Vortex Coronagraphy

Gene Serabyn
Jet Propulsion Laboratory
California Institute of Technology

Exoclimes
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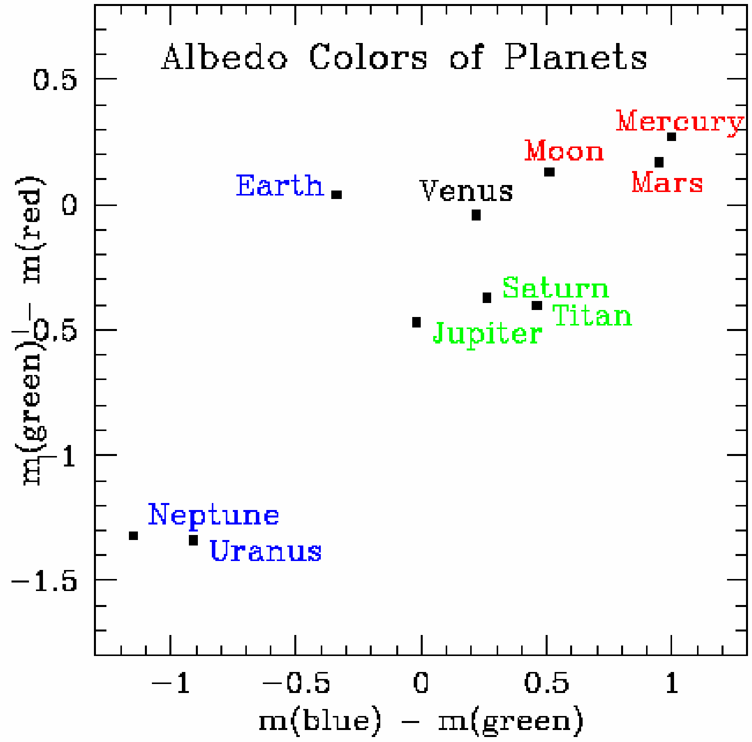
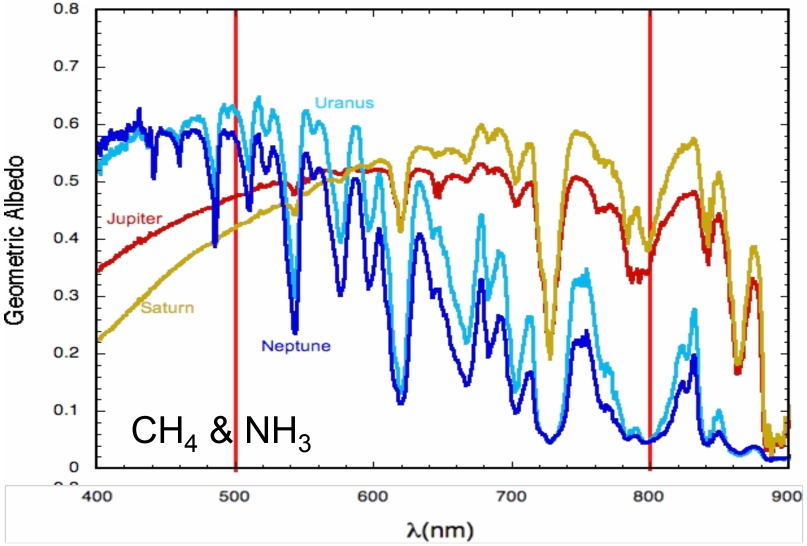
Goal: Arbitrary Exoplanet Imaging and Spectroscopy

- *Planetary census at large radii*
- *Orbits*
- *Rotation (rates, surface properties)*
- *Albedo & Colors*
- *Atmospheric Spectroscopy*
- *Polarization*
- *Ultimate goals:*
  - *Composition & Evolution of Atmospheres*
  - *Evidence of H_2O and life*

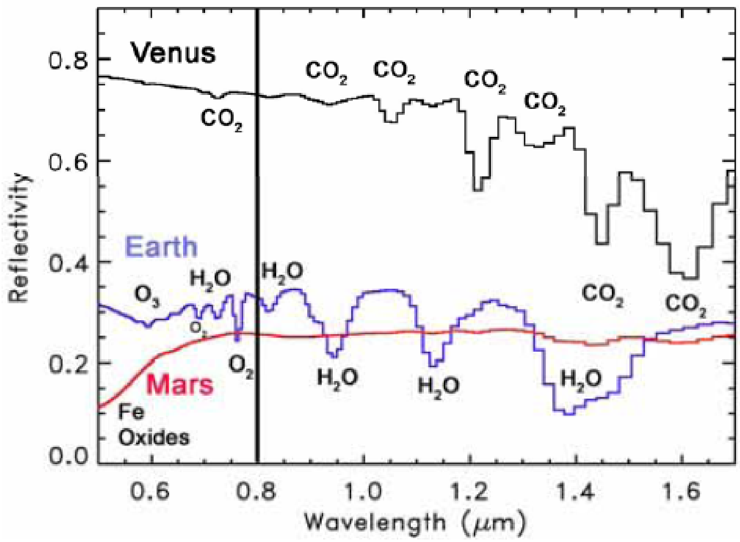


Jovian Spectra:



NASA TPF STDT report: Levine et al. 2006

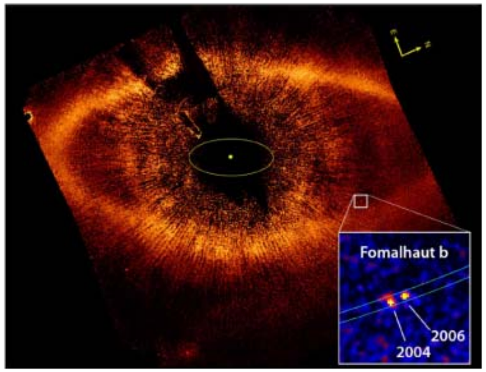
Terrestrial exoplanets:



Recent Progress in Exoplanet Imaging

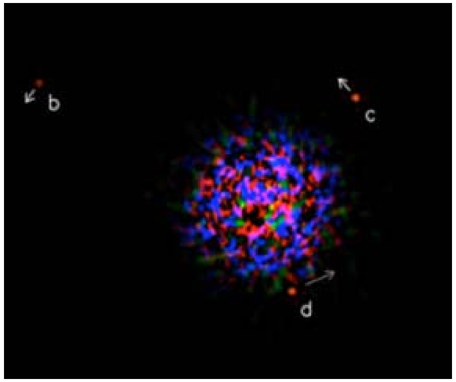
Complementary in radius to radial velocity: imaging works from the outside in

Fomalhaut
sep. ~ 15”



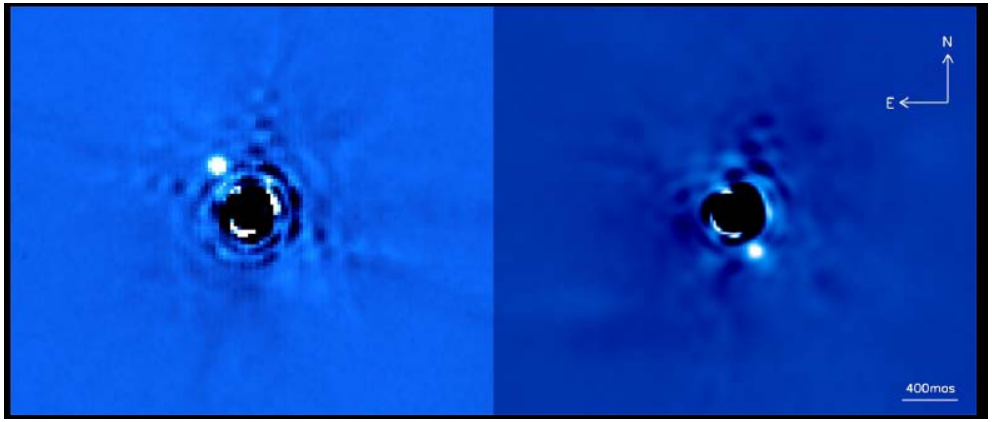
Kalas et al. 2008

HR8799:
contrast > 10^{-5}



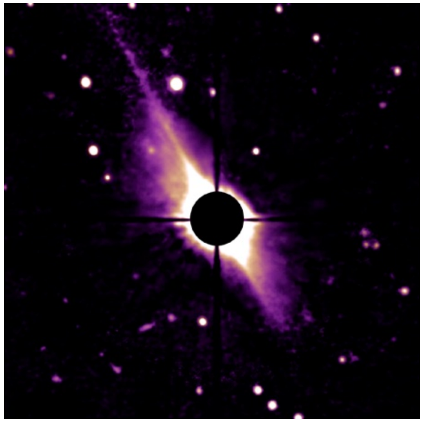
Marois et al. 2008

β Pictoris planet



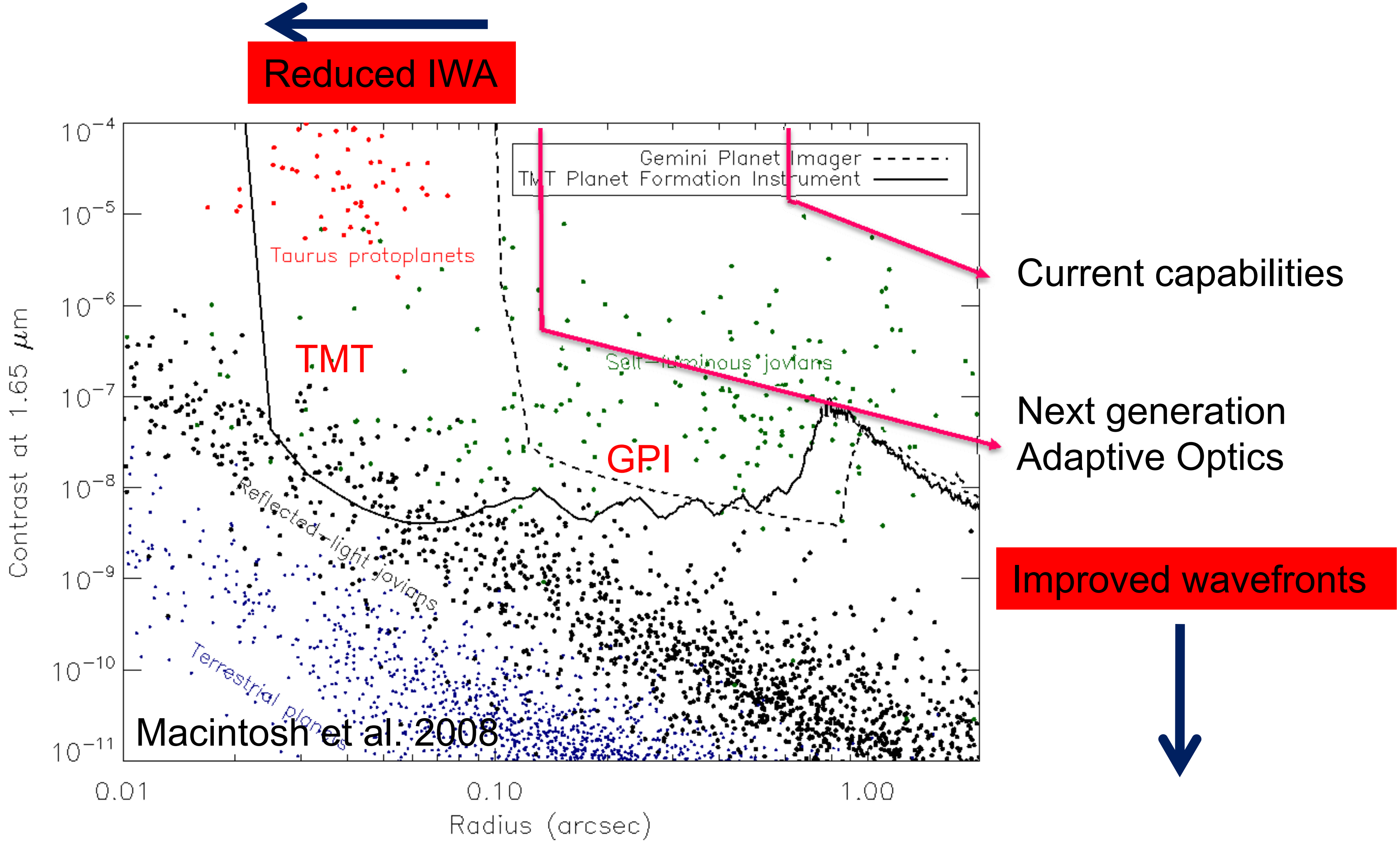
Lagrange et al. 2008

and disk



All with 8-10 m telescopes; planets at many λ/D

High-Contrast Imaging: Needs and Capabilities



Reduced IWA

Current capabilities

Next generation Adaptive Optics

Improved wavefronts

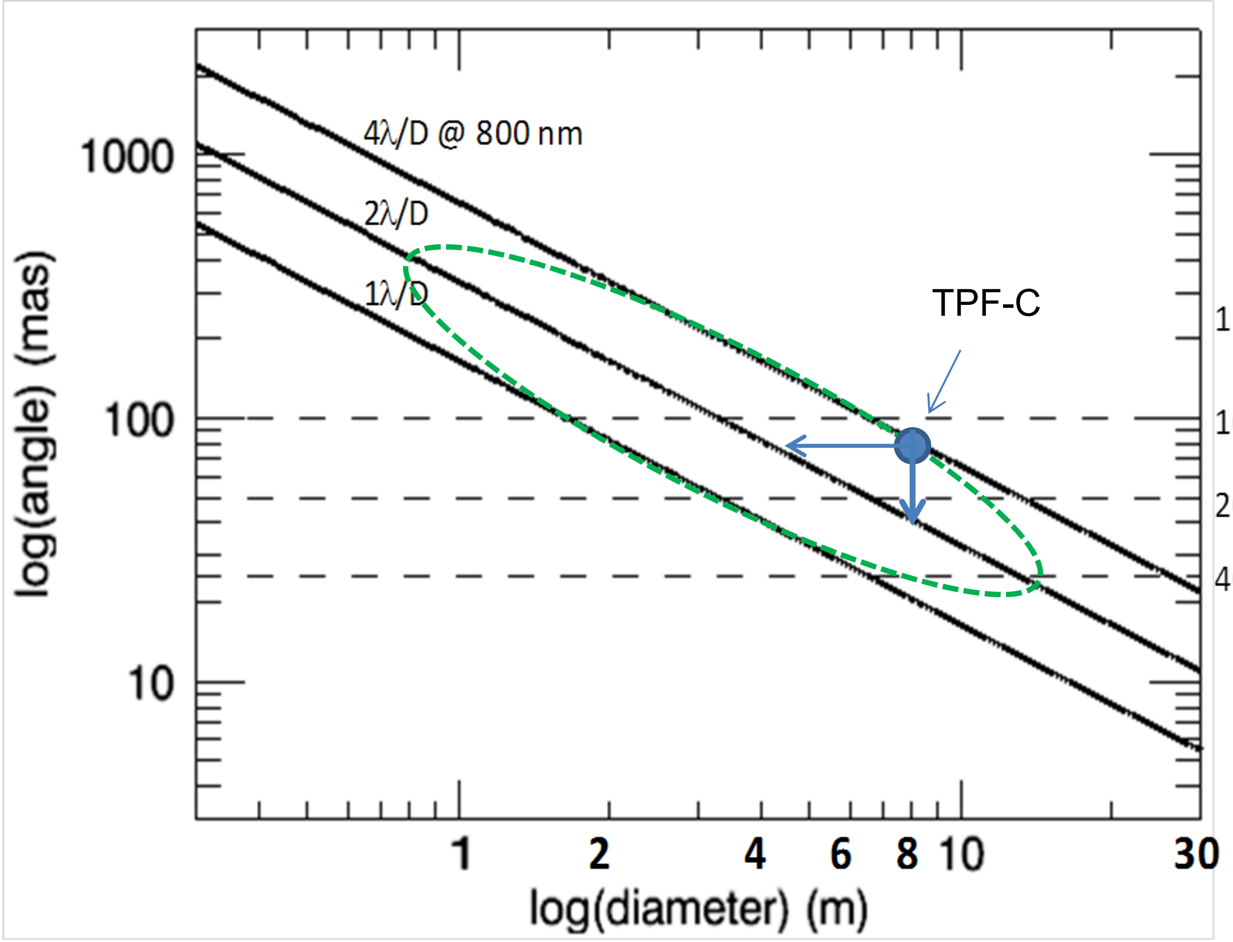
Macintosh et al. 2008

Faint exoplanet imaging very close to bright stars requires:

1) Nearly perfect wavefront to reduce scattered starlight → next gen. AO or space
2) Nearly perfect rejection of ideal diffraction pattern → an “ideal coronagraph”

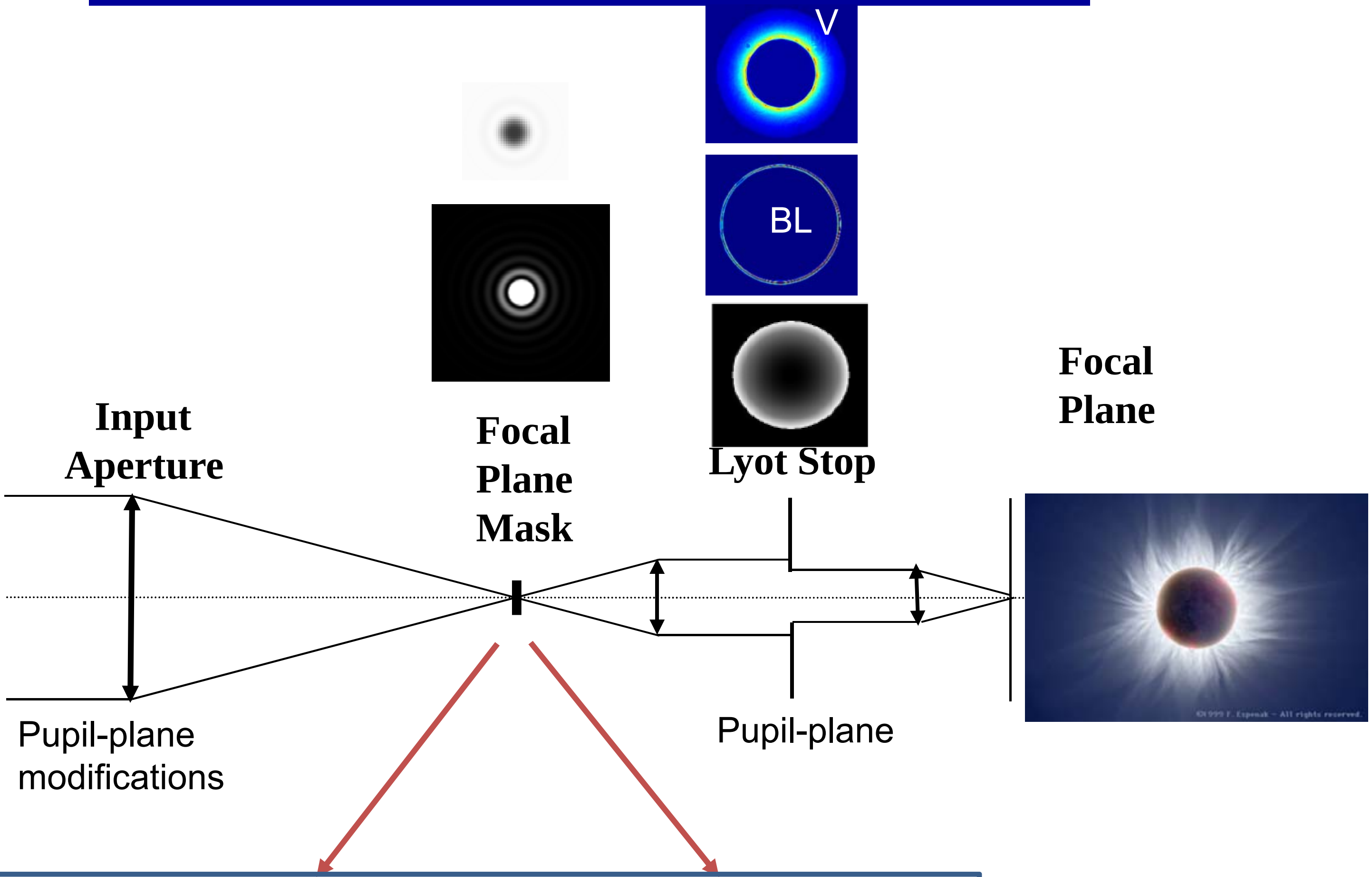
Small-Angle Observations

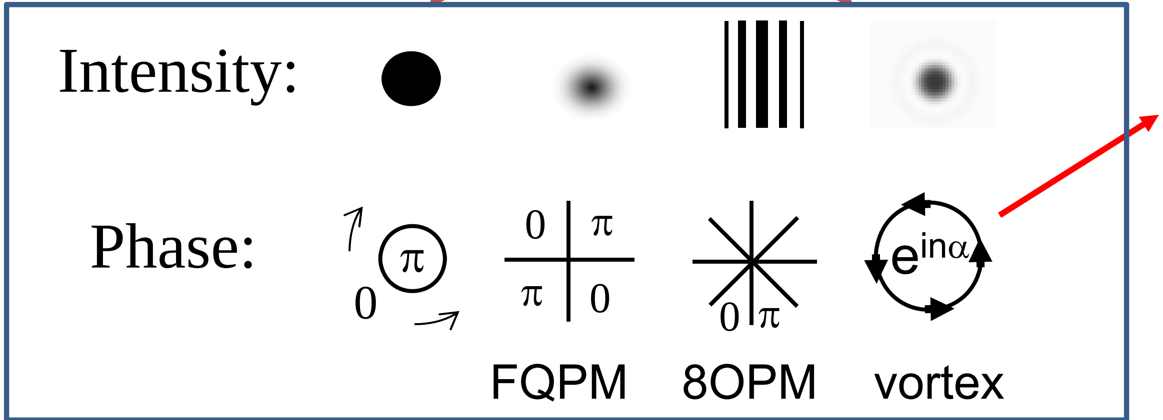
Goal: Observe as close as possible to bright stars
Why? Reach the habitable zone; enable smaller potential space telescopes



IWA = fλ/D

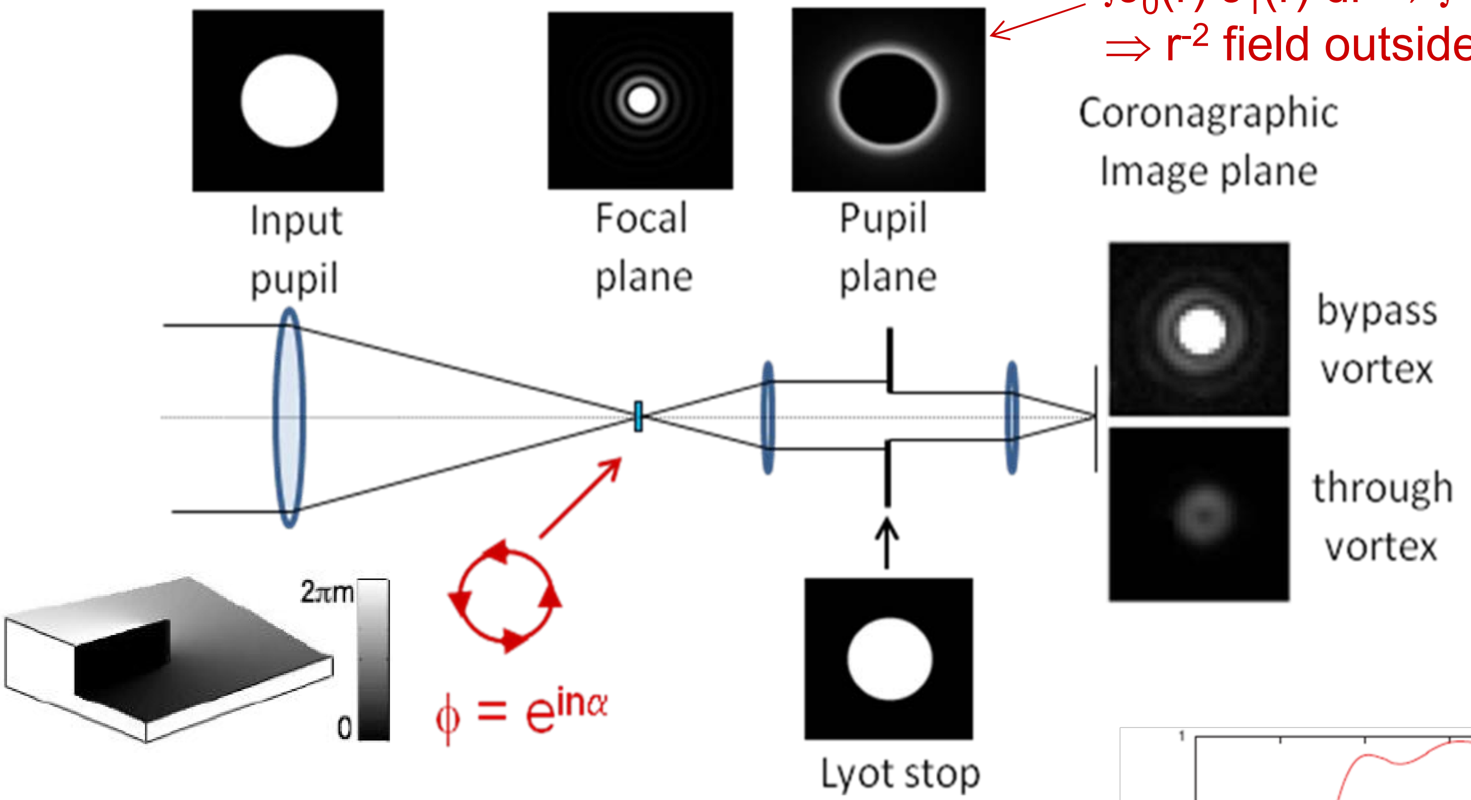
New Coronagraph Types





- Phase masks:
  No central blocker
  ⇒ small IWA & high throughput
  ⇒ smaller telescopes

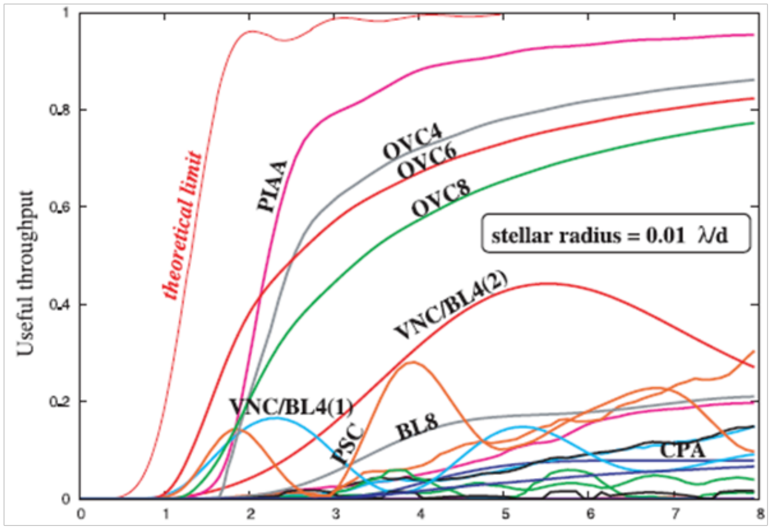
The Vortex Coronagraph



$\int J_0(r)\, J_1(r)\, dr \rightarrow \int J_2(r)\, J_1(r)\, dr$

$\Rightarrow r^{-2}$ field outside aperture

Guyon et al. 2006



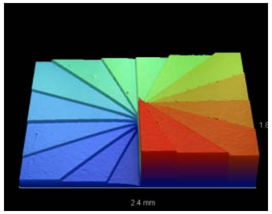
Advantages:

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

Nearly ideal performance:

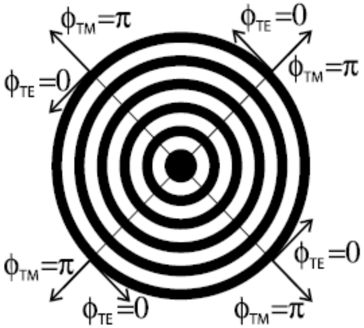
Two Types of Vortex Phase Masks

Scalar Vortex:



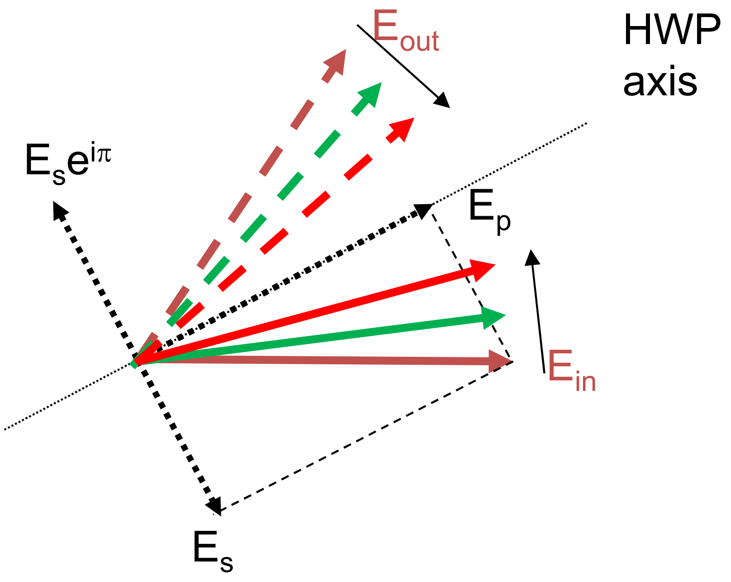
- Longitudinal (dielectric) phase ramp
  - e.g. Palacios et al. 2005, Masarri et al. 2011

Vector Vortex:



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

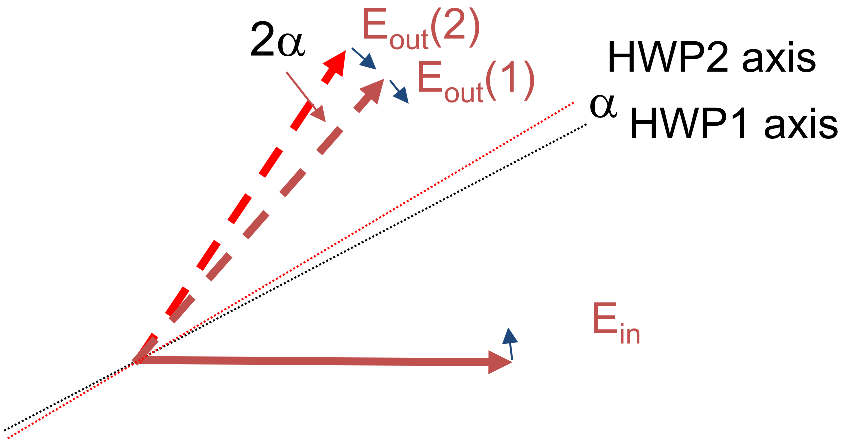
The Vector Vortex: A Rotationally Symmetric HWP



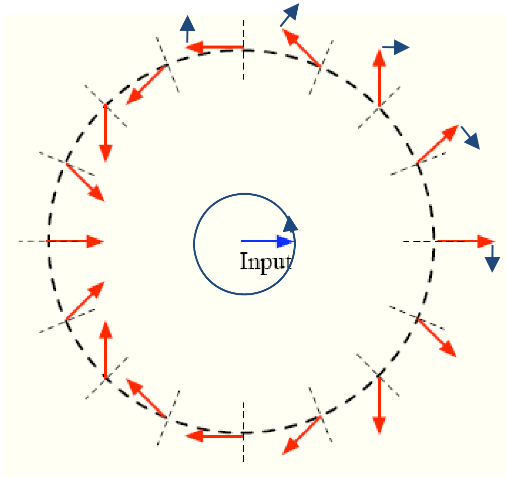
Half-wave plate (HWP):
- flips field across fast axis
- reverses circular polarization state

Altering fast axis orientation changes the phase of the CP state

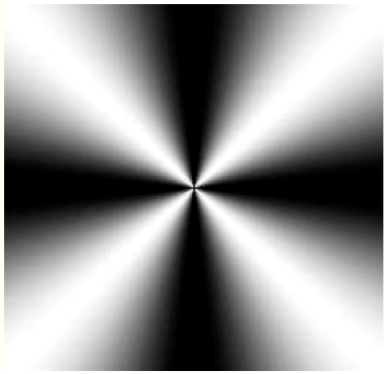
"Geometric" phase shift



Rotationally symmetric HWP:
Phase of CP increases linearly with azimuth



$$e^{ilp\theta}$$

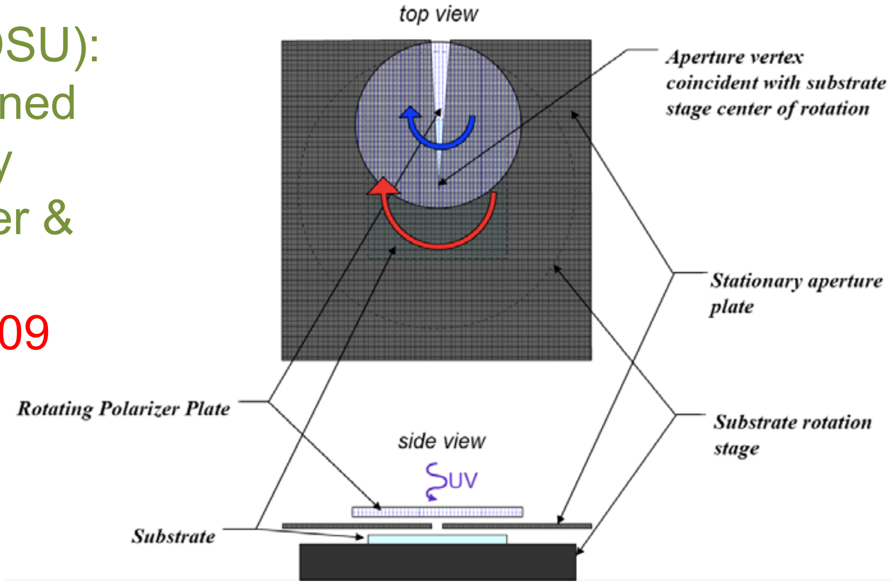


Mawet et al. 2009

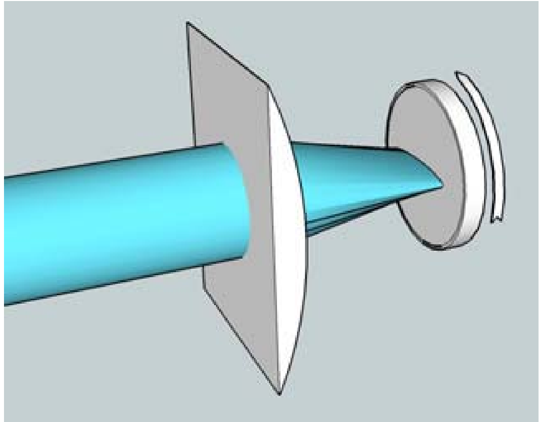
Rot. Sym. HWP between crossed polarizers

Liquid Crystal Polymer Vector Vortex Masks

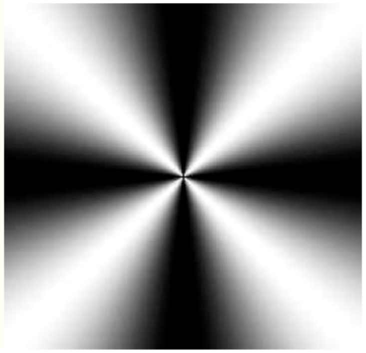
Approach 1 (JDSU): Orientation defined mechanically by rotating polarizer & substrate
Mawet et al. 2009



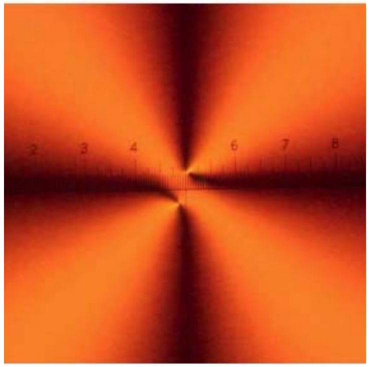
Approach 2 (Beam Co.): Orientation defined by line focus and "printing"
Tabiryan et al. 2012



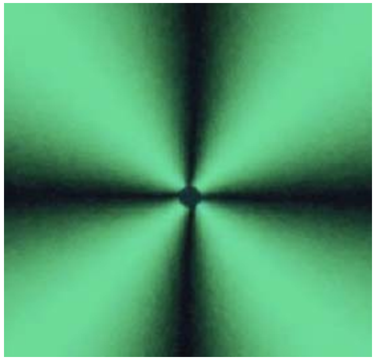
Reducing central disorientation region (~ 30 μm):
(Vortices between crossed polarizers)



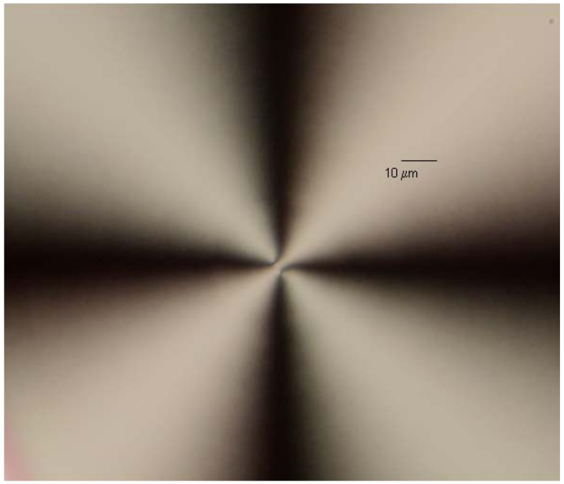
Theory



1st Gen.

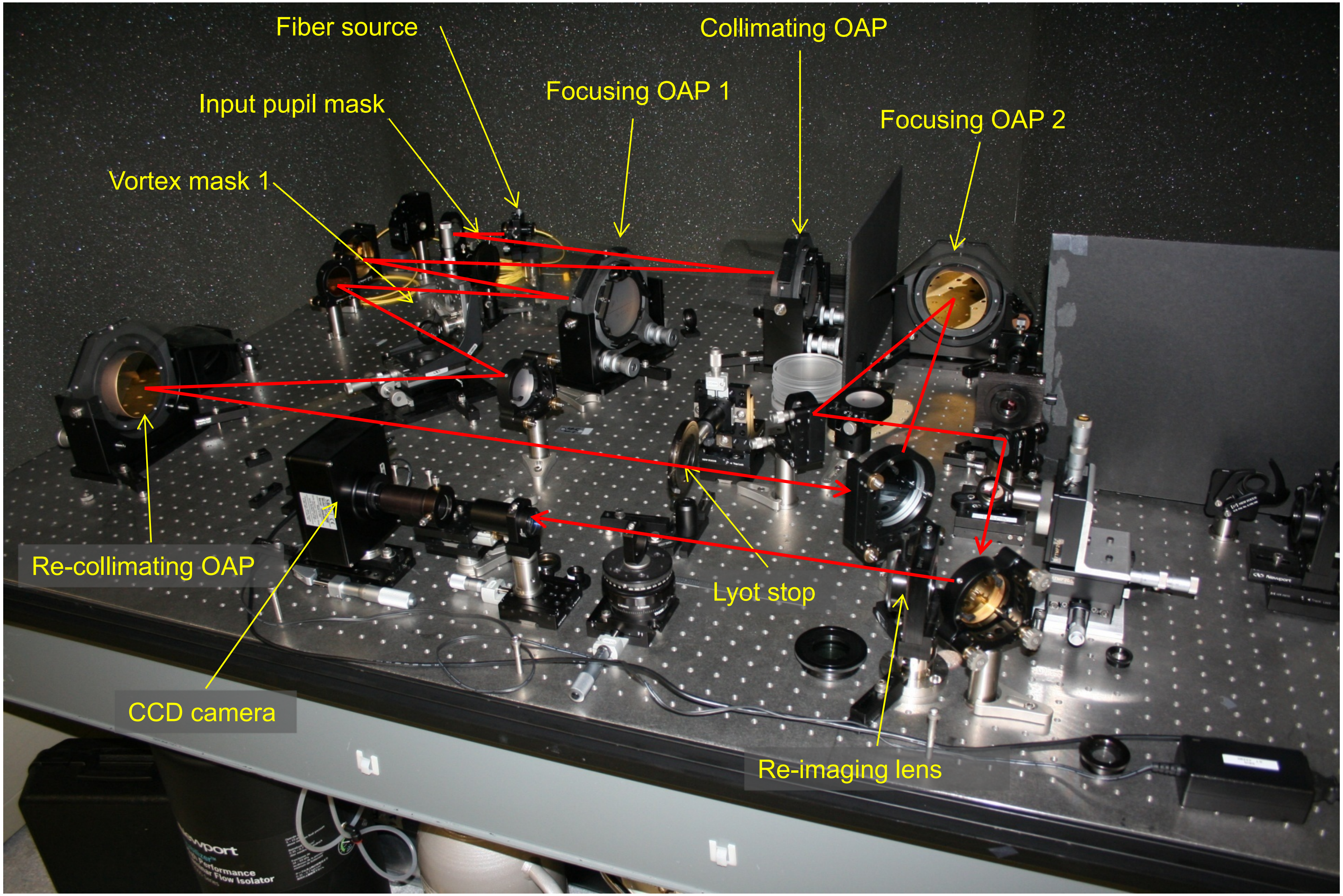


2nd Gen.

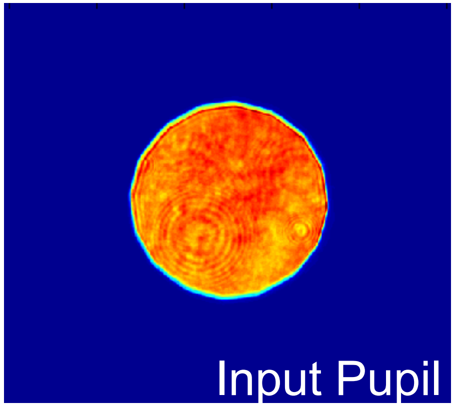


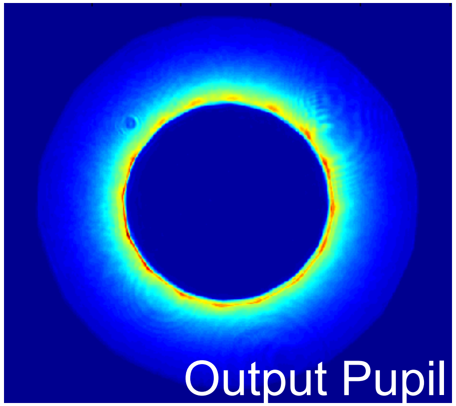
5 μm central region

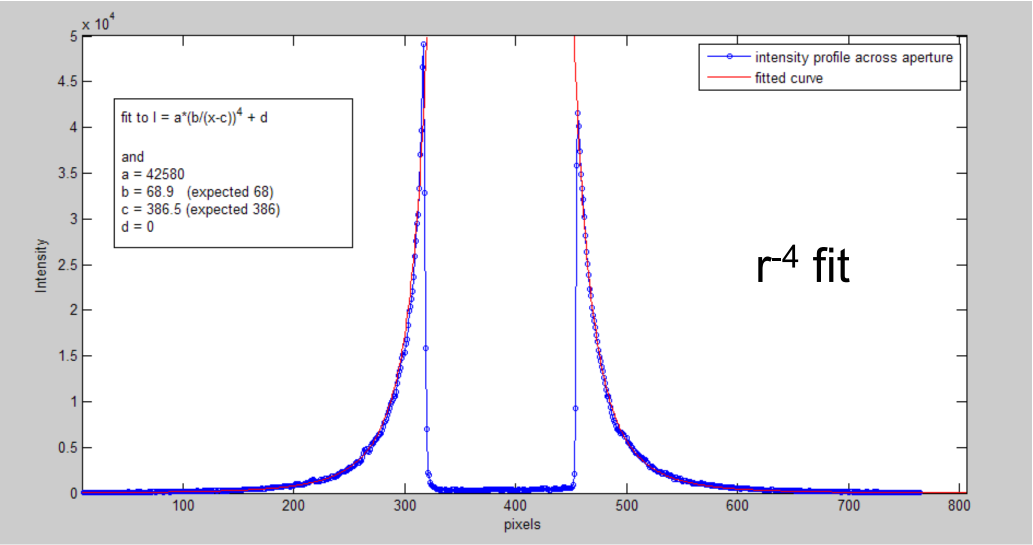
Infrared Coronagraphic Testbed (IRCT)

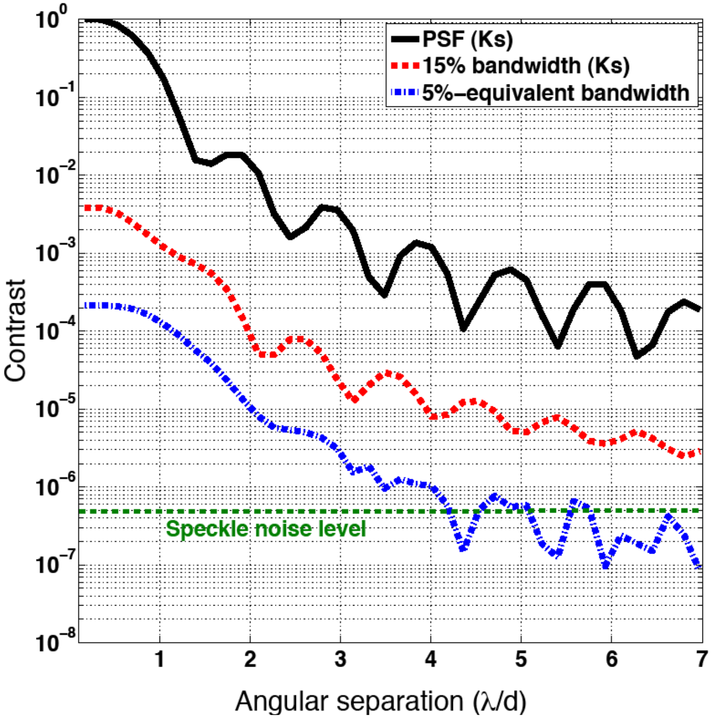


Single Vortex IRCT Measurements









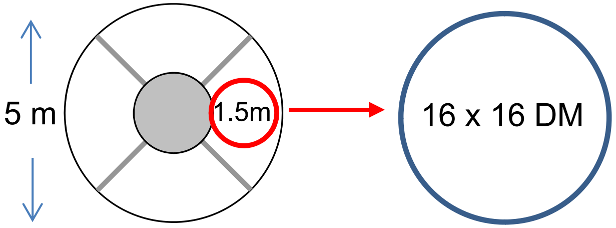
- 15% BW raw contrast ~ 10^{-4} @ 2λ/D
- 5% BW raw contrast ~ 10^{-5} @ 2λ/D
- < 10^{-2} beats the atmosphere

⇒ ready for ground-based ExAO

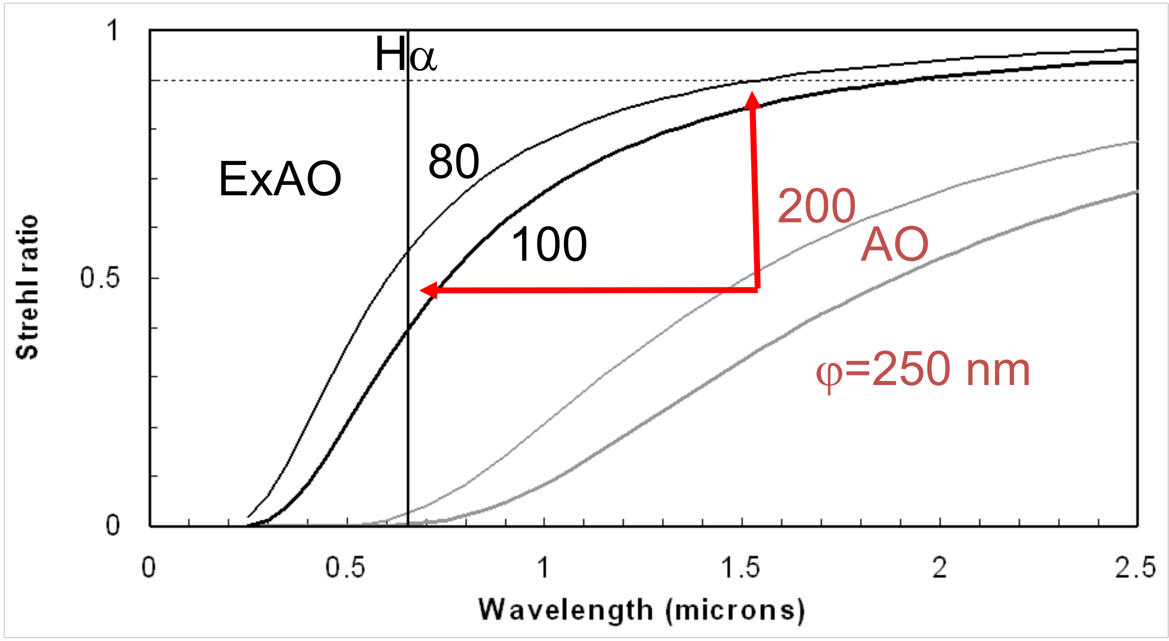
- Not yet for space (need 10^{-9} -10^{-10})

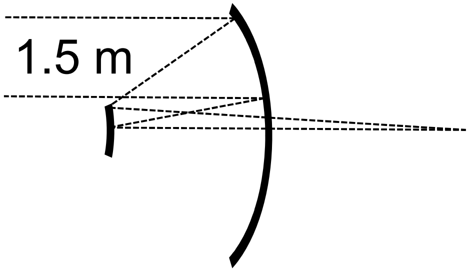
On-Sky: The Palomar “Well Corrected Subaperture”

- Need nearly perfect wavefront for coronagraphy: Strehl > 0.9
- Use existing AO system to correct telescope subaperture to ExAO levels

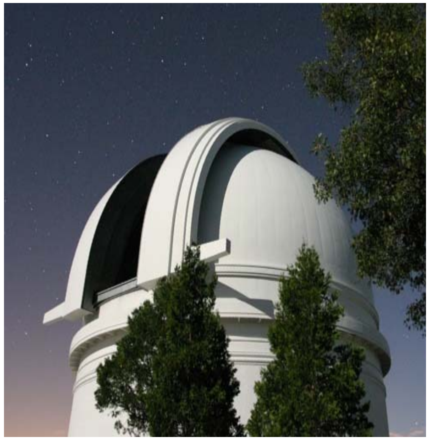


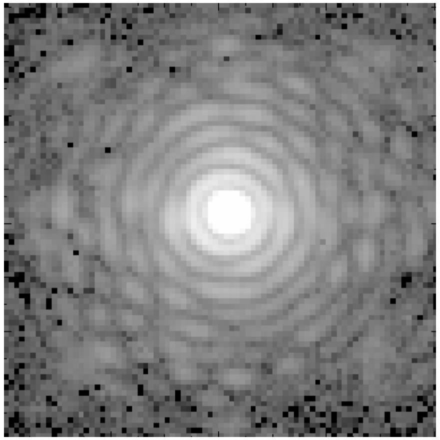
Palomar:
Aperture: 5 m → 1.5 m
Actuator spacing: 30 cm → 10 cm





- **Off axis system:**
  - **Low diffraction**
  - **Good analog for space missions**
  - **Small telescope requires small IWA**
  - **→ Phase mask coronagraph required**

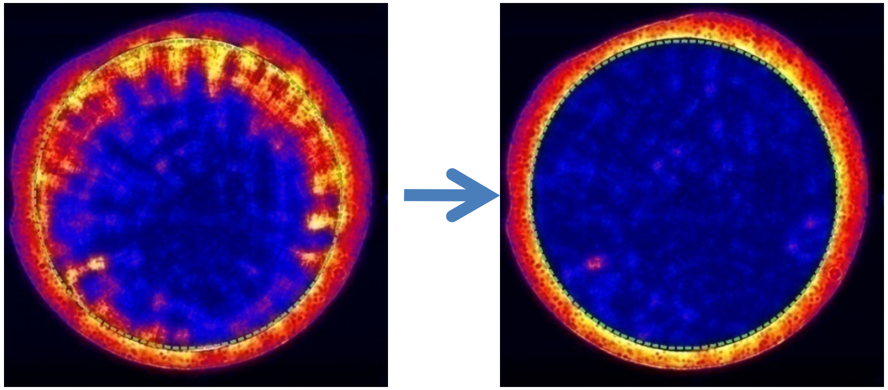


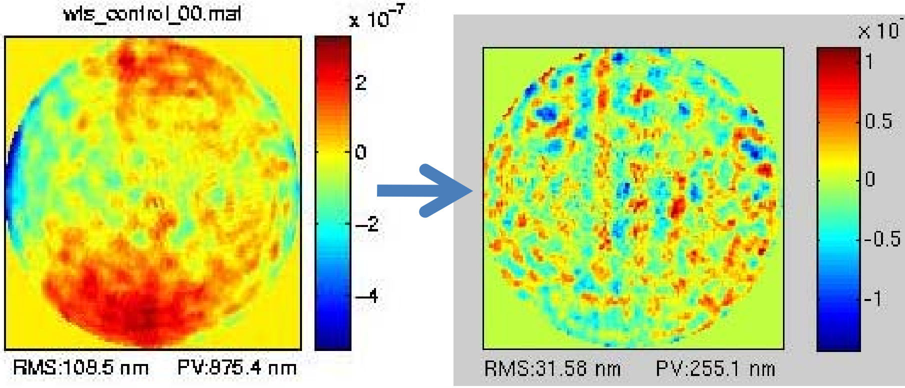


WCS stellar image
Serabyn et al. 2007

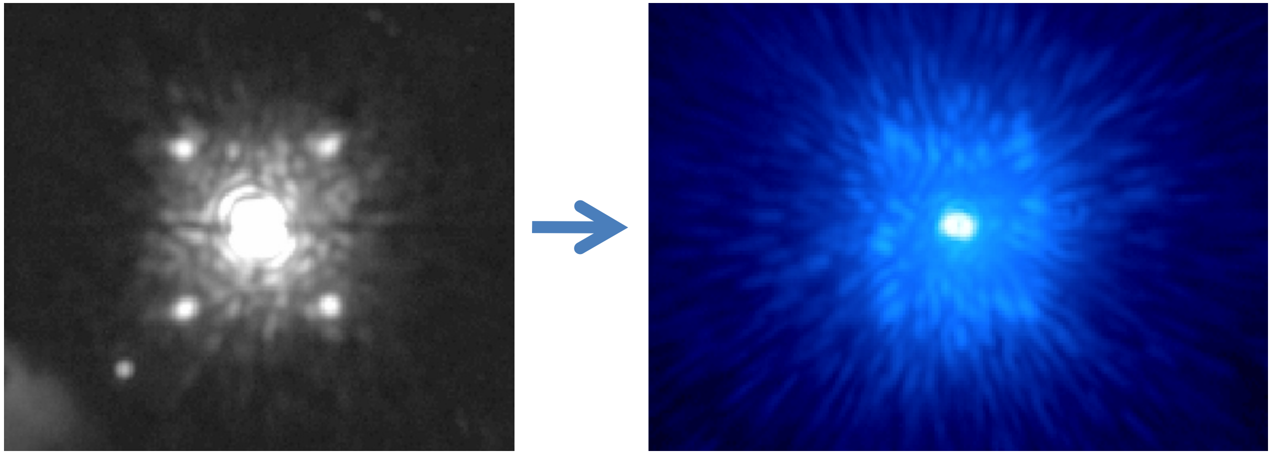
WCS Wavefront Improvements at Palomar

- Pointing: new mounts/actuators: now a few milli-arc seconds
- Focus: focus onto vortex mask rather than detector array (by making pupil dark)





- Speckle reduction with phase retrieval algorithm (through-focus images):
  - raw wavefront error reduced from ~ 110 nm (λ/20) to ~ 30 nm (λ/70)
- Coronagraph: moved to vector vortex masks



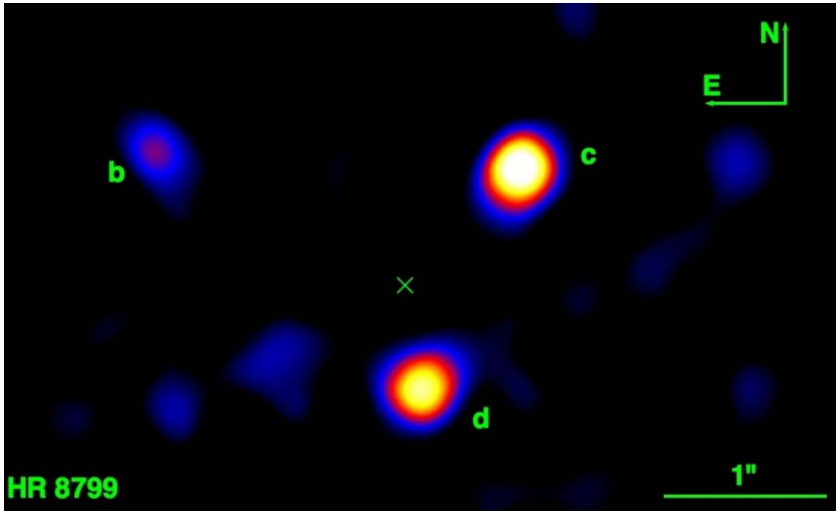
dark hole
contrast ~ 10^{-5}
in to ~ 1-2 λ/D

Burruss et al. 2010

The HR8799 Exoplanets with the Palomar WCS Vector Vortex Coronagraph

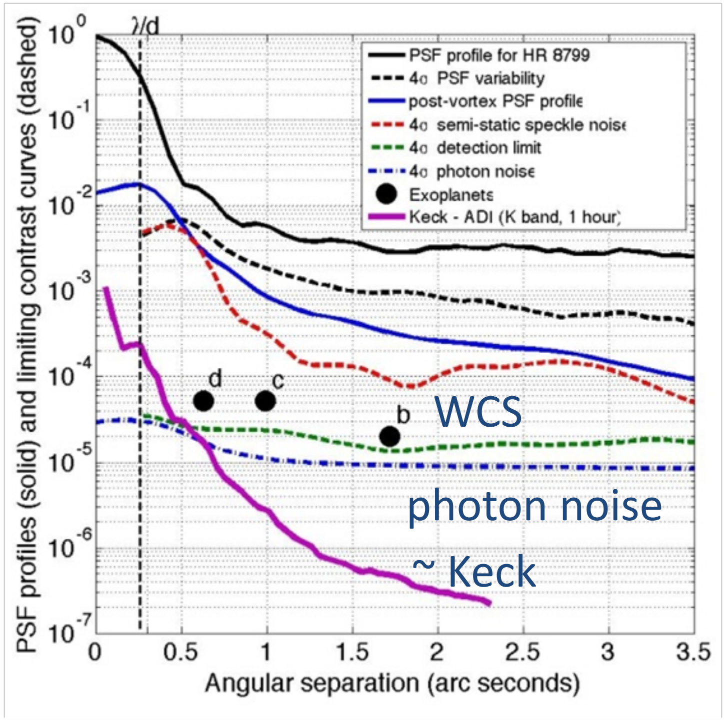
bypass
vortex

thru
vortex



- 1.5 m aperture
- λ = 2.2 μm

- "d" is at ~ 2 λ/D



- Results:
  - 4σ contrast ~ 2 x10^{-5} (~7 nm wavefront error)
  - IWA and (inner) contrast similar to Keck
  - Final contrast very near photon noise limit

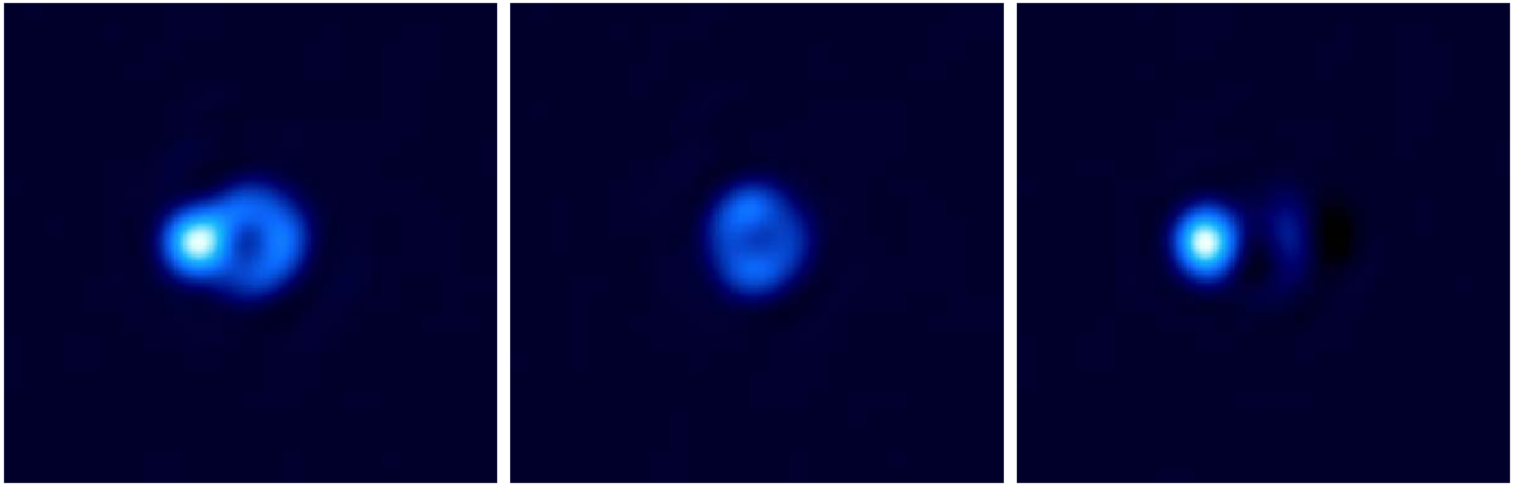
- WCS ~ the size of potential initial space coronagraphs

Serabyn et al. 2010

Reaching Even Smaller Angles

- Companion to ε Ceph (F0 IV) detected with the Palomar vortex coronagraph
  - at ~ 1.1λ/D; ~ 50:1 contrast
  - near K/M boundary if true companion

(Mawet et al. 2011)



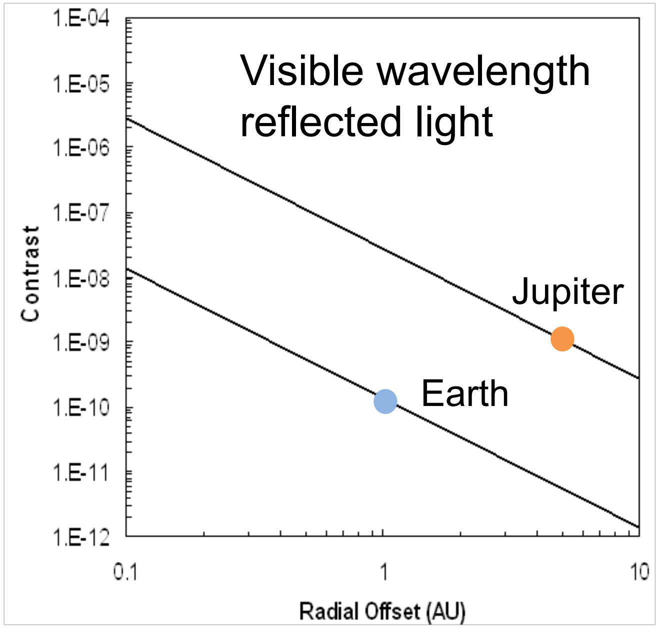
ε Ceph image Calibrator star Difference

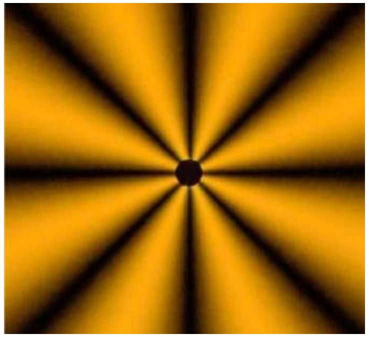
  - 1 λ/D is ¼ of NASA's earlier IWA requirement for a TPF coronagraph mission
    $\Rightarrow$ Telescope size can be reduced with a vortex
  - Bigger telescopes are always better, but more expensive:
    - Need to collect enough photons for spectroscopy
    - May not get all the way in to 1 λ/D because of stringent pointing requirement
  - Can seriously consider smaller exoplanet telescopes

Optical Vortex Masks for Space

TPF-C goal: 10^{-10}

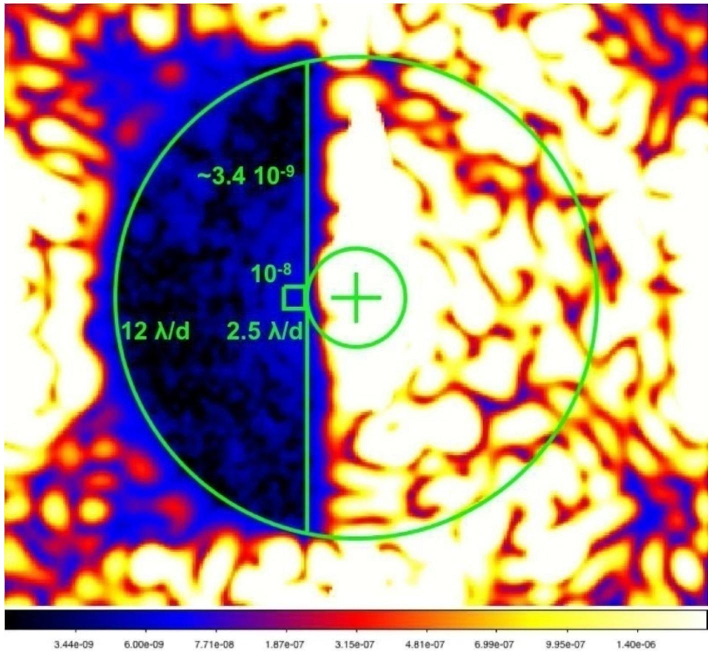
Potential precursors: 10^{-9}





- 4th order (JDSU) mask (8π per circuit) to ease pointing requirement

- Test masks in HCIT
- Optical wavelengths:
  - first monochromatic: 785 nm laser



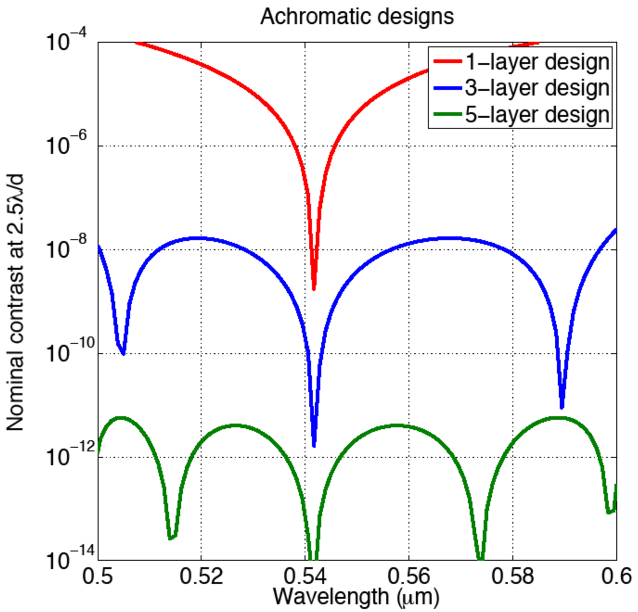
Median contrast = 3.4 x 10^{-9} between 2.5-12 λ/d

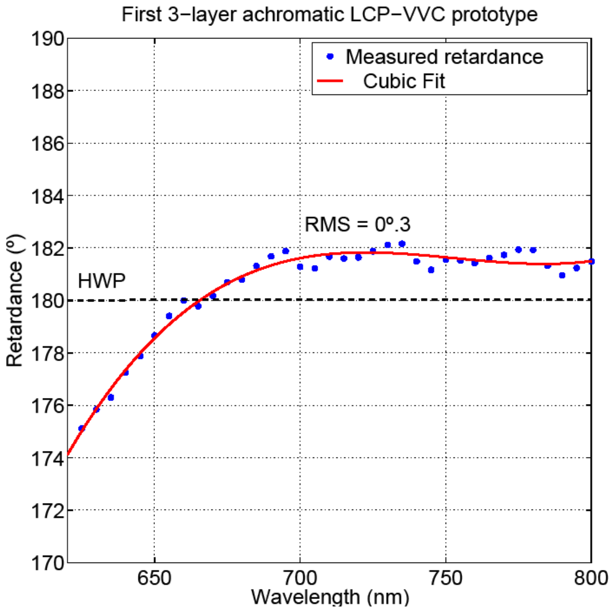
(Mawet et al. 2011)

Bandwidth

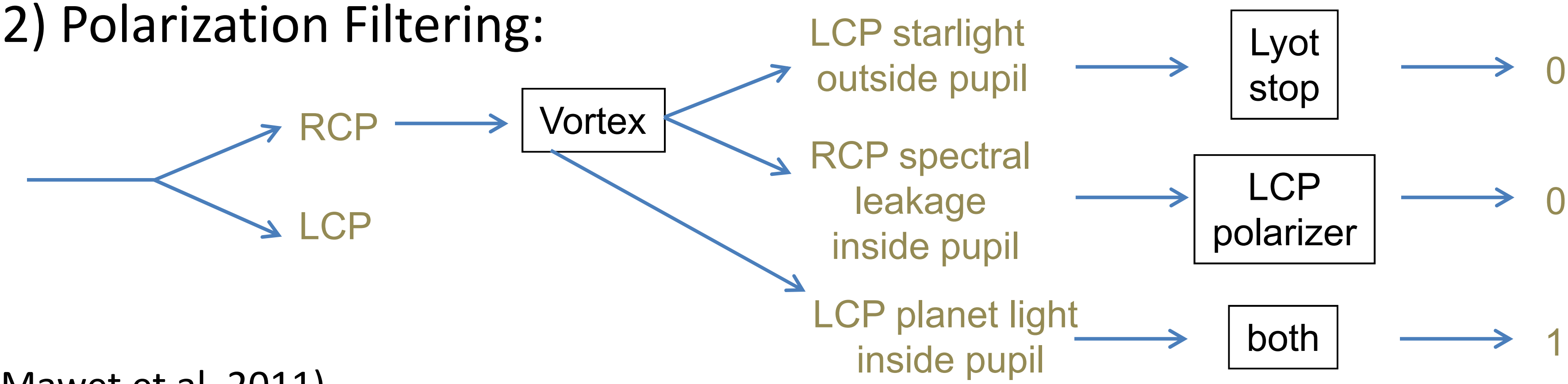
1) Three-layer half-wave-plate vortex mask

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





2) Polarization Filtering:



RCP

LCP

Vortex

LCP starlight outside pupil

Lyot stop

0

RCP spectral leakage inside pupil

LCP polarizer

0

LCP planet light inside pupil

both

1

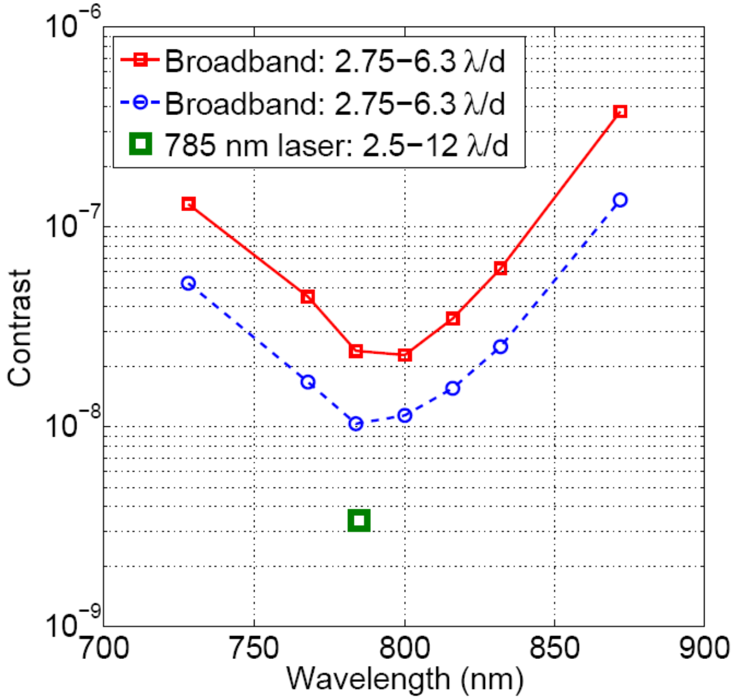
(Mawet et al. 2011)

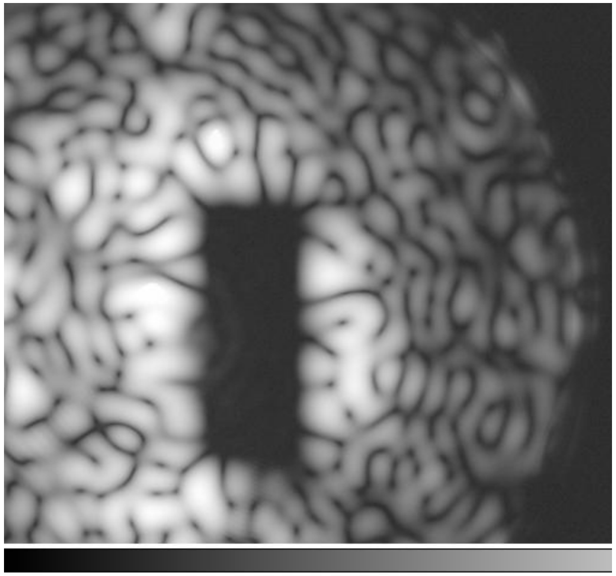
Broadband HCIT Results

- 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

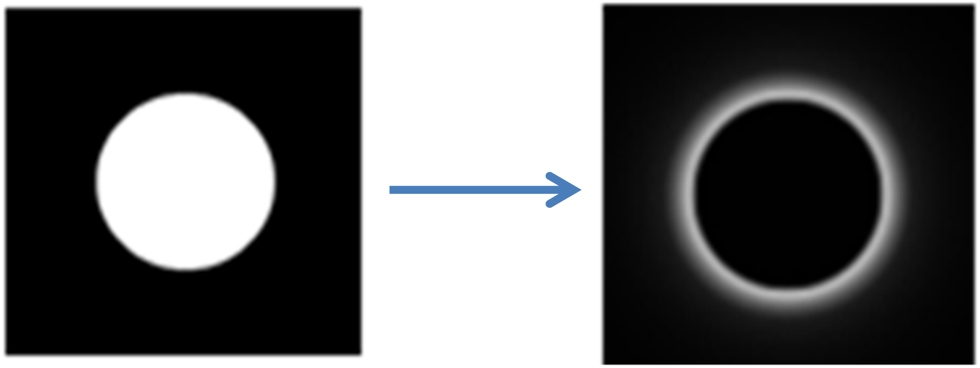
- Blue curve:
  top half of dark hole (y = 0 to 6.3 λ/D),
  (less residual light there)
- Best contrasts:
  1.0e-8 in best 2% passband
  1.6e-8 for a 10% passband.
  3.8e-8 for a 20% passband

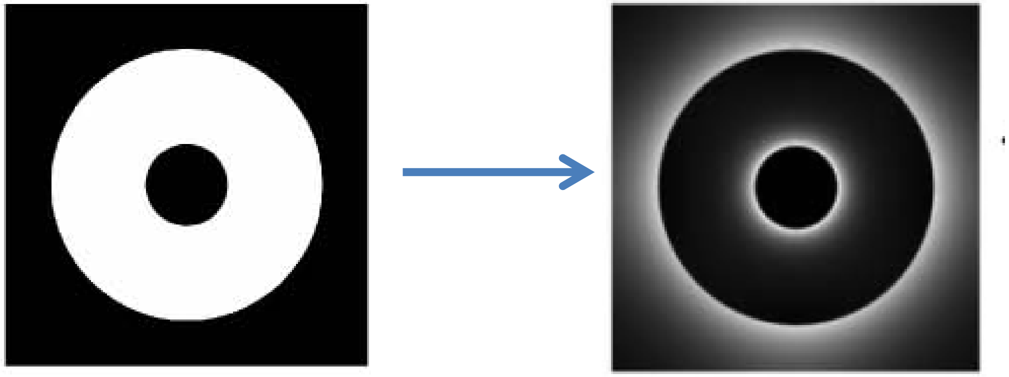




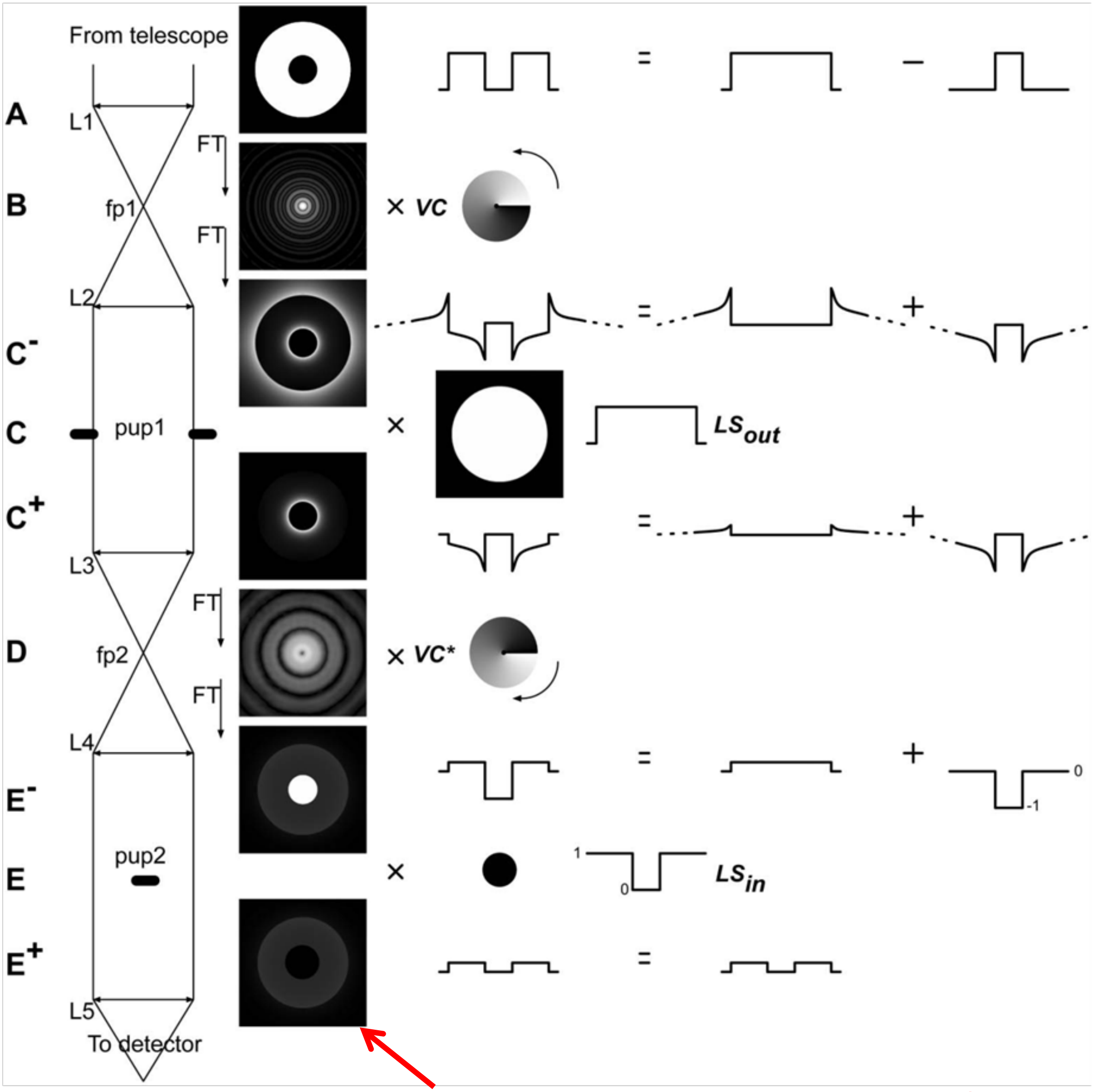
(Serabyn et al. 2011; Mawet et al. 2011)

What about an On-Axis Telescope?





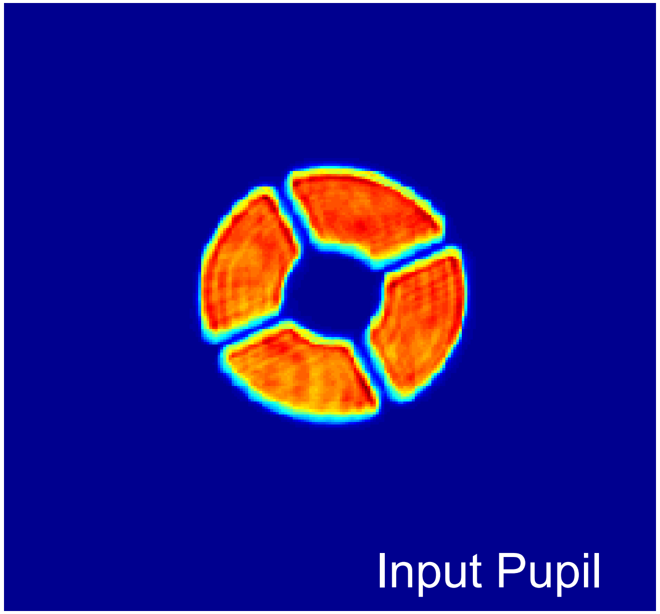
On-Axis Telescopes: The Dual-Stage Vortex

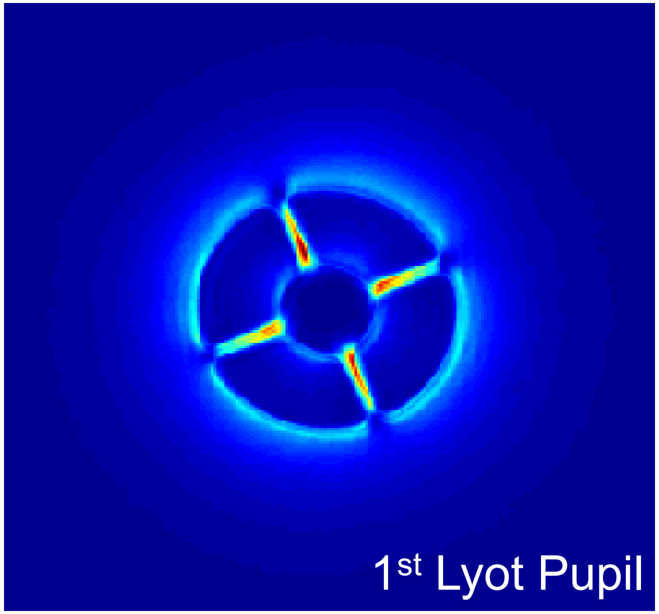


Starlight reduced by $(d/D)^4$

Mawet
et al. 2011

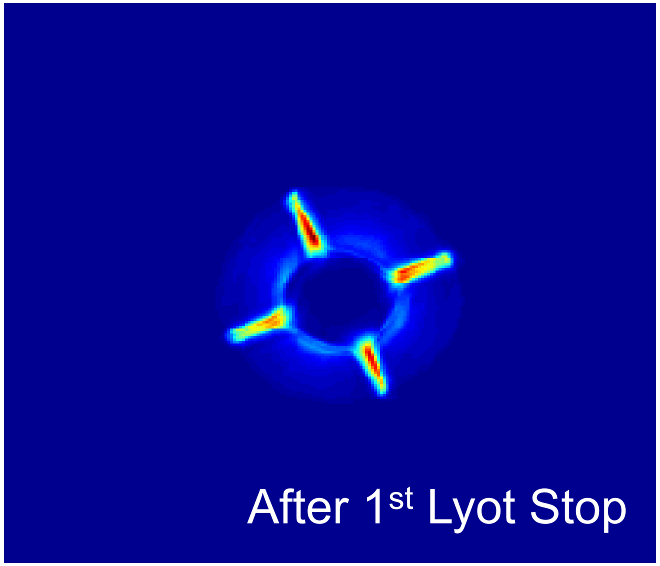
IRCT Measurements of On-Axis Dual-Vortex

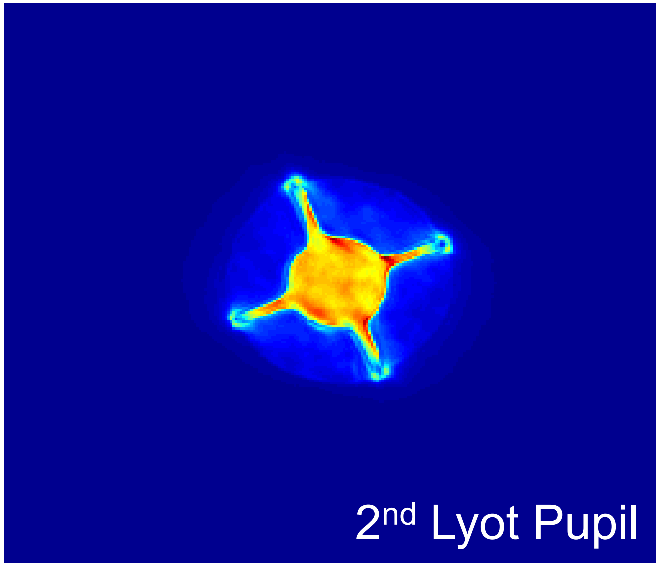

Input Pupil


1st Lyot Pupil

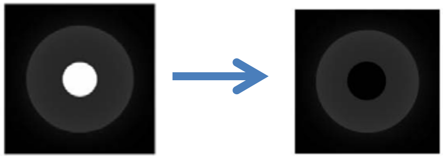
1st Lyot plane:
Residual light outside primary & secondary diameters

- the latter light lies within the primary


After 1st Lyot Stop

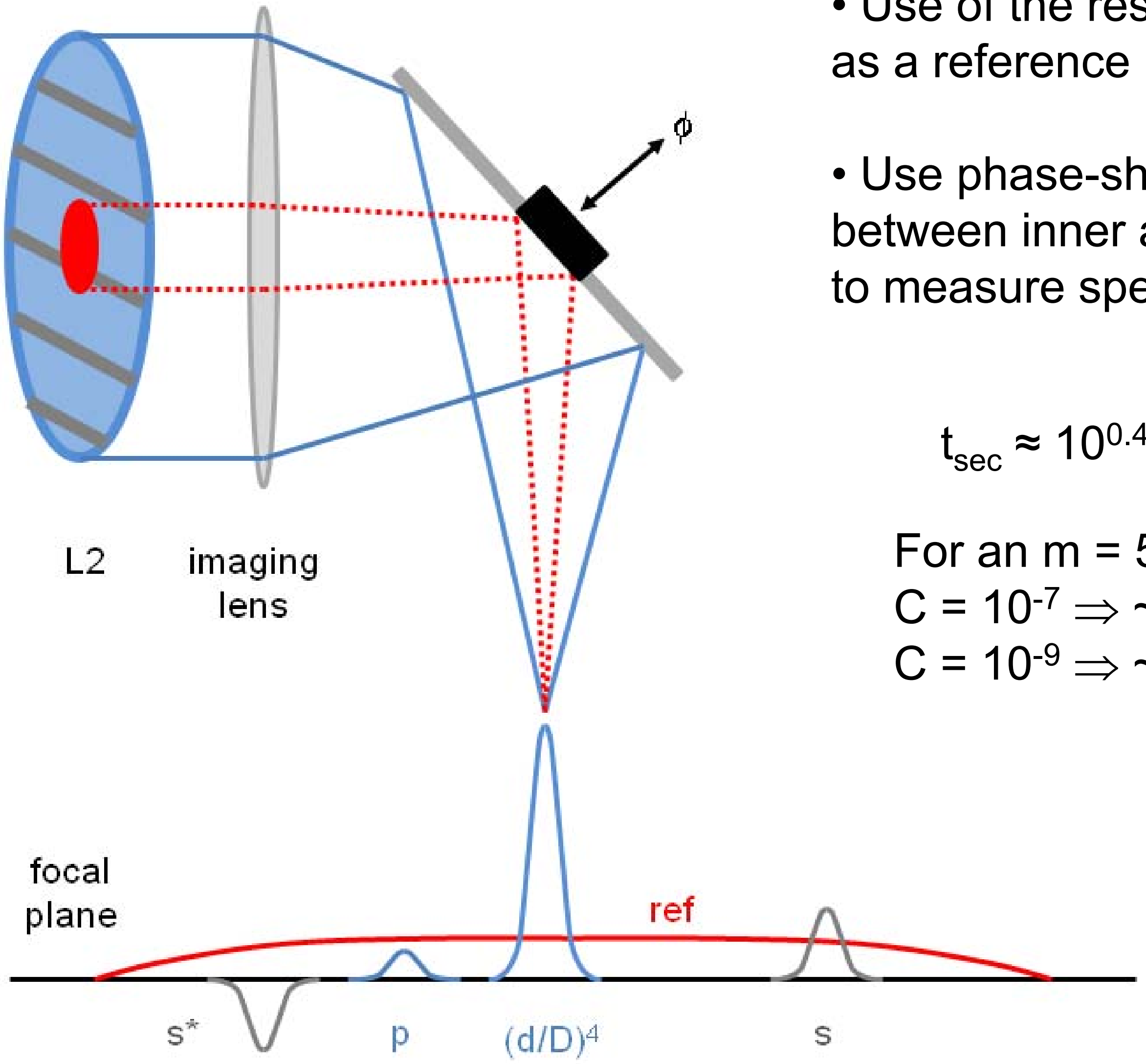

2nd Lyot Pupil

2nd Lyot plane:
Residual light concentrated in center, where it can be blocked



Serabyn et al. 2011, SPIE

Speckle Phase Sensing with a Double Vortex



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

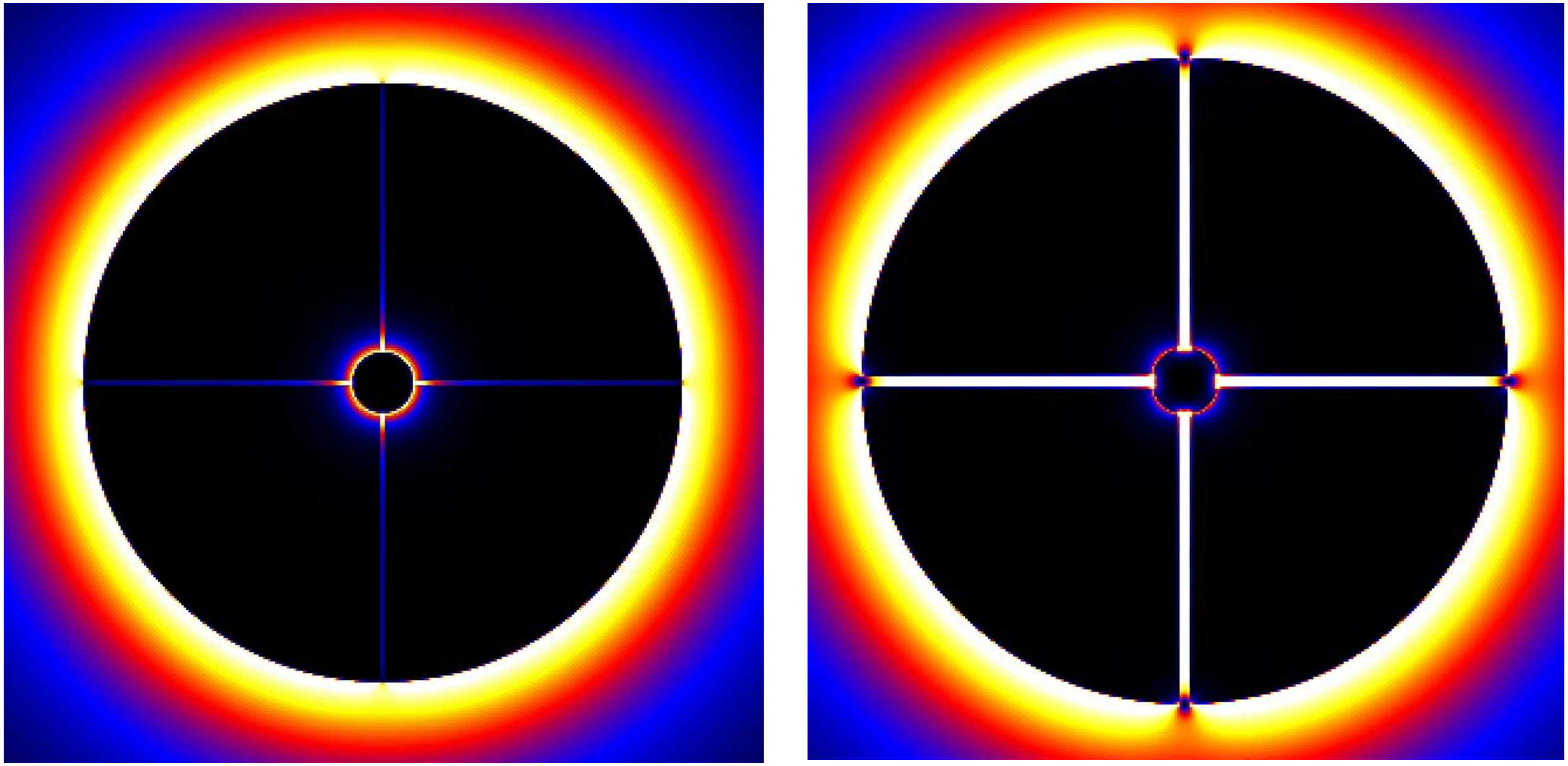
- Use phase-shifting interferometry between inner and outer pupils to measure speckle phases

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

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)

Modeling the Effect of Secondary Support Legs



0.5%D

2%D

Serabyn et al. 2011, SPIE

Summary

- New vortex devices:
  - Small inner working angle
  - High contrast
  - Beginnings of broadband performance
- Tandem vortex coronagraph:
  - Allows possibility of on-axis telescope
  - Enables direct sensing of speckle phases
- The future:
  - Vortices on large ground-based telescopes
  - Performance already nearly sufficient for small first-generation coronagraphic imaging mission
  - TPF-C not required to be excessively large