# *The path to detecting extraterrestrial life with astrophotonics*

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*California Institute of Technology*

*SPIE Optics + Photonics*

*August 22nd, 2023*

# ACKNOWLEDGEMENT SLIDE


University of California, Irvine
Steph Sallum
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University of Central Florida
Rodrigo correa
Stephanos Yerolatsitis

California Institute of Technology
Yinzi Xin
Danial Echeverri
Pradip Gatkine
Greg Sercel
Svarun Soda
Dimitri Mawet
Chas Beichman

UCLA David Geffen School of Medicine
Michael Fitzgerald
Jonathan Lin
Yoo-Jung Kim

Subaru Telescope
Julien Lozi
Olivier Guyon
Sebastien Vievard
Vincent Deo

The University of Sydney
Peter Tuthill
Barnaby Norris
Marc-Antoine Martinod
Sergio-Leon Saval
Chris Betters

Jet Propulsion Laboratory, California Institute of Technology
James Kent Wallace
Jeffrey Jewell
Stephanie Leifer
Gautam Vasisht

Bright Integrated Photonics
Ronald Broeke
Katarzyna Ławniczuk

Observatoire de la Côte d'Azur, Université Côte d'Azur
Nick Cvetojevic

Macquarie University
Simon Gross
Michael Withford
Alexander Arriola

# ROADMAP

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## 2023 Astrophotonics Roadmap: pathways to realizing multi-functional integrated astrophotonic instruments

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Accepted Manuscript online 18 July 2023 •

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DOI 10.1088/2515-7647/ace869

JPhys Photonics

From the publisher of the *Journal of Physics* series

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2023 Astrophotonics Roadmap

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GUEST EDITORS

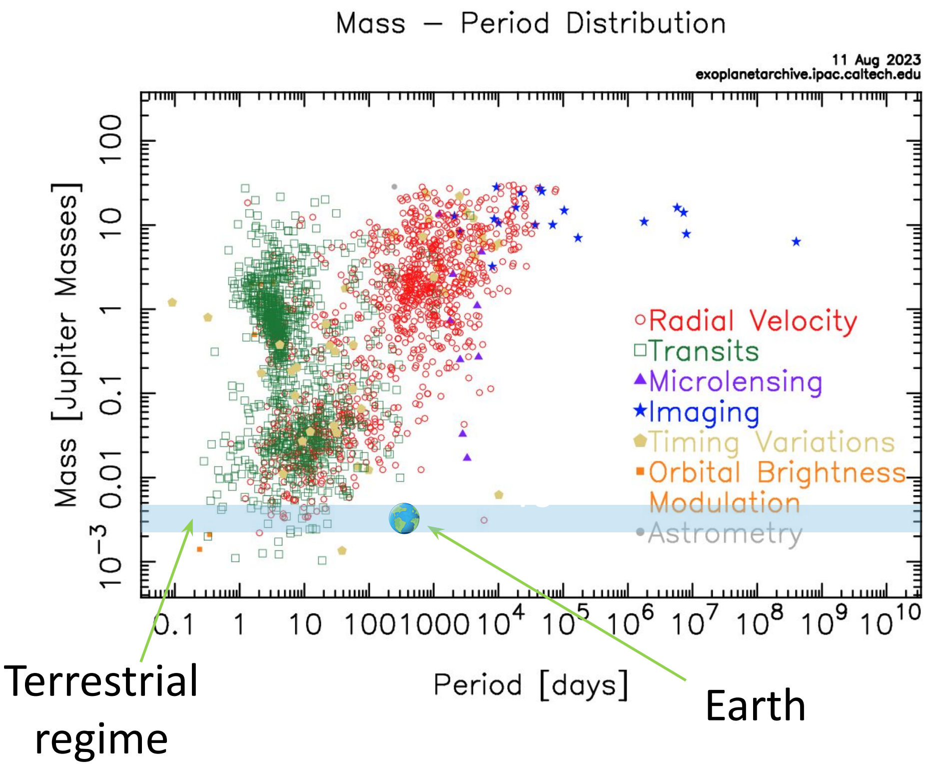
**Nemanja Jovanovic and Pradip Gatkine** (Caltech) with contributions from 80 authors across 50+ institutions

IOP Publishing

**DOI** 10.1088/2515-7647/ace869

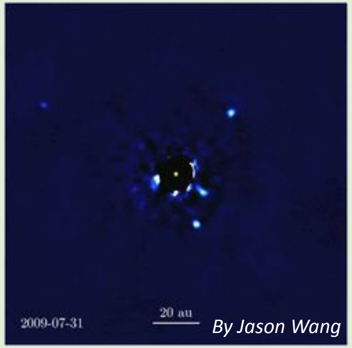
# EXOPLANET DETECTION

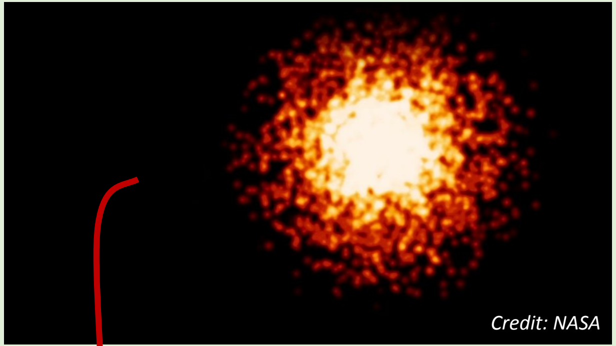
- 5400+ confirmed exoplanets to date
- The field is focusing on characterization of known planets
- Handful of terrestrial planets detected, with much smaller orbital periods.
- These are mostly not in the habitable zones of their host stars.
- No true Earth/Sun analogs in the habitable zone confirmed yet.



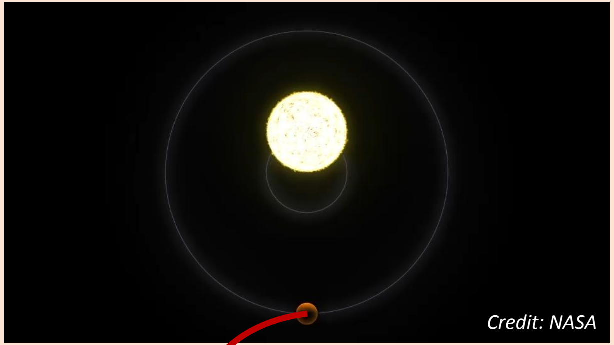
# EXOPLANET CHARACTERIZARION TECHNIQUES

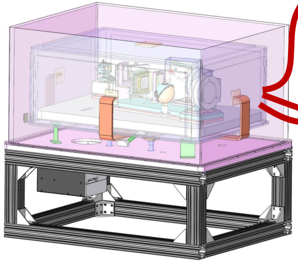
## Direct Imaging



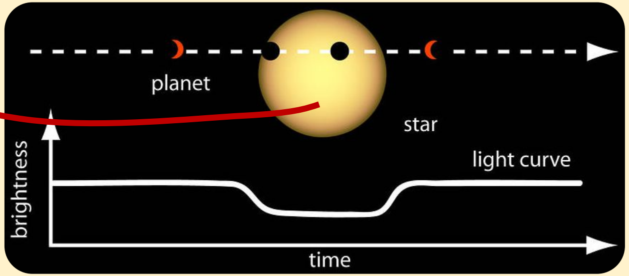



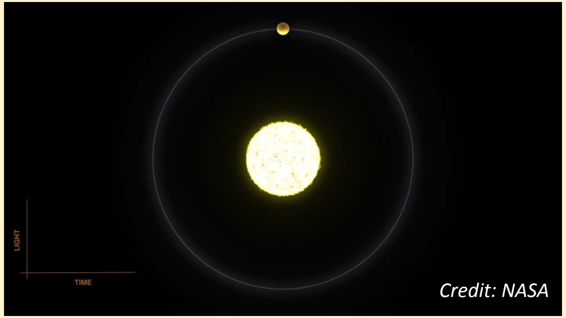

## Radial velocity



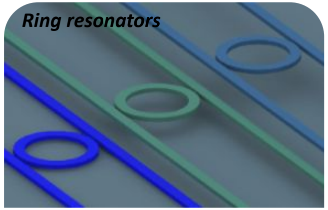
## Transit



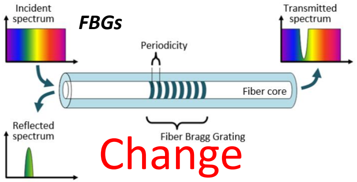



# MANY PHOTONIC FUNCTIONS TO PLAY WITH

## Spectral filtering

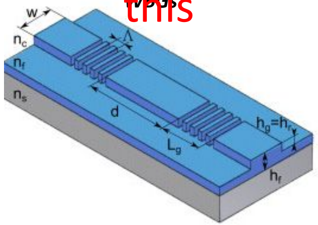



*FBGs*



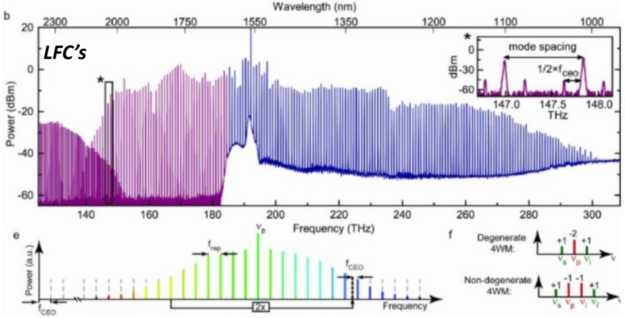

Change this

*WBGs*



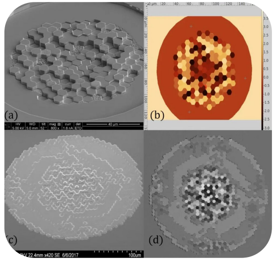

## Comb generation/calibration

*LFC's*

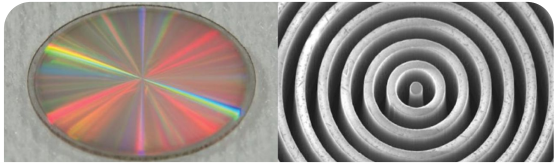



*P. Del'Haye et al. Phys Rev Lett (2011)*

## Phase masks



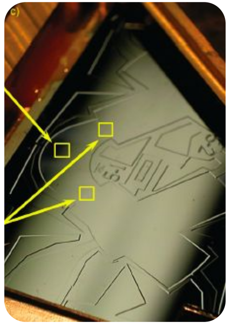
*Knight et al. SPIE (2018)*



*Mawet et al.*

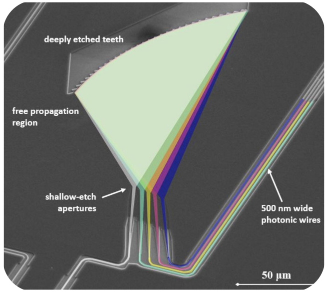
## Spectral Dispersion

*Arrayed Waveguide gratings*



*Cvetojevic et al, Opt. Exp. (2012)*

*Planar Concave gratings*

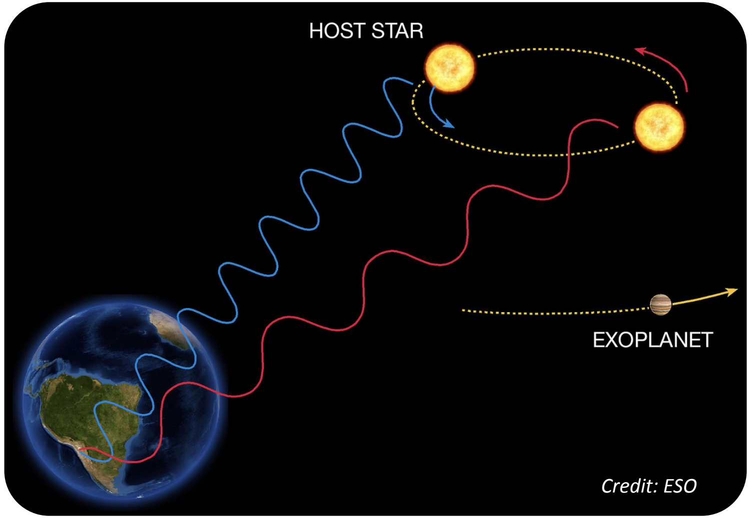



*E. Ryckeboer et al. SPIE (2016)*

# HOW TO DETECT AN EARTH-LIKE PLANET

# USING RADIAL VELOCITY TO DETECT EARTH'S

- By measuring the periodic wobble in the spectrum of the star, one can infer the presence of an orbiting planet
- Earth like planets induce velocity shifts of <1 m/s in the velocity of the starlight.
- This is a fractional velocity shift of ~1 /300 000 000
- We must therefore sense a shift in the spectral lines of a star to this level!!!!
- For an Earth-like planet, in the habitable zone of a G star, the velocity shift will occur over a full year. Extremely low rate of change in a small velocity!

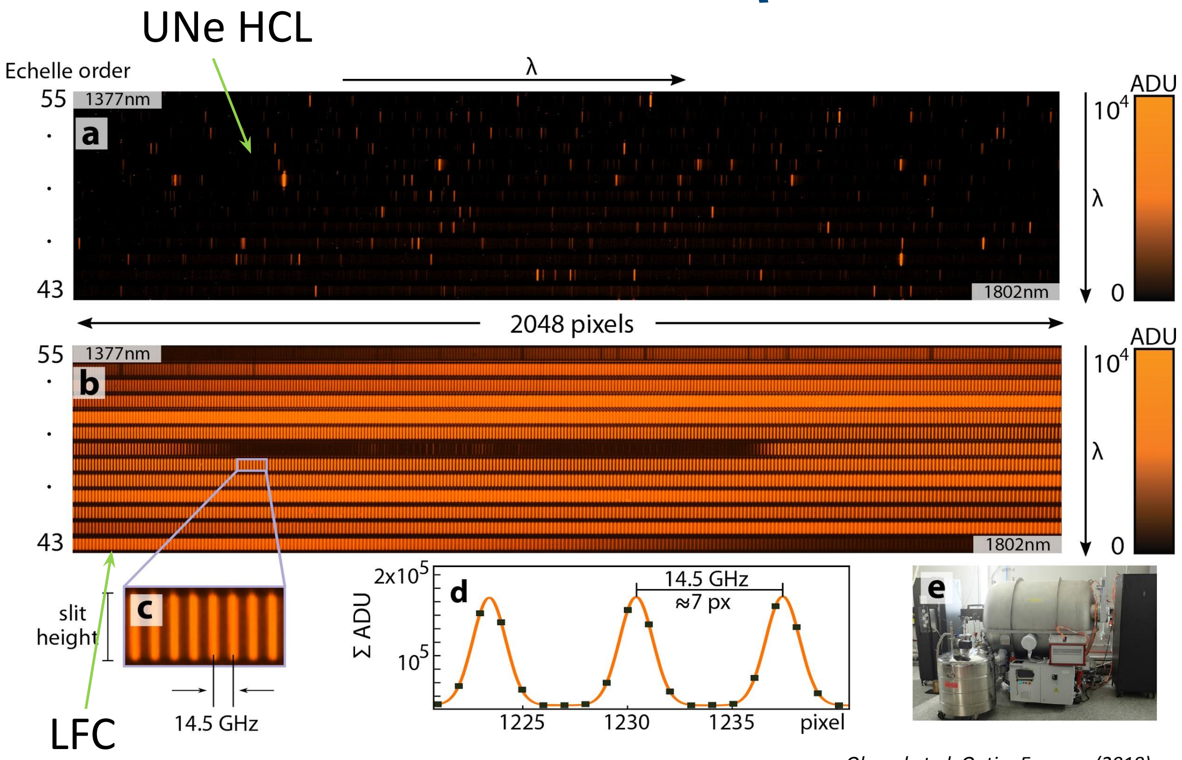


# SPECTRAL CALIBRATION

# LASER FREQUENCY COMBS

Key features:

- Create a periodic array of lines that span a broad bandwidth
- Absolute frequency and interline spacing can be ultra-stable with locking to various reference clocks – GNSS (relative uncertainty $10^{-12}$ or $10^{-13}$), f-2f (relative uncertainty $10^{-18+}$), etc
- Enables very precise wavelength measurements over decades!!




*Obrzud et al. Optics Express. (2018)*

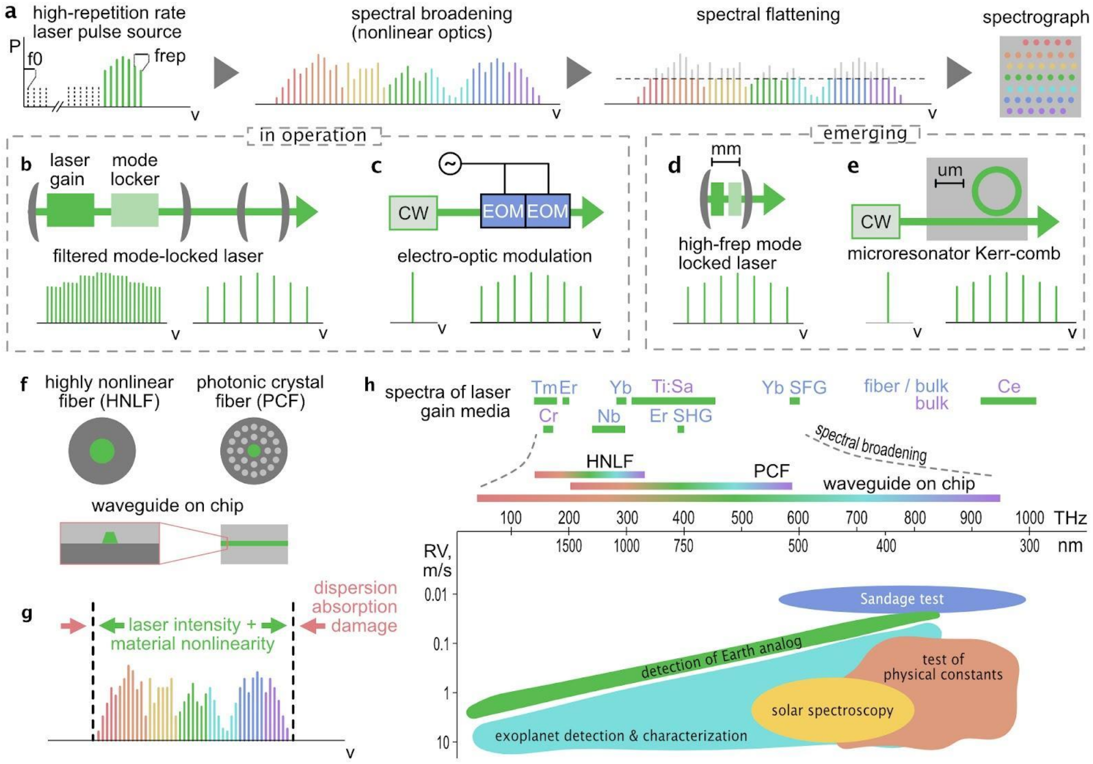
# LASER FREQUENCY COMBS

Common combs:

- Mode-locked laser combs – *Li et al. Nat. (2008)*
- *Electro-optic frequency comb - Yi et al. Nat Comms. (2016), Kashiwagi et al, Opt. Exp. (2016), Obrzud et al. Opt. Exp. (2018).*
- Soliton micro-combs – *Suh et al. Nat Phot. (2019)*

*Electro-optic combs has 10 ish GHz line spacing's – used by PARVI, HZPF, IRD and HISPEC/MODHIS*

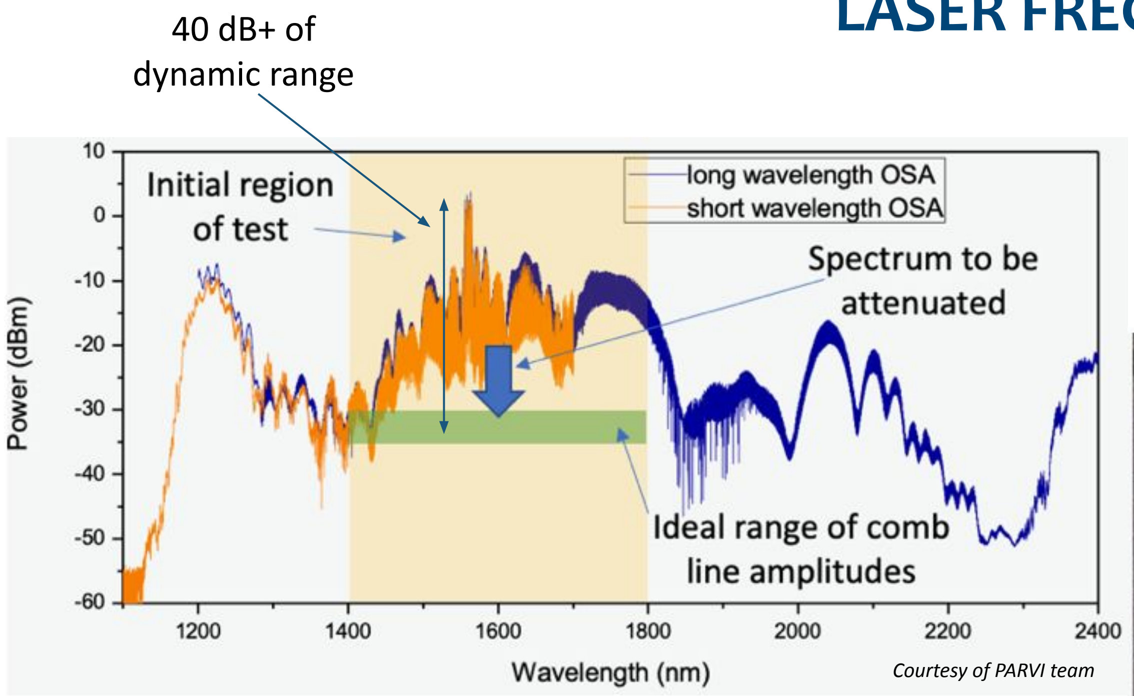
*Many applications of combs in non-exoplanet fields for precision timing*



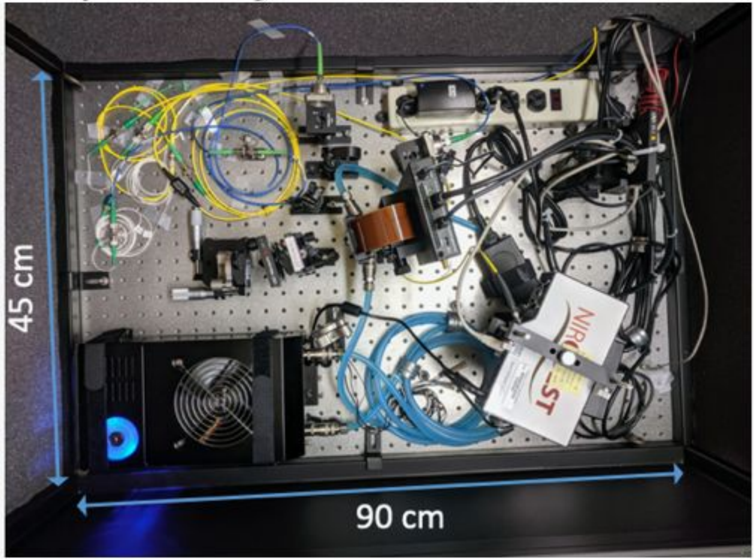

*Jovanovic et al. JPhys. Phot. (2023)*

# SPECTRAL FLATTENING

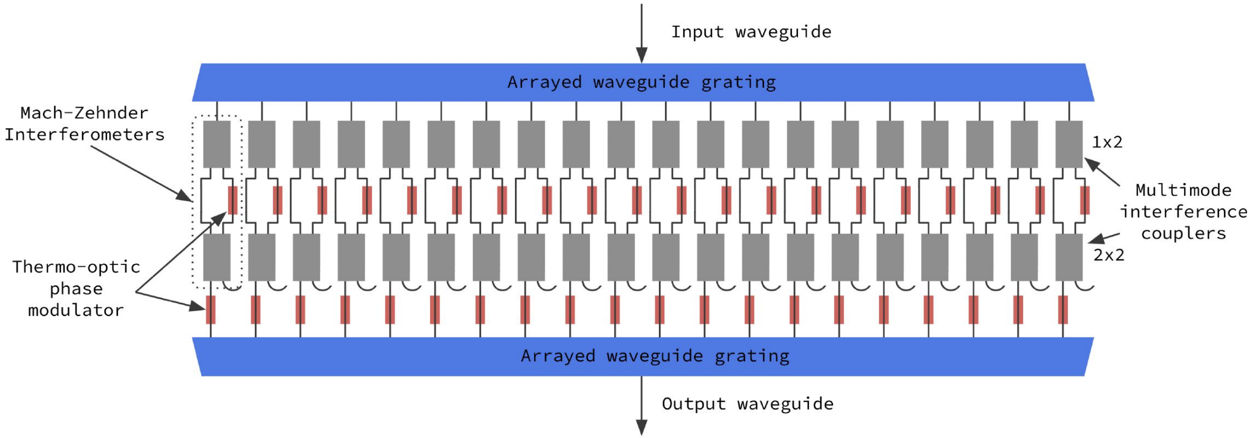
# LASER FREQUENCY COMB SPECTRUM



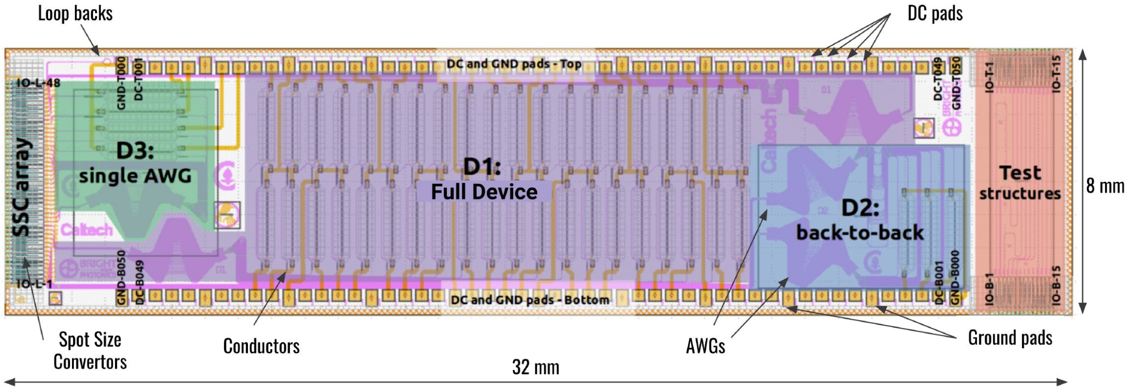

*Courtesy of PARVI team*



# ALL PHOTONIC SPECTRAL SHAPING




*Jovanovic et al Opt. Exp. (2022)*



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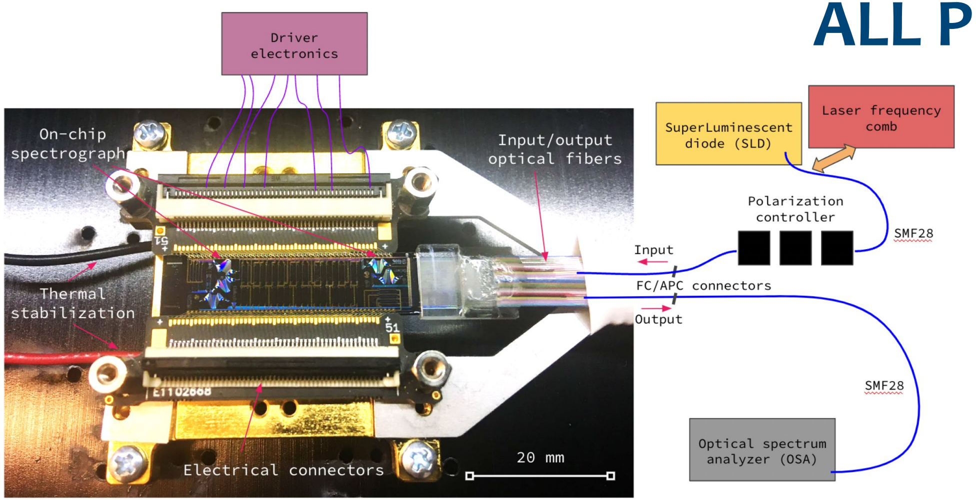
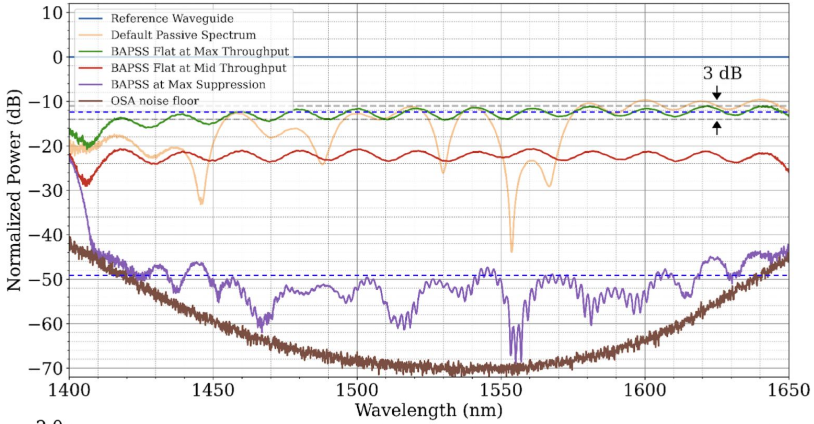
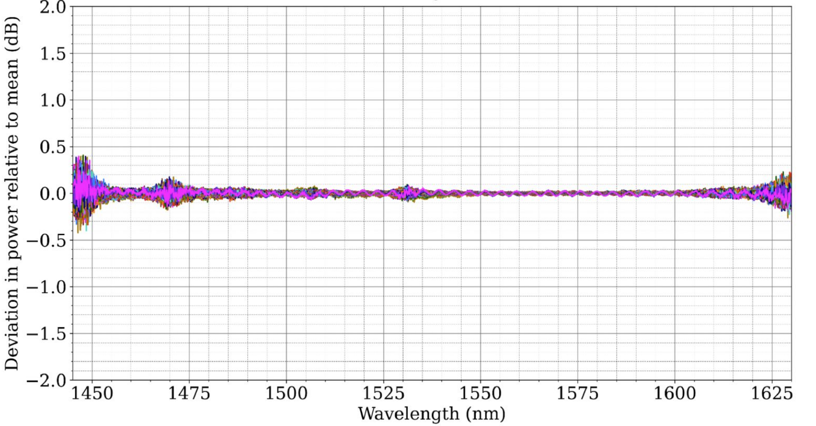


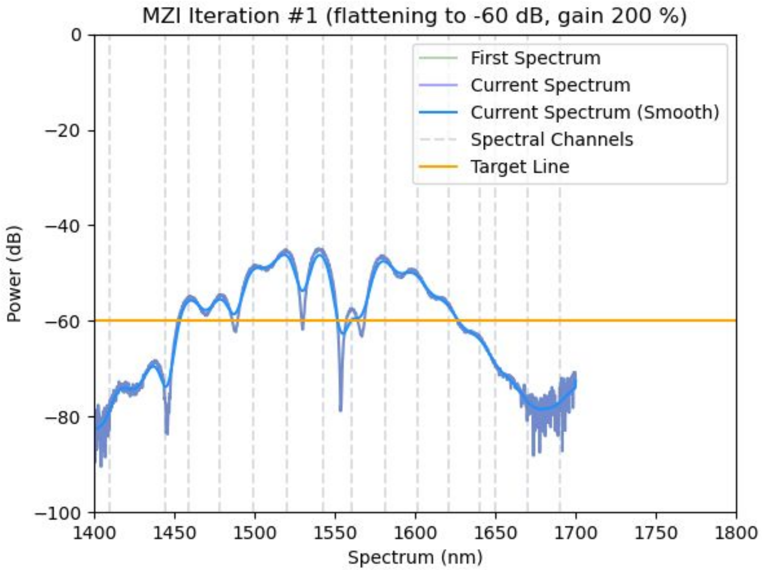



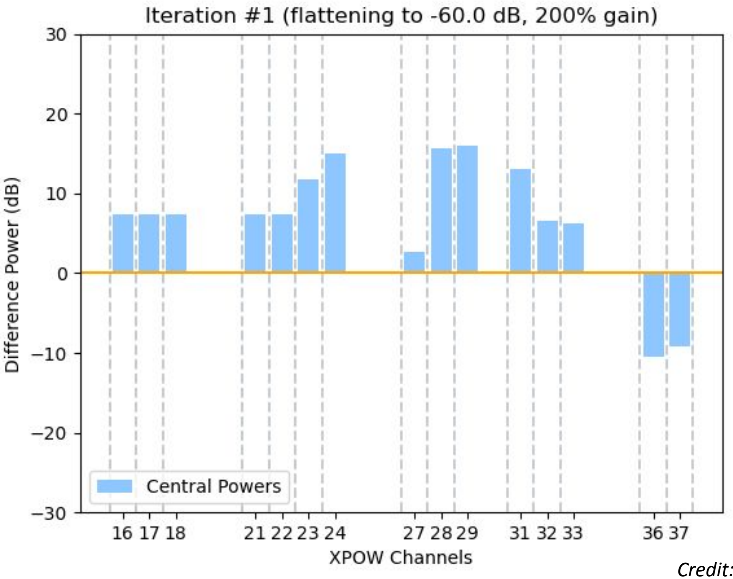




- Extremely compact, and fully packaged device
- Offers 38 dB of dynamic range across 250 nm
- Lowest loss is around 11 dB + coupling.
- Operates on a single polarization
- < 0.1 dB RMS stability over 24 hrs.

*Jovanovic et al Opt. Exp. (2022)*

# CLOSED LOOP FLATTENING AND CONTROL

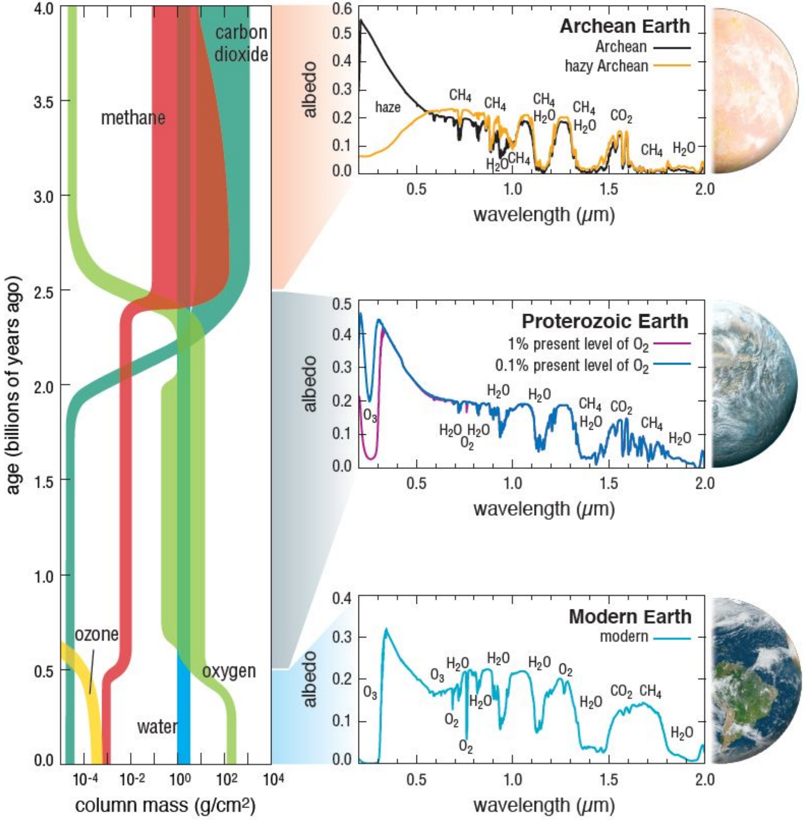


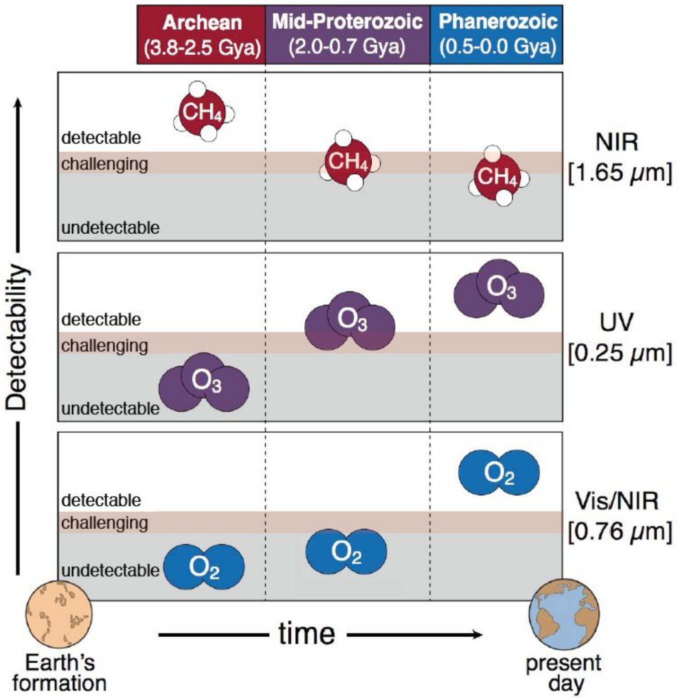




*Credit: Svarun Soda*

# HOW TO CHARACTERIZE AN EARTH-LIKE PLANET & DETECT BIO-SIGNATURES

# HOW TO CHARACTERIZE A TERRESTRIAL PLANET




*Credit: LUVOIR Final report, NASA*

Take a spectrum of the planet itself

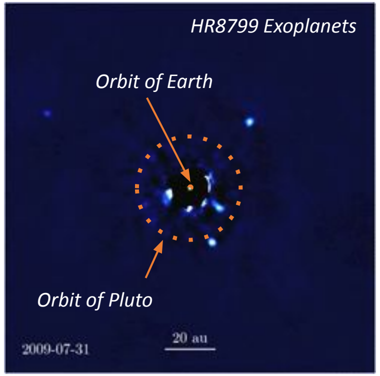
# STARLIGHT SUPPRESSION

# HIGH CONTRAST IMAGING OF EXOPLANETS

High Contrast Imaging or direct imaging of exoplanets

- Extreme contrasts are needed –
  - Earth to our sun contrast is $1:10^{10}$!!!!
  - larger planets can be as low as $1:10^{4}$
- Extremely close to the star – The habitable zone of stars like our sun is very close to the star

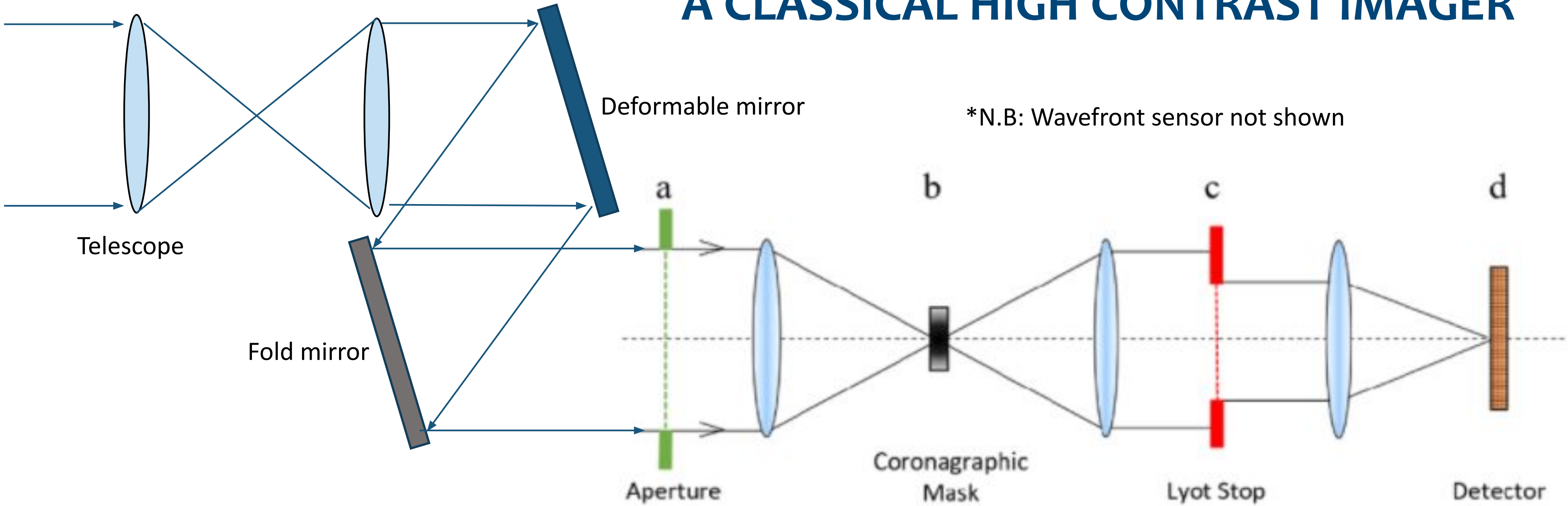
**Analogy:** Like searching for a firefly next to a lighthouse in Boston, from San Francisco.




By Jason Wang

Credit: American Institute for Economic Research

# A CLASSICAL HIGH CONTRAST IMAGER

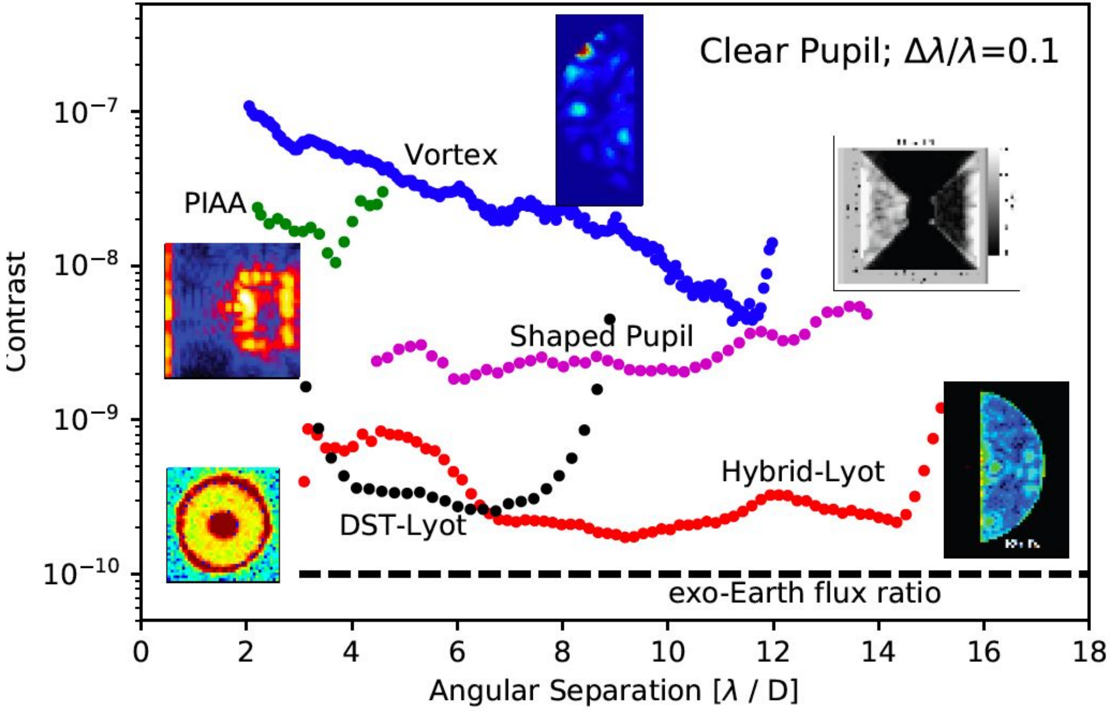



Key elements include:

A deformable mirror and wavefront sensor, a coronagraph, a science instrument

# WE ARE GETTING THERE

- Results achieved in vacuum testbeds at JPL.
- 10% spectral bandwidth
- Some coronagraphs needs to run on a single polarization – polarization dependent aberrations become an issue




*A huge amount of work done by the teams at the Jet Propulsion Laboratories*

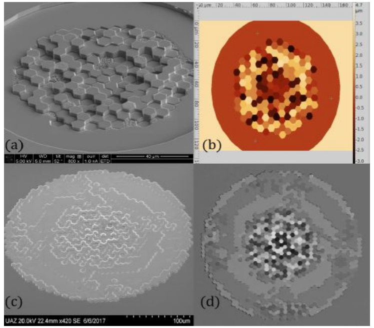
# ADVANCED CORONOGRAPH MASKS

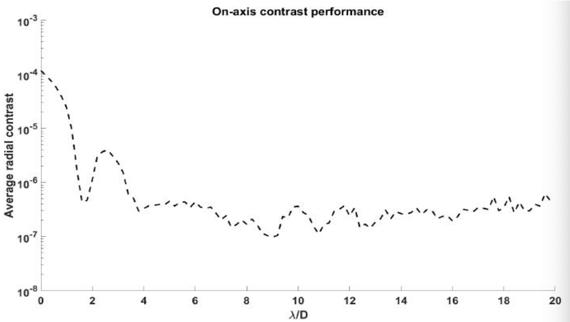
Advanced coronography:

- All about controlling diffracted light and pushing inwards towards the star
- Phase masks are commonly used these days
- Polychromatic solutions are highly desirable

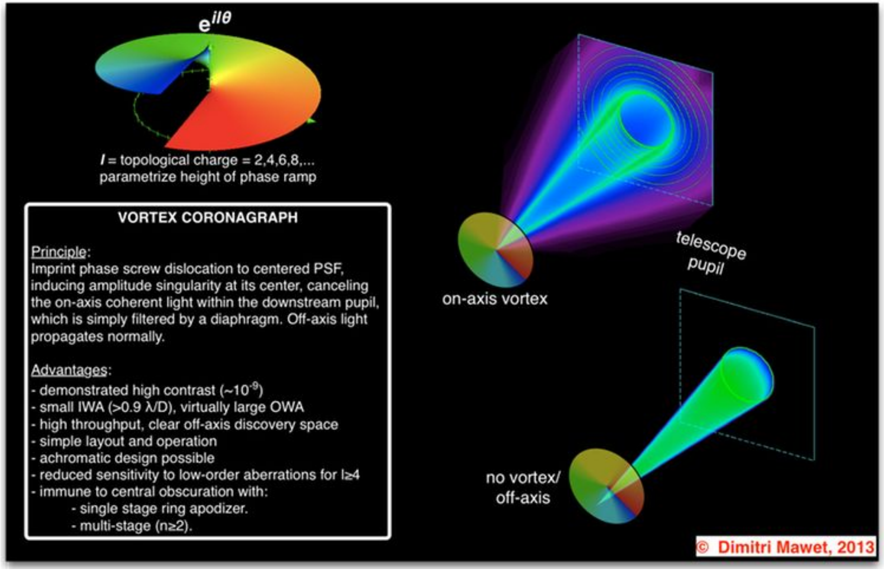
See for example….

- Niyati Desai's poster - 12680-85 – Wednesday evening
- Skyler Palatnick talk - 12680-26 1:40pm today
- Lorenzo König talk - 12680-27 – 2:00 pm today




Knight et al. SPIE (2018)




***A huge amount of work done in this area by: the Jet Propulsion Laboratories, Princeton, University of Arizona, NASA Ames, Leiden University, Liege, Observatoire de Paris, Caltech and so on***

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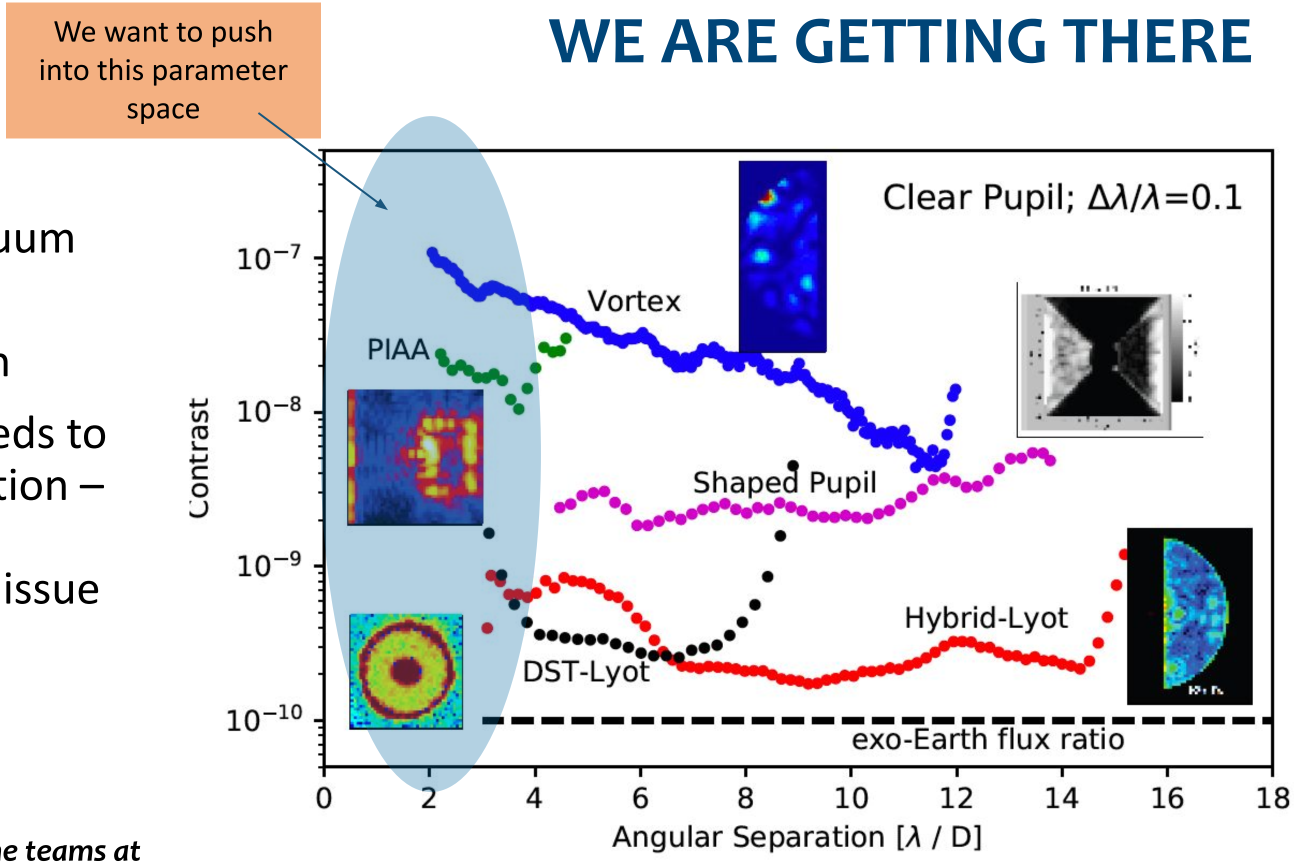


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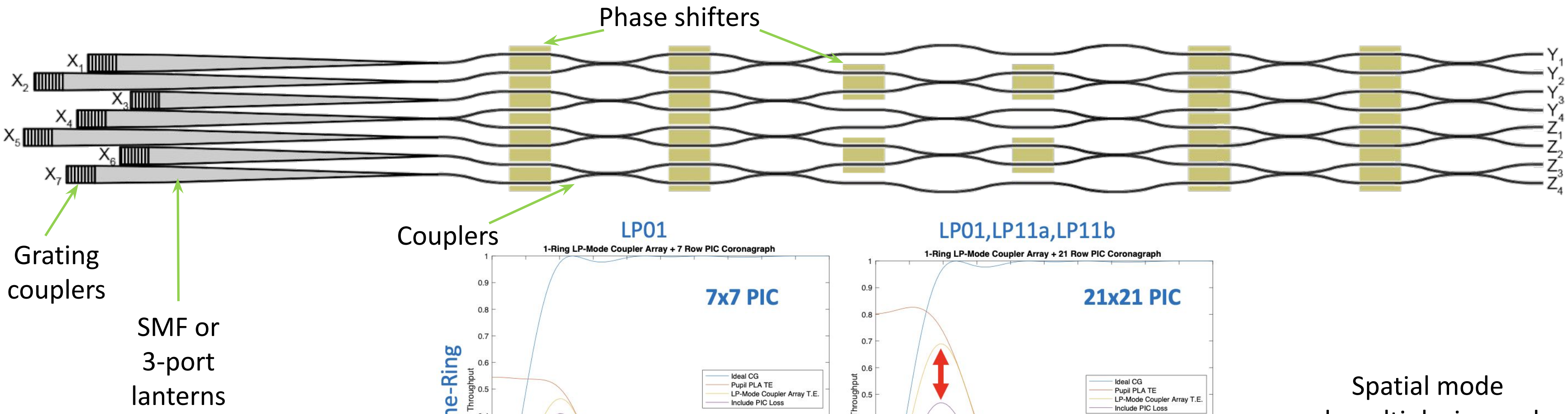
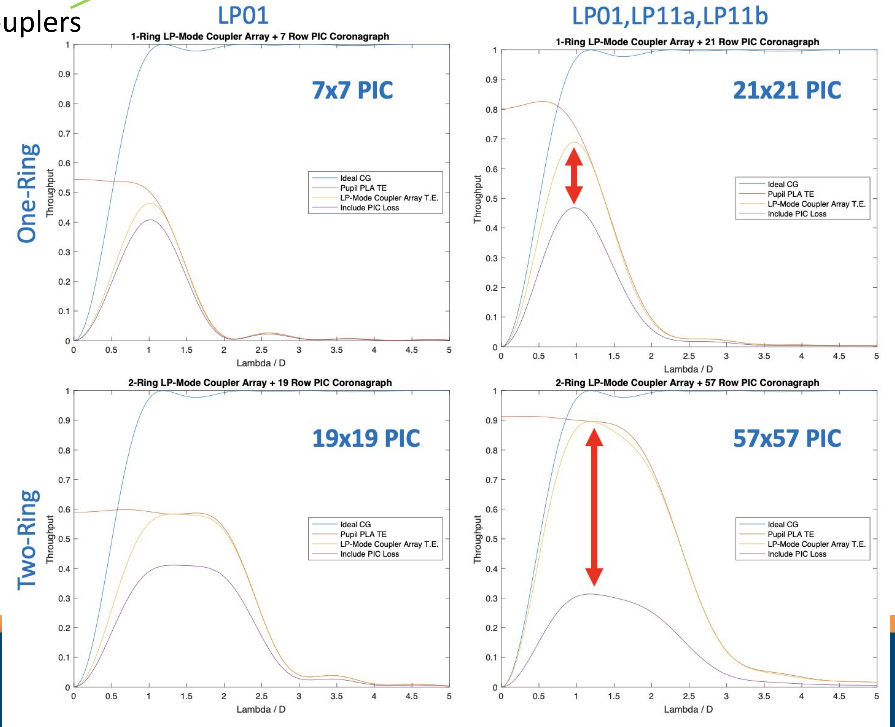
# THE PHOTONIC CORONAGRAPH v1

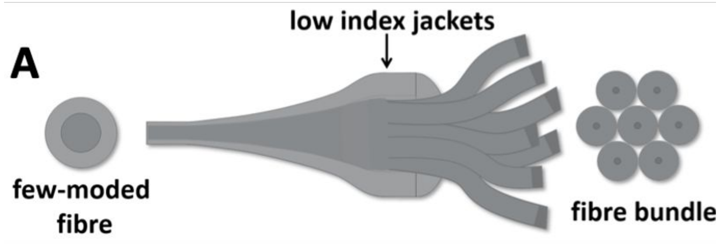


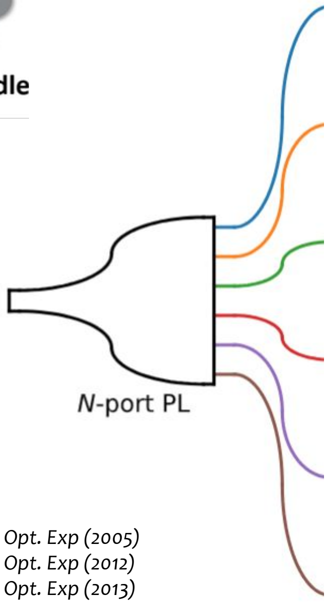

Spatial mode demultiplexing and cancellation.

*Credit: Jeffrey Jewell (JPL)*

# THE PHOTONIC CORONAGRAPH v2




- Mode converting devices – few/multimode to single mode
- One input – multiple outputs
- Can be extremely efficient – 1x19 devices with >97% efficiency at 1550 nm
- Can be used with a seeing-limited beam or a behind an AO system



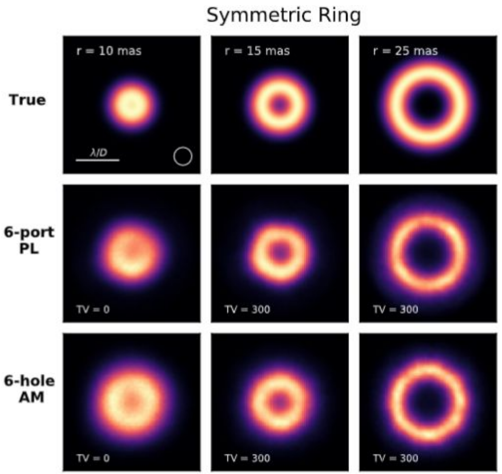


*Leon-Saval et al. Opt. Exp (2005)*
*Leon-Saval et al. Opt. Exp (2012)*
*Leon-Saval et al. Opt. Exp (2013)*
*Leon-Saval et al. Opt. Exp (2017)*
*Birks et al. Opt. Exp. (2012)*
*Birks et al. Adv. Opt. Phot. (2015)*
*Noordegraaf et al. Opt. Exp. (2009)*
*Noordegraaf et al. Opt. Exp. (2010)*
*Noordegraaf et al. Opt. Exp. (2012)*


*Kim et al submitted. (2023)*

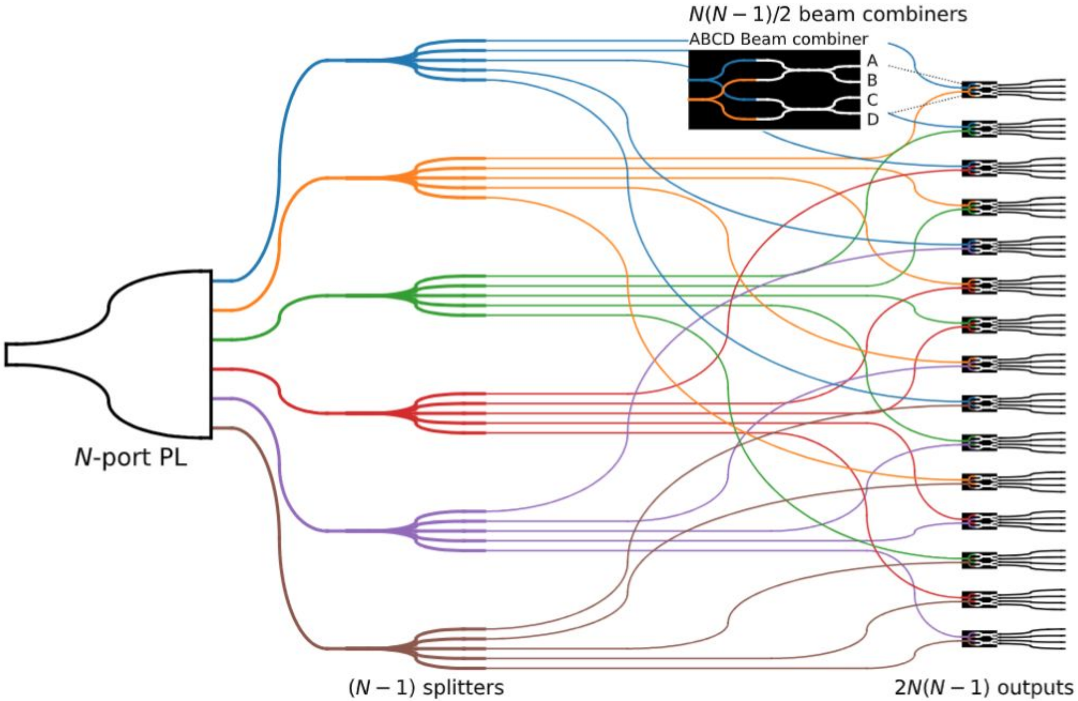
# THE PHOTONIC CORONAGRAPH v2

- Proposed in the context of image reconstruction.



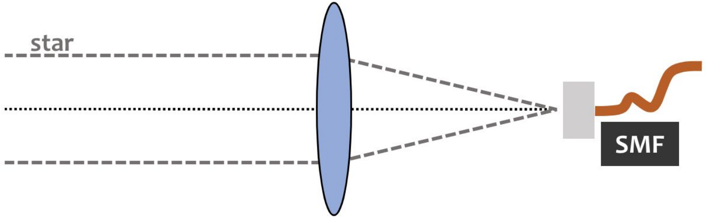

*See Yoo-Jung Kim's talk (12680-21) at 10:30 am and Danial Levinstein's talk (12680-20) after the break*

- Small modifications of the circuit could allow it to cancel out the light.




*Kim et al submitted. (2023)*

# VORTEX FIBER NULLING




Ruane et al. AJ (2018), Echeverri et al. Opt. Lett. (2019)

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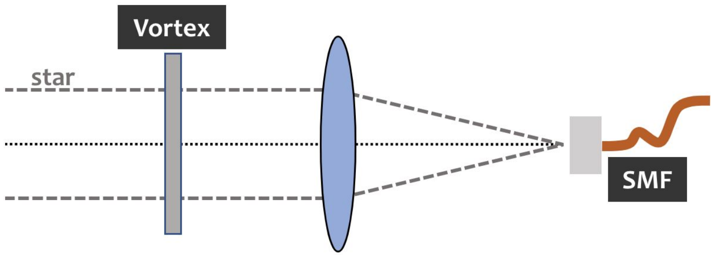
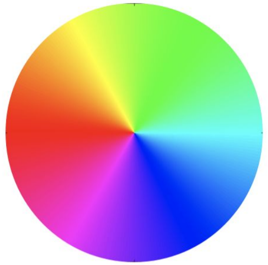



(on axis) **Star doesn't couple** into fiber

Vortex = $e^{il\theta}$

$l$ = charge*
(*must be an integer)



*Ruane et al. AJ (2018), Echeverri et al. Opt. Lett. (2019)*

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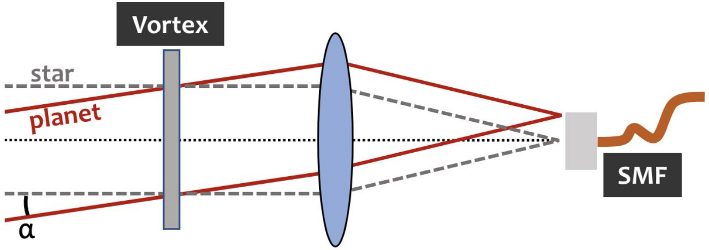


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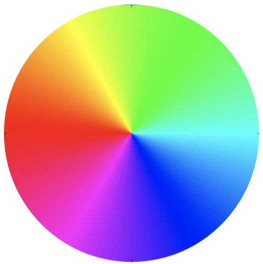
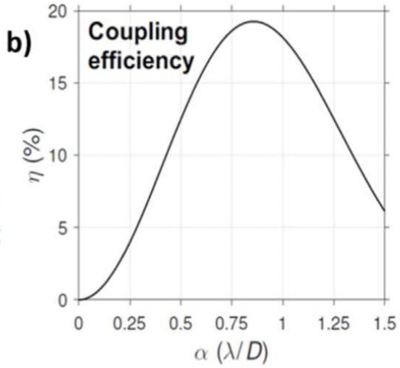


(on axis) **Star doesn't couple** into fiber

(off axis) **Planet partially couples** into fiber

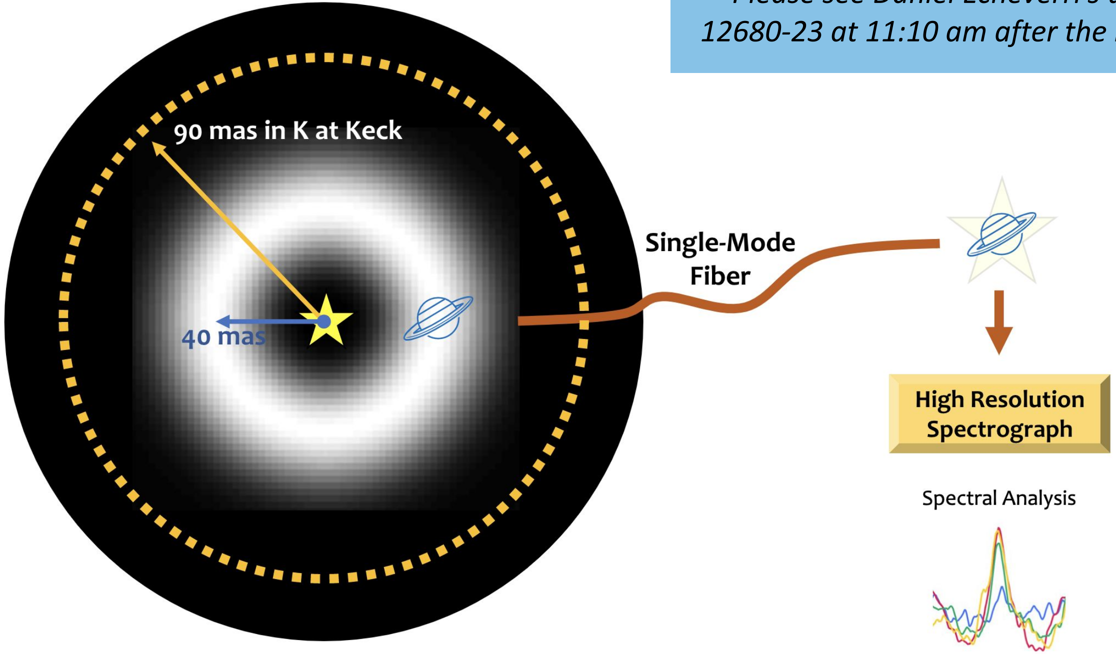
- Charge 1 → 20% coupling at $0.9\lambda/D$
- Charge 2 → 10% coupling at $1.4\lambda/D$



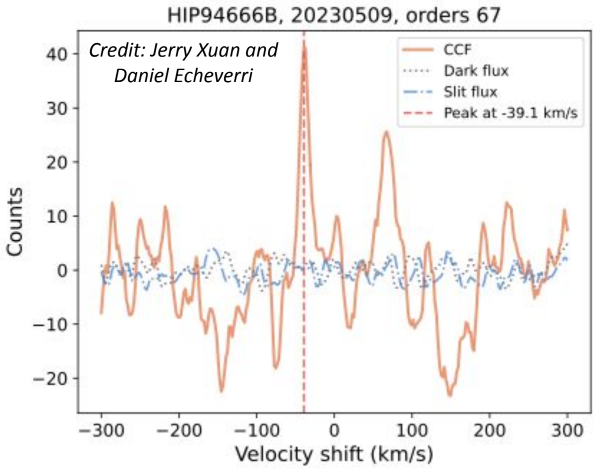

*Ruane et al. AJ (2018), Echeverri et al. Opt. Lett. (2019)*

# VORTEX FIBER NULLING

*Please see Daniel Echeverri's talk 12680-23 at 11:10 am after the break*




***On-sky detections***

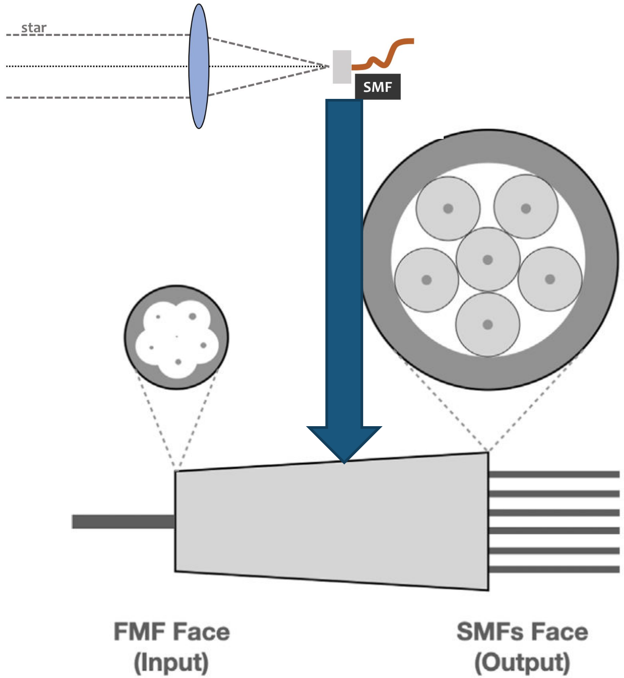



100:1 K band flux contrast

Separation of 37 mas (<1 lambda/D)

***More recently a companion detected at 300-500:1 at 1.4 lambda/D***

# PHOTONIC LANTERN ENHANCEMENT



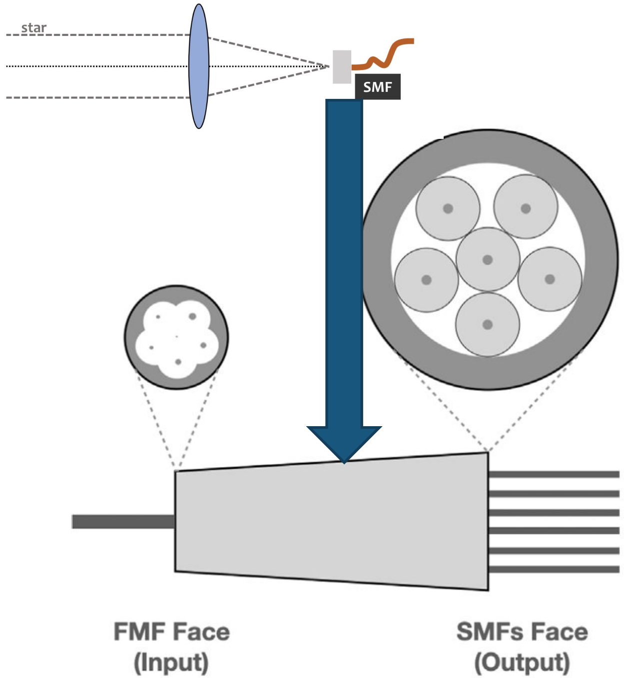

Replace SMF with a mode selective photonic lantern

*Xin et al. ApJ (2022)*

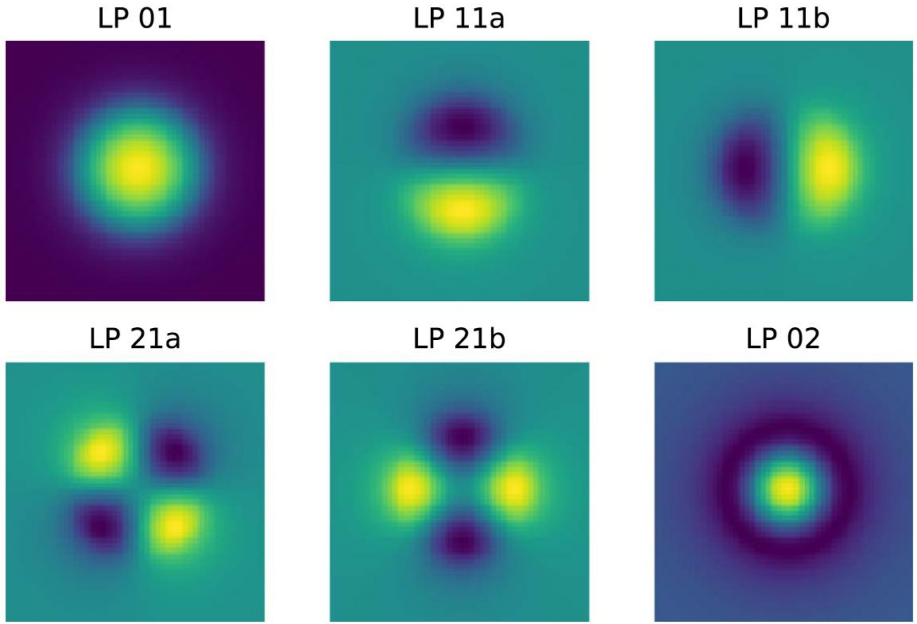
- Mode converting devices – few/multimode to single mode
- One input – multiple outputs
- Can be extremely efficient – 1x19 devices with >97% efficiency at 1550 nm
- Can be used with a seeing-limited beam or a behind an AO system


*Leon-Saval et al. Opt. Exp (2005)*
*Leon-Saval et al. Opt. Exp (2012)*
*Leon-Saval et al. Opt. Exp (2013)*
*Leon-Saval et al. Opt. Exp (2017)*
*Birks et al. Opt. Exp. (2012)*
*Birks et al. Adv. Opt. Phot. (2015)*
*Noordegraaf et al. Opt. Exp. (2009)*
*Noordegraaf et al. Opt. Exp. (2010)*
*Noordegraaf et al. Opt. Exp. (2012)*

# PHOTONIC LANTERN ENHANCEMENT



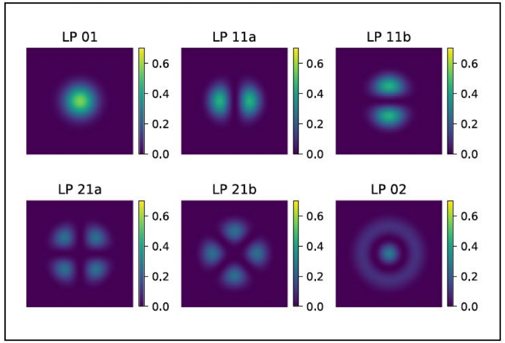

Xin et al. ApJ (2022)

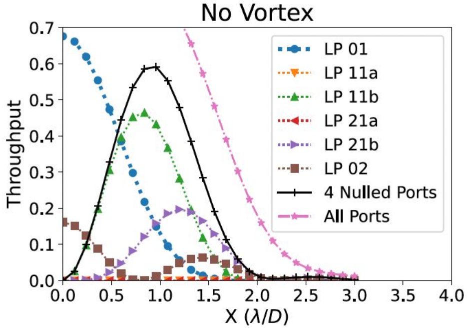



Replace SMF with a mode selective photonic lantern

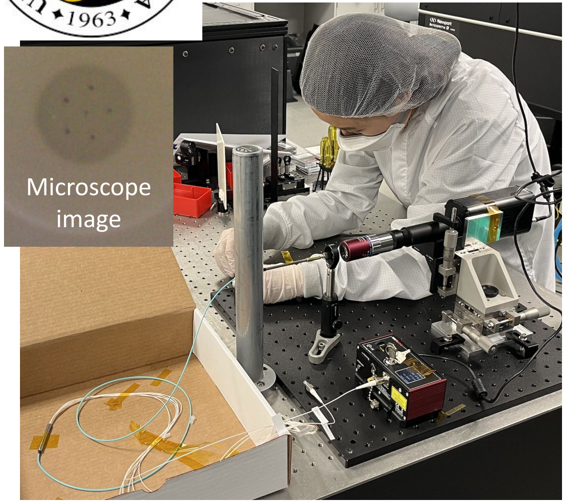
# PHOTONIC LANTERN NULLING

No Vortex *Xin et al. ApJ (2022)*

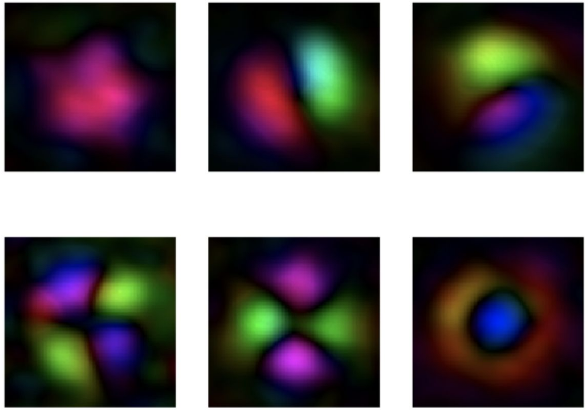



Total throughput in nulled ports has been greatly improved




Electric field profiles



*Courtesy of Yinzi Xin*

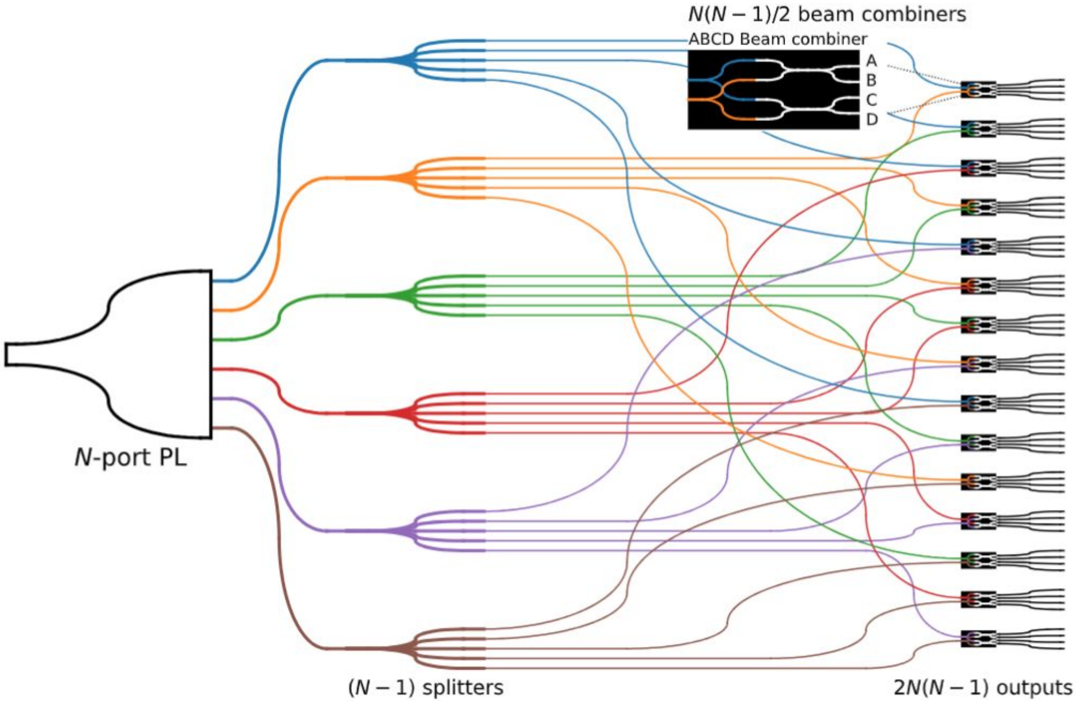
- Custom mode selective 6-port photonic lantern fabricated
- Optimized at 1550 nm
- Characterized in the lab and tested in the nulling testbed.

*See Yinzi Xin's talk (12680-19) at 9:20 am today*

# THE PHOTONIC CORONAGRAPH v2.2

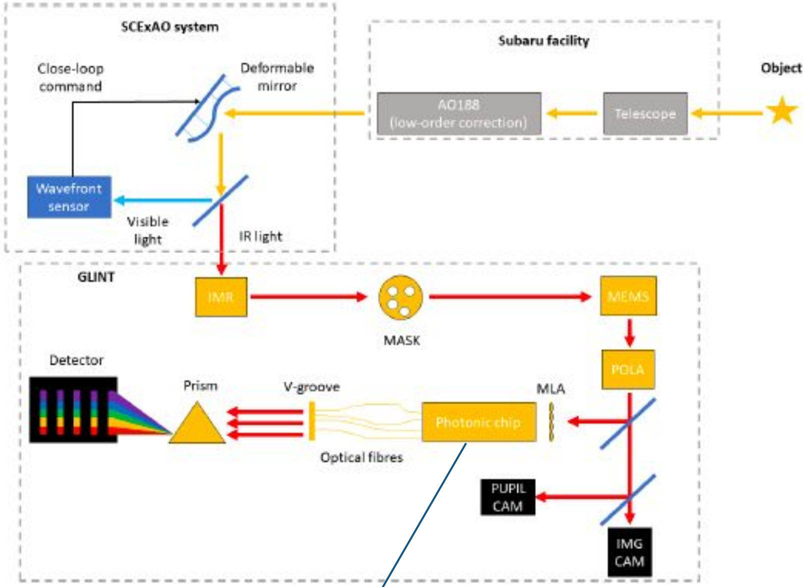
- Swap a standard lantern with the mode selective lantern.
- Two stages of nulling:
  - PLN
  - Beam combiner back end clean up

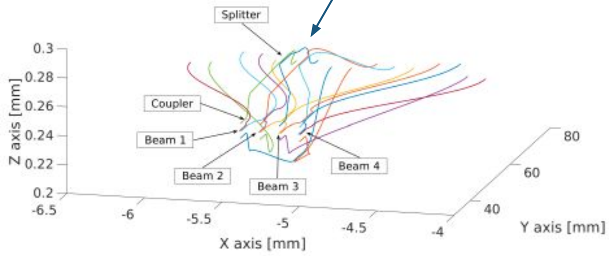
*See Yoo-Jung Kim's talk (12680-21) at 10:30 am*

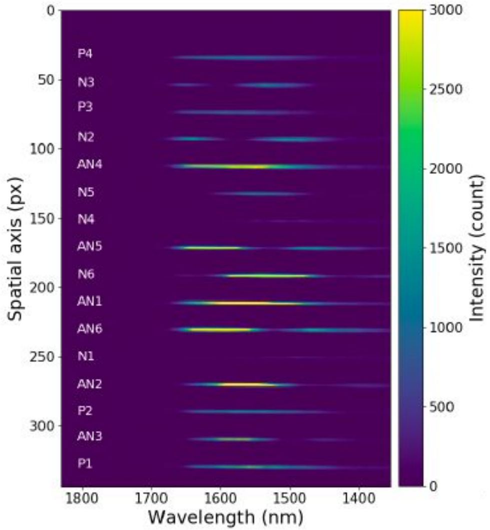


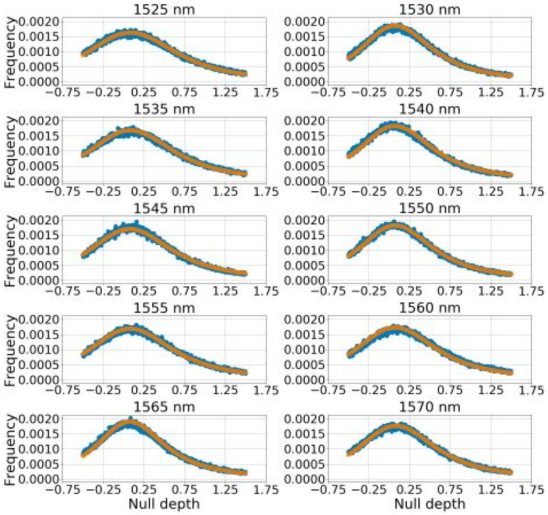

*Kim et al submitted. (2023)*

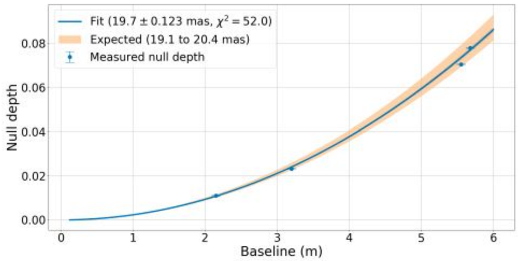
# PUPIL SEGMENTATION NULLING



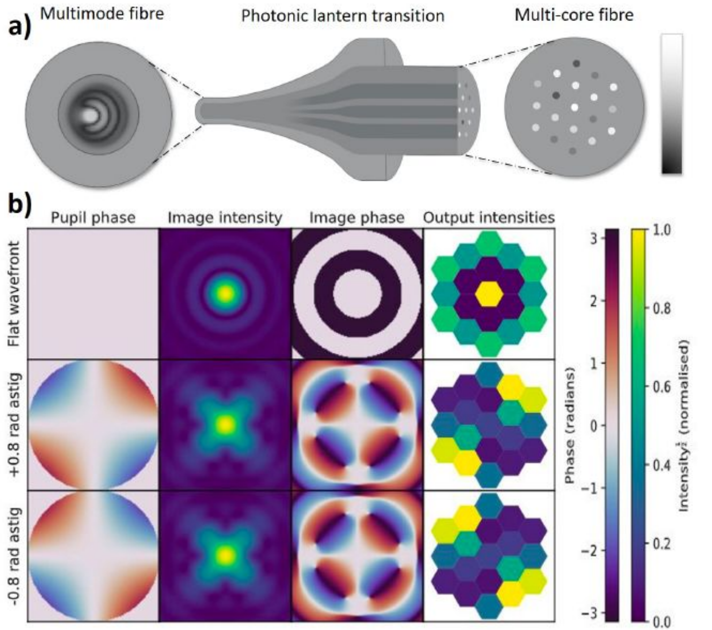



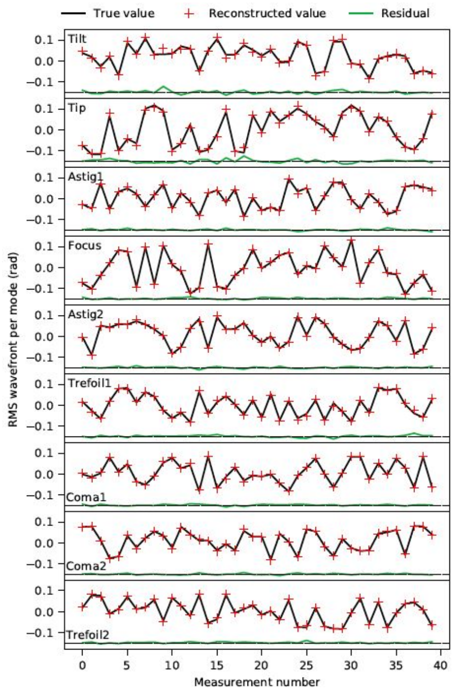

*Norris et al. MNRAS (2019)*
*Martinod et al. Nat. Comms. (2021)*

# PHOTONIC WAVEFRONT CONTROL

# PHOTONIC LANTERN WAVEFRONT SENSOR



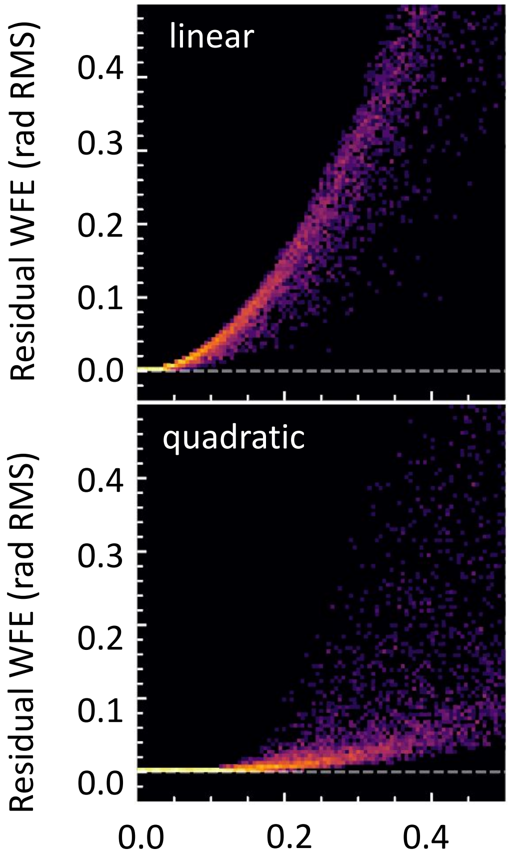

*Norris et al. Nat. Comms. (2020)*




Photonic lanterns are ideal for focal plane wavefront sensing – eliminate non-common path and chromatic errors.

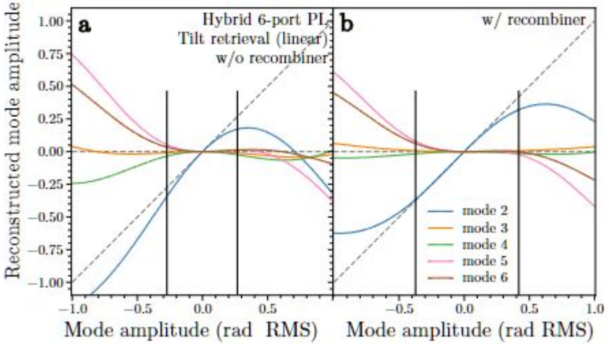
# PHOTONIC LANTERN WAVEFRONT SENSOR

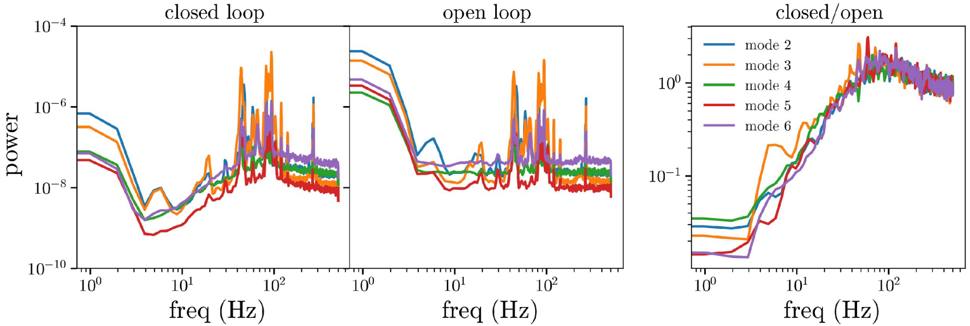
*From Lin+ 22*




**Numerical modelling**: testing 3-19 port PLs with linear/low-order nonlinear reconstruction

**Optimization**: investigating strategies to increase WFS performance, including using beam recombiners (*Lin+ submitted)*



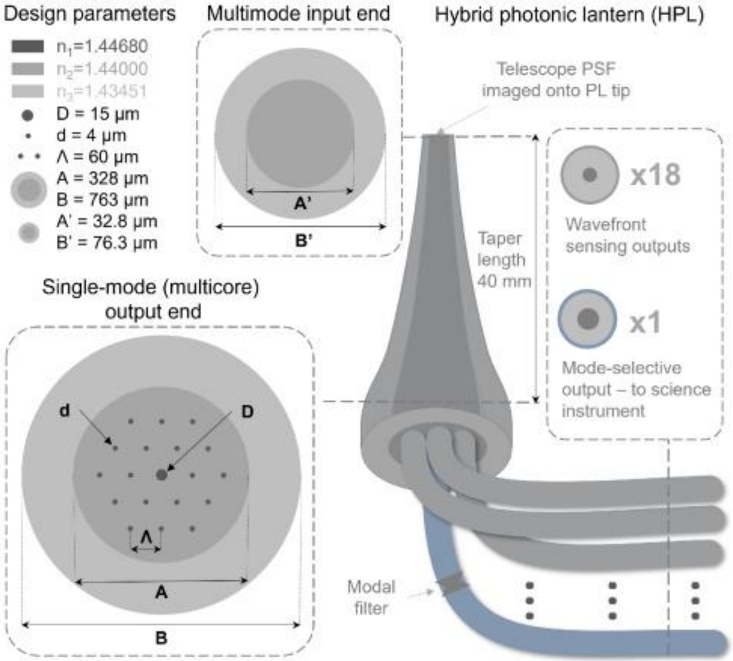




**Lab demo**: using SCExAO to test real-time correction w/ PLs

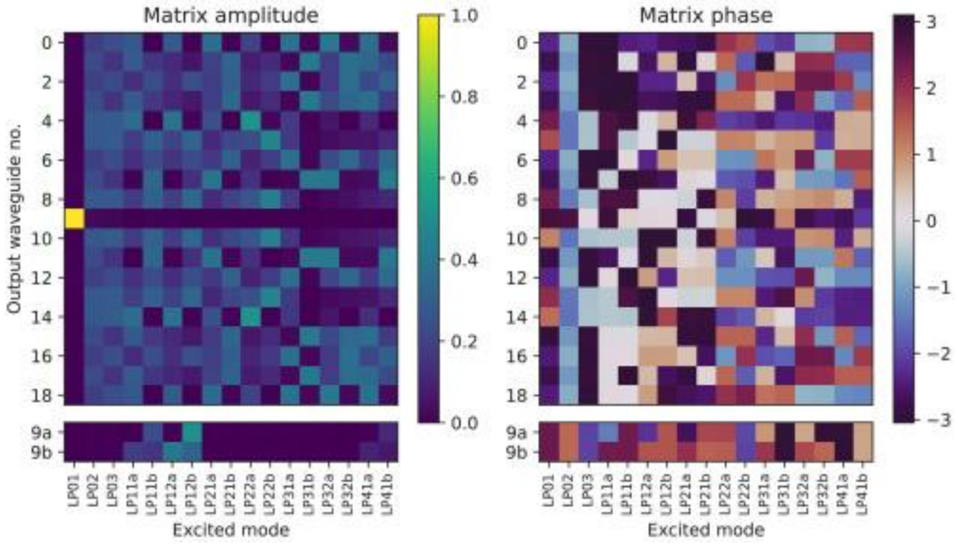


See Jon Lin's talk (12680-22) at 10:50 am today

# PHOTONIC LANTERN WAVEFRONT SENSOR




Norris et al. Opt. Exp. (2022)

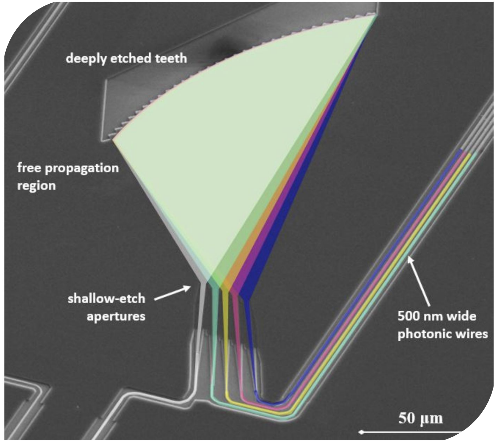



- Hybrid lanterns can extract light in certain spatial modes.
- Extracting LP01 is useful if you want to send that for spectroscopy of the target while higher order mode mixing is used for WFSing.
- Can we make lanterns with other modes extracted?

# PHOTONIC SPECTROSCOPY

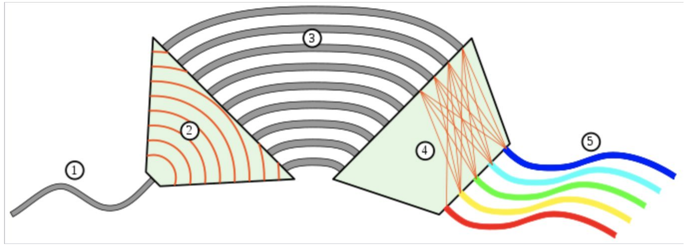
# PHOTONIC SPECTROGRAPH TECHNOLOGIES

## Planar Concave Gratings



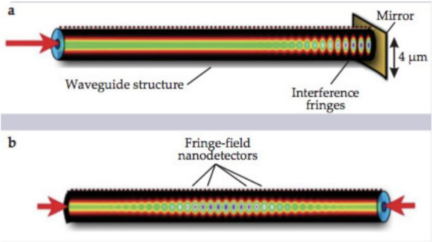

*E. Ryckeboer et al. SPIE (2016)*

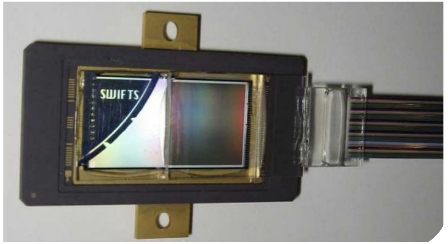
## Arrayed Waveguide Grating




*Courtesy: Wikipedia*

## Stationary Wave Integrated Fourier Transform Spectrometer

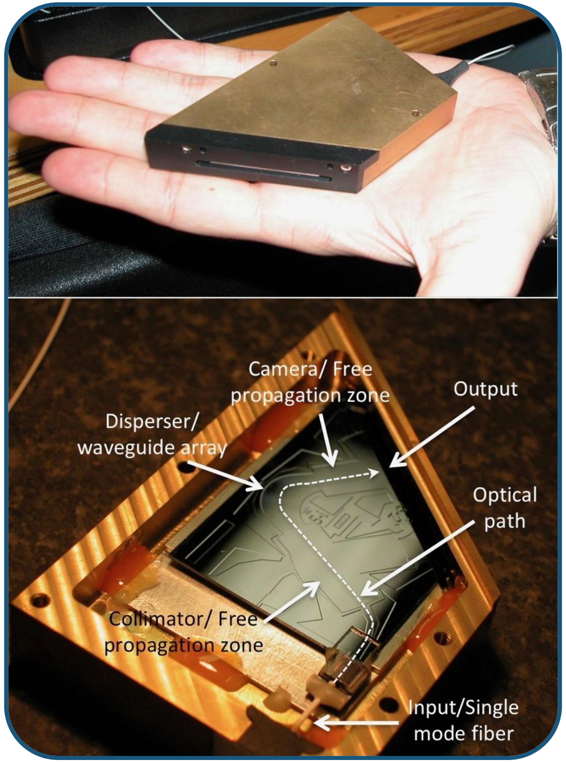



*E. Le Coarer et al. Nat. phot. (2007)*

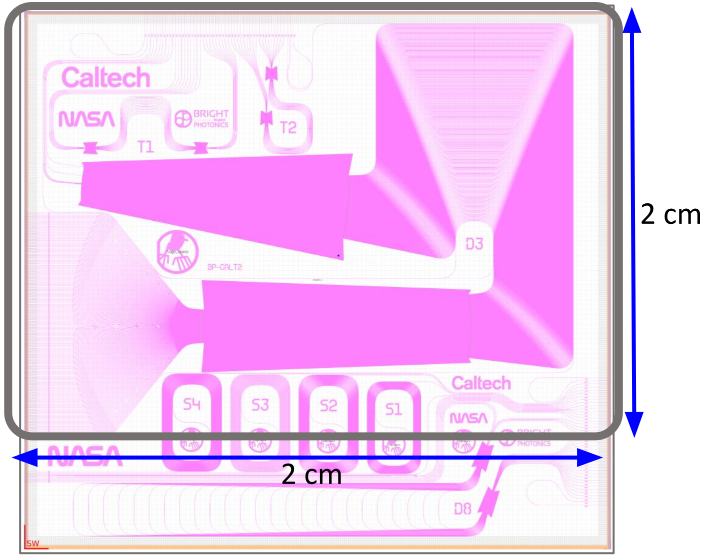
# PLAYING WITH OFF-THE-SHELF DEVICES

- AWG + SMF fiber feed
- Silica-on-silicon technology
- *R*=7000 native resolving power, $\Delta\lambda$ = 0.22 nm
- FSR = 52 nm, m=27, CWL = 1550 nm
- No polarization dependence



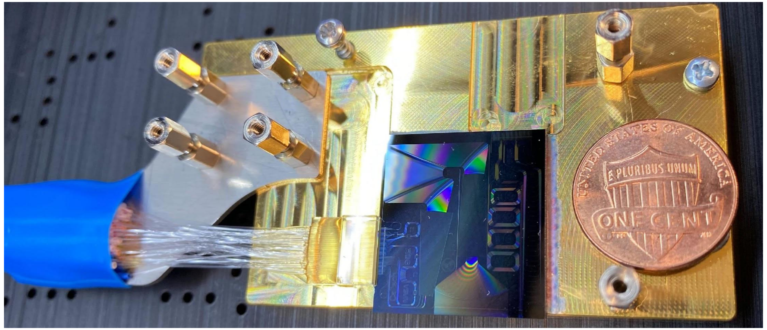

*Cvetojevic et al Opt. Exp. 2012*

# PUSHING TO HIGH RESOLVING POWER: R ~ 26,000

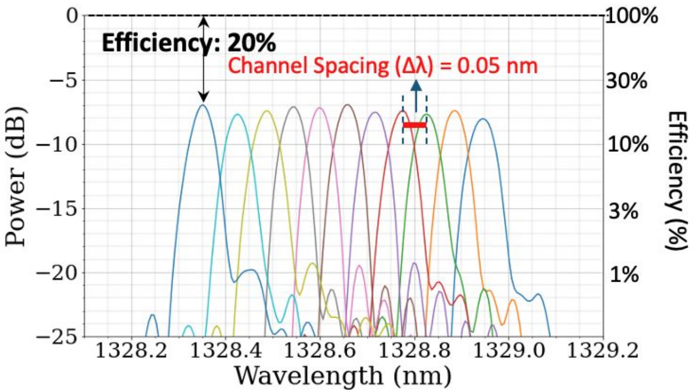



**SiN platform** (200 nm thickness)

**Resolving Power:** ~ 26,000
**Free Spectral Range:** ~ 15 nm
**Wideband:** 1200 – 1700 nm (J+H)

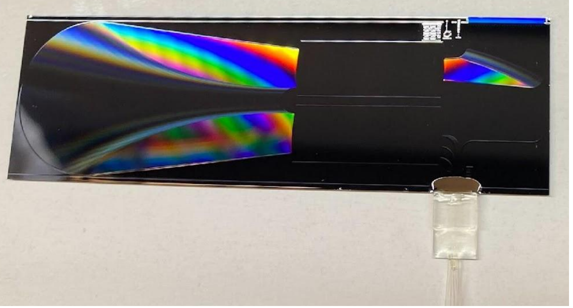


*Courtesy: Pradip Gatkine, Greg Sercel, Jeffrey Jewell, Kent Wallace*



# HIGH RESOLVING POWERR AND HIGH-THROUGHPUT

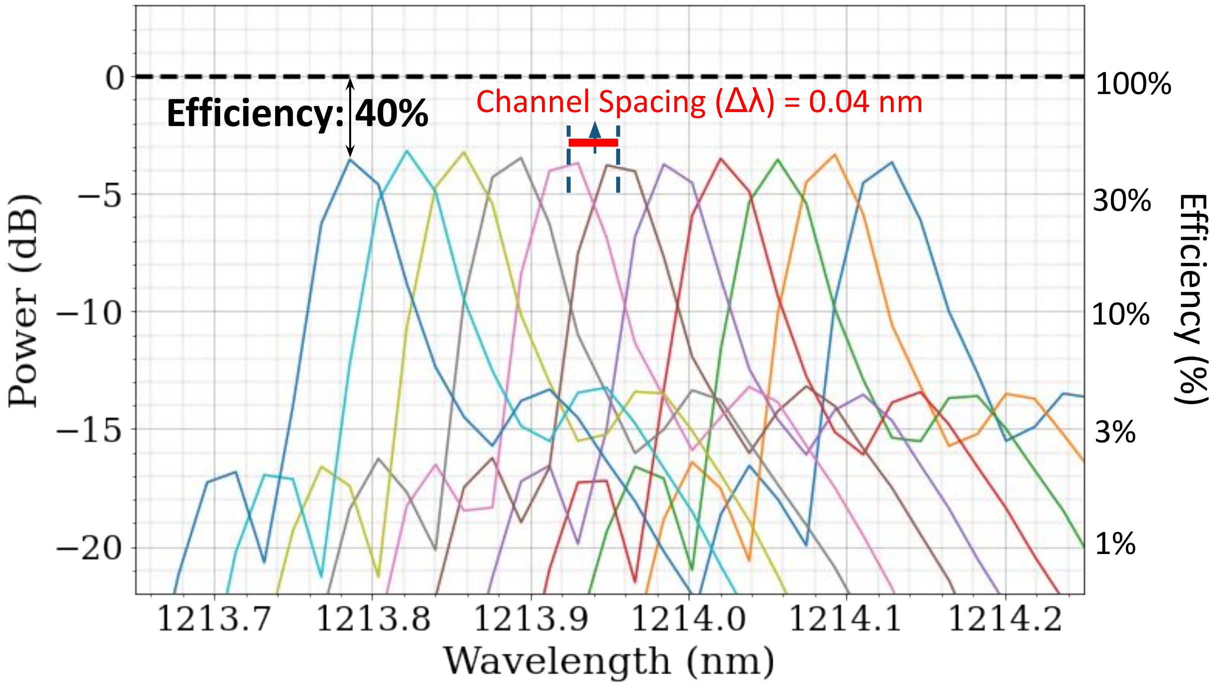
Doped SiO2 offers a higher
**fiber-to-chip coupling efficiency**



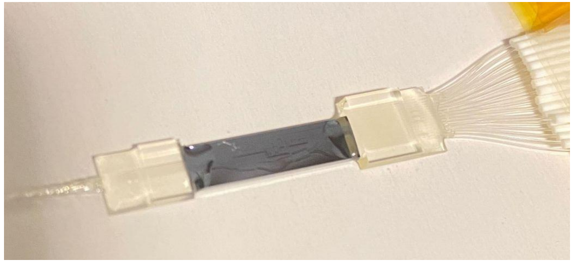
**Doped $SiO_2$ platform**

**Resolving Power: ~ 30,000**
**Free Spectral Range: ~ 13 nm**
**Wideband:** 1200 – 1700 nm (J+H)

*Courtesy: Pradip Gatkine, Greg Sercel*



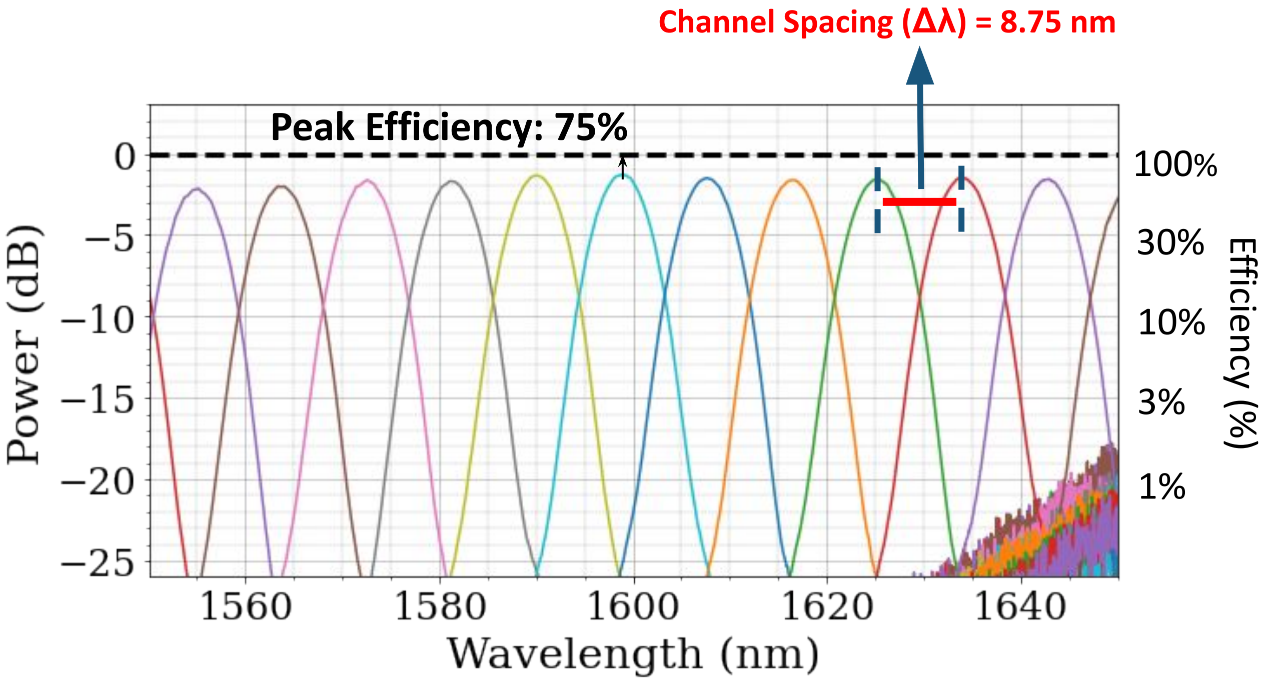
# BROADBAND, LOW-RESOLUTION: R ~ 180



Chip size: 20 mm x 5 mm

Doped $SiO_2$ platform

**Resolving Power:** ~ 180
**Free Spectral Range:** ~ 220 nm
**Wideband:** 1200 – 1700 nm (J+H)




*Courtesy: Pradip Gatkine, Greg Sercel*

# Funding acknowledgements

This work was supported by

- National Science Foundation under Grant No. 2109231 (via an ATI)
- Wilf Family Discovery Fund in Space and Planetary Science, funded by the Wilf Family Foundation.
- National Aeronautics and Space Administration (NASA) (via a CIF)
- Jet Propulsion Laboratory (JPL) (via a PDRDF and SRTD, TRTD)

National Science Foundation

Wilf Family FOUNDATIONS

NASA

JPL

Jet Propulsion Laboratory
California Institute of Technology


OBRIGADO
gracias
どうも
ARIGATO
hvala
DANK U
takk
MERSI
merci
謝謝
obrigado
danke schön
köszi
سپاس
PALDIES
muchas gracias
ありがとう
TEŞEKKÜR EDERIM
MOLTE GRAZIE
GO RAIBH MAITH AGAT
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grazas
GRAZZI
THANK YOU
благодаря
TAK
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qujan
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asante
muchas gracias
vielen dank
PALDIES
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OBRIGADO
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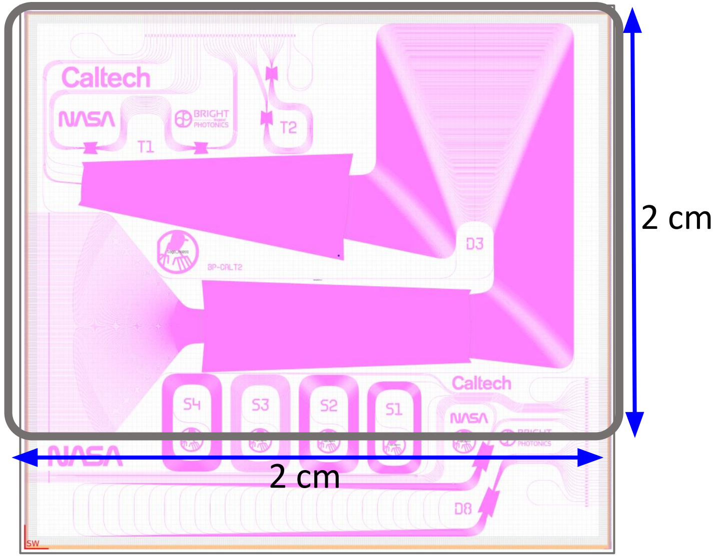
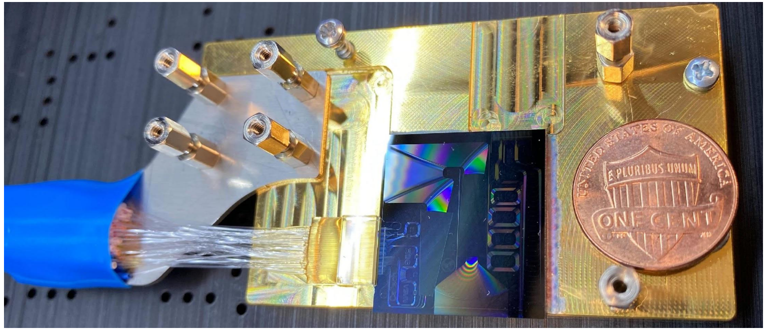
grazie
DZIĘKI
спасибо
MULTUMESC
danke
TACK
Gràcies
多謝
شكراً
감사합니다
köszi
TEŞEKKÜR EDERIM
NA GODE
muchas gracias
obrigado

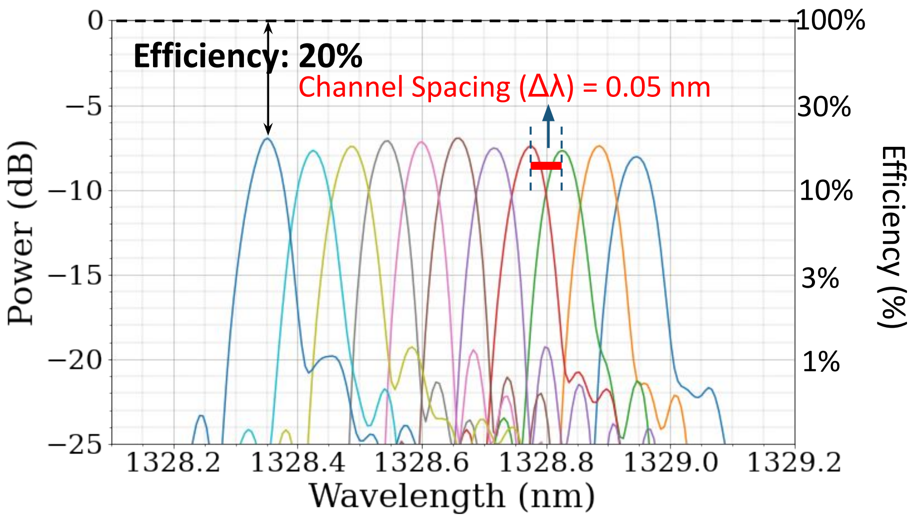
# PUSHING THE RESOLVING POWER TO R ~ 26,000




**SiN platform** (200 nm thickness)

**Resolving Power:** ~ 26,000
**Free Spectral Range:** ~ 15 nm
**Wideband:** 1200 – 1700 nm (J+H)

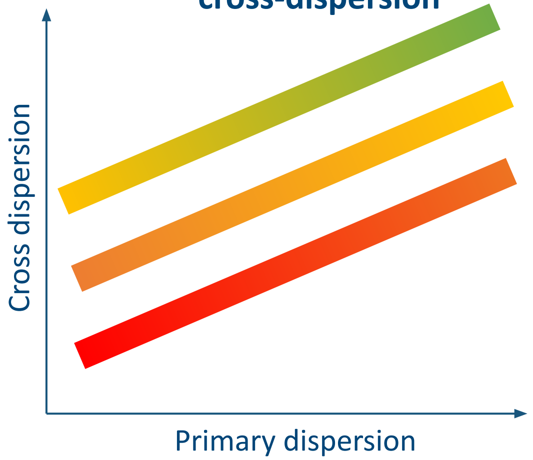


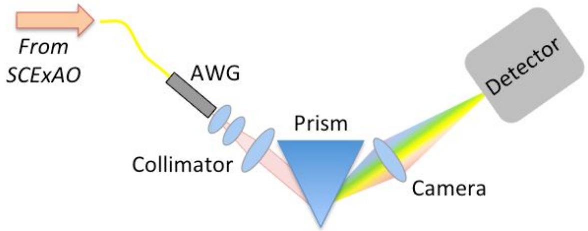


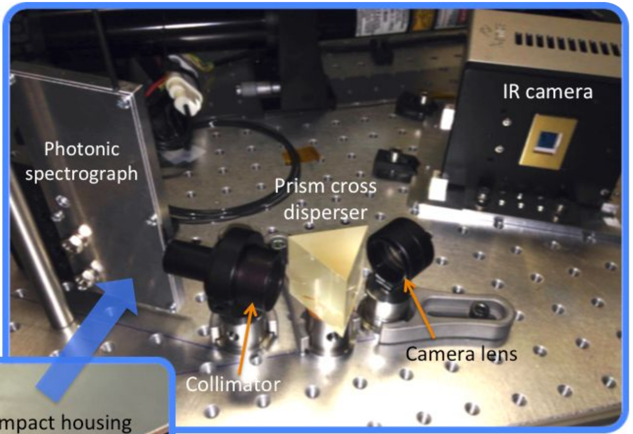
# BUILDING A PHOTONIC INSTRUMENT

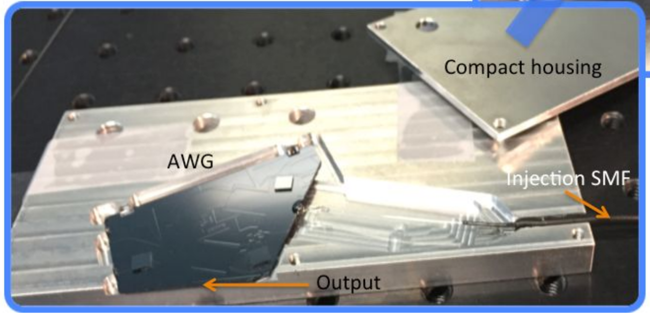
**Single order of AWG at output**

**Multiple orders separated via cross-dispersion**



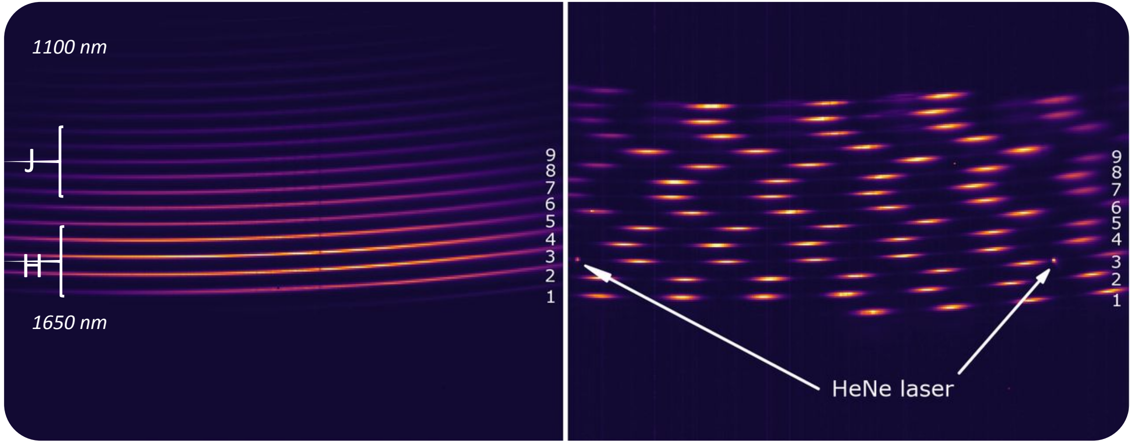




*Jovanovic et al. Opt. Exp. 25, 17753 (2017)*

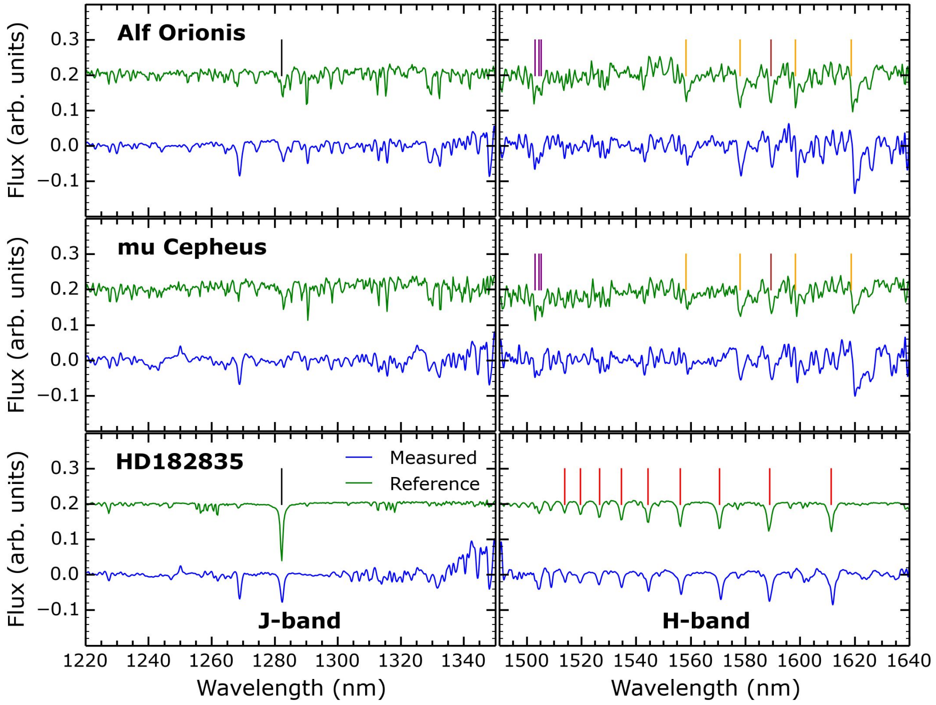
# PHOTONIC SPECTROGRAPH PERFORMANCE

| Element | Throughput (%) | Optimized throughput (%) |
|---|---|---|
| **Pre-injection** | | |
| Atmosphere | 97 | 97 |
| Telescope | 92 | 92 |
| ADC | 92 | 92 |
| AO188 | 79 | 79 |
| SCExAO | 68 | 72 |
| Apodization optics | 55 | 96 |
| **Throughput to injection** | **24** | **45** |
| **Post-injection** | | |
| Reflection at fiber tip | 96 | 0.995 |
| AWG | 77 ± 5 | 77 ± 5 |
| AWG bonding/splices | 79 | 95 |
| Collimating lens | 90 | 90 |
| Prism | 82 | >90 |
| Camera lens | 97 | 97 |
| **Spectrograph throughput** | **42** | **57** |
| Coupling | S.R.×0.74 + 1.84 | S.R.×0.74 + 1.84 |
| **Total throughput** | **5** | **13** |




*Jovanovic et al. Opt. Exp. 25, 17753 (2017)*

# ON-SKY SAMPLE SPECTRA




*Jovanovic et al. Opt. Exp. 25, 17753 (2017)*

*Reference spectra courtesy of IRTF catalog*