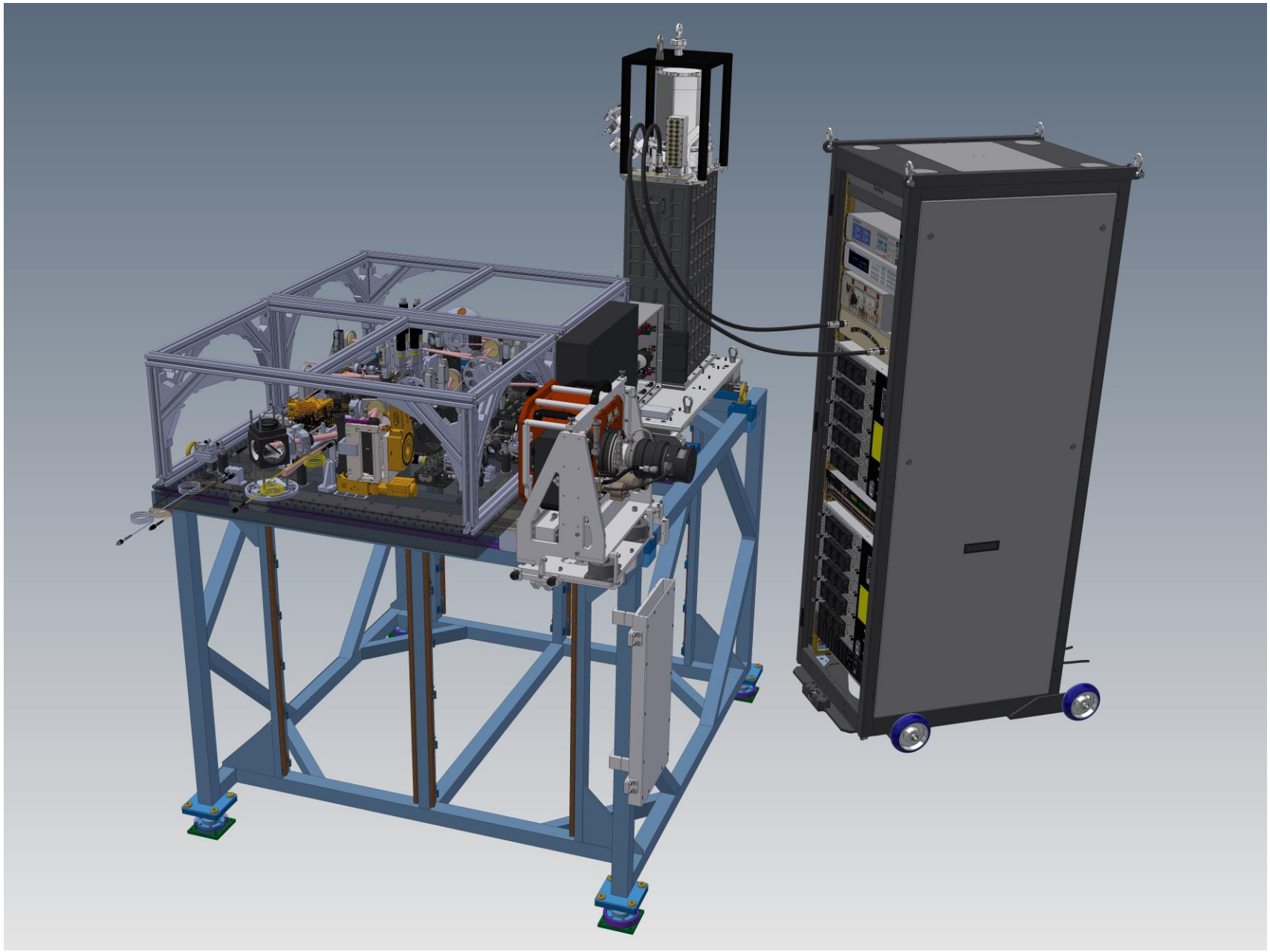
- MEC is a 20 kpix version of DARKNESS for Subaru SCExAO





MEC is the thesis project of Alex Walter

MEC at SCExAO



MEC Performance on Nearby Stars

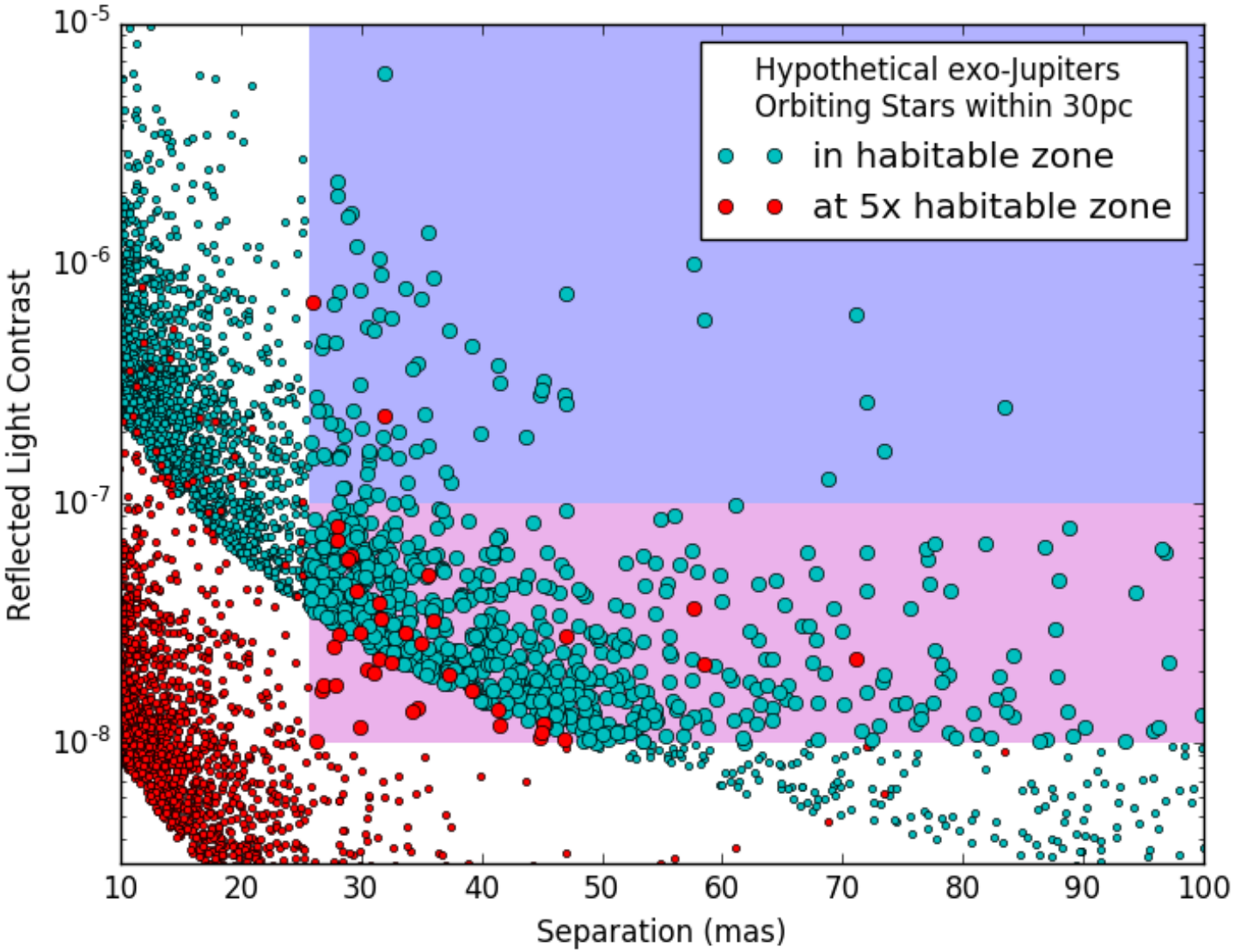


Figure from O. Guyon and A. Walter

MagAO-X

- Newly funded high contrast system for 6.5m Magellan Tel. in Chile
- Uses the same hardware and software infrastructure as SCExAO
- We are funded to bring DARKNESS for observations in ~3 years
- Proxima Cen b is at 38 mas and ~5e-8 contrast at 800 nm
  - We have a (very very long) shot!

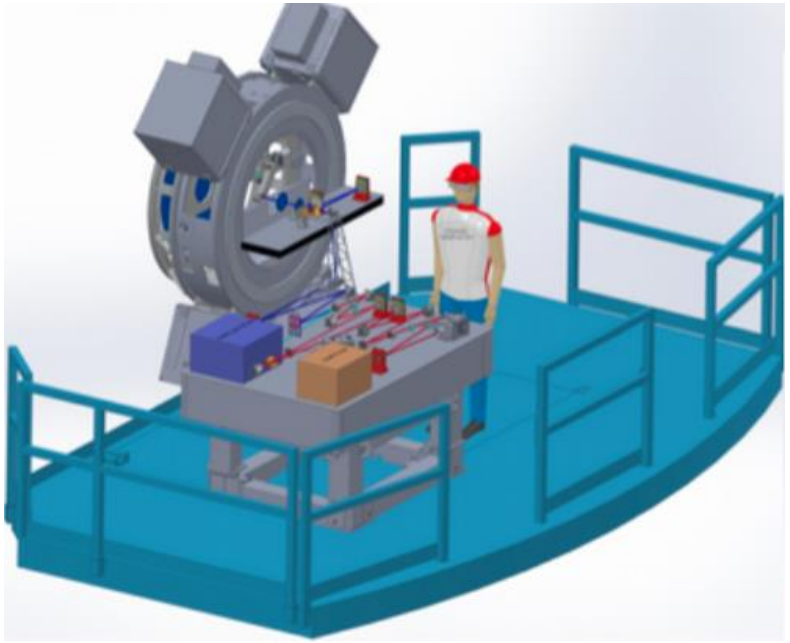
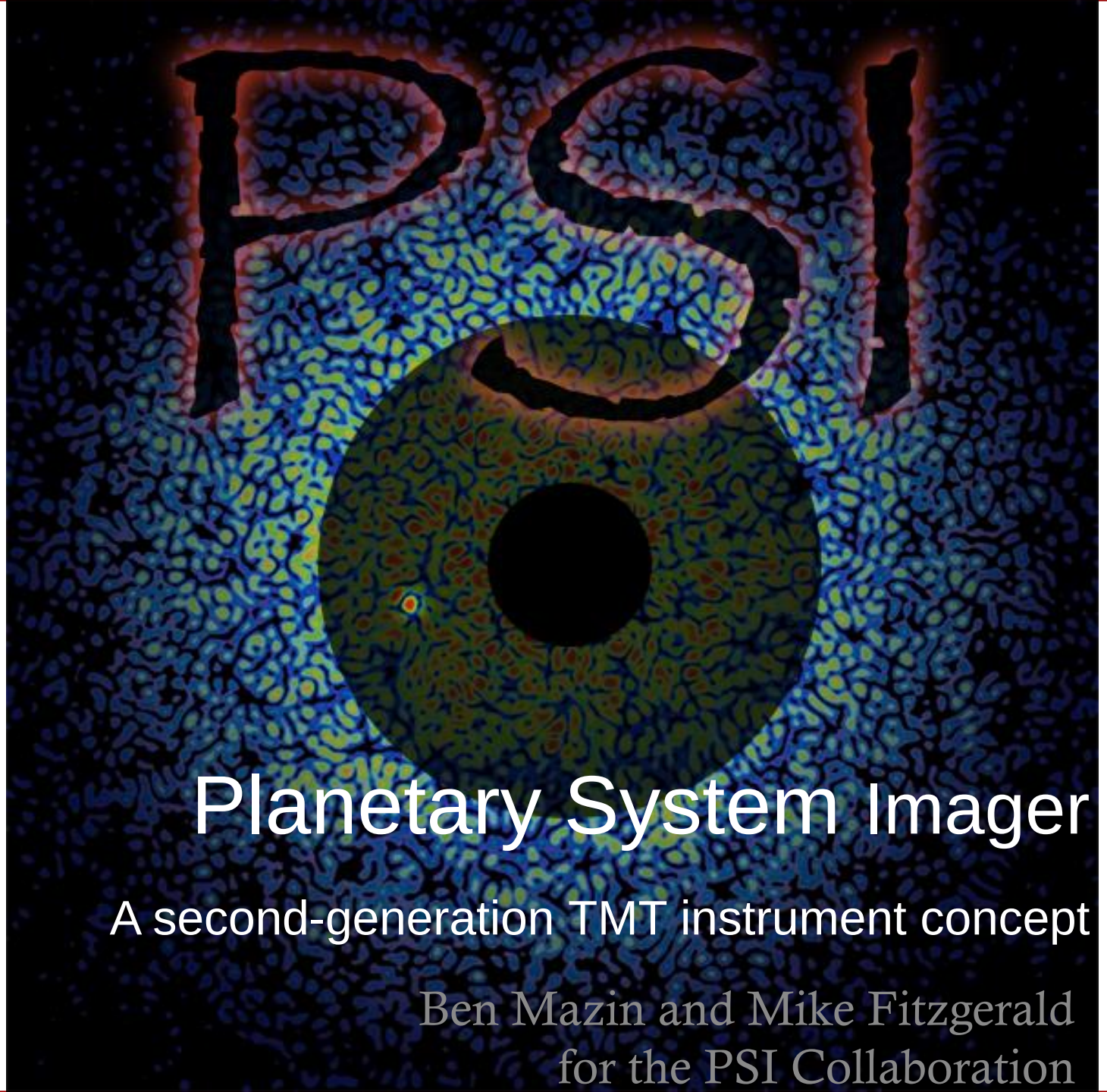


Image Credit: Carnegie Observatory

Image Credit: ESO/M. Kornmesser



Planetary System Imager

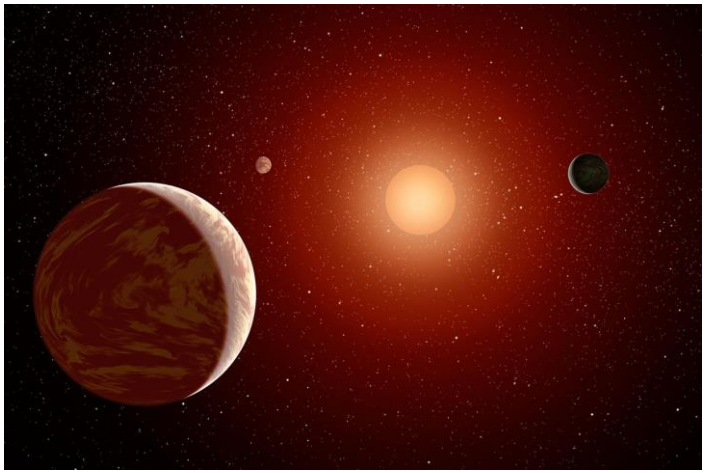
A second-generation TMT instrument concept

Ben Mazin and Mike Fitzgerald
for the PSI Collaboration

Large Apertures are Vital for Direct Imaging of Exoplanets

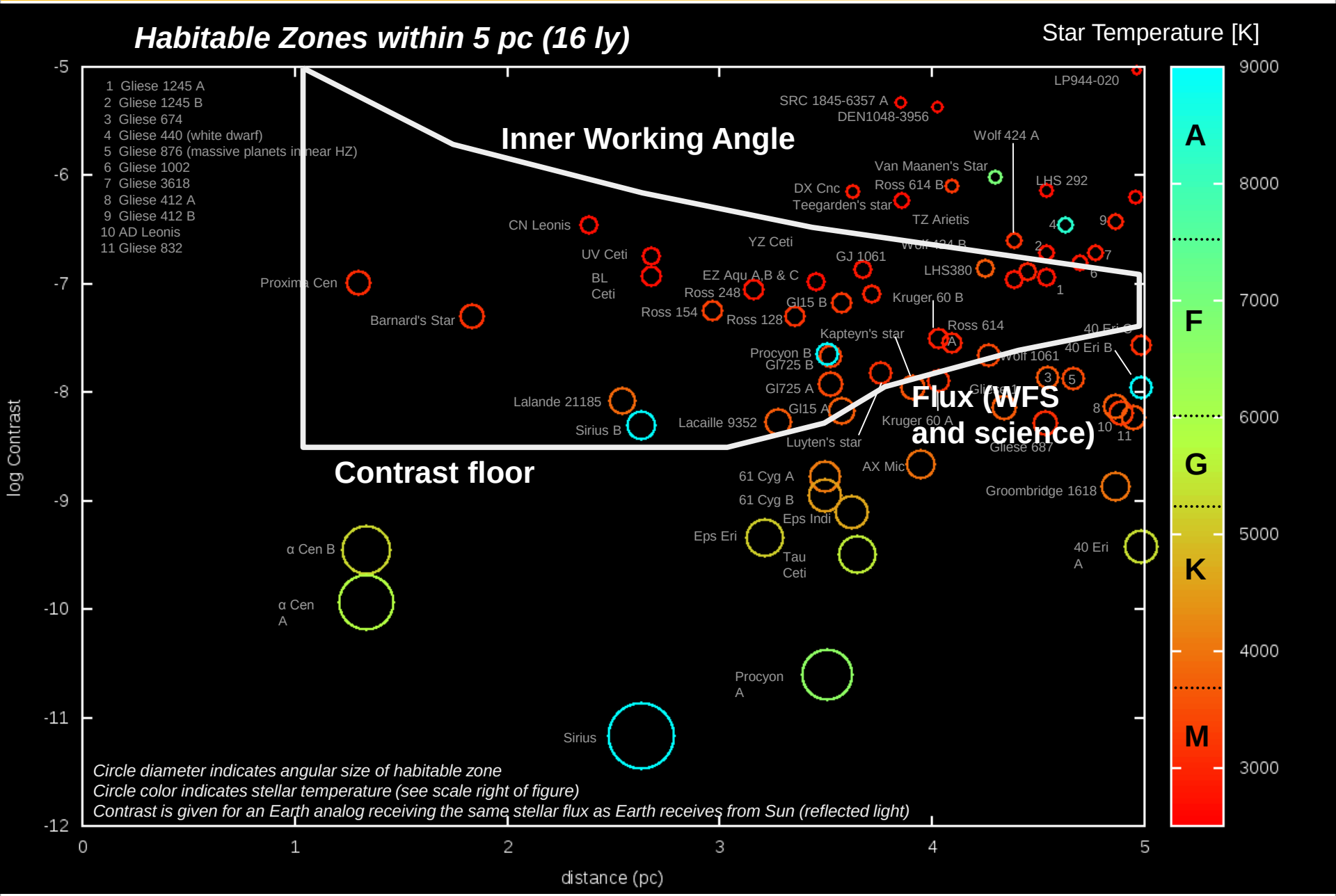
- GPI/SPHERE/SCExAO/P1640 show planets are rare past 10 AU
- Going inside 10 AU pushes us to large aperture and short wavelengths for a small IWA
  - 2λ/D for TMT at 1.3 micron = 10 mas!
  - 0.1 AU at 10 pc
    - M star habitable zones at 10^{-8} contrast ratios
    - 275 M stars within 10 pc
      - 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

Figure from O. Guyon



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?

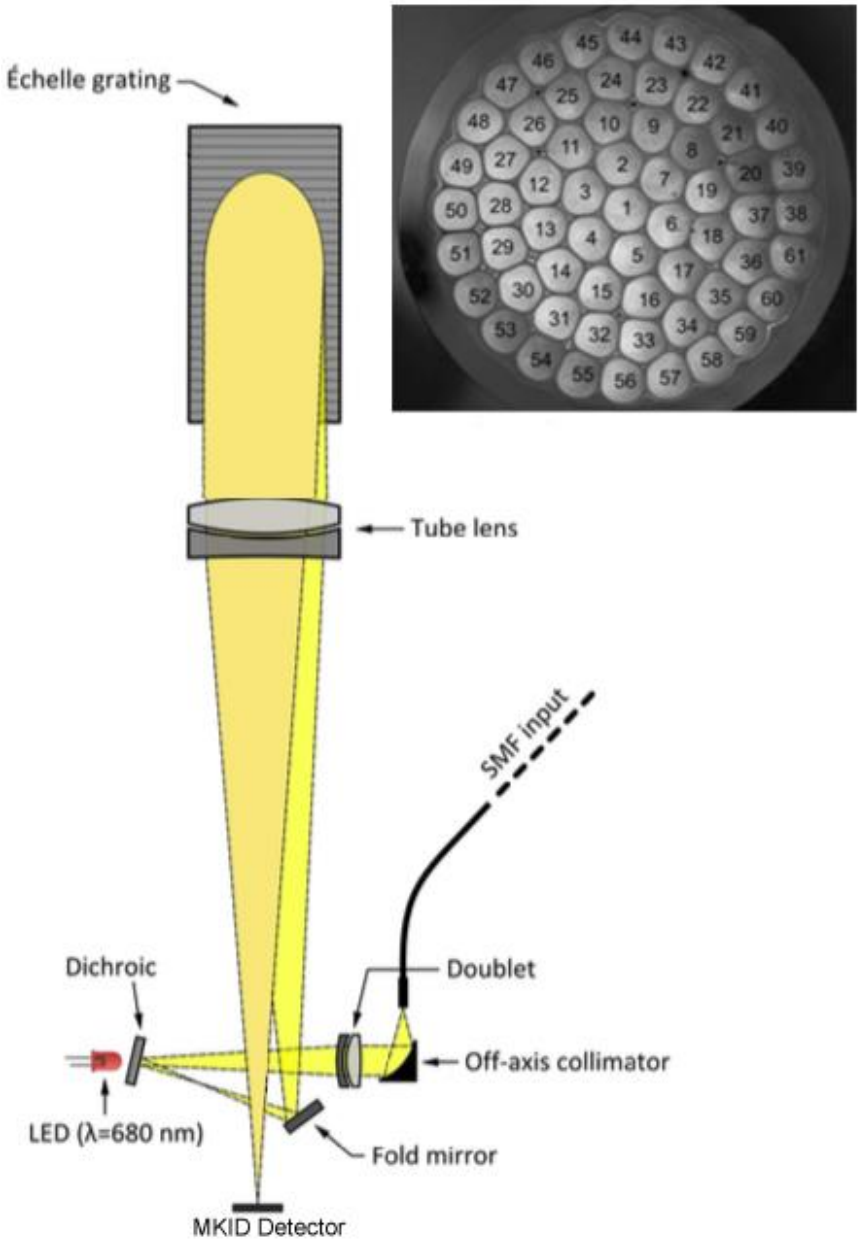
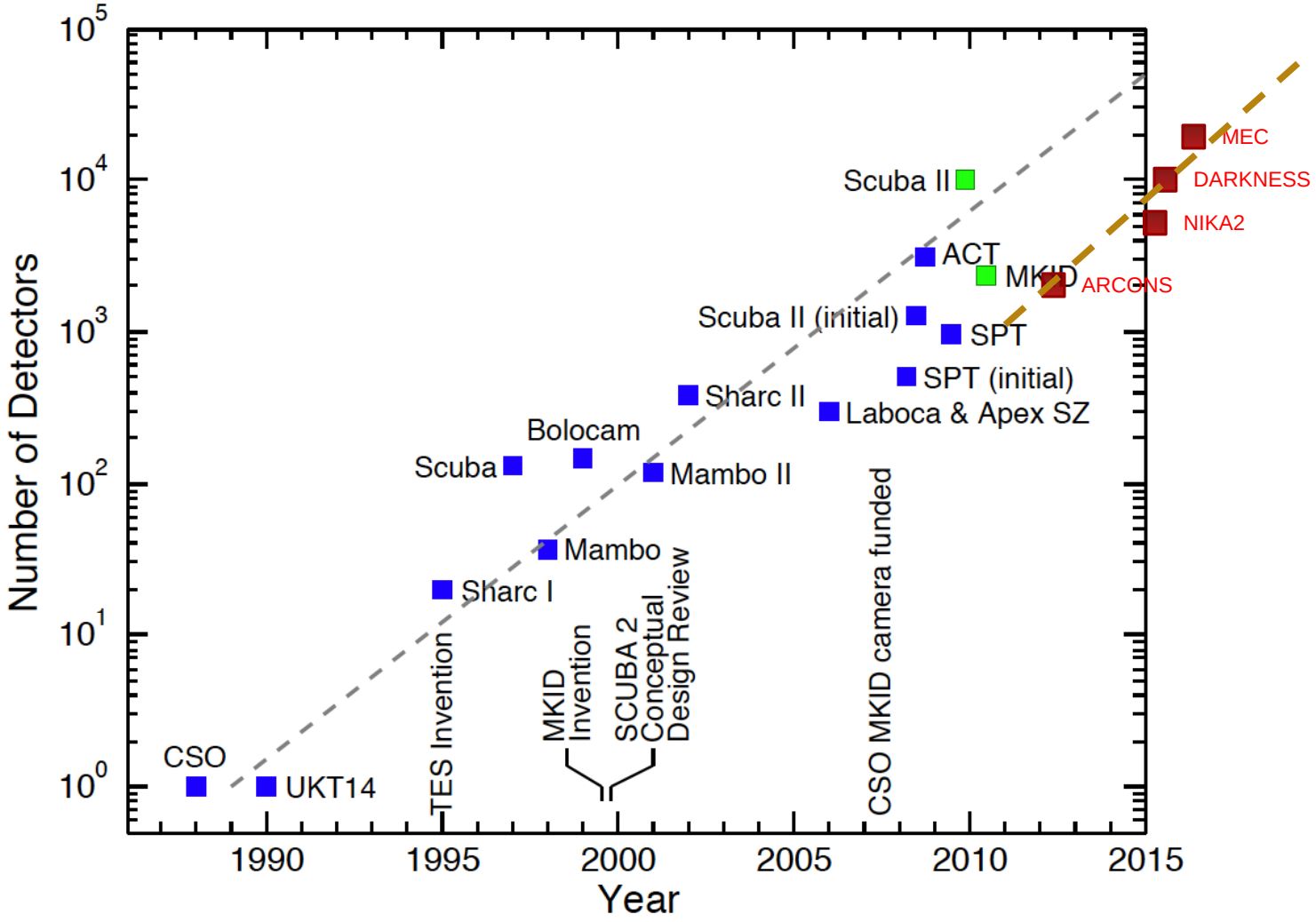


Figure adapted from RHEA/Feger et. al.

MKID Scaling

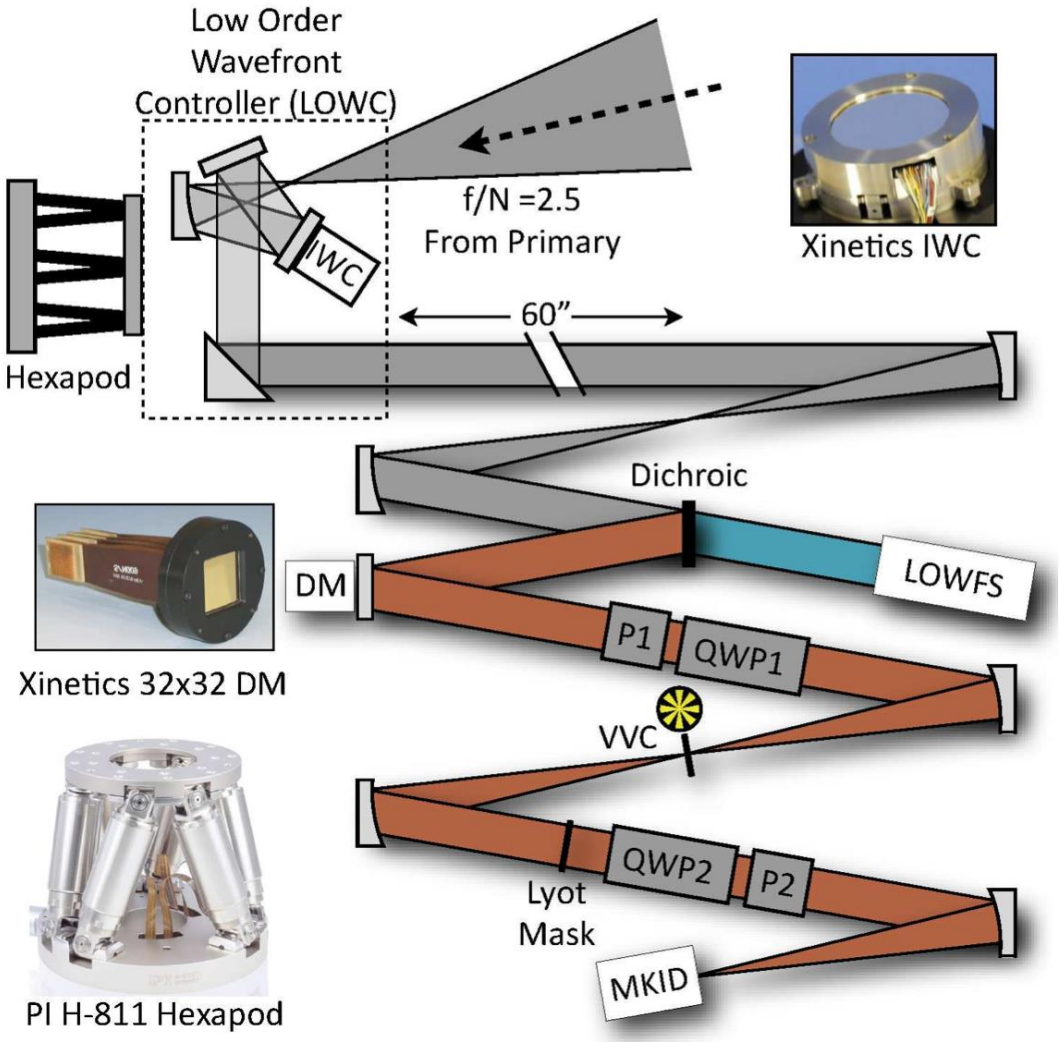


Original plot from J. Zmuidzinas

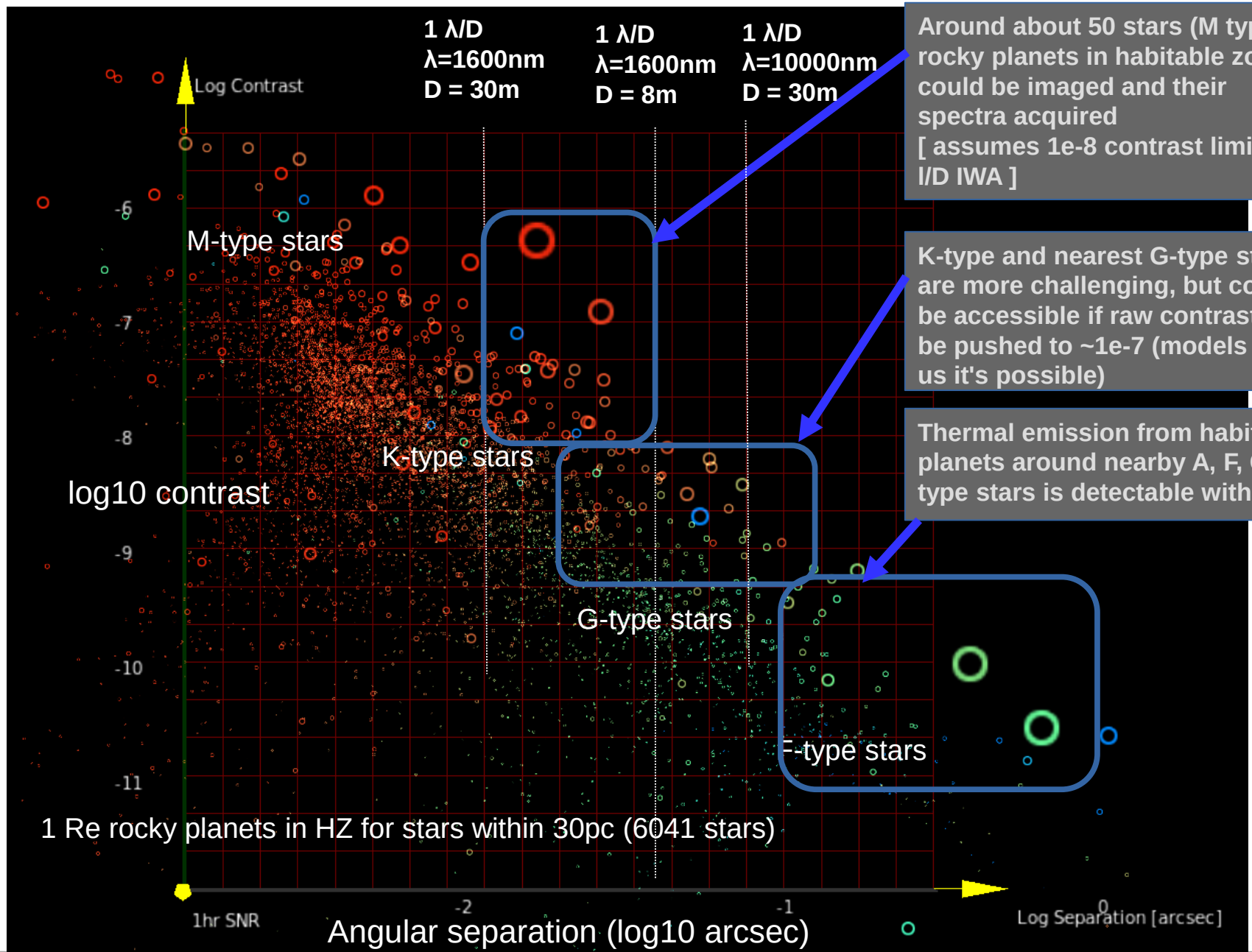
Backup Slides

PICTURE-C Balloon

- NASA Stratospheric Balloon Mission
  - 10 kpix MKID IFU
  - 550 nm
  - Vector Vortex Coronagraph
  - Search for Exoplanets and Exozodiacal disks
  - Flight demonstration for MKIDs and VV
  - Flight ~2019



Figures from O. Guyon

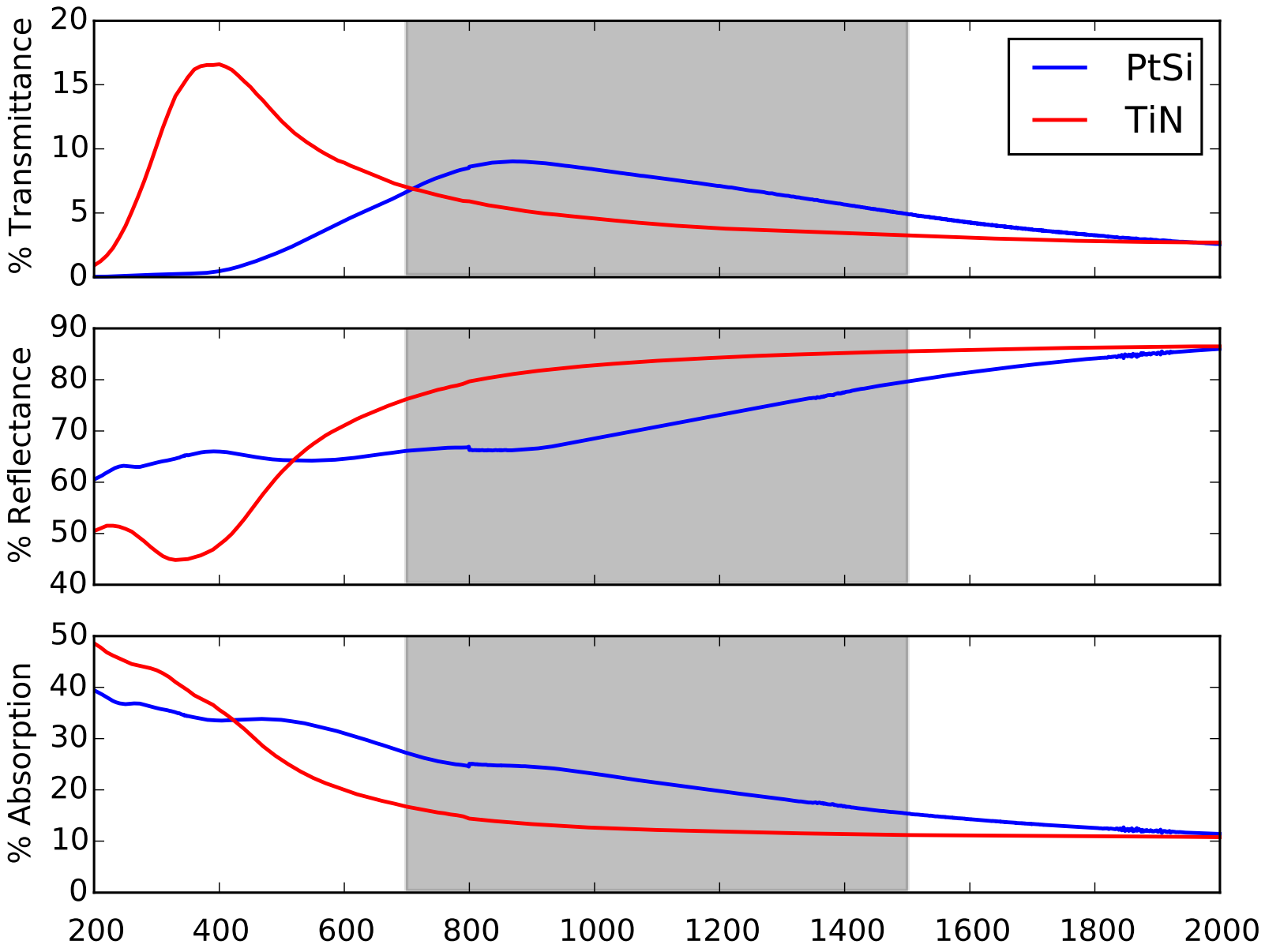


Around about 50 stars (M type), rocky planets in habitable zone could be imaged and their spectra acquired
[assumes 1e-8 contrast limit, 1 l/D IWA]

K-type and nearest G-type stars are more challenging, but could be accessible if raw contrast can be pushed to ~1e-7 (models tell us it's possible)

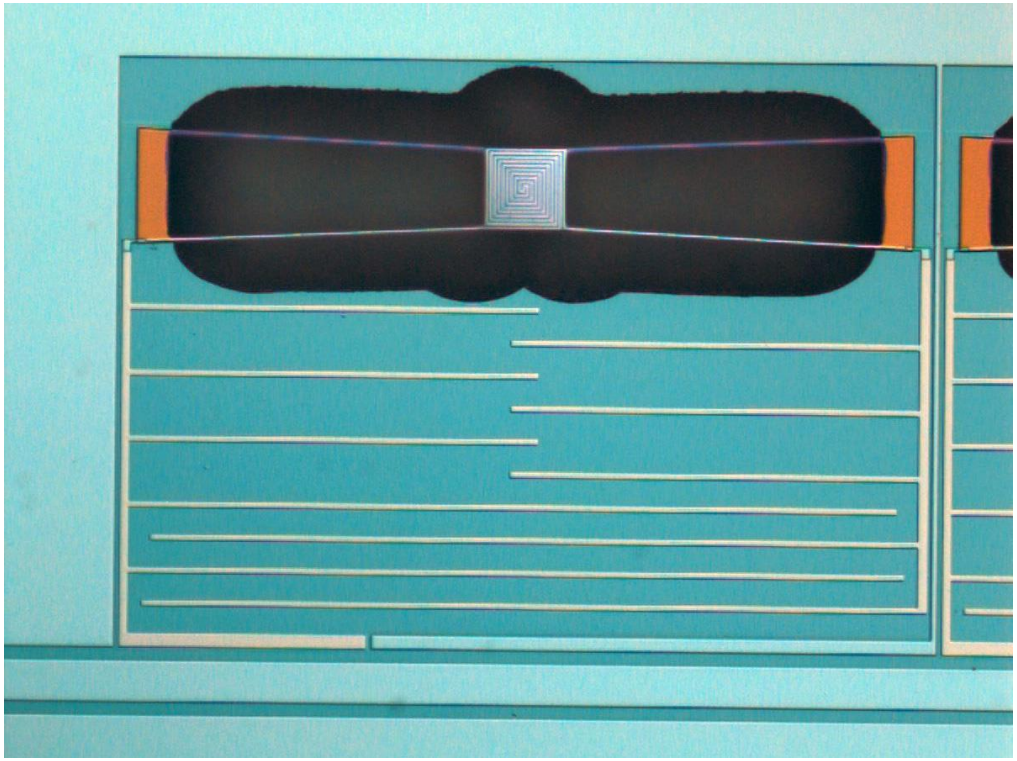
Thermal emission from habitable planets around nearby A, F, G type stars is detectable with ELTs

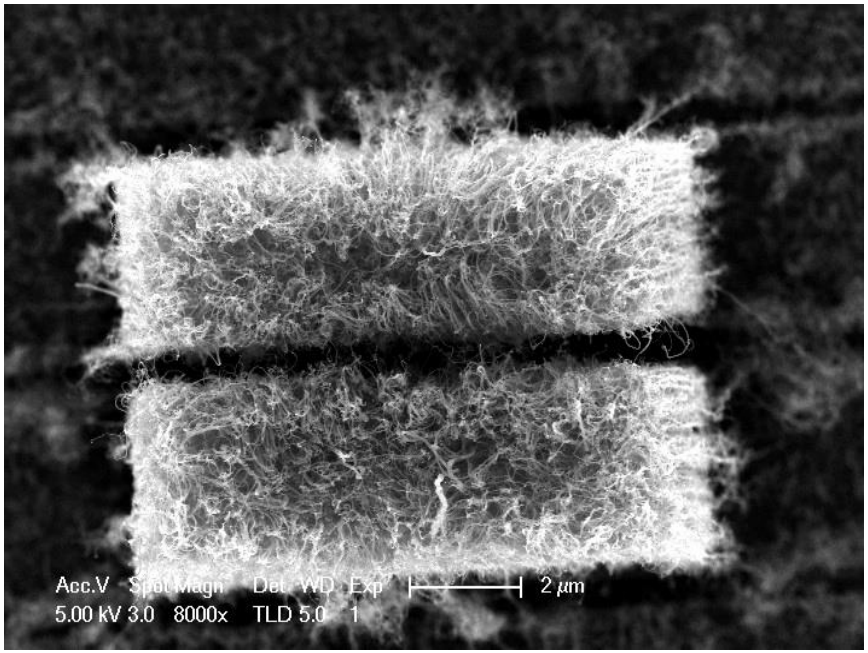
PtSi Quantum Efficiency



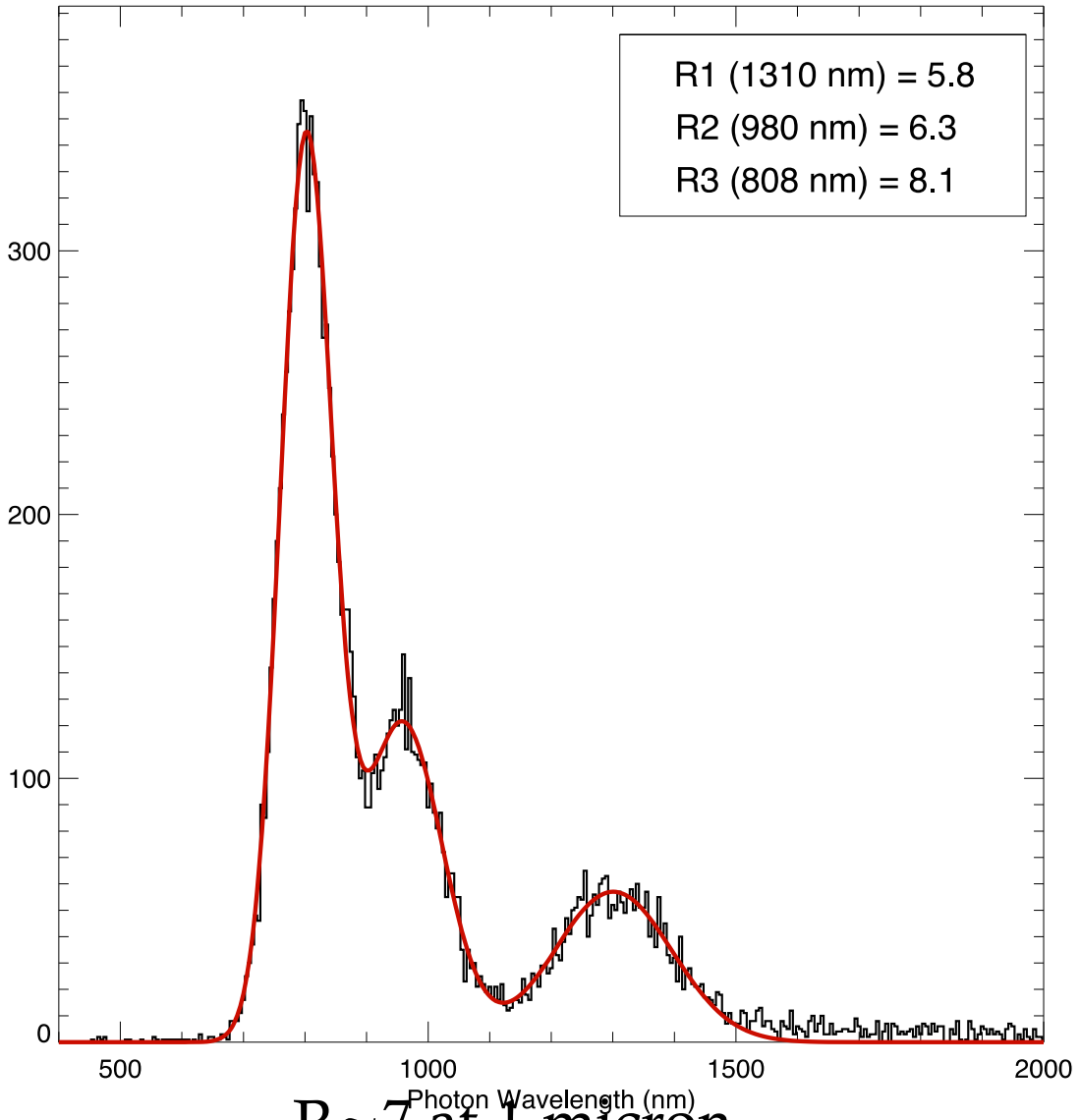
Quantum Efficiency

- VACNTs could get QE to >99%!
- TKID design shown below





PtSi

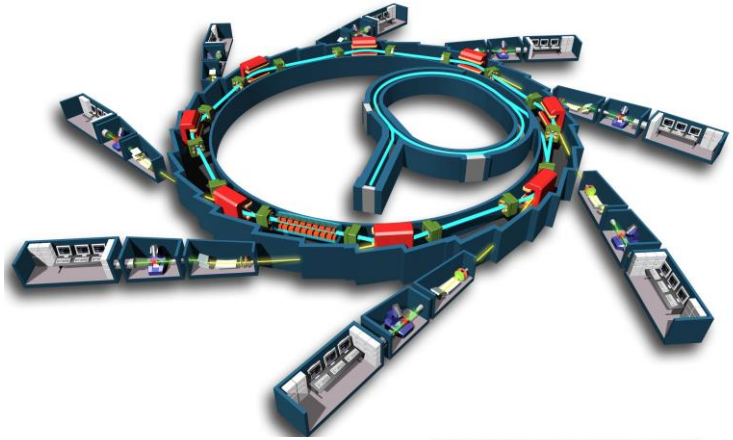


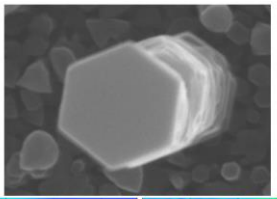
R~7 at 1 micron

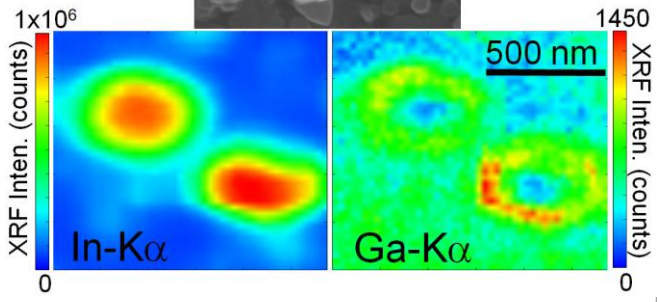
First Light, July 24 2016

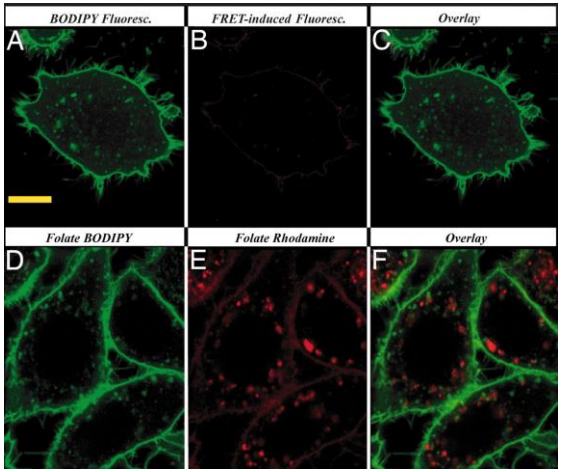
Other Applications

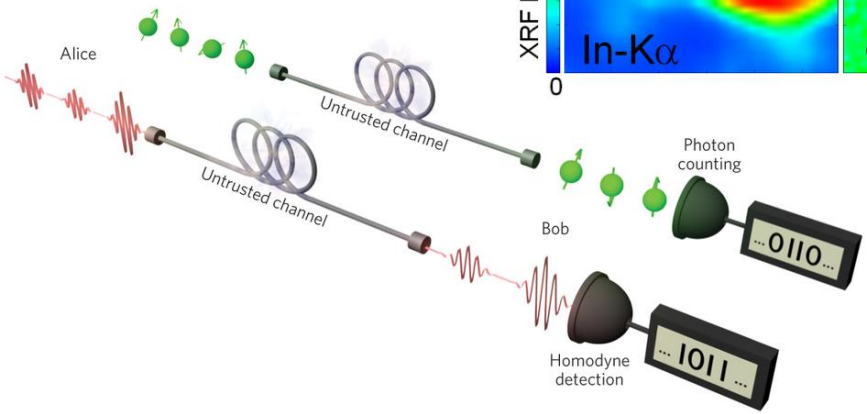
- There are a significant number of other potential applications:
  - Satellite-based reconnaissance
  - X-ray beam line studies
  - Semiconductor process debugging (XRF)
  - Laser communications
  - Quantum Key Distribution
  - Biological Imaging (FRET, etc.)
  - Fundamental Physics/Dark Matter
   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





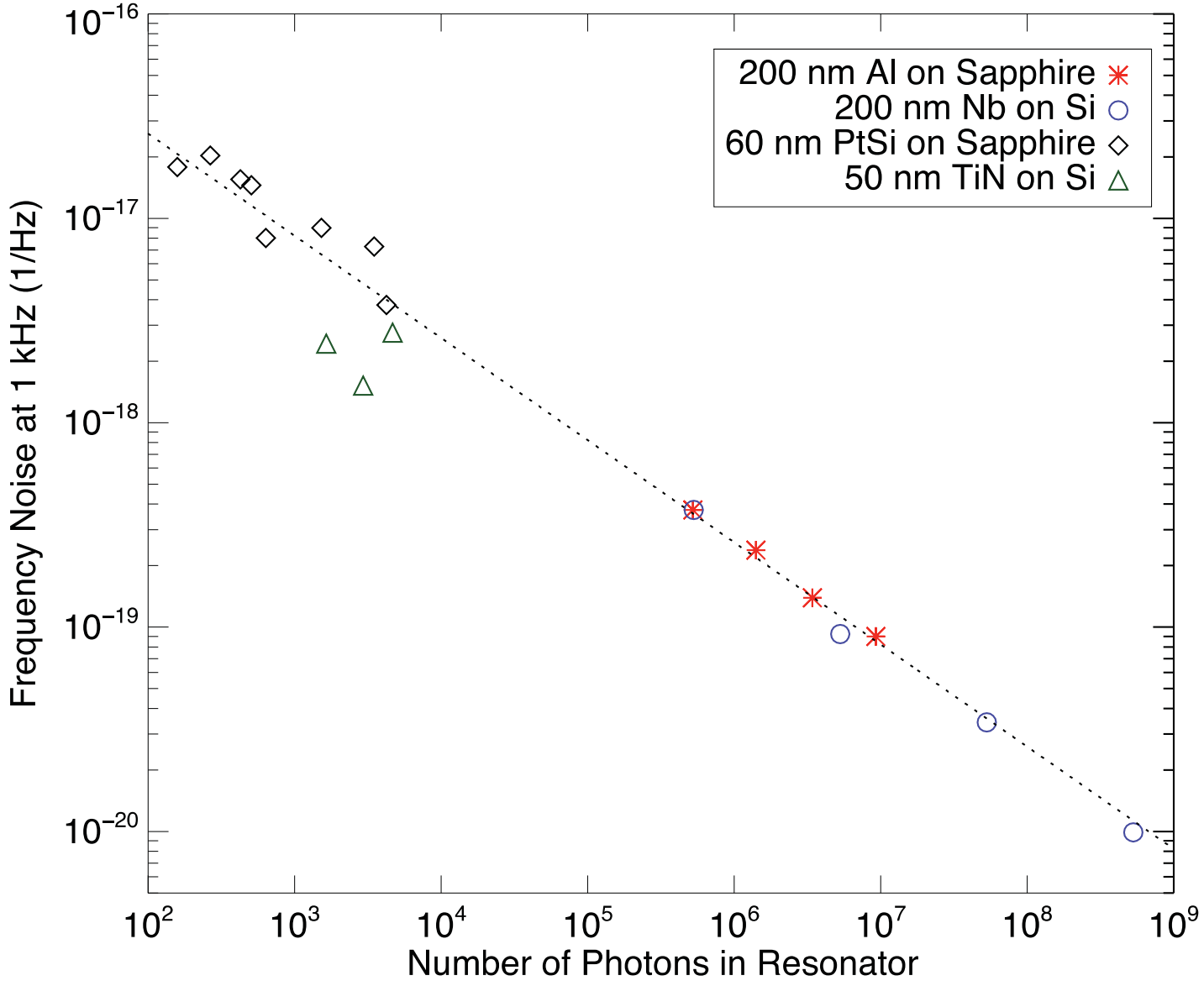






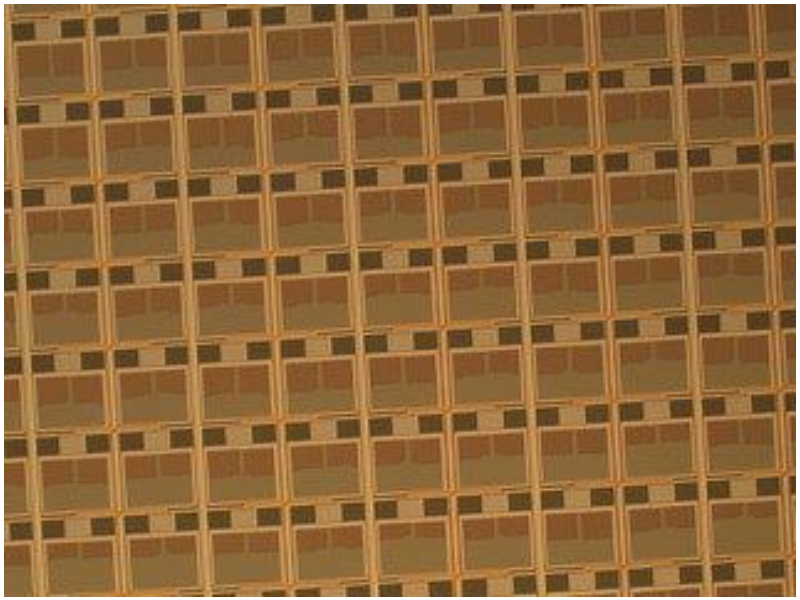
PtSi Noise

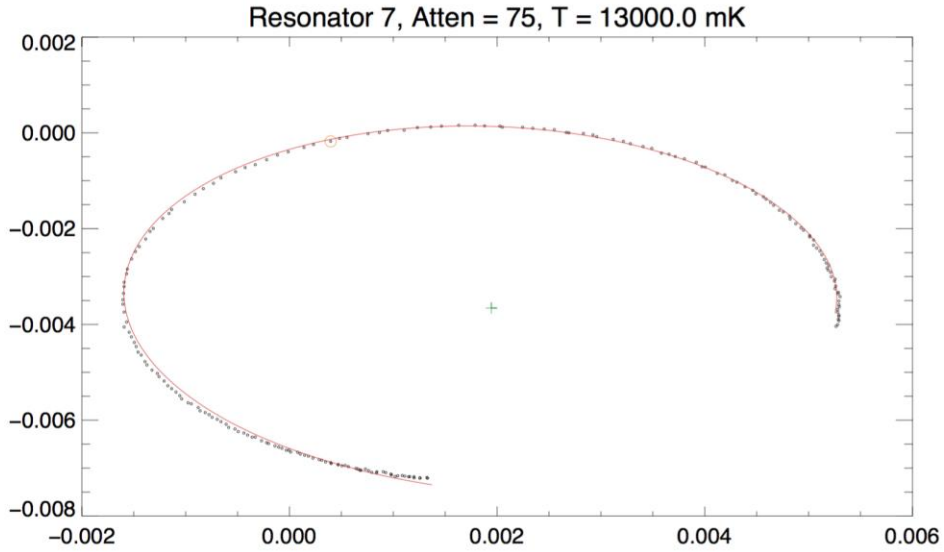
- Fractional Frequency noise of 3-2 CPW resonators

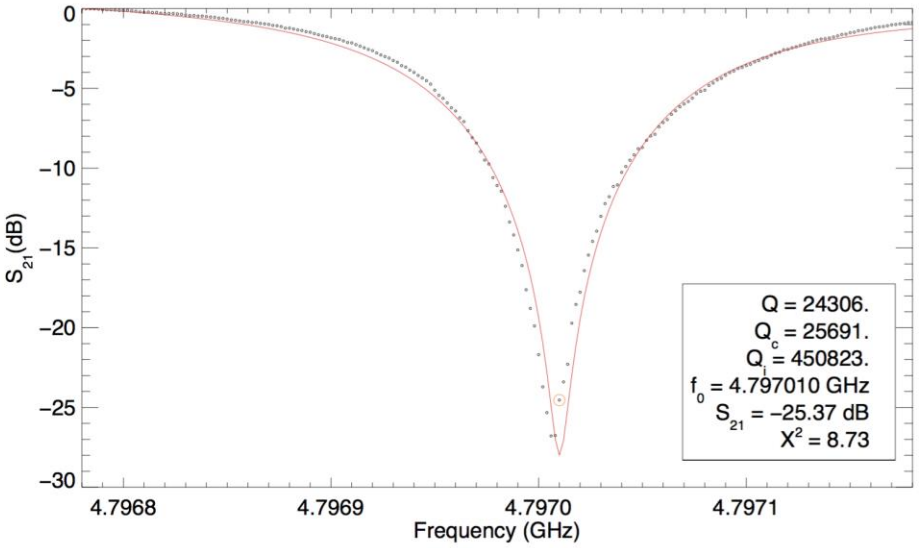


PtSi

- We are now making high Q resonators using PtSi on sapphire
  - Resistivity: 50 μΩ cm
  - T_c = 850 mK
  - We aim for 60 nm films with ~10 pH/sq inductance
  - Published in ApL
    - Szypryt *et al.* 2016

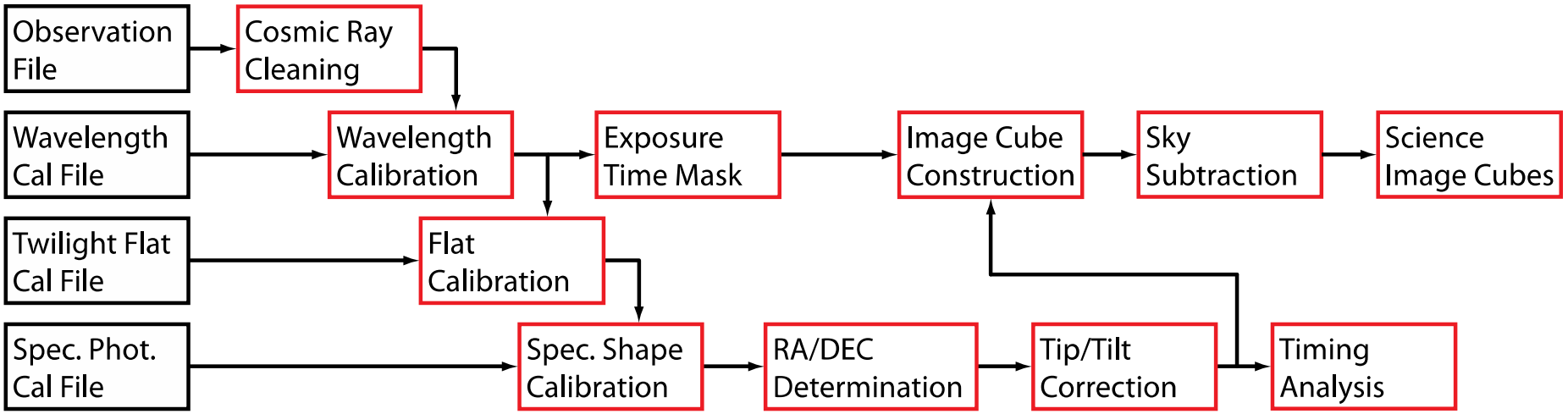


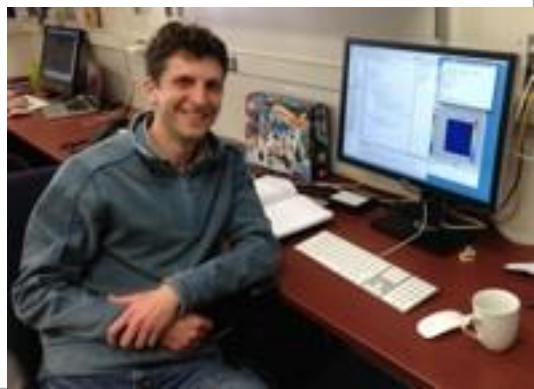




Data Pipeline

- 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





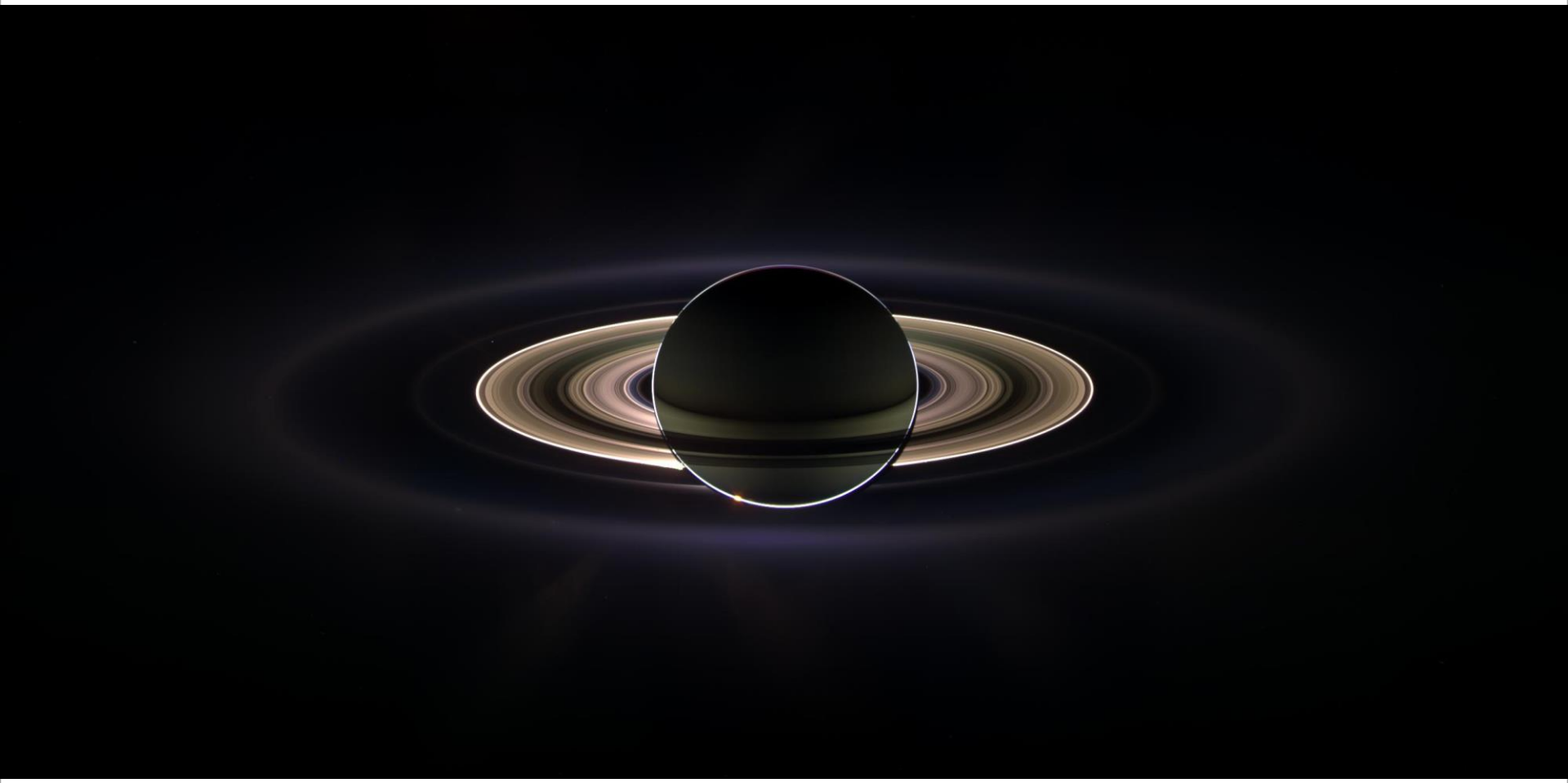
Survey of Projects

- Current Projects
  - [Ongoing UVOIR MKID Development]
  - [Ongoing X-ray TKID Development]
  - DARKNESS – Commissioned, now done 3 observing runs
  - MEC – Deploys to Subaru in the summer
  - PICTURE-C – Flies in 2019
  - MagAO-X + DARKNESS – Deploys in 2020

- Future Projects
  - KRAKENS – Awaiting MRI funding decision, deploys 2021
  - HRMOS – lab demo in progress
  - PSI – TMT Second Generation Instrument team organized
  - Giga-z – Working with Fermilab on concept

Exoplanet Direct Imaging

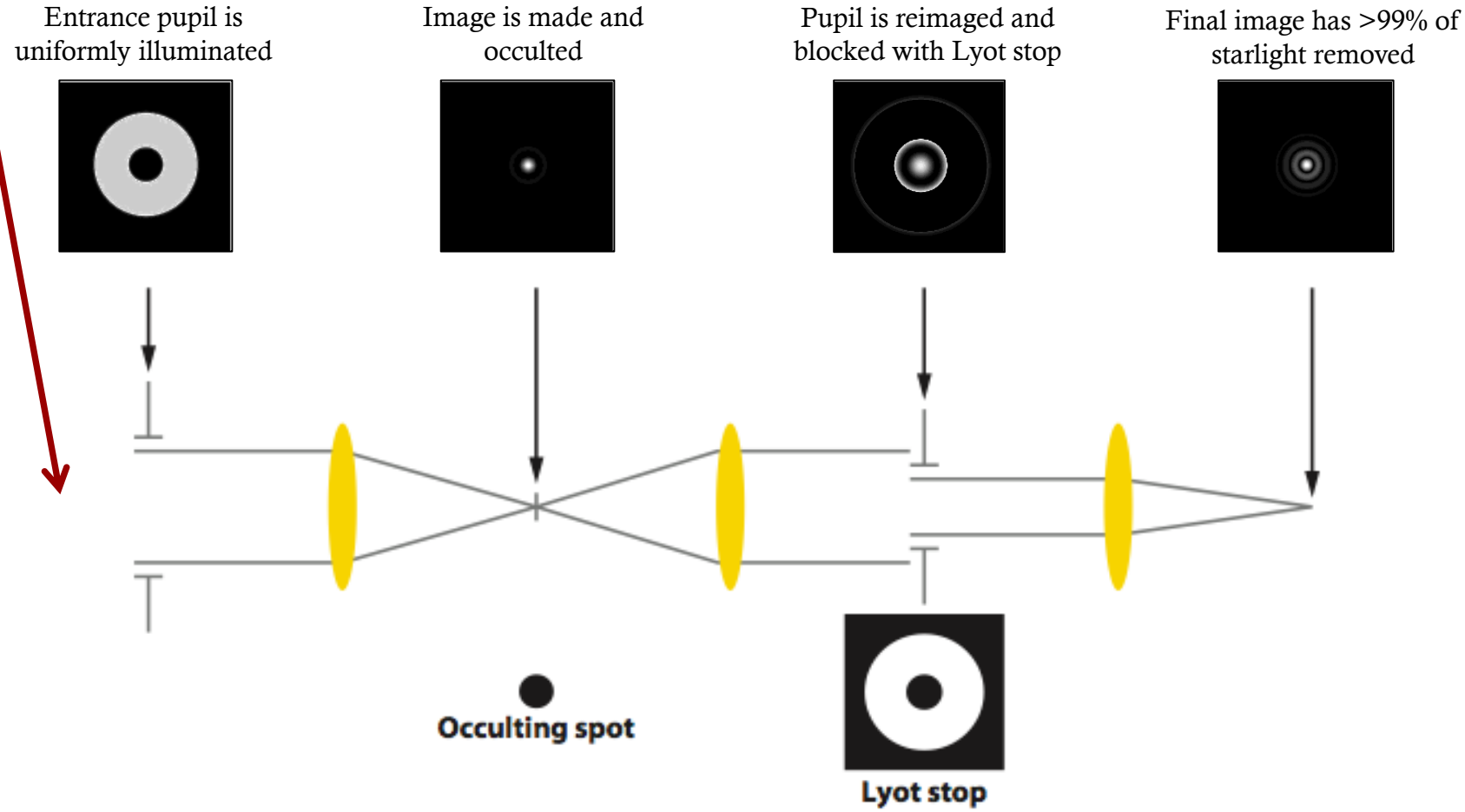
- Are we alone?



- Our best estimate is that 5-25% of stars (and maybe every M dwarf??) have a ~Earth radius planet in their habitable zone!
- Most likely one around the nearest star – Proxima Centauri b!

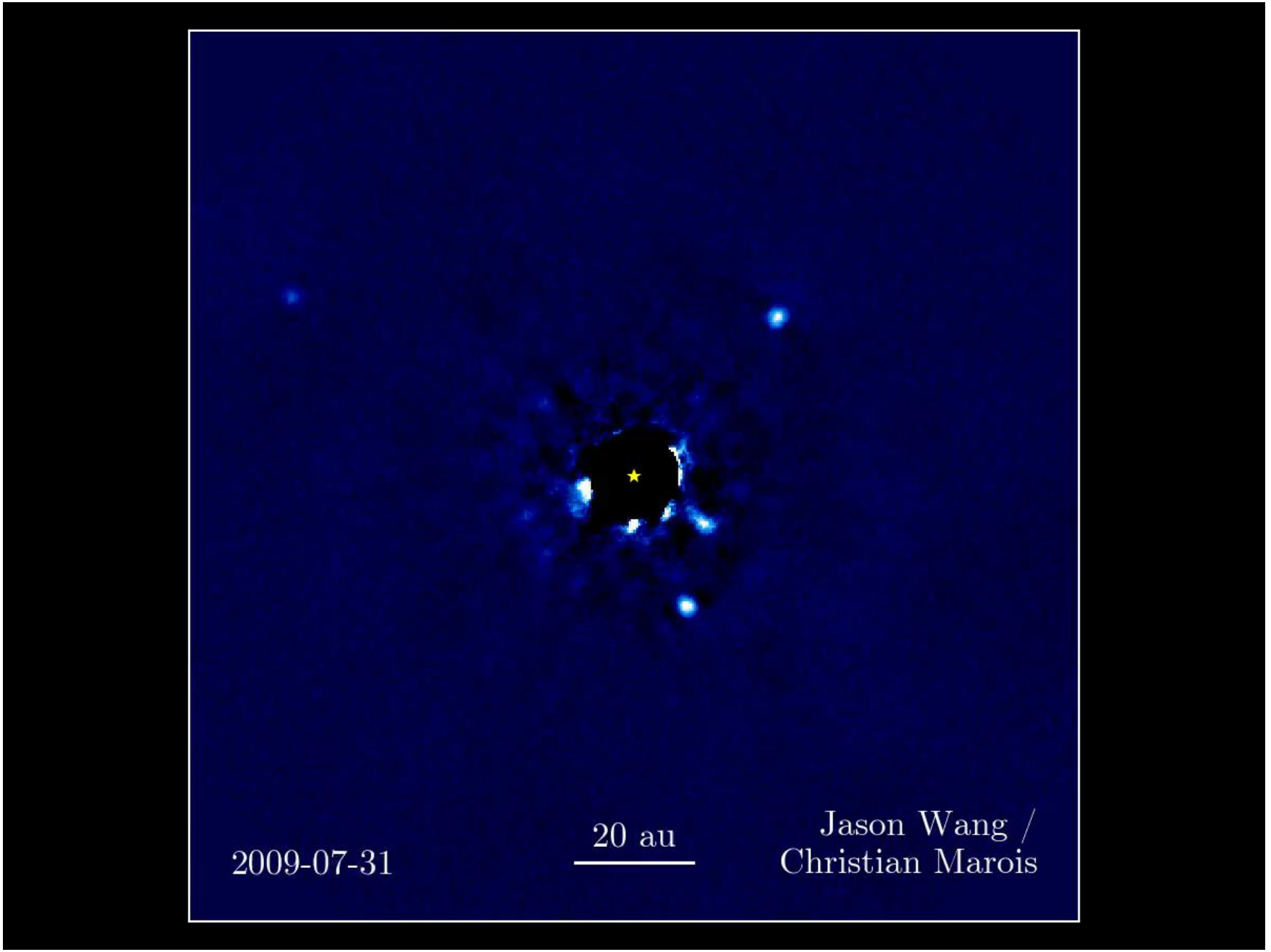
Coronagraphy

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

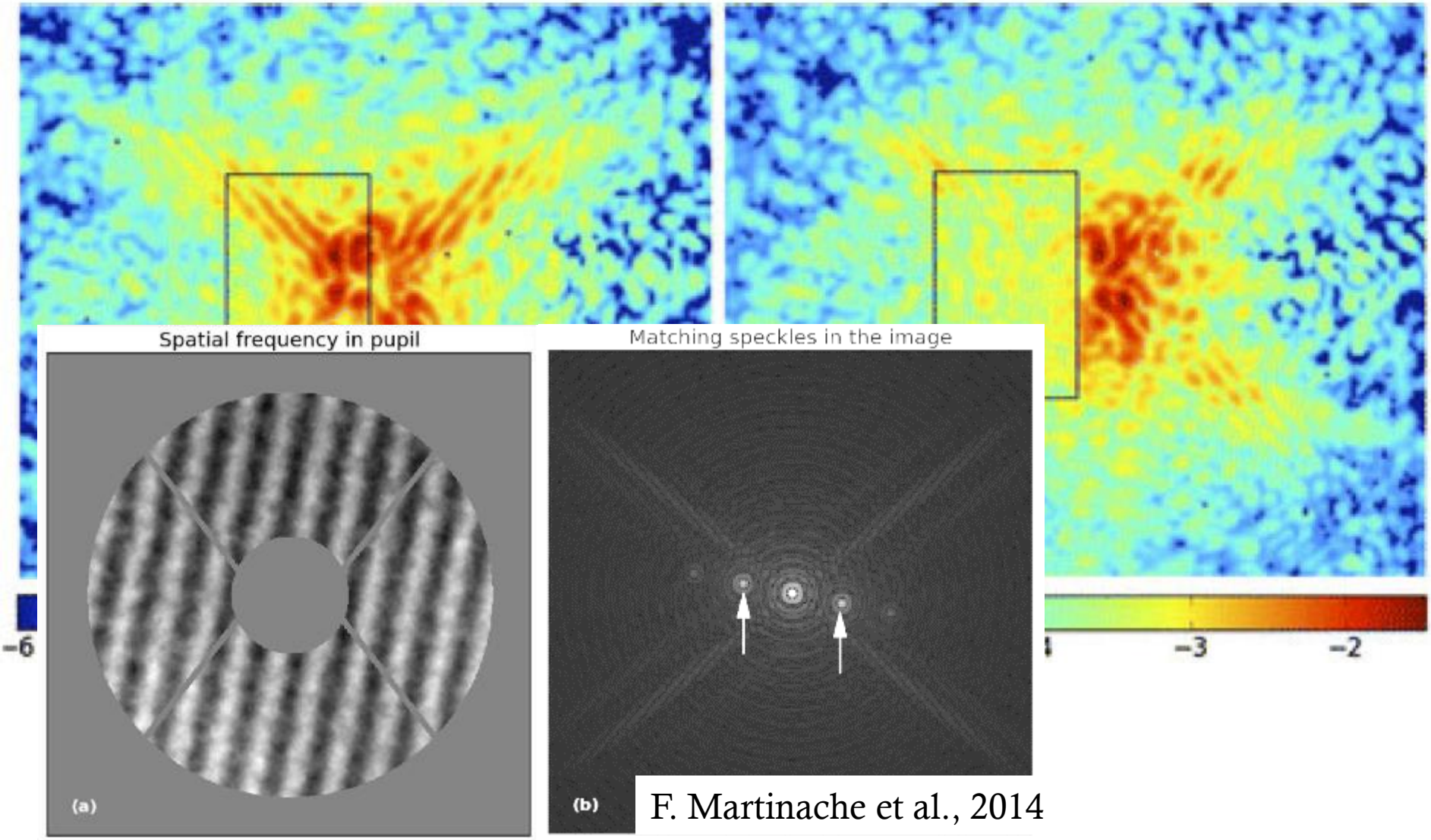


Adapted From Oppenheimer & Hinkley (2009), which adapted it from Sivaramakrishnan et al. (2001)

HR8799



Active Speckle Nulling



F. Martinache et al., 2014

F. Martinache et al., 2012