Phase-shifting coronagraph

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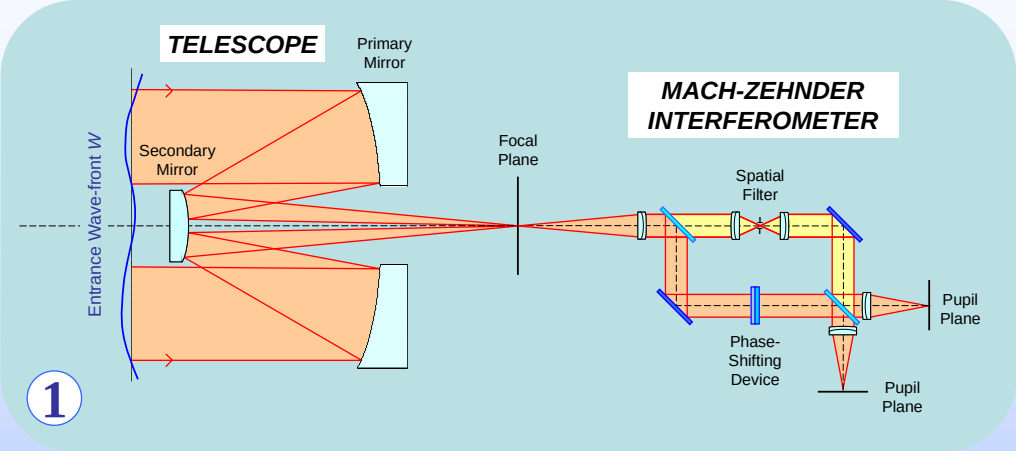
Plan of presentation

- Goal of the study
- Principle
- Optical design
- Numerical model
  - Simulation of measures intensities
  - Wavefront reconstruction procedure
- Numerical simulations
  - Three different phase-shifting schemes
  - Three types of phase mask coronagraphs
  - Two typical wavefront errors (to be measured)
- Interpretation of the results
- Conclusion

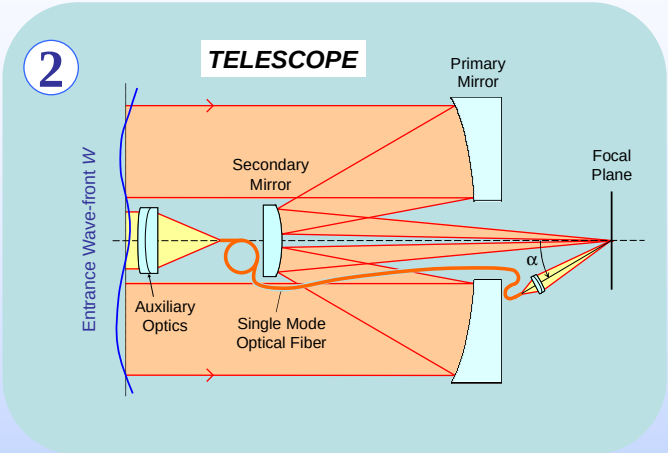
Goal of the study

- Evaluate the measurement accuracy of wavefront sensing phase-shifting methods **from inside a coronagraph**
- Put the phase-shifting device as far as possible within the coronagraph to compensate for Non common path aberrations (NCPA)
- Compare phase-shifting in the pupil plane with phase-shifting in the image plane
- Evaluate validity range:
  - Limited to weak aberrations or only by 2π-ambiguity $[-\lambda/2,+\lambda/2]$?
  - Real or low-order wavefront sensor ?

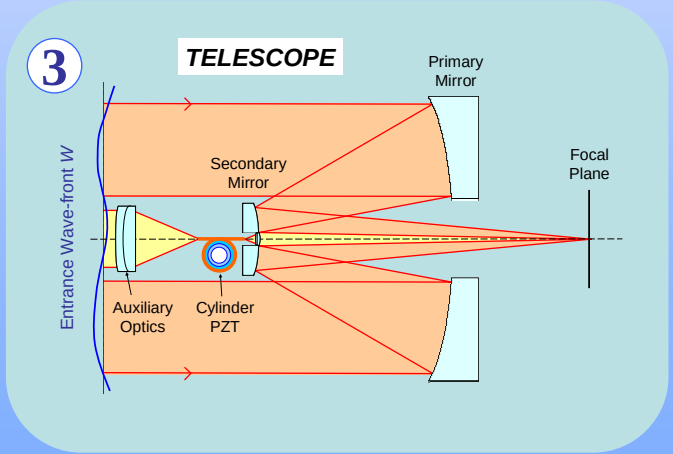
A brief history of phase-shifting telescopes



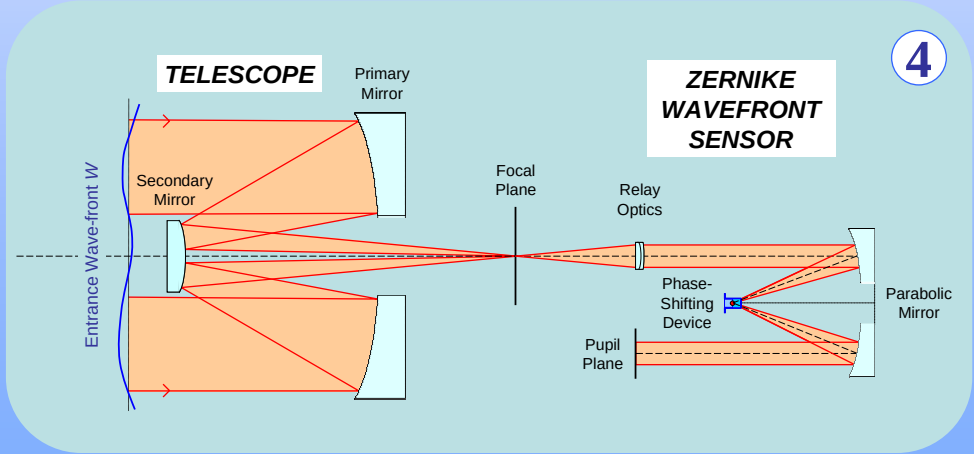
R. Angel, Nature (1994)



F. Hénault, Applied Optics (2005)



F. Hénault, Optics Communications (2006)



J. K. Wallace *et al*, Proc. SPIE (2011)

Principle

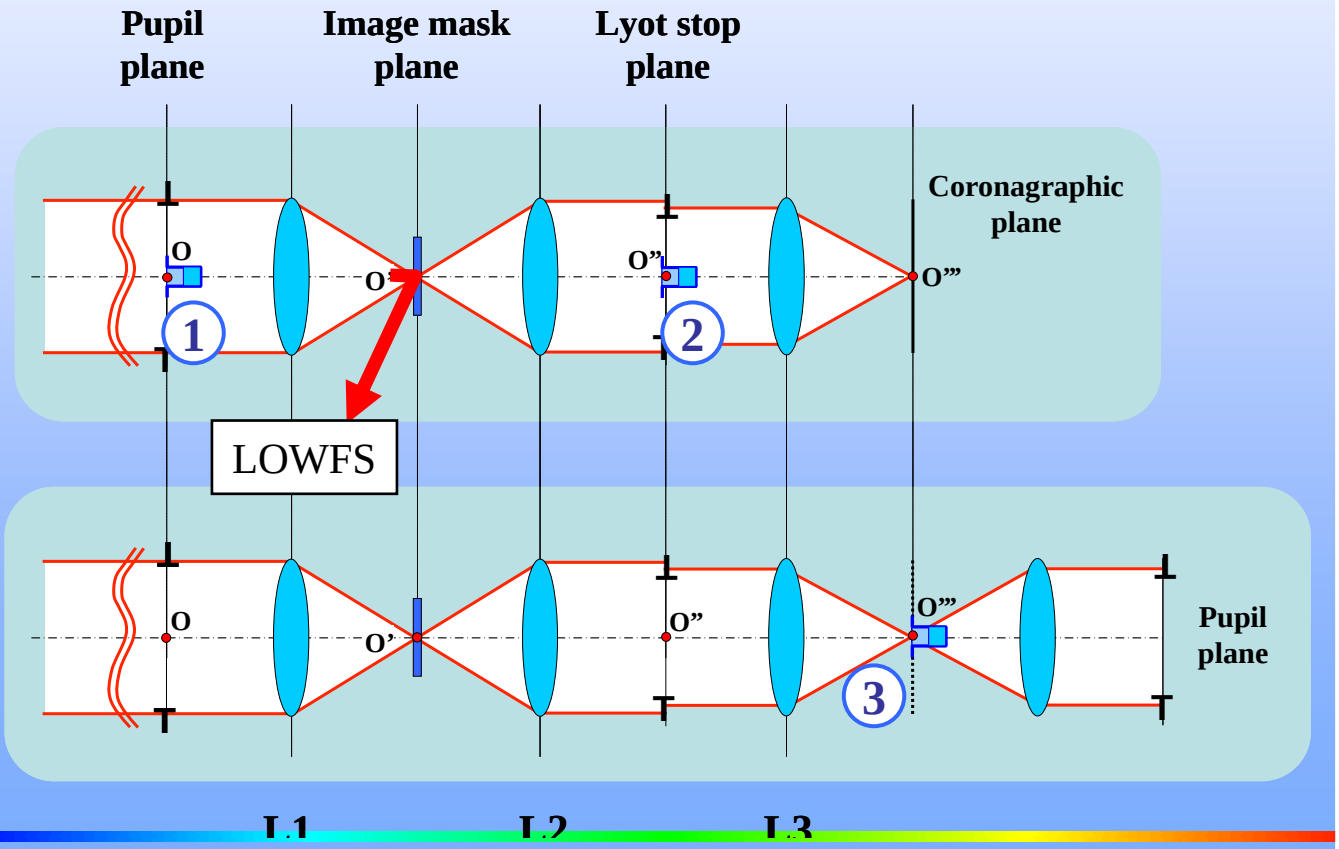
- Three different phase-shifting schemes:

Phase-shifting device

1 - In telescope pupil plane

2 - In Lyot stop plane

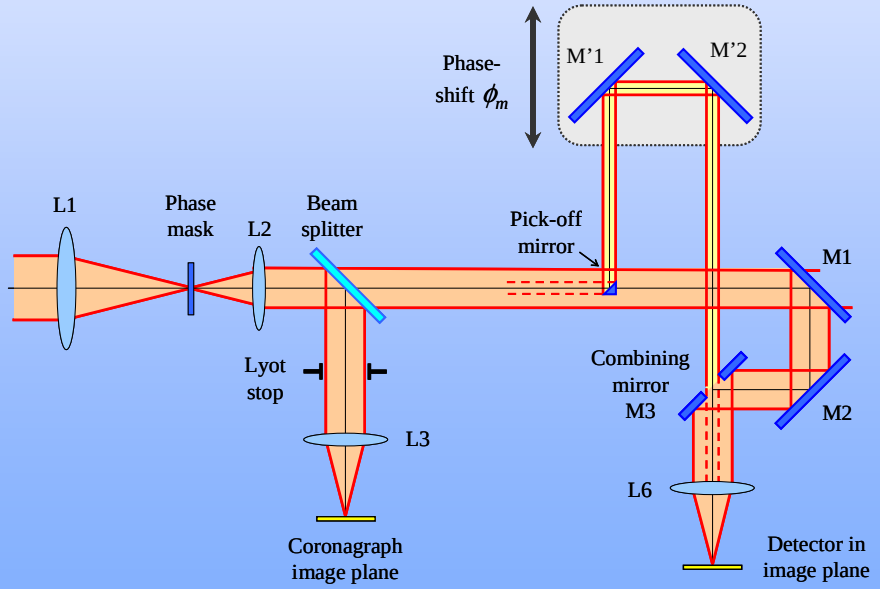
3 - In coronagraph image plane



Optical design

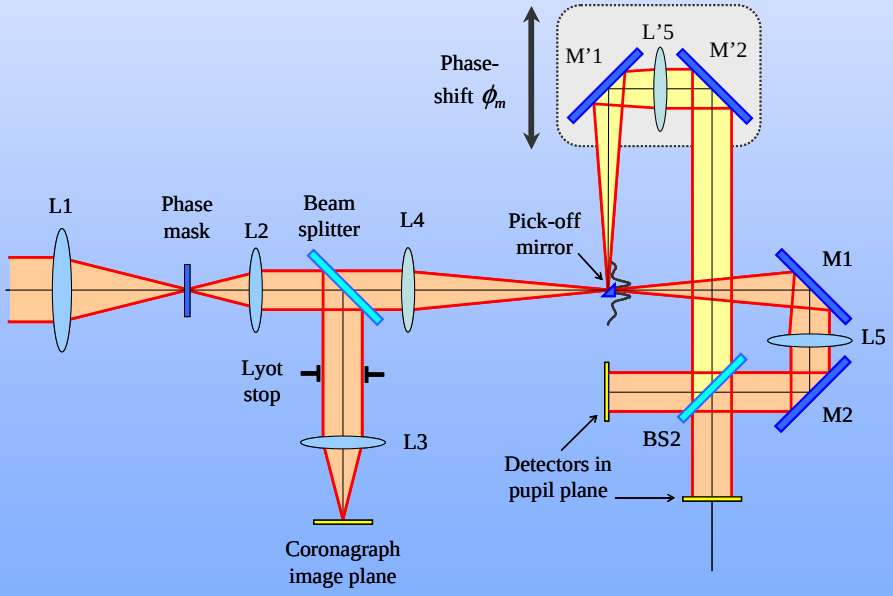
Phase-shifting in **Pupil**/Lyot stop plane

→ **Sensing in image plane**



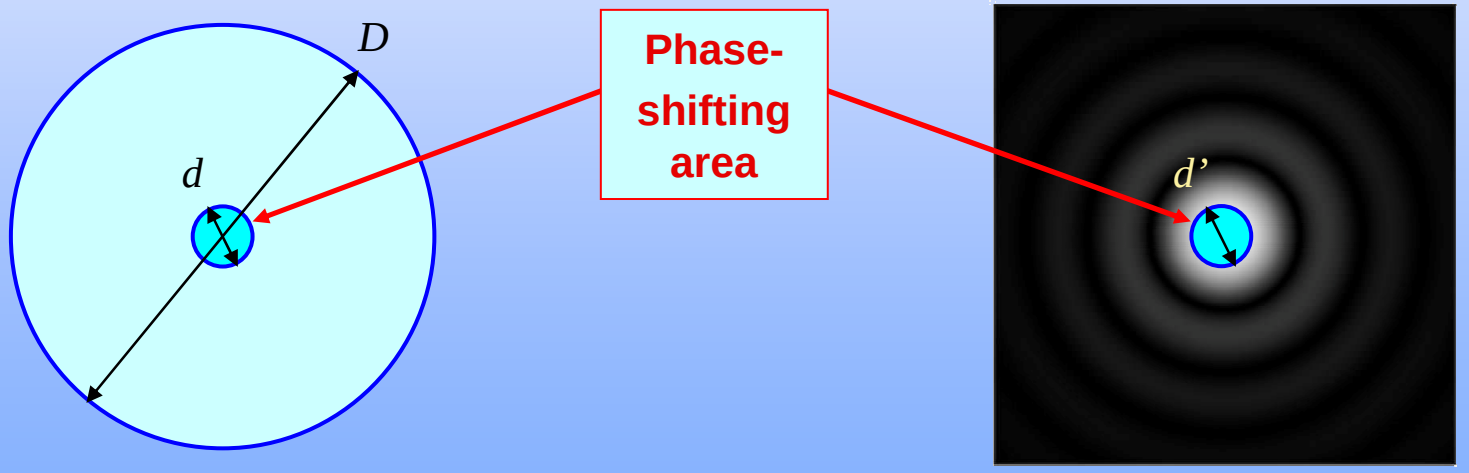
Phase-shifting in coronagraph **image** plane

→ **Sensing in pupil plane**



Numerical model

- **Module 1**: Complex amplitude propagation from plane to plane via Fourier transforms (see next slides)
- **Module 2**: Simplified WFE reconstruction procedure using two Dirac “Delta” approximations



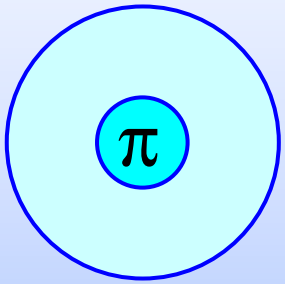
Delta approximation
in pupil plane $d / D << 1$

Delta approximation
in image plane $d' < \lambda F/D$

Numerical simulations

- Three different types of phase mask coronagraphs

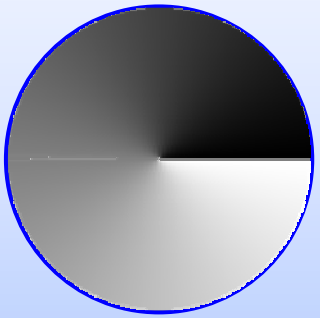
Roddier



Four-Quadrant

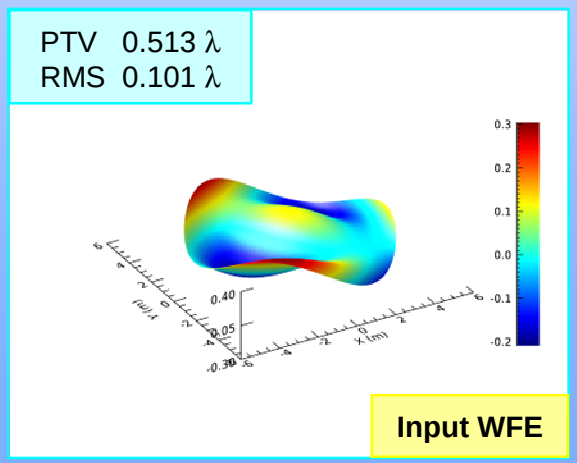
π	0
0	π

Vortex

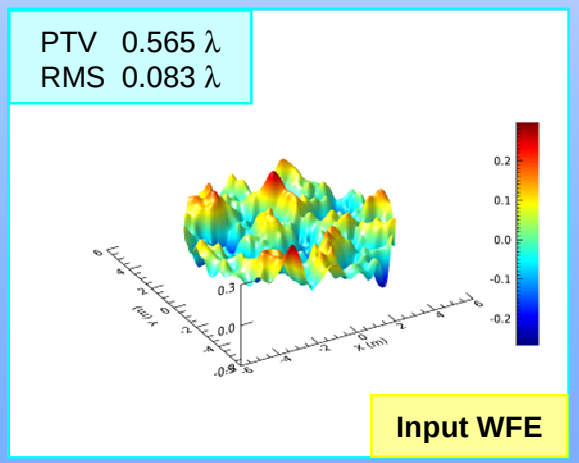


- Two typical wavefront errors

Low spatial frequency WFE

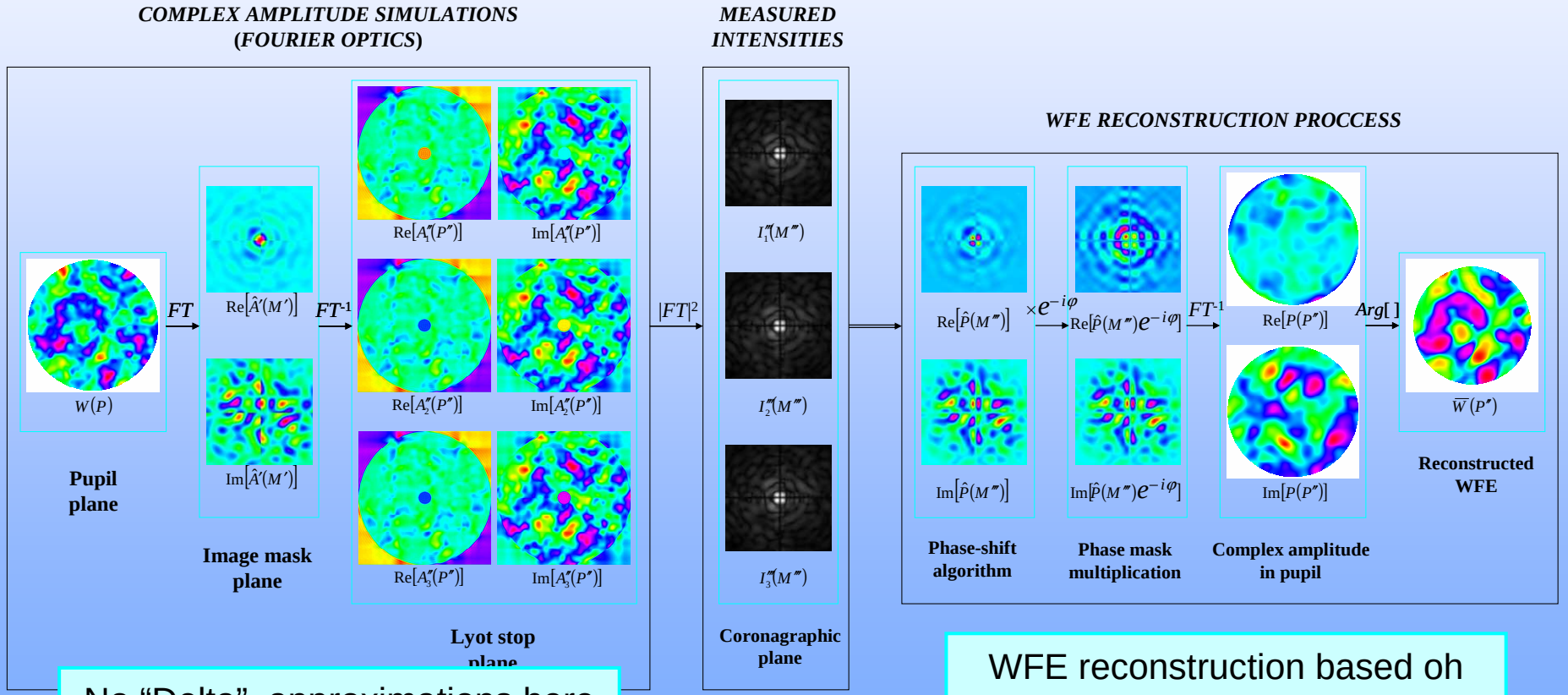


Mid spatial frequency WFE



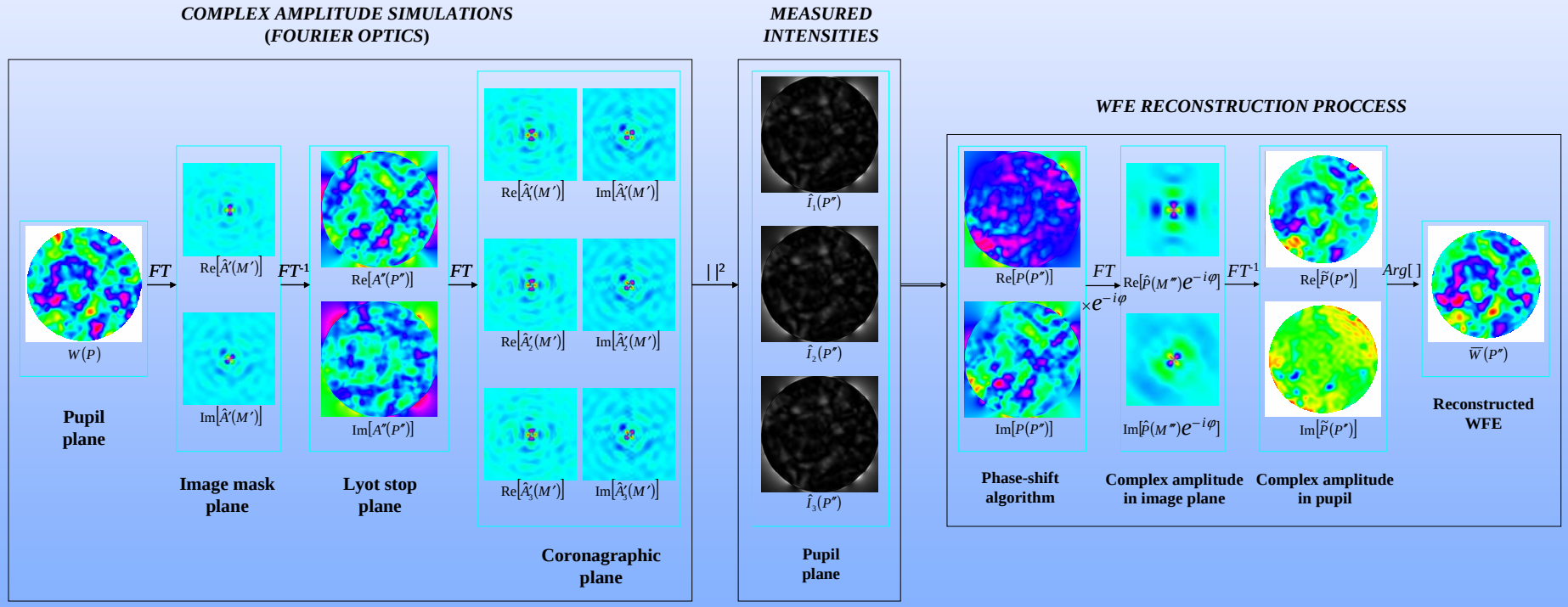
Numerical simulations

- Phase-shifting in Lyot stop plane (four-quadrant phase mask)



Numerical simulations

- Phase-shifting in coronagraph image plane (vortex phase mask)



Measured intensities – 3 sequential phase-shifts

$\phi_m = 0, 2\pi/3$ and $4\pi/3$

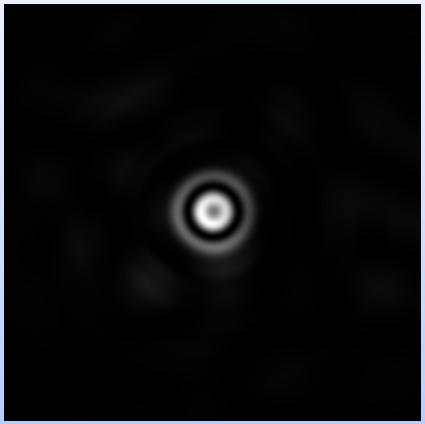
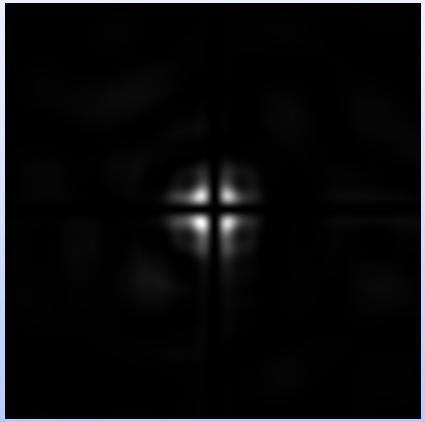
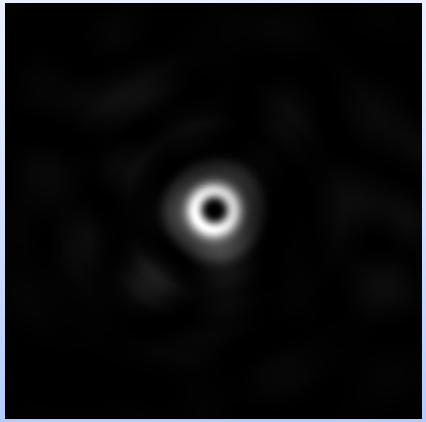
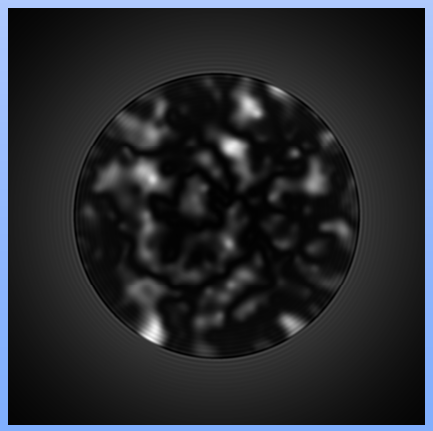
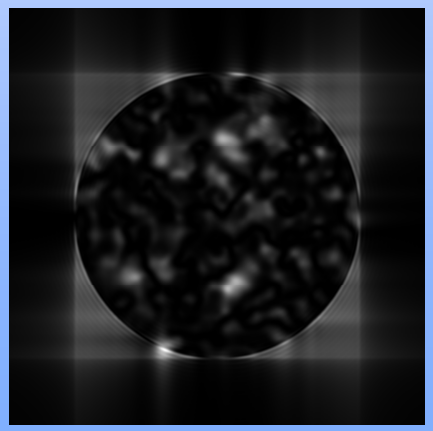
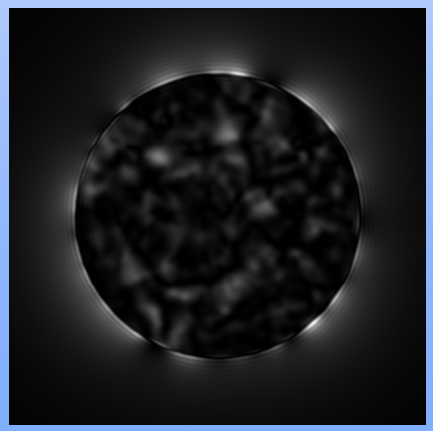
- Phase-shifting in pupil plane
- Sensing in image plane

- Phase-shifting in image plane
- Sensing in pupil plane

Behind Roddier phase mask

Behind 4-quadeants phase mask

Behind Vortex phase mask

Numerical results

- Measurement accuracy is fairly **similar for all cases**
  - Low spatial frequency WFE: Typically in the range **5-10 %** well below **λ/100 RMS**
  - Mid spatial frequency is slightly worse: 10-15 %
  - As good as when there is no phase mask, except for the four-quadrant

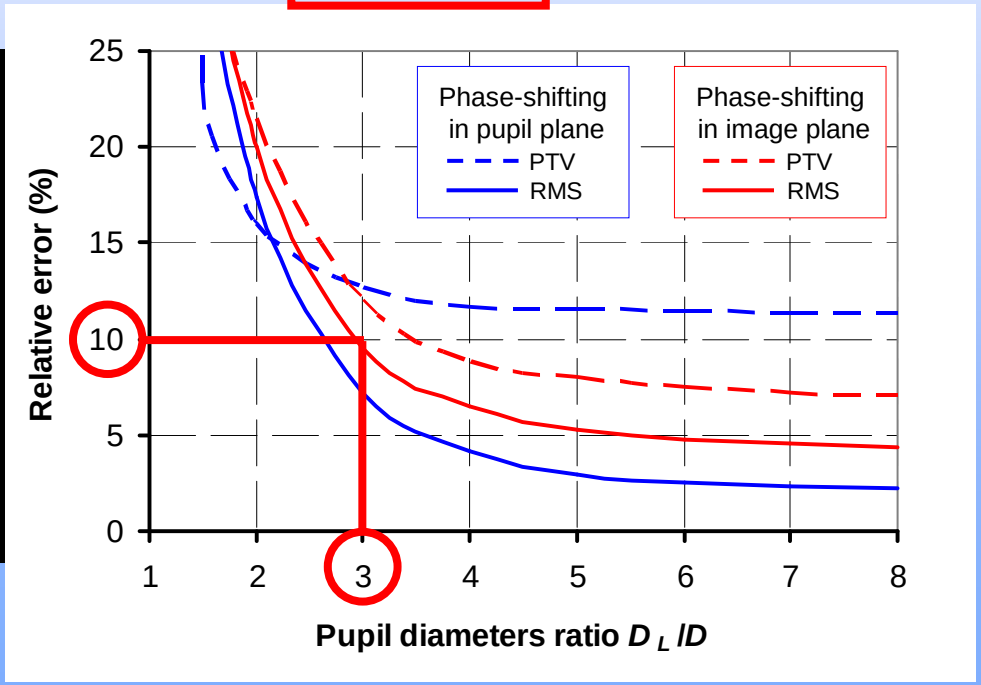
Initial WFE
PTV 0.513 λ
RMS 0.101 λ

Type of Coronagraph	PHASE-SHIFT LOCATION									
	Telescope pupil plane ρ = 0.05; Λ = 4; 0.1 < η < 0.9			Lyot stop plane ρ = 0.05; Λ = 4; 0.1 < η < 0.9			Image plane $\varepsilon = 0.1^{(*)}$; Λ = 4; 0 < η < 0.95			
	Measured (waves)	Difference (waves)	Relative error (%)	Measured (waves)	Difference (waves)	Relative error (%)	Measured (waves)	Difference (waves)	Relative error (%)	
No coronagrah	0.098	0.005	5	0.098	0.005	5	0.106	0.002	2	RMS
	0.489	0.037	7	0.489	0.036	7	0.516	0.017	3	PTV
Roddier	0.107	0.008	8	0.110	0.009	9	0.104	0.007	6	RMS
	0.520	0.072	14	0.540	0.035	7	0.504	0.039	8	PTV
4-Quadrants	0.108	0.009	9	0.107	0.008	8	0.114	0.022	21	RMS
	0.519	0.079	15	0.518	0.046	9	0.542	0.080	16	PTV
Vortex (m=2)	0.101	0.004	4	0.100	0.007	7	0.110	0.006	5	RMS
	0.502	0.042	8	0.498	0.067	13	0.531	0.040	8	PTV

Numerical results – Effect of Lyot stop

- Measurement accuracy is degraded by the Lyot stop
- WFE cannot be reconstructed if the diameters D and D_L of the telescope pupil and Lyot stop are equal
- Best measurement accuracy achieved when $D_L / D \geq 3$

D_L/D ratio	Relative errors (%)			
	Phase-shift in Lyot stop plane		Phase-shift in coronagraph plane	
	RMS	PTV	RMS	PTV
Negative	89	85	85	85
1	*Fail*		*Fail*	
1.5	34	23	37	35
2	17	16	20	21
3	7	13	10	12
4	4	12	6	9
5	3	12	5	8
6	2	11	5	8
7	2	11	5	7
8	2	11	4	7



Conclusion

- Phase-shifting techniques enable wavefront sensing behind the phase mask of a coronagraph
  - Potential reduction of Non common path aberration (NCPA)
- Phase-shifting can be implemented either in pupil or in image plane. In both cases measurement accuracy is well below $\lambda/100$ RMS
  - This type of WFS is not limited to weak aberration, but only by 2π-ambiguity
  - It not limited to low order spatial frequency (low order Zernike modes) and could operate in open loop
- Their performance is degraded when operating behind the Lyot stop
  - Optical solutions to be investigated: Independent optical arm ? “Dichroic” Lyot stop ? Integral field spectrograph ?

Phase-shifting coronagraph is good !

- Questions ?