DARKNESS: The First Microwave Kinetic Inductance Detector Integral Field Spectrograph for Exoplanet Imaging

Seth R. Meeker

Jet Propulsion Laboratory, California Institute of Technology

March 27, 2019

Jet Propulsion Laboratory
California Institute of Technology

© 2019 California Institute of Technology. Government sponsorship acknowledged.

The DARKNESS Team

Mazin Lab @ UCSB:

Ben Mazin, Alex Walter, Clint Bockstiegel, Neelay Fruitwala, Gregoire Coiffard, Miguel Daal, Isabel Lipartito, Nick Zobrist, Jeb Bailey, Kristina Davis, Rupert Dodkins, Sarah Steiger, Noah Swimmer, Jenny Smith

JPL/IPAC: Mike Bottom, Chris Shelton, Gene Serabyn, Gautam Vasisht , Bruce Bumble, Julian van Eyken

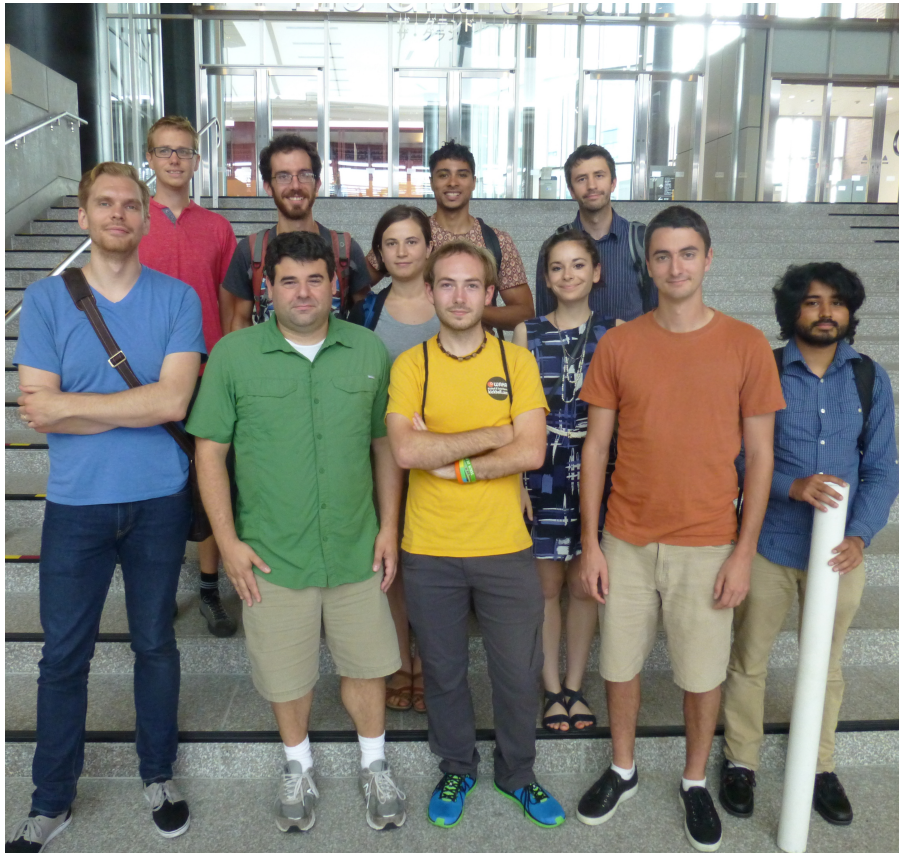
Caltech: Dimitri Mawet

NIST: Paul Szypryt

Dublin: Gerhard Ulbricht

Durham: Kieran O'Brien

Fermilab: Juan Estrada, Gustavo Cancelo, Neal Turner



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

UCSB

Jet Propulsion Laboratory
California Institute of Technology

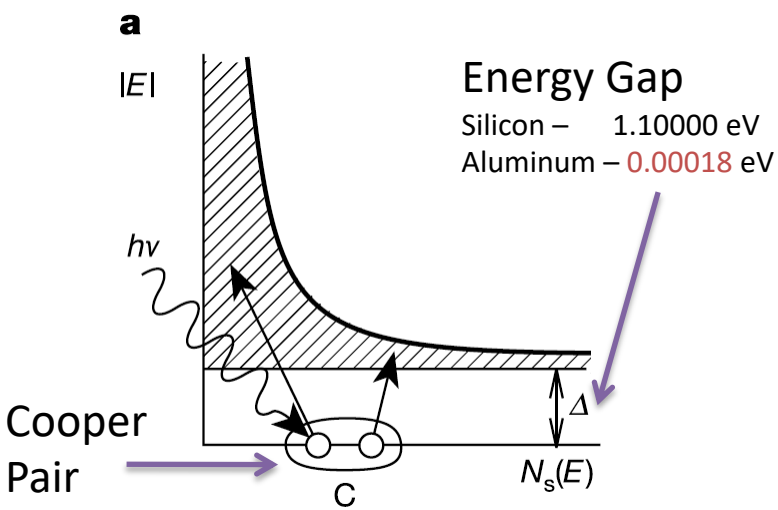
Outline

- Microwave Kinetic Inductance Detectors
  - Principle of Operation
  - A brief history
  - ARCONS
- Exoplanet Imaging
  - Speckle Suppression at fast frame-rates
- DARKNESS
  - Design
  - Early results

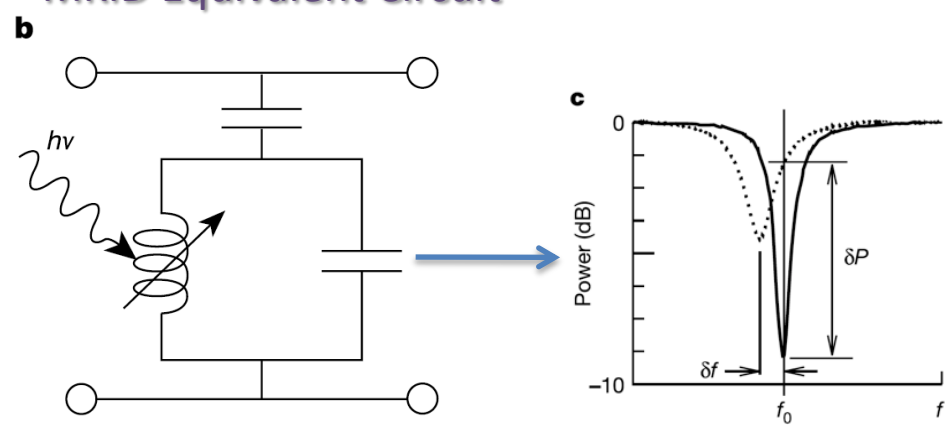
Microwave Kinetic Inductance Detectors

- Superconducting detector technology, operates at ~100mK
  - Originally conceived at Caltech/JPL for sub-millimeter and X-ray applications
  - Developed at UCSB for UV, optical, and near-IR astronomy

- Single photon counting with ~microsecond timing
- Energy resolving (R~10) with no dispersive element
- Continuously read-out with no analogue to read-noise or dark current
- Excellent cosmic ray rejection



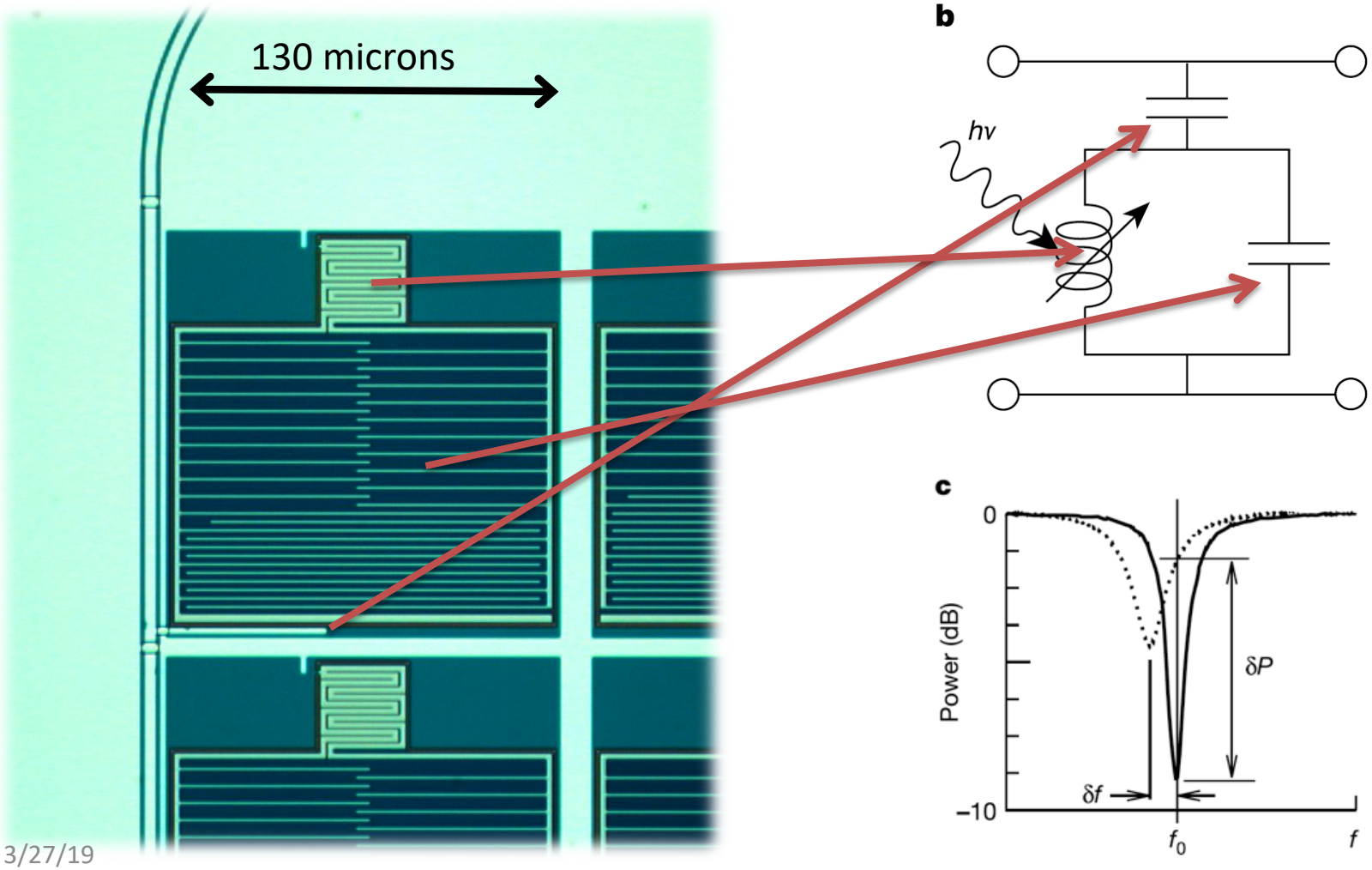
MKID Equivalent Circuit



Inductor is a Superconductor!

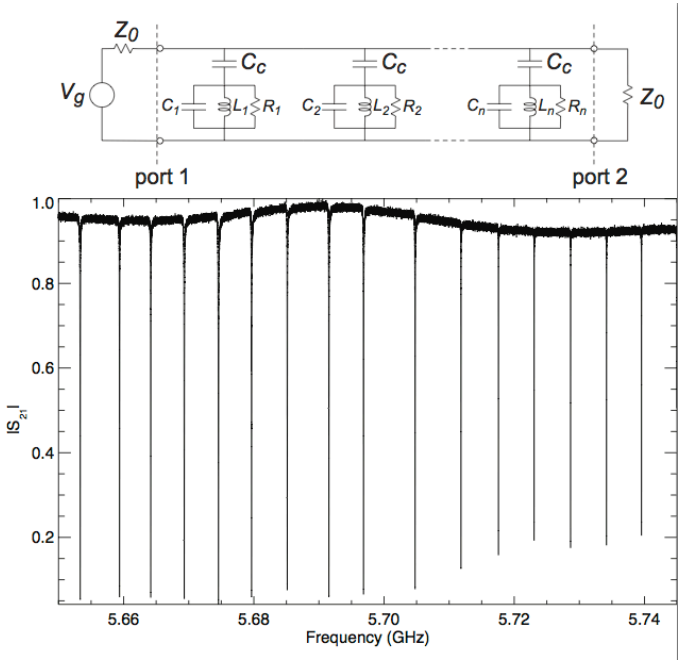
MKID Anatomy

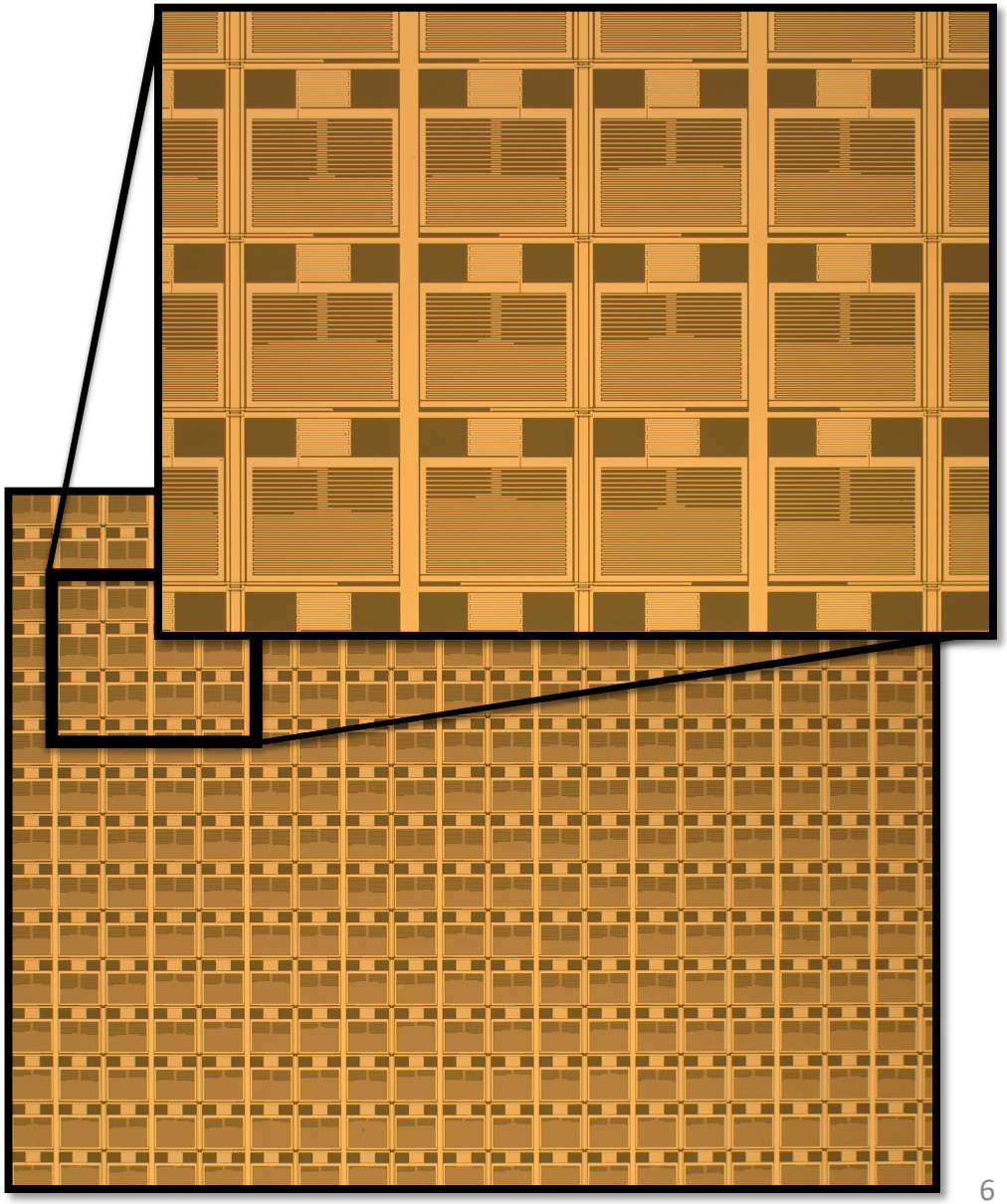
- Every pixel is a microresonator with a photo-sensitive inductor



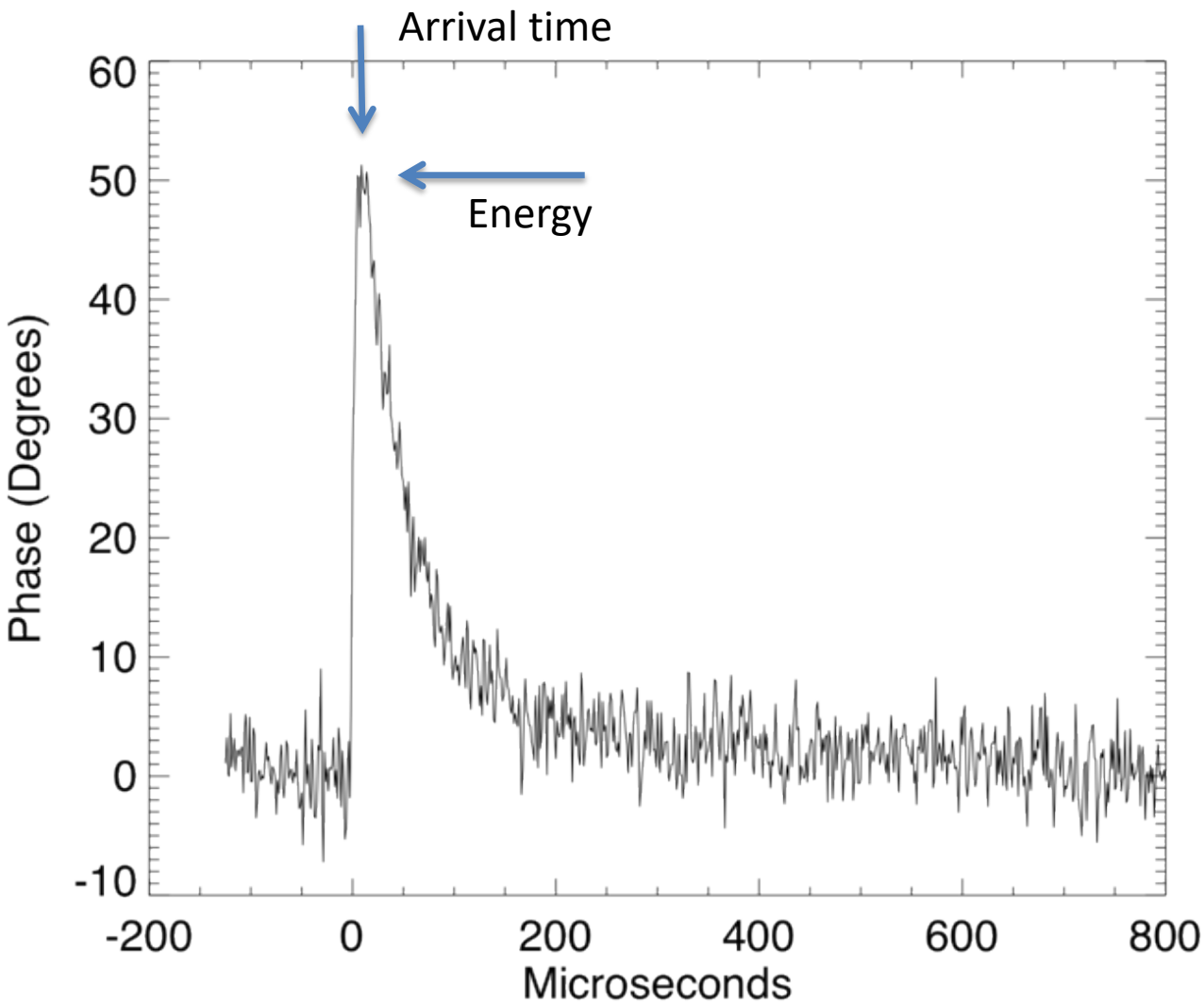
Kilo-pixel Arrays

Frequency Domain Multiplexed



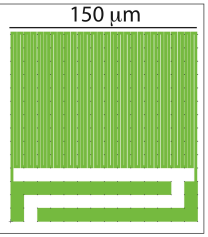


A Photon "Pulse"



UVOIR MKID Timeline

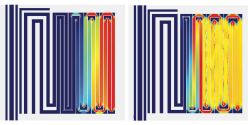
OLE1- FIRST TiN OLE MKIDS Suffered from bad crosstalk



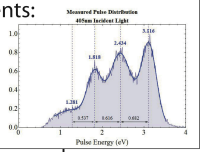
SCI1 - First OLE MKID array 32x32 Pixels - High Crosstalk between 2 separate feedines

OLE6 - First High Q_i Multi-layer Device Using SiO2 Protect over TiN

OLE7- Optimized Inductor Tapering - More uniform response

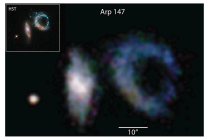


OLE8-11 - Thicker TiN (60 nm) Removed Substrate events:



SCI3 - 44x46 Pixel OLE11 Array w/Gold on Nb ground layer for improved thermalization Extremely B-field sensitive

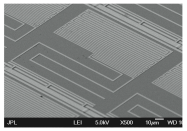
PALOMAR - DECEMBER, 2012 SCI4 ON SKY!



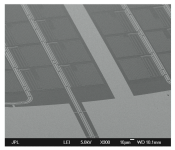
2009 — 2010 — 2011 — 2012 — 2013

OLE4 - New Inductor Geometry Improves inter-pixel Crosstalk

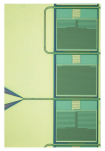
OLE5- New Feedline/ Coupling Design More uniform coupling Q (Q_c)



SCI2 - Center Ground strap fixes crosstalk.

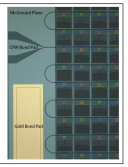


PALOMAR - JULY, 2011 FIRST OLE MKIDS ON SKY!

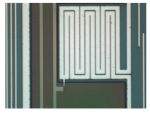


LICK - SEPTEMBER, 2012 SCI3 ON SKY!

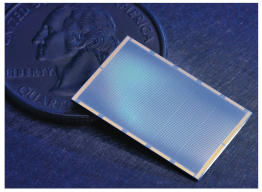
SCI4 - First MKIDs to produce astronomical science!



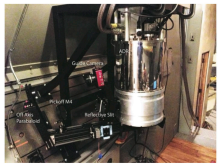
SCI5 - Grounding strip added at inductor virtual ground. New process developed to preserve multilayer TiN films.



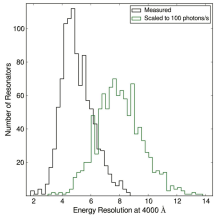
D1 - 10,000 Pixel near-IR optimized array for DARKNESS

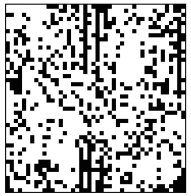


ARCONS paper published in PASP
Mazin et al 2013



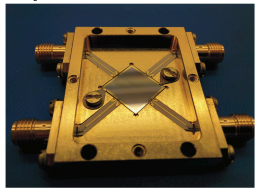
SCI4 PERFORMANCE





~ 70% Pixel Yield

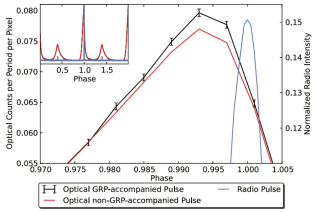
PALOMAR - SEPT & OCT, 2014 SCI6 ON SKY!



2013 — 2014 — 2015

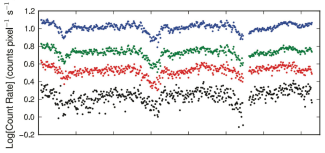
First MKID Astronomy Published

Strader et al. 2013.
Detected enhanced optical emission from Crab Pulsar during giant radio pulses using ARCONS'Palomar 2012 data.

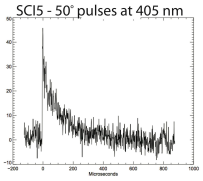


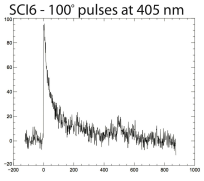
PALOMAR DEC, 2013 SCI5 ON SKY! (BAD WEATHER)

More MKID Astronomy Published.
Szypryt et al. 2014. Orbital expansion of AM CVn system measured with ARCONS in Palomar 2012 data.

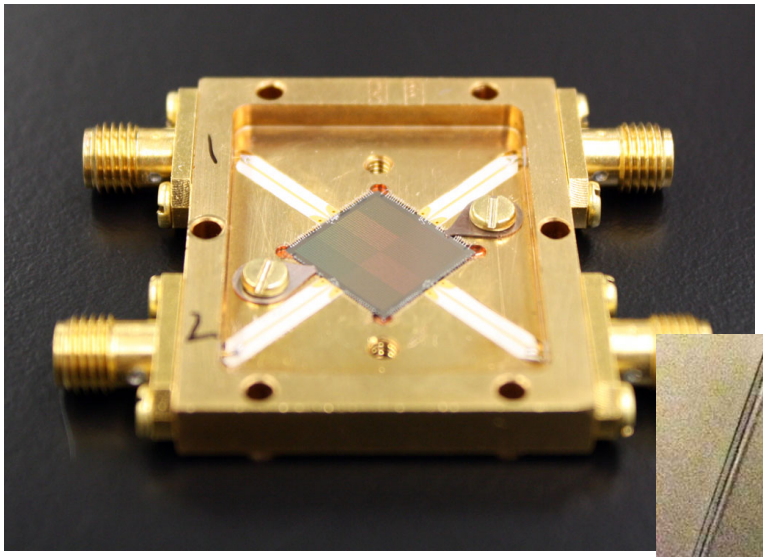


SCI6 - Modified OLE11 design for ultra-high optical sensitivity.



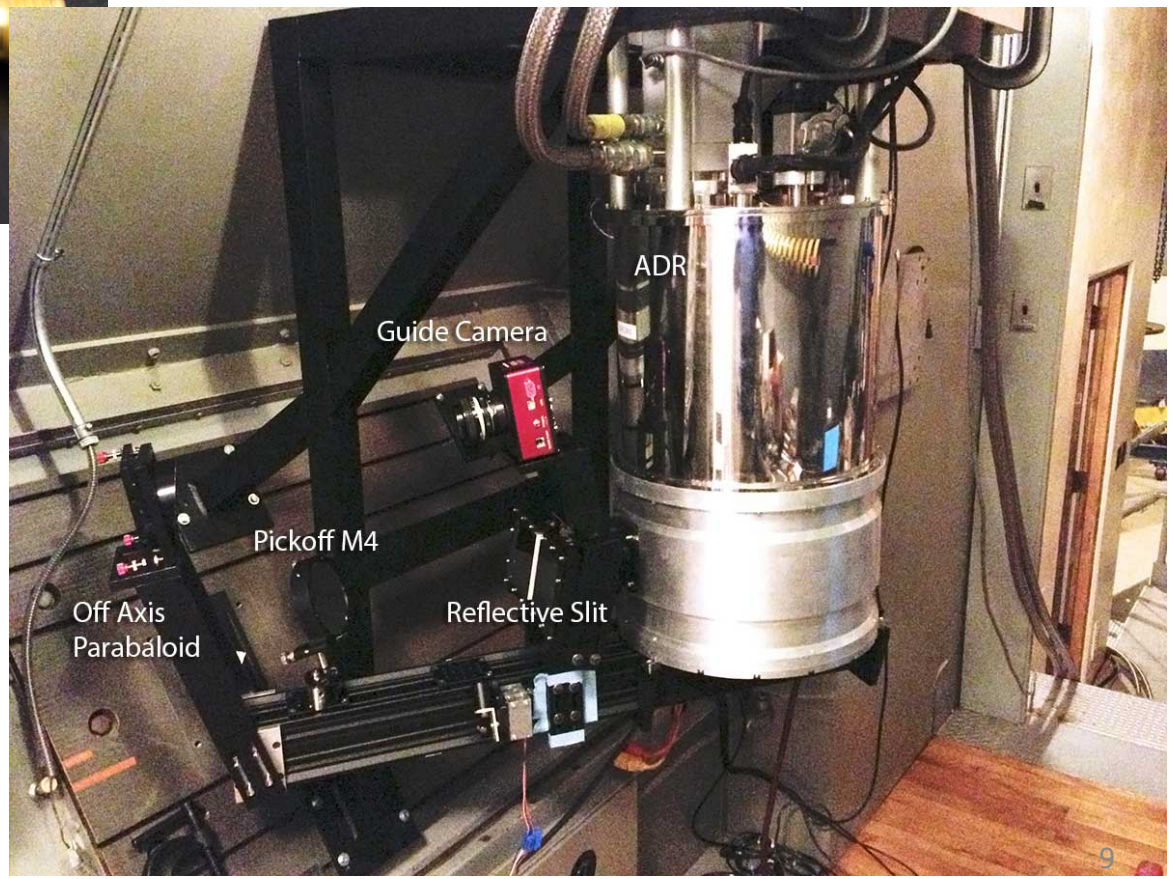


ARCONS



2024 Pixel MKID array.

0.4 to 1.1 microns, R~8 energy resolution.

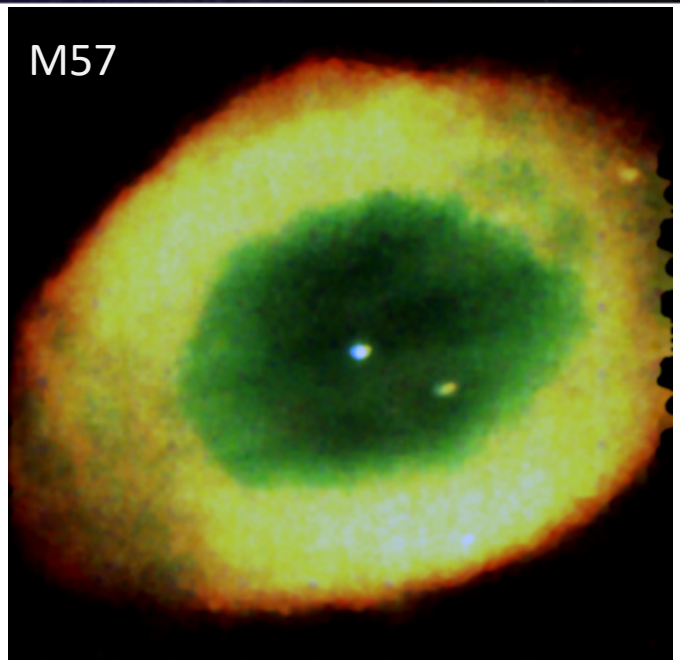


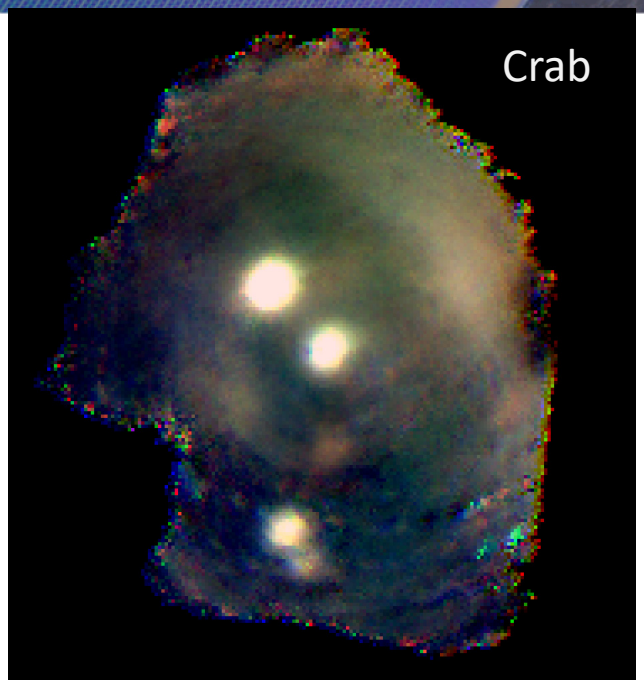
Adiabatic Demagnetization Refrigerator for 100 mK operation.

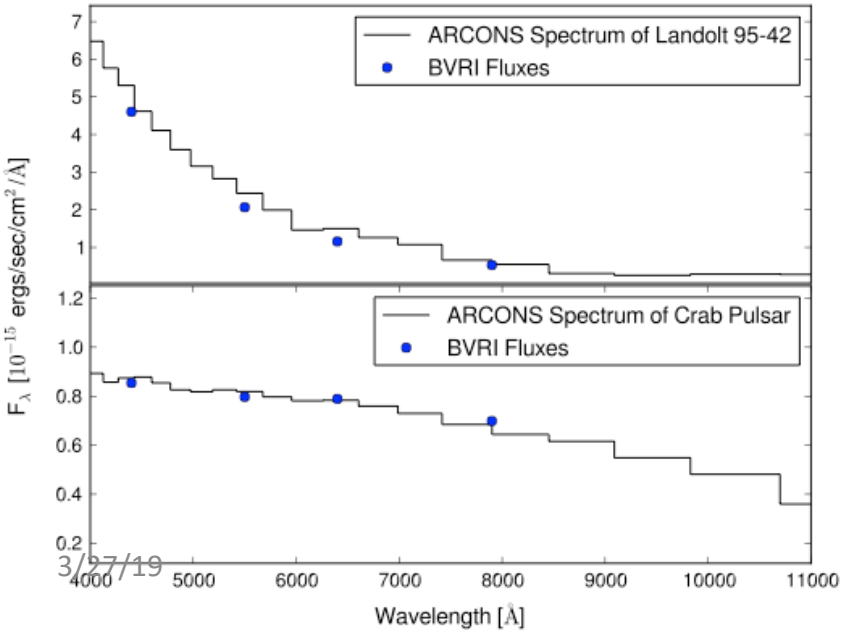
Seeing limited for Coude focus at Palomar and Lick.

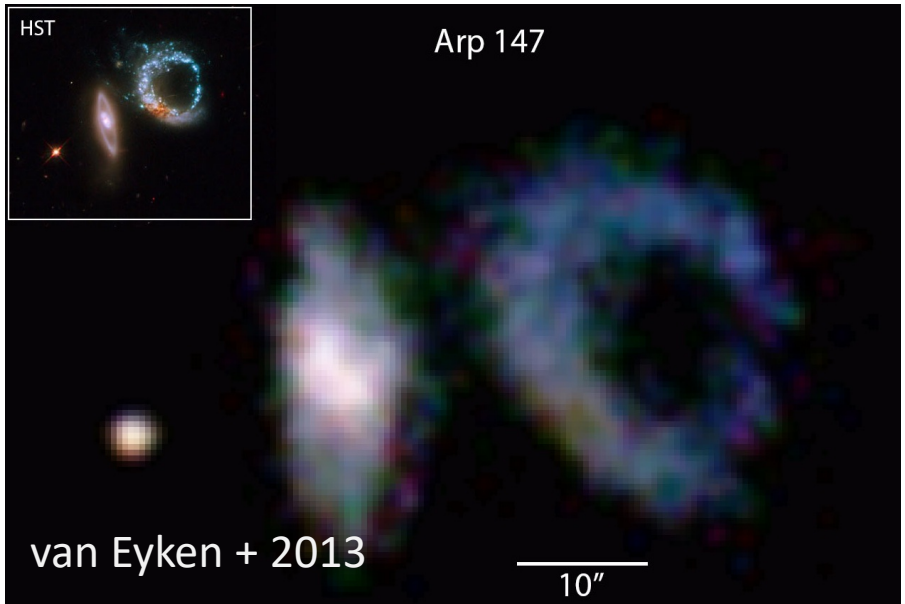
Mazin+2012, 2013

ARCONS Results

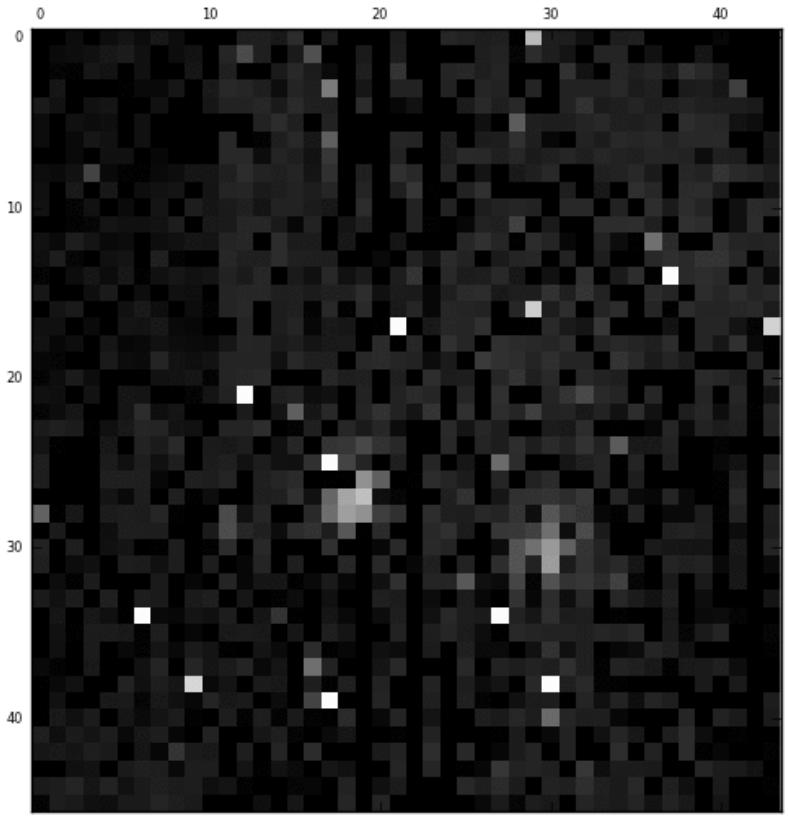


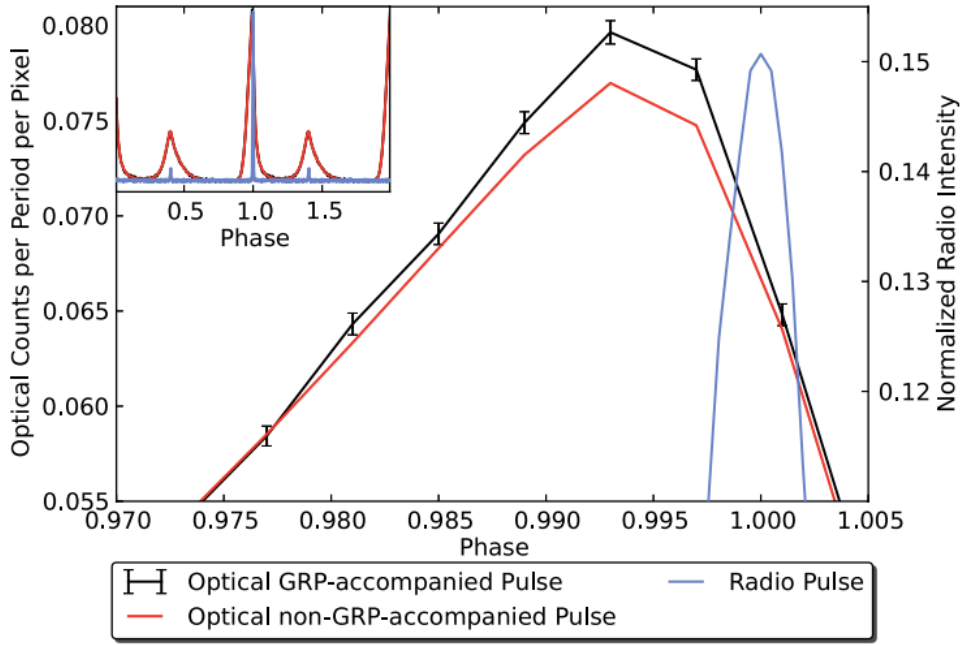






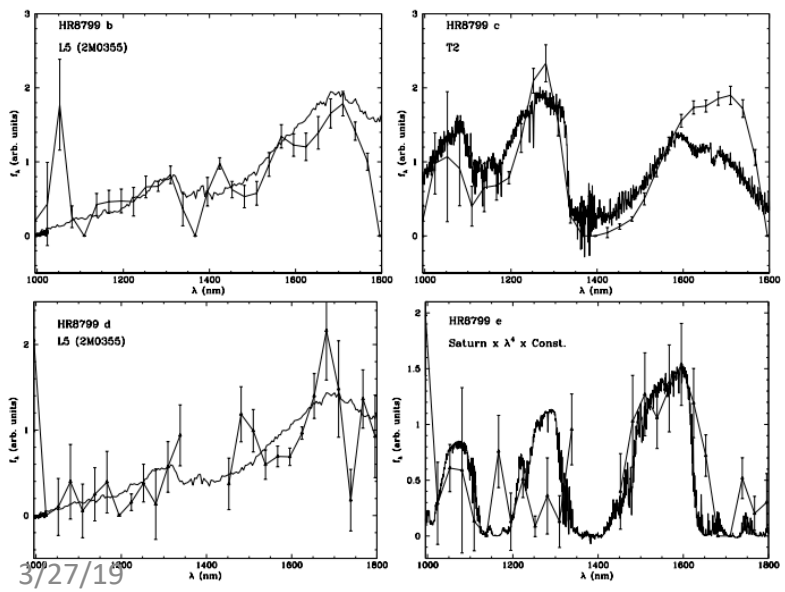
Crab Pulsar





Strader+2012

Direct Exoplanet Imaging



HR8799 discovery paper (2008) cited >**1449** times according to Google Scholar

- **With Integral Field Spectrograph, obtain spectrum at every spatial element**

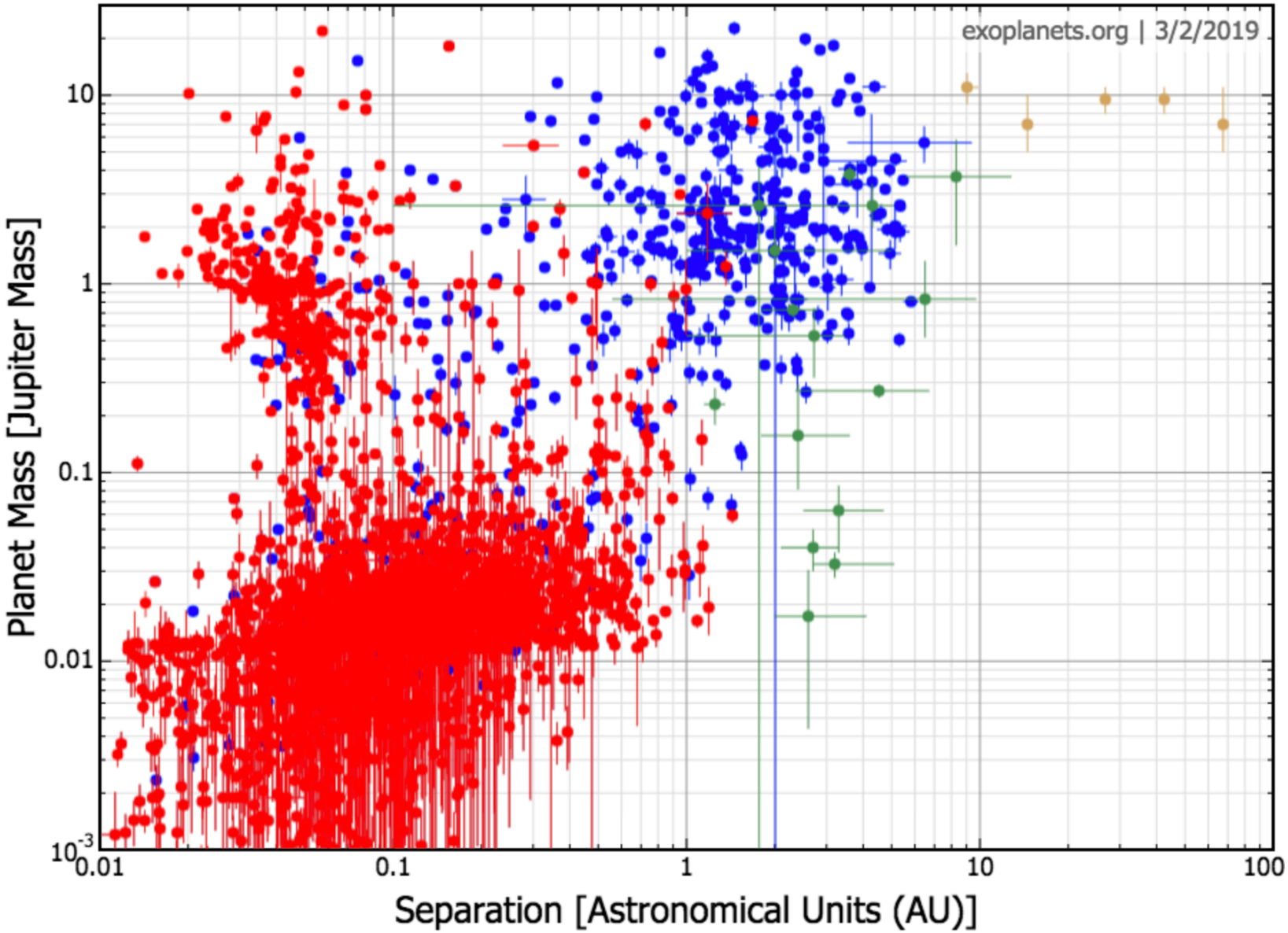
- Atmospheric composition, non-equilibrium chemistry in exoplanet atmospheres.

- Formation and migration history. Formation mechanisms.

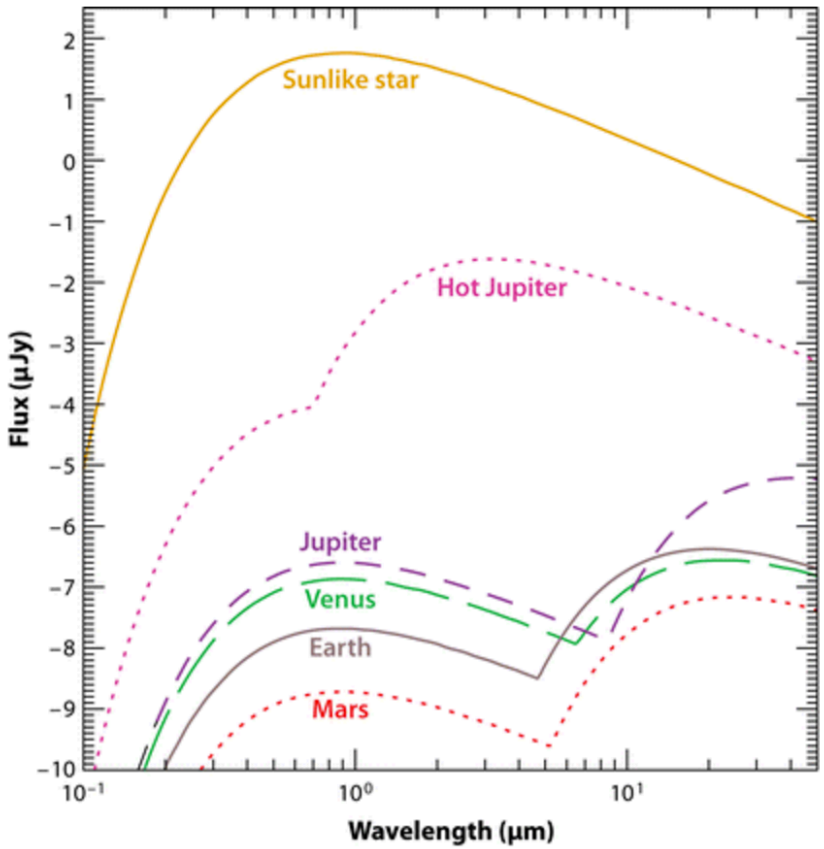
The ultimate goal: biosignature characterization of terrestrial planets

Figure credit: Oppenheimer et al. 2013

Direct Exoplanet Imaging

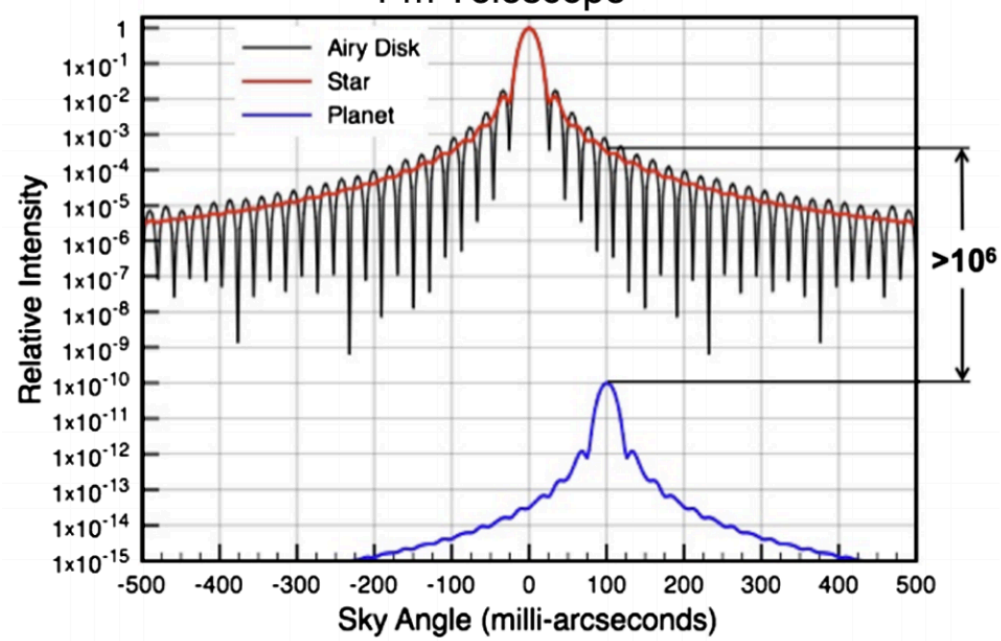


The High Contrast Challenge



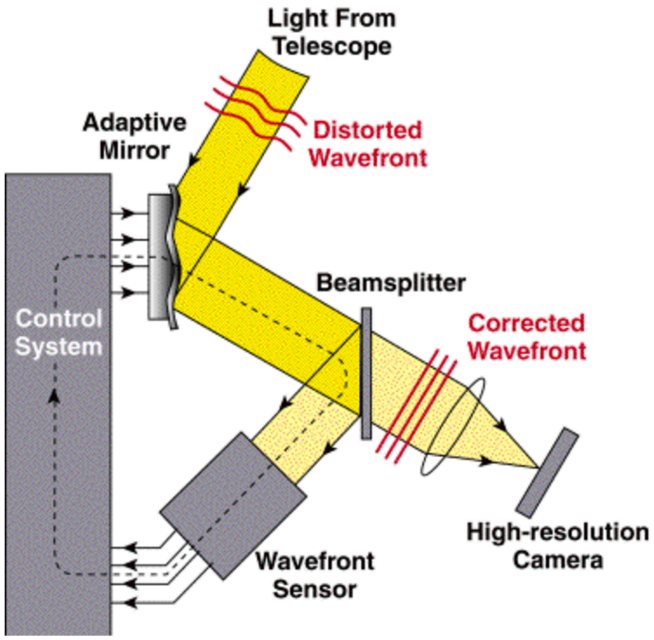
Seager & Deming (2010)

"Perfect"
4-m Telescope



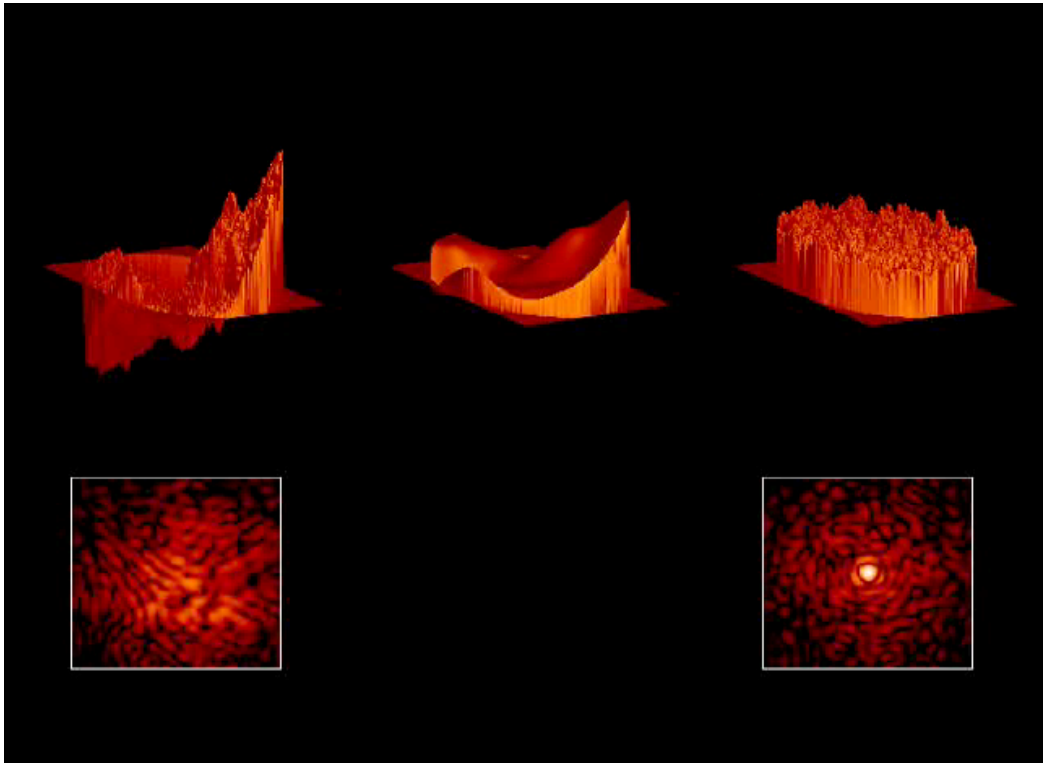
Lyon & Clampin (2012)

Extreme Adaptive Optics (XAO)

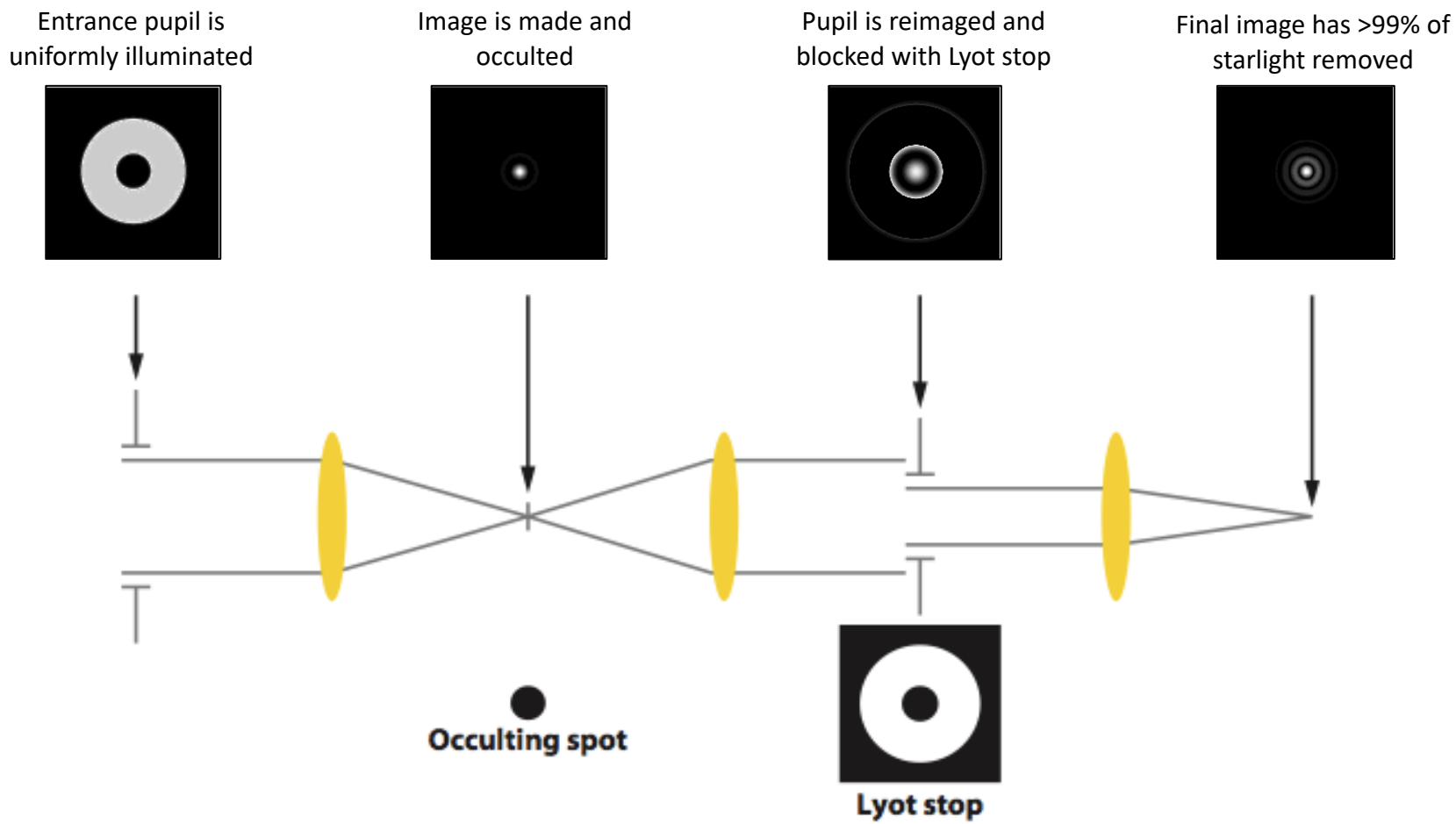


c.o. lyot.org
& Claire Max

c.o. lyot.org &
Rebecca
Oppenheimer

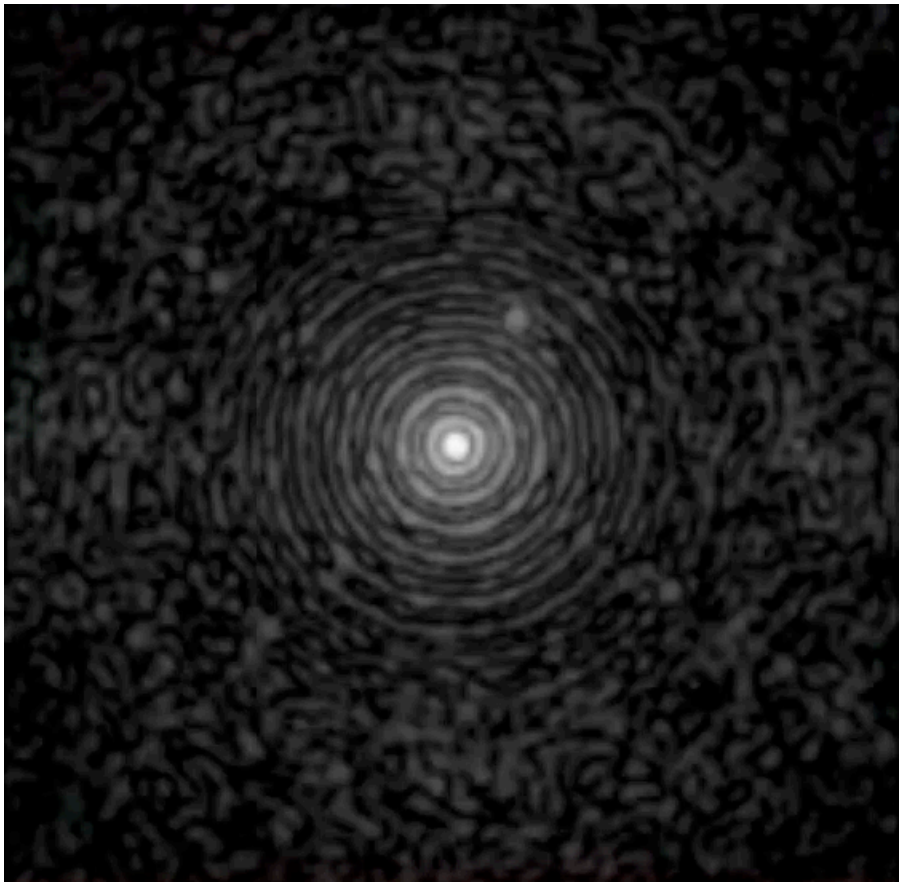


Coronagraphy Basics



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

Killing Speckles



Markus Feldt – “90 seconds of Astronomy”

<u>Speckle Types and Lifetimes:</u>

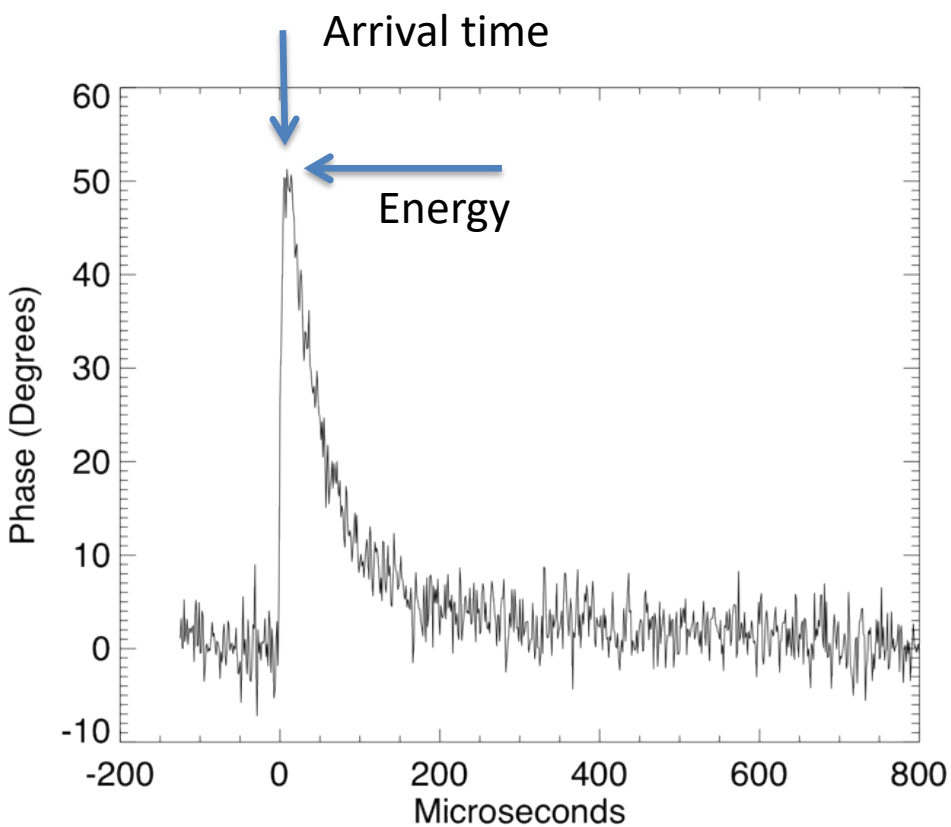
Quasi – static:

- Caused by static aberrations
- Governed by gravity vector/temperature changes.
- Decorrelate on *many minutes timescales*

Atmospheric:

- Caused by residual atmospheric aberrations
- Governed by AO error source
- AO measurement error -> *ms timescales*
- AO bandwidth or fitting error -> decorrelation set by telescope aperture clearing time, *~1s timescales*

MKIDs should be perfect for speckle suppression



Single photon counting with ~microsecond timing

+

Continuous read out with no read-noise

+

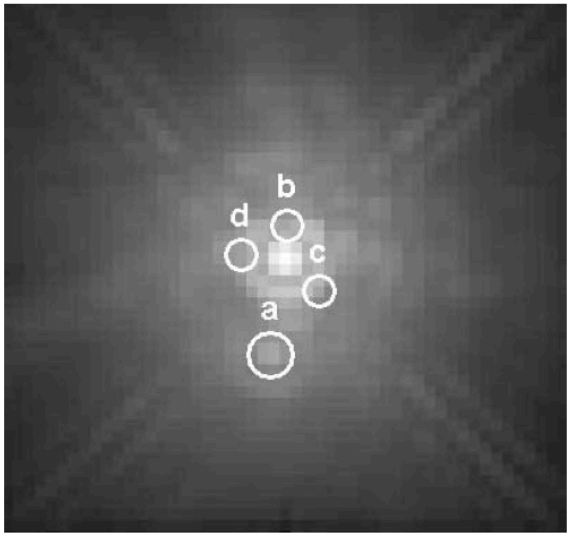
Energy resolution (R~10) with no dispersive element

=

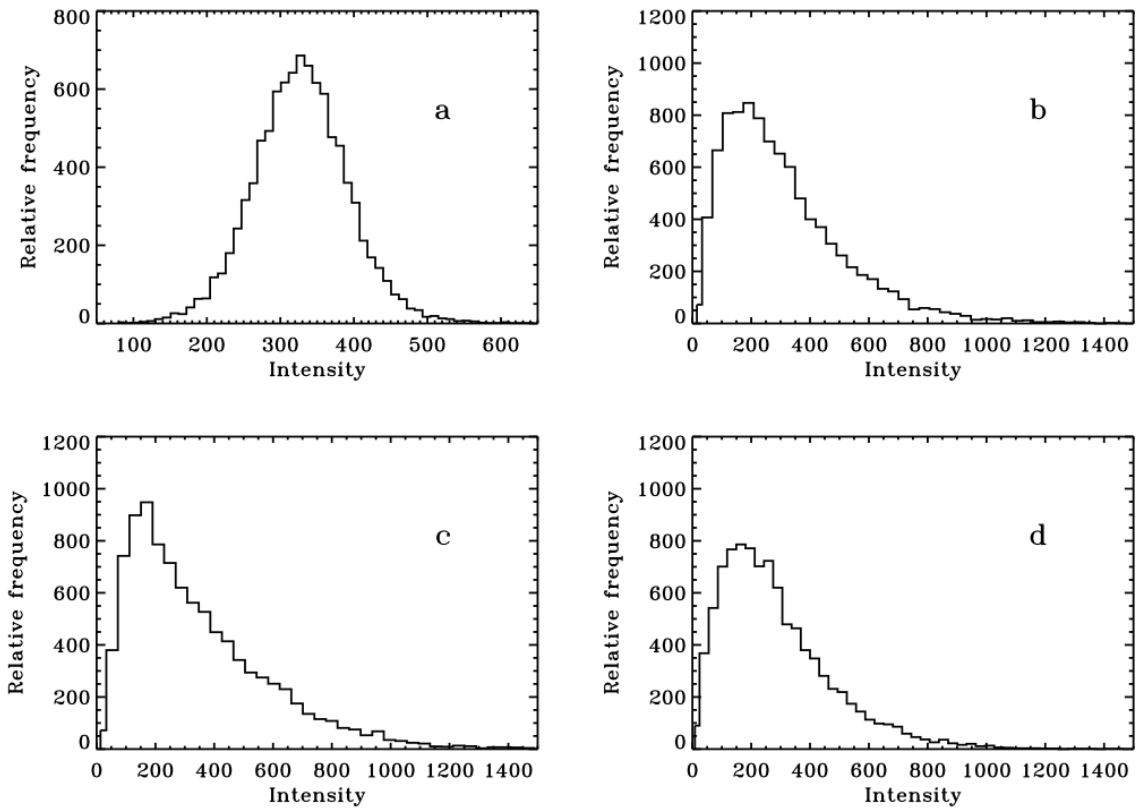
kHz frame rates to track atmospheric speckles, perform SDI, and do spectroscopy

Stochastic Speckle Discrimination

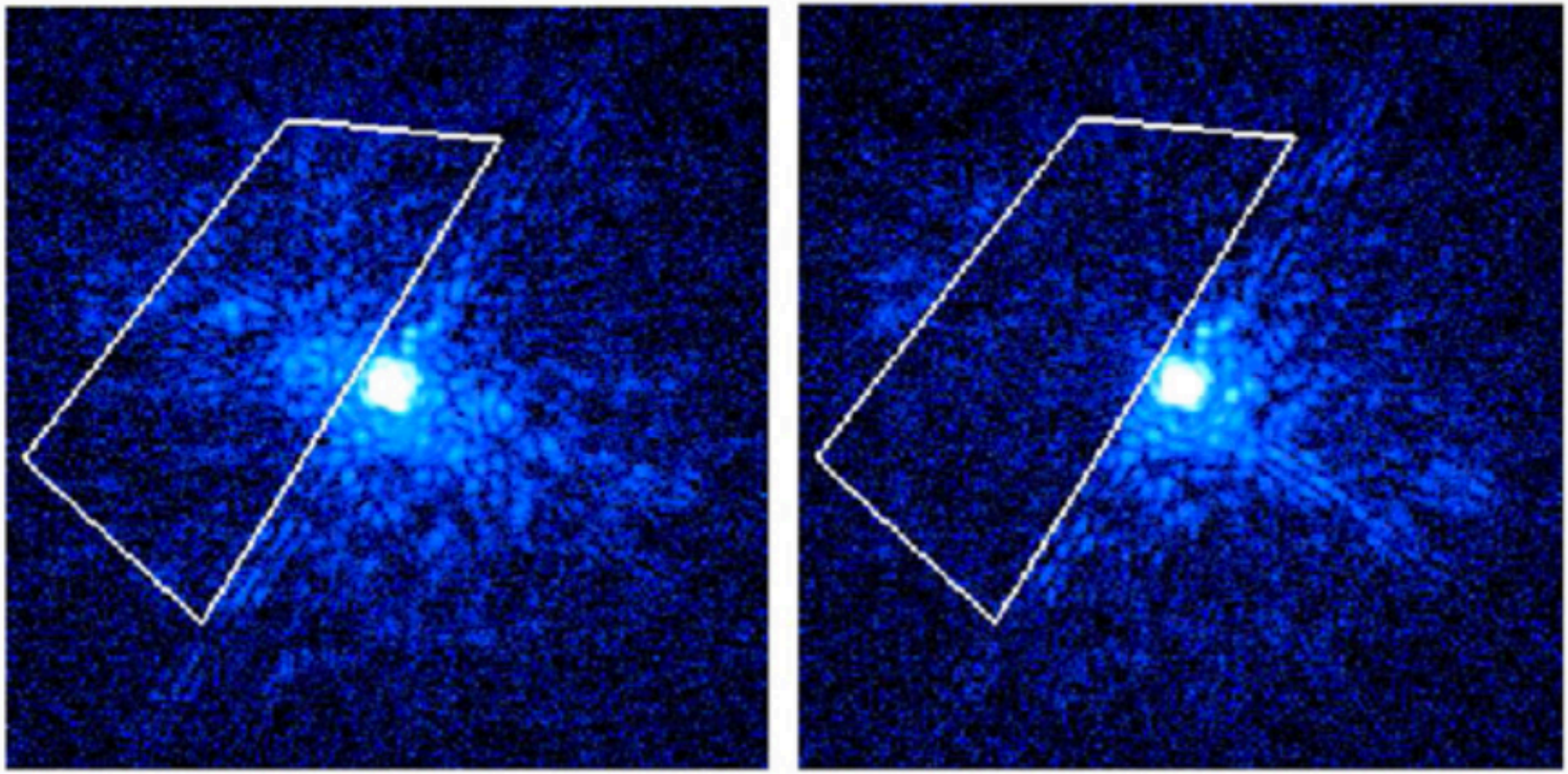
$$p_{MR}(I) = \frac{1}{I_s}\exp\left(-\frac{I+I_c}{I_s}\right)I_0\left(\frac{2\sqrt{II_c}}{I_s}\right)$$



Gladysz and Christou 2008, 2009



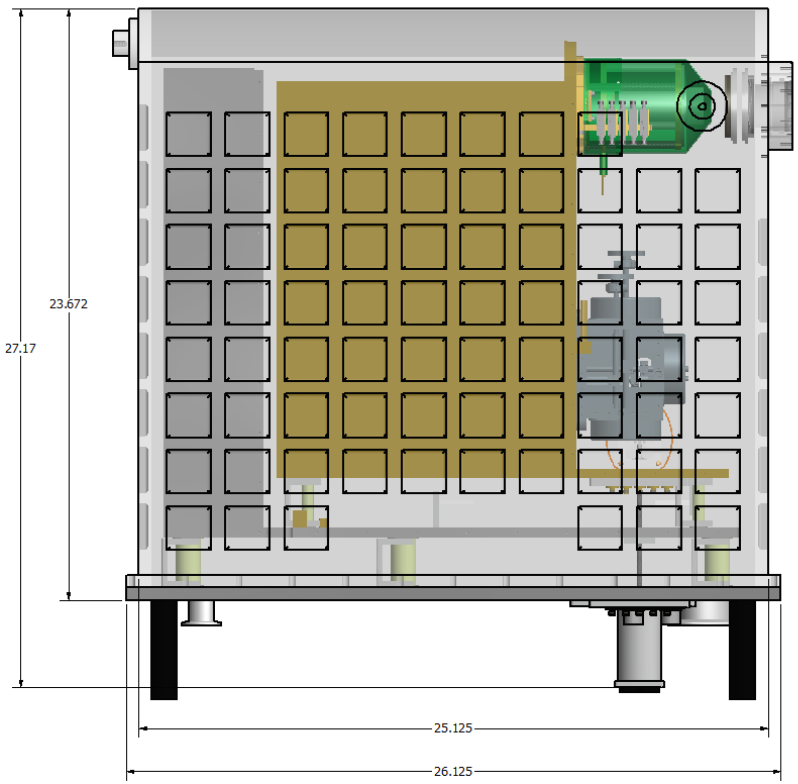
Active Speckle Nulling

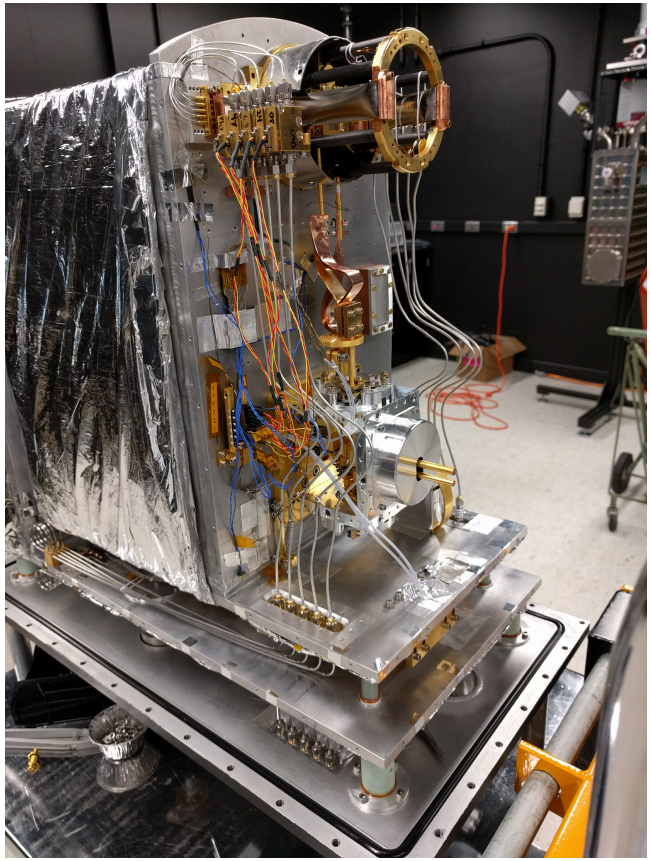


Bottom+ 2016

DARKNESS

- NSF Funded - **10,000 pixel** MKID IFS
- 0.8 to 1.4 microns observing band (roughly z_s, Y, and J near-IR bands)
- Custom cryostat, LHe cooled to 4K. ADR cooled to 100 mK
- **Deployed in July 2016 with the Stellar Double Coronagraph at Palomar, then again in November 2016, April 2017, October 2017**





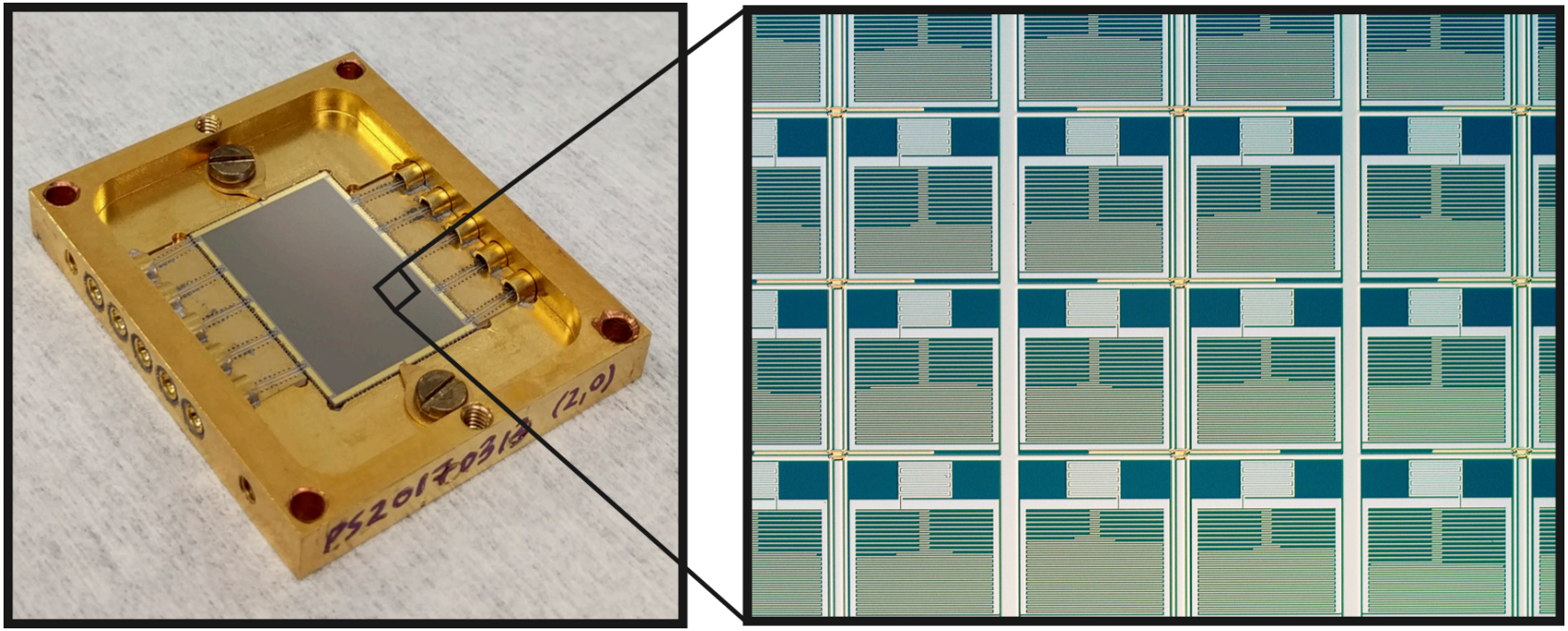
Meeker+ 2015, 2018

10,000 Pixel D-3 Array

PtSi MKID array, median **R (λ/Δλ) = 7** at 800 nm

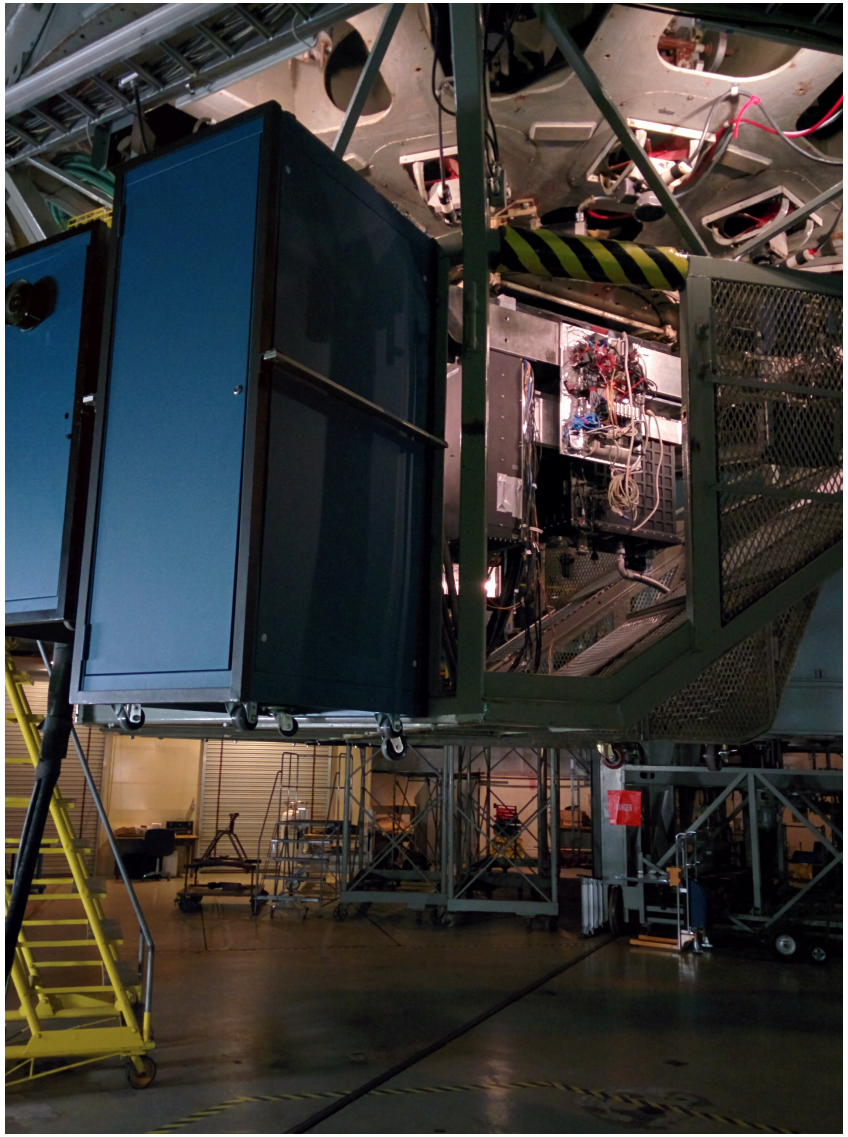
80 x 125 pixels, 150 µm pixel pitch

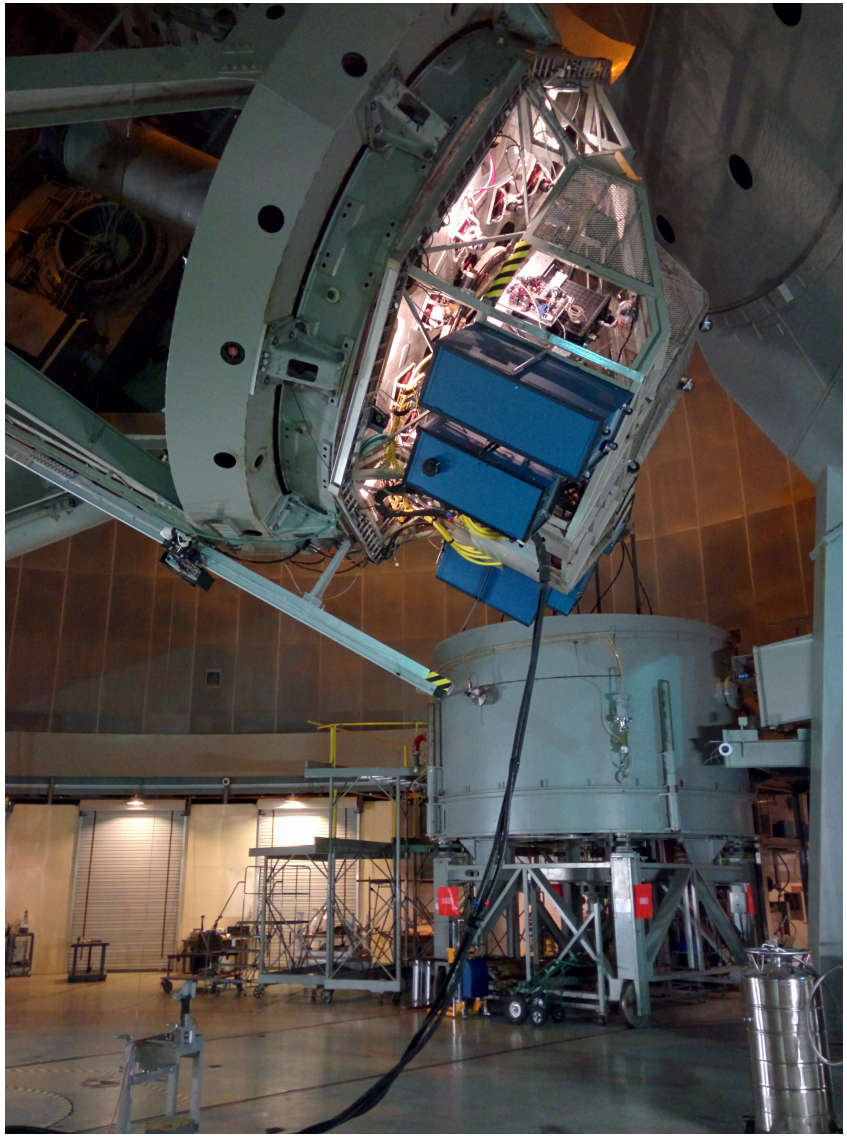
Fabricated at UCSB and JPL



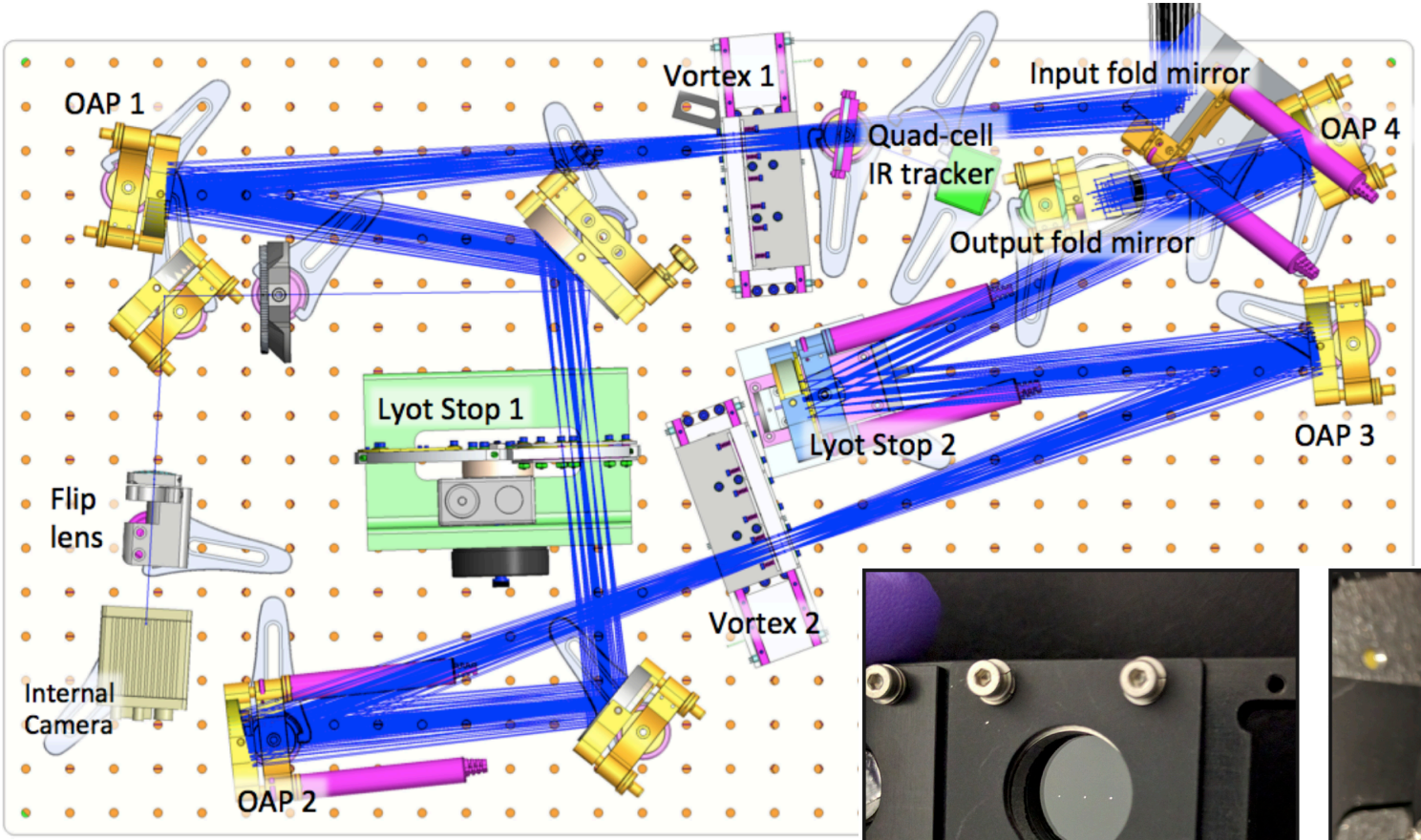
July 2016: DARKNESS + SDC Commissioning

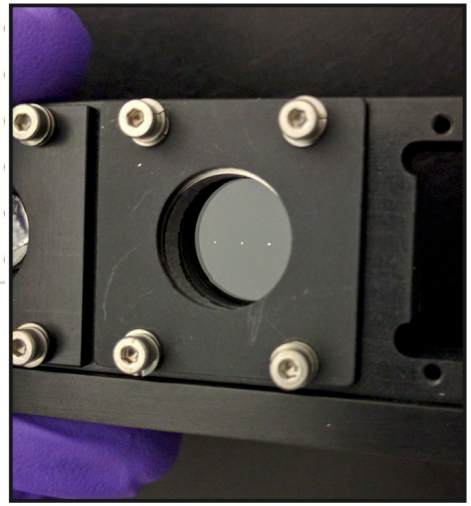
On-sky, July 23 2016

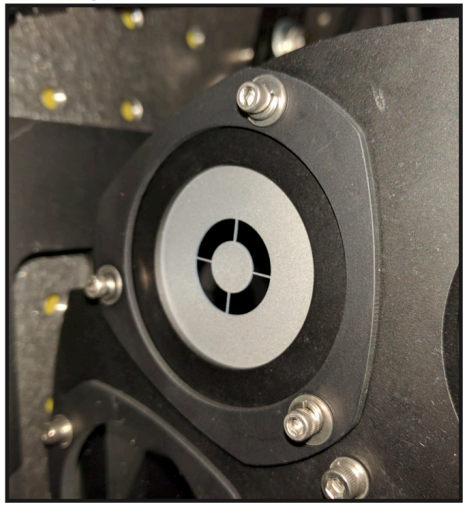




The Stellar Double Coronagraph

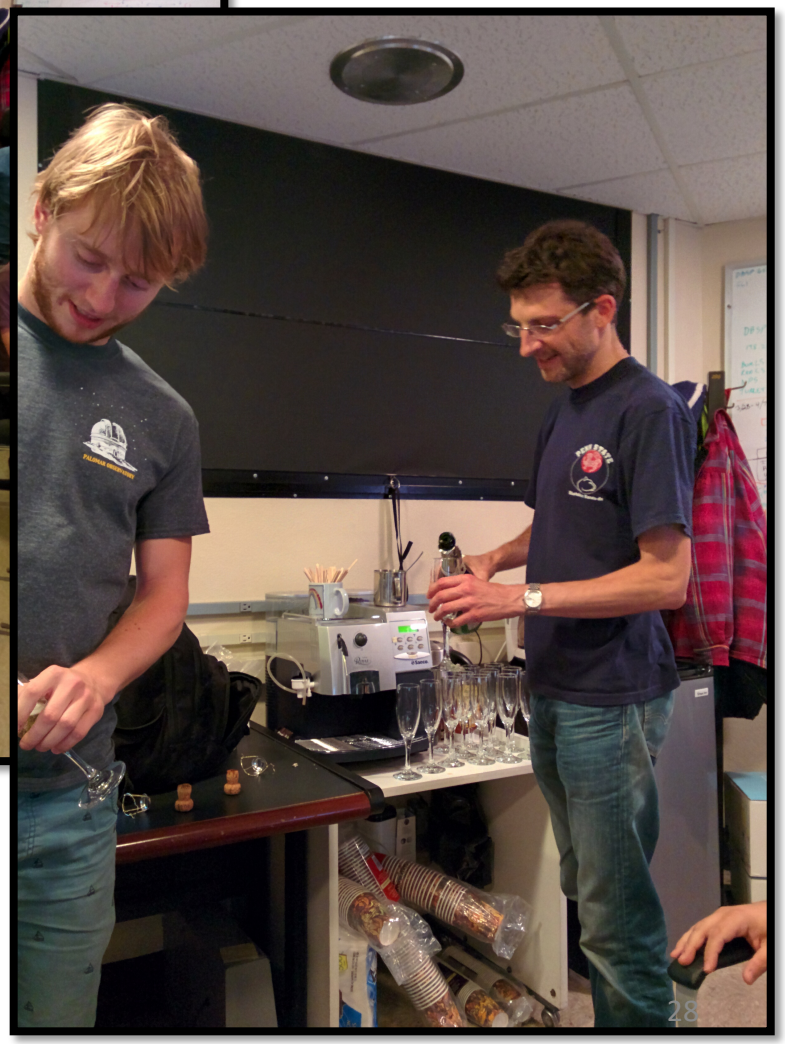




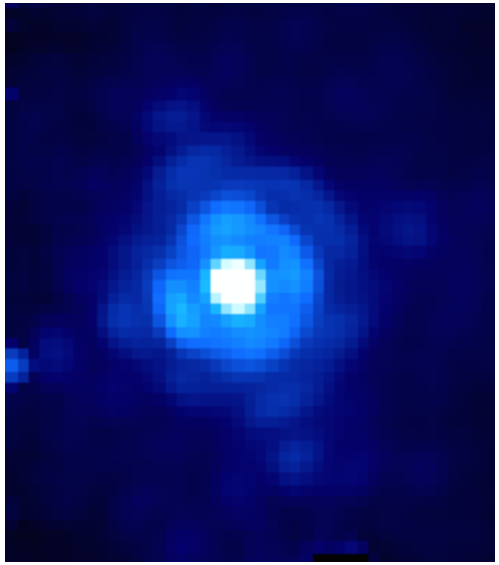


Bottom+2015

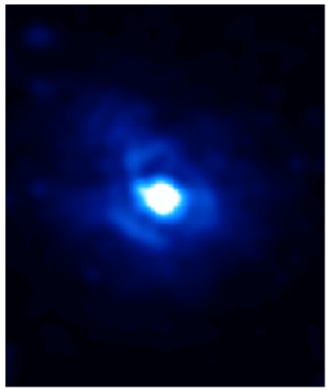
First-light Party!!

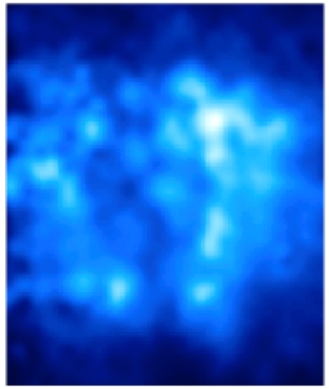


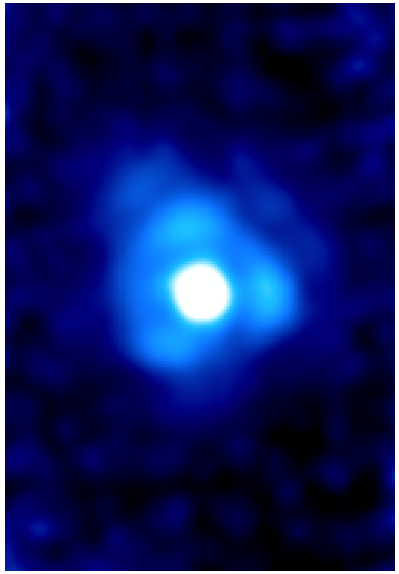
Some J-band PSFs



WL source

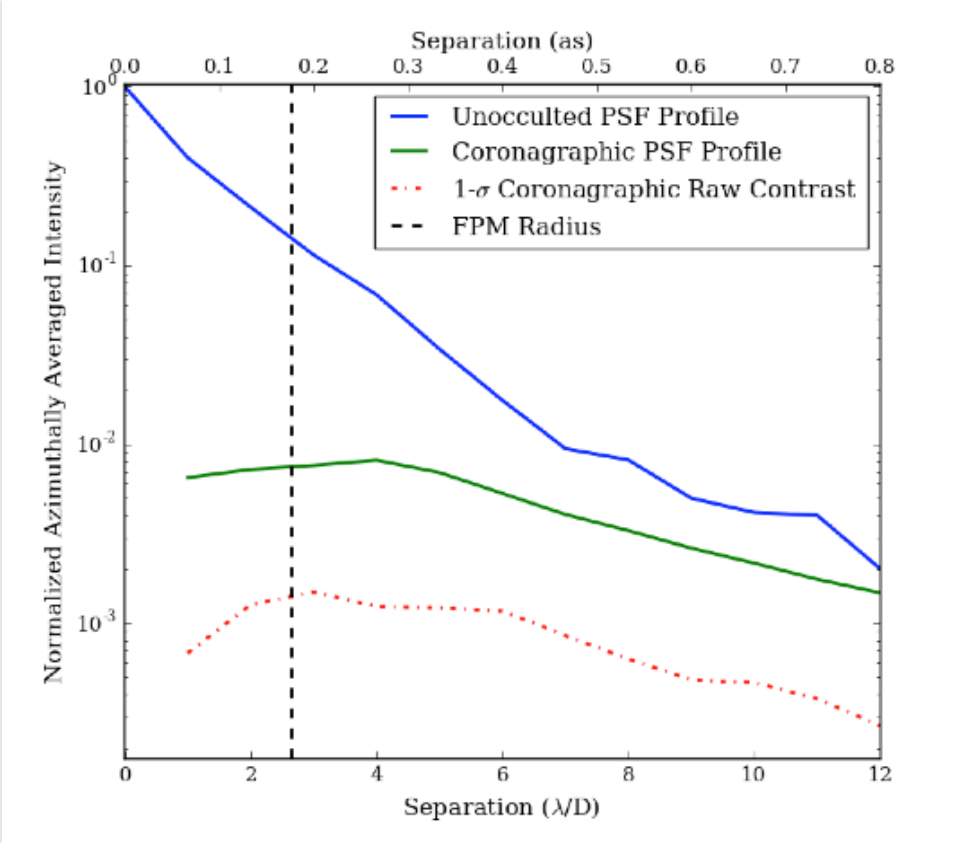




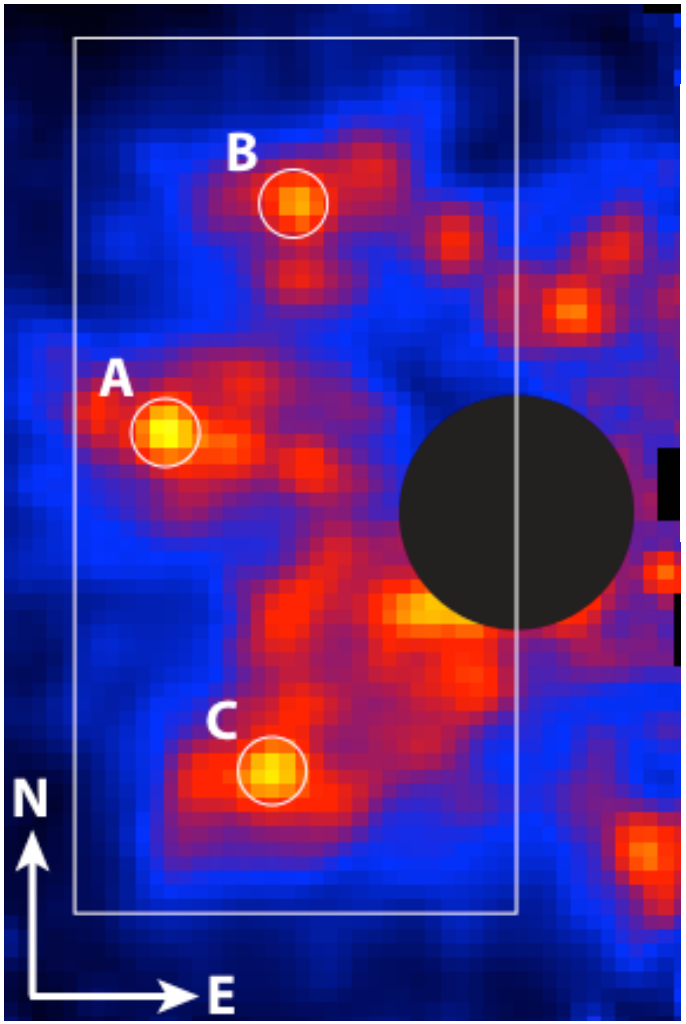


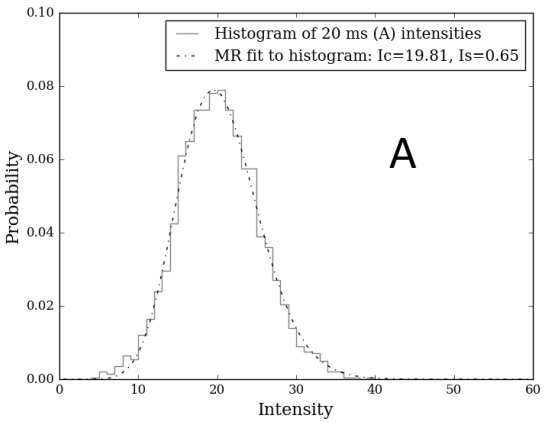
V=4 SAO star

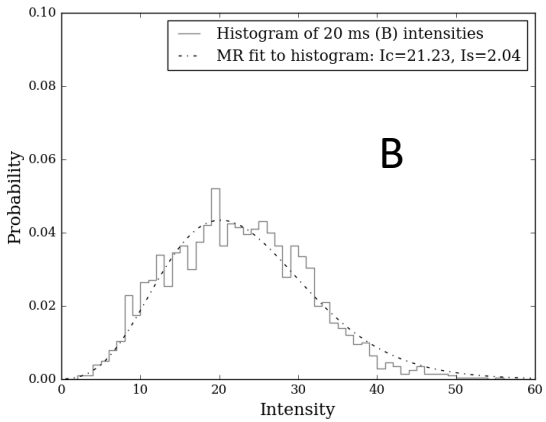
π Herculis

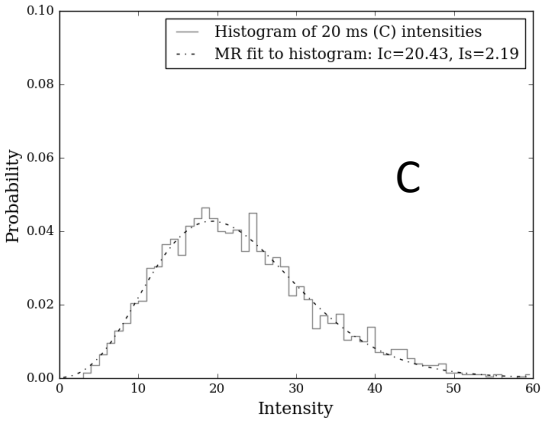


32 Peg Ab with Satellite Speckles

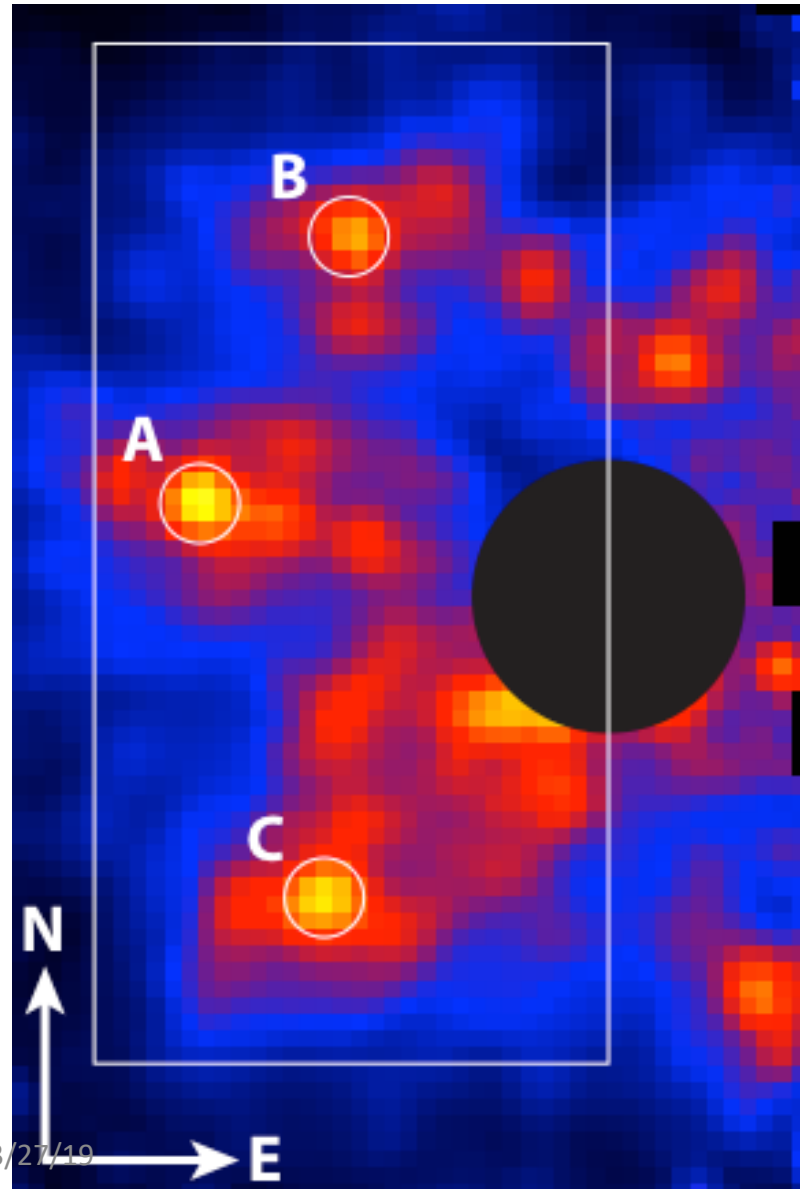


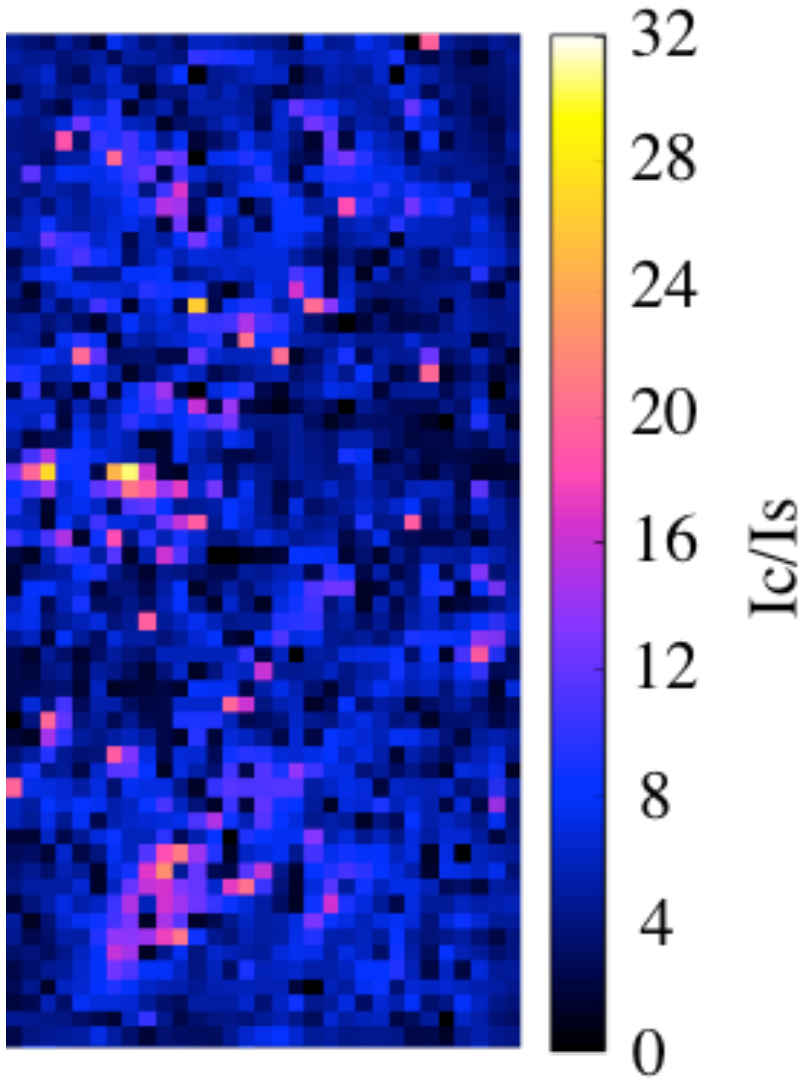






Ic/Is from Modified Rician fitting





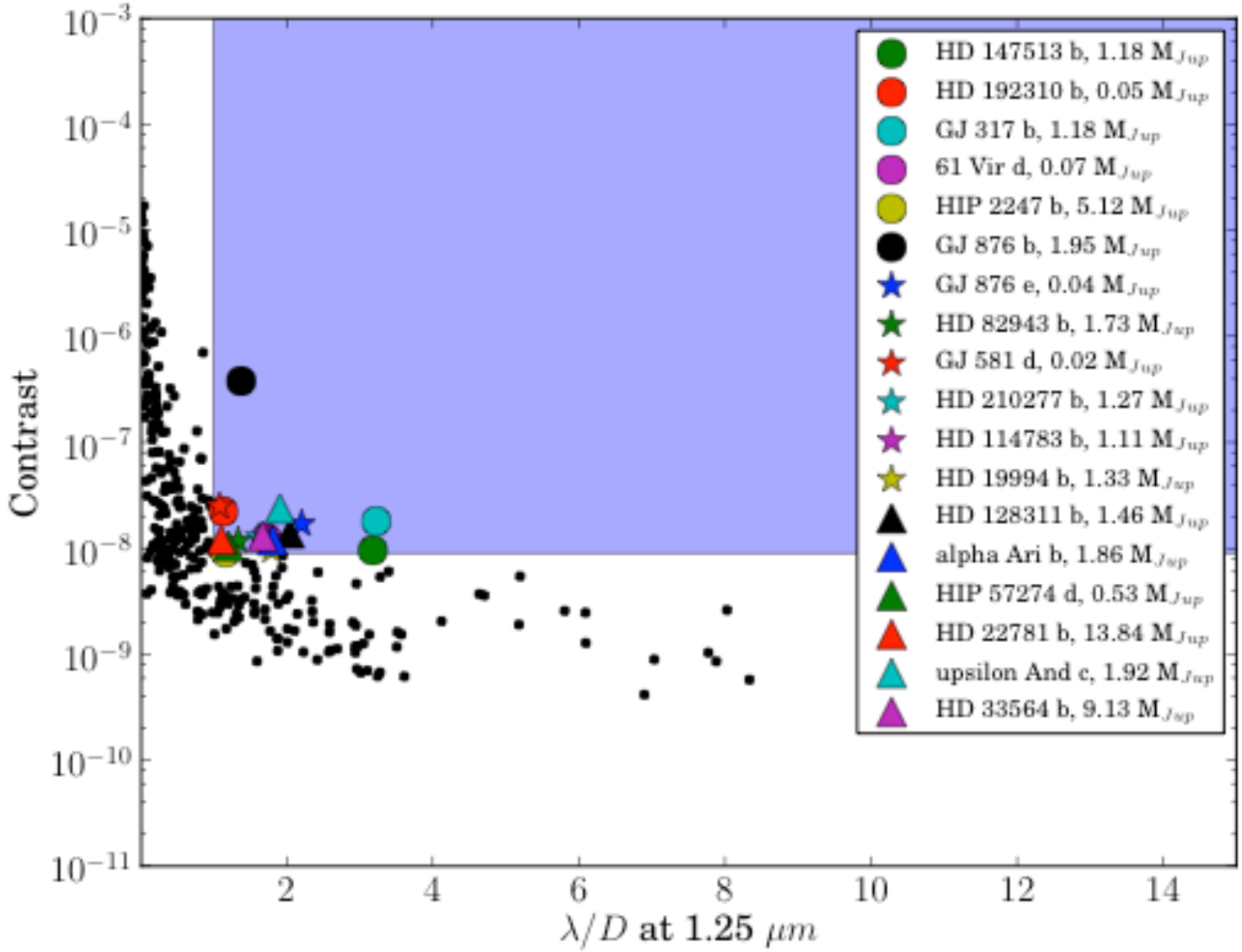
Meeker *et al.* 2018

The MKID Exoplanet Camera (MEC)

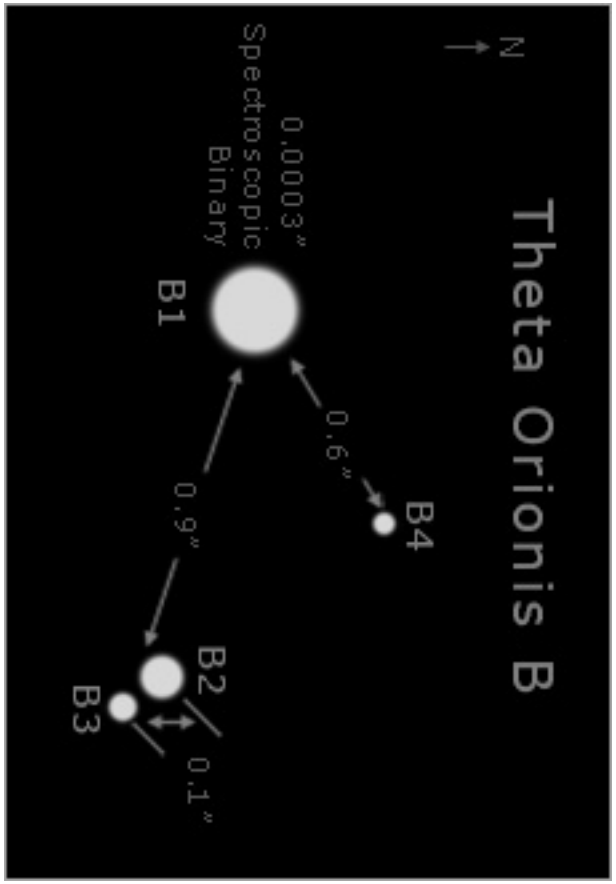
- MEC is a 20 kpix version of DARKNESS for Subaru SCExAO
  - 20 kpix MKID IFU
  - SCExAO at Subaru Observatory
    - PIAA/Vortex Coronagraphs
  - Observe cold gas giants in reflected light?

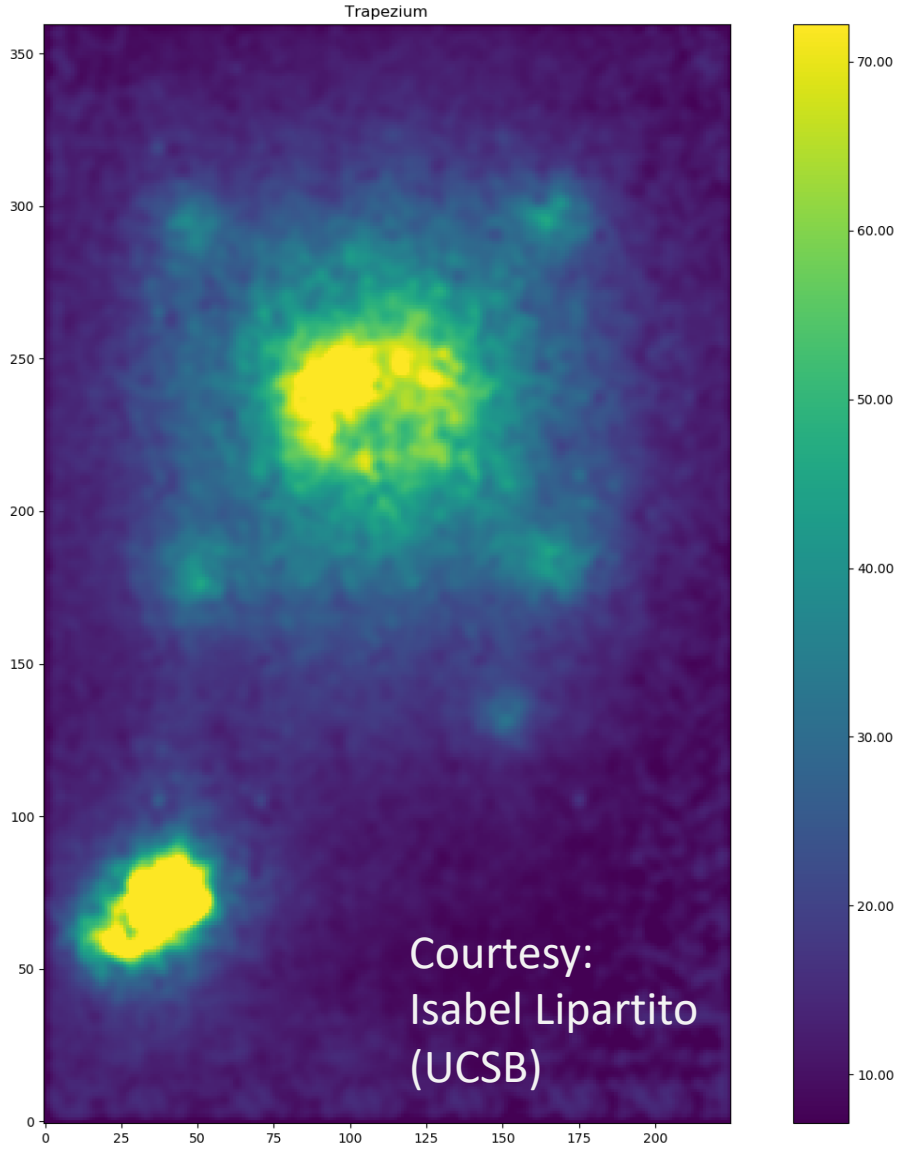
MEC is the thesis project of Alex Walter (UCSB)

MEC Science with known RV planets



First MEC images





Courtesy:
Isabel Lipartito
(UCSB)

PICTURE-C

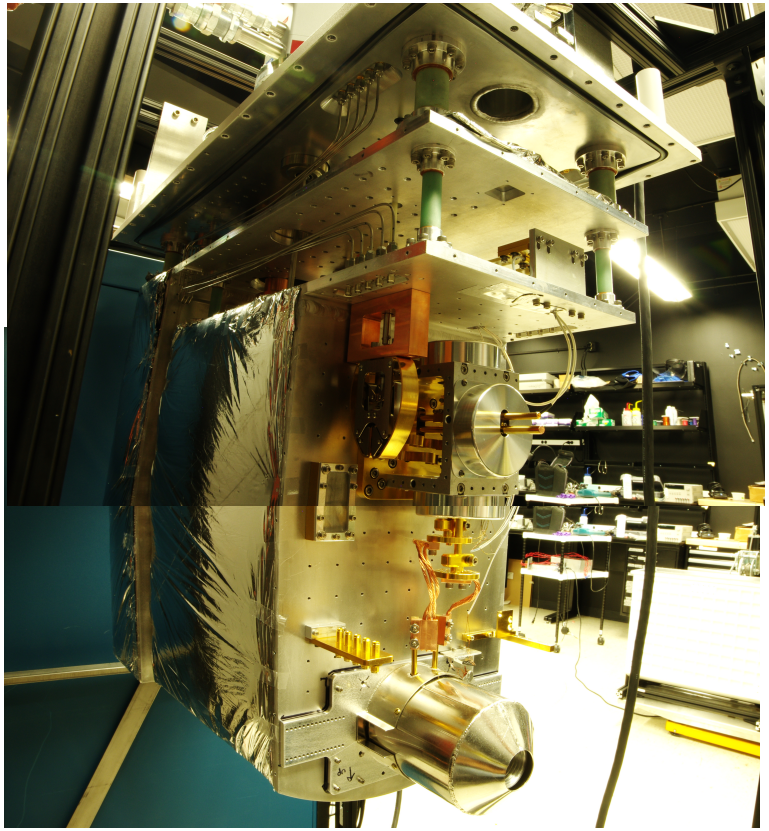


Photo courtesy:
Clint Bockstiegel (UCSB)

Cook et al. 2015

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

Science objectives: image exoplanets and exozodiacal disks

Technology objectives: **demonstrate flight capability of Vortex coronagraph and MKIDs**

Future

DARKNESS is the first MKID instrument optimized for near-IR, high-contrast application.

Pipeline development and data analysis are progressing full-steam.
Initial results in statistical speckle discrimination (as well as speckle temporal dynamics and speckle nulling, not shown today) are promising.

Slated to travel to Magellan in 2020 for operation behind MagAO-X

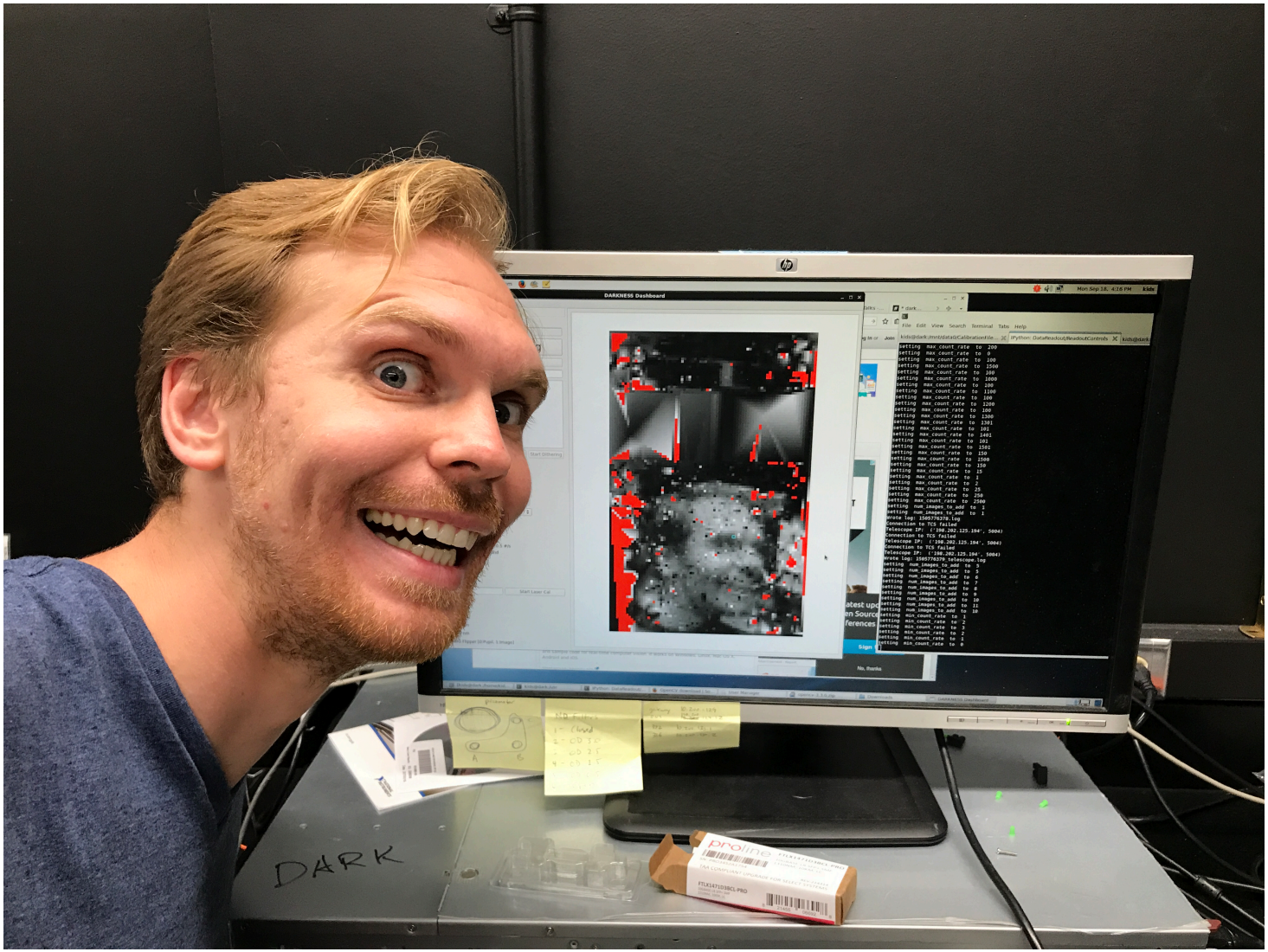
The MKID Exoplanet Camera (MEC) has achieved first-light at Subaru with SCExAO
Commissioning is ongoing.

PICTURE-C will fly a DARKNESS clone in 2020.

The goal is to bring these capabilities to TMT where the extended aperture could enable direct imaging of M-dwarf habitable zones.

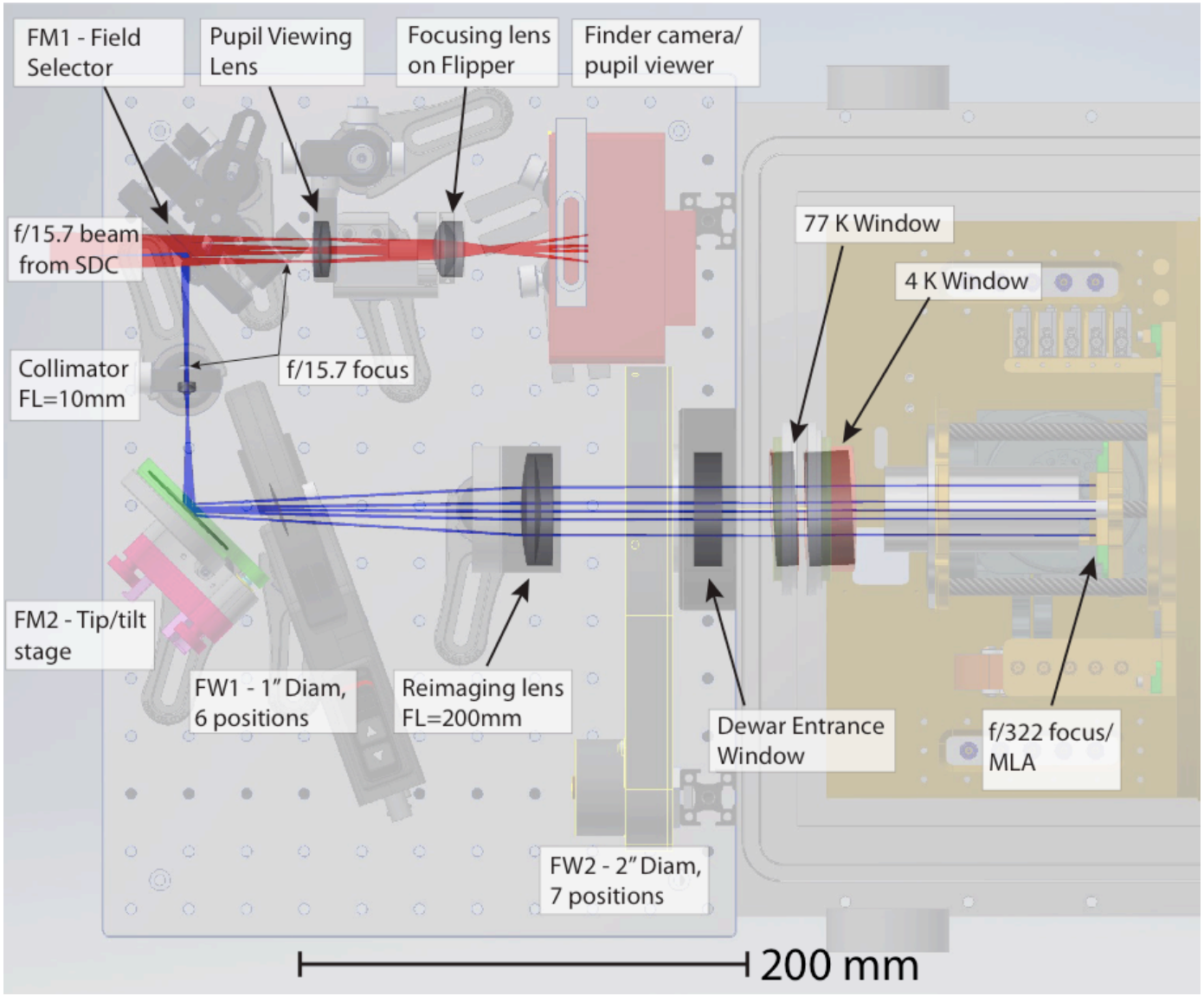
All papers can be found at mazinlab.org

Thanks!

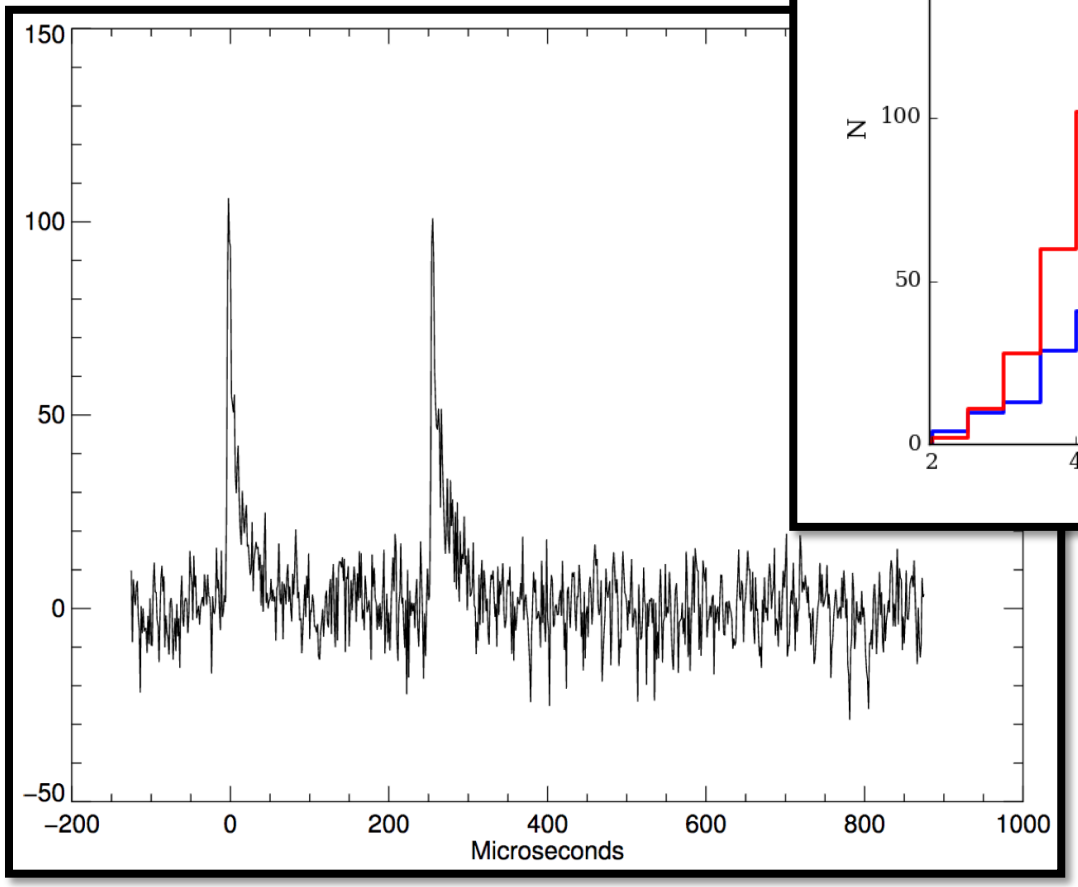


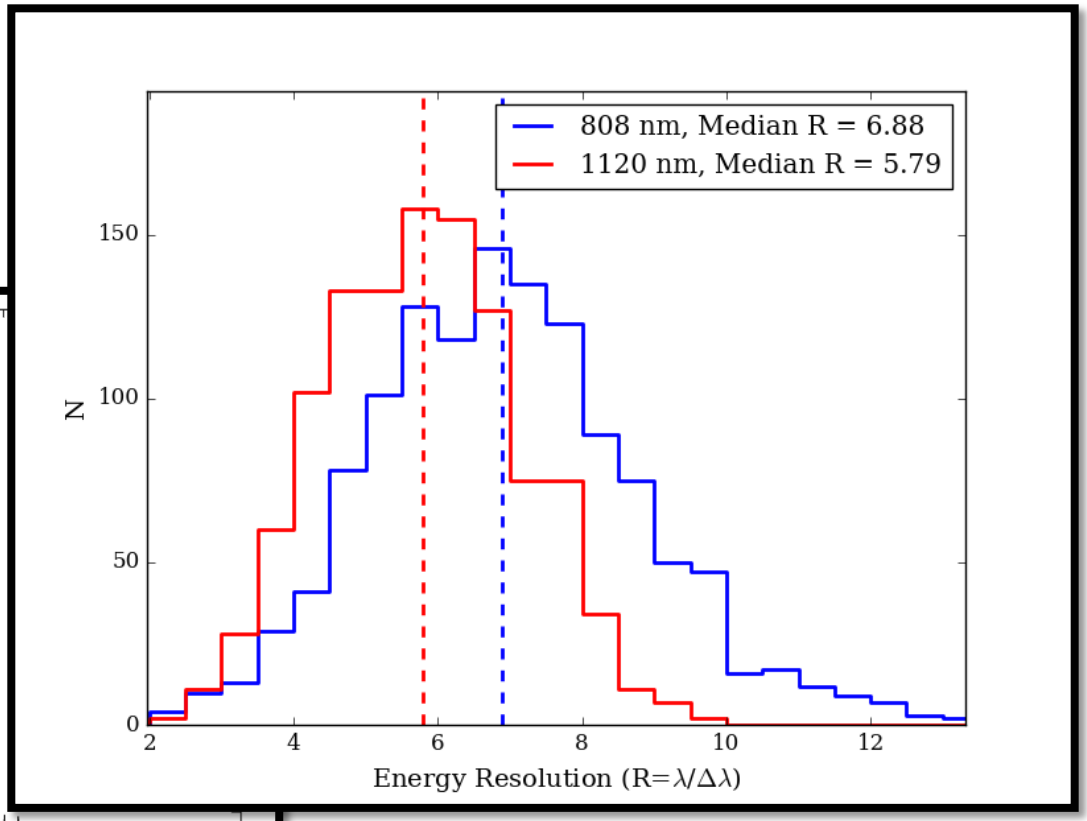
Extra Slides

Optical Integration with the SDC

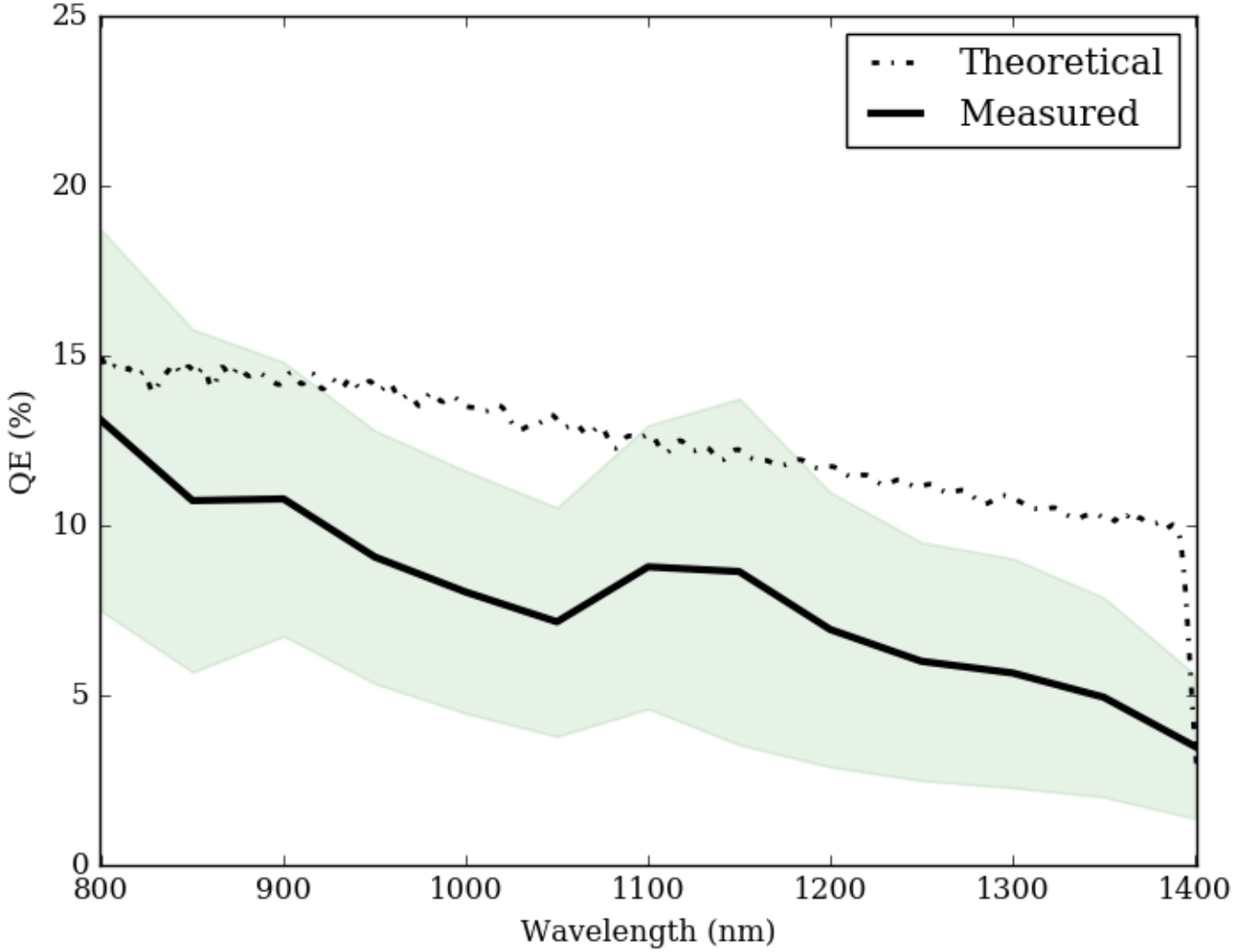


D-3 Sensitivity and Energy Resolution

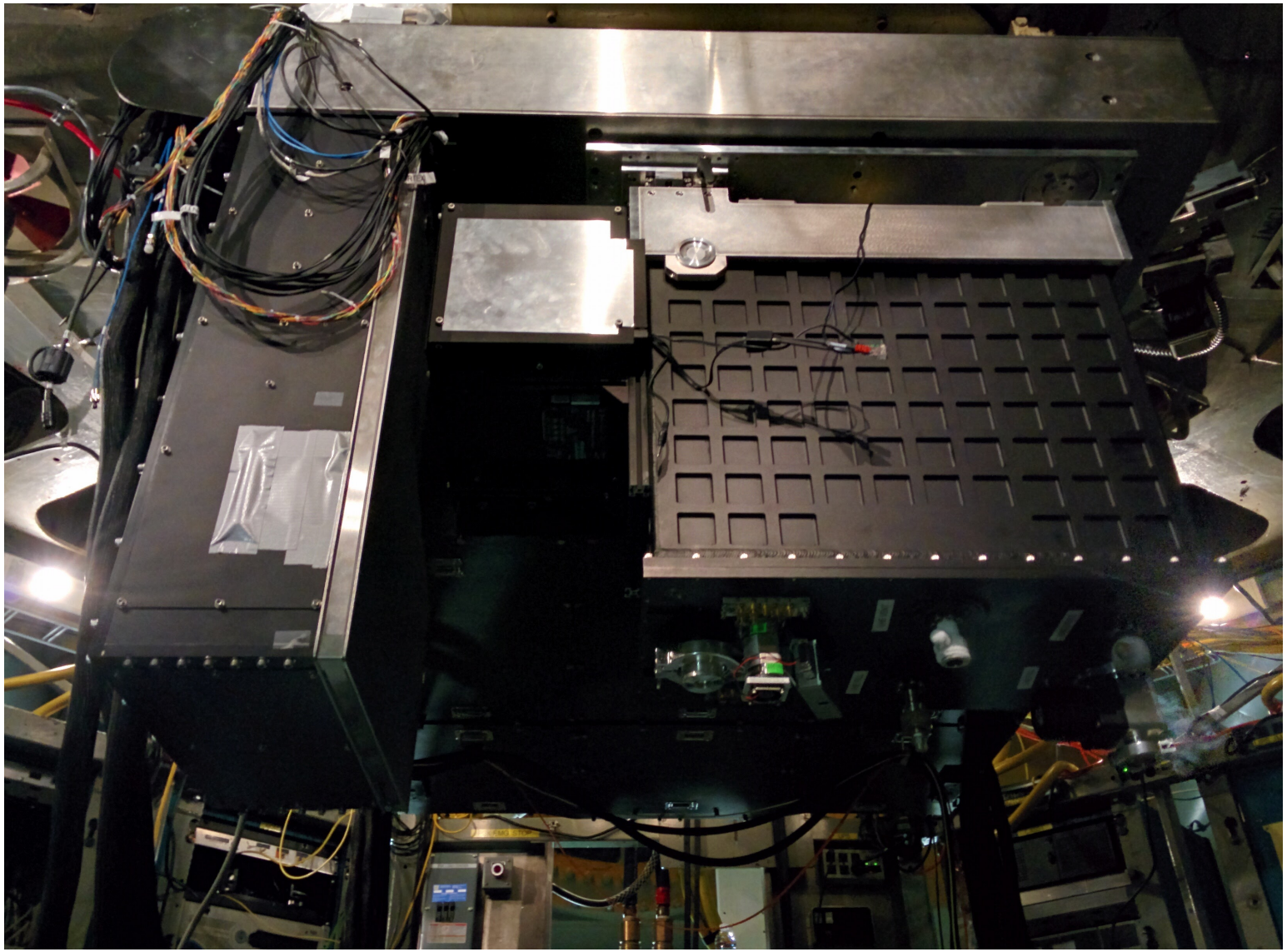




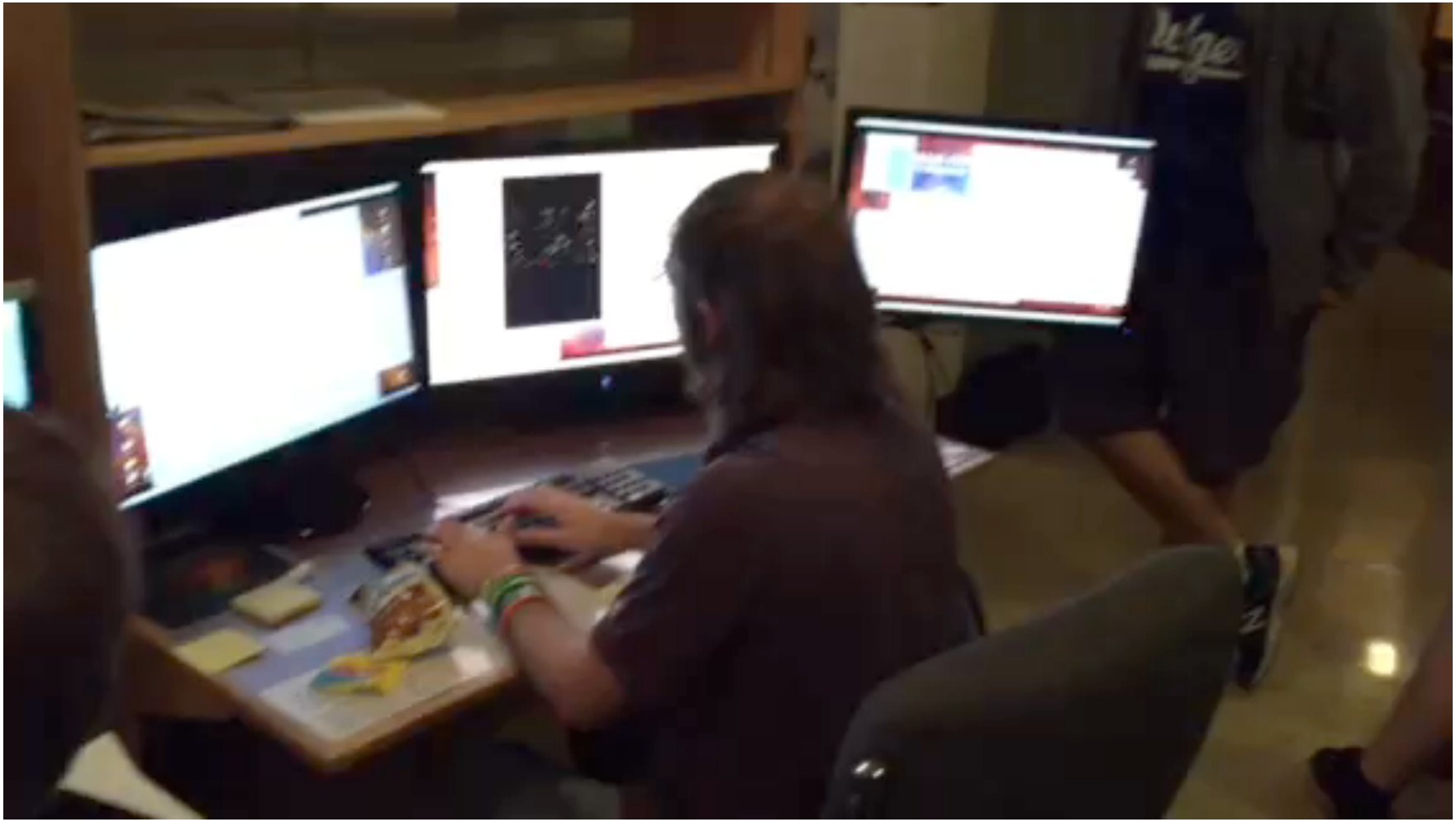
Total Throughput



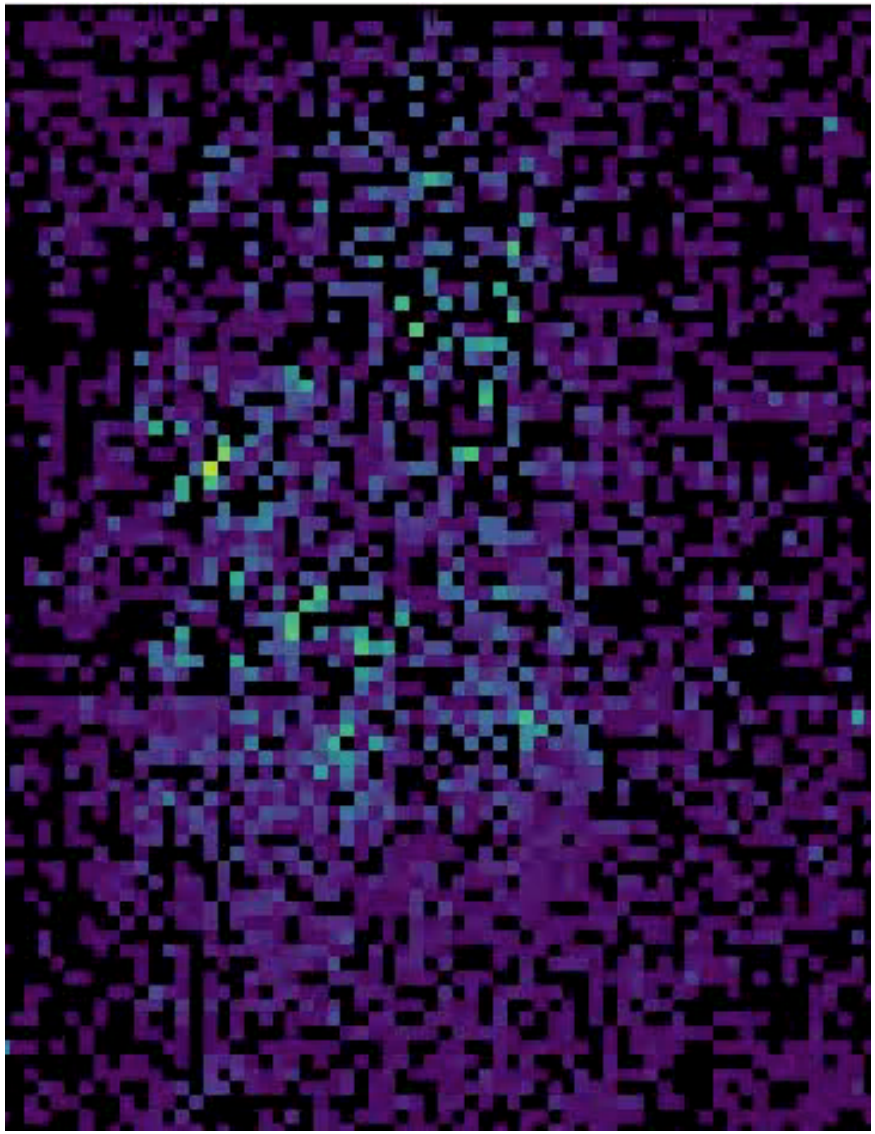
DARKNESS + SDC On the telescope



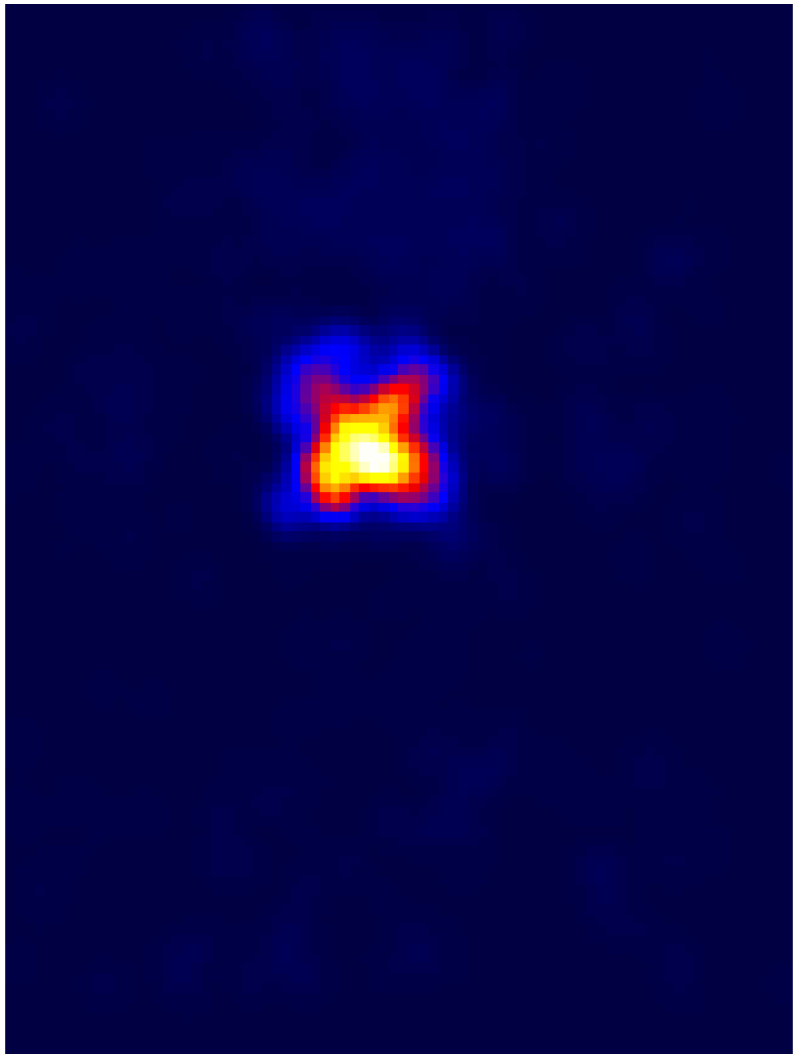
First light, July 24 2016



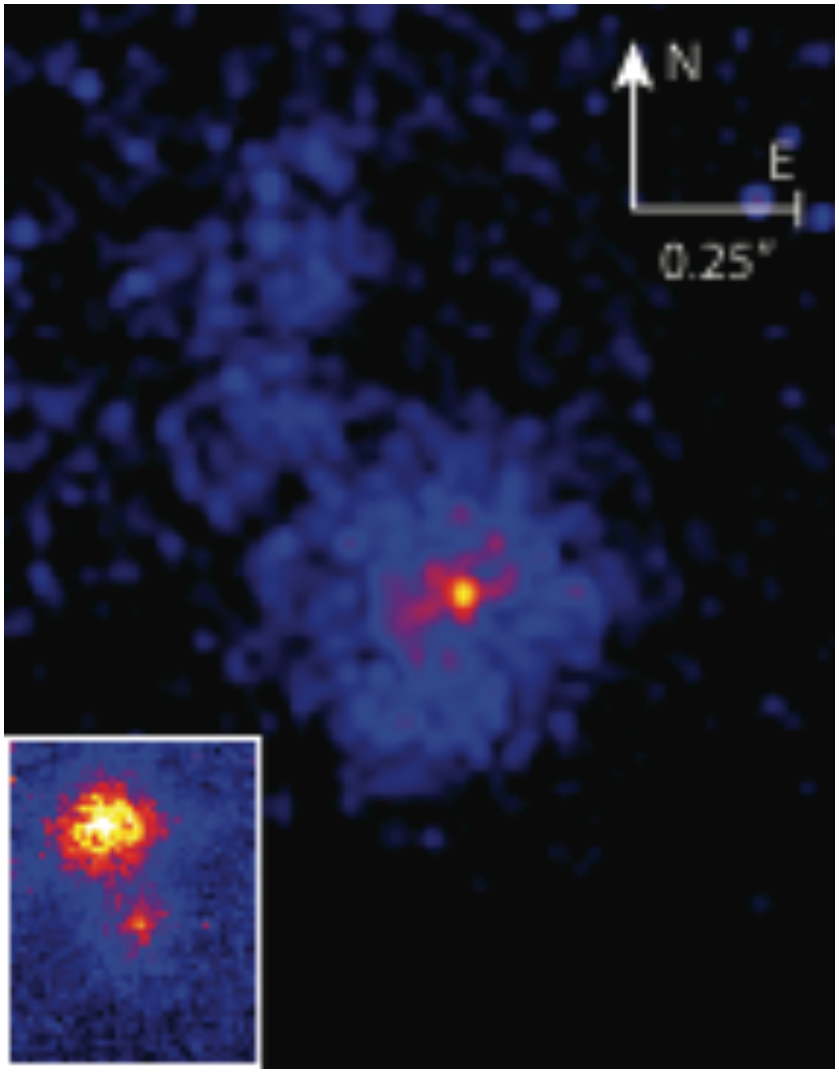
DARKNESS Speckle Nulling



Commissioning Results



First light: SAO 65485
July 24, 2016



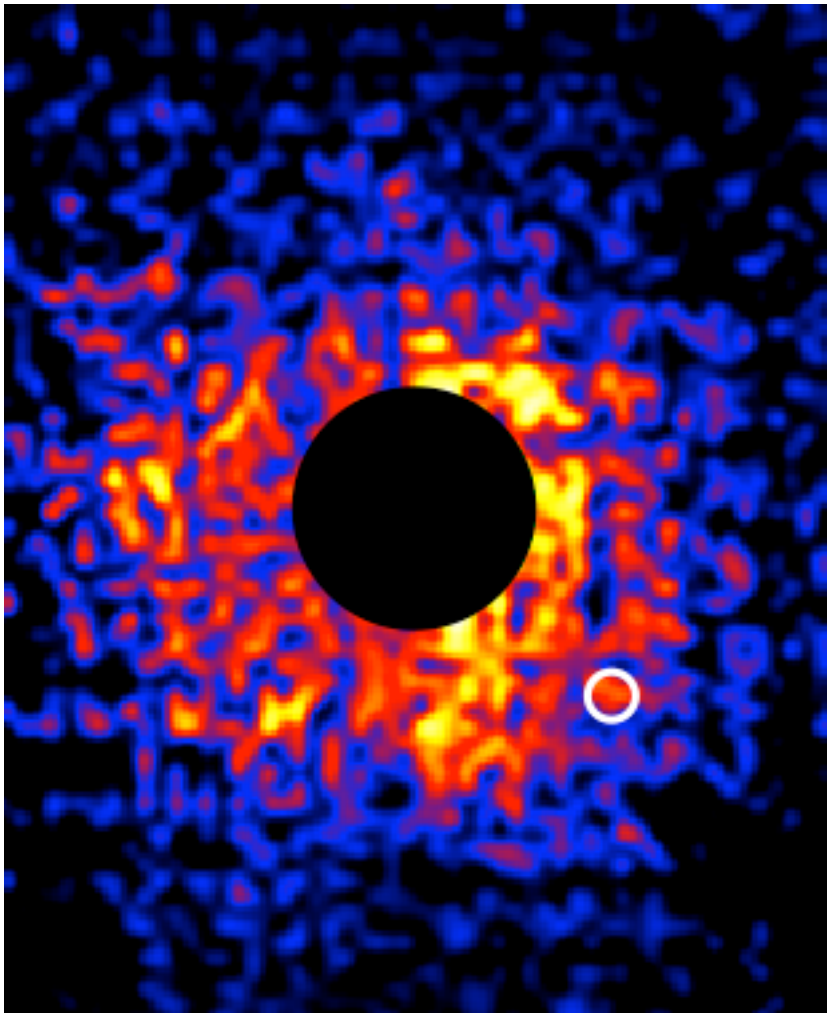
10 Uma B
Nov 22, 2016

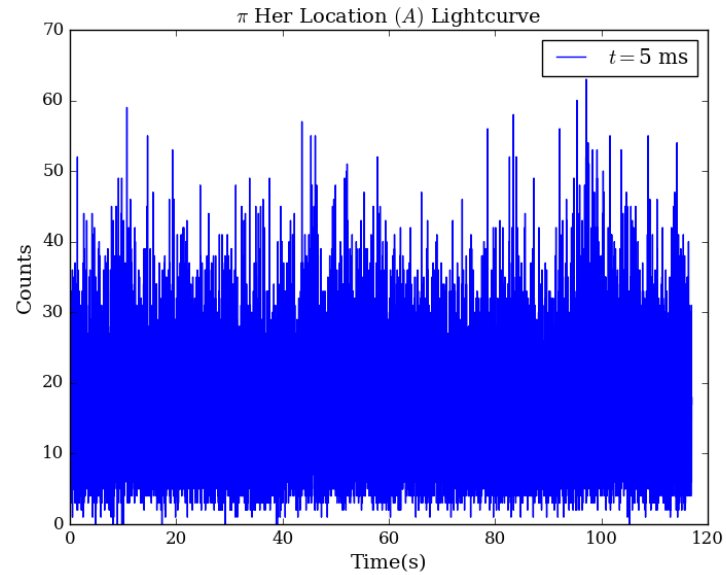
Speckle Decorrelation Times

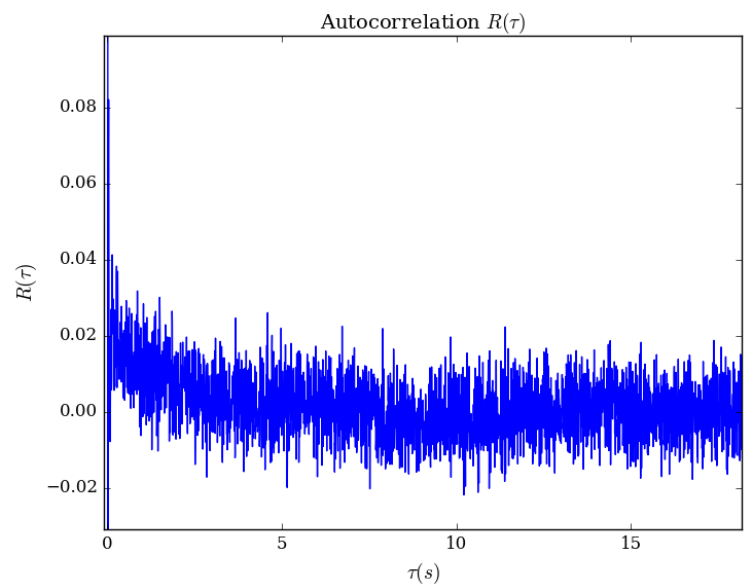
Error Source	Equation	Expected value for Palomar conditions*
AO Measurement Error	$\tau_{meas} = \Delta t_{AO}$	~ 1 milliseconds
AO Bandwidth Error	$\tau_{atmo} = 0.6 \text{ x } D_{tel}/v_{wind}$	0.4 seconds
Atmospheric Coherence	$\tau_0 = 0.3 \text{ x } r_o/v_{wind}$	12 milliseconds
Flexure, temperature drift	$\tau_{Quasi\text{-}static} = \text{Long}$	Ignored

* Palomar conditions means: 5 m telescope, 7 m/s wind, r_0(1250 nm) ~30 cm, AO rate of 1-2 kHz

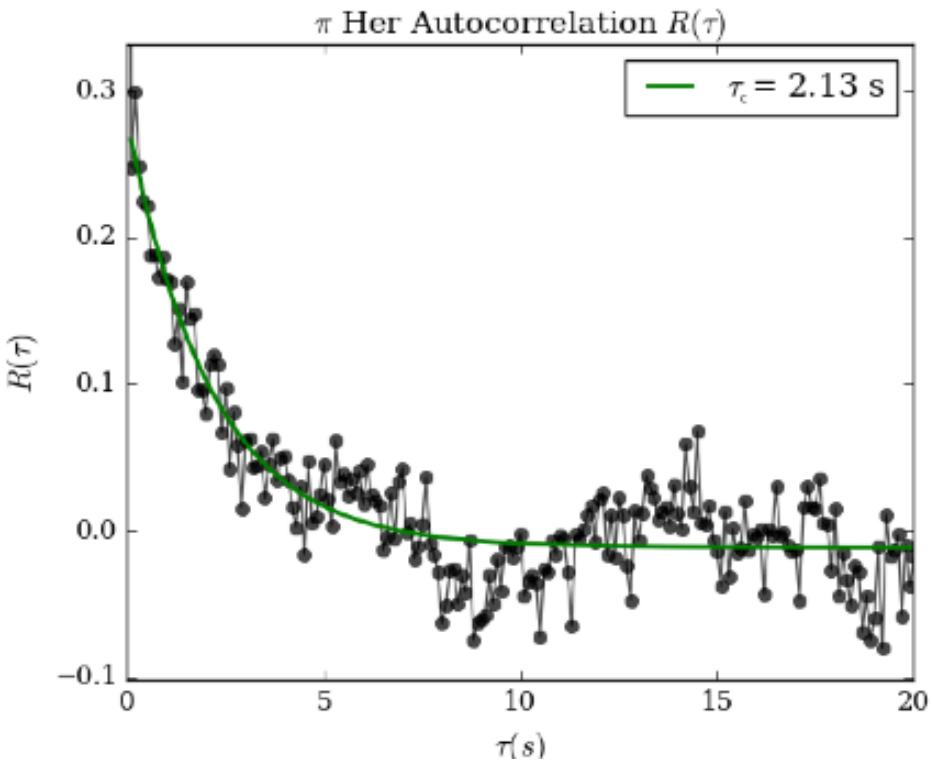
On-sky Speckles: Pi Herculis

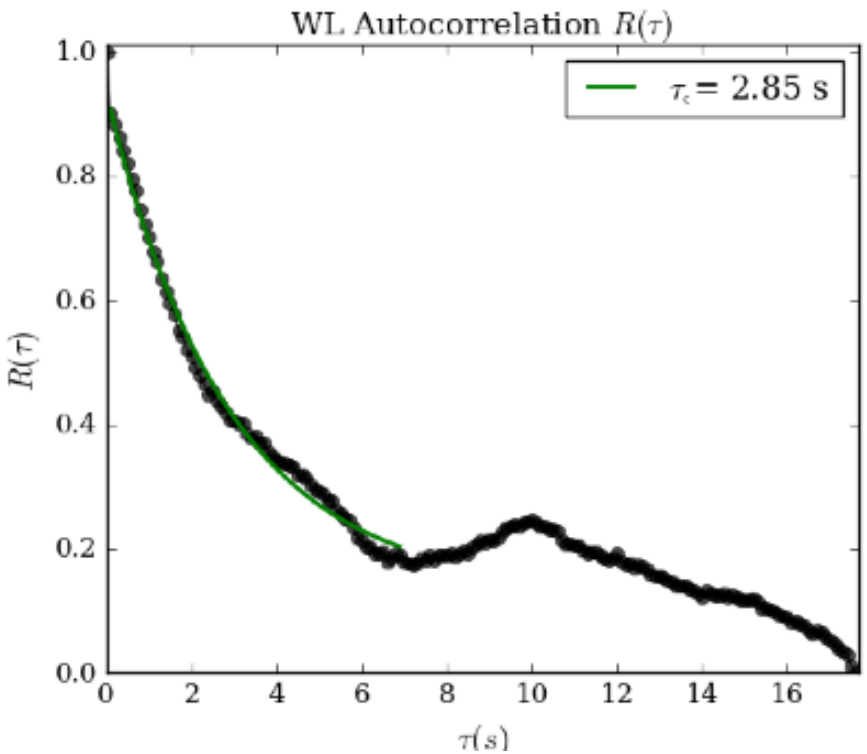




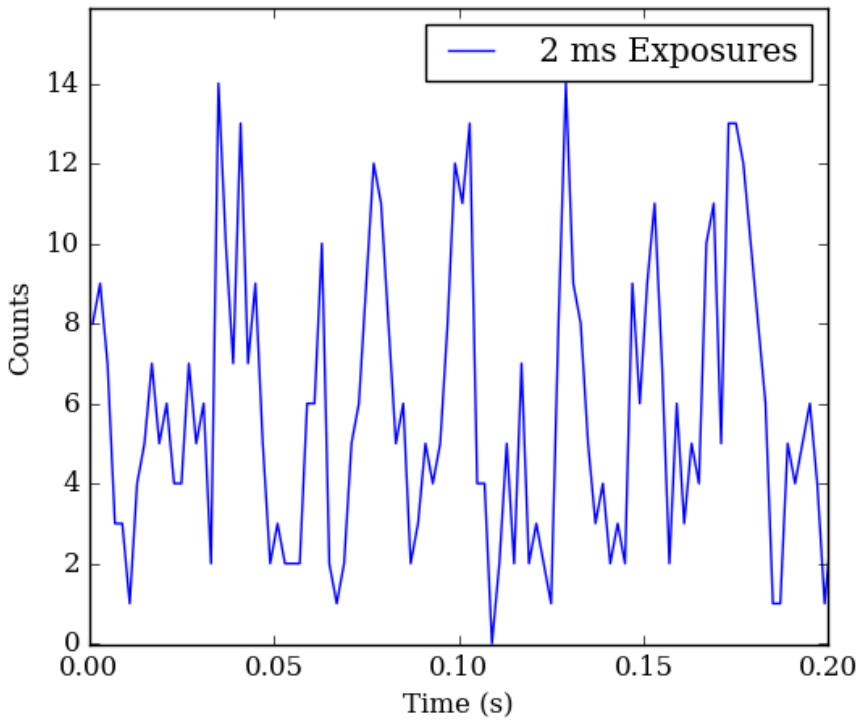


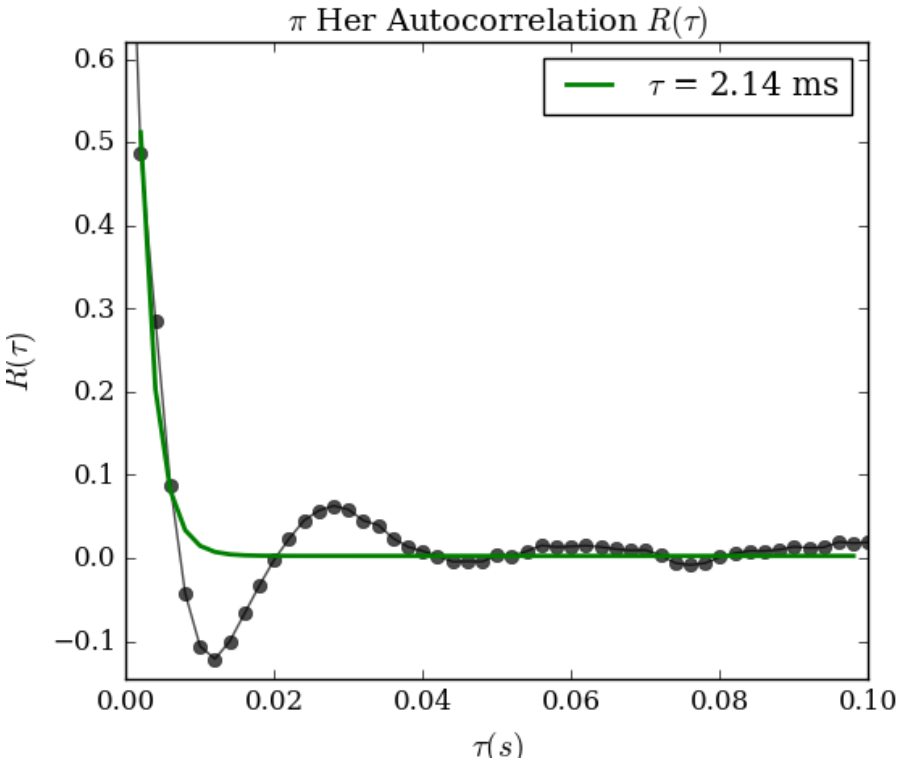
On-sky Speckles: Pi Herculis



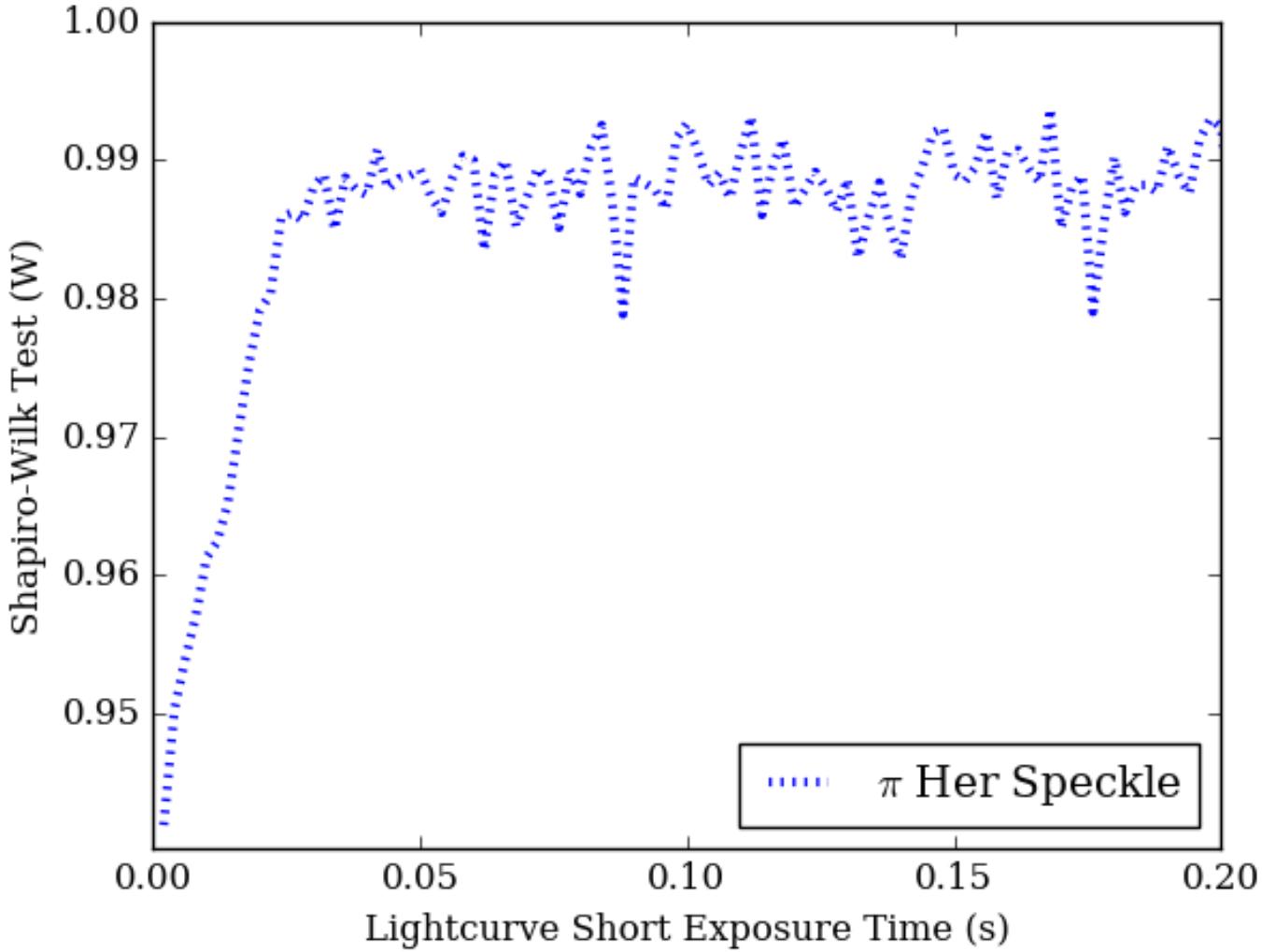


On-sky 40 Hz Modulation?

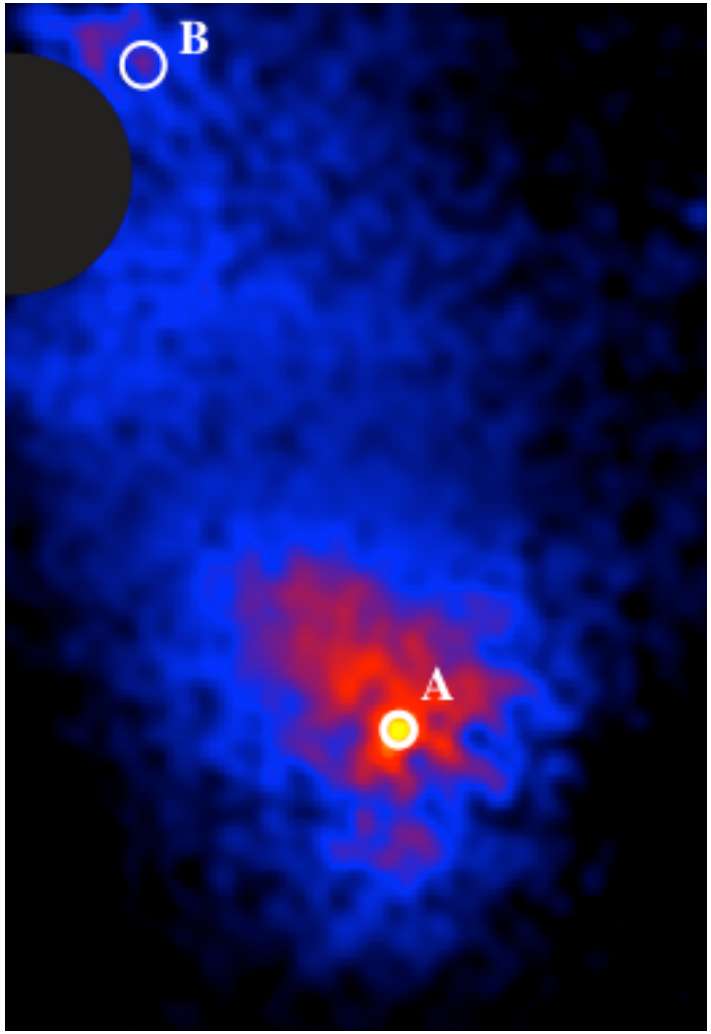




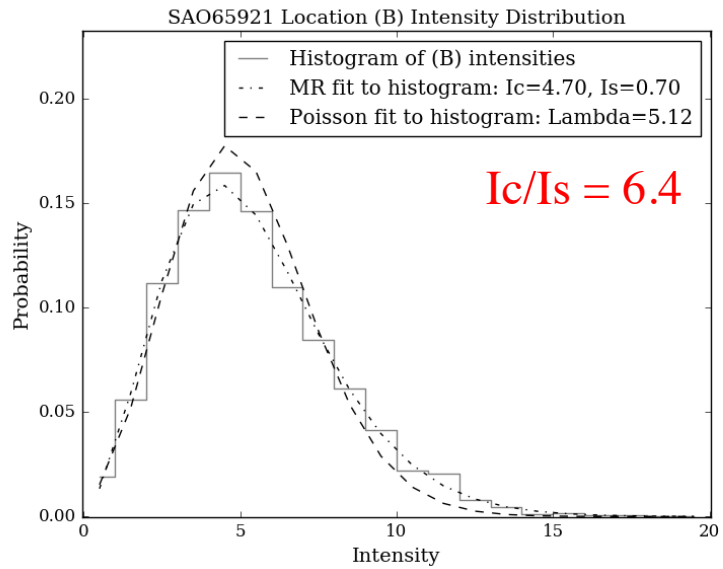
Shapiro-Wilk Test for Normality

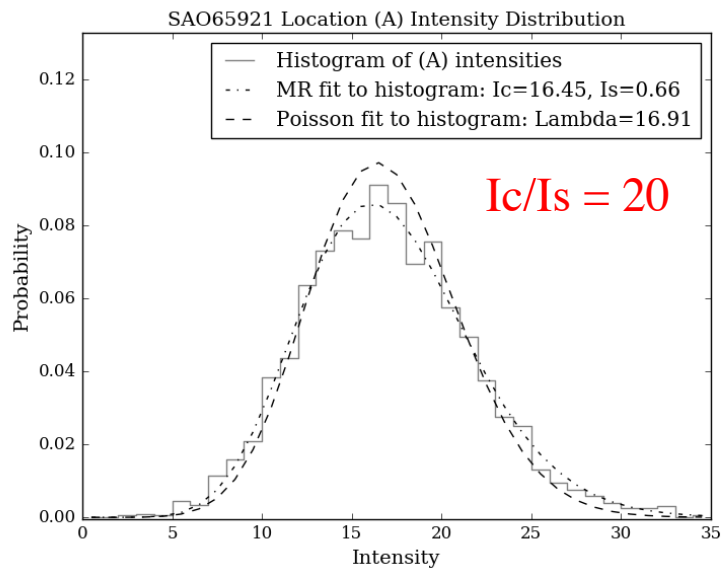


Beginnings of Statistical Speckle Suppression

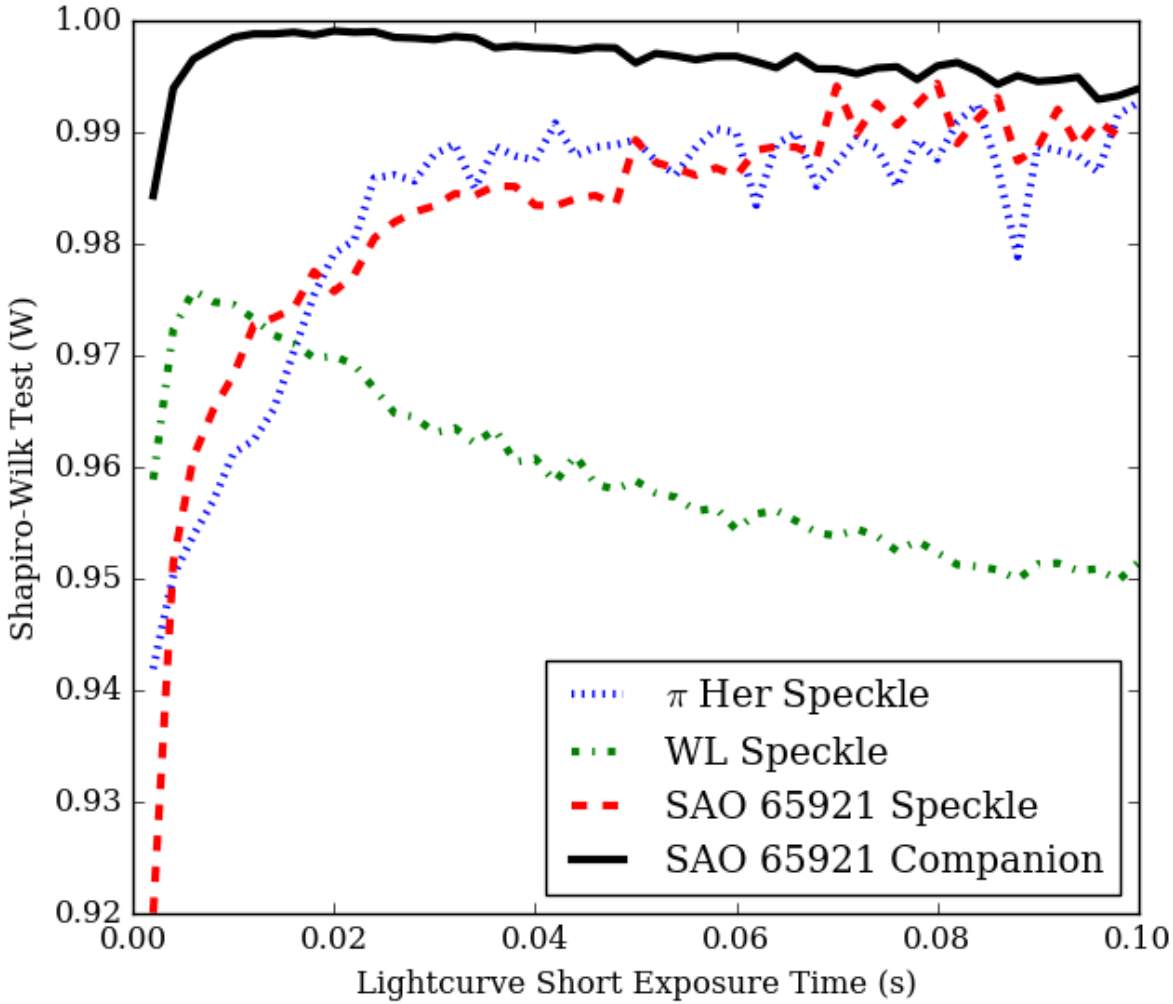


SAO65921 B (at location A) vs. Speckle at location B

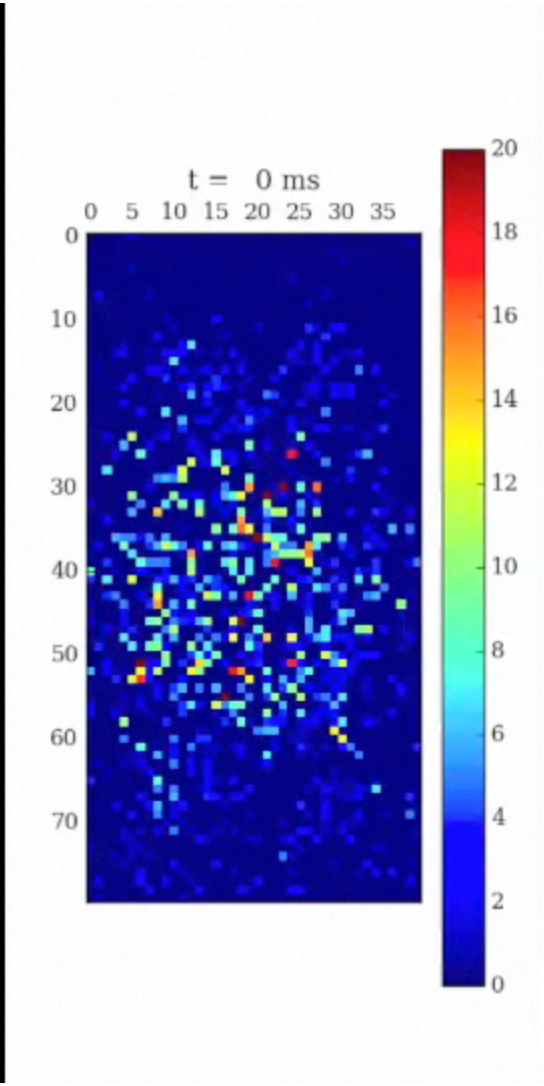




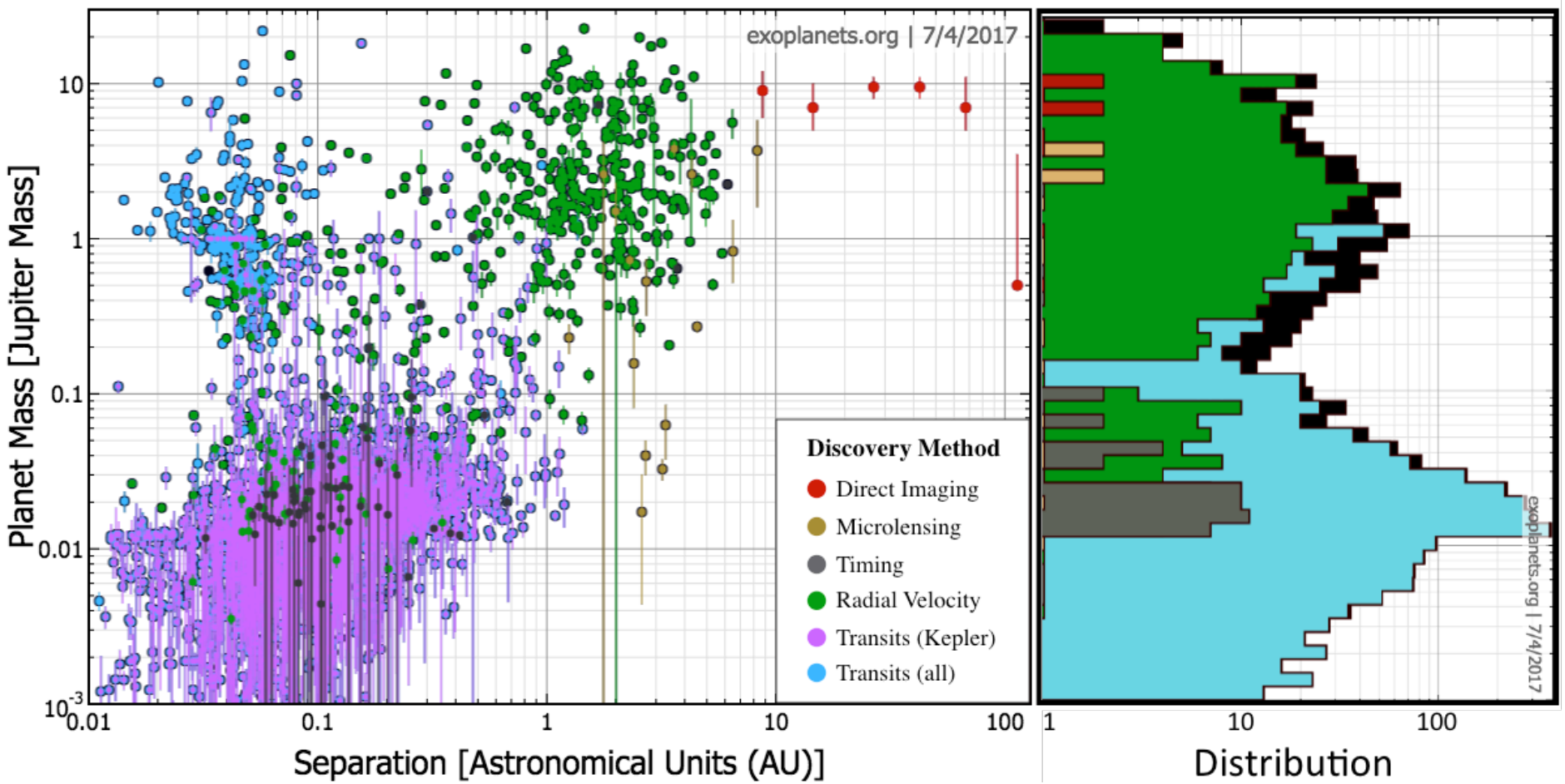
Companion vs. Speckle Shapiro-Wilk Test



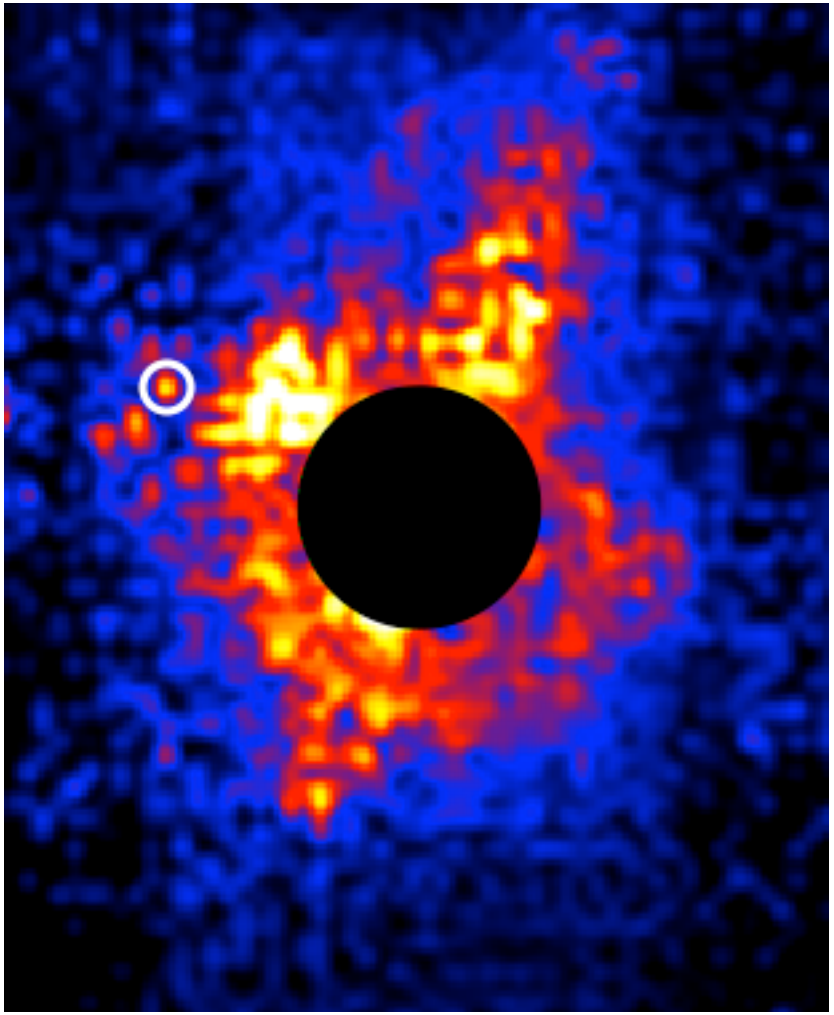
Pi Her, 5 ms exposures

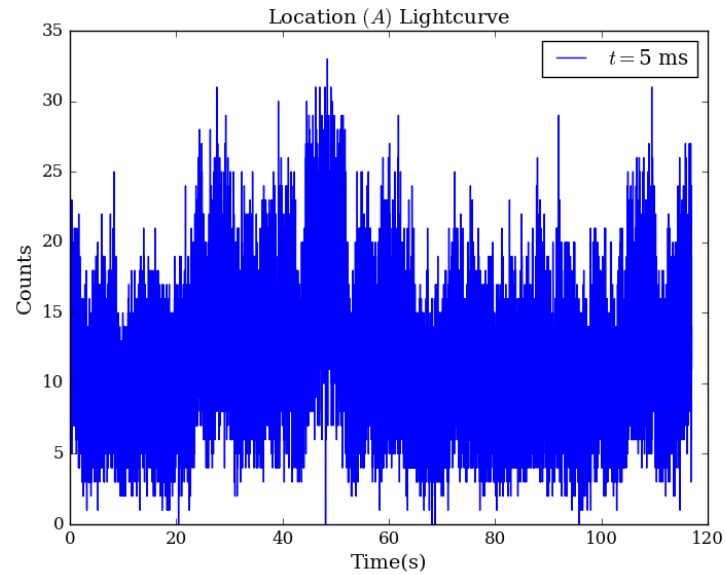


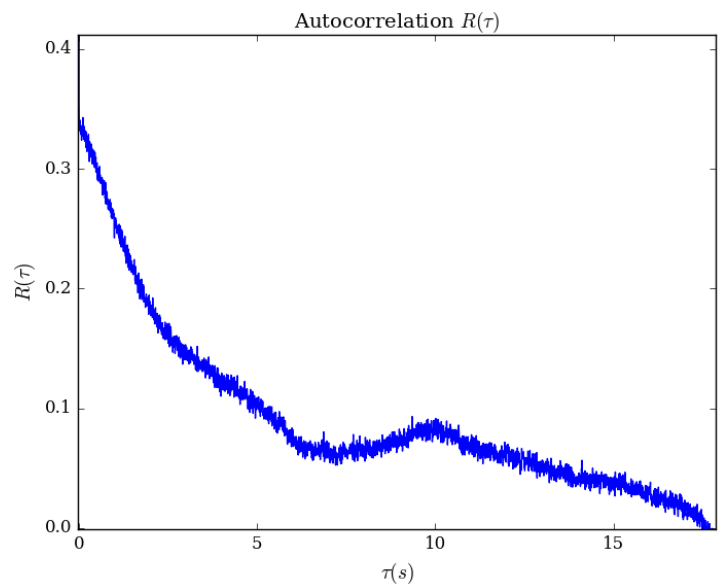
Known Exoplanets



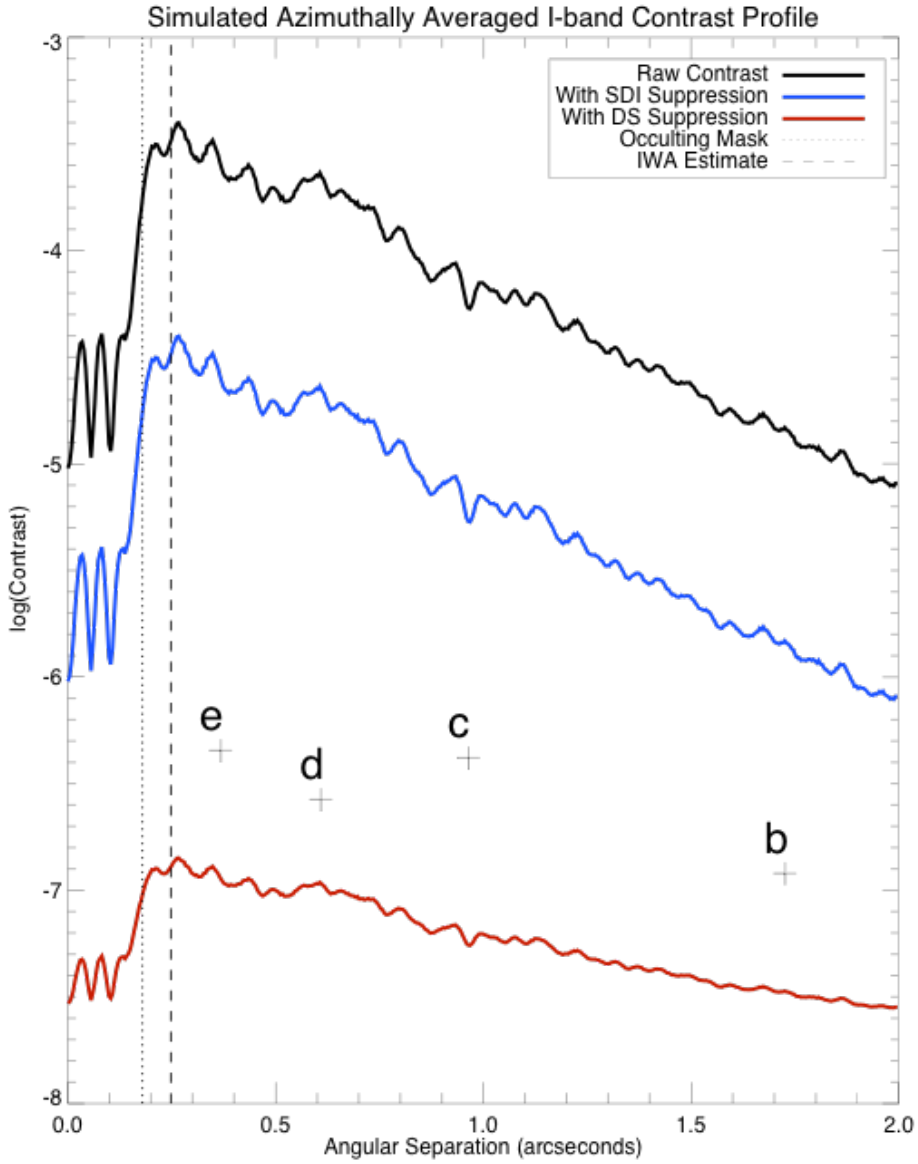
Calibration Source Speckles

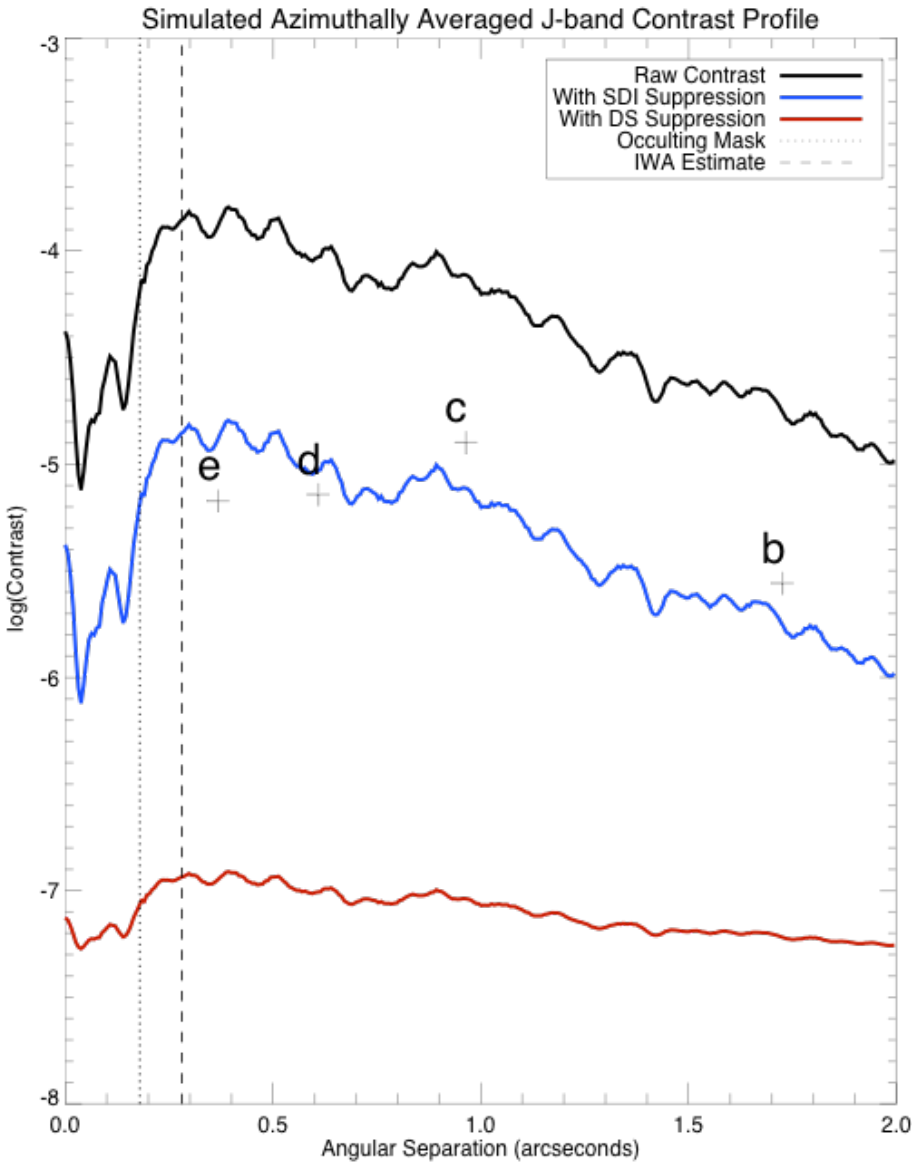






Contrast Prediction



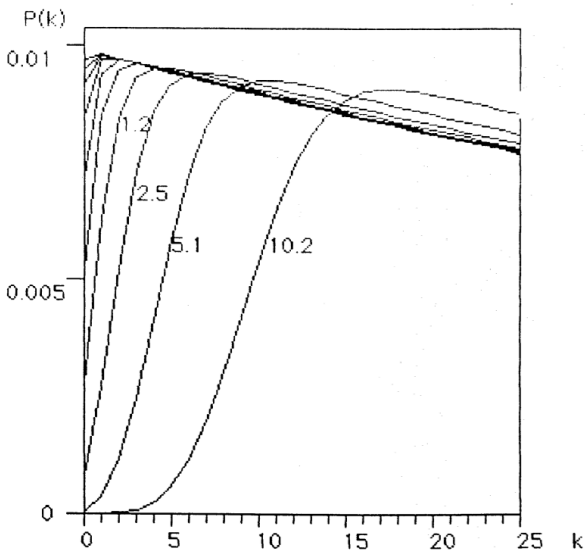


Dark Speckle

- Presented in Labeyrie 1994 and refined by Boccaletti et al. 1998b. Regions of highly destructive interference in the speckle pattern will leave completely black spots with zero photon counts.

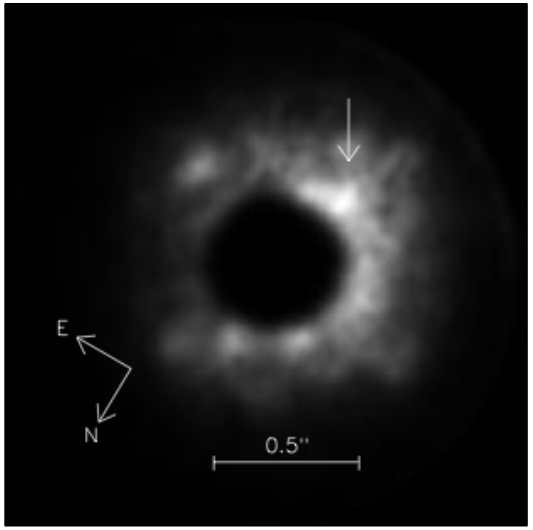
- Planets stick out as regions that always measure non-zero counts

- Must sample faster than speckles (milliseconds)

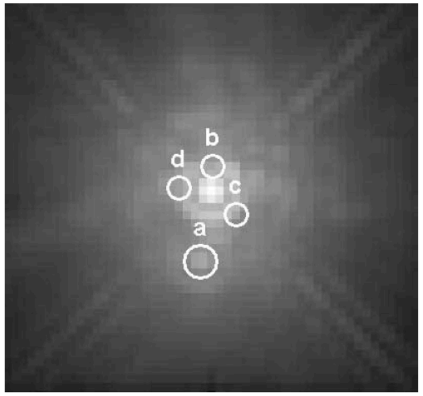


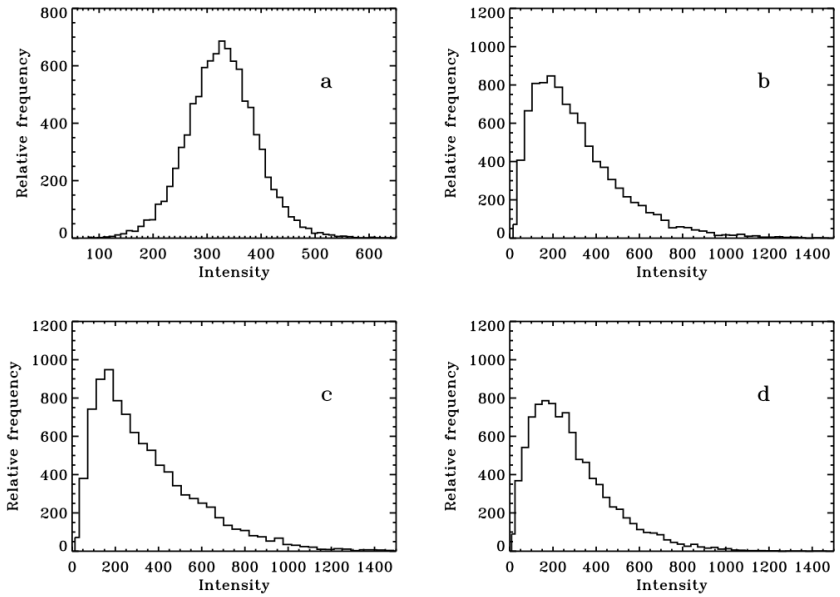
Photon-counting/Arbitrarily Short exposures

Zero dark current or read-noise



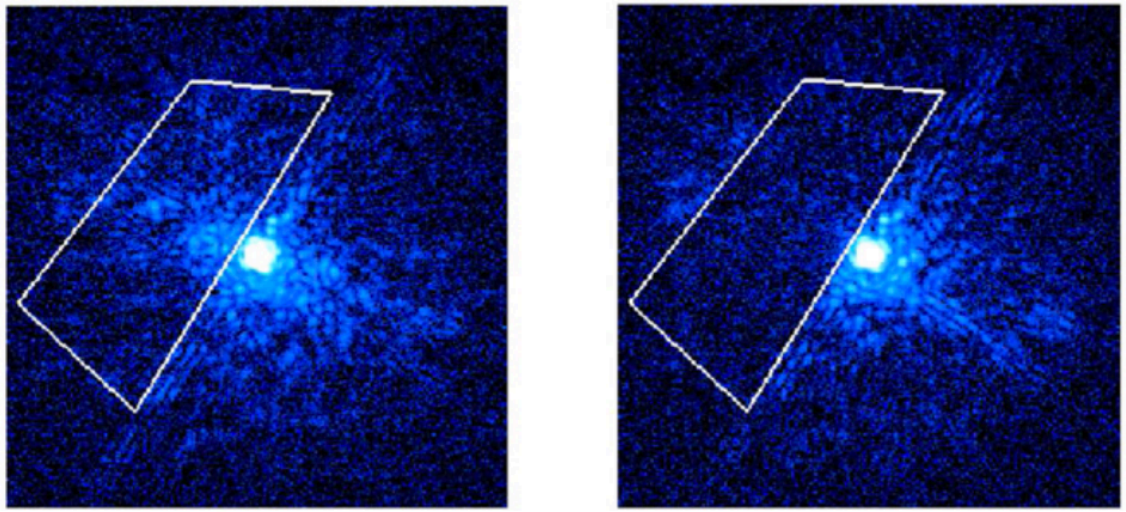
Speckle Mitigation Reminder





Post-processing Statistical Discrimination

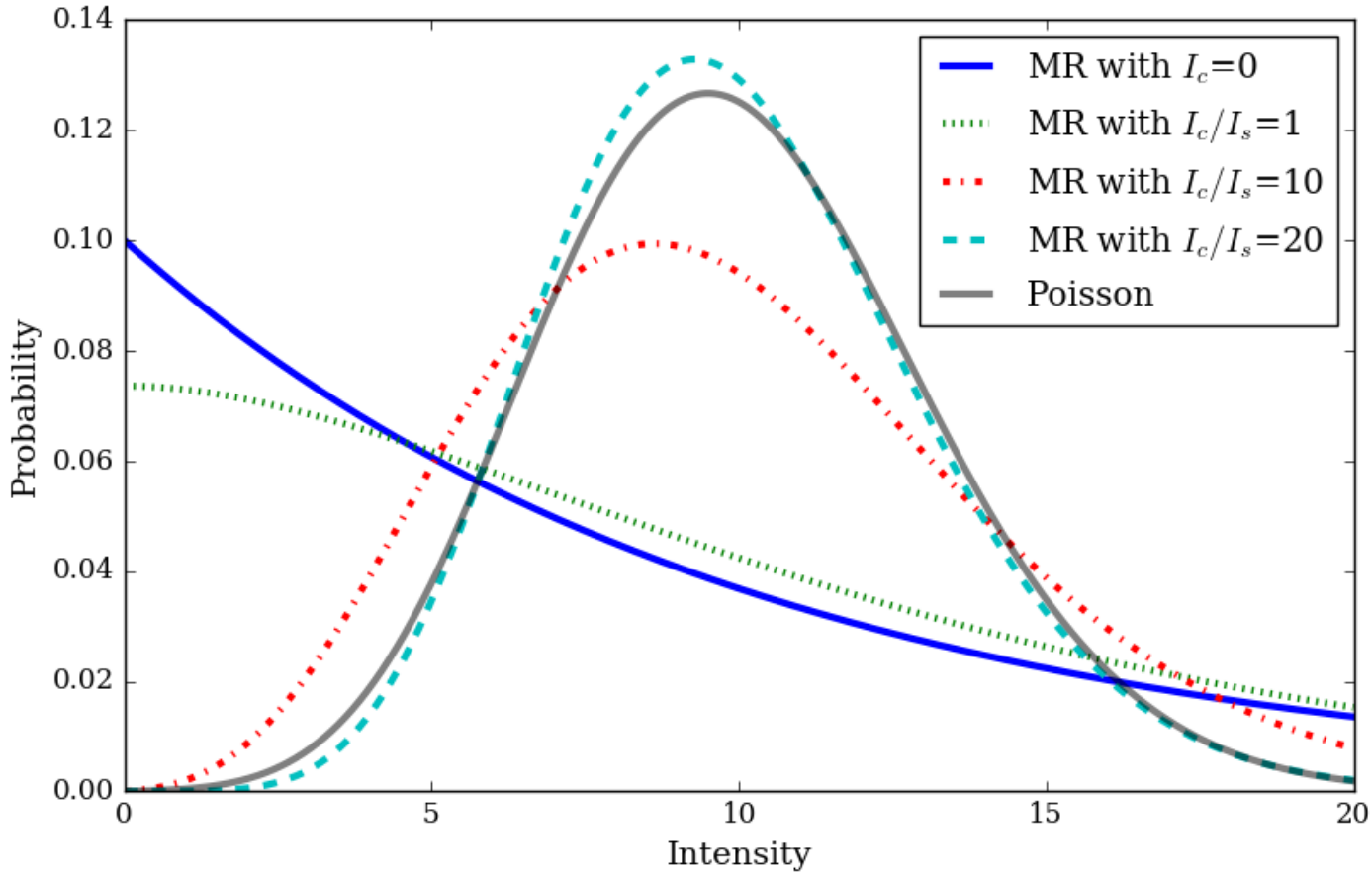
Active Speckle Nulling



Bottom+ 2016

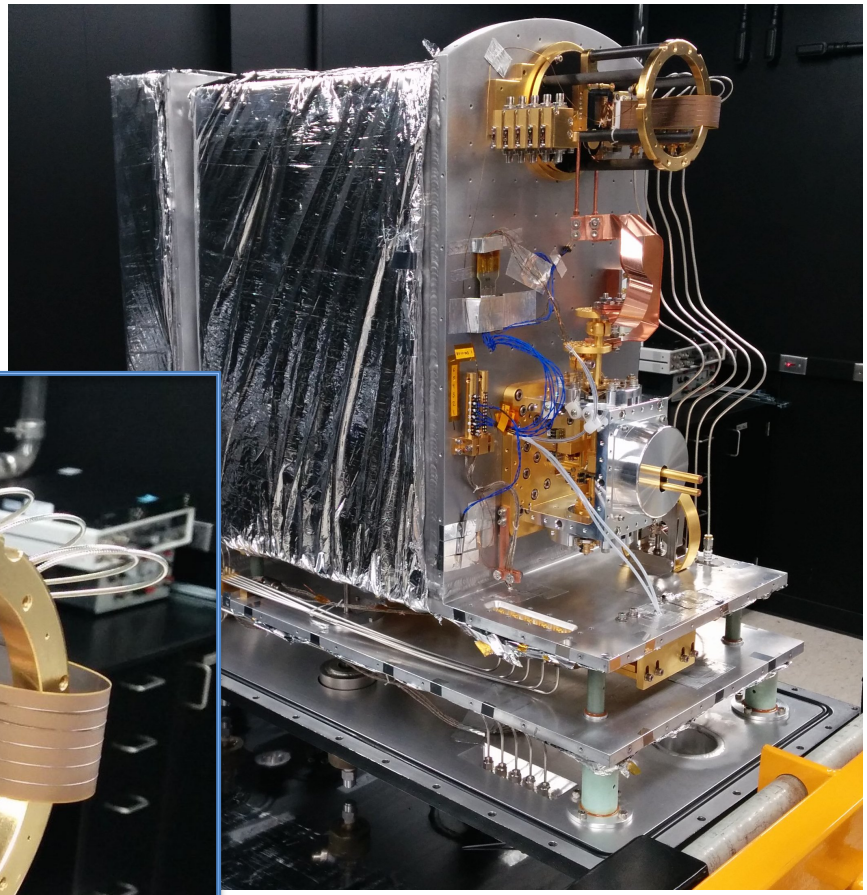
Speckle Statistics: Modified Rician PDF

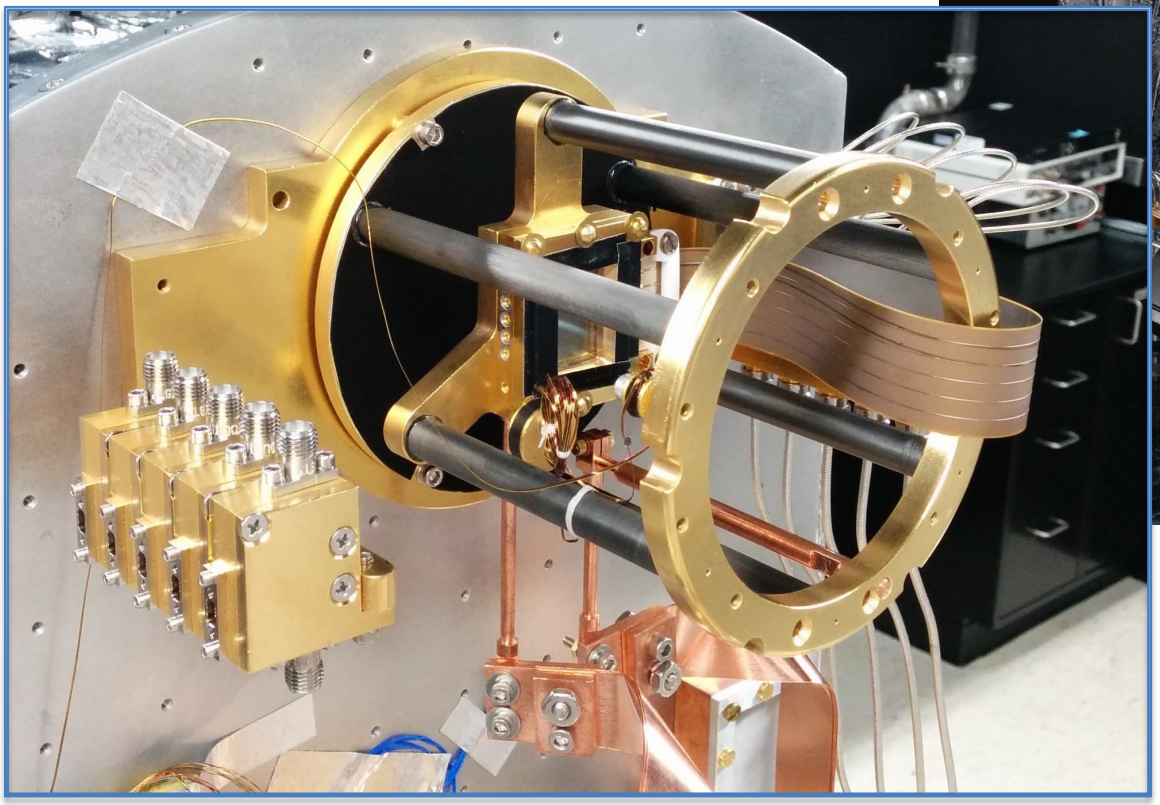
$$p_{MR}(I) = \frac{1}{I_s}\exp\left(-\frac{I+I_c}{I_s}\right)I_0\left(\frac{2\sqrt{II_c}}{I_s}\right)$$



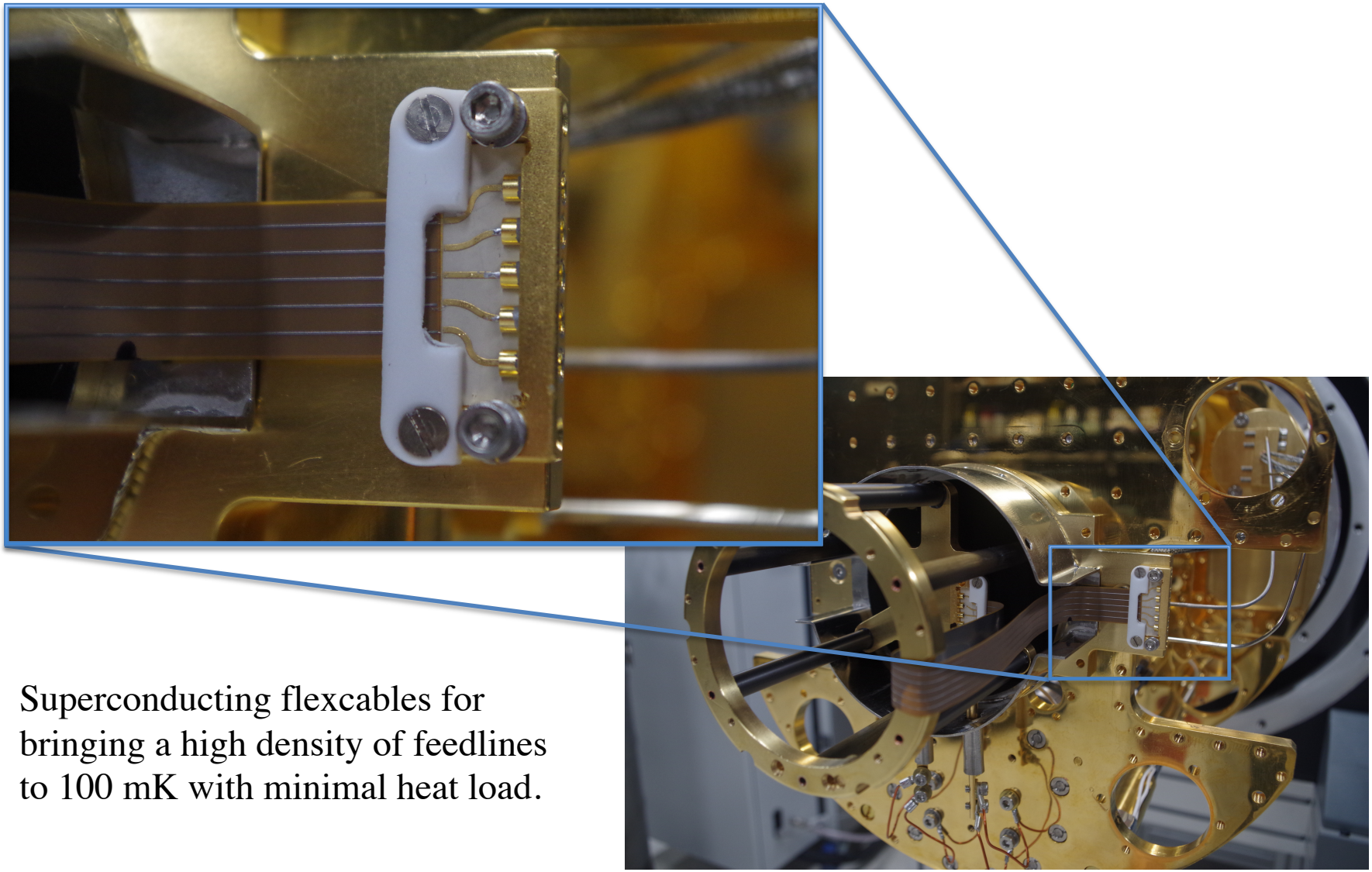
Device Mounting

Carbon fiber and vespel support structure designed for rigidity and thermal isolation of 100 mK stage





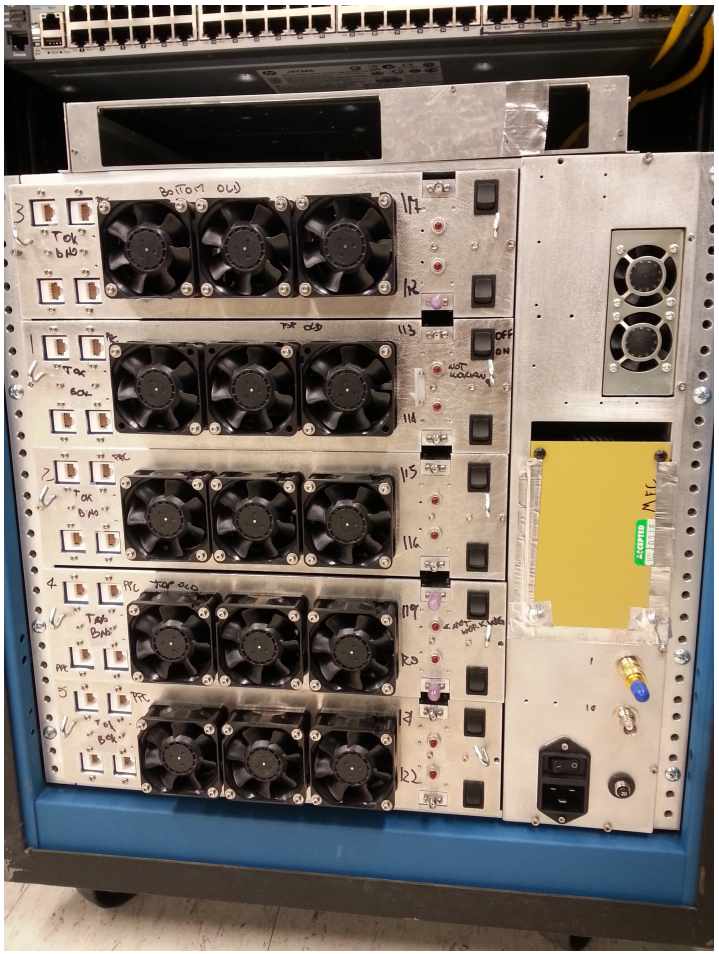
Wiring

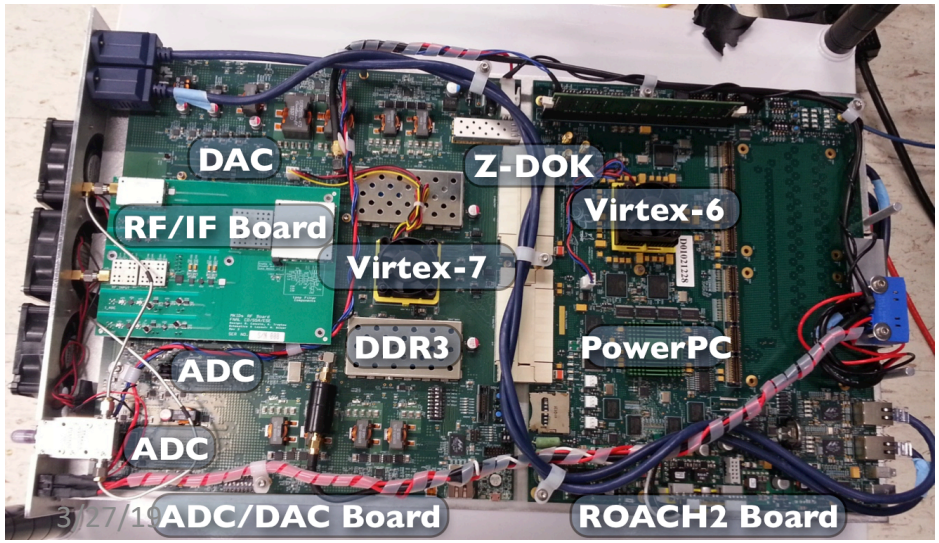


Superconducting flexcables for bringing a high density of feedlines to 100 mK with minimal heat load.

Gen. 2 Readout

- Design presented last LTD by Matt Strader
- 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

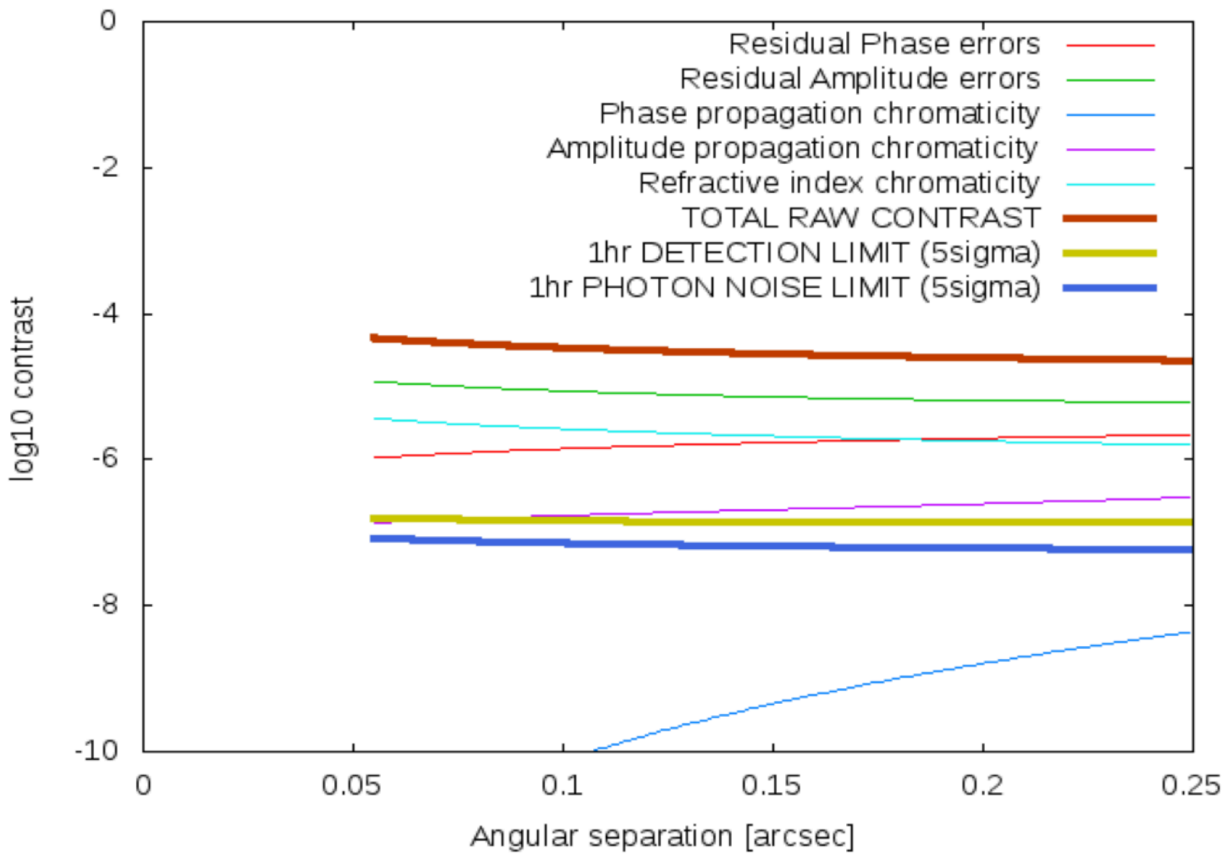




See Poster PB-7: "*A Second Generation Digital Readout for Large Photon Counting UVOIR MKID Arrays*" by N. Fruitwalla

Fast Speckle-Nulling Prediction

Slide courtesy of Olivier Guyon



Assumptions:

I mag = 8 (WFS > 100 targets)
H mag = 6 (Science)

Noiseless detector
1.3 l/D IWA coronagraph
30% system efficiency
40% bandwidth in both WFS and science
Time lag = 1.5 WFS frames

Mauna Kea “median” atmosphere