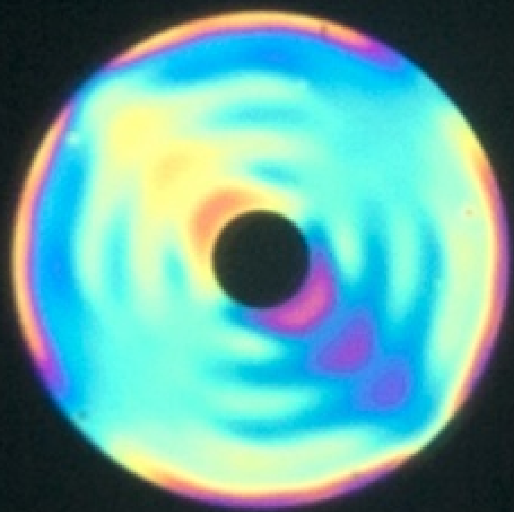
vector Apodizing Phase Plate coronagraph

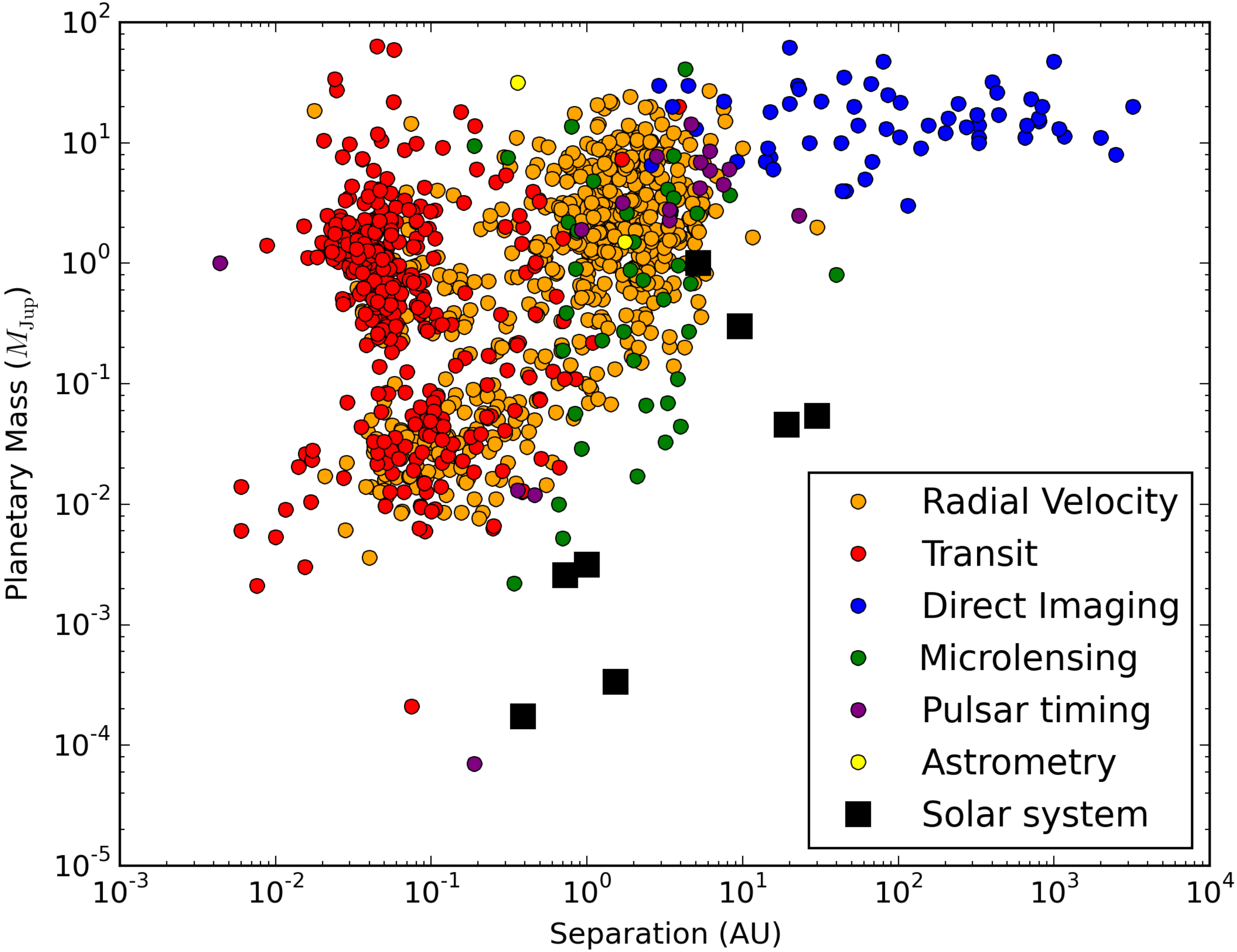


Gilles Otten

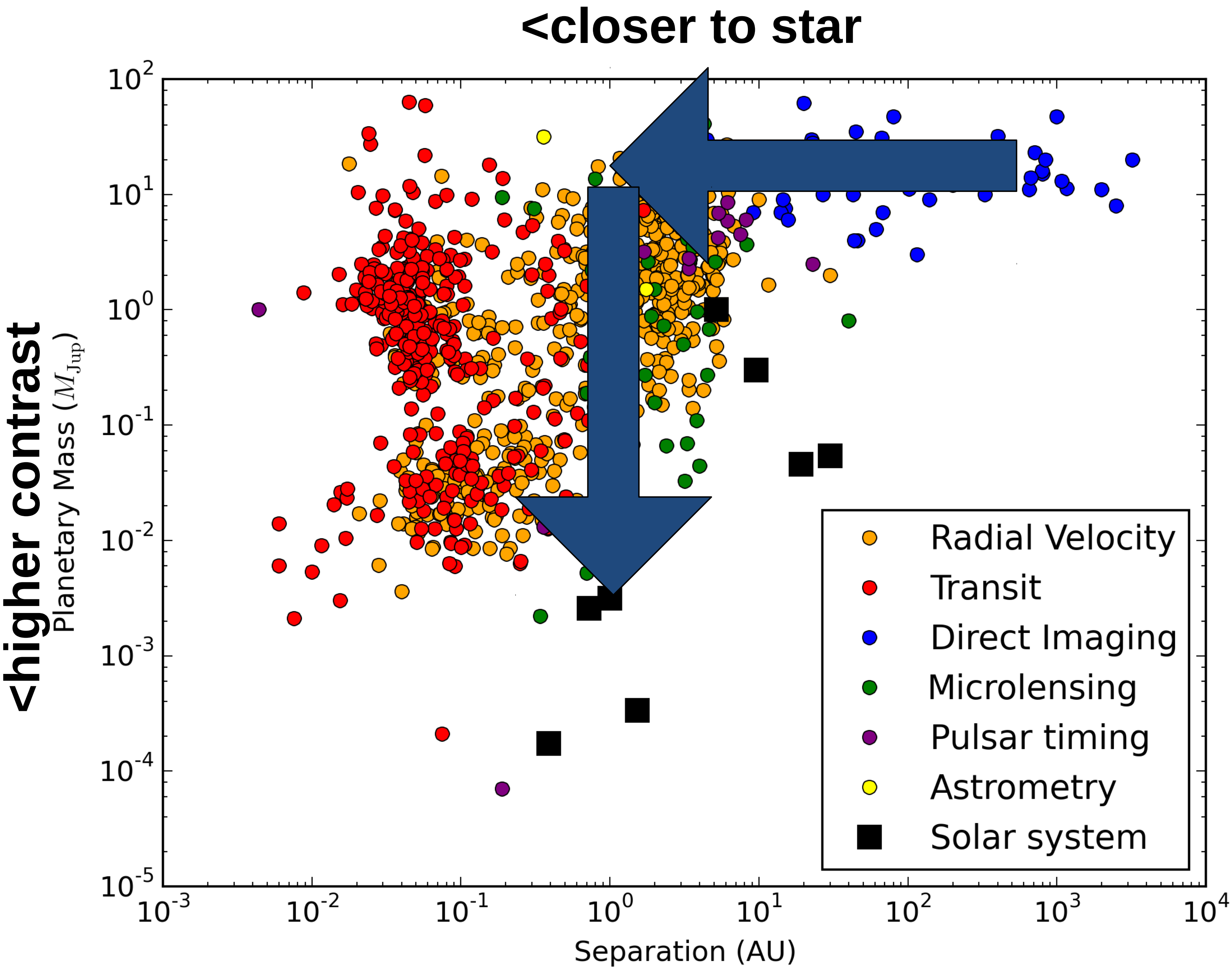
Frans Snik, Matthew Kenworthy, Christoph Keller
Leiden Observatory, the Netherlands

Jared Males, Katie Morzinski, Laird Close, Johanan Codona, Phil Hinz
University of Arizona, USA

Kathryn Hornburg, Leandra Brickson, Matt Miskiewicz, Ravi Komanduri, Michael Escuti
North Carolina State University, USA



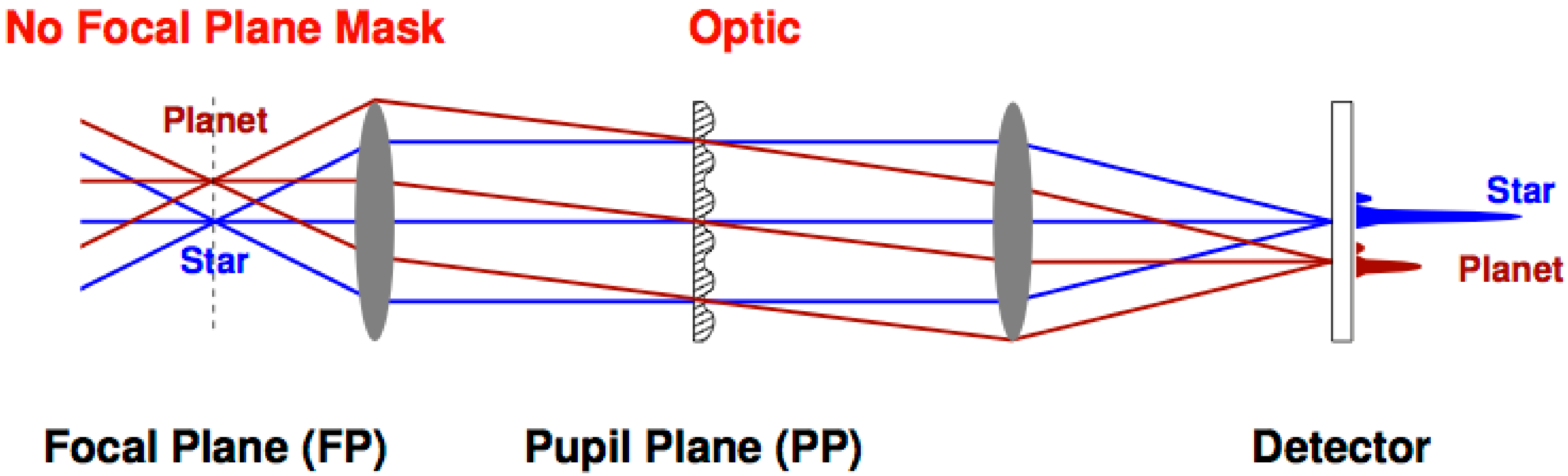
Planetary Mass ($M_{\rm Jup}$)
Separation (AU)
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
Radial Velocity
Transit
Direct Imaging
Microlensing
Pulsar timing
Astrometry
Solar system


<closer to star
<higher contrast
Planetary Mass ($M_{\rm Jup}$)
Separation (AU)
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
Radial Velocity
Transit
Direct Imaging
Microlensing
Pulsar timing
Astrometry
Solar system

Approach

1. Spatially resolve planets
   Large Earth-based telescopes
2. Correction of turbulent atmosphere
   Adaptive Optics
3. Separating star and planet light
   Starlight subtraction techniques
4. Suppressing residual starlight
   Coronagraphs [my PhD thesis]

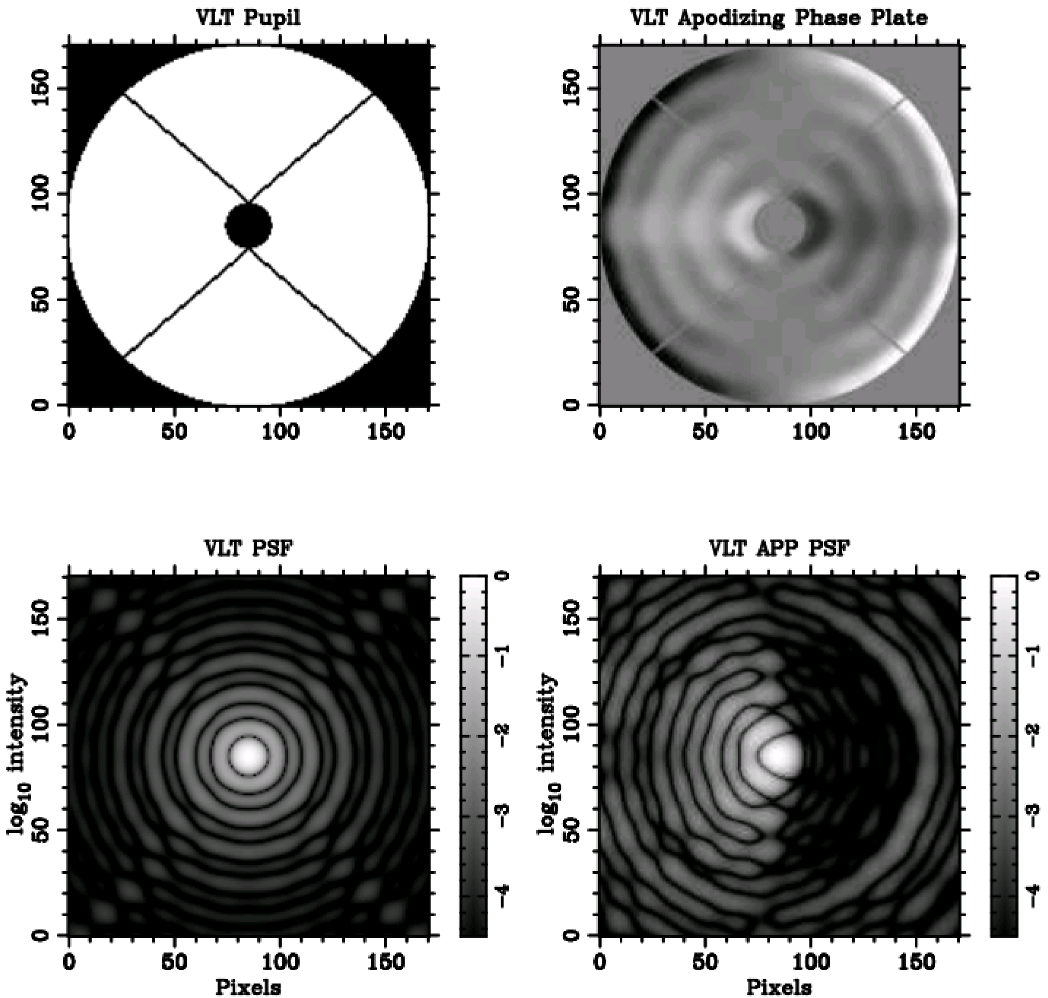
Pupil-plane coronagraphs

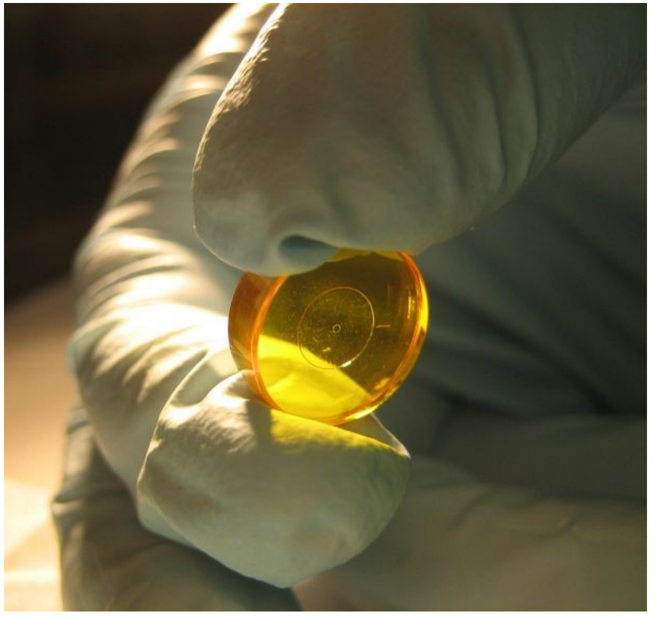


Matt Kenworthy

- insensitive to tip/tilt errors
- permits nodding for IR background subtraction
- single plane in telescope

Apodizing Phase Plate (APP)

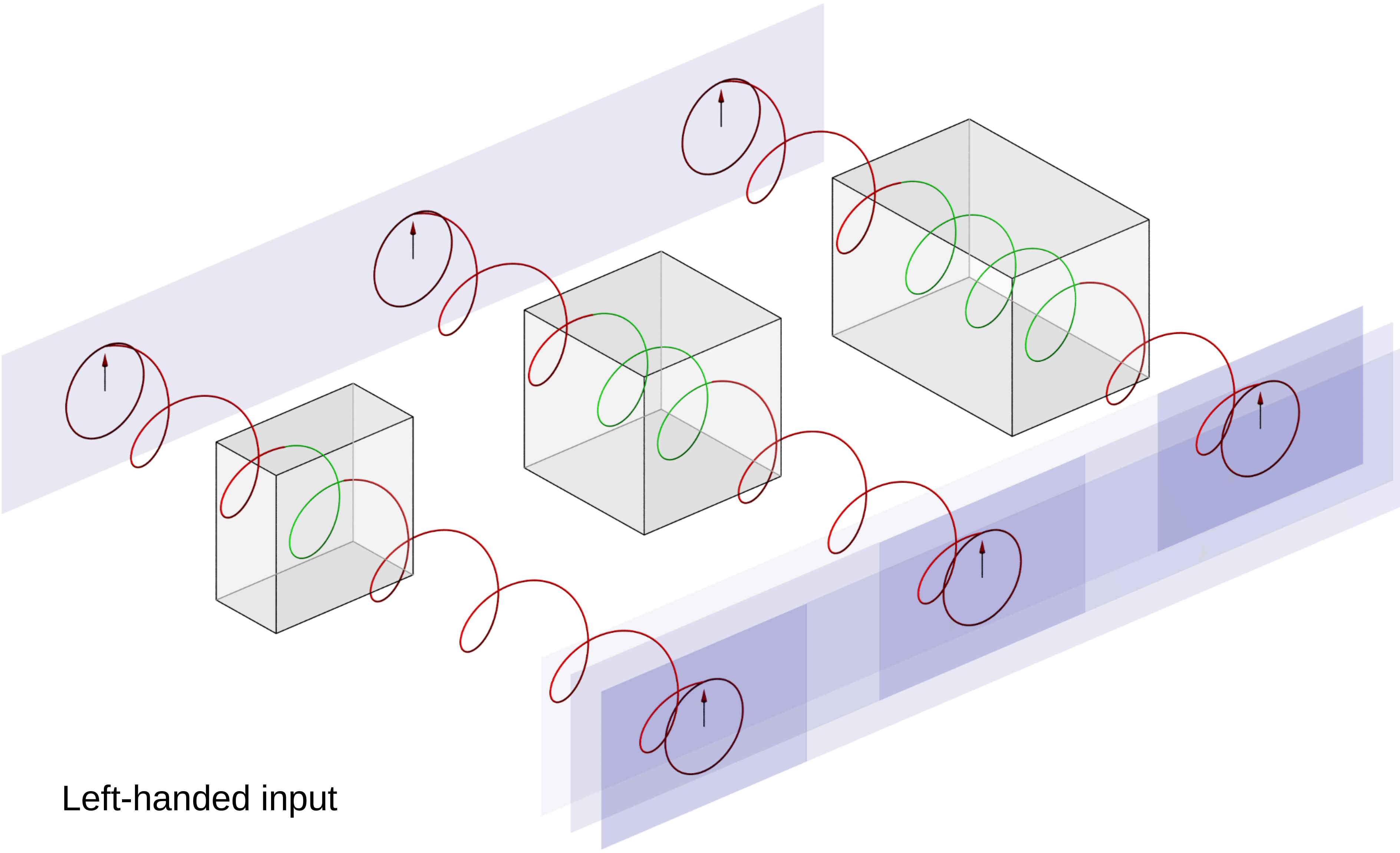




Optic is diamond turned out of Zinc Selenide

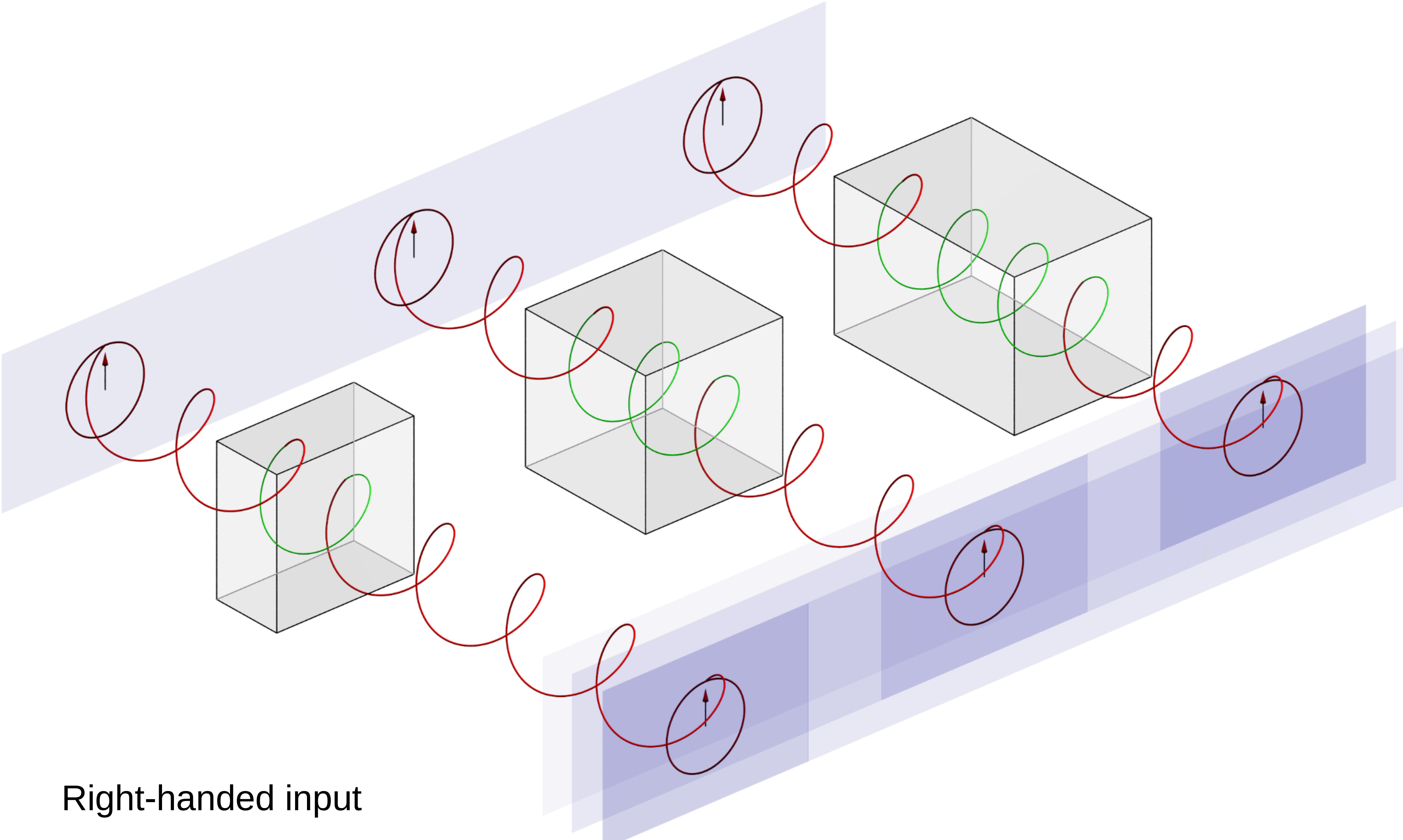
Codona & Angel, (2004)
Codona et al. (2006)
Kenworthy et al. (2007)

Classical Phase



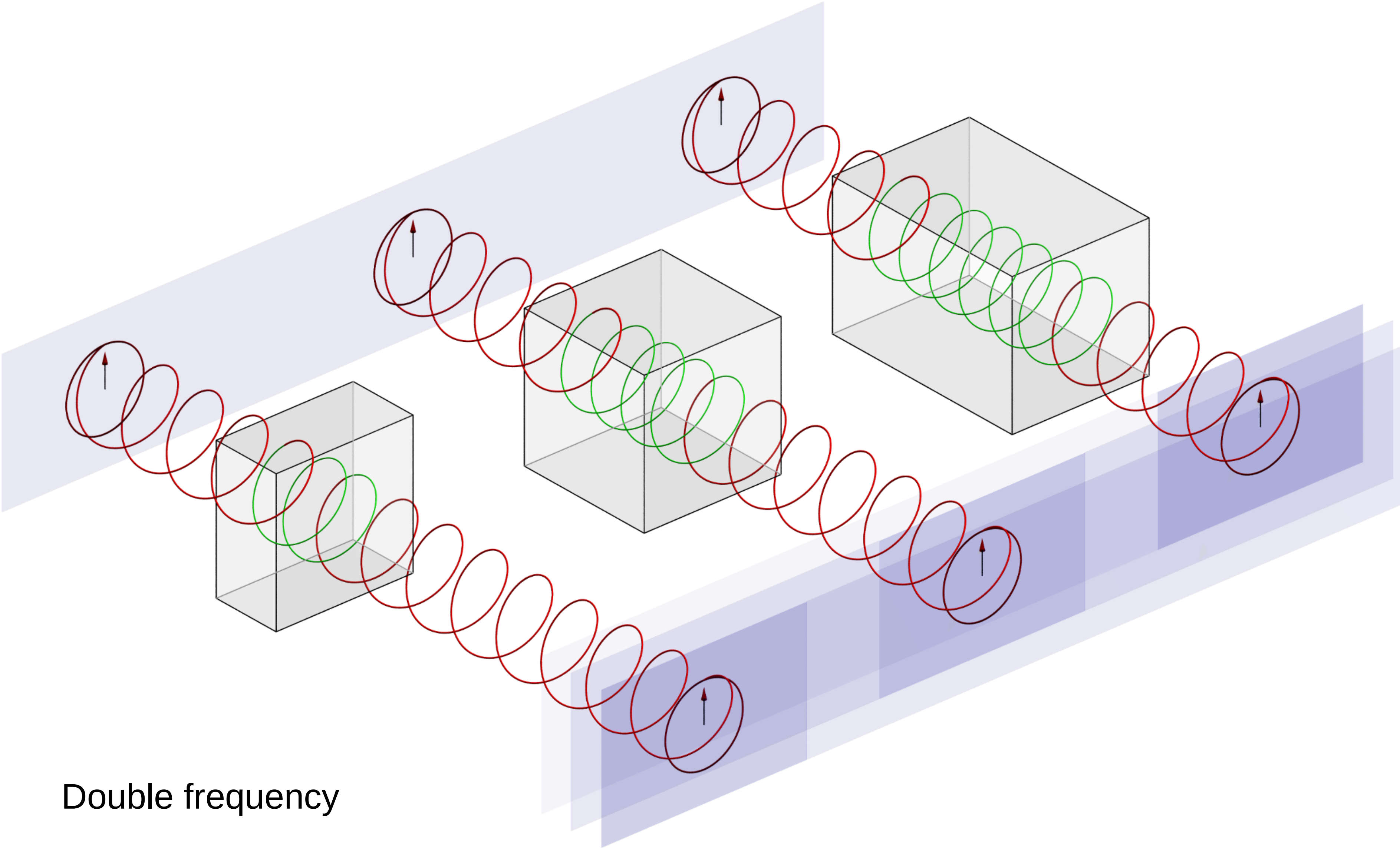
Left-handed input

Classical Phase



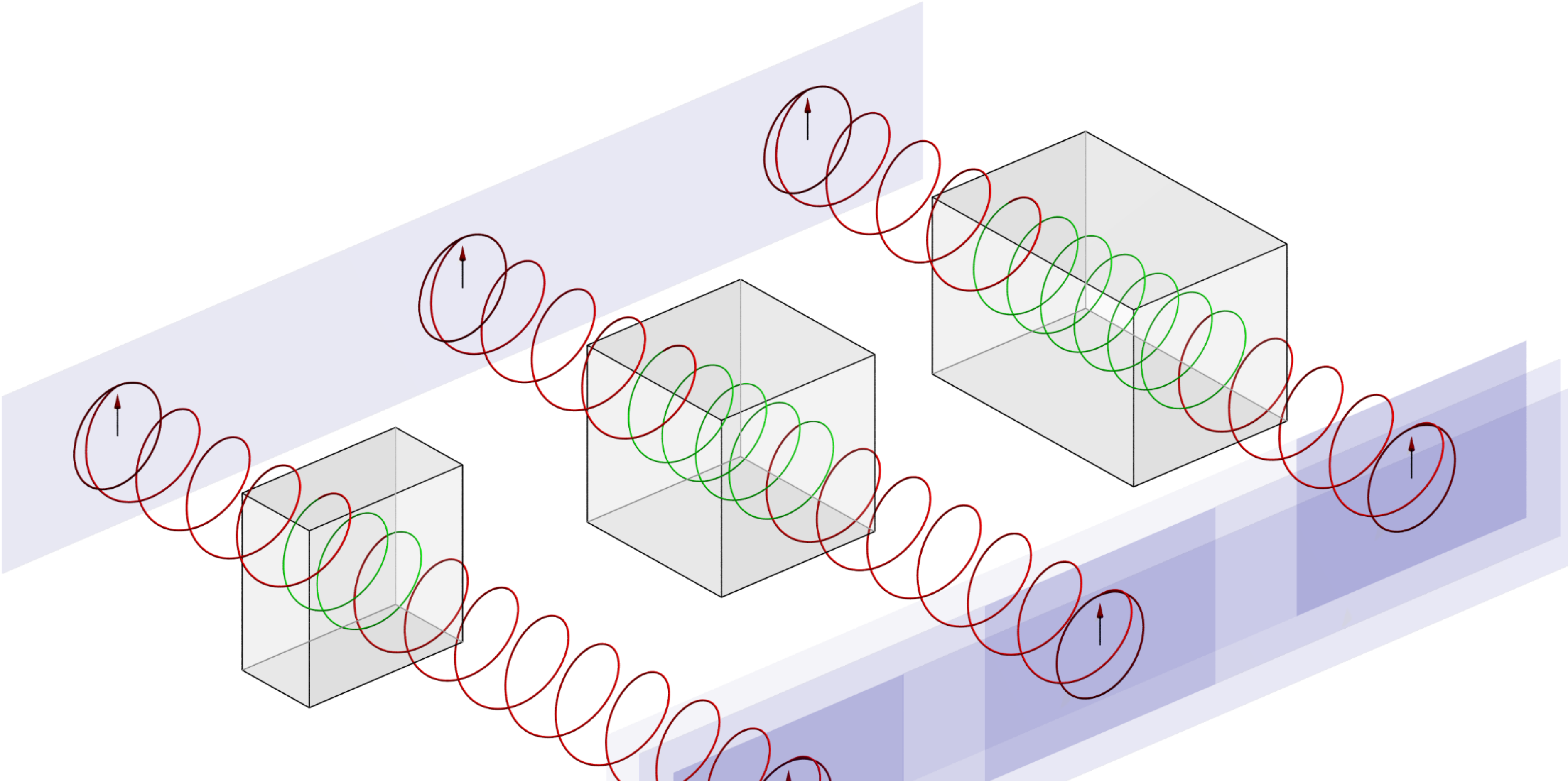
Right-handed input

Classical Phase



Double frequency

Classical Phase

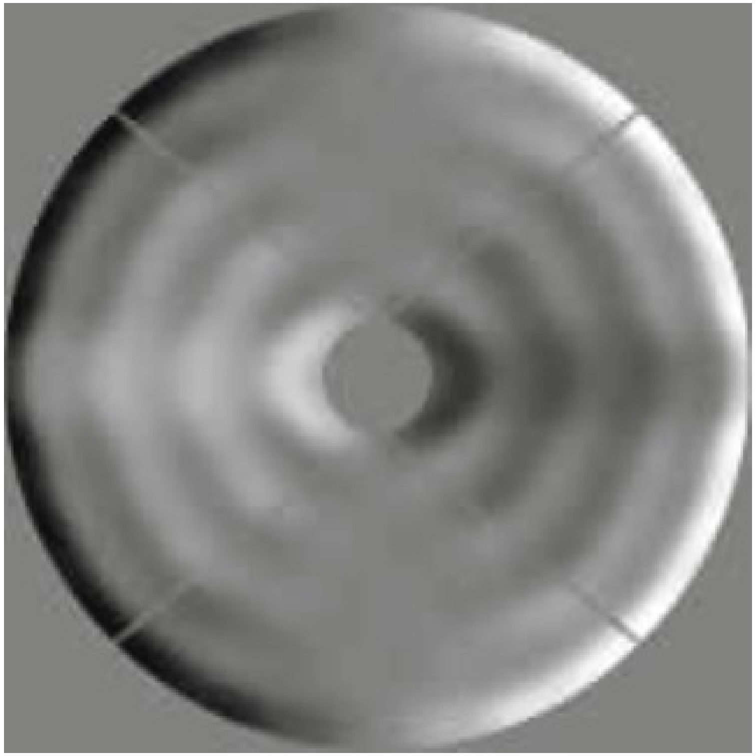


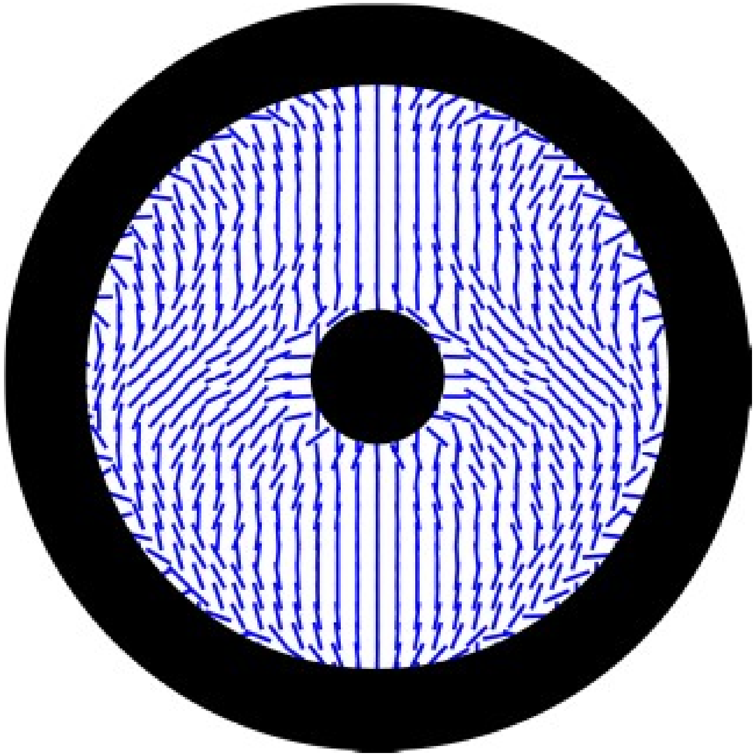
$$\Delta\phi = 2\pi\,(n-1)\Delta x/\lambda$$

Pros and Cons of APP

+ Single optic
+ Easy alignment
+ Insensitive to tip-tilt errors
+ Small inner working angle
+ High contrast
- One-sided PSF
- Chromatic
- Extreme phase patterns cannot be manufactured with diamond turning

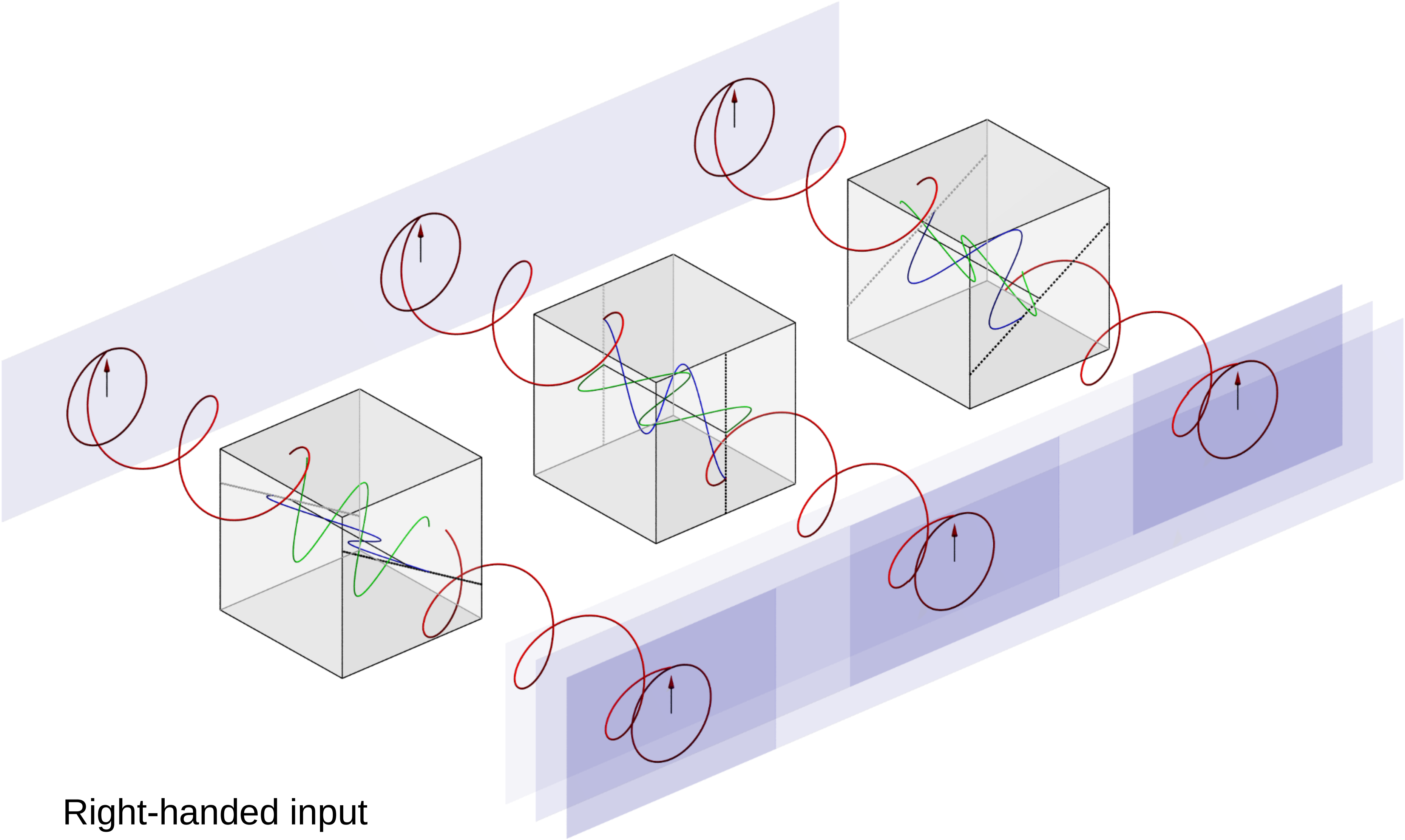
Classical => Geometric Phase





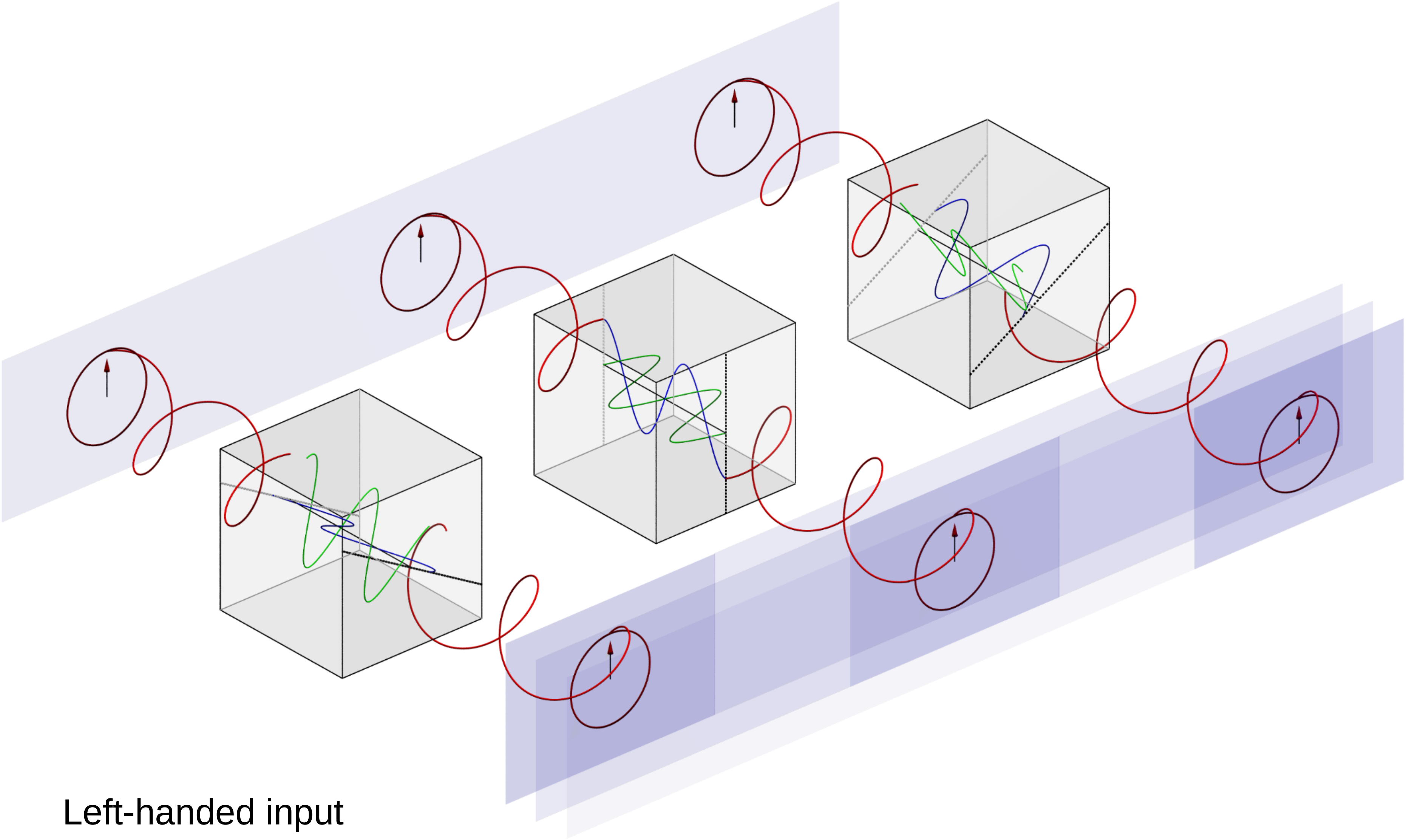
From thickness variations in ‘glass’ to
fast axis orientations in a half-wave retarder

Geometric Phase



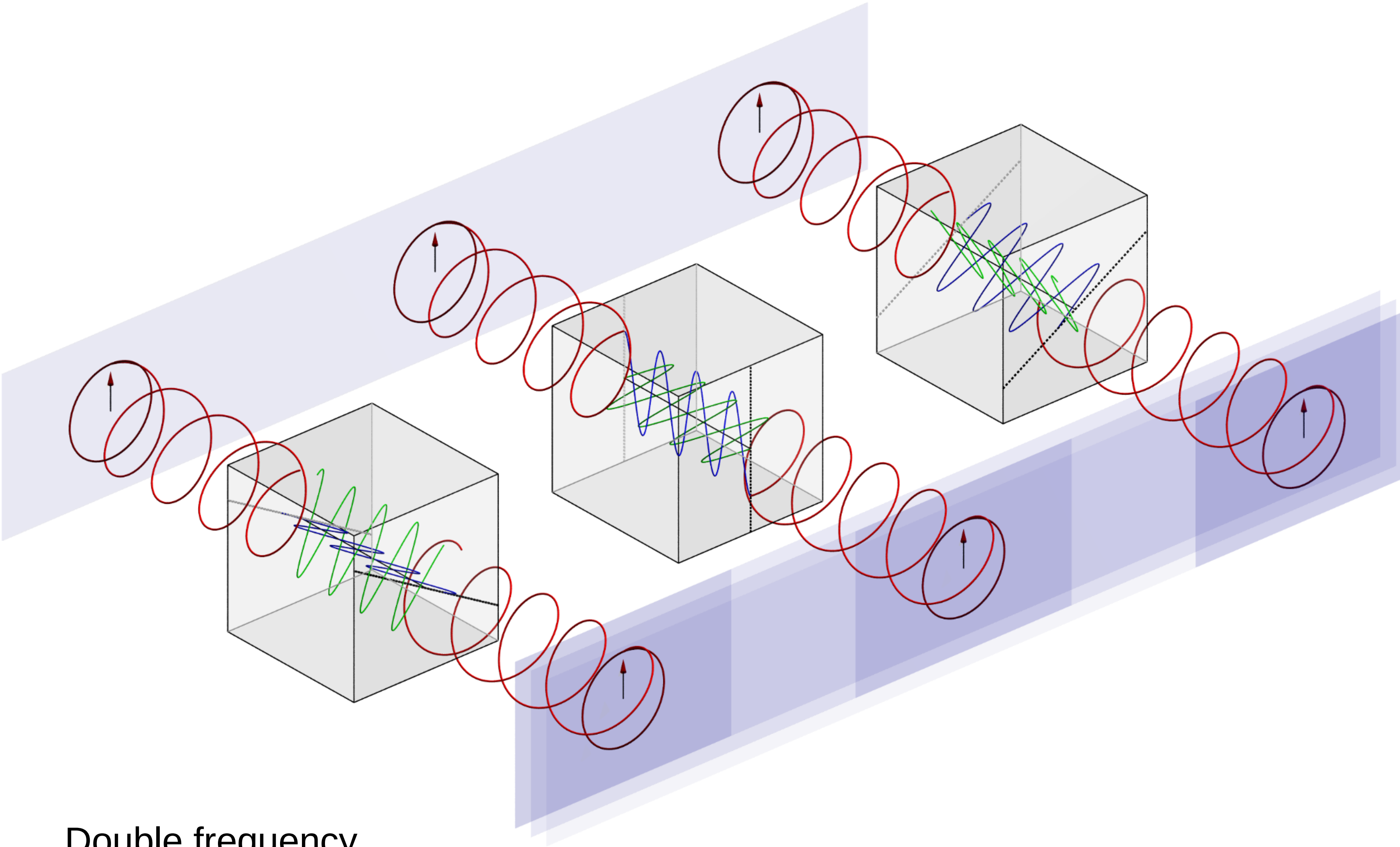
Right-handed input

Geometric Phase



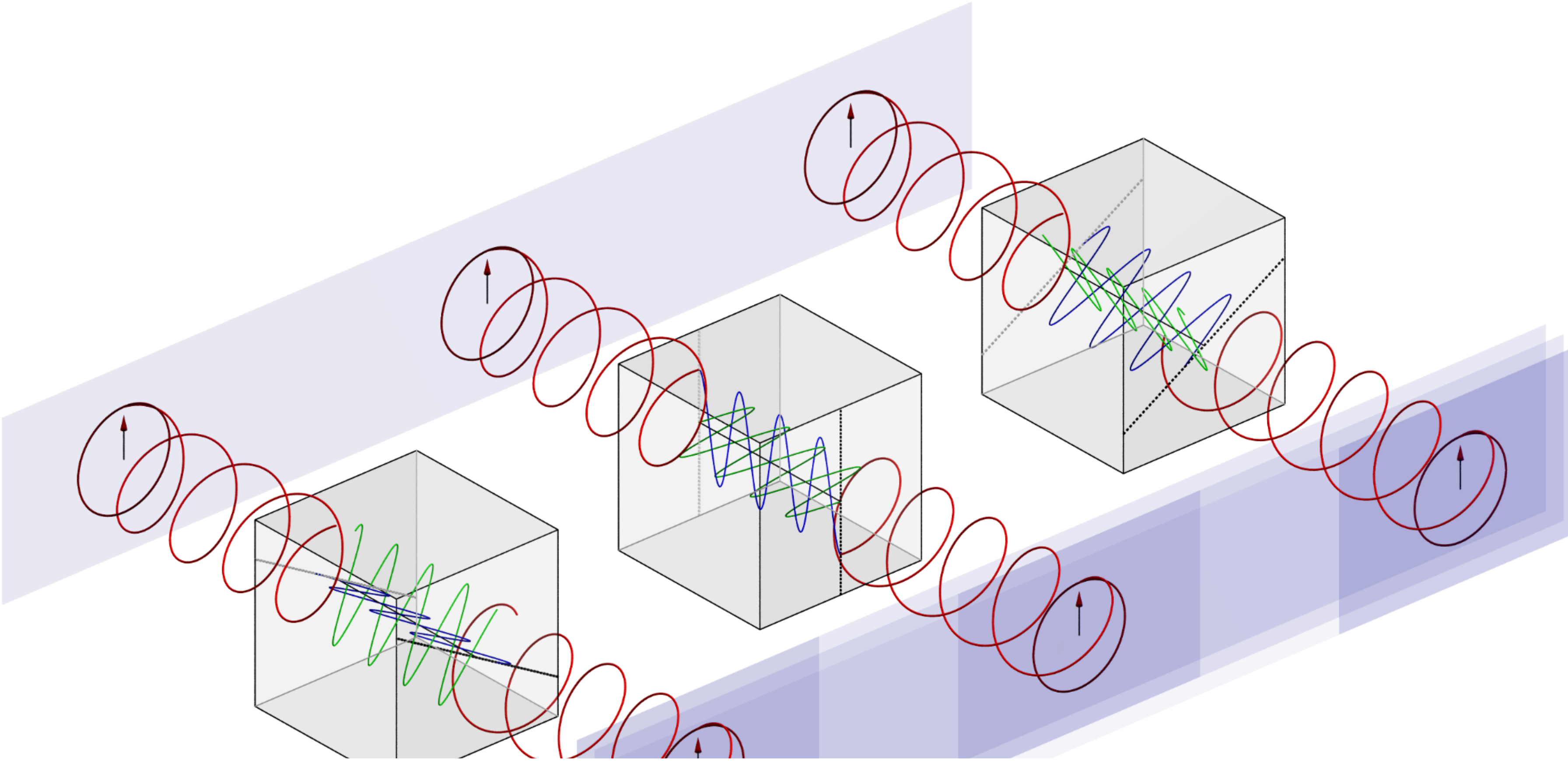
Left-handed input

Geometric Phase



Double frequency

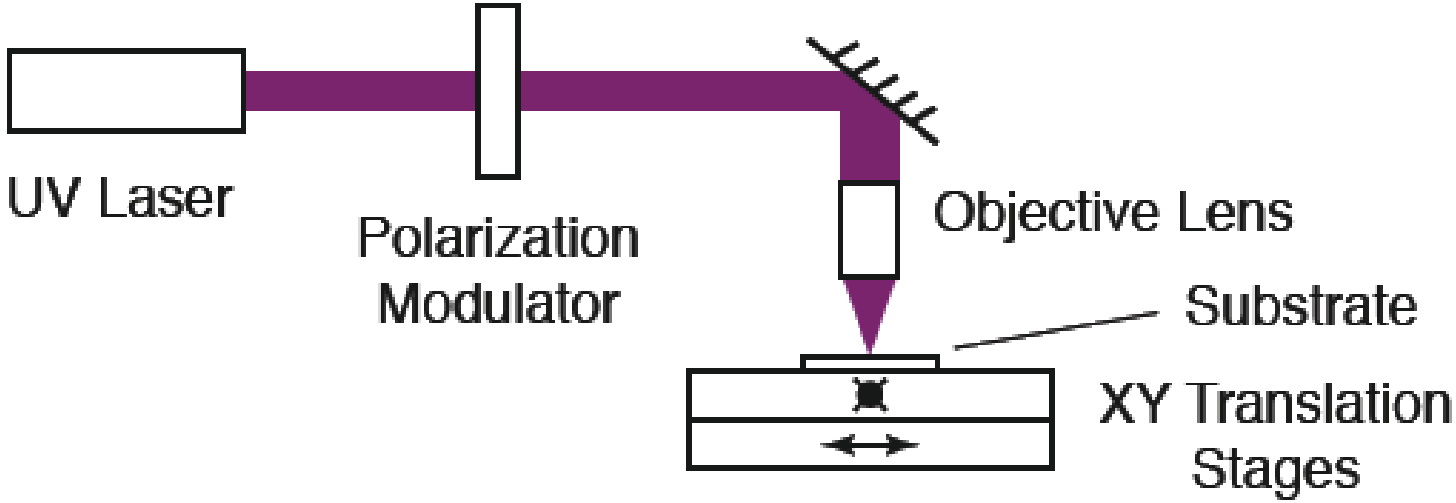
Geometric Phase



$$\Delta\phi = \pm 2\,\Delta\theta$$

Liquid crystal manufacturing

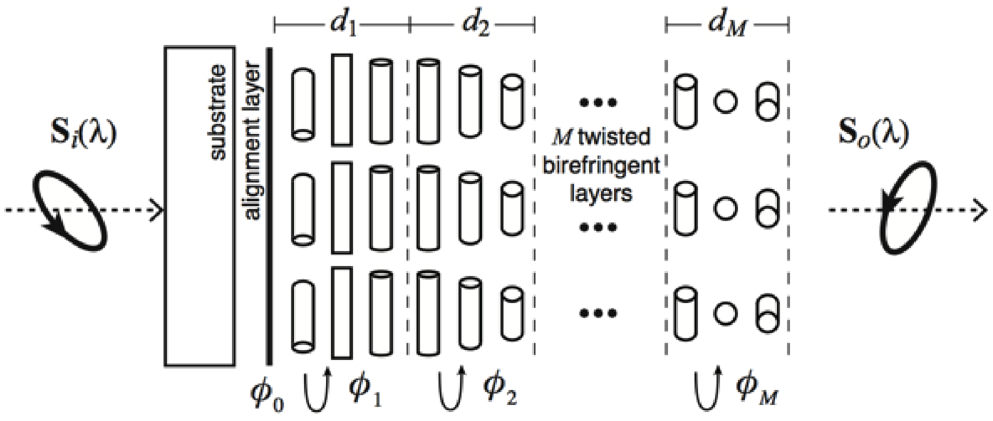
1. **any phase pattern** thanks to direct-write technique

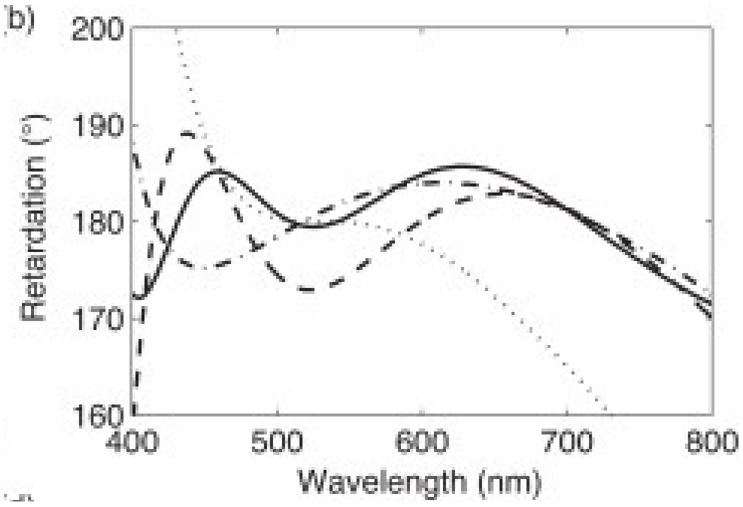


Miskiewicz & Escuti (2014)

Liquid crystal manufacturing

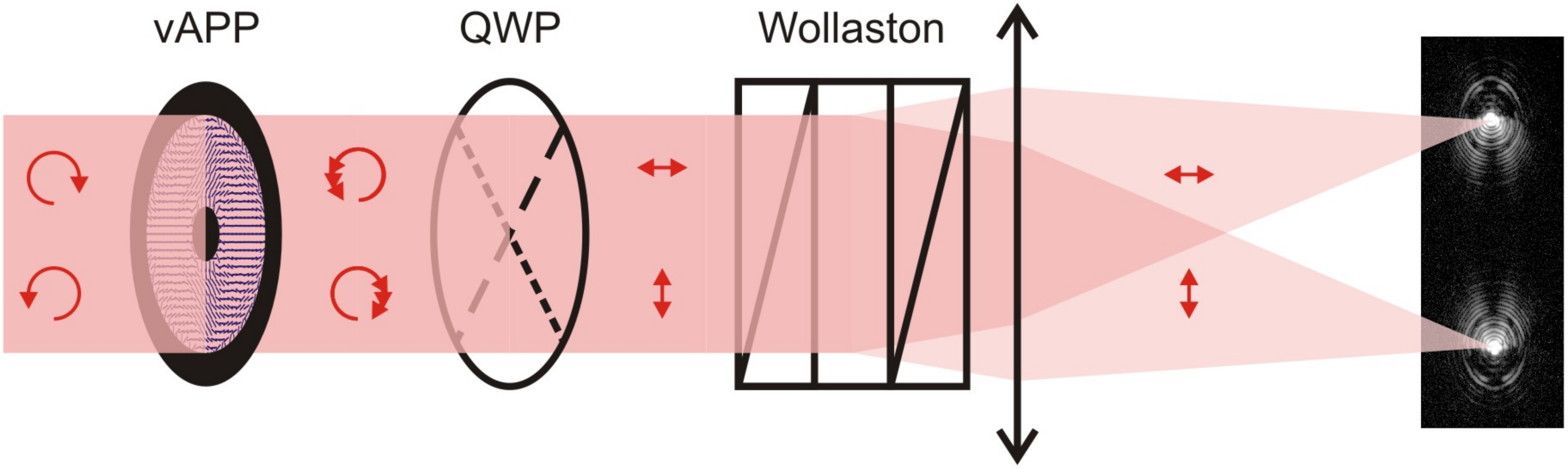
2. achromatization thanks to self-aligning multi-twist liquid crystal retarder





Komanduri et al. (2013)

vector-APP (vAPP) layout



Snik, Otten et al. (Proc. SPIE 8450, 2012)

Pros and Cons of APP

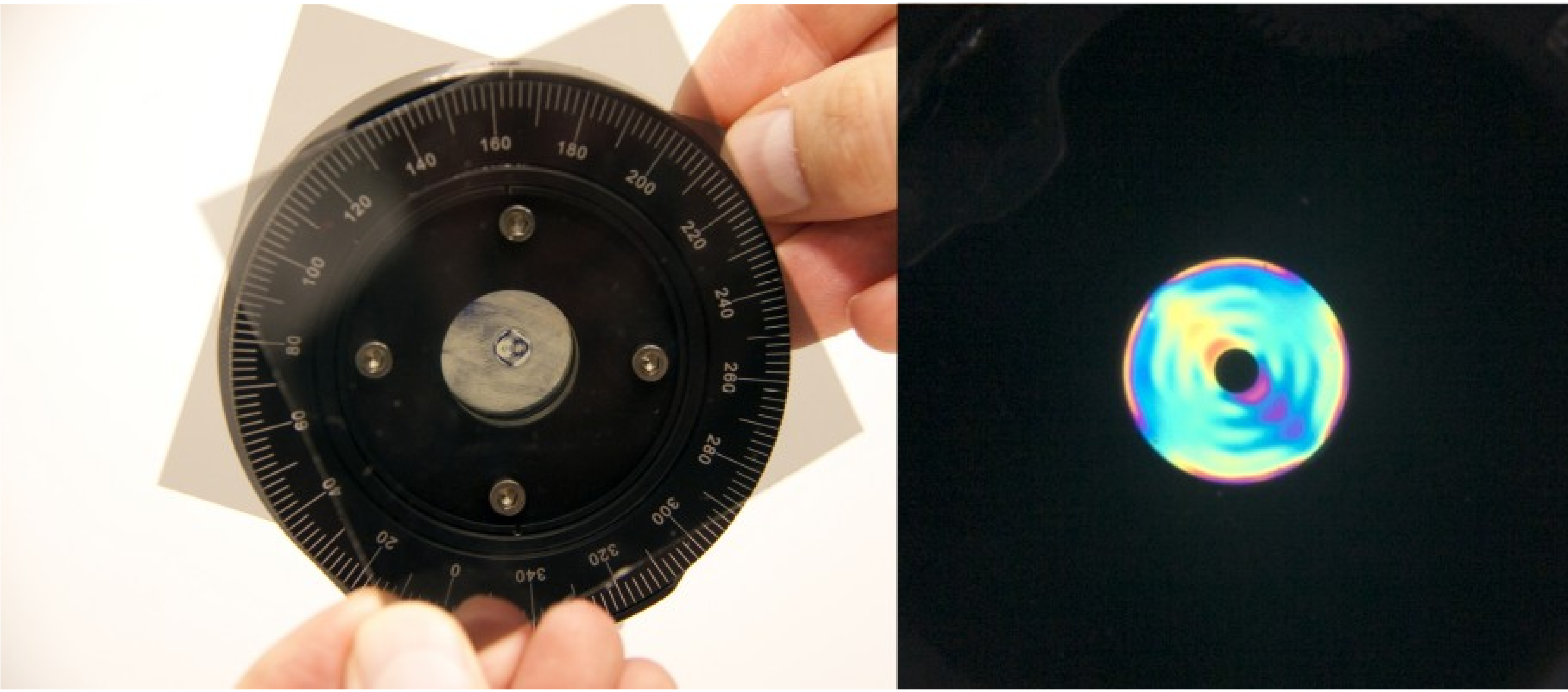
+ Single optic
+ Easy alignment
+ Insensitive to tip-tilt errors
+ Small inner working angle
+ Potentially high contrast

- One-sided PSF
- Chromatic
- Extreme phase patterns cannot be manufactured with diamond turning

Pros and Cons of vAPP

+ Single optic
+ Easy alignment
+ Insensitive to tip-tilt errors
+ Small inner working angle
+ Potentially high contrast
+ Full coverage around star
+ Achromatic
+ Extreme phase patterns possible

First broad-band vAPP prototype



Optimized for 500 – 900 nm

Otten et al, Optics Express, (2014)
Phase design by John Codona

vAPP prototype

Otten et al, Optics Express, (2014)

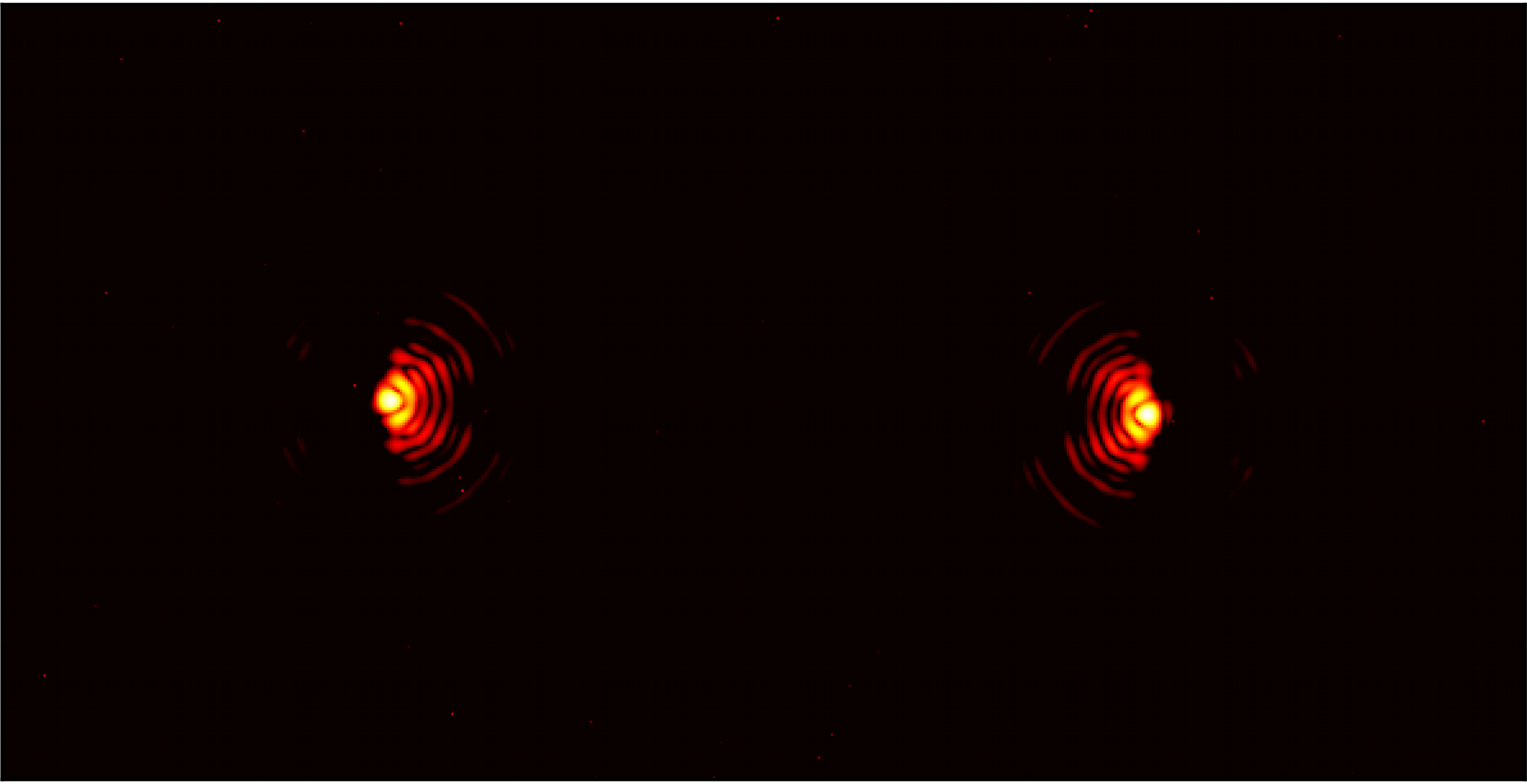
vAPP prototype

Otten et al, Optics Express, (2014)

vAPP prototype

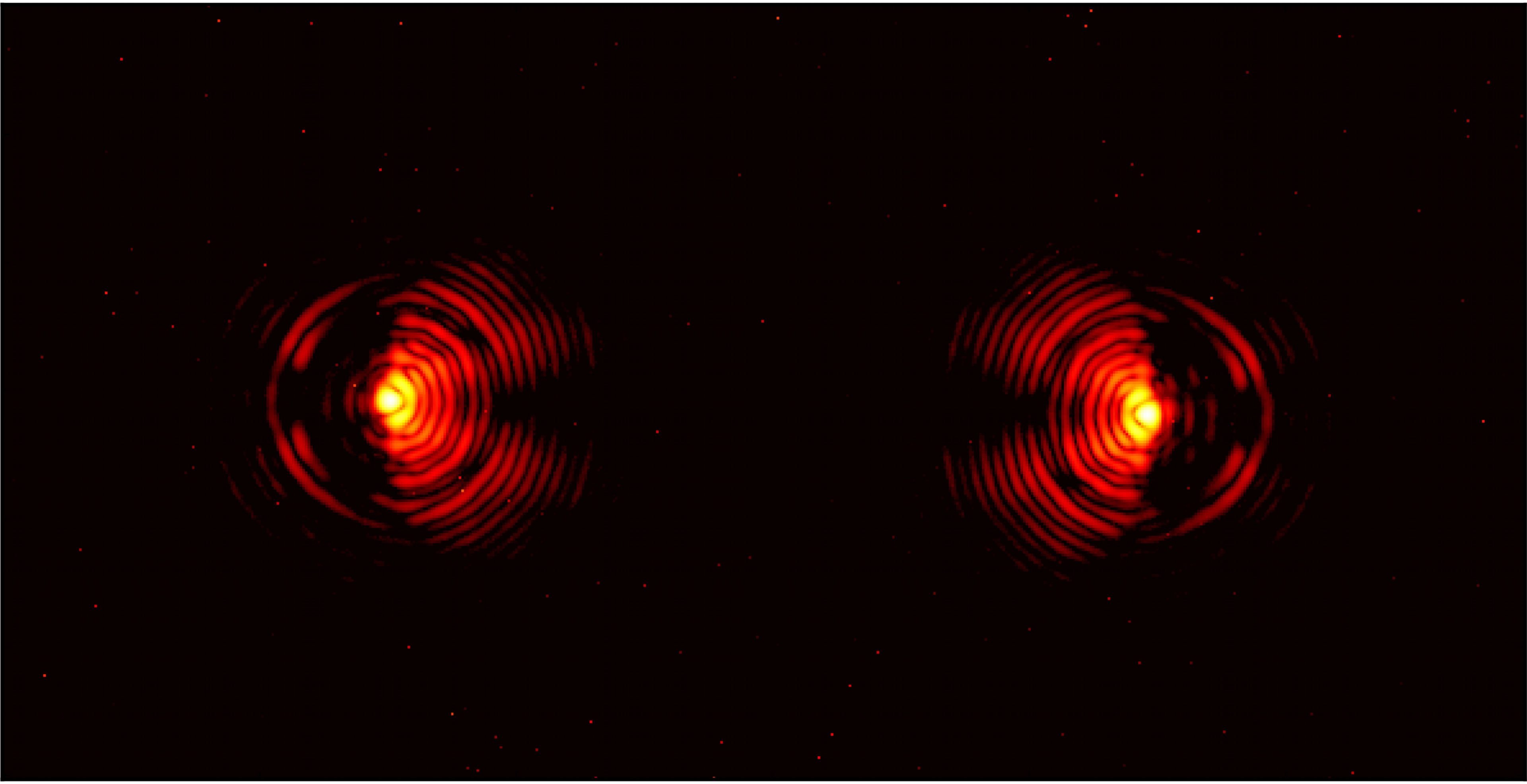
Otten et al, Optics Express, (2014)

vAPP prototype

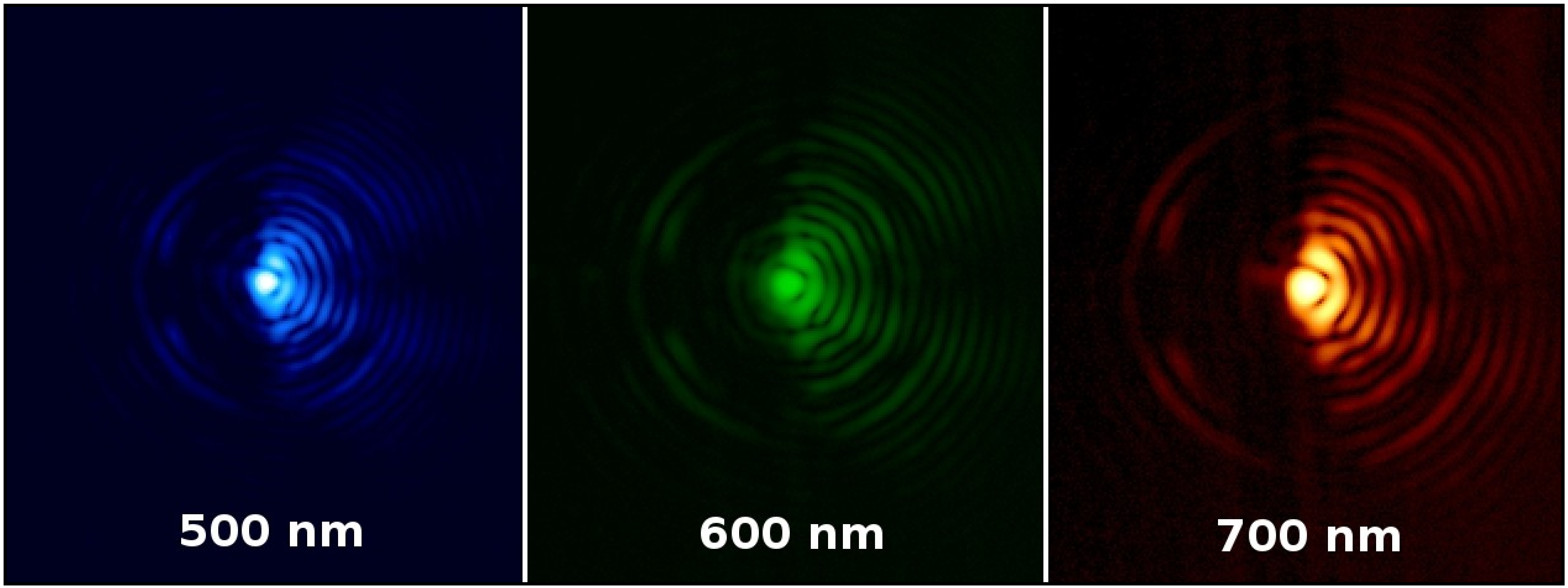


Otten et al, Optics Express, (2014)

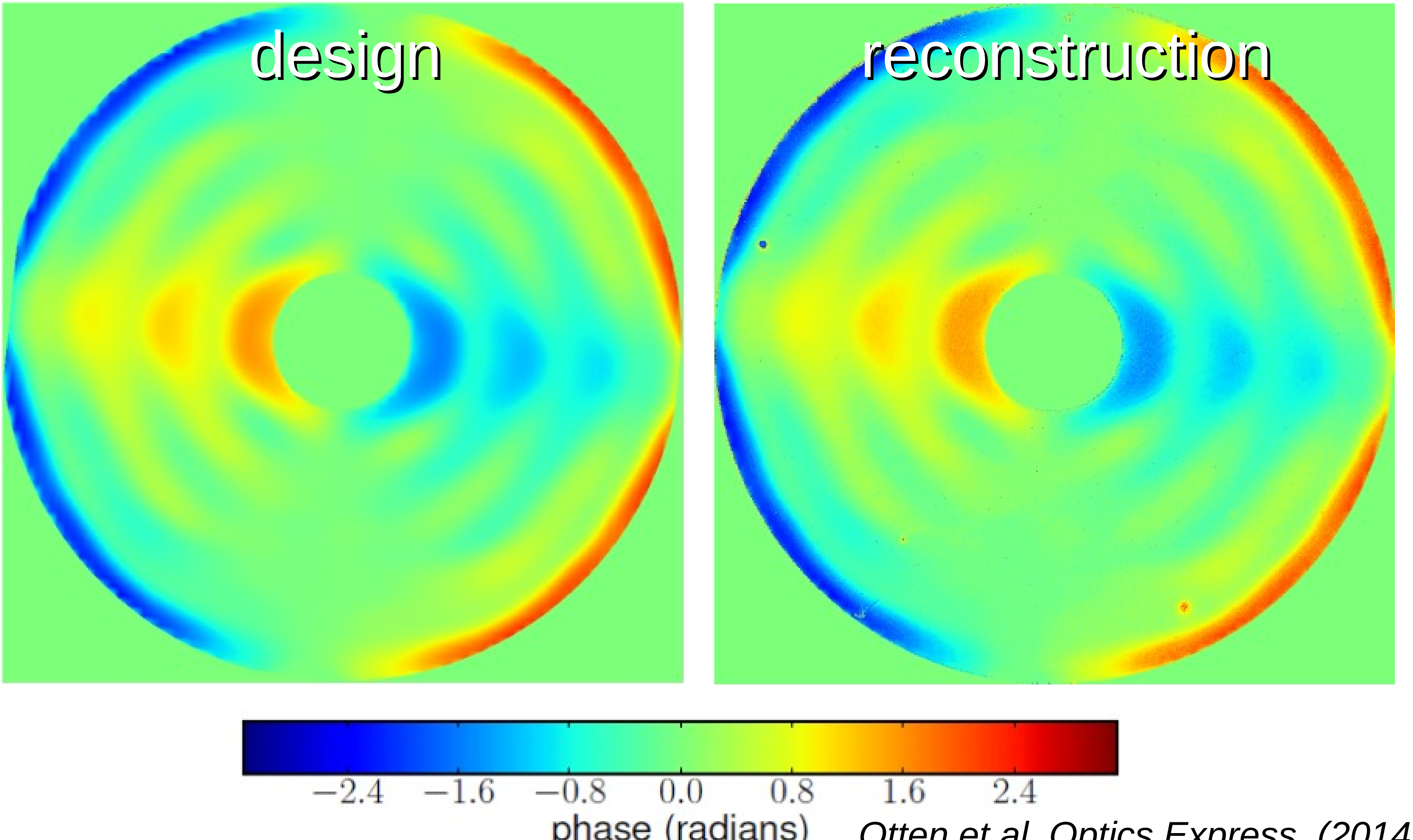
vAPP prototype



Otten et al, Optics Express, (2014)

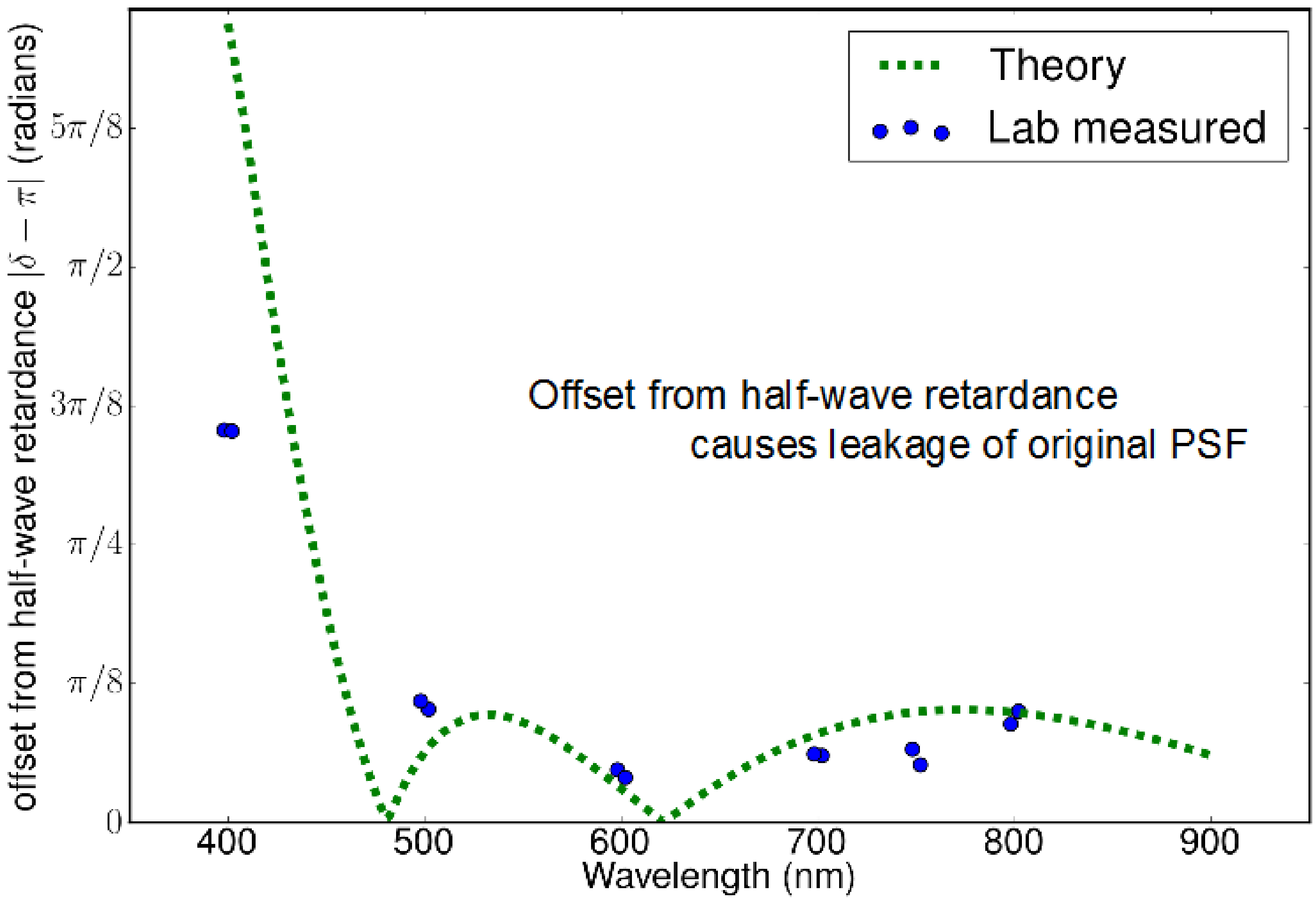

500 nm
600 nm
700 nm

Phase map



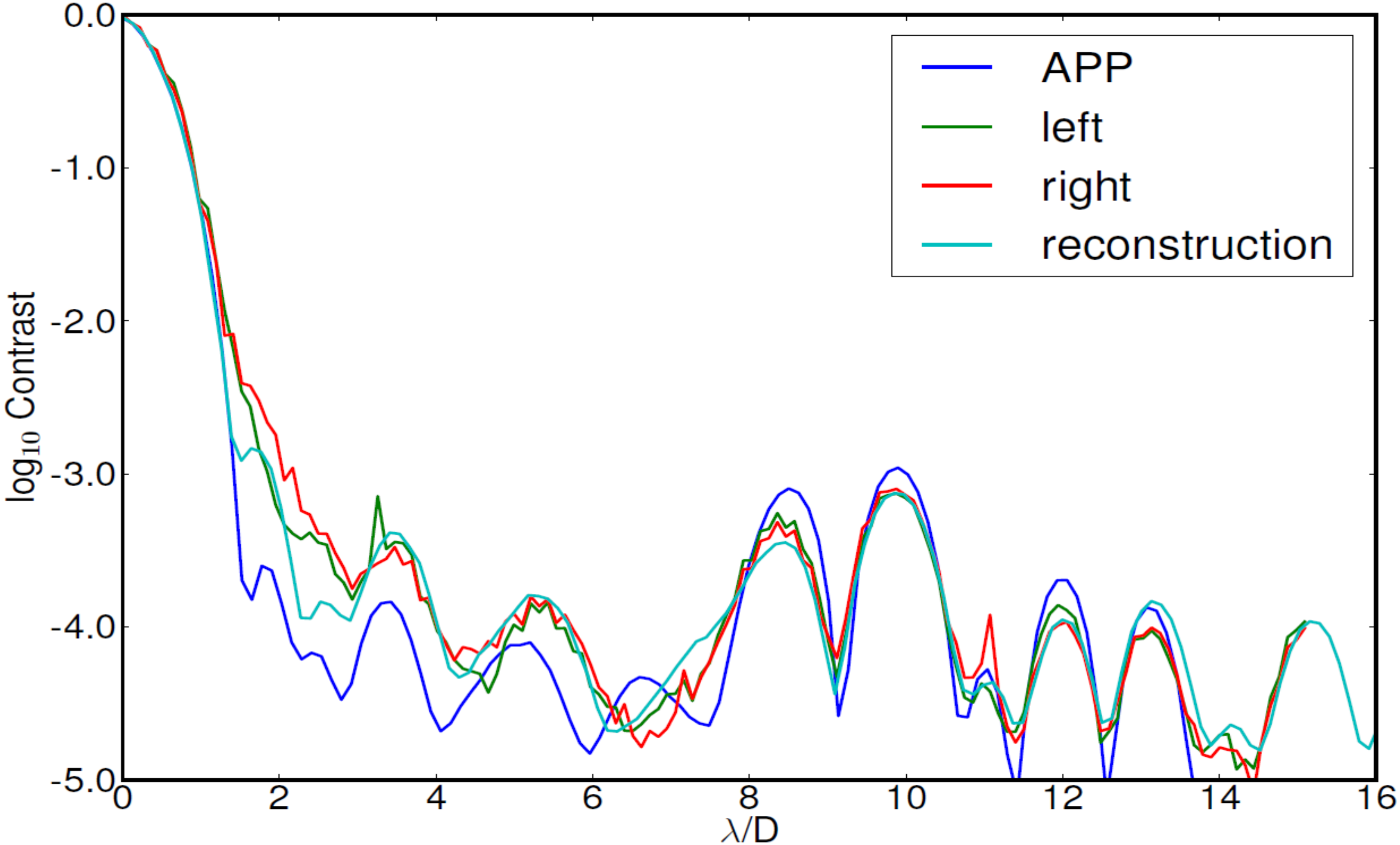
Otten et al, Optics Express, (2014)

Retardance vs wavelength



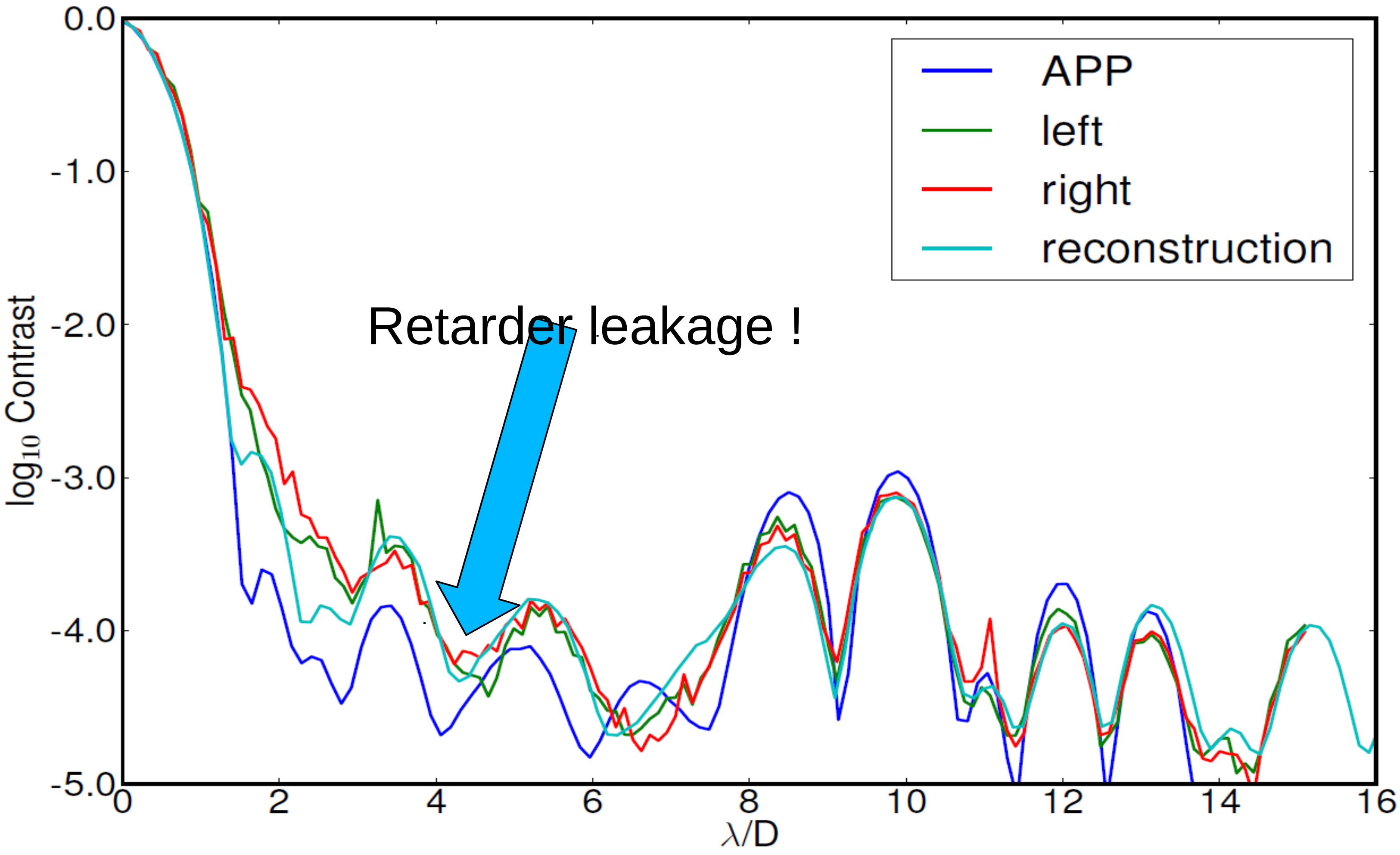
Otten et al, Optics Express, (2014)

Intensity profile



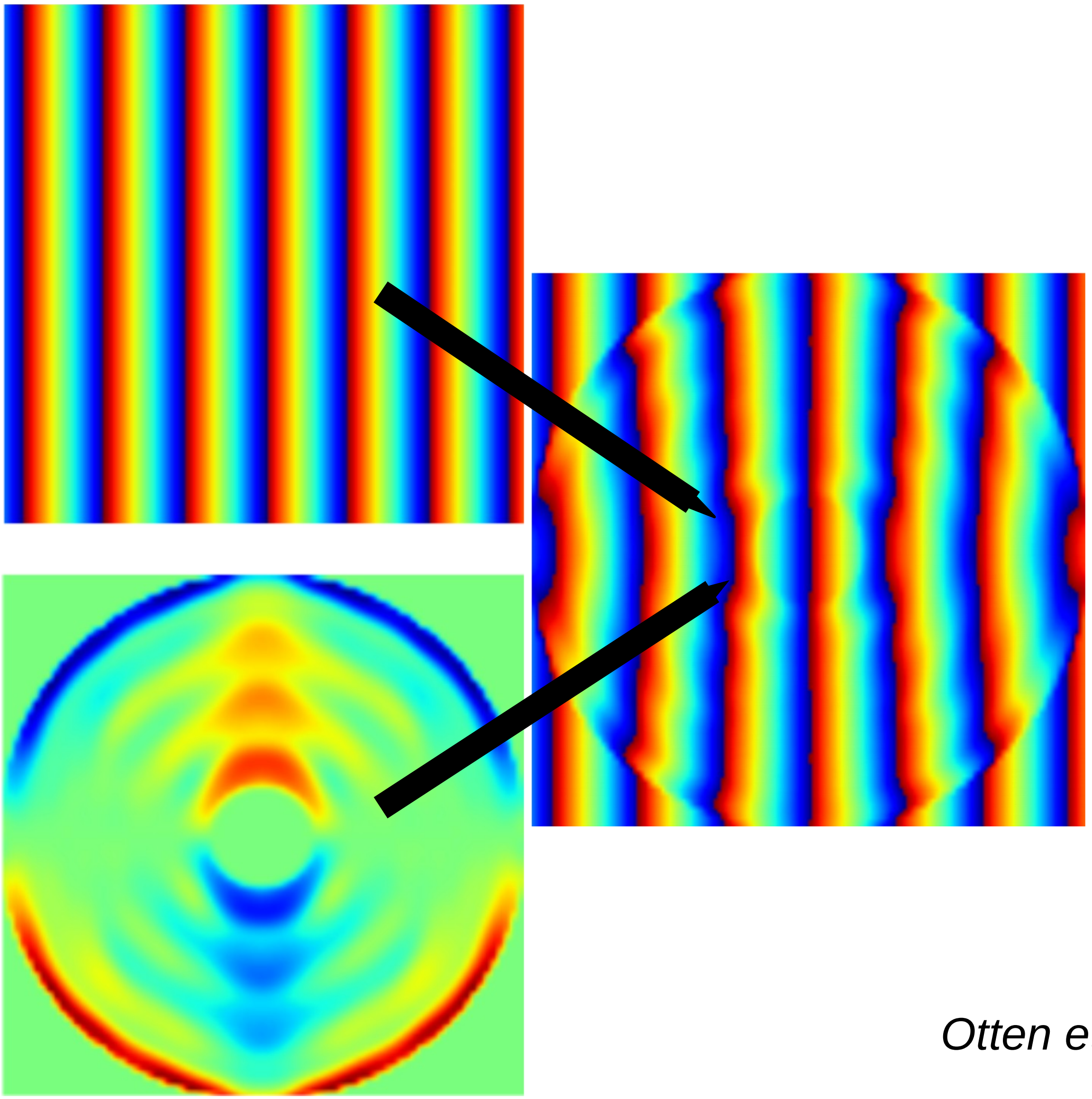
Otten et al, Optics Express, (2014)

Intensity profile



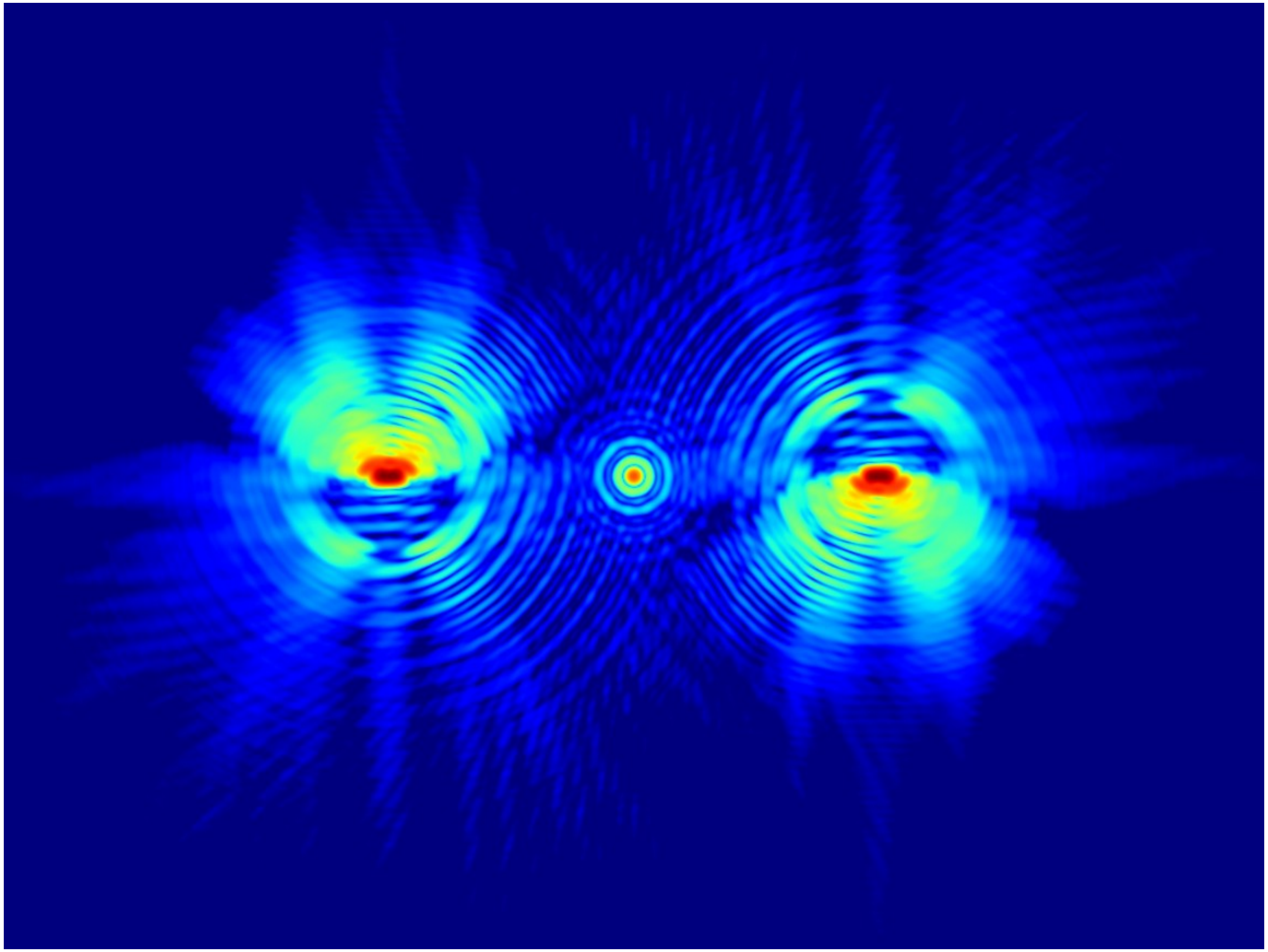
Otten et al, Optics Express, (2014)

grating-vAPP (gvAPP)



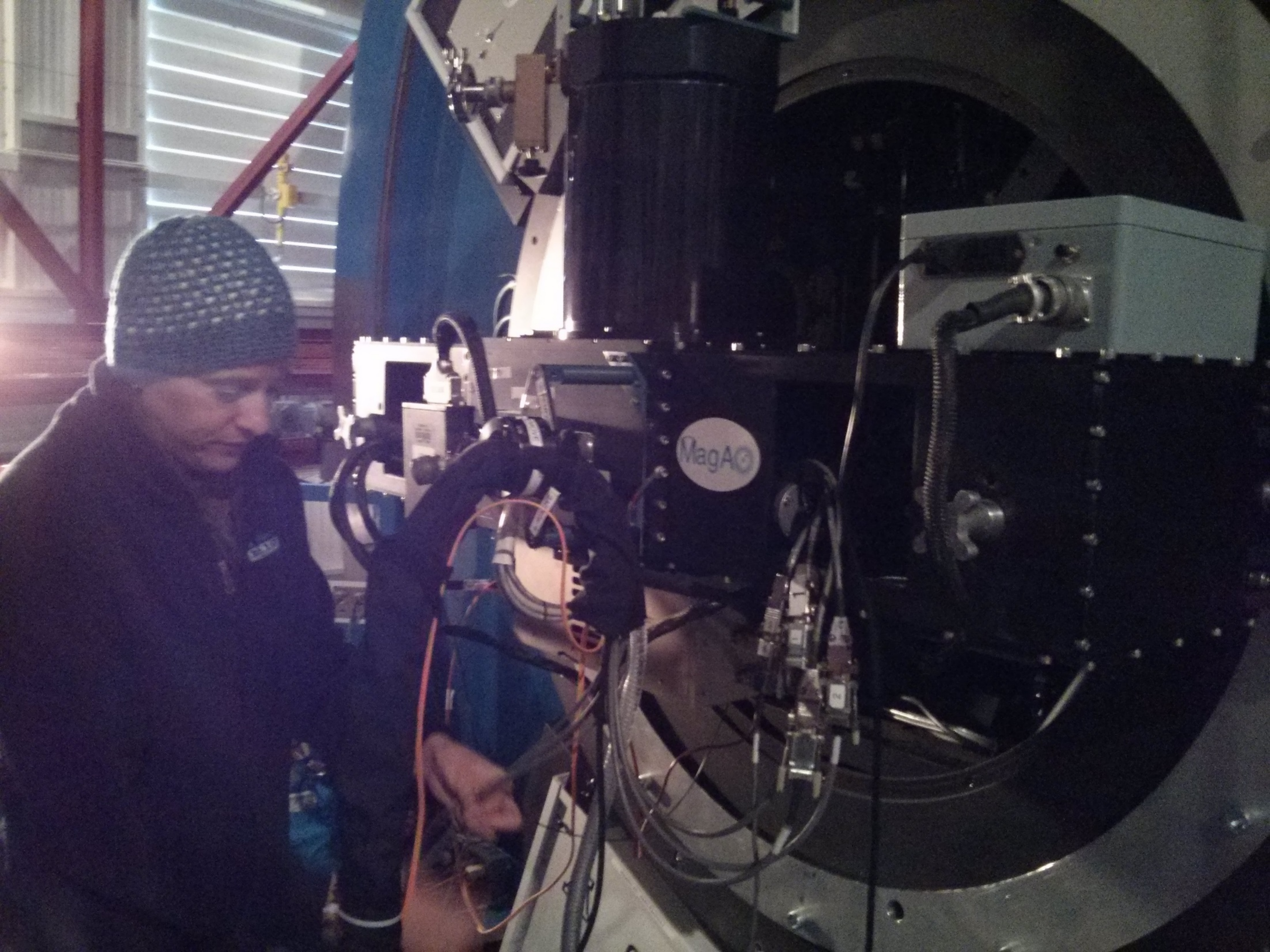
Otten et al, SPIE, 2014

grating-vAPP (gvAPP)

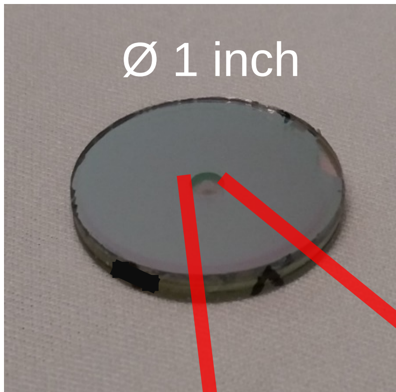


Otten et al, SPIE, 2014

Clay/MagAO

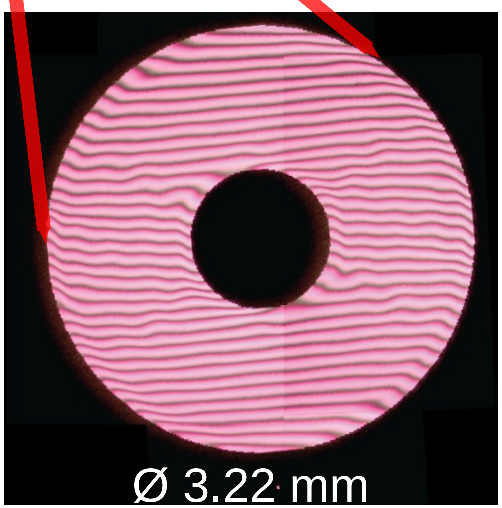

MagAO

Installation



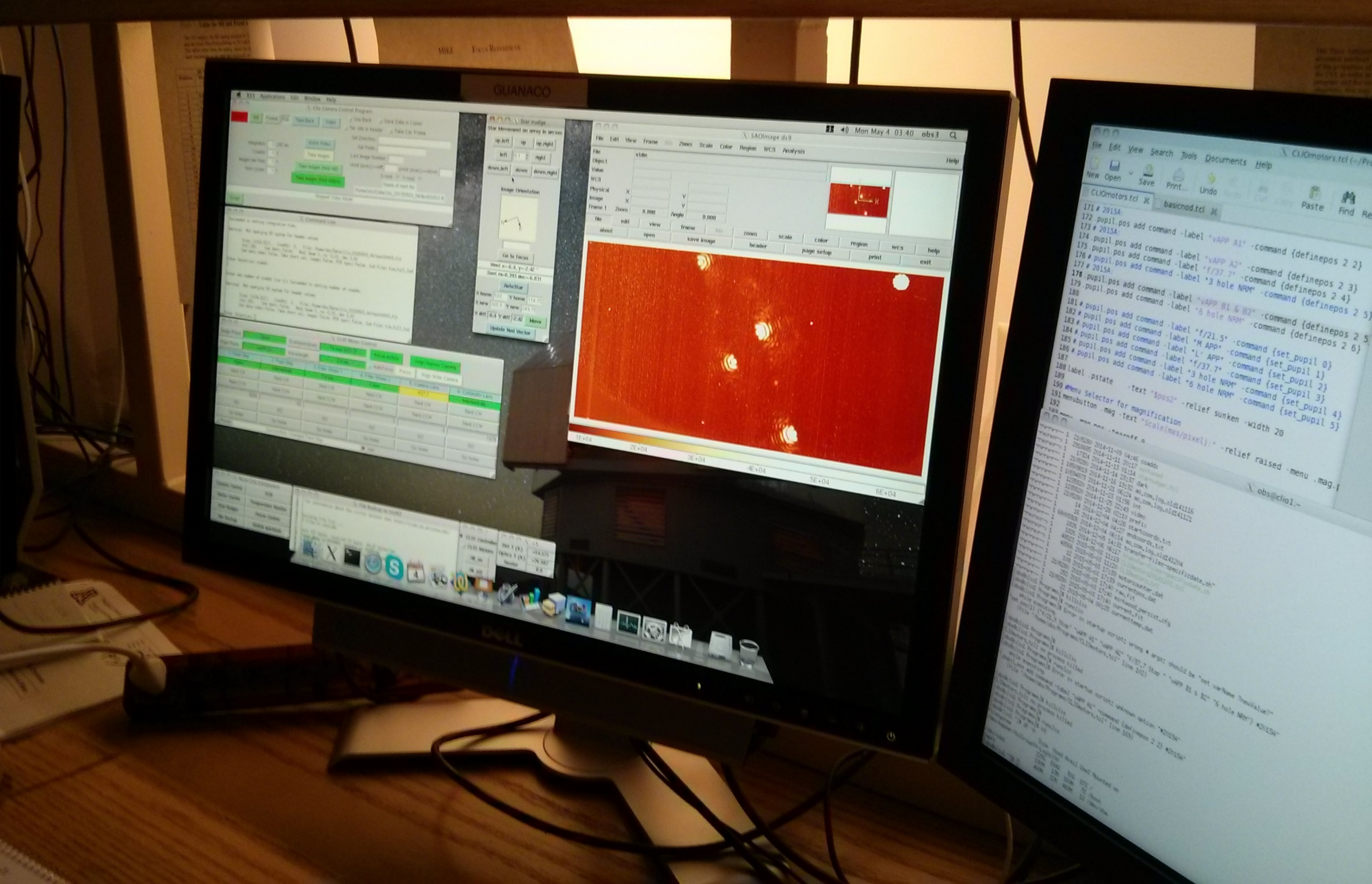
ImagineOptix &
Geometric-Phase
Photonics Lab NCSU

Phase design by
Christoph U. Keller

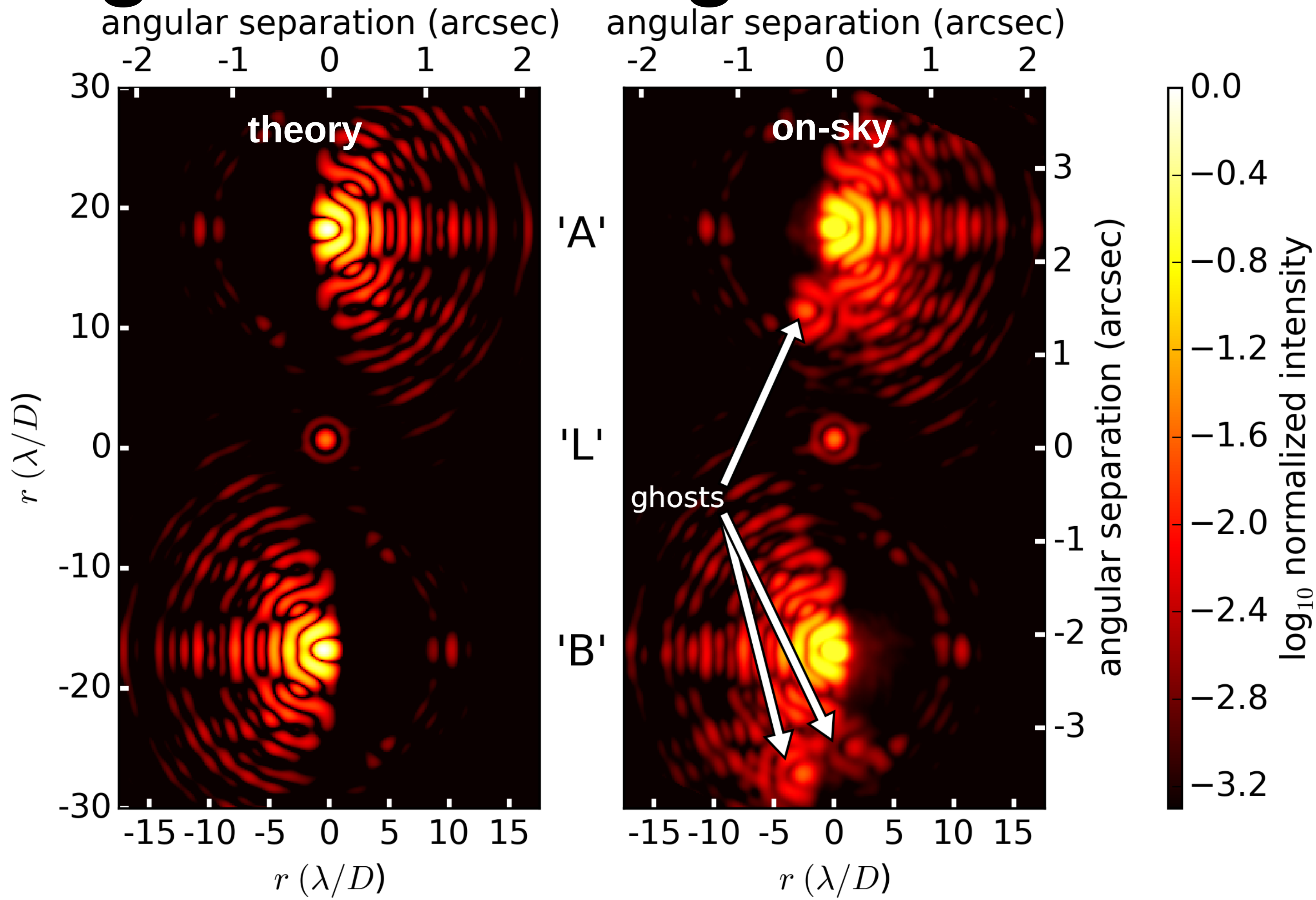


Jared Males

First light at MagAO – May 2015

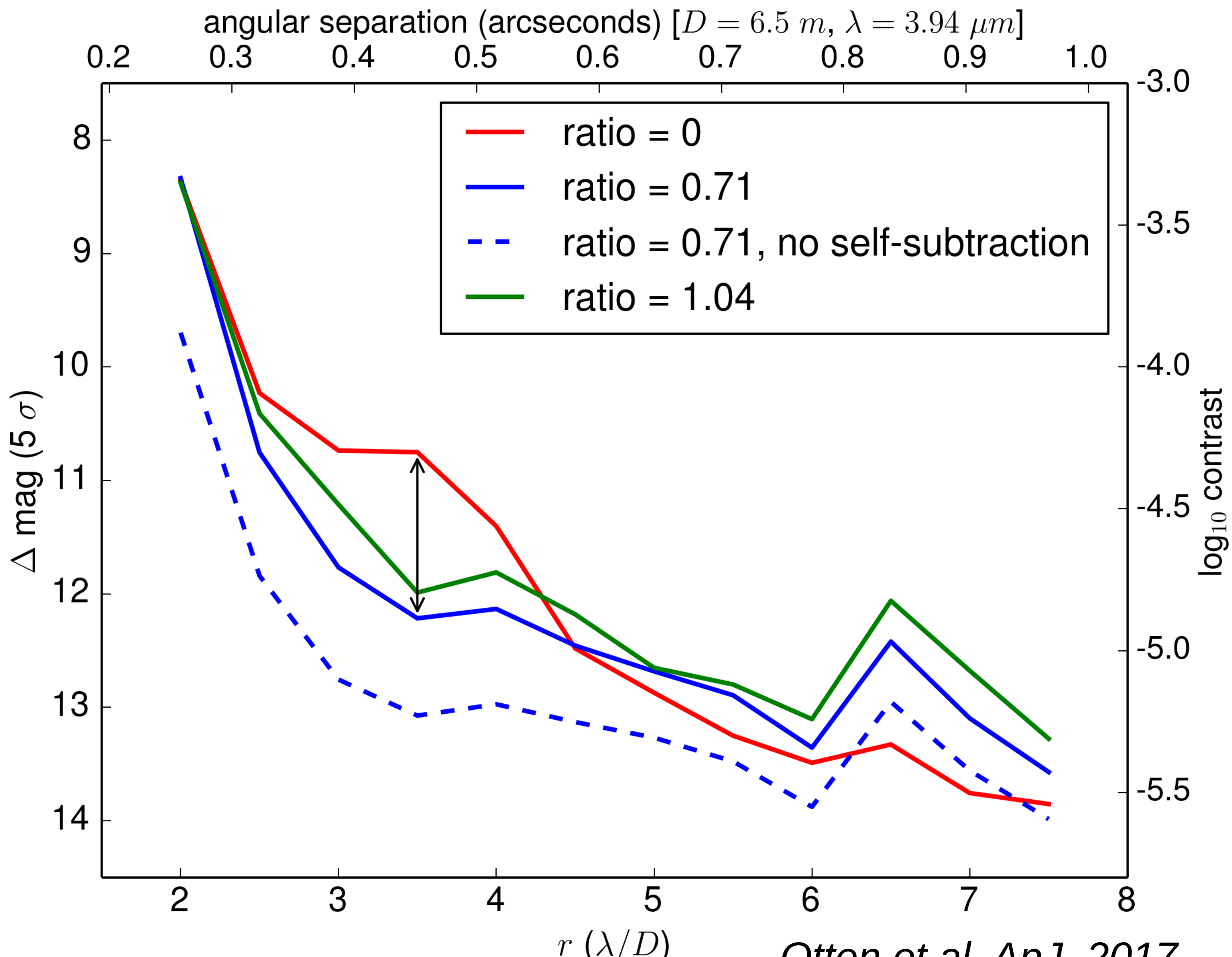


gvAPP on MagAO/Clio2



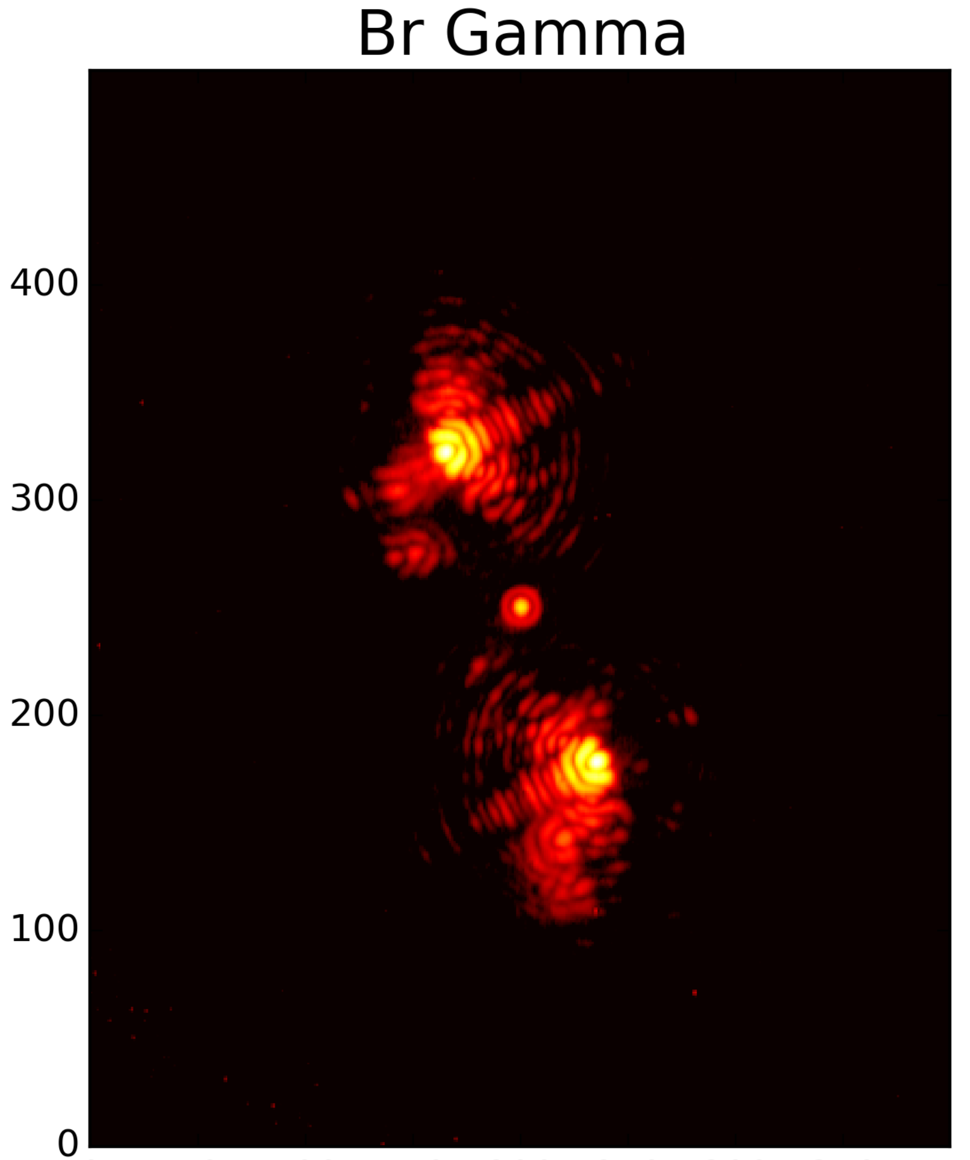
Otten et al, ApJ, 2017

on-sky contrast

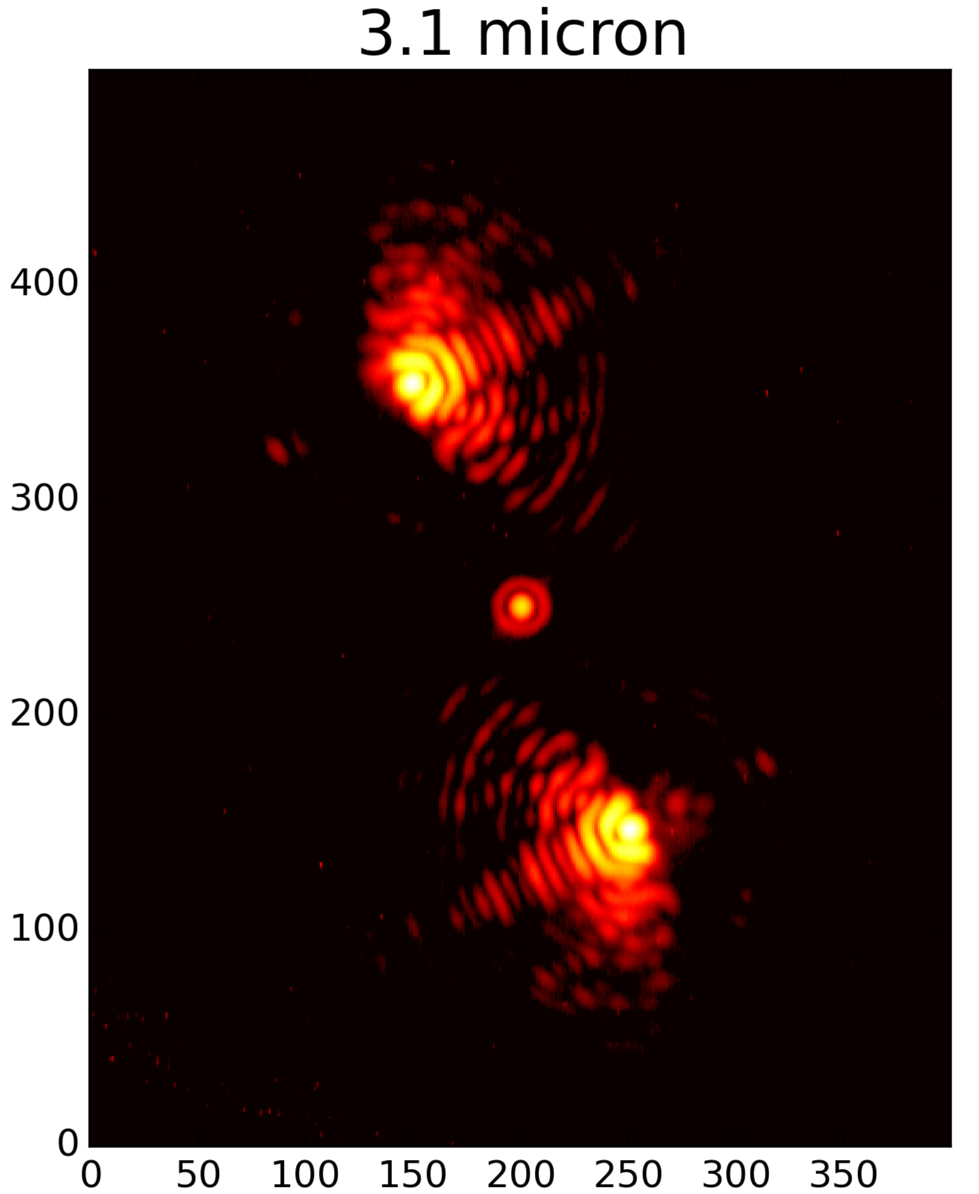


Otten et al, ApJ, 2017

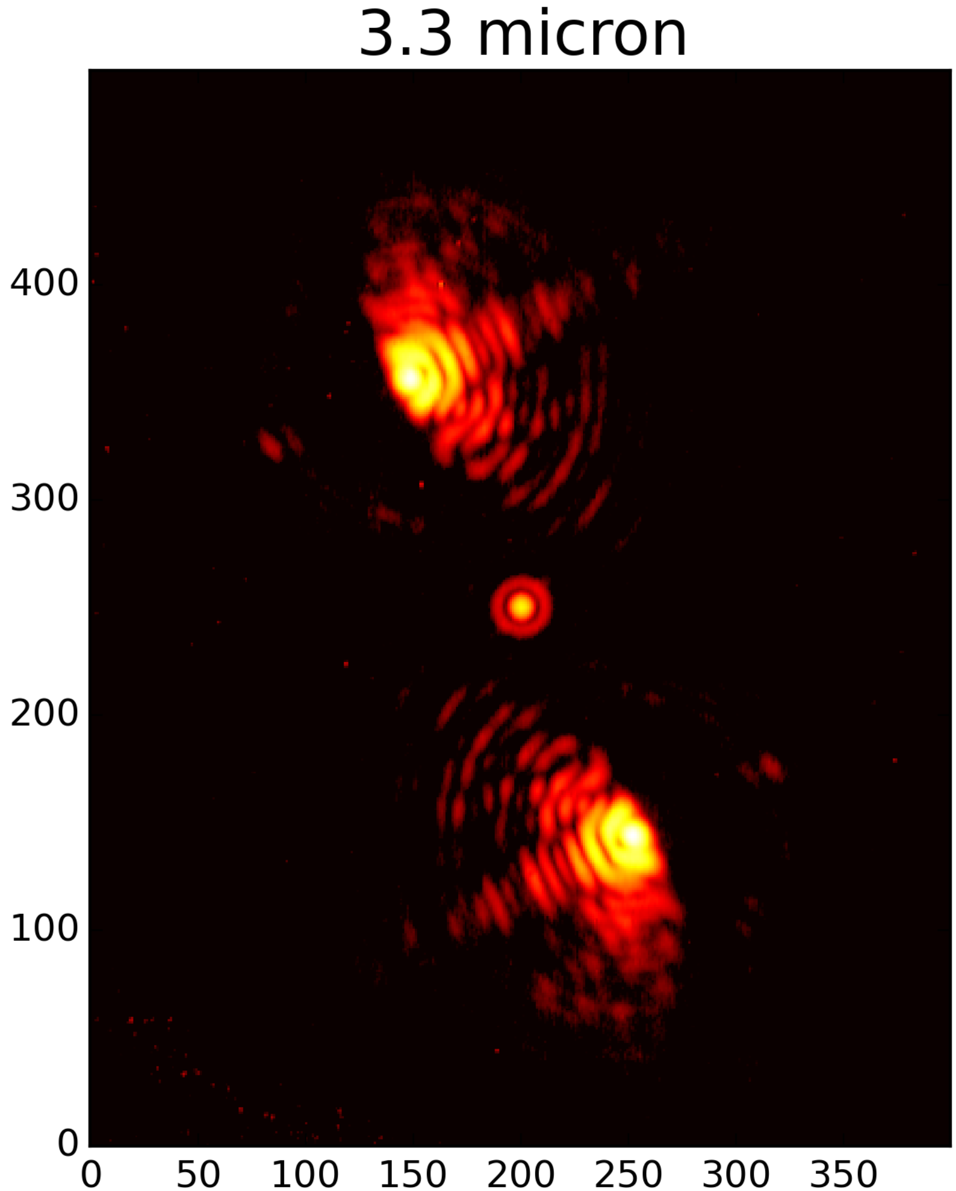
Achromatic behaviour



Achromatic behaviour

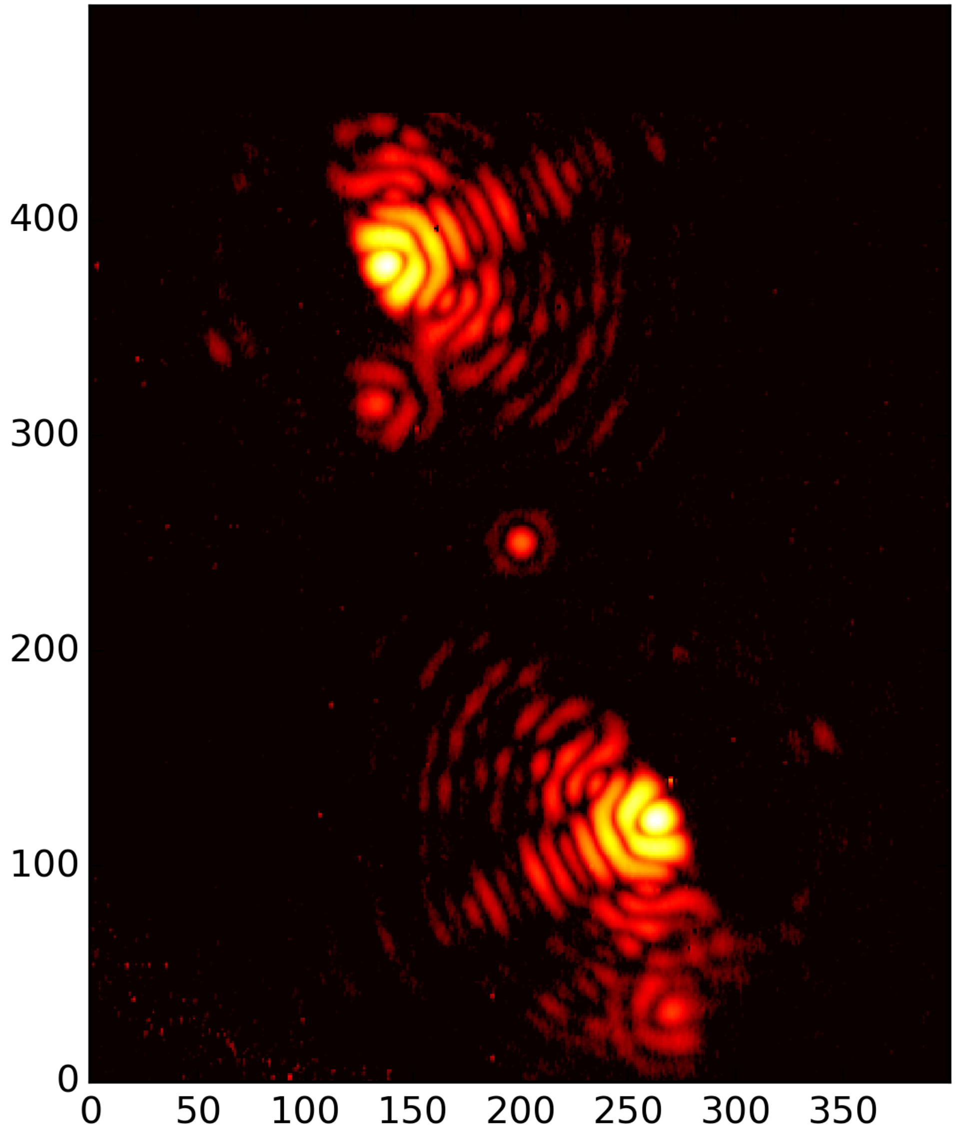


Achromatic behaviour

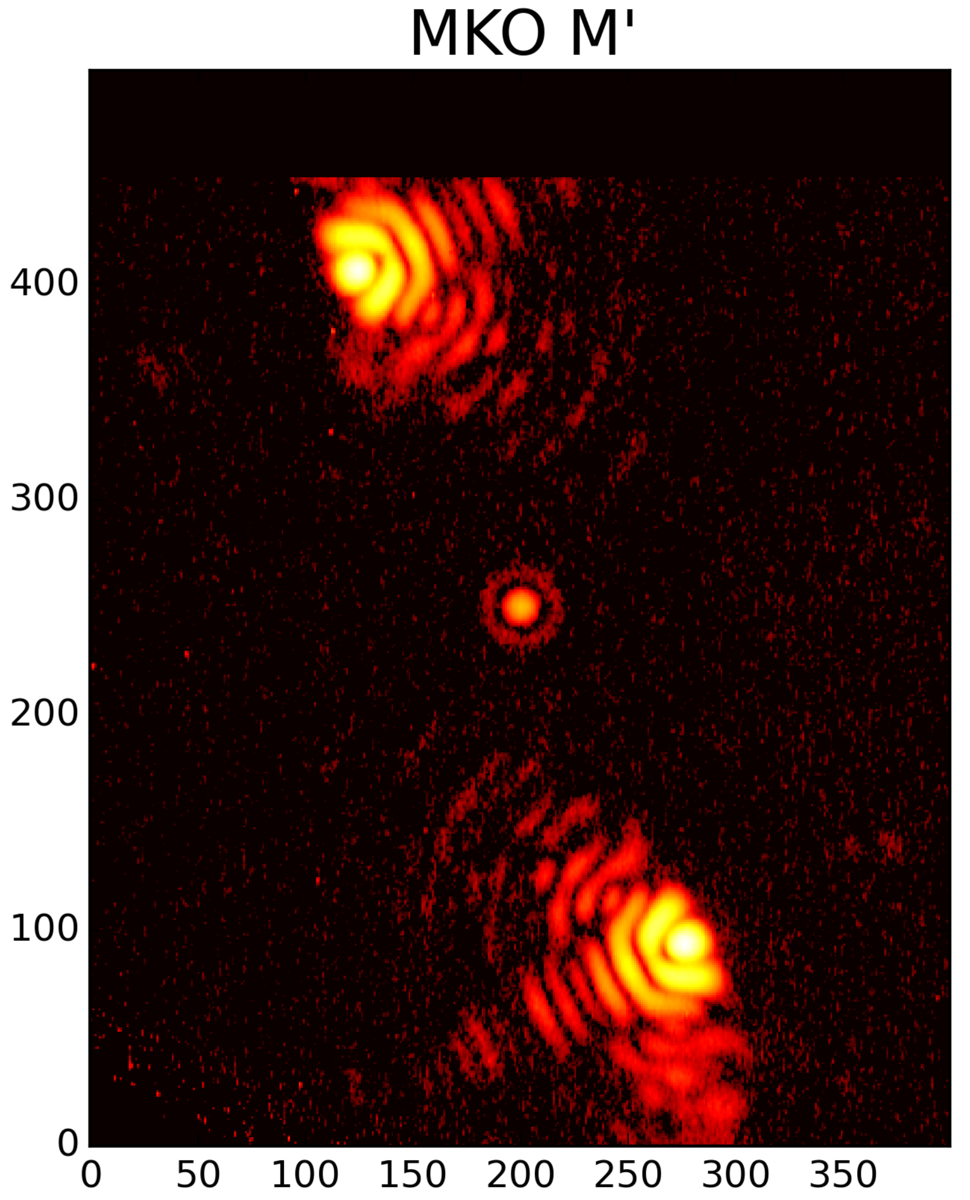


Achromatic behaviour

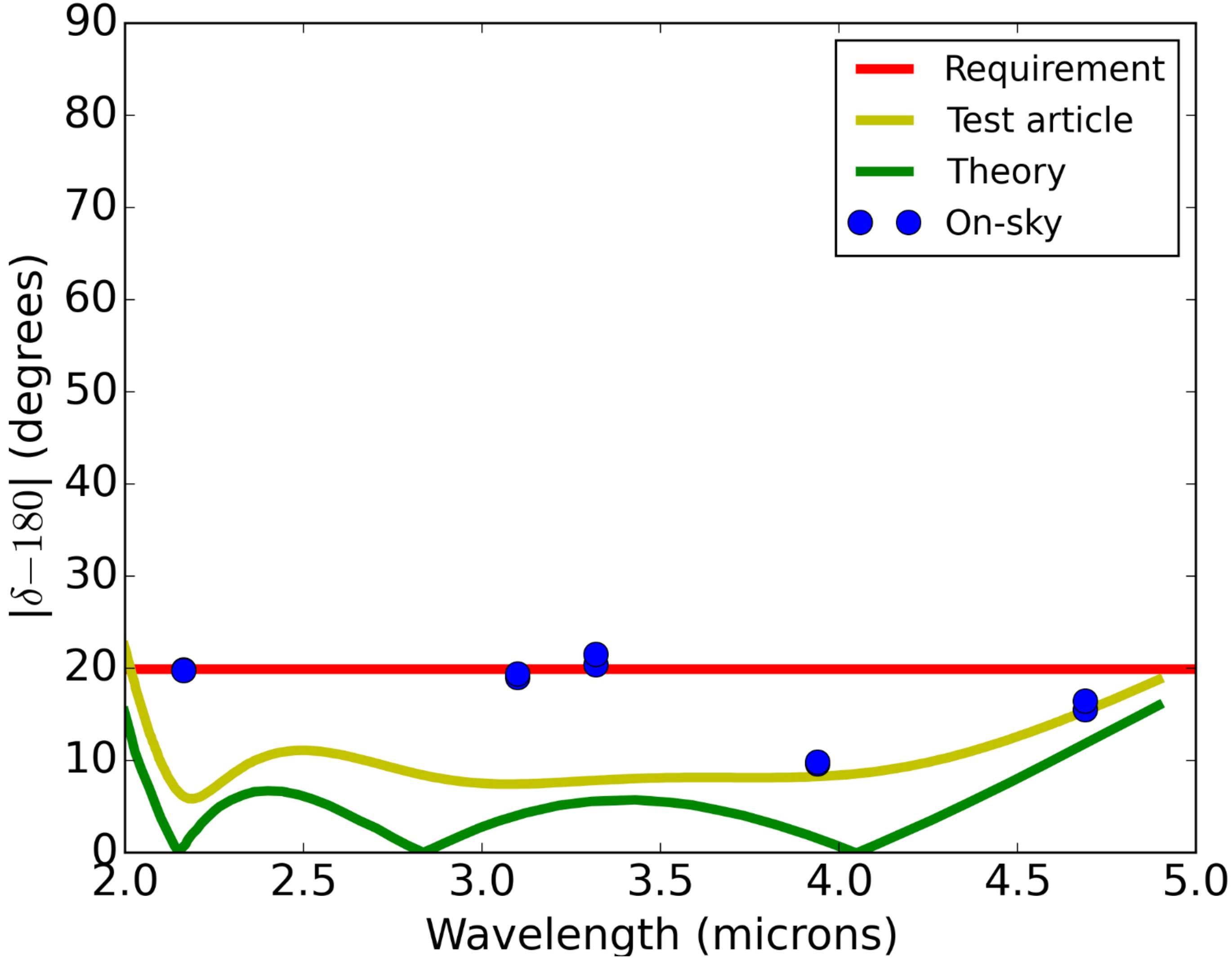
3.9 micron



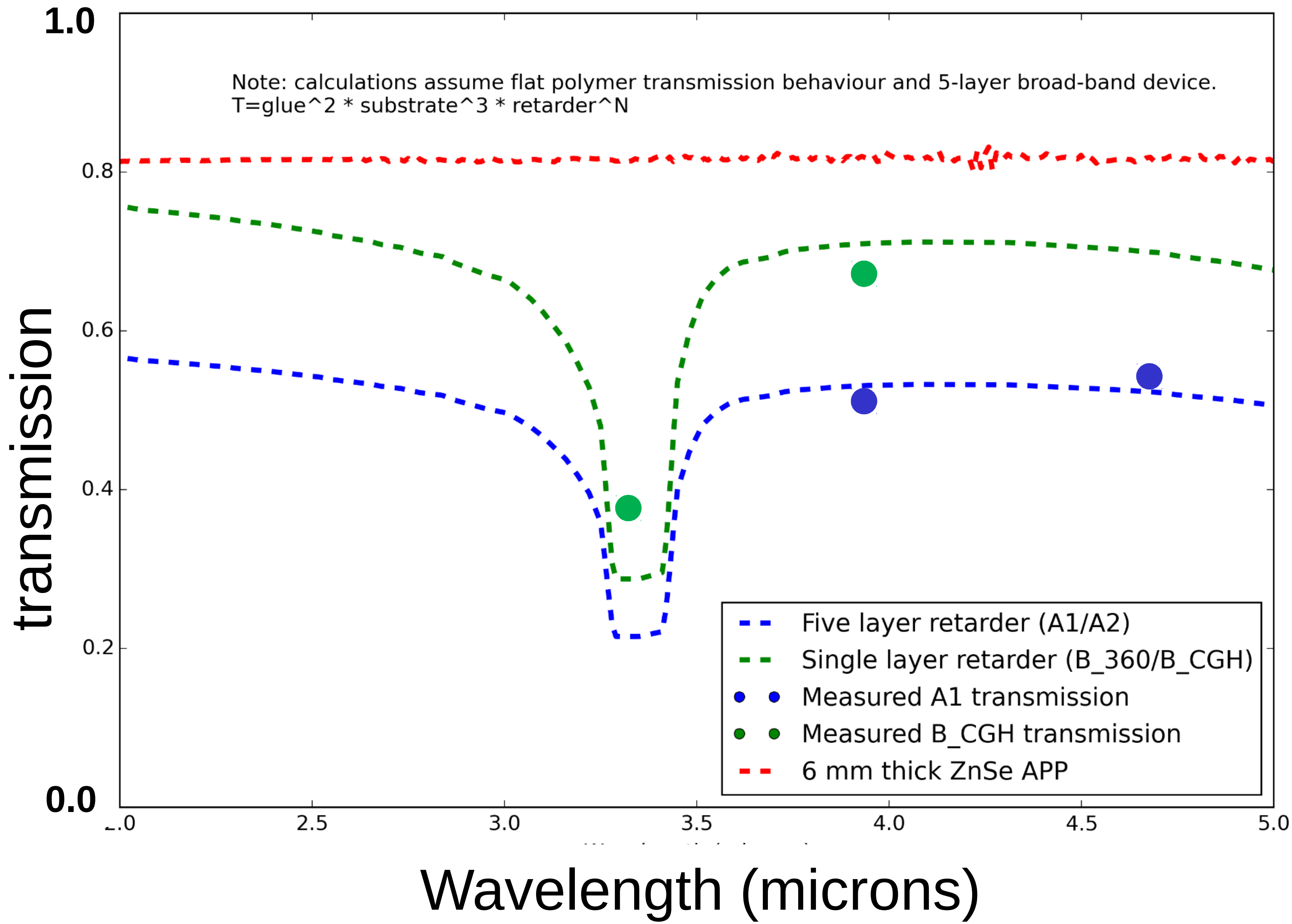
Achromatic behaviour



Derived retardance

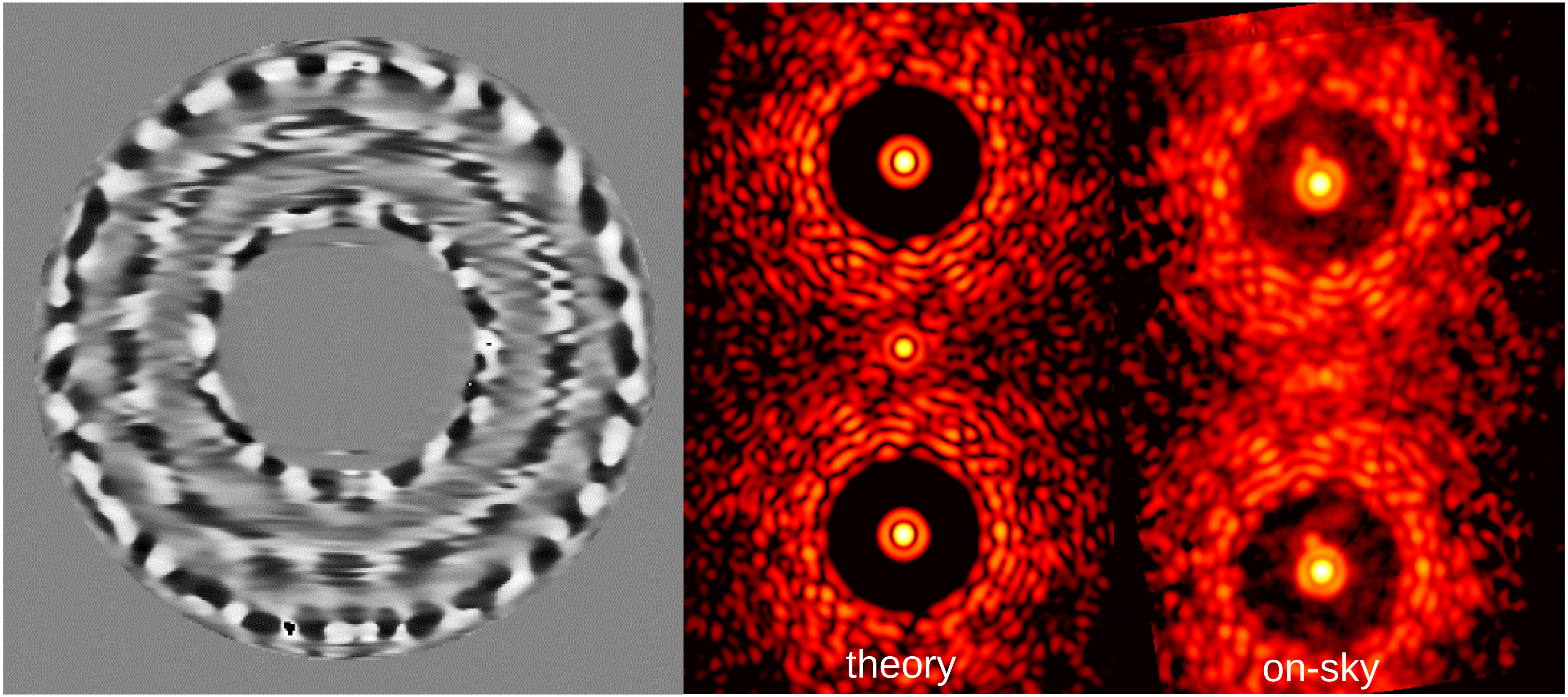


Throughput



1.0
0.8
0.6
0.4
0.2
0.0
transmission
Note: calculations assume flat polymer transmission behaviour and 5-layer broad-band device.
T=glue^2 * substrate^3 * retarder^N
Five layer retarder (A1/A2)
Single layer retarder (B_360/B_CGH)
Measured A1 transmission
Measured B_CGH transmission
6 mm thick ZnSe APP
2.5
3.0
3.5
4.0
4.5
5.0
Wavelength (microns)

Improved phase designs



Phase pattern: Christoph U. Keller

Many more tricks and latest work with liquid crystal optics in talk
by Frans Snik, Friday March 16 @ 11h, Amphi, LAM