HOKKAIDO UNIVERSITY

24-25 Jan., 2013
NAOJ Conf.「将来装置による地球型系外惑星直接検出および撮像」

フォトニック結晶技術による焦点面マスクコロナグラフ装置の開発

Development of Focal-Plane Phase-Mask Coronagraphs Based on Photonic Crystal Technology

Naoshi Murakami
(Hokkaido Univ.)

Collaborators
Jun Nishikawa, Motohide Tamura (NAOJ)
Wesley Traub, Dwight Moody, Brian Kern, John Trauger, Eugene Serabyn (JPL)
Dimitri Mawet (ESO)
Olivier Guyon, Frantz Martinache (Subaru/NAOJ)
Shoki Hamaguchi, Fumika Oshiyama, Hayato Shoji,
Kazuhiko Oka, Naoshi Baba (Hokkaido Univ.)

国立天文台 NAOJ National Astronomical Observatory of Japan
JPL
ESO

Today's Talk

Development of Focal-Plane Phase-Mask Coronagraphs Based on Photonic Crystal Technology

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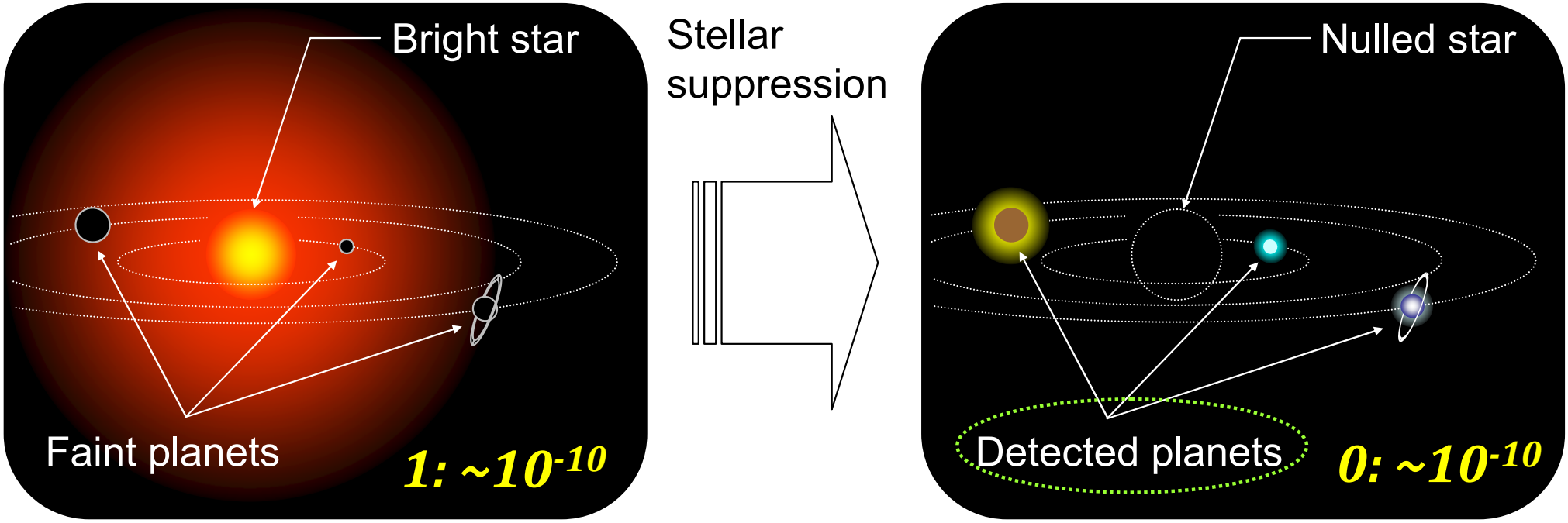
R& D for next-generation coronagraphs

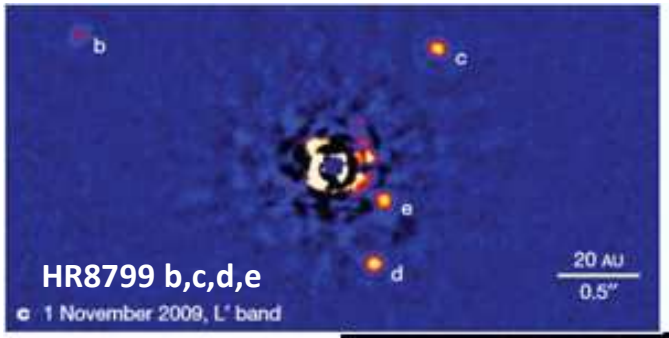
- ➔ ***Focal-plane phase-mask coronagraphs***
- ➔ ***Expecting for both ground-based and space observations***
- ➔ ***Direct detection of habitable Earth-like planets***

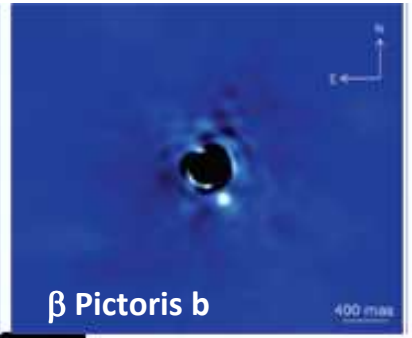
- ✓ ***Introduction***
- ✓ ***Mask Designs***
- ✓ ***Mask Manufacture***
- ✓ ***Lab. Tests @NAOJ and Hokkaido Univ.***
- ✓ ***Lab. Tests @HCIT/JPL***
- ✓ ***Polarimetric Coronagraph***
- ✓ ***Towards Ground-based Observations***

Introduction:

Direct Detection of Exoplanets

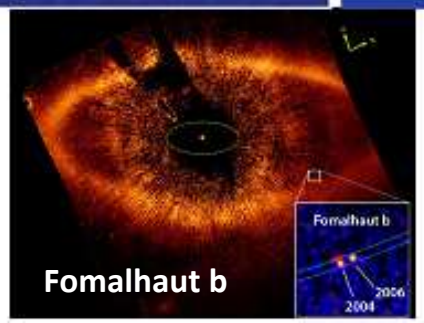


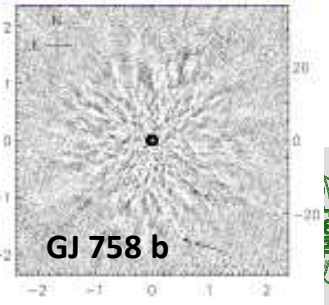




Analysis (Characterization)

Photometry
Spectroscopy
Polarimetry …



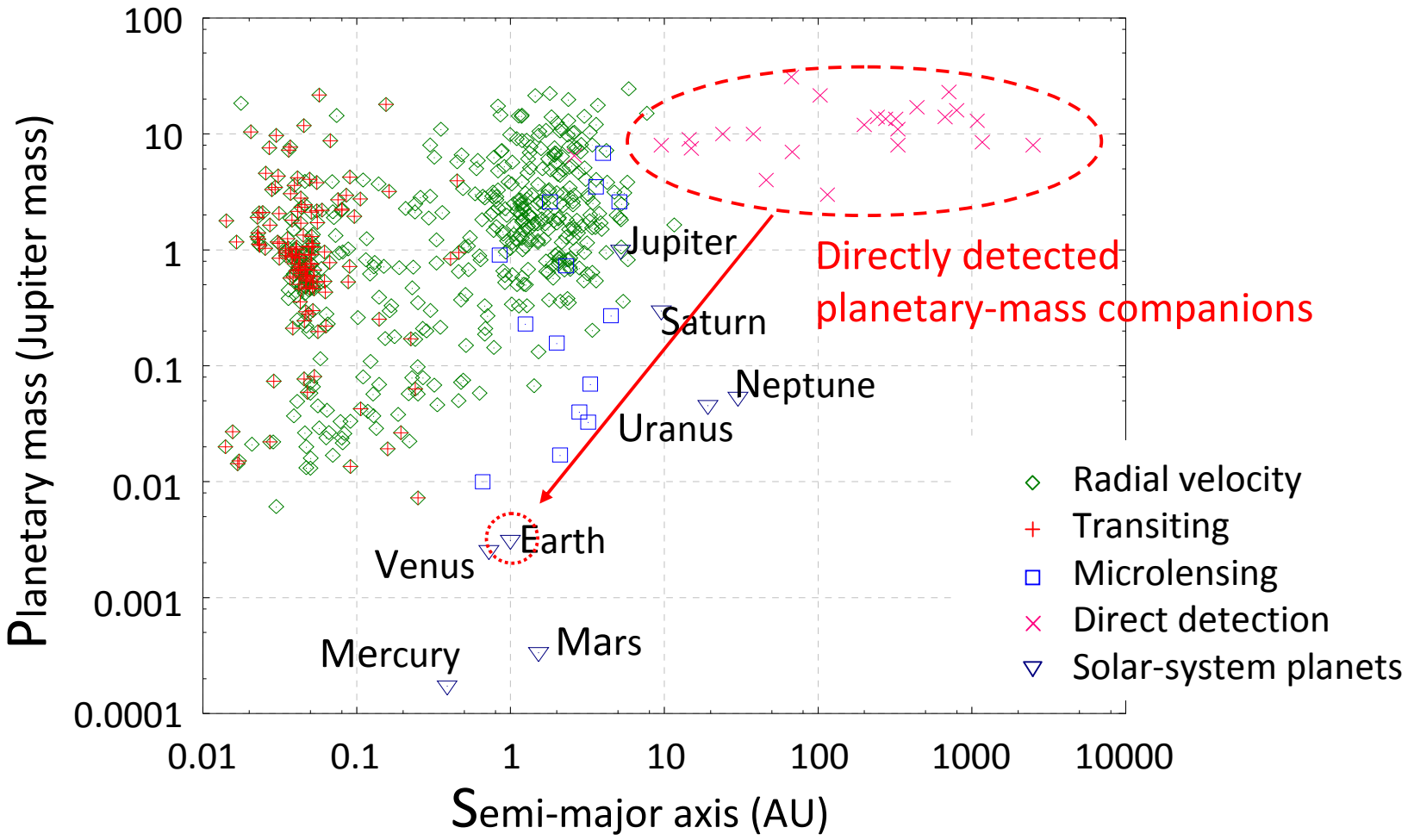


Marois et al. (2010), Nature, 468, 1080
Lagrange et al. (2010) Science, 329, 57
Kalas et al. (2008), Science, 322, 1345
Thalmann et al. (2009), ApJ, 707, L123

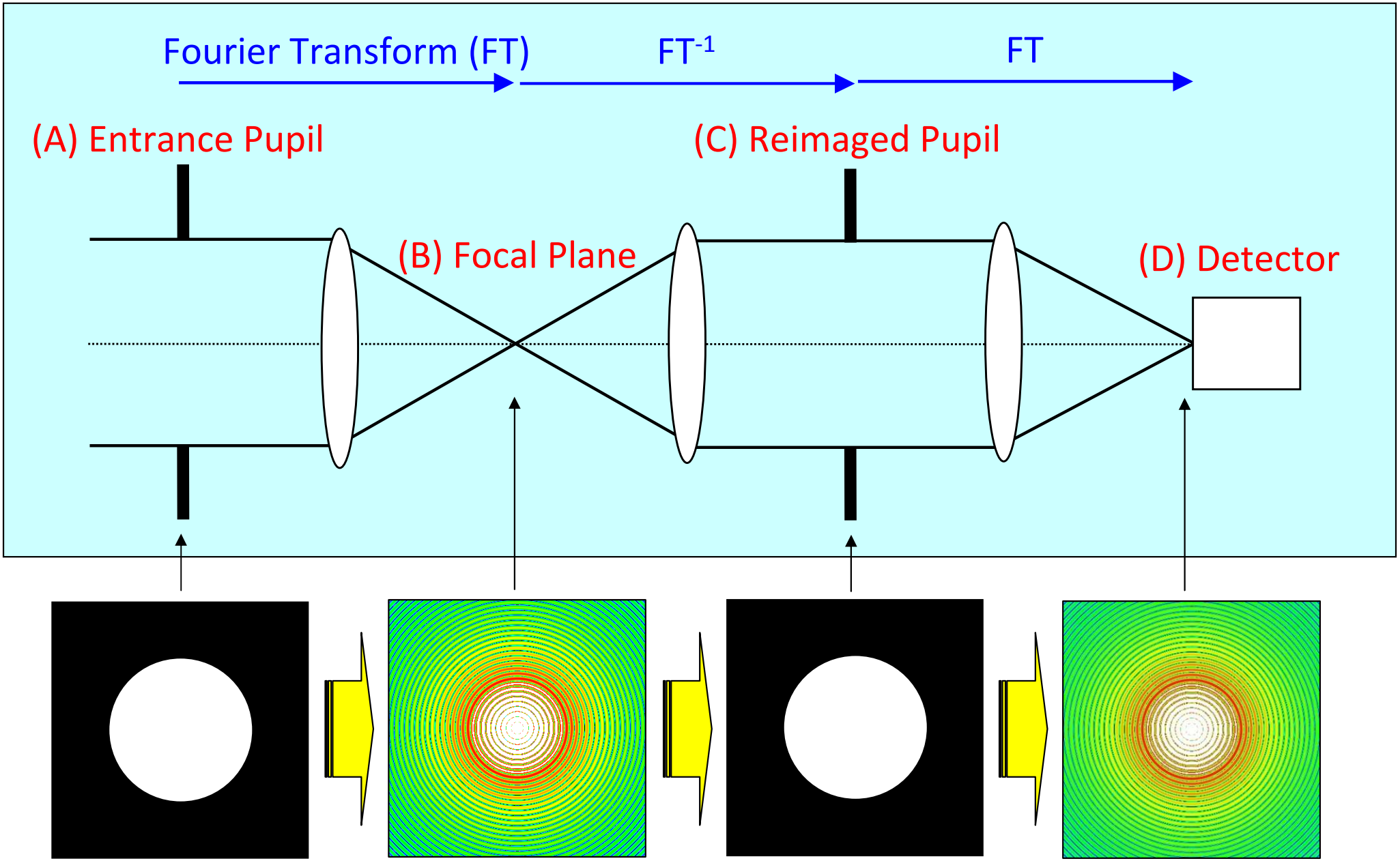
Introduction:

Towards Earth-like planets

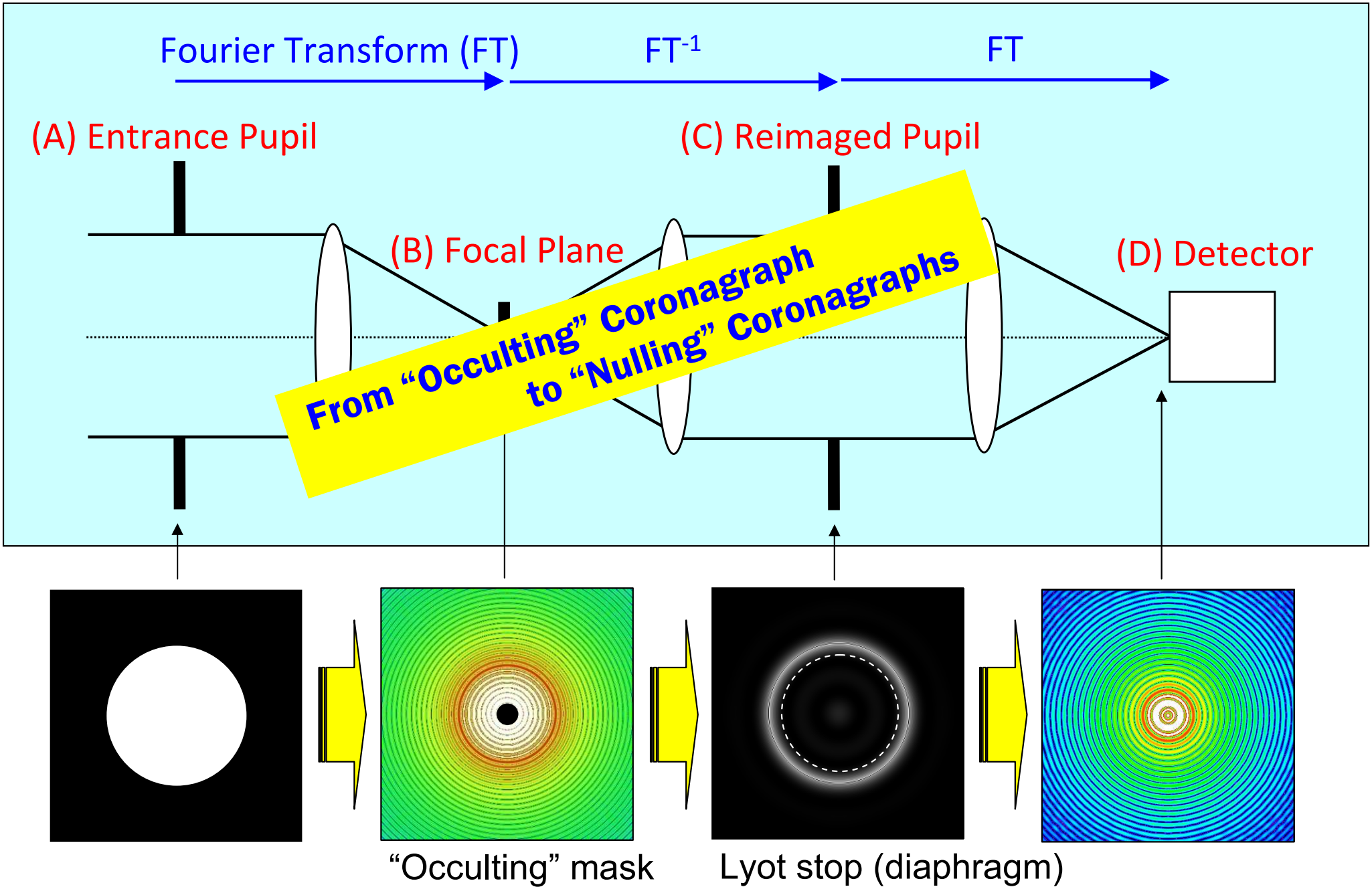
From "The Extrasolar Planets Encyclopaedia (http://exoplanet.eu/)"



Classical Lyot Coronagraph



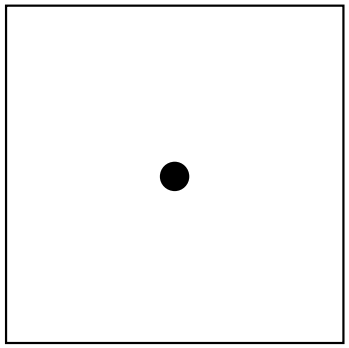
Classical Lyot Coronagraph



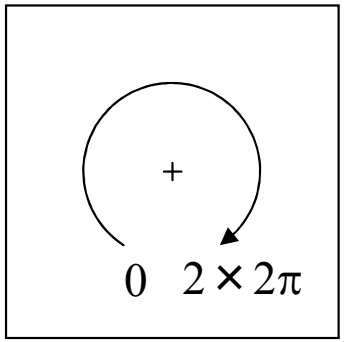
Advanced Coronagraph: Mask Designs and Lyot-stop Images

Phase masks

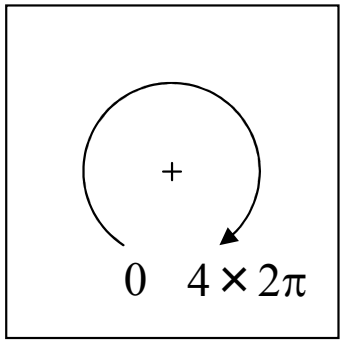
Classical Lyot



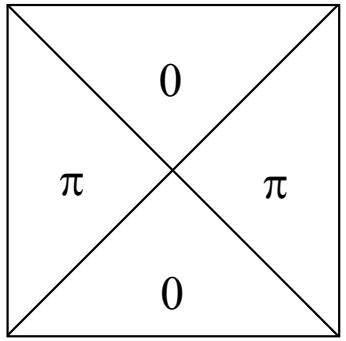
2nd-order vortex (L=2)



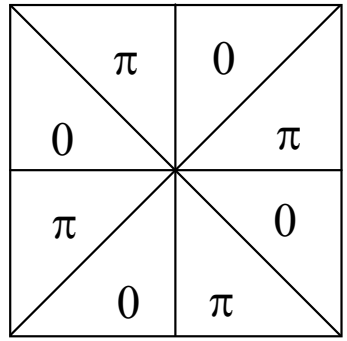
4th-order (L=4)



4-Quadrant

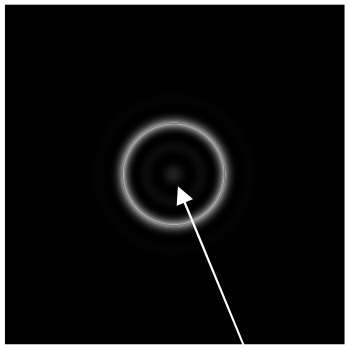


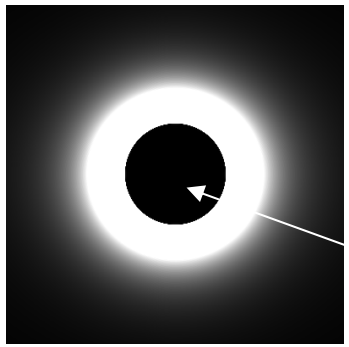
8-Octant

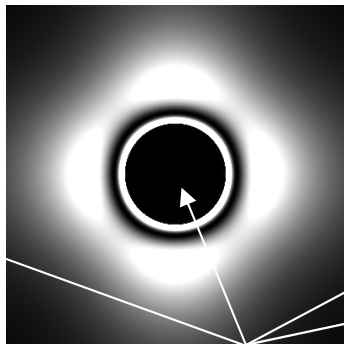


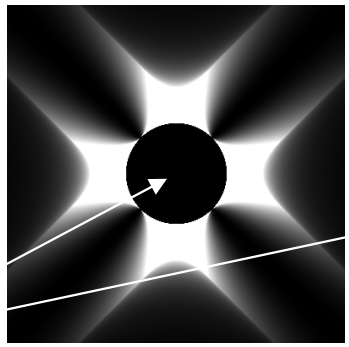
L: Topological charge

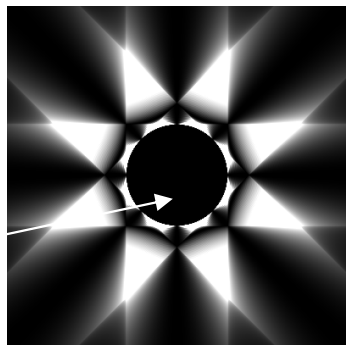
Lyot-stop images









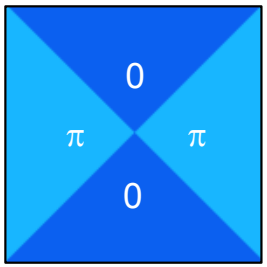


Intensity inside telescope pupil ≠ 0

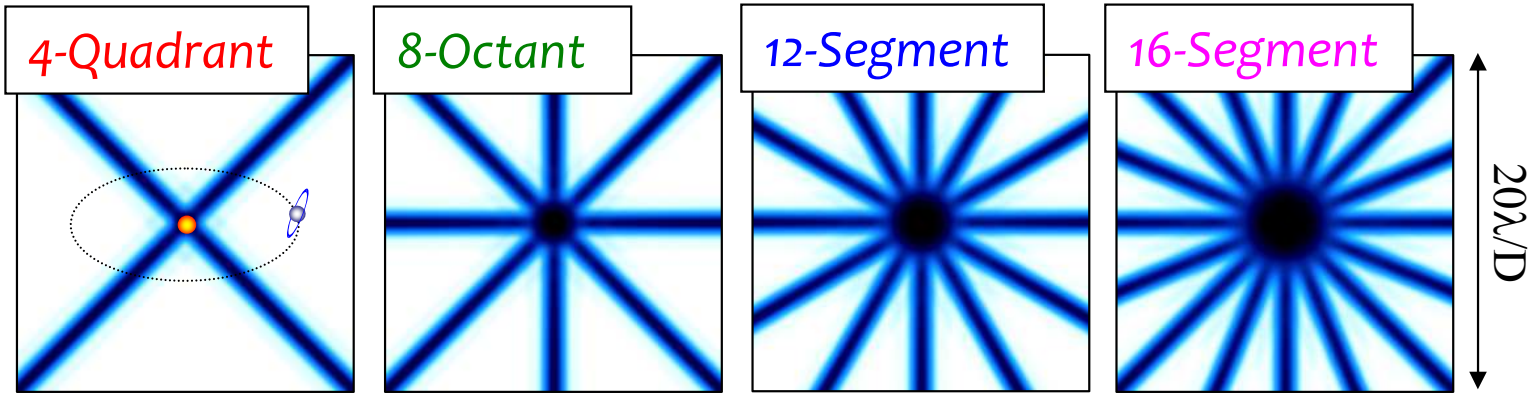
Intensity inside pupil = 0 (perfect stellar suppression!)

Sky Coverage

0/π Phase Masks



etc.

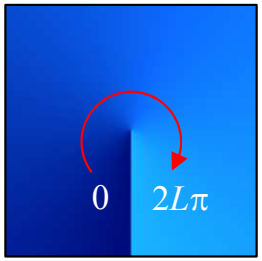


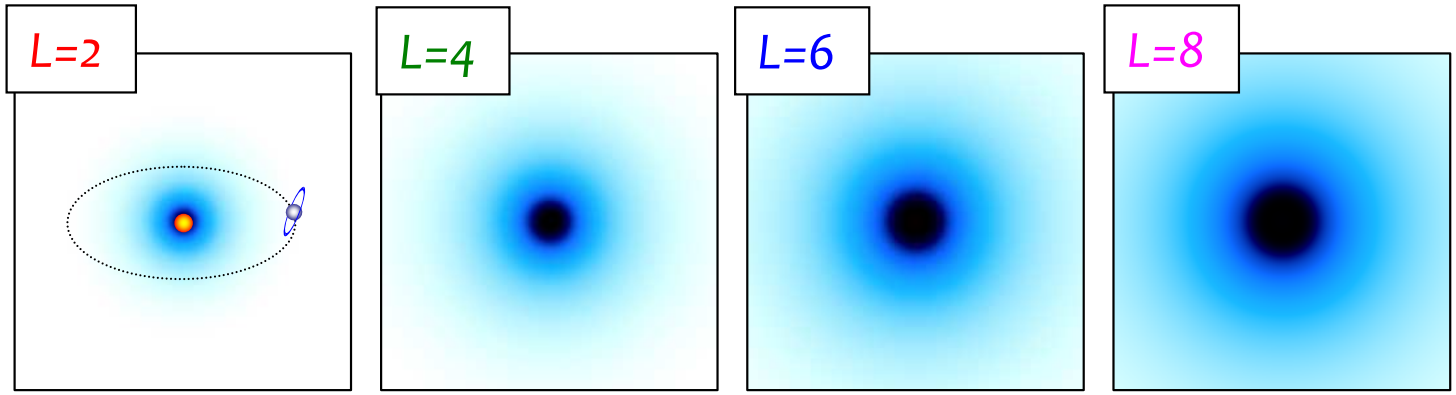
IWA~1λ/D | IWA~2λ/D | IWA~3λ/D | IWA~4λ/D

Simple mask design

Small IWA ⟷ **Tolerant of stellar size**

Vortex Masks





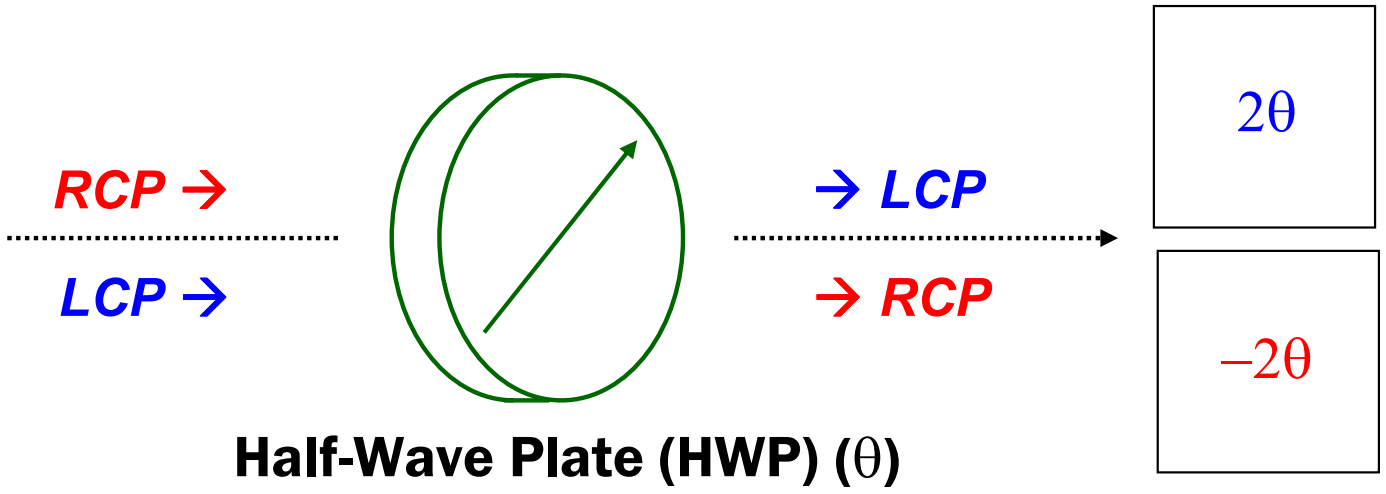
IWA~0.85λ/D | IWA~1.6λ/D | IWA~2.3λ/D | IWA~3λ/D

Full field of view

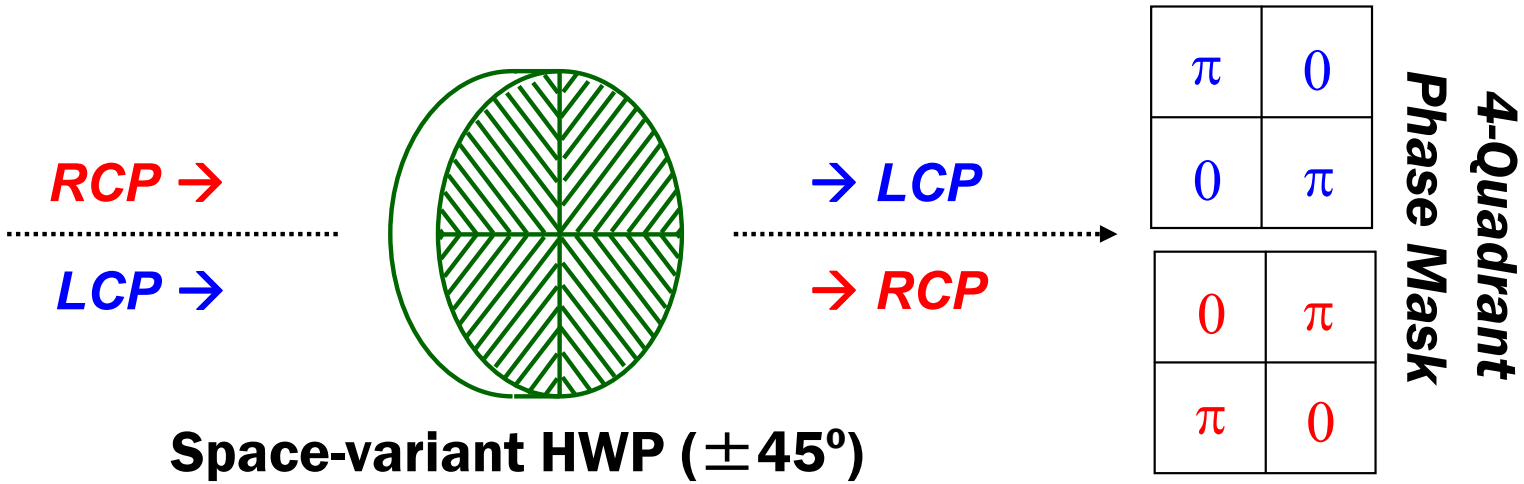
IWA= Inner Working Angle

Principle of Coronagraph Phase Mask: Pancharatnam-Berry's Phase Modulation

Pancharatnam-Berry's phase (a.k.a. "Geometric" phase)



Half-Wave Plate (HWP) (θ)

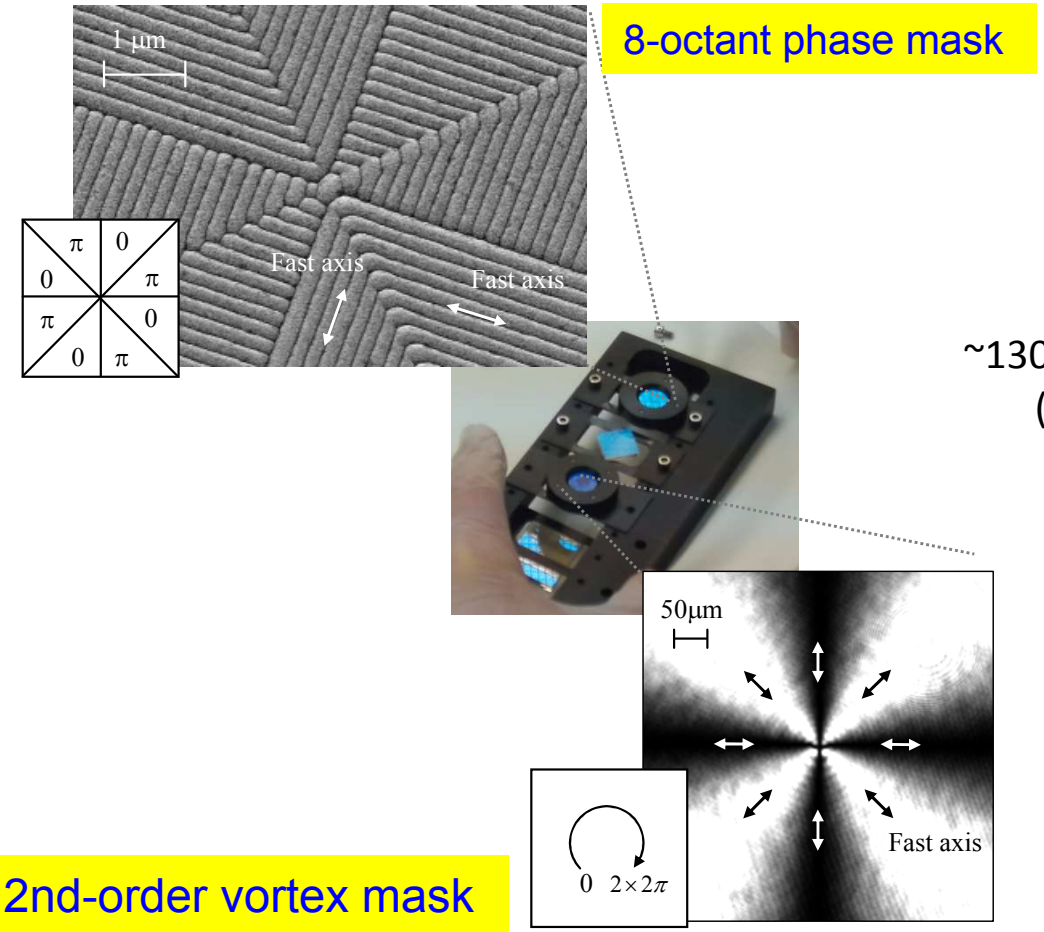


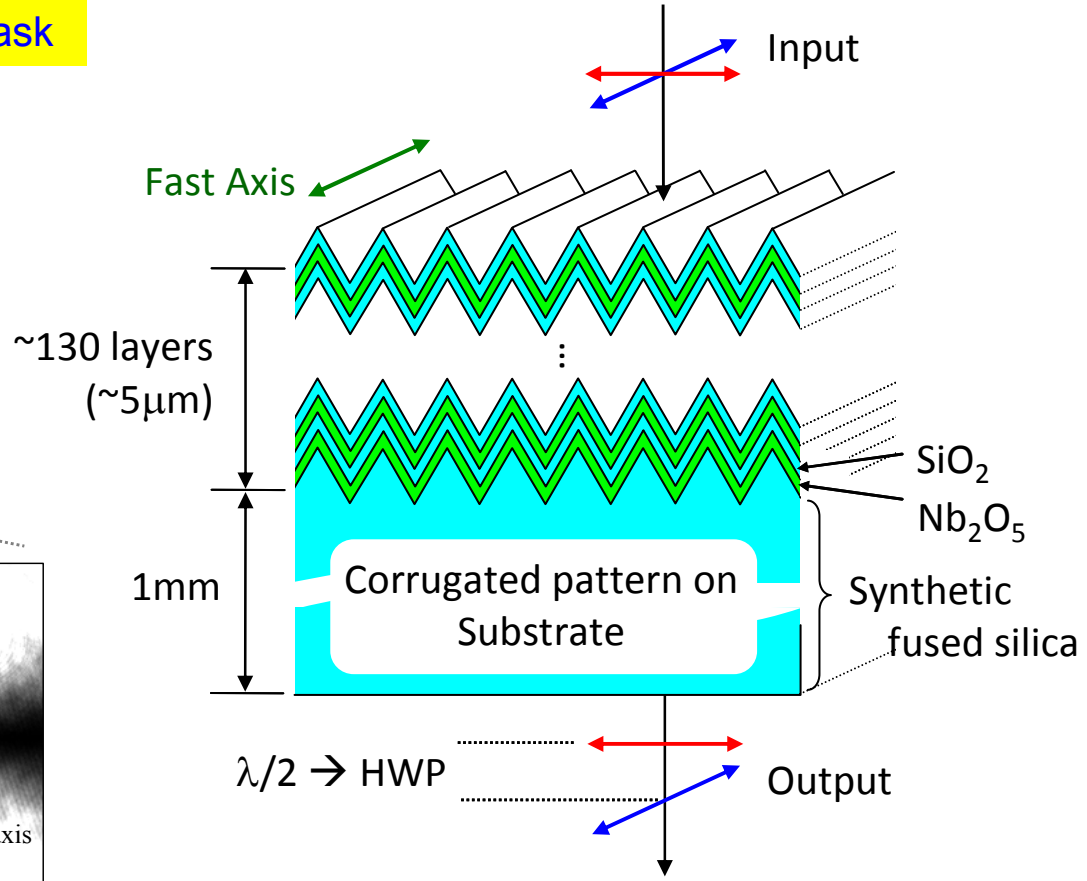
Space-variant HWP (±45°)

RCP: Right-handed Circular Polarization
LCP: Left-handed Circular Polarization

Manufactured Masks based on Photonic-Crystal Technology

- **Photonic-crystal coronagraph masks (Manufactured by Photonic Lattice Inc.)**
  - **Photonic crystal = Periodic nanostructure of high and low refractive indices**



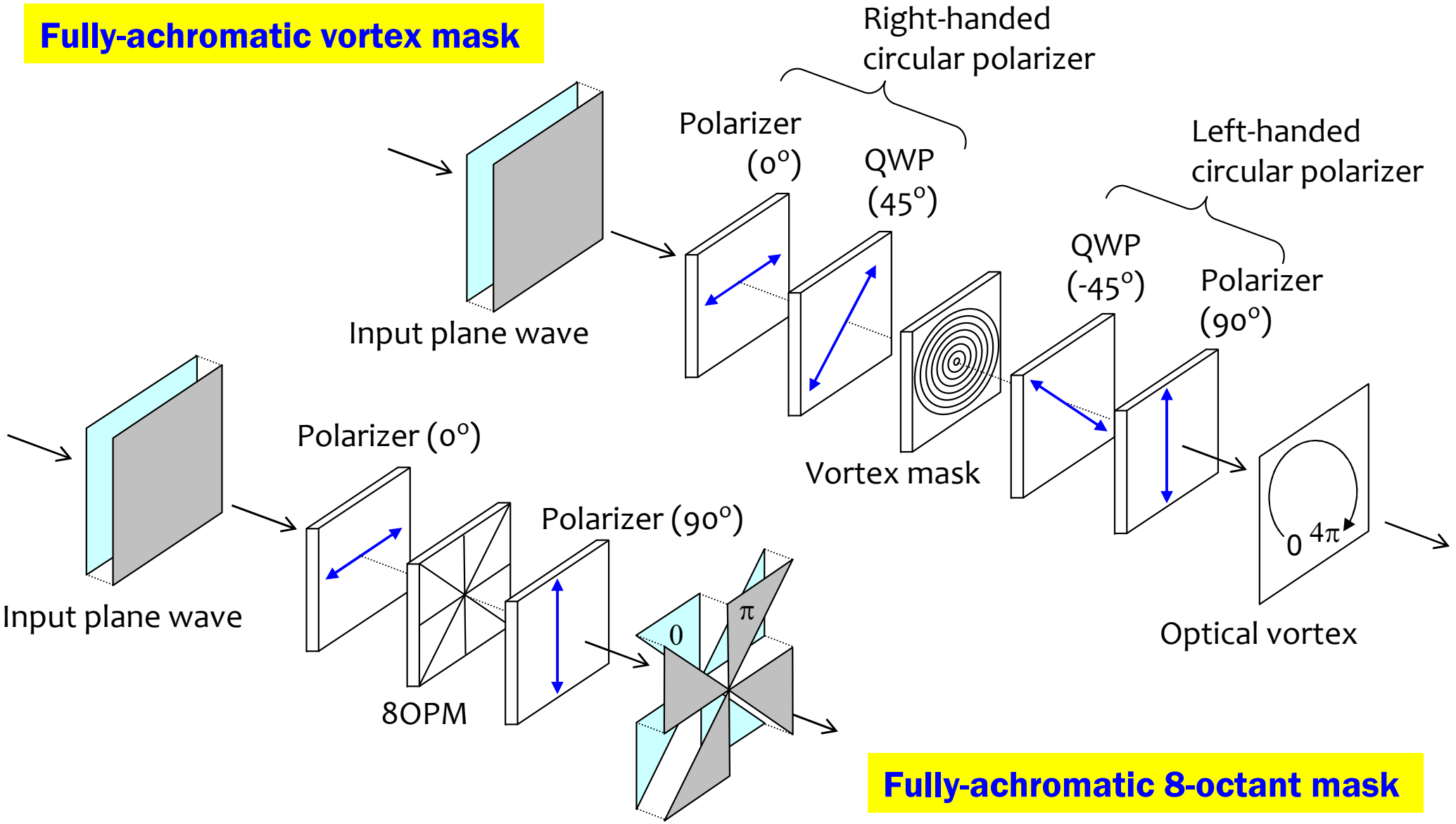


Murakami et al., Proc. SPIE, 8442, 844205 (2012).

Murakami et al., ApJ., 714, 772 (2010)

Fully Achromatic Design: Polarization Filtering

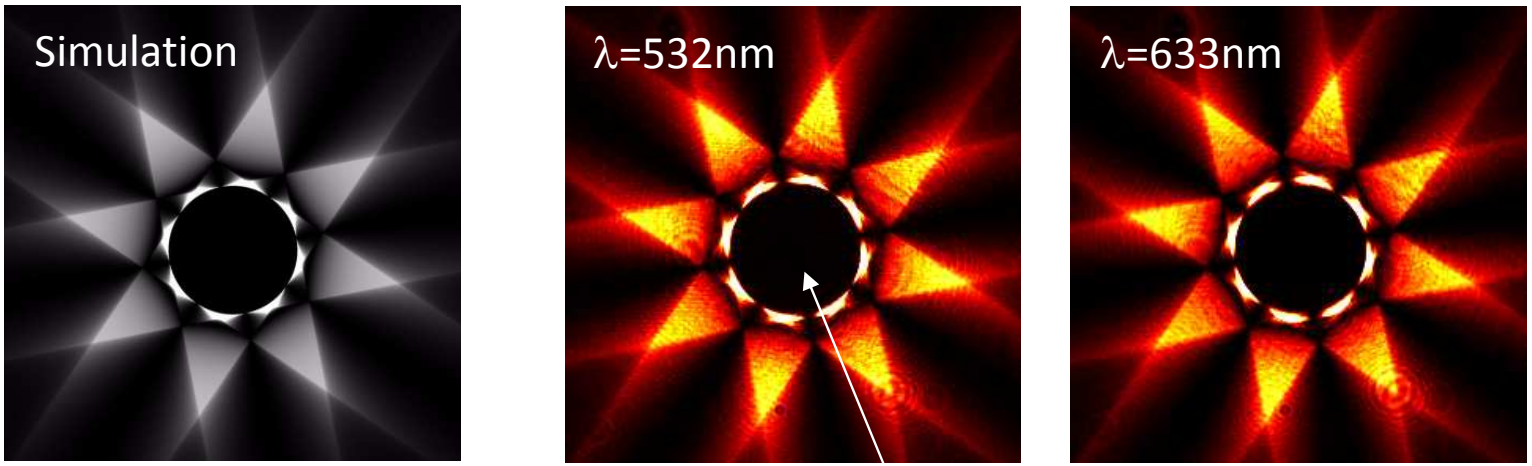
Fully-achromatic vortex mask



Fully-achromatic 8-octant mask

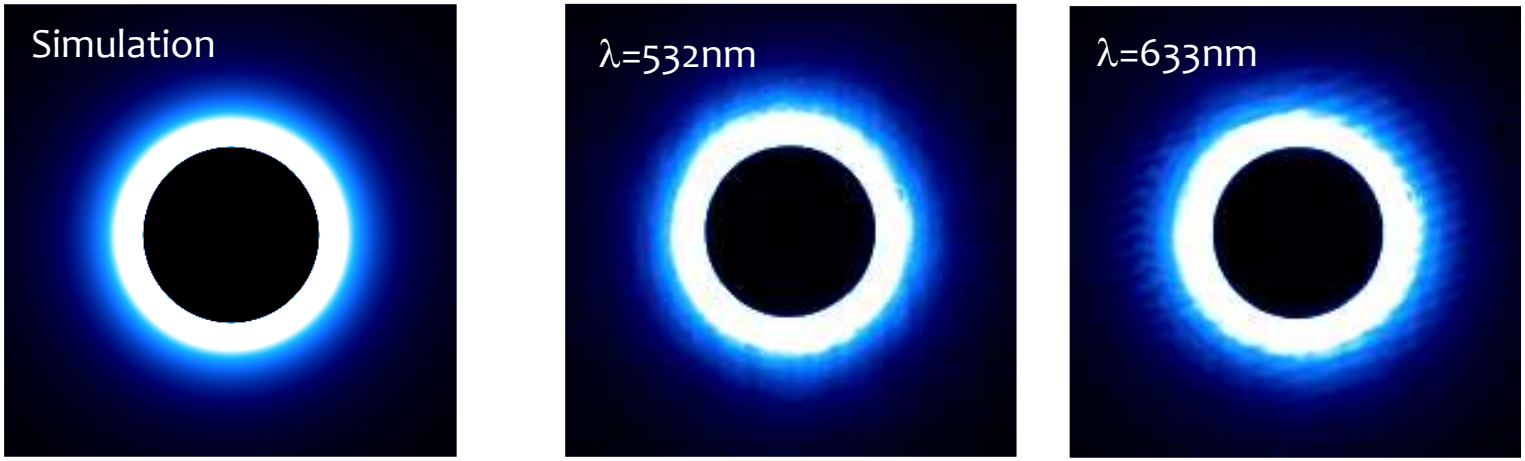
Lab. Test of 8OPM and Vortex Coronagraphs: Lyot stop images

8-Octant



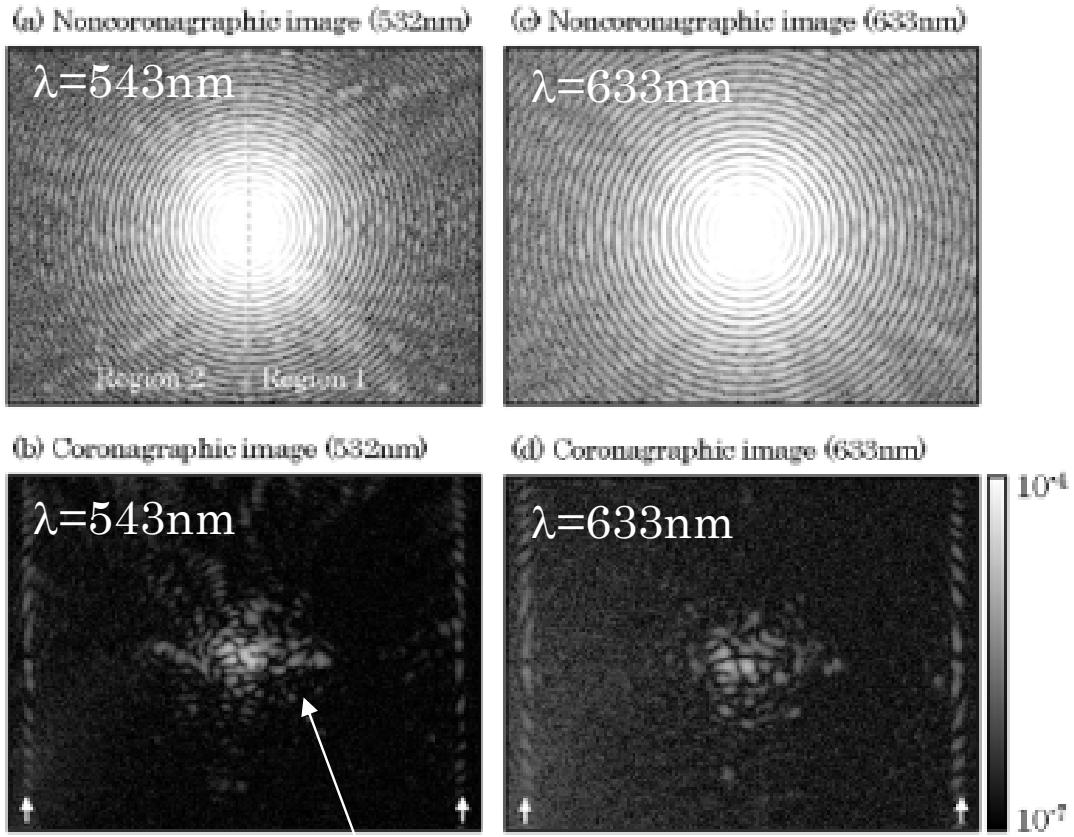
Intensity inside telescope pupil ≠ 0

2nd-order vortex



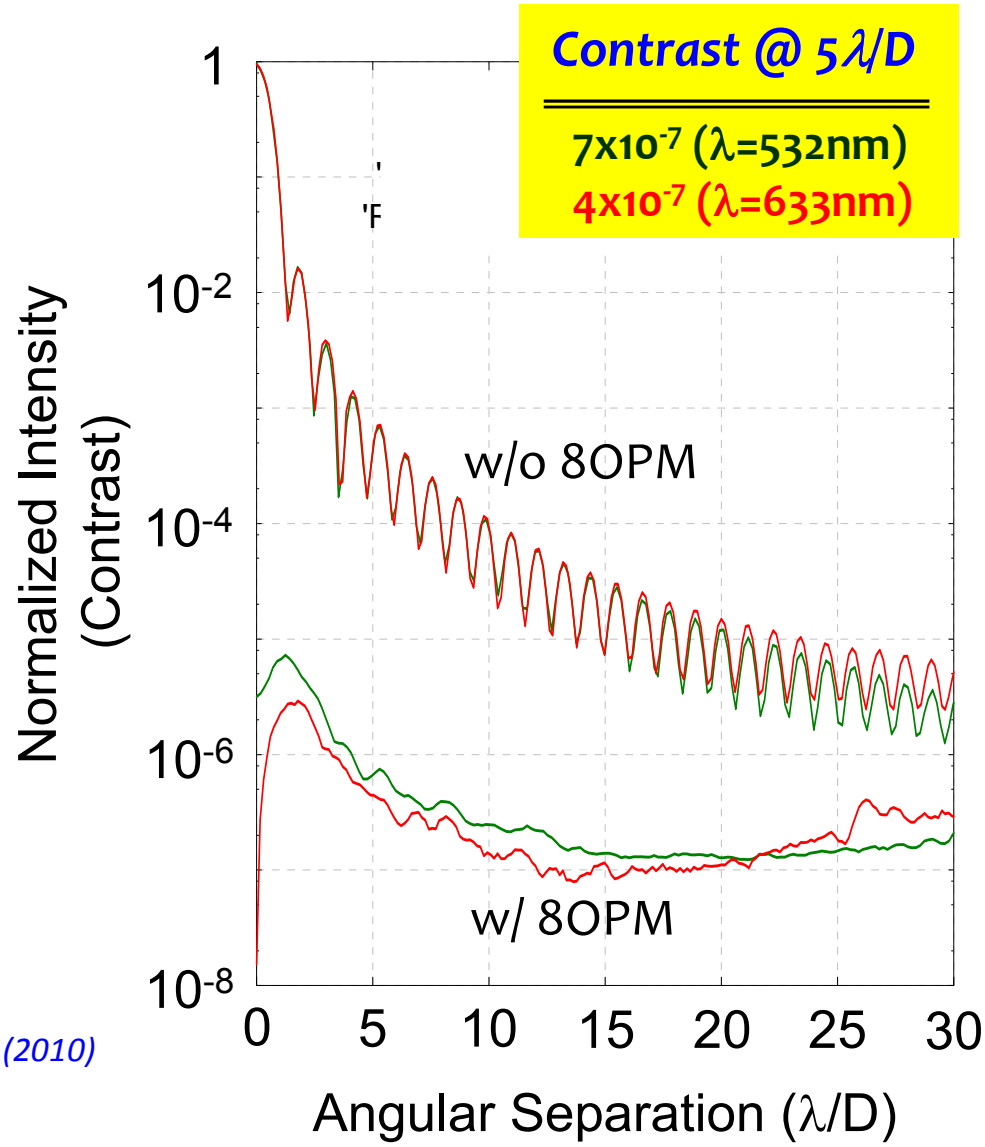
Lab. Test of 8OPM Coronagraph: Final Images

(Top) w/o 8OPM, (bottom) w/ 8OPM



☹ **Residual speckles due to wavefront error**

Murakami et al., ApJ., 714, 772 (2010)



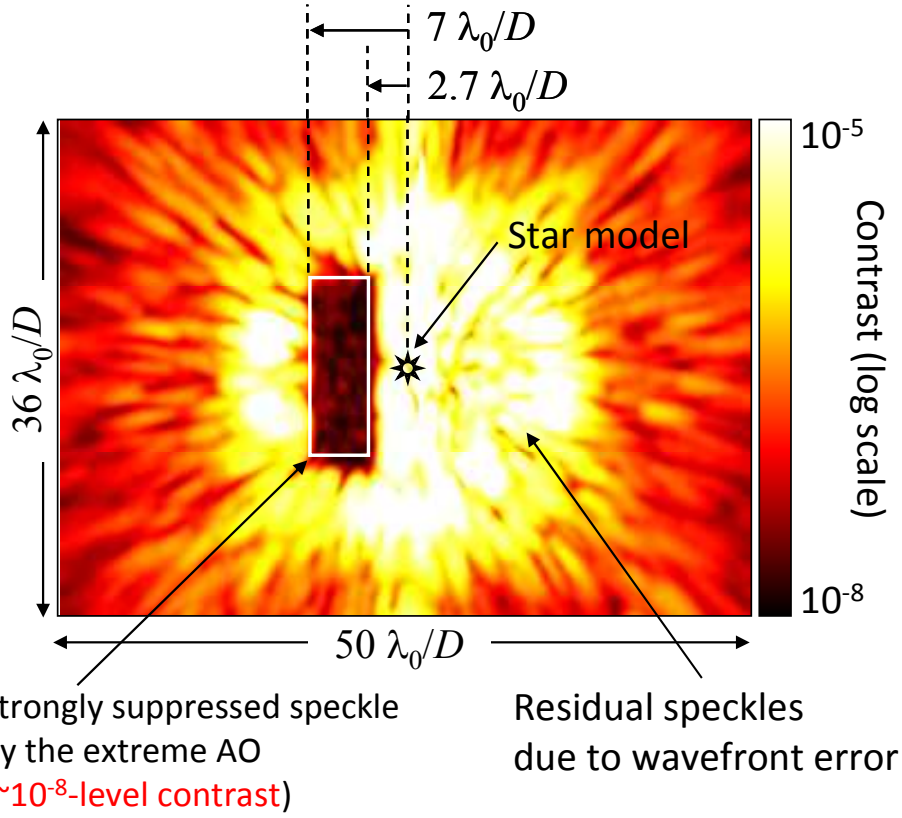
Lab. Tests of the 8OPM Coronagraph: High Contrast Imaging Testbed (HCIT/JPL)

HCIT (@ Jet Propulsion Laboratory)

- ✓ **A state-of-the-art coronagraph simulator in a vacuum chamber**
- ✓ **Extreme AO system for suppressing residual speckles**
  - ✓ **64x64 Deformable Mirror (DM)**
- ✓ **Lab. tests of the 8OPM coronagraph have been carried out (Mar 2011)**

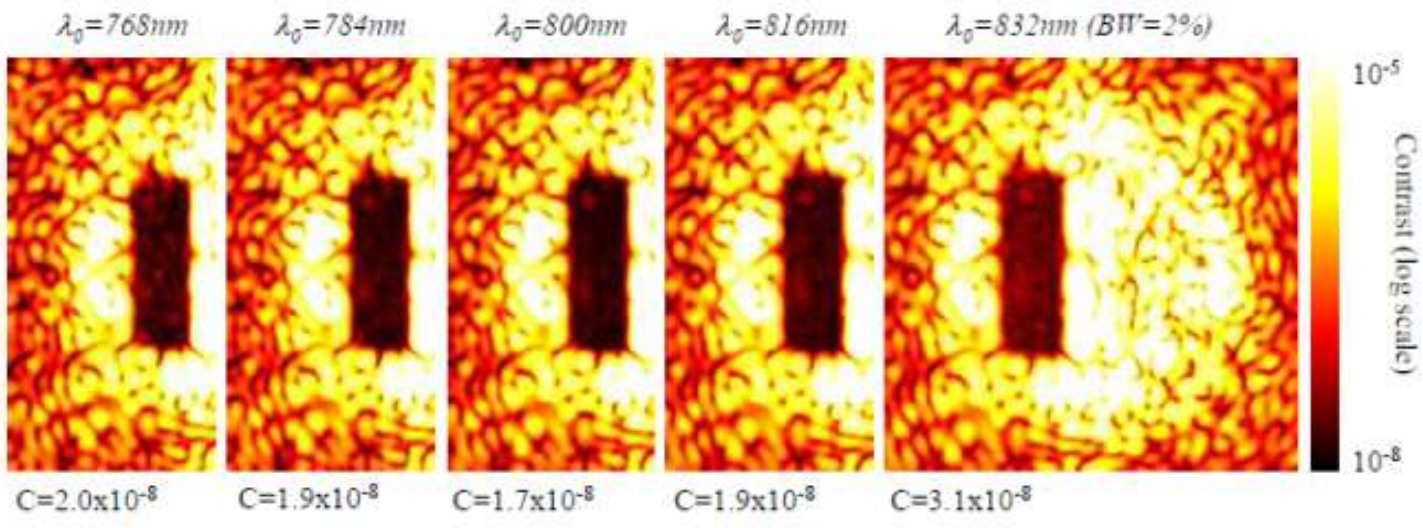
Coronagraph image with polychromatic light with 20%-bandpass filter

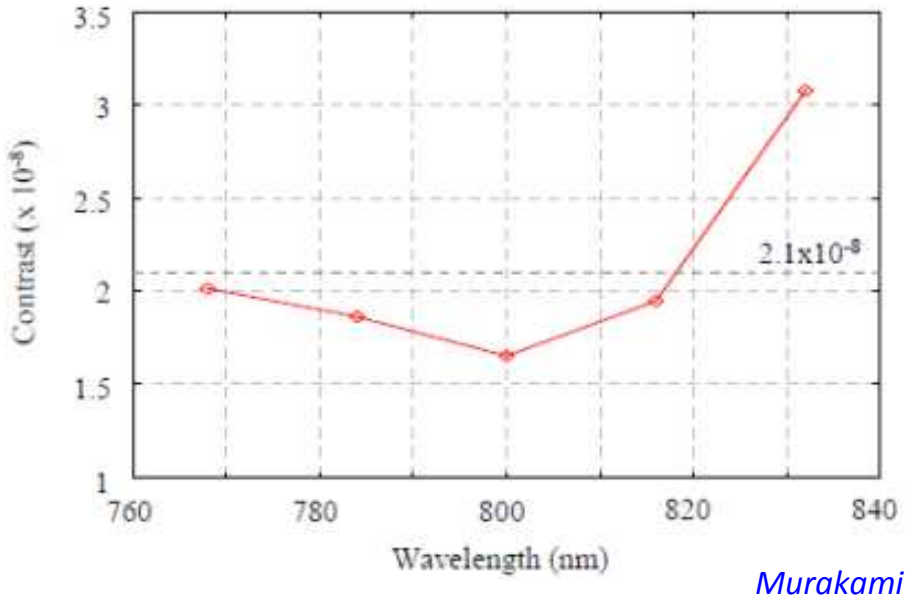
λ_0=800nm, $\Delta\lambda$=160nm (BW=20%)



Murakami et al., Proc. SPIE, 8442, 844205 (2012).

Lab. Tests of the 8OPM Coronagraph: High Contrast Imaging Testbed (HCIT/JPL)

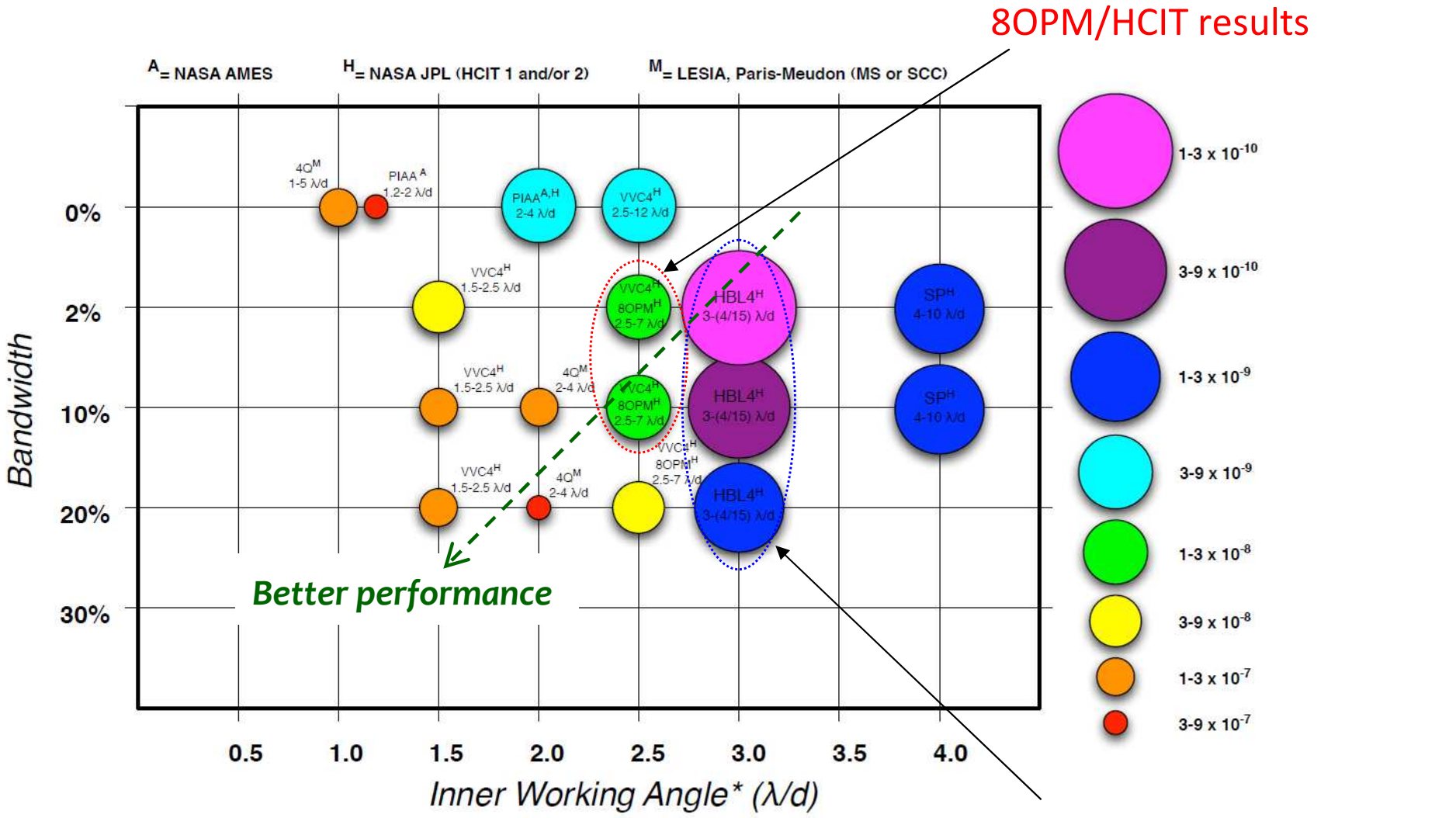




Mean contrast:
2.1x10^{-8} over 10% bandwidth

Murakami et al., Proc. SPIE, 8442, 844205 (2012).

Summary of Currently Achieved Contrasts

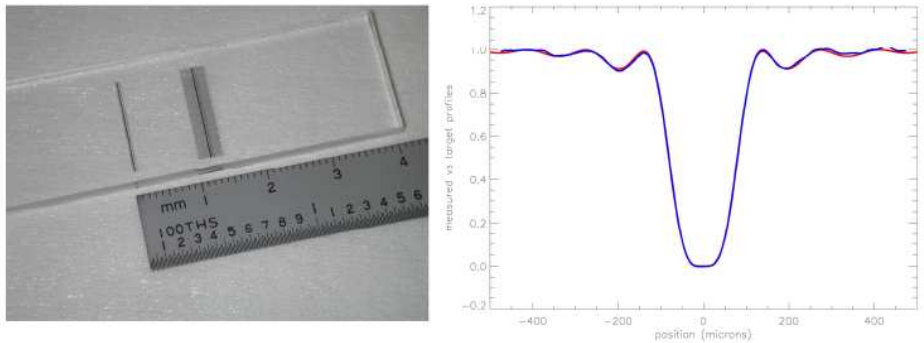


Mawet et al., Proc. SPIE, 8442, 844204 (2012).

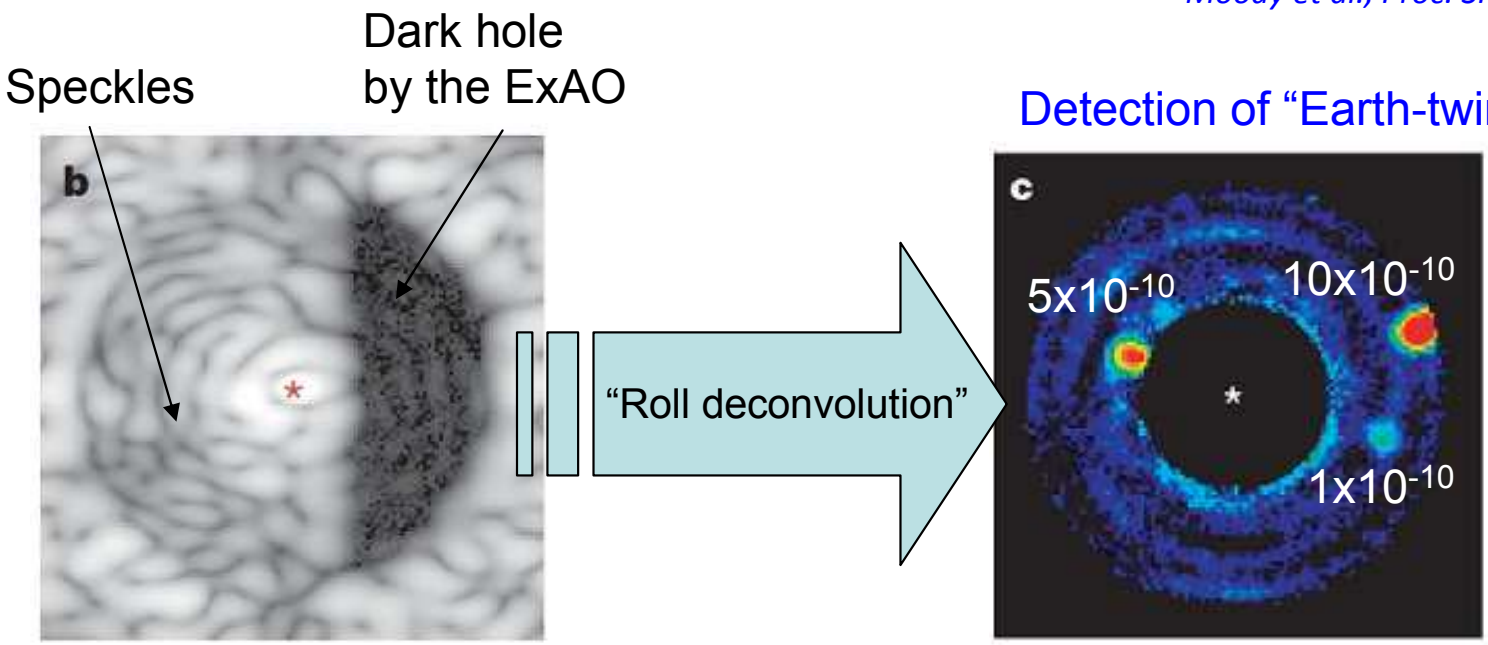
Summary of Currently Achieved Contrasts

Lab. Demonstrations of Band-Limited Mask Coronagraph

Manufactured mask



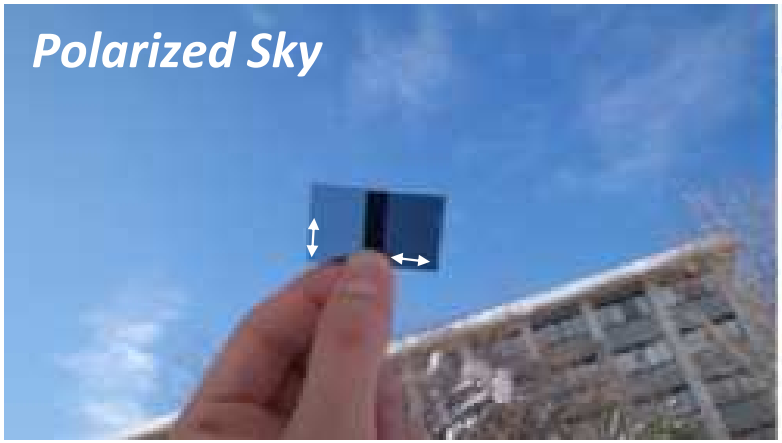
Moody et al., Proc. SPIE, 7010, 70103P (2008)



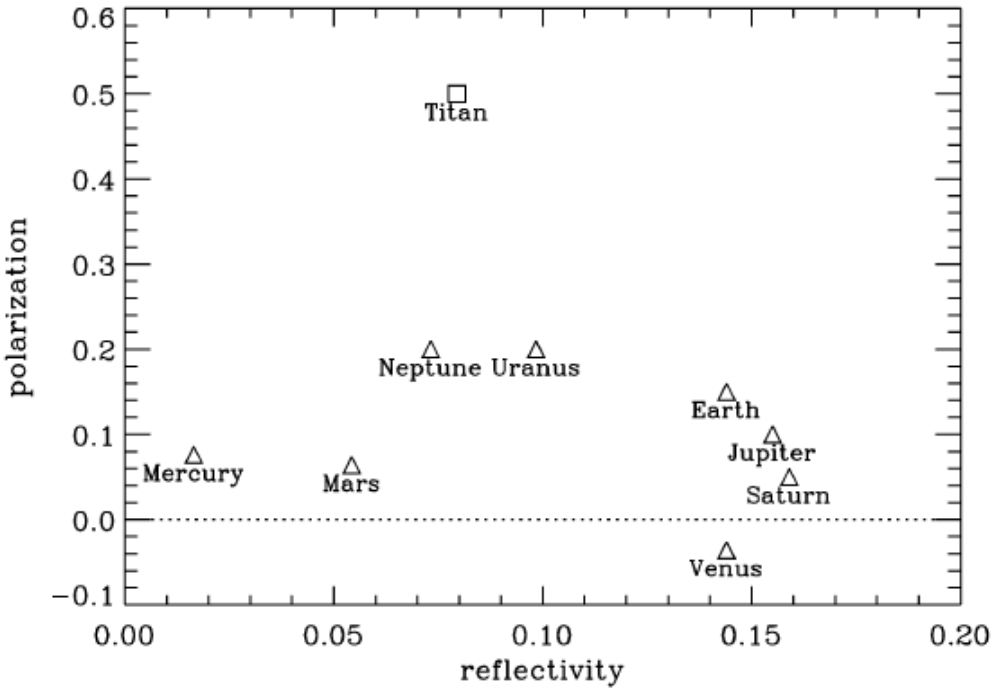
Trauger & Traub, Nature 446, 771 (2007)

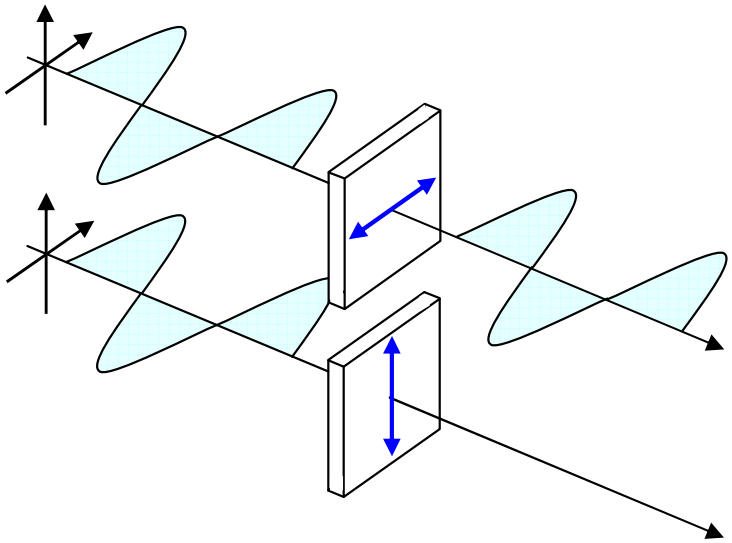
High-Contrast Polarimetry

Polarizations of Planets → due to scattering and reflection



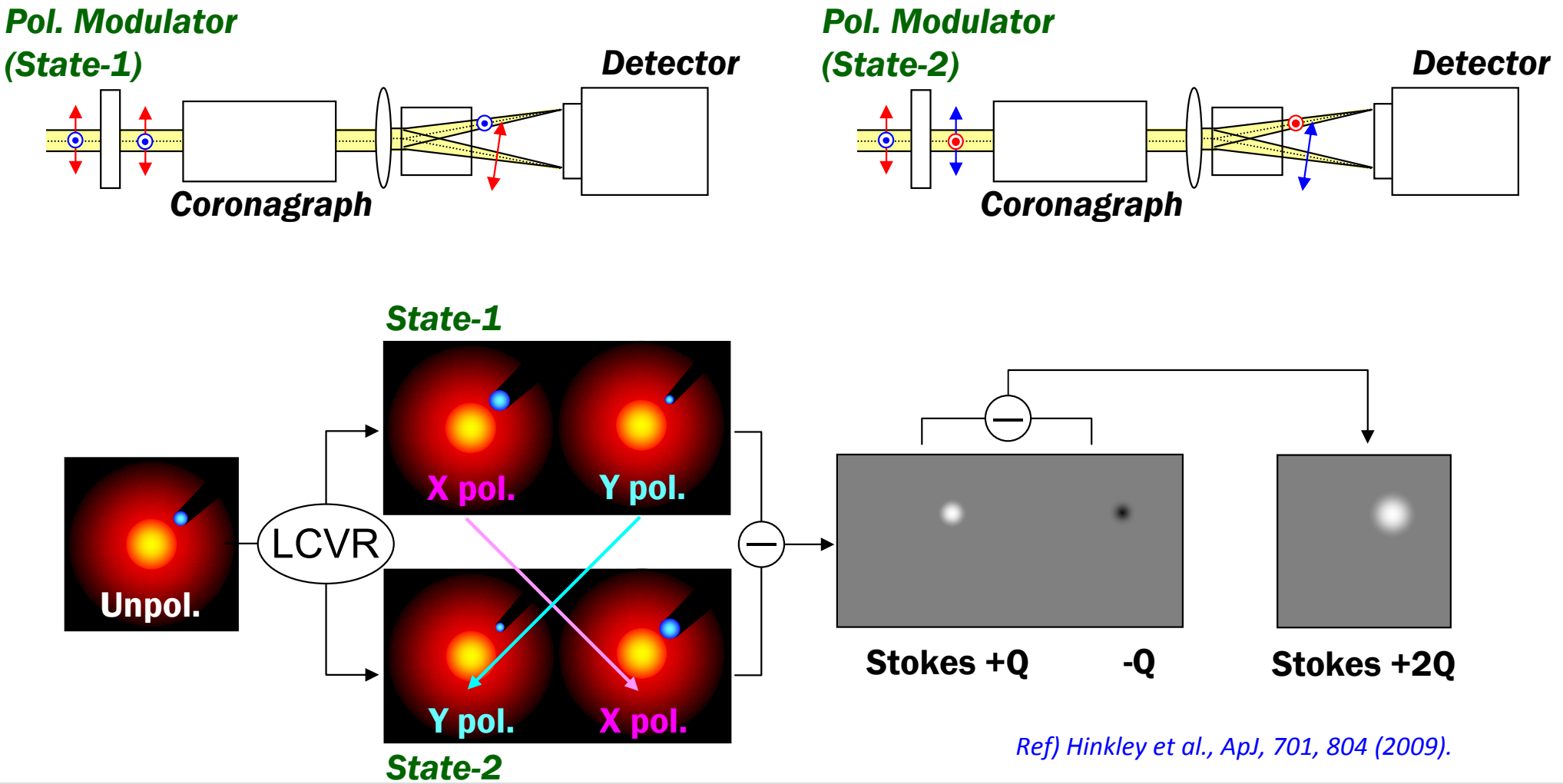
Schmid et al., Proc. AIU, 200, 165 (2006).





High-Contrast Polarimetry

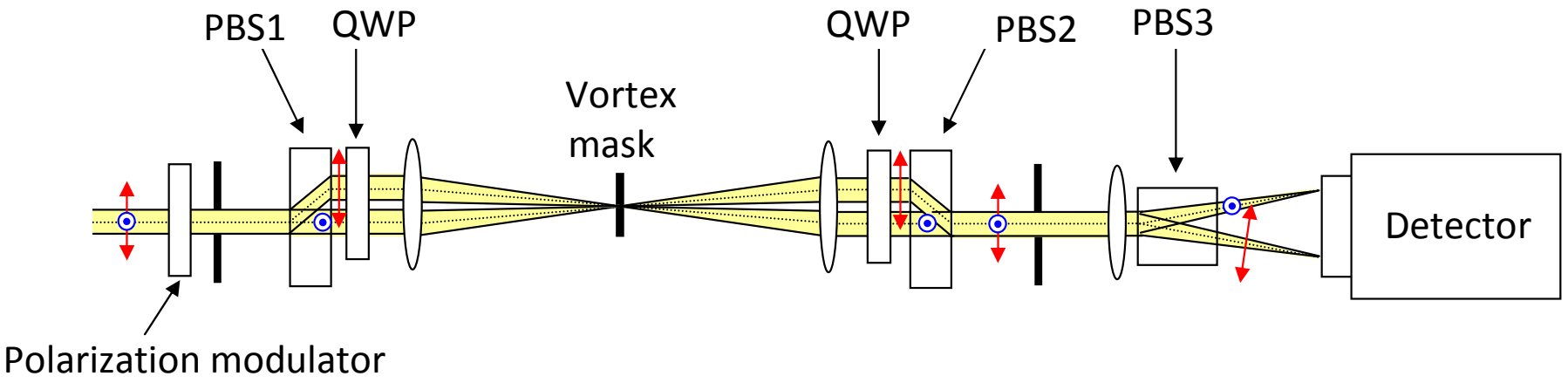
"Double Difference" Technique → Cancel out unpolarized speckles



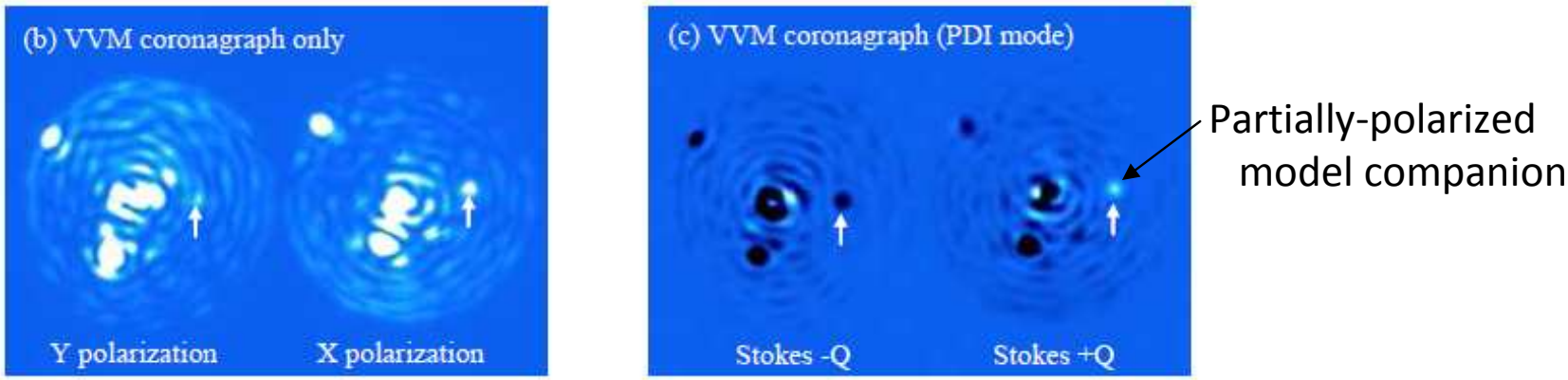
Ref) Hinkley et al., ApJ, 701, 804 (2009).

High-Contrast Polarimetry

Dual-channel polarimetric coronagraph

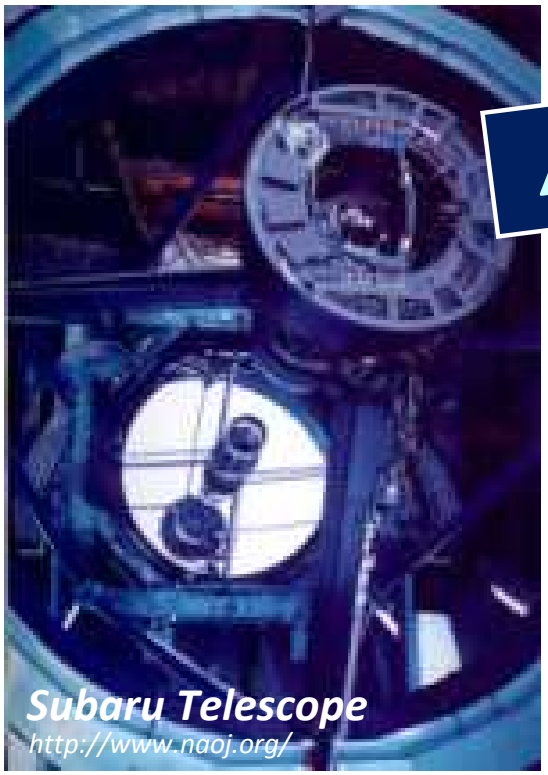


Experimental results of the double-difference technique using the polarimetric coronagarph

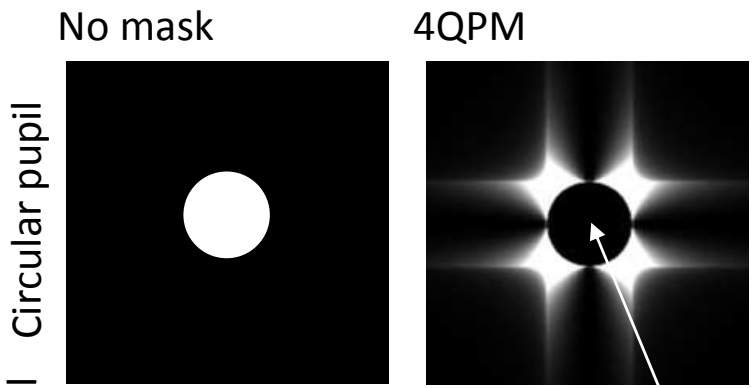


Murakami et al., Proc. SPIE, 8442, 844205 (2012).

Towards Ground-based Observations



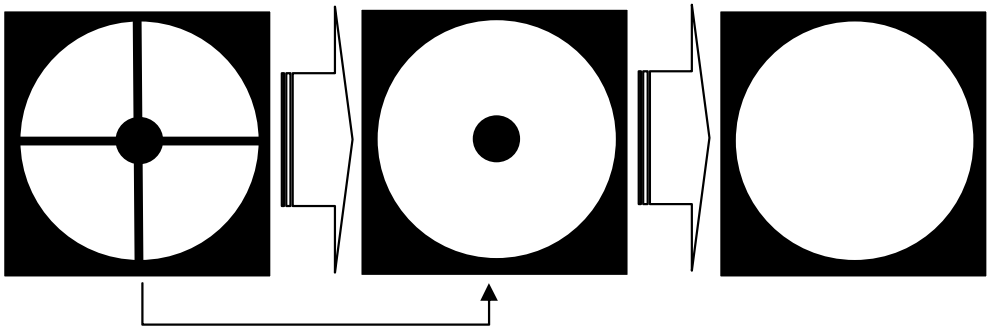
Against Secondary Mirror and Spider Vanes



Intensity inside telescope pupil ≠ 0

☹ *Secondary mirror (+ Spider vanes)*

➔ *Perfect stellar rejection cannot be feasible …*



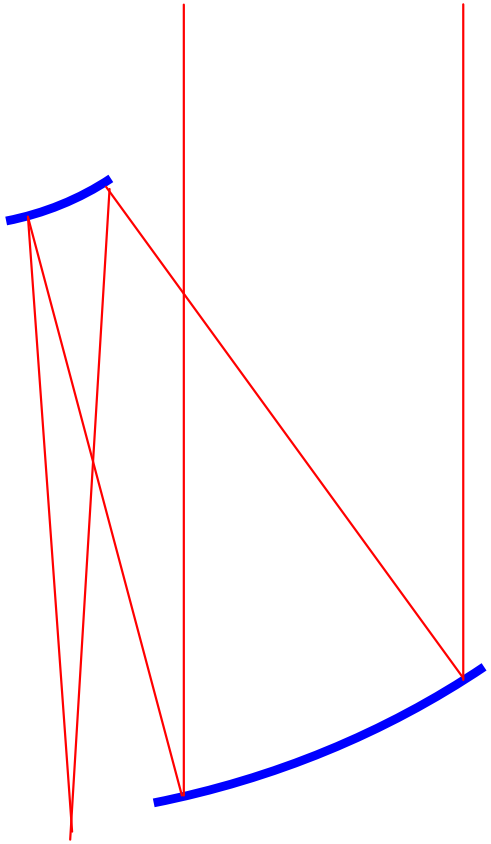
"Spider Removal Plate (SRP) in context of SExAO (Subaru Coronagraphic Extreme AO)

Ref) Lozi et al. (2009), PASP, 121, 1232 / Martinache et al. (2009), Proc. SPIE, 7440, 74400O

Removal of Centrally Obscuration

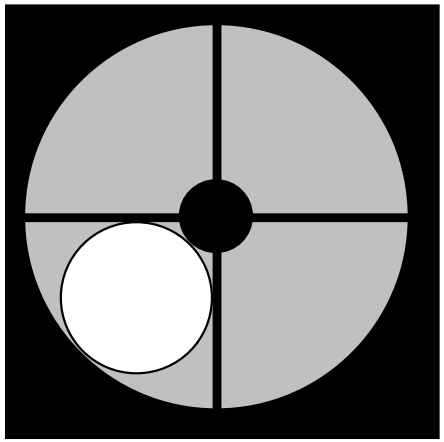
We need clear circular apertures

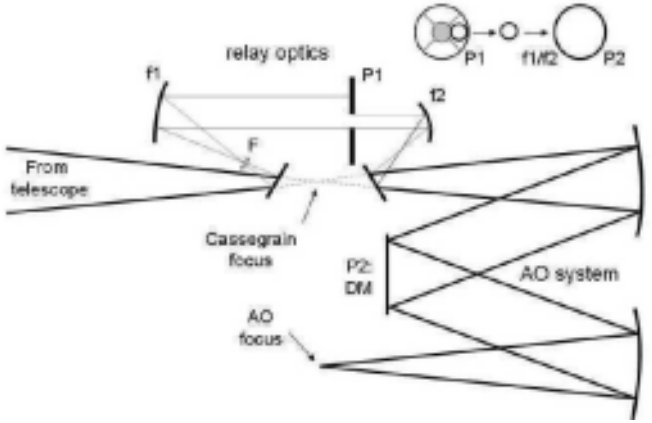
(1) Off-axis telescope



(2) Subaperture

Ex) The Palomar 200" Telescope:
Well Corrected Subaperture (D=1.6m)

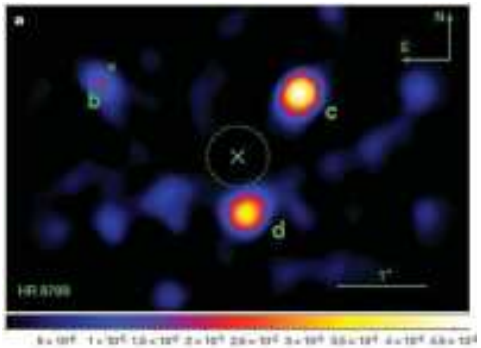




Serabyn et al. (2007), ApJ, 658, 1386

Directly imaged HR 8799b-d:
A vector vortex coronagraph based on liquid-crystal polymers*ref

Ref) Mawet et al. (2009), Opt. Express, 17, 1902

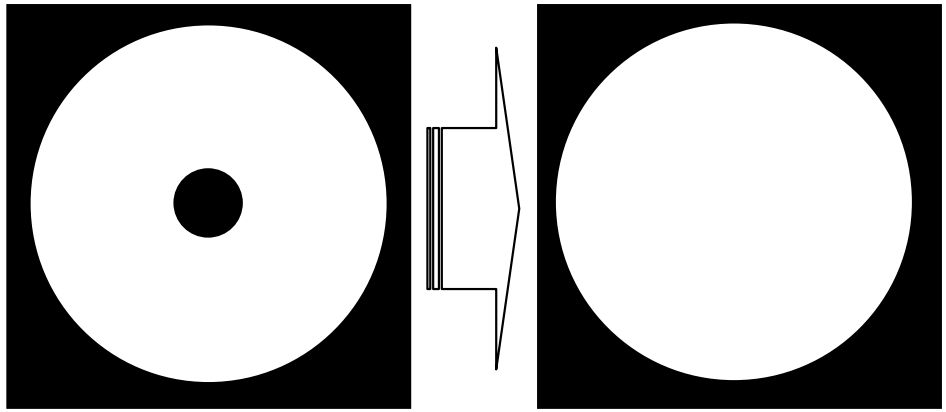


Serabyn et al. (2010), Nature, 464, 1018

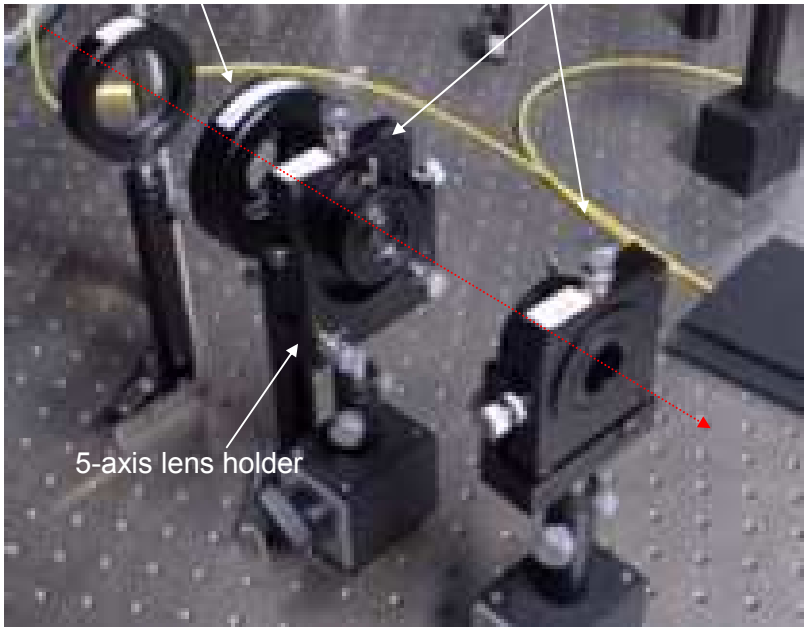
Removal of Centrally Obscuration

We need clear circular apertures

(3) Beam-shaping lenses or mirrors (our approach)



Ex) Manufacturing of MPIAA lenses



Preliminary experimental results

MPIAA = Modified Phase-Induced Amplitude Apodization

Summary

- *The photonic-crystal phase masks for coronagraphy*
  - *8-octant phase mask*
  - *Continuous optical vortex (second order)*
  - *32-Sector optical vortex (fourth order) → New*
- *Lab. tests at the HCIT/JPL (with an extreme AO)*
  - *10^{-8}-level contrast with broadband light (BW=10%)*
- *Dual-channel polarimetric coronagraph*
  - *10^{-8}-level contrast by the speckle subtraction and post processing technique (Murakami et al. in prep.)*
  - *Characterization of planets via polarization*
- *Next Milestone*
  - *On-sky observations with ground-based telescopes*