

Enhancing Coronagraphy on the Habitable Worlds Observatory through astrophotonics

NASA Ames Team (ARC)

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

Stanford ECE

Prof. Olav Solgaard
Prof. David Miller
Carson Valdez
Anne Kroo

Collaborators:

Prof. Olivier Guyon (U. Arizona)
Nem Jovanovic (CalTech)
Jeffrey Jewell (JPL)
Emiel Por (UCSC)

***CAMOS Panel
May 19th 2025
Washington, DC***



H A B I T A B L E
W O R L D S
O B S E R V A T O R Y

Research supported by STMD's Early Career Initiative (ECI) program

Overview

1. *Coronagraphy Background*

High-contrast direct imaging
Ground- and space-based coronagraphy

2. *Current and Future Space Missions*

Roman Space Telescope
Habitable Worlds Observatory (HWO)

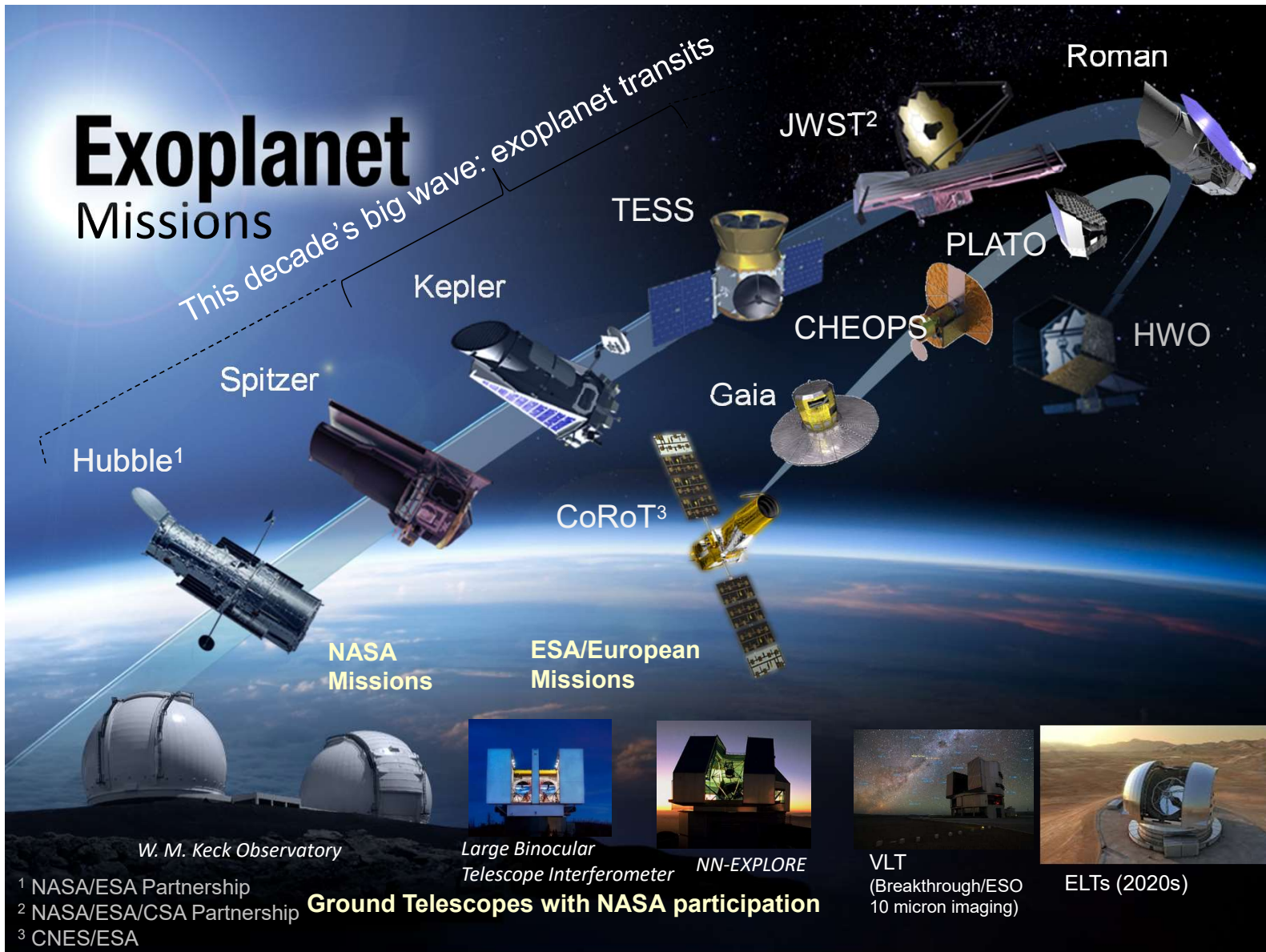
3. *Emerging Technology Areas for astrophysics*

AstroPIC coronagraph: concept & status

H A B I T A B L E
W  R L D S
O B S E R V A T O R Y

Exoplanet Missions

This decade's big wave: exoplanet transits



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

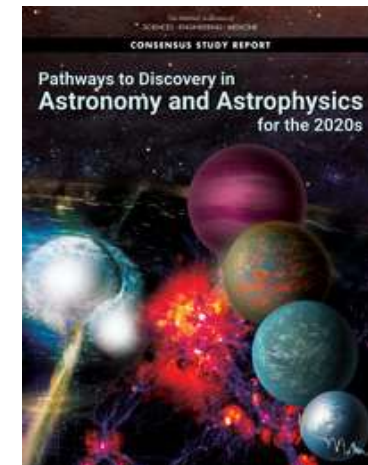


Image Credit: National Academies Astro2020 Decadal Survey

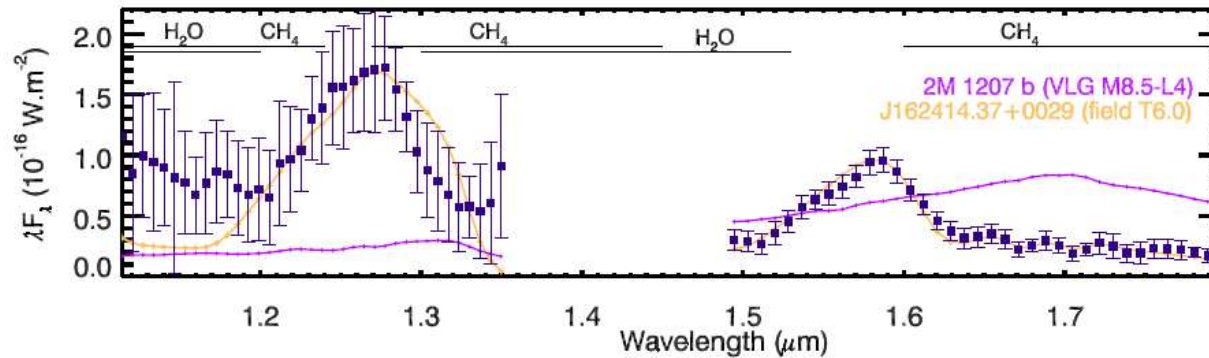
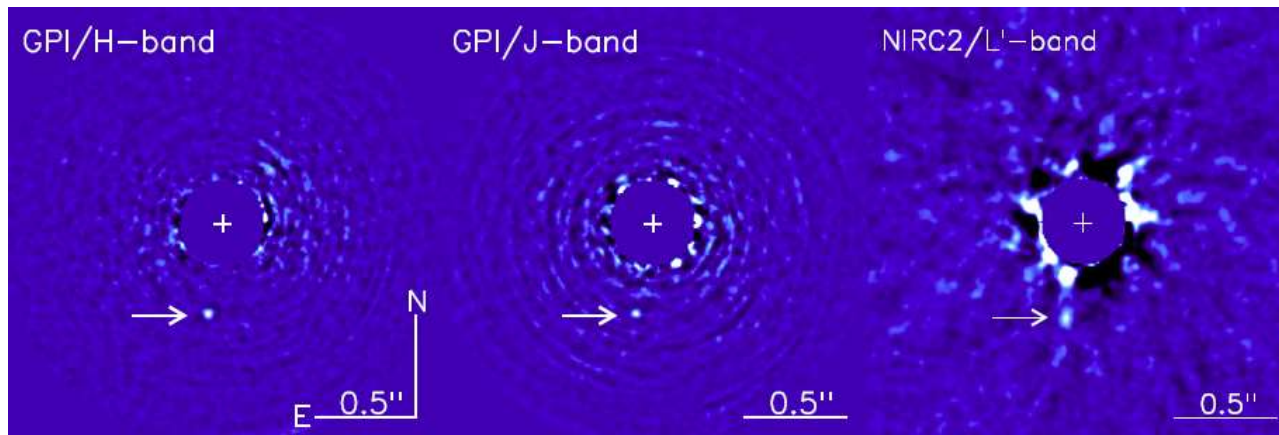
¹ NASA/ESA Partnership

² NASA/ESA/CSA Partnership

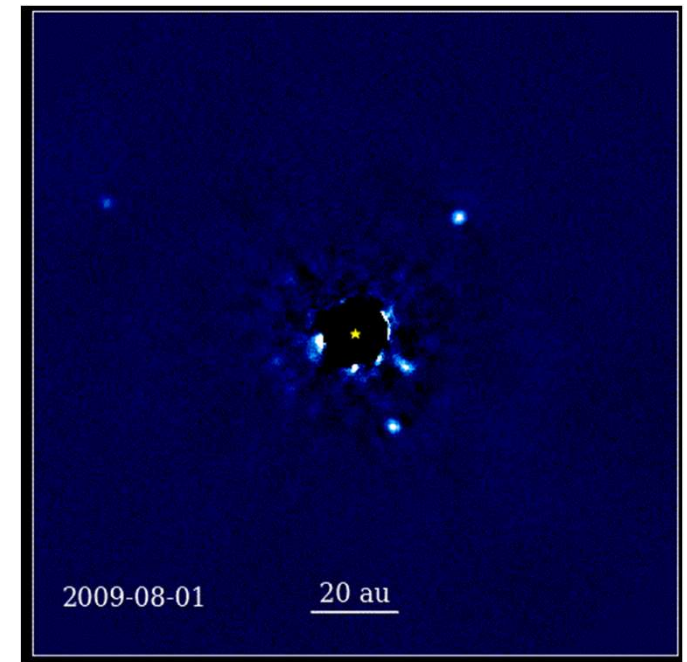
³ CNES/ESA

The Case for Direct Imaging

Discovery and characterization of 51 Eri b (Macintosh et al, 2015)

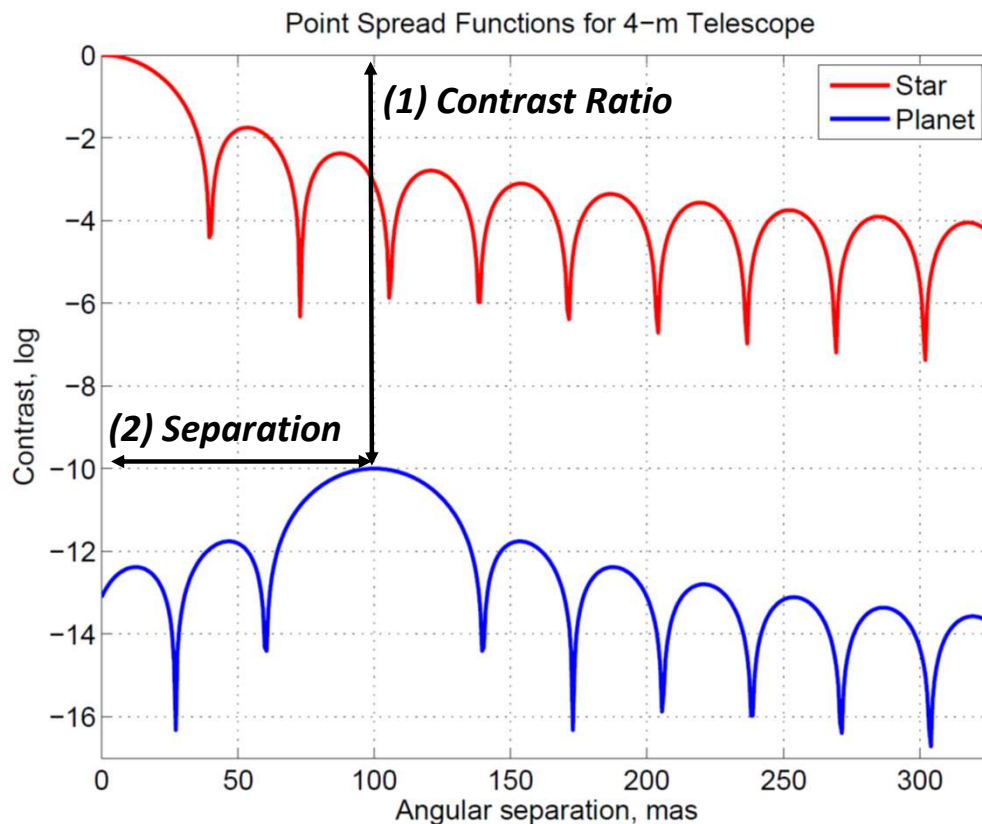


12-year timelapse of HR 8799



Jason Wang 2021

The Challenge of Direct Imaging



(1) **Contrast ratio** between star's and Earth-like planet's point spread function (PSF) peak is *10 orders of magnitude* at visible bands.

(2) **Angular separation** of *100 mas* needed to image an exoplanet at 1 AU in the habitable zone for stars at 10 parsec away is between star's and Earth-like planet's point spread function (PSF)

To reach deep contrast ratios consistent with exoplanet imaging a space telescope needed.

Coronagraphy

- Bernard Lyot built and tested three solar coronagraphs at the Pic du Midi Observatory from 1930-1939

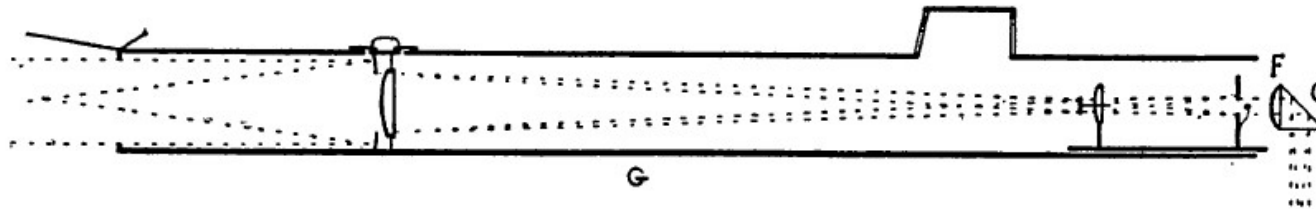


Image source: Lyot, 1939

- Apodized Pupil Lyot Coronagraph (APLC) architecture describes most stellar coronagraph types which share the same architecture but have different requirements (Contrast, Separation, Field of View, etc.)

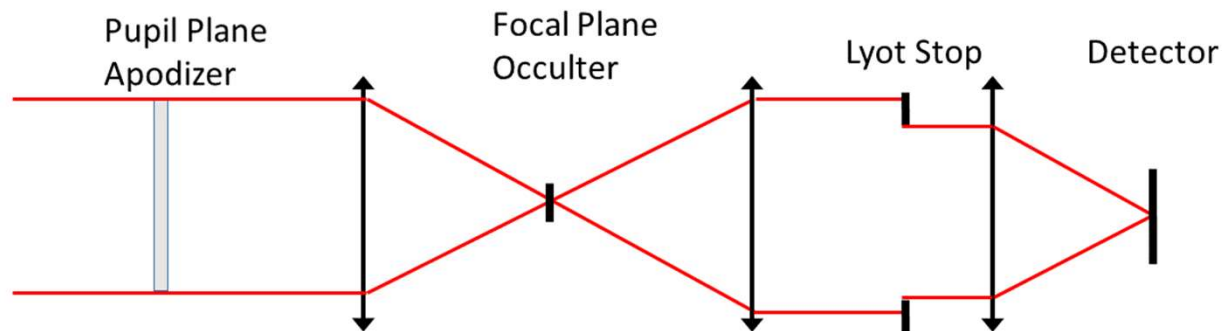


Image source: Based on Sivaramakrishnan, 2001

Roman Coronagraph Instrument

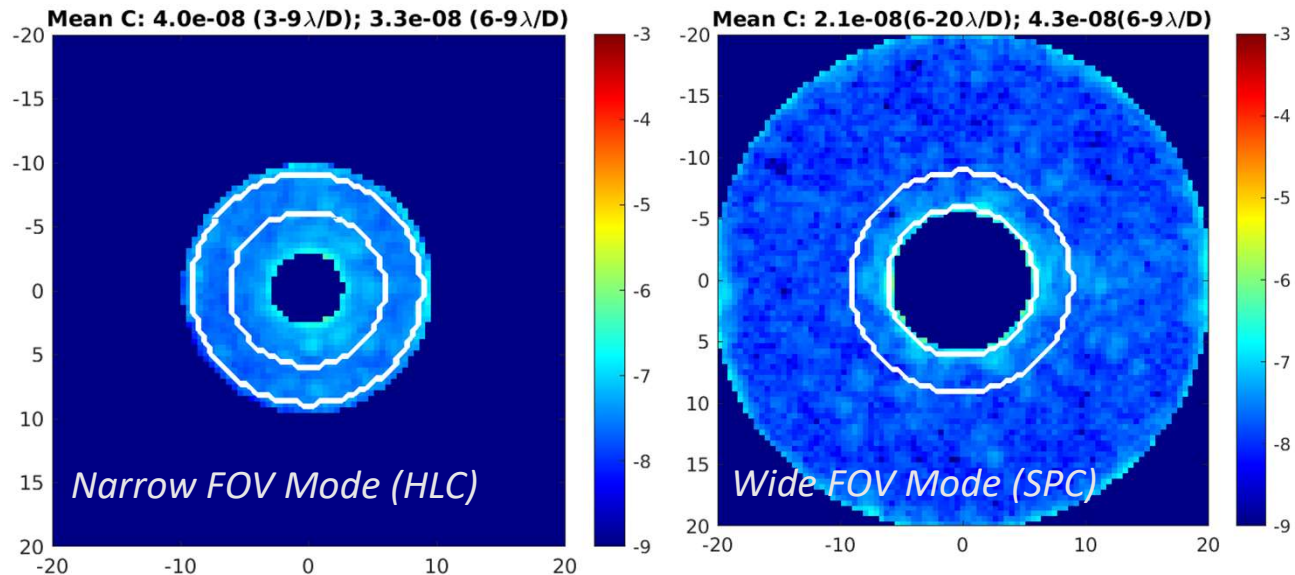


*Image Credit:
NASA GSFC
Coronagraph
integration with
Roman Space
Telescope*



*Credit: Caltech/JPL
Roman Coronagraph
Instrument*

- Roman coronagraph is a technology demonstration instrument on the Roman Space Telescope



*Credit: Performance summary
Eric Cady et al (2025 – JATIS)*

- Roman coronagraph has demonstrated contrast requirements in TVAC tests for two coronagraph configurations
- Coronagraph instrument assembled and integrated with Roman Space Telescope
- Contrast levels of reaching $\sim 3\text{e-}8$ consistent with imaging Jupiter-sized exoplanets in reflected light

Habitable Worlds Observatory Large UV-Optical-IR Telescope

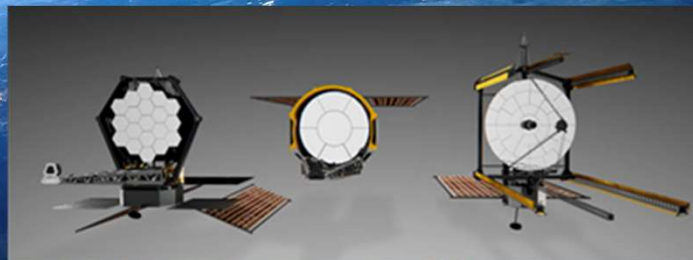
Image Credit: HWO Technology
Project Office (TMPO), Burns (2024)



First telescope designed
specifically to search for signs
of life on planets
outside our solar system

HWO is a large UV/Optical/IR telescope optimized for directly imaging habitable earth-like planets and do transformative general astrophysics

- Aperture: ~6-8-m diameter
- Ultra stable system (~picometer)
- Coronagraph capable of high-contrast imaging (10^{-10})
- Target launch ~first half of 2040's
- Cost: ~\$15B



EAC 1	EAC 2	EAC 3
Off-axis, hexagon segmentation 8-m diameter	Off-axis, keystone segmentation 6-m diameter	On-axis, hexagon segmentation 7.2-m outer diameter

Pre-Phase A has begun:
Exploratory Analytic Cases 1-3
defined by TMPO being studied for
on-axis and off-axis telescope
pupils with segmentations.
EAC 4-5 being currently defined

***Credit: Feinberg (HWO Townhall,
January AAS 2025)***

Searching for Global Biosignatures

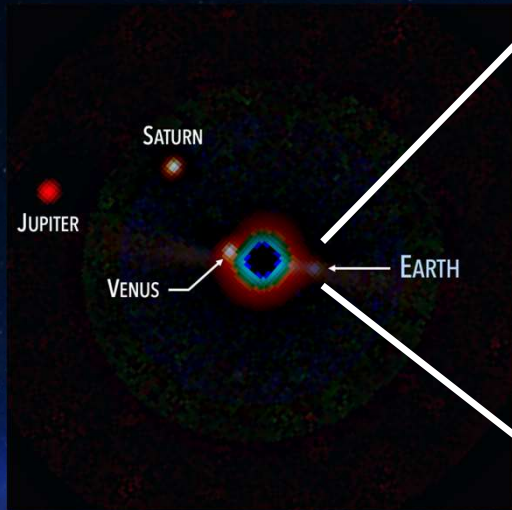
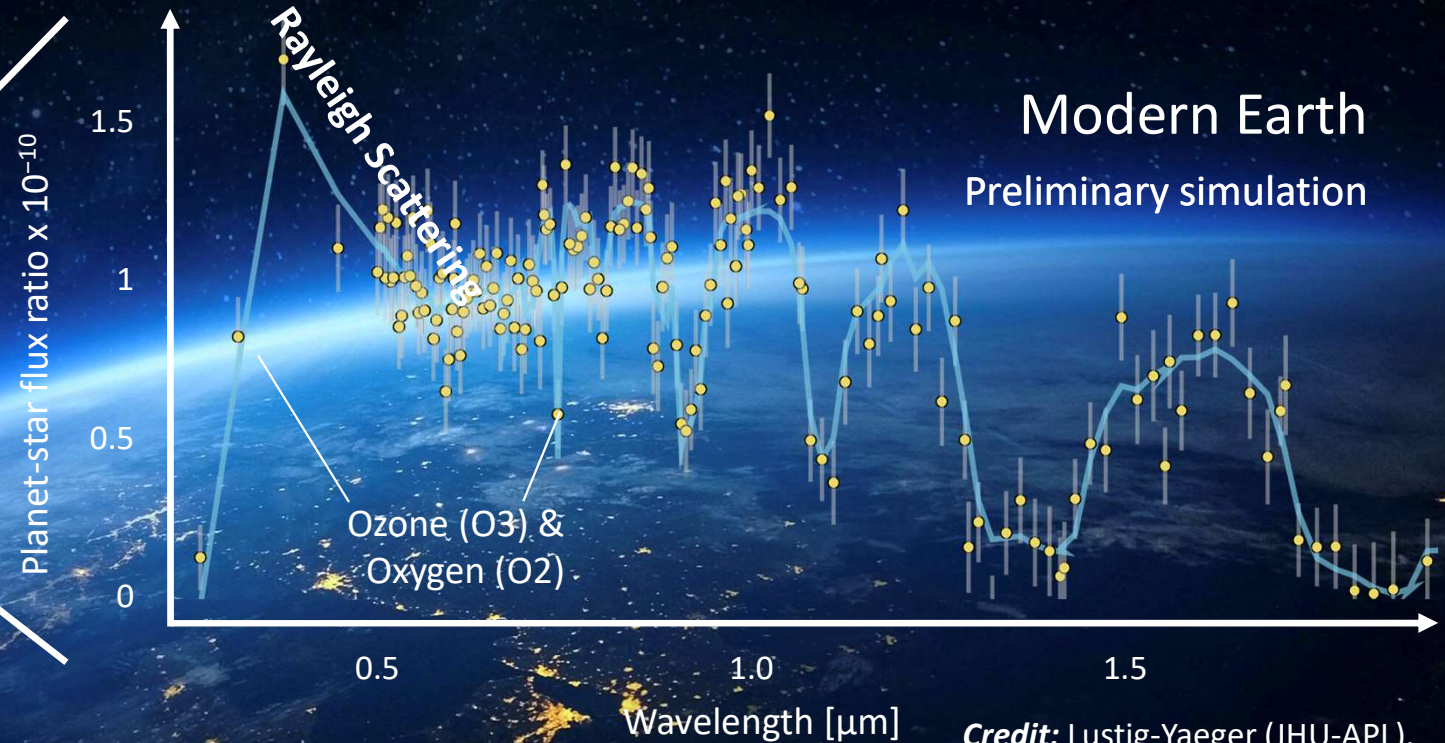


Image Credit: Kammerrer, Pueyo, Juanola-Parramon



Credit: Lustig-Yaeger (JHU-APL), Robinson (NAU), Arney (GSFC)

Analyze light directly reflected by the planet, with little or no starlight mixed in

Emerging Technologies in Astrophysics Workshop

Cross-disciplinary meeting with experts across four emerging technology areas:

Astrophotonics
(imaging and
spectroscopy)

Quantum
Sensing
(imaging and
algorithms)

Artificial
Intelligence
and Machine
Learning
algorithms

Advanced
Materials: 3D
printing, meta
materials and
composites

➔ In this presentation I will focus on AstroPIC as an example of emerging astrophotonic technology development that can benefit HWO

Meeting co-chairs Mario Perez, mario.perez@nasa.gov and Nick Siegler, nicholas.siegler@jpl.nasa.gov

March 25-27, 2025

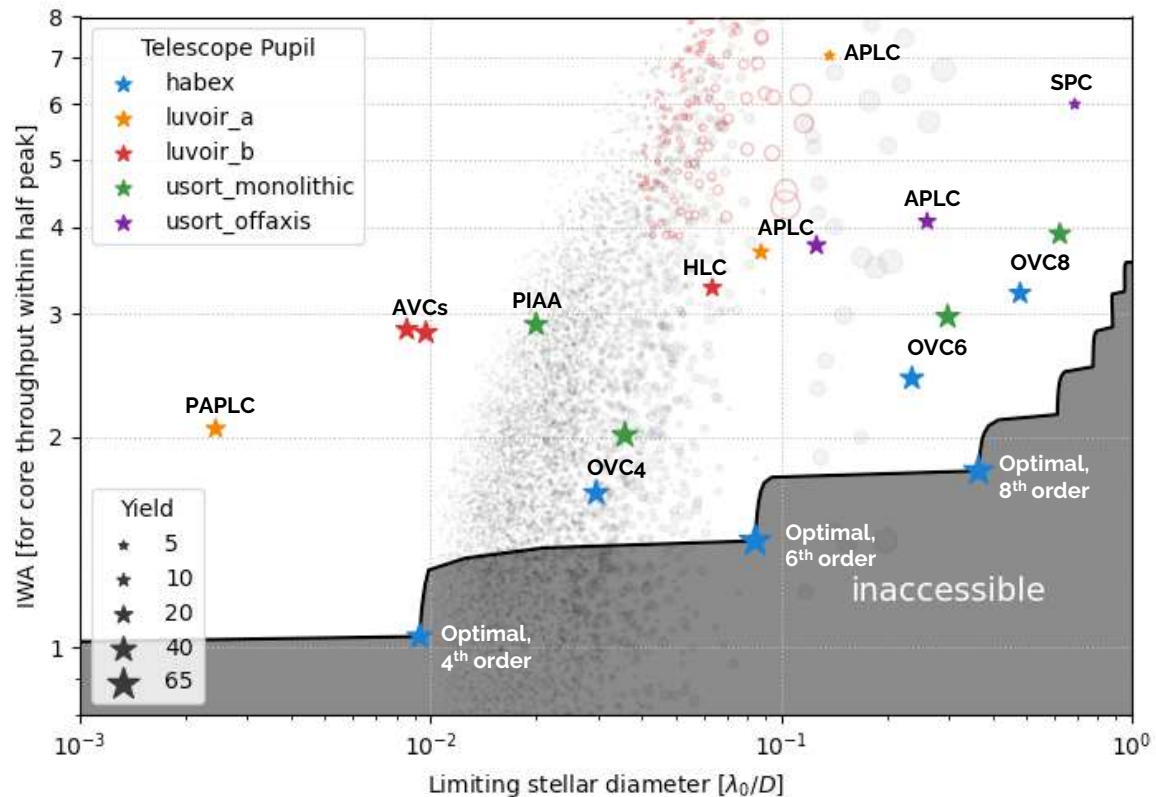
NASA Ames Research Center in Silicon Valley

<https://www.nasa.gov/emerging-technologies-for-astrophysics-missions-workshop/>



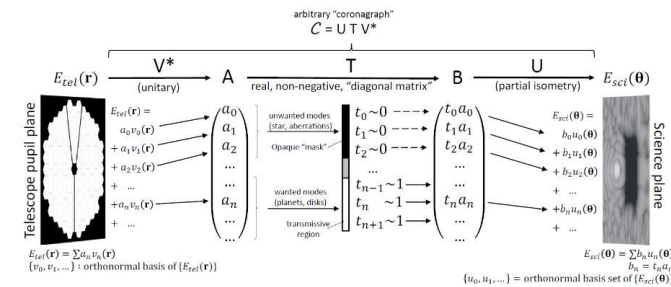
Theoretically optimal coronagraphs have 2-4x improved yield to current designs

Performance gap in state-of-the-art coronagraphs:

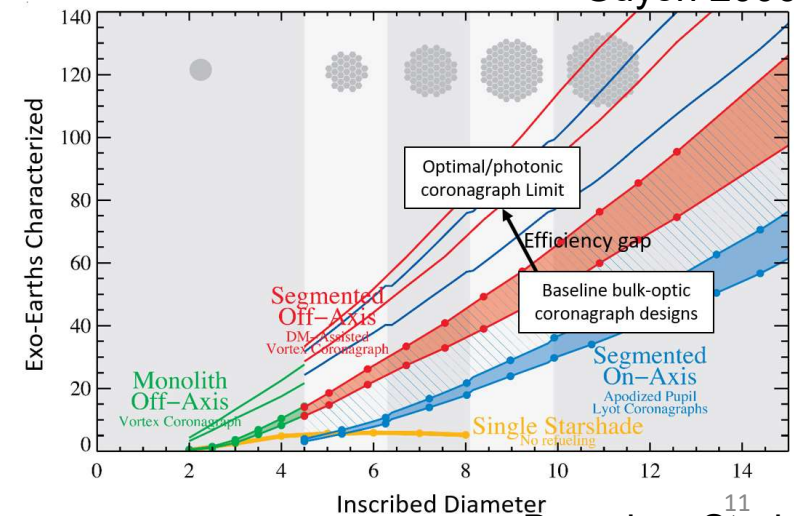


Por 2023 (CDS coronagraphs)

Coronagraph as an optimal linear operator:



Guyon 2006



Based on Stark 2021

Theoretically optimal coronagraphs fully suppress some modes and pass the rest

What is a 2N-th order optimal coronagraph?

Taylor series expansion for off-axis point response

$$CE_{\theta} = \mathcal{C} [Ae^{2\pi i r \cdot \theta}]$$

$$\begin{aligned}
 &= \mathcal{C} A \\
 &\quad + i\pi \mathcal{C} [A r e^{+i\Delta\phi}] \theta + \dots + \frac{(i\pi)^n}{n!} \mathcal{C} [A r^n e^{in\Delta\phi}] \theta^n + \dots \\
 &\quad + i\pi \mathcal{C} [A r e^{-i\Delta\phi}] \theta + \dots + \frac{(i\pi)^n}{n!} n \mathcal{C} [A r^n e^{i(n-2)\Delta\phi}] \theta^n + \dots \\
 &\quad + \dots + \dots + \dots + \dots \\
 &\quad + \dots + \frac{(i\pi)^n}{n!} \binom{n}{\frac{n-m}{2}} \mathcal{C} [A r^n e^{im\Delta\phi}] \theta^n + \dots \\
 &\quad + \dots + \dots + \dots + \dots \\
 &\quad + \dots + \frac{(i\pi)^n}{n!} \mathcal{C} [A r^n e^{-in\Delta\phi}] \theta^n + \dots + \dots
 \end{aligned}$$

Mode blocked by 2nd order optimal coronagraph

Modes blocked by 4th order optimal coronagraph

Modes blocked by 2(n+1)th order optimal coronagraph

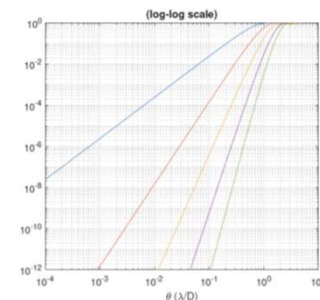
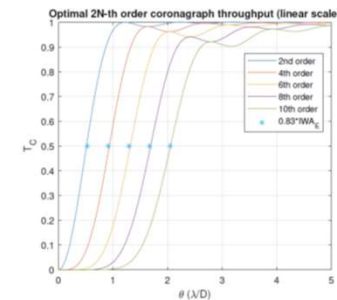
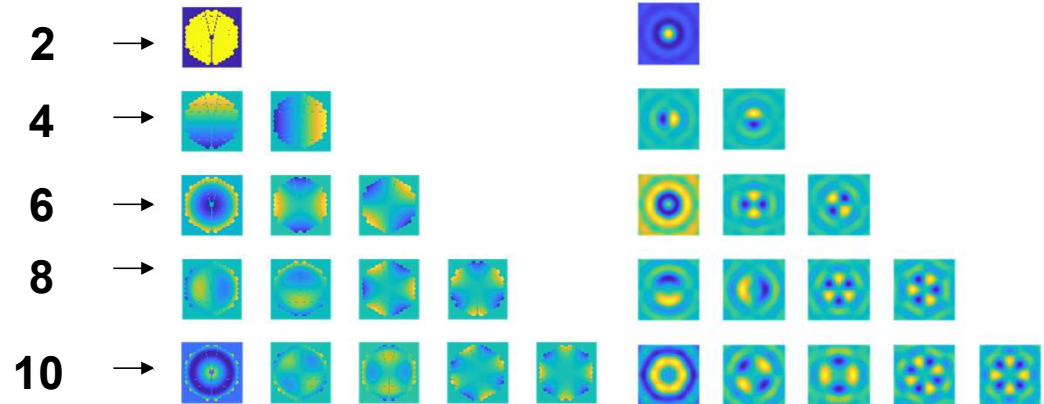
Theoretical benefits of optimal coronagraphy:

- (1) Best possible combination for maximal off-axis throughput and smallest inner working (for nth order mode suppression)
- (2) Best robustness to low-order aberrations (including tip/tilt or finite stellar diameter) at a specific inner working angle
- (3) performance is almost independent of aperture shape, obstruction, and segmentation

See Belikov 2021 for theoretical framework

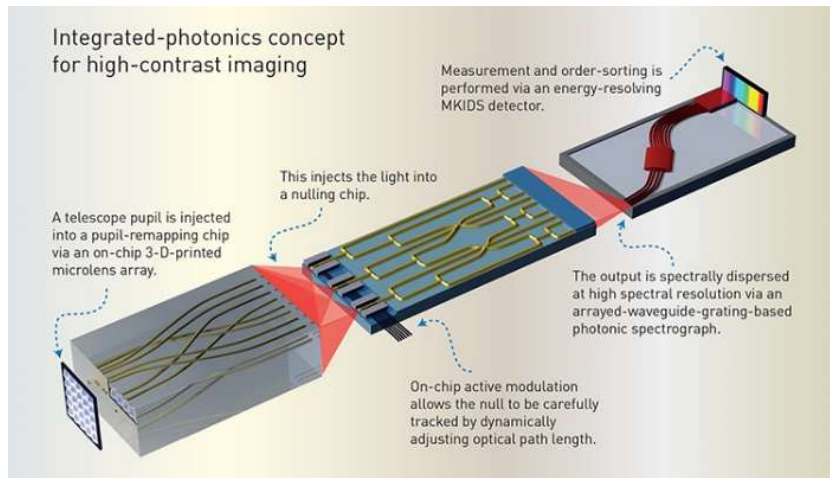
Pupil plane representation of suppressed mode orders

Science Plane representation (without coronagraph)



Photonic integrated circuits provide a practical method to implement optimal coronagraphy

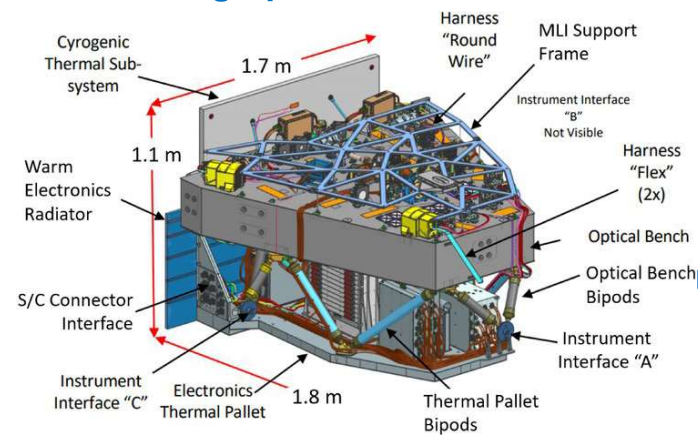
Architecture of Photonic Integrated Circuit - based coronagraph



Decomposes beam into constituent modes that can be suppressed/recombined for space coronagraphy using a Mach-Zehnder Interferometric (MZI) mesh

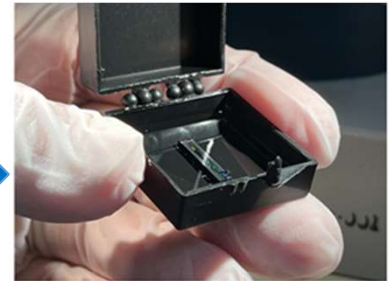
Saunders, Optica 2021

Coronagraph



Bailey 2023

Photonic Integrated Circuit (PIC) chip



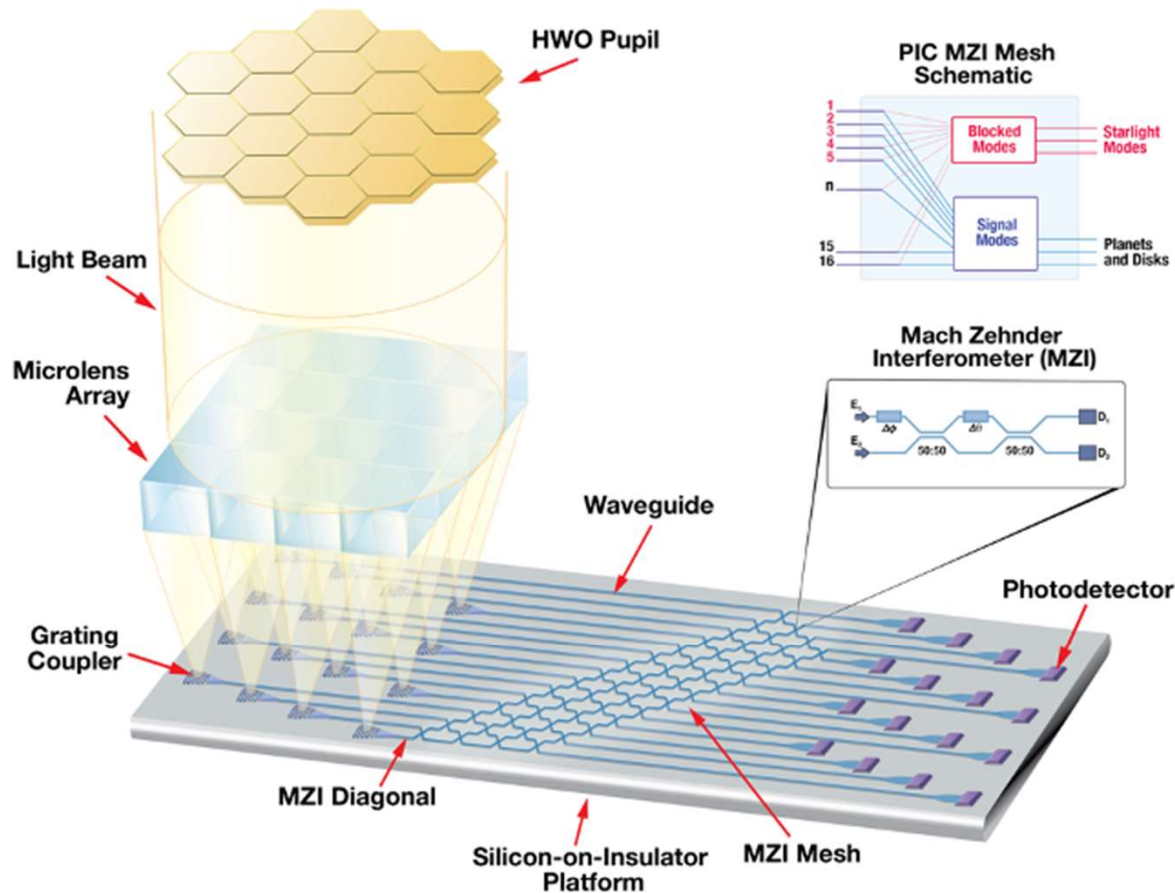
NASA Tech Thursdays (2025)
<https://www.linkedin.com/feed/update/urn:li:activity:7290806967332155392/>

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), synergize with traditional coronagraph instrument (small angular separations)
- **improve risk margins:** relaxes Habitable Worlds Observatory telescope requirement doubling # of characterized ExoEarths

AstroPIC

Photonic Integrated Circuit High-Contrast Imaging for Space Astronomy

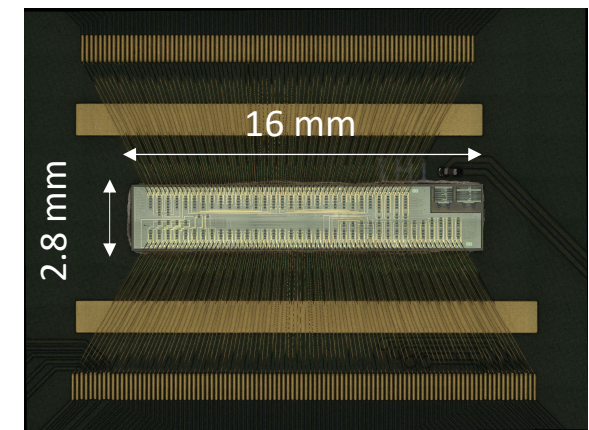


AstroPIC architecture:

- microlens array samples telescope pupil
- grating coupler feed light into waveguides
- Mach-Zehnder Interferometric mesh composed of two phase shifters

Prototype photonic chip

- 9-input x 9 output MZI mesh

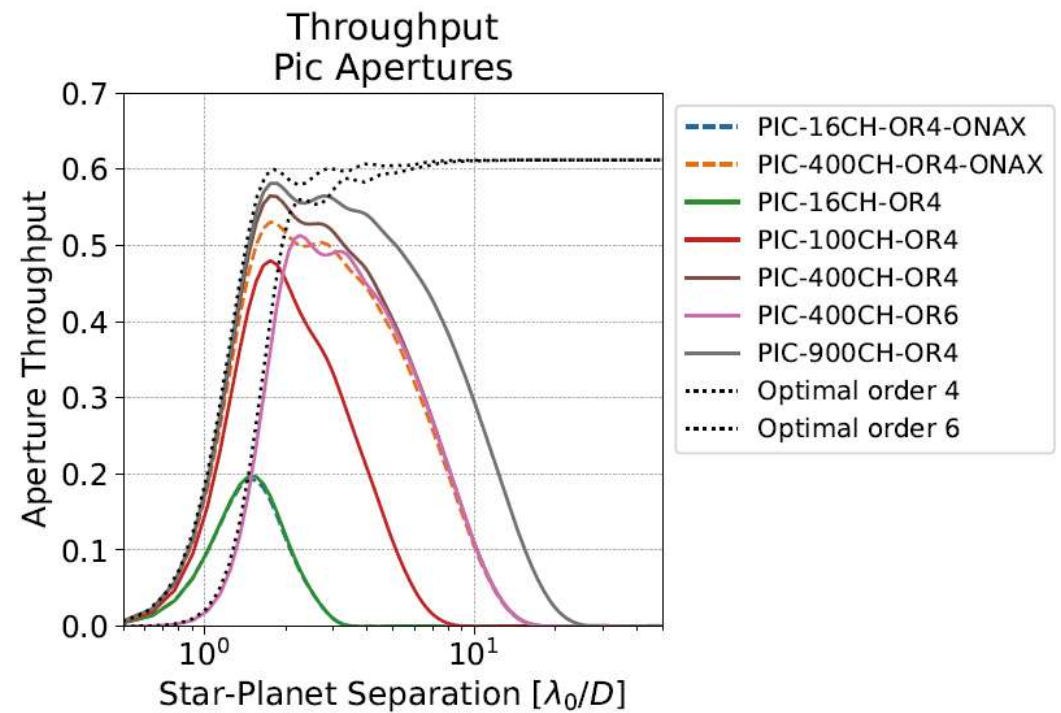


Microscope image of AstroPIC prototype chip

Credits: design by NASA Ames and Stanford, manufacture by ANT, , wirebonding and microscope photo by Silitronics

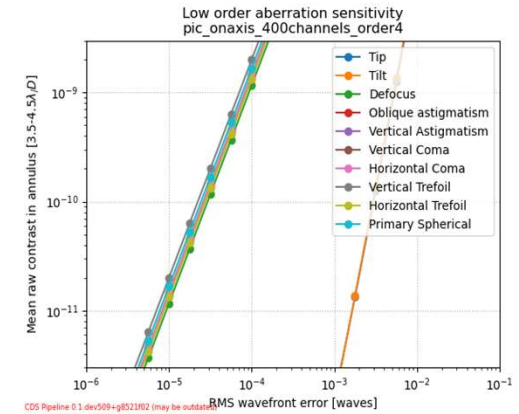
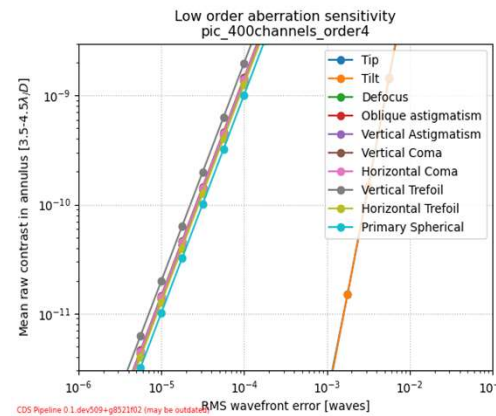
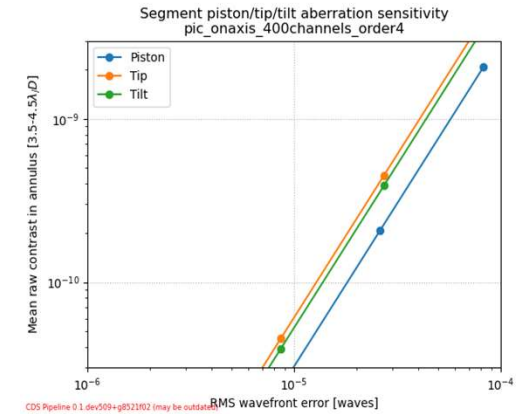
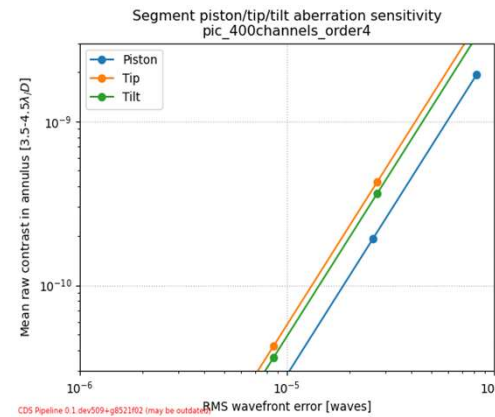
Practical PIC coronagraph achieve close to theoretical performance in mesh simulation

- **PIC throughput approximately theoretical maximum that can obtained by a coronagraph**
 - But only in the region of frequency-space well-sampled by channels
 - Limited number of channels affects outer working angle of discovery region
- **Enables best possible trade-off between throughput and IWA, low-order aberration robustness**
 - Throughput, IWA, robustness set by the coronagraphic order
 - AstroPIC can be configured to change number of modes blocked



Sirbu et al 2024

AstroPIC Aberration Sensitivity is Insensitive to Telescope Geometry



USORT Off-Axis/
EAC1



USORT On-Axis/
EAC3



Fogarty et al 2025

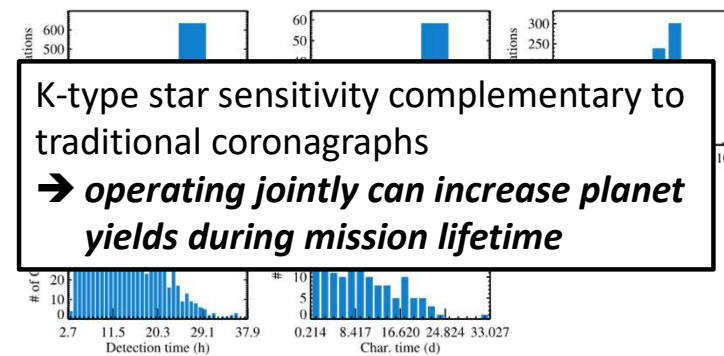
Yield Evaluation of AstroPIC at NIR shows significant scientific utility

Two AstroPIC designs evaluated using CDS pipeline:

➔ 16-channel PIC (“Hybrid AstroPIC”) shows significant sensitivity improvements for K-type stars due to small IWA and throughput

➔ 400-channel PIC (“Full Photonic AstroPIC”) approaches optimal coronagraph limit and improves by 2-4x (but are low TRL and require additional development)

Hybrid AstroPIC sensitivity to target stars



	Focal-Plane Coronagraphs			Pupil-Plane Coronagraphs		Hybrid Coronagraphs			Emerging Technologies	
	HLC	VC (monolith)	DMAVC (segmented)	SPC	PIAA (classic)	AAVC	APLC	PAPLC	Full Photonic Chip	Optimal Coro. Limit
Science Yields										
EEC Yield (VIS detections only)	16% (13)	68% (54)	57% (45)	30% (24)	64% (51)	44% (35)	43% (34)	39% (31)	81% (65)	100% (78)
EEC Yield (Detect + orbits + H2O search)	15% (9)	67% (40)	55% (33)	13% (8)	56% (34)	47% (28)	36% (22)	46% (28)	81% (49)	100% (60)
EEC Yield (Detect + orbit + CO2 search)	5% (2)	50% (15)	32% (10)	2% (1)	29% (9)	28% (8)	15% (5)	44% (13)	86% (26)	100% (30)
Total yield of all planet types	13% (170)	62% (838)	47% (635)	12% (157)	45% (605)	43% (582)	25% (333)	40% (543)	65% (875)	100% (1345)
Exposure Times										
Median detection time for blind survey	5.6x (31 hrs)	1.3x (7 hrs)	1.4x (8 hrs)	3.2x (18 hrs)	1.3x (7 hrs)	2.1x (11 hrs)	2.1x (11 hrs)	2.9x (16 hrs)	1.4x (8 hrs)	1x (8 hrs)
Median detection time for fiducial stars	102x (107 hrs)	2.5x (2.6 hrs)	4.0x (4.2 hrs)	310x (325 hrs)	2.5x (2.6 hrs)	8.6x (9.0 hrs)	6.6x (6.9 hrs)	8.5x (8.9 hrs)	3.0x (3.1 hrs)	1x (1.1 hrs)
Median char. time for fiducial stars										

Sirbu et al 2024

Yield packages generated with CDS pipeline (Kevin Fogarty), evaluated in AYO (Chris Stark)

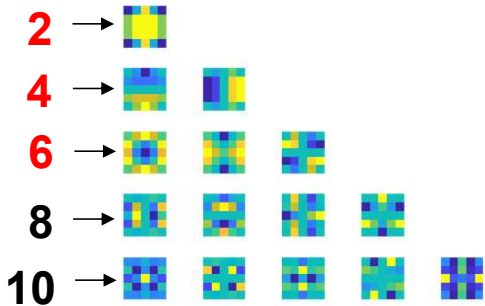
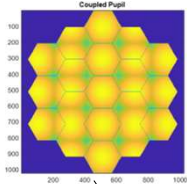
Designs of input grating couplers show high coupled efficiencies are possible

Top-level architecture for AstroPIC Cycle-1 (NIR channel design for HWO)

Pupil coupling: with 5x5 lenslet array (few channels)

with 30x30 lenslet array (high channels)

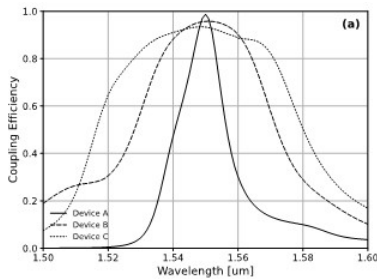
HWO/USORT
off-axis pupil



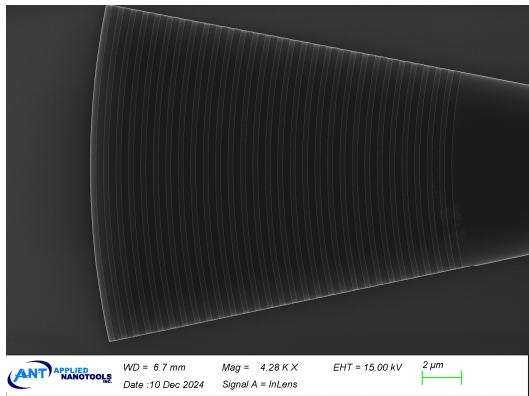
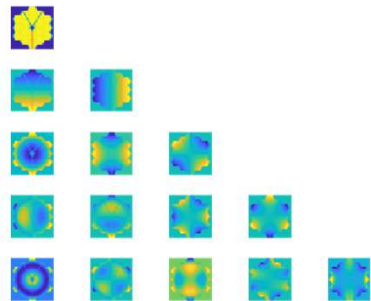
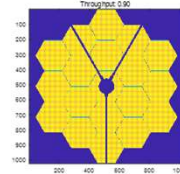
Mode from input grating coupler (Valdez et al, 2023)



Device	Coupling Efficiency	1 dB Bandwidth
A	98.6% (−0.06 dB)	8 nm
B	95.6% (−0.2 dB)	29 nm
C	93.4% (−0.3 dB)	48 nm



HWO/USORT
on-axis pupil

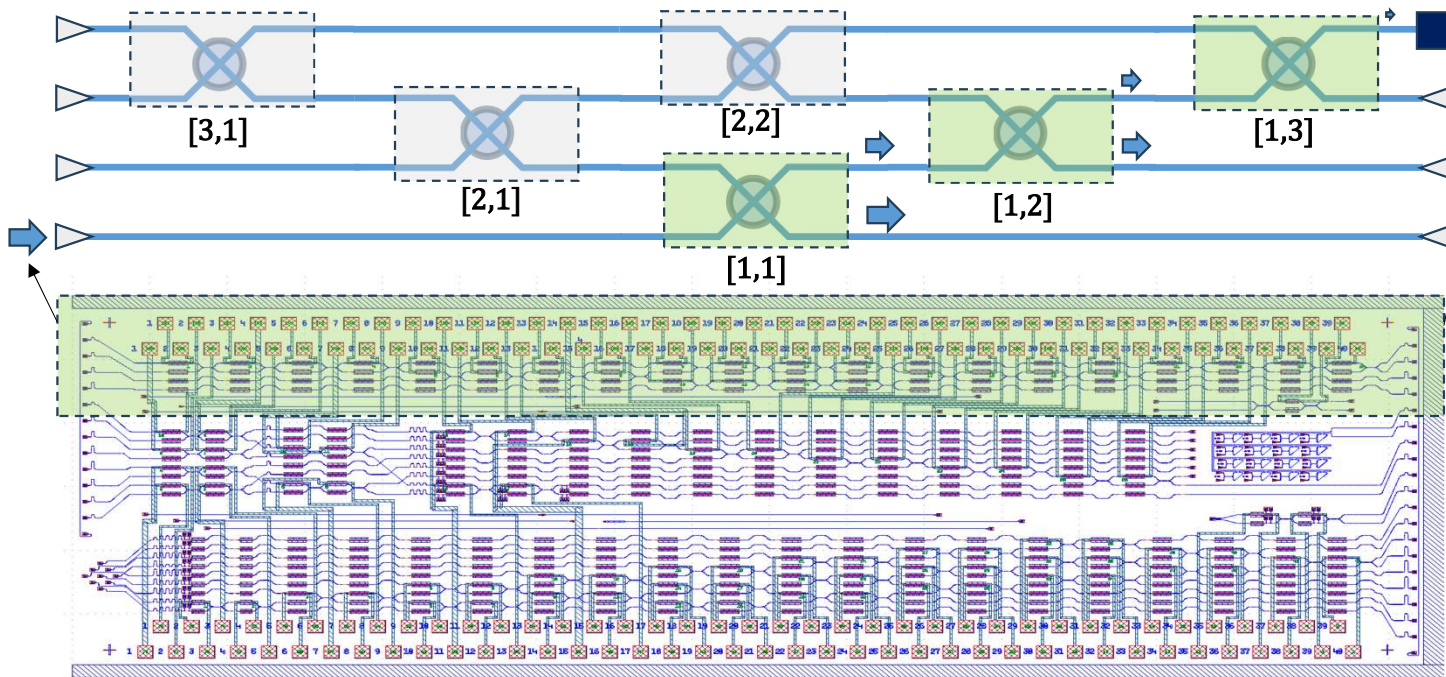


Prototype input grating
coupler component
(Feb 2025)

Early results confirm 2-
3x improvement on
standard foundry
coupler designs

7.9e-9 contrast enabled by a simple on-chip setup

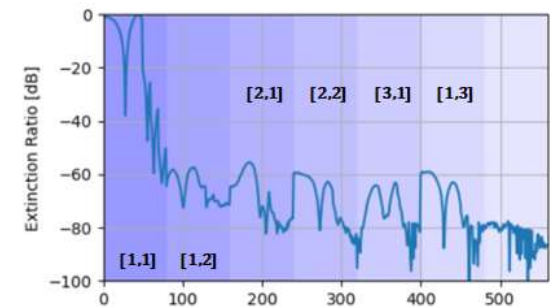
Stanford team demonstration of deep photonic nulling of a single channel using additional diagonal line in Perfect Mach Zehnder Interferometer



Existing PIC prototype layout re-purposed for high-contrast demonstrations!

For more details on photonic nulling experiment see: Valdez et al 2025

Single-channel suppression

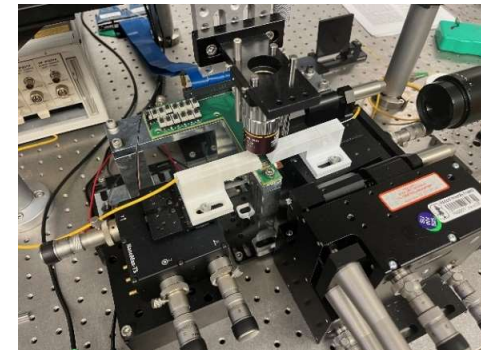
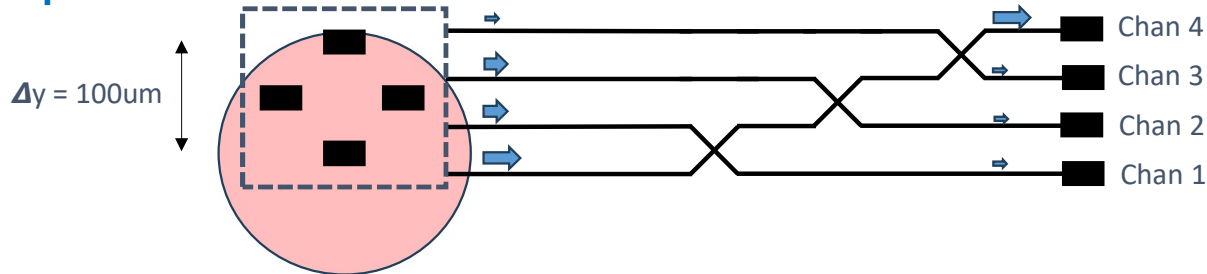


Iterative process to tune phase shifters minimizes leakage:

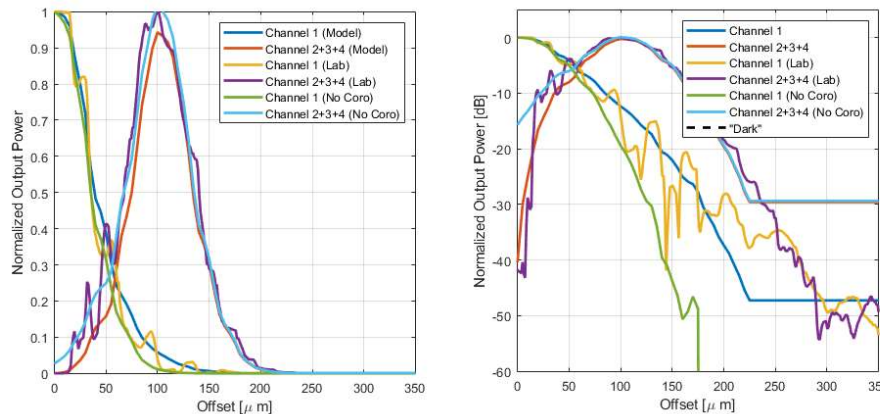
- (1) Measured **7.9e-9 contrast (81 dB suppression)** at thermal equilibrium conditions
 - (2) Improvement from off-diagonal phase shifters indicates light leakage/cross talk
- ➔ Additional diagonal lines will likely improve contrast
- ➔ ~10% measured throughput

Free-space coupling of PIC with input gratings and model comparison

Coronagraphic throughput measurement as free-space beam profile is moved



Photonic coronagraph test-stand at Stanford laboratory



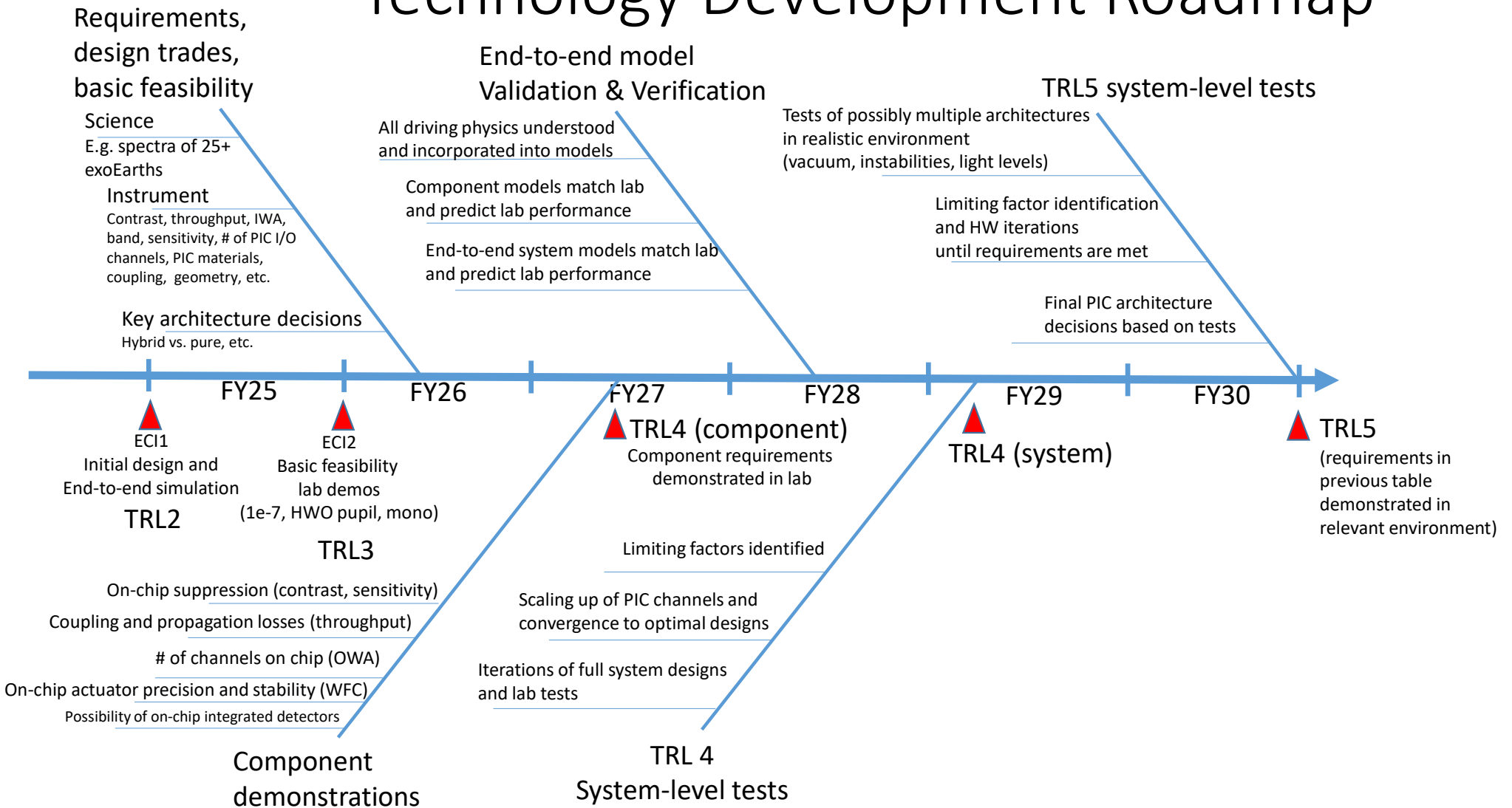
Stanford experiment: Carson Valdez
Ames model: Kevin Fogarty

Comparison of experimental data with photonic coronagraph mesh model shows good agreement

Measures coronagraphic throughput for existing MZI prototype with 4-input grating coupler and 1 stellar mode nulling

- next step: free-space coupling using microlens array (to maximize fill-factor)

Technology Development Roadmap



Conclusions

Key Takeaways:

Emerging technologies such as astrophotonics can enable and enhance coronagraphy on HWO

Theoretically optimal coronagraphs increase HWO yield by factors of 2-4, and are almost independent of aperture shape.

PICs MZI meshes are flexible and reconfigurable – we have demonstrated compatibility with all HWO apertures being considered for HWO including: on- and off-axis, hexagonal- and keystone-segmented

AstroPIC Current Status:

- Manufactured and tested two cycles of photonic chip prototypes
- Developed simulation pipeline to estimate MZI mesh performance including computing estimated science yields
- Upcoming free-space coupling experiments with 9x9 input mesh and additional nulling suppression experiments

For more details about AstroPIC see Papers/Presentations:

- C. Valdez et al. 2025 (81 dB experiment)
- R. Morgan et al. AAS Winter Meeting 2025 (Experiment overview)
- K. Fogarty et al. AAS Winter Meeting 2025 (Simulator details)
- C. Valdez et al. Opt. Letters 49(9), 2024 (High Efficiency Grating Designs)
- D. Sirbu et al. SPIE Astronomical Telescopes + Instrumentation. Proc. SPIE 13092-65, 2024. (AstroPIC Concept)
- D. Sirbu et al. AAS Winter Meeting 2024. (Overview)

Upcoming:

- R. Morgan et al, DPSC Meeting (September 2025)
- R. Belikov et al, HWO25 (July 2025)
- K. Fogarty et al, SPIE Optics + Photonics (Aug 2025)
- E. Bendek et al, SPIE Optics + Photonics (Aug 2025)
- D. Sirbu et al, SPIE Optics + Photonics (Aug 2025)

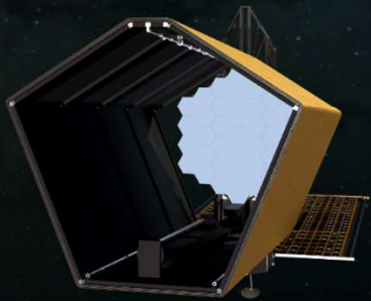
Questions?



PRELIMINARY SPECS & CANDIDATE INSTRUMENTS

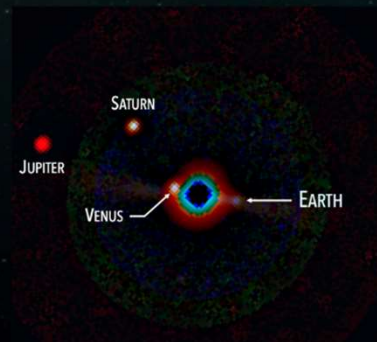
Telescope

Diameter	~6.0 m (inner)
Bandpass	~100-2500 nm



Coronagraph

High-contrast imaging and imaging spectroscopy	
Bandpass	~200-1800 nm
Contrast	$\lesssim 1 \times 10^{-10}$
R ($\lambda/\Delta\lambda$)	Vis: ~140 NIR: ~70, 200



Wide-Field Imaging Camera

UV/Vis and NIR imaging	
Bandpass	~200-2500 nm
Field-of-View	3' x 2'
67 science filters + grism	
High-precision astrometry?	



Ultraviolet Multi-Object Spectrograph

UV/Vis multi-object spectroscopy and FUV imaging	
Bandpass	~100-1000 nm
Field-of-View	2' x 2'
Apertures	~840 x 420
R ($\lambda/\Delta\lambda$)	500-50,000



Astro2020 Recommendations

Two of the top recommendations of Astro2020 decadal survey:

The decadal survey recommends a large (~6m diameter) **Infrared/Optical/Ultraviolet space telescope with high-contrast imaging and spectroscopy as the first mission to enter the Great Observatories Mission and Technology Maturation Program**. This is an ambitious mission with the goal of searching for biosignatures from habitable zone exoplanets and providing a powerful new facility for general astrophysics. If mission and technology maturation are successful, as determined by an independent review, implementation should start in the latter part of the decade with a target launch in the first half of the 2040's.

Given the large costs and development timescales for the next generation of space telescopes, the decadal survey recommends that NASA create the **Great Observatories Mission and Technology Maturation Program** as a new approach for planning and implementing large missions. The program would provide **early investment in technology development** for multiple mission concepts to lower the risks and costs of projects before they become too complex, large, and costly. The **first entrant** for the maturation program should be a large **Infrared/Optical/Ultraviolet space telescope**. The second entrants should be strategic Far-Infrared and X-ray missions.

Astro2020 cost appraisal for GOMTMP: \$1.2B this decade (FY2020\$, see p. S-8, table S.5)

