UV, Optical, and Near-IR Detectors for Astronomy

Ben Mazin, July 2019

The UVOIR MKID Team:

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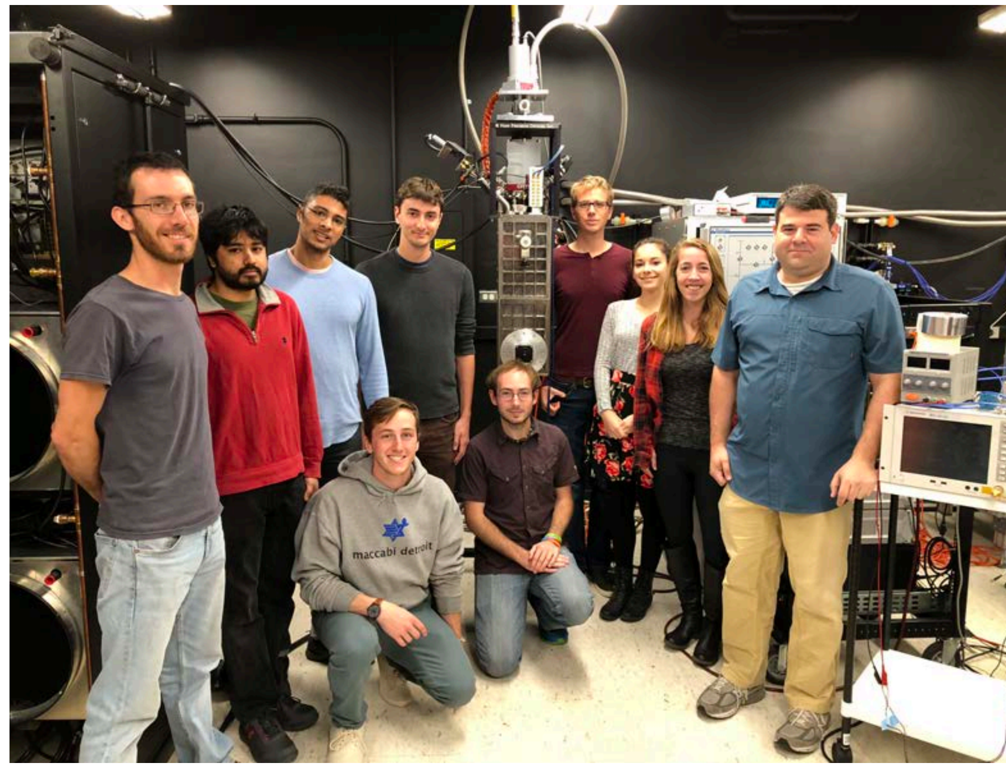
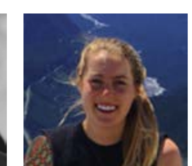


All of the wavelengths
All of the times
mazinlab.org



How did I get here?

- Always liked to build things
  - Built Tesla coil, lasers and made holograms, etc.
  - Made a CVD Diamond Deposition system in my basement
  - Got involved in instrumentation at Yale working on QUEST camera
  - Went to Caltech without a clear project in mind
    - Worked a little with Chris Martin on GALEX, but decided space wasn't for me
    - Moved to a MKID program very early on – risky!
  - Need to be lucky AND good

What is a photon?

- A discrete packet of electromagnetic energy
- Carries energy E=hc/λ but has no mass
- Is it a wave or particle? Technically both, but in UVOIR detectors (not gratings or inteferometers!) you are almost always going to have better intuition if you think of it as a particle

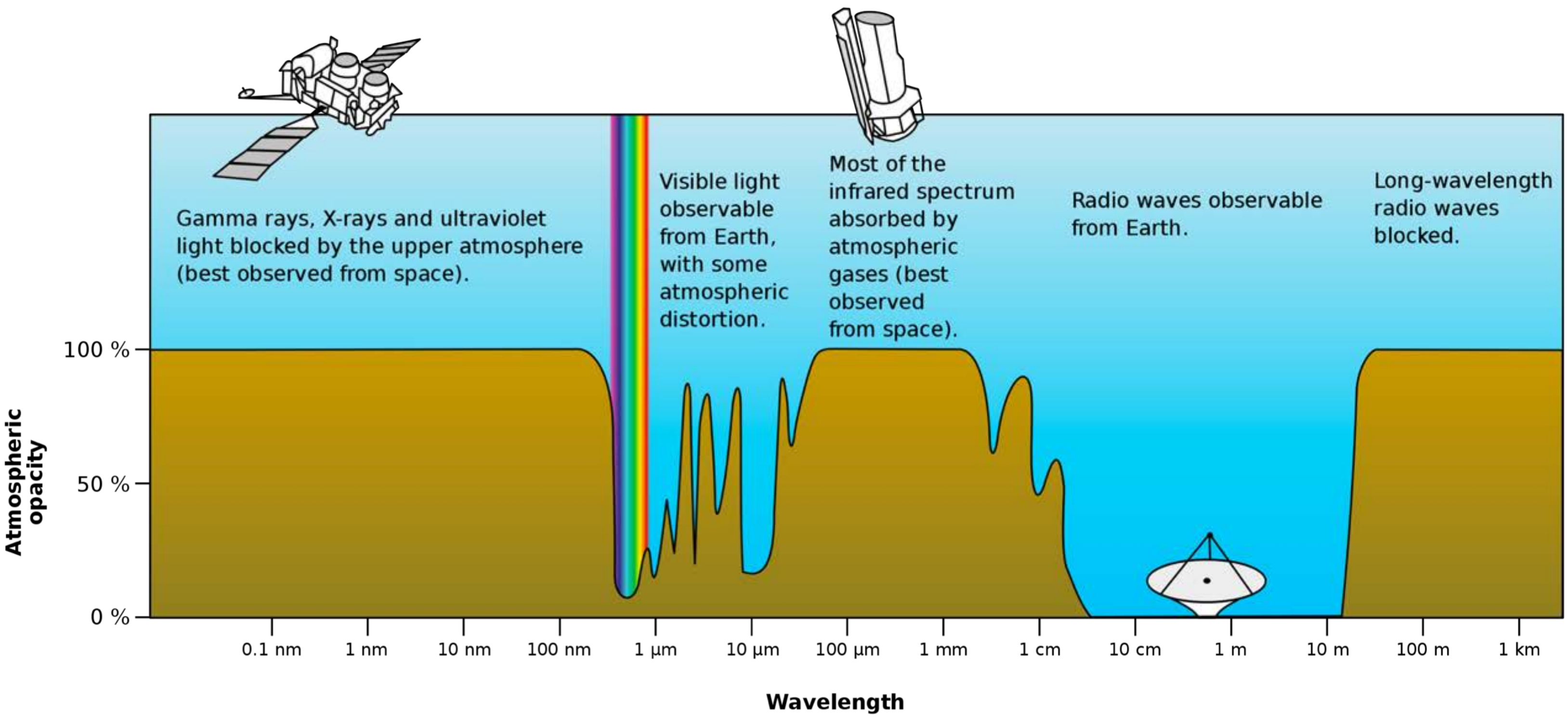


Image Credit: NASA

How can we detect photons?

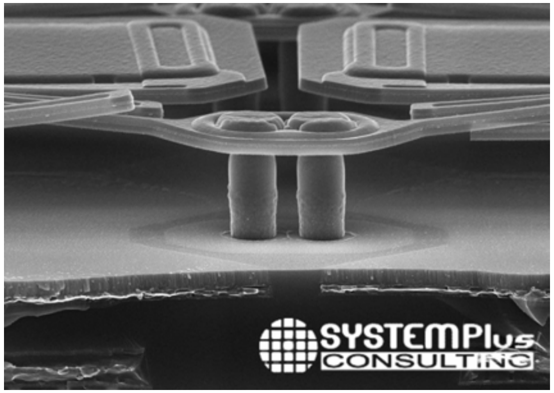
- Lets brainstorm some ideas

What makes a good detector?

- Detect as many photons as possible
  - We call the fraction of photons that hit the detector that are counted device quantum efficiency (QE)
  - We will also sometimes talk about system quantum efficiency, which is the the QE of some larger system usually including detector QE
- Low added noise – think of noise as error on measurement of # of photons
- Large formats (lots of pixels!)
- Uniformity and cosmetics (every pixel the same, low defects)
- Wide wavelength range
- Speed – how long does it take to read out?
- Polarization sensitivity
- Intrinsic spectral resolution (color!)
- Stability (detector doesn't change with time)
- And more… what actually matters is very application dependent!

Detectors

- Most UVOIR detectors we use fall into two categories
  - Equilibrium detectors: Measure a temperature change caused by photons
    - Examples: FLIR 10 μm bolometers



  - Non-equilibrium detectors: Measure some excited state caused by a photon
    - Semiconductor Detectors
    - Much more common!

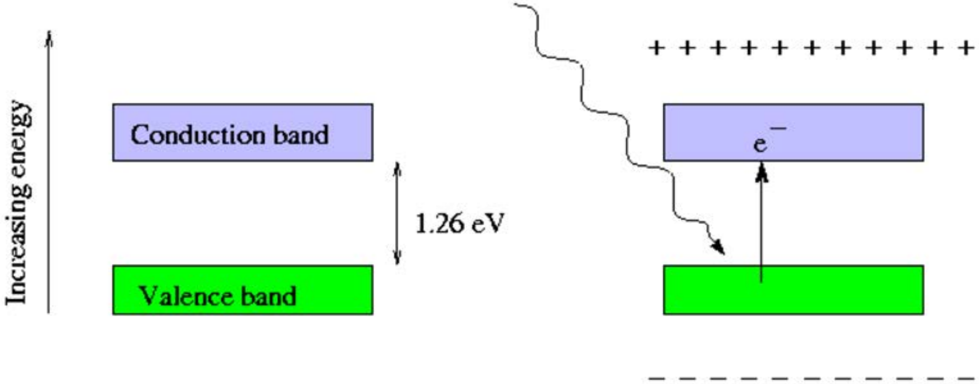
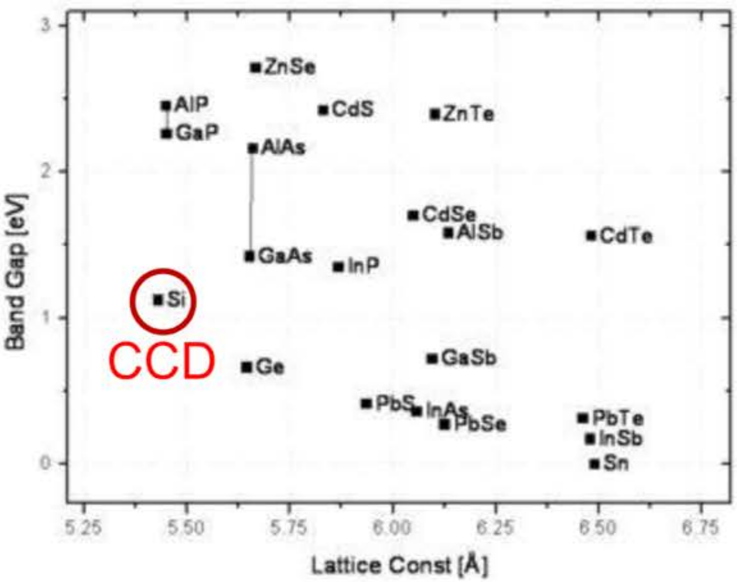


Image Credit: RIT

Semiconducting Detectors

- Based on photoelectric effect
- Excitations (usually a single electron in the conduction band) created by:
  - Thermal effects (usually bad!) – dark current
  - Photon Absorption (good, if it is the photons you care about)
- Wavelength of photons you can observe set by bandgap
  - $\lambda = hc/E_g = 1.24\ \mu m/E_g(eV)$
- Electrons need to be manipulated to be read out
  - Moved
  - Amplified
  - Digitized

Semiconductors



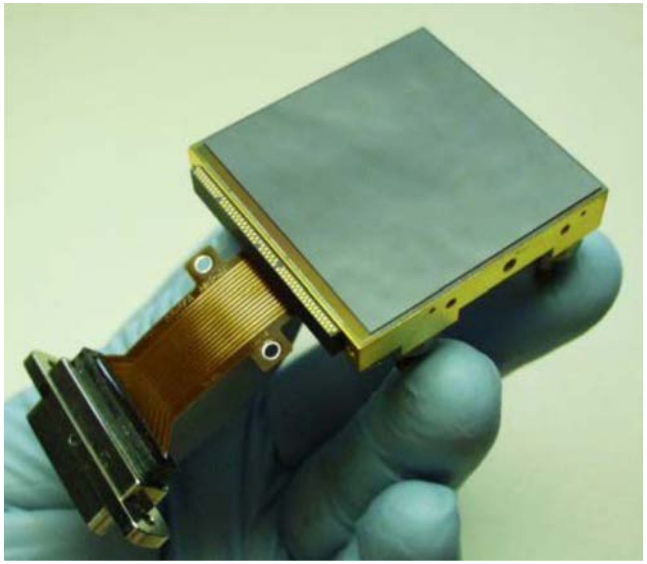
Material	*Band gap (eV)*	*Longest wavelength (μm)*
ZnS	3.6	0.345
CdS	2.41	0.52
CdSe	1.8	0.69
CdTe	1.5	0.83
Si	1.12	1.10
Ge	0.67	1.85
PbS	0.37	3.35
InAs	0.35	3.54
Te	0.33	3.75
PbTe	0.3	4.13
PbSe	0.27	4.58
InSb	0.18	6.90

Material Name	Symbol	E_g (eV)	λ_c (μm)
Silicon	Si	1.12	1.1
Indium-Gallium-Arsenide	InGaAs	0.73 – 0.48	1.68* – 2.6
Mer-Cad-Tel	HgCdTe	1.00 – 0.07	1.24 – 18
Indium Antimonide	InSb	0.23	5.5
Arsenic doped Silicon	Si:As	0.05	25

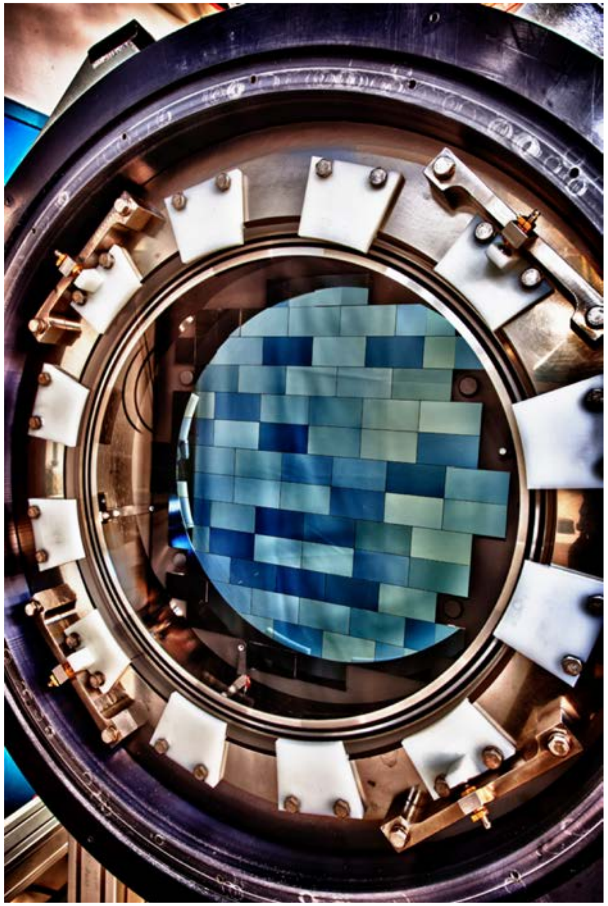
Slide from Properties and Detection of Light (last year's talk)

Semiconductor Detectors

- Astronomers typically use CCDs and CMOS detectors in the optical/near-IR range to convert photons into electrical signals
- Photoelectric effect means at most 1 electron per photon



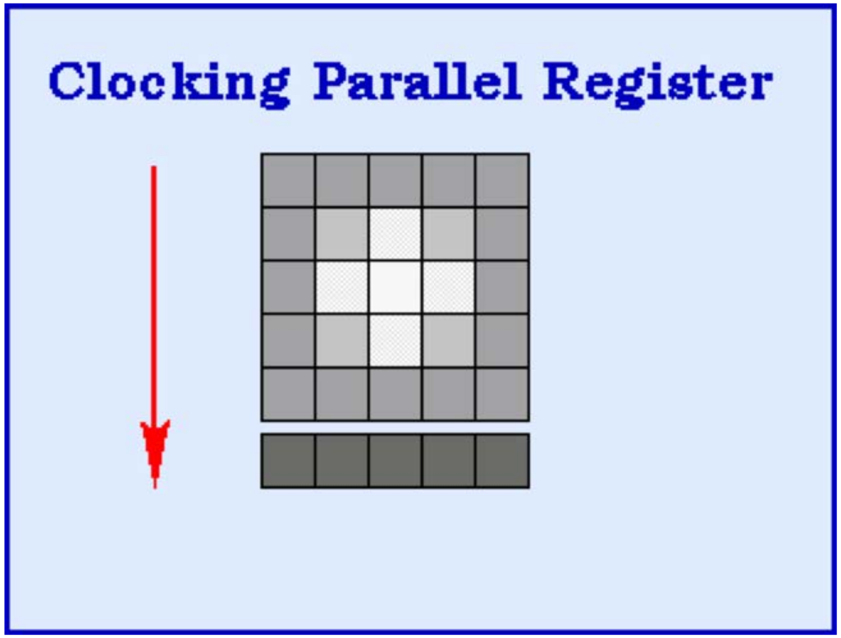
Hawaii2rg HgCdTe Array



DECam CCD Mosaic

CCD Operations

- Photoelectric effect frees electrons in a semiconductor
- Electric fields (voltages) move electrons around
- Bucket brigade moves the electrons to a readout amplifier
- Tons of details at https://en.wikipedia.org/wiki/Charge-coupled_device



Read Noise

- Semiconducting detectors have an amplifier that adds noise every time you read out the charge in a pixel
- In a well designed device this adds means the charge read out is usually ±3 electrons
  - Badly designed systems can have much more, and it can be very non-white (like pattern noise)
- Some clever design (Electron Multiplying CCD, EMCCD) can get around this
  - At a cost: good at telling 0 from 1 photon, but not 1 from 2

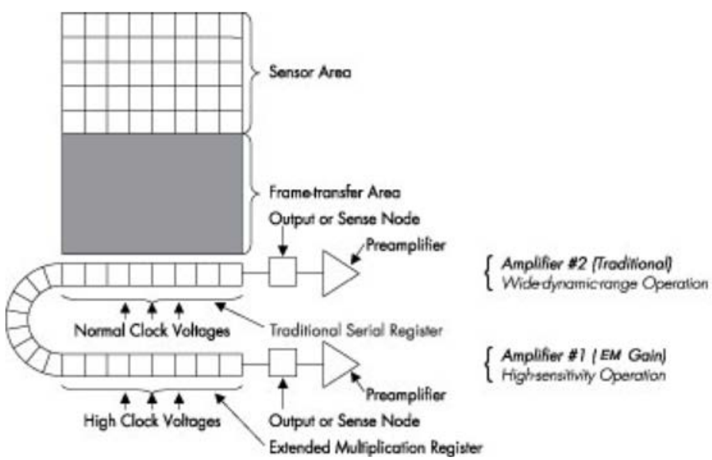


Image credit: Teledyne

Dark Current

- Thermal generation of charge can be a real problem
- To get rid of it we usually operate CCDs cold, T~100K
- It is exponential with T until we hit a plateau

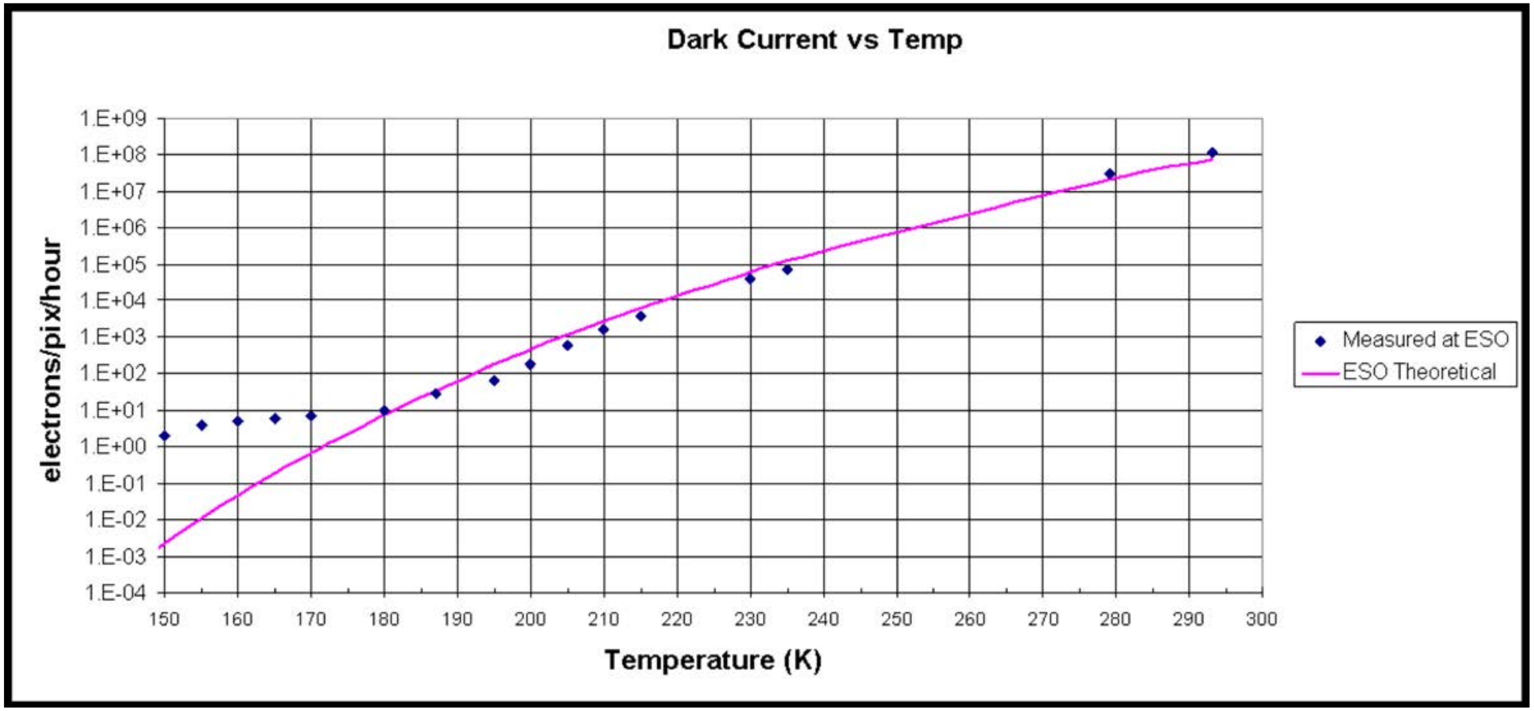


Image Credit: ESO

Cosmic Rays

- Muons and radioactive decays can leave charge in your detector
- Bad!
  - Very bad in space!
- Only real way to fix in effected areas is to take multiple exposures

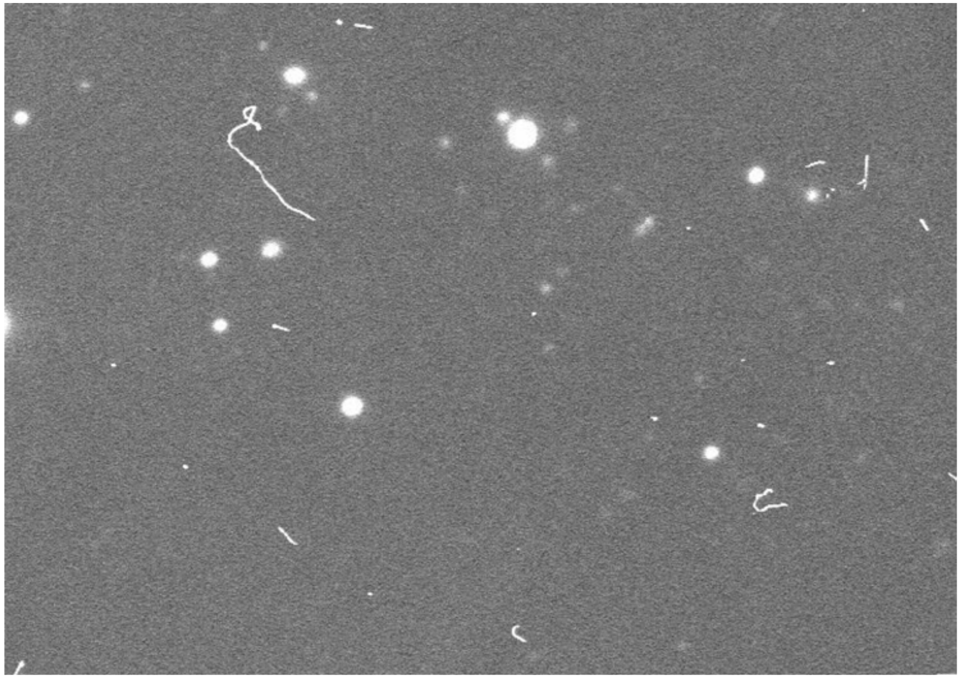


Image Credit: OSU

Full Well

- CCDs have a maximum amount of charge that a pixel can hold before is spills out into adjacent pixels
- We call this the "Full Well"
- It varies a lot from device to device
  - Several thousand to hundreds of thousand electrons

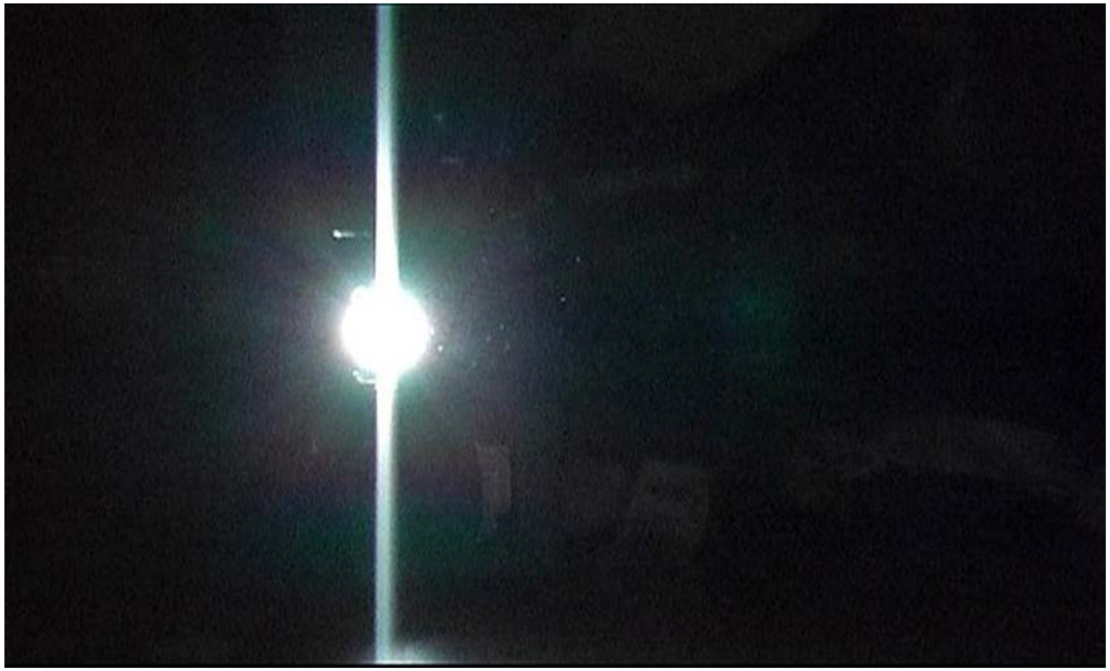


Image Credit: Wikipedia

CTE/CIC/Traps

- Sometimes life is rough
  - CTE – Charge Transfer Efficiency
    - Sometime charge doesn't make it from one pixel to the next
    - Sometimes imperfections in the silicon trap an electron and release it sometime later
    - This makes precision measurements (<1%) hard
  - CIC – Clock Induced Charge
    - If you try to move the electrons around too fast you can accidently generate more
      - Don't do this
  - Scattered Light
    - Sometime your optical system puts light where you don't want it
      - Ghosts
      - Scatter off gratings
      - Only real fix is designing a better optical system!
  - Whole slew of other nasty effects when you try to do precise measurement

Digitization

- Have to turn # of electrons into a number in the computer
  - Digitization!
- # of bits is important
  - Quantization noise
- Can lead to errors if your ADC isn't linear or has a bias
- Also more subtle effects
- There are many ways to do this digitization process
  - Correlated Double Sampling
  - Fowler Sampling (CMOS)
  - Skipper CCD (slow!)
  - Up the Ramp (CMOS)

Calculating Signal to Noise

- This is probably the most important slide I will show you today

Total number of photons detected from a distant star is

$$N^* = \eta \frac{F_\nu^* A}{h\nu} \Delta\nu \Delta t$$

- Quantum efficiency – η
- Fractional band pass – $\Delta\nu/\nu = \Delta\lambda/\lambda$
- Integration time Δt
- Telescope collecting area – $A \approx \pi R^2 = \pi D^2/4$

In the absence of detector noise or confusing foreground emission, e.g., sky, zodiacal light, &c. the signal-to-noise from Poisson statistics is

$$SNR = \frac{N^*}{\sqrt{N^*}} = \sqrt{\eta \frac{\pi F_\nu^*}{h} \frac{\Delta\nu}{\nu} \Delta t} \left(\frac{D}{2}\right)$$

SNR scales linearly with telescope diameter and as the square root of integration time. At constant SNR the "speed" of a telescope $\Delta t \propto D^2$

Slide from Properties and Detection of Light (last year's talk)

Calculating Signal to Noise

When the "background" is significant, signal & background contribute Poisson noise

- Number of background photons is

$$N^B = \eta \frac{I_\nu^B A}{h\nu} \Delta\Omega \Delta\nu \Delta t$$

- I^B is the surface brightness of the background
- $\Delta\Omega$ is the beam size. $\Delta\Omega = (\pi/4)(\lambda/D)^2$ at the diffraction limit

The total photon count is

$$N^* + N^B = \frac{\eta}{h\nu}\left(F_\nu^* + I_\nu^B \Delta\Omega\right) A \Delta\nu \Delta t$$

For faint sources ($F^* \ll I^B\Delta\Omega$) and $N^B \gg N^*$

$$SNR = \frac{N^*}{\sqrt{N^B}} \approx F_\nu^* \sqrt{\frac{\eta A \Delta\nu \Delta t}{h\nu I_\nu^B \Delta\Omega}} = F_\nu^* \sqrt{\frac{\eta \Delta\nu \Delta t}{h\nu I_\nu^B}} \frac{D^2}{\lambda}$$

At constant SNR the "speed" of a diffraction-limited telescope $\Delta t \propto D^4$

Slide from Properties and Detection of Light (last year's talk)

Work a Problem

- Star has a flux of 10 photons/sec/pixel/m^2 in V filter above the atmosphere
- Background has a flux of a)1 or b)100 photons/sec/pixel/m^2
- PSF has a FWHM of 2 pixels
- Keck Telescope (aperture)
- How long do we need to integrate to get to a signal to noise of 100 in case a and b?

- You need to do these kind of problems until they become trivial

CMOS Detectors

- Sort of like a CCD except every pixel has its own amplifier
- Tends to be significantly faster than CCDs
  - Most digital cameras (and phone cameras) use CMOS
- Used in the near-IR above silicon's bandgap

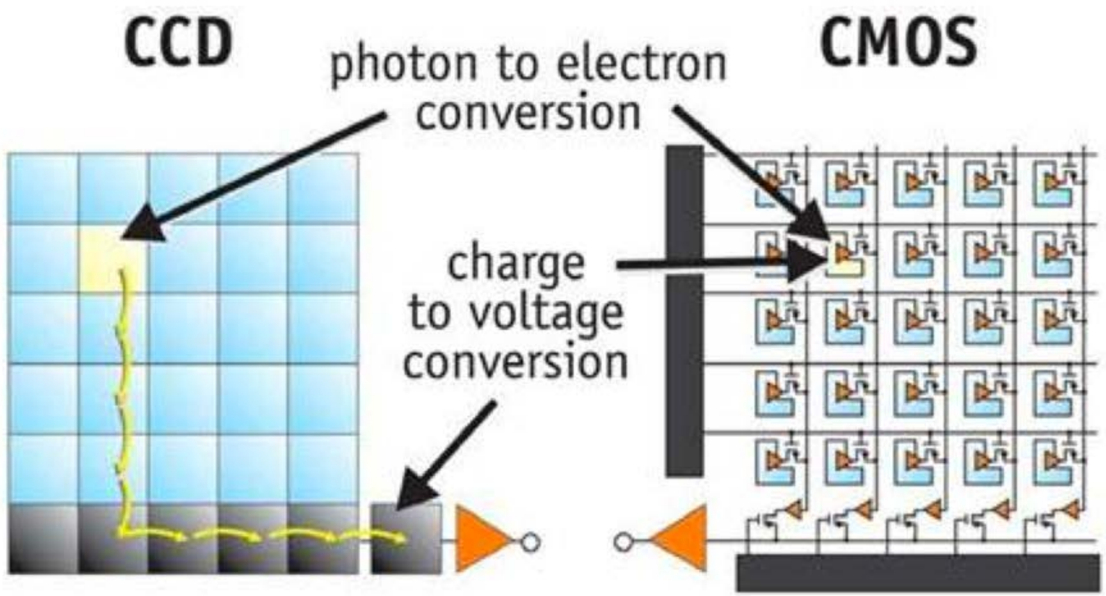


Image Credit: CERN

UV Detectors (100-350 nm)

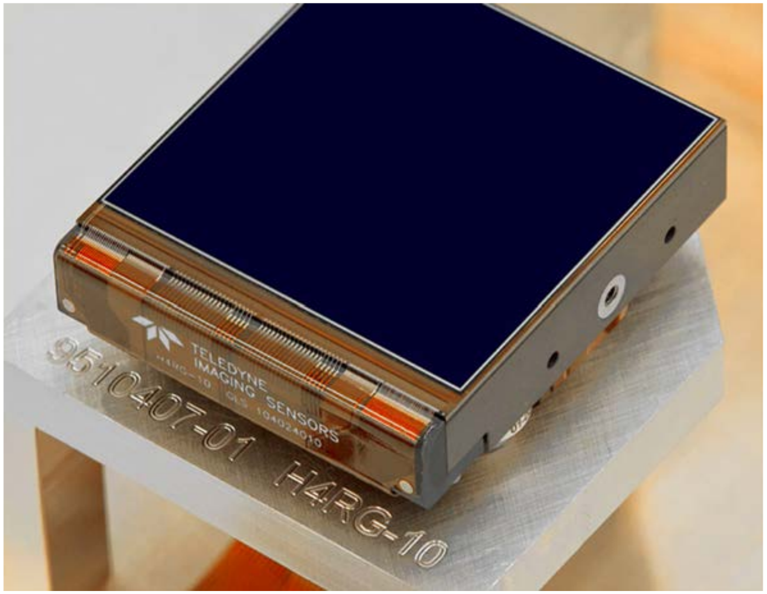
- Microchannel Plates
  - An array version of a photomultiplier tube
  - Large format and low dark rate, but low QE
  - Often want to be "solar blind" → high gap photocathodes
  - Room temperature but high voltage
- Delta Doped CCDs and similar
  - Specially manipulate CCD surface to improve UV QE by eliminating dead zone
  - Can get high QE and all the benefits of CCDs
  - UV is very susceptible to contamination (a thin layer or hydrocarbons on an optical surface will kill your QE) so they worry a lot about cryogenics

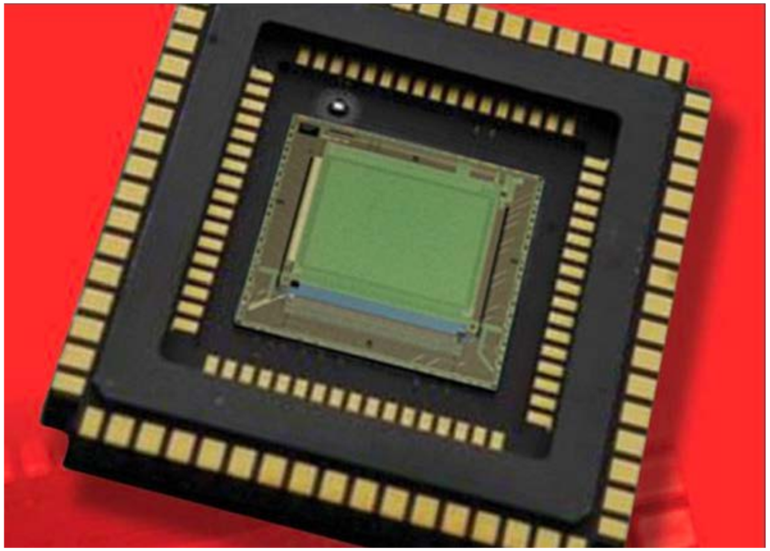
Optical Detectors (350-1000 nm)

- CCDs
- CMOS
- APD - Avalanche Photodiodes
  - Super fast: LIDAR, etc.
- Silicon Diodes (calibration standards)
- Microchannel Plates

Near-IR Detectors (1-3 μm)

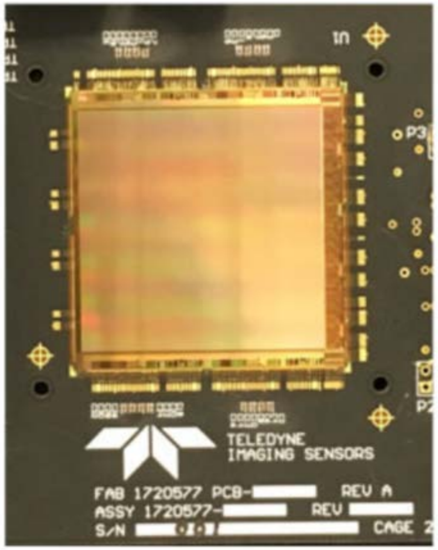
- HgCdTe Arrays
  - Hawaii series
    - The standard for astronomical NIR - 4k x 4K off the shelf
    - Moderate read noise
    - Works from 0.4-5.5 μm (maybe not in the same array)
  - SAPHIRA
    - 320x256 format only now, larger promised
    - Photon Counting Mode
    - Read Free Mode
      - *But not at the same time!*
    - >kHz frame rates
    - 0.8-2.5 μm



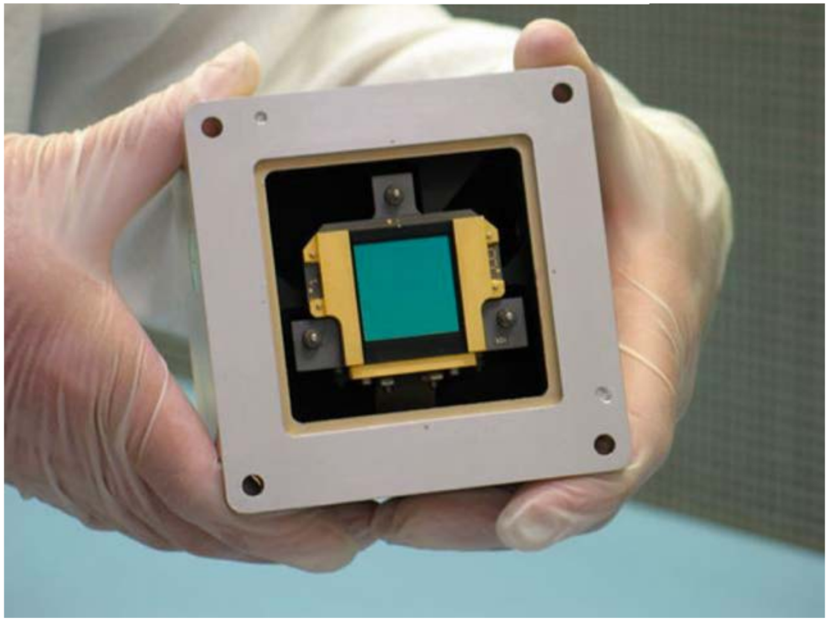


Mid-IR Detectors (3-20 μm)

- HgCdTe – Hawaii and GEOSNAP (3-14 μm)
  - Things start getting 4 Kelvin cold around here
- AQUARIUS (~10 μm)
  - Lots of ELF
    - Extra Low Frequency nosie
- Arsenic doped Silicon (JWST MIRI 1k x 1k, 5-28 μm)
  - Not the greatest detectors the world has ever seen since there is not much demand at these wavelengths



ROIC



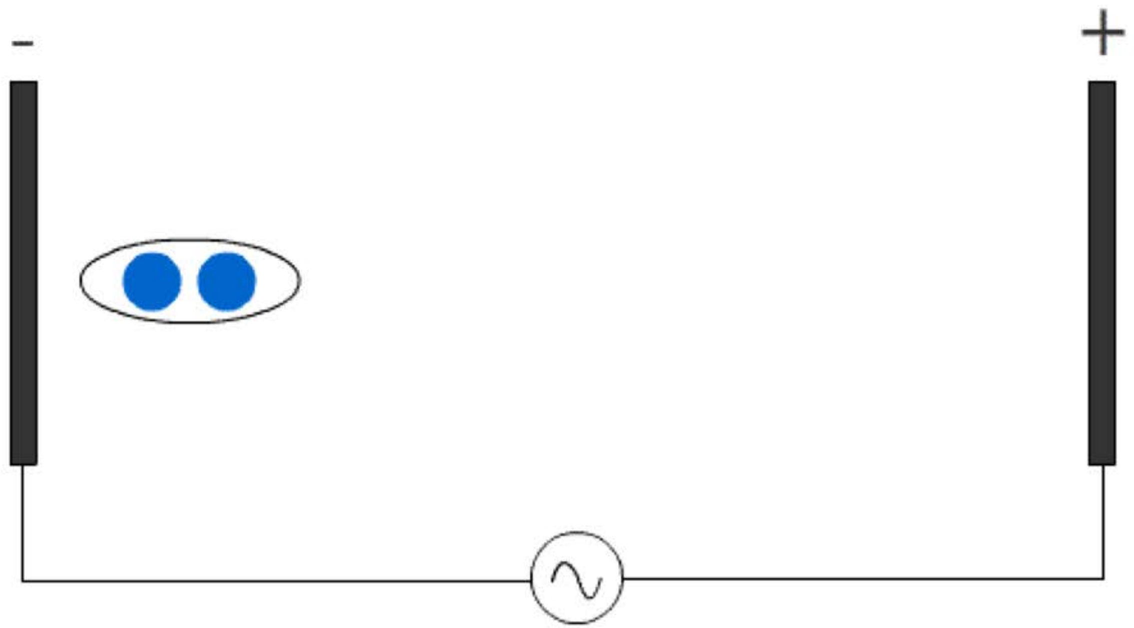
Superconductors

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

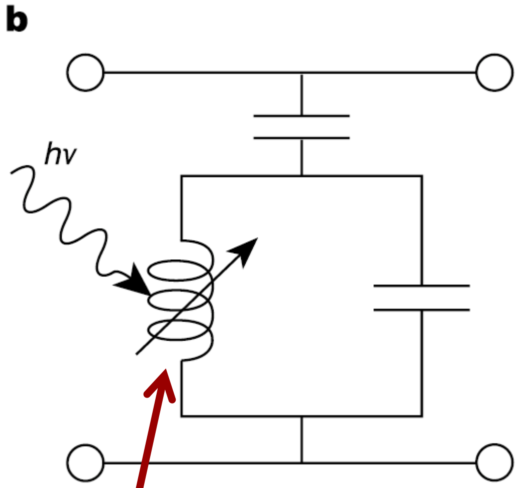
- Like a semiconductor, there is a "gap" in a superconductor, but it is 1000-10000x lower than in Si
- So instead of one electron per photon in a semiconductor, you get ~5000 electrons per photon in a superconductor – much easier to measure (no noise and energy determination)! We call these excitations quasiparticles.
- However, superconductors don't support electric fields (perfect conductors!) so CCD tricks of shuffling charge around don't work
- Excitations are short lived, lifetimes of ~1-100 microseconds

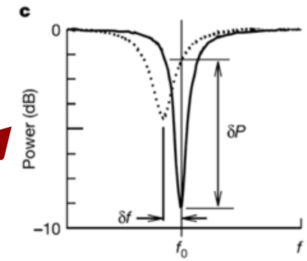
Kinetic Inductance Effect

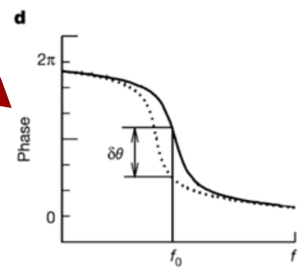
Kinetic Inductance = extra inductance from stored kinetic energy in Cooper Pairs



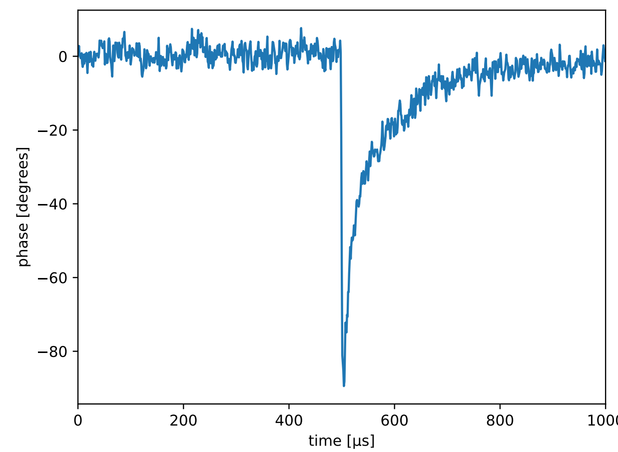
MKID Equivalent Circuit



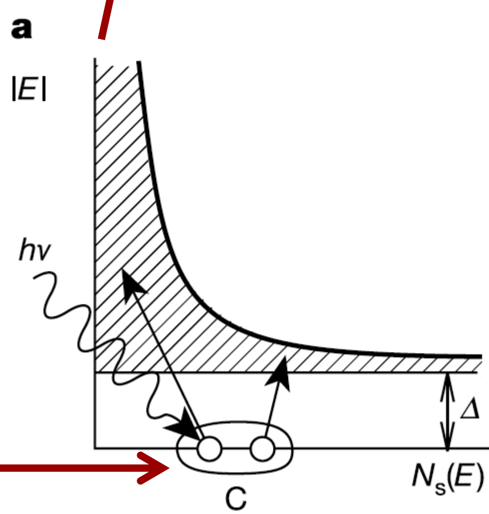




Typical Single Photon Event



Inductor is a Superconductor!



Cooper Pair

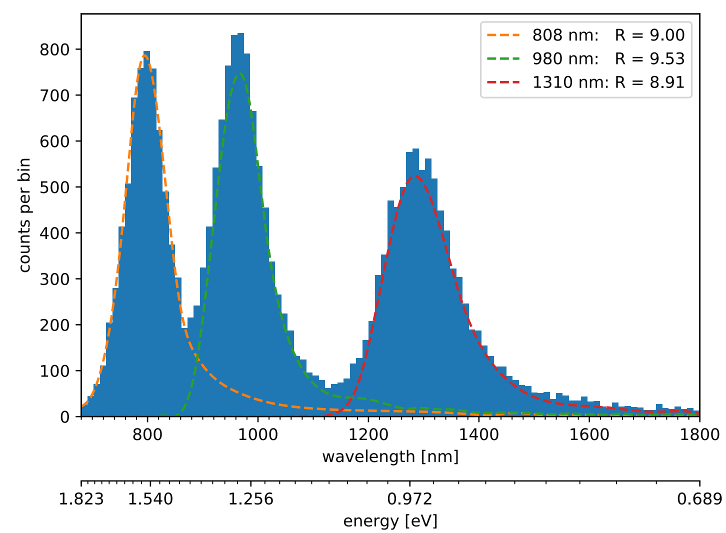
Energy Gap

Silicon – 1.10000 eV

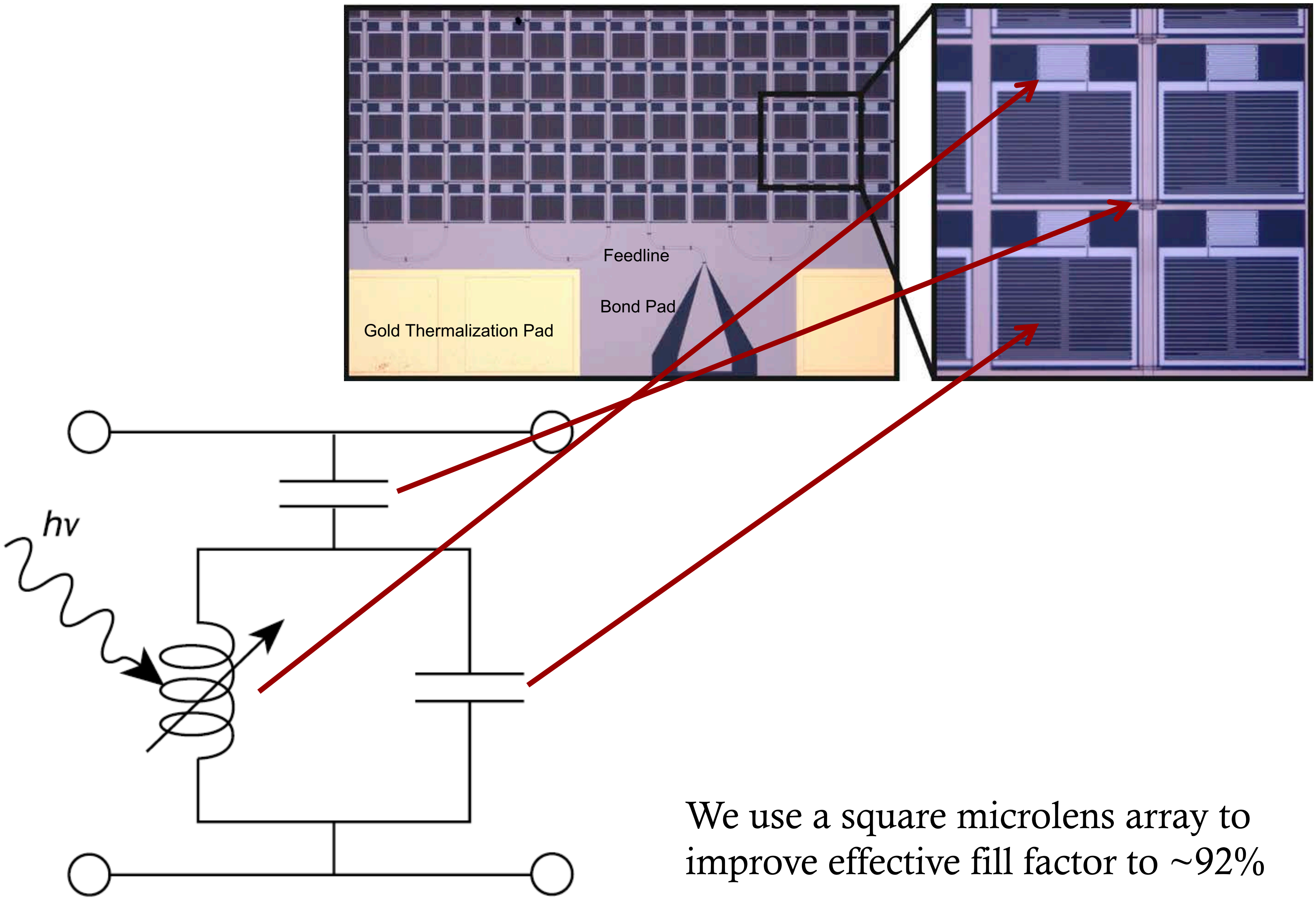
PtSi or TiN – **0.00013** eV

Energy resolution:

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

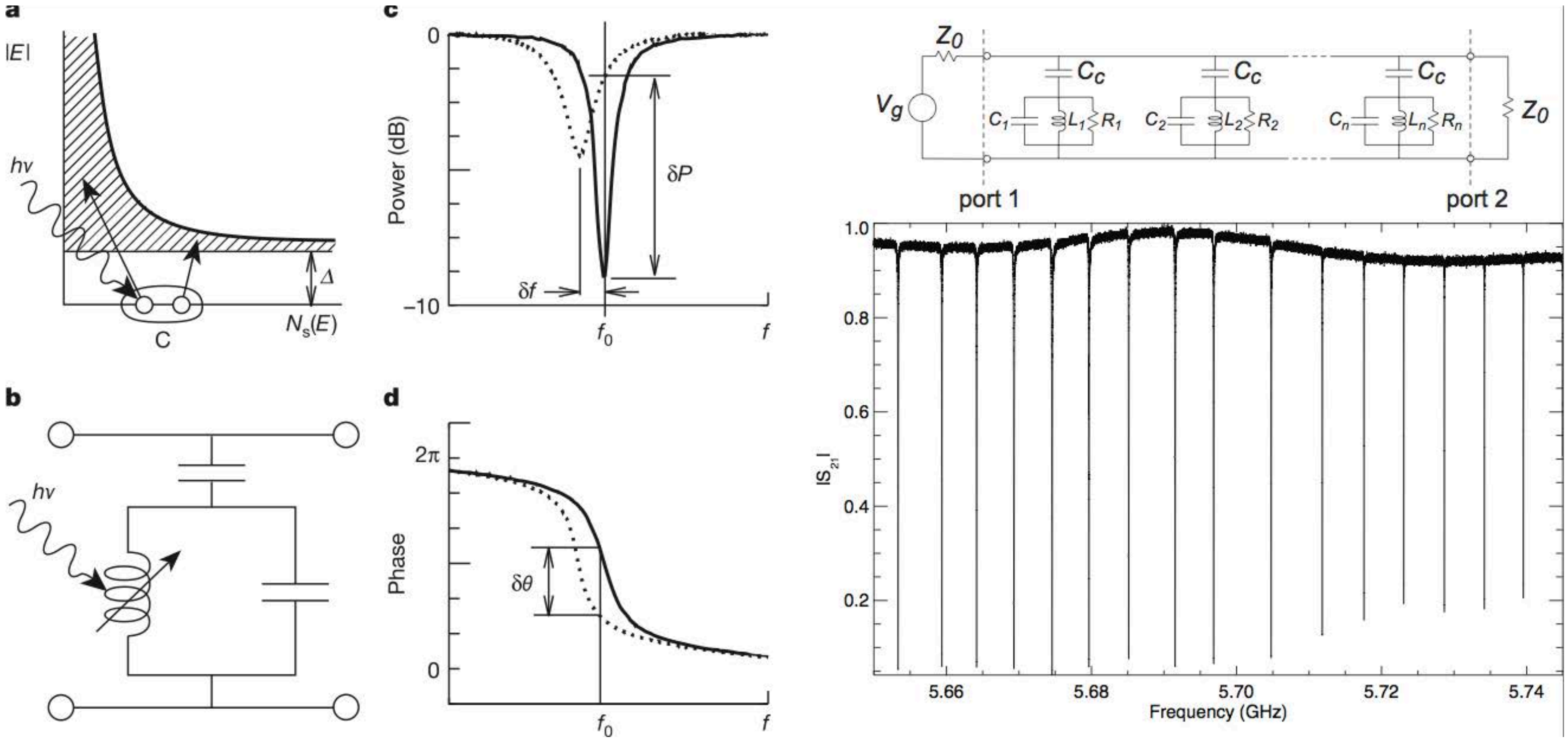


What is a Kinetic Inductance Detector ?



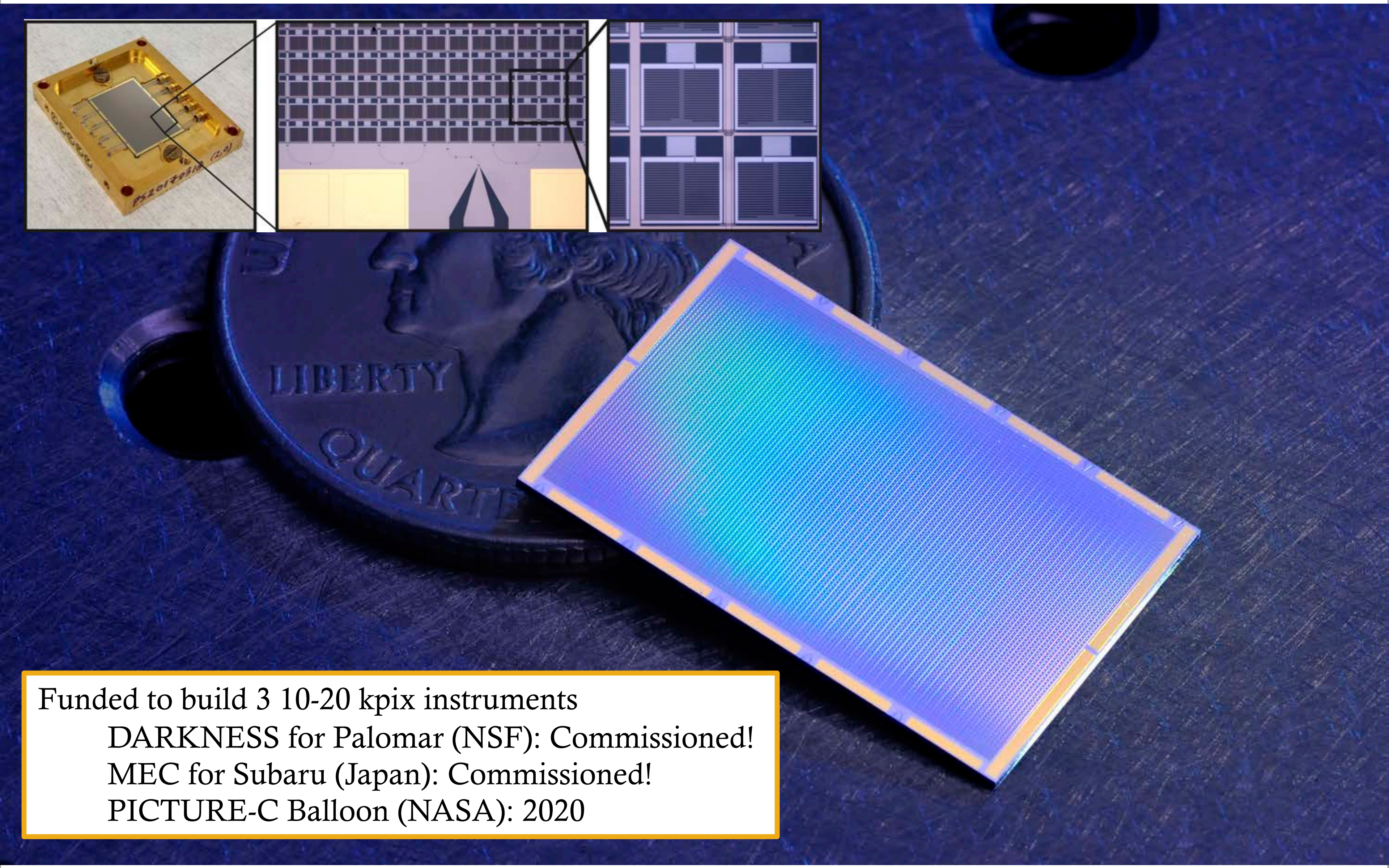
We use a square microlens array to improve effective fill factor to ~92%

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

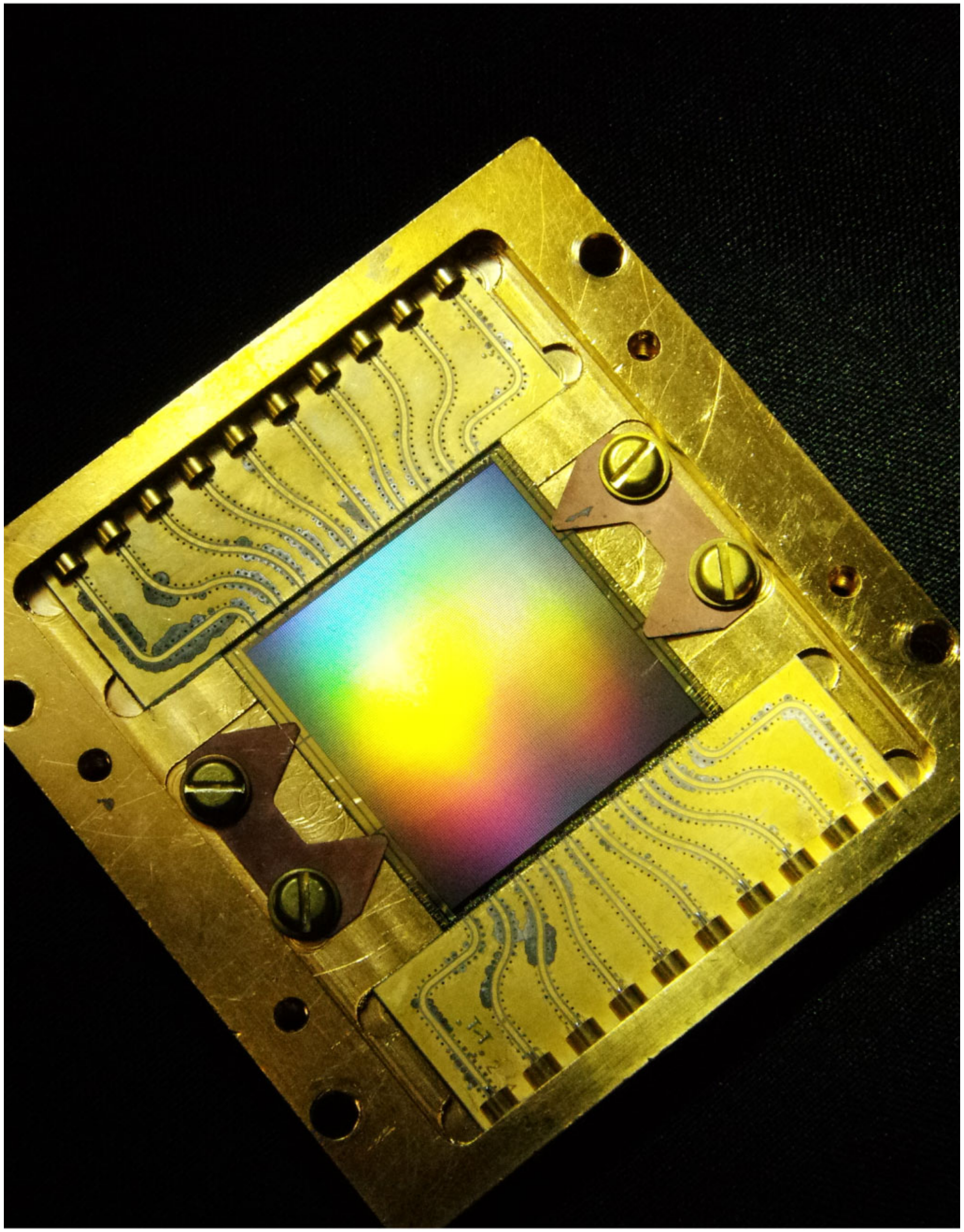


Funded to build 3 10-20 kpix instruments

- DARKNESS for Palomar (NSF): Commissioned!
- MEC for Subaru (Japan): Commissioned!
- PICTURE-C Balloon (NASA): 2020

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. Coiffard.

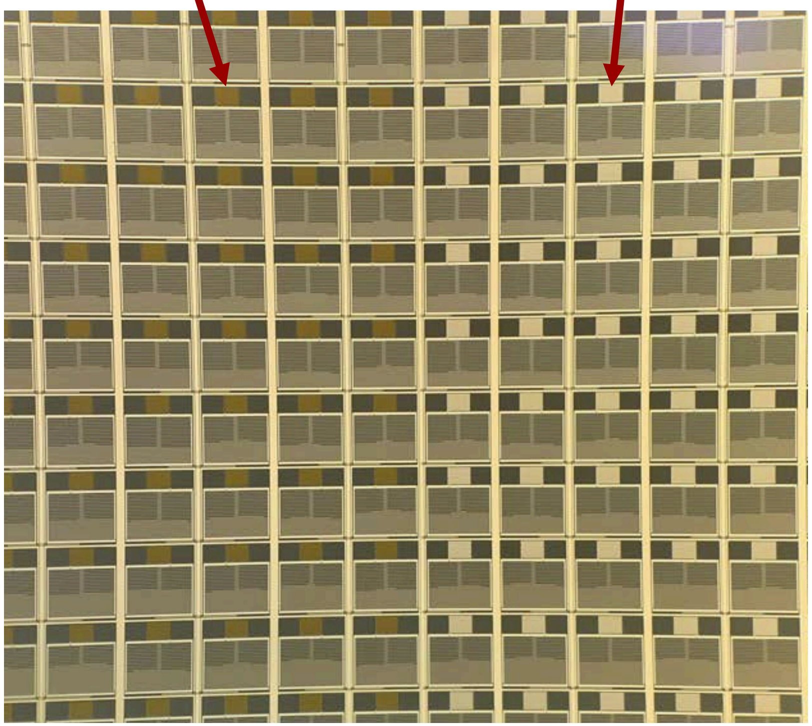
Szypryt et al. 2017, Optics Express

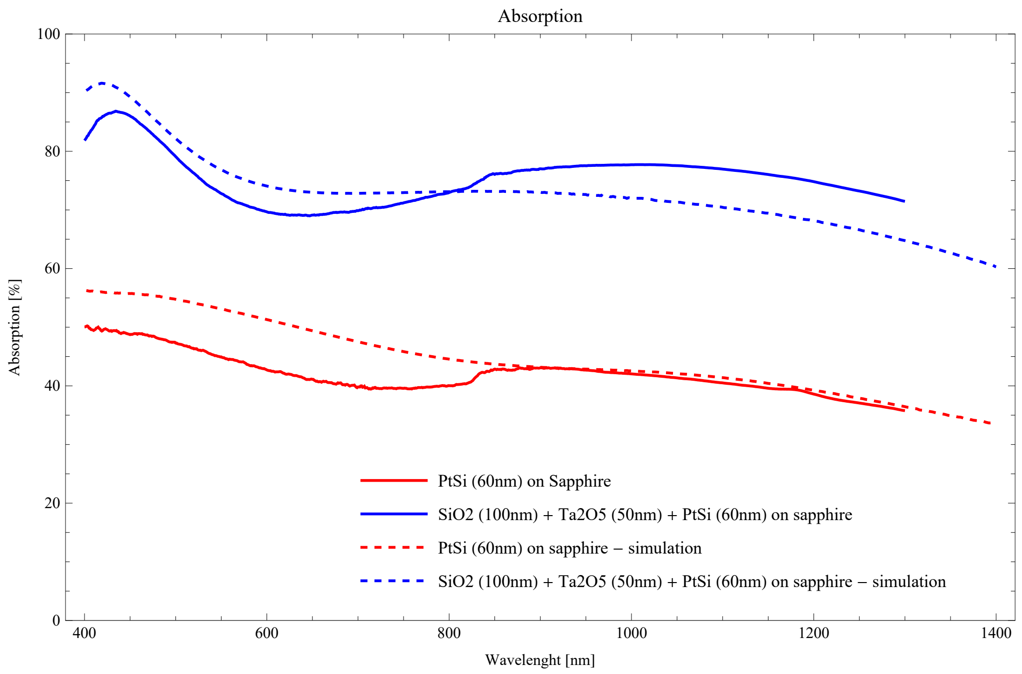
Quantum Efficiency

- QE increased with Anti-Reflection (AR) Coatings
- No degradation in Spectral Resolution R

With AR

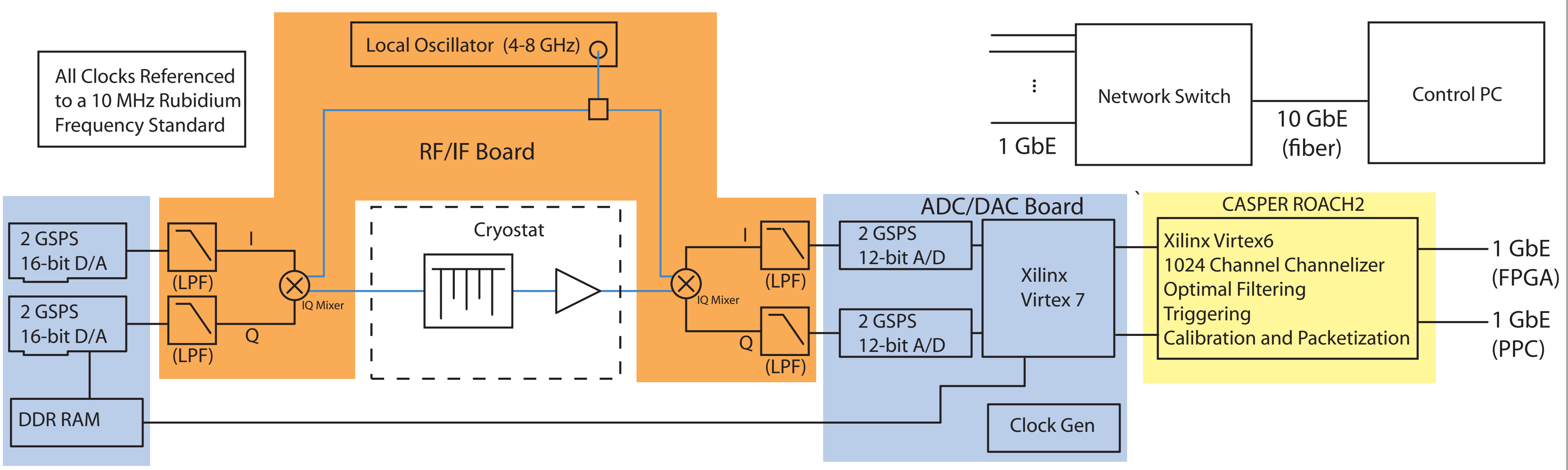
No AR





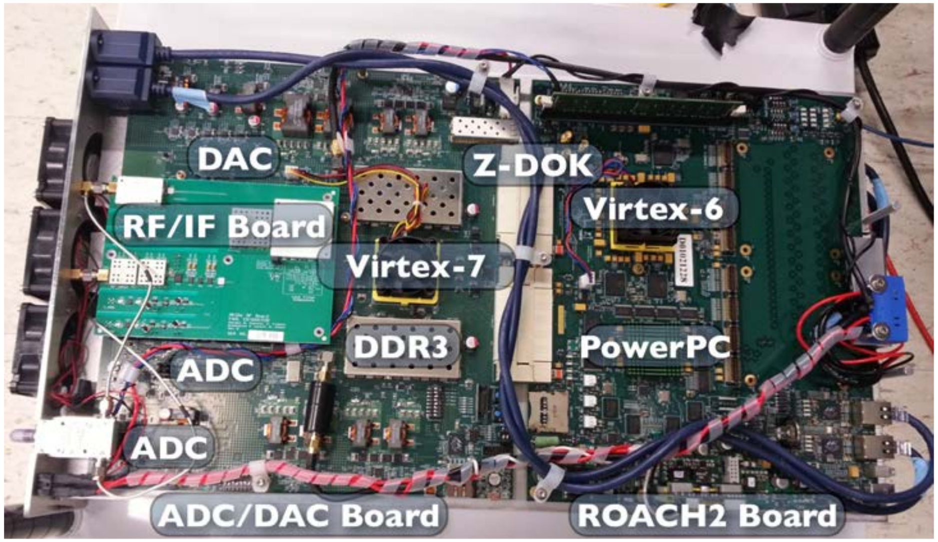
Digital MKID Readout

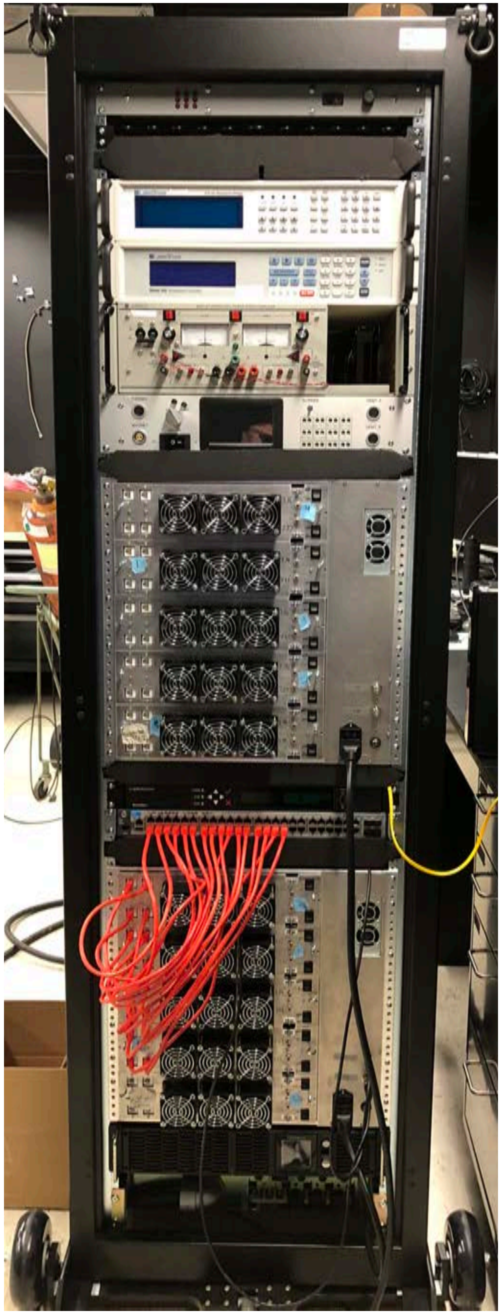
- Software Defined Radio (SDR) Overview
  - Leverages massive industry investment in ADCs/FPGAs
  - Generate frequency comb and upconvert to frequency of interest
  - Pass through MKID and amplify
  - Downconvert and Digitize
  - "Channelize" signals in a powerful FPGA
  - Process pulses (optical/UV/X-ray)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



Gen 2 Readout

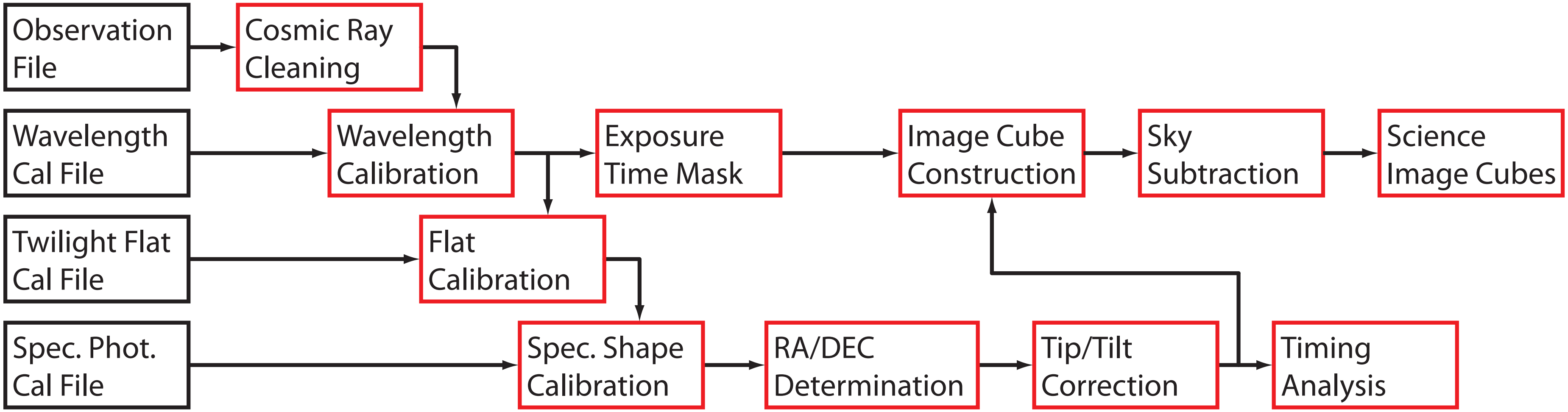
- Designed in collaboration with **Fermilab**
- Based on Casper ROACH2 (Virtex 6)
- Uses dual 2 GSPS 12 bit ADC
- Reads out 1024 pixels in 2 GHz
- 2 boards per feedline in 4-8.5 GHz band
  - scalable to 30+ kpix
- Air to Water/Glycol heat exchangers
- Cost: ~$5-10/pixel, excluding HEMT and FPGAs





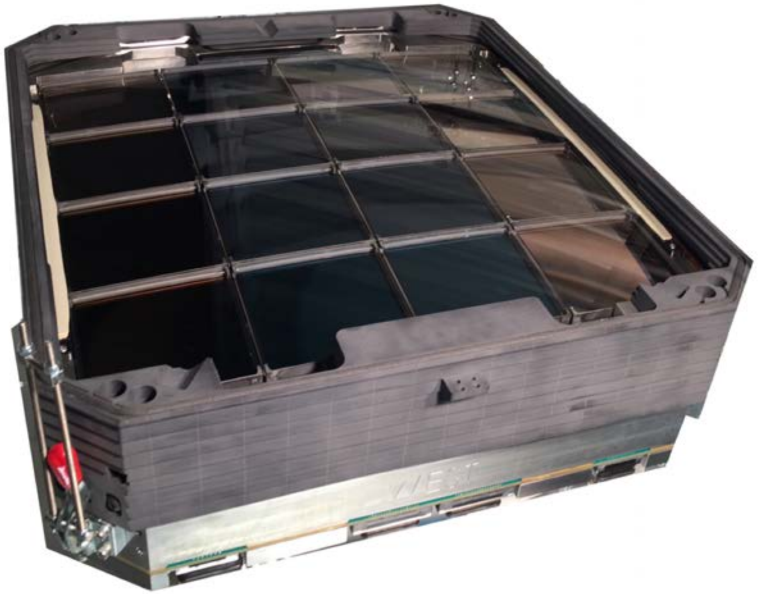
Data Pipeline

- Man person-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 https://github.com/MazinLab



Use Case: Seeing Limited Camera

- Examples (all CCD!)
  - DECam
  - Pan-STARRS
  - ZTF
  - LSST
- Usually just about packing as many pixels in as possible with small gaps (buttable CCDs)
- Usually optical since near-IR arrays are expensive
- Filters start getting very expensive
- Sometimes you need a curved focal plane



Roger Smith/Michael Feeney, Caltech Optical Observatories

Image Credit: Richard Wainscoat

Use Case: High Resolution Spectrograph

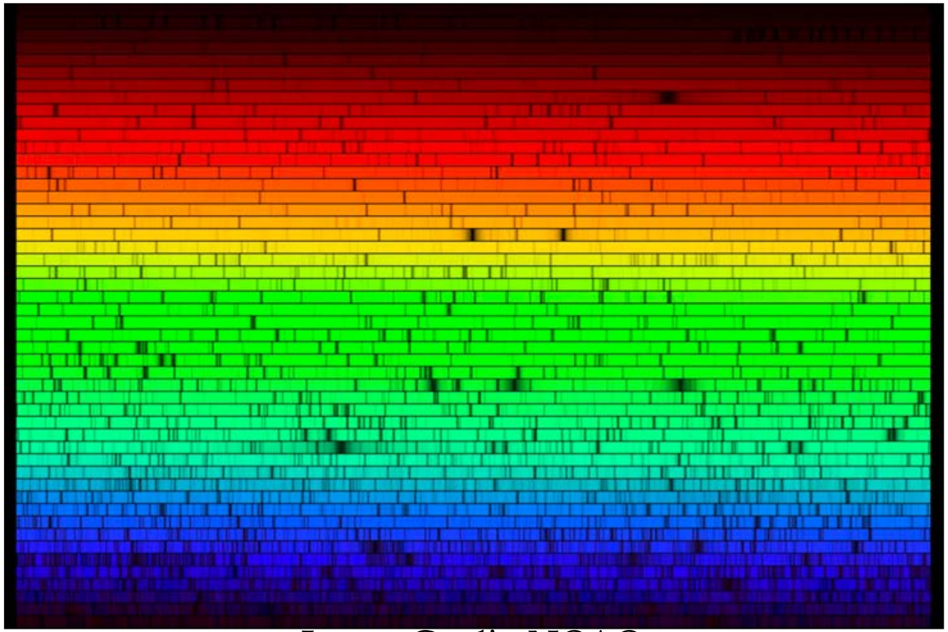
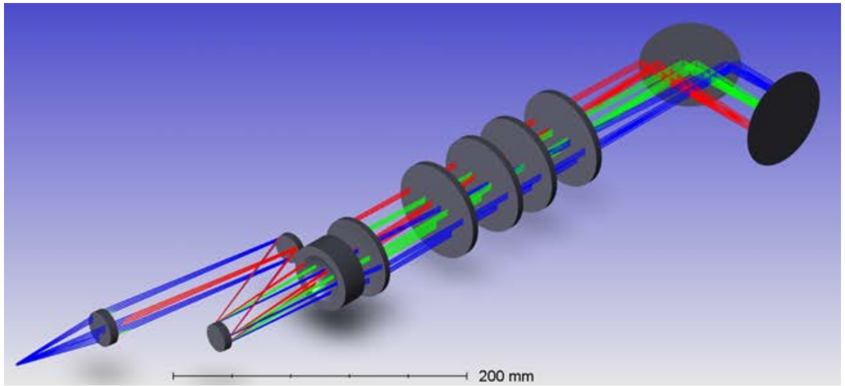


Image Credit: NOAO

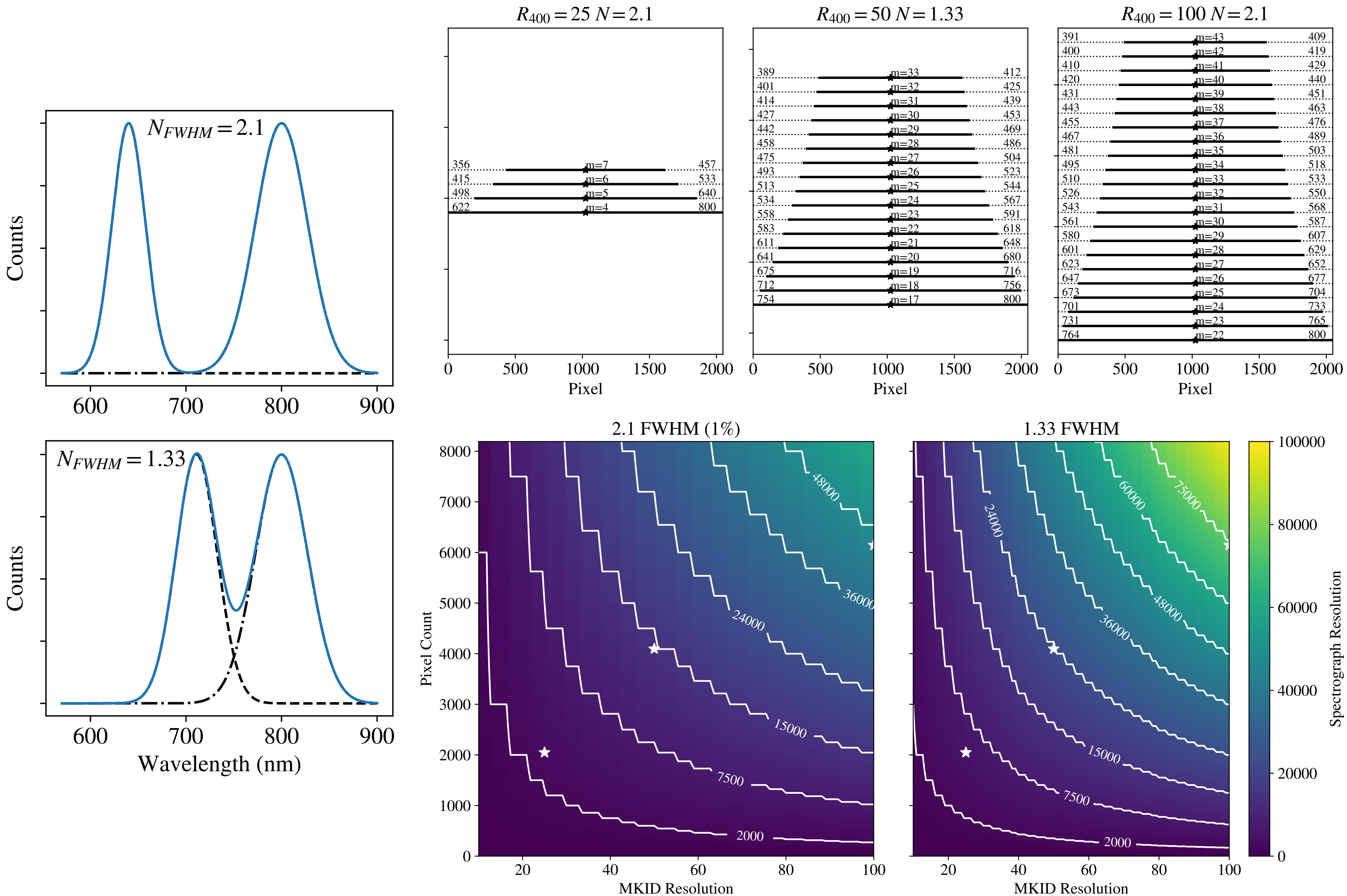
- HiRes spectrographs use an echelle grating to disperse the light in y and a cross-disperser to disperse in x
- Need a lot of pixels!
- Light is spread out over many many pixels so read noise can become very important
- Application changes requirement
  - RV – high thermal stability, very high R
  - Wide wavelength coverage – multiple arms
  - Best possible blue coverage – no fibers
- Conventional instruments scale with telescope d - $$$ for ELT

Use Case: High Resolution Spectrograph

- MKID version!
- MKID ability to determine every photon's energy means we can eliminate cross disperser – higher throughput, more compact!
- 1d echellogram means we can pack many spectra in
  - A true high resolution multiobject spectrograph (HRMOS)
- Can make a R>50k multiobject spectrograph
  - 100+ simultaneous fibers?
  - Looking at this for "High Dispersion Coronography"
  - Earth analogues from TMT?



Linear MKID Arrays



Use Case: Wavefront Sensor

- Determine wavefront distortion quickly for adaptive optics
  - >1 kHz frame rate
  - Not a lot of pixels needed
  - Low noise
- EMCCD!

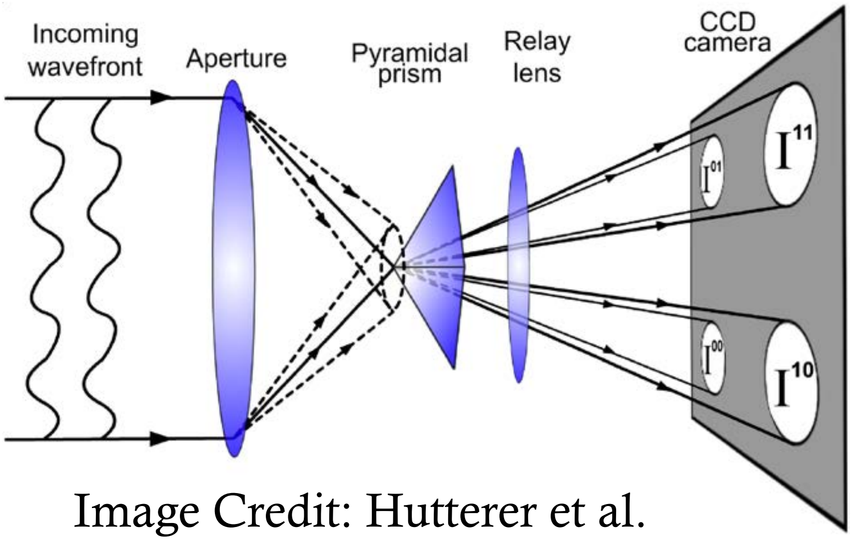
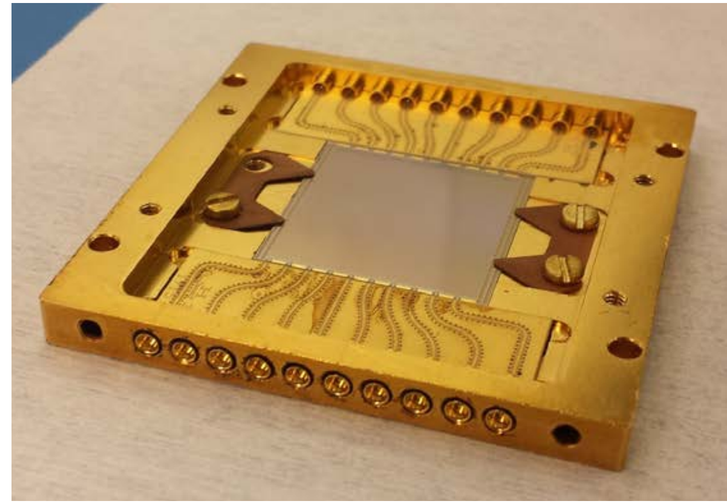


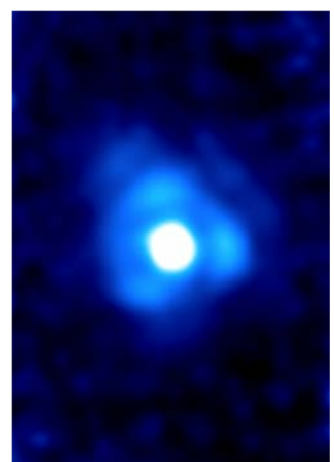
Image Credit: Hutterer et al.

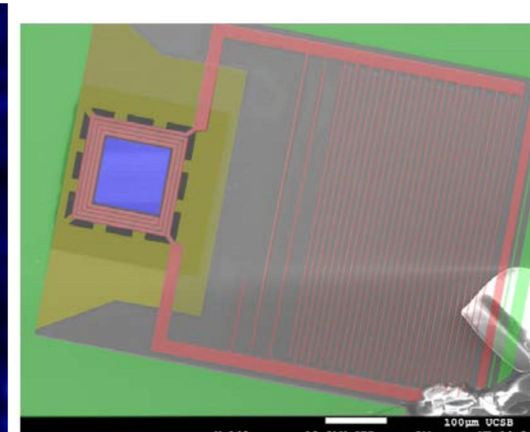
MKID Take Aways

- We've built superconducting optical/near-IR detector arrays that can count individual photons and determine their energy without filters or gratings
- On a pixel for pixel basis, these are **the most powerful UVOIR detectors in the world**
- We're going to use these detectors to revolutionize astronomy by taking spectra of EVERYTHING, starting with extrasolar planets
- We also make X-ray detectors using the same technology (Ulbricht et. al 2015)



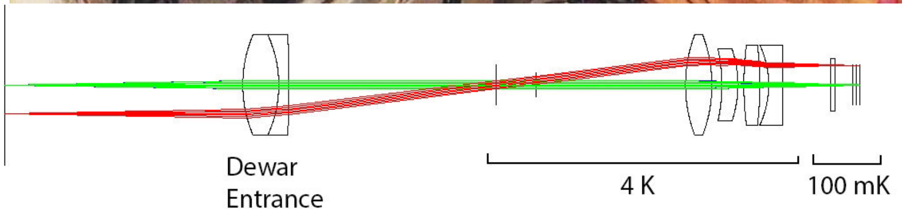
Day *et al.*, Nature, 2003
Mazin *et al.*, Optics Express 2012
Mazin *et al.*, PASP 2013
Szypryt *et al.*, Optics Express 2017
Meeker *et al.*, PASP, 2018

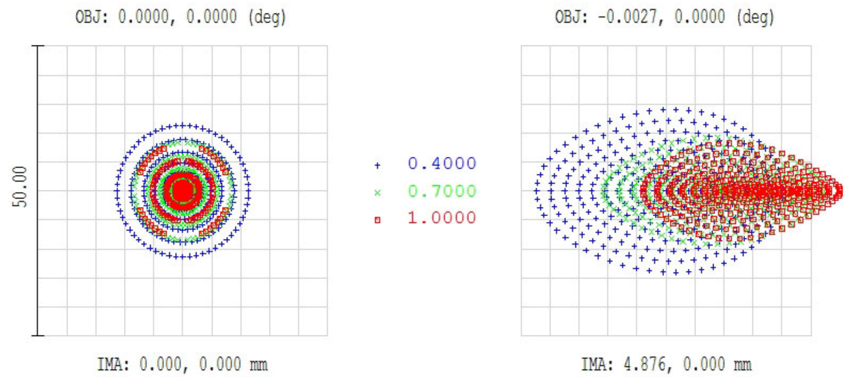




Proven at the Telescope with ARCONS

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



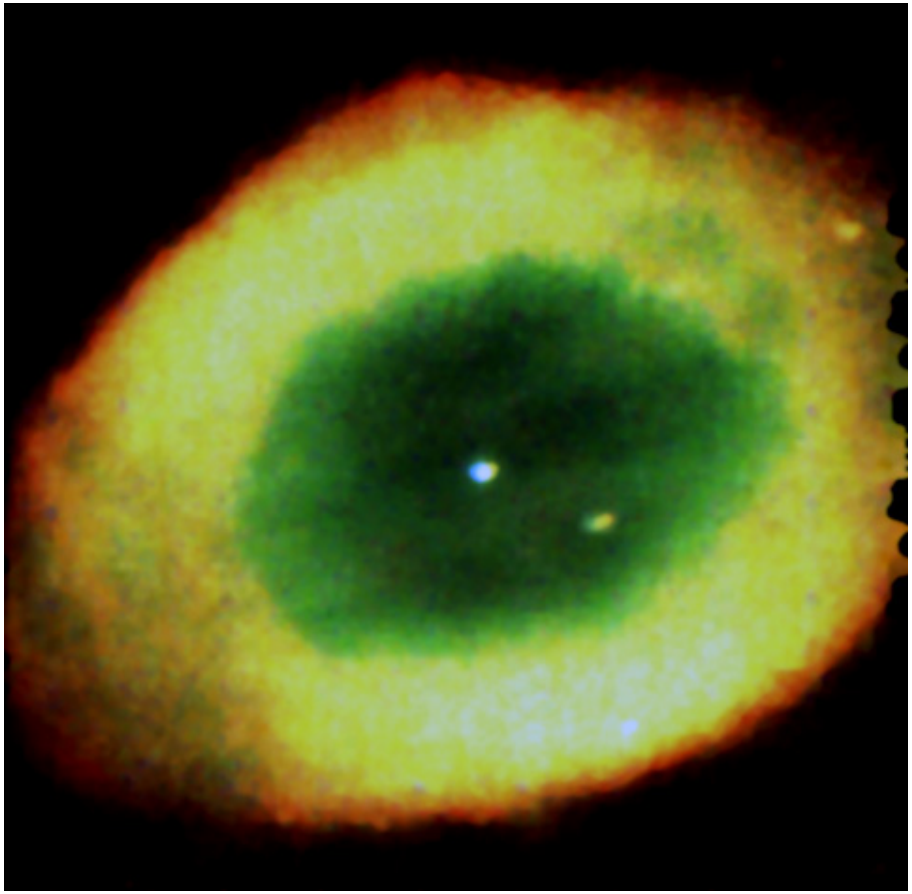


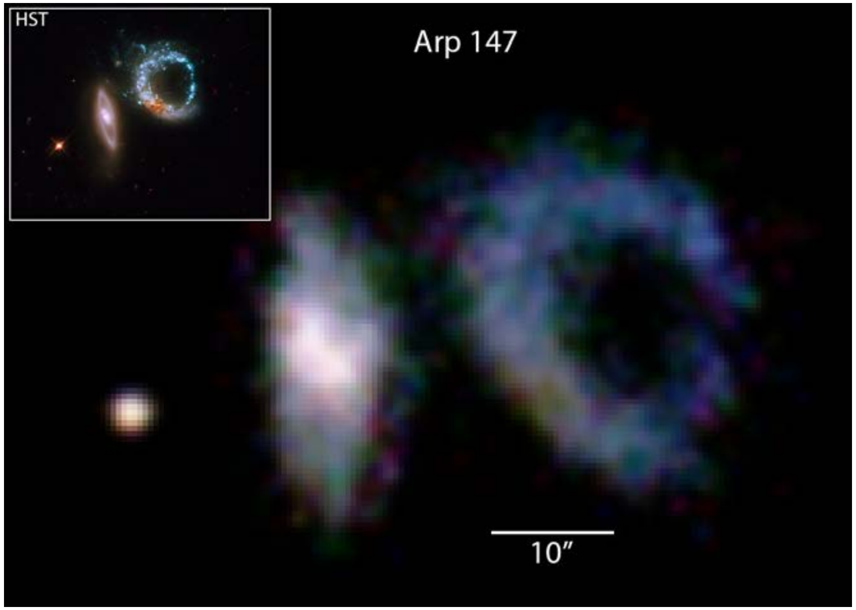
Mazin et al. 2013, PASP

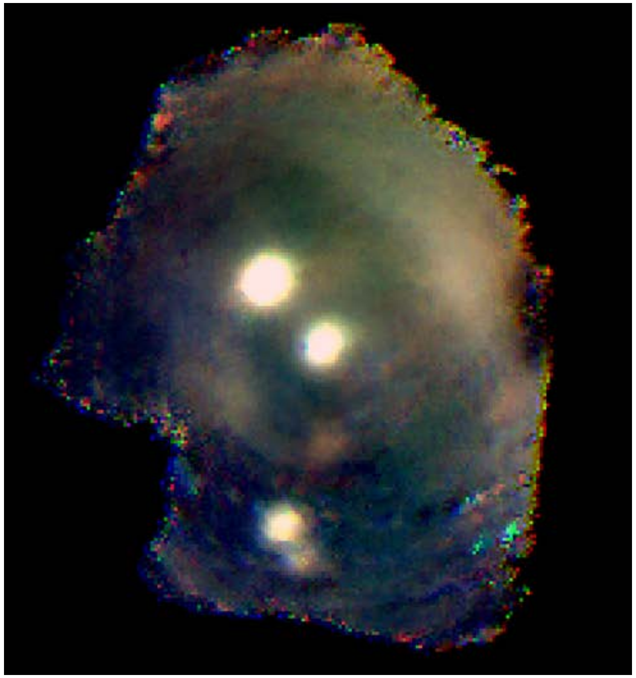
Crab Pulsar

- Made on the mountain during our first ARCONS Palomar run!

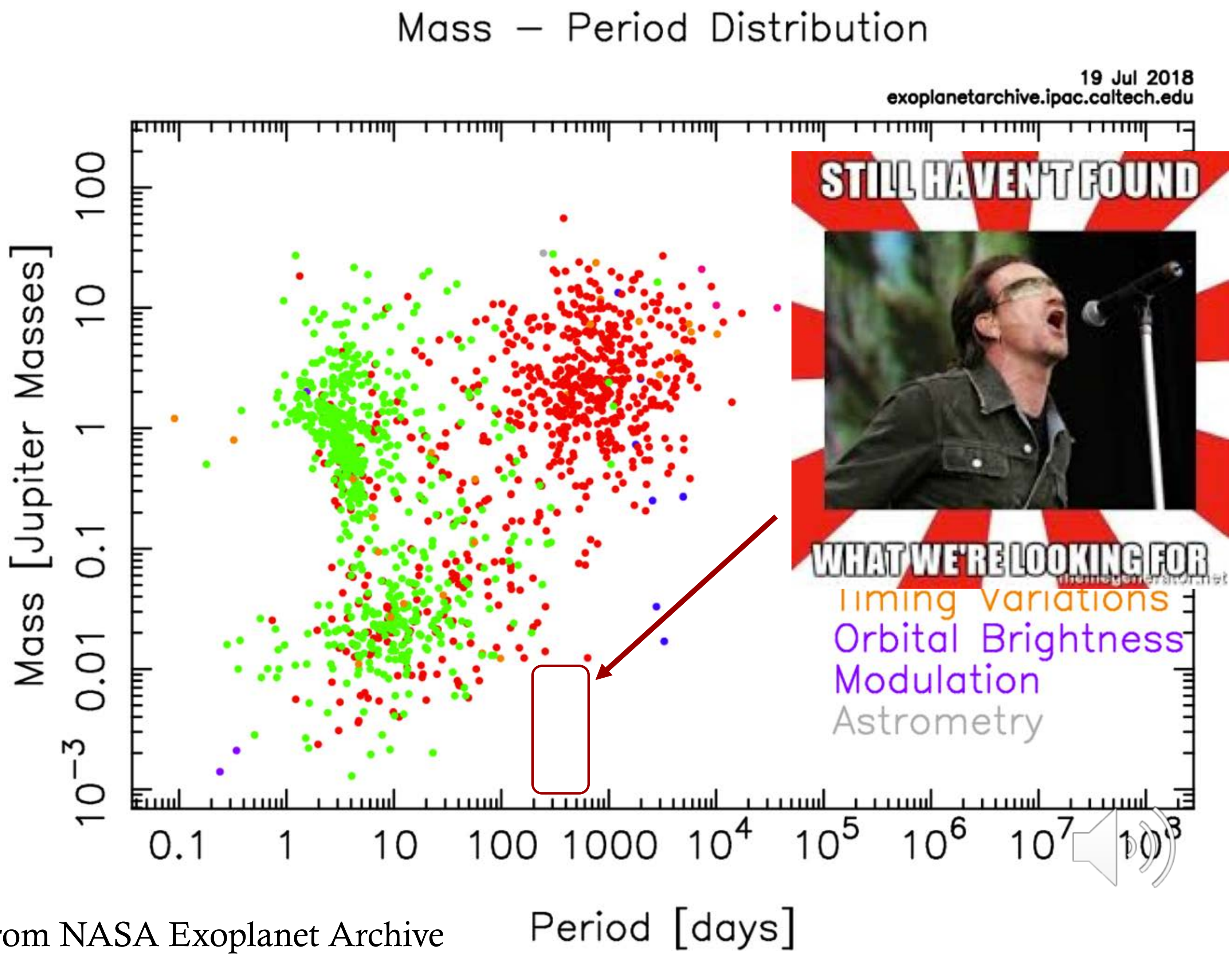
Images from ARCONS and DARKNESS





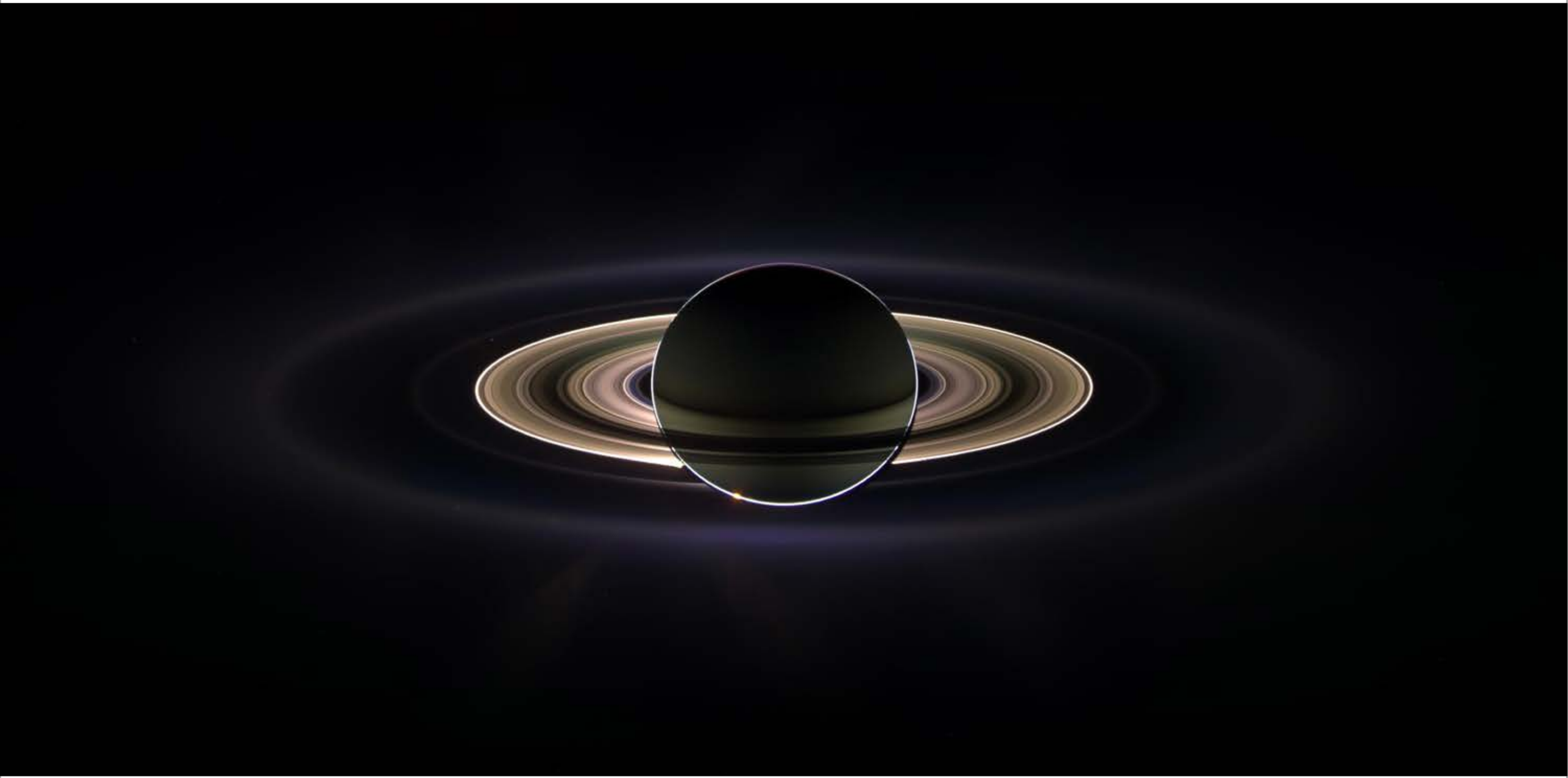


We still have a lot to learn



Plot from NASA Exoplanet Archive

Exoplanets



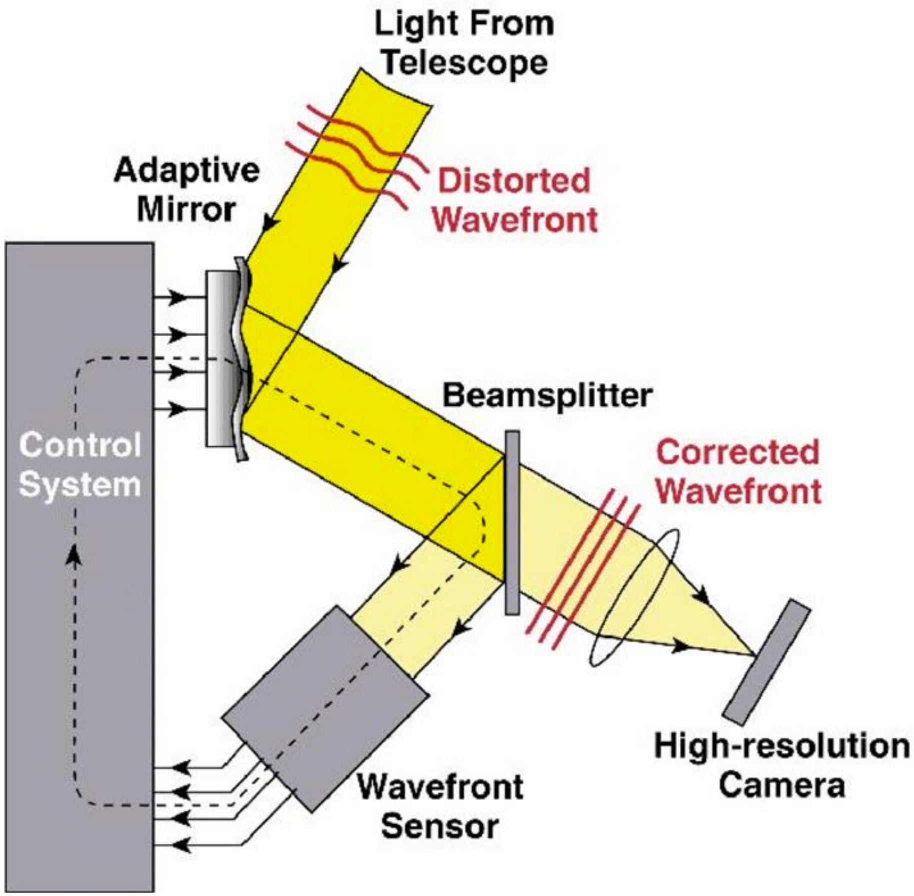
- Our best estimate is that 5-25% of stars (and maybe every M dwarf?) have an ~Earth radius planet in their habitable zone!
- Most likely one around the nearest star – Proxima Centauri b
- How can we find and characterize these planets?
  - Huge potential payoff: Atmospheres out of chemical equilibrium → **Life**

Methods of Exoplanet Detection

- **Radial Velocity:** Good for massive planets around well behaved stars with lots of sharp features in their spectrum
- **Transit:** Good for only the 1% of stars that are aligned correctly for us to see transits
- RV and Transit ets but not tell us about their atm . Is there hope?

Step 1: Adaptive Optics

- The atmosphere messes up incoming starlight
  - Twinkling stars!
  - Good for kids rhymes, bad for astronomy
- Fix it with (lots and lots of) technology!



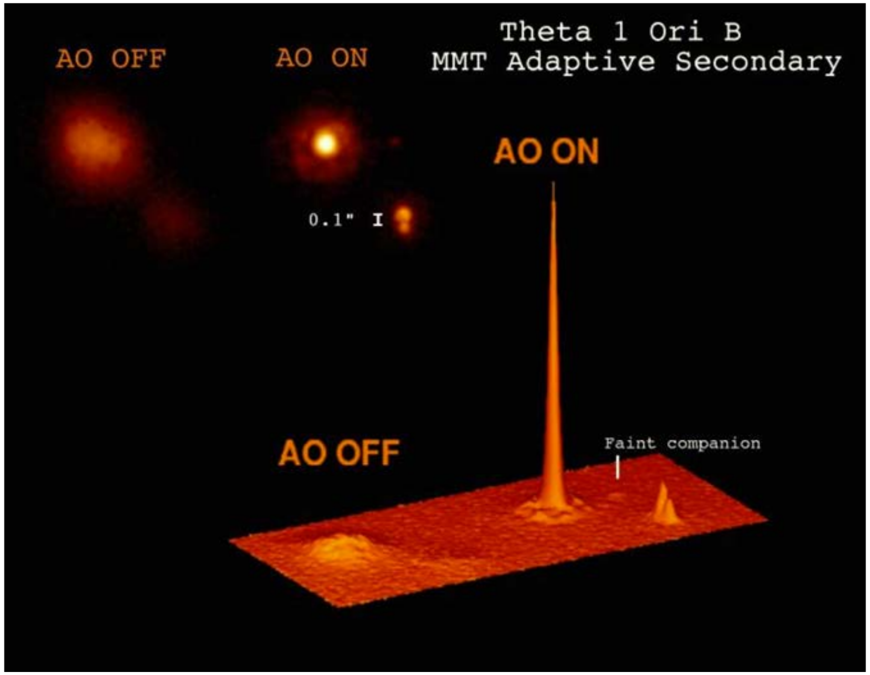
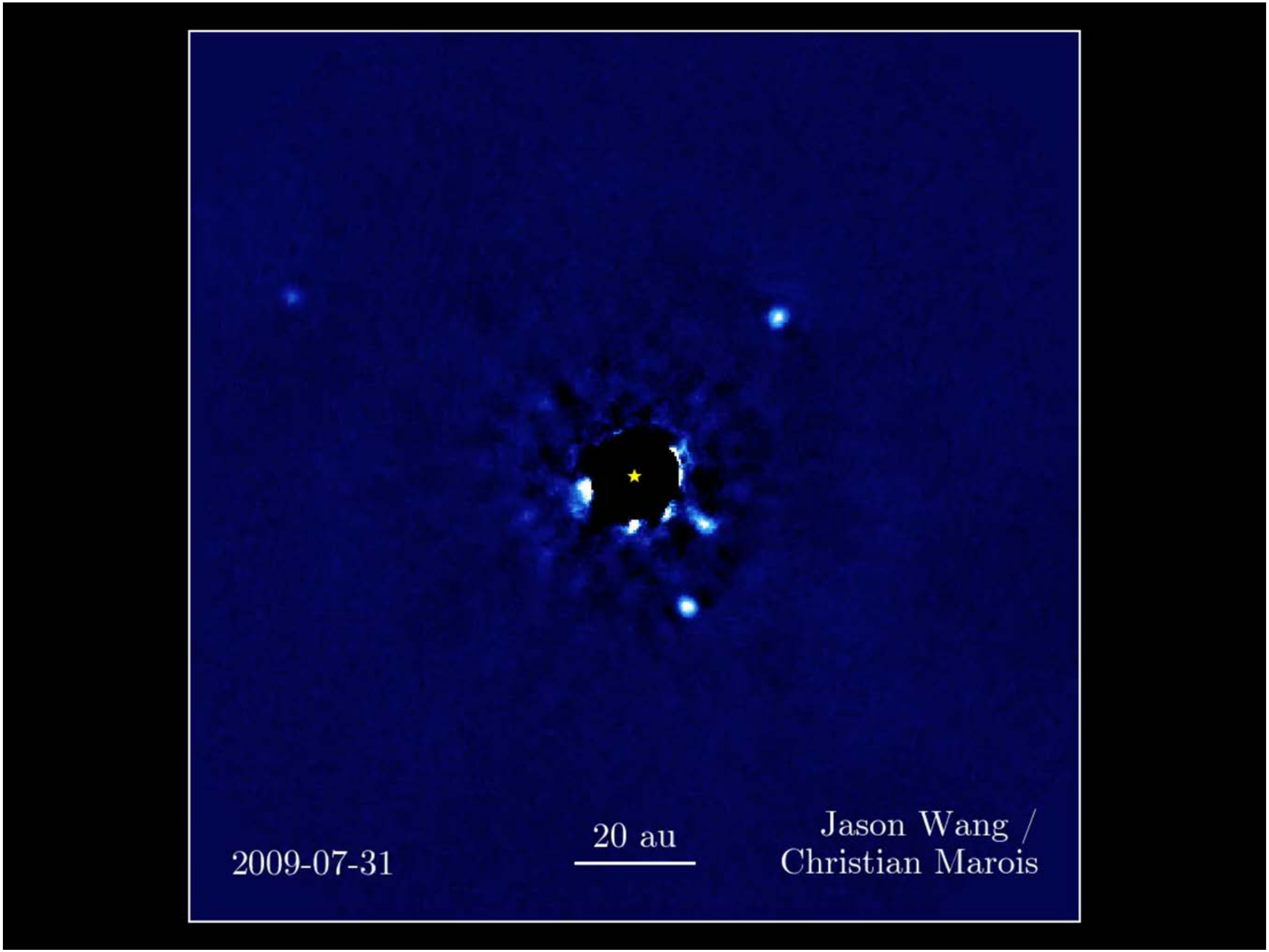


Image Credit: Above: Clare Max, CfAO
Left: Laird Close, UoA

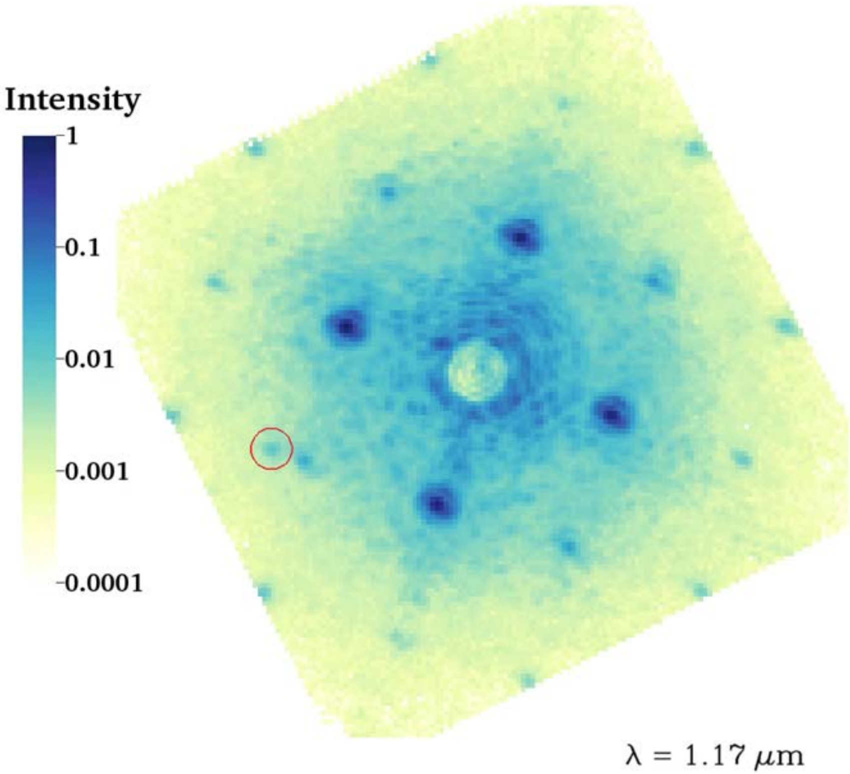
HR8799



Step 2: Coronagraphy

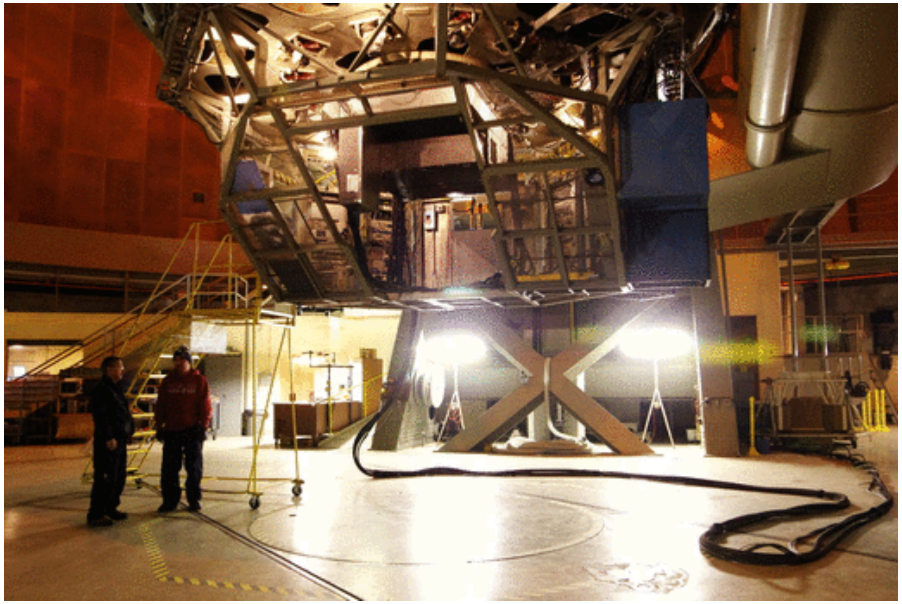
Step 3: Detection

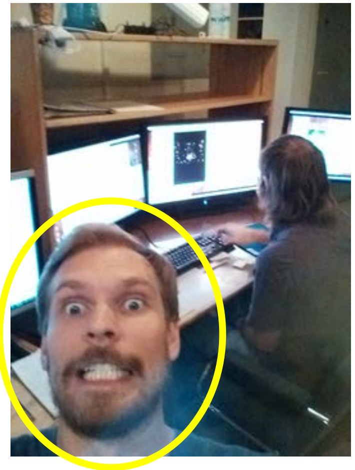
- Coronagraphs are limited by speckles from scattered and diffracted light
  - Speckles are *coherent* and *chromatic* and have a variety of lifetimes
    - Quasi-static: many minutes
    - Atmospheric: <1 second
  - Energy-resolving focal planes increase sensitivity by a factor of up to **10-100**
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

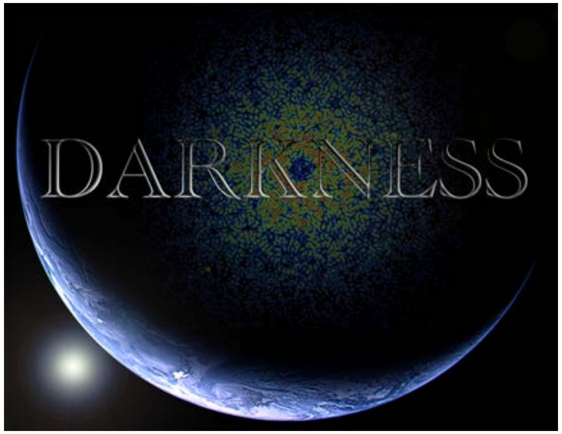


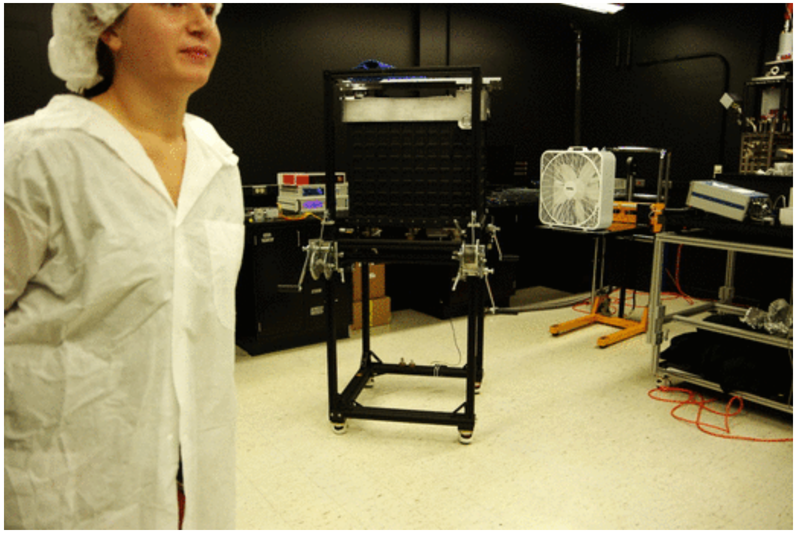
- Data on brown dwarf HD1160B from Tim Brandt and CHARIS/SCExAO

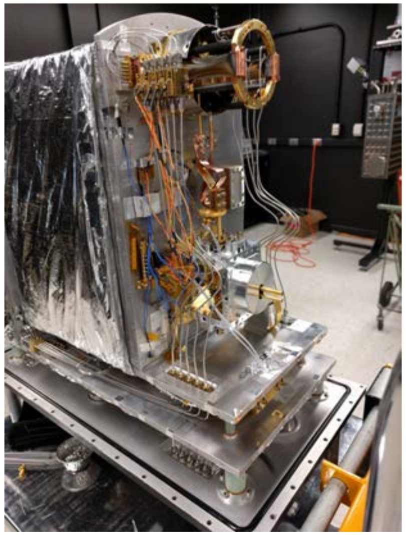
DARKNESS





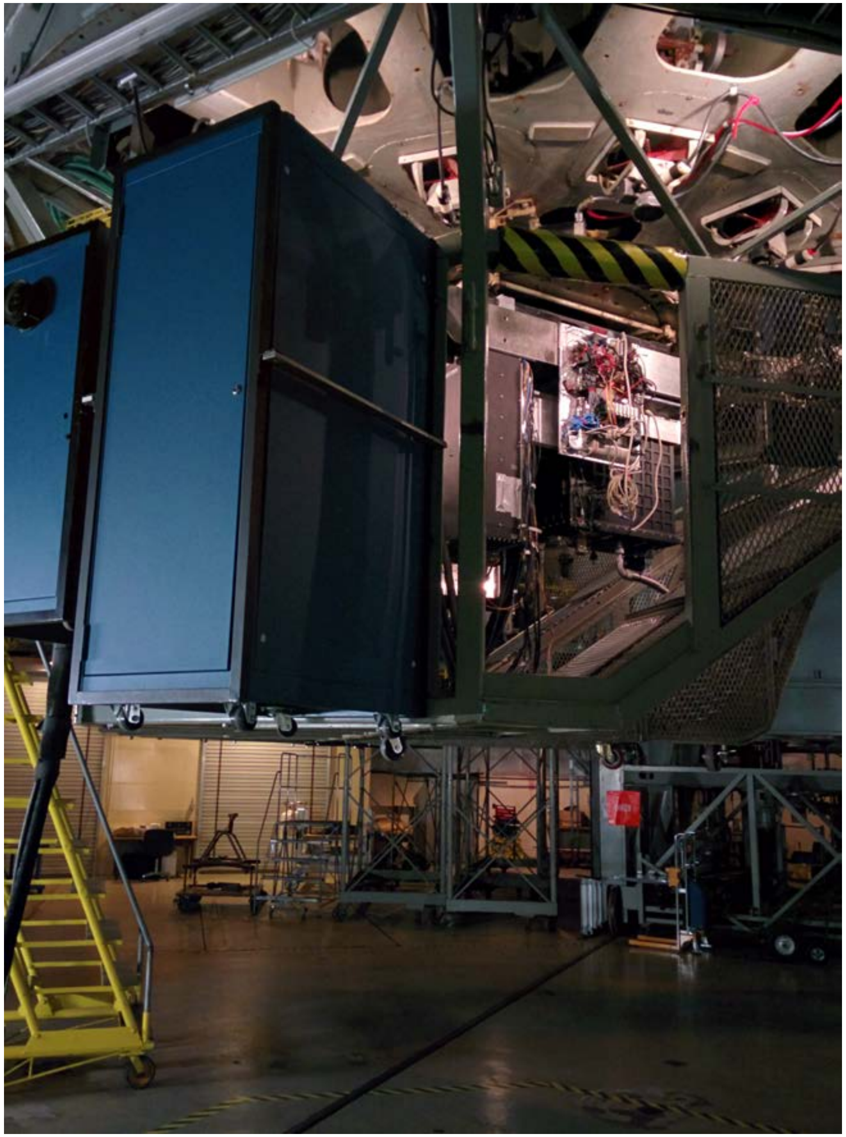


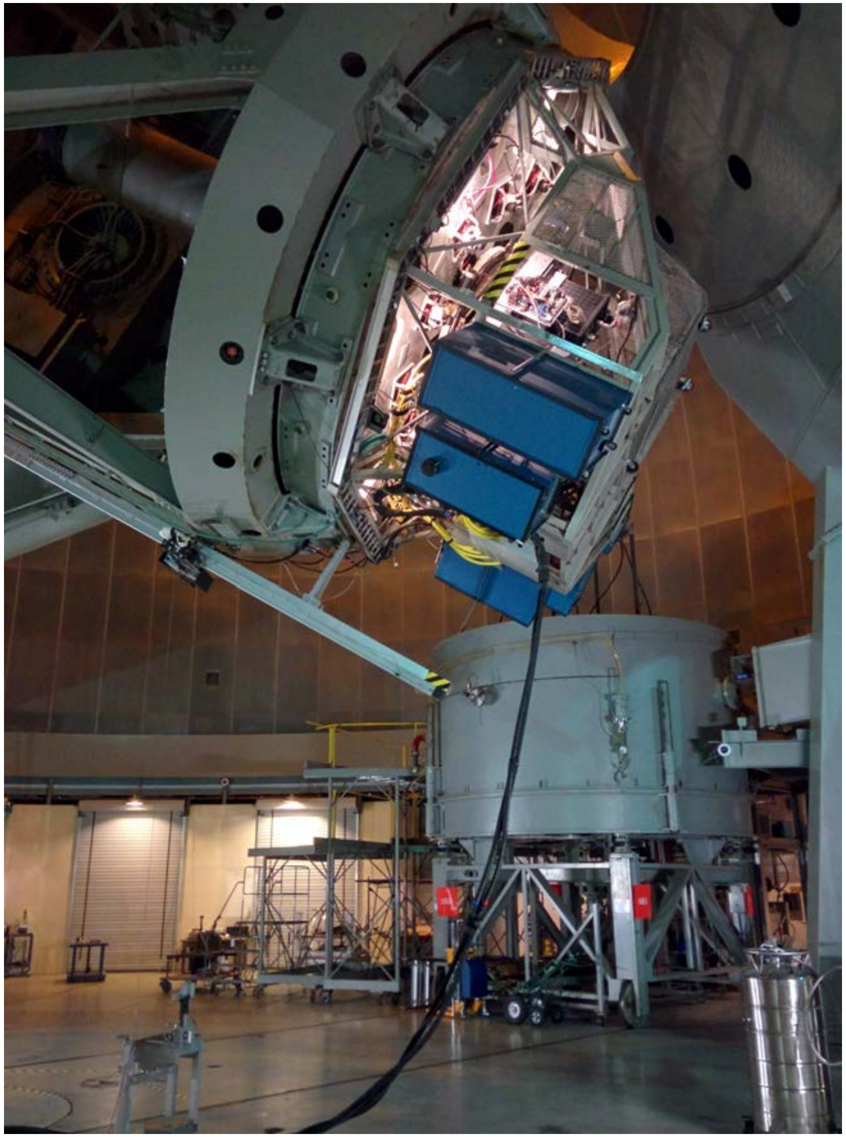




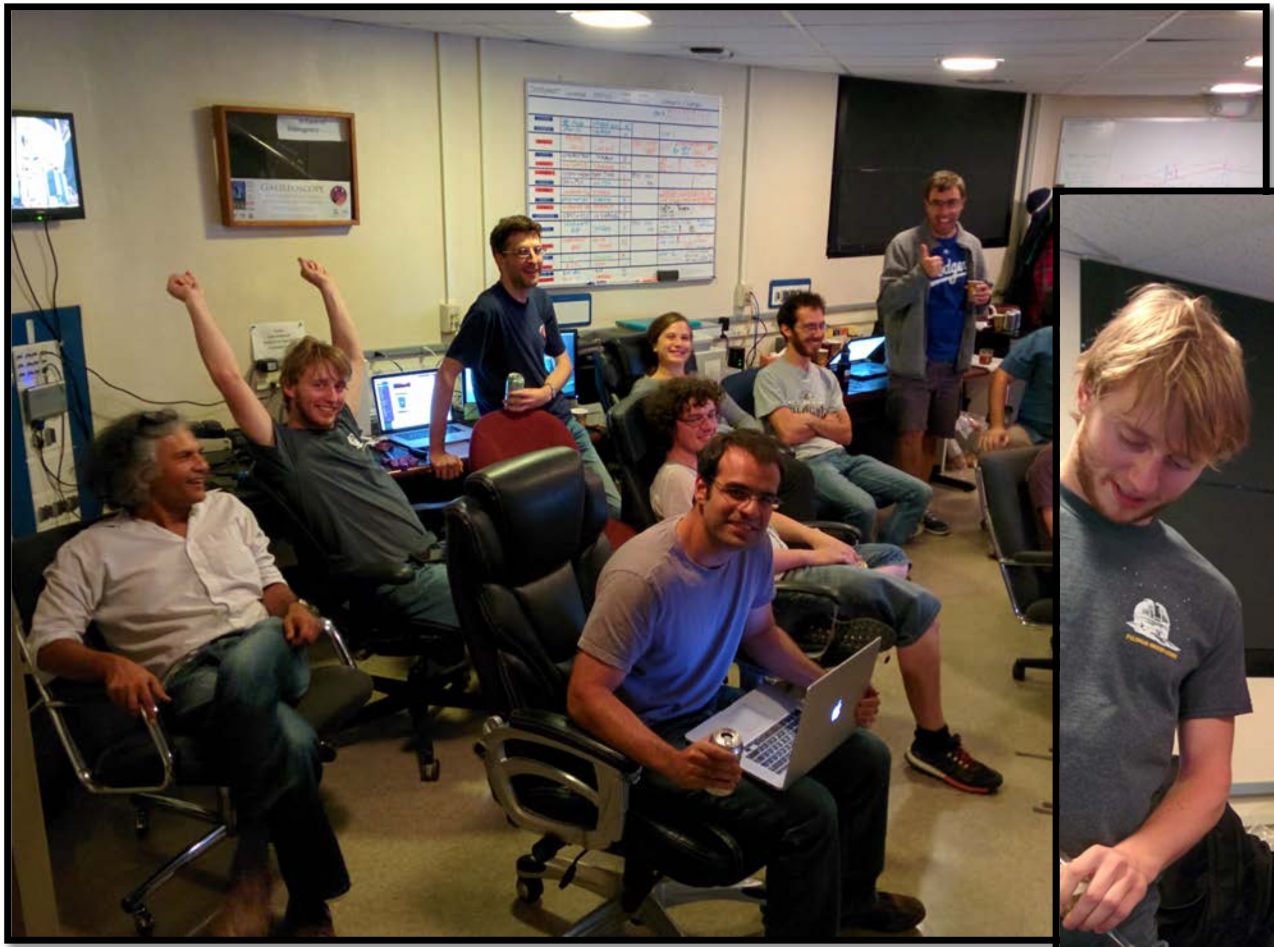
DARKNESS is the thesis project of Seth Meeker (Meeker et. al. 2018, PASP)

DARKNESS Commissioning, July 2016



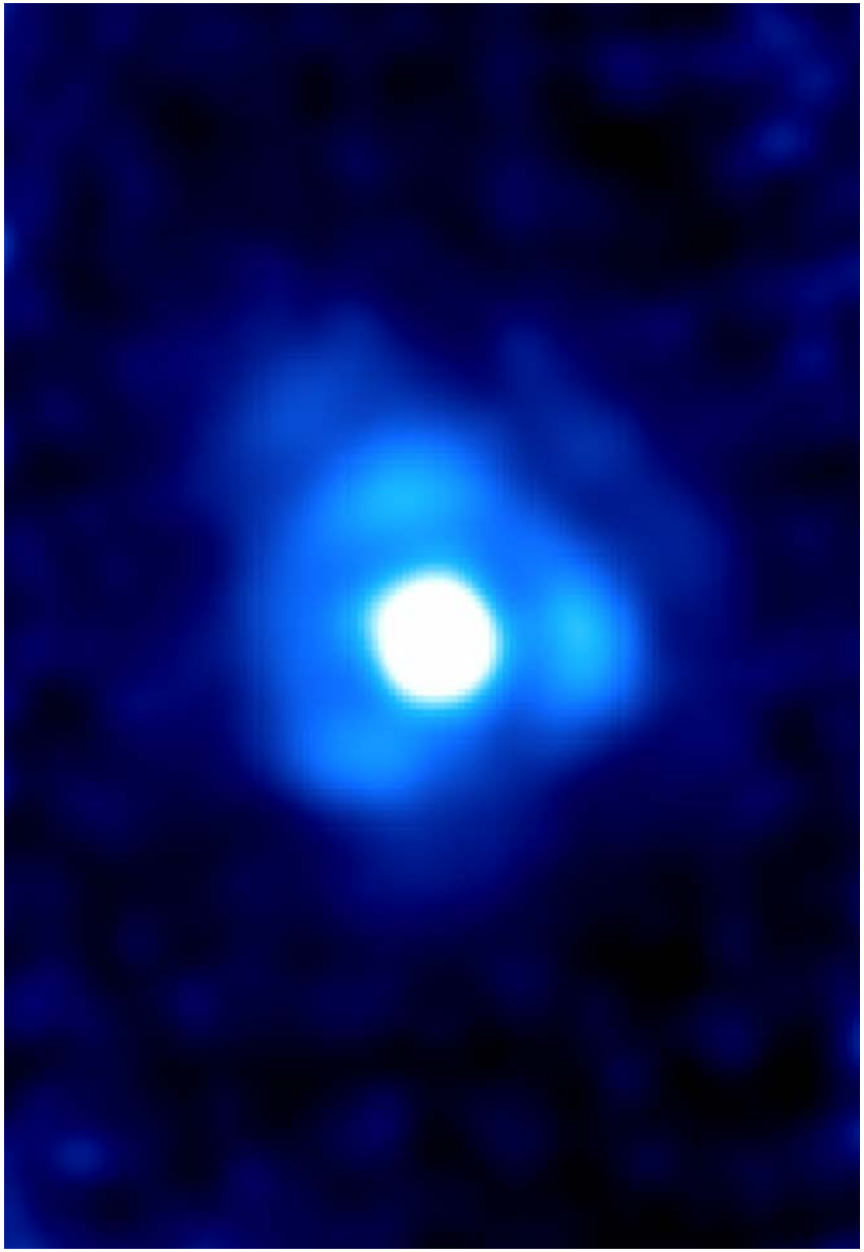


Party



It works!

- Diffraction limited star in J-band with DARKNESS

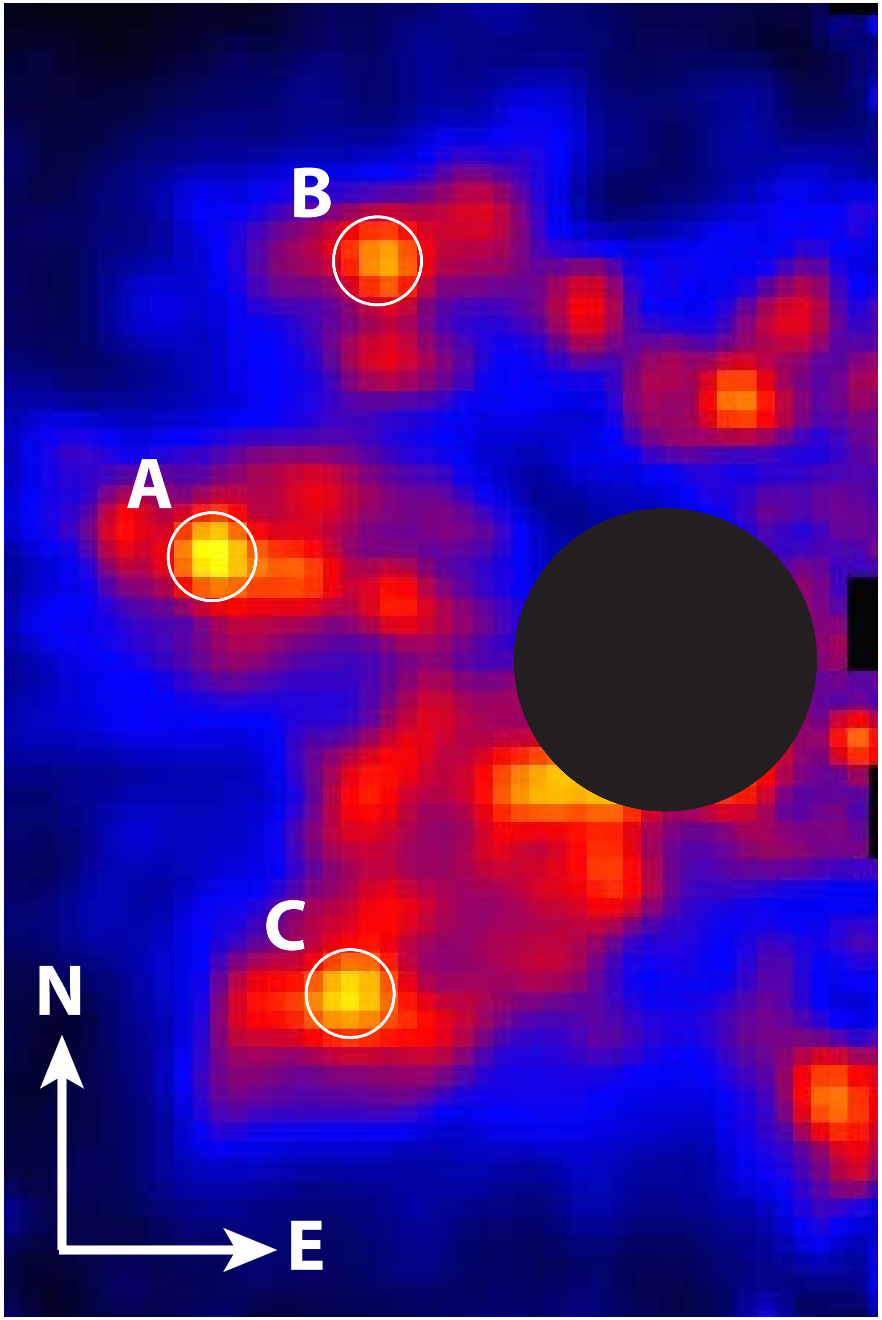


32 Pegasi (SAO 90440)

Shown here as the median frame of a long dither sequence.

Companion (32 Peg Ab) is at location A

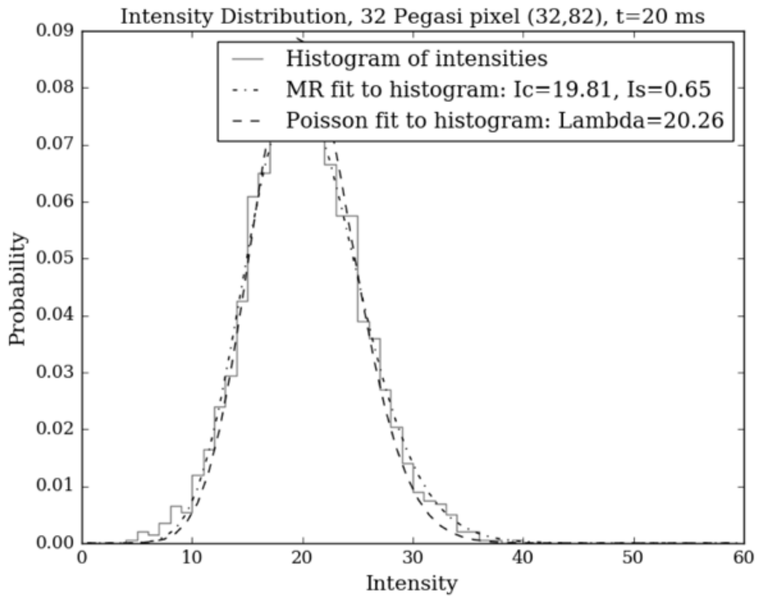
Satellite speckles placed by us at similar radii and intensity as secondary at locations B, C



Figures courtesy of Dr. Seth Meeker

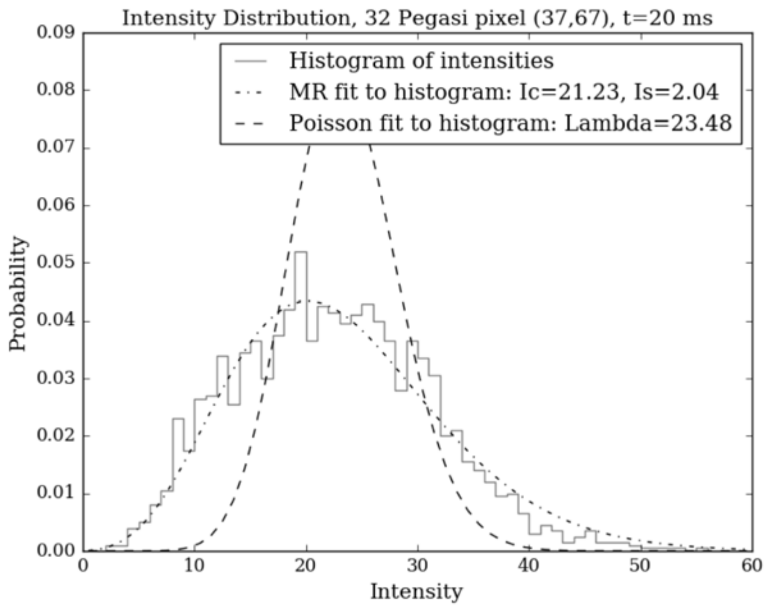
Histogram location A (companion)

Mean intensity ~20 photons / 20 ms



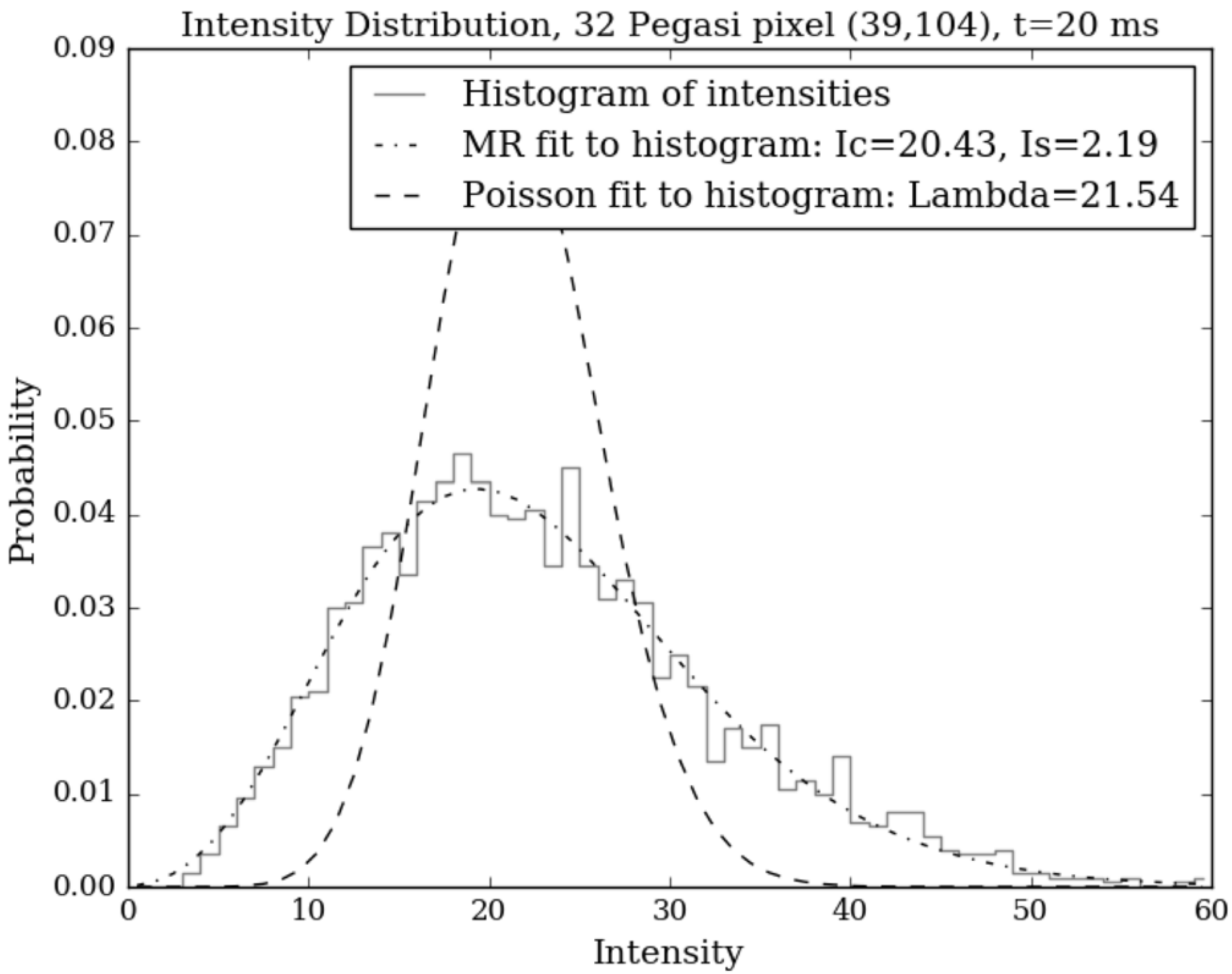
Histogram location B (satellite speckle)

Mean intensity ~23 photons / 20 ms

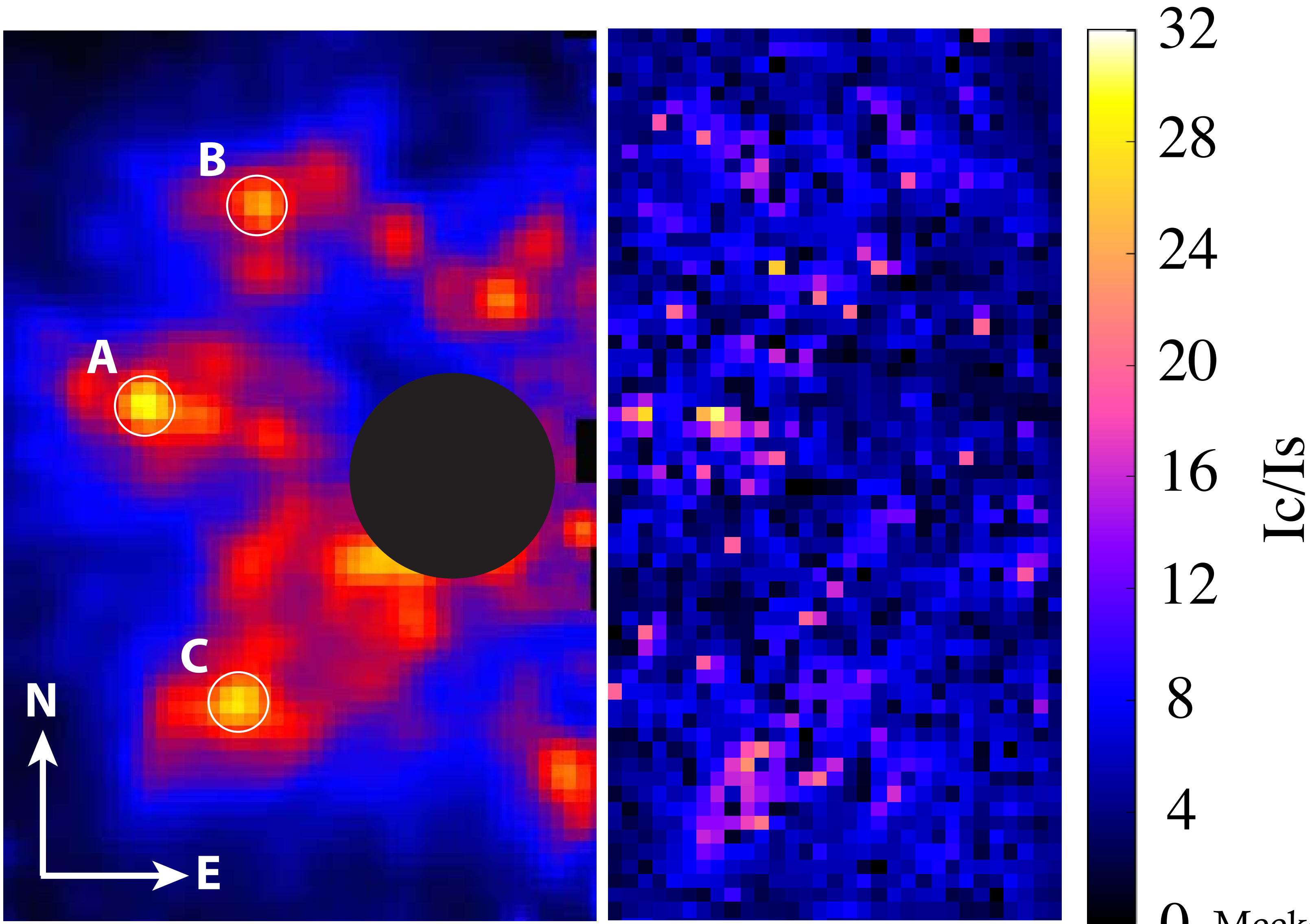


Histogram location C (satellite speckle)

Mean intensity ~21 photons / 20 ms



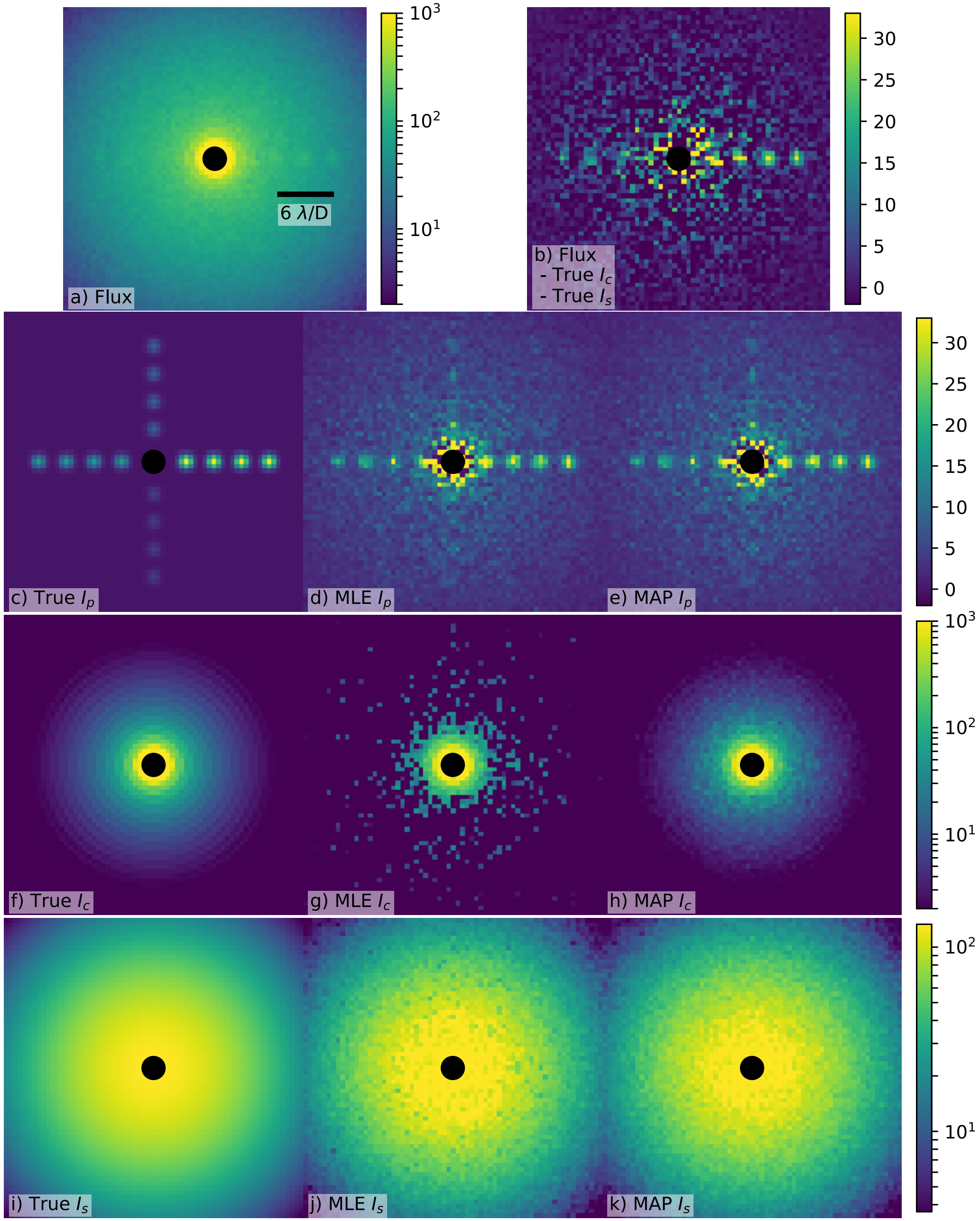
Map of I_c/I_c. Companion clearly stands out here with high SNR



Meeker *et al.* 2018 PASP

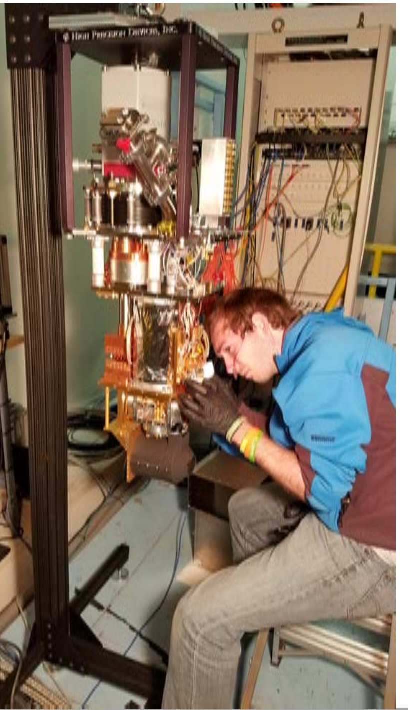
New SSD Method!

Walter et al., 2019 PASP Submitted



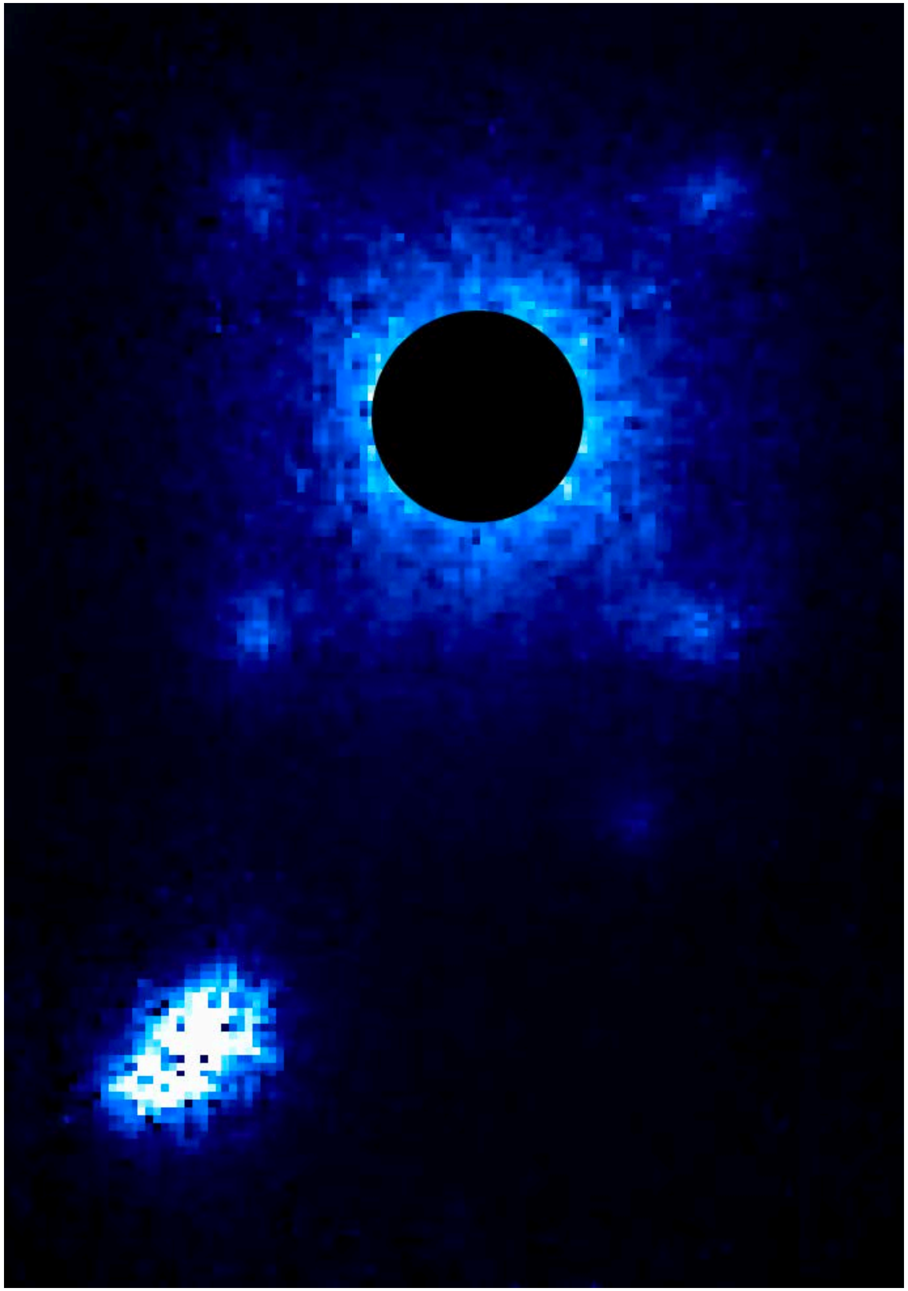
- MEC is a 20 kpix version of DARKNESS for Subaru SCExAO
  - 20 kpix MKID IFU
  - SCExAO at Subaru Observatory
    - PIAA/Vector Coronagraph
  - Observe cold gas giants in reflected light?

MEC is the thesis project of Alex Walter



It works!

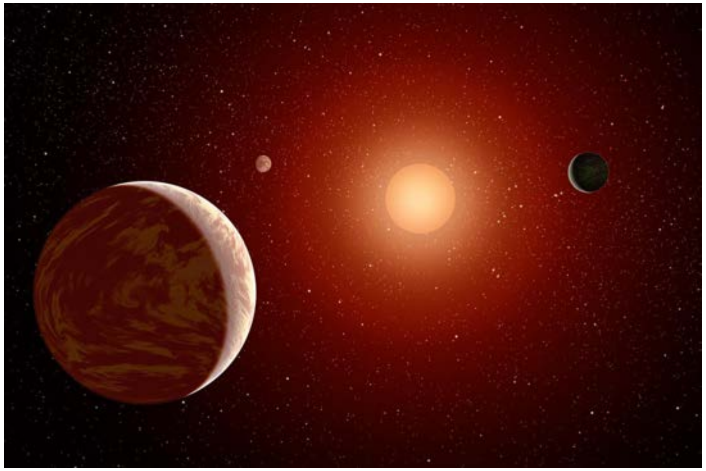
- Theta Orionis B



Large Apertures are Vital for Direct Imaging of Exoplanets

- GPI/SPHERE/SCExAO/P1640/etc. show planets are rare past 10 AU
- Going inside 10 AU pushes us to large aperture and short wavelengths for a small inner working angle (IWA)
  - $2\lambda/D$ 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

ELTs

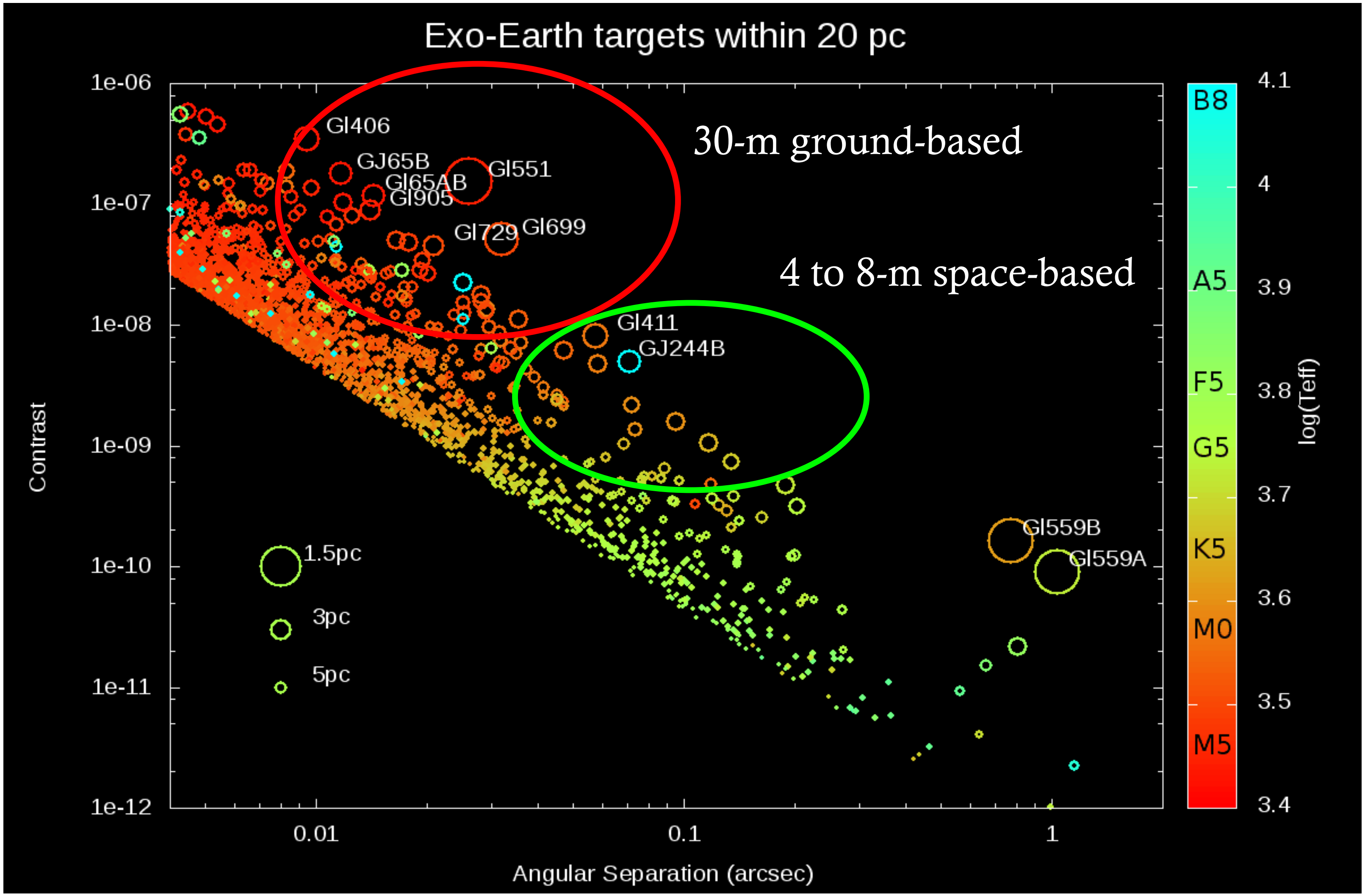
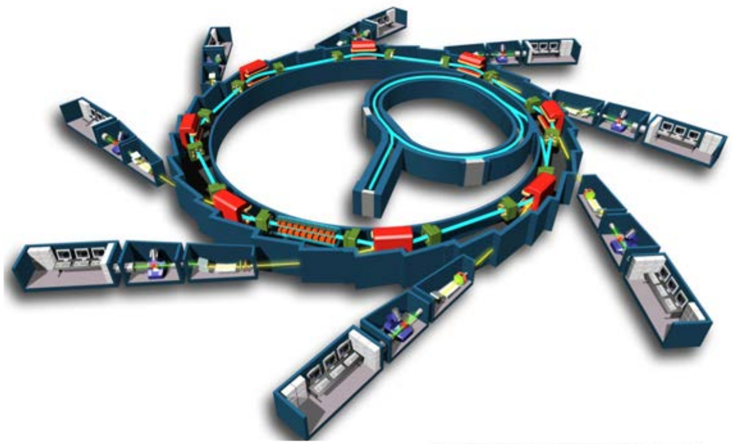
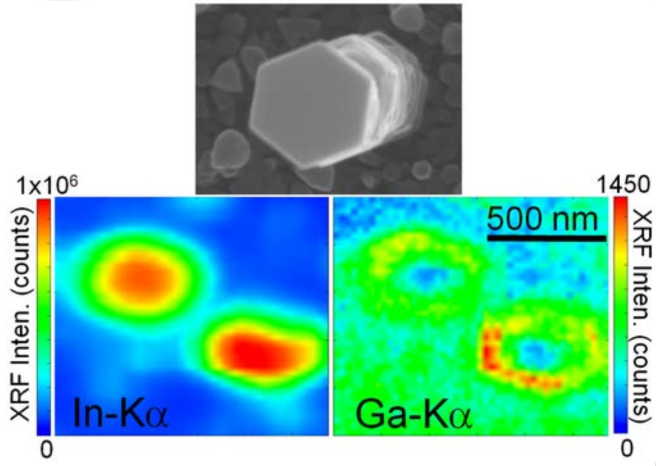


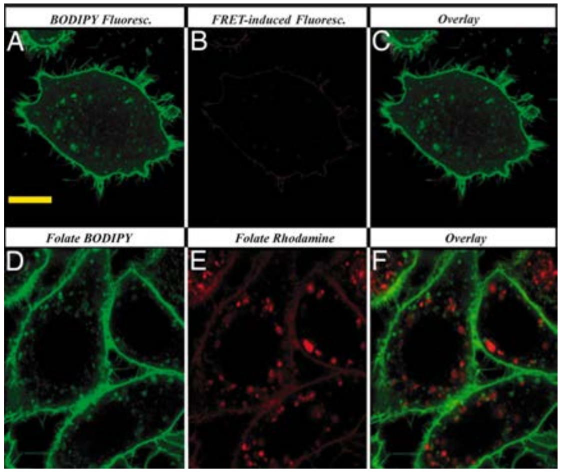
Figure from
O. Guyon

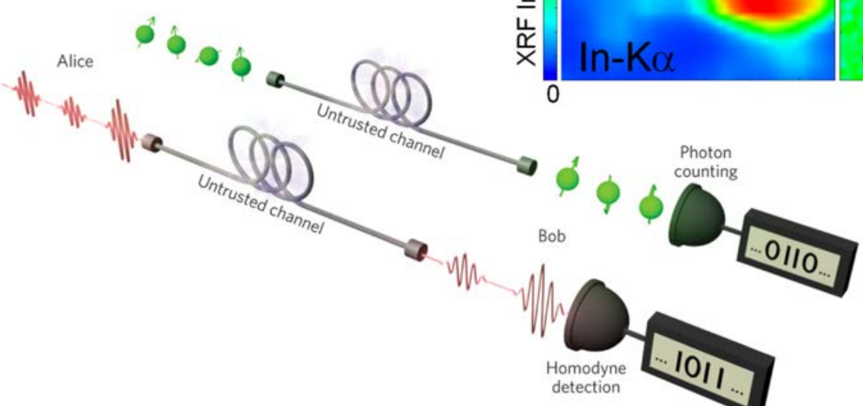
Other Applications

- 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!

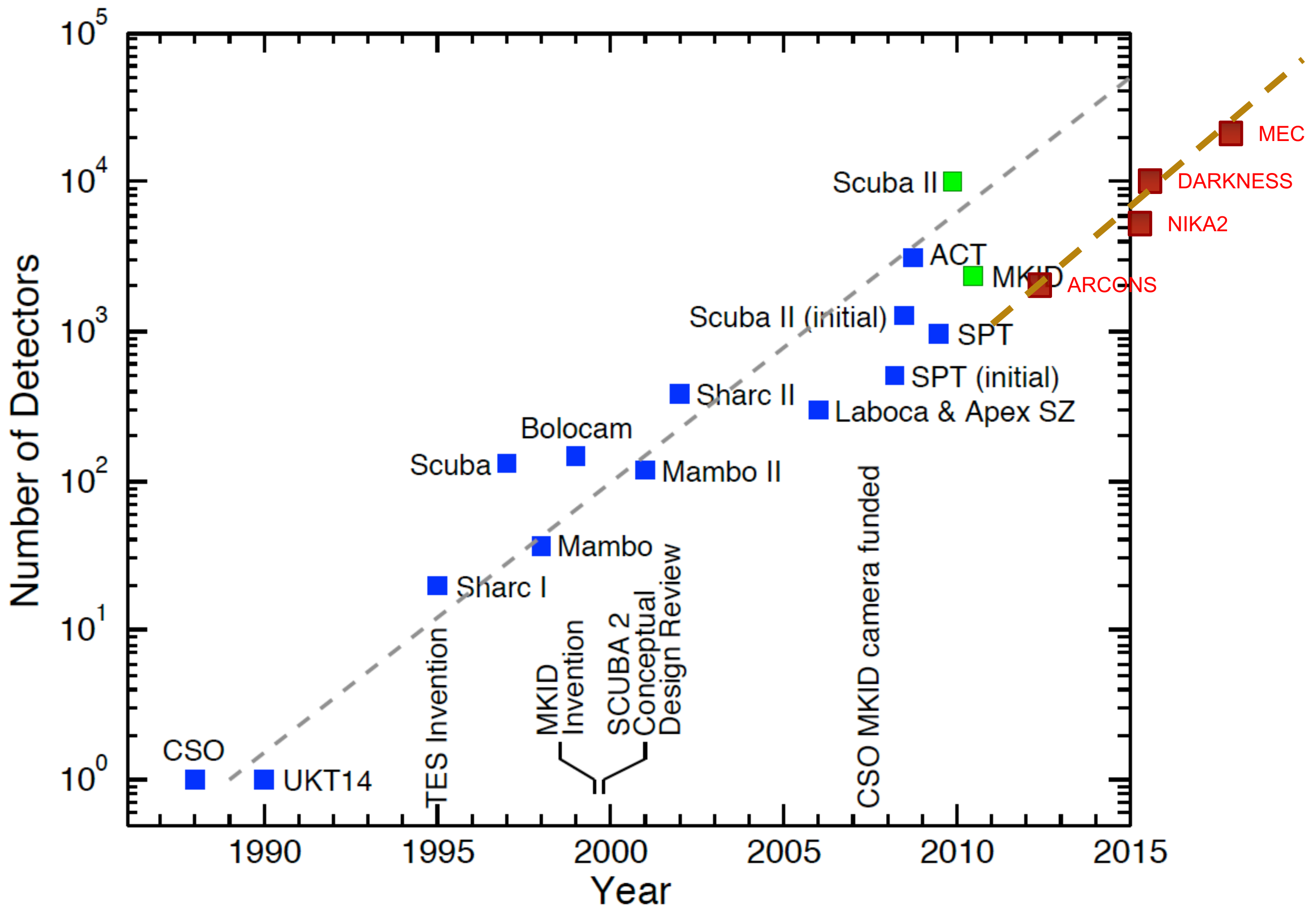








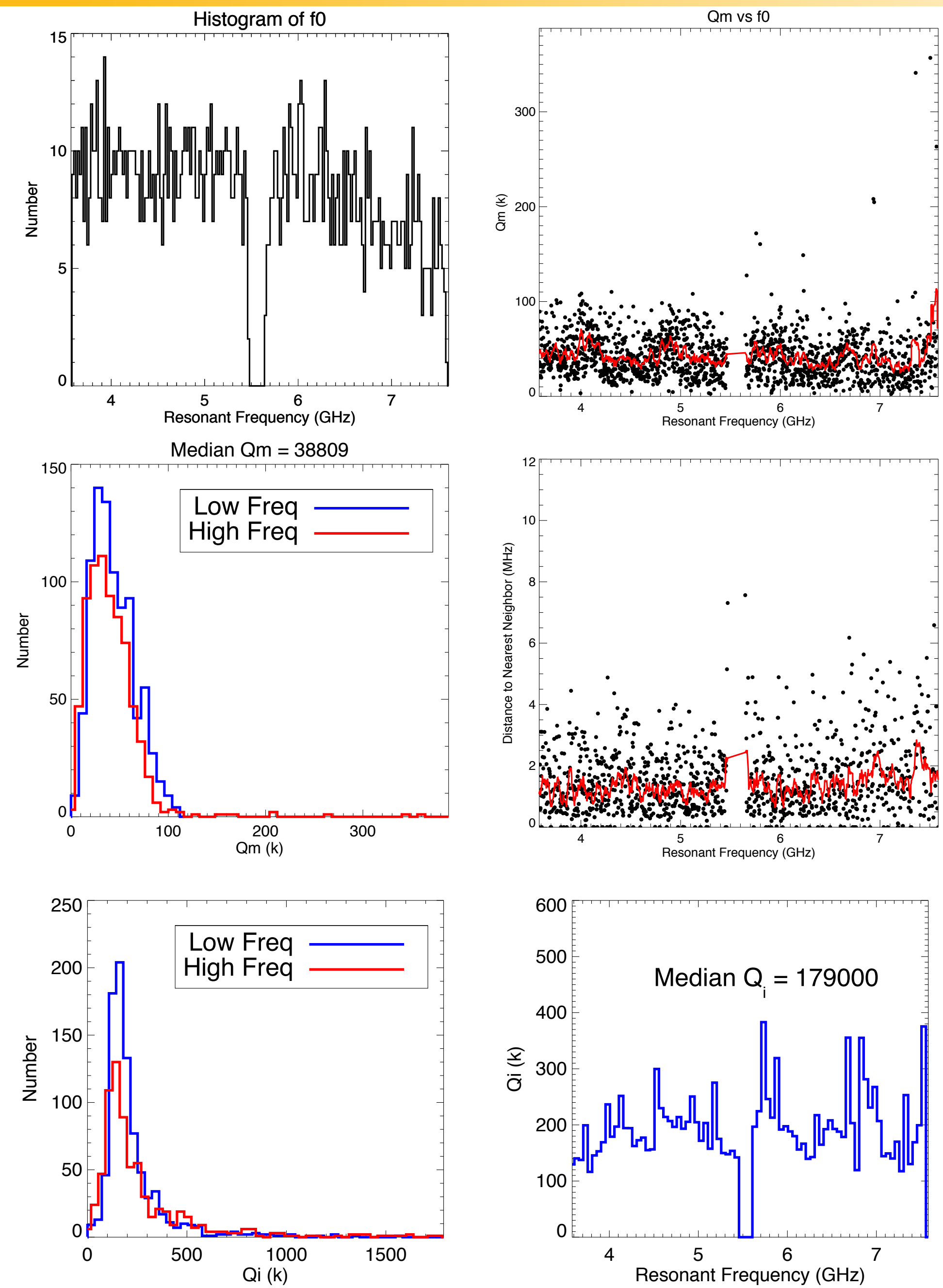
MKID Scaling



Original plot from J. Zmuidzinas

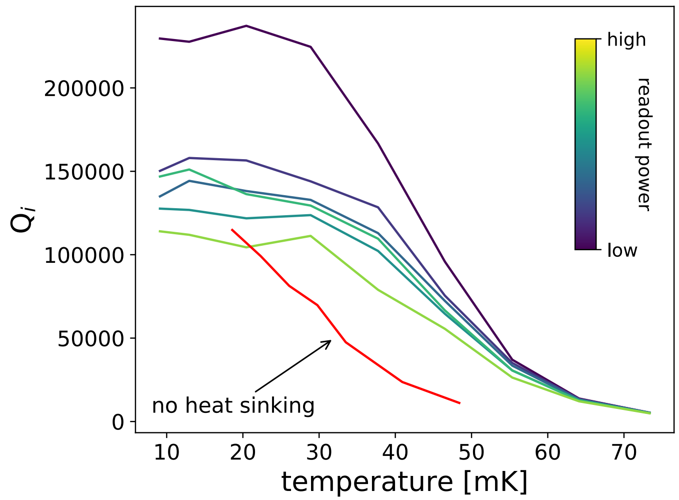
- MKID Backup Slides

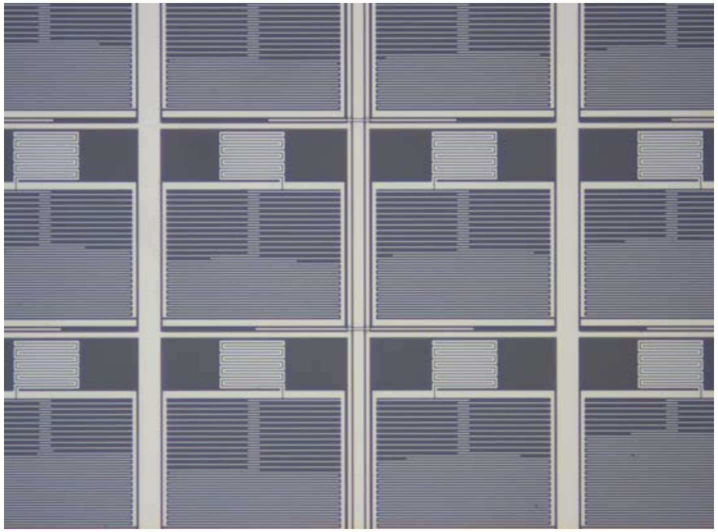
Uniformity

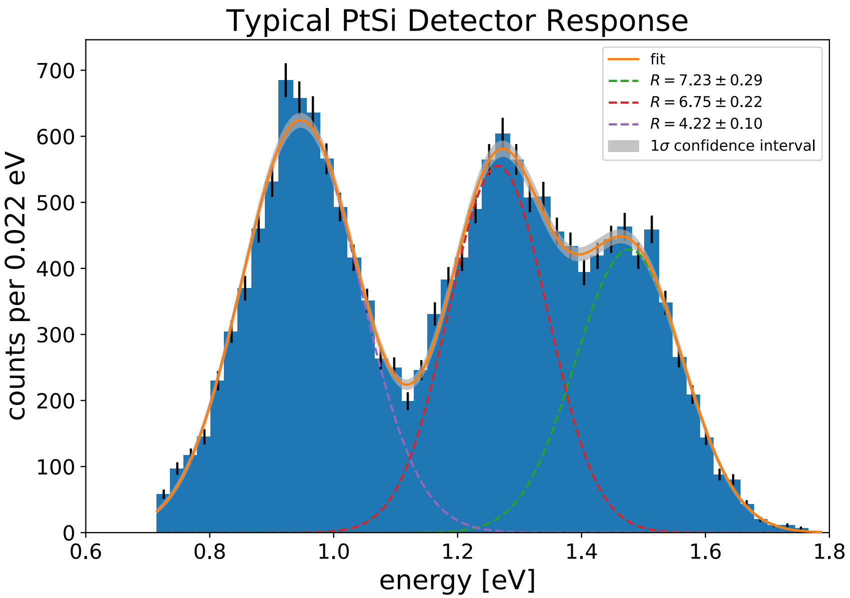

Histogram of f0
Number
Resonant Frequency (GHz)
Qm vs f0
Qm (k)
Resonant Frequency (GHz)
Median Qm = 38809
Low Freq
High Freq
Number
Qm (k)
Distance to Nearest Neighbor (MHz)
Resonant Frequency (GHz)
Low Freq
High Freq
Number
Qi (k)
Median Q_i = 179000
Qi (k)
Resonant Frequency (GHz)

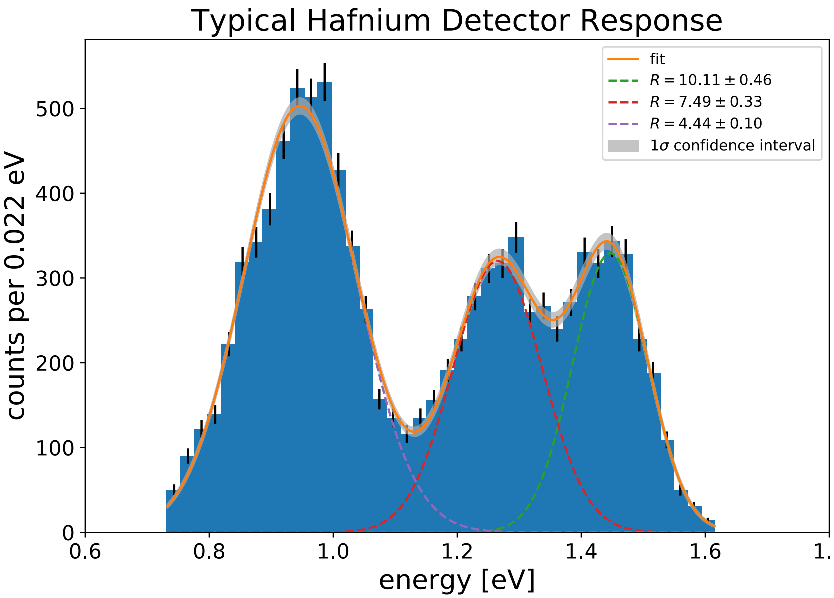
Hf MKIDs

- We are now making high quality MKIDs from Hafnium (Hf) with T_c~450 mK, τ_{qp} = 80 μs



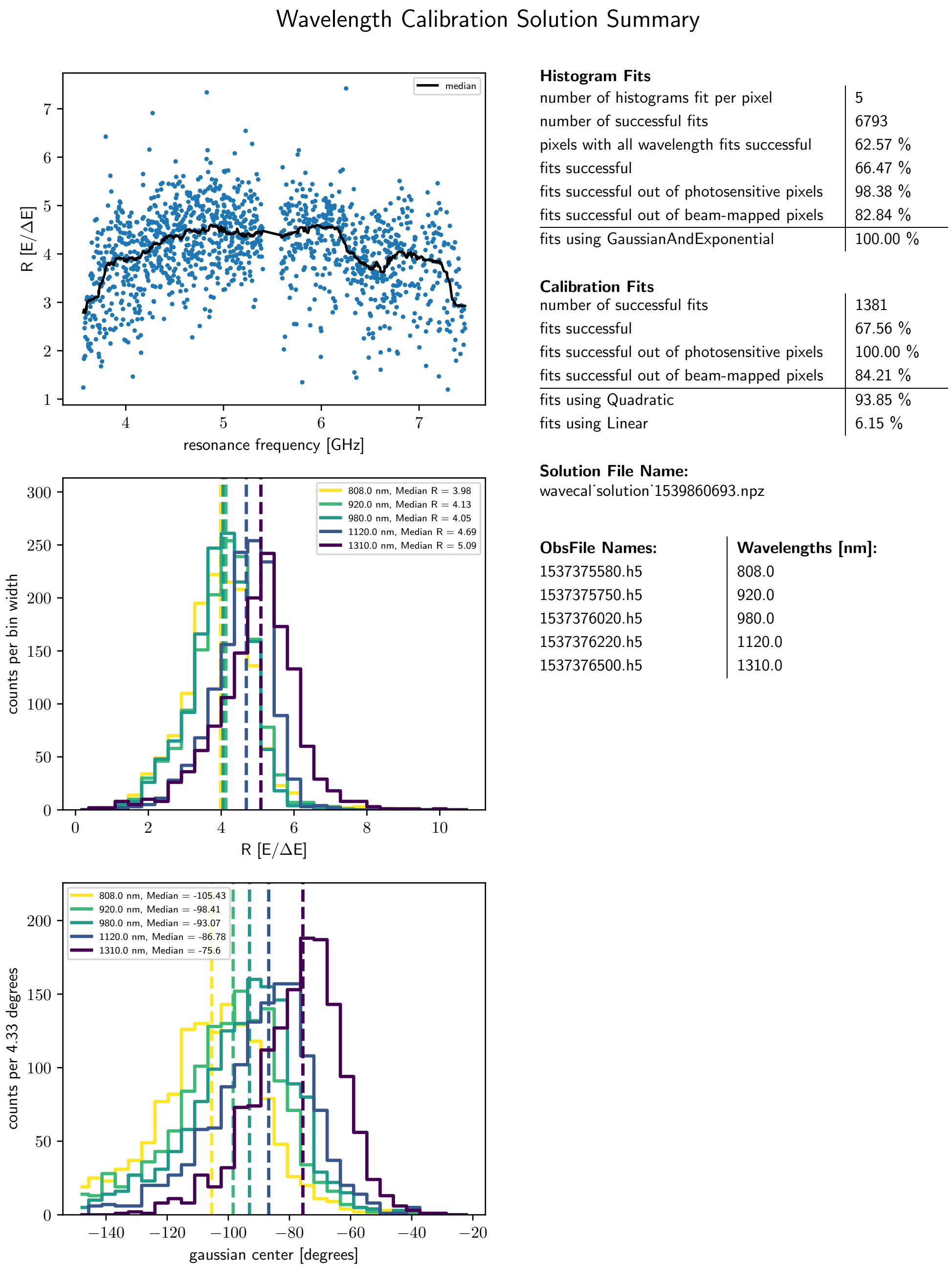




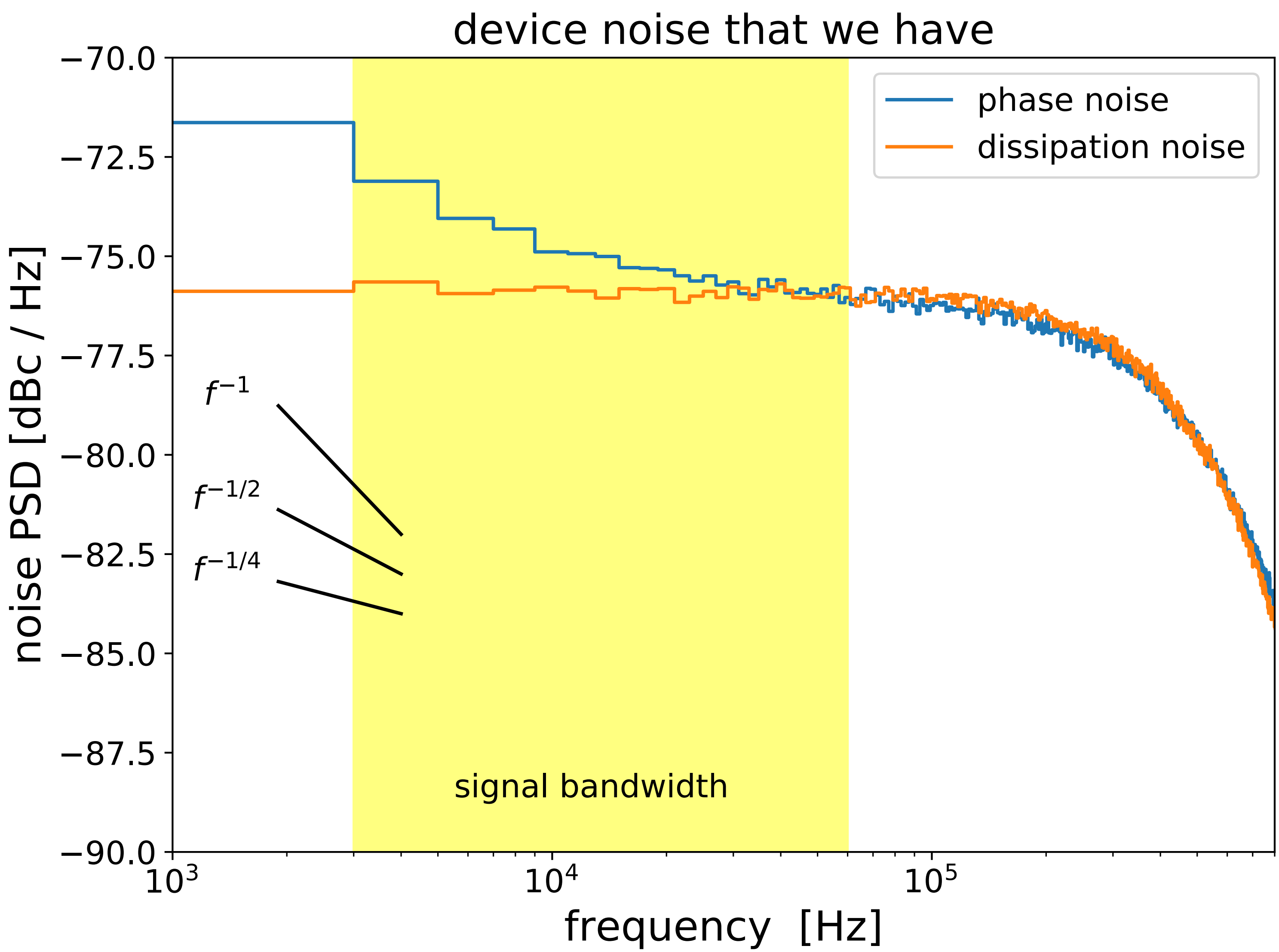


Array Spectral Resolution

- Yield increased with PtSi
  - 90% of resonators photosensitive
  - 80% survive quality cuts
  - Will improve further with fine tuning of fabrication and setup procedures

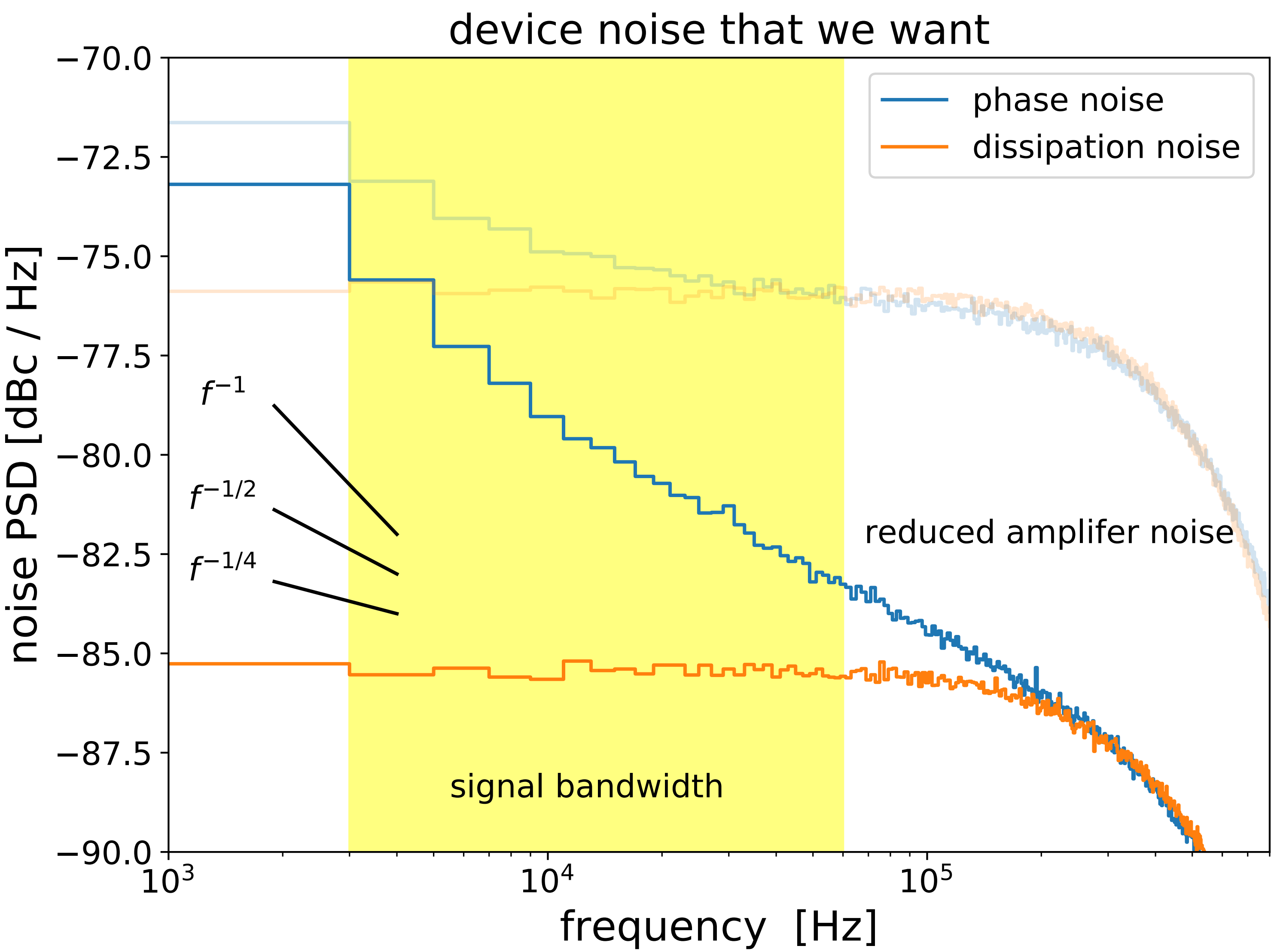


Performance Limits



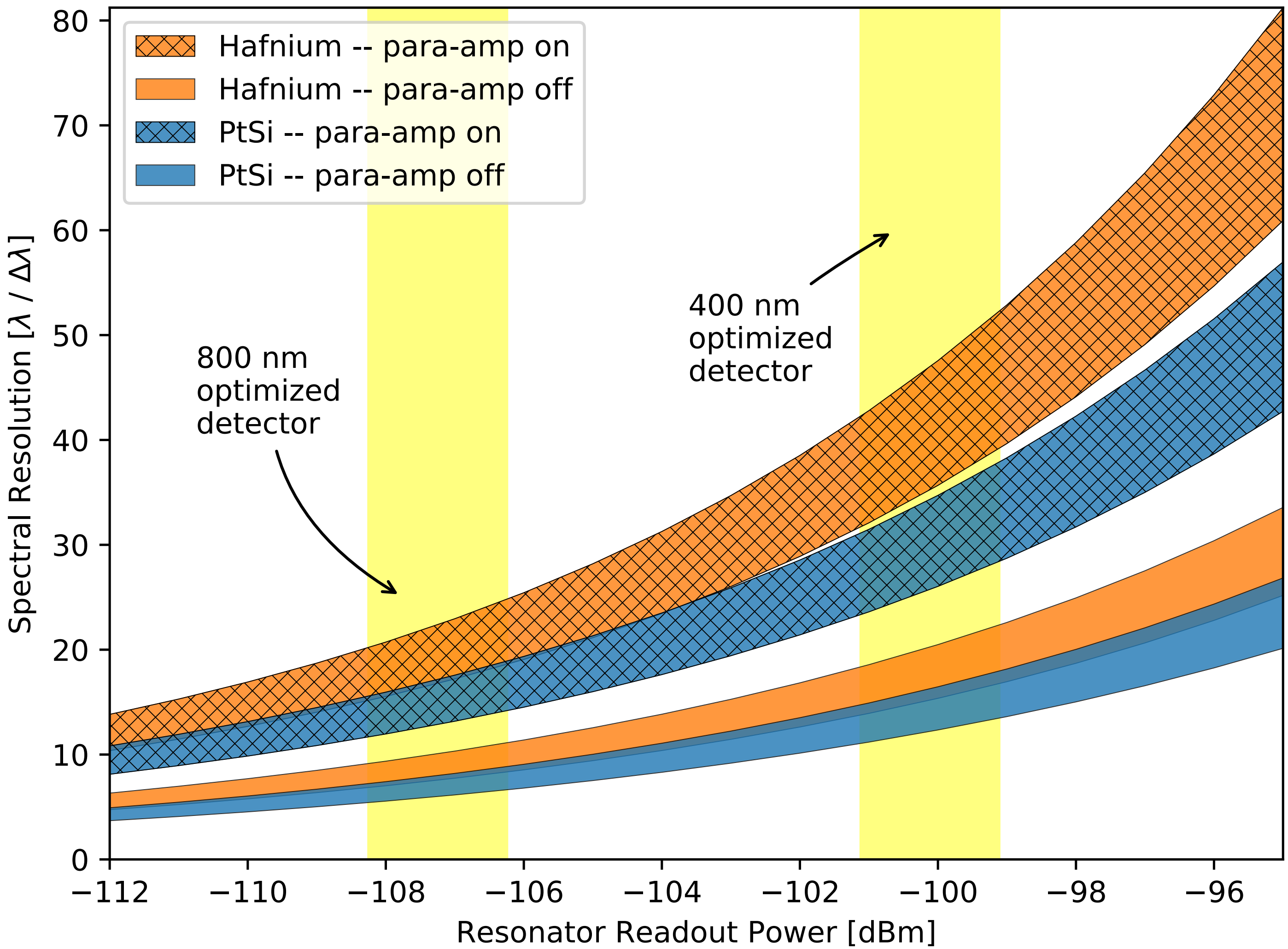
Hf slides from Nick Zobrist

Performance Limits



MKID Improvements

- New low-T_c material (Hf) and Parametric Amplifiers enable large gains in R



Currently looking at Gen3

- Xilinx RFSOC looks like a huge advance – 8x the readout at 1/20th the power
  - 8x 4.0 GSPS 12-bit ADCs
  - 8x 6.5 GSPS 14-bit DACs
  - >8000 resonators on one board!