Vortex Coronagraphy

Gene Serabyn

Jet Propulsion Laboratory

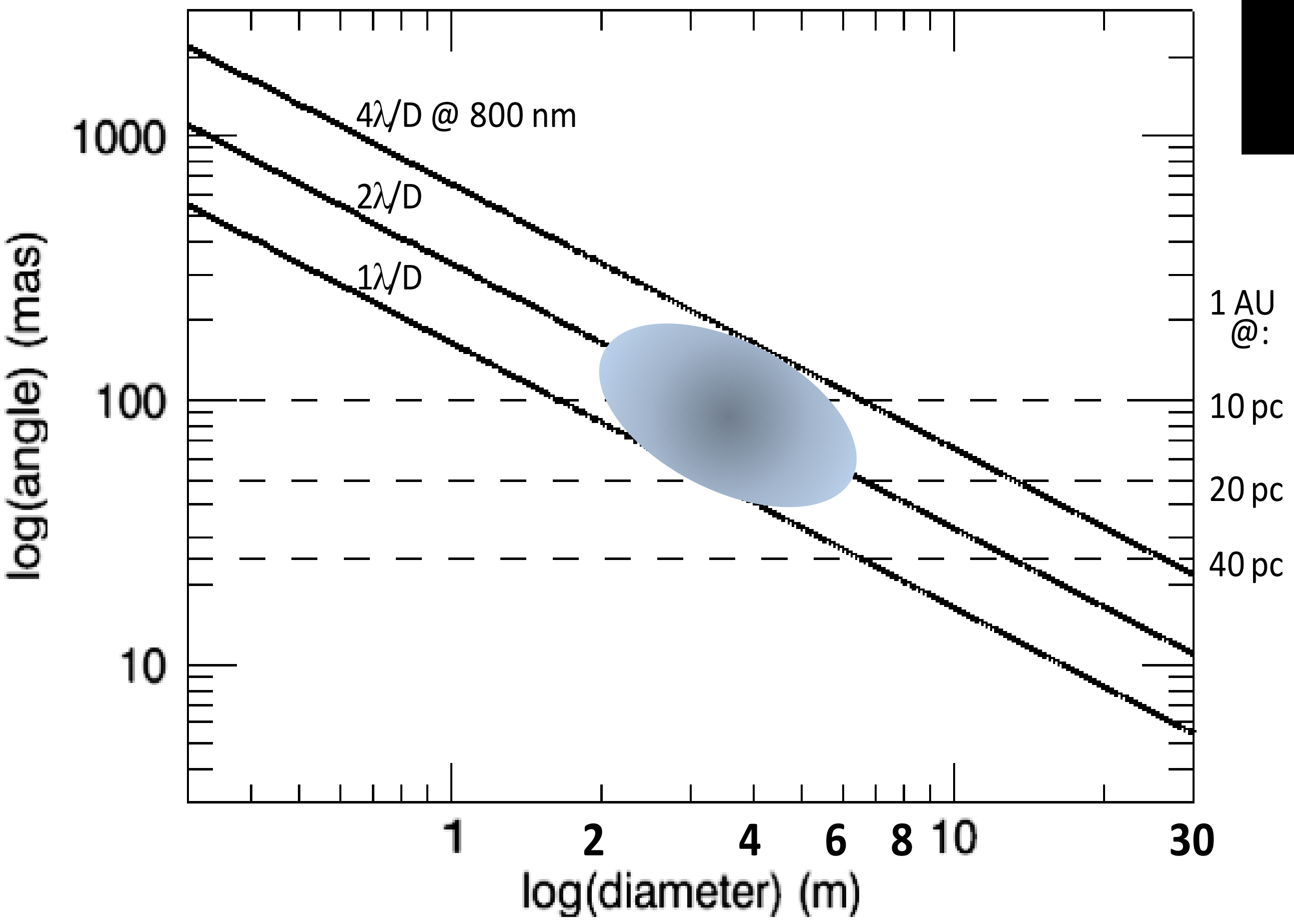
California Institute of Technology

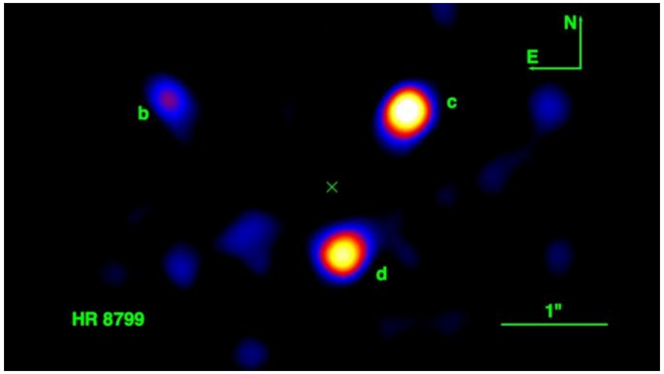
ExoPAG 5

Austin, Jan 2012

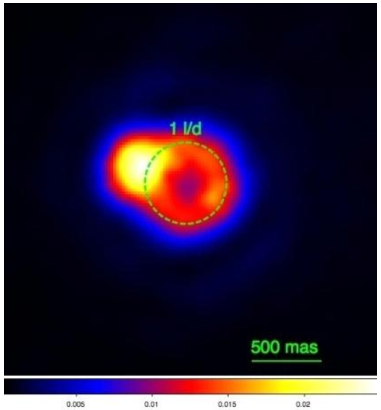
Small-Angle Observations

Goal: observe as close as possible to bright stars





Planets seen to 2 λ/D
HR8799
contrast ~ 10^{-5}
(Serabyn et al. 2010)

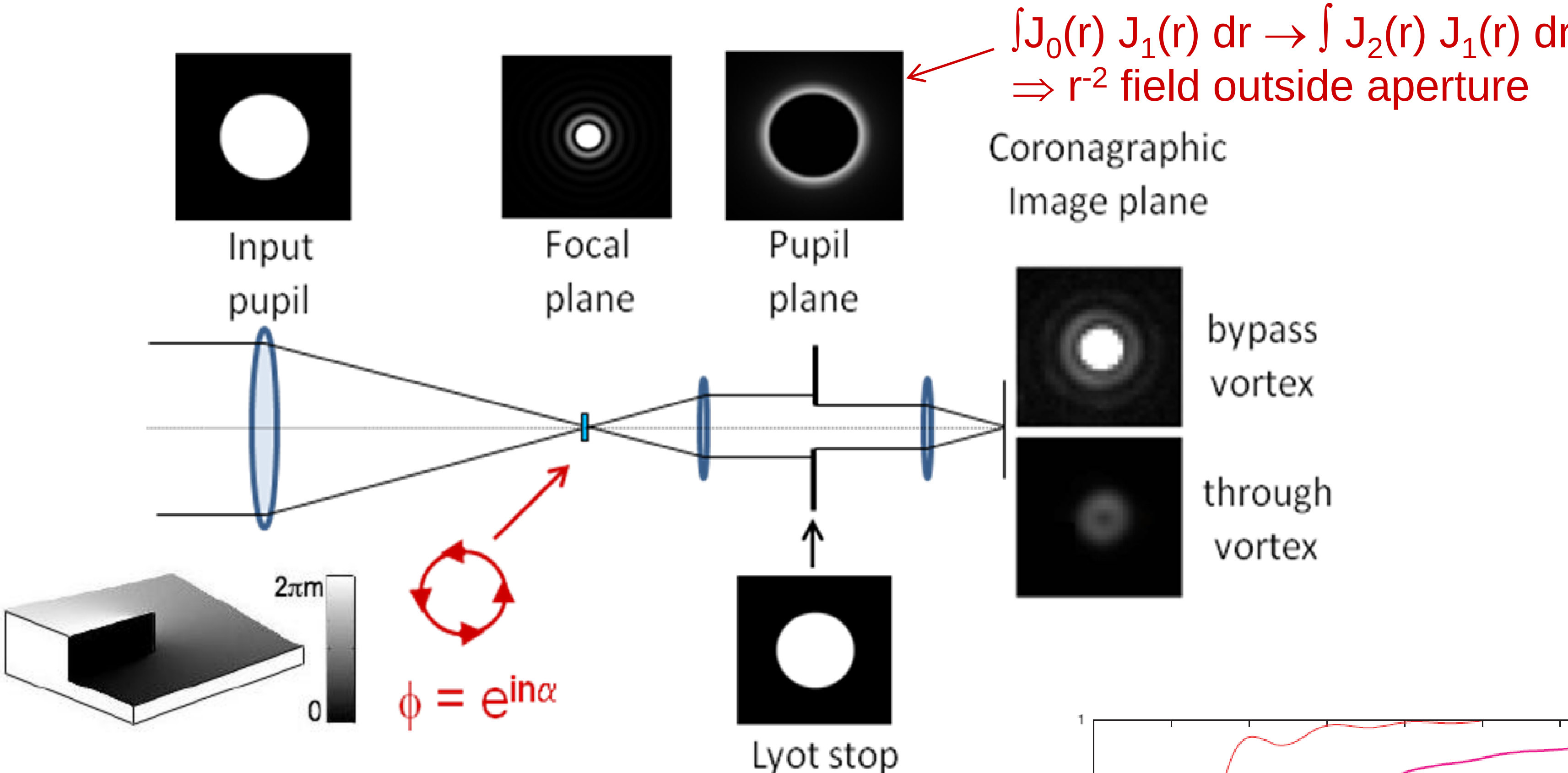


Stars to 1.1 λ/D
εCeph
contrast ≈ 50:1
(Mawet et al. 2011)

Desirable capabilities of a space coronagraph & potential solutions provided by vortex phase masks

Subsystem/metric	Goal	Potential Vortex-based Solution
Telescope	Modest size	Phase masks in general
Telescope	On-axis optics	Multi-stage vortex configuration
Throughput	High throughput for exoplanet light	Optical vortex phase mask
Throughput	Broadband	Multi-layer vortex or Polarization-filtering
Throughput	Dual-polarization	Multi-layer vortex or Polarization-split vortex system
Field of view	Small inner working angle	Phase masks in general
Field of view	Large outer working angle	Phase masks in general
Field of view	All azimuths available	Vortex phase mask
Wavefront quality	Low sensitivity to pointing & low-order errors, or ability to correct them	Higher order vortex
Wavefront quality	Ability to correct high-order errors	Direct speckle amplitude & phase sensing in a multi-stage vortex

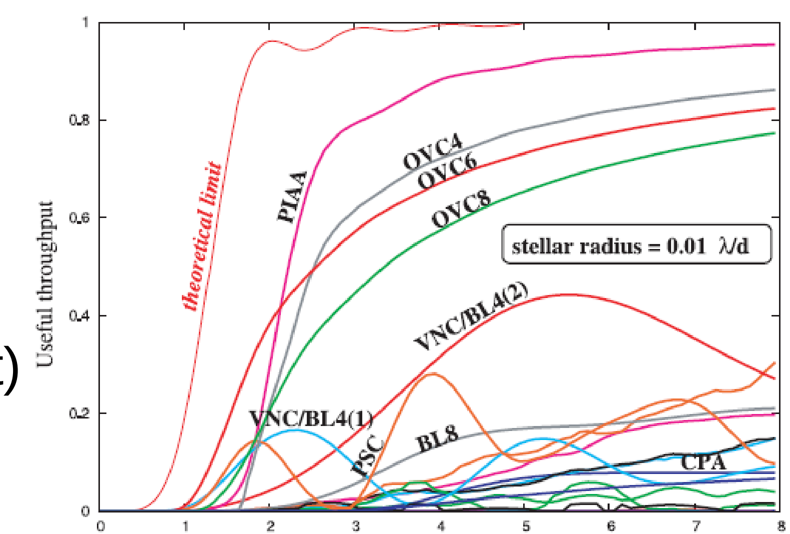
The (Single) Vortex Coronagraph



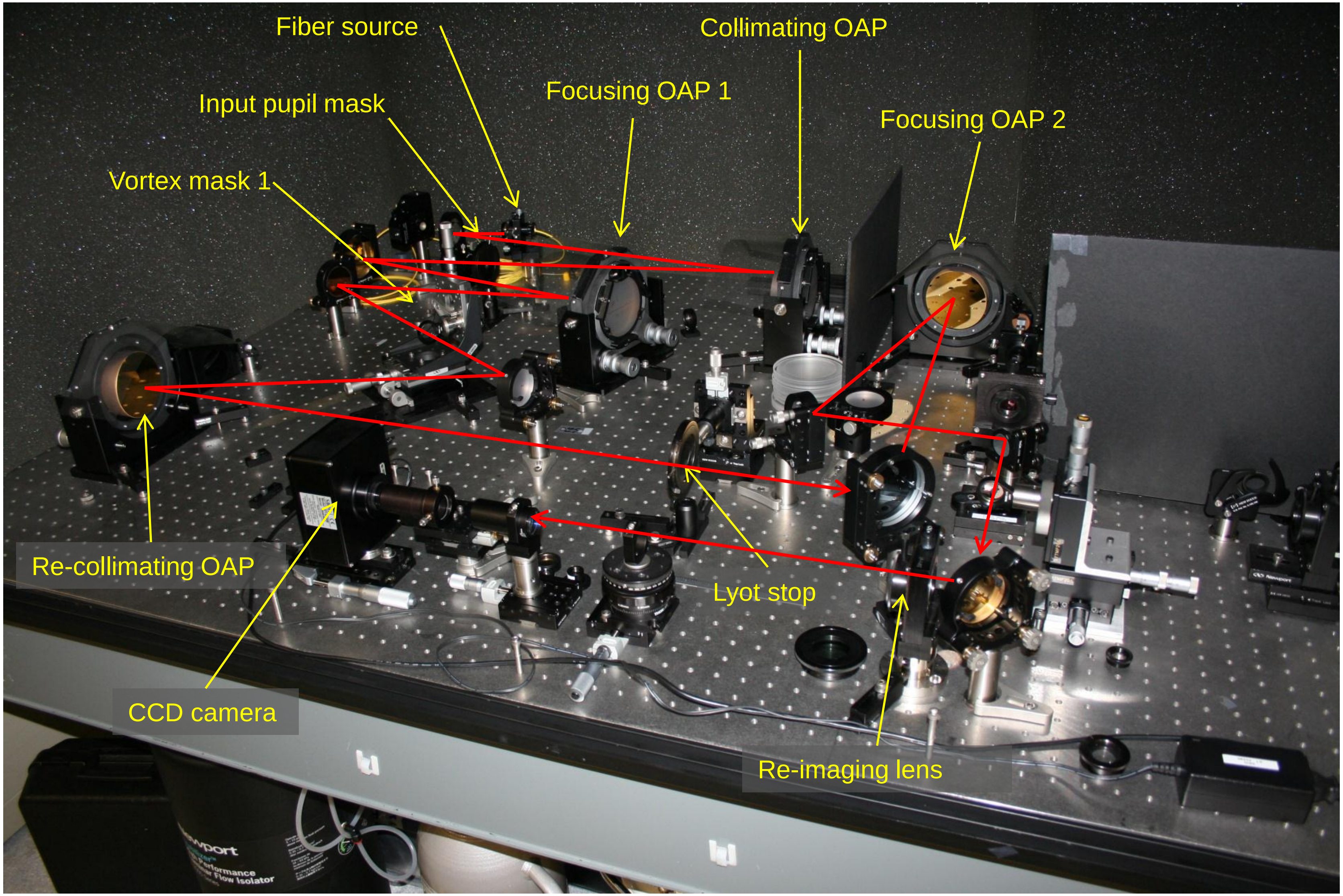
Advantages:

Phase mask ⇒ Small inner working angle
High throughput
Clear 360° azimuth FOV
Simple layout (common to Lyot)

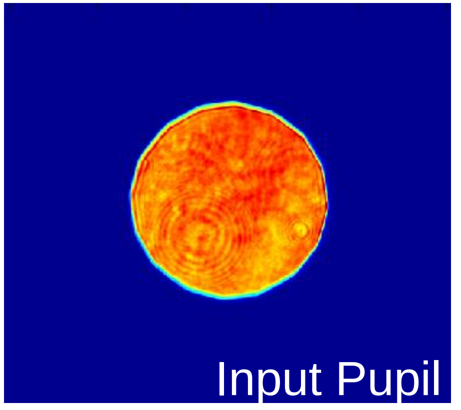
Nearly ideal performance:

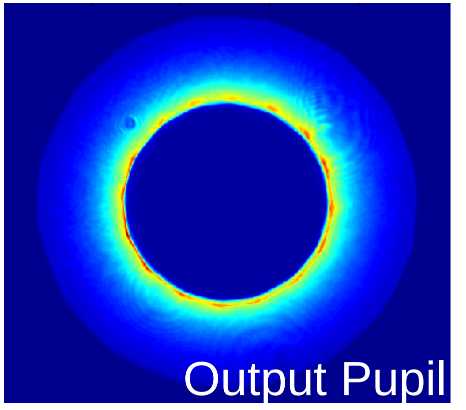


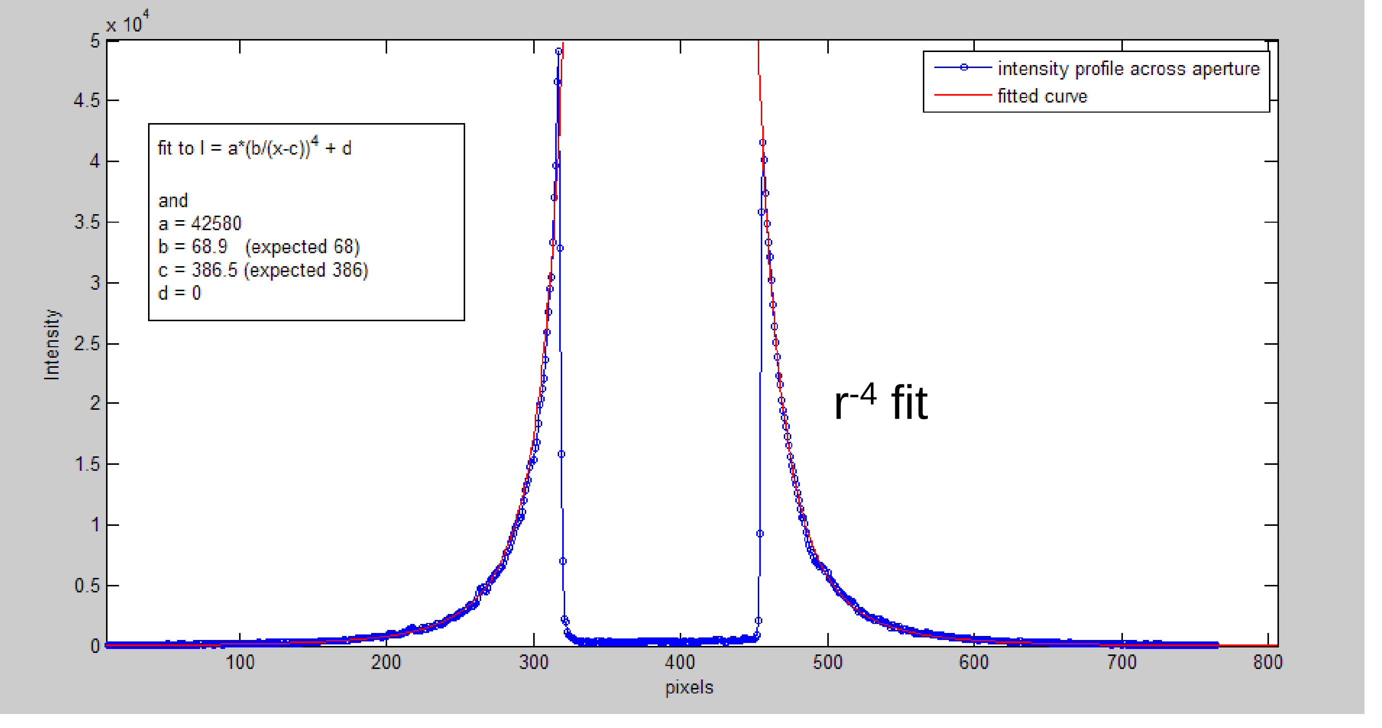
Infrared Coronagraphic Testbed (IRCT)



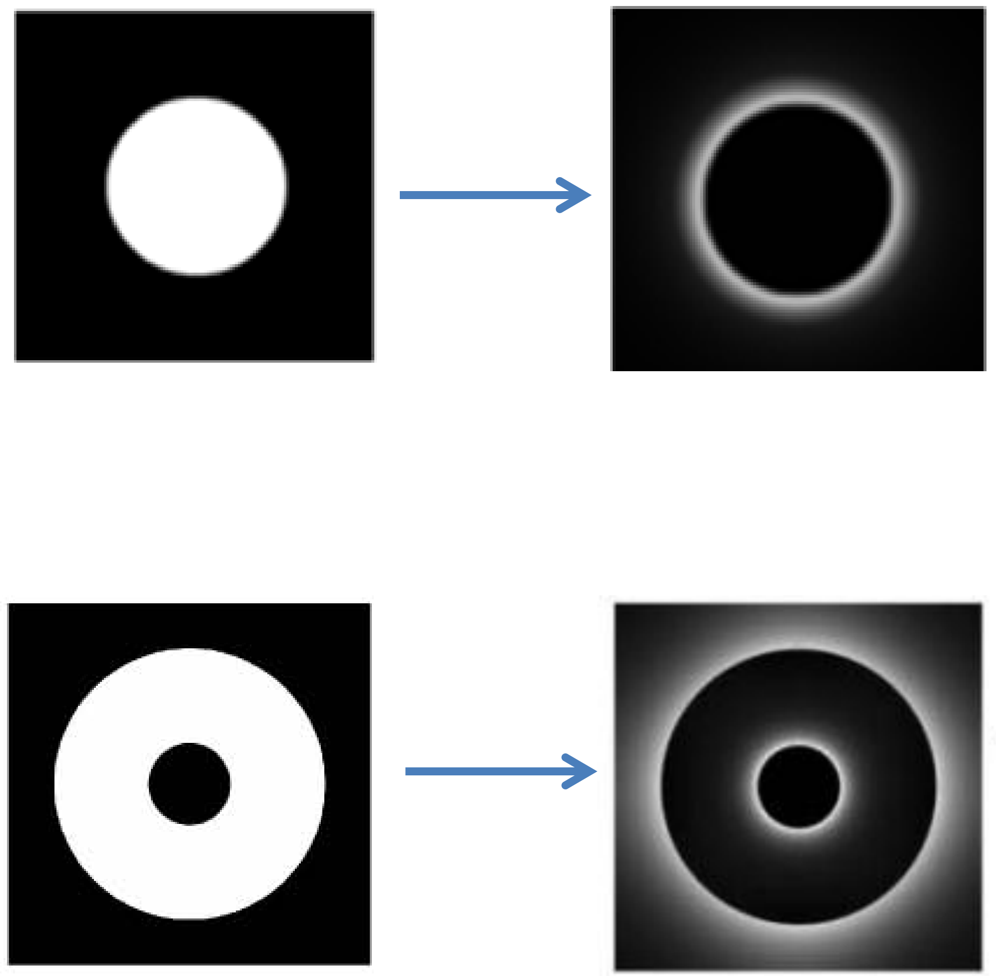
Single Vortex IRCT Pupil Measurements



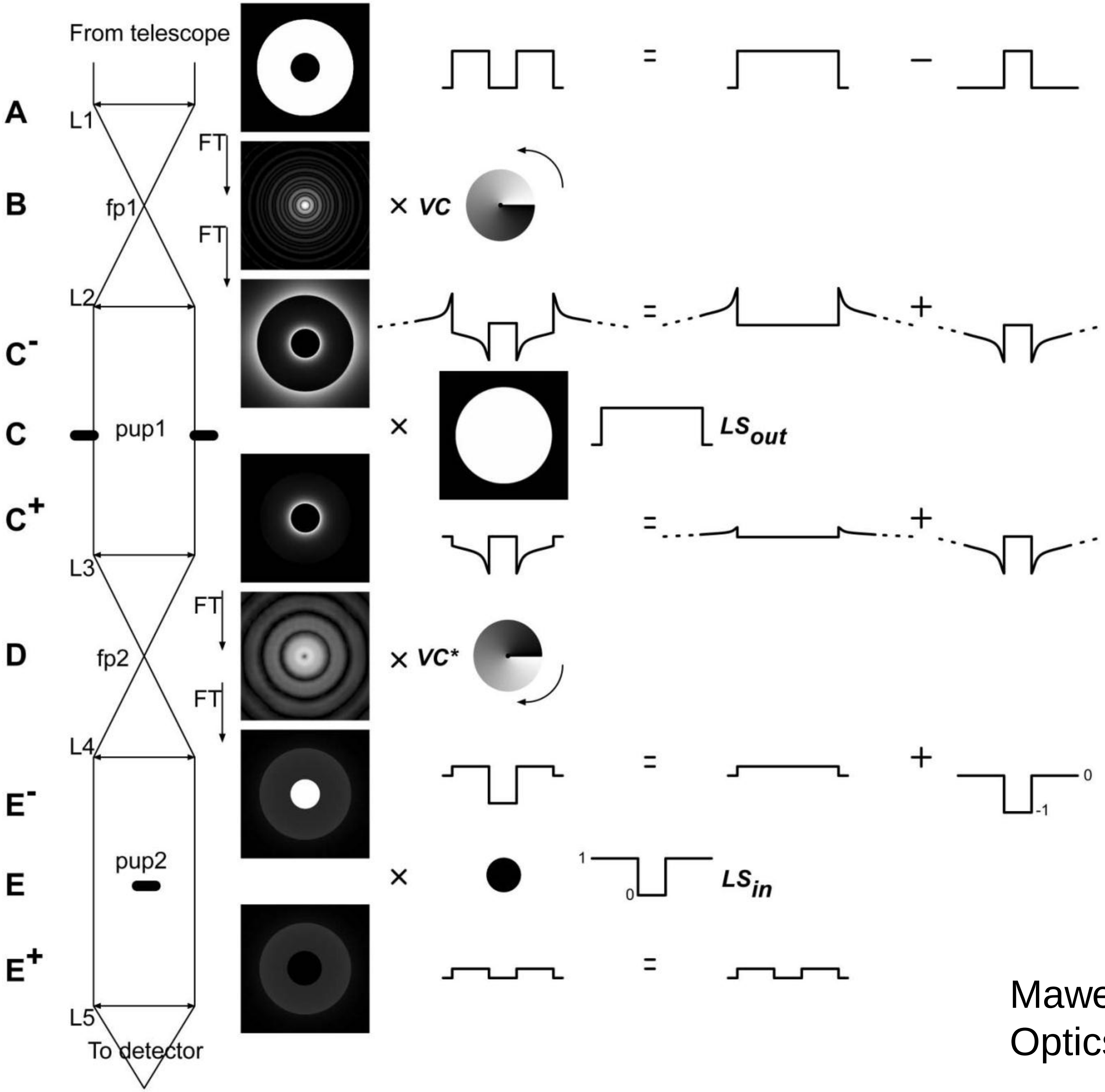




What about an On-Axis Telescope?

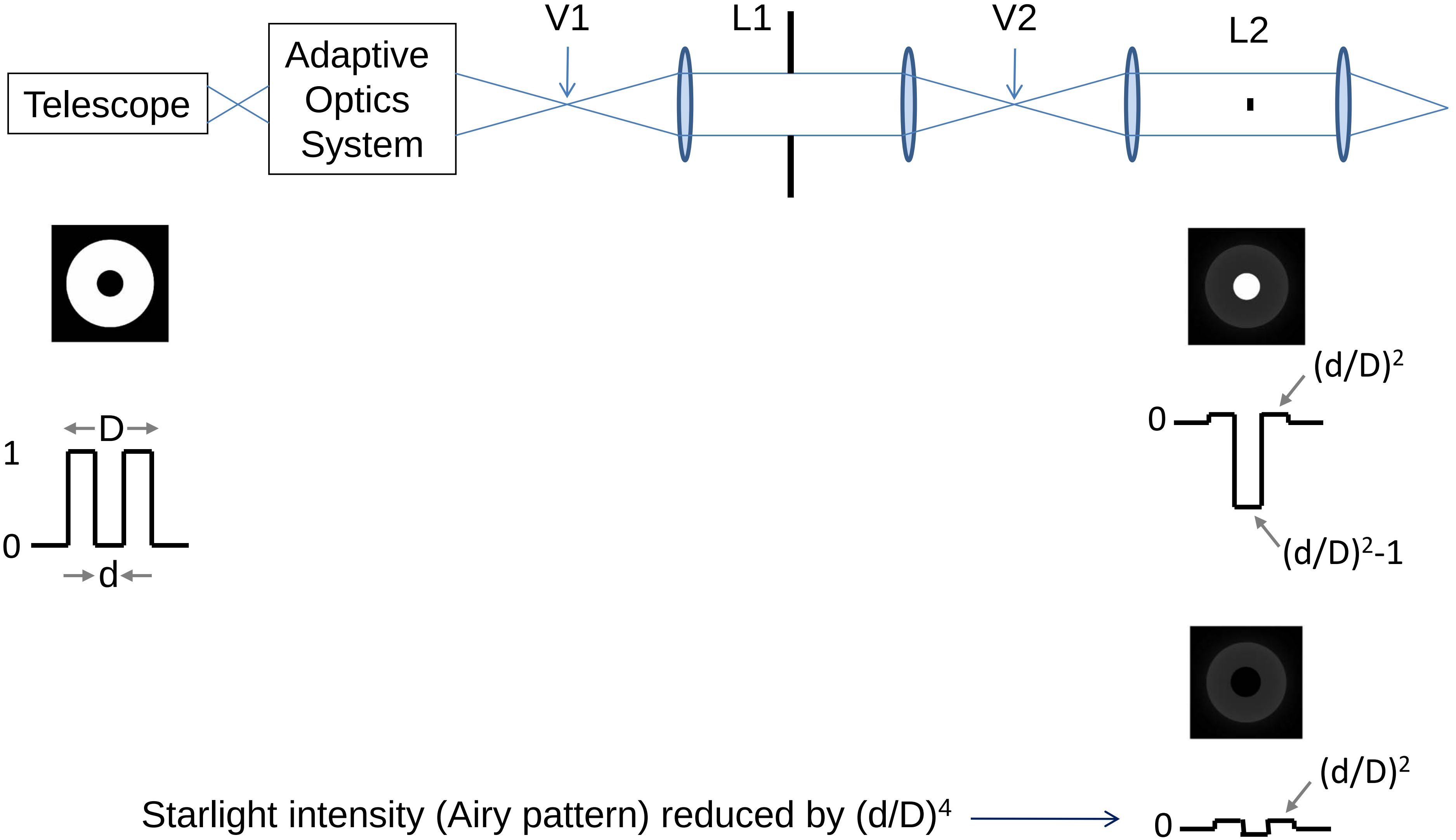


The Dual-Stage Vortex



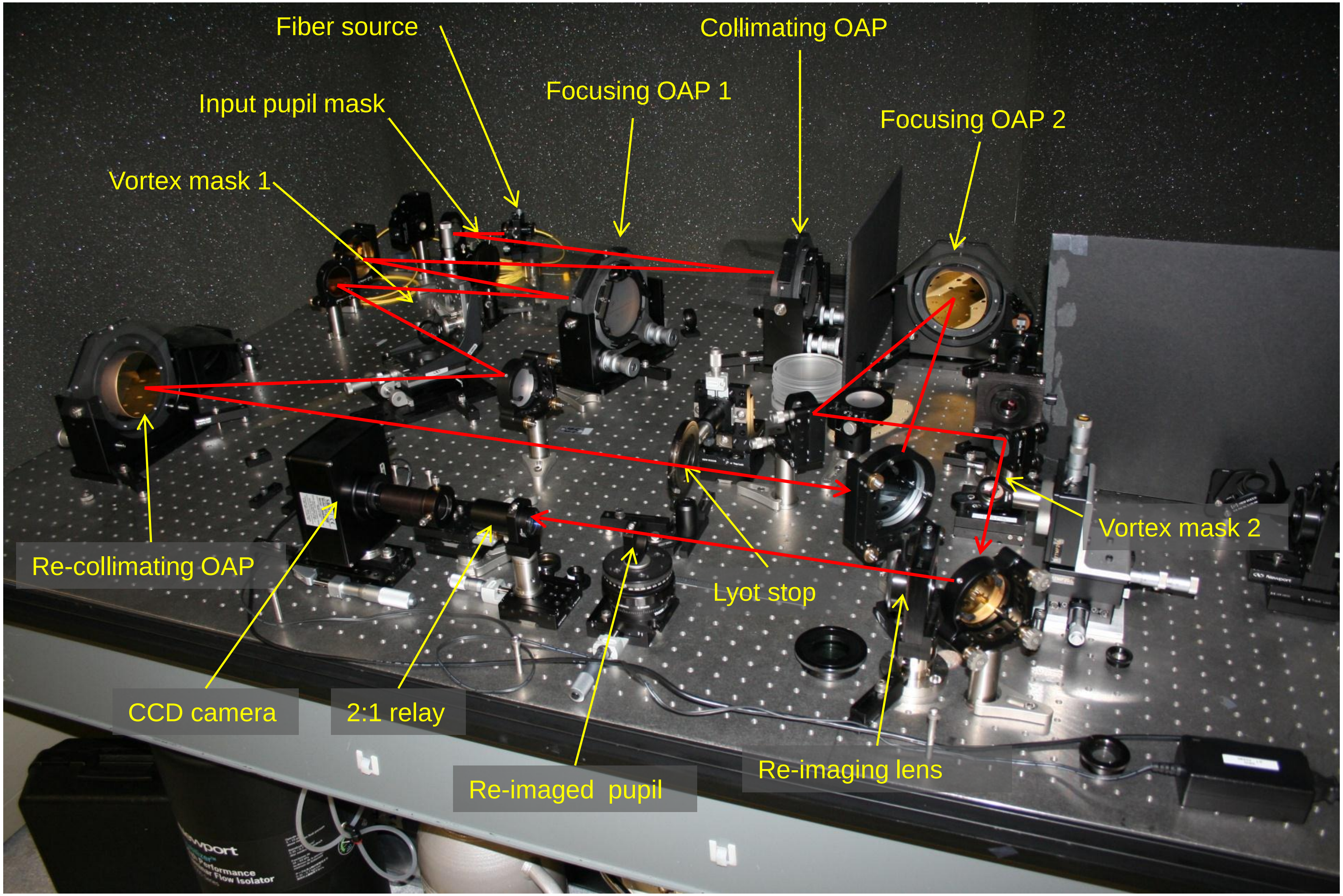
Mawet et al. 2011
Optics Letters

Net Result

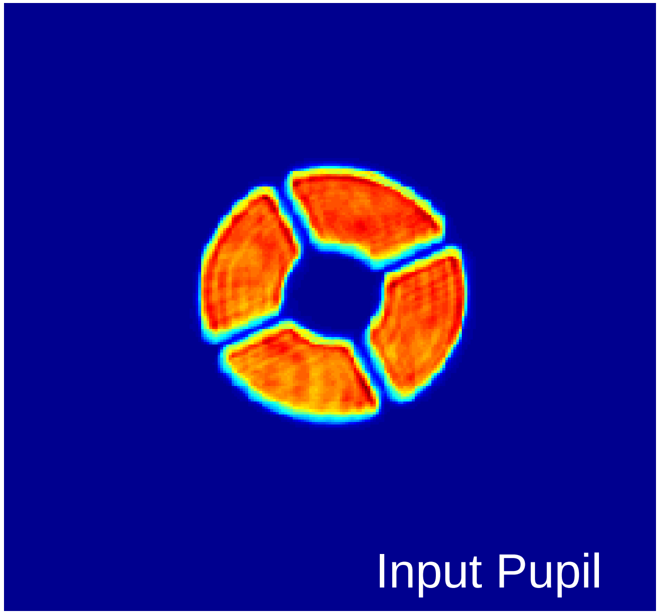


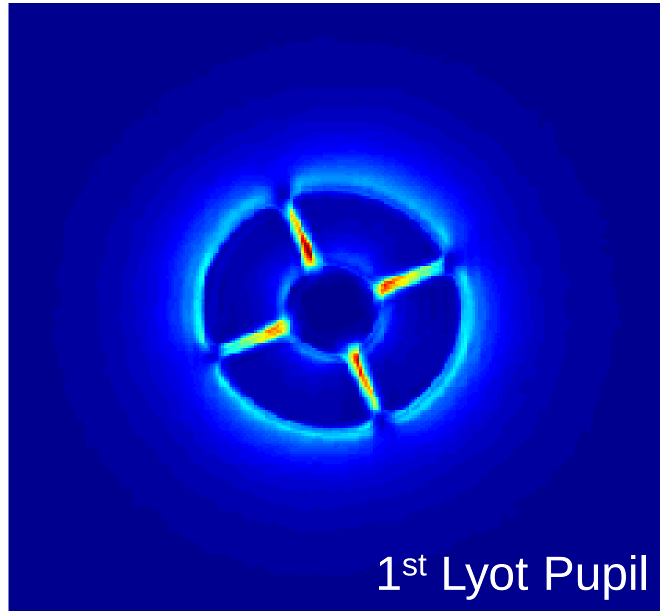
Starlight intensity (Airy pattern) reduced by $(d/D)^4$

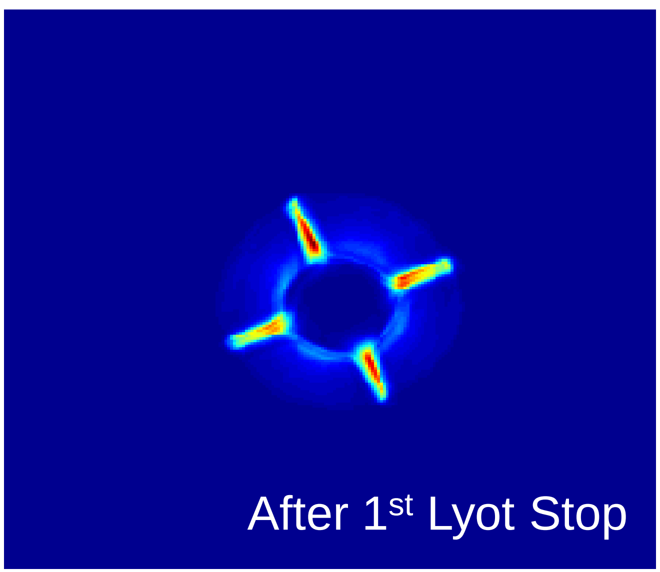
Double Vortex on the IRCT

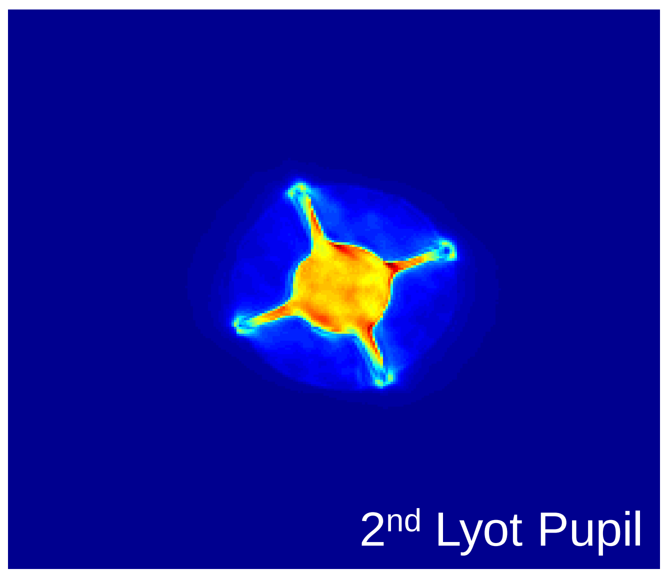


IRCT Measurements of On-Axis Dual-Vortex

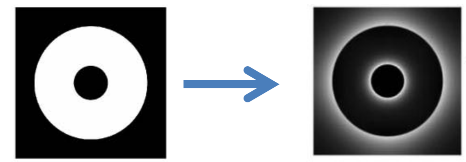








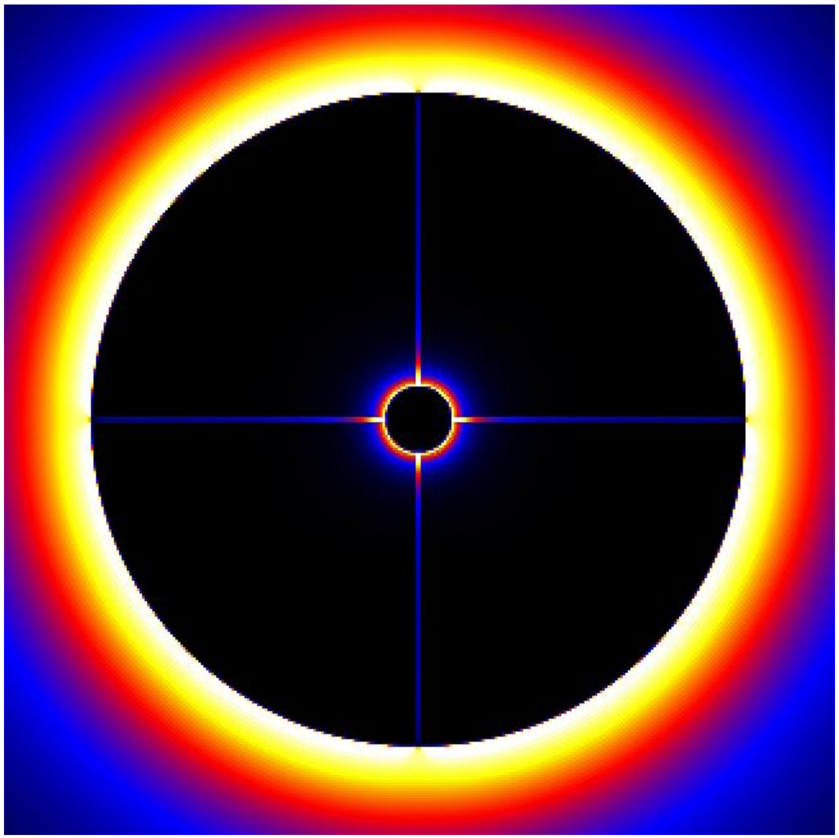
1st Lyot plane:
Residual light outside primary & secondary diameters
- the latter light lies within the primary



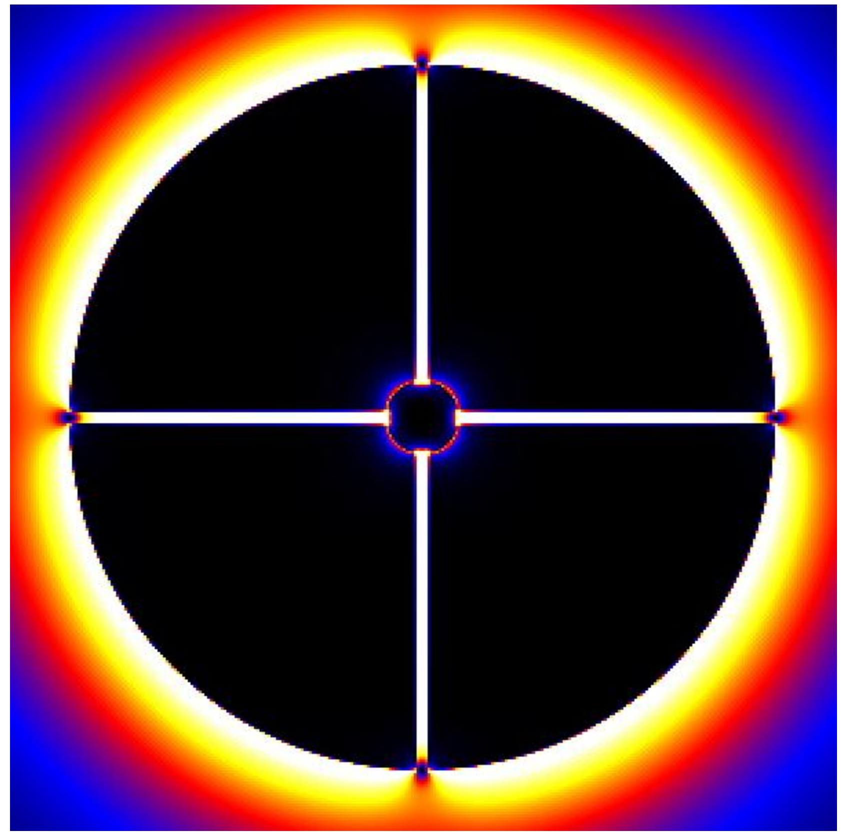
2nd Lyot plane:
Residual light concentrated in center
- it can be blocked.

Serabyn et al. 2011, SPIE

Modeling the Effect of Secondary Support Legs

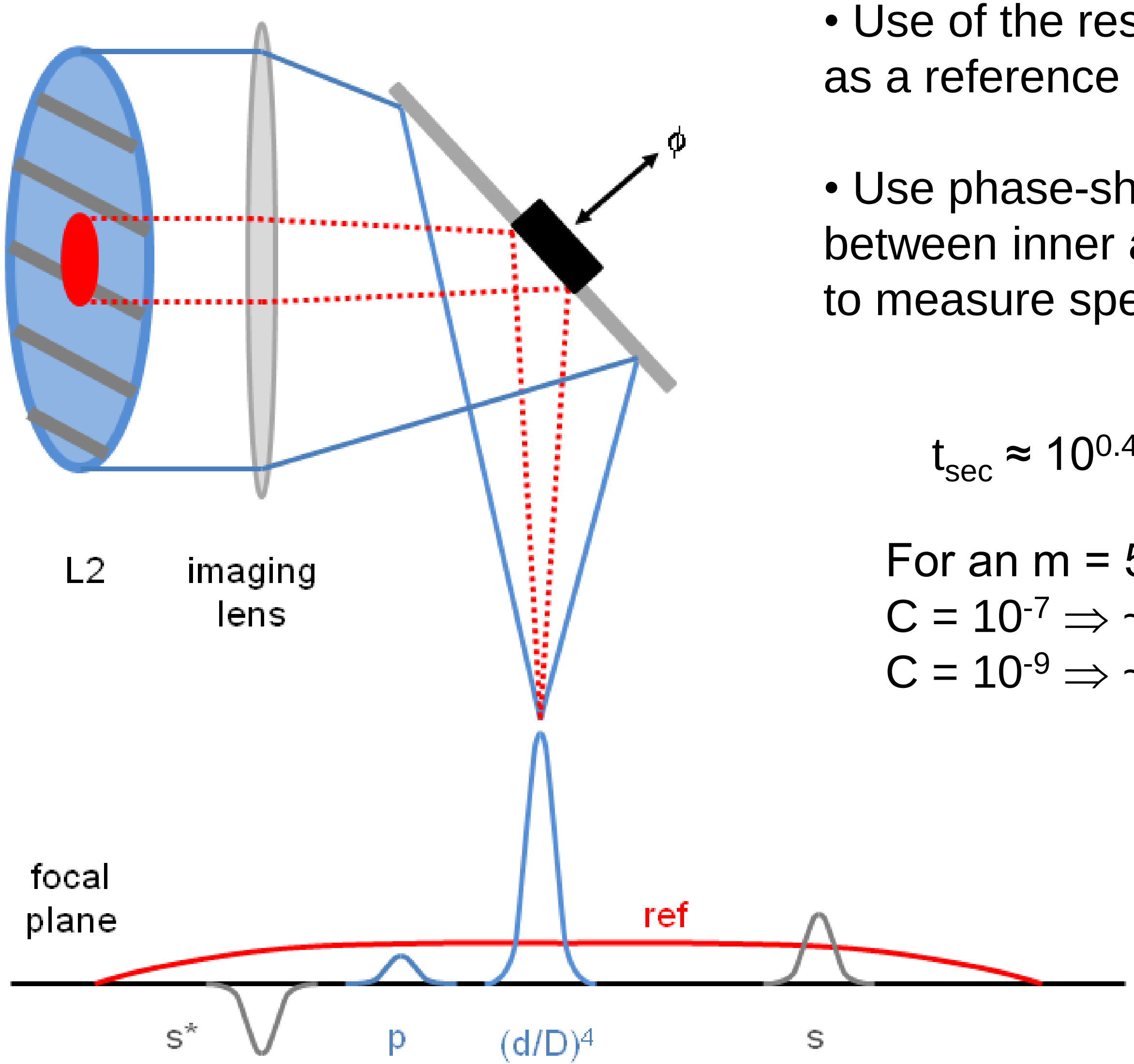


0.5%D



2%D

Speckle Phase Sensing with a Double Vortex



- Use of the residual central light as a reference beam:

- Use phase-shifting interferometry between inner and outer pupils to measure speckle phases

$$t_{sec} \approx 10^{0.4m-9} / (C(d')^2)$$

For an m = 5 star, and d′ = 1 – 0.1 m,
$C = 10^{-7} \Rightarrow \sim 1 - 100$ sec
$C = 10^{-9} \Rightarrow \sim 100$ sec to 10^4 sec.

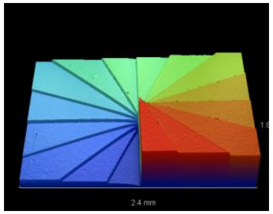
(Serabyn et al. 2011, Applied Optics)

Masks and Performance

Subsystem/metric	Goal	Potential Vortex-based Solution
Telescope	Modest size	Phase masks in general
Telescope	On-axis optics	Multi-stage vortex configuration
Throughput	High throughput for exoplanet light	Optical vortex phase mask
Throughput	Broadband	Multi-layer vortex or Polarization-filtering
Throughput	Dual-polarization	Multi-layer vortex or Polarization-split vortex system
Field of view	Small inner working angle	Phase masks in general
Field of view	Large outer working angle	Phase masks in general
Field of view	All azimuths available	Vortex phase mask
Wavefront quality	Low sensitivity to pointing & low-order errors, or ability to correct them	Higher order vortex
Wavefront quality	Ability to correct high-order errors	Direct speckle amplitude & phase sensing in a multi-stage vortex

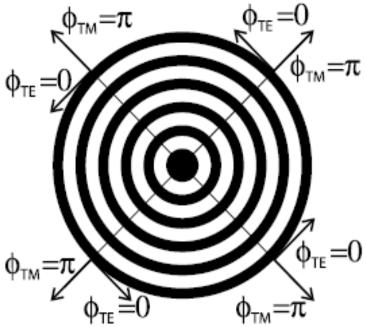
Vortex Phase Masks

Scalar Vortex:



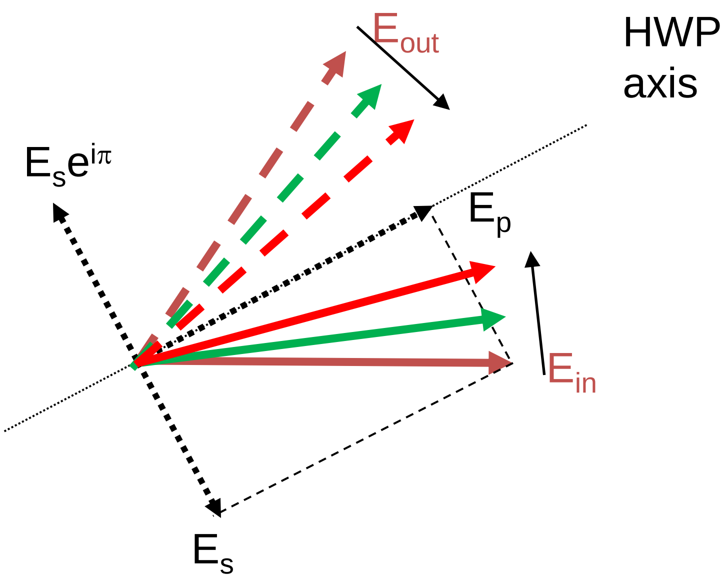
- Longitudinal (dielectric) phase ramp
  - e.g. EBL; Palacios et al. 2005, Masarri et al. 2011

Vector Vortex:



- Geometric (Pancharatnam-Berry) phase (polarization direction)
  - e.g. Mawet et al. 2005

The Vector Vortex: A Rotationally Symmetric HWP

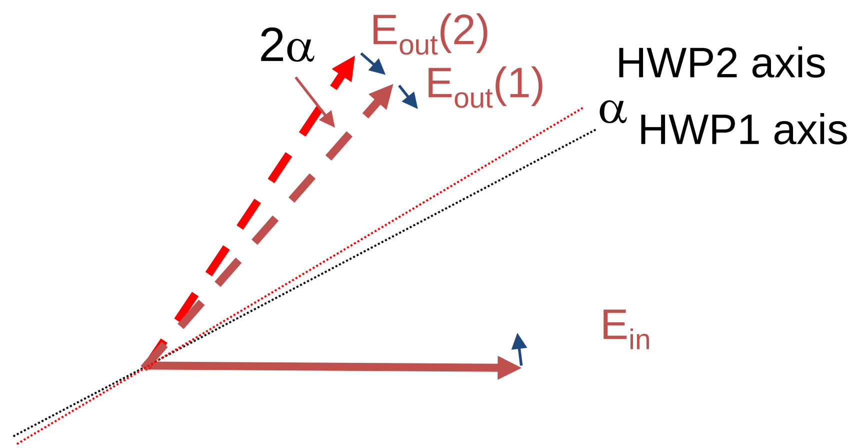


Half-wave plate (HWP):

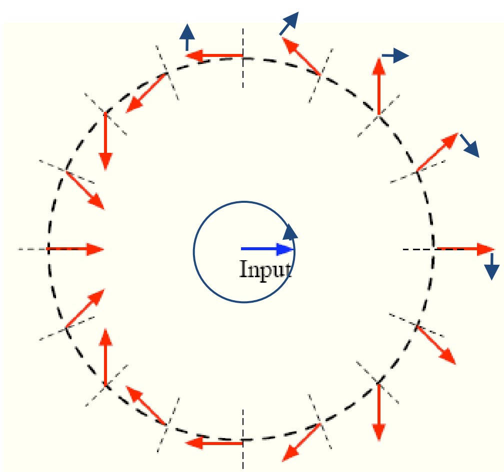
- flips field across fast axis
- reverses circular polarization state

Altering fast axis orientation changes the phase of the CP state

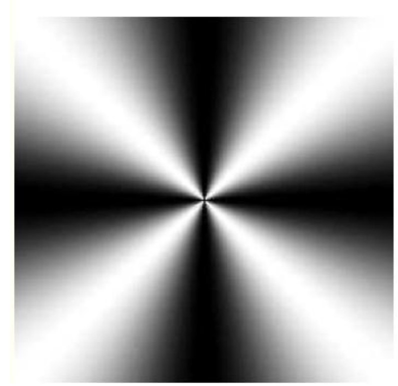
“Geometric” phase shift



Rotationally symmetric HWP:
Phase of CP increases linearly with azimuth



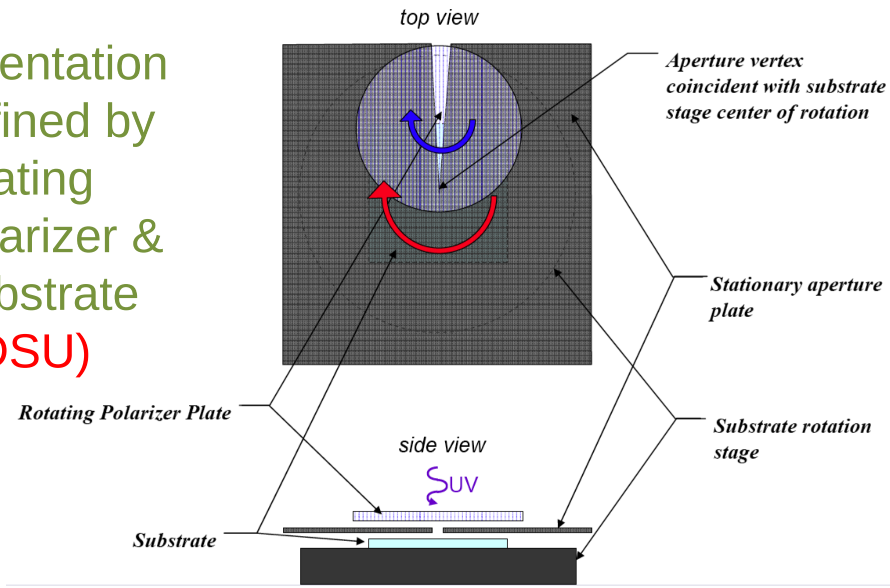
$$e^{il p\theta}$$



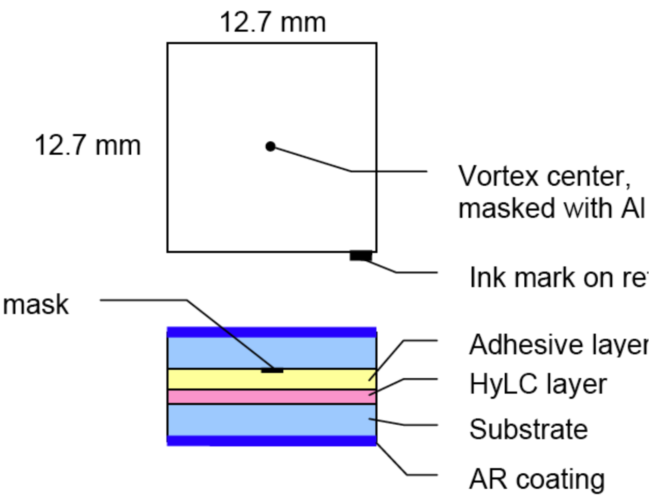
Rot. Sym. HWP between crossed polarizers

Liquid Crystal Polymer Vector Vortex Masks

Orientation defined by rotating polarizer & Substrate (JDSU)

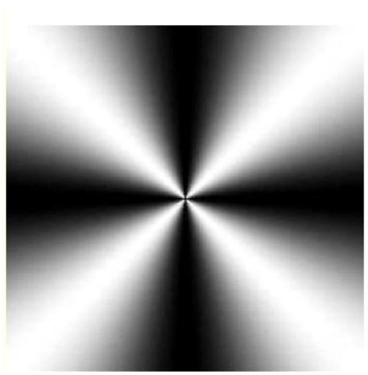


Cross-Section:

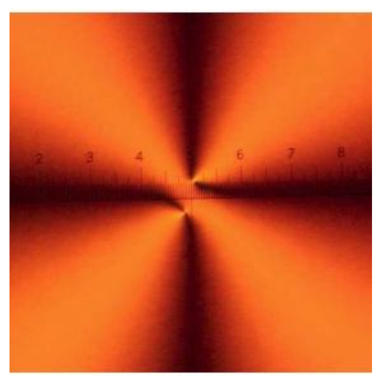


Central disorientation region:

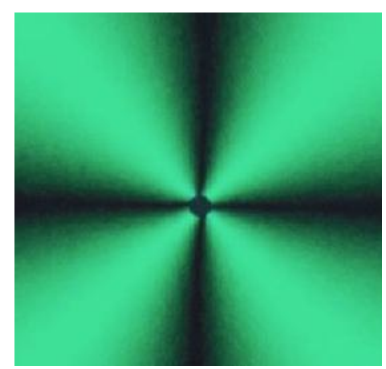
Vortices between crossed polarizers (mask at center):



Theory

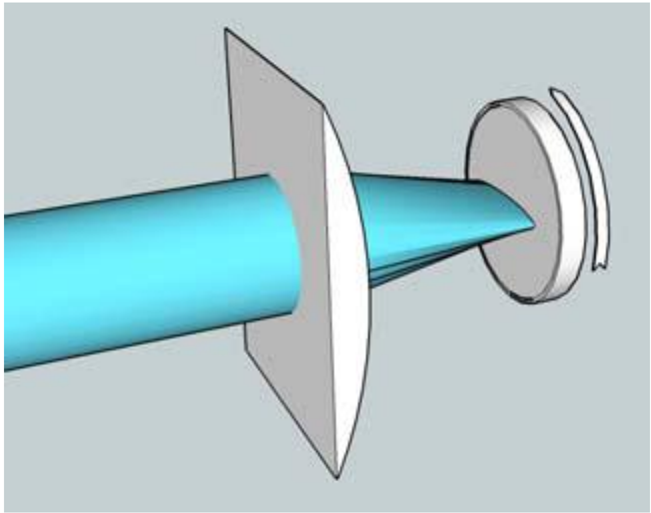


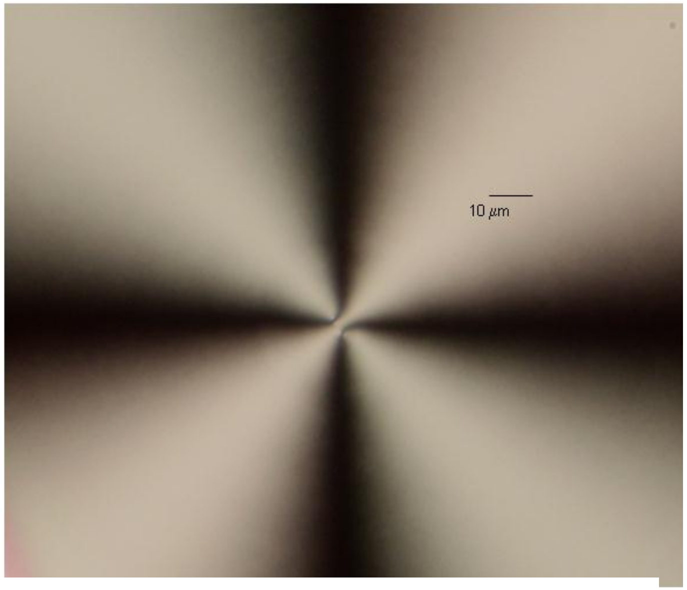
JDSU First Gen.

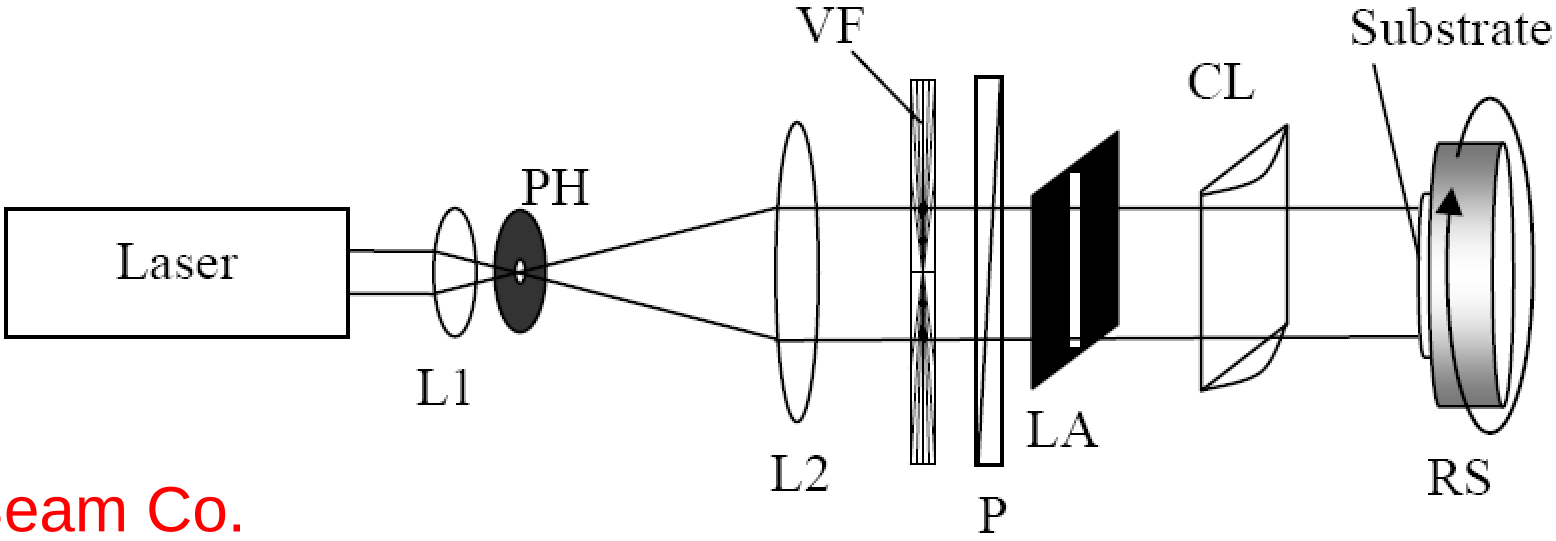


JDSU Second Gen.

Central Disorientation Region Reduction





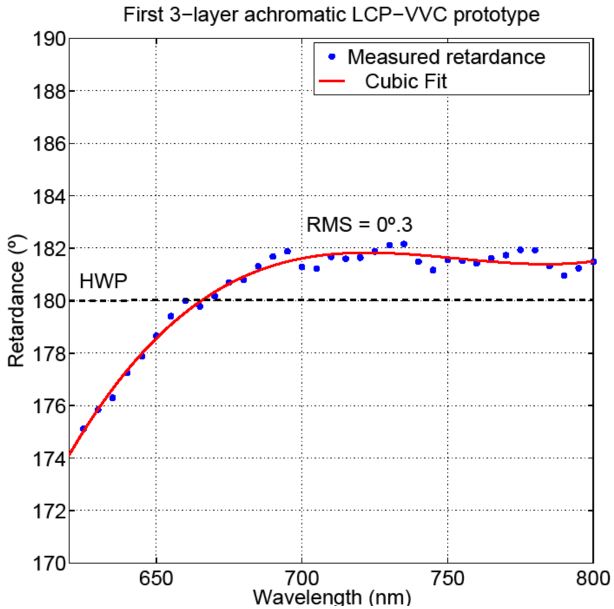


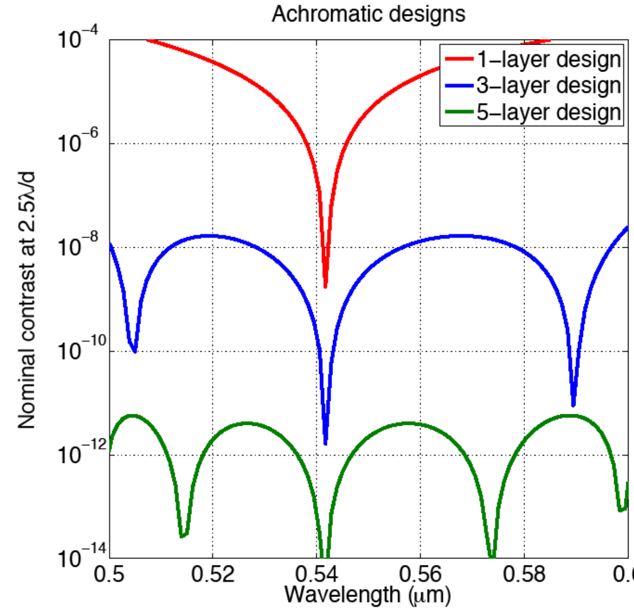
Beam Co.

Broadbanding

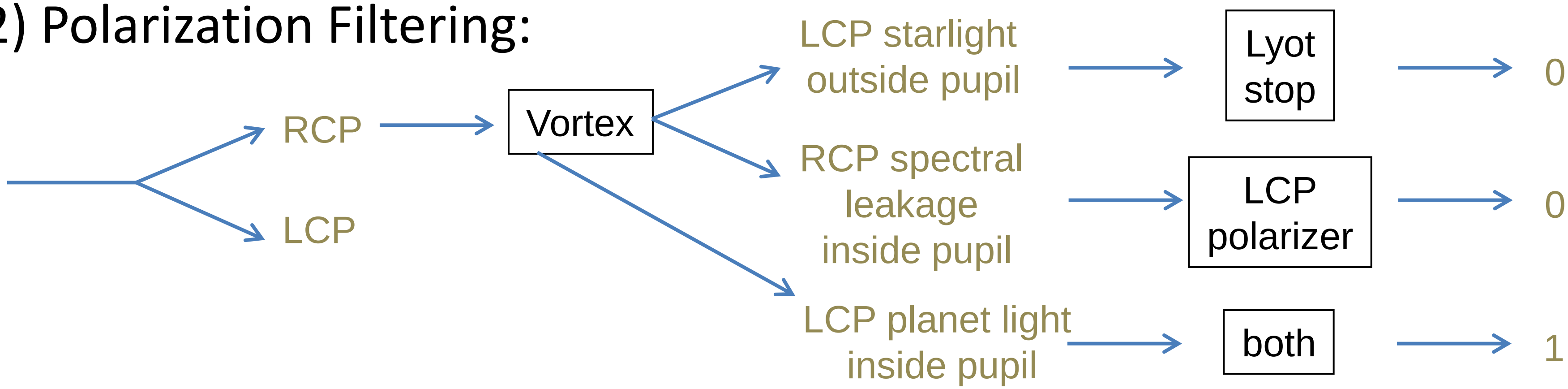
1) Three-layer half-wave-plate vortex mask

– First attempt has acceptably achromatic (flat) response, but at ~ 182°

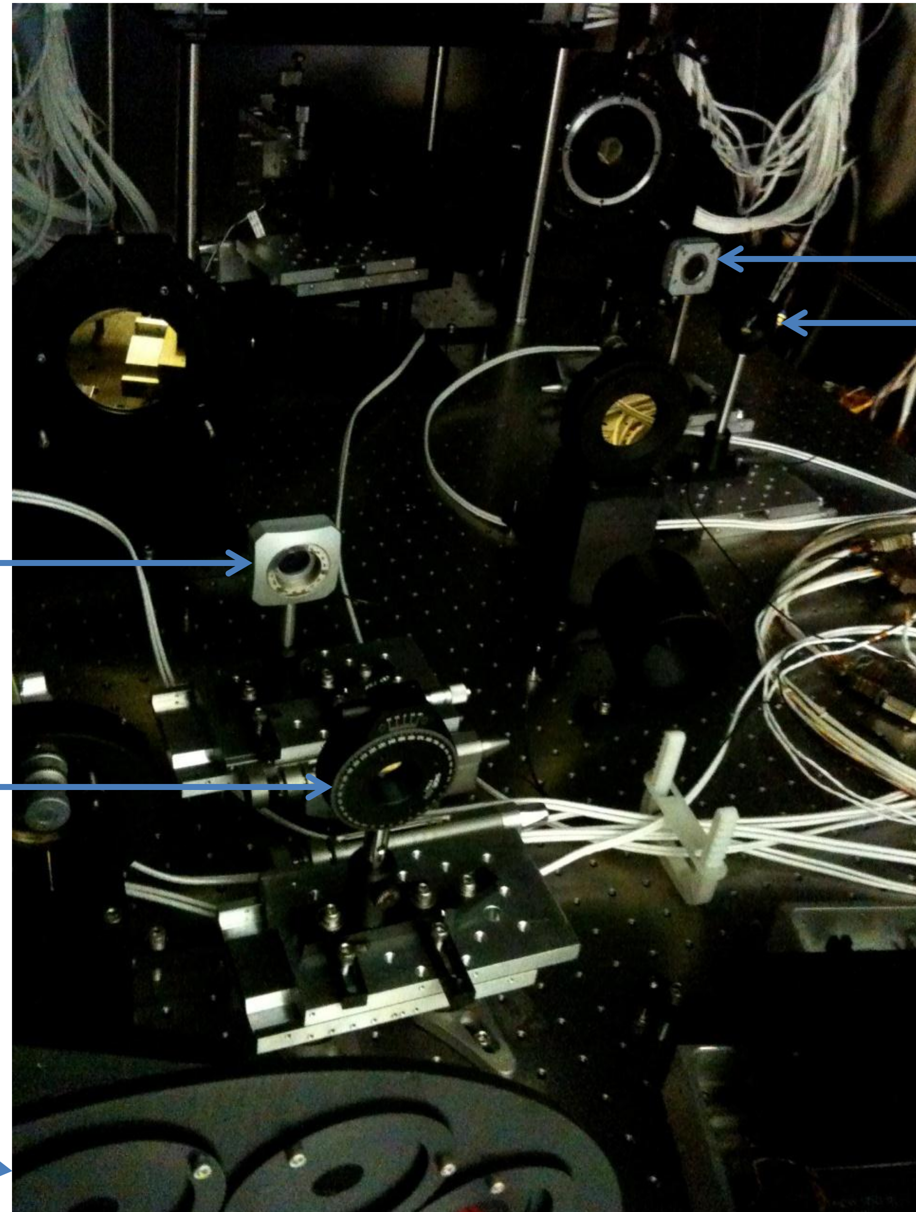




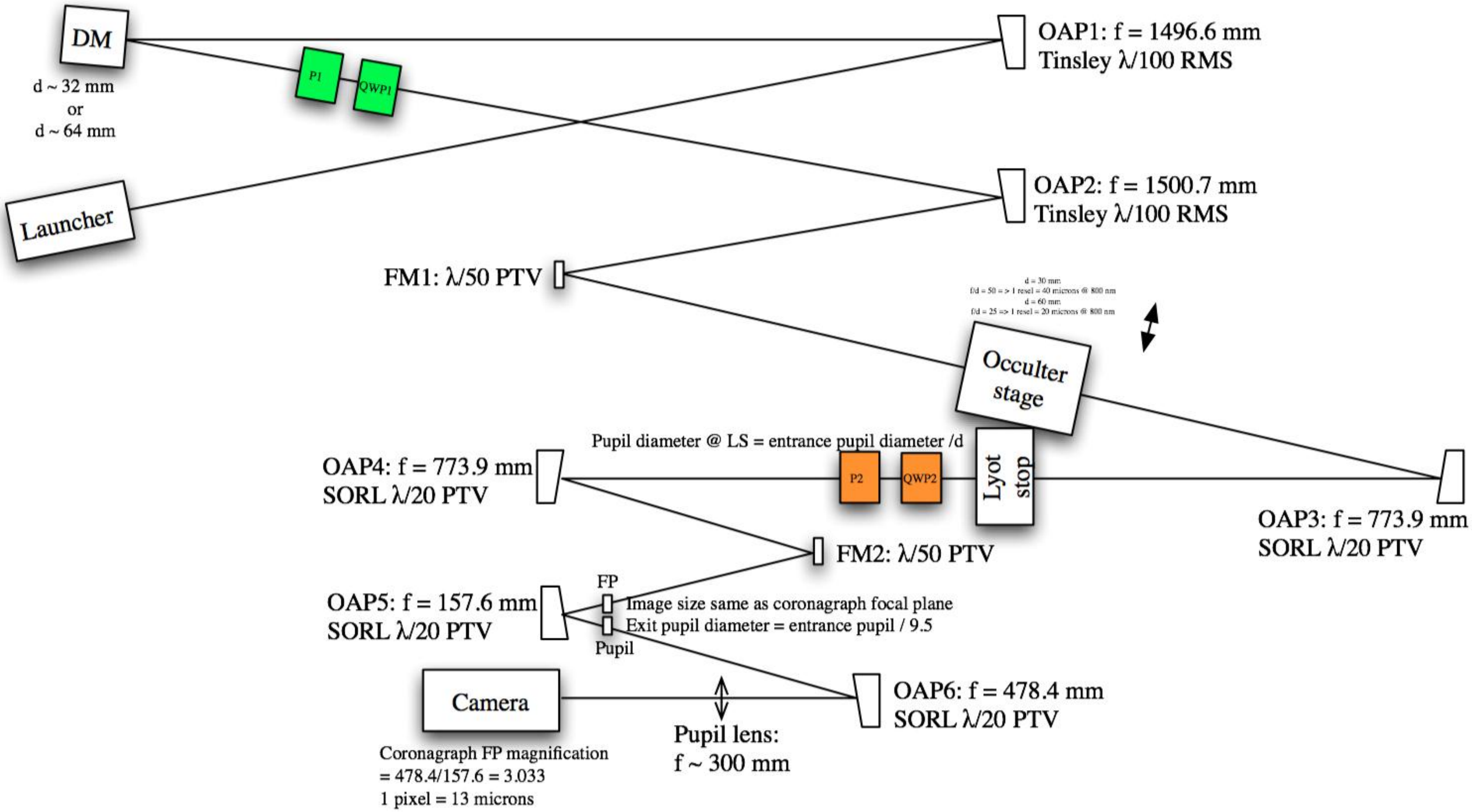
2) Polarization Filtering:



Polarization Components in the HCIT



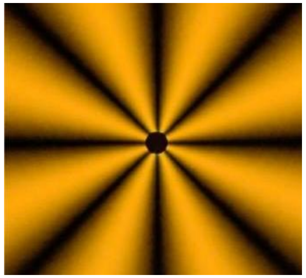
Contrast & Bandwidth Tests in HCIT



Polarization filtering : Pol 0/QWP 45/vortex/QWP -45/Pol 90

Vortex Mask Test Results in the HCIT

- Optical wavelengths
- 4^{th} order mask (8π in one circuit)
- IWA = 1.7 λ/D vs. 0.9 λ/D



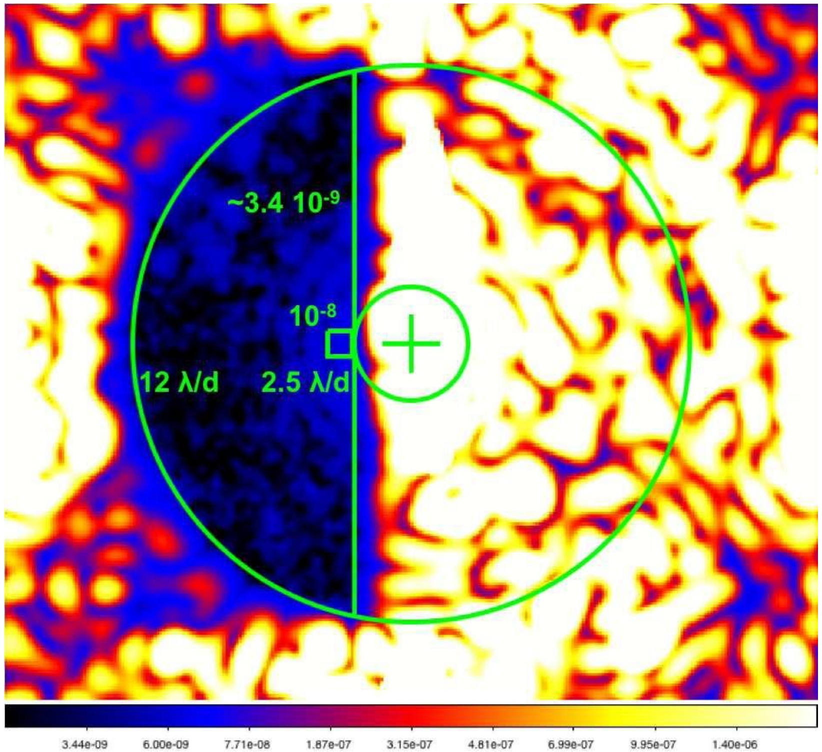
Monochromatic: 785 nm laser

Median contrast = 3.4×10^{-9}

between 2.5-12 λ/d:

TPF-C goal: 10^{-10}

Potential precursors: 10^{-9}

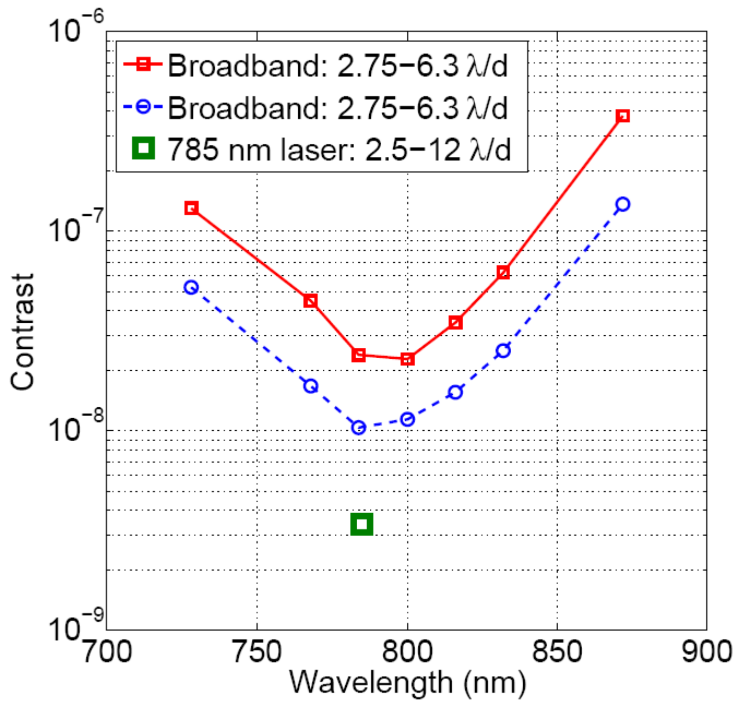


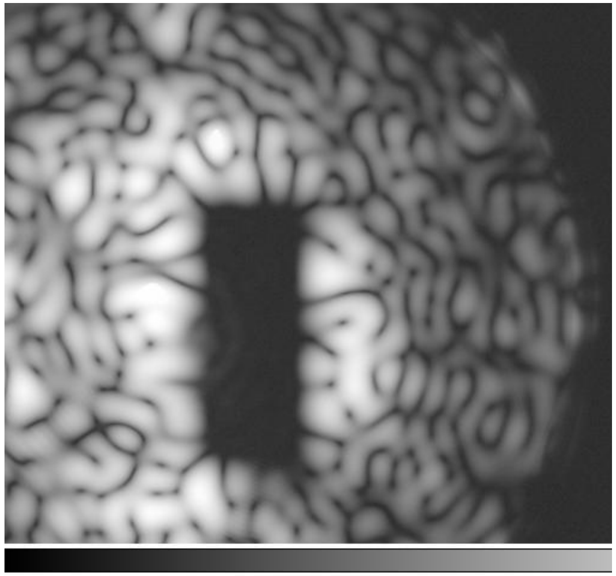
Broadband HCIT Results

- Setup:
  - Seven 2% filters
  - Optimized DM at central λ
  - Dark hole: 2.75-6.3 λ/D
    - limited by upstream QWP & pol.

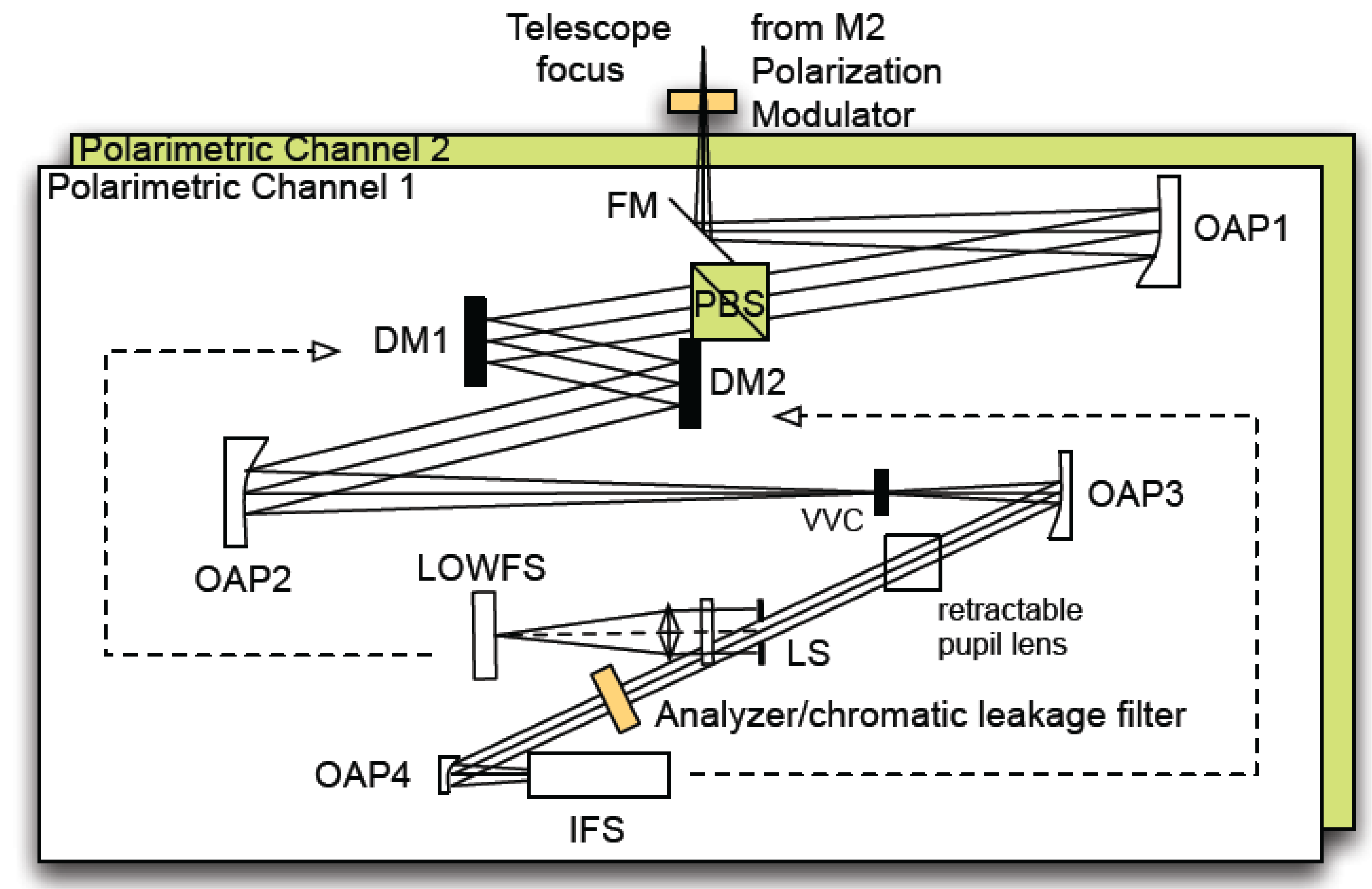
- Red curve: results for the entire dark hole

- Blue curve:
  top half of dark hole (y = 0 to 6.3 λ/D),
  (less residual light there)
- Contrasts:
  1.0e-8 in best 2% passband
  1.6e-8 for a 10% passband.
  3.8e-8 for a 20% passband





Potential Mission Configuration



Desirable capabilities of a space coronagraph & potential solutions provided by vortex phase masks

Subsystem/metric	**Goal**	**Potential Vortex-based Solution**
Telescope	Modest size	Phase masks in general
Telescope	On-axis optics	Multi-stage vortex configuration
Throughput	High throughput for exoplanet light	Optical vortex phase mask
Throughput	Broadband	Multi-layer vortex or Polarization-filtering
Throughput	Dual-polarization	Multi-layer vortex or Polarization-split vortex system
Field of view	Small inner working angle	Phase masks in general
Field of view	Large outer working angle	Phase masks in general
Field of view	All azimuths available	Vortex phase mask
Wavefront quality	Low sensitivity to pointing & low-order errors, or ability to correct them	Higher order vortex
Wavefront quality	Ability to correct high-order errors	Direct speckle amplitude & phase sensing in a multi-stage vortex

Summary

- Vortex devices:
  - Small inner working angle
  - High contrast (3.4×10^{-9} monochromatic)
  - Broadband performance (few 10^{-8})
- System-level: tandem vortex coronagraph
  - Possibility of an on-axis telescope
  - Possibility of the direct measurement of speckle phases
- Very promising:
  - Vortices beginning to be used on ground-based telescopes
  - Performance already close to sufficient for small first-generation exoplanet imaging mission in space
  - TPF flagships do not need to be prohibitively large