14 March 2011 Seminar @JPL

Coronagraph focal-plane masks based on photonic crystal technology

Development of eight-octant and vector-vortex masks

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(Hokkaido University)

Contributors

Eight-octant phase mask based on photonic crystal technology

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Optical vortex mask based on photonic crystal technology

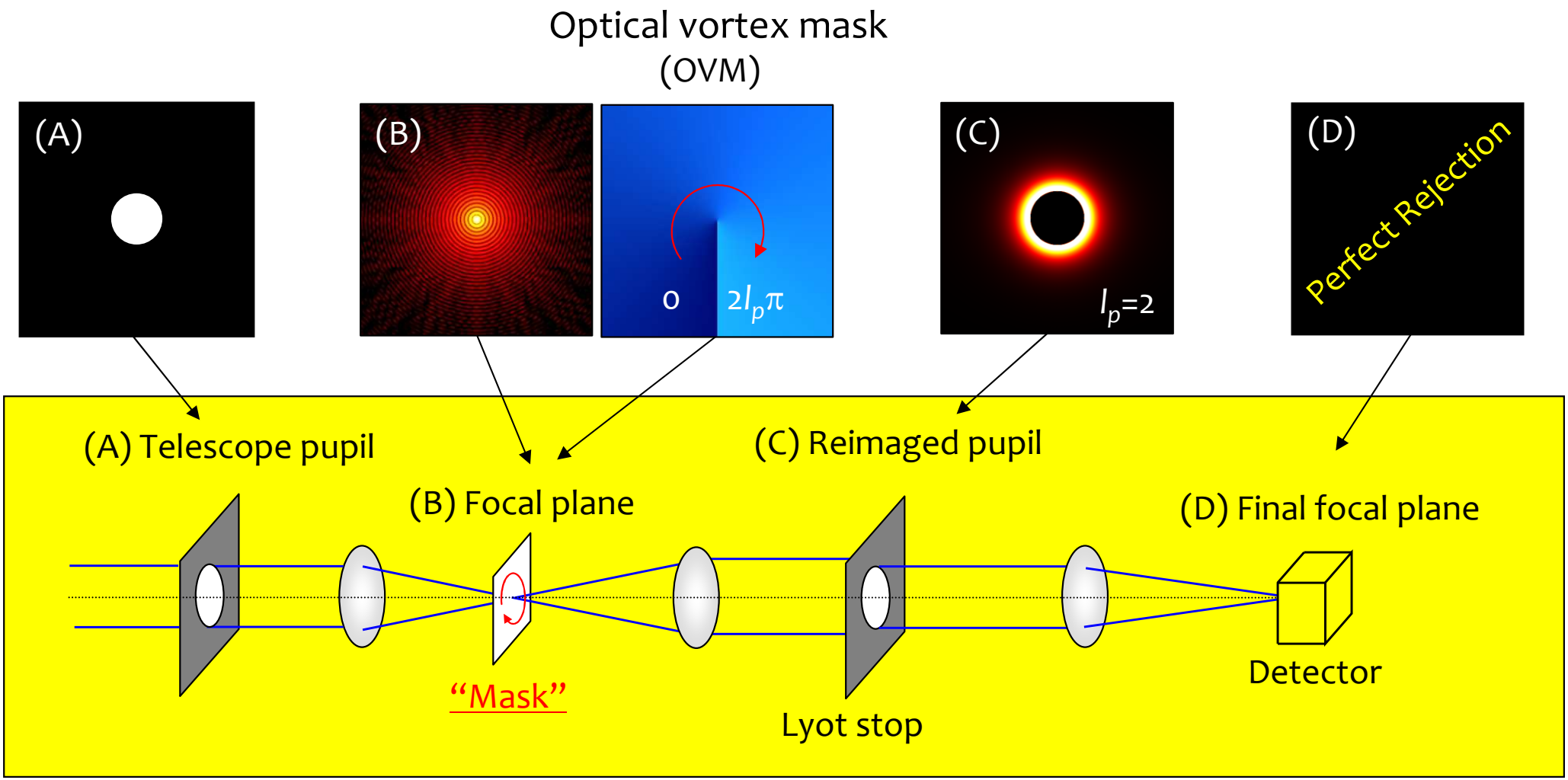
S. Hamaguchi, K. Oka, M. Sakamoto, A. Ise, N. Baba
Hokkaido University

Our history: Proposals of high-contrast imagers

- ☐ **Nulling interferometry by use of Pancharatnam's phase**
  (N. Baba, N. Murakami, T. Ishigaki, Opt. Lett., **26**, 1167, 2001)
- ☐ **Ferroelectric liquid-crystal 4QPM coronagraph**
  (N. Baba, N. Murakami, T. Ishigaki, N. Hashimoto, Opt. Lett., **27**, 1373, 2002, etc.)
- ☐ **Polarization differential imaging with 4QPM coronagraph**
  (N. Baba & N. Murakami, PASP, **115**, 1363, 2003/
  N. Murakami, N. Baba, Y. Tate, Y. Sato, M. Tamura, PASP, **118**, 774, 2006, etc.)
- ☐ **Spectro-polarimetric differential imager using channeled spectrum**
  (N. Murakami, L. Abe, M. Tamura, N. Baba, ApJ, **661**, 634, 2007)
- ☐ **4QPM coronagraph with Jacquinot Lyot stop**
  (N. Murakami, R. Uemura, N. Baba, Y. Sato, J. Nishikawa, M. Tamura, ApJ, **677**, 1425, 2008)
- ☑ **Eight-octant phase-mask (8OPM) coronagraph**
  (N. Murakami, R. Uemura, N. Baba, J. Nishikawa, M. Tamura, N. Hashimoto, L. Abe, PASP, **120**,1112, 2008/
  N. Murakami, J. Nishikawa, K. Yokochi, M. Tamura, N. Baba, L. Abe, ApJ, **714**, 772, 2010)
- ☐ **Common-path lateral-shearing nuller using Savart plates**
  (N. Murakami & N. Baba, Opt. Lett., **35**, 3003, 2010)
- ☑ **Optical vortex mask (OVM) coronagraph**
  (N. Murakami, S. Hamaguchi, K. Oka, N. Baba, 2011, in prep.)

Today's topics:
8OPM** and **OVM** coronagraphs based on **photonic crystal technology

Optical vortex mask (OVM) coronagraph



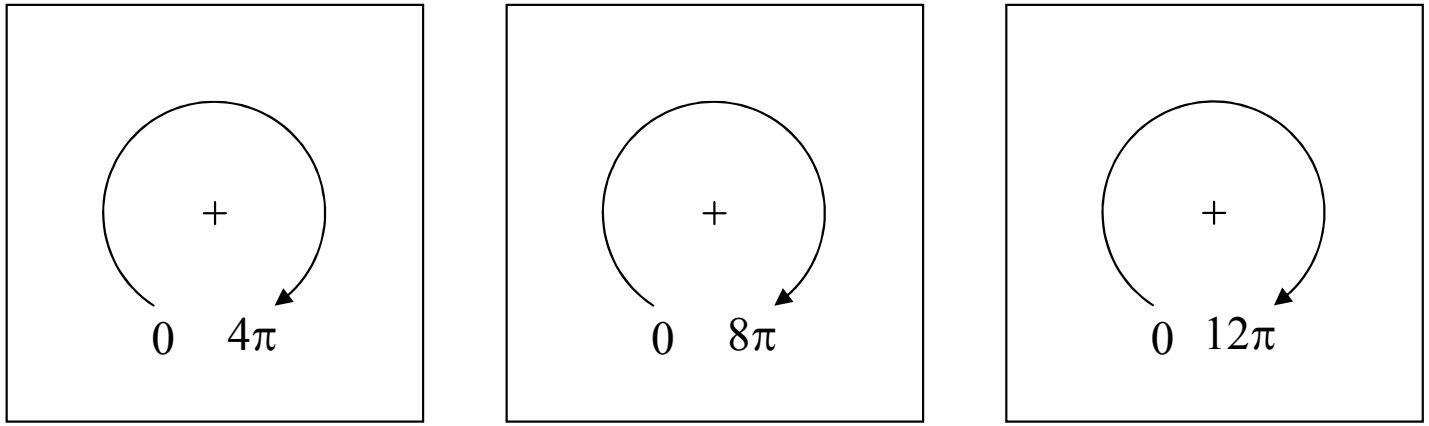
l_p: Topological charge (TC)

Mawet et al., ApJ, 633, 1191 (2005) / Foo et al., Opt. Lett., 30, 3308 (2005)

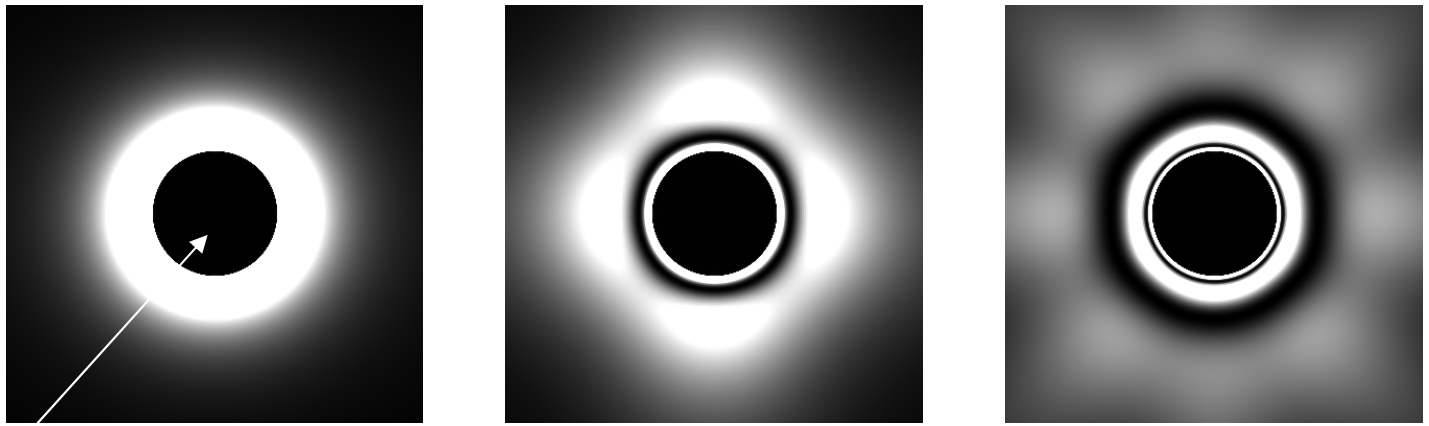
Optical vortex mask (OVM) coronagraph

TC =2 | TC=4 | TC=6

Mask function



Lyot-stop image



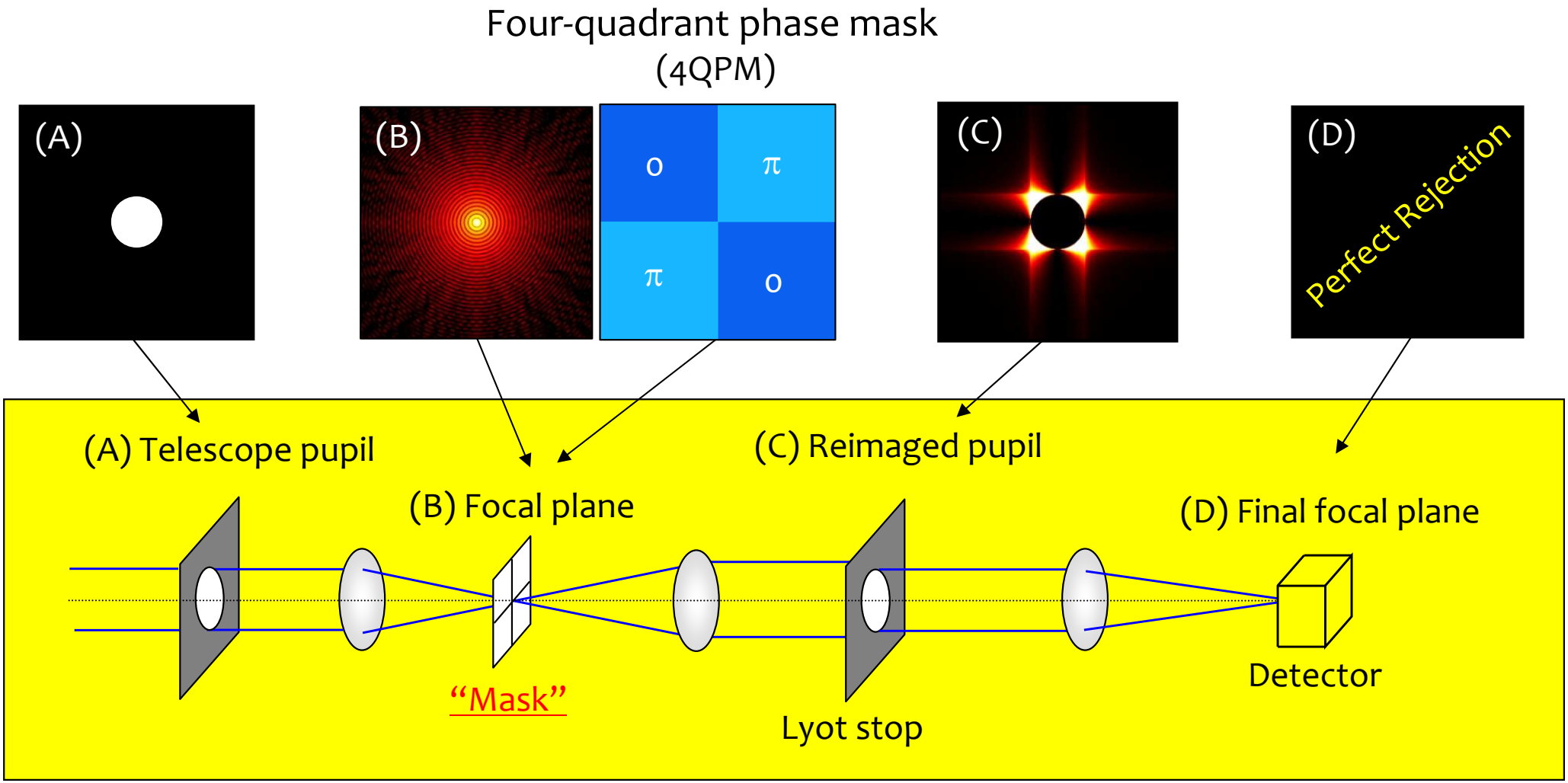
Zero-intensity inside pupil
(for point-like stars)

→ Higher order:
Tolerant of partially-resolved large stars

TC: Topological charge

Perfect stellar suppression by **even-charged** OVMs

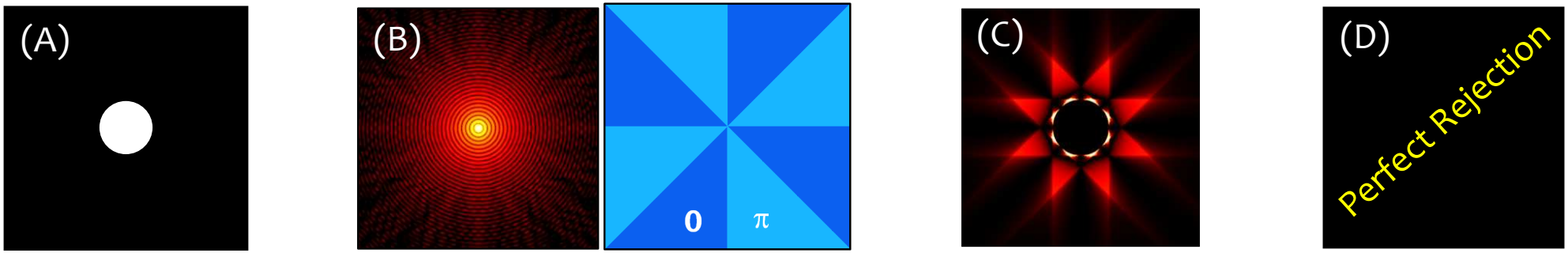
Four-quadrant phase-mask (4QPM) coronagraph



Rouan et al., PASP, 112, 1479 (2000)

Eight-octant phase-mask (8OPM) coronagraph

Eight-octant phase mask
(8OPM)



4QPM realizes perfect rejection for point-like stars

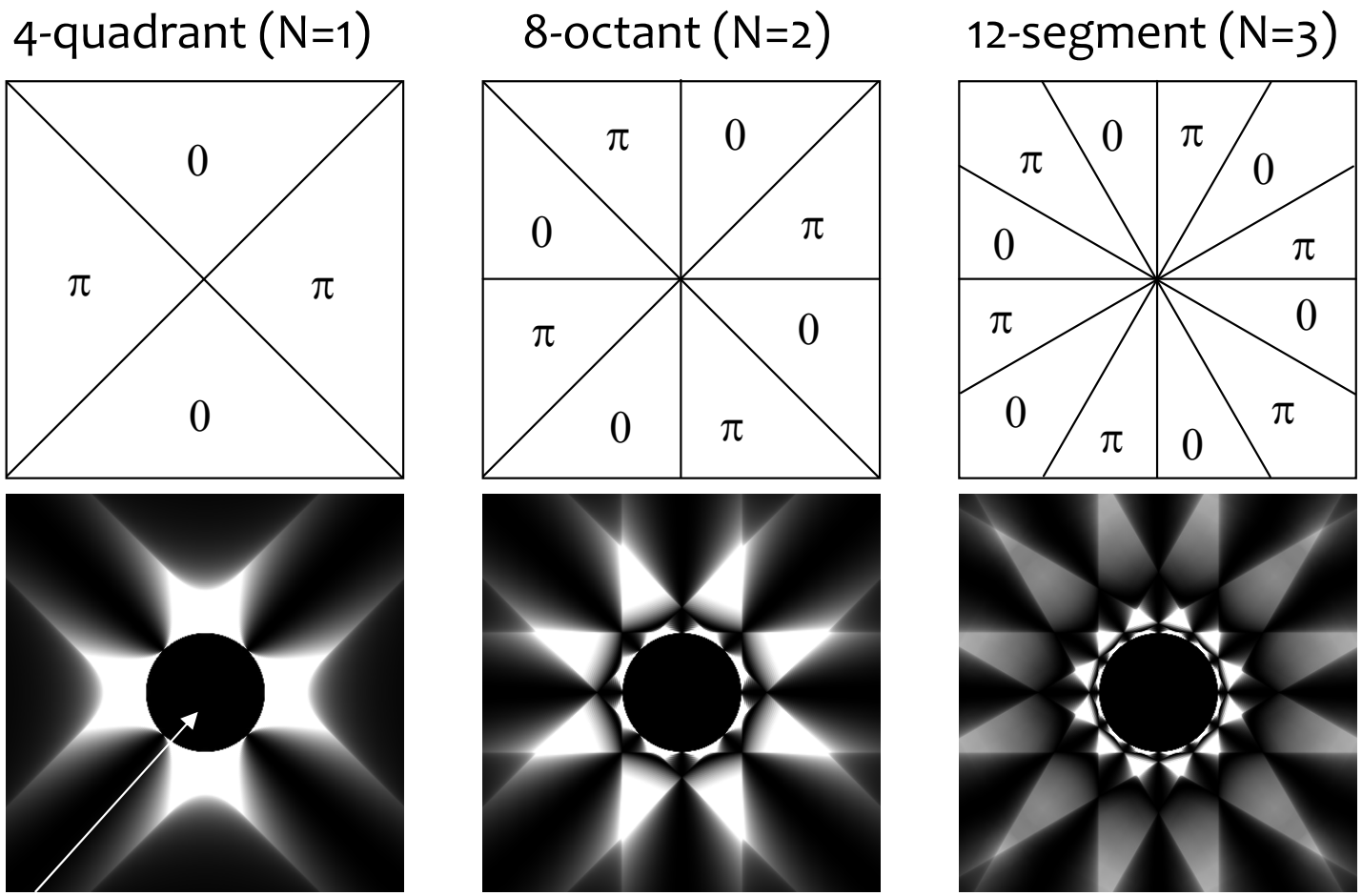
→ We proposed an 8OPM for effectively suppressing also partially resolved stars
(Murakami et al., PASP, 120, 1112, 2008)

→ 4N-segment phase masks (4N-SPM) are also effective (N=2 for 8OPM).
(Carlotti et al., A&A, 504, 663, 2009)

4N-segment phase-mask (4N-SPM) coronagraph

Mask function

Lyot-stop image



Zero-intensity inside pupil
(for a point-like star)

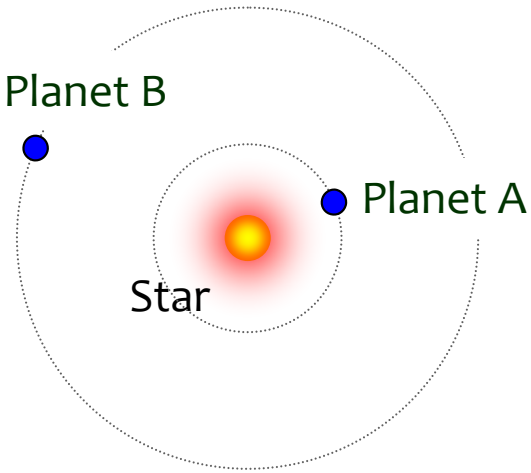
→ Higher order:
Tolerant of partially-resolved large stars

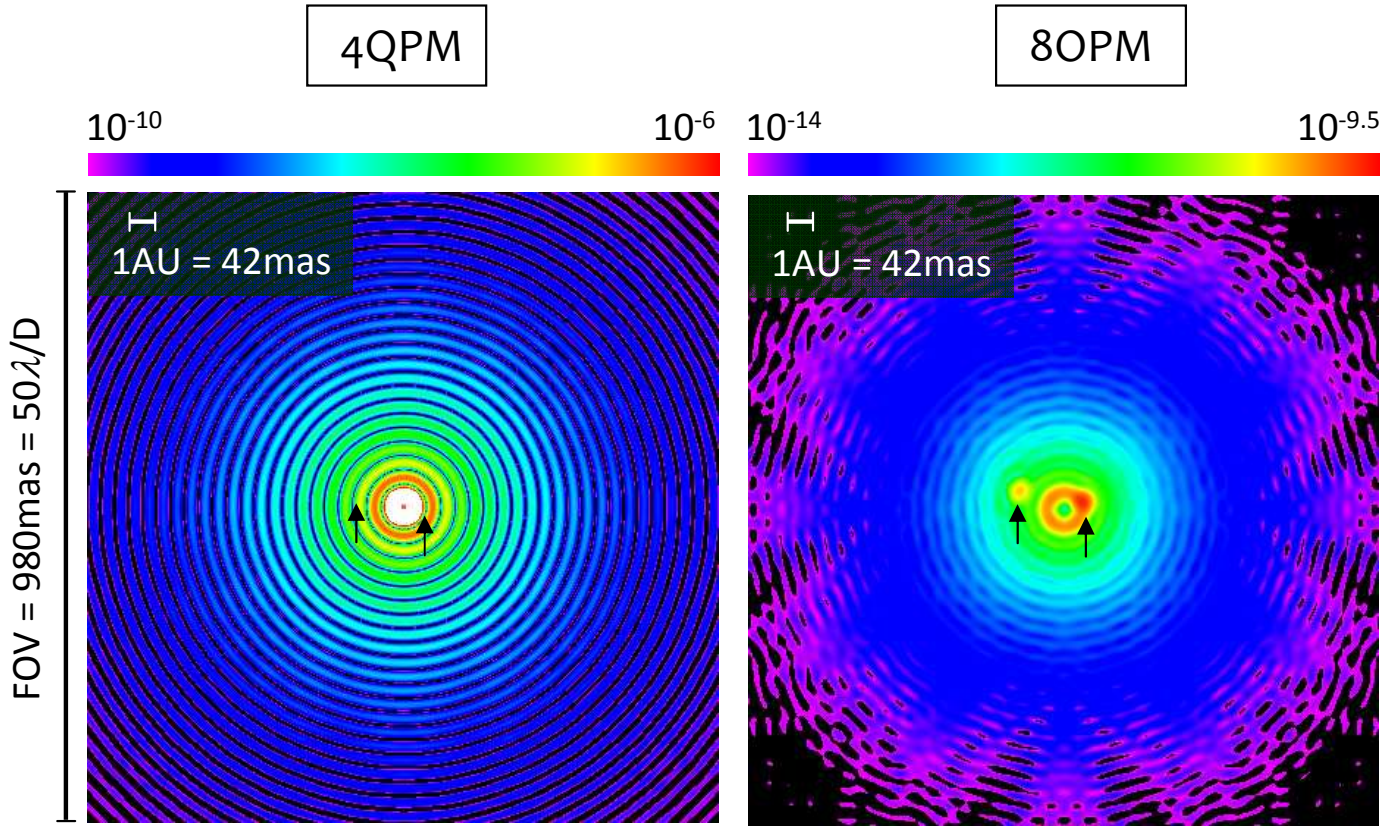
Perfect stellar suppression by **4N-segment** phase masks

HOKKAIDO UNIVERSITY

Simulation: Planets around a partially-resolved star

Simulated planetary system





Stellar size: 0.4mas
(corresponding to a Sun at 24 pc)
Planet A: 5×10^{-10} @32mas (0.75AU at 24 pc)
Planet B: 1×10^{-10} @76mas (1.8 AU at 24pc)

Optical parameters:
D=8m, λ=0.76μm (λ/D~20mas)

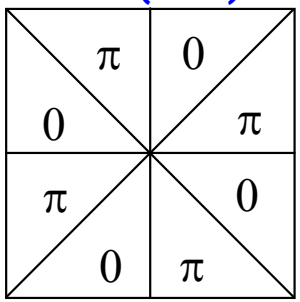
Two planets are directly imaged by the 8OPM coronagraph (black arrows).

4N-SPM coronagraph: A family of an OVM coronagraph

Mathematically, the 4N-segment phase masks can be expressed as a weighted sum of the optical vortex masks with various topological charges (by Fourier expansion).

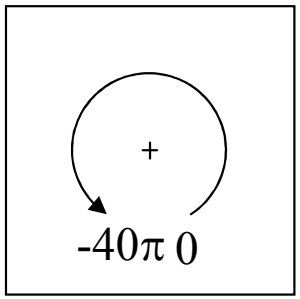
4N-SPM mask function: $$m(\theta) = \frac{2}{i\pi}\sum_{m=0}^{\infty}\frac{1}{2m+1}\underbrace{\left\{e^{2iN(2m+1)\theta} - e^{-2iN(2m+1)\theta}\right\}}_{\text{OVM mask functions}}$$

8OPM (N=2)



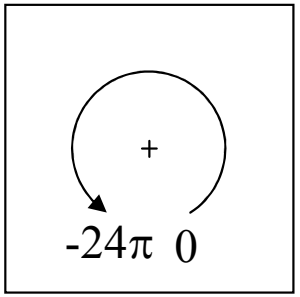
$$= \cdots + a_{-20} \times$$

TC=-20



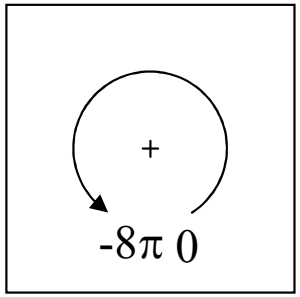
$$+ a_{-12} \times$$

TC=-12



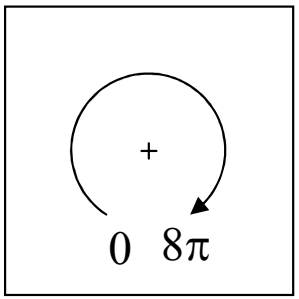
$$+ a_{-4} \times$$

TC=-4



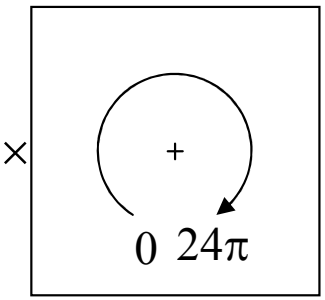
$$+ a_{4} \times$$

TC=+4



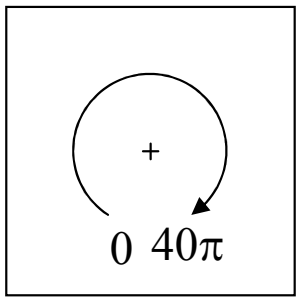
$$+ a_{12} \times$$

TC=+12



$$+ a_{20} \times$$

TC=+20



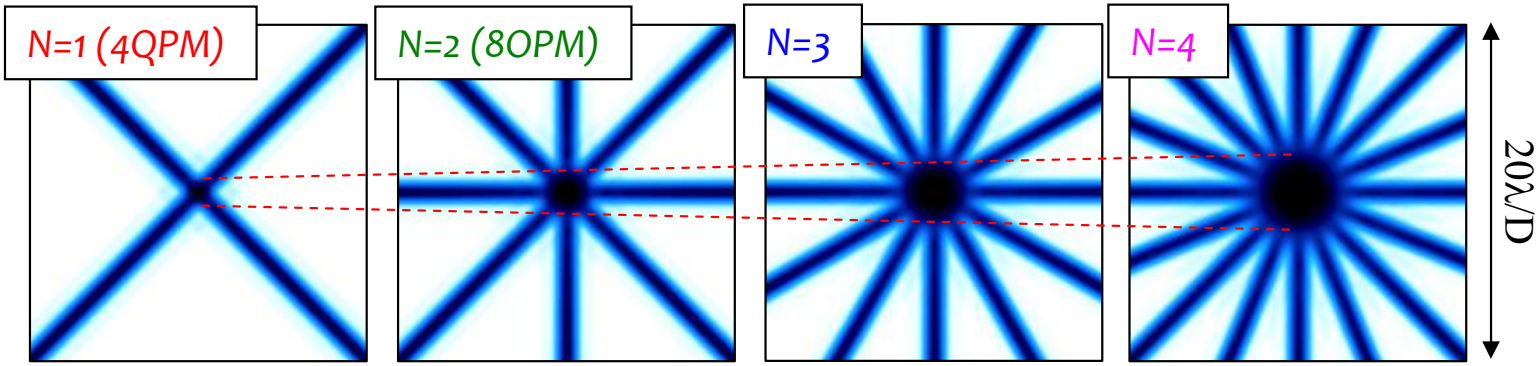
$$+ \cdots$$

a_m: Fourier coefficients
θ: Azimuth angle
TC: Topological charge

Murakami, Uemura, Baba, Nishikawa, Tamura, Hashimoto, Abe, PASP, 120, 1112 (2008) / Jenkins, MNRAS, 384, 515 (2008) / Carlotti et al., A&A, 504, 663 (2009)

4N-SPM and OVM: On-sky transmittance

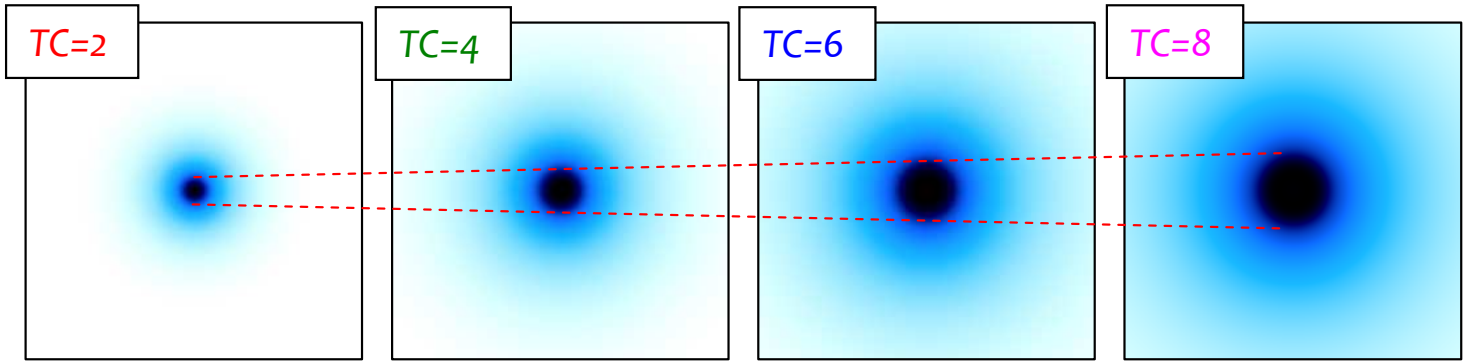
4N-SPM ➔ There are on-sky "dead zones" along transitions of the phase masks (Two exposures are required for obtaining a full FOV)



IWA~1λ/D IWA~2λ/D IWA~3λ/D IWA~4λ/D

→ ***Higher order***

OVM ➔ There are no "dead zones" (A full FOV can be obtained by only one exposure)

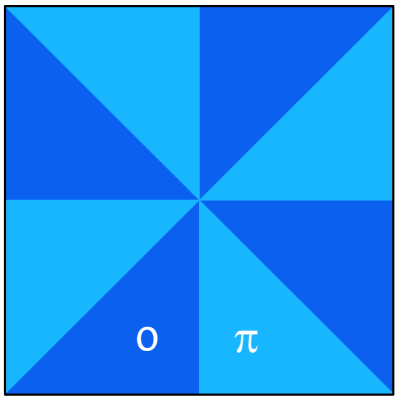


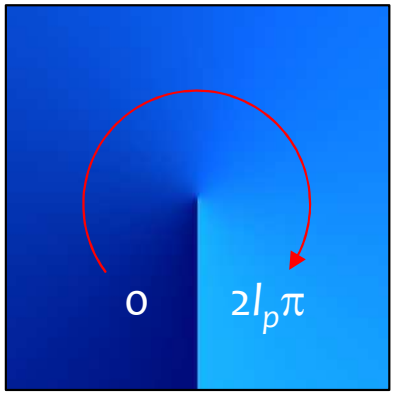
IWA~0.85λ/D IWA~1.6λ/D IWA~2.3λ/D IWA~3λ/D

Higher order: Tolerant of partially-resolved large stars

4N-SPM and OVM: Advantages and disadvantages

Advantages and **disadvantages** of the 4N-segment and optical vortex masks
(from my personal point of view…)





Simple mask geometry ☺
(binary structure)
On-sky dead zones ☹

☹ Complex mask geometry
(continuous structure)
☺ No on-sky dead zones

For the both cases …

- ✓ We must realize extremely **small manufacturing defects**
  (e.g., central singularity and transitions between segments)
- ✓ We must **achromatize** the masks
  (e.g., 0.5-1.0μm for space coronagraph missions)

Our approach

✓ For realizing the extremely small manufacturing defects, **we propose to use photonic crystal technology**

✓ For achromatizing the masks, **we propose to use Pancharatnam's phase**

Photonic crystal = Periodic nanostructure of refractive indices

Mask manufacturing: Autocloning technique (Photonic Lattice Inc.)

➔ Details of the manufacturing technique:

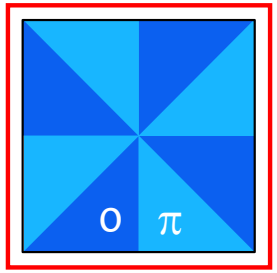
Kawakami et al., Appl. Phys. Lett., **74**, 463 (1999)
Kawashima et al., Appl. Phys. Lett., **77**, 2613 (2000)
http://www.photonic-lattice.com/en/index.html

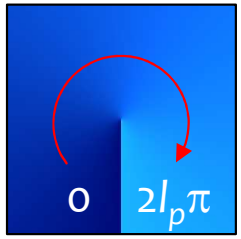
Topic 1: Eight-octant phase mask

Eight-octant phase mask based on photonic crystal technology

N. Murakami[1], J. Nishikawa[2], K. Yokochi[2,3], M. Tamura[2], N. Baba[1], H. Murakami[4], L. Abe[5]

[1] Hokkaido University,
[2] National Astronomical Observatory of Japan,
[3] Tokyo Univ. of Agriculture and Technology,
[4] Institute of Space and Astronautical Science/Japan Aerospace Exploration Agency,
[5] Univ. de Nice-Sophia Antipolis





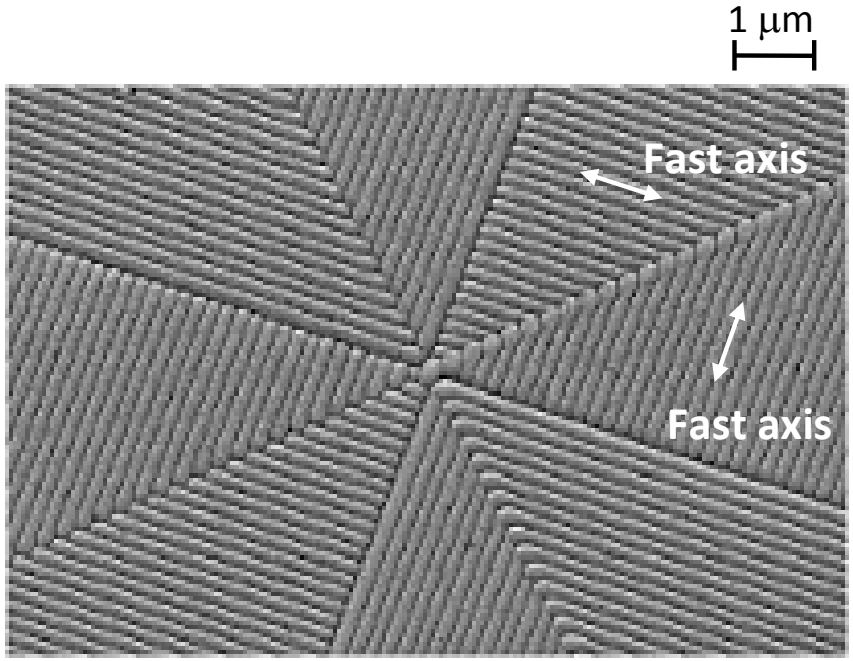
Reference

[1] N. Murakami, J. Nishikawa, K. Yokochi, M. Tamura, N. Baba, L. Abe, "Achromatic eight-octant phase-mask coronagraph using photonic crystal," ApJ, 714, 772 (2010).

Manufactured 8OPM: Overview

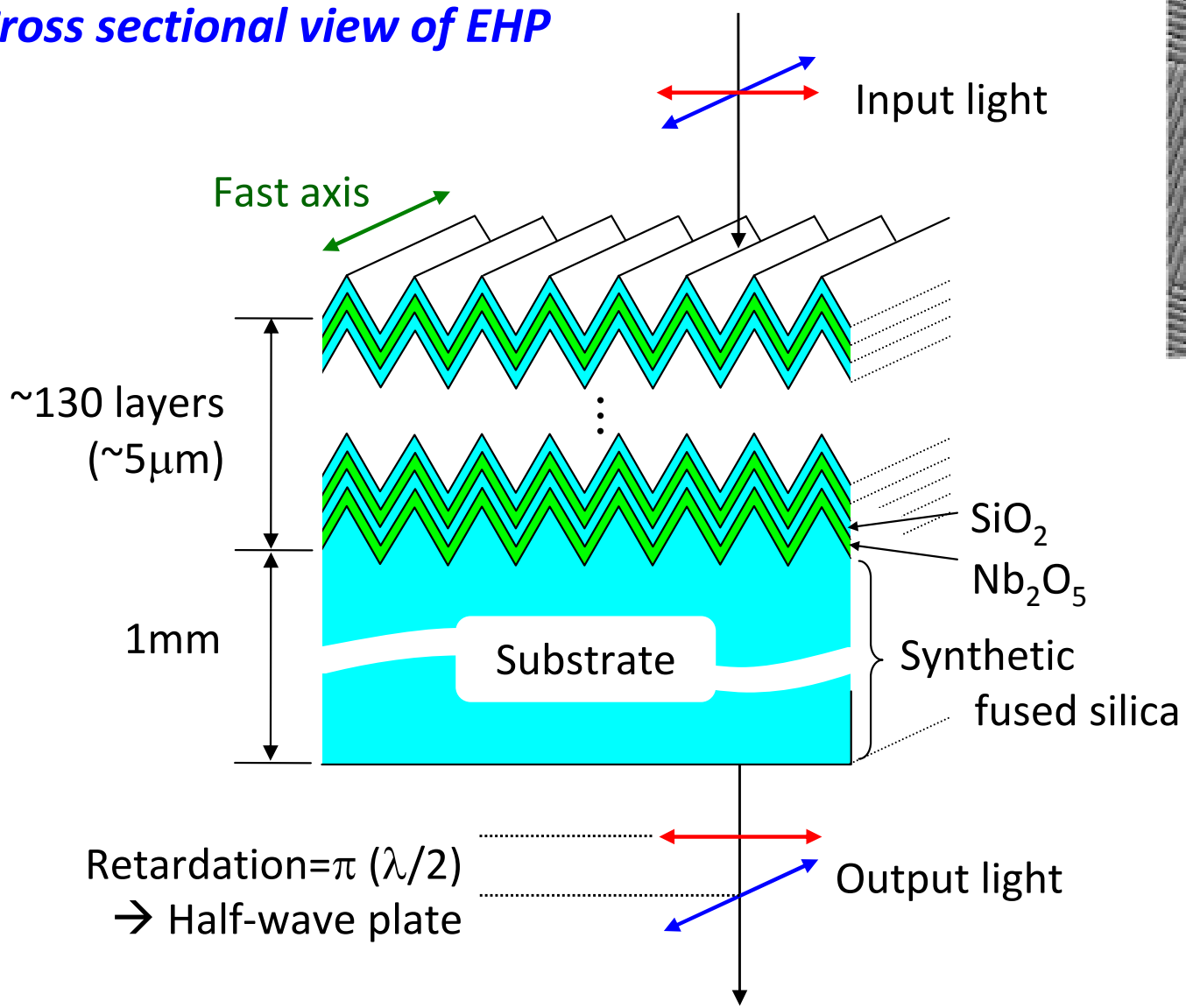
- Eight-octant phase mask (8OPM) = Eight-octant half-wave plate (EHP)
- Specifications
  - Optimized wavelength: 633nm
  - Transitions between eight segments ~100nm
  - Central defect ~300nm

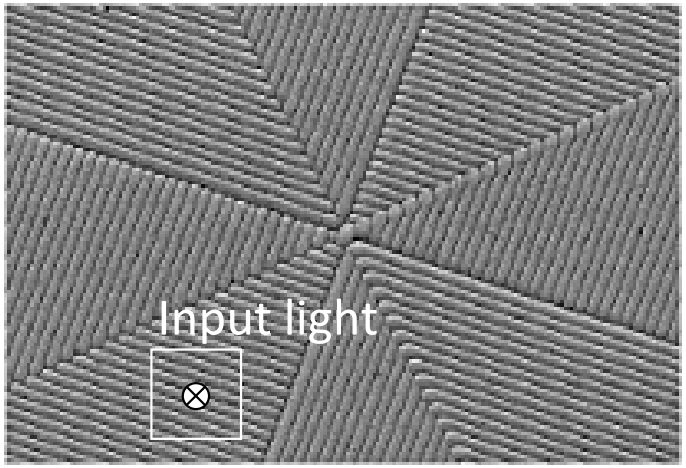
Manufactured by Photonic Lattice Inc.



Manufactured 8OPM: Structure

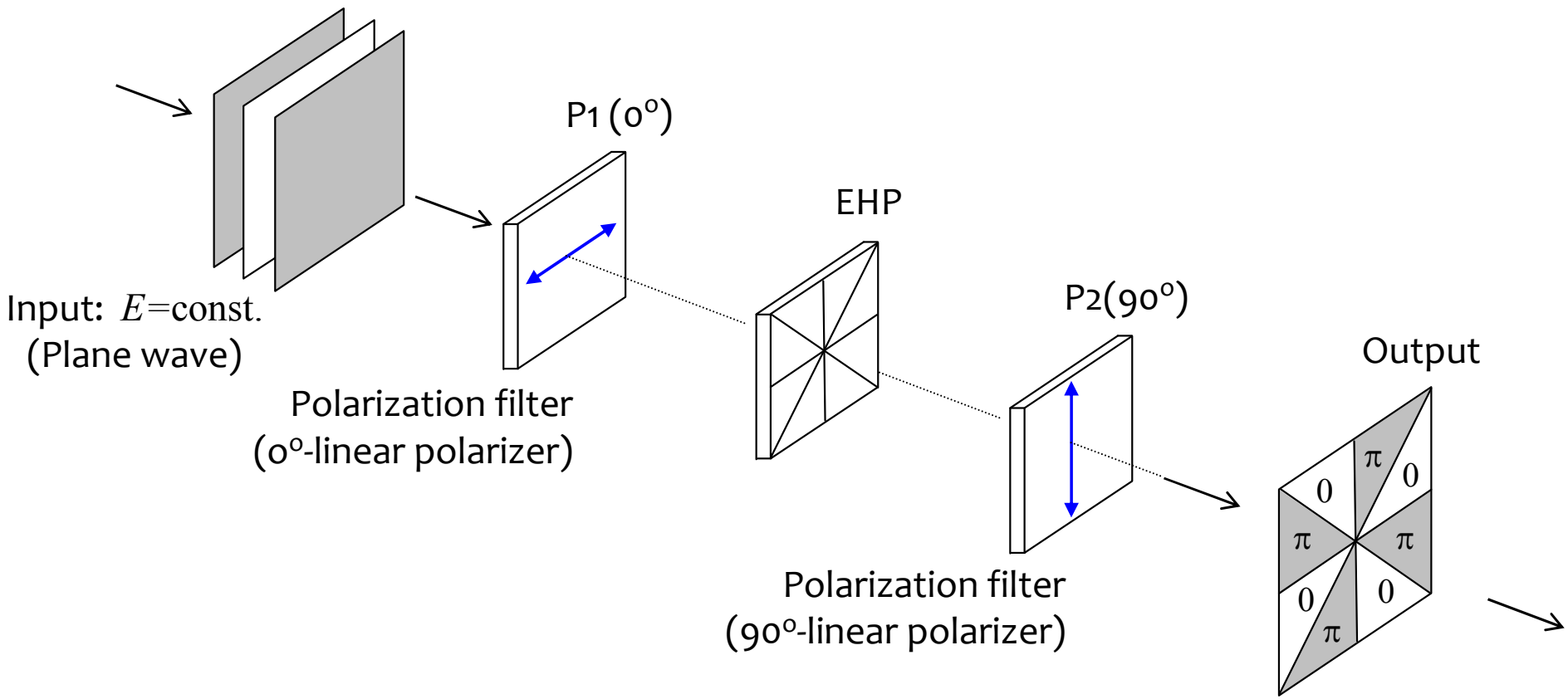
Cross sectional view of EHP



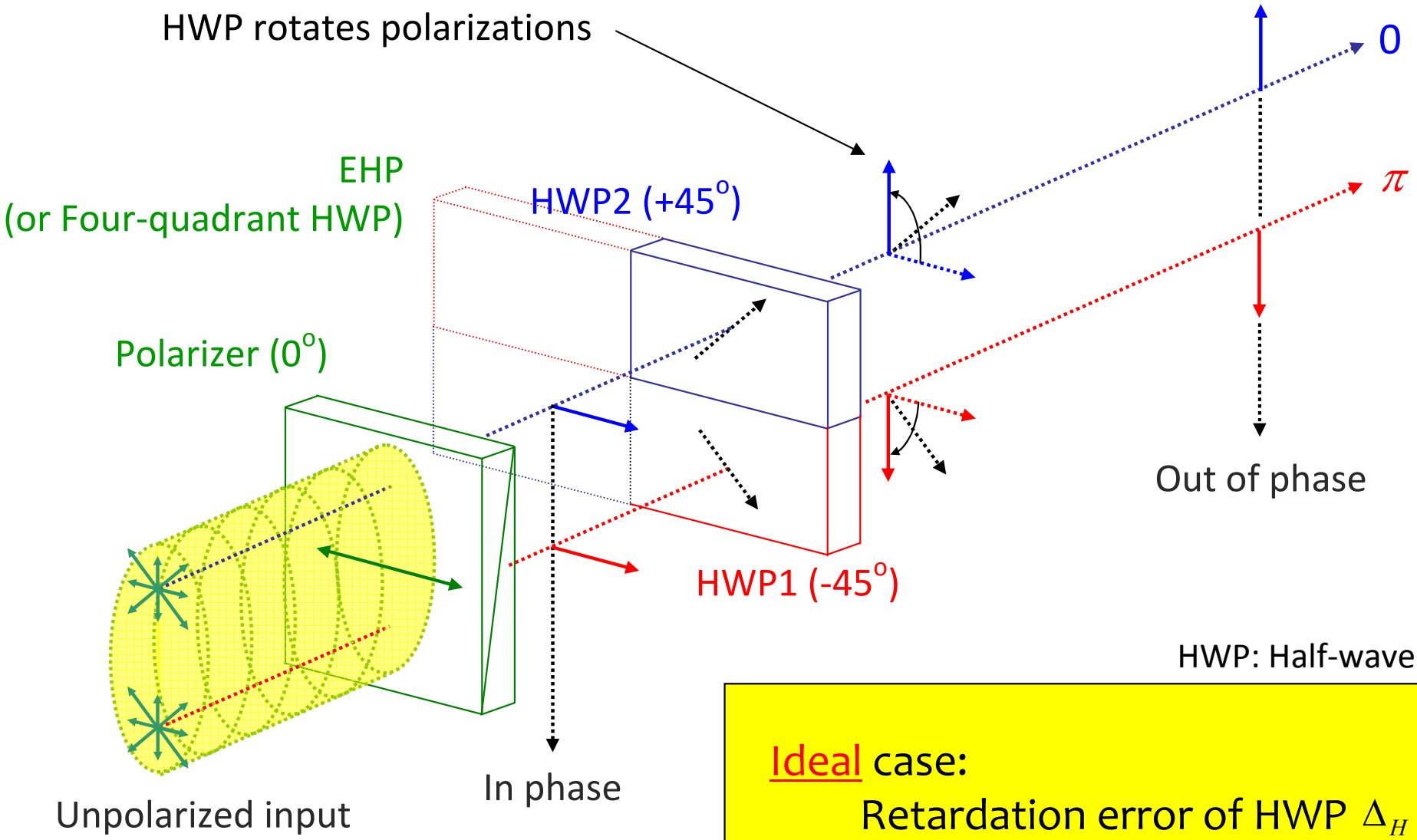


Fully-achromatic 8OPM: Principle

EHP is placed between polarization filters (Polarization-filtered EHP)
→ Fully-achromatic 8OPM can be realized by Pancharatnam's phase



Fully-achromatic 8OPM: Details of operation

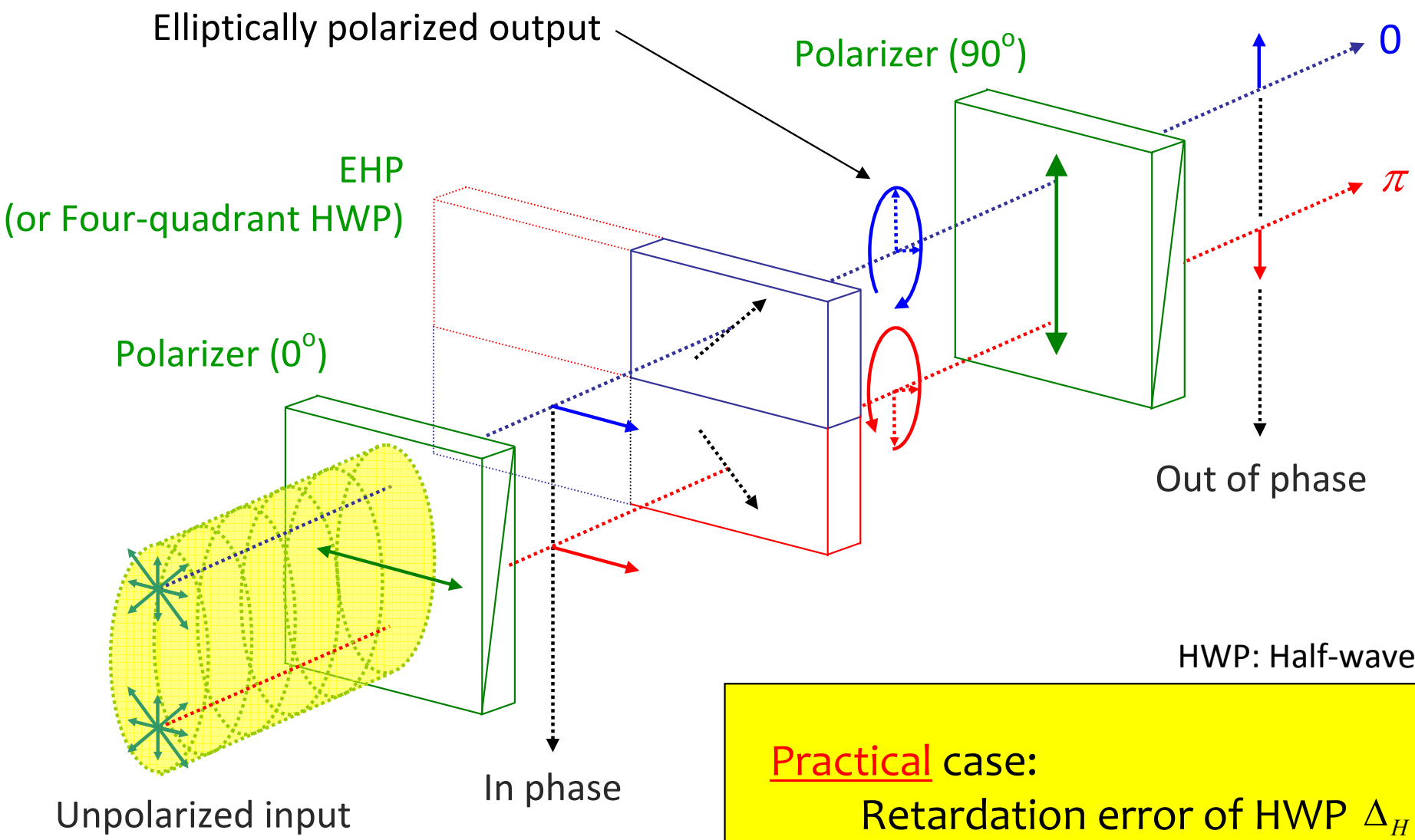


HWP: Half-wave plate

Ideal case:

Retardation error of HWP $\Delta_H = 0$

Fully-achromatic 8OPM: Details of operation

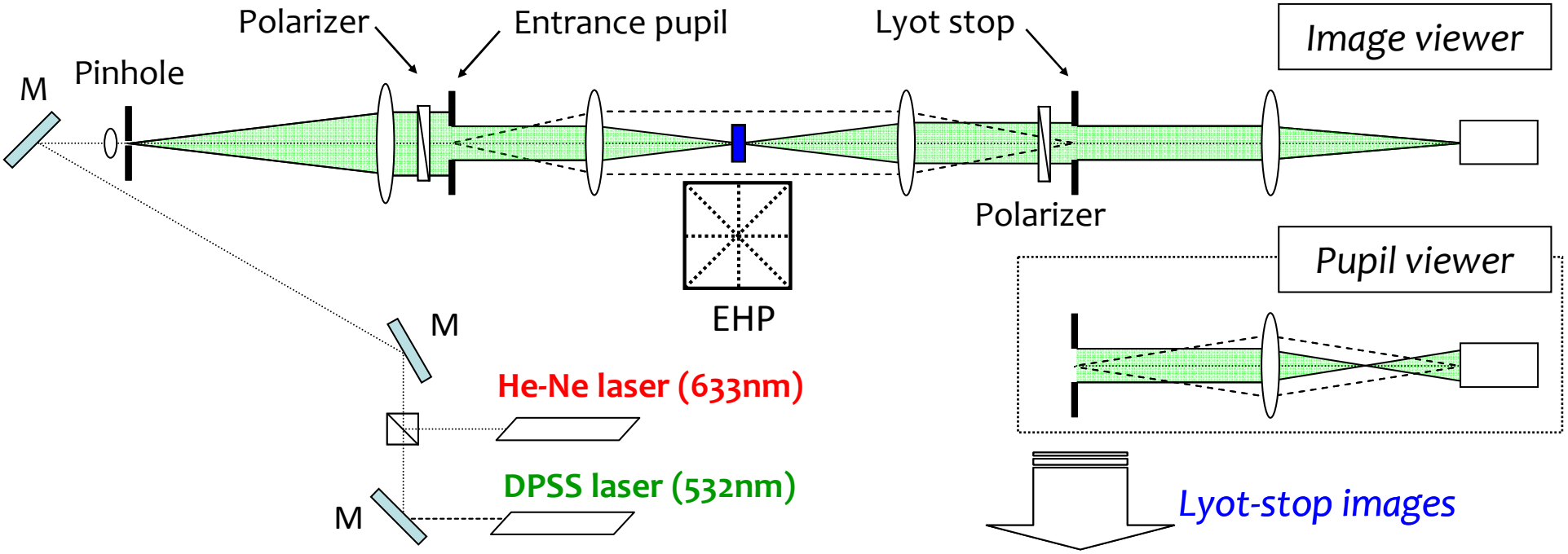


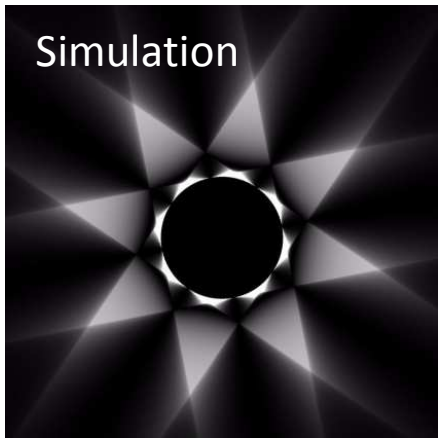
HWP: Half-wave plate

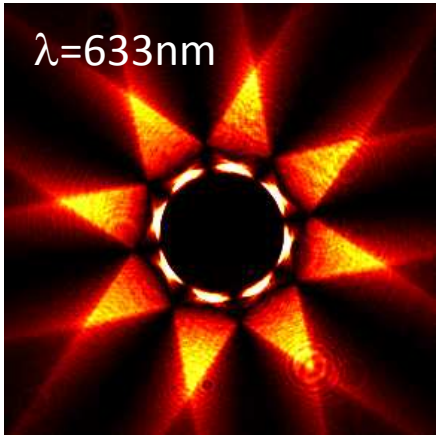
Practical case:

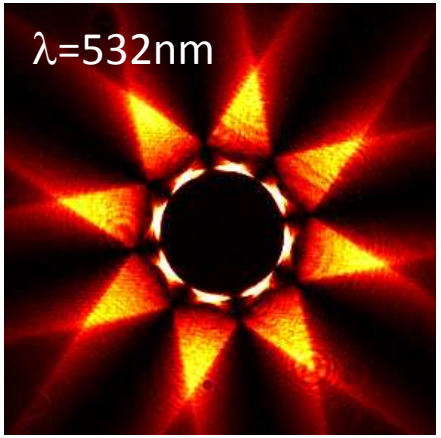
Retardation error of HWP $\Delta_H \neq 0$

Laboratory demonstration: Lyot-stop images



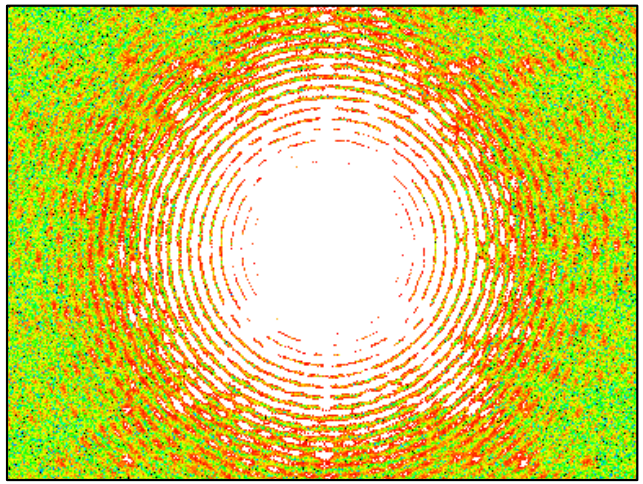




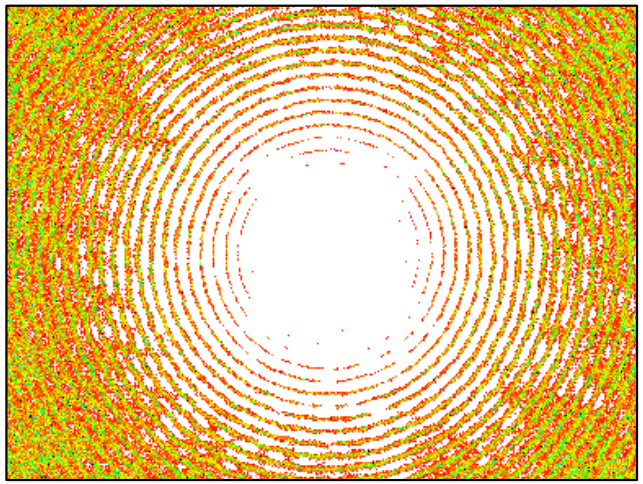


Laboratory demonstration: Final images

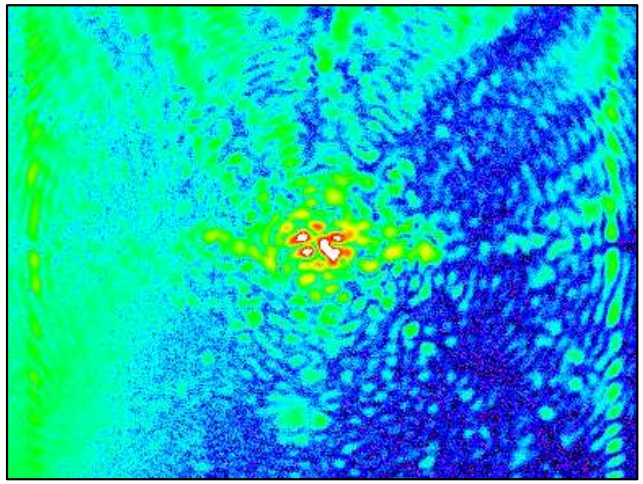
Without coronagraph (532nm)



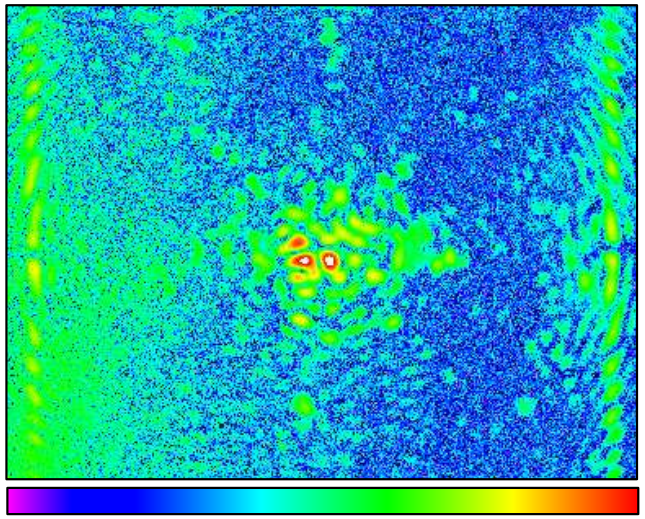
Without coronagraph (633nm)



With coronagraph (532nm)



With coronagraph (633nm)

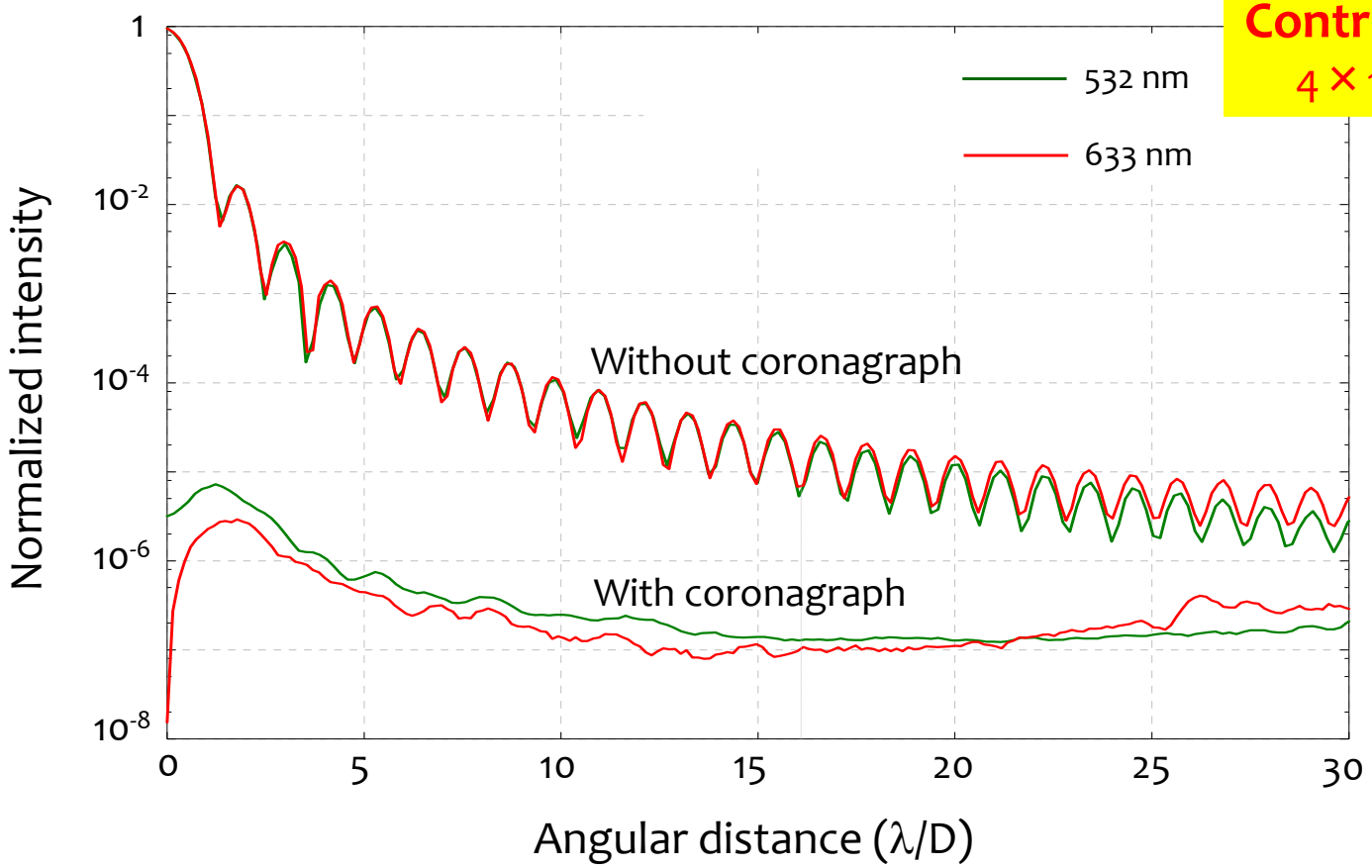


1E-8 1E-5

Laboratory demonstration: Final images

Radial profiles of final images

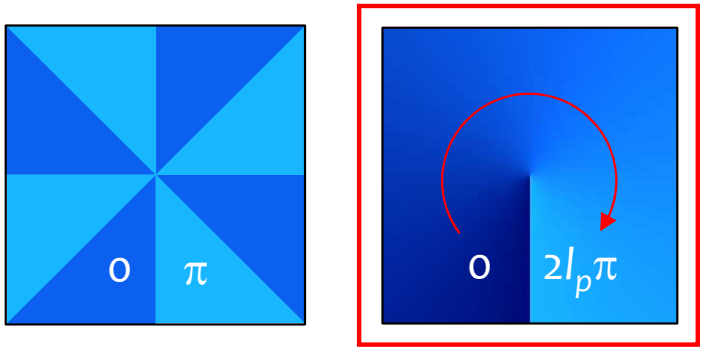
Contrast (λ=532nm)
7×10^{-7} (@5λ/D)
Contrast (λ=633nm)
4×10^{-7} (@5λ/D)



Topic 2: Optical vortex mask

Optical vortex mask based on photonic crystal technology

N. Murakami, S. Hamaguchi, K. Oka, M. Sakamoto, A. Ise, N. Baba
(Hokkaido University)



References

[1] N. Murakami, N. Baba, A. Ise, M. Sakamoto, K. Oka, "Laboratory demonstration of an optical vortex mask coronagraph using photonic crystal," In the Spirit of Lyot (2010).
[2] N. Murakami, S. Hamaguchi, K. Oka, N. Baba, "Two-channel vector vortex coronagraph for high-contrast astronomy (a tentative title)," in prep. (2011).

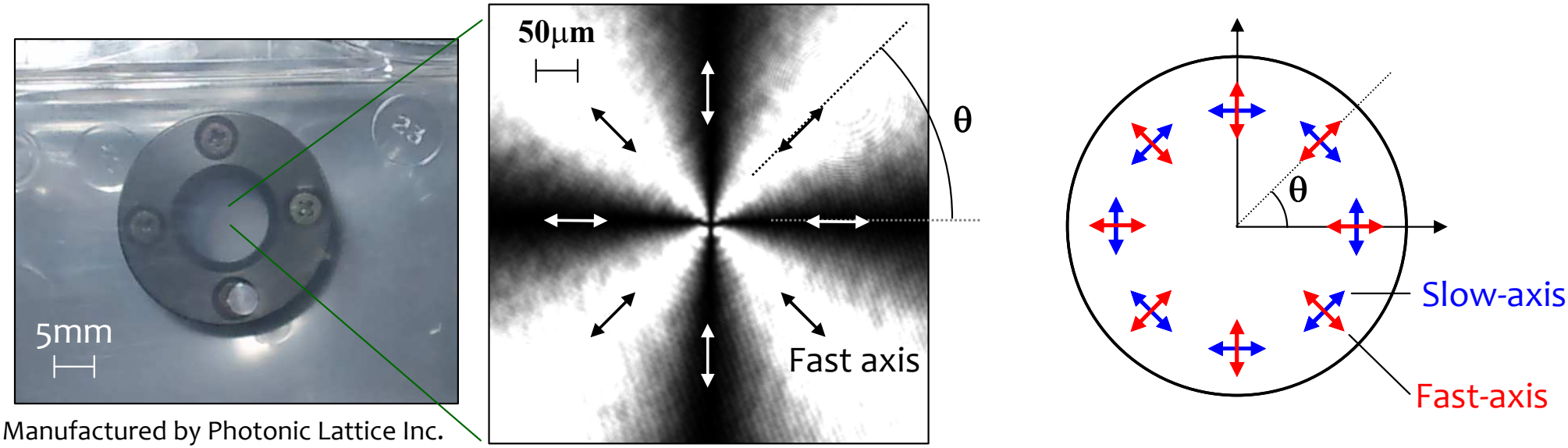
Precursor works

[1] D. Mawet et al., "Annular groove phase mask coronagraph," ApJ, 633, 1191 (2005).
[2] D. Mawet et al., "Optical vectorial vortex coronagraphs using liquid crystal polymers: theory, manufacturing, and laboratory demonstration," Opt. Exp., 17, 1902 (2009).

Manufactured "VVM": Overview

- Optical vortex mask (OVM) = Axially-symmetric half-wave plate (AHP)
  - Also known as "vector vortex mask (VVM)"
    (Mawet et al., Opt. Exp., 17, 1902, 2009)
- Specifications
  - Designed wavelength: 633nm
  - Central phase singularity < 3μm (possibly submicron)

AHP placed between two polarizers



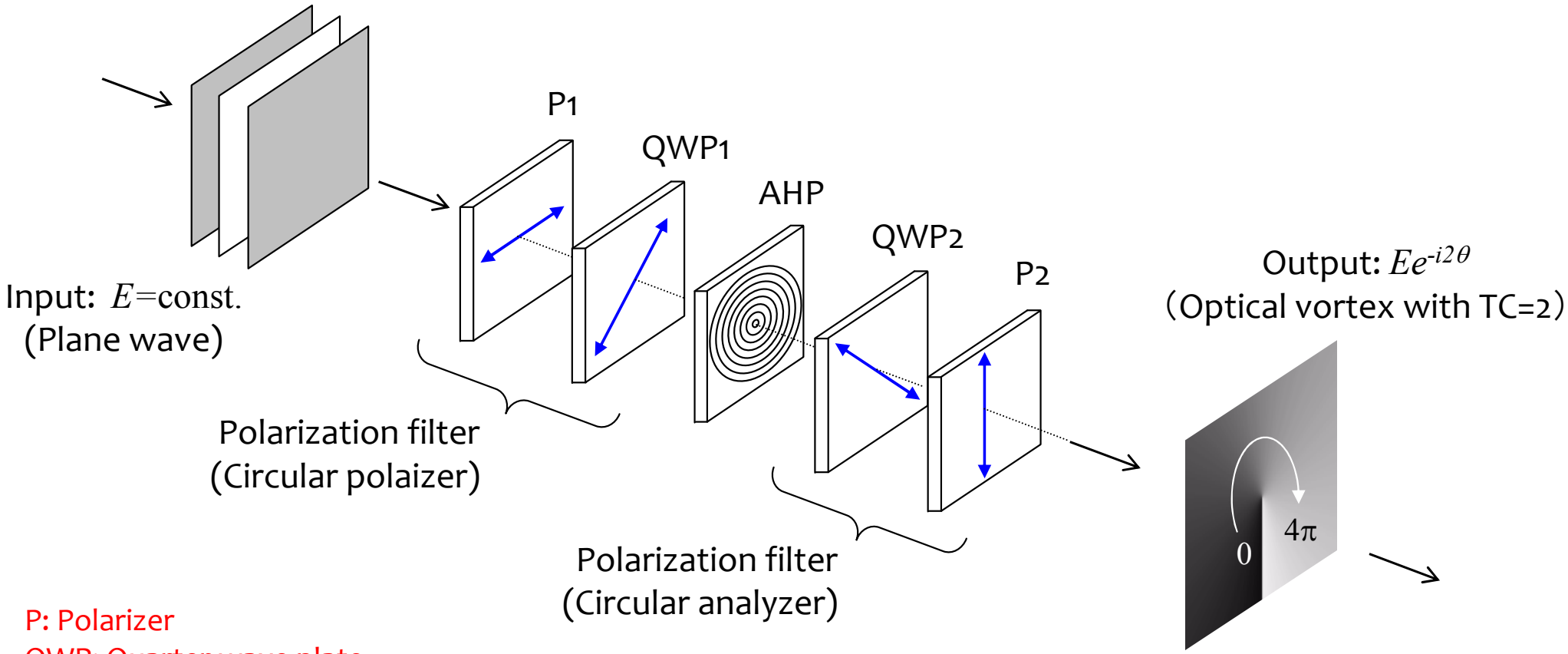
Manufactured by Photonic Lattice Inc.

Fully-achromatic VVM: Principle

AHP is placed between polarization filters (Polarization-filtered AHP)

→ Achromatic optical vortex (TC=2) can be realized by Pancharatnam's phase

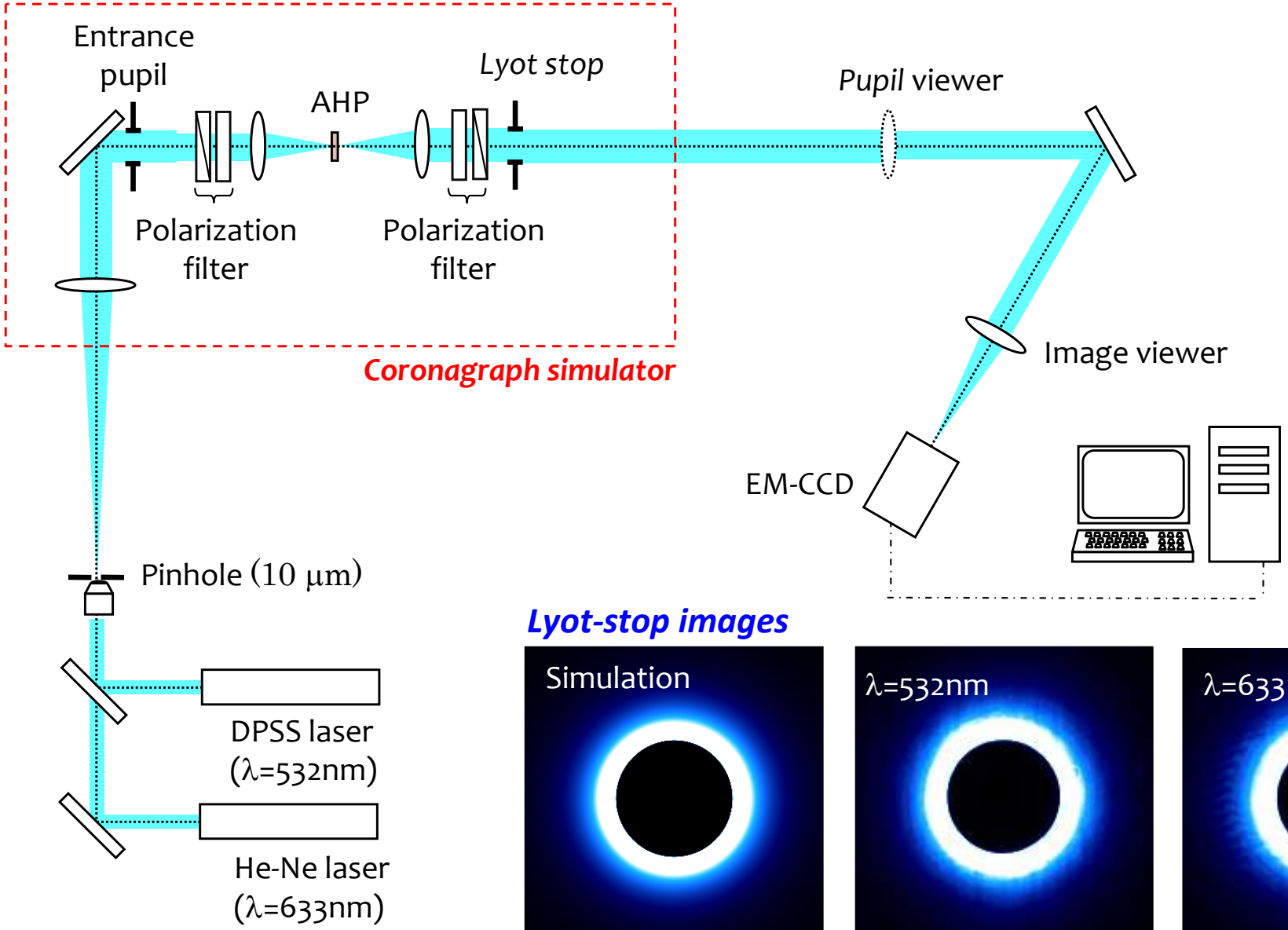
(Murakami et al., in prep.)



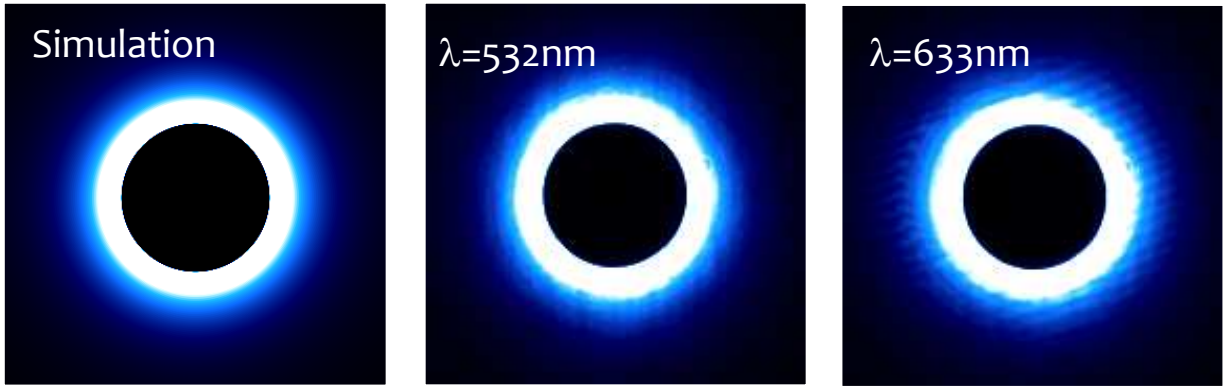
P: Polarizer

QWP: Quarter-wave plate

Laboratory demonstration: Lyot-stop images

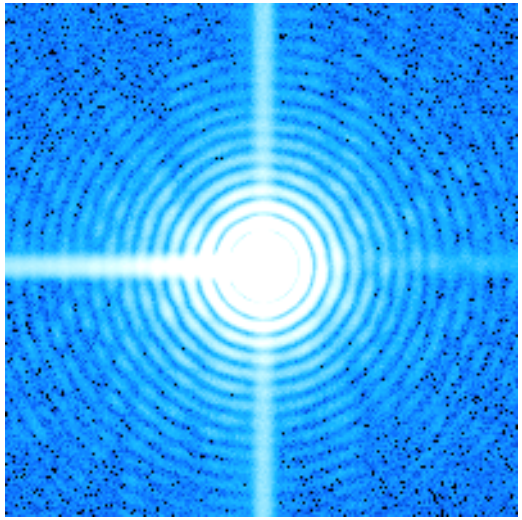


Lyot-stop images

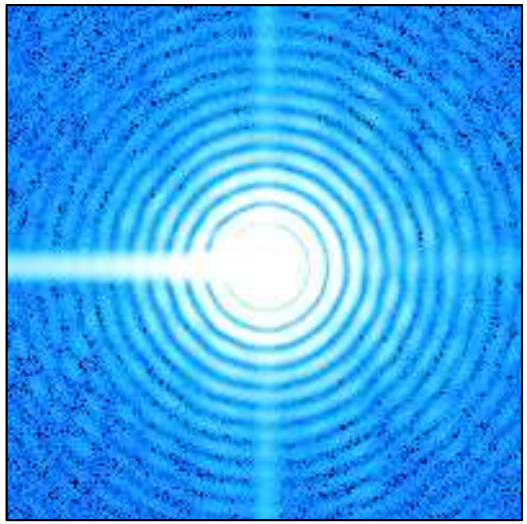


Laboratory demonstration: Final images

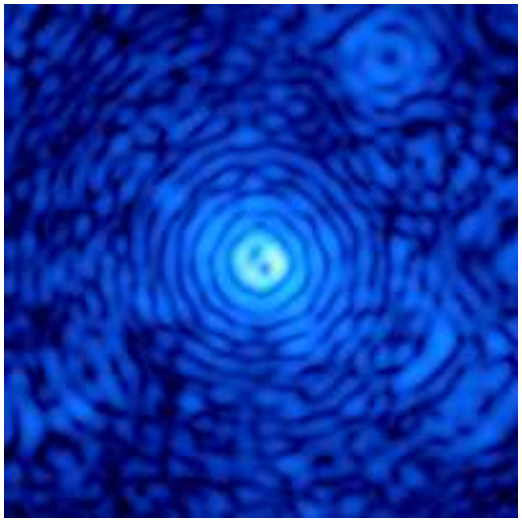
Without coronagraph (532nm)



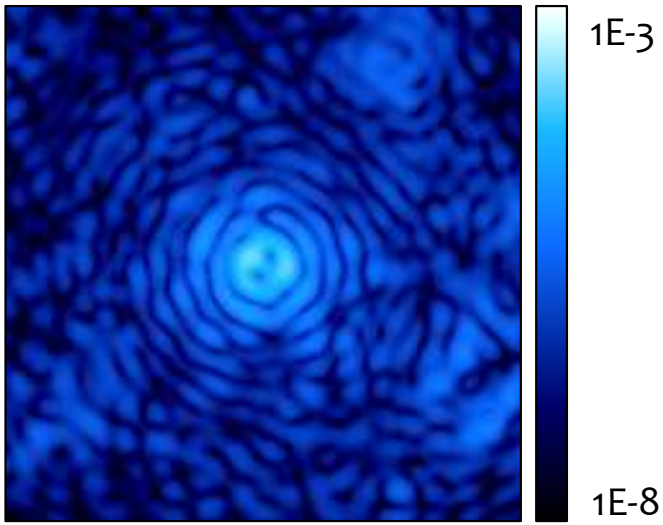
Without coronagraph (633nm)



With coronagraph (532nm)



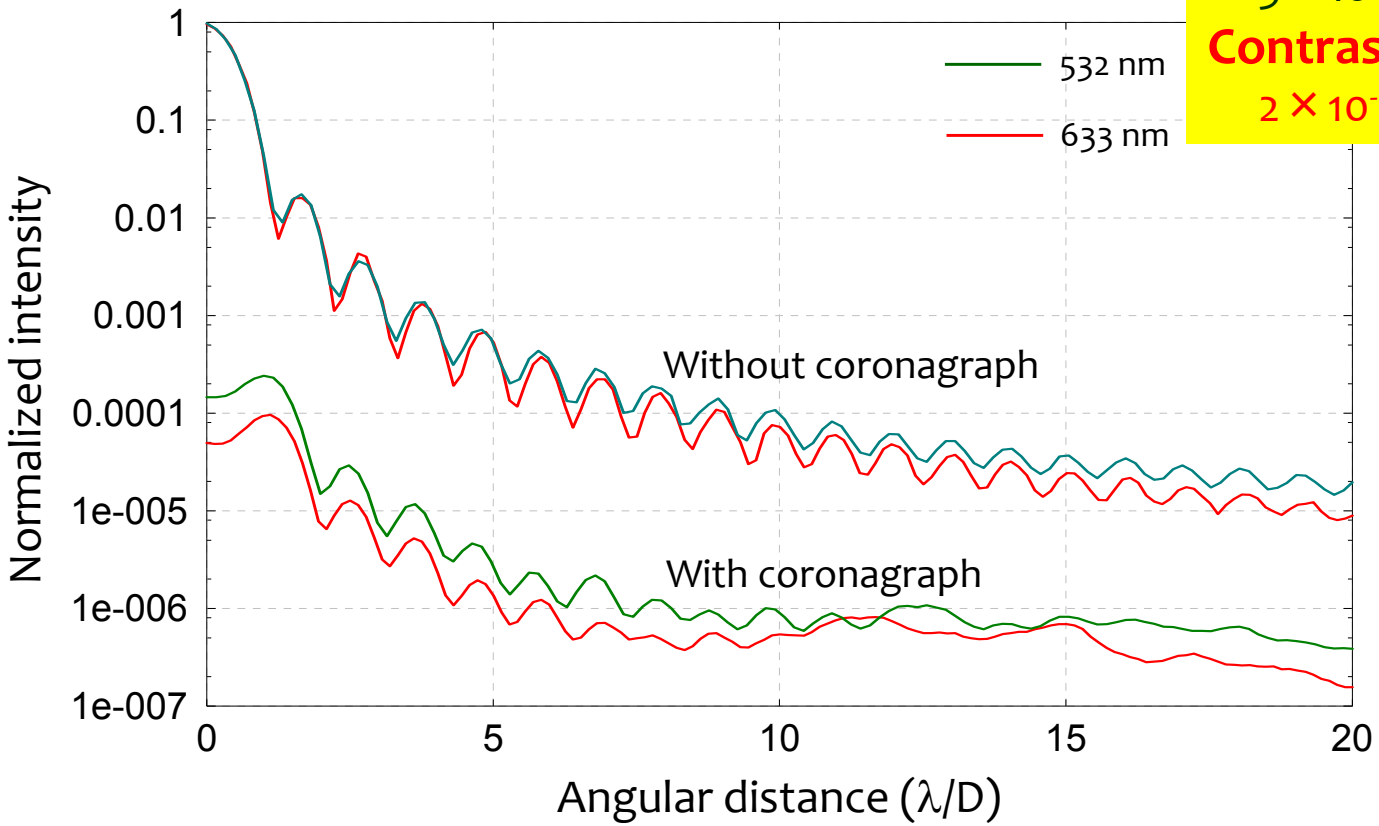
With coronagraph (633nm)



Laboratory demonstration: Final images

Radial profiles of final images

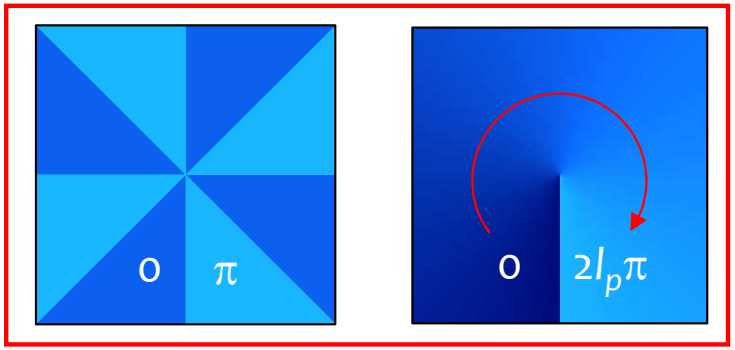
Contrast (λ=532nm)
3×10^{-6} (@5λ/D)
Contrast (λ=633nm)
2×10^{-6} (@5λ/D)



Recently, we have achieved higher contrast $<10^{-6}$ @5λ/D over λ=543-633nm (Murakami et al., in prep., 2011)

Two-channel coronagraph

Two-channel coronagraph configuration for improved system throughput



References

[1] N. Murakami, J. Nishikawa, K. Yokochi, M. Tamura, N. Baba, L. Abe, "Achromatic eight-octant phase-mask coronagraph using photonic crystal," ApJ, 714, 772 (2010).

[2] N. Murakami, T. Inabe, T. Komatsu, J. Nishikawa, N. Hashimoto, M. Kurihara, N. Baba, M. Tamura, "Polarization-interferometric eight-octant phase-mask coronagraph using ferroelectric liquid crystal for exoplanet detection," Proc. SPIE, 7731, 77314E (2010).

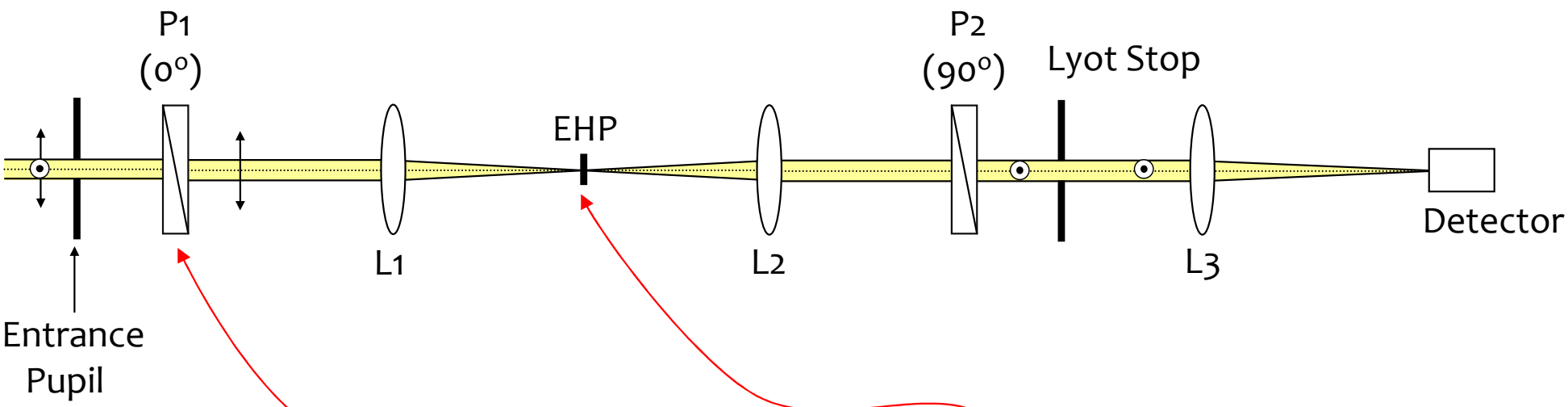
[3] N. Murakami, N. Baba, A. Ise, M. Sakamoto, K. Oka, "Laboratory demonstration of an optical vortex mask coronagraph using photonic crystal," In the Spirit of Lyot (2010).

[4] N. Murakami, S. Hamaguchi, K. Oka, N. Baba, "Two-channel vector vortex coronagraph for high-contrast astronomy (a tentative title)," in prep. (2011).

Two-channel coronagraph: Principle

A problem of "single-channel" 8OPM or VVM coronagraph

→ Low system throughput

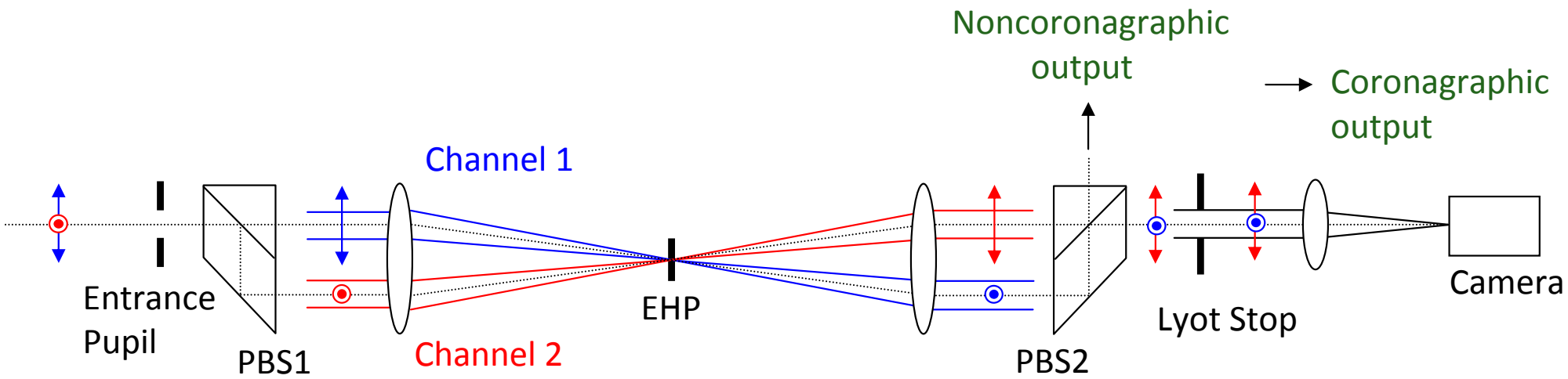


System throughput: $T = \frac{1}{2}\cos^2\frac{\Delta_H}{2}$

Where Δ_H is a retardation error of EHP (or AHP)

Two-channel coronagraph: Principle

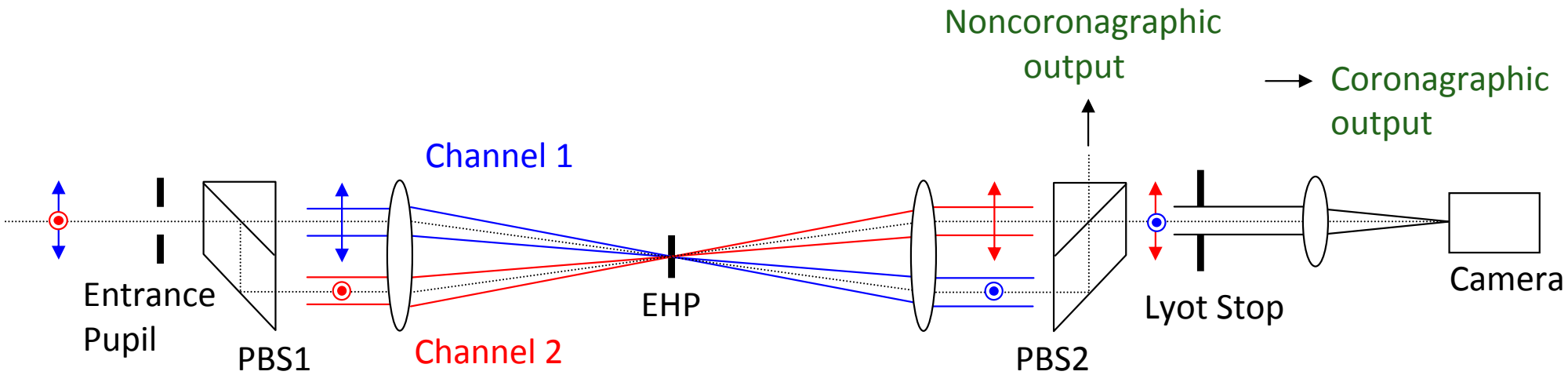
"Two-channel" coronagraph → System throughput becomes twice!!



System throughput: $T = 2 \times \frac{1}{2} \cos^2 \frac{\Delta_H}{2}$

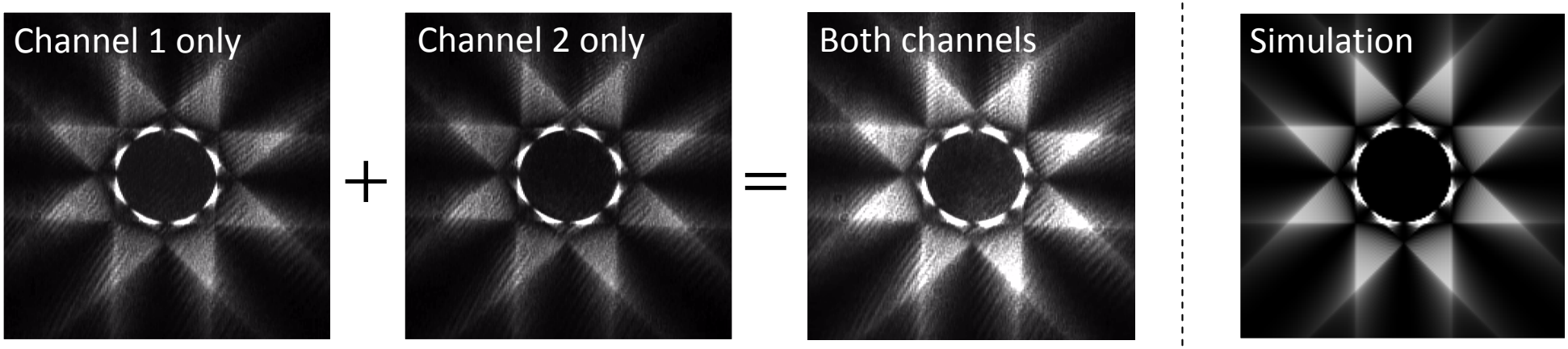
Where Δ_H is a retardation error of EHP (or AHP)

Two-channel coronagraph: Laboratory demonstration



Lyot-stop images acquired with two-channel coronagraph:

He-Ne laser, ferroelectric liquid-crystal EHP (manufactured by CITIZEN HOLDINGS Co., Ltd.) are used

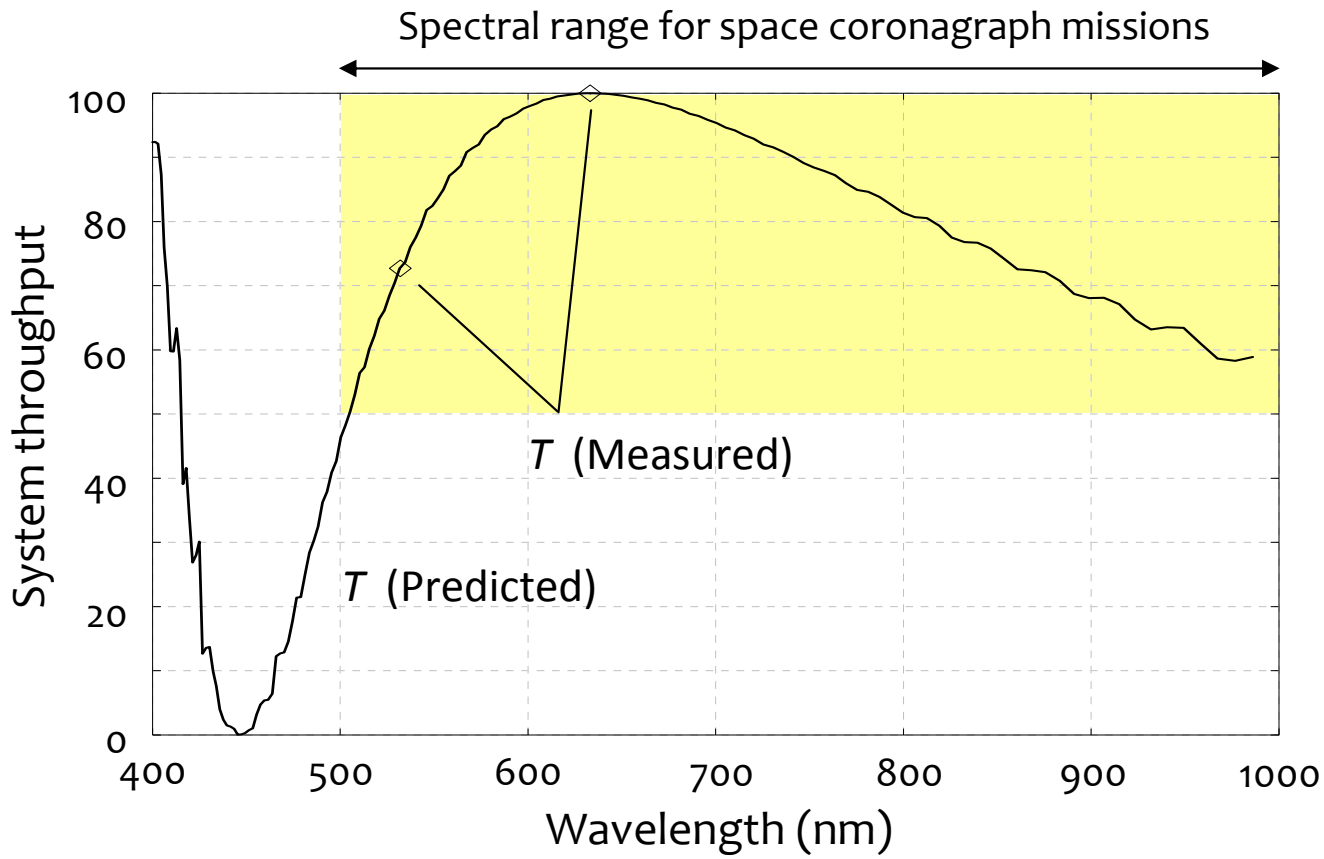


Two-channel coronagraph with photonic-crystal VVM has also been proposed and demonstrated (Murakami et al., in prep., 2011)

Two-channel coronagraph: System throughput

System throughput estimated from retardation data of the photonic-crystal EHP and AHP

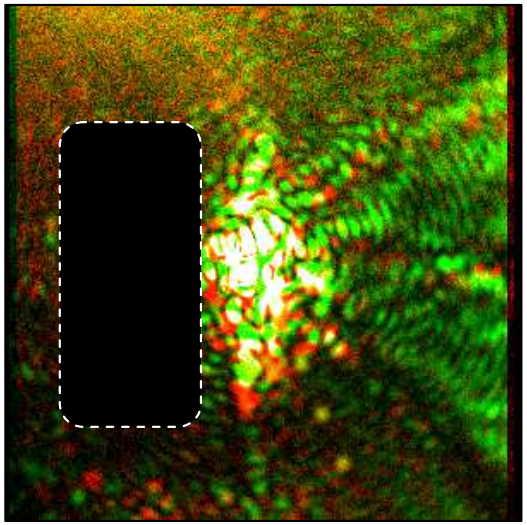
→ System throughput becomes twice and reaches to ~100% at the optimized wavelength



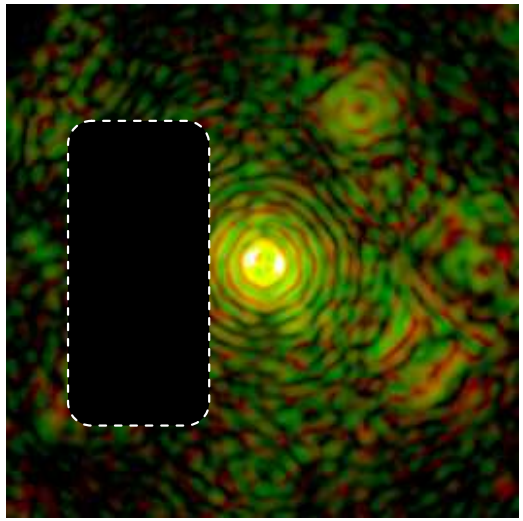
Summary

- We proposed to use photonic crystal technology for focal-plane coronagraph masks (8OPM and VVM)
  - Photonic-crystal technology → Small manufacturing defects (~submicron)
  - Polarization filters → Fully achromatic
  - Two-channel configuration → High throughput

8OPM result (two λs)



VVM result (two λs)



Although there are several issues to be dealt with …

8OPM

☹ On-sky "dead-zone"

VVM

☹ Difficult to realize "higher-order" masks

☺ Both approaches are very promising indeed!

We are creating "dark holes" at HCIT/JPL!!

Thank you very much for your kind attention

Acknowledgments

We really appreciate Wesley Traub, Dimitri Mawet, John Trauger, Dwight Moody, Brian Kern, and all of the JPL colleagues for providing us with an opportunity for the HCIT tests of our coronagraph masks!