Jet Propulsion Laboratory
California Institute of Technology

Advances in AO systems (new technologies)

Seth R. Meeker

383F Adaptive Optics and Astronomical Instrumentation
April 04, 2018

Technology Trade-offs

- NGS wavefront sensor styles
  - Shack-Hartmann vs. Pyramid vs. focal plane
- Deformable mirrors
  - Piezo vs. MEMS vs. Adaptive Secondary
  - Stroke, pitch, actuator count/yield, speed/settling time
- Detectors
  - Visible vs. near-IR
  - Photon counting vs. not (photon starved vs. not)
- Low order wavefront sensors (LOWFS)
- Fiber Injection

Technologies targeted by ELTs

Adaptive Secondaries (Microscale/ADS)
Pyramid WFS

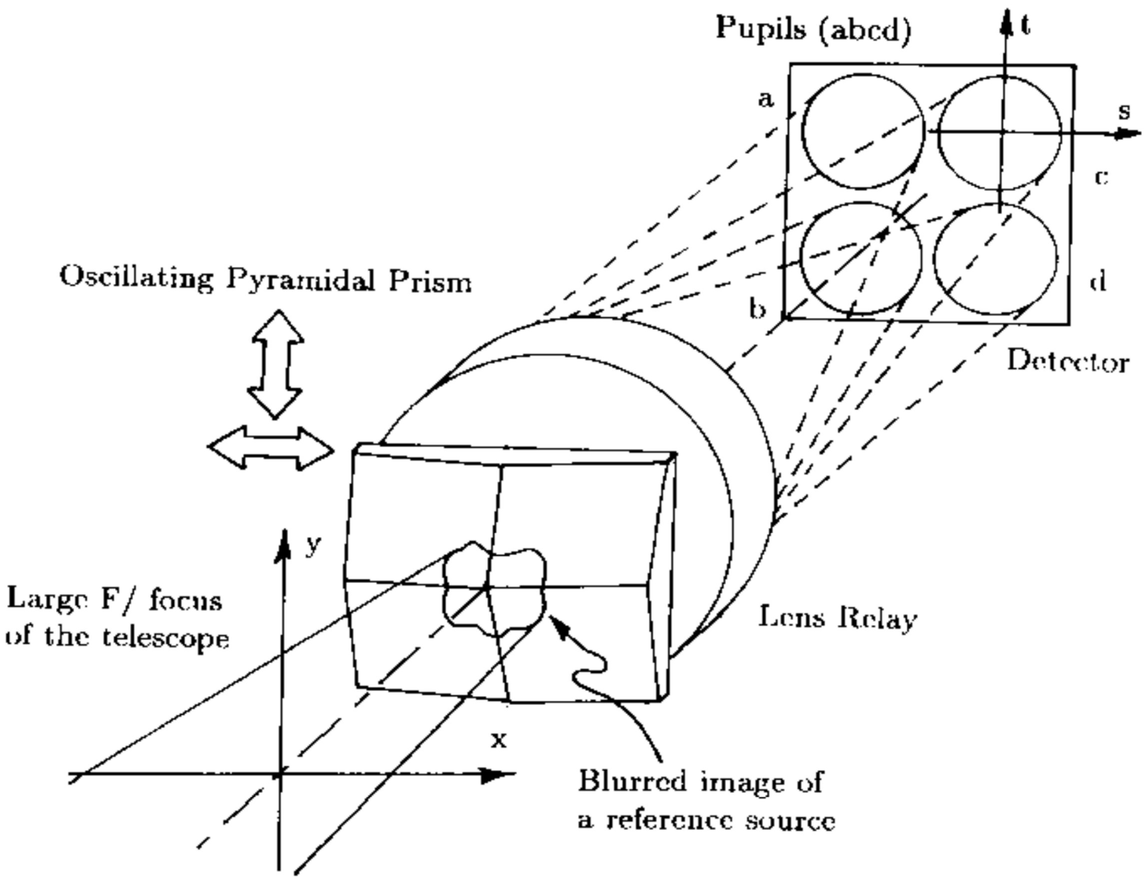
E-ELT NGS: CMOS
E-ELT METIS: SAPHIRA IR-APD
E-ELT EPICS: ?

GMT NGS: OCAM EM-CCD
GMT GMagAO-X: OCAM EM-CCD, ALPAO and BMC DMs

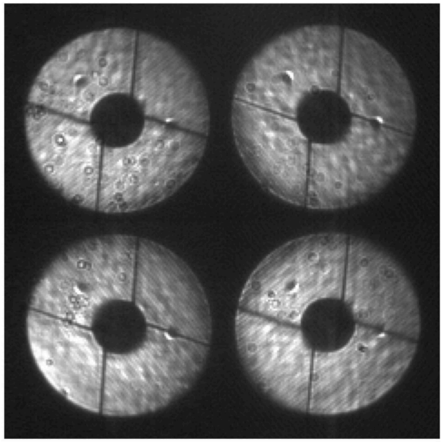
TMT NFIRAOS NGS: FT-CCD, Piezo DMs (Cilas/Xinetics)
TMT PSI: MKIDs

Pyramid Wavefront Sensor

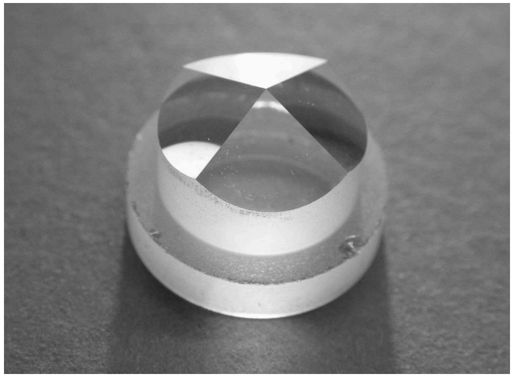
- Improved sensitivity over Shack-Hartmann (-> improved sky coverage)
- Requires modulation of focus around point of pyramid for improved linearity
- Currently deployed on SCExAO, soon on Keck (KPIC) and Magellan (MagAO-X)



Ragazzoni, 1996



Jovanovic et al. 2015



Tozzi et. Al. 2008

Key DM Technologies

Madec, 2012 SPIE

Overview of Deformable Mirror Technologies for Adaptive Optics and Astronomy

P-Y Madec[1]
European Southern Observatory, Karl Schwarzschild Str 2, D-85748 Garching

ABSTRACT

From the ardent bucklers used during the Syracuse battle to set fire to Romans' ships to more contemporary piezoelectric deformable mirrors widely used in astronomy, from very large voice coil deformable mirrors considered in future Extremely Large Telescopes to very small and compact ones embedded in Multi Object Adaptive Optics systems, this paper aims at giving an overview of Deformable Mirror technology for Adaptive Optics and Astronomy.

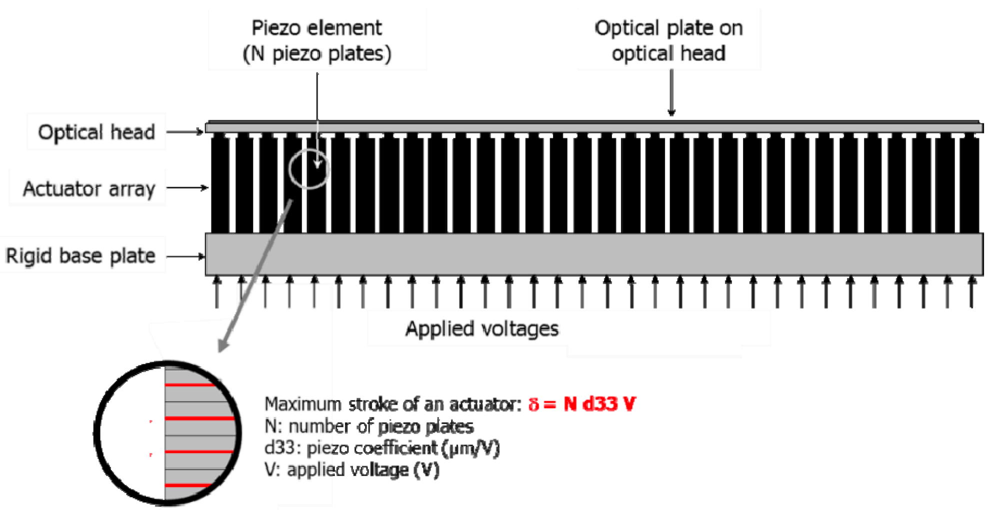
First the main drivers for the design of Deformable Mirrors are recalled, not only related to atmospheric aberration compensation but also to environmental conditions or mechanical constraints. Then the different technologies available today for the manufacturing of Deformable Mirrors will be described, pros and cons analyzed. A review of the Companies and Institutes with capabilities in delivering Deformable Mirrors to astronomers will be presented, as well as lessons learned from the past 25 years of technological development and operation on sky. In conclusion, perspective will be tentatively drawn for what regards the future of Deformable Mirror technology for Astronomy.

Keywords: deformable mirror, piezoelectric material, electrostrictive material, MEMS, bimorph mirror, membrane mirror, stacked array mirror

Key DM Technologies

Piezoeletric Actuators

- Typically PZT and PMN (lead zirconate titanate and lead manganese niobate) ceramics
- Elongation prop. to applied voltage
- Actuators made from stacks of PZT plates (Cilas)
- TMT prototyping 76x76 actuator piezo DMs from Cilas and AOA Xinetics for NFIRAOS NGS
- Single crystal PMN for drastically increased stroke vs. ceramics (Microscale)

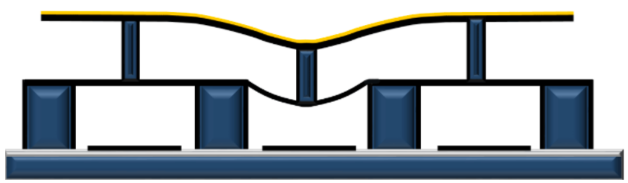


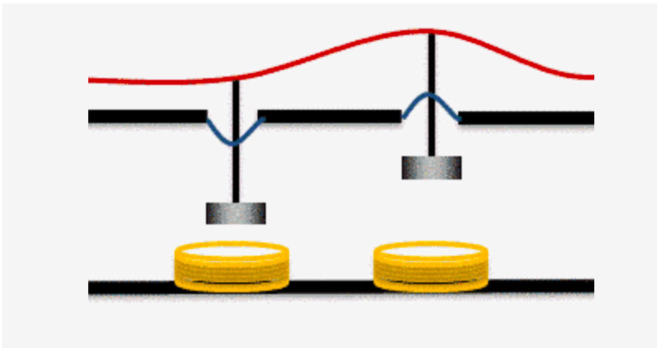
Cilas stack array DM (Pagés et al. 2016)

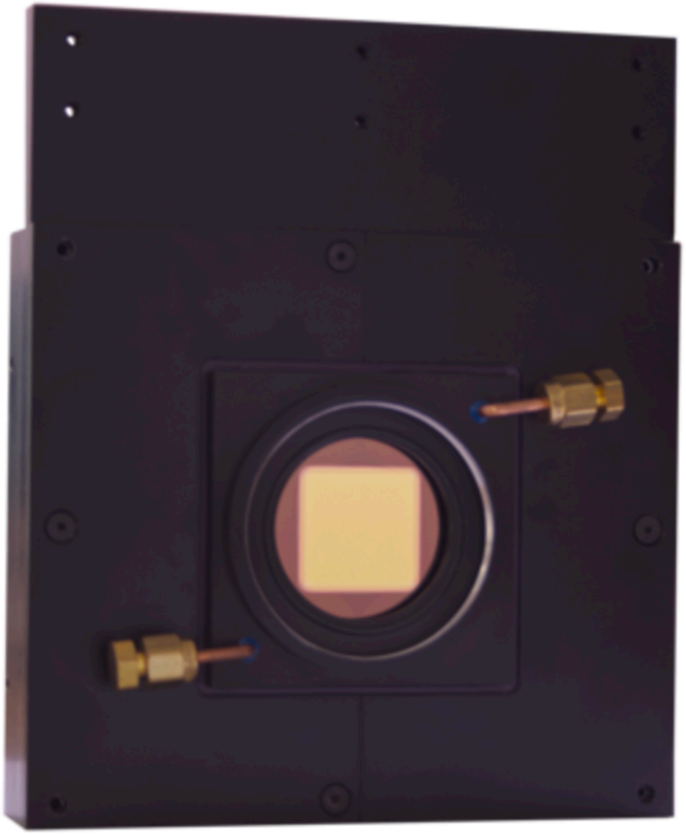
Key DM Technologies

Microelectromechanical systems (MEMS)

- Boston Micromachines (BMC), ALPAO
- High order (64 across)
- Small pitch (0.4mm, 1.5mm)
- <100 μs response, limited stroke (3 μm)
- Larger stroke (10 μm), slower (0.5 ms)





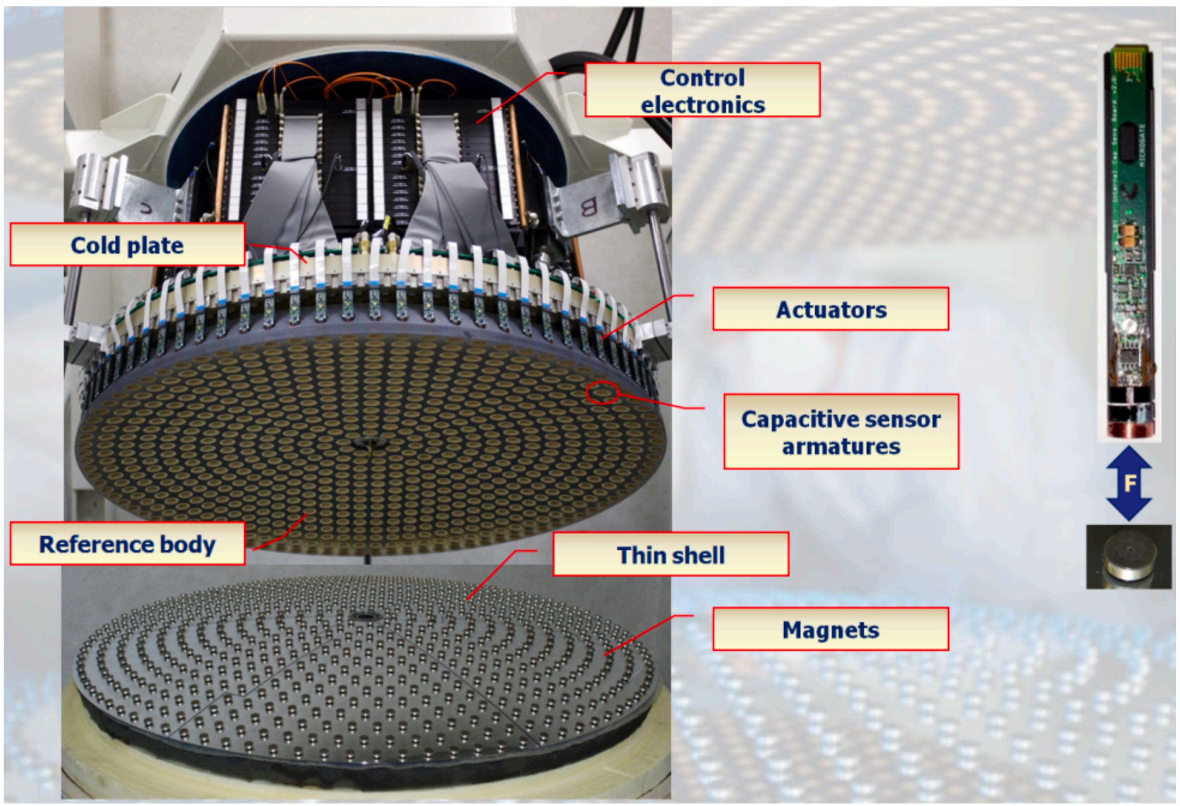


BMC 4K-DM

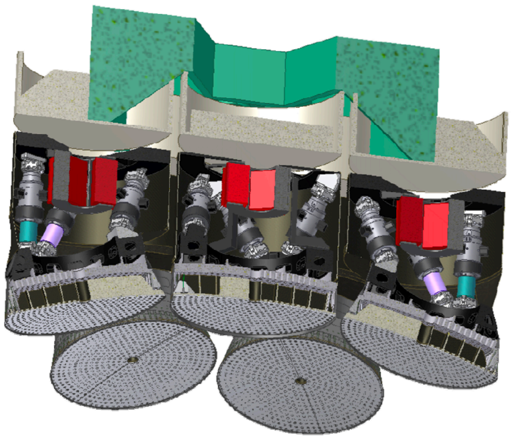
Key DM Technologies

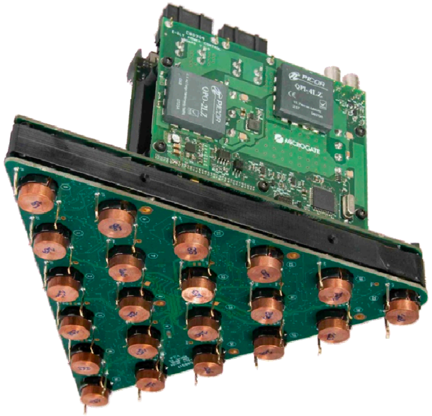
Adaptive Secondaries (Voice coil actuators)

- First installed at 6.5m MMT
- LBT, Magellan, VLT examples of current gen
- Microgate/ADS planned for E-ELT, GMT (E-ELT M4 w/ >6300 actuators)
- TMT launched AM2 design study in 2017



Biasi et al. 2010





Key Detector Technologies

Adkins 2014, SPIE

Review of the latest developments in fast low noise detectors for wavefront sensing in the visible

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ABSTRACT

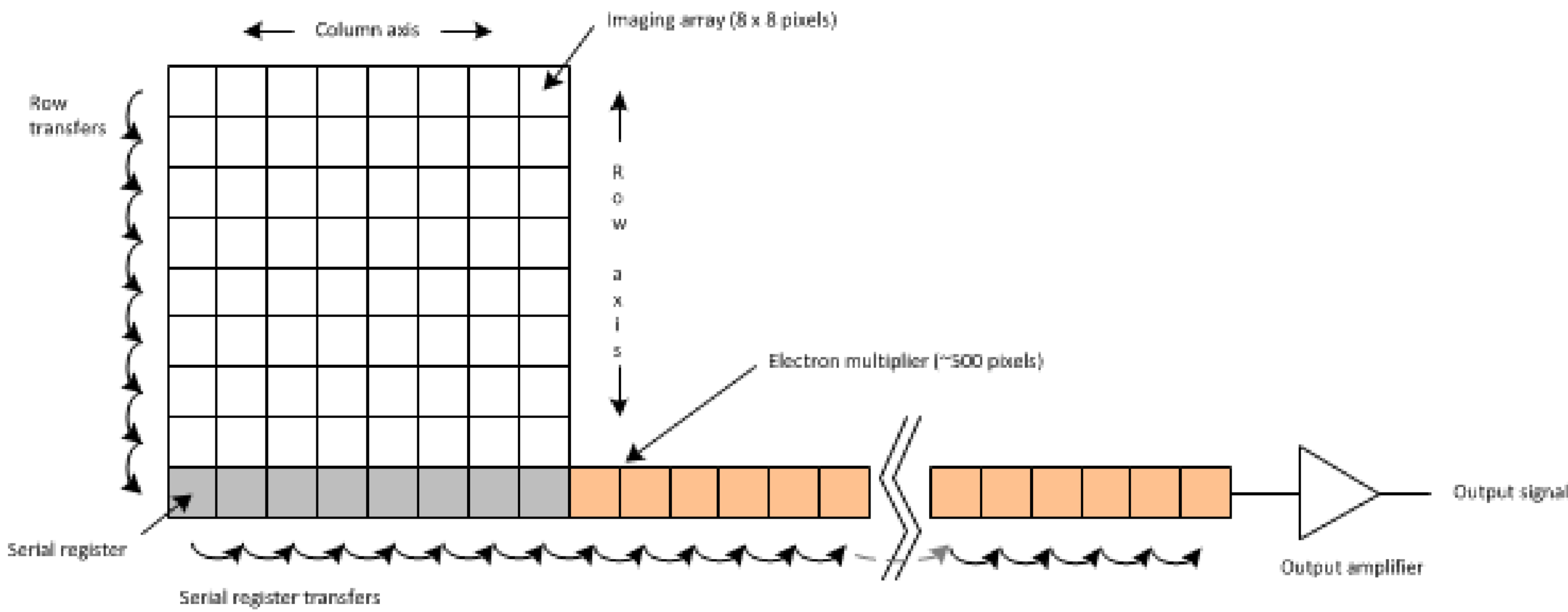
In this paper we describe the development of fast low noise detectors intended primarily for use in Shack Hartmann wavefront sensors for natural and laser guide star wavefront sensing in the future adaptive optics systems of the Thirty Meter Telescope Project and the Next Generation Adaptive Optics system at the W. M. Keck Observatory. This work results from collaboration among the W. M. Keck Observatory, the Thirty Meter Telescope Project, the Lincoln Laboratory of the Massachusetts Institute of Technology, and the Starfire Optical Range of the Air Force Research Laboratory. Testing of backside thinned, packaged detectors has been completed and performance results including read noise, readout speed, charge diffusion, dark current, and quantum efficiency will be reported. Proposed developments of readout systems to compliment this detector will be described, and performance compared to alternative detector solutions.

Keywords: Adaptive Optics, Charge Coupled Device, Detector, EMCCD, CMOS, Shack Hartmann, Laser Guide Star, Wavefront Sensing

Key Detector Technologies

Electron Multiplying CCDs (EMCCDs)

- Benefits of conventional CCD: ~100% fill factor, high QE, and efficient charge transfer
- EMCCD: extended serial register in which avalanche multiplication takes place
- Operated in conventional integrating mode or photon counting
- Noise dominated by clock induced charge; rad testing underway (Harding et al. 2016 JATIS)
- Aging can occur when applying EM gain

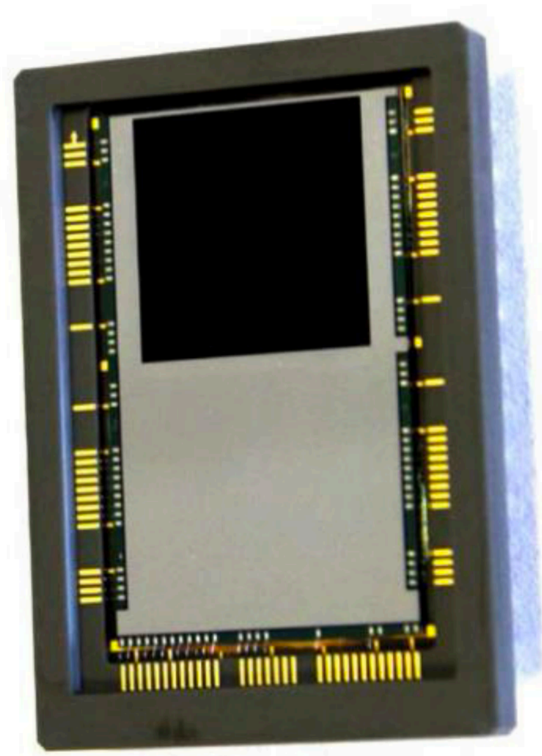


Adkins, 2016

Key Detector Technologies

Electron Multiplying CCDs (EMCCDs)

- e2v offers devices up to 1600 x 1600 pixels
- Targeted for WFIRST CGI
- Readily available off the shelf with First Light OCAM2



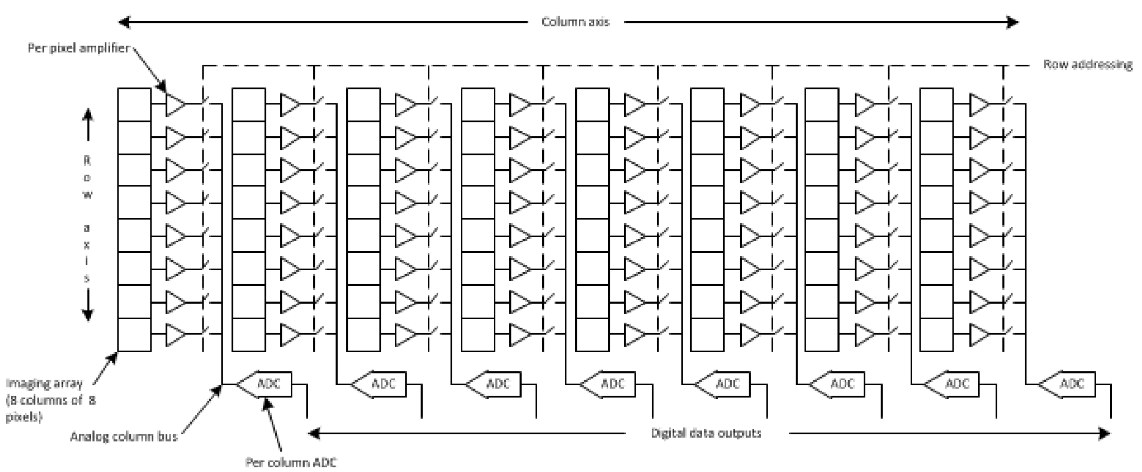
CCD201-20, 1024x1024
Harding et al. 2016

OCAM2K, first-light.fr

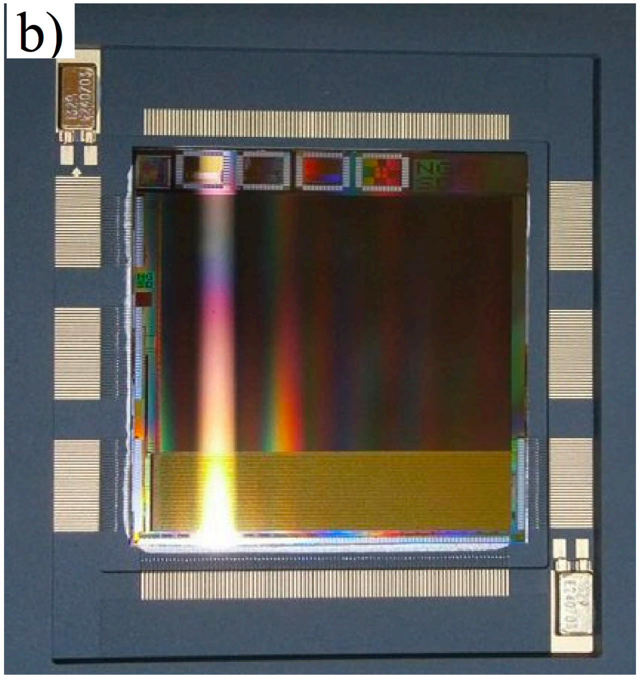
Key Detector Technologies

Scientific CMOS

- Active pixels benefitting from advances in MOSFET transistor technology.
- Per pixel amplification competes with photo-absorption real estate, leads to greater inter pixel variation
- E-ELT prototyping NGSD 880x840 pixel devices, camera integration in 2018
- Few e- rms read noise



Adkins, 2014

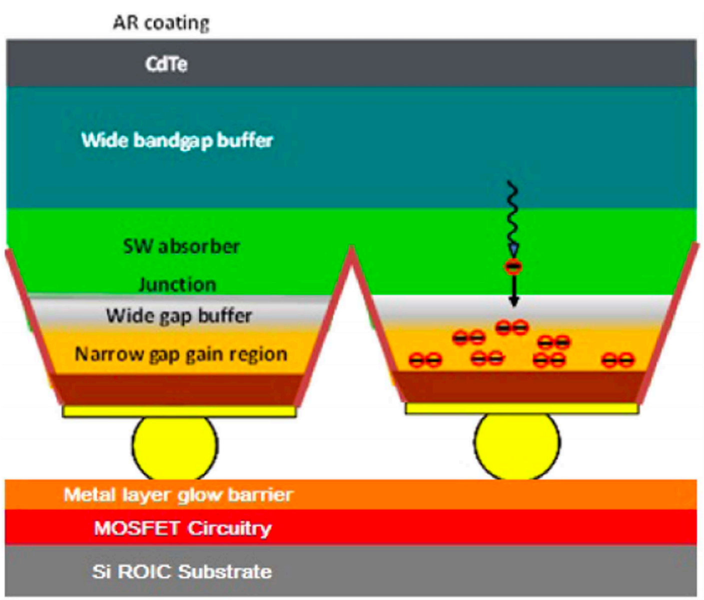


Downing et al. 2016

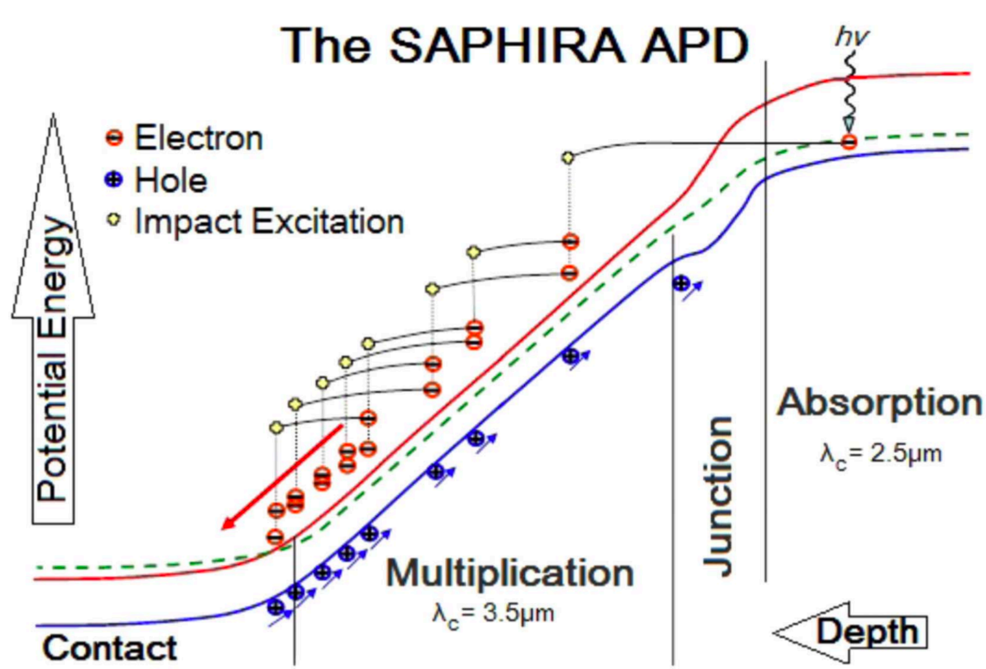
Key Detector Technologies

IR Avalanche Photo Diodes (IR-APDs)

- HgCdTe performance integrated into an avalanche photodiode architecture (single carrier, i.e. only the electrons produce secondary pairs)
- High frame rate for IR-WFS, <1 e- rms read noise
- Limited by dark current for general low background astrophysics



Atkinson et al. 2017



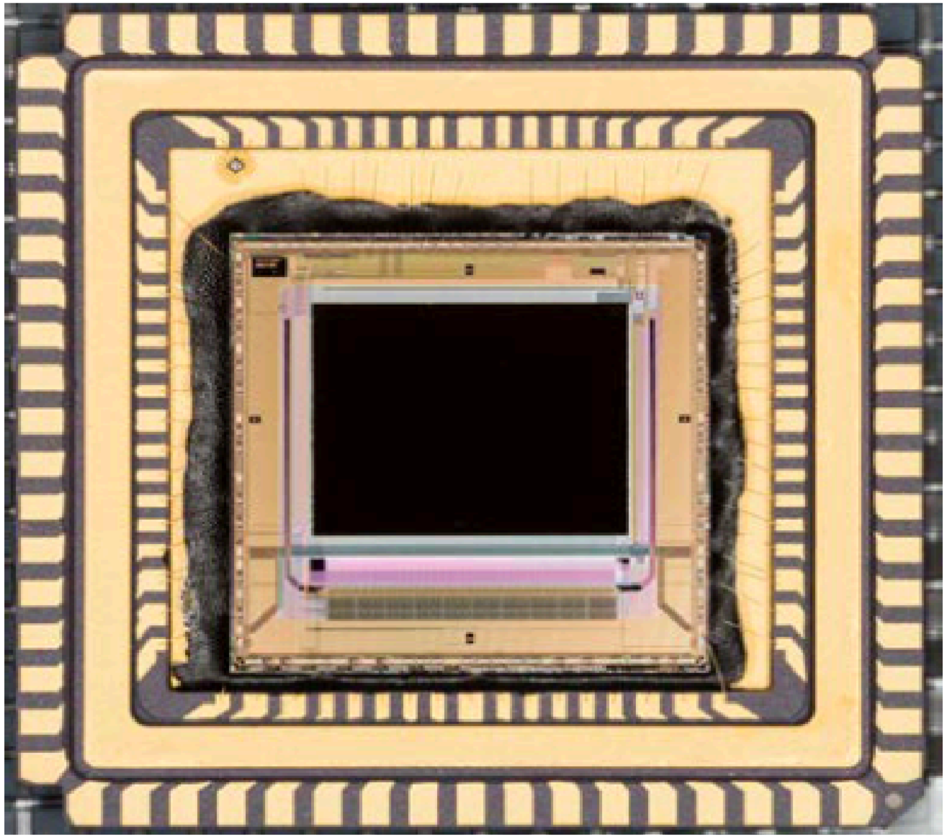
Key Detector Technologies

IR Avalanche Photo Diodes (IR-APDs)

State-of-the-art SAPHIRA array fielded with:
GRAVITY (WFS)
SCExAO (FPWFS)
Robo-AO (T/T)
KPIC (PyWFS, coming soon)

C-RED One camera from First-Light

1024x1024 arrays under development

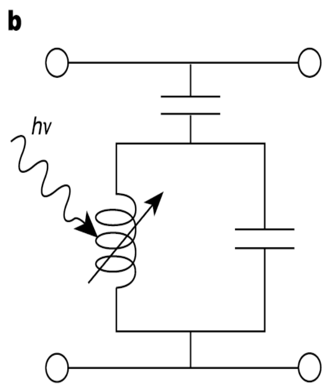


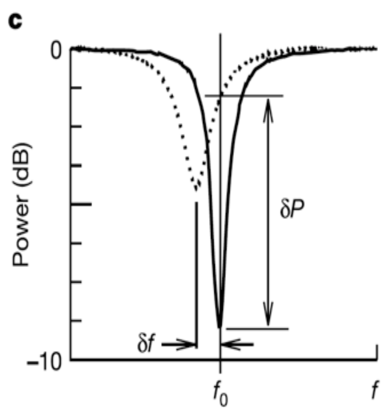
Leonardo (ne Selex) 320x256 SAPHIRA

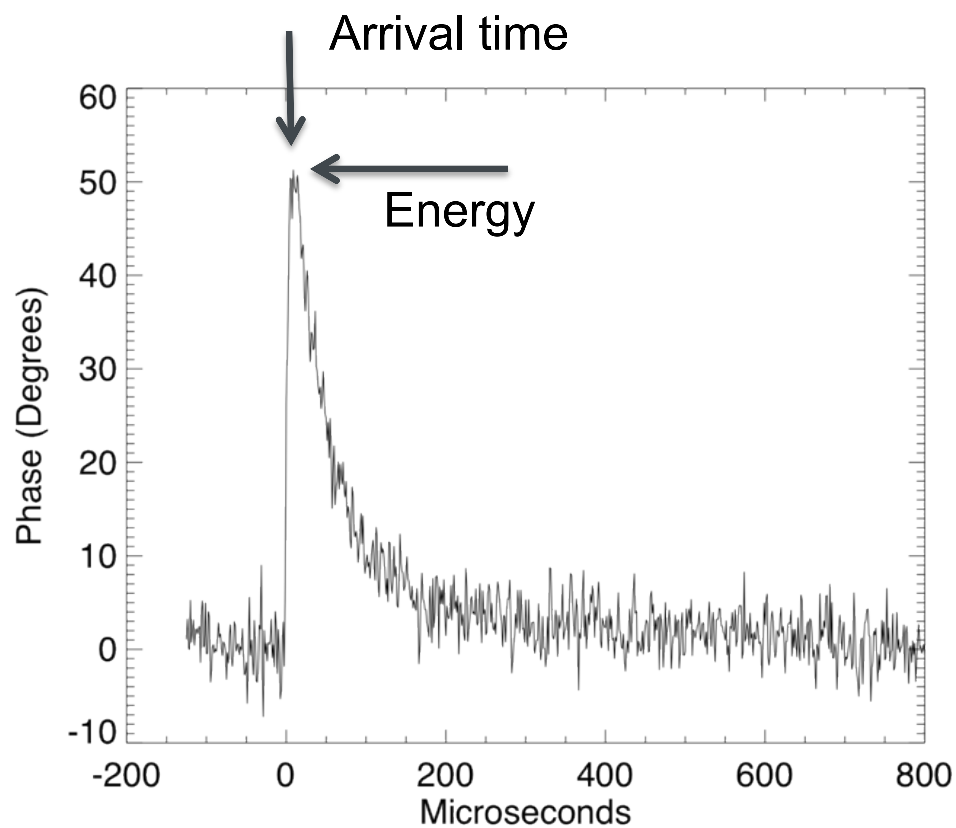
Key Detector Technologies

Microwave Kinetic Inductance Detectors (MKIDs)

- Superconducting micro-resonator pixels (operated at ~100mK) where photons impart a frequency shift
- Single photon counting with ~microsecond timing
- Energy resolving with no dispersive element (R~8 for near-IR arrays)
- Continuously read-out with no analogue to read-noise or dark current
- Large pixels (~150 μm), low dynamic range (few thousand : 1)



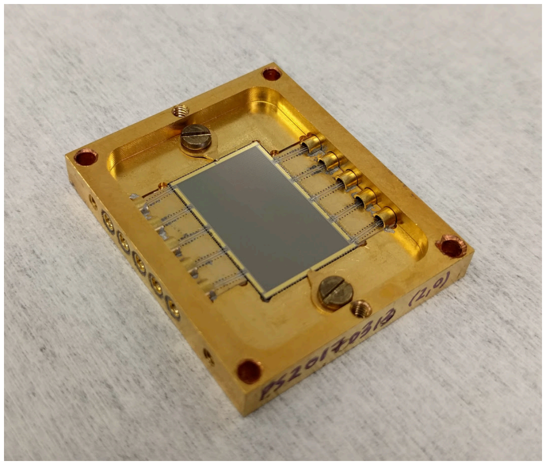


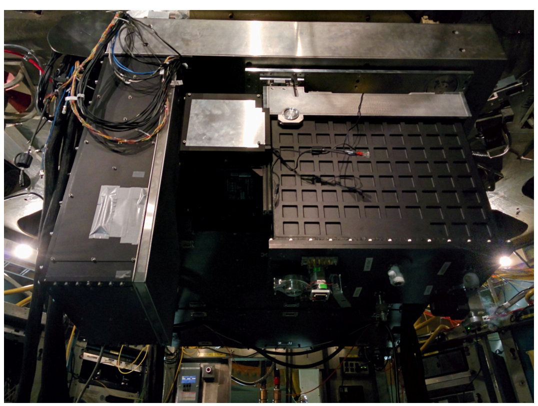


Key Detector Technologies

Microwave Kinetic Inductance Detectors (MKIDs)

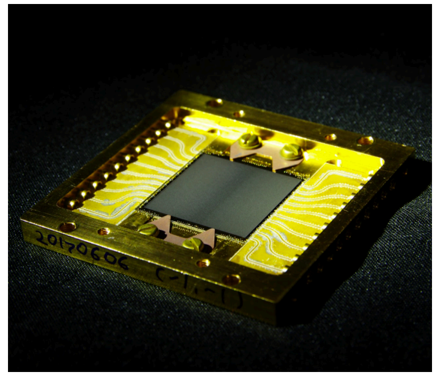
DARKNESS (2016)
10kpix, P3K/SDC

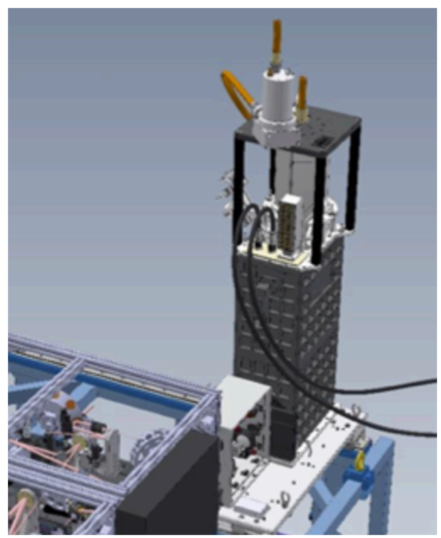




Meeker et al. 2018

MEC (2018)
20kpix, SCExAO

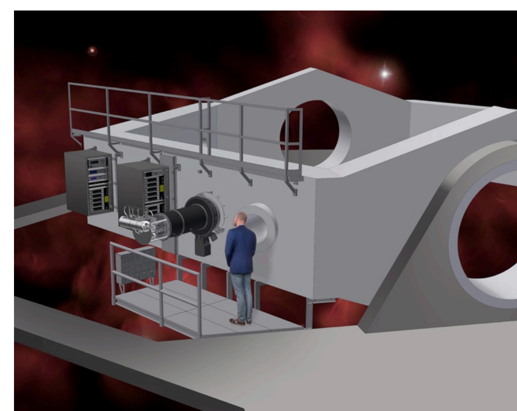




mazinlab.org

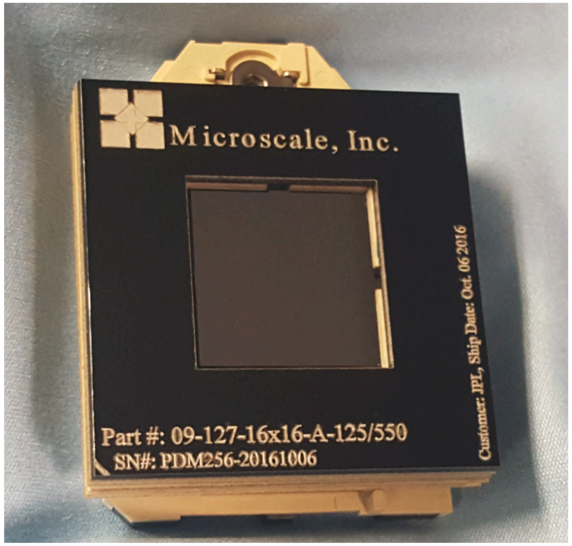
PICTURE-C (2019)
10kpix, WASP Gondola

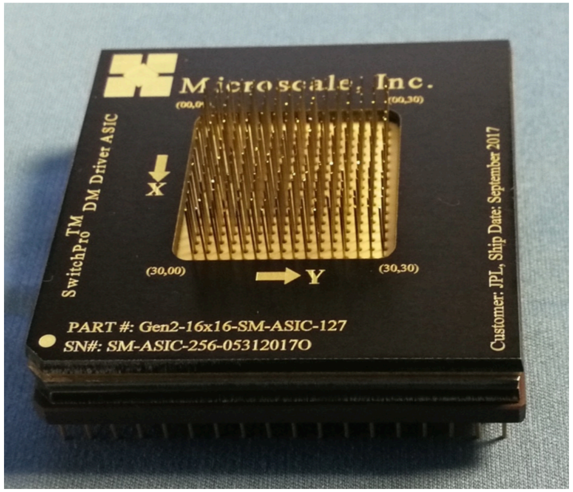
KRAKENS (proposed)
30kpix, Keck

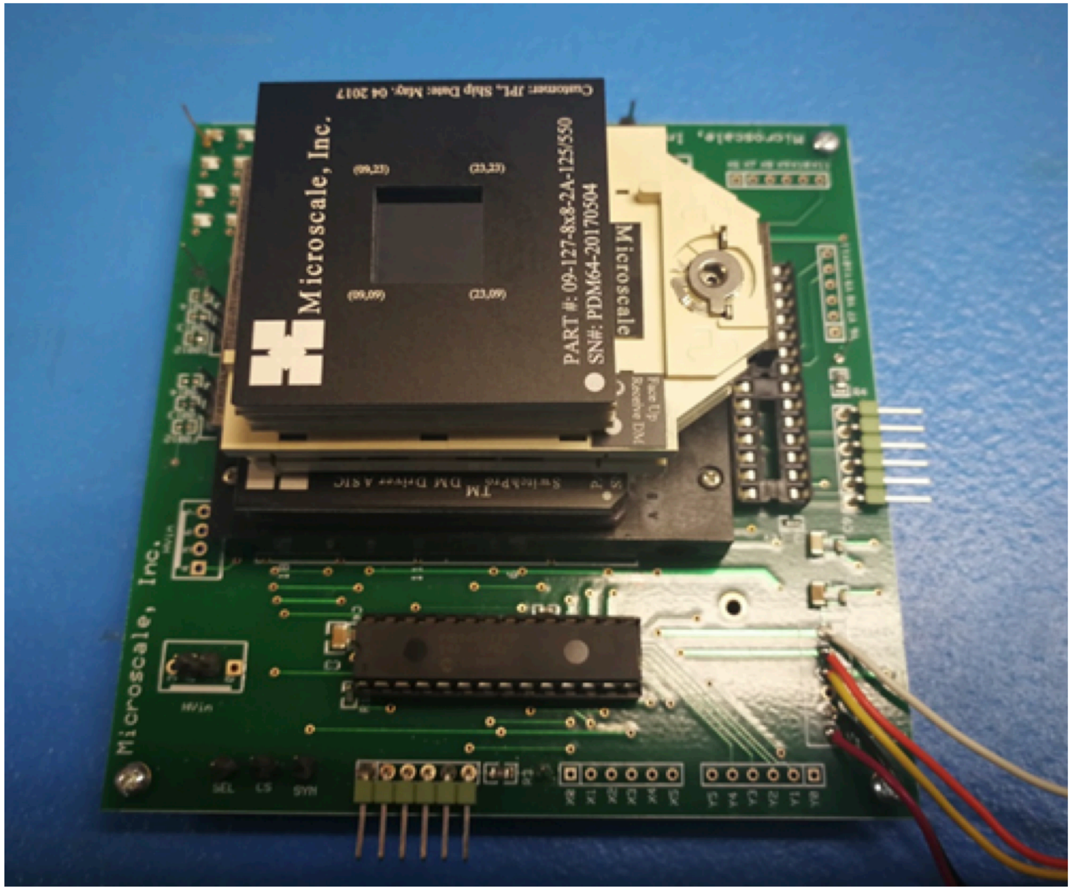


Future Directions

Low-power DMs with integrated ASICs





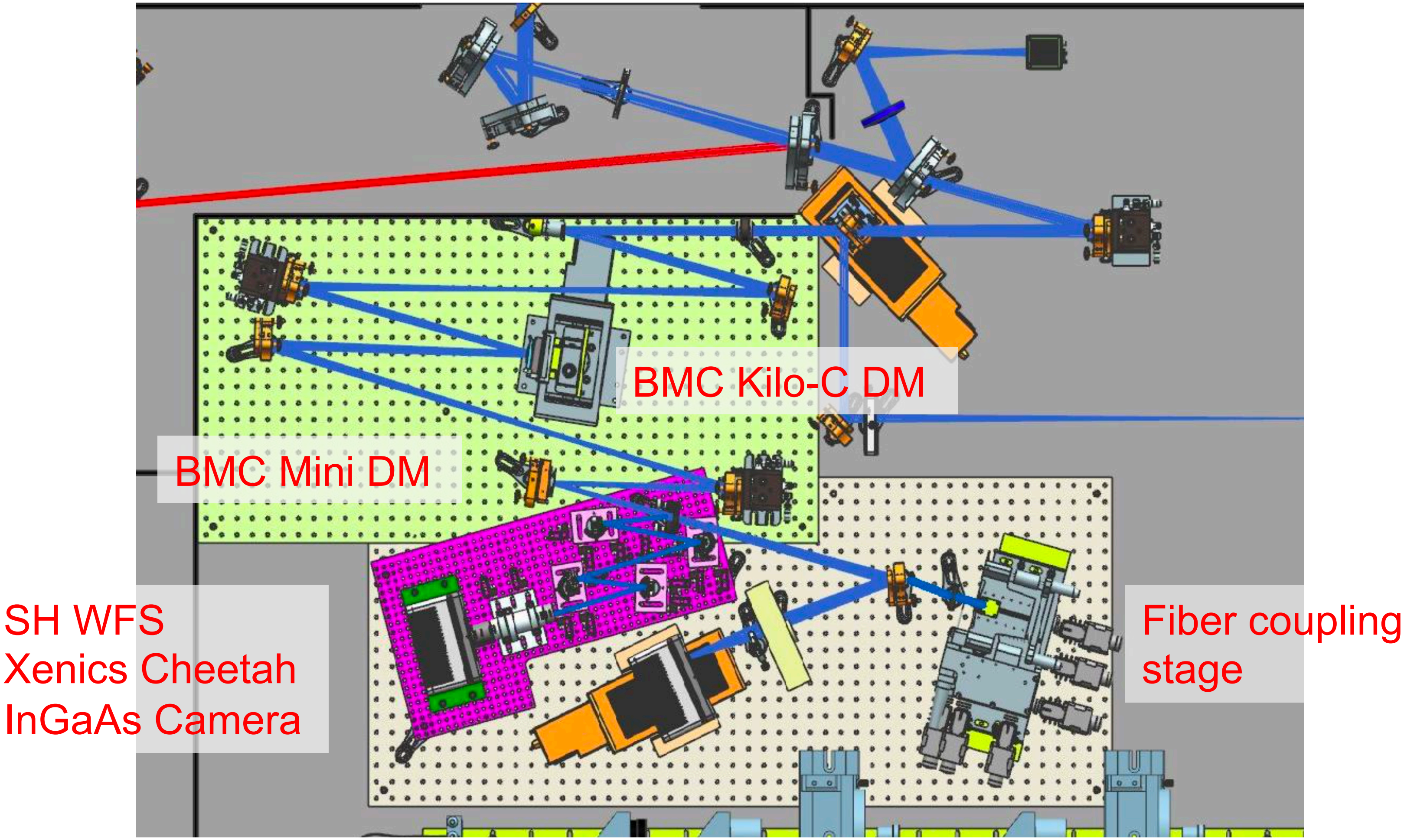


Wu et al. 2015

Future Directions

AO-fed Fiber Injection for Optical Comm. Downlink

- The Integrated Optical System (IOS) developed at JPL for NASA's Laser Communication Relay Demonstration (LCRD)
- 28x AO system capable of 20kHz rates for efficient coupling of a satellite downlink laser into fiber.



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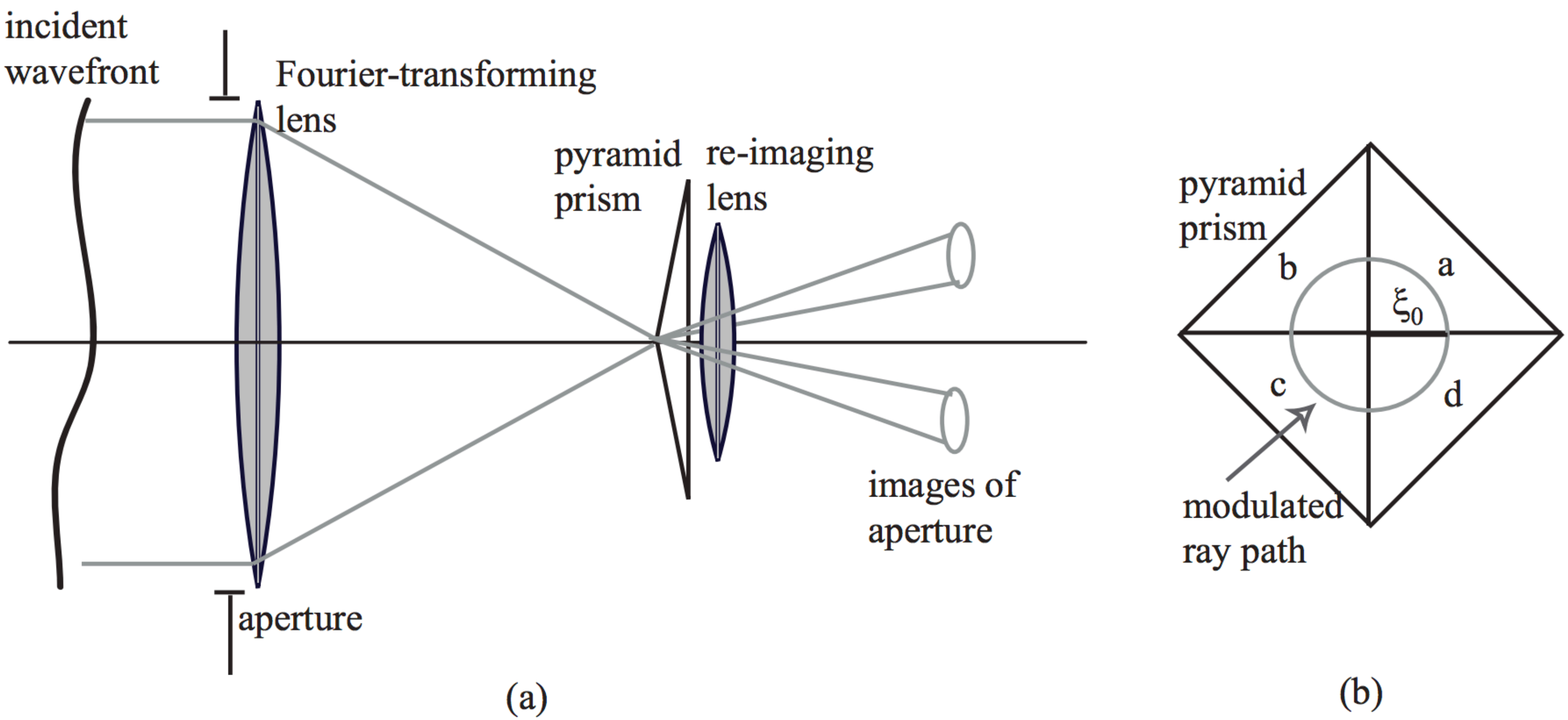
jpl.nasa.gov

Pyramid Wavefront Sensor

- Improved sensitivity over Shack-Hartmann (-> improved sky coverage)
- Requires modulation of focus around point of pyramid for improved linearity
- Currently deployed on SCExAO, soon on Keck (KPIC) and Magellan (MagAO-X)

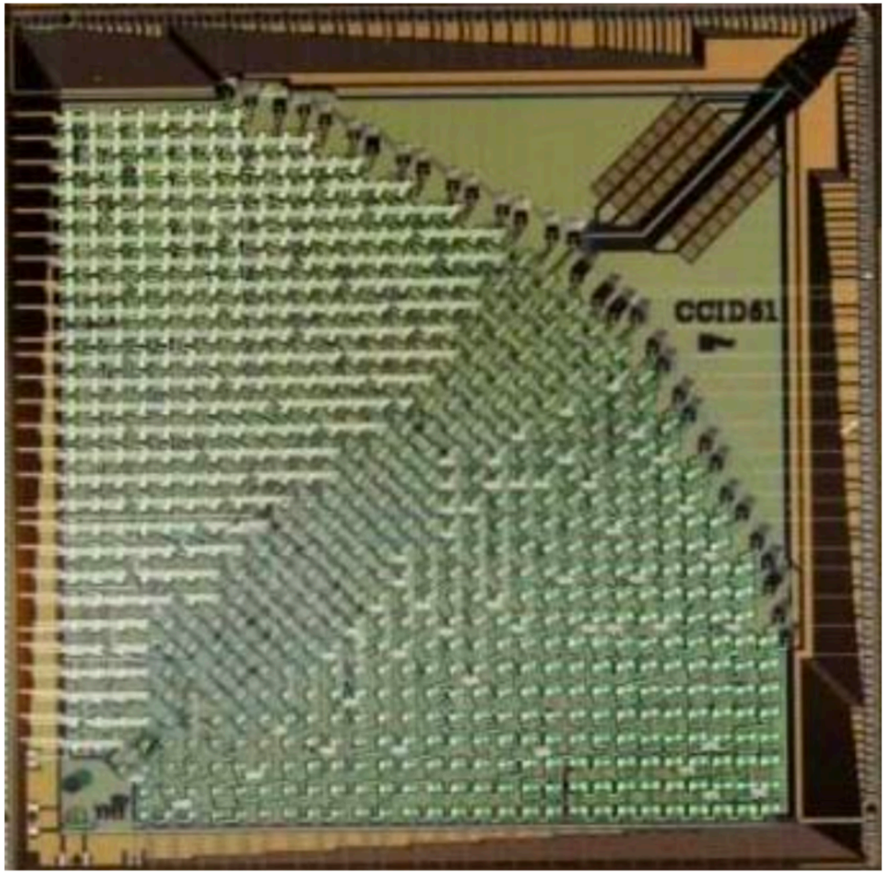


Burvall et al. 2006

Key Detector Technologies

Polar Coordinate Split Frame Transfer CCD

TMT NFIRAOS



CCID61 from Adkins, 2012