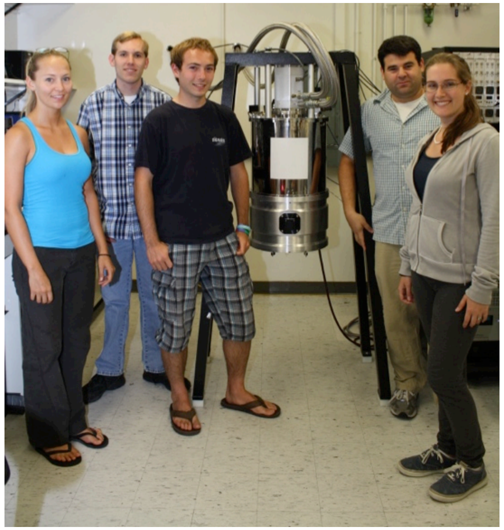
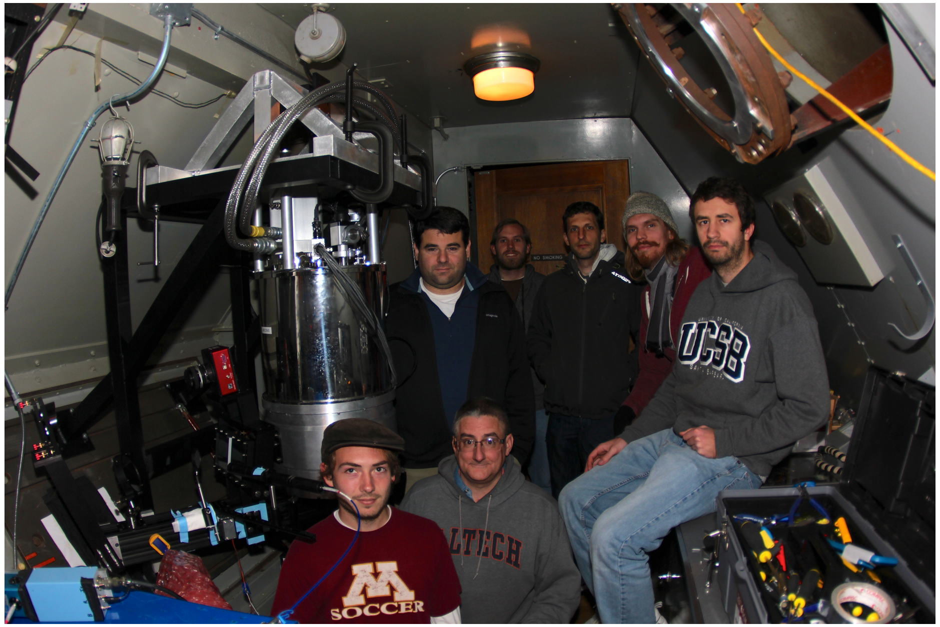


MKIDs for TMT

Ben Mazin, July 2014

The Optical/UV MKID Team:

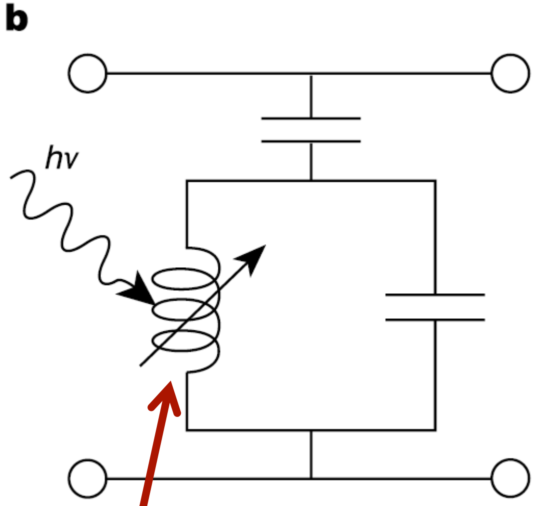
UCSB: Ben Mazin, Seth Meeker, Matt Strader, Paul Szypryt, Gerhard Ulbricht, Julian van Eyken, Alex Walter, Clint Bocksteigel
JPL/Caltech: Bruce Bumble, Rebecca Jensen-Clem, Shri Kulkarni, Tom Prince
Oxford: Kieran O'Brien
Fermilab: Chris Stoughton, Juan Estrada, Gustavo Cancelo and more…

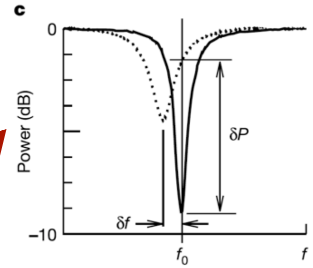


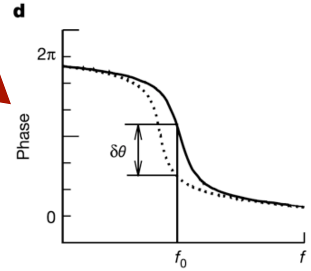
Mazin Lab @ UCSB JPL

MKIDs

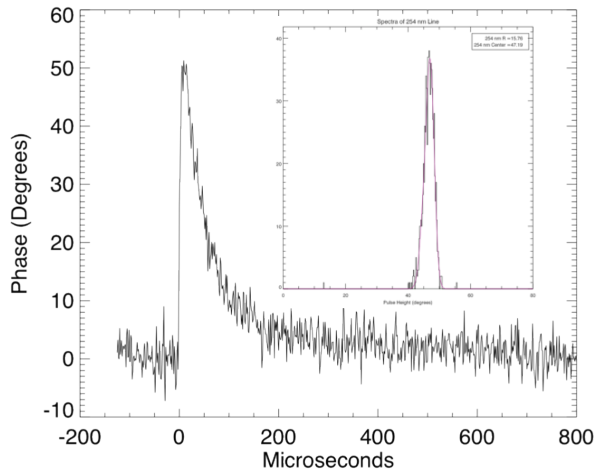
MKID Equivalent Circuit



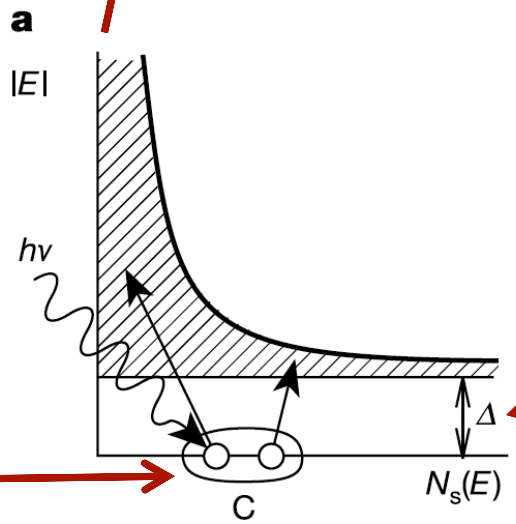




Typical Single Photon Event



Inductor is a Superconductor!



Cooper Pair

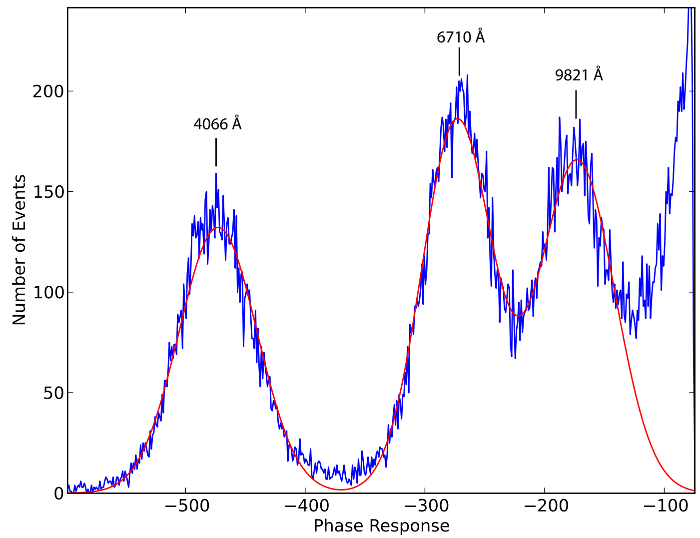
Energy Gap

Silicon – 1.10000 eV

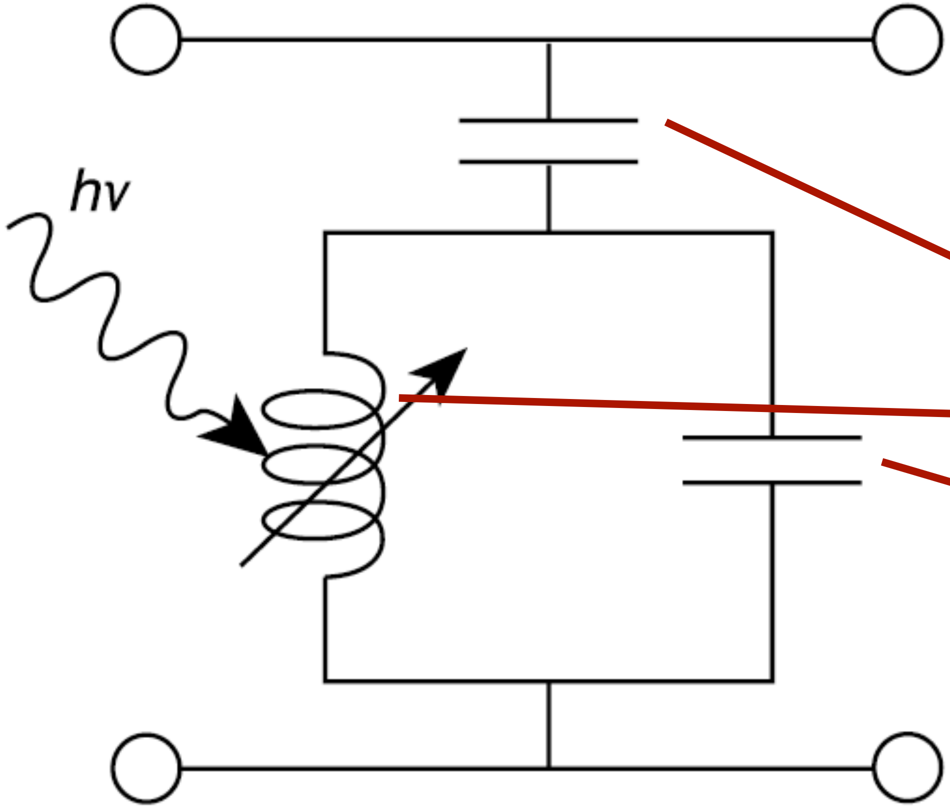
Aluminum – 0.00018 eV

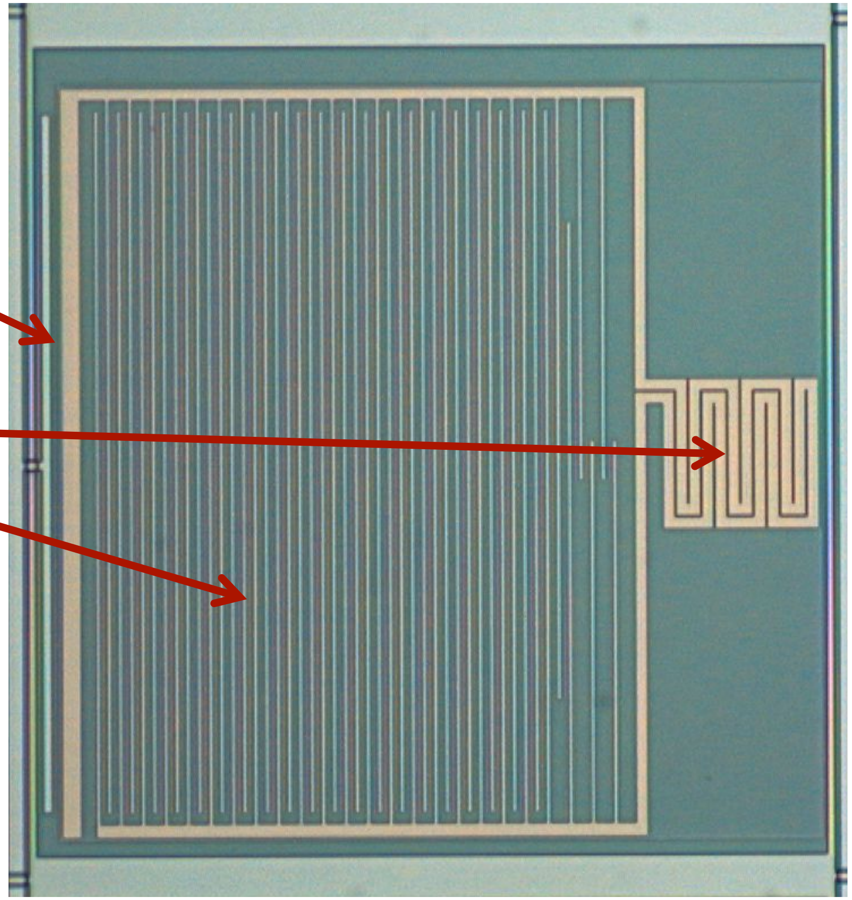
Energy resolution:

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



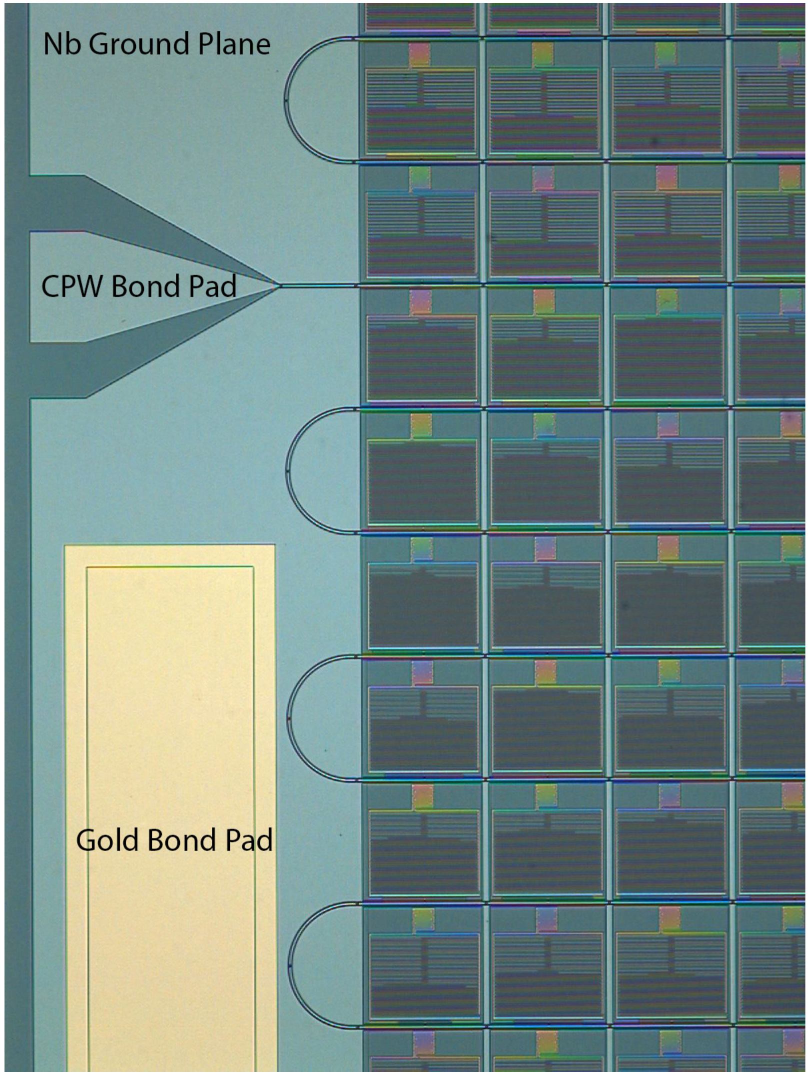
What is a Kinetic Inductance Detector ?

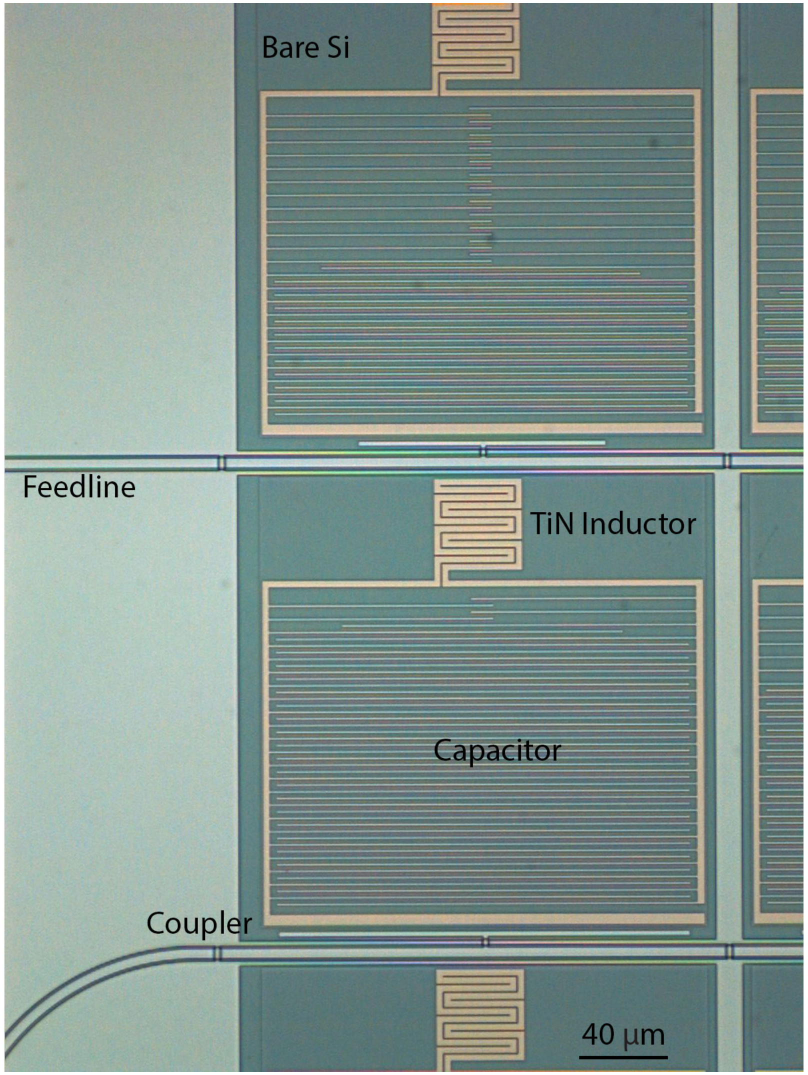




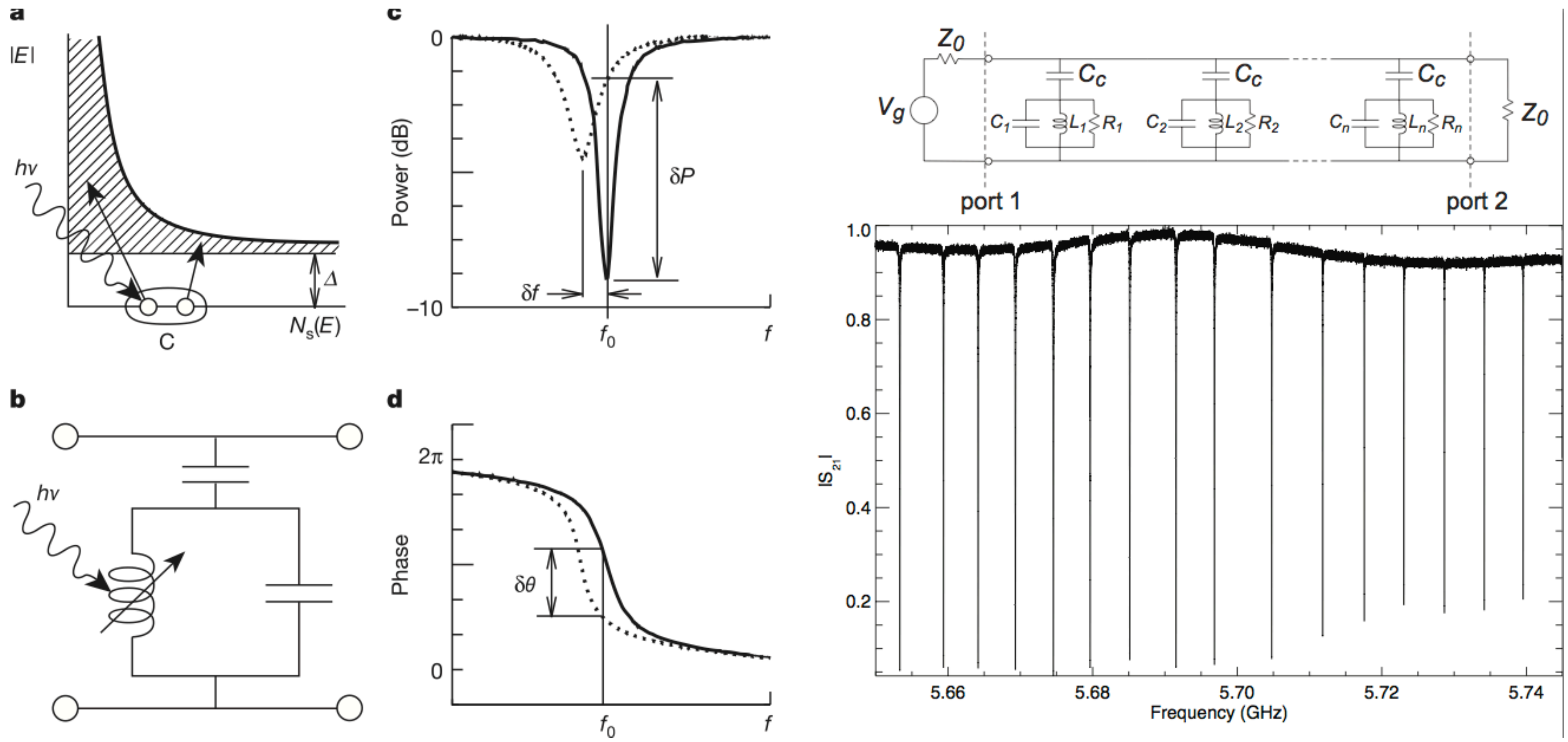
UVOIR MKIDs

- Directly absorb photons in the TiN_x (800 mK) MKID inductor
- Nb ground planes with SiO_2 crossovers: ~5 layers, ~3 man-days to fab at JPL
- Microlens array boosts fill factor to 92%. QE is 70% in blue, 30% in red – will improve!
- Large pixels are well suited to large telescopes



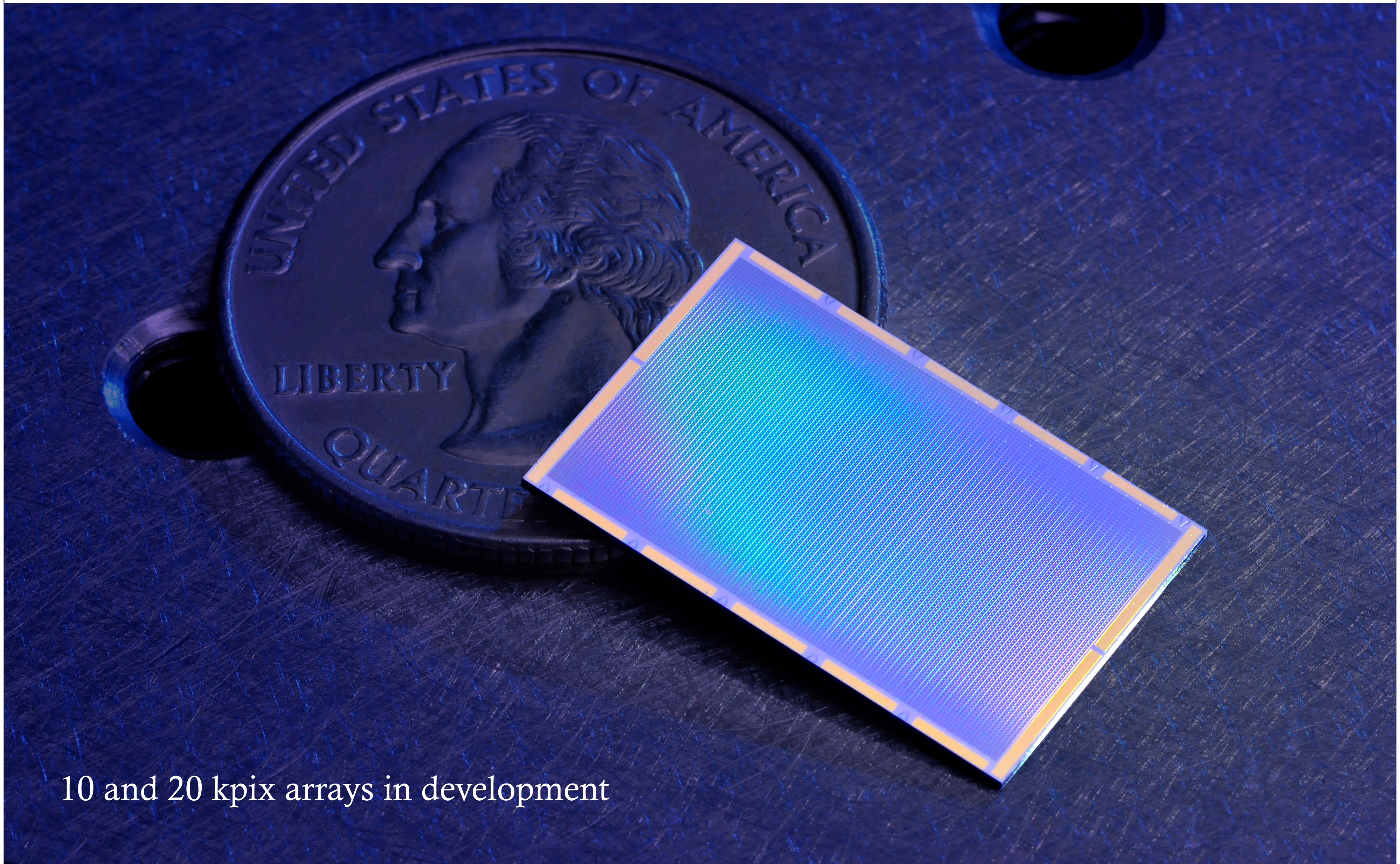


Frequency Domain Multiplexing



- 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

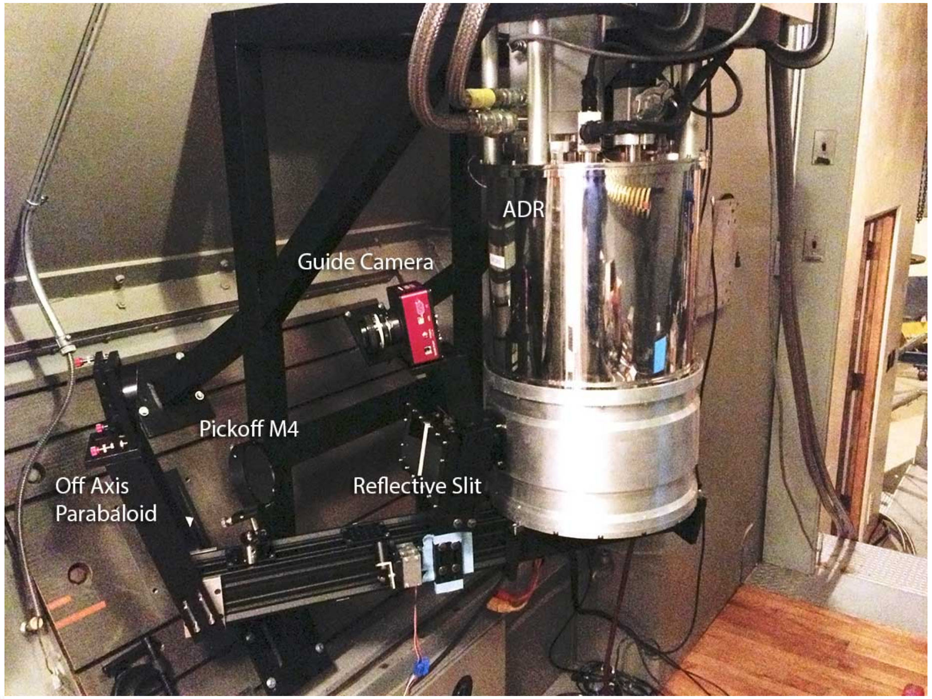


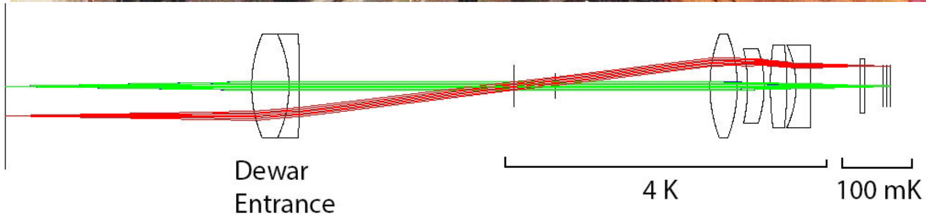
10 and 20 kpix arrays in development

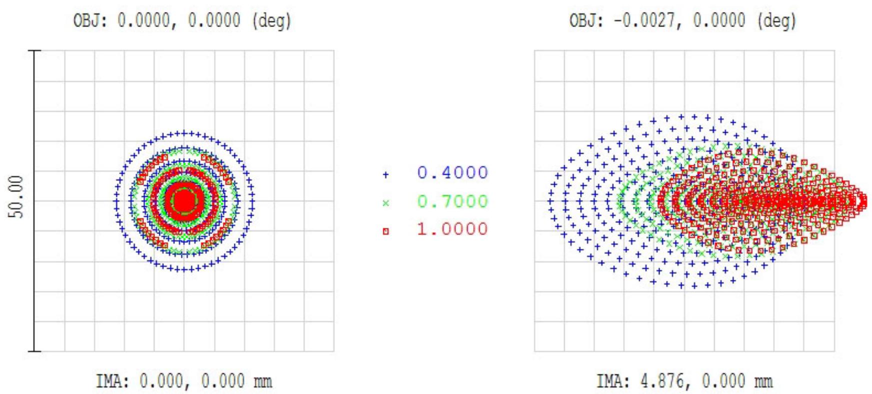
Proven at the Telescope with ARCONS

- Array Camera for Optical to Near-IR Spectrophotometery (ARCONS)
- First Light: July 28, 2011, Palomar 200” Coudé
- Now 29 observing nights (Palomar+Lick)
- Lens coupled 2024 (44x46) pixel array in cryogen-free ADR
- 0.5” pixels yields 22”x23” FOV
- 400 nm to 1100 nm simultaneous bandwidth with maximum count rate of ~2000 cts/pixel/sec
- 350-1350 nm soon
- Energy resolution R~8 at 400 nm

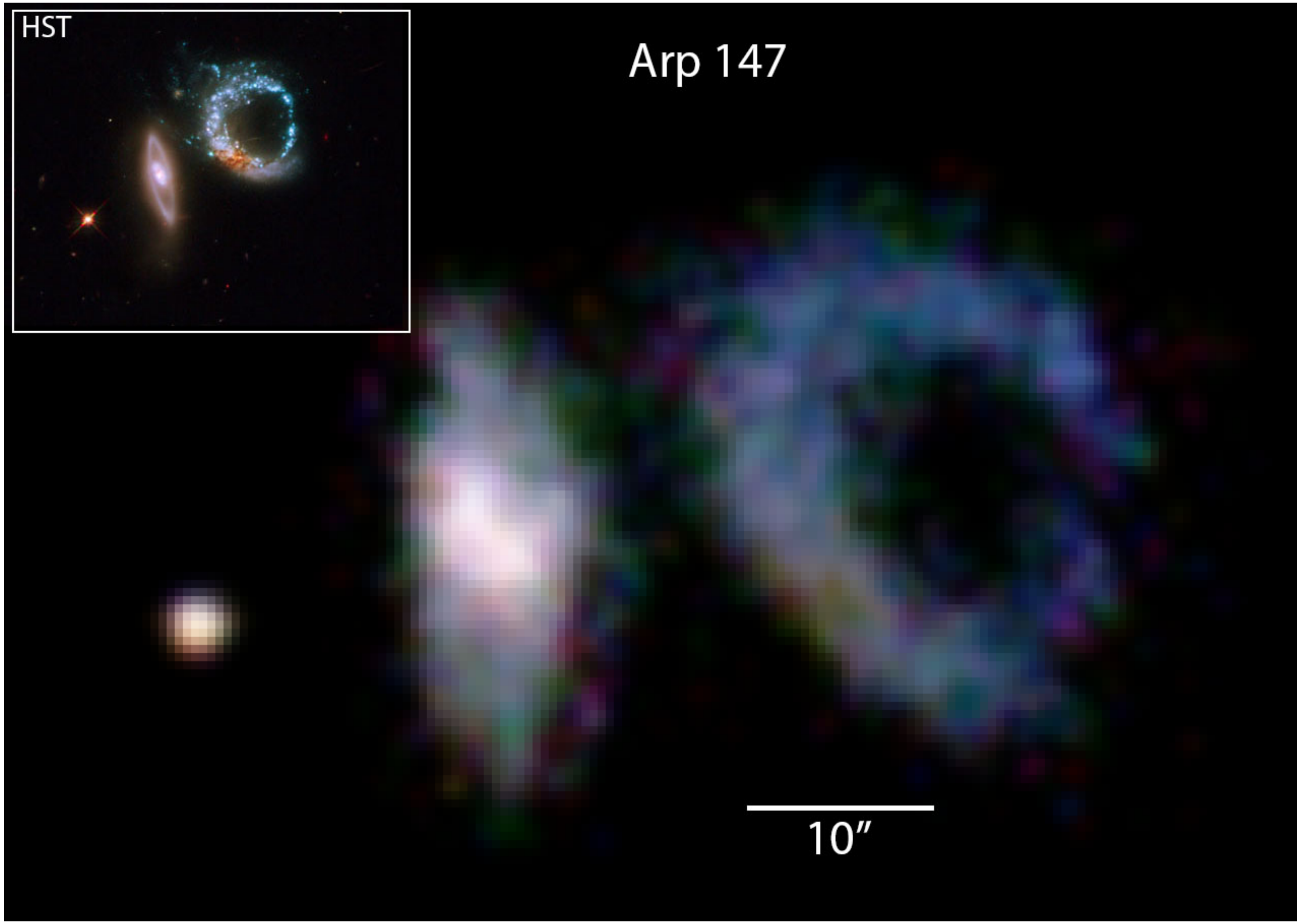
Mazin et al. 2013, PASP







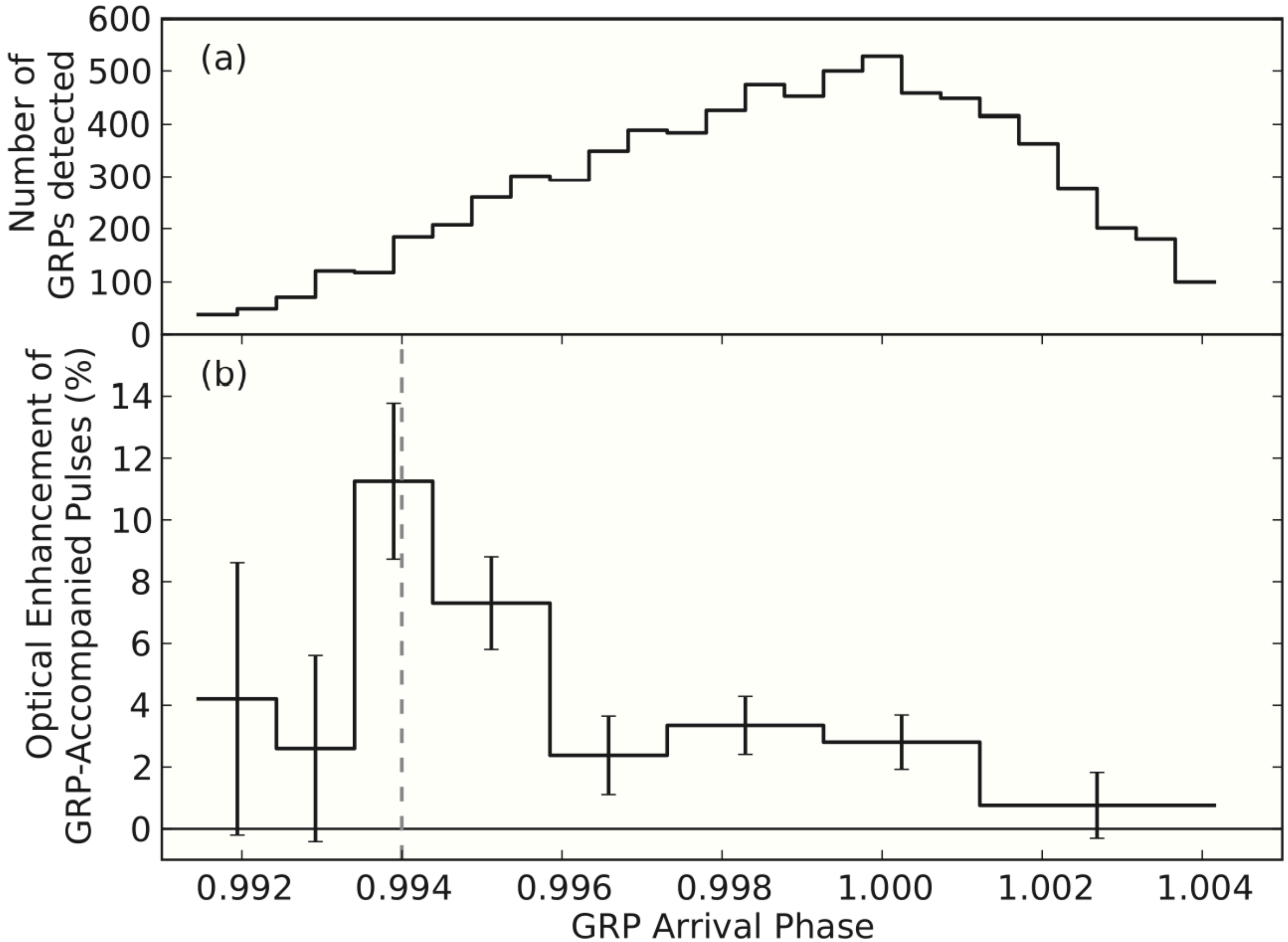
Mosaic of Arp 147



- 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!

Crab Phase/Brightness Correlation!

- Unexpectedly, we see a correlation between GRP arrival phase and optical flux. This has never been seen before, and seriously challenges established models of pulsar emission.

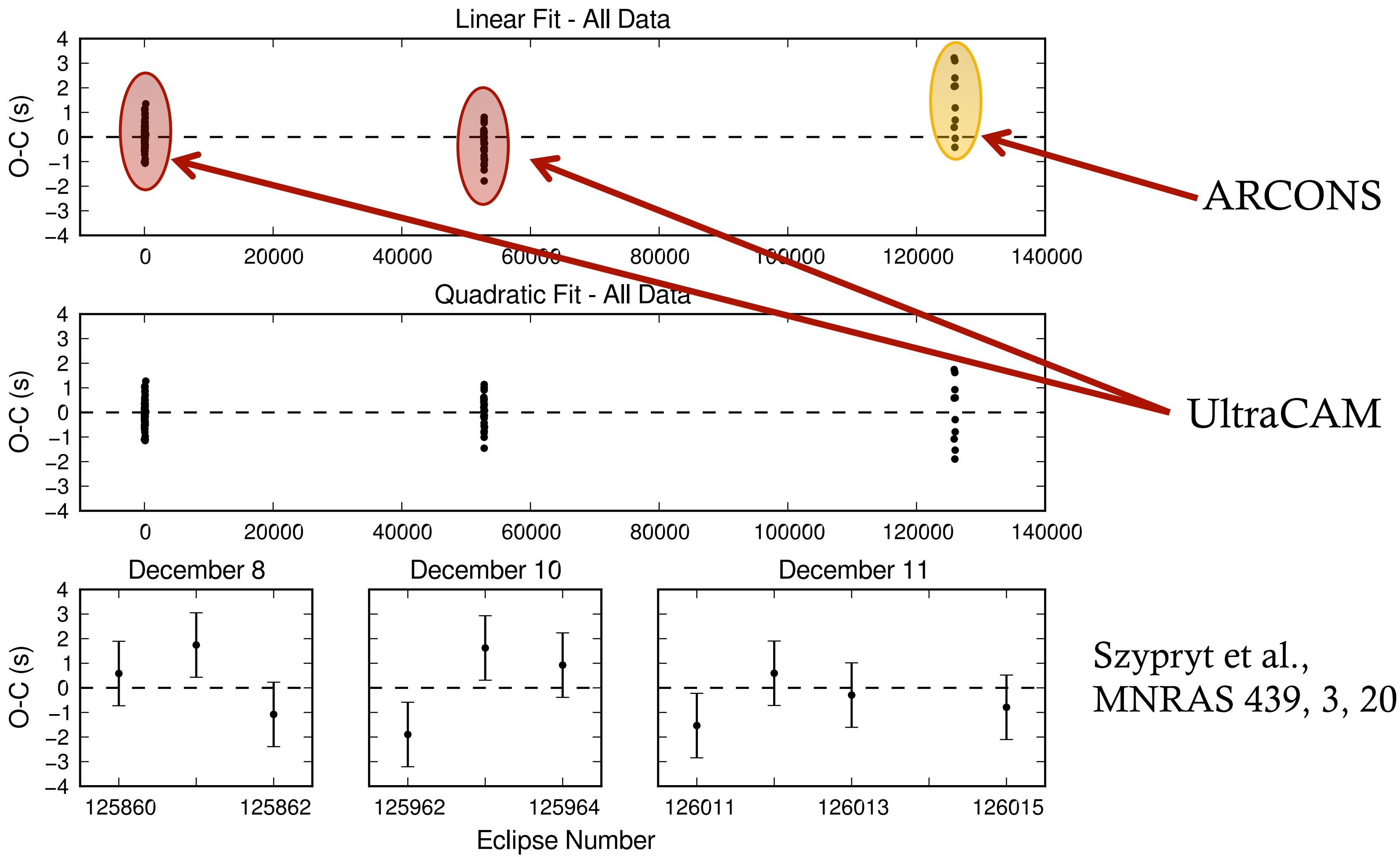


This is the first science paper published using MKID data at any wavelength!

Strader et al. ApJL, 779:L12, 2013

Am CVn Ephemeris

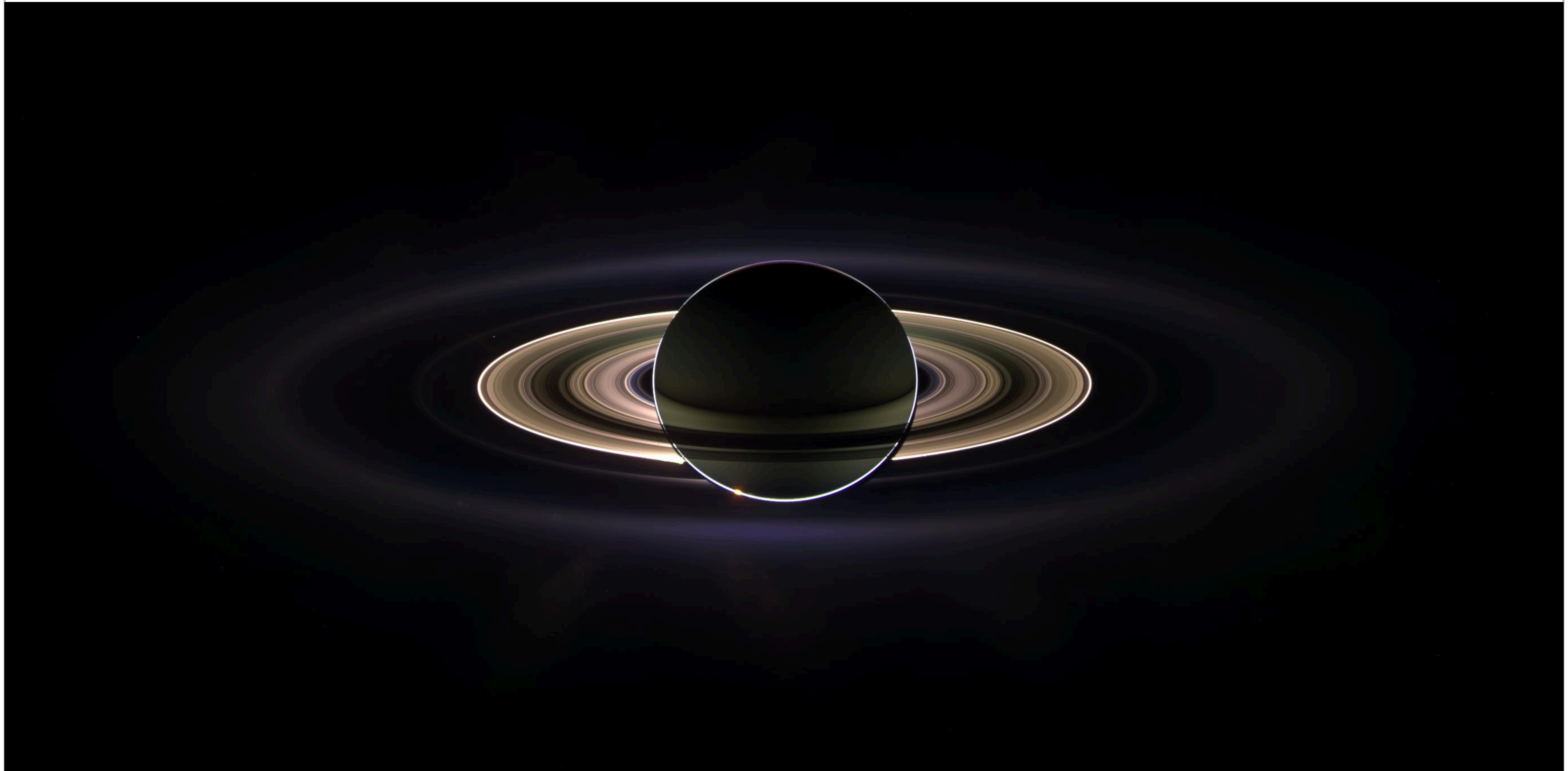
- Combining with data from Copperwheat 2011 (UltraCAM) allows 6 year baseline to determine ephemeris
- Pdot = 3.0 ± 0.5 x 10^{-13} detected for the first time!



Szypryt et al., MNRAS 439, 3, 2014

Now to the really fun part

- Are we alone?

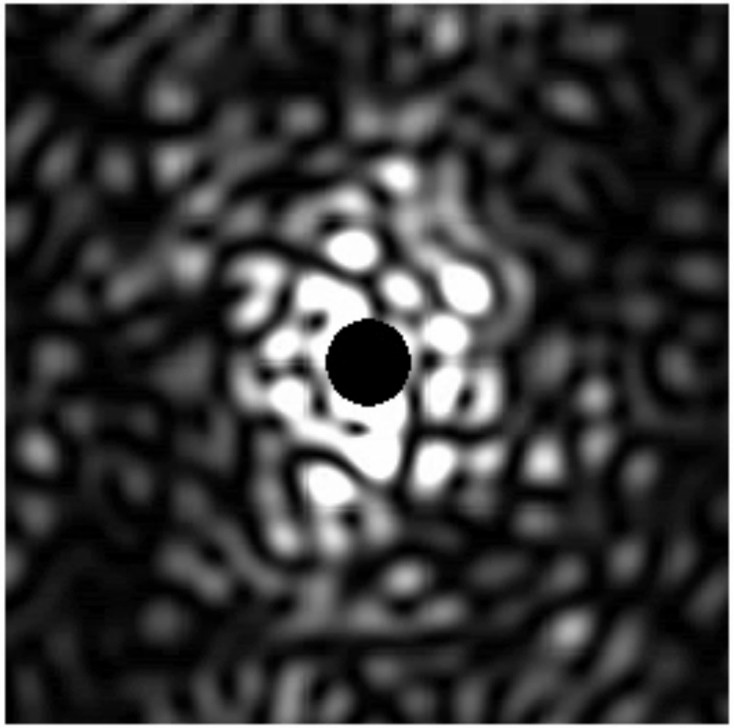


- This is now a well posed scientific question
  - Our best estimate is that 5-25% of stars have a ~Earth radius planet in their habitable zone!

IFU for Planet Finding

- Coronagraphs are limited by speckles from scattered and diffracted light
  - Energy-resolving focal planes (SDI) increase sensitivity by 10x
  - Time resolution, zero read noise (Dark Speckle, or DSI) can increase sensitivity by **100x**!
  - SDI and DSI are independent, should stack (simulations in progress by R. Jensen-Clem)
  - Direct feedback from MKID science camera to DM can remove atmospheric speckles, further increasing contrast
  - Gives the spectra of all planets in the dark box
  - DARKNESS for P1640/SDC recently funded by NSF
  - MEC for SCExAO recently funded by Japan

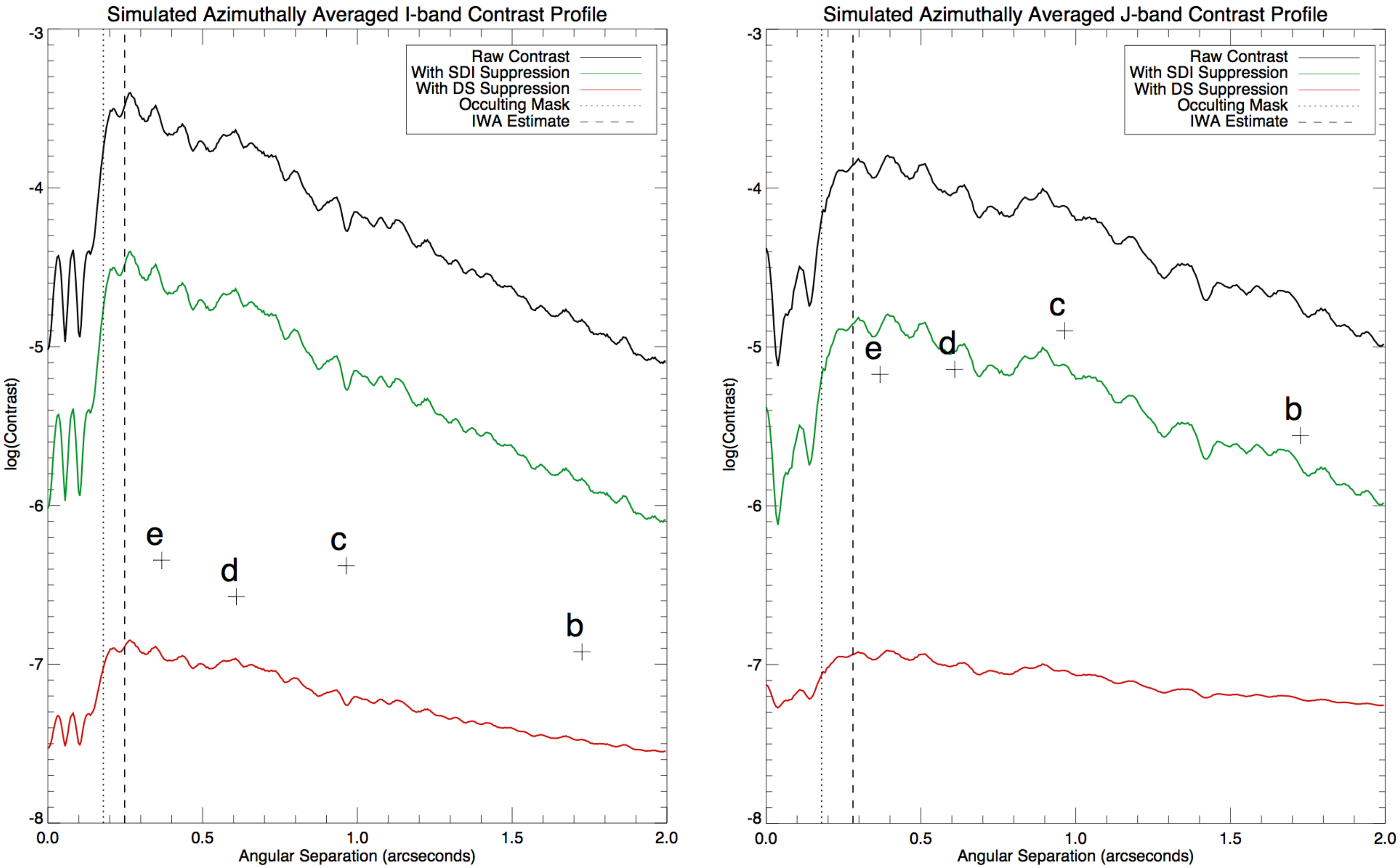
1.2



- Simulation from S. Remi and B. Oppenheimer
- DARKNESS paper just submitted to PASP, ask me for a preprint

P1640+DARKNESS Performance

- Simulated improvement of P1640 contrast using MKIDs and the Dark Speckle technique
  - Simulations by S. Meeker



TMT

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

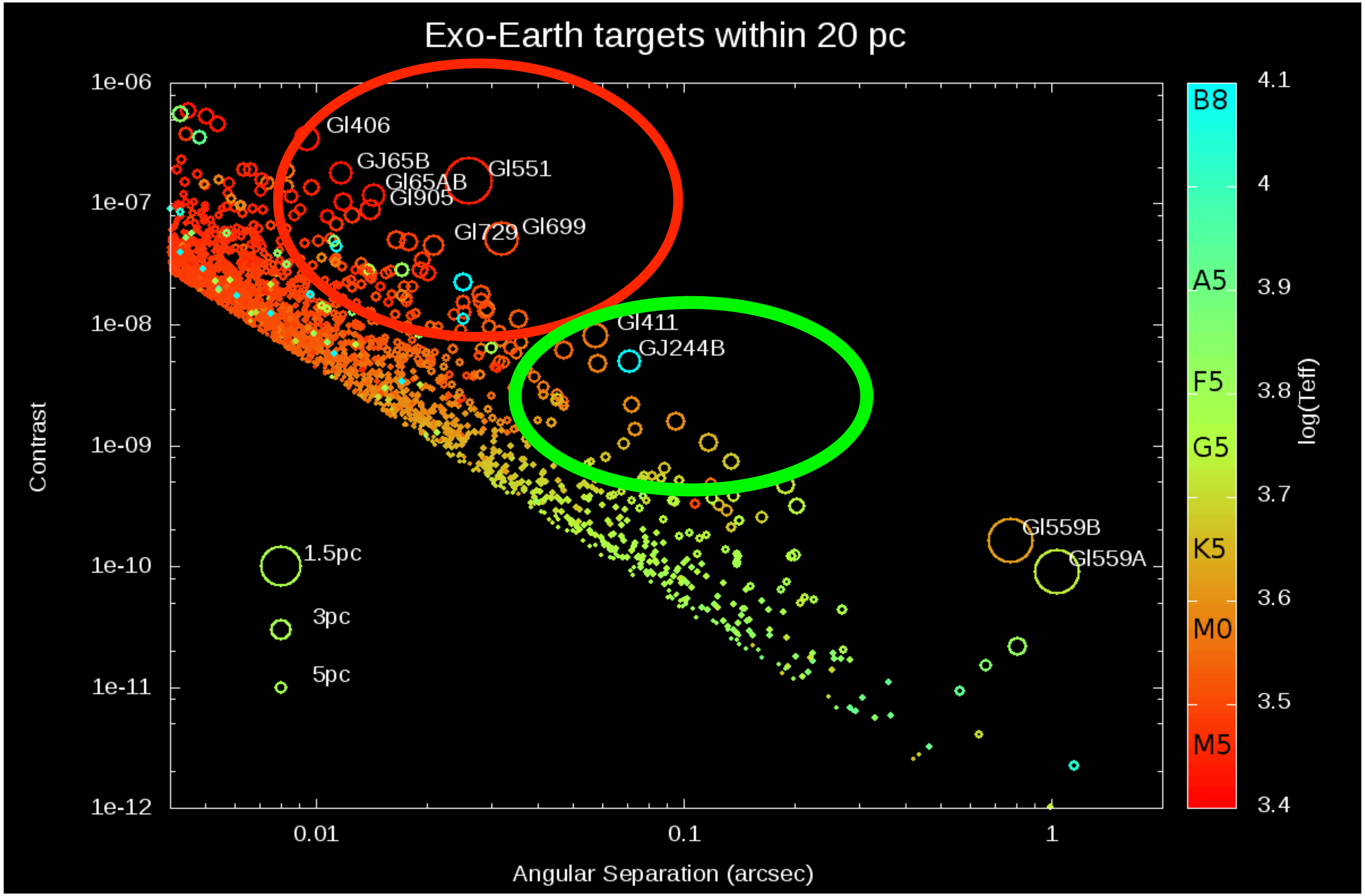


Figure from
O. Guyon

TMT PFI or Similar

- As we heard yesterday, ESO is fast tracking their E-ELT planet finder (EPICS)
- We must move up the schedule of the TMT planet finder or we will be scooped on what could be the cornerstone of TMT's scientific legacy!
- It is possible that SCExAO+MEC, with 10 years of tuning up and some minor optical modifications, could be moved from Subaru to TMT to allow M dwarf habitable zones to be imaged soon after first light at minimal expense, while a more powerful general purpose planet imager like PFI is built

Serendipitous Imager for TMT

- IRIS/IRMS use a VERY small fraction of the focal plane
- If we place a ~Megapixel MKID camera outside the footprint of NFIRAOS we get a nearly ***free***, deep, low resolution survey
  - Initial idea from Horrobin using CCDs, but MKIDs have many advantages:
    - The field is rotating, so MKIDs simultaneous imaging and spectroscopy allows more than one color
    - No integration time means that field rotation and telescope movement is no problem – no communication with IRIS/IRMS observers required.
    - AO experts at TMT predict seeing would be no worse than natural seeing
  - Some Issues:
    - Count rate limitations mean we would need small pixels or to limit bandwidth
    - Very high data rates
- Could be a dual purpose instrument with a different set of optics to interface to the third NFIRAOS port for pointed integrations on the faintest sources.
  - Optical pulsar timing of millisecond pulsars for GW detection?

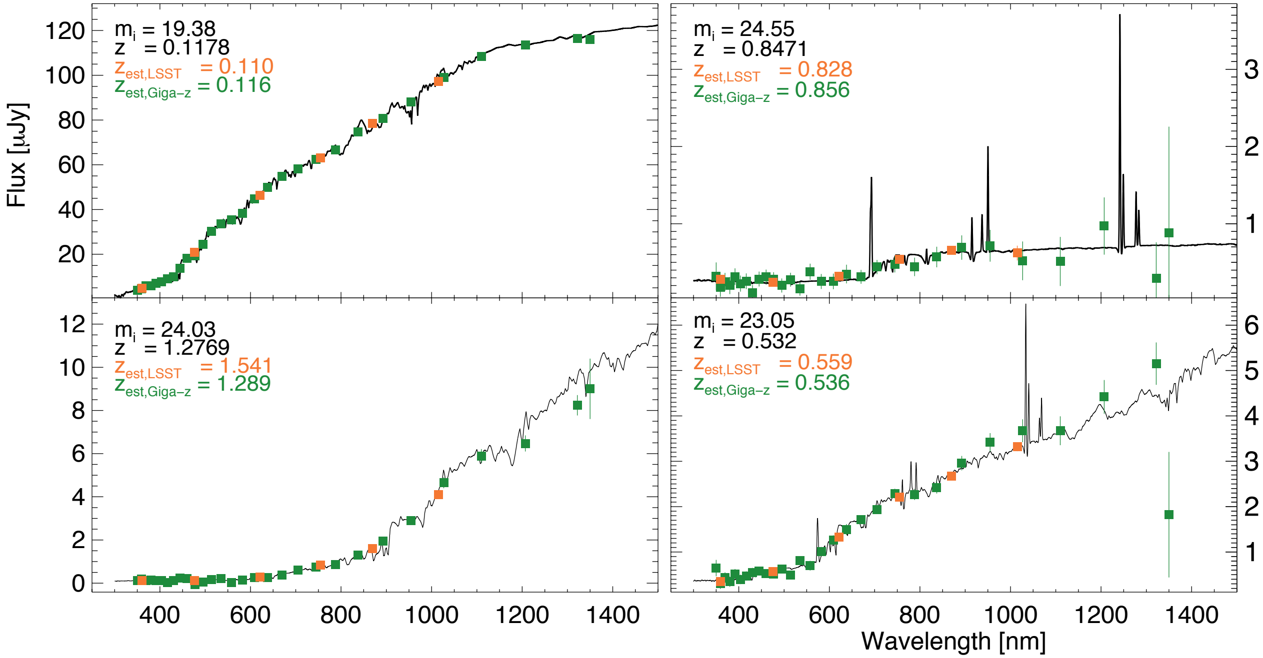
Mazin Lab at UCSB
http://goo.gl/ePAvg

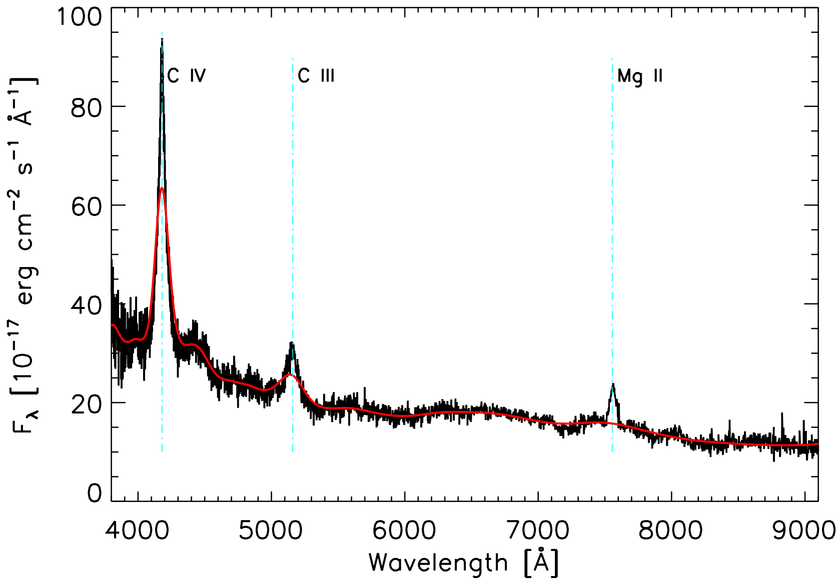
Giga-z Simulated Galaxy Spectra

Science is very similar to proposed Giga-z survey, but ~2 magnitudes deeper and gives images.

$\sigma_z/1+z < 0.01$ for field galaxies
$\sigma_z/1+z < 0.005$ for LRGs

Full Giga-z paper:
Marsden et al. 2013
ApJS, 208, 8
arXiv:1307.5066





KIDspec

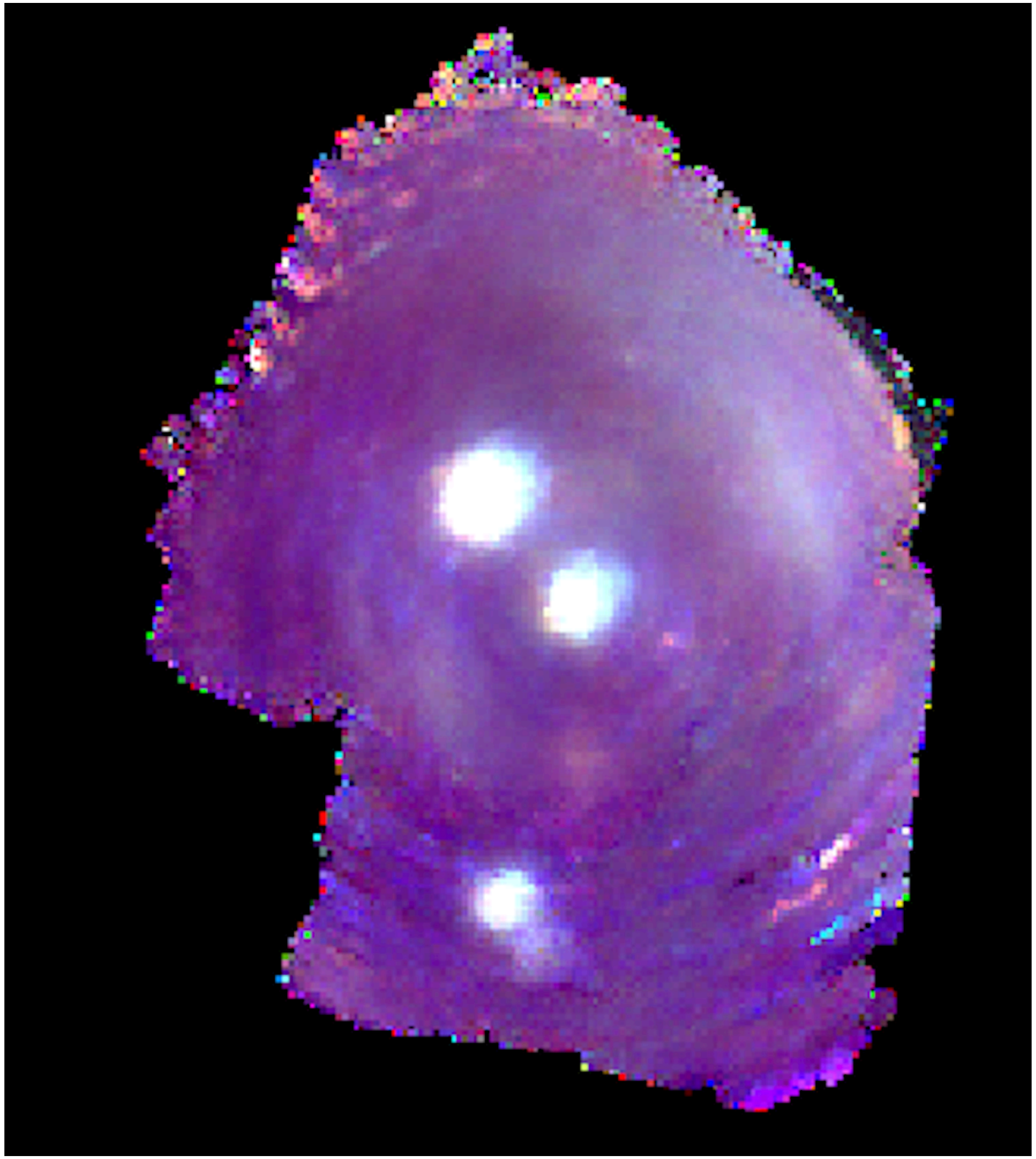
- Recently presented concept by Kieran O'Brien at SPIE, based on an older idea from Cropper to use an energy resolving detector as an echelle order sorter for an X-shooter like long slit spectrometer
- X-shooter is the most oversubscribed instrument on VLT
- High efficiency since no cross disperser, much simpler and more compact optical design
- Wide bandwidth: 0.3-2.5 microns
- Medium resolution: R=5000-10000
- Probably uses two arms to optimize MKIDs, gratings, and coatings
- Photon counting readout without integration time allows better sky subtraction since you can track sky lines on short time scales

Summary

- The best telescope needs the best detectors!
  - 2 kpix MKID camera doing science at Palomar 200”
  - 10 kpix DARKNESS for P1640/SDC in Fall 2015
  - 20 kpix MEC for SCExAO in Spring 2016
    - May be capable of seeing known RV planets in reflected light!
  - 30-100 kpix KRAKENS for Keck I Bent Cass. Funded by Keck SSC to develop science case.
    - Complements K1DM3 for time domain science
    - Forming a team to define science case for KRAKENS
      - Especially non-time domain science
    - Talk to me if interested!
  - While this seems like a lot of instruments, they are actually very simple imagers and share most parts
- Proposals in for Balloon-borne MKIDs
- Megapixel arrays in 5-10 years
- Increasing energy resolution, yields, and QE – lots of room for improvement!
  - By 2024, we hope to have Megapixel arrays with R=50 at 400 nm and 90% QE

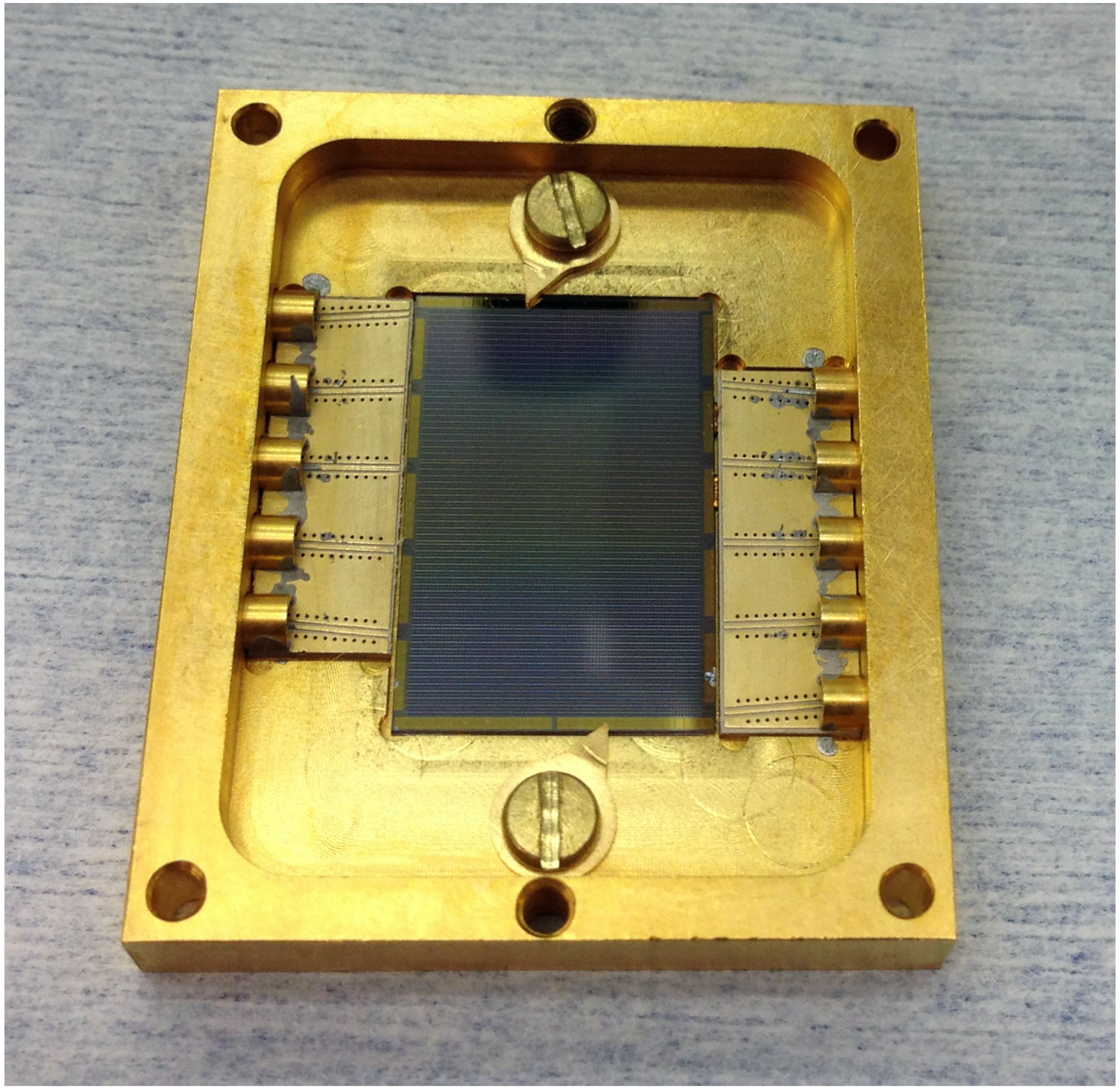
2 hours on Crab Pulsar

- Crab



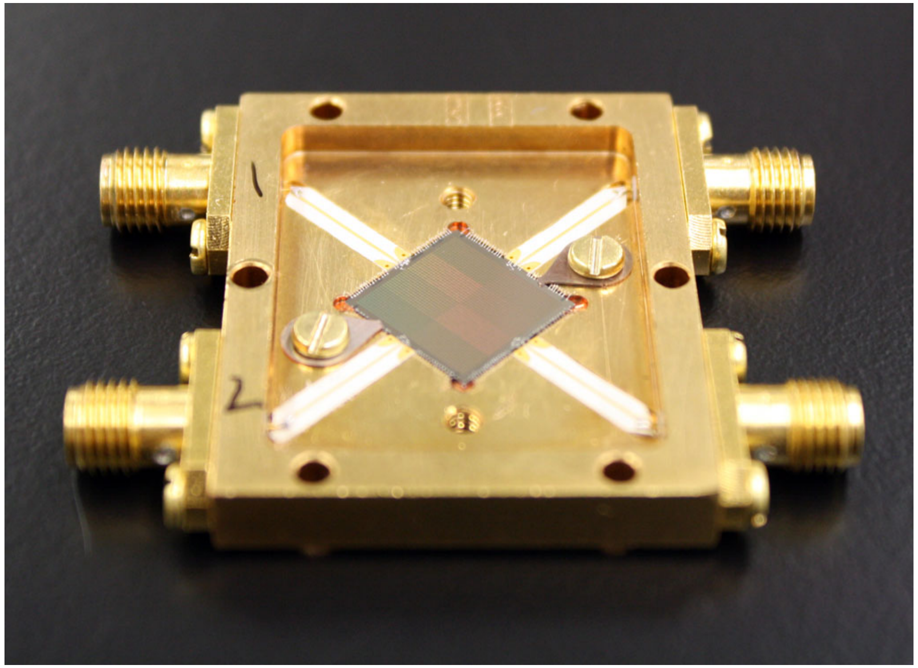
Mounting Box

- Using new G3PO connectors



UVOIR MKIDs

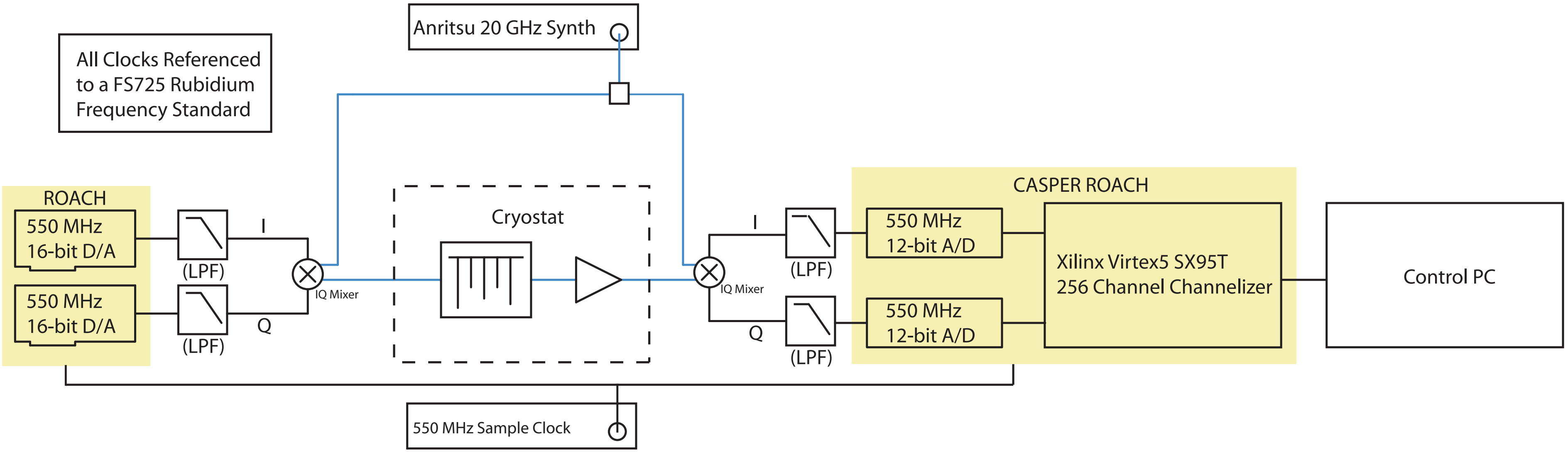
- Current State-of-the-Art
- 2024 (44x46) pixel array
- 222 micron pixel pitch
- 2 feedlines
- 2 MHz resonator spacing
- ~92% resonator yield
- ~70% “good” pixel yield
  - Frequency collisions dominate yield!
  - More uniform TiN (multilayer, ALD) should significantly improve yield
- 110 mK operating temp.



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

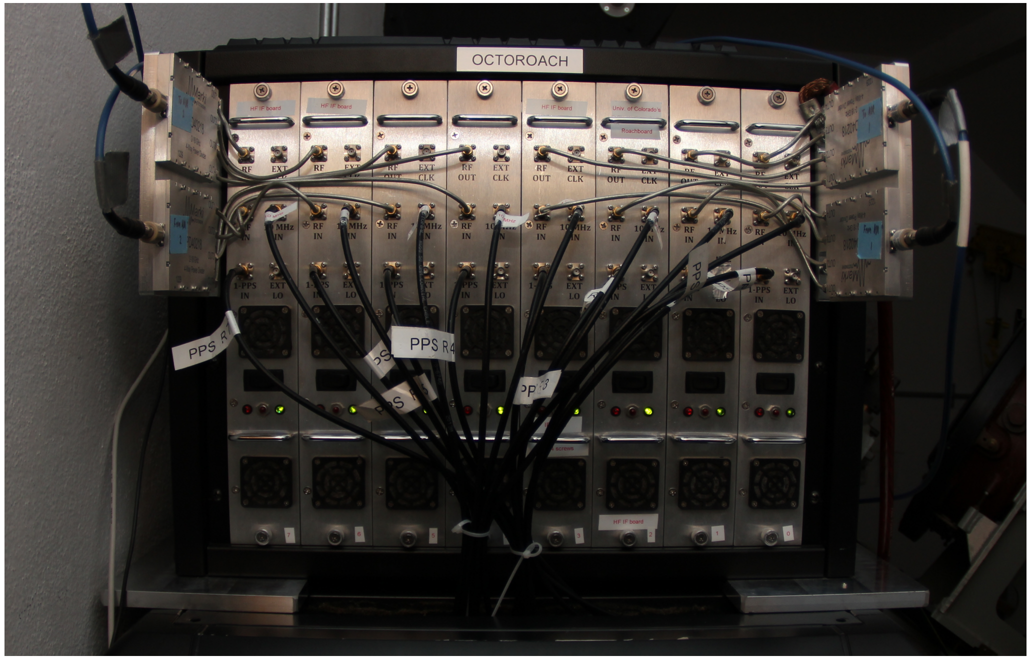
Digital MKID Readout

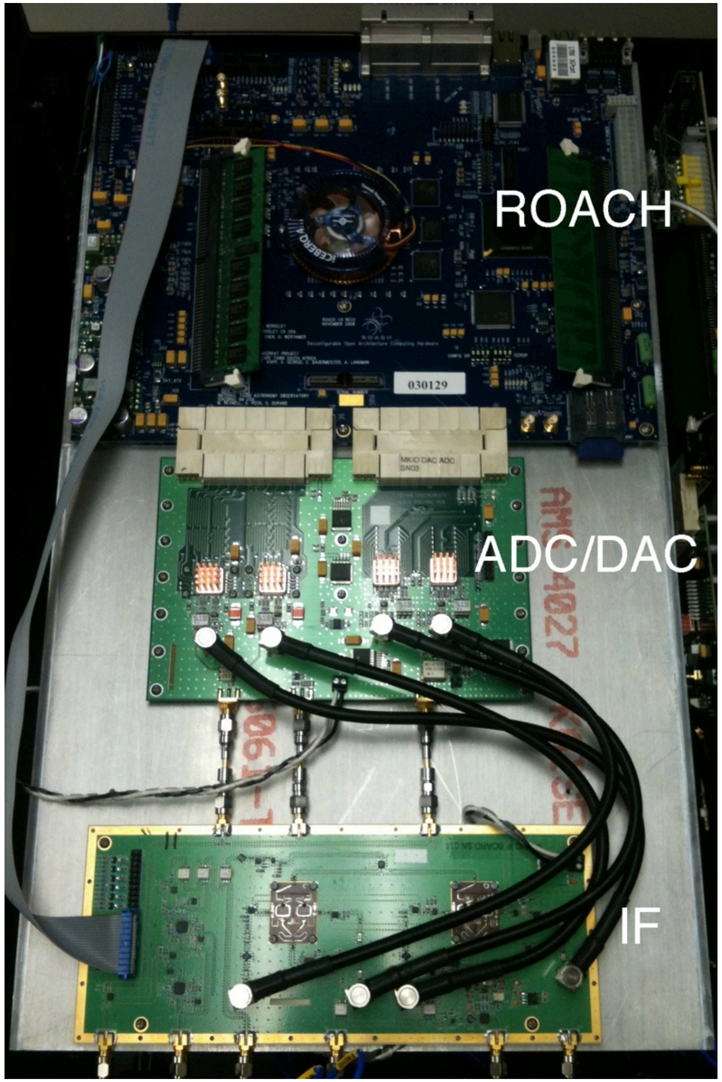
- Software Defined Radio (SDR) Overview
  - Leverages massive industry investment in ADCs/FPGAs
  - Generate frequency comb and upconvert to frequency of interest
  - Pass through MKID and amplify
  - Downconvert and Digitize
  - "Channelize" signals in a powerful FPGA
  - Process pulses (optical/UV/X-ray) or just output time stream (submm)



Current Readout System (Gen 1)

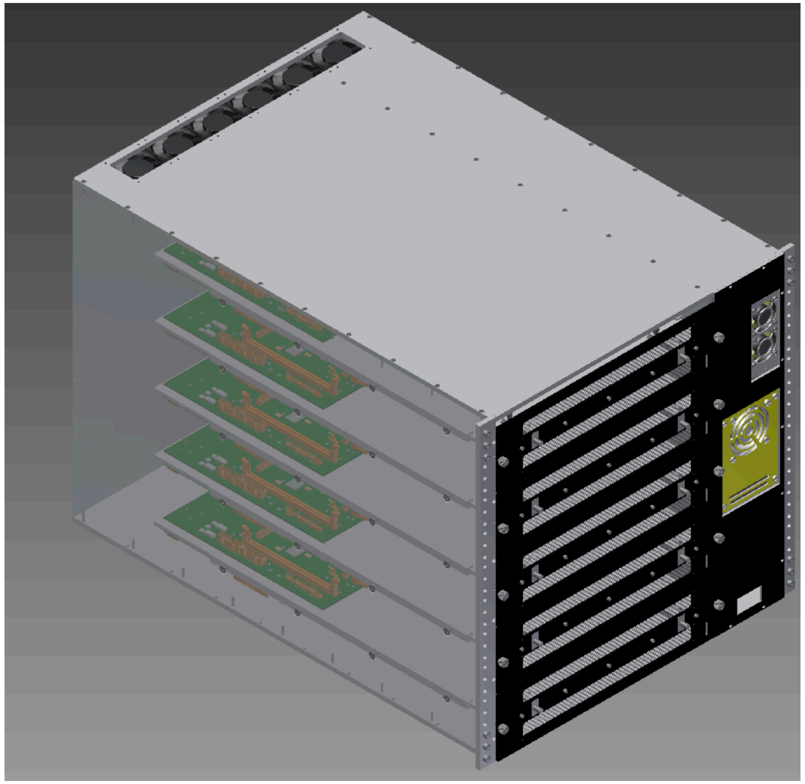
- Dual 1 GSPS 16-bit DACs
- Dual 550 MSPS 12-bit ADCs
- ROACH with Virtex 5 SX95T
- Complete readout for 256 resonators in 550 MHz of bandwidth
- 8 ROACH boards read out 2048 pix
- ~$25/pixel

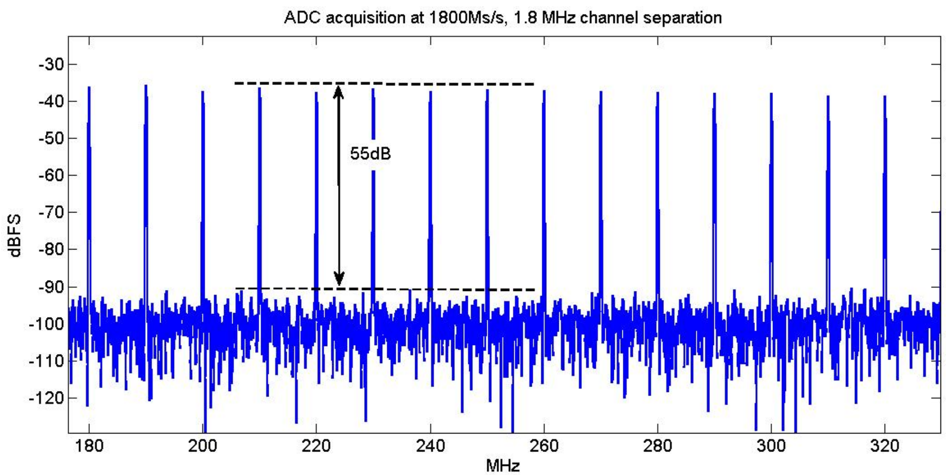


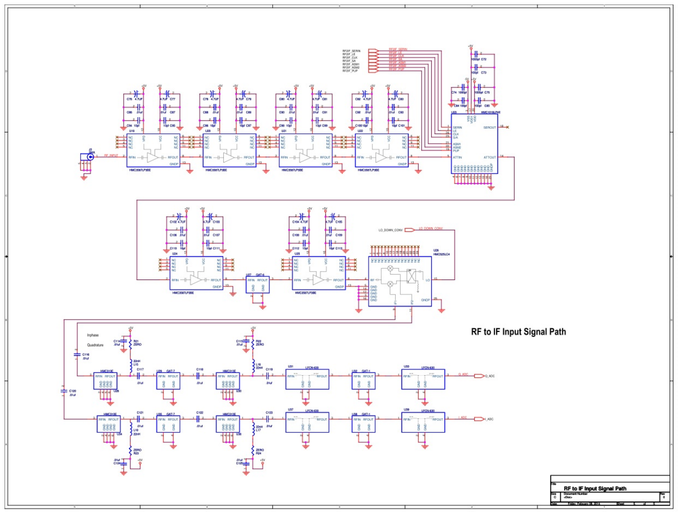


Gen 2 Readout

- Designed in collaboration with Fermilab
- Based on Casper ROACH2 (Virtex 6)
- Uses TI Dual 1.8 GSPS 12 bit ADC
- Will read out 1024 resonators in 1.8 GHz
- 2 boards per feedline in 4-8.5 GHz band
  - scalable to 30+ kpix
- Incorporates many lessons from Gen1!
- Prototypes by September
- Cost Goal: ~$5/pixel, excluding HEMT and FPGA

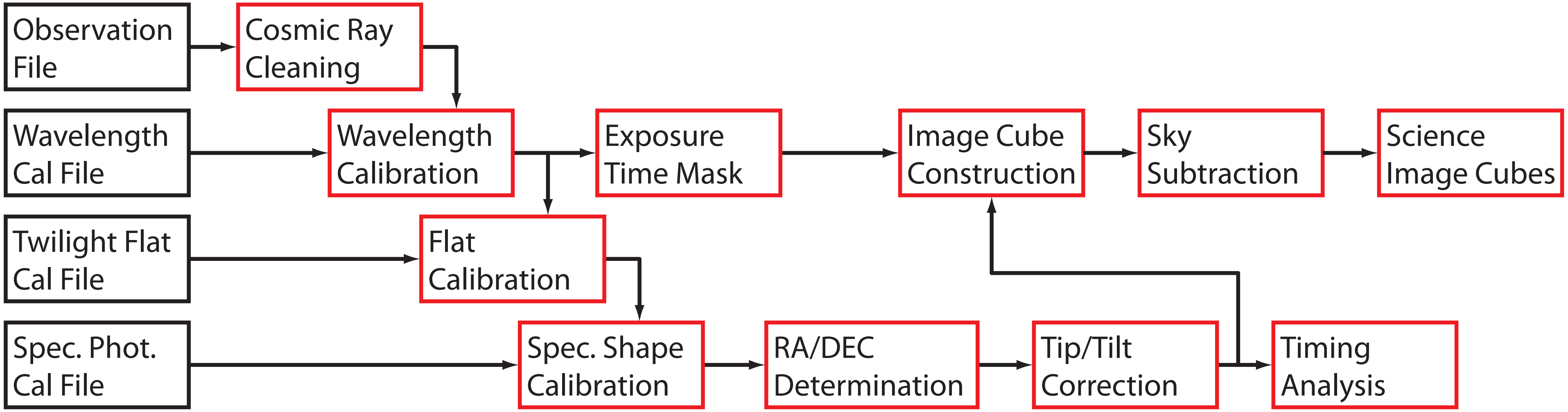






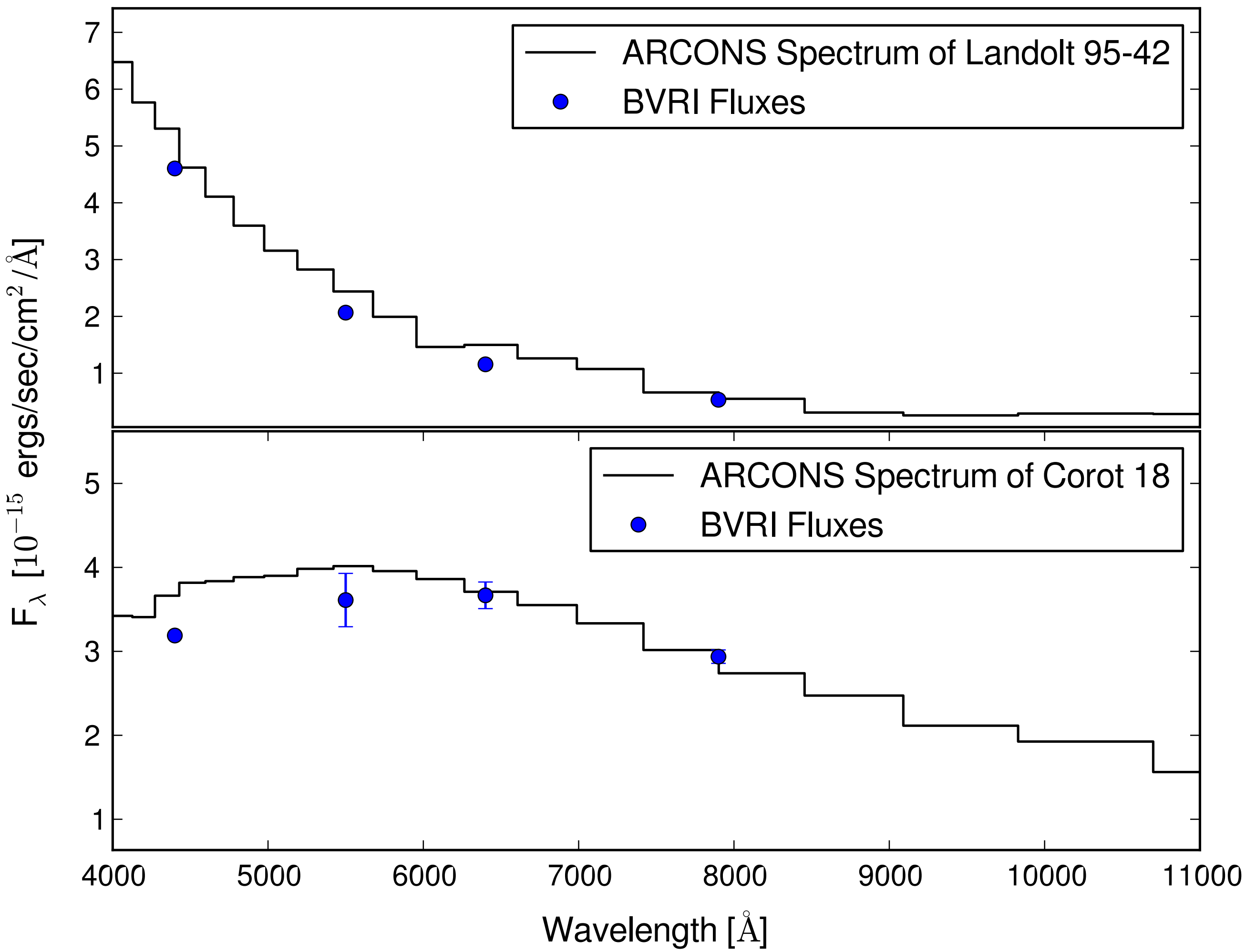
Data Pipeline

- Man man-years already invested, many more to go…
- Complex!
- Data format is HDF5, with each photon stored as a 64-bit packet



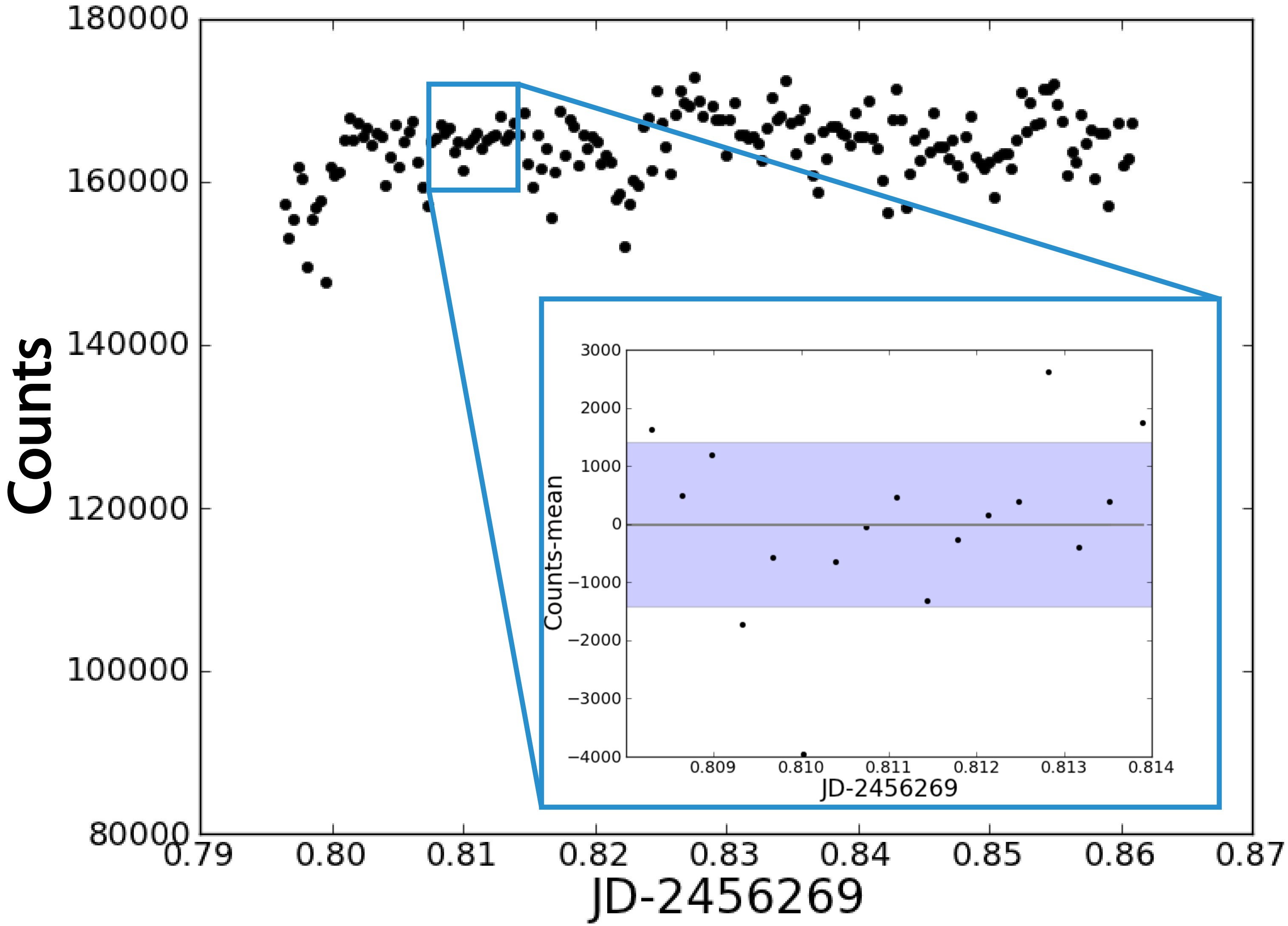
Mazin Lab at UCSB
http://goo.gl/ePAvg

Flux Calibrated Spectra



- Spectra of standard stars match pre-existing photometry

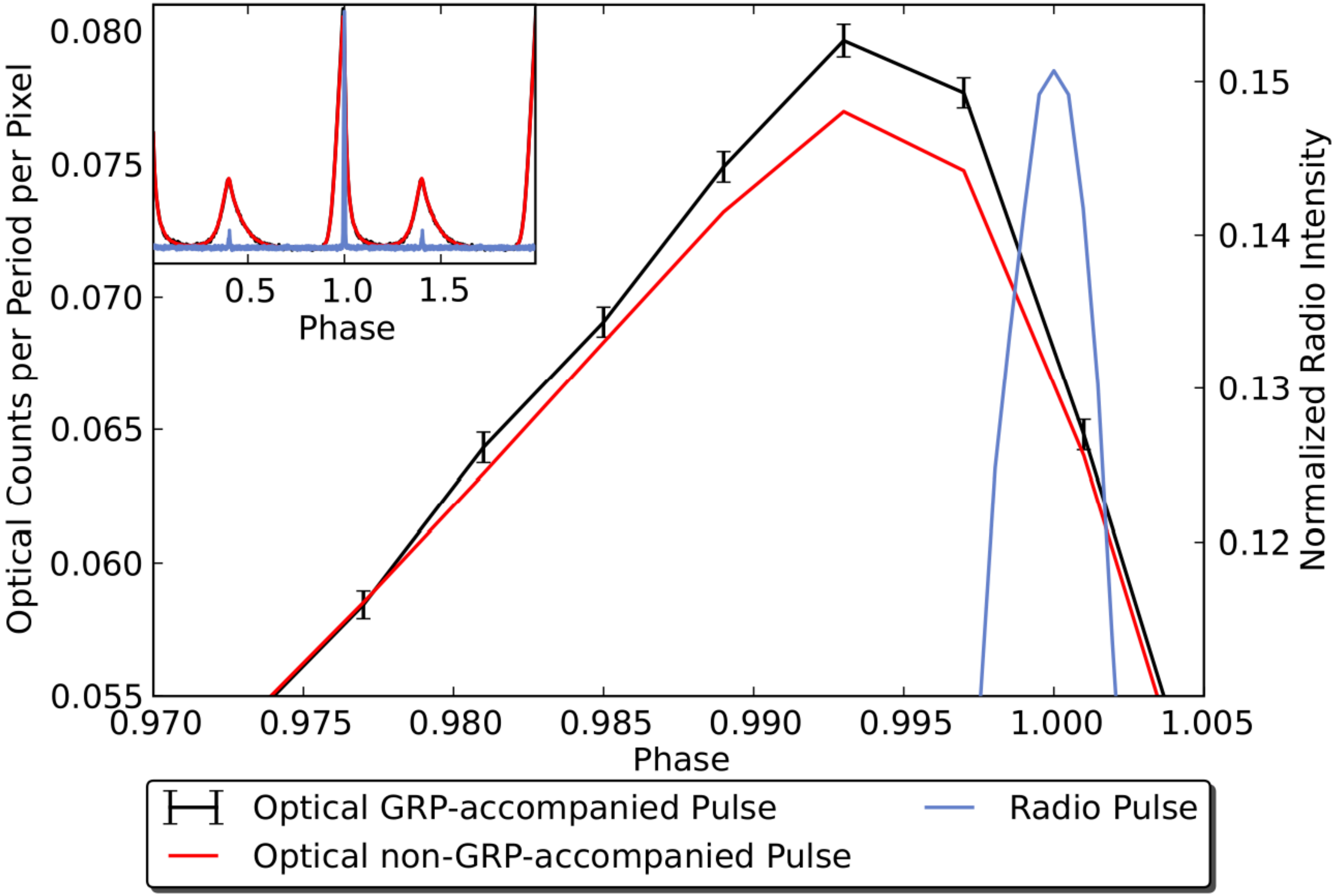
Photometric Stability for mV~15



0.6% photometry on a mv=15 star over 10 minutes

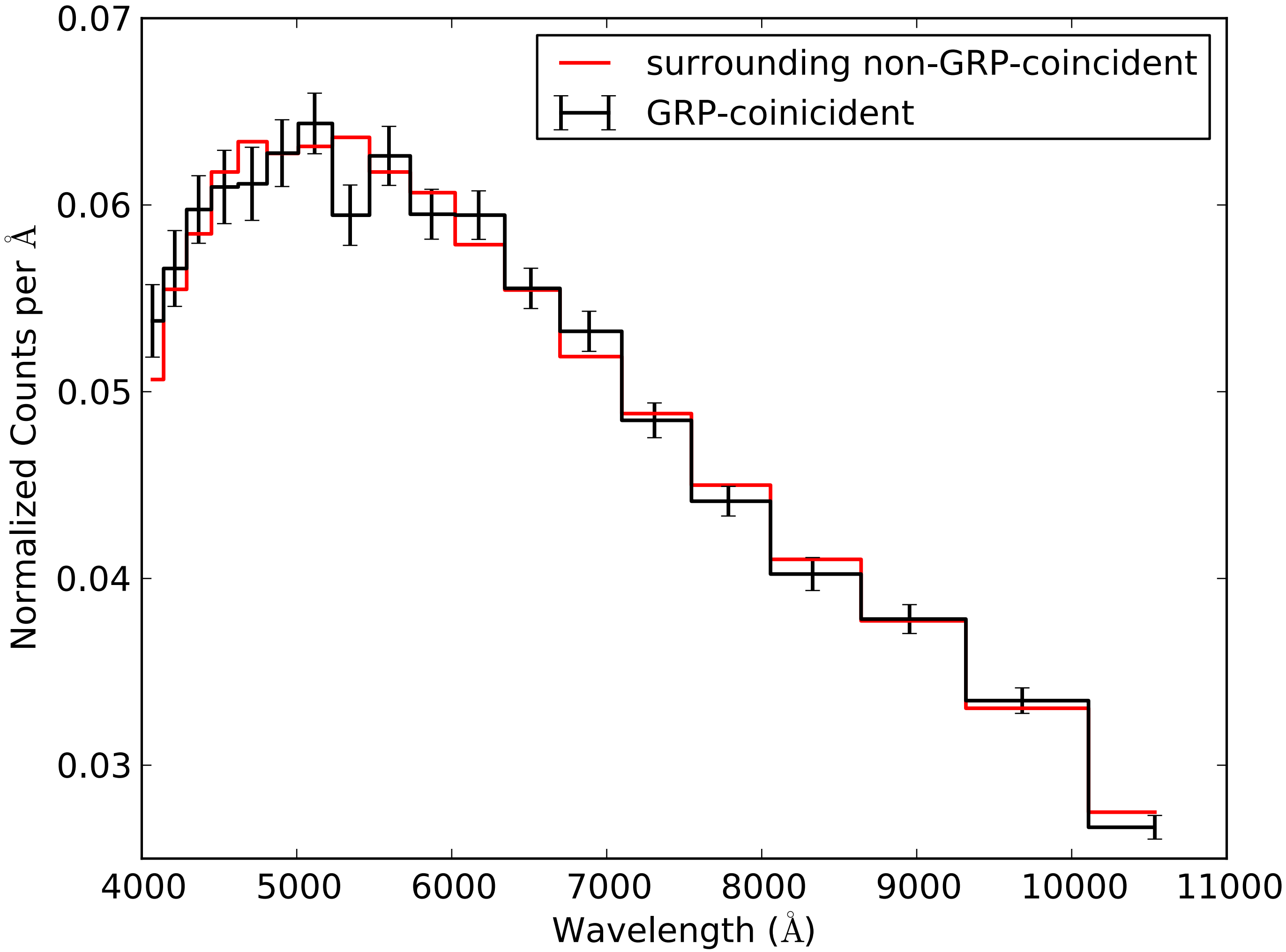
Crab and GBT Observations

- Shearer et al. 2003 saw a 3% enhancement in optical flux coincident with Crab Giant Radio Pulses (GRPs)
- We see it, too. (Analysis mainly by Matt Strader at UCSB)



Simultaneous ARCONS + GBT

- We also see no appreciable spectral differences between GRP and non-GRP coincident pulses

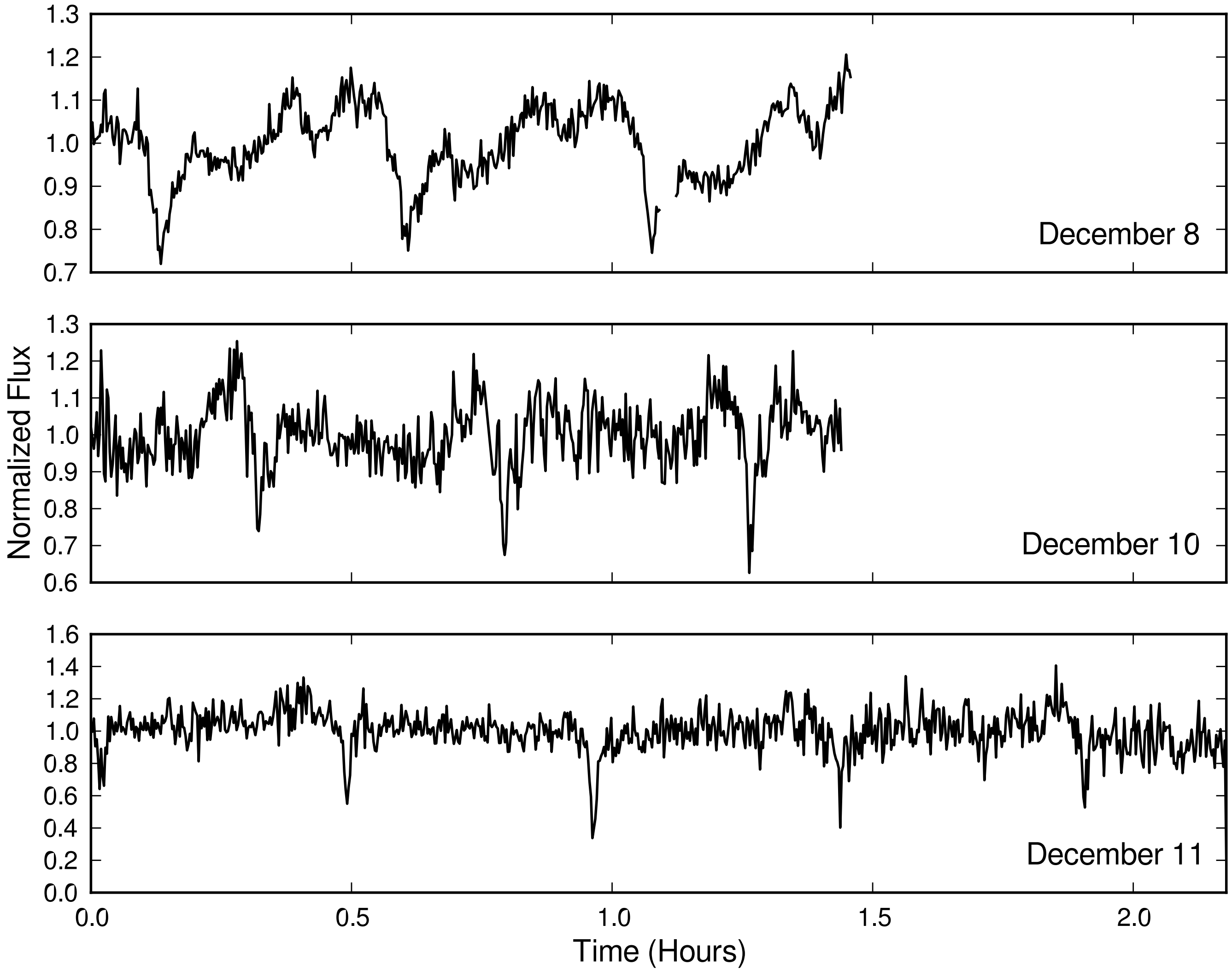


Am CVns

- Short period white dwarf binaries (10-30 minutes!!)
- Helium gets transferred from one white dwarf to the other (Roche Lobe Overflow, or RLOF)
- Possible progenitors for Type 1a supernova
- Possible LISA gravitational wave sources

Eclipsing Am CVn SDSS J0926+36

- Measured light curves of eclipsing Am CVn J0926+3624
- $m_i = 19.4$

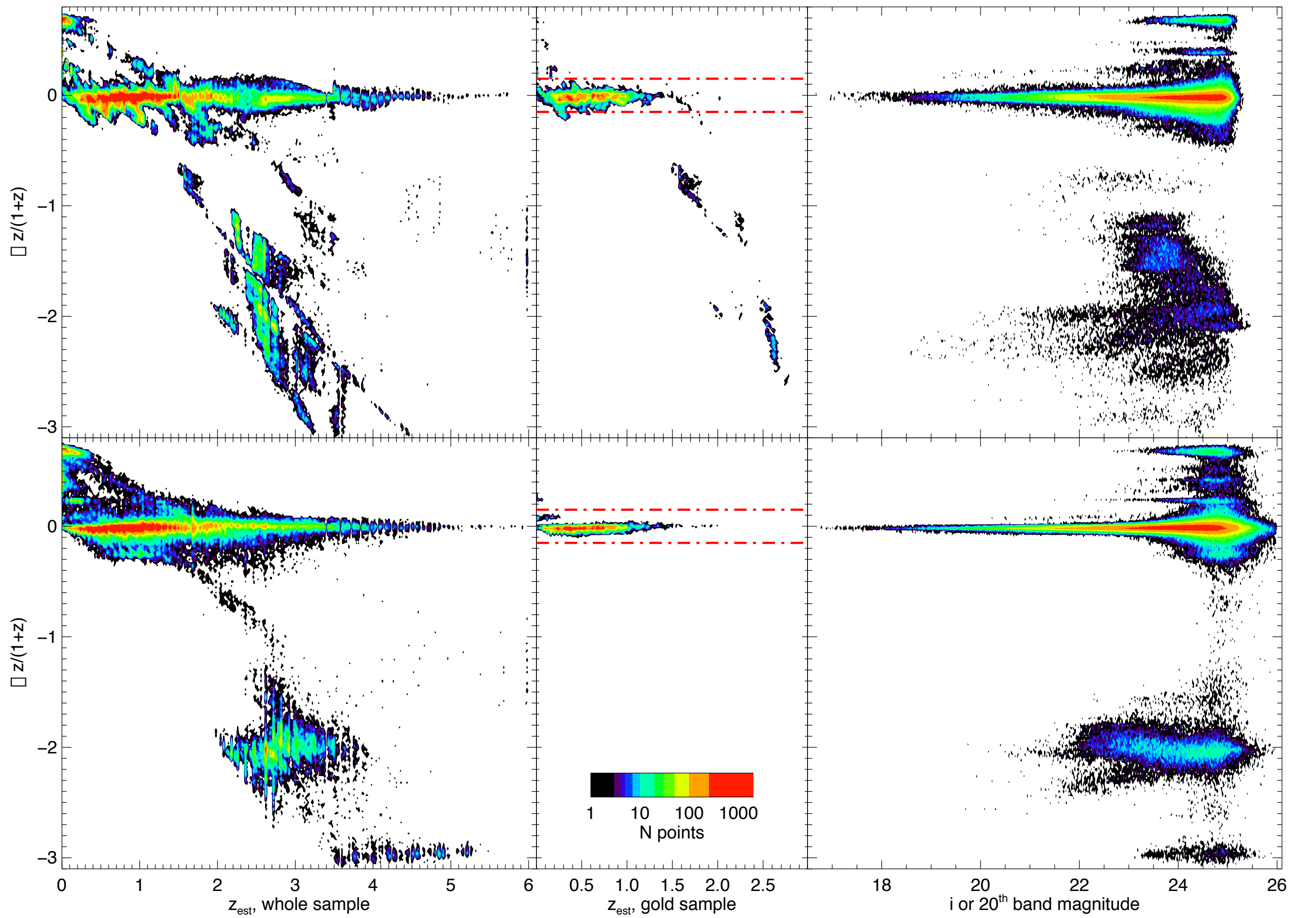


Redshift Determination

- Simple simulations show:
  - $\sigma_z/1+z \sim 0.01$ for field galaxies
  - $\sigma_z/1+z \sim 0.005$ for LRGs

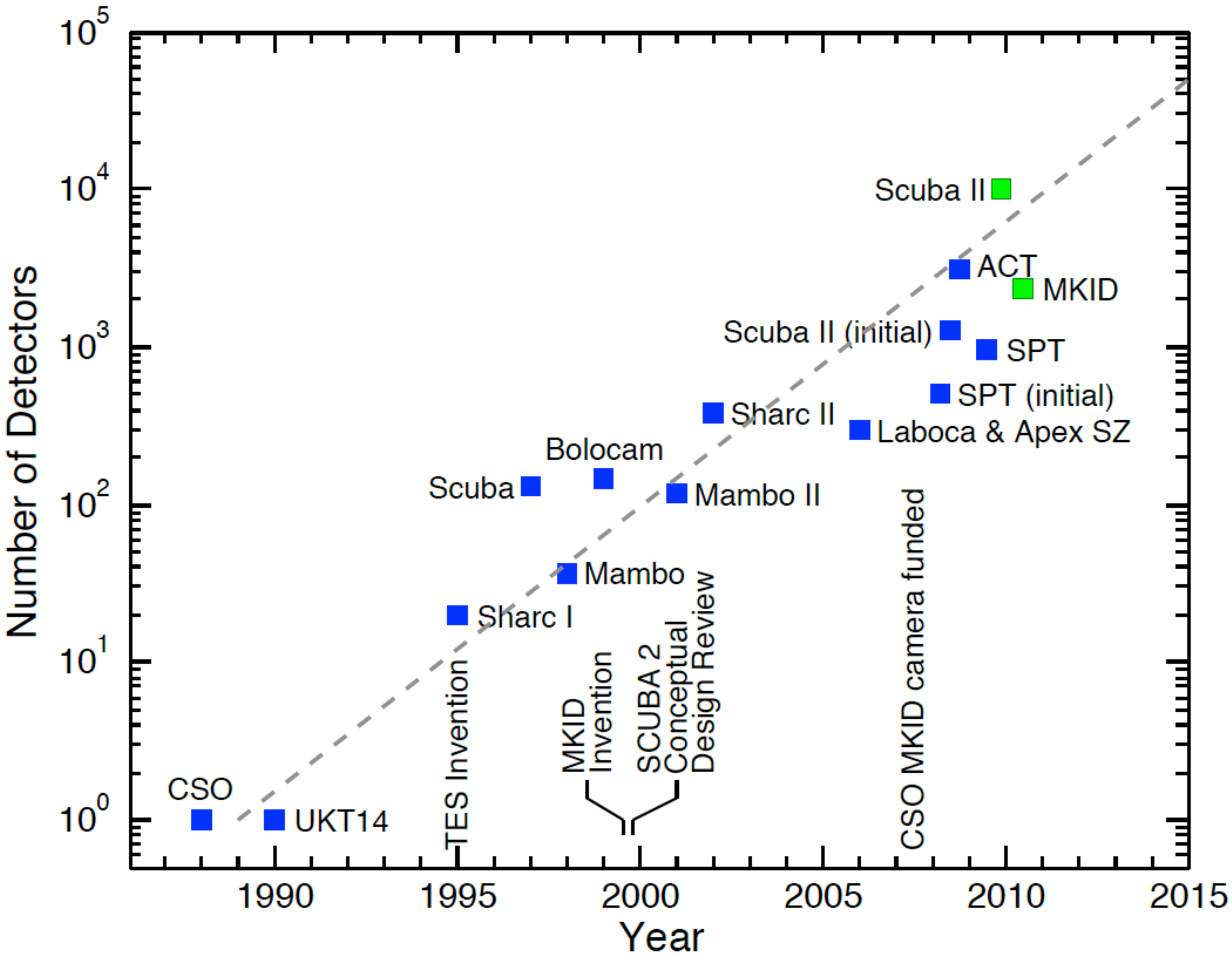
LSST

Giga-*z*



3x better than LSST alone, with a much lower catastrophic failure rate. Likely better with optimized techniques.

MKID Scaling



Plot from J. Zmuidzinas

Future Plans

- Continue MKID development, focusing on spectral resolution, yield and QE
- Continue observations with ARCONS at Palomar 200”
- Seek fun
  - Keck: K
- Build an
- Work wi