Durham University

CfAI Centre for Advanced Instrumentation

The pupil-modulated point-diffraction interferometer

Concept, status, prospects

table of **Contents**

motivation

Quasi-static aberrations

- corrected to >10 nm rms for direct detection of exo-planets
- PSF evolves in the order of 10~60 minutes

Direct measurement

- most methods are indirect: phase-diversity, speckle-nulling, angular differential imaging
- some are iterative and have converging times of a few minutes or faster

Cophasing

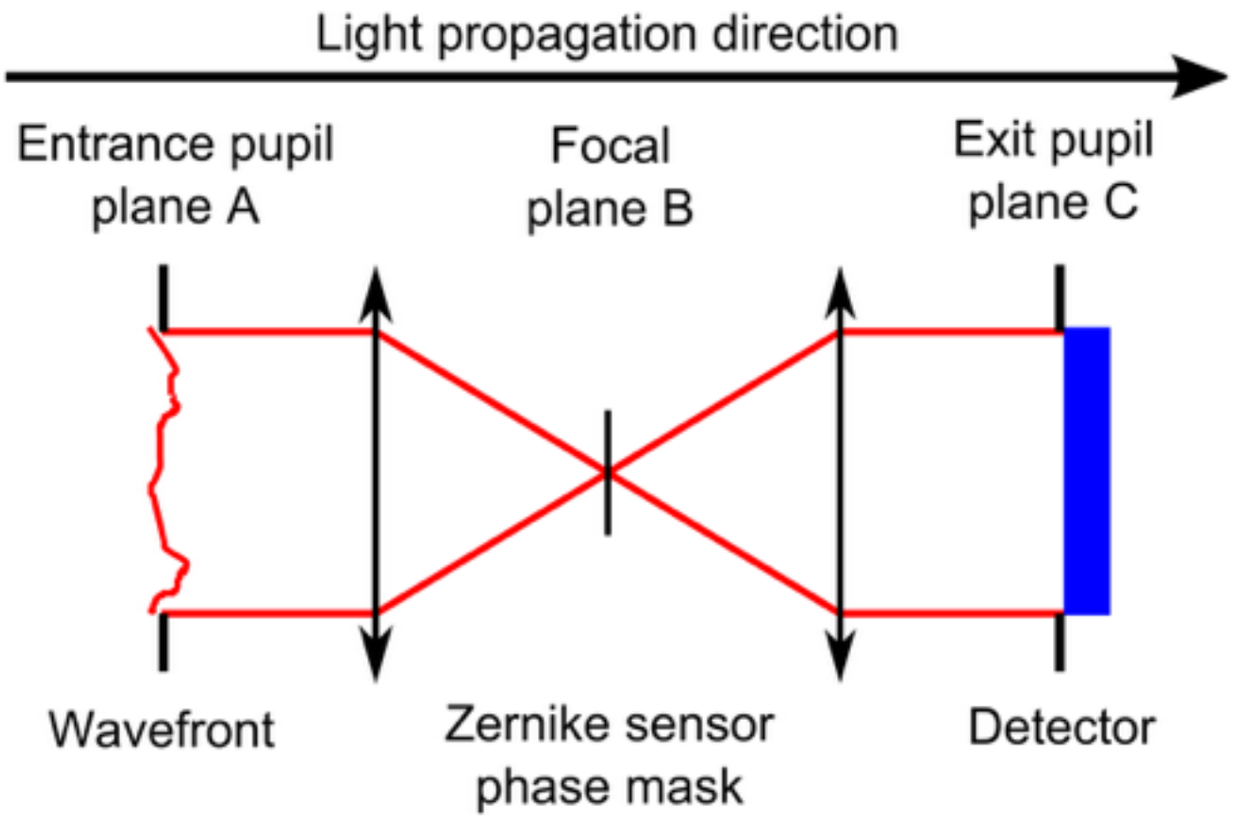
- Conventional WFSs struggle
- PDIs have been shown to work

XAO

- requires high accuracy, resolution, low noise
- potentially disconnected segments

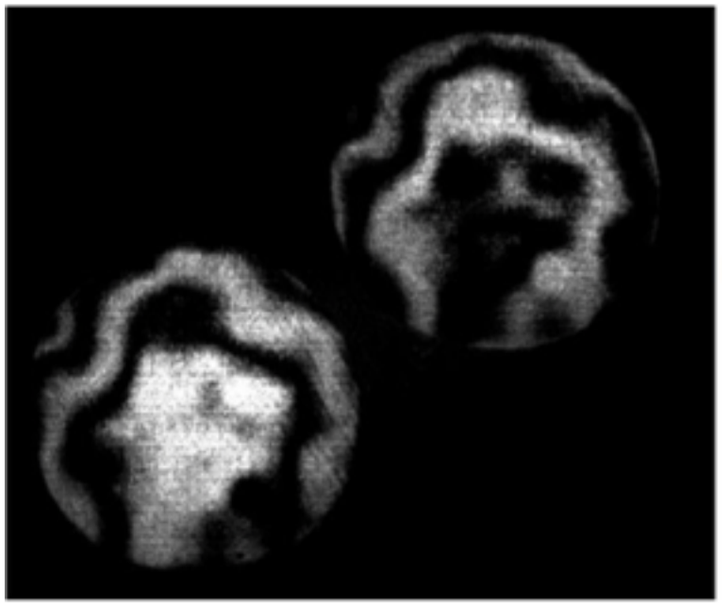
point-diffraction interferometers

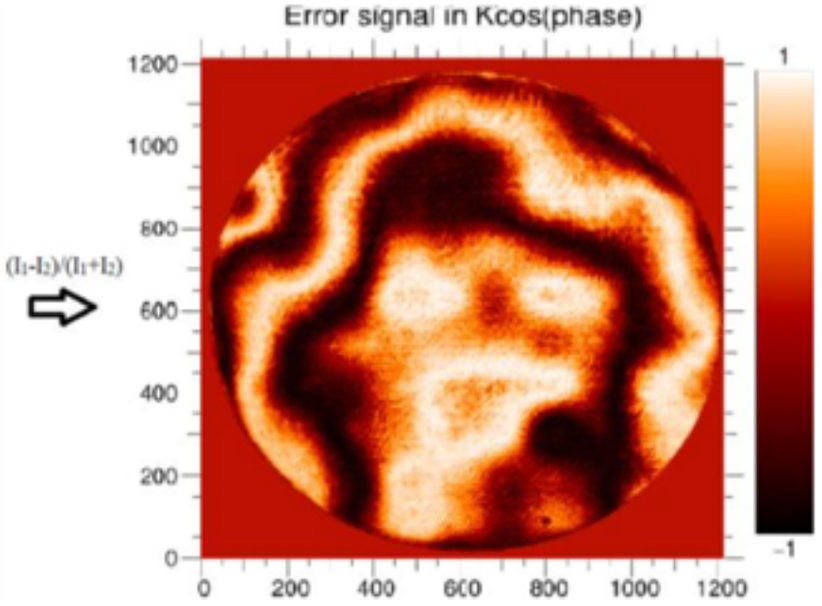
or just **PDI**



ZELDA Zernike sensor
(N'Diaye *et al.* 2013)

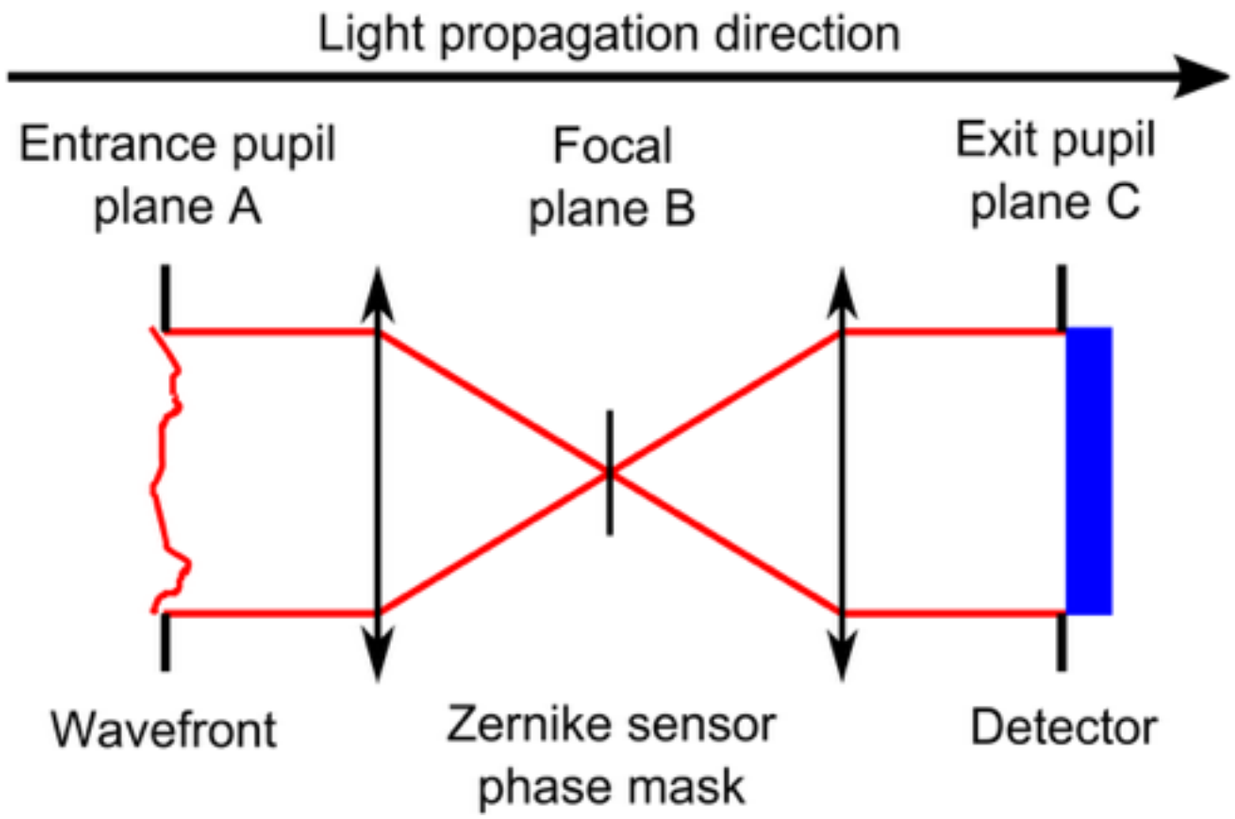
Mach-Zehnder wavefront sensor
(Loupias *et al.* 2016)





point-diffraction interferometers

or just **PDI**



$\pm\pi/2$ *(a prior)*

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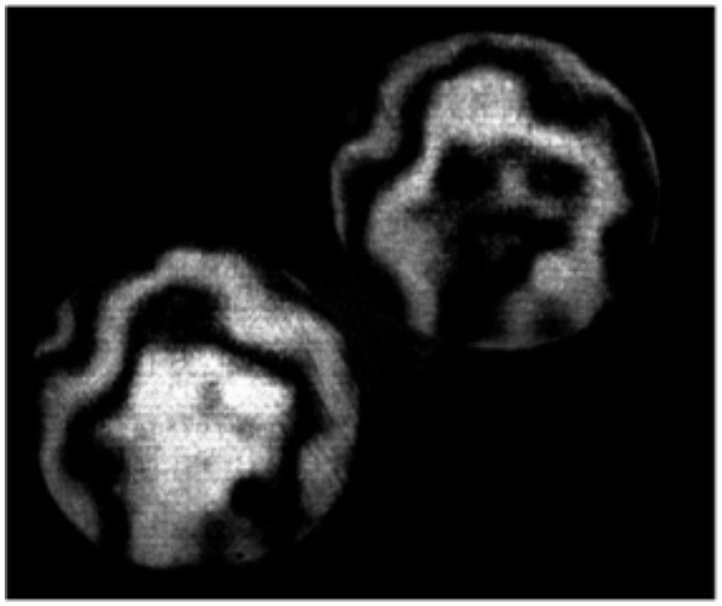
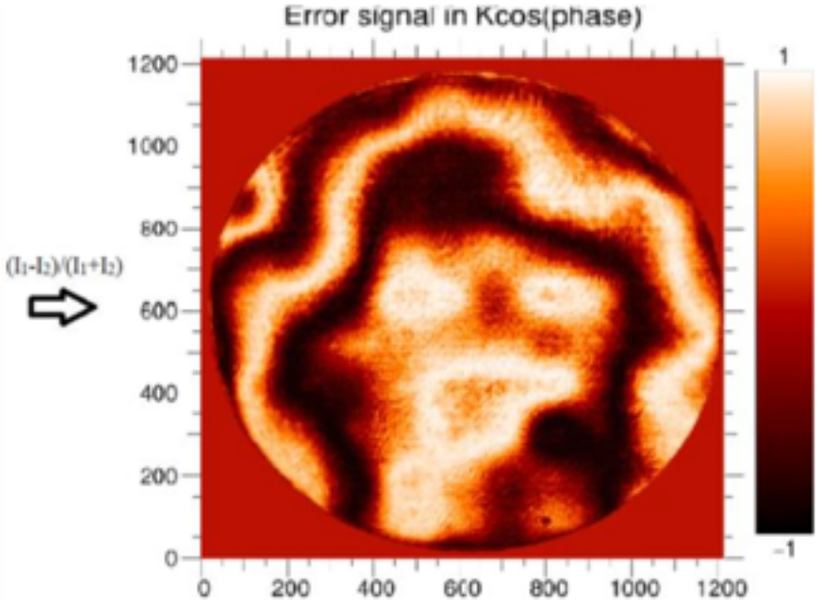
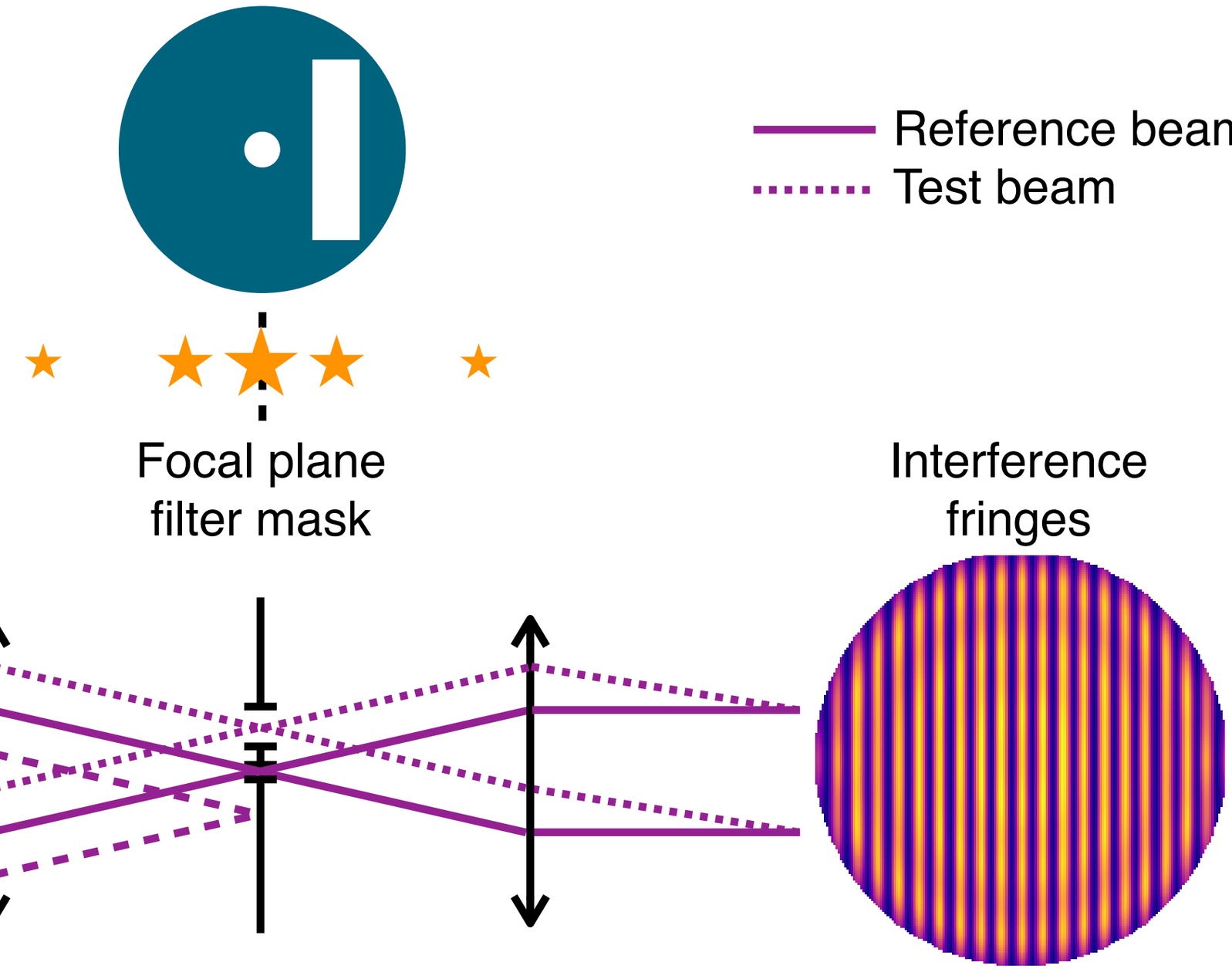


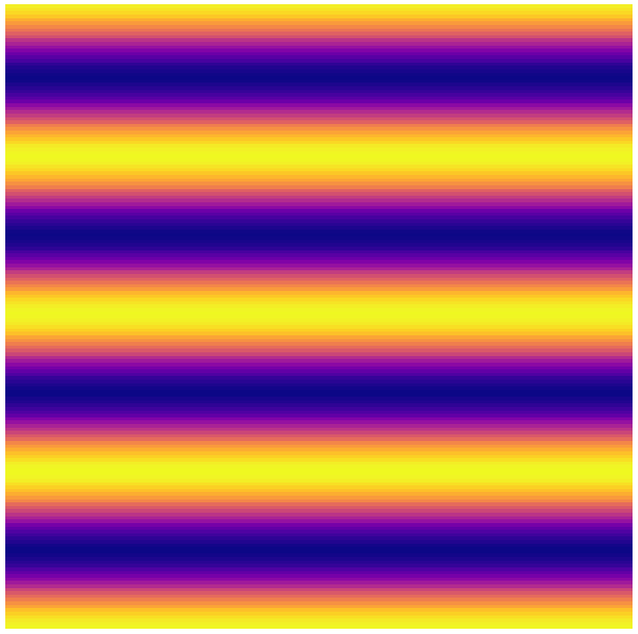


pupil-**modulated PDI**

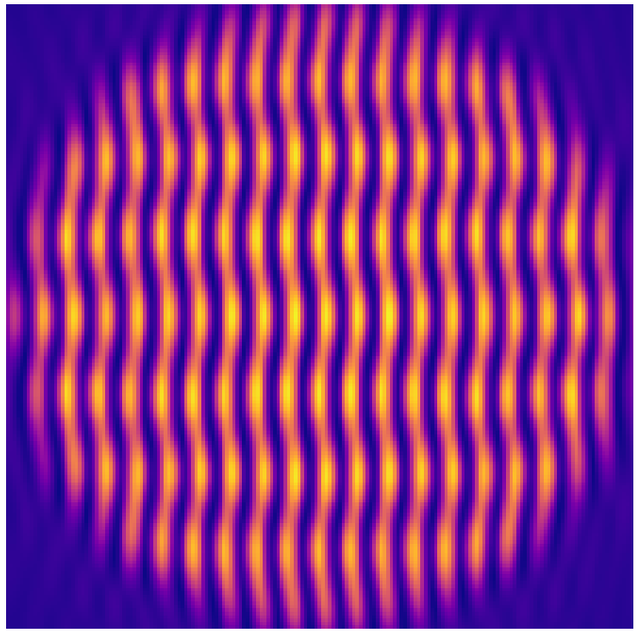
or just **m-PDI**



phase **modulation**

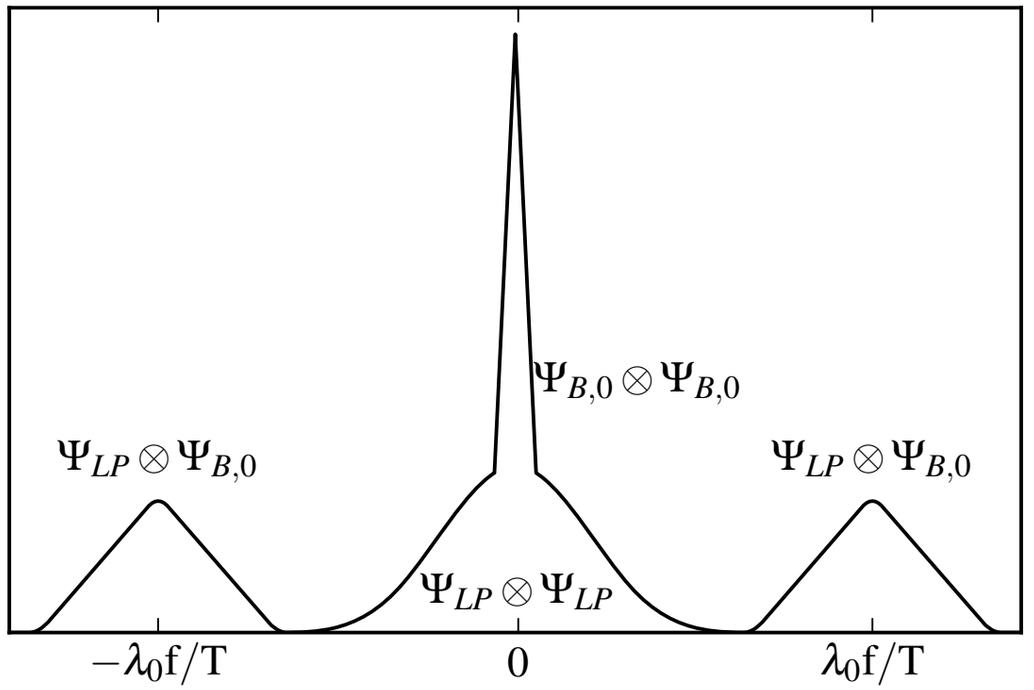


Input
phase



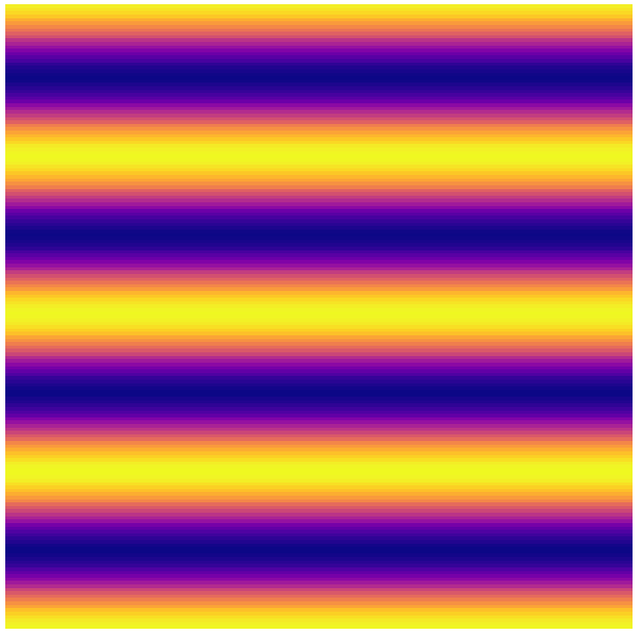
Intensity
output

FFT



FFT of
Intensity output

phase **modulation**



Input
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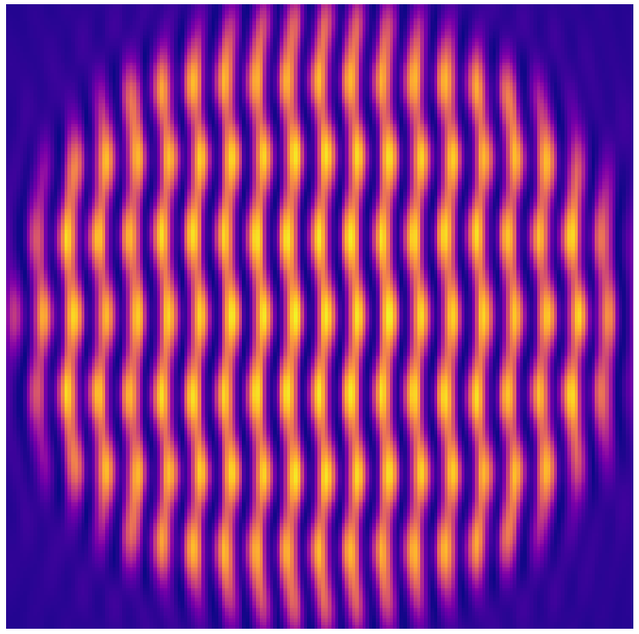

Intensity
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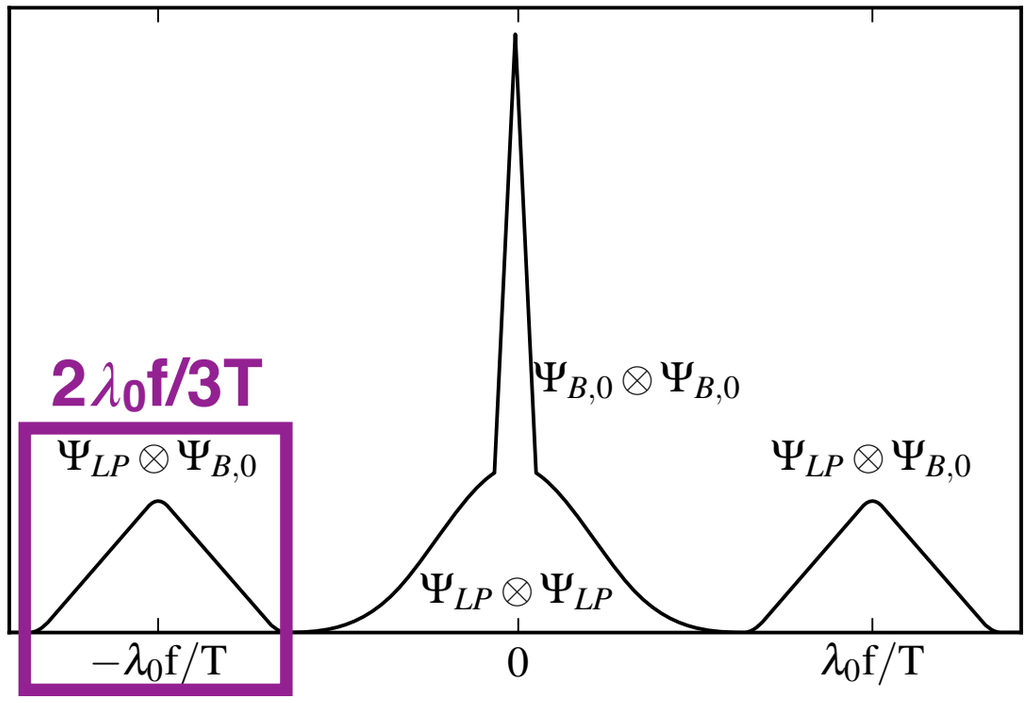
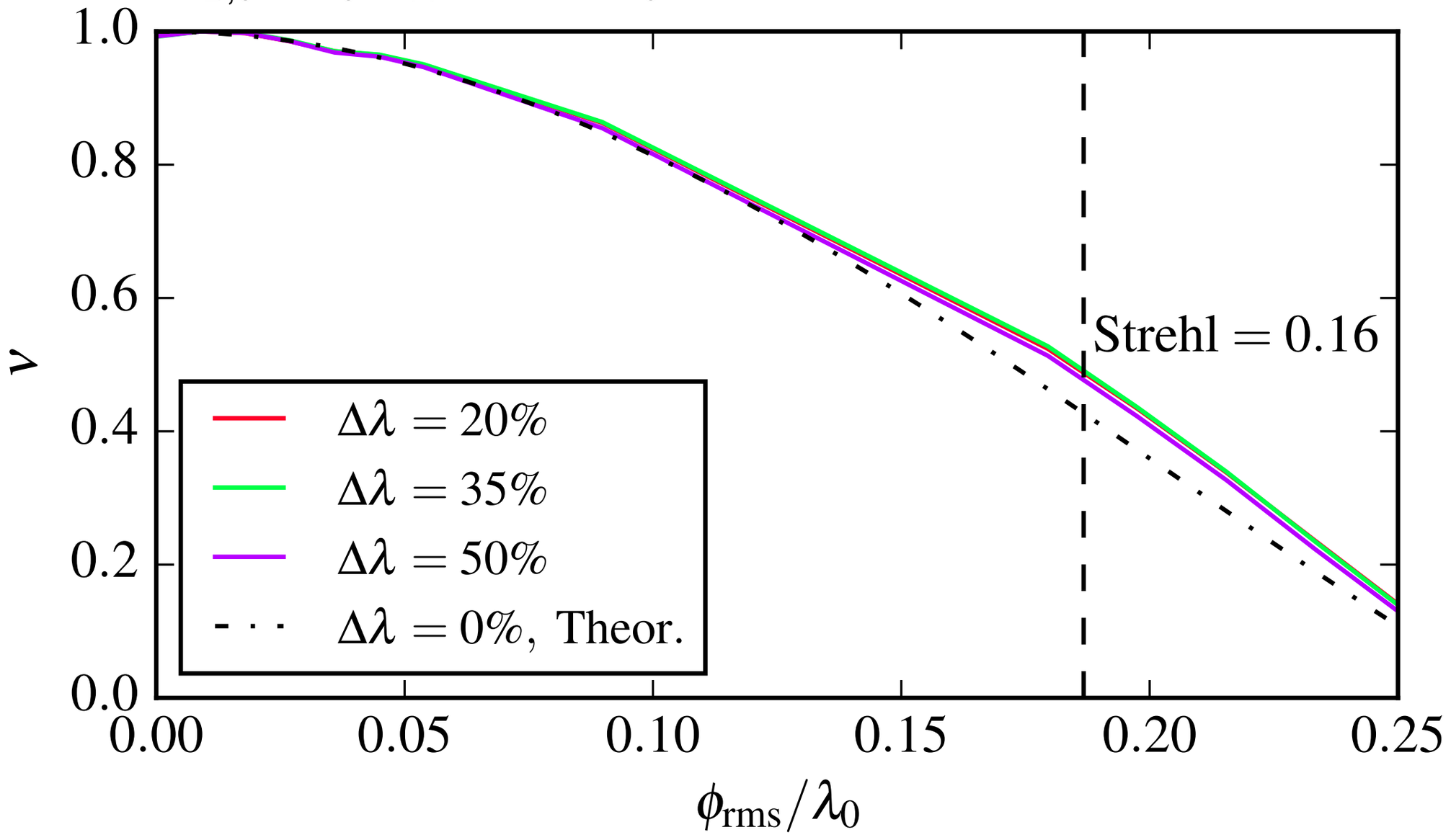
FFT



FFT of
Intensity output

visibility and **chromaticity**

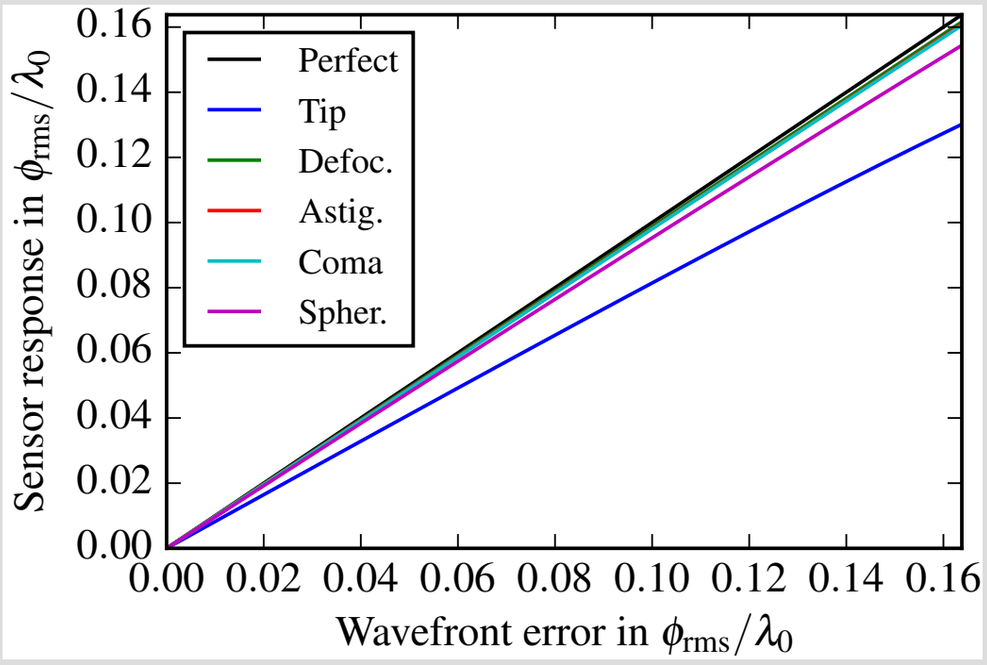
$D_{B,0} = \lambda_0/D_A$ ➔ $b/P_0 = 0.22$



accuracy and **dynamic range**

(i) Initial configuration

λ_0 =557nm, $\Delta\lambda$=0%, $D_{B,0} = \lambda_0 / D_A$, N_G=30, N_P=8



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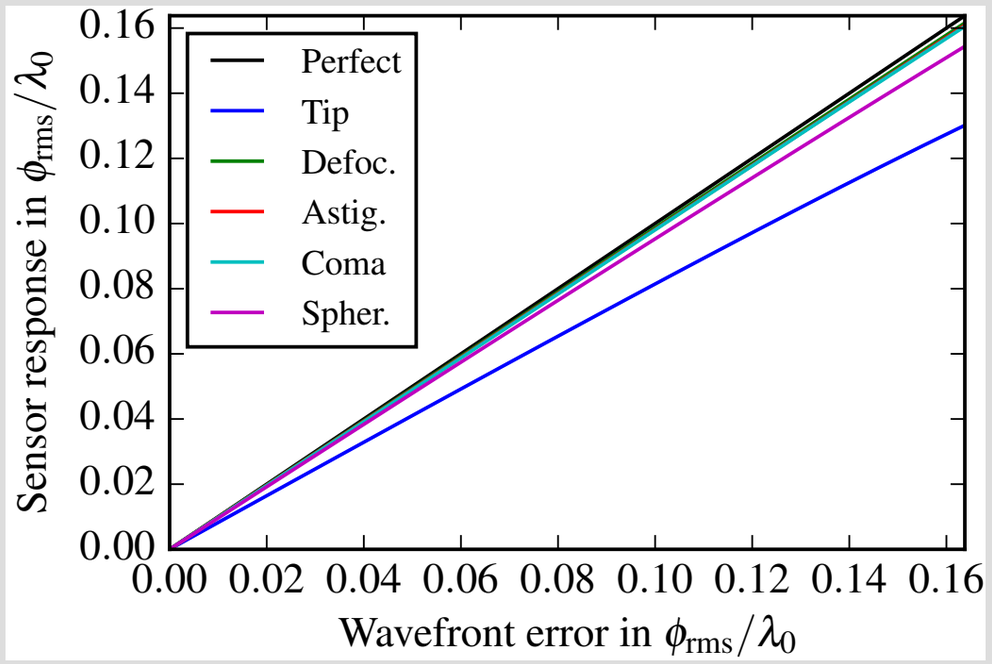
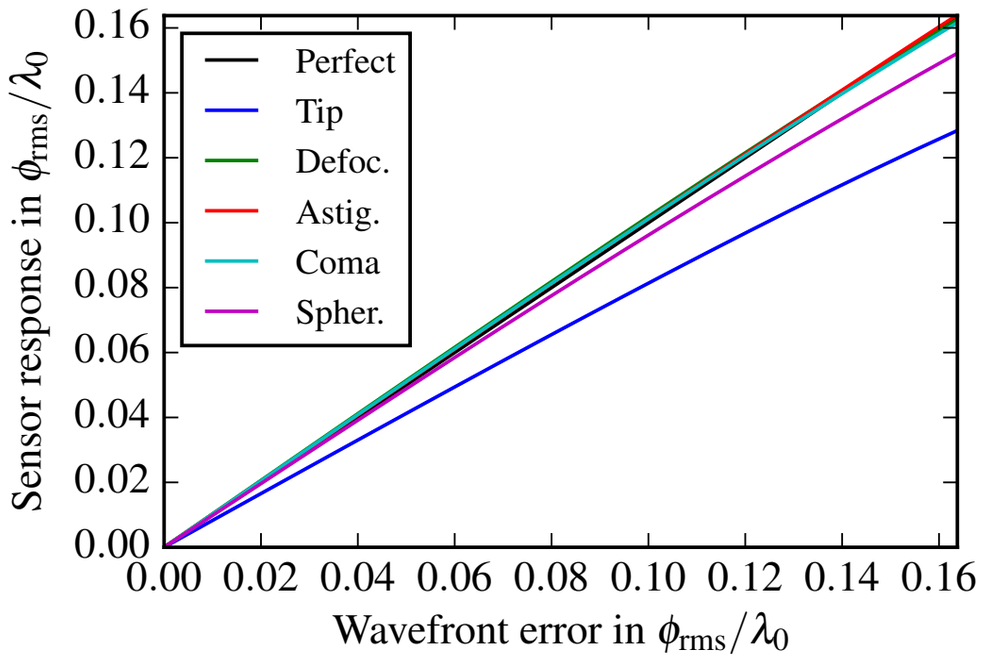


(ii) $\Delta\lambda$=50%



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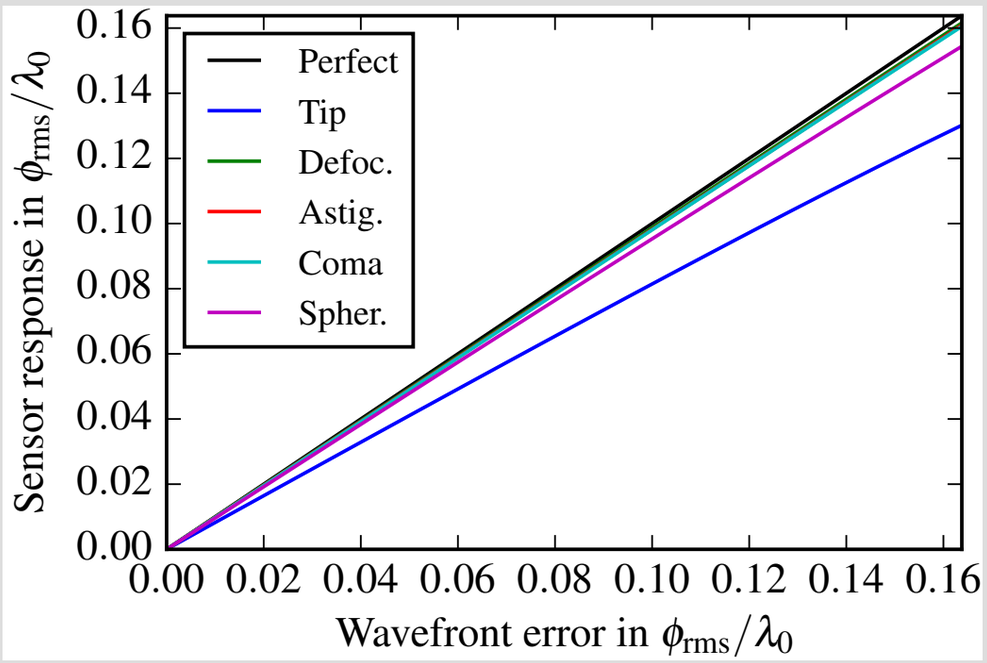

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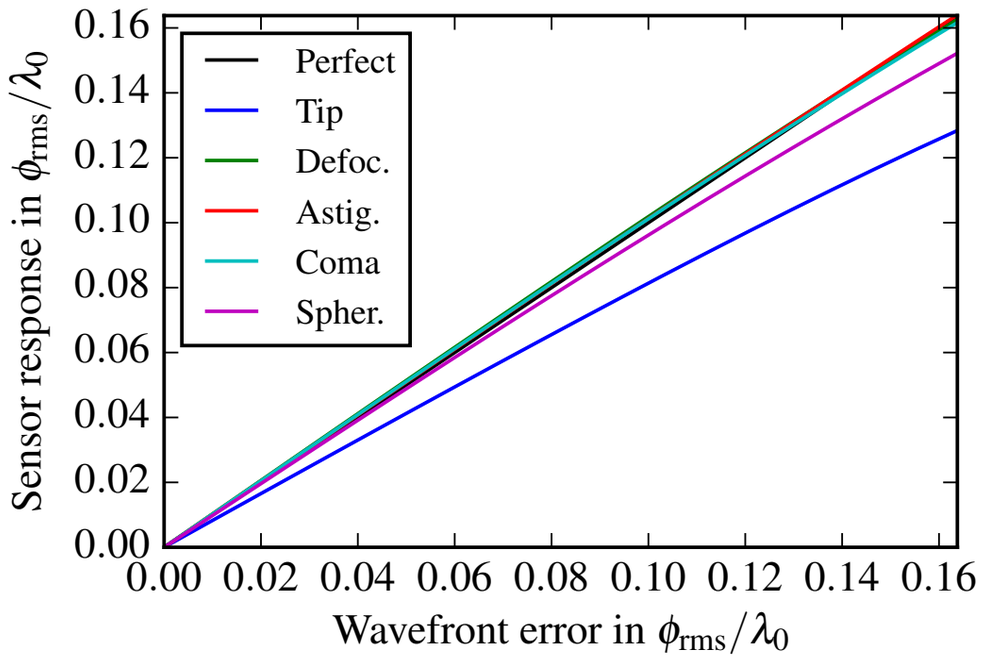
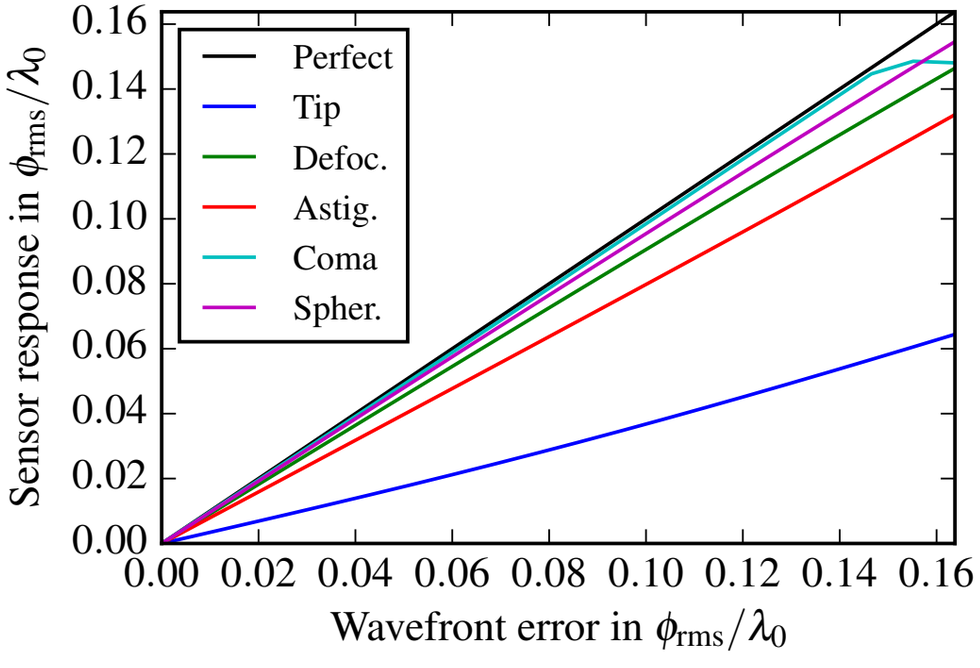


(iii-a) $D_{B,0} = 2\lambda_0 / D_A$



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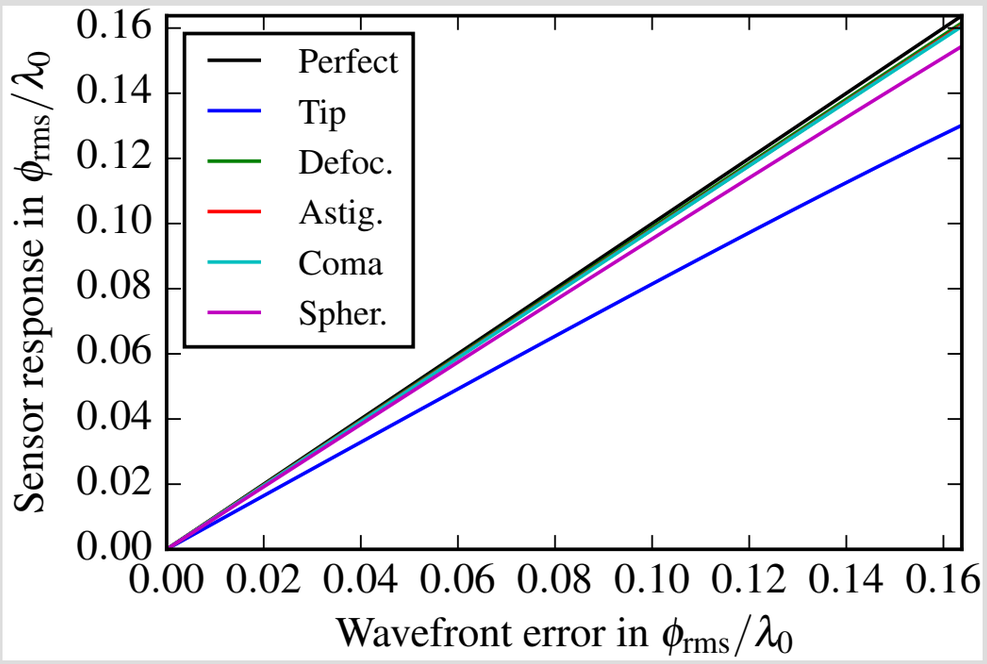

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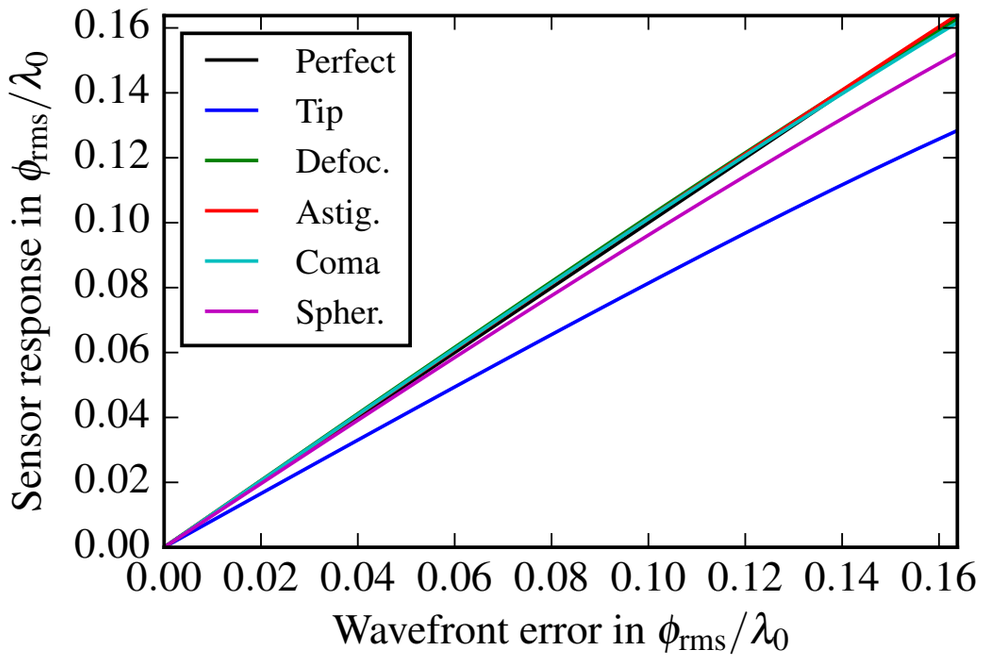

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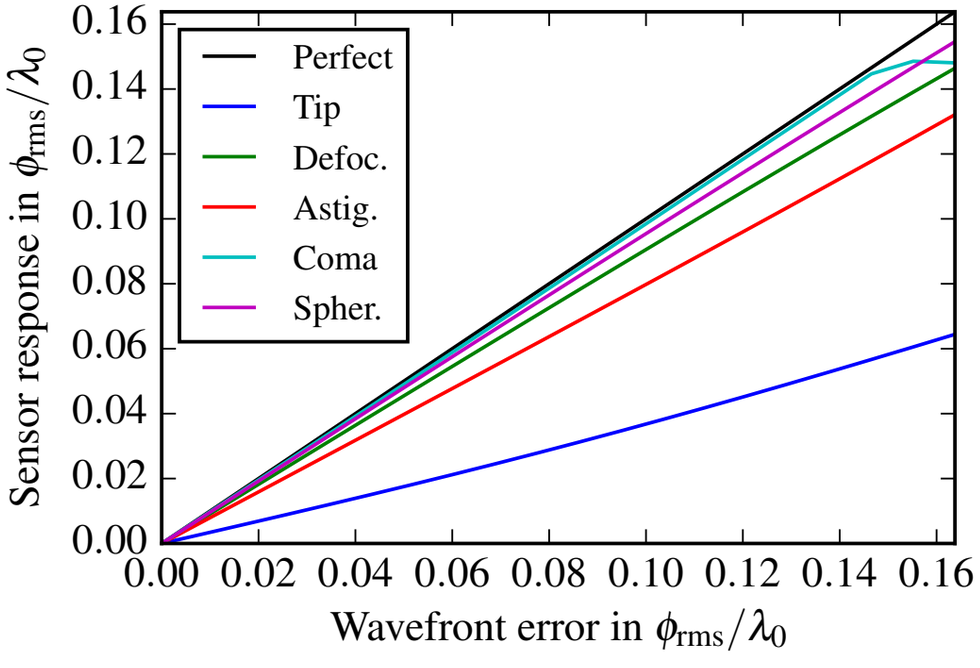
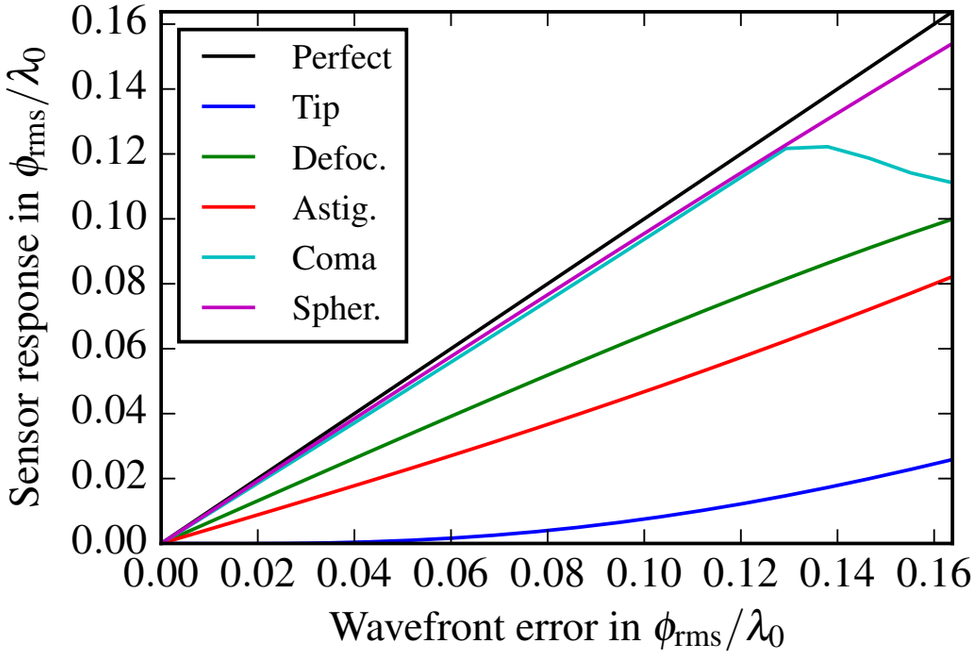
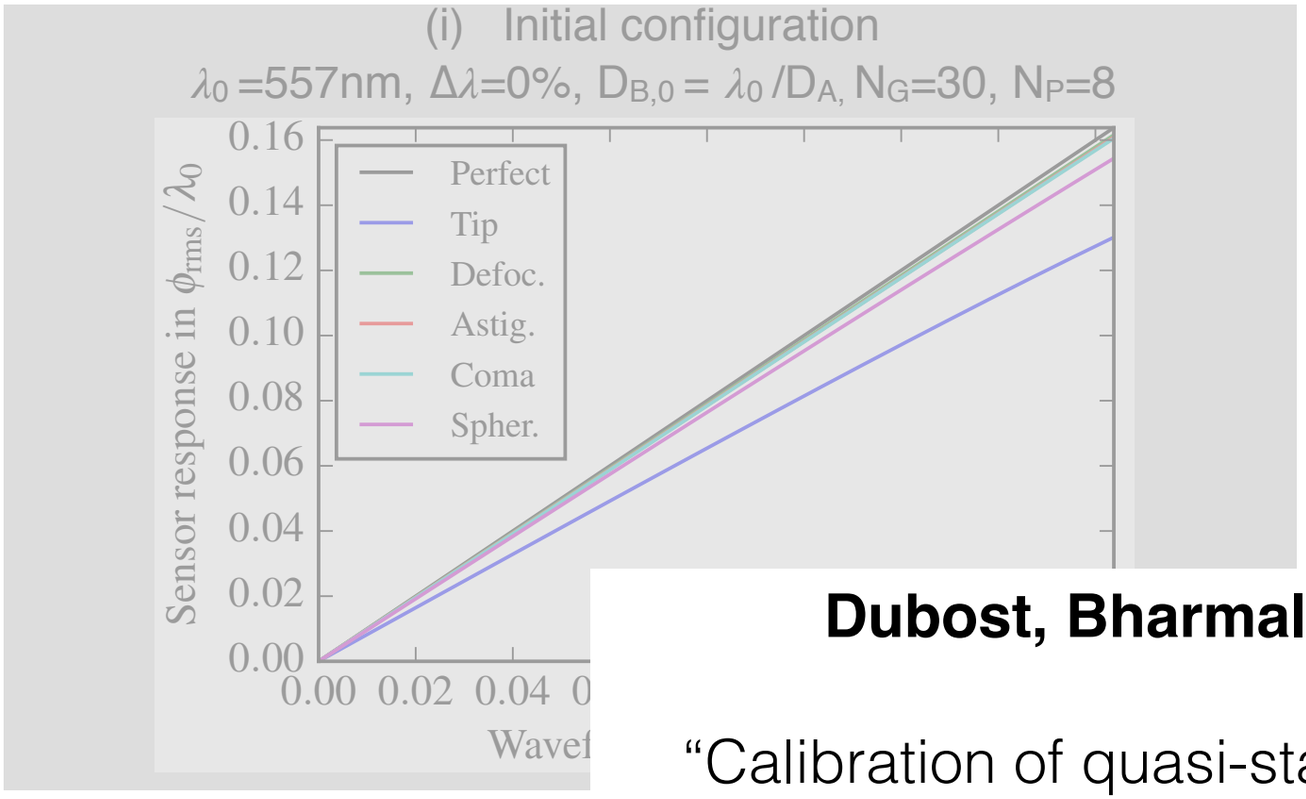
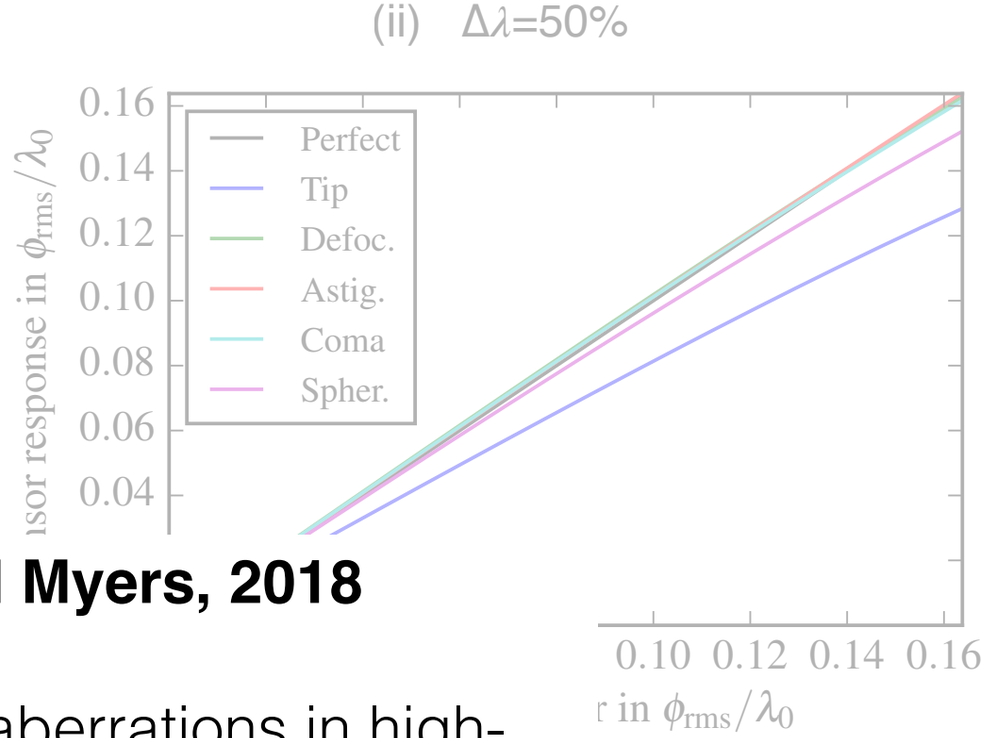


(iii-b) $D_{B,0} = 2.5\lambda_0 / D_A$



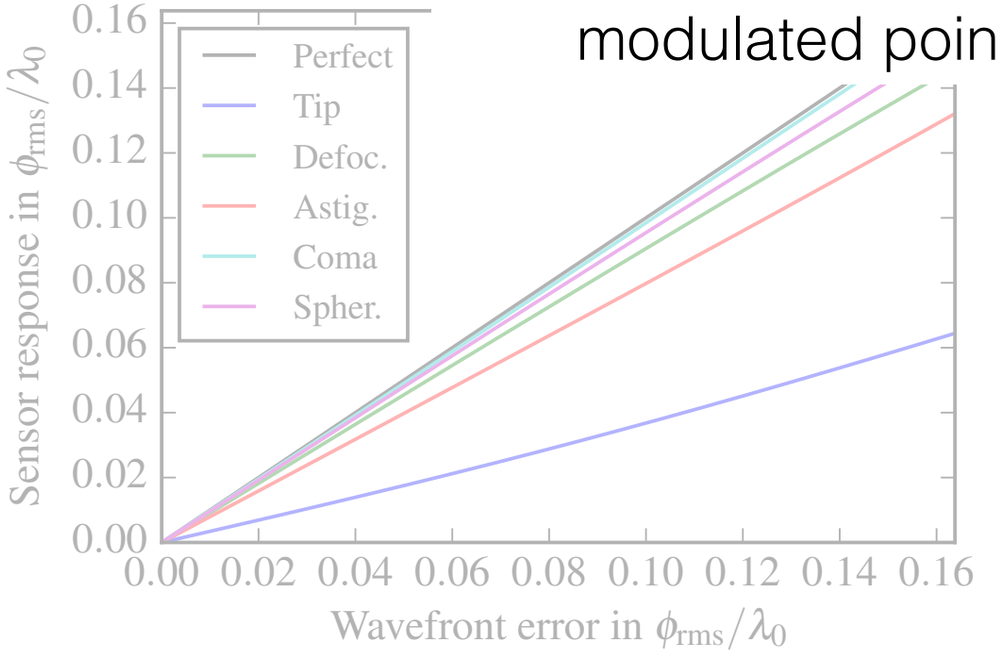
accuracy and **dynamic range**

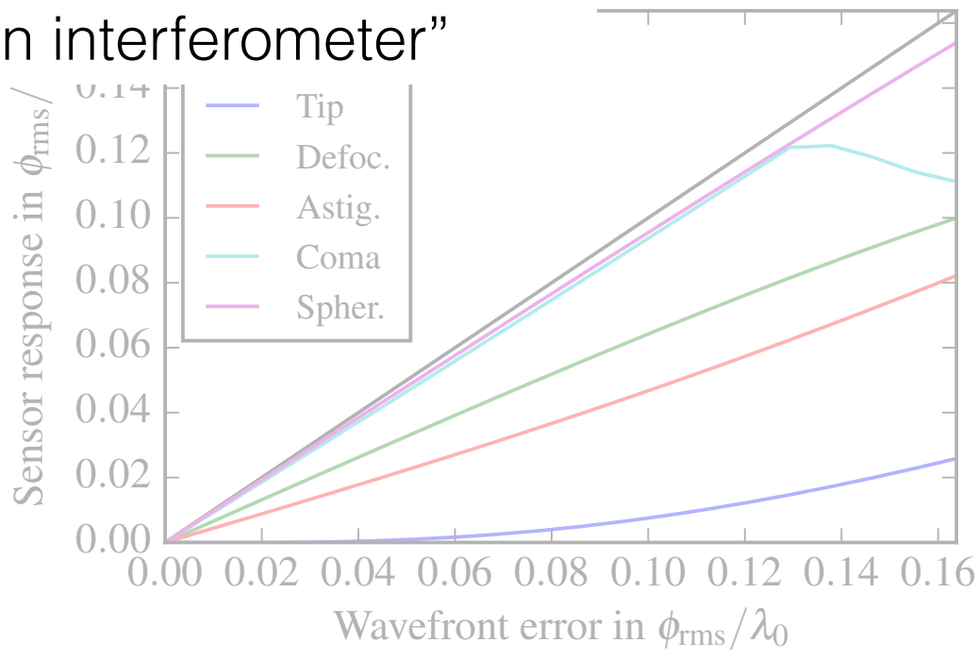




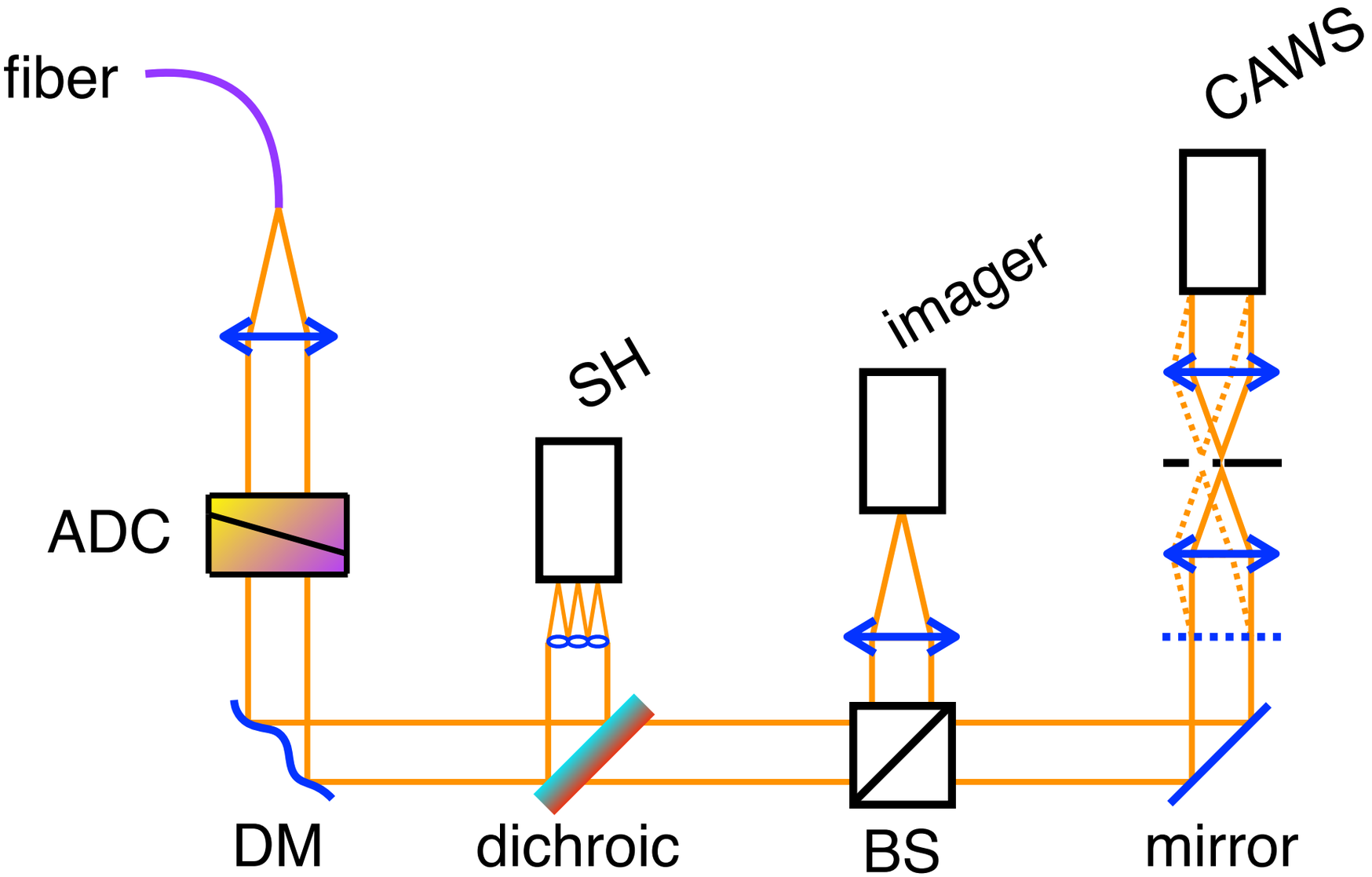
Dubost, Bharmal and Myers, 2018

"Calibration of quasi-static aberrations in high-contrast astronomical adaptive optics with a pupil-modulated point-diffraction interferometer"





integration of **CAWS** into **CHOUGH**



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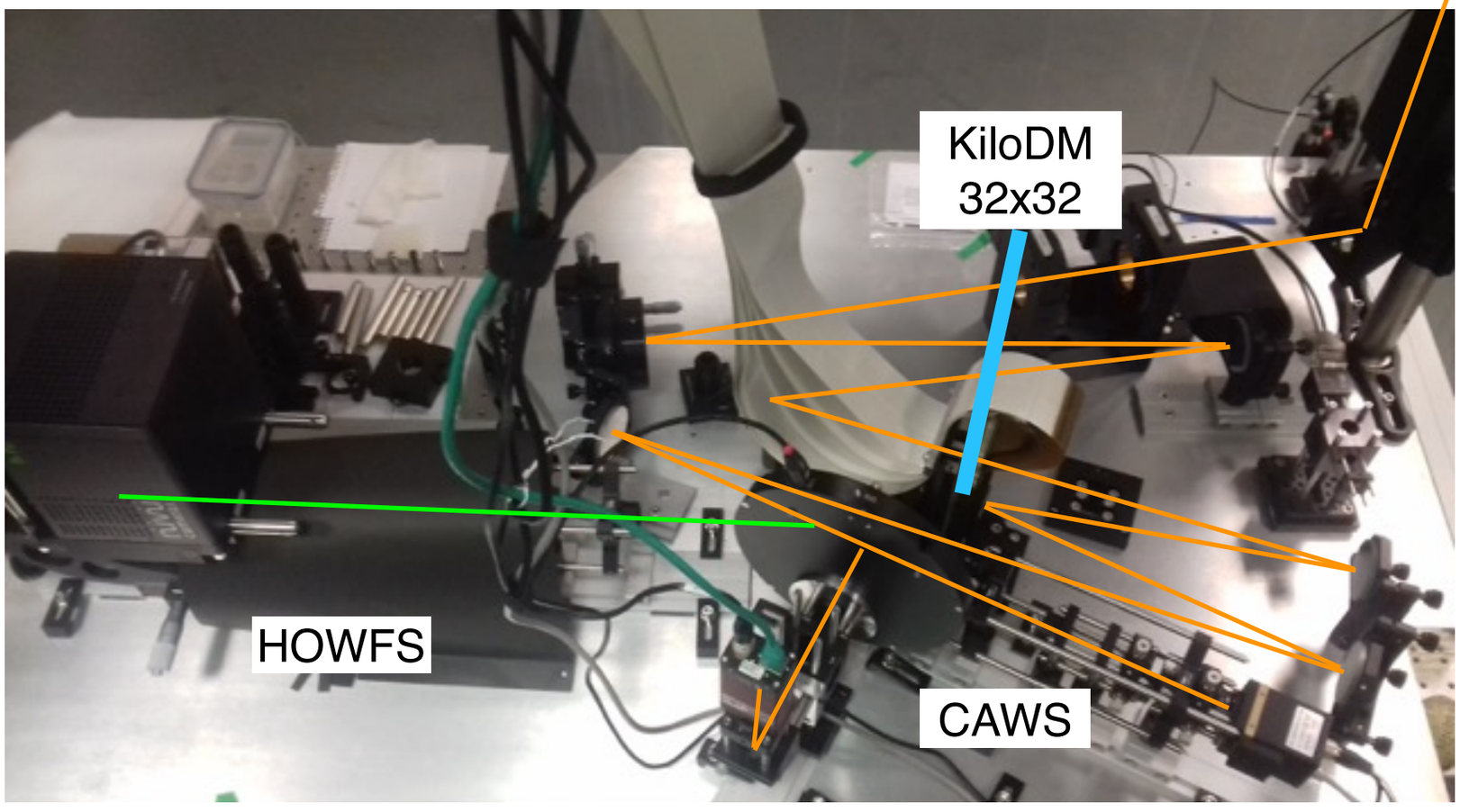
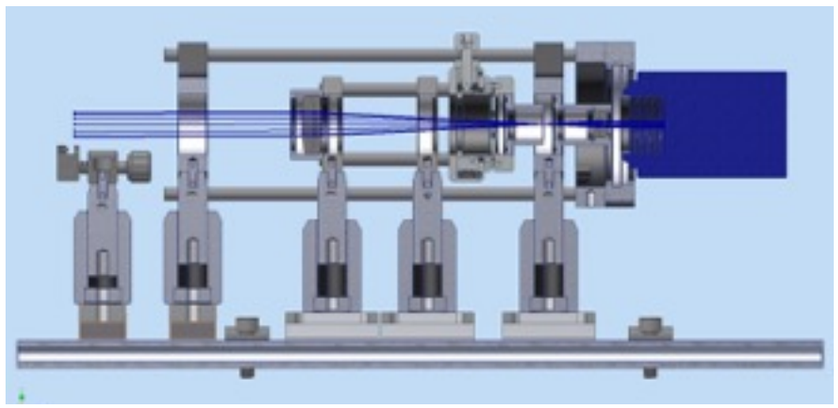
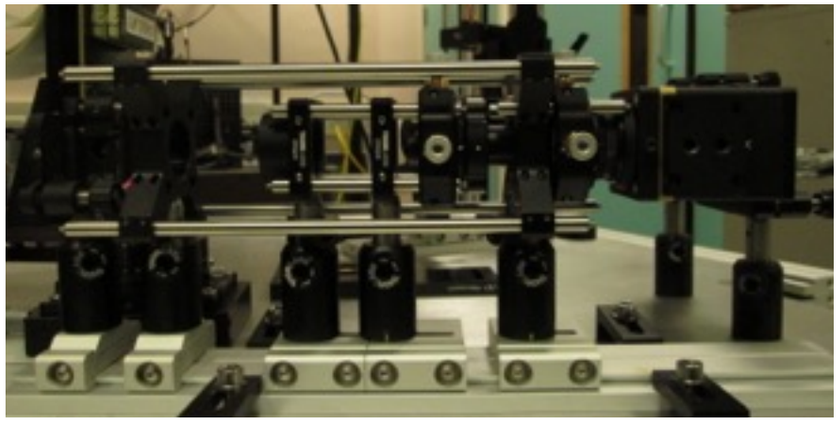




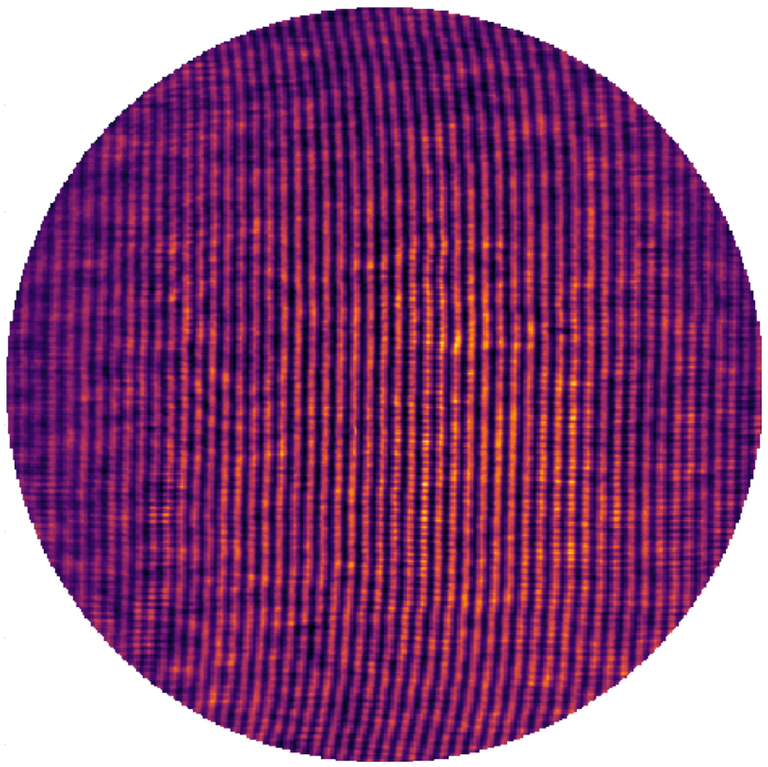


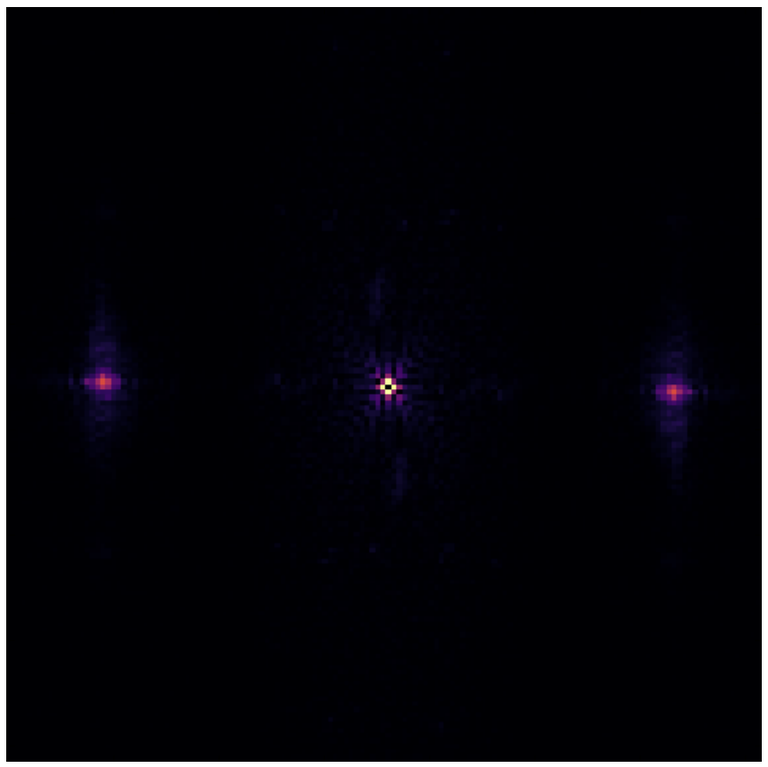
CHOUGH
1.2k Hz

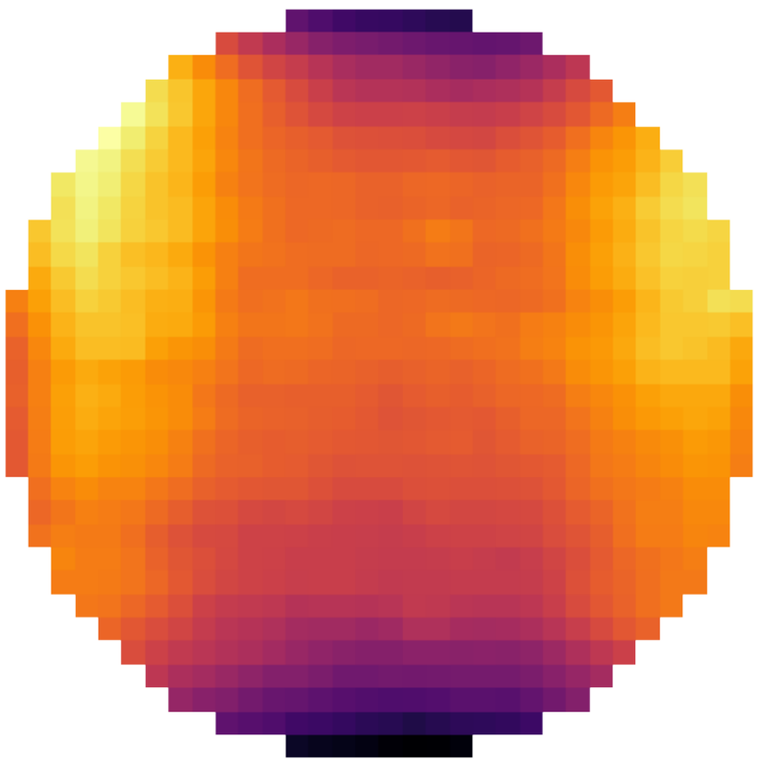
T_G = 0.2 mm
$N_G \approx 52$

Bobcat
648x484 pix
7.4 μm
200 Hz

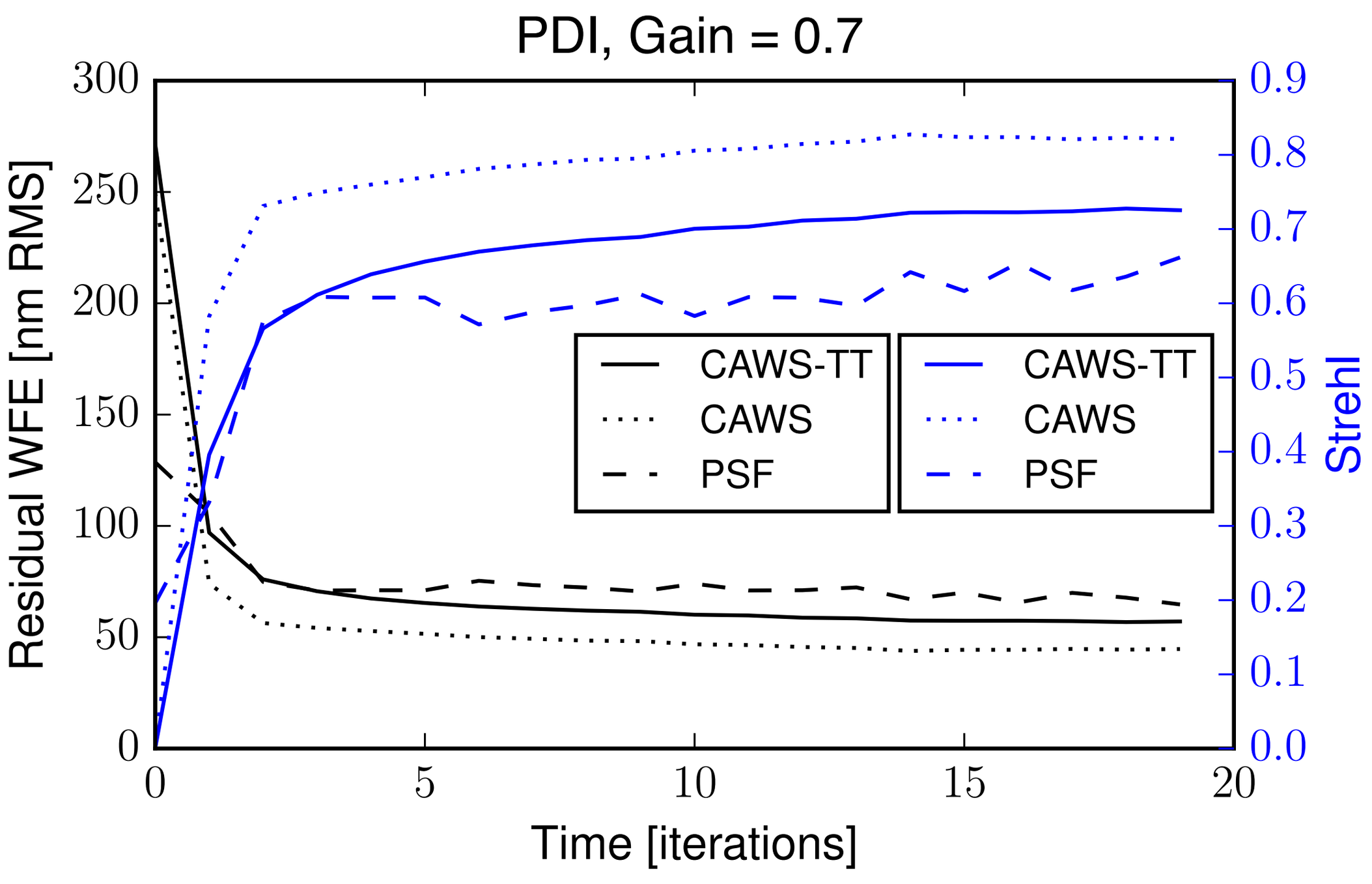
bench **data**







monochromatic closed-loop



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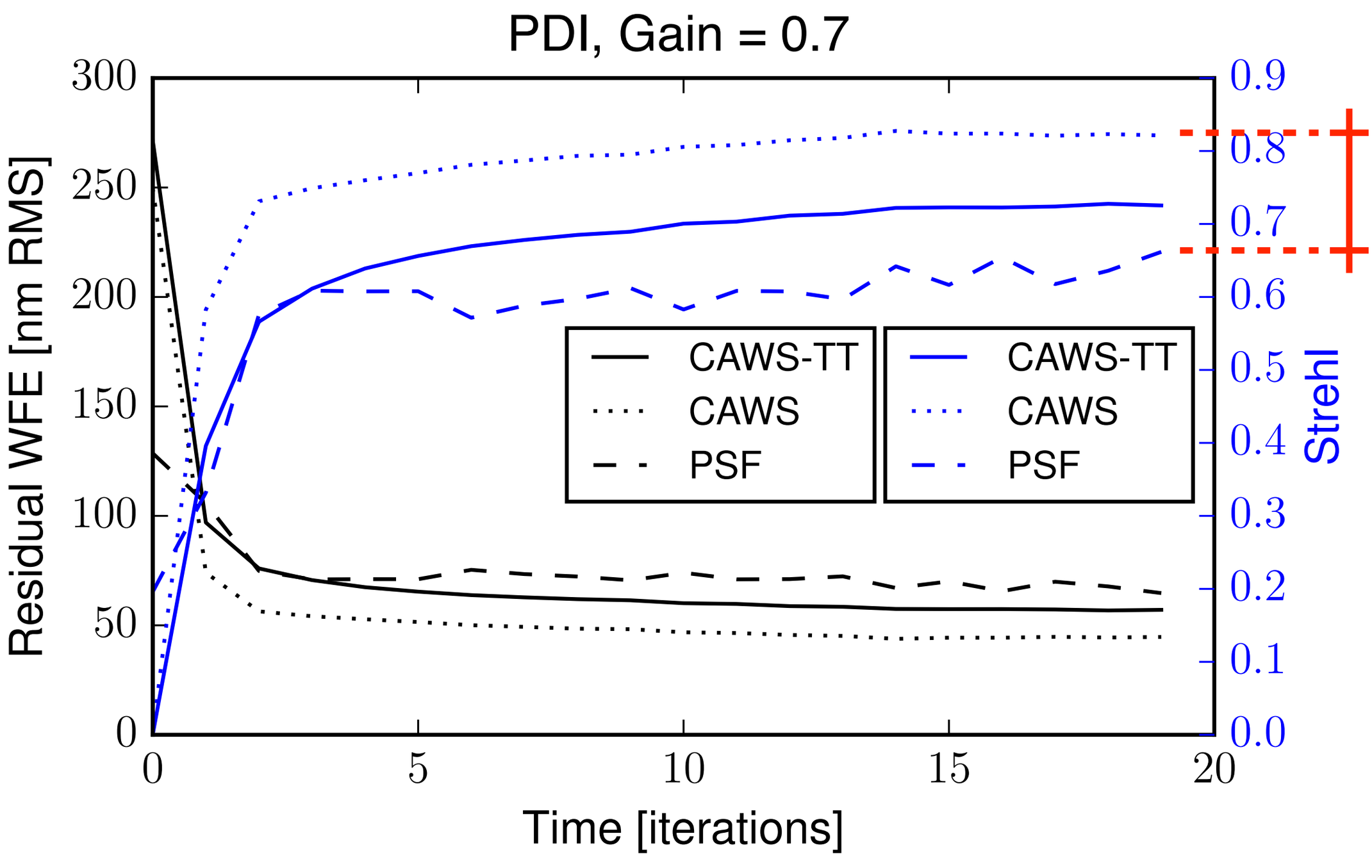
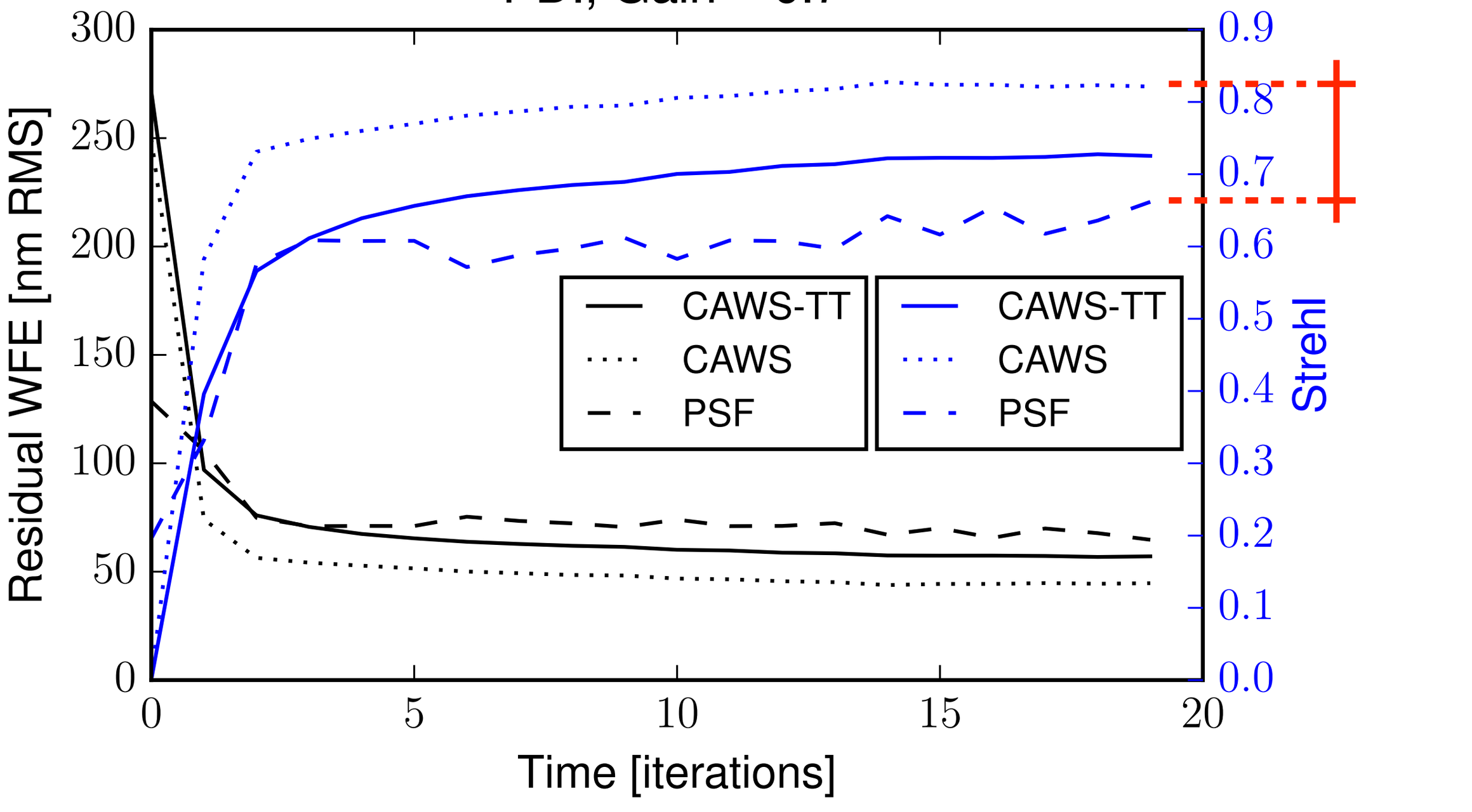
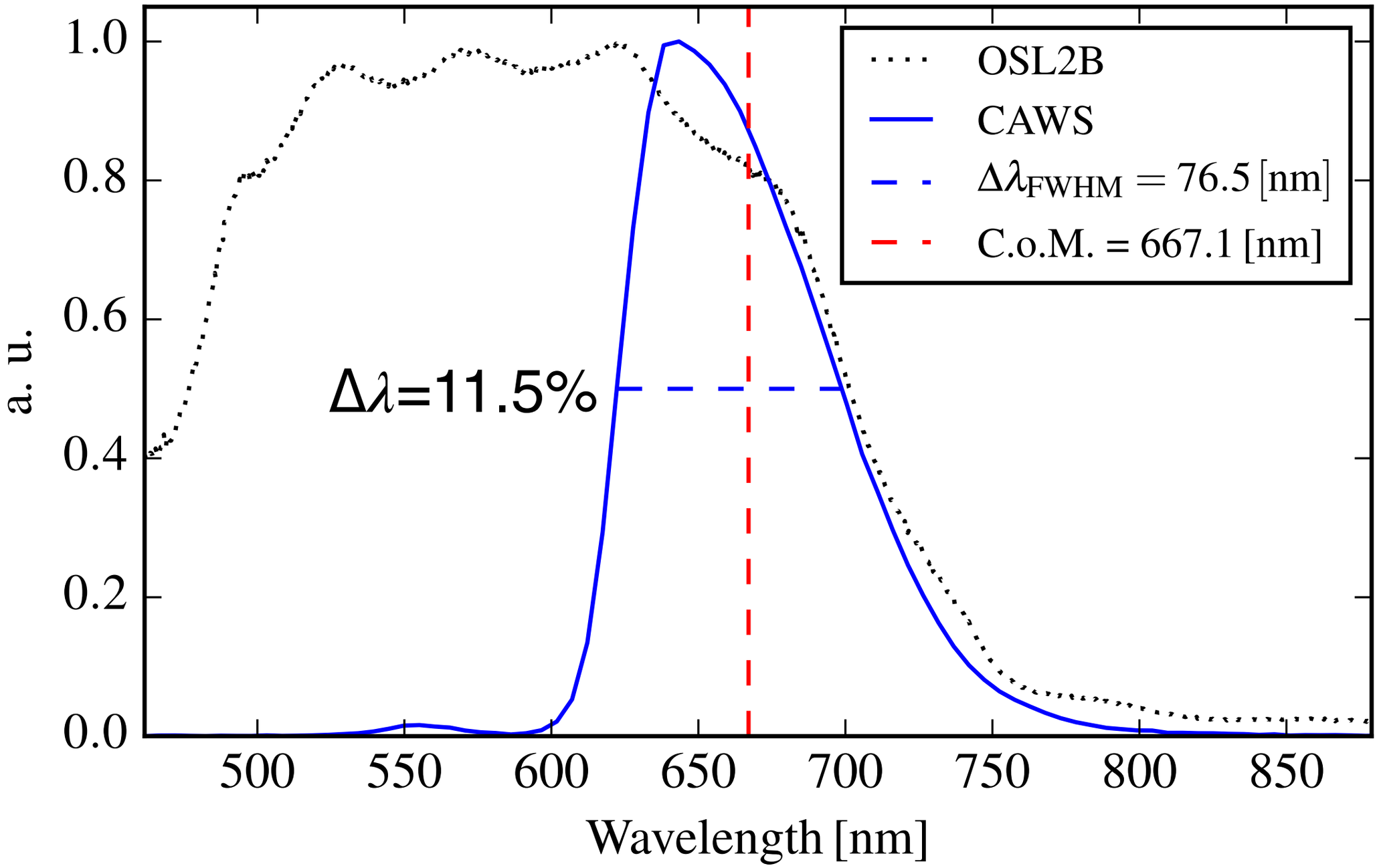


monochromatic closed-loop

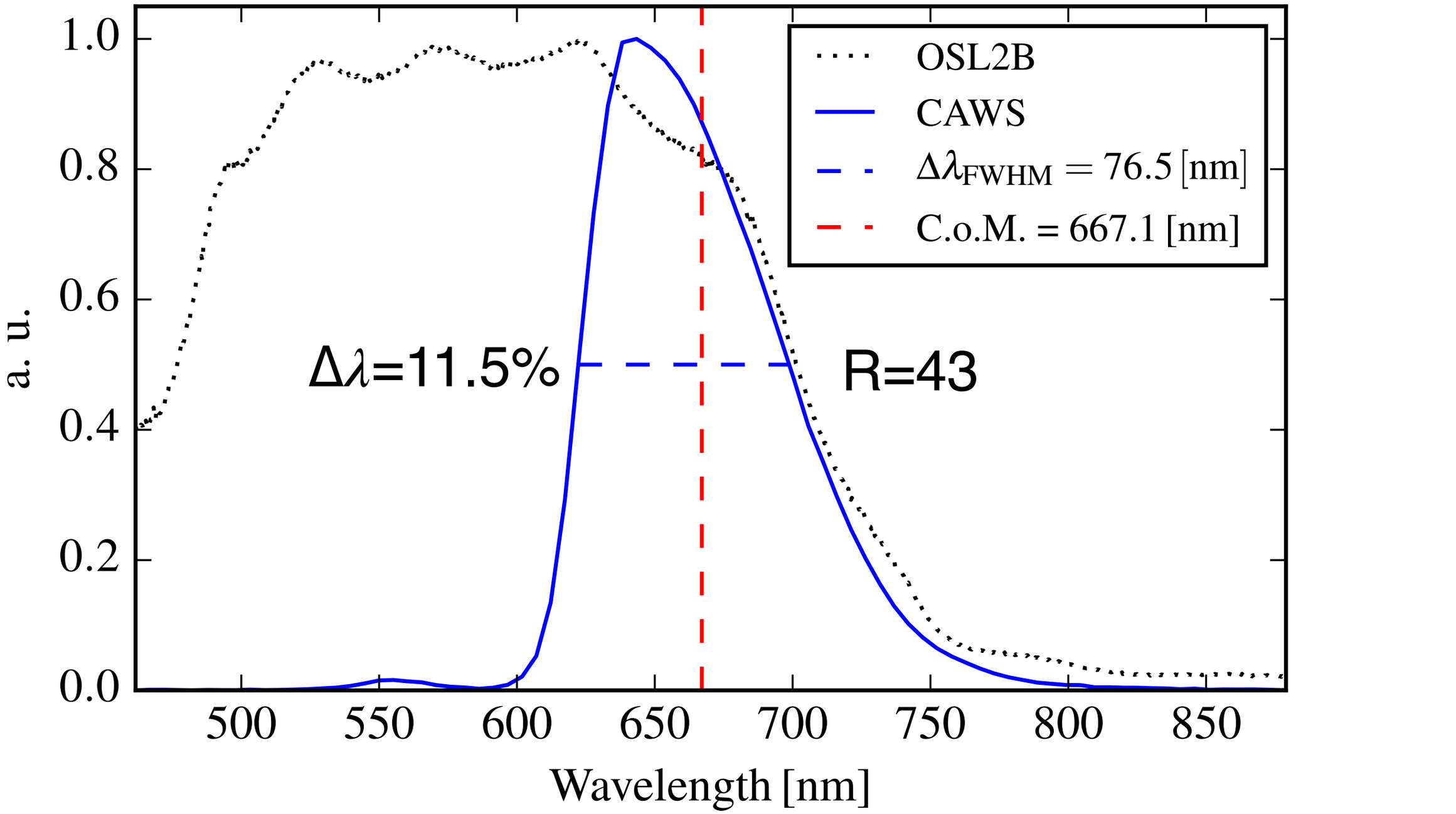
NCPA?
Large pin-hole:
-> Low order modes?



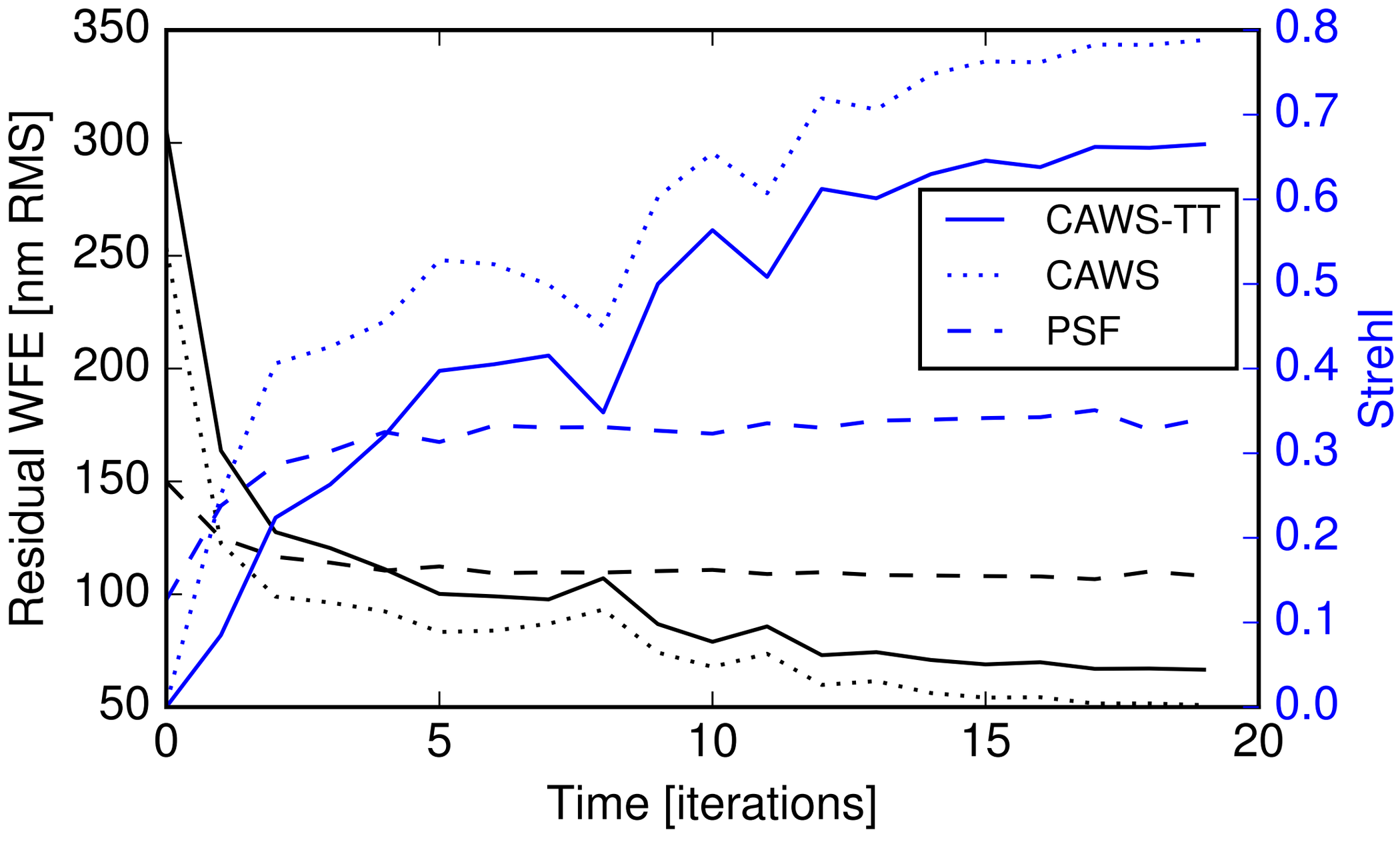
broadband illumination



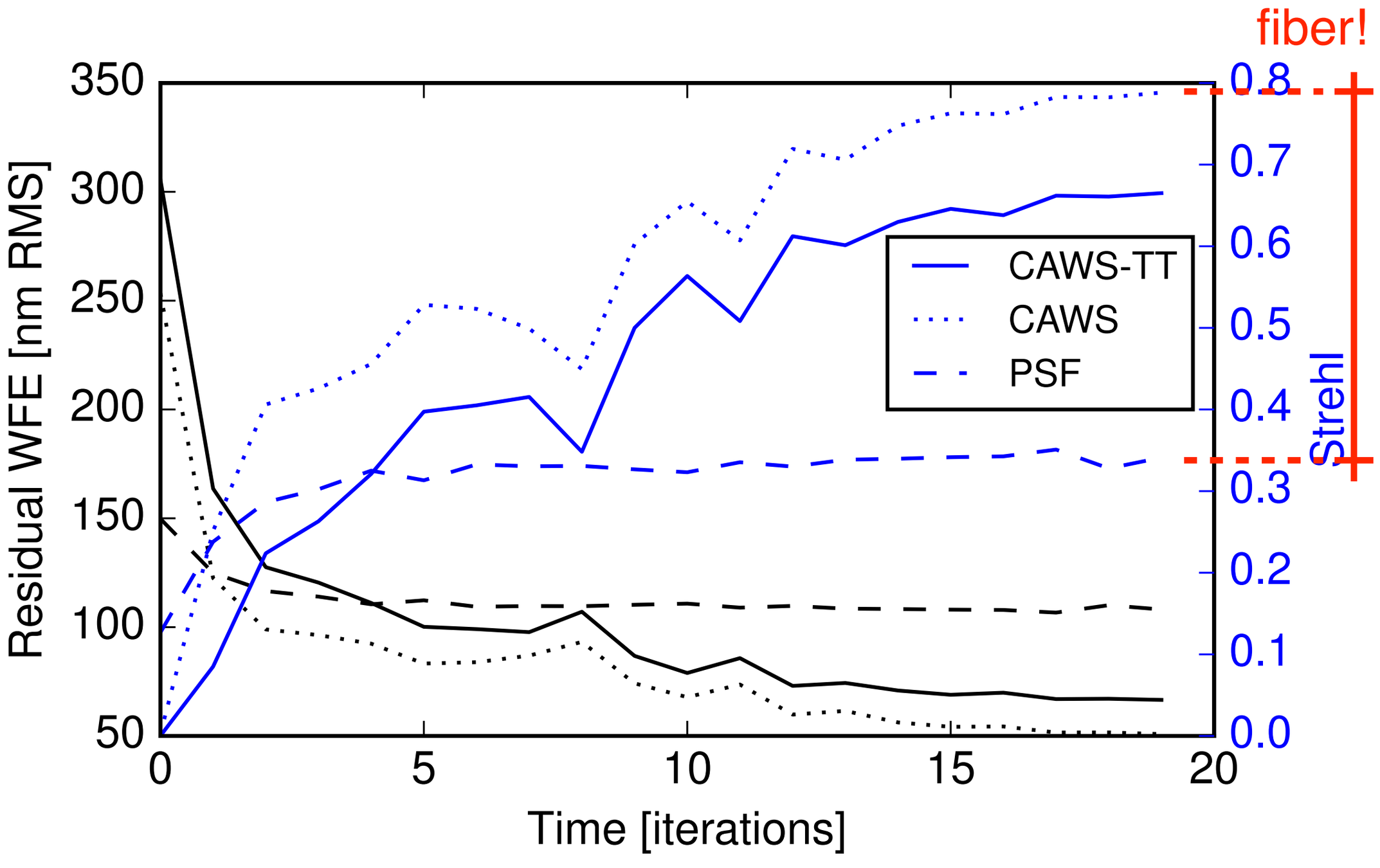
broadband illumination



polychromatic closed-loop

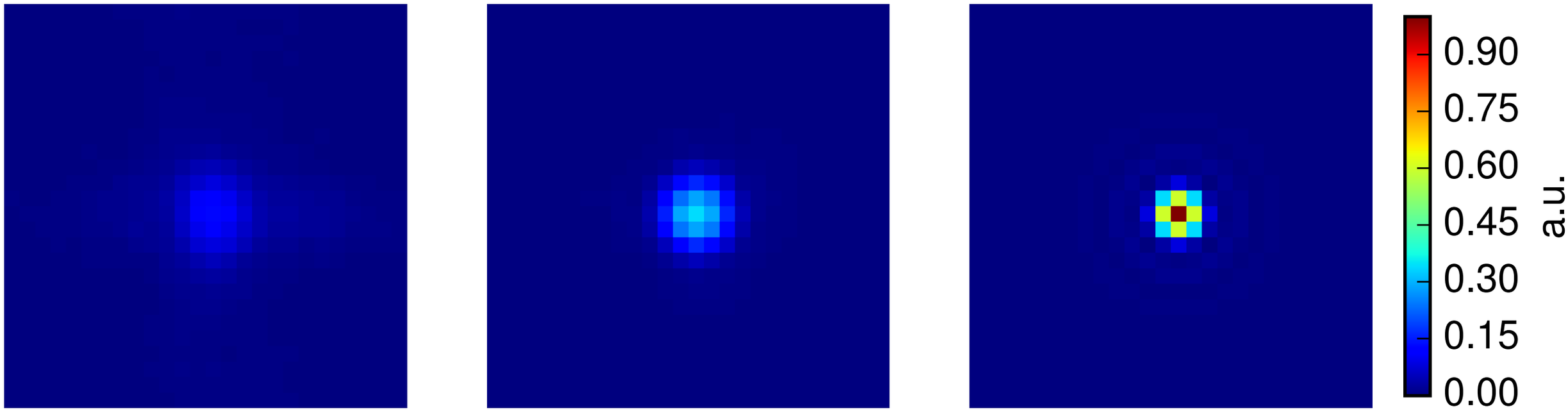


polychromatic closed-loop



polychromatic closed-loop

with WRONG FIBRE

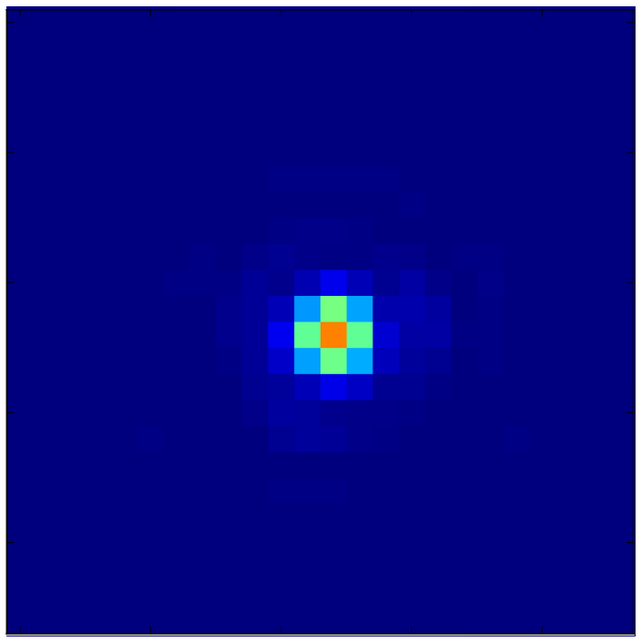


Real PSF, S = 0.13 | Real PSF, S = 0.34 | Perfect PSF

polychromatic closed-loop

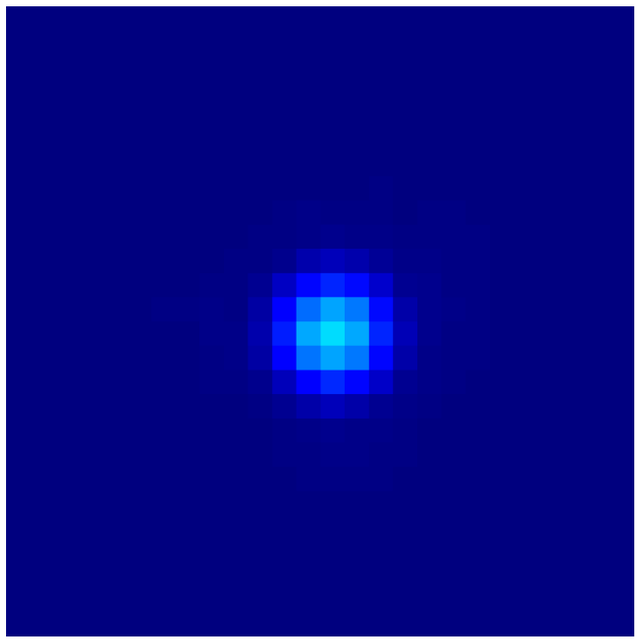
NICO - REPLOT GOOD FIBRE

with RIGHT FIBRE

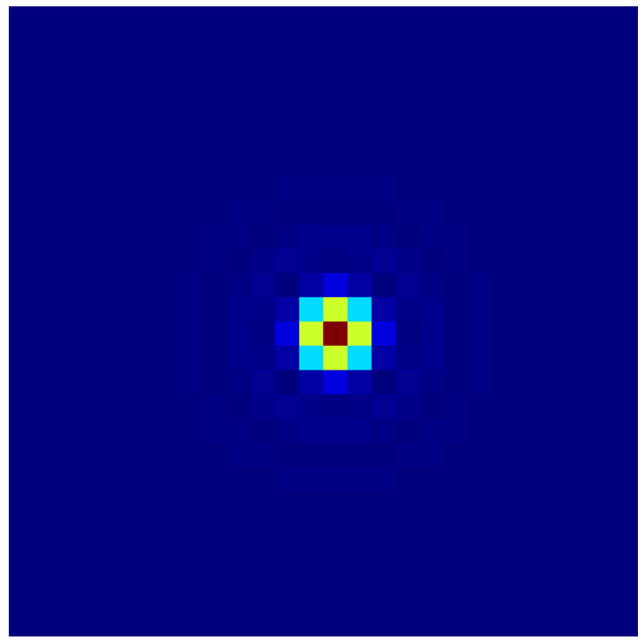


Real PSF, S=0.74

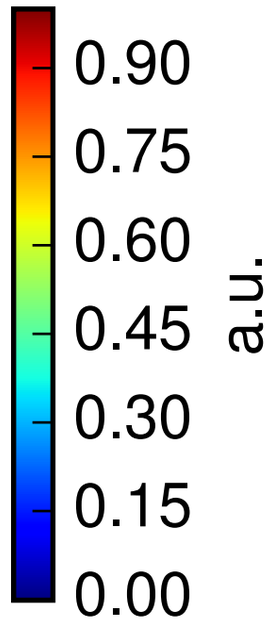
with WRONG FIBRE



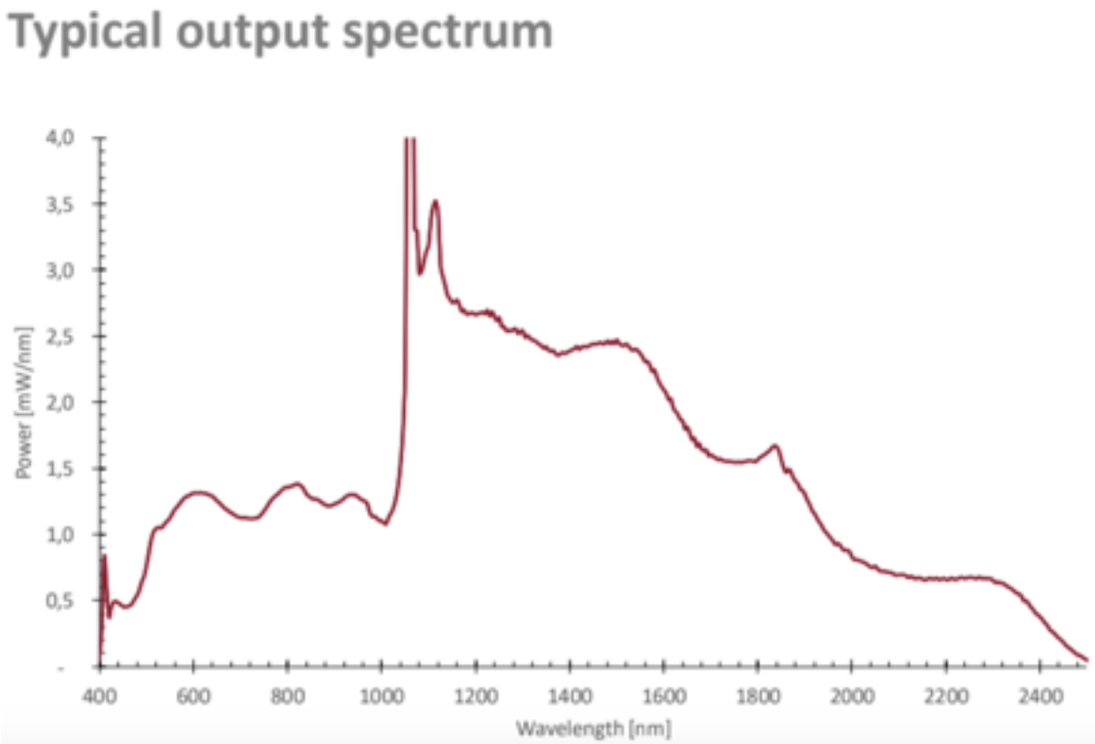
Real PSF, S = 0.34



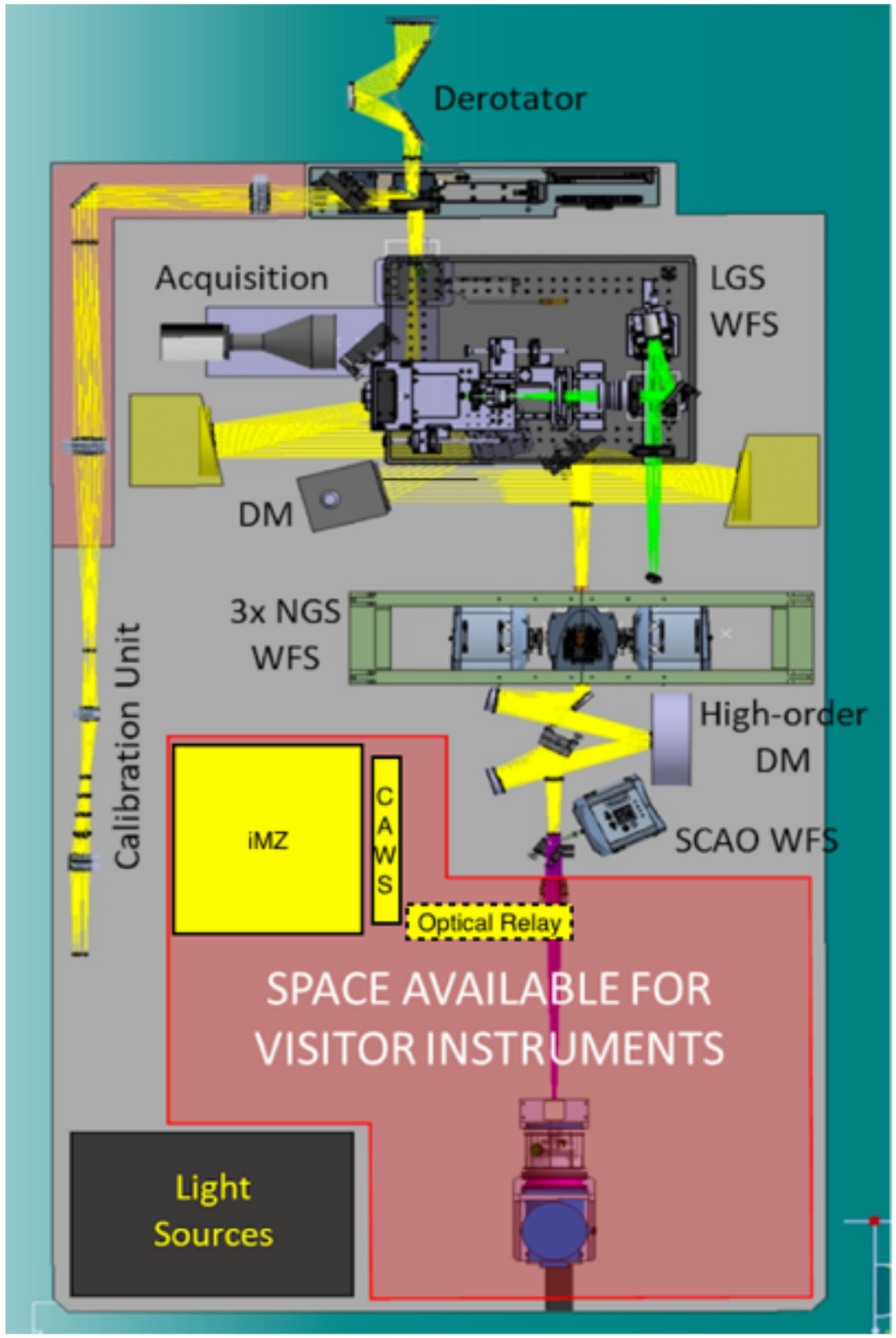
Perfect PSF



polychromatic tests



canary-opticon on-sky run



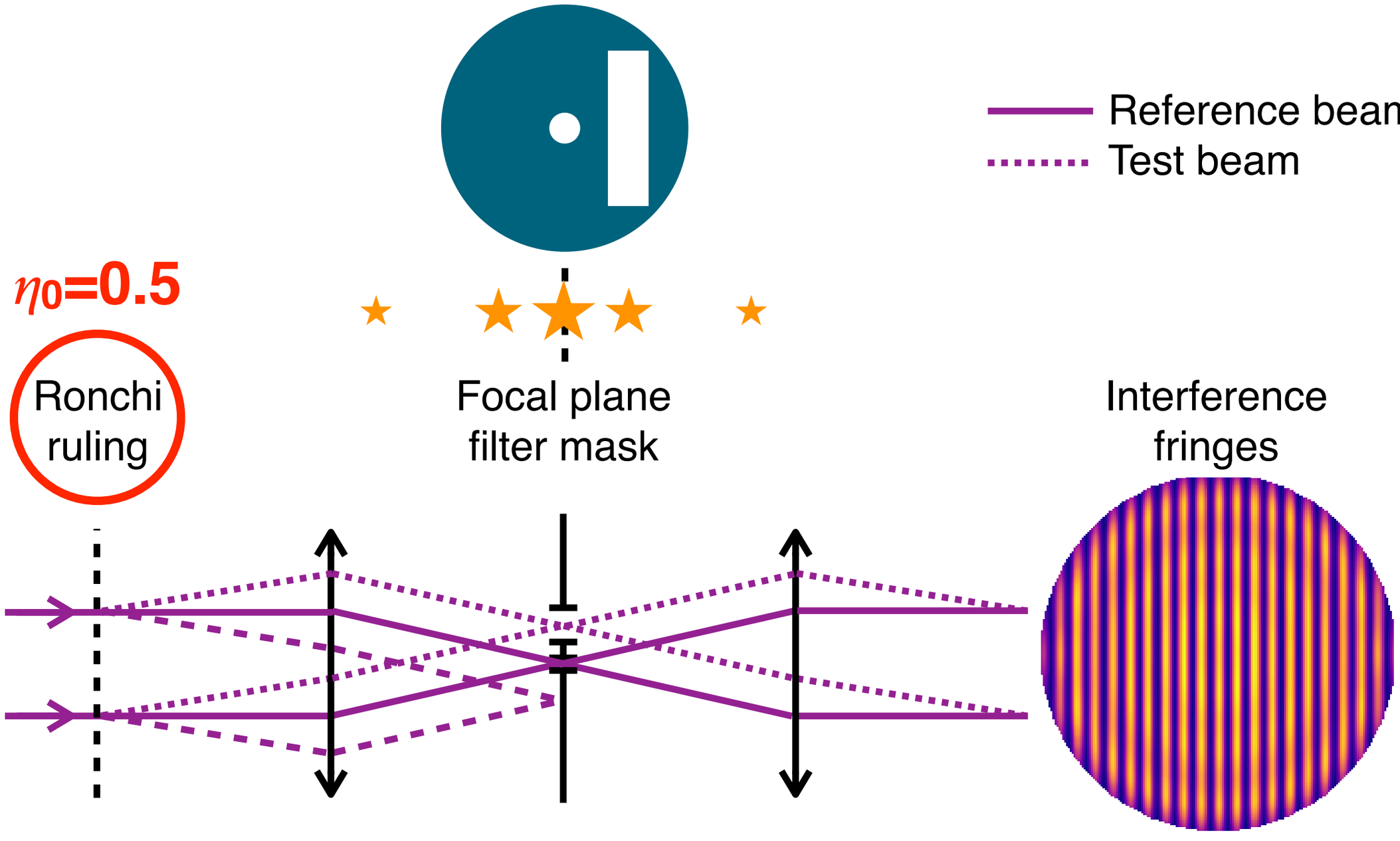
17-21 July

Phase 0: Off-sky, NCPA

Phase 1: SCAO,
Open-loop WFS

Phase 2 (**?**): Close-loop

throughput improvements



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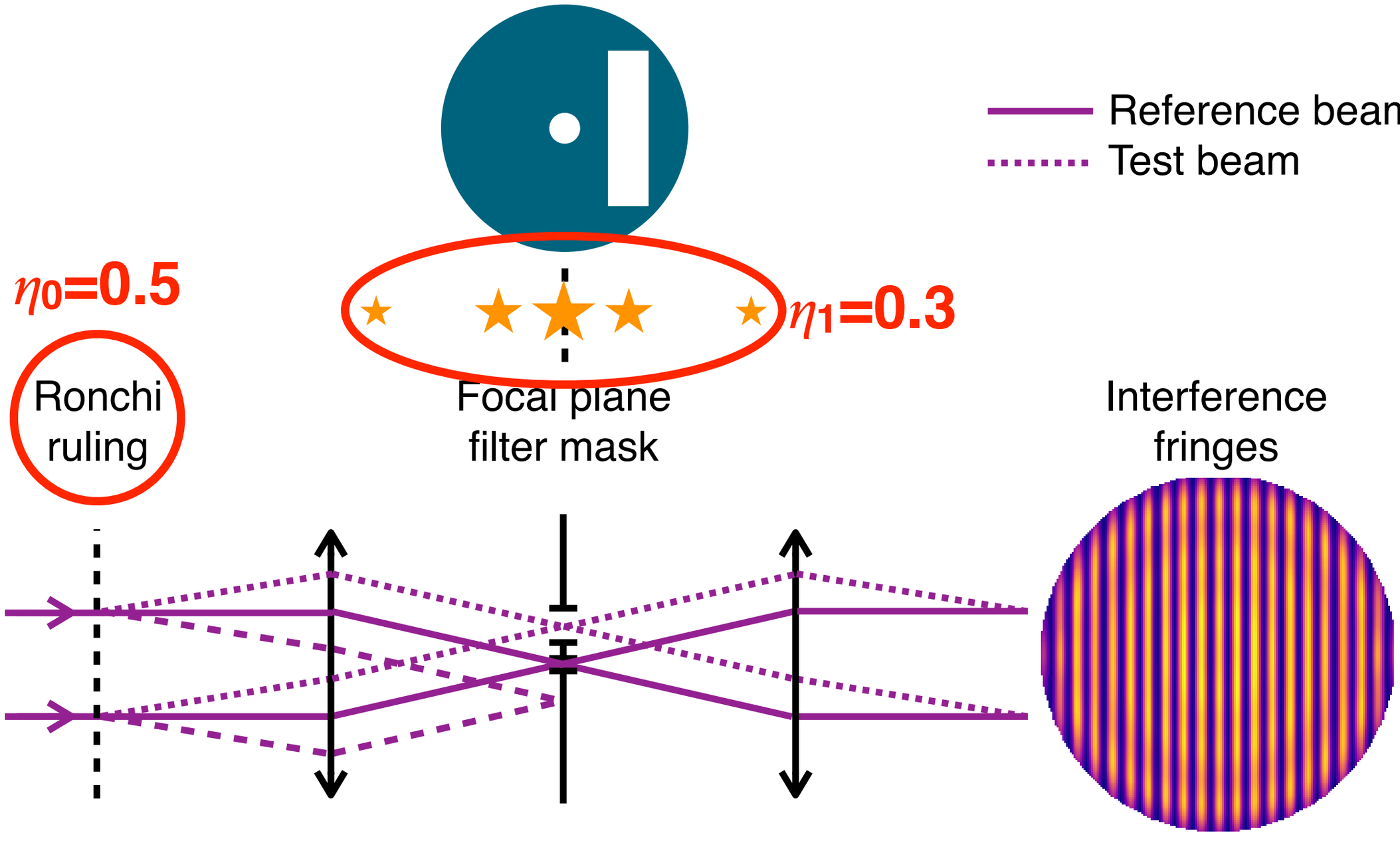

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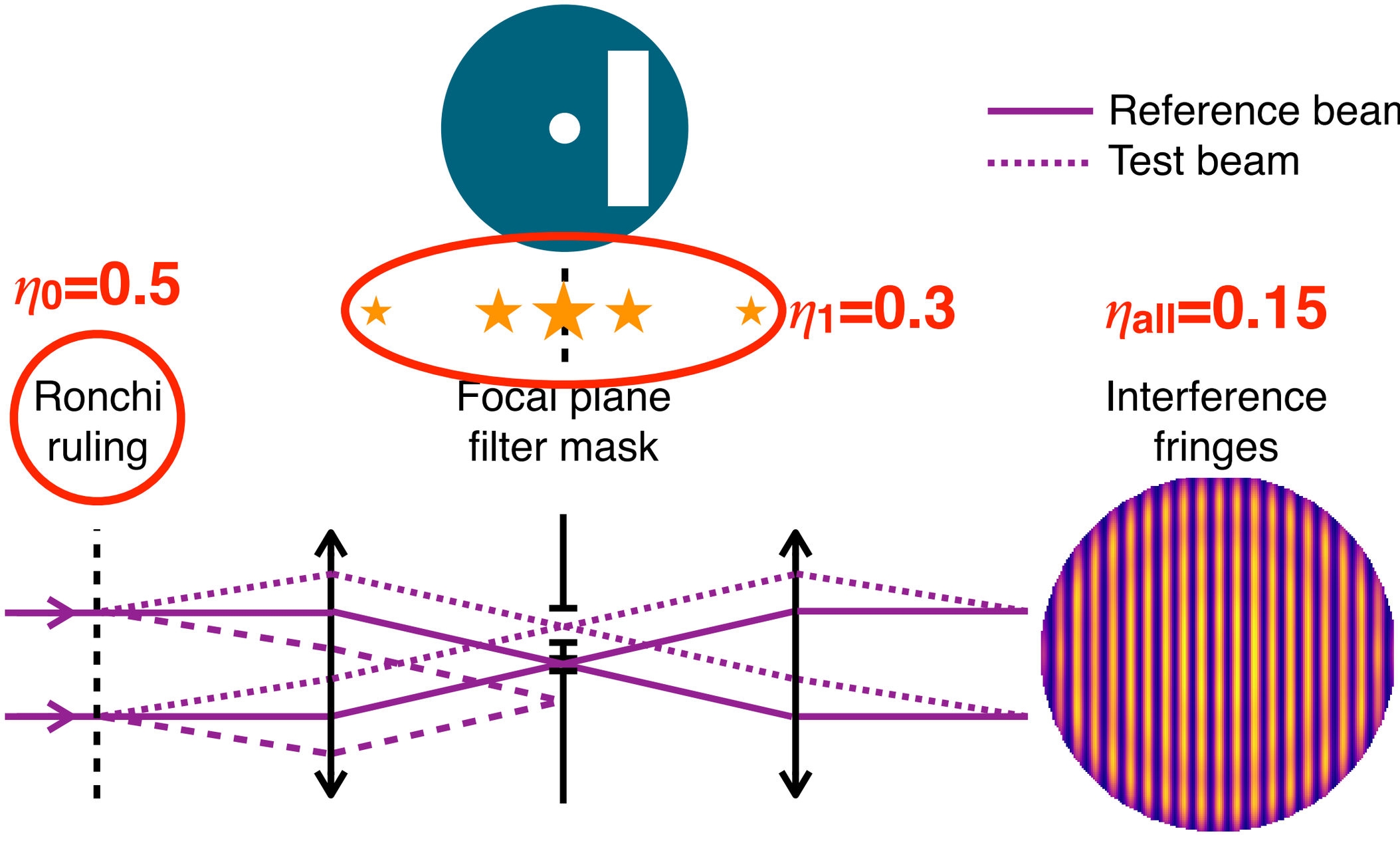
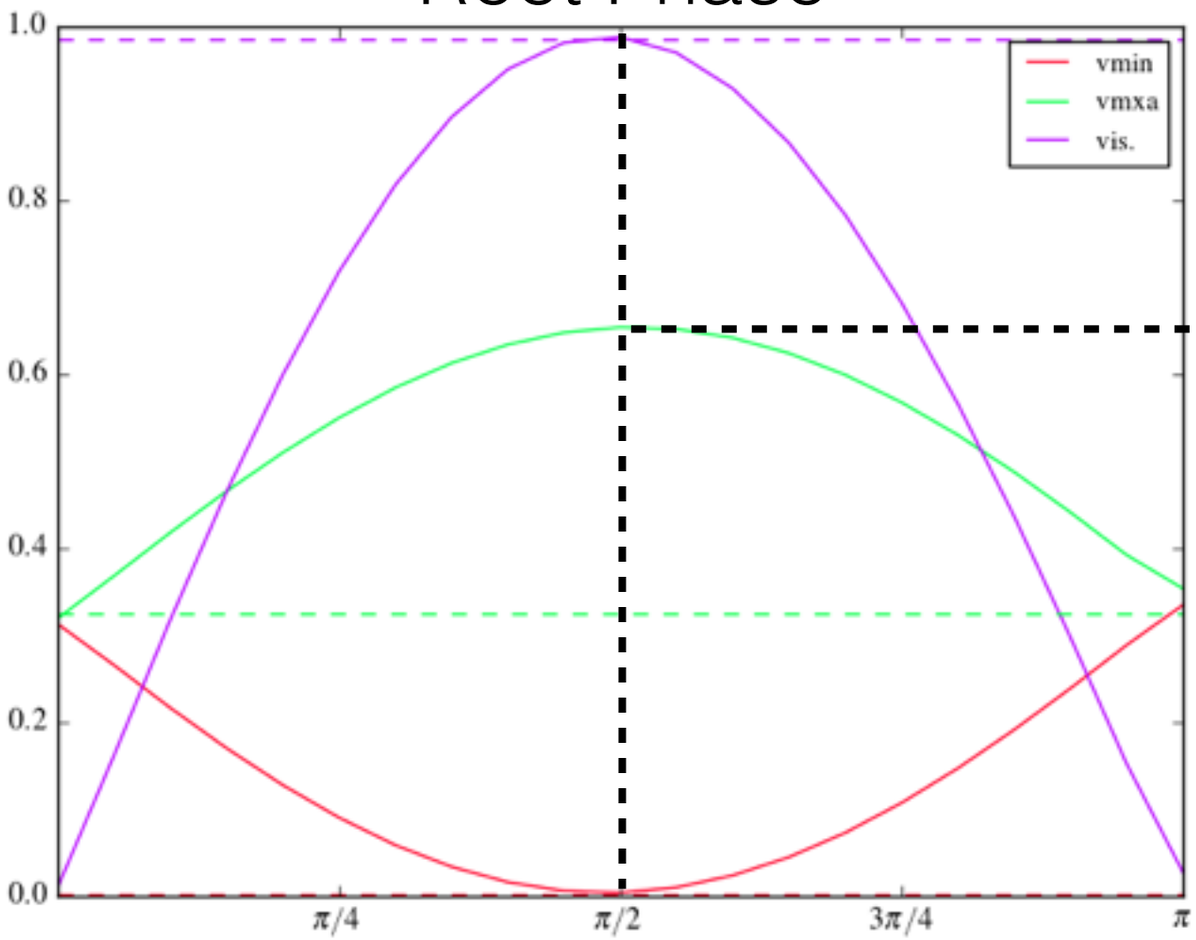
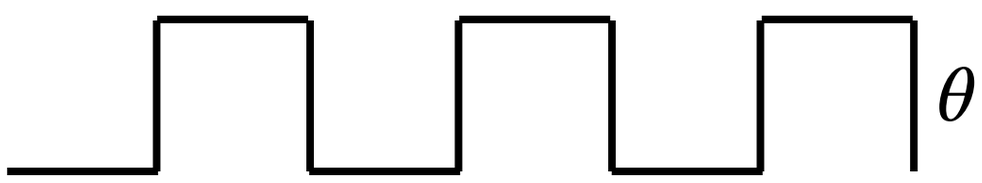


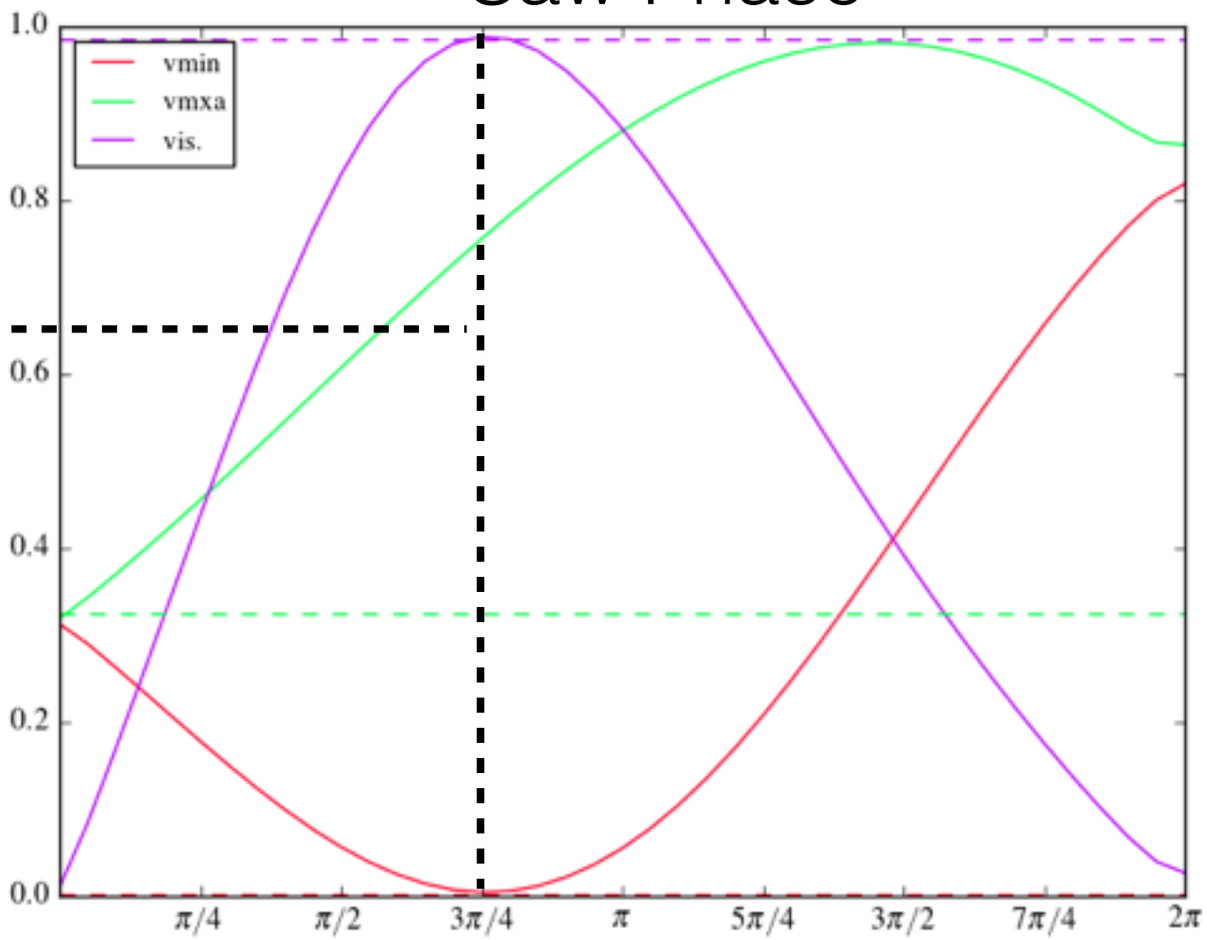
throughput improvements

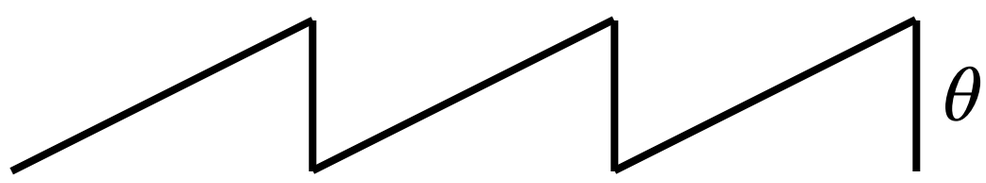
Rect Phase





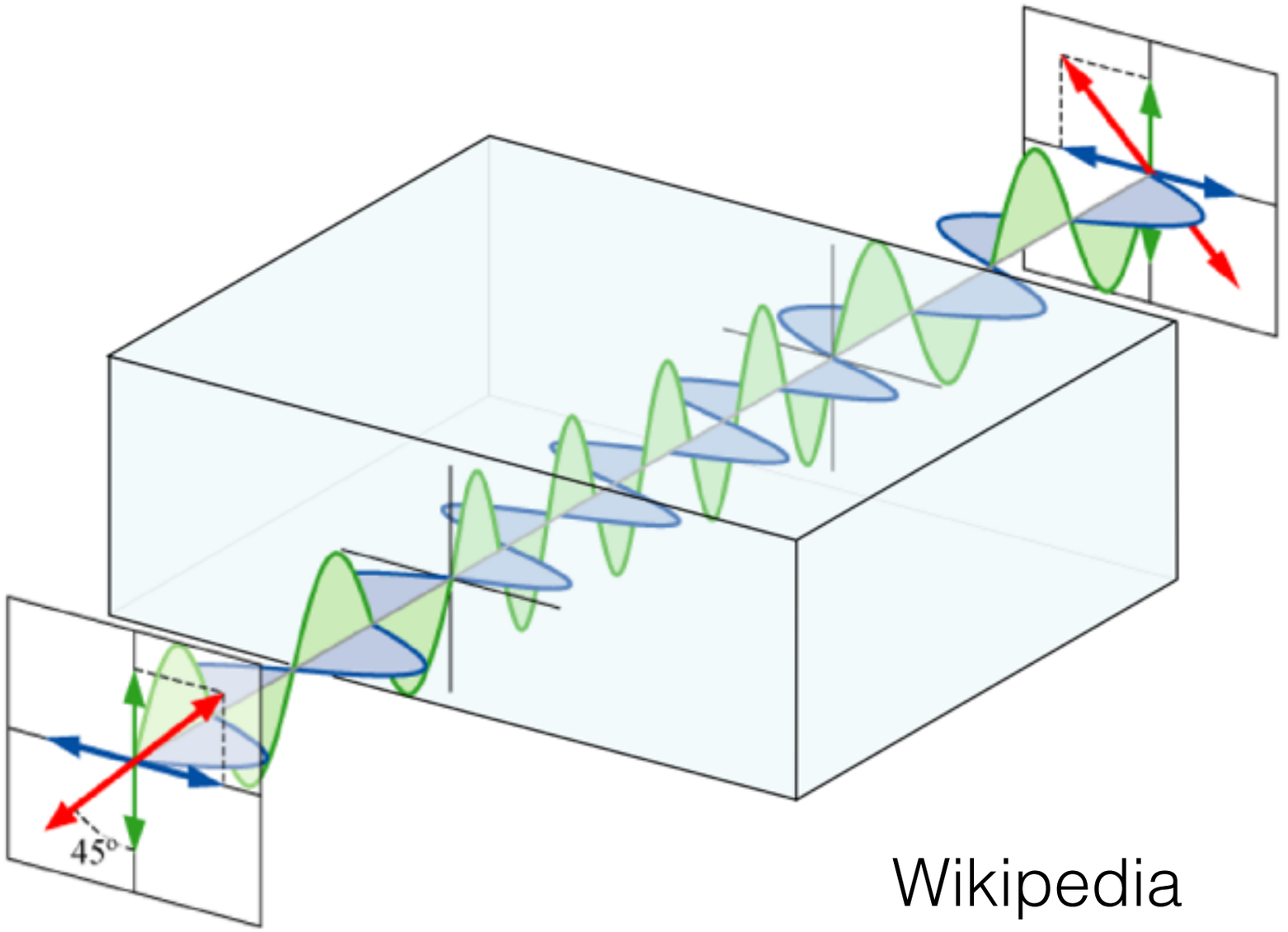
Saw Phase





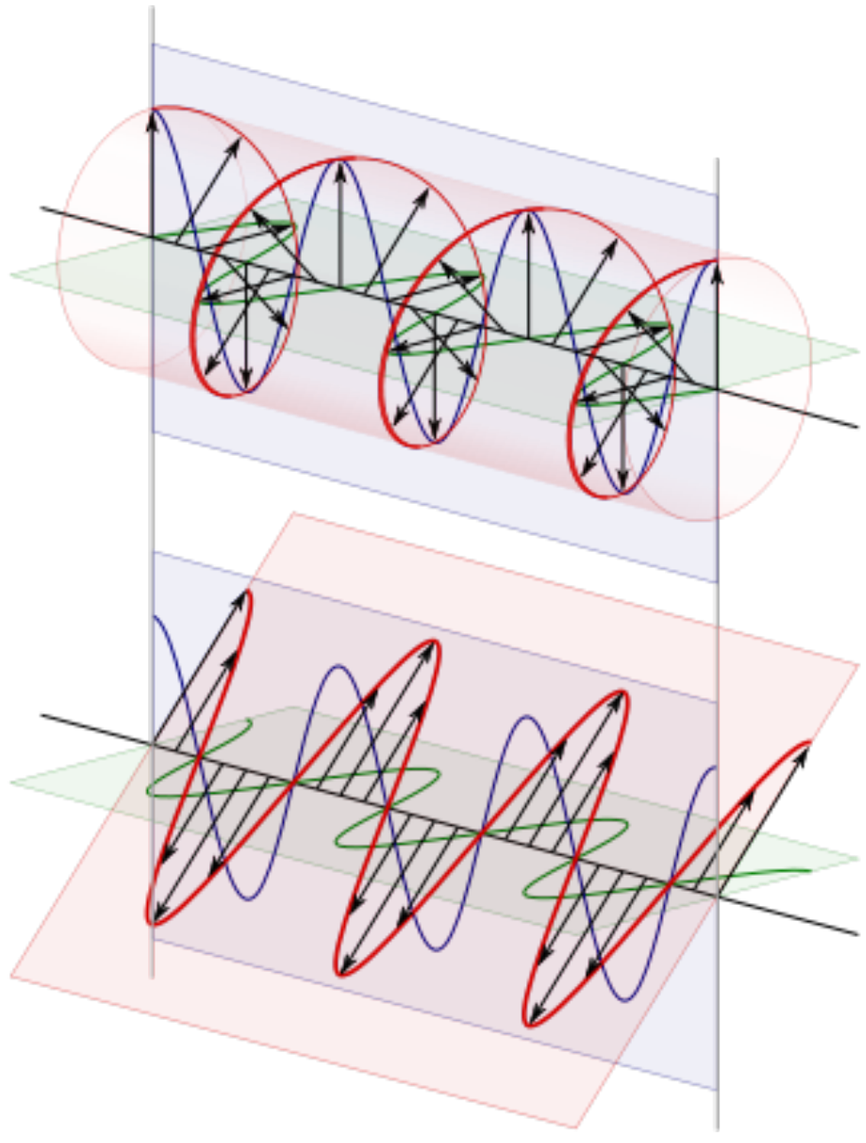
what about **waveplates**

Half

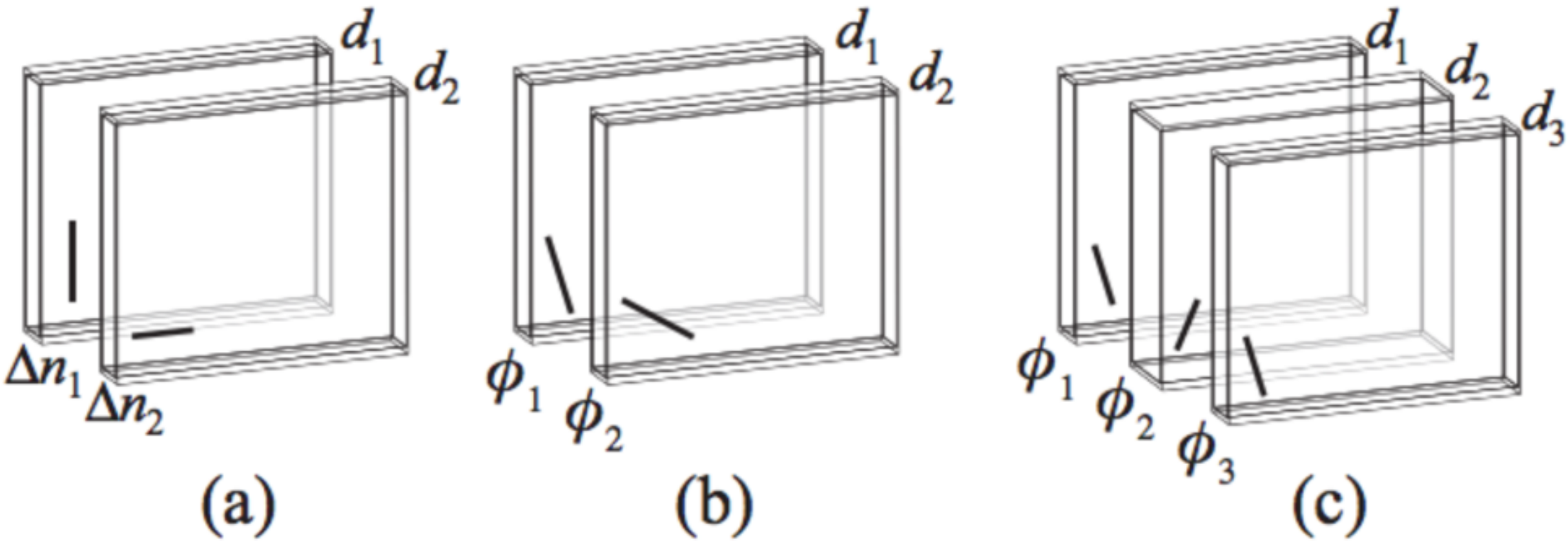


Wikipedia

Quarter

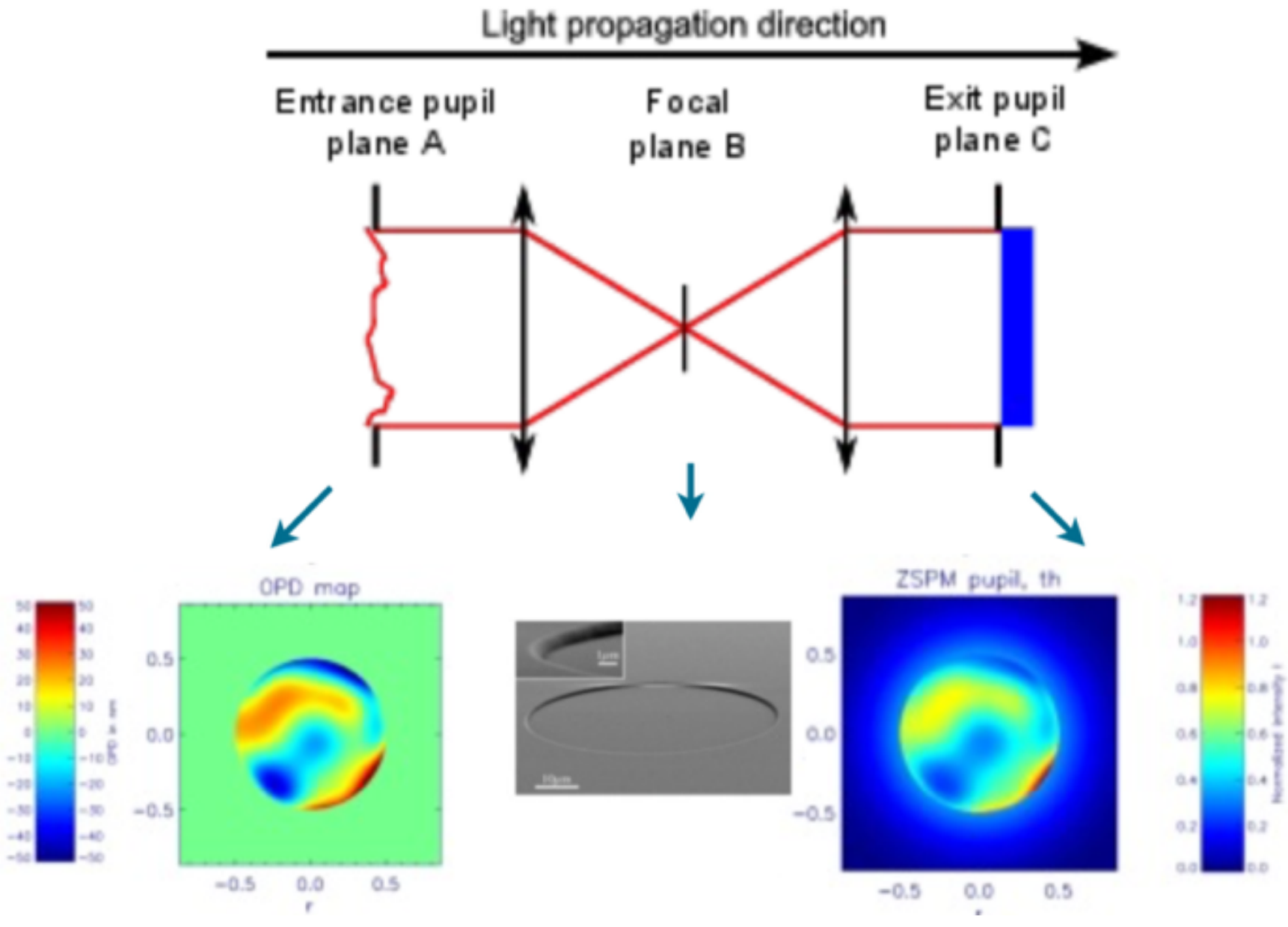


they can be pseudo-**achromatic**



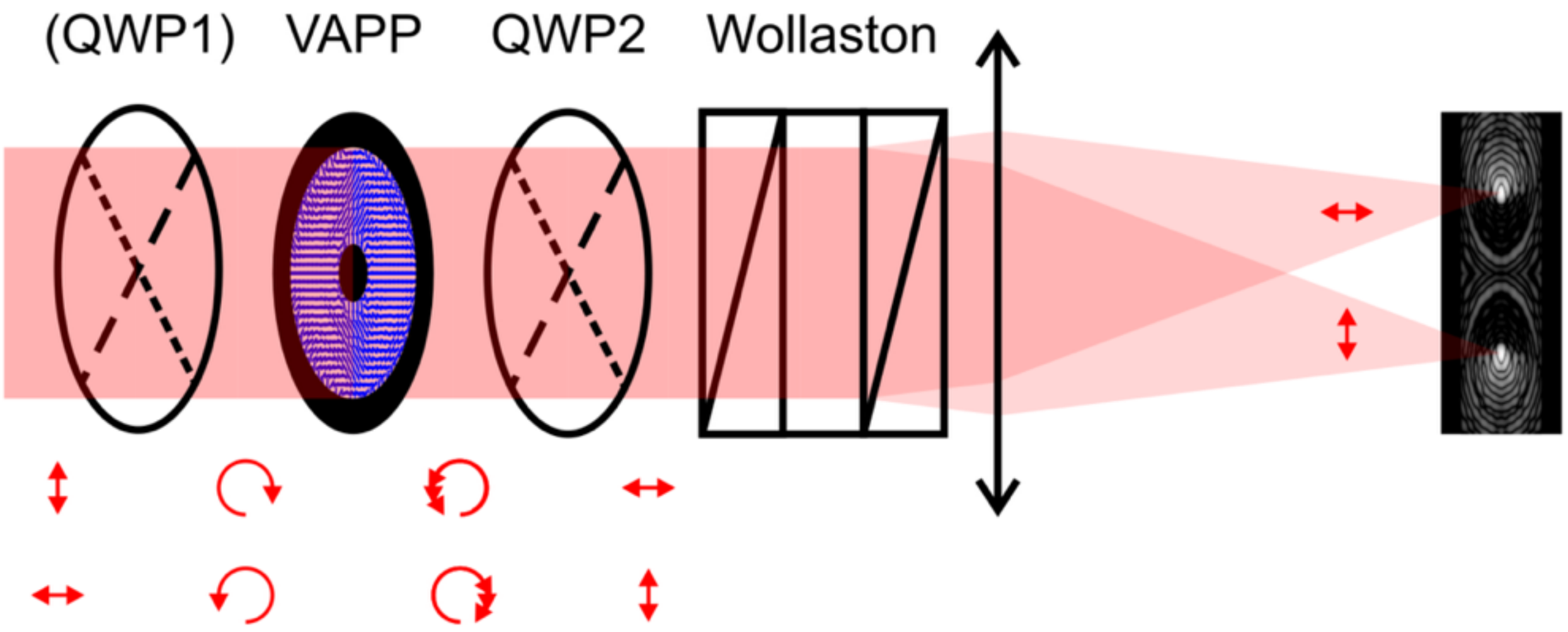
Komanduri 2013

other WFSs **examples**



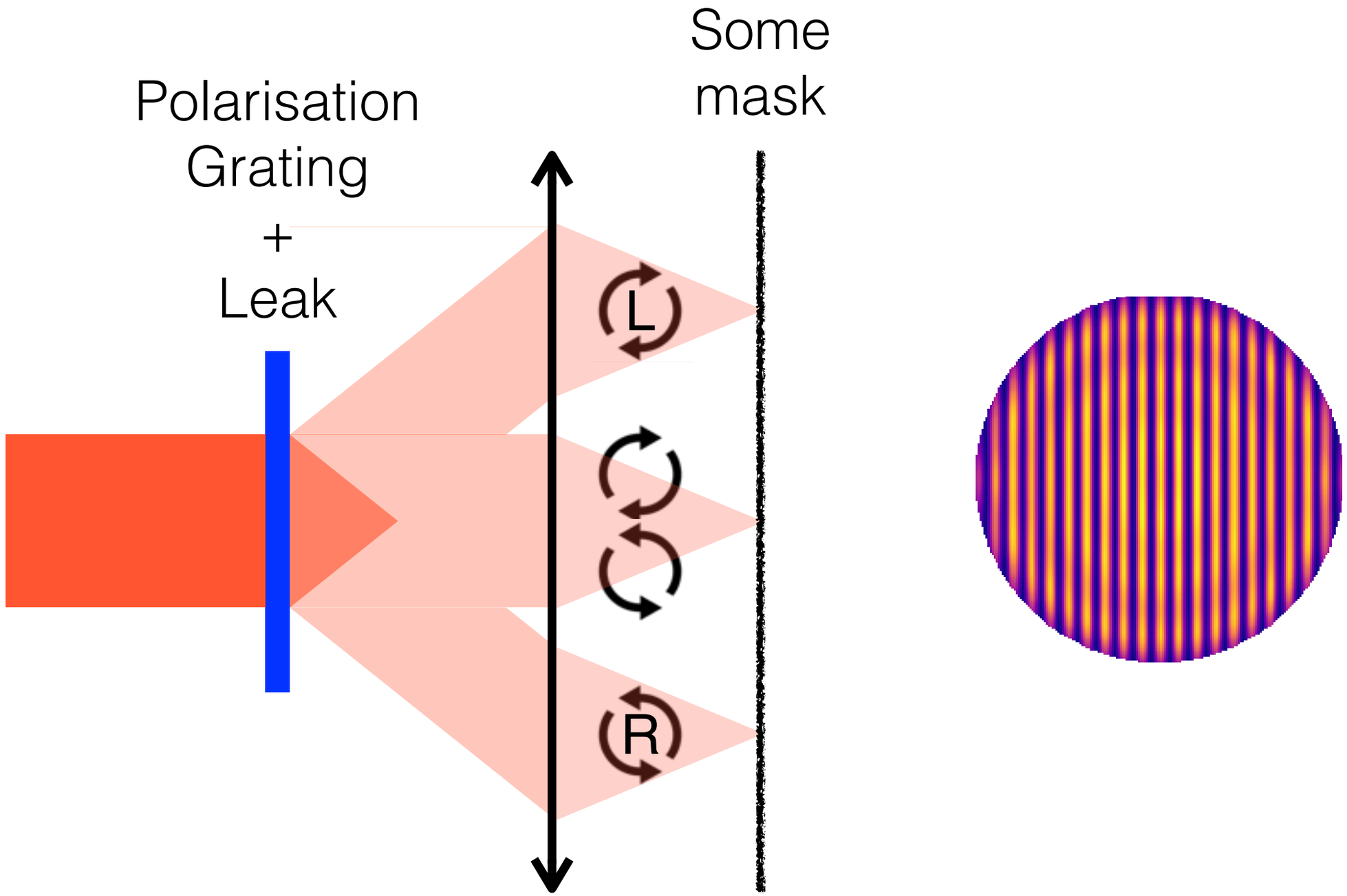
NDiaye 2014 - Doelman 2017

allowing broadband **phase shift**



Snik 2012

allowing broadband **phase shift**



Summary

Properties

- highly achromatic
- low throughput, for now

Status

- monochromatic loop closed
- polychromatic in progress

Future work

- polychromatic lab tests
- improving throughput
- on-sky tests

Durham University

CfAI Centre for Advanced Instrumentation

Thanks

Ali Bharmal, Richard Myers, Marc Dubbeldam, Daniel Hölck

list of **values**

Simulations

$D_{B,0} = \lambda_0/D_A$

b=0.22

($\Delta\lambda$=50%, η = 0.15) ➔ ($\Delta\lambda$=7.5%, η = 1)

CAWS

f_G = 5 lp/mm ➔ $N_G \approx 52$

$D_{B,0} = 2.2\lambda_0/D_A, 2.5\lambda_0/D_A$ ➔ 14, 16 μm

λ_0 = 675 nm, $\Delta\lambda$ = 15%, λ_c = 633 nm

KiloDM

32x32 acts

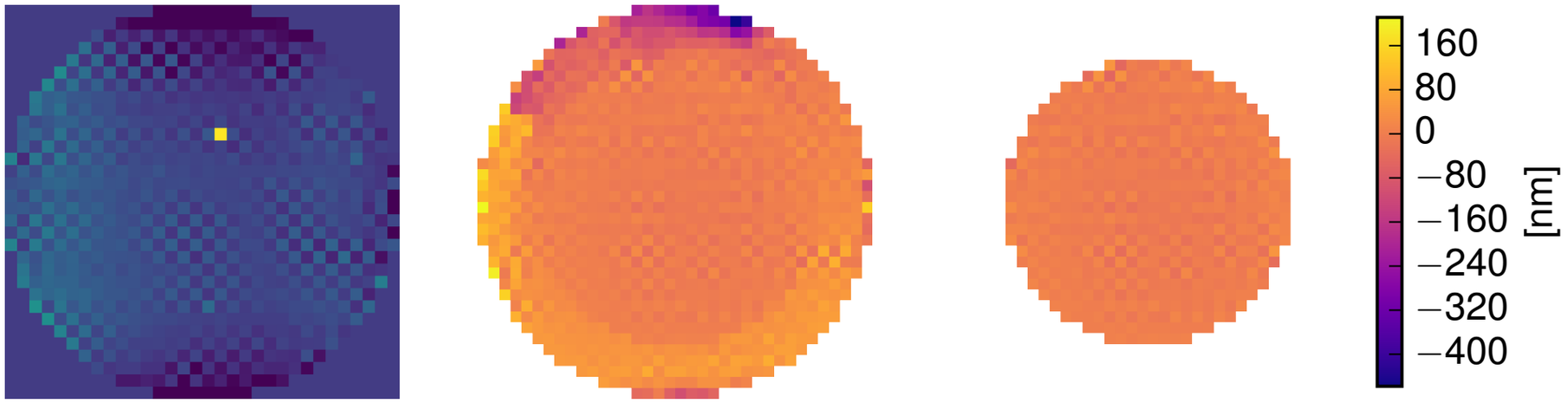
Bobcat Imperex

648x480 pix

μ_p = 7.4 μm

$N_P \approx 6.8$

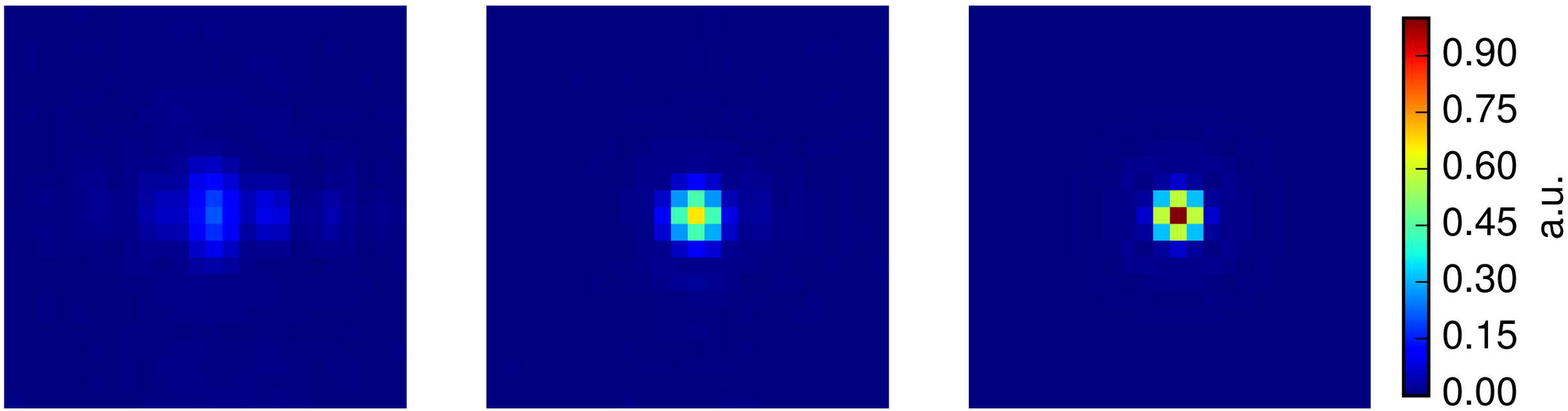
monochromatic closed-loop



DM Commands

WFE_{RMS} = 55.3 [nm]

WFE_{RMS} = 12.5 [nm]

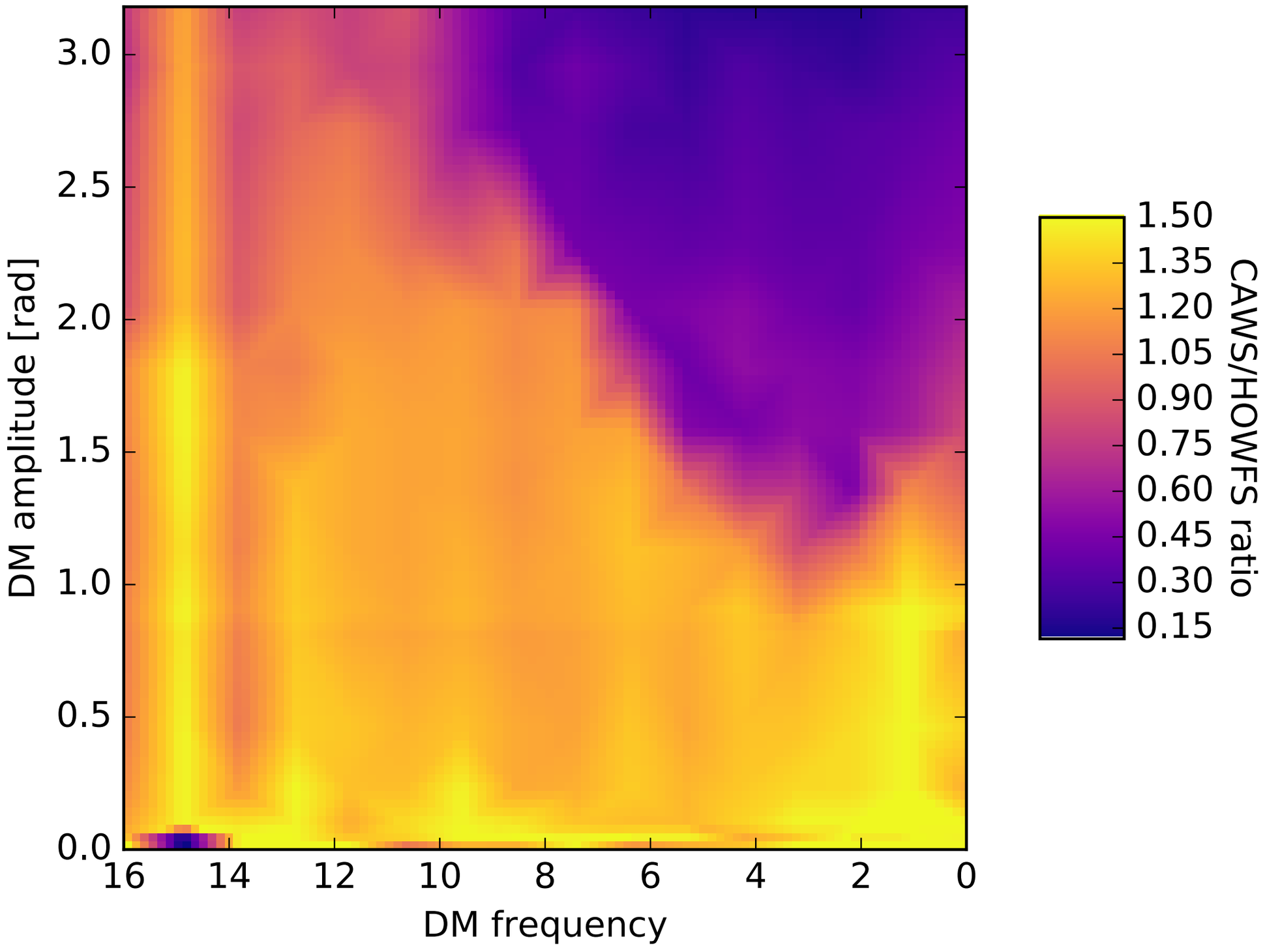


Real PSF, S = 0.20

Real PSF, S = 0.66

Perfect PSF

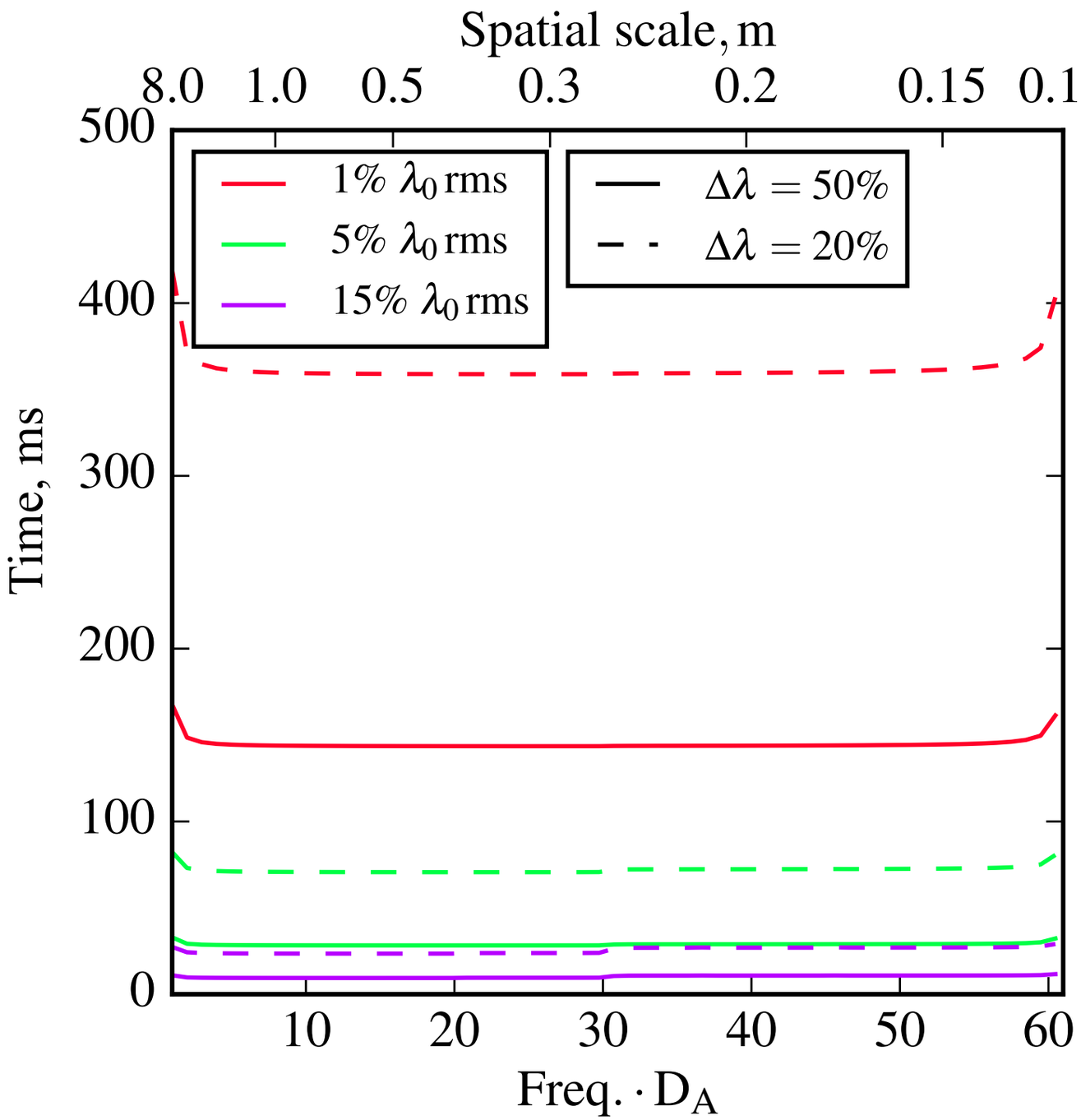
SH **comparison**



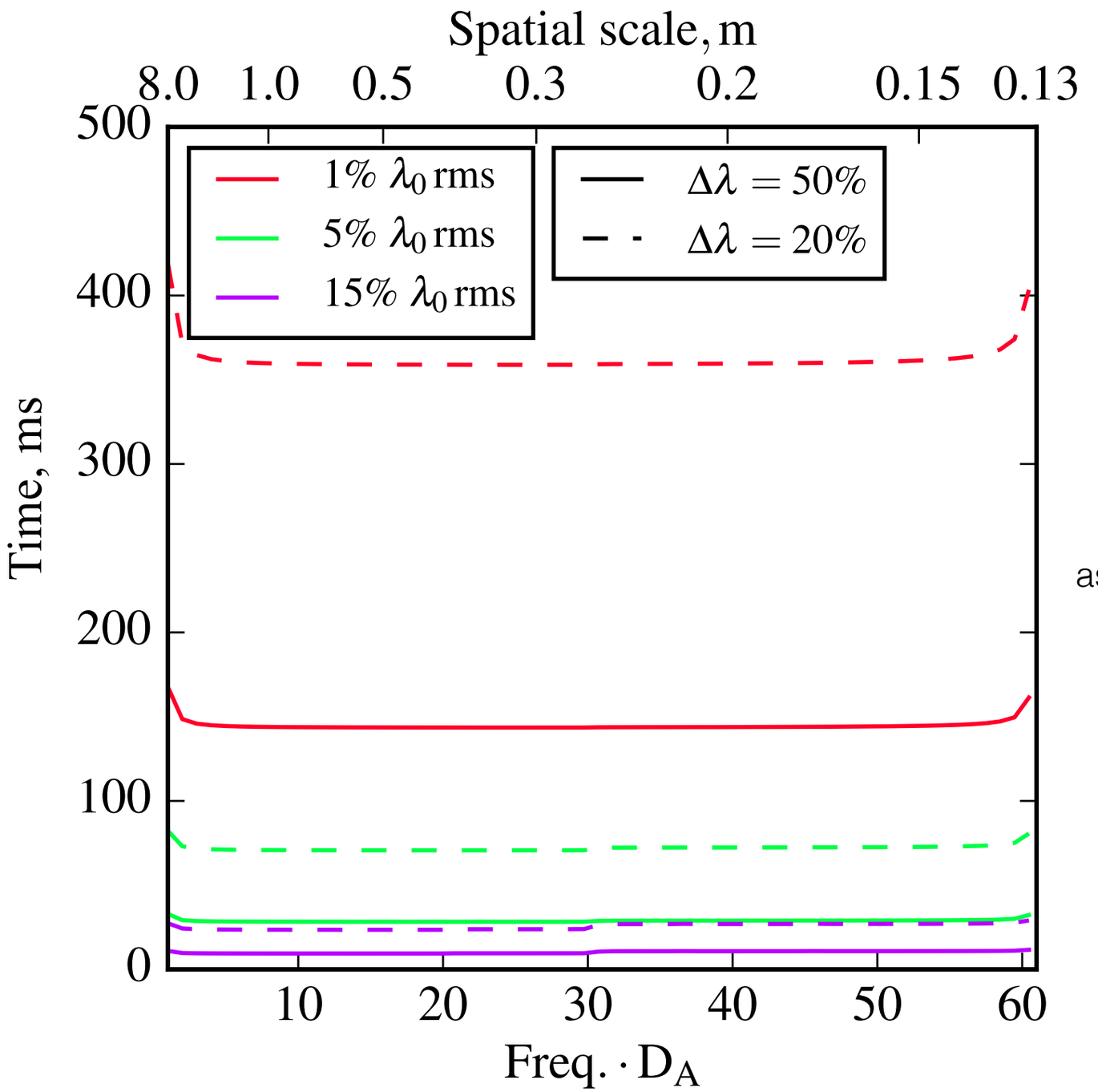
parameters

parameters	**values**
central wavelength λ_0	1.625 μm
bandwidth $\Delta\lambda$	20%, 50%
zero mag. flux density	1080 Jy
apparent star magnitude	10
telescope diameter	8 m
telescope transmission T_{tel}	40%
beamsplitter transmission T_{BS}	5%
line-pairs across pupil N_G	185
pixels per line-pair N_P	4
read-out noise	1 e^{-1}

signal-to-noise ratio

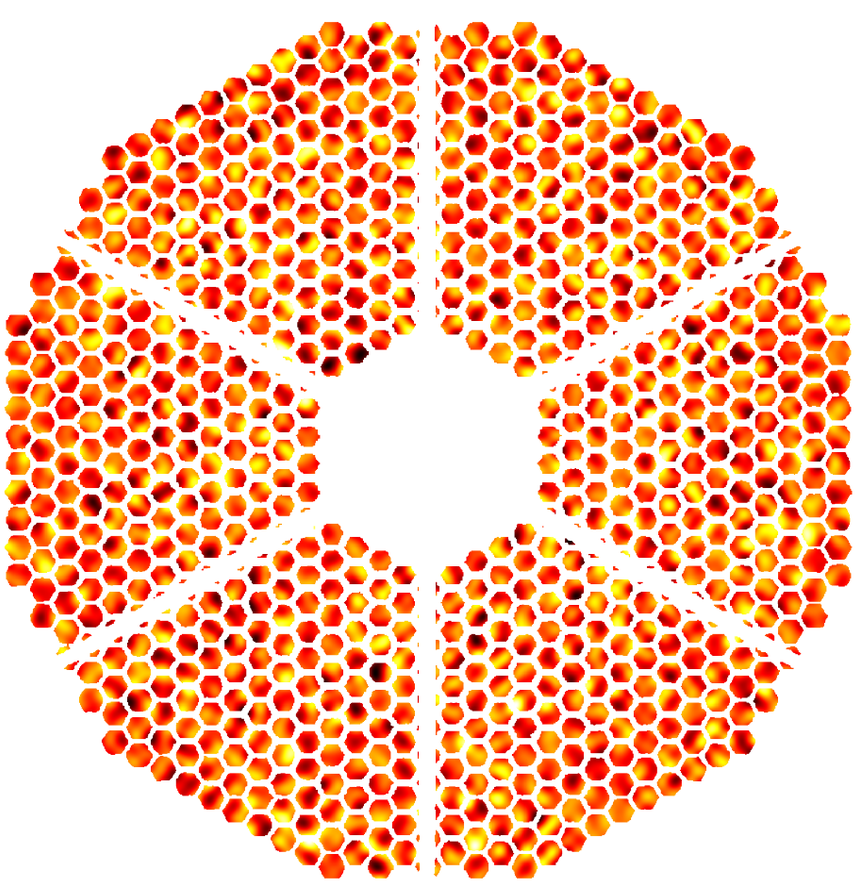


signal-to-noise ratio



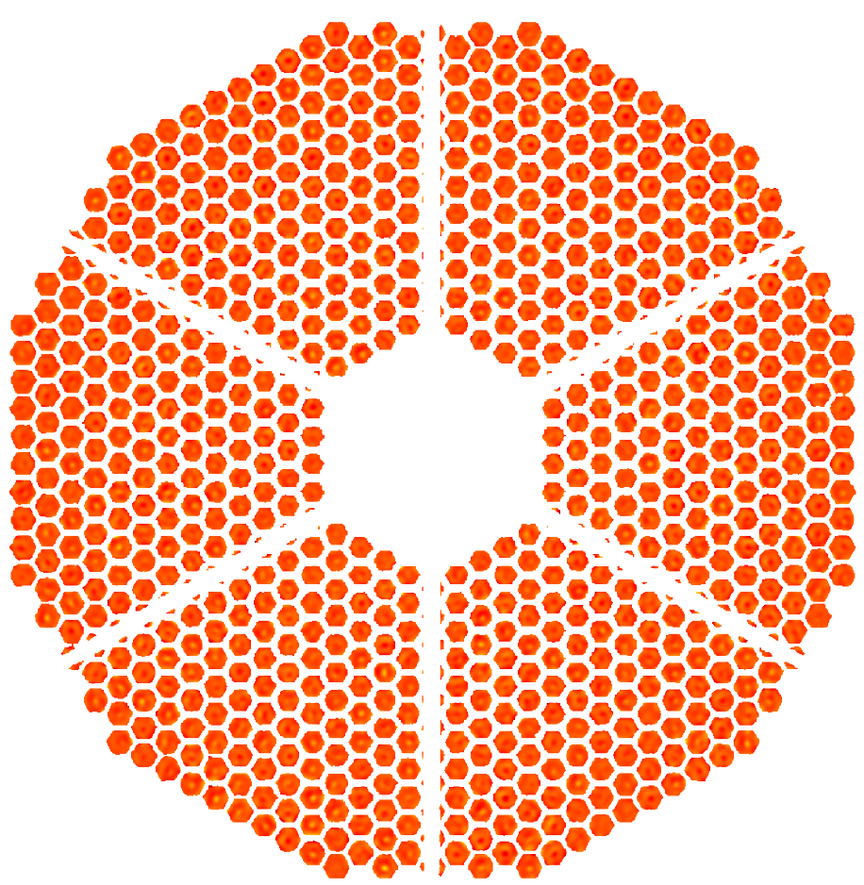
Dubost, Bharmal and Myers, 2018
"Calibration of quasi-static aberrations in high-contrast astronomical adaptive optics with a pupil-modulated point-diffraction interferometer"

fine **co-phasing**



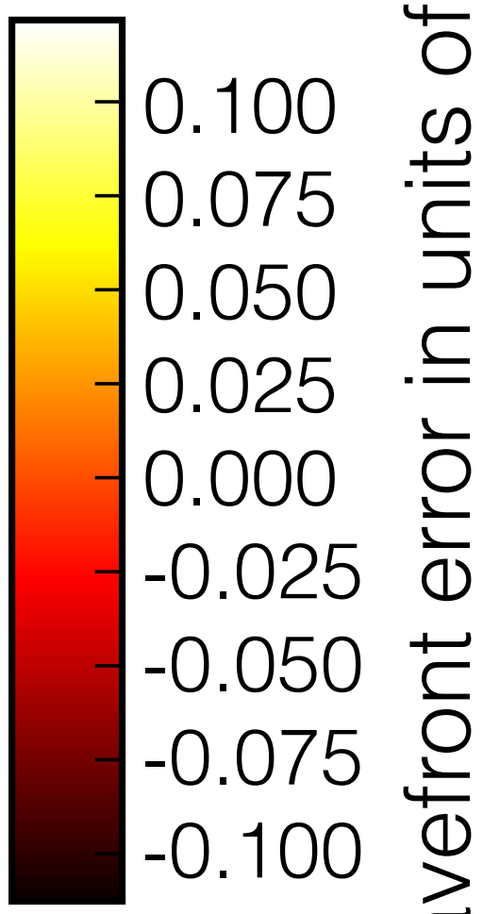
Segmented pistons

φ_{error} = 0.0314 λ_0-rms

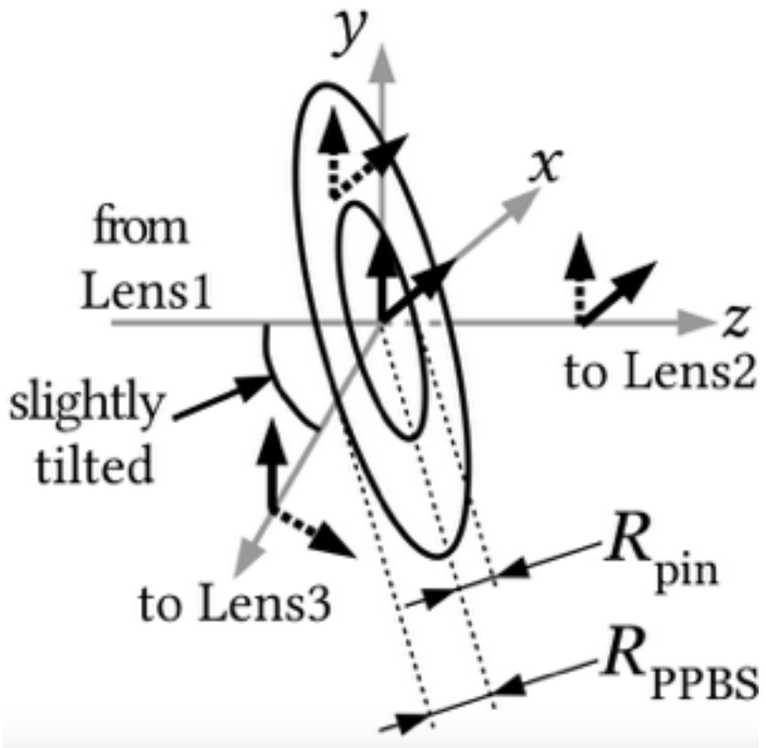


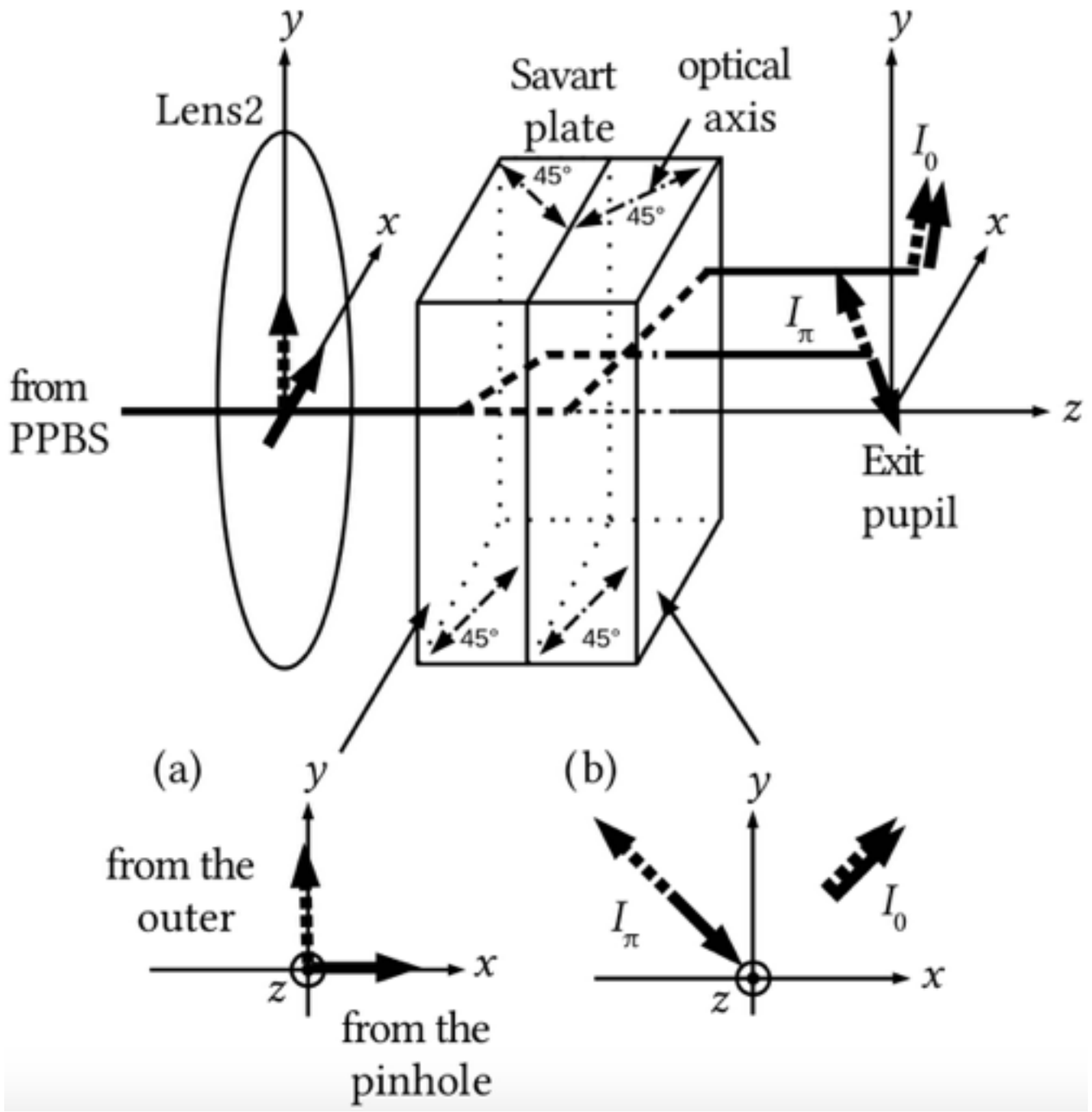
Recon. Error

φ_{error} = 0.0084 λ_0-rms



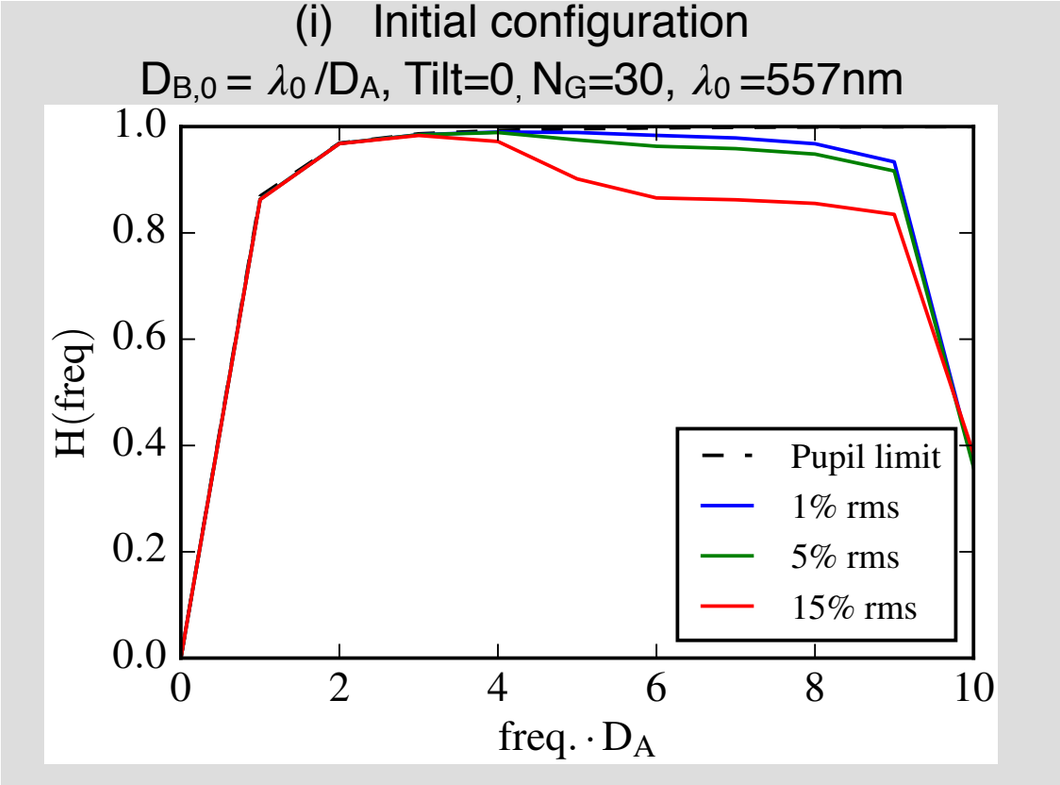
other WFSs **examples**





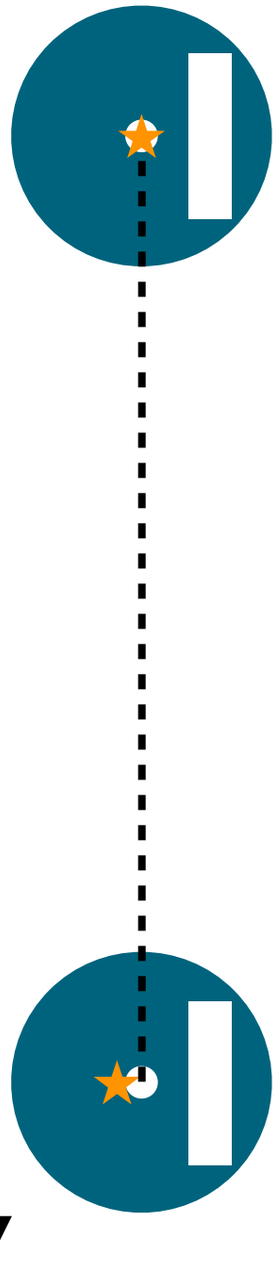
Imada 2018 - Real-time WFS

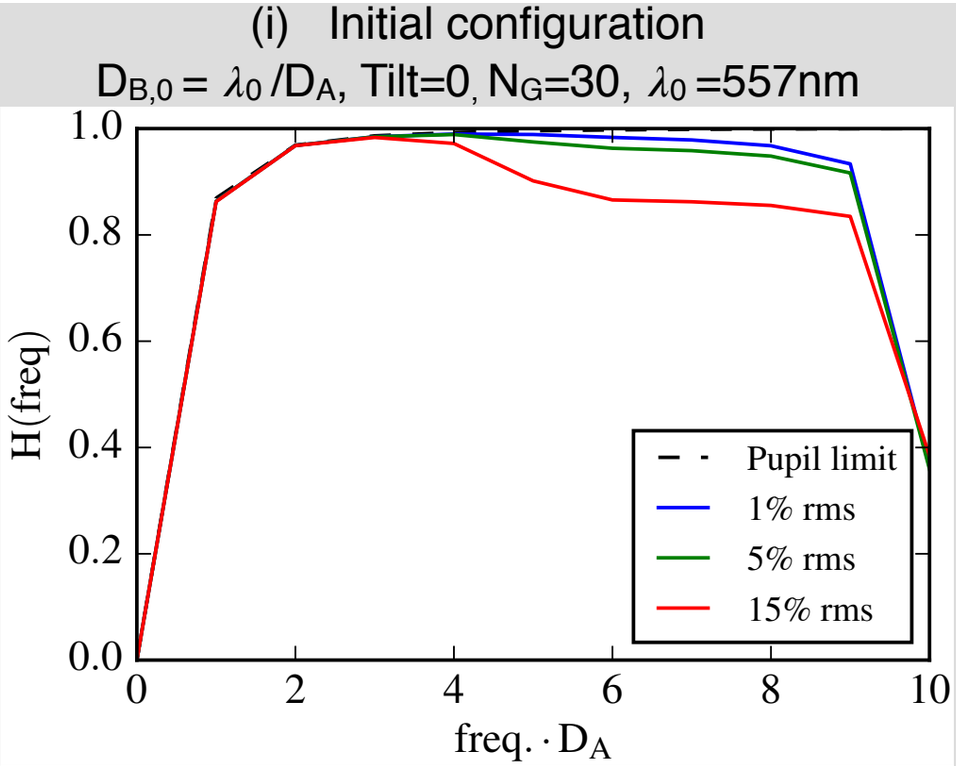
filtering and **dynamic range**

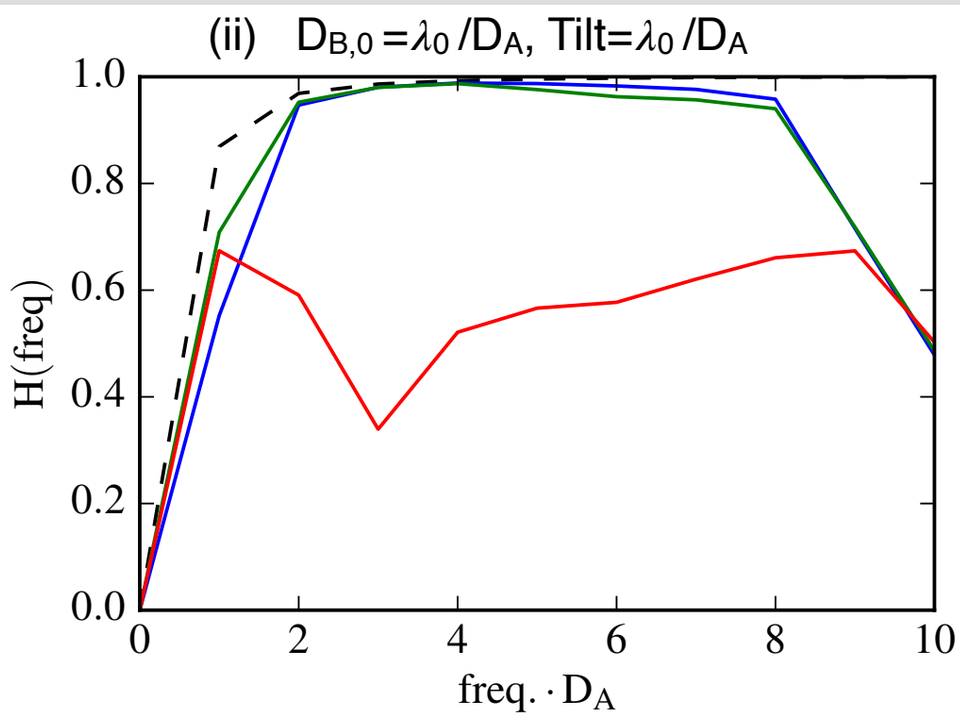


filtering and **dynamic range**

Residual tilt



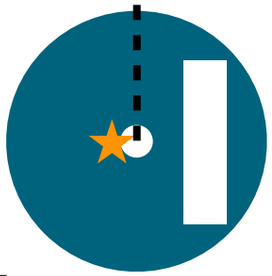




filtering and **dynamic range**

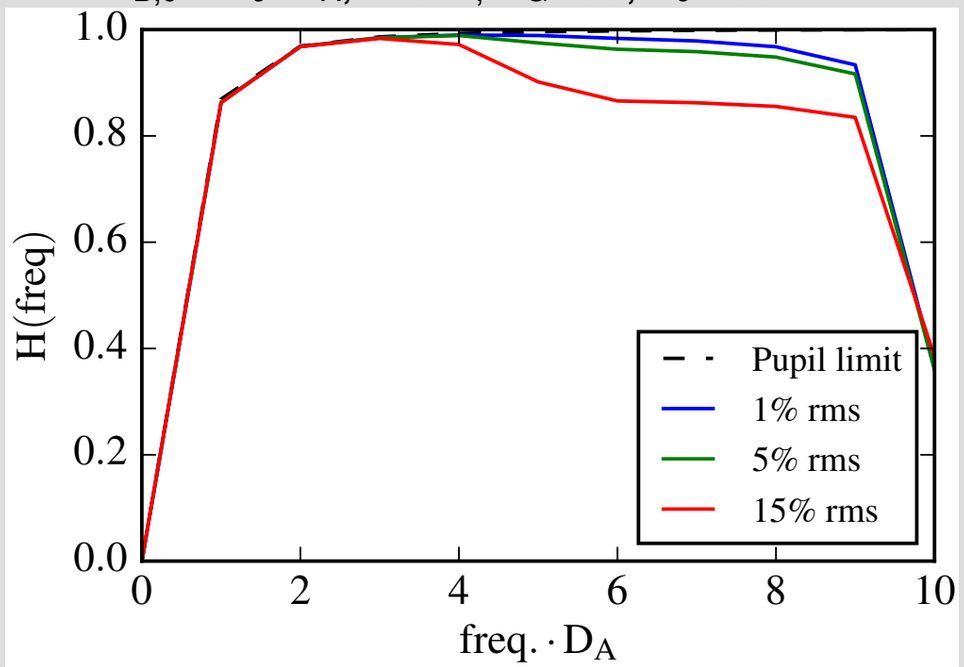
Pinhole size

Residual tilt

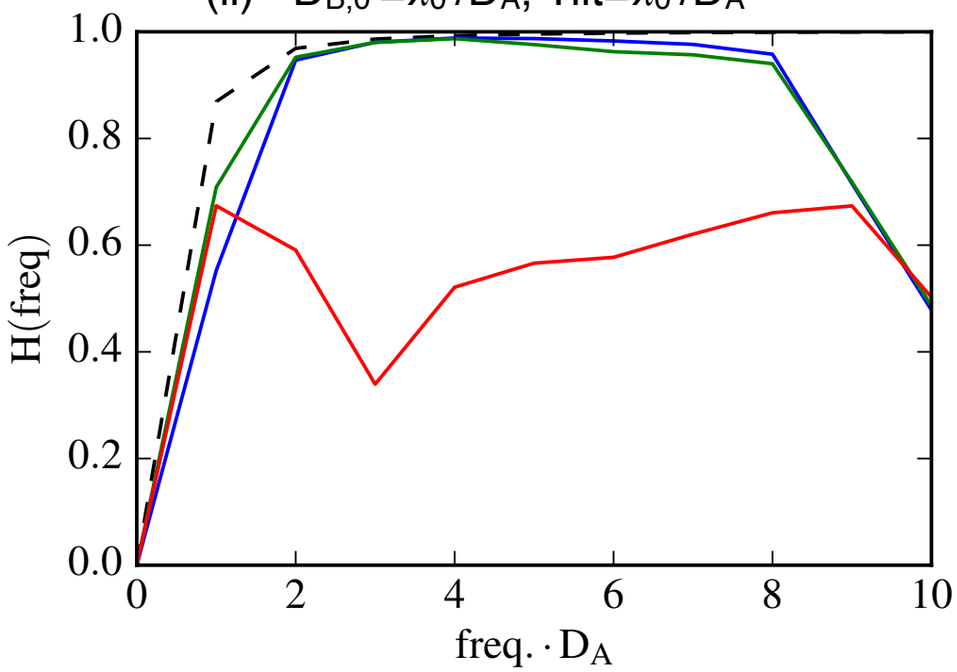


(i) Initial configuration

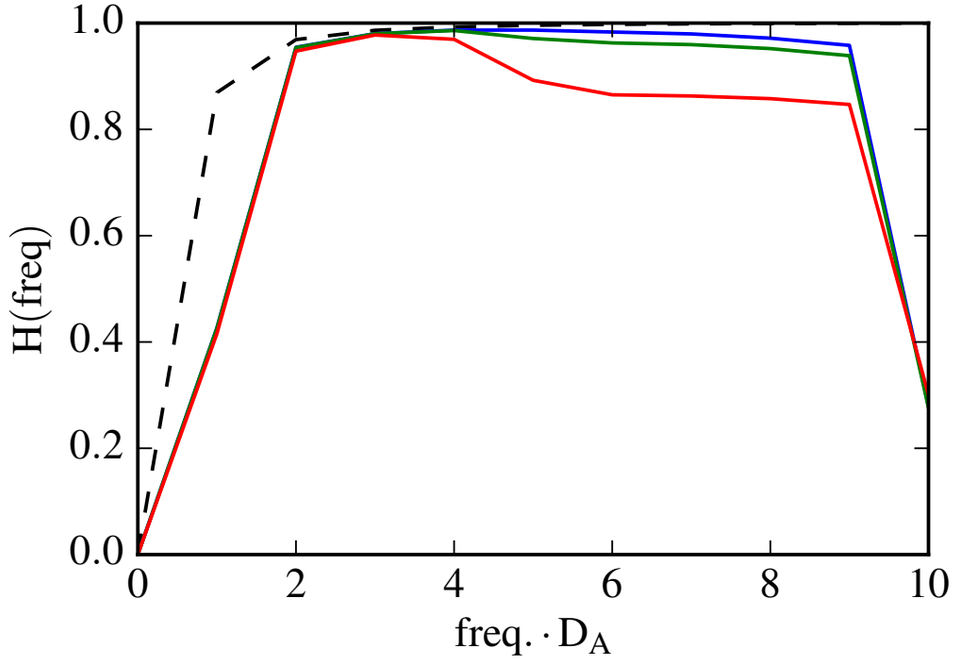
$D_{B,0} = \lambda_0 / D_A$, Tilt=0, N_G=30, λ_0 =557nm



(ii) $D_{B,0} = \lambda_0 / D_A$, Tilt=$\lambda_0 / D_A$



(iii) $D_{B,0} = 2.5\lambda_0 / D_A$, Tilt=0



filtering and **dynamic range**

Pinhole size

Residual tilt

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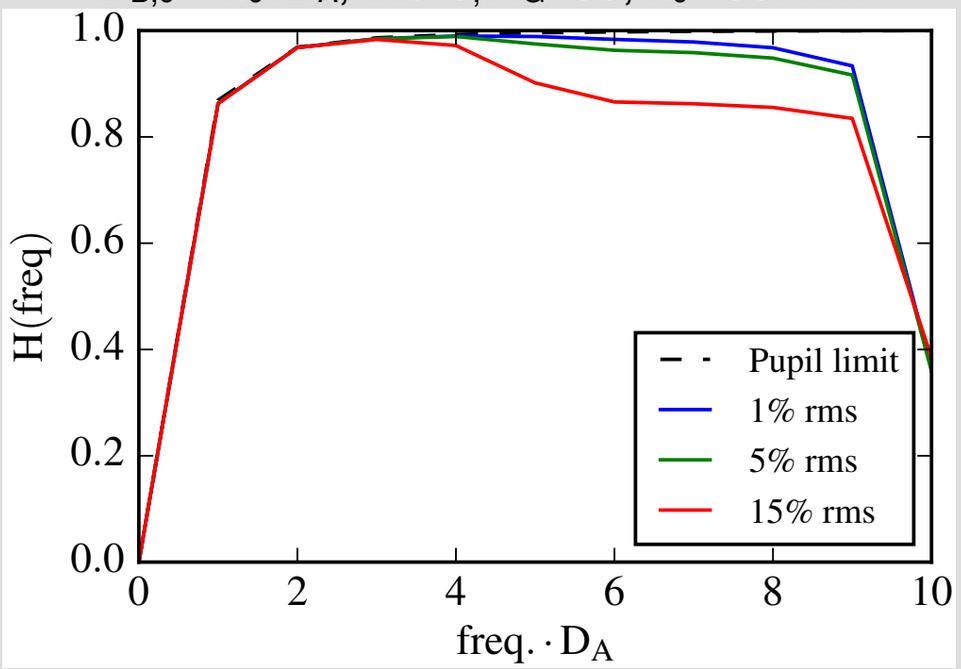
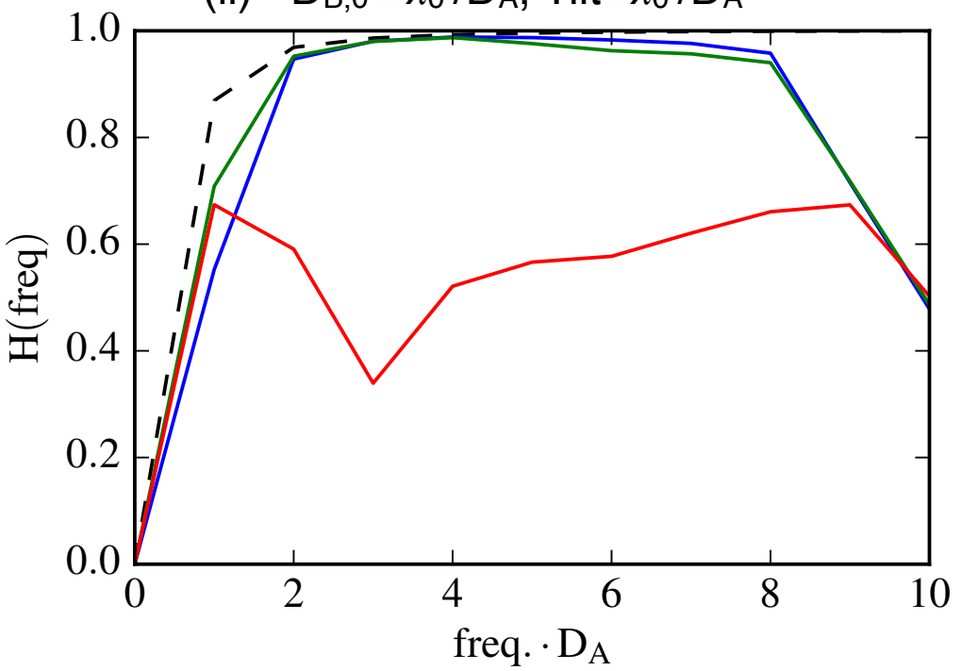
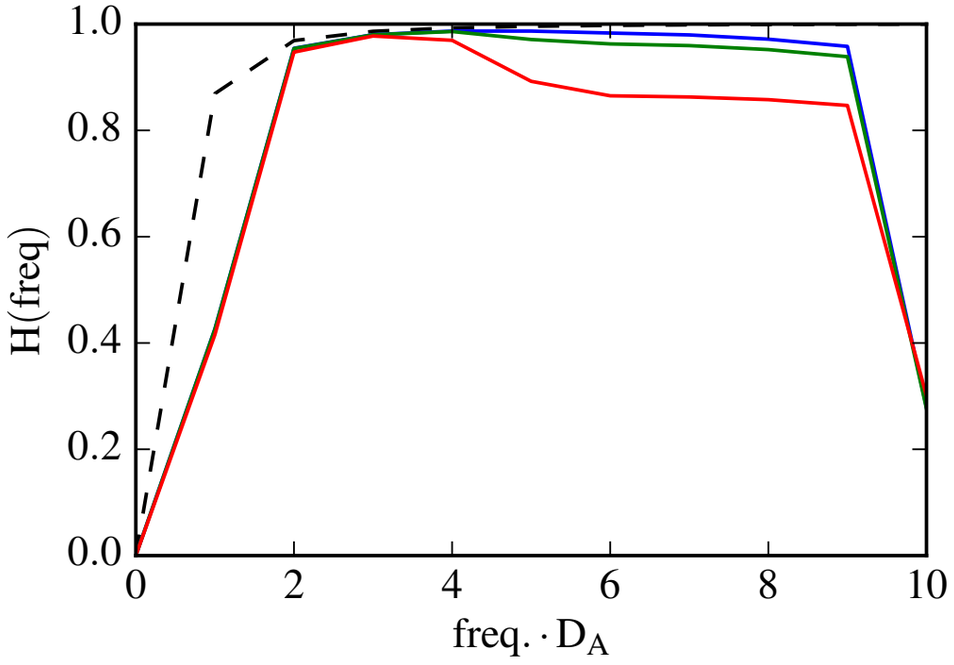


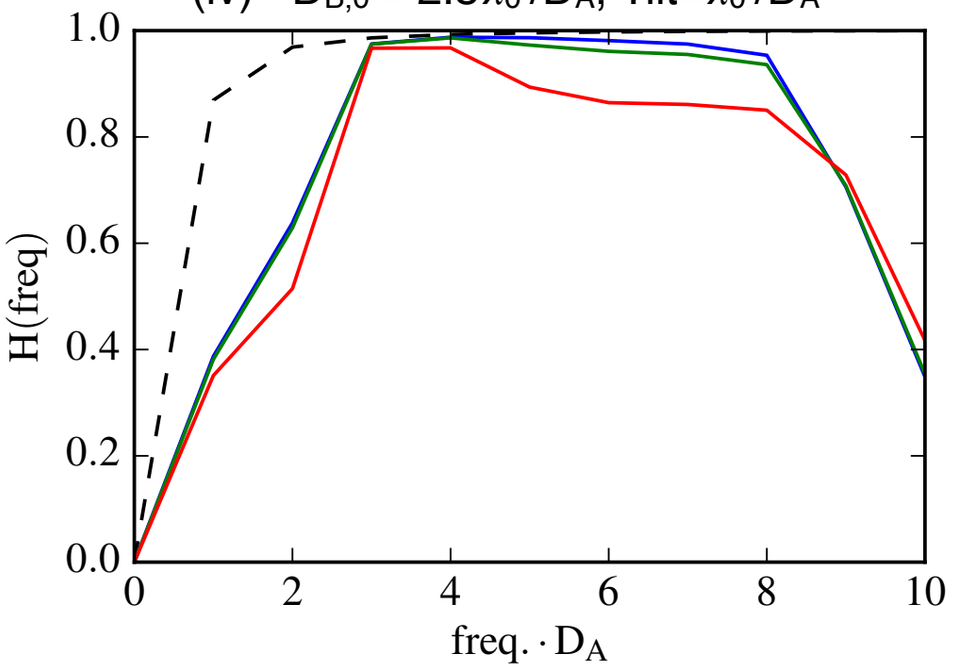
(ii) $D_{B,0} = \lambda_0 / D_A$, Tilt=$\lambda_0 / D_A$



(iii) $D_{B,0} = 2.5\lambda_0 / D_A$, Tilt=0

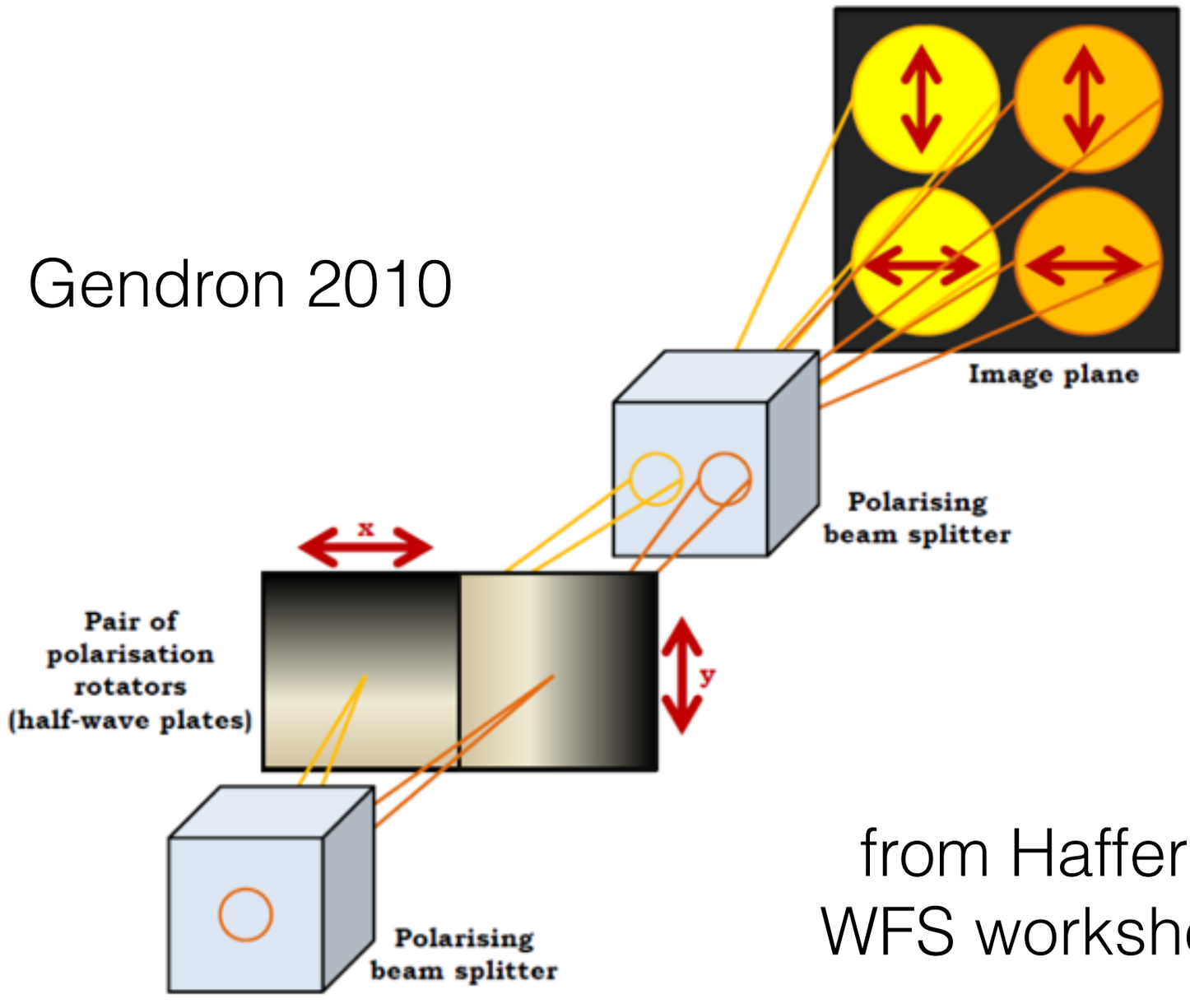


(iv) $D_{B,0} = 2.5\lambda_0 / D_A$, Tilt=$\lambda_0 / D_A$



other WFSs **examples**

Gendron 2010



from Haffert's 2017 talk
WFS workshop II, Padova