Status and predicted performance of the AstroPIC integrated photonic coronagraph testbed at NASA Ames

Ames Team (ARC)
Dan Sirbu
Rachel Morgan (SETI)
Kevin Fogarty
Ruslan Belikov
Eduardo Bendek (SETI)
Natasha Batalha
Kevin Sims

Stanford ECE
Carson Valdez
Annie Kroo
Zhanghao Sun
Marek Vlk
Prof. Olav Solgaard
Prof. David A.B. Miller

Collaborators
Olivier Guyon (Subaru/UfoA)
Jeff Jewell (JPL)
Nem Jovanovic (Caltech)
Emiel Por (UCSC)

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SPIE Optics and Photonics 2025

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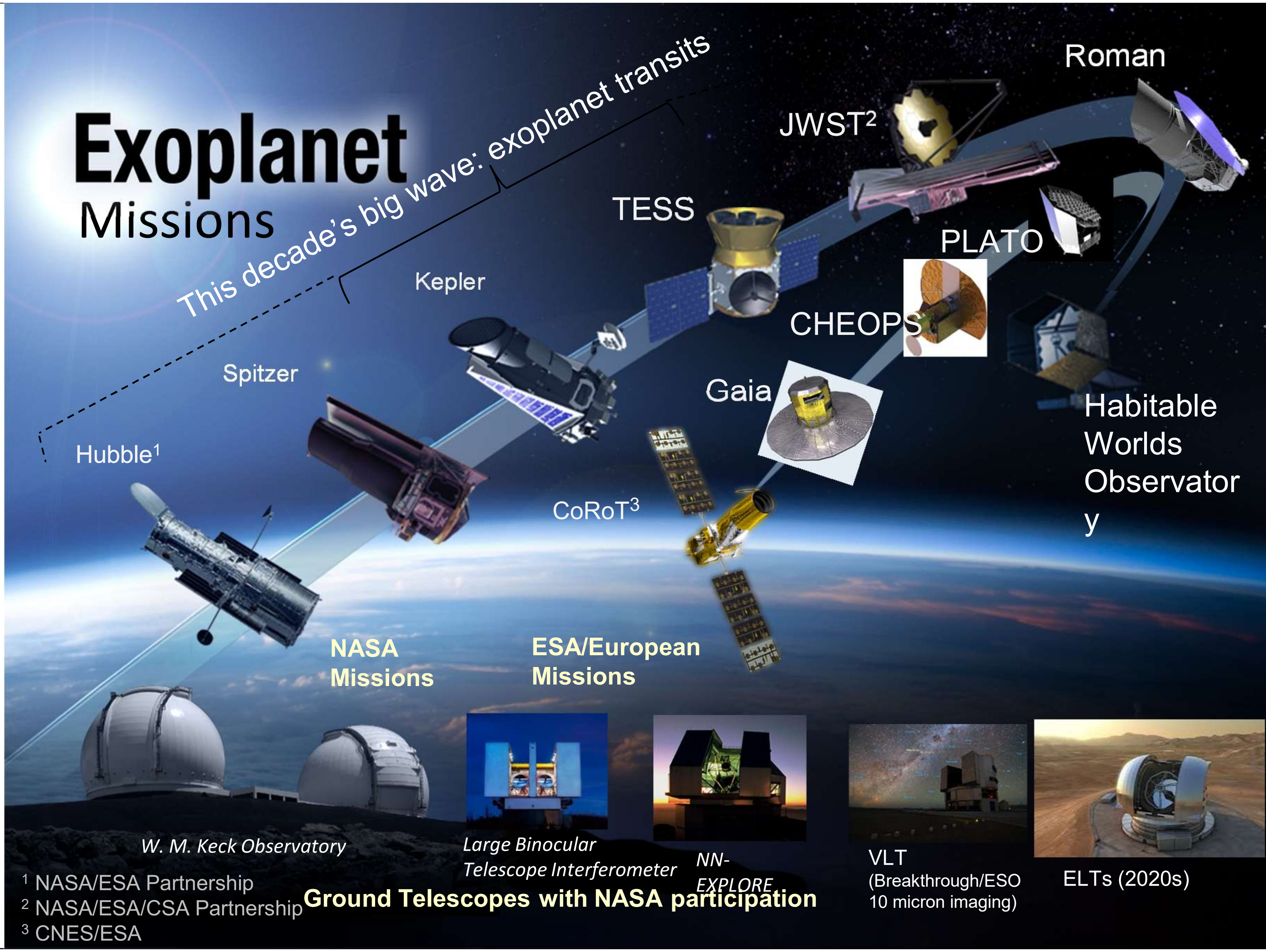
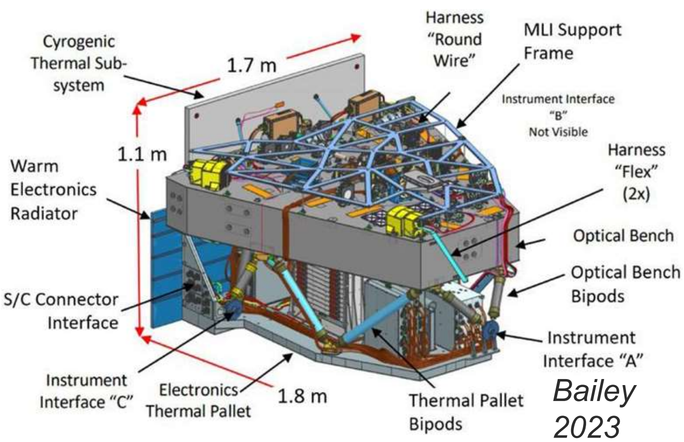


Next big wave (2020-30s): Direct imaging of exoplanets from space and from ground

To Date:
5600+ Confirmed Exoplanets
~2600 from Kepler (Ames mission)

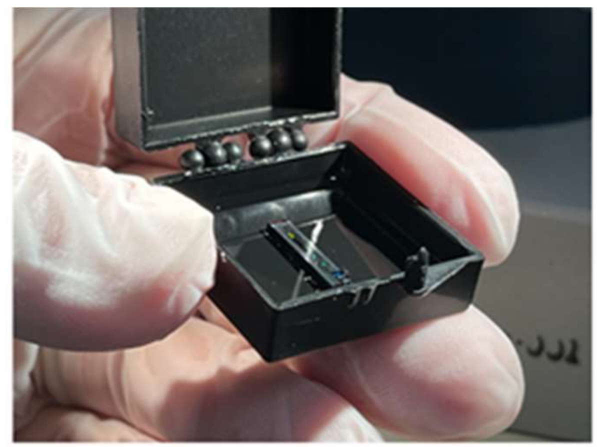
HWO to survey nearby ~100 stars with the goal of characterizing 25 Exoearths

Bulk-optics Coronagraph



Bailey 2023

Integrated Photonic Coronagraph



NASA Tech Thursdays (2025)
https://www.linkedin.com/feed/update/urn:li:activity:7290806967332155392/

Benefits of PIC-based coronagraphy:

- **minimize mass/power footprint:** over 100x lighter, 30x smaller
- **significantly improve efficiency:** enables multiple, simultaneous bandwidth channels (wide-spectrum characterization), synergizes with traditional coronagraph instrument (small angular separations)
- **improve risk margins**: relaxes HWO telescope requirements by doubling # of characterized ExoEarths

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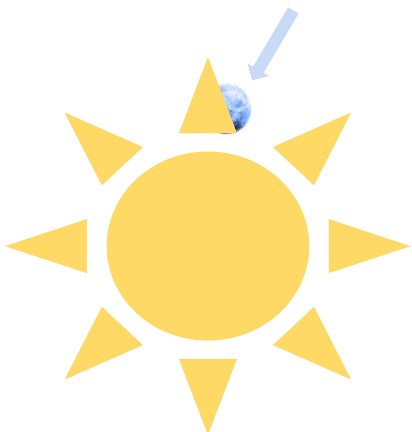
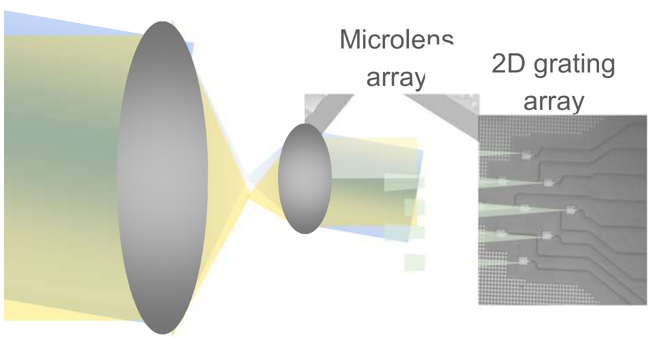
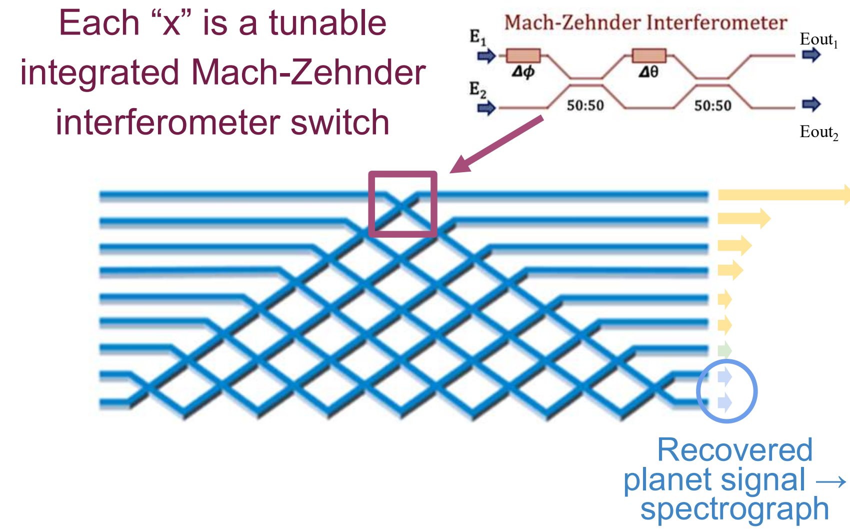
AstroPIC Concept of Operations







ExoEarth is much dimmer and extremely close to host star

AstroPIC chip samples light in telescope pupil plane, where planet and starlight overlap but occupy different **spatial modes**

Integrated photonic interferometric mesh performes **spatial mode sorting** to separate planet light from starlight

Ames PIC Testbed Goals:

- Characterize AstroPIC photonic integrated coronagraph and demonstrate 1e-9 or better contrast sensitivity for a single channel input
- Demonstrate end-to-end system with a pupil relevant to HWO with 1e-7 or better contrast sensitivity and understand the limiting factors
- Provide relevant test data to inform photonic chip development for HWO (i.e. comparing chips from different foundries, test data to compare to simulations)

Requirements:

- Couple light on and off the chip with 3/6-axis stages for alignment of optical fibers or free-space input
- Control 72 phase shifters and measure readout of 9 output channels simultaneously
- Measure “signal” channel with 100 dB dynamic range
- Provide thermal control of PIC to minimize impact of thermal cross talk
- IR microscope for diagnostic visualization of alignment

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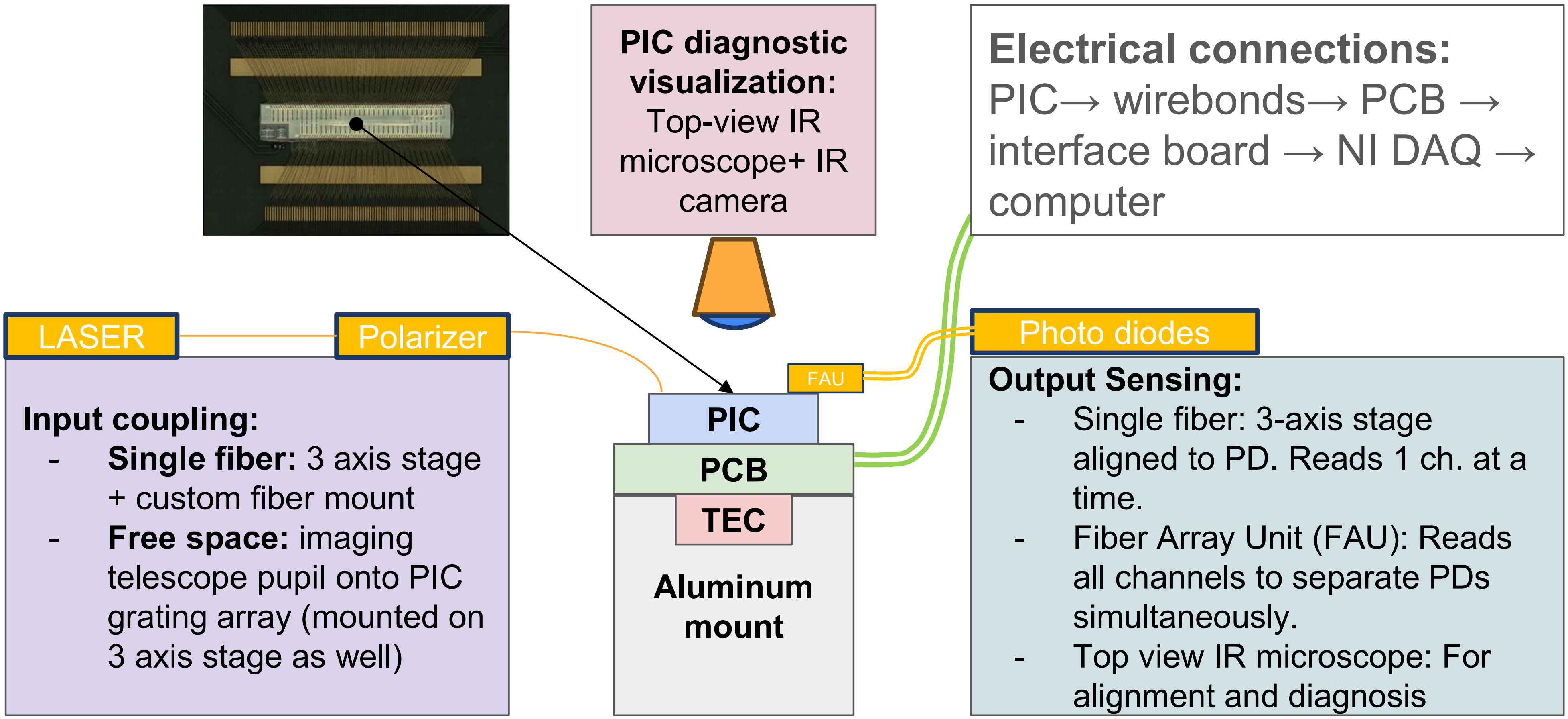

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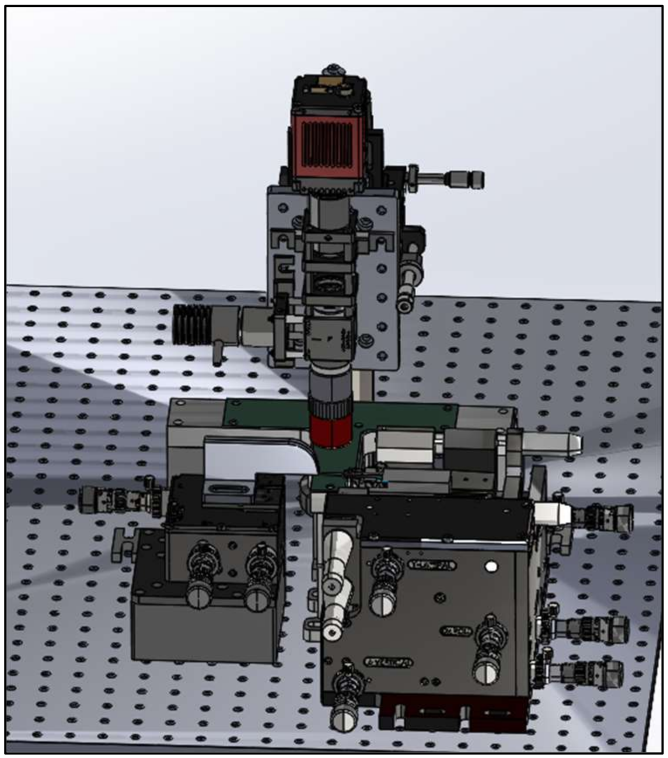
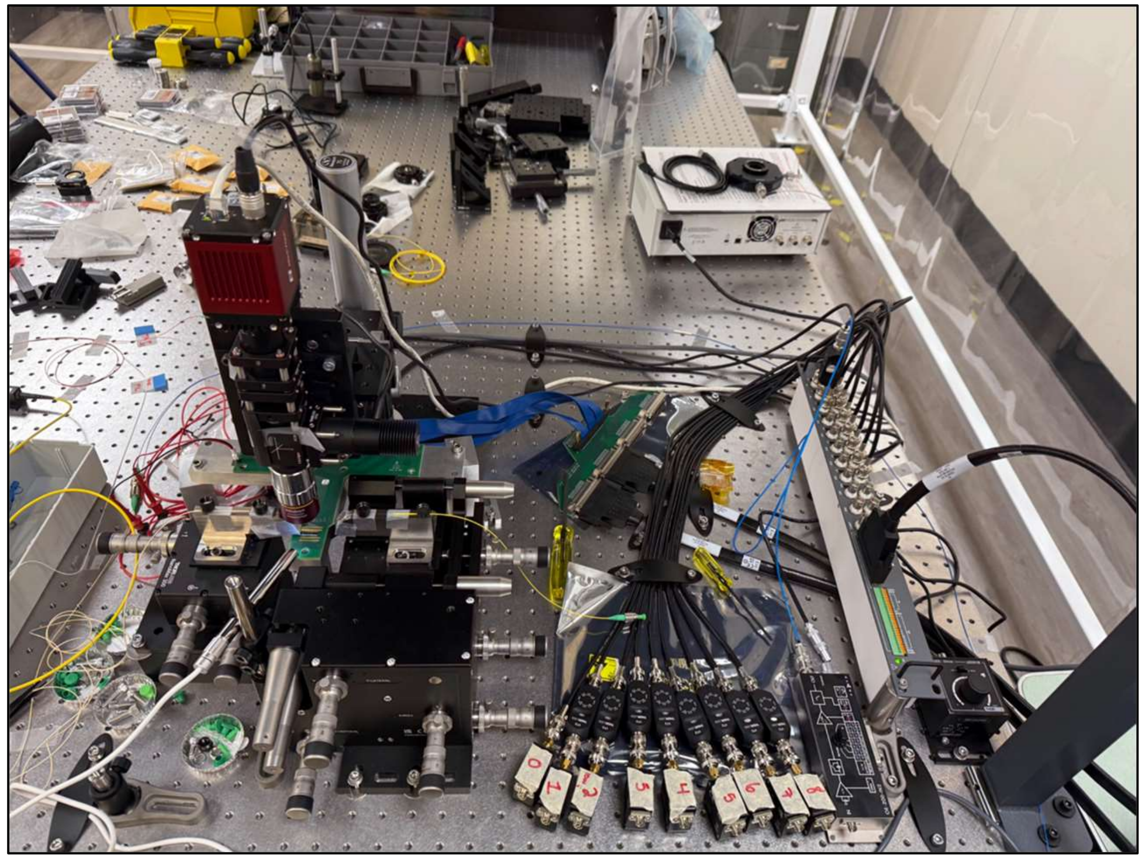
Testbed development led by Rachel Morgan and Eduardo Bendek (SETI/Ames)



Above: CAD Model of PIC Station



Above: Laboratory setup after first light and 87 dB suppression demo

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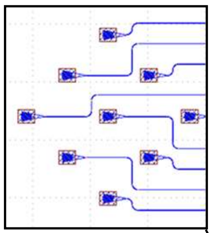
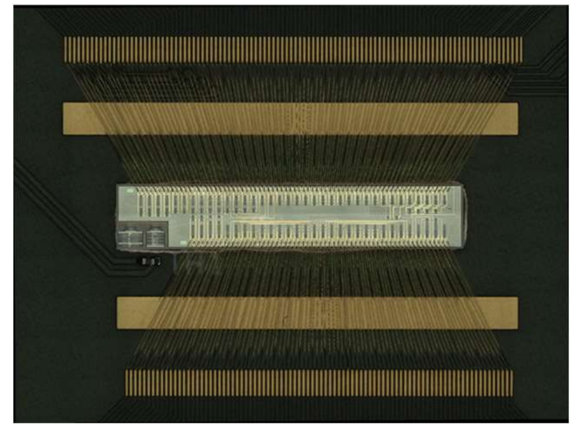
First tapeout: July 2024

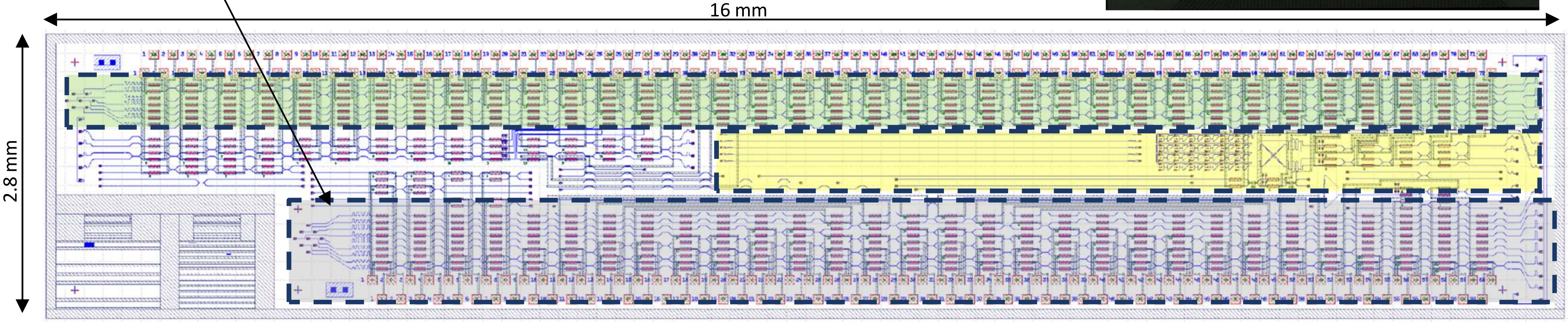
9-channel Full Triangular Mesh:



- 9 input single-layer grating couplers
- microlens array used to couple light from pupil plane into waveguides
- maximum number of channels is currently limited by MPW (multi-project wafer run) chiplet size/bond pads

AstroPIC chip wirebonded to PCB:





Credits:
Design lead: Carson Valdez
Model lead: Kevin Fogarty

Cycle-1, SOI with thermal phase shifters
Foundries: AMF and ANT

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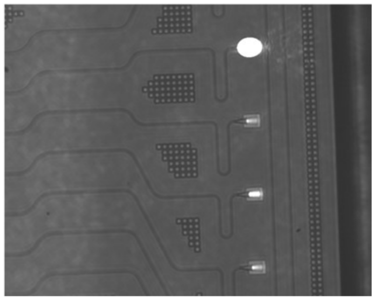
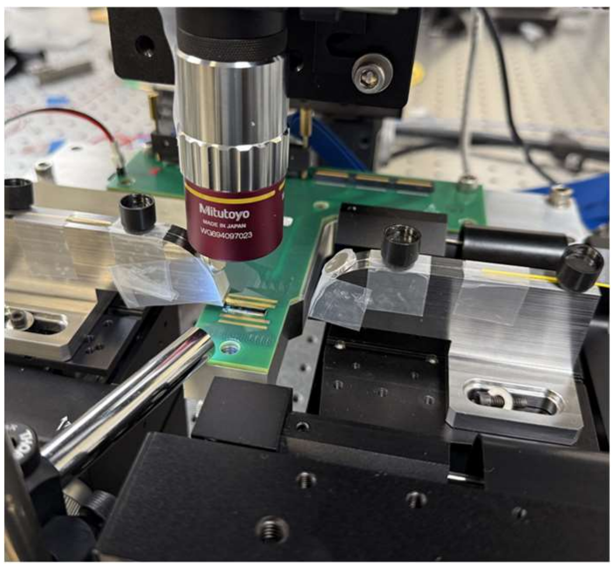


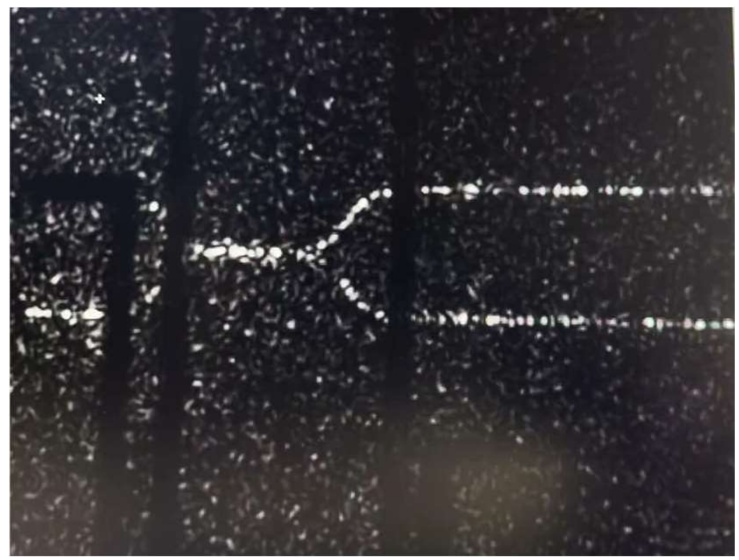
Left: First-light NIR image of output ports on AstroPIC chip at Ames

First light milestones:

- ACT-Photonics testbed is now active and used for AstroPIC characterization
- July 8th, 2025 -- ***first light*** with input light in a single channel and multiple output ports imaged with NIR camera from above
- July 11th, 2025 – ***first active light*** with a thermally-actuated phase shifter controlling light at the Mach-Zehnder Interferometer (MZI) optical switching



Above: Picture of ACT-Photonics testbed

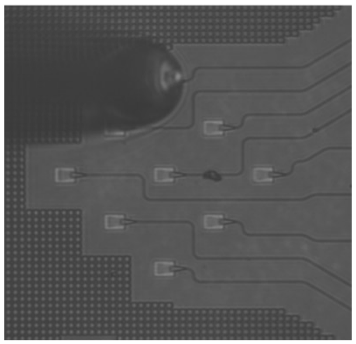


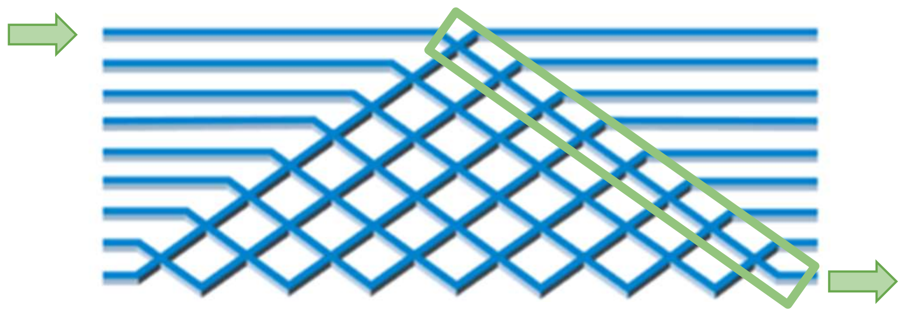
Above: First light demonstrating active control on a thermally-actuated optical switch

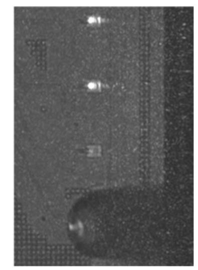
First suppression experiment using Ames PIC Coronagraph Testbed

- 8 phase shifters along the first mesh diagonal tuned to minimize light in bottom output channel (no pre-calibration)
- Preliminary suppression measurements demonstrate 2.0e-9 extinction (87 dB) (world record contrast!)

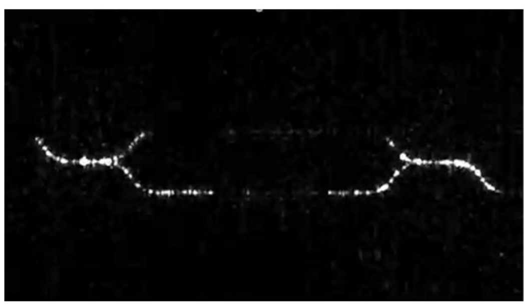
Illuminated input channel



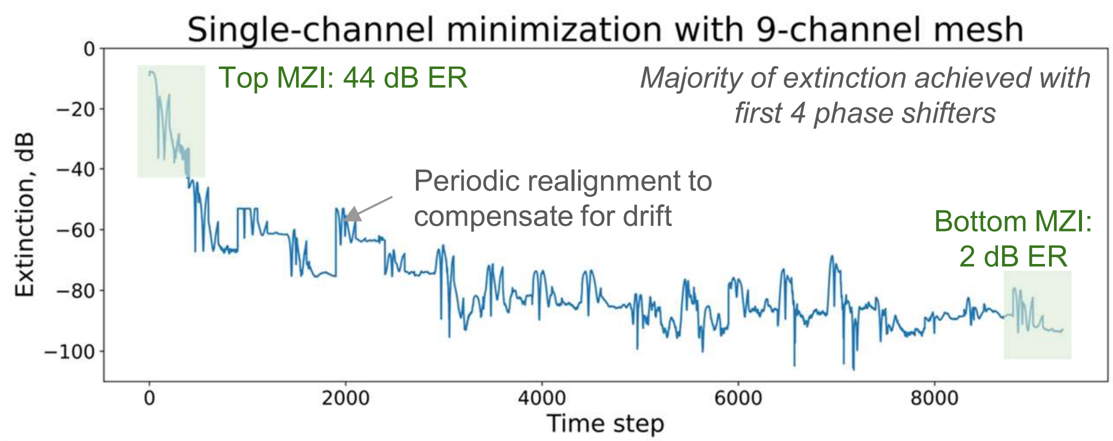




Minimized output channel



Voltage is swept with successively smaller increments until DAQ resolution limit is reached



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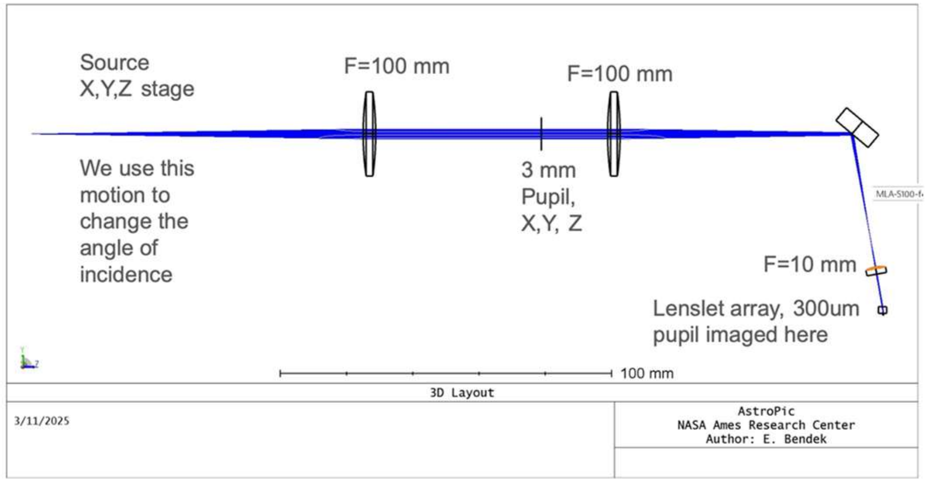
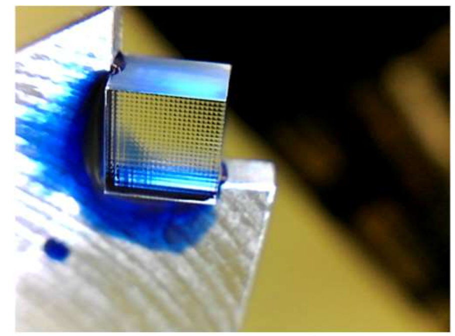
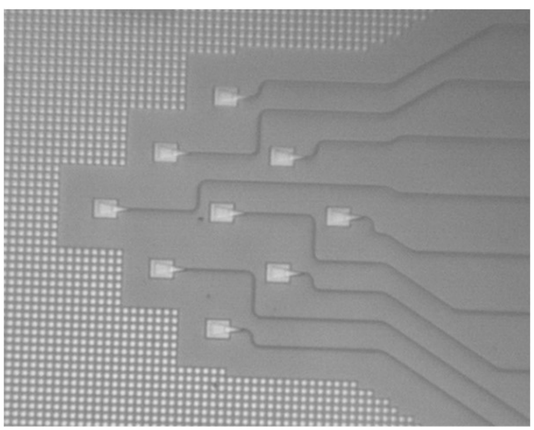
Next step: Free-space coupling of realistic pupil

- Front end equipped with a pupil reimaging system
- Microlenses used to inject a pupil section of 100x100um on each grating coupler

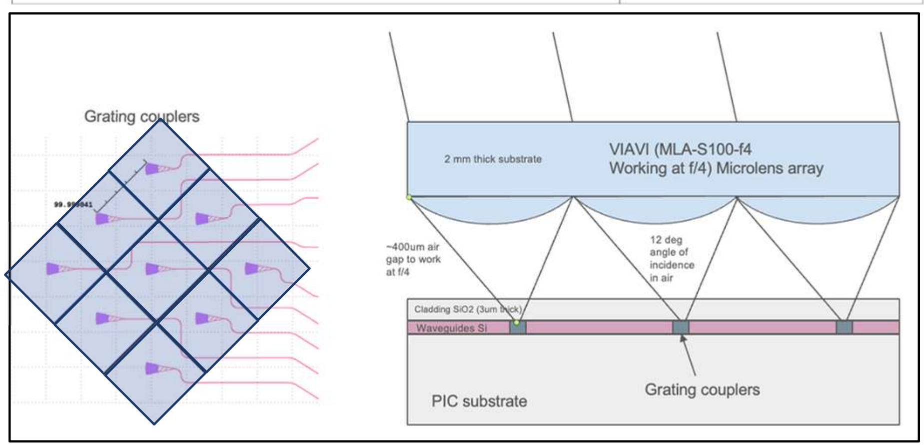


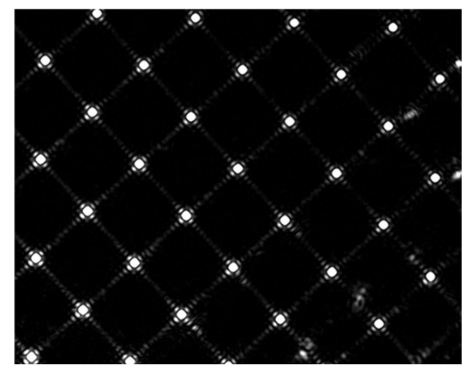


Microlens array



IR Image of Grating Couplers





Microlens array PSFs

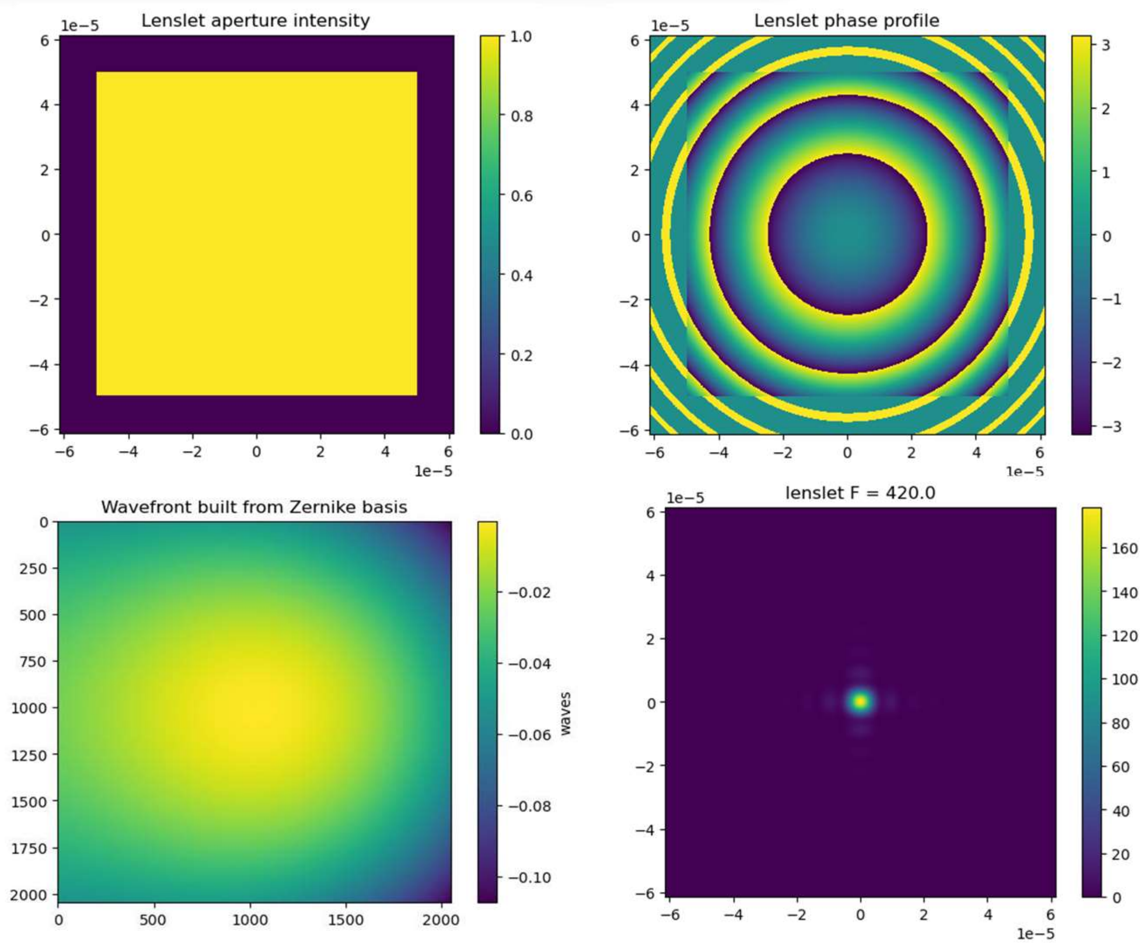
Input coupling efficiency simulations

E1, H1 are complex matrices from EM simulations of grating coupler designs

E2, H2 are incident field (lenslet PSF or fiber mode):

1. Calculate incident E field profile of SMF gaussian mode or lenslet PSF
2. Apply tilt to phase front (linear tilt around y)
3. Compute H field from E field from Maxwell's equations:
4. Calculate overlap integral with E and H:

$$\text{overlap} = Re\left[\frac{(\int \overrightarrow{E_1} \times \overrightarrow{H_2^*} \cdot \overrightarrow{dS})(\int \overrightarrow{E_2} \times \overrightarrow{H_1^*} \cdot \overrightarrow{dS})}{\int \overrightarrow{E_1} \times \overrightarrow{H_1^*} \cdot \overrightarrow{dS}}\right] \frac{1}{Re(\int \overrightarrow{E_2} \times \overrightarrow{H_2^*} \cdot \overrightarrow{dS})}$$



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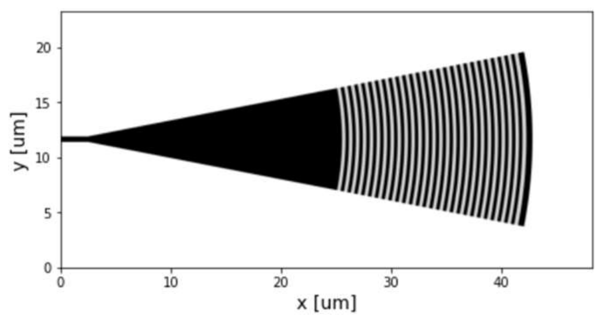
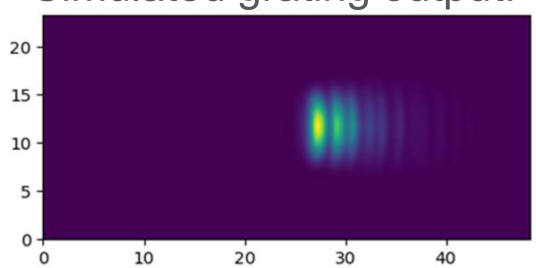
Input coupling efficiency: current grating design

Single-layer grating design:



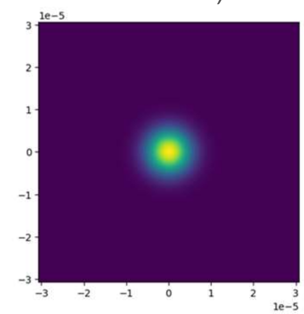
Simulated grating output:

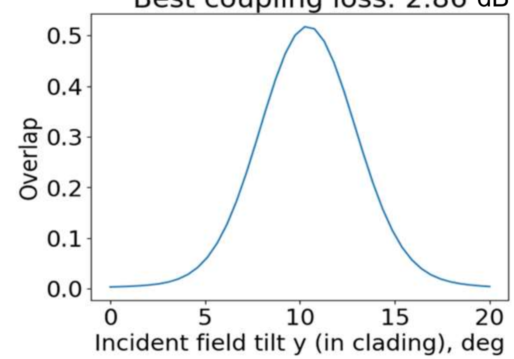


Upwards directivity: 67%

Single-fiber input coupling:

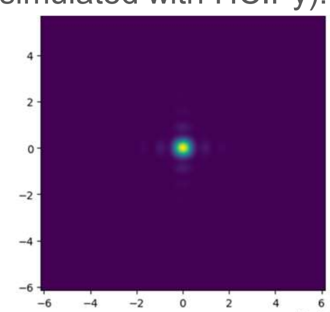
SMF-28 output mode (beam waist of 5.2 um, Thorlabs):



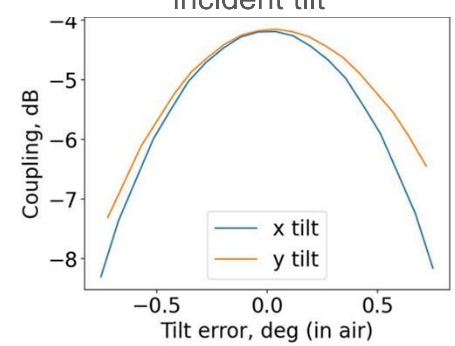


Microlens array coupling:

PSF of F/4.2 lenslet (simulated with HCIPy):



Coupling efficiency vs incident tilt



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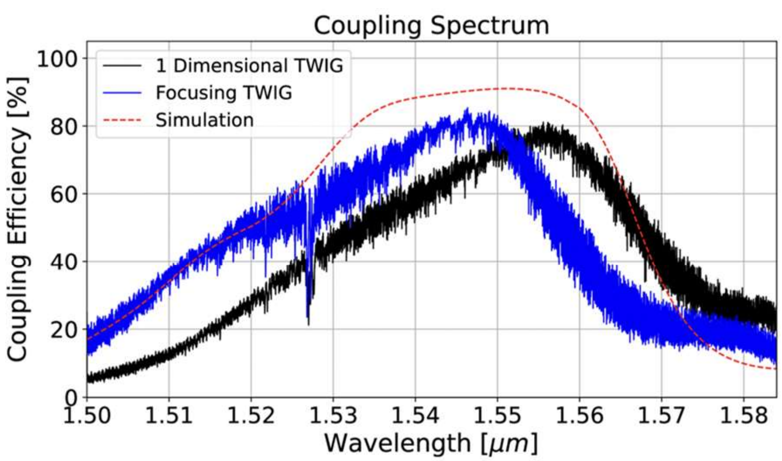
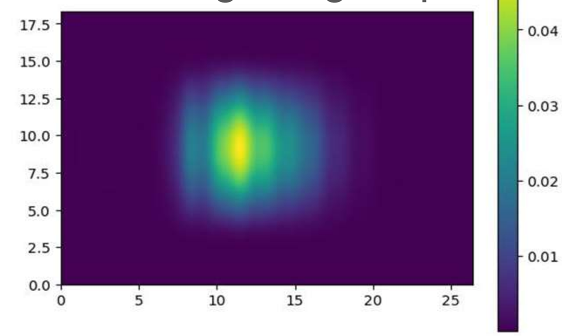
Coupling efficiency with new 2-layer gratings:

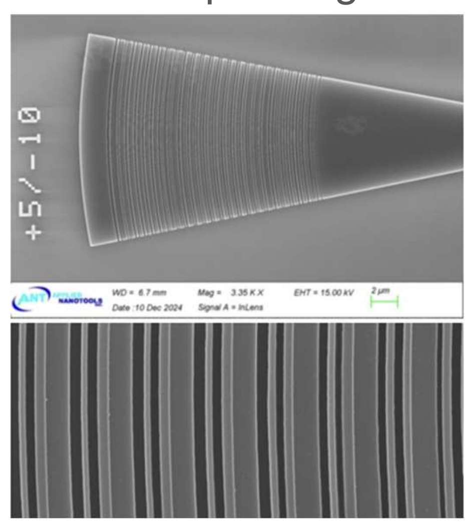
- SMF fiber input: 85.4% (-0.69 dB) coupling efficiency and 20 nm 1 dB bandwidth
- TWIG (three-wave interaction grating) design documented in C. Valdez et al. 2025

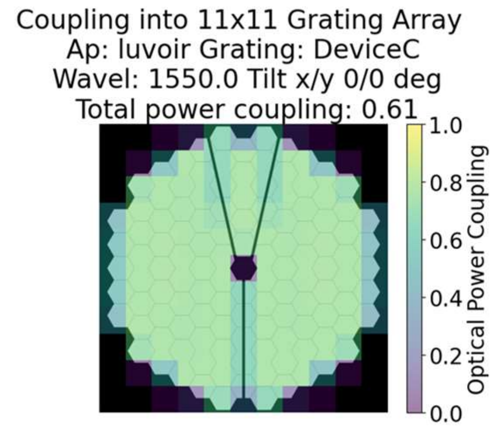


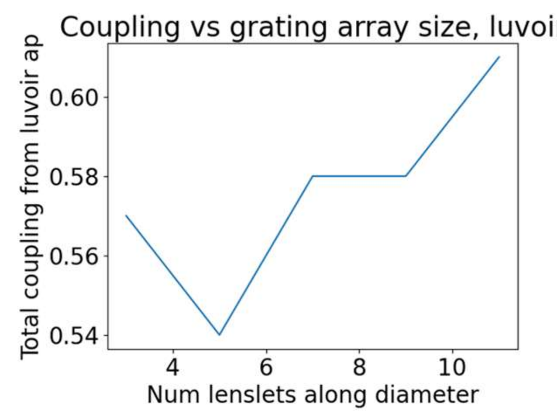
Simulated grating output:



Microscope images:

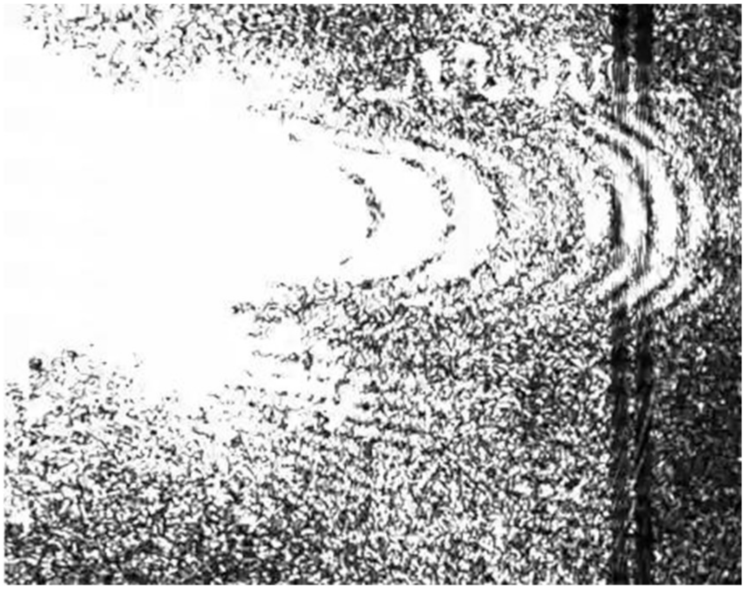






Conclusions

- PICs have the potential to **miniaturize coronagraphs and increase their resilience** to aberrations and pupil obscurations
- New Ames PIC coronagraph testbed achieved first light and reached **2e-9 (87 dB) extinction of single channel illumination** using 9-channel full triangular mesh
  - Testbed is capable of measuring 6.3e-11 (102 dB) ER → we are currently limited by stray light
- Next step: free-space coupling of **HWO-like telescope pupils into PIC**
- AstroPIC team has developed **AstroPIC simulation suite** to simulate input coupling, mesh operation, and expected coronagraph yield
- **New 2-layer grating design** achieved > 90% coupling efficiency from single-mode fiber (C. Valdez 2025) with 20-nm 1 dB bandwidth
- **Scalability**:
  - Current bandwidth est. 8 nm (based on C. Valdez 2024 result) → we are working on broadband component designs to increase this to 20-50 nm
  - Wirebonding packaging approach is feasible up to 100's of channels → can increase further by moving to flip-chip configuration
  - Thermal phase shifters draw ~100 mW power per MZI → non-thermal phase shifters (electroopic, mechanical) considered for long-term scalability



"Tour" of AstroPIC 9-channel mesh in minimized state