Enhancing the Vector Vector Vortex Coronagraph:

Achromatic design and chromatic filtering
Mitigation of susceptibility to aberrations and stellar size
Immunization to central obscuration, segment gaps and spiders

Dimitri Mawet

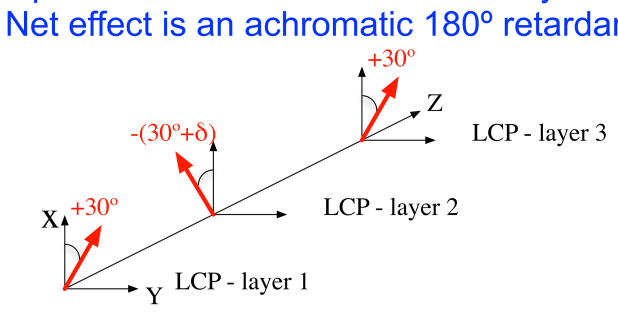
Jet Propulsion Laboratory - California Institute of Technology

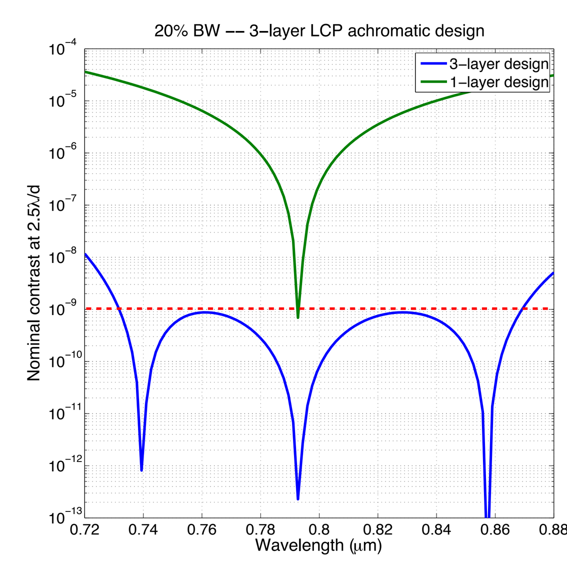
Disclaimers:
- Looking for ground-based L-band coronagraphy ? Go see Absil's poster and Delacroix's talk.
- If you don't know what the VVC is, go see my other poster first.

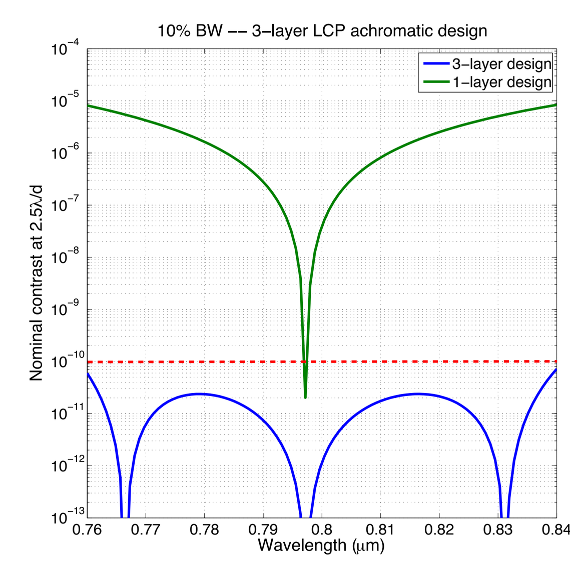
Achromatic 3-layer design

Based on the Pancharatnam phase achromatization principle:
Used for decades to manufacture achromatic waveplates:

- Needs 3 identical LCP layers.
- Optical axis offset between the 3 layers.
- Net effect is an achromatic 180º retardance.



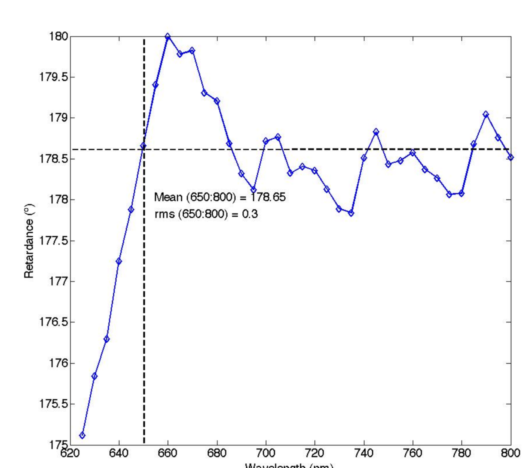


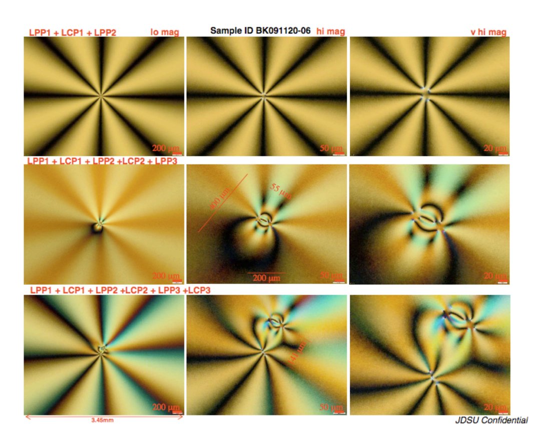


First attempt at realizing the 3-layer design (JDSU):

- Achromaticity good for 10^{-9} contrast.
- The current apparatus misses a layer registration mechanism.
- Central region messed up.

- New manufacturer, new technique (projection lithography vs contact lithography).





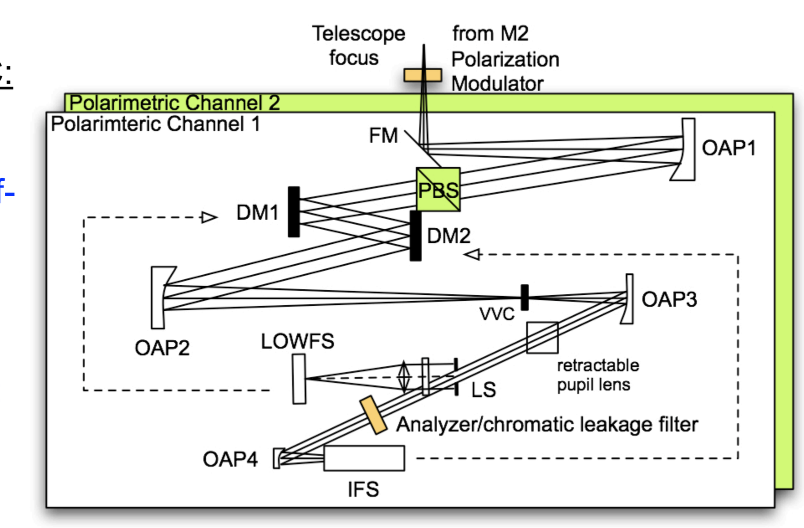
Residual chromatic leakage filtering - polarimetric differential imaging

$$J_v(r,\theta) = V\begin{bmatrix} \cancel{0} & e^{il\theta} \\ e^{-il_p\theta} & \cancel{0} \end{bmatrix} + L\begin{bmatrix} \cancel{1} & 0 \\ 0 & \cancel{1} \end{bmatrix}$$

Take advantage of the vectorial nature of the VVC:

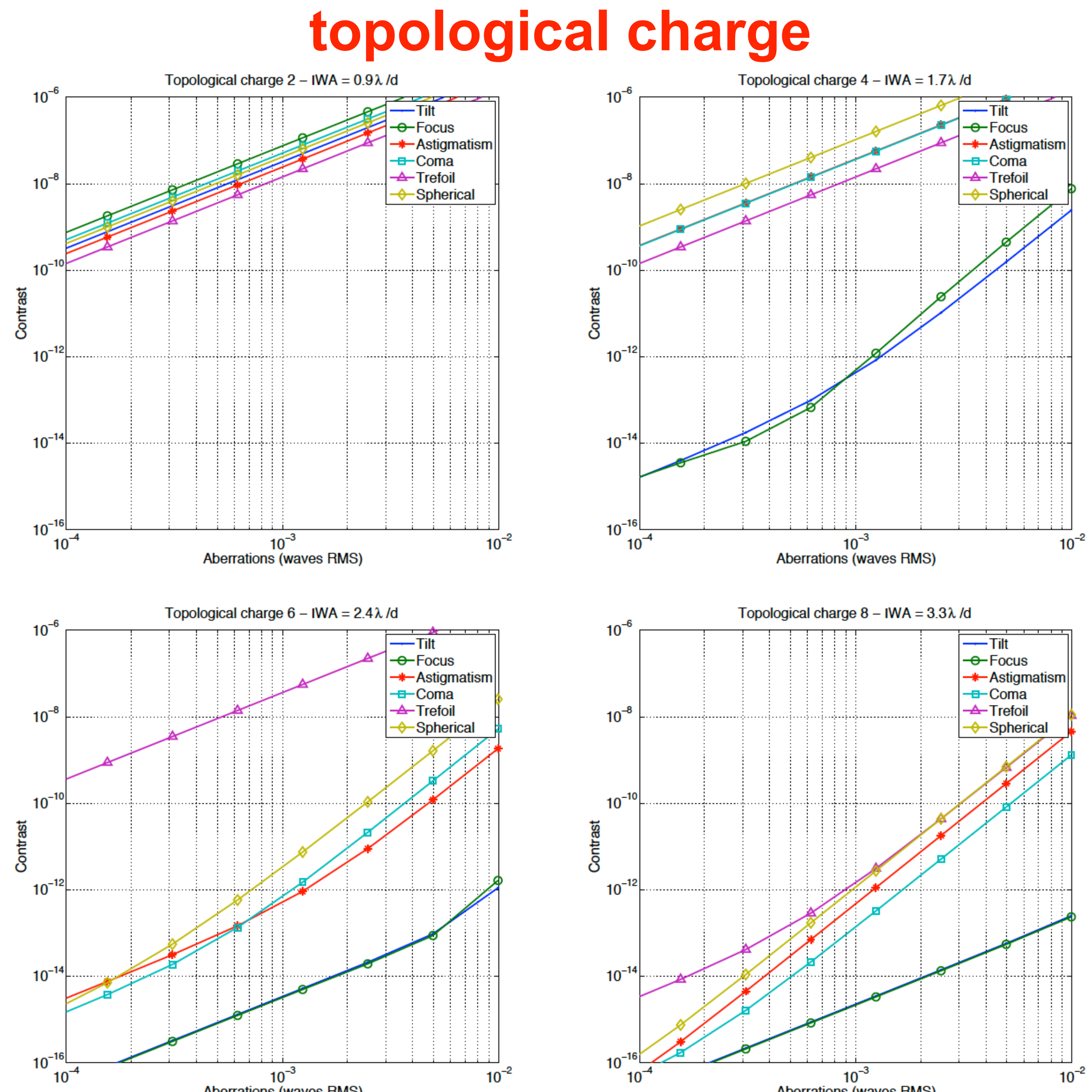
- The chromatic leakage has an orthogonal polarization to the main vortex term and any off-axis companion.
- Can be removed in polarized light by a simple analyzer.
- The gain in contrast of the filtering process is related to the quality of the analyzer as follows:

$$G \approx \left[\frac{1}{ER} + \Delta\phi^2_{QWP}\right]^{-1}$$



Bandwidth	Modifier angle	Contrast at $\sim 2.5\ \lambda/d$	Leakage filtering
10%	0.1	$\sim 10^{-10}$	$< 10^{-10}$
20%	0.4	$\sim 10^{-9}$	$< 10^{-10}$
40%	1.0	$\sim 10^{-7}$	$\sim 10^{-10}$
60%	2.5	$\sim 10^{-6}$	$\sim 10^{-9}$

Low-order aberration sensitivity as a function of the topological charge



Sensitivity decreases with the topological charge, so does the IWA => Trade-OFF

Stellar size matters

Contrast at 3λ/d as a function of star apparent diameter and topological charge

Topological charge	IWA (λ/d)	$s = 0.01\lambda/d$	$s = 0.1\lambda/d$
2	0.9	1×10^{-8}	1×10^{-6}
4	1.7	3×10^{-13}	3×10^{-9}
6	2.4	8×10^{-18}	8×10^{-12}
8	3.3	2×10^{-22}	1×10^{-14}

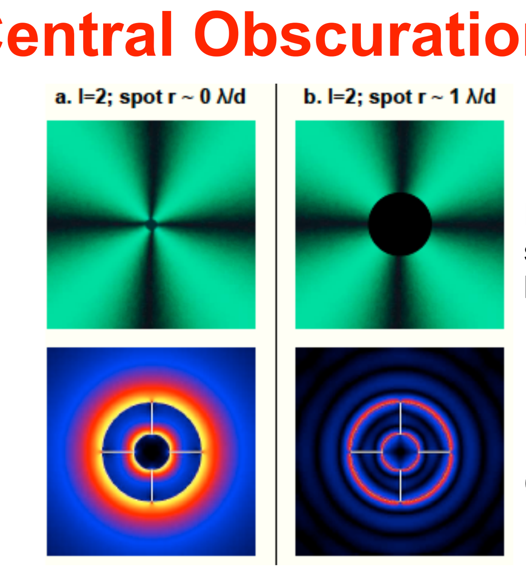
Immunization to Central Obscuration

Solution 1, trade throughput with contrast:

- Hybridization of the VVC.
- Joint optimization of the central opaque spot and lyot stop size.

- Typically for 15-25% central obscuration:
  - Contrast ~ 10^{-7}
  - Throughput loss of ~ 50-90 %

- See Mawet et al. 2010 (SPIE).

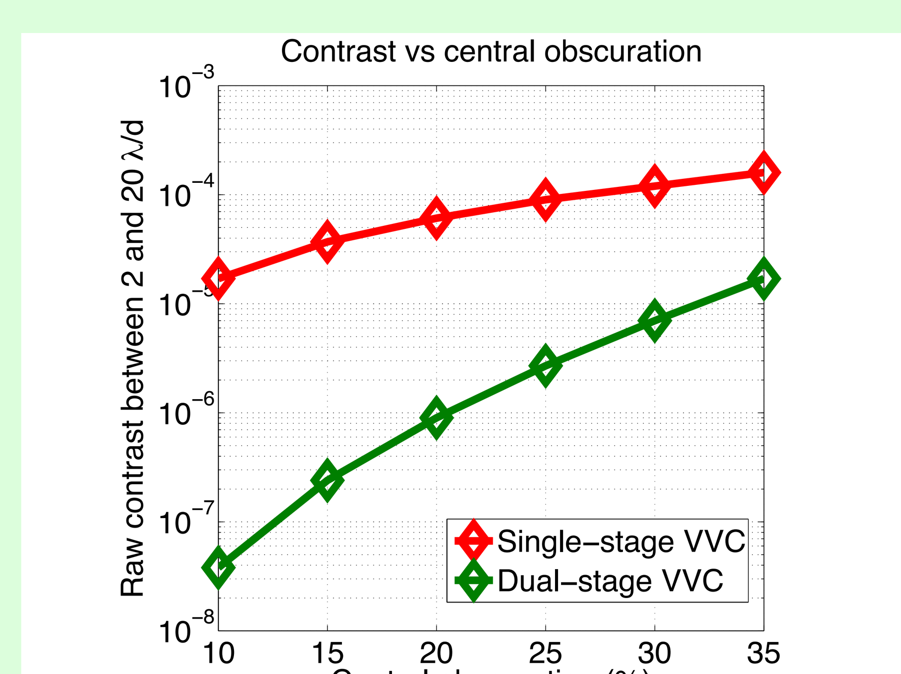


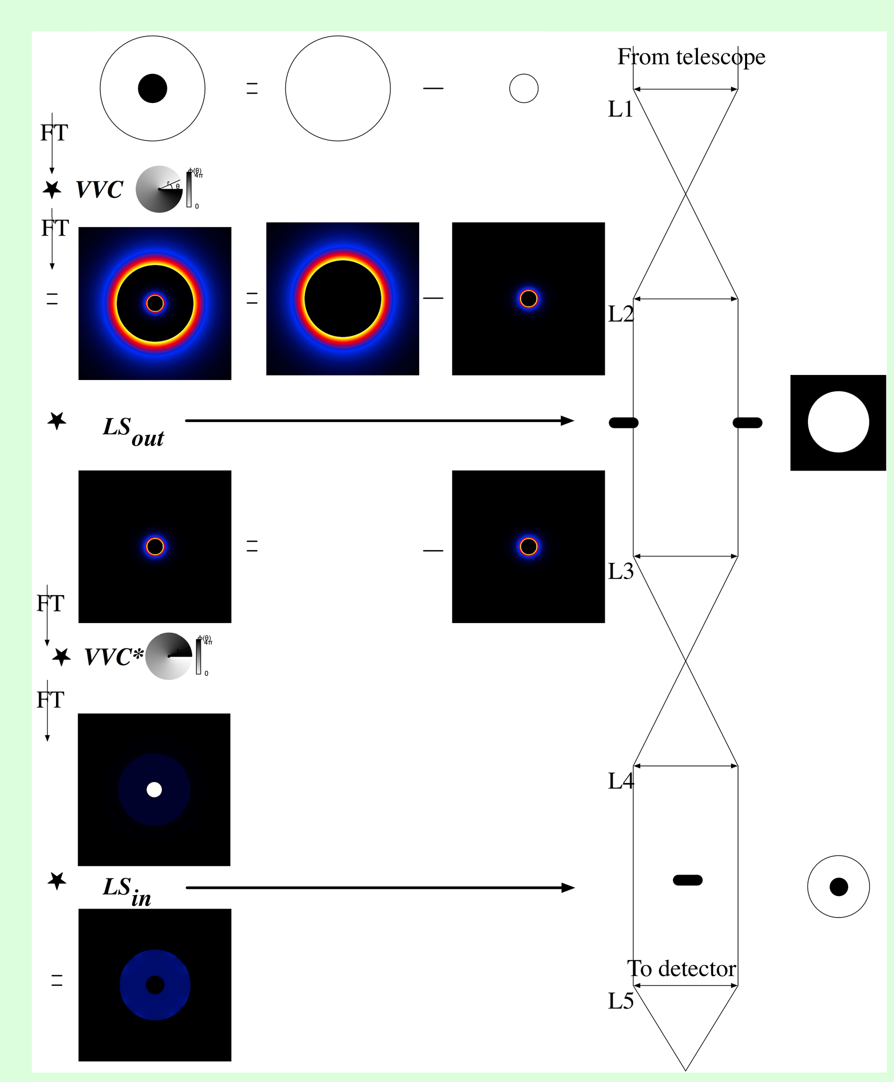
Hybrid mask: VVC + central spot, note that the spot is never bigger than the IWA

Pupil diffraction pattern (same scale)

Solution 2, the return of the ~~jedi~~ dual-stage coronagraph:

- Amazing property of the VVC: phase-induced amplitude redistribution.
- No THROUGHPUT LOSS !!!
- Known advantages of the multi-stage approach:
  - Reduced chromaticity.
  - Reduced sensitivity to stellar size/low-order aberrations.

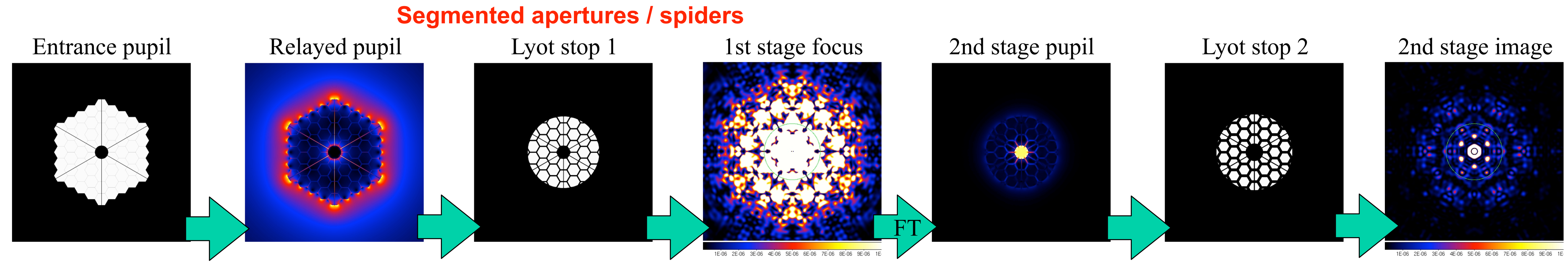




Segmented apertures / spiders

The VVC is not afraid of segmented pupils, and spiders !

- Use the edge-enhancement property of the VVC to our advantage.
- Careful optimization of the Lyot stop allows mitigating the high spatial frequency content of spiders and gaps between segments.
- The two-stage VVC provides additional leverage to remove diffracted light.
- Conclusions: deep raw contrast of 10^{-7} are not ruled out on segmented obscured pupils with carefully designed coronagraphs !!!



Average contrast ~ 5 10^{-6}

Average contrast ~ 1 10^{-7}

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California
www.nasa.gov

Perspectives

The VVC coronagraph family provides a set of handles to mitigate chromaticity, sensitivity to low-order aberrations, stellar size, central obscuration, gaps between segments and spiders. A particular property of the VVC, called phase-induced amplitude redistribution can be used in a dual-stage layout to dramatically reduce the effect of central obscuration while maximizing the throughput, reduce chromaticity, stellar leakage and sensitivity to low-order aberrations. ***The results presented here and recent advances in wavefront control technology and post-processing techniques put phase-mask coronagraphs on the table again as potential solutions for extremely large and large ground-based telescopes.***