Coronagraph concepts

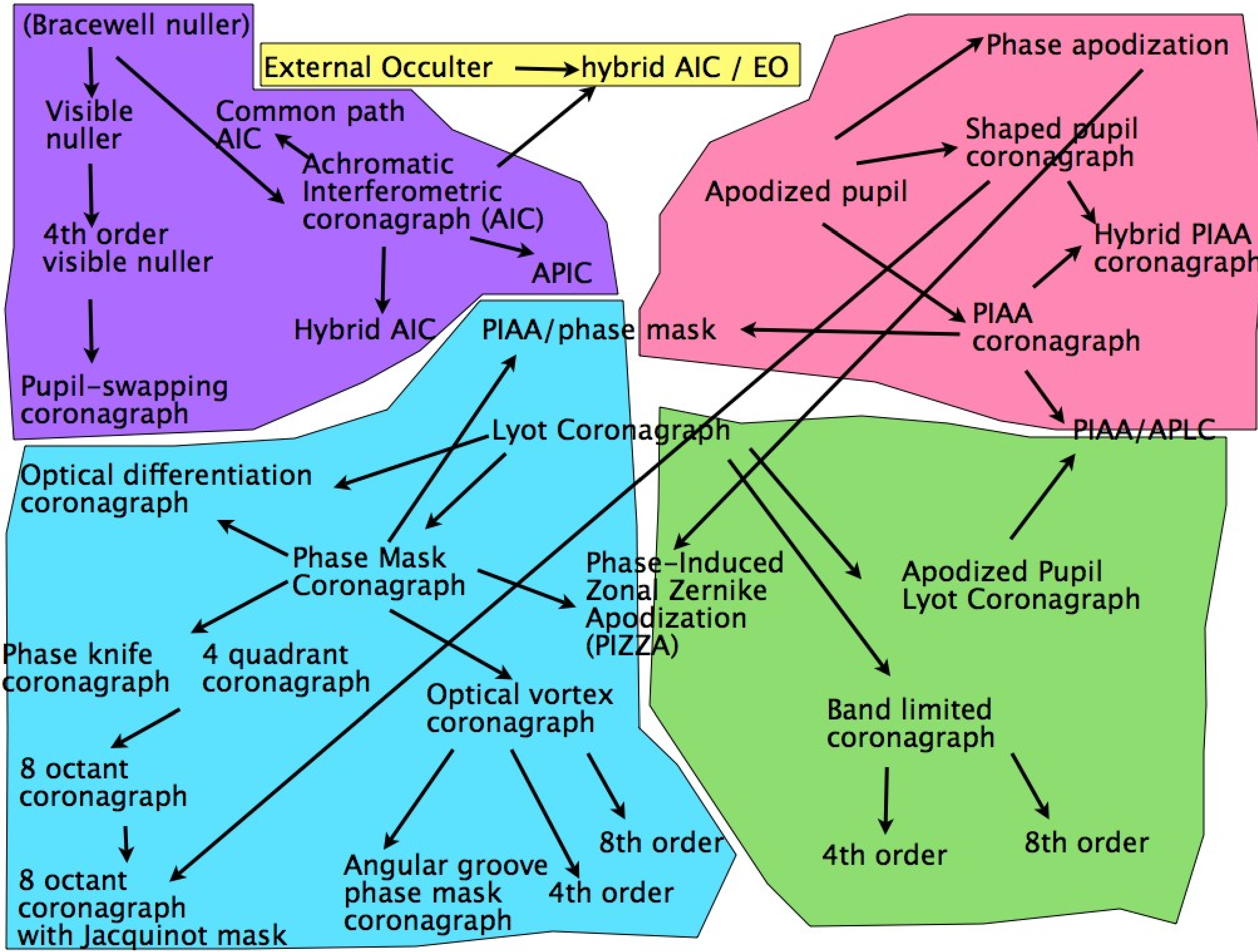
Types of coronagraphs

- Lyot coronagraph(s)

  Understanding Lyot coronagraphs with Fourier Transforms
  - Amplitude focal plane mask
  - Phase focal plane mask
  - Pupil apodization

- Pupil apodization
  - Conventional
  - PIAA
  - Pupil apodization and Lyot coronagraphs

Interferometric coronagraphs / nulling interferometers

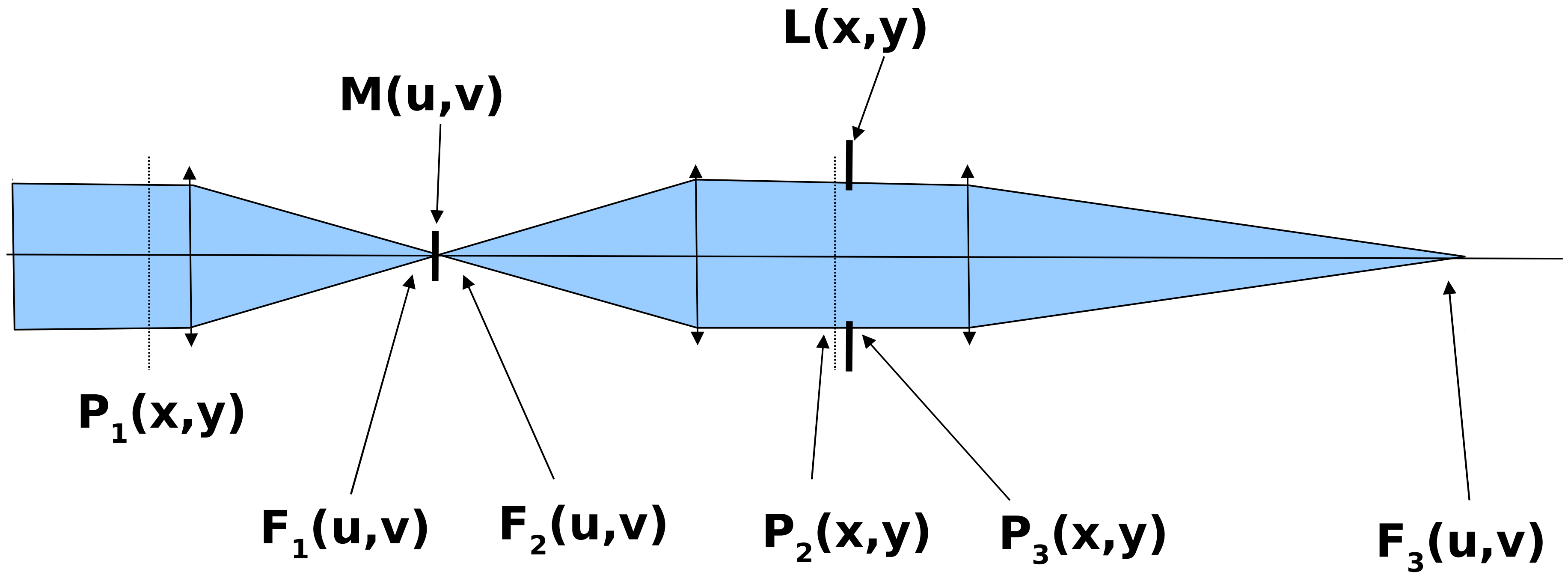

(Bracewell nuller)
Visible nuller
4th order visible nuller
Pupil-swapping coronagraph
Common path AIC
Achromatic Interferometric coronagraph (AIC)
APIC
Hybrid AIC
External Occulter
hybrid AIC / EO
Phase apodization
Shaped pupil coronagraph
Apodized pupil
Hybrid PIAA coronagraph
PIAA coronagraph
PIAA/phase mask
PIAA/APLC
Lyot Coronagraph
Optical differentiation coronagraph
Phase Mask Coronagraph
Phase-Induced Zonal Zernike Apodization (PIZZA)
Apodized Pupil Lyot Coronagraph
Phase knife coronagraph
4 quadrant coronagraph
Optical vortex coronagraph
Band limited coronagraph
8 octant coronagraph
8 octant coronagraph with Jacquinot mask
Angular groove phase mask coronagraph
8th order
4th order
4th order
8th order

Lyot Coronagraph explained by Fourier transforms

Pupil plane complex amplitude ↔ focal plane complex amplitude

→ Fourier transform
← Inverse Fourier transform

Coordinates in pupil plane: x,y
Coordinates in focal plane : u,v
 * denoting convolution (product = convolution in Fourier transform)



Lyot Coronagraph explained by Fourier transforms

Entrance pupil of telescope: $P_1(x,y)$

Focal plane complex amplitude (before focal plane mask): $F_1(u,v)$

$F_1(u,v) = FT (P_1(x,y))$

Focal plane mask complex amplitude transmission: $M(u,v)$

Focal plane complex amplifude (after focal plane mask): $F_2(u,v)$

$F_2(u,v) = F_1(u,v) \times M(u,v) = FT(P_1(x,y)) \times M(u,v)$

Exit pupil plane:

$P_2(x,y) = FT^{-1}(F_2(u,v)) = FT^{-1} (FT(P_1(x,y) \times M(u,v)) = P_1(x,y) * FT^{-1}(M(u,v))$

With * denoting convolution

$P_3(x,y) = L(x,y) \times P_2(x,y)$

$\mathbf{P_3(x,y) = L(x,y) \times (P_1(x,y) * FT^{-1}(M(u,v)))}$

$F_3(u,v) = FT(L(x,y)) * (F_1(u,v) \times M(u,v))$

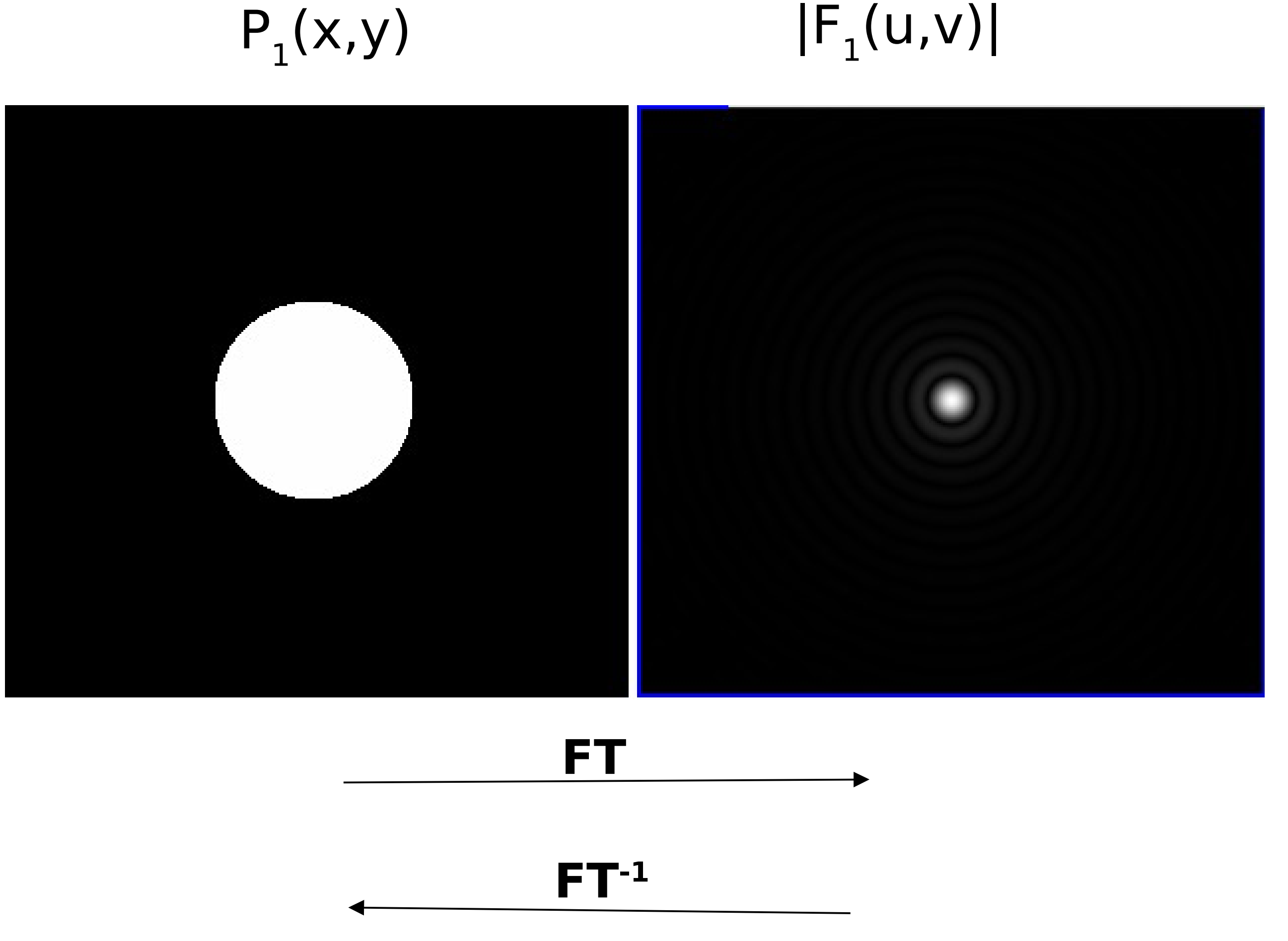
Coronagraphy problem: minimize $P_3(x,y)$ for on-axis point source

Lyot Coronagraph explained by Fourier transforms

Entrance pupil of telescope: $P_1(x,y)$

Focal plane complex amplitude (before focal plane mask): $F_1(u,v)$

$F_1(u,v) = FT\ (\ P_1(x,y)\ )$



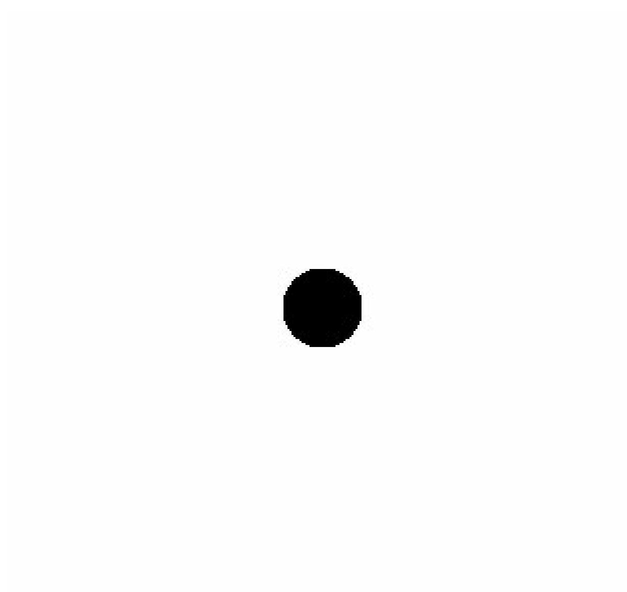
Lyot Coronagraph explained by Fourier transforms

Focal plane mask complex amplitude transmission: M(u,v)

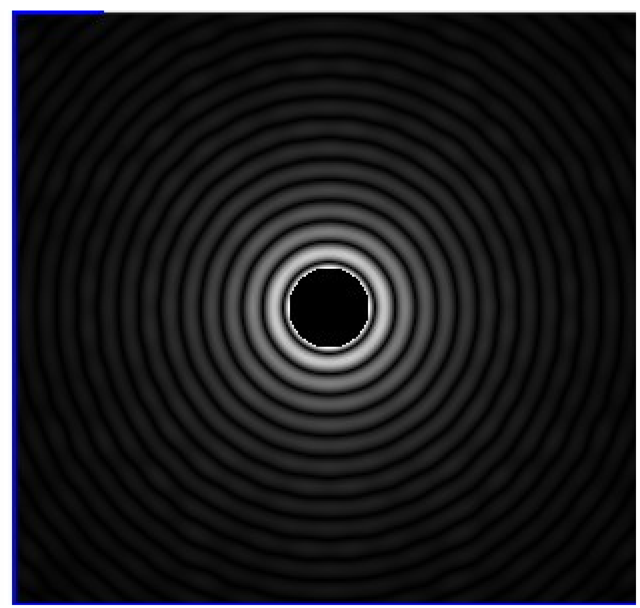
Focal plane complex amplifude (after focal plane mask): $F_2(u,v)$

$F_2(u,v) = F_1(u,v) \times M(u,v) = FT(P_1(x,y)) \times M(u,v)$

M(u,v)



$|F_2(u,v)|$



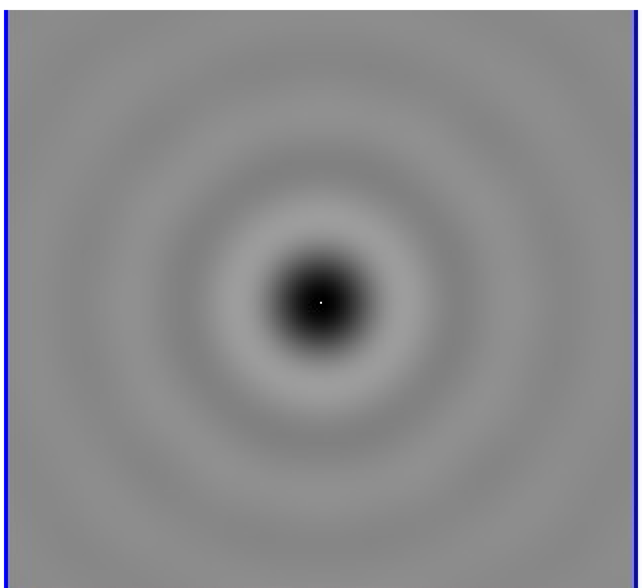
Lyot Coronagraph explained by Fourier transforms

Exit pupil plane:

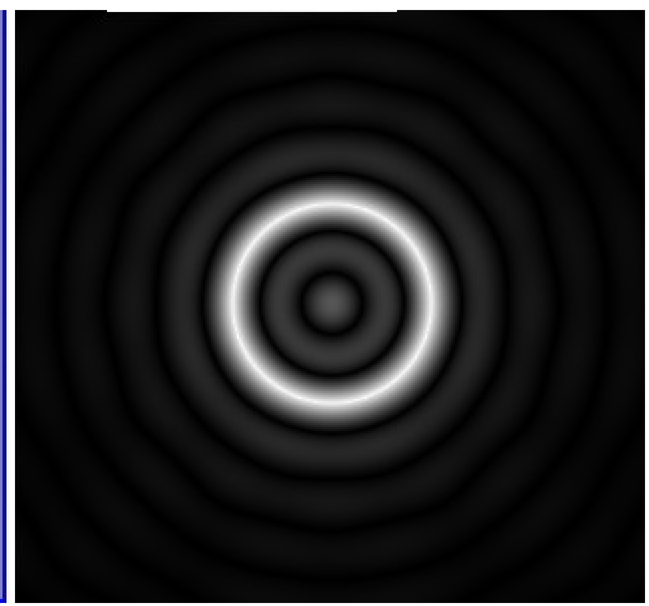
$P_2(x,y) = FT^{-1}(\ F_2(u,v)\ )$

$= FT^{-1}\ (\ FT(P_1(x,y) \times M(u,v)\ ) = P_1(x,y) * FT^{-1}(M(u,v))$

$FT^{-1}(M(u,v))$



$|P_2(x,y)|$



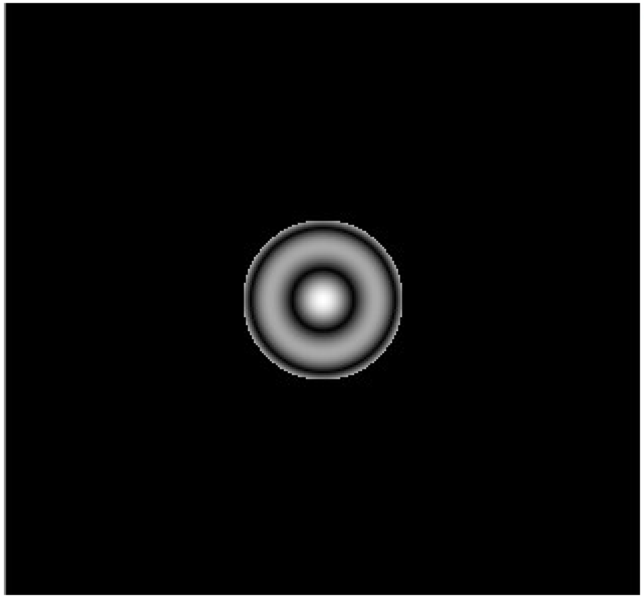
Lyot Coronagraph explained by Fourier transforms

$P_3(x,y) = L(x,y) \times P_2(x,y)$

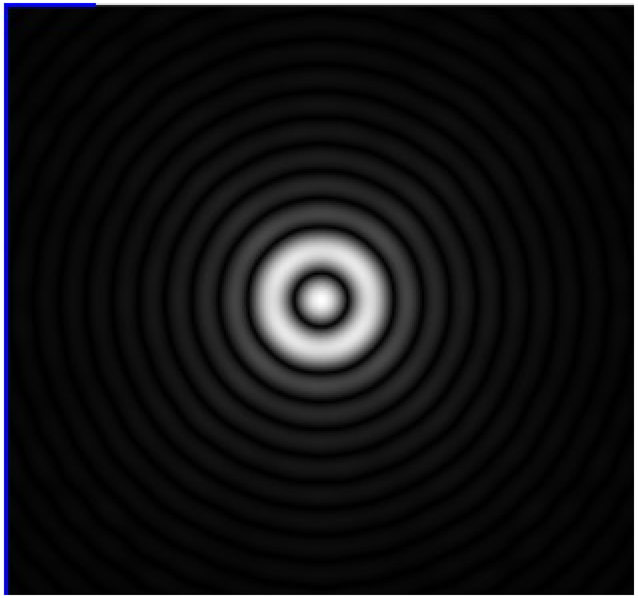
$\mathbf{P_3(x,y) = L(x,y) \times (P_1(x,y) * FT^{-1}(M(u,v)))}$

$F_3(u,v) = FT(L(x,y)) * (F_1(u,v) \times M(u,v))$

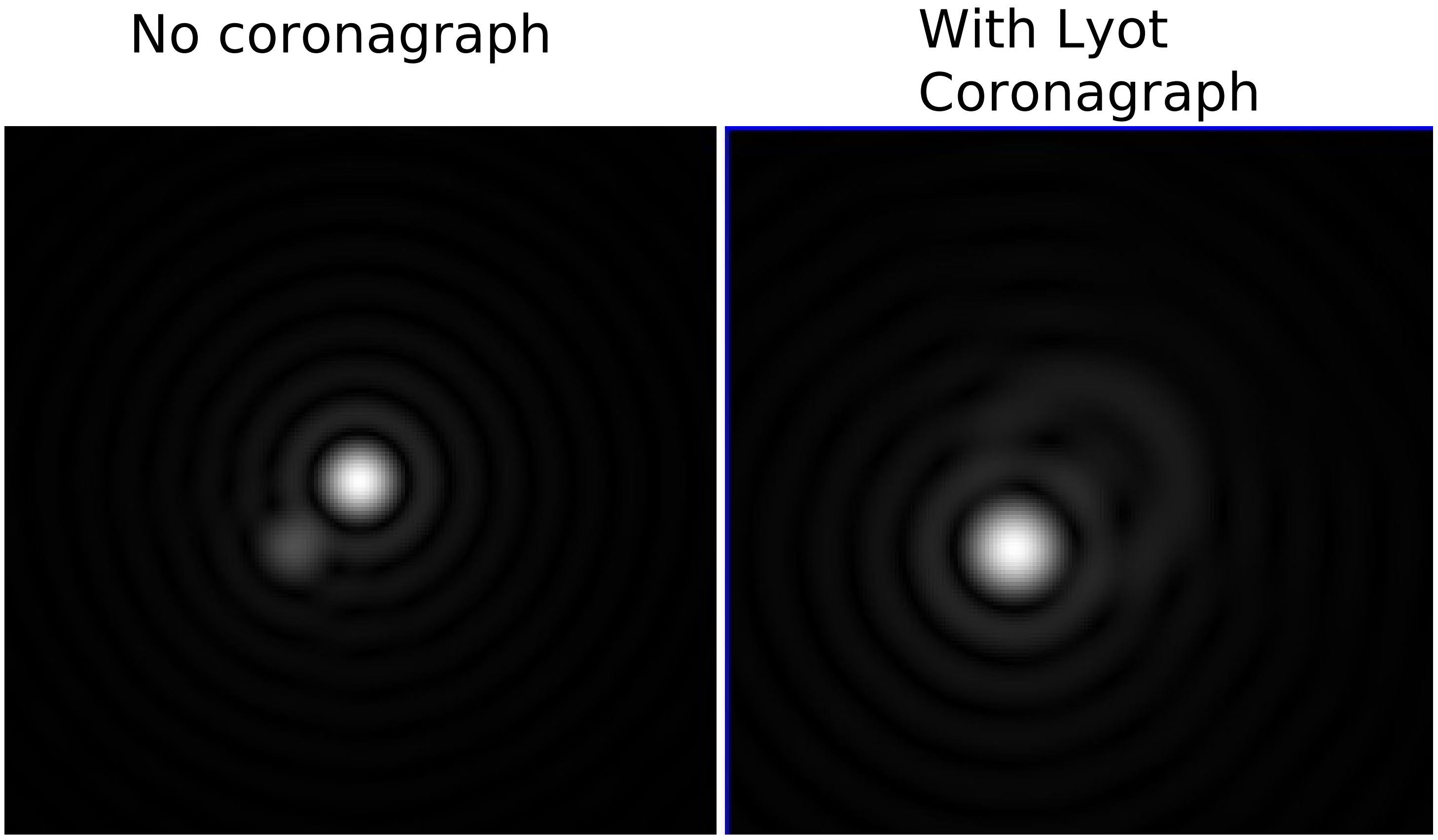
$|P_3(x,y)|$



$|F_3(u,v)|$



Numerical simulation of final image for 10:1 contrast



Lyot Coronagraph : optimizations

Conventional Lyot coronagraph is limited in performance:

- cannot reach extremely high contrast (some light in pupil)
- tradeoff between throughput and contrast
- not able to get high contrast close to the optical axis

Optimization goal: make pupil dark inside Lyot mask

Possible optimizations include:

(1) Redesign of focal plane mask

- Band-limited
- Use phase as well as (or instead of) amplitude

(2) Apodize entrance aperture

Next slides illustrate these optimizations

Band-Limited mask Coronagraph (BL4, BL8)

Focal plane mask optimized to maintain fully dark central zone in pupil (band-limited mask).

Integral of Mask Fourier Transform = 0
Mask Fourier transform = 0 outside some domain (band-limited)

4^{th} or 8^{th} order extinction.

Kuchner & Traub 2002
Kuchner 2005

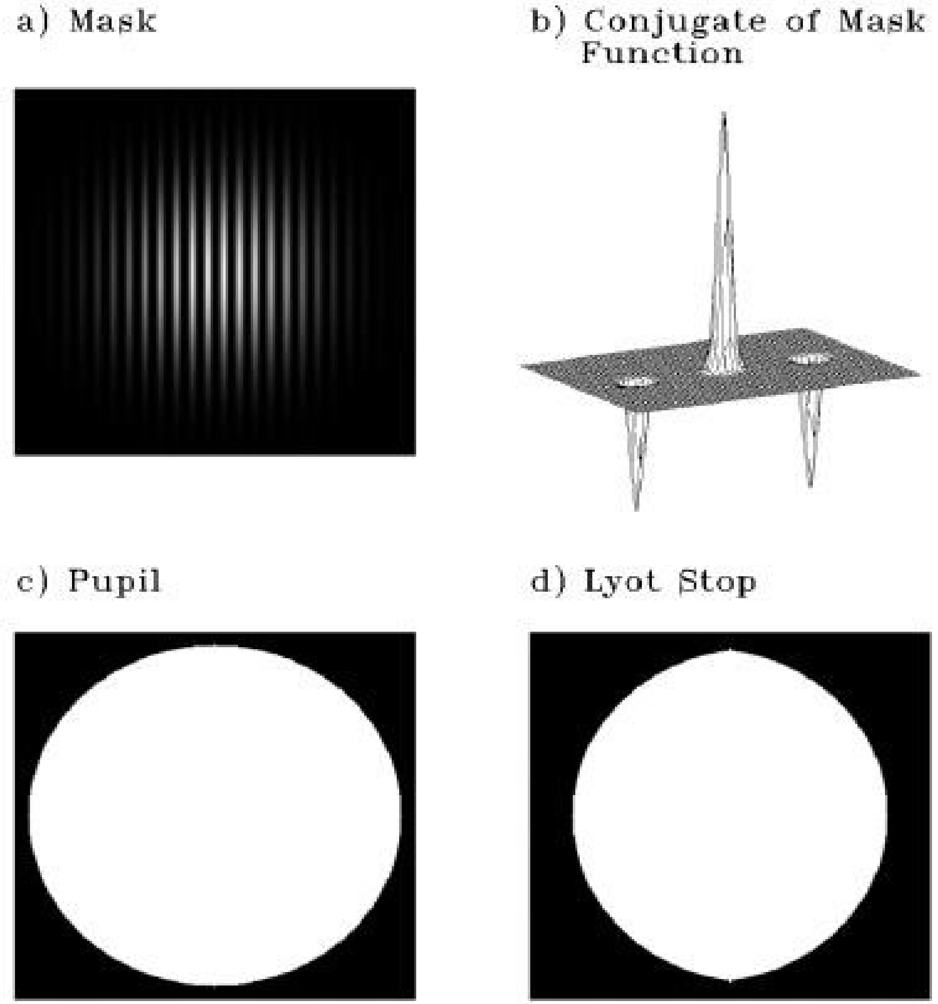


FIG. 4.—Simplest band-limited mask, analogous to a single-baseline nulling interferometer. (*a*) Mask ITF $\sin^4(x)$ multiplied by a slow taper. Dark areas are opaque. (*b*) Conjugate of the mask ATF (eq. [13]). This occulting mask can be used with any aperture shape, but for the circular aperture shown in (*c*), the corresponding Lyot stop is (*d*).

Apodized Pupil Lyot Coronagraph (APLC)
= Prolate Apodized Lyot Coronagraph (PALC)

Lyot Coronagraph with apodized entrance pupil.
Prolate apodization is optimal, and can bring contrast to 1e10.
Focal plane mask is smaller than Central diffraction spot: challenging to achromatize

Output pupil (in Lyot plane) is prolate itself, and can serve as input for another Lyot coronagraph: Multistep APLC.

Adopted for Gemini Planet Imager (GPI).

Soummer et al. 2003, A&A, 397, 1161
Aime & Soummer 2004, SPIE, 5490, 456
Abe

Phase Mask Coronagraph (PM)

Lyot-like design with PI-shifiting (-1 amplitude) circular focal plane mask:

- smaller mask
- smaller IWA

Requires mild prolate pupil apodization.

Phase shift needs to be achromatic
Mask size should be wavelength dependant

Dual zone PM coronagraph mitigates chromaticity

2^{nd} order null only.

Roddier & Roddier 1997, PASP, 109, 815 (basic concept)
Guyon & Roddier 2000, SPIE, 4006, 377 (pupil apodization with PM)
Soummer et al. 2003, A&A, 397, 1161 (pupil apodization with PM)

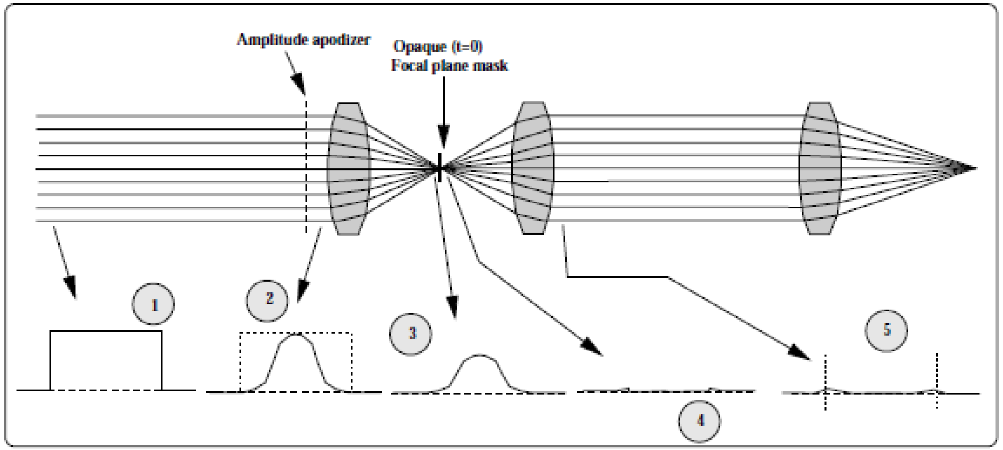
Coronagraphs using pupil apodization

Conventional pupil apodization
Pupil shape is modified to reduce Airy rings

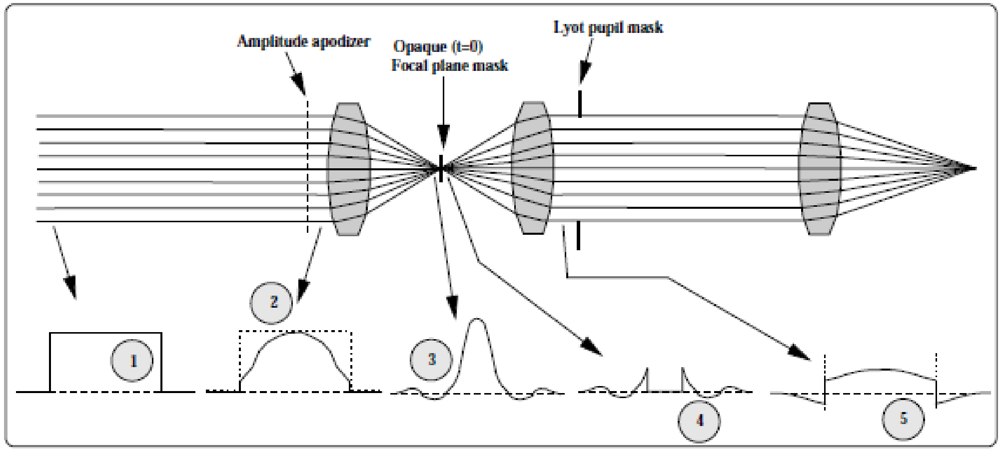
Apodized Pupil Lyot Coronagraph (APLC)
In a Lyot coronagraph, apodization of the entrance pupil offers large improvement of coronagraph performance

Apodized Pupil Complex Mask Lyot Coronagraph (APCMLC)
By including phase in the focal plane mask, it can be made smaller and offer smaller inner working angle

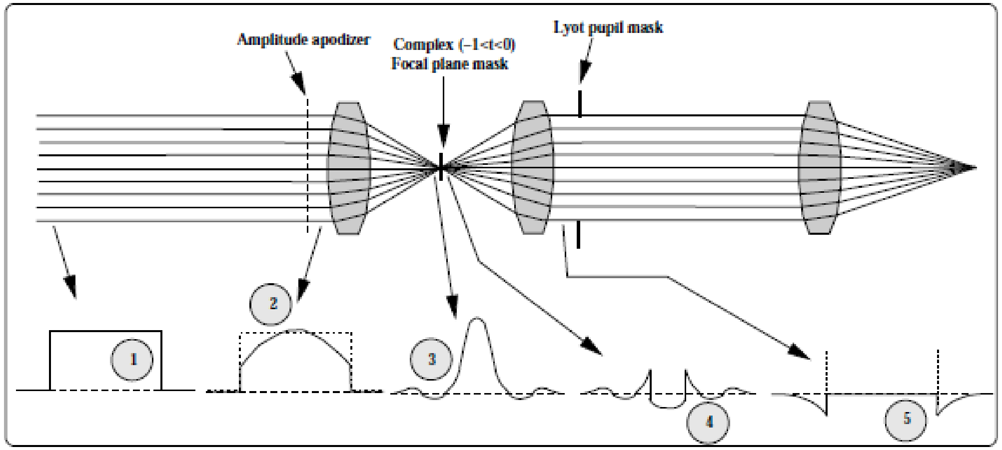
Conventional Pupil Apodization (CPA)



Apodized Pupil Lyot Coronagraph (APLC)



Apodized Pupil Complex Mask Lyot Coronagraph (APCMLC)



4 Quadrant Phase Mask (4QPM)

Lyot-like design with PI-shifiting (-1 amplitude) of 2 opposize quadrants in focal plane:

- Does not require pupil apodization.
- less chromatic

Phase shift still needs to be achromatic

2nd order null only.

Used on VLT for science obs.

Rouan et al. 2000, PASP, 112, 1479

PHASE CORONAGRAPH WITH FOUR QUADRANTS. I. 1481

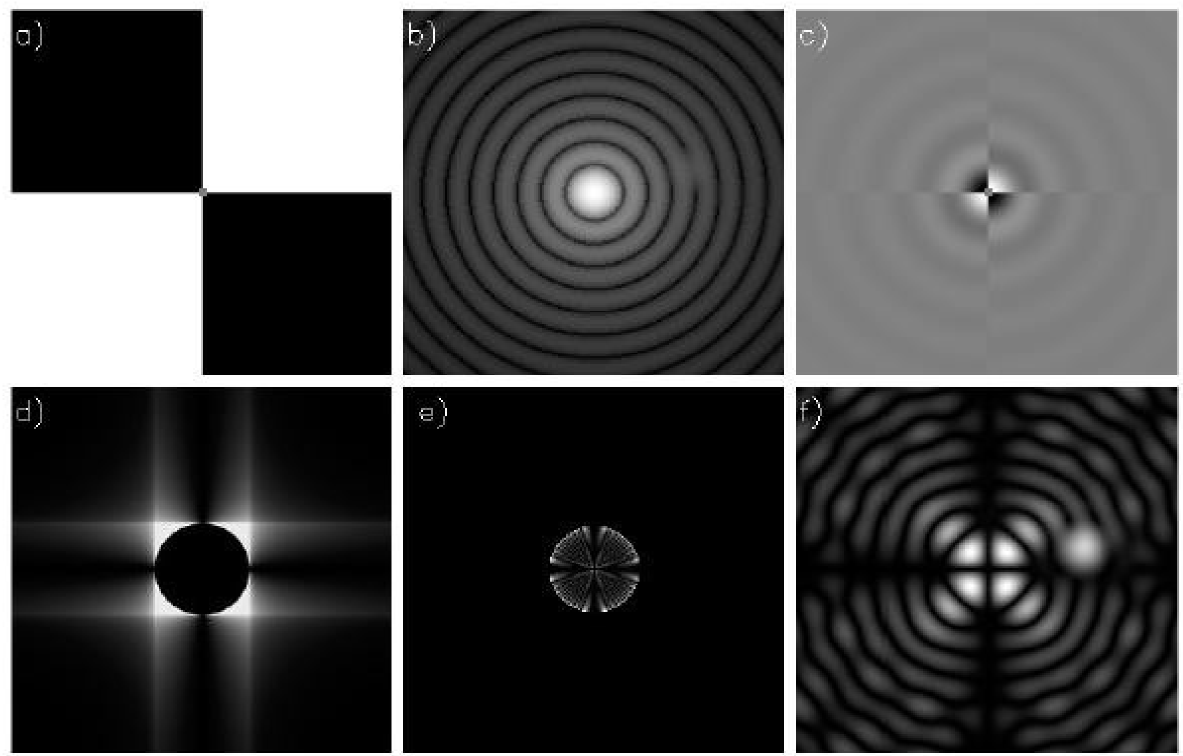


FIG. 2.—Numerical simulation illustrating the principle of the four-quadrant coronagraph. A companion 15 mag fainter (flux ratio of 10^6) is located $2.1\lambda/D$ away from the star. The individual images show (*a*) the shape of the phase mask (white for 0 phase shift, black for π phase shift), (*b*) the Airy pattern displayed in intensity, (*c*) the complex amplitude of the star phase shifted by the mask, (*d*) the exit pupil, (*e*) the exit pupil through the Lyot stop (95% of the pupil diameter), and (*f*) the coronagraphic image where the companion is clearly visible. Images are displayed with nonlinear scale.

Achromatic Phase Knife Coronagraph (APKC)

Same basic principle as 4QPM. Addresses chromaticity problem with dispersion along one axis.

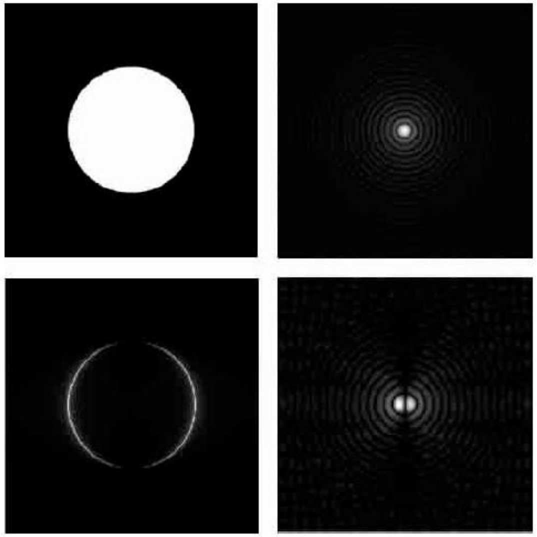


Fig. 1. Pupil intensity with perfect wavefront and its corresponding Airy pattern (*top left and right*). Intensity distribution after the Phase Knife Coronagraph has been applied (*bottom-left*): the two thin crescents encircle the pupil area perpendicular to the Knife-Edge direction. "Butterfly shape" of the point spread function of a system where half the amplitude is π-shifted in the image plane (*bottom-right*), and where a Lyot stop has been applied in the conjugate pupil plane of (c).

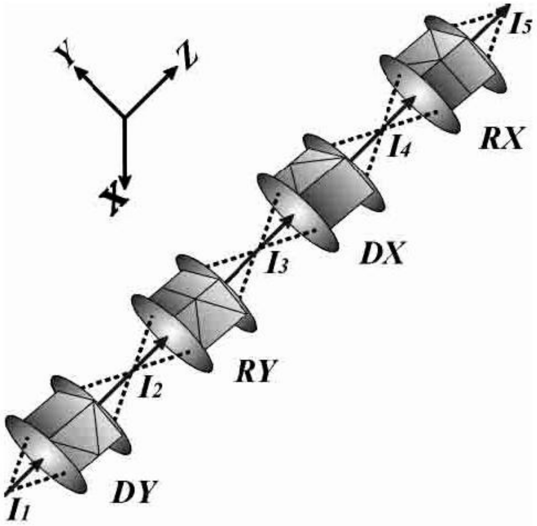


Fig. 2. Generic 3D optical scheme of the PKC. I1 is the input Airy pattern, DY is a direct vision dispersing prism in the Y direction, I2 corresponds to the first chromatic phase-knife parallel to Y. RY is a second direct-vision prism rotated by 180 degrees with respect to DY which superimposes the dispersed phase-knived airy patterns after DY. The following DX and RX operate exactly the same as DY and RY but orthogonal to them. The final coronagraphic pseudo-Airy pattern is depicted in Fig. 3 bottom-right.

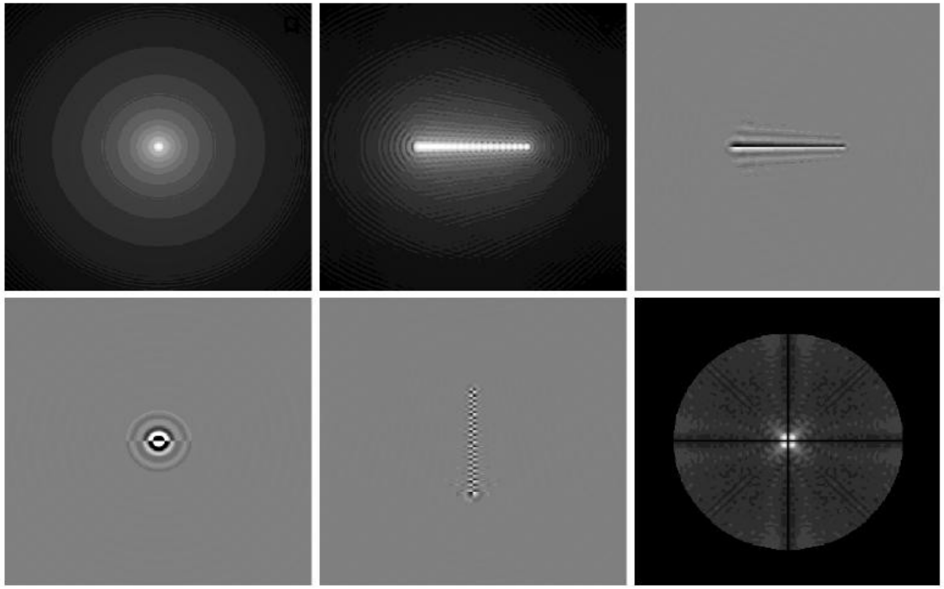
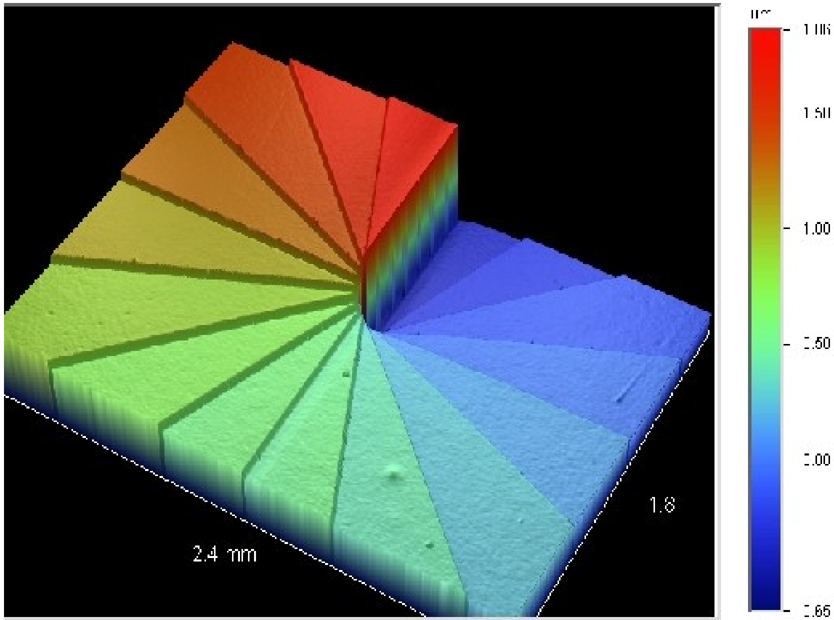


Fig. 3. Different steps of the phase-knife screen effect: (*top-left*) polychromatic Airy pattern (bandwidth: 400–800 nm) (corresponding to step I1 in Fig. 2), (*top-middle*) dispersed Airy disc, (*top-right*) the polychromatic phase-knife where the optical retardation follows the dispersion law (step I2), (*bottom-left*) an intermediate image plane where the Airy discs are de-dispersed (step I3), (*bottom-middle*) the polychromatic phase-knife applied in the perpendicular direction (step I4), (*bottom-right*) the polychromatic mutually phase-knived pseudo-Airy disc.

Abe et al. 2001, A&A, 374, 1161

Optical Vortex Coronagraph (OVC)

Phase in focal plane mask = Cst x PA



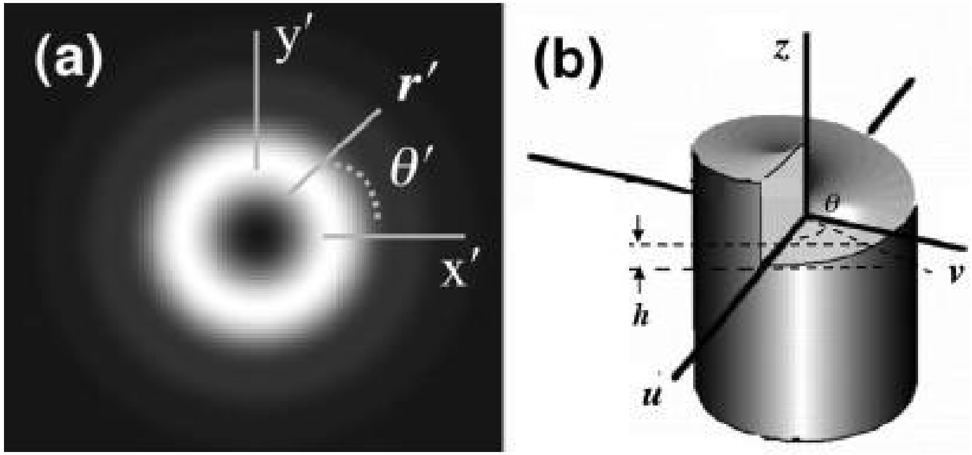


Fig. 2. (a) Intensity profile, $|U(x',y')|^2$ of a beam containing an optical vortex. (b) Surface profile of a VPM.

Palacios 2005, SPIE 5905, 196
Swartzlander 2006, Opt. Letters
Foo et al. 2005, Opt. Letters

Mawet et al. 2005, ApJ, 633, 1191 (AGPMC)

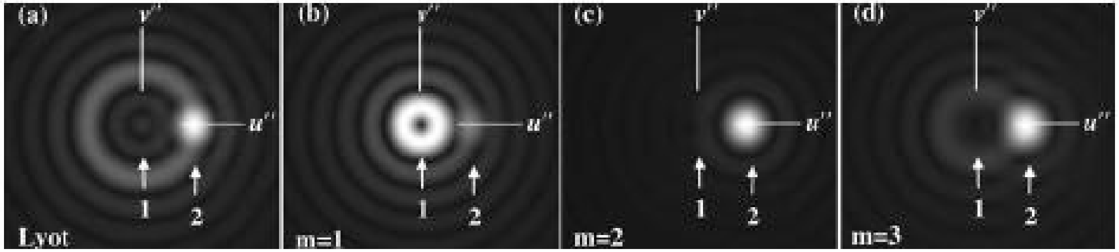
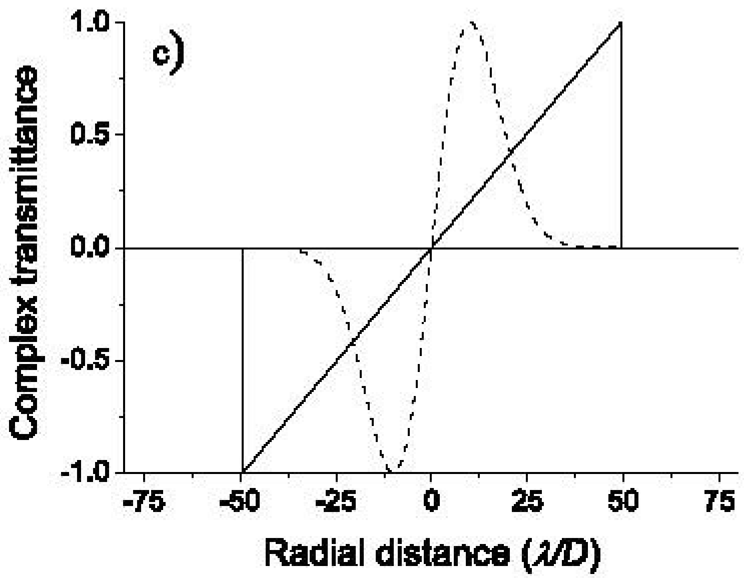


Fig. 3. Comparisons for $\alpha_2 = \alpha_{\text{diff}}$ and $A_1{}^2/A_2{}^2 = 100$. (a) Lyot coronagraph where $R_{\text{OM}} = r_{\text{diff}}$. (b), (c), (d) Vortex coronagraphs where $m=1$, $m=2$, $m=3$, respectively. In (c) the starlight is essentially eliminated, revealing a high-contrast image of the planet when $m=2$.

Optical Differentiation Coronagraph (ODC)

Optimized version of a single axis phase knife coronagraph.



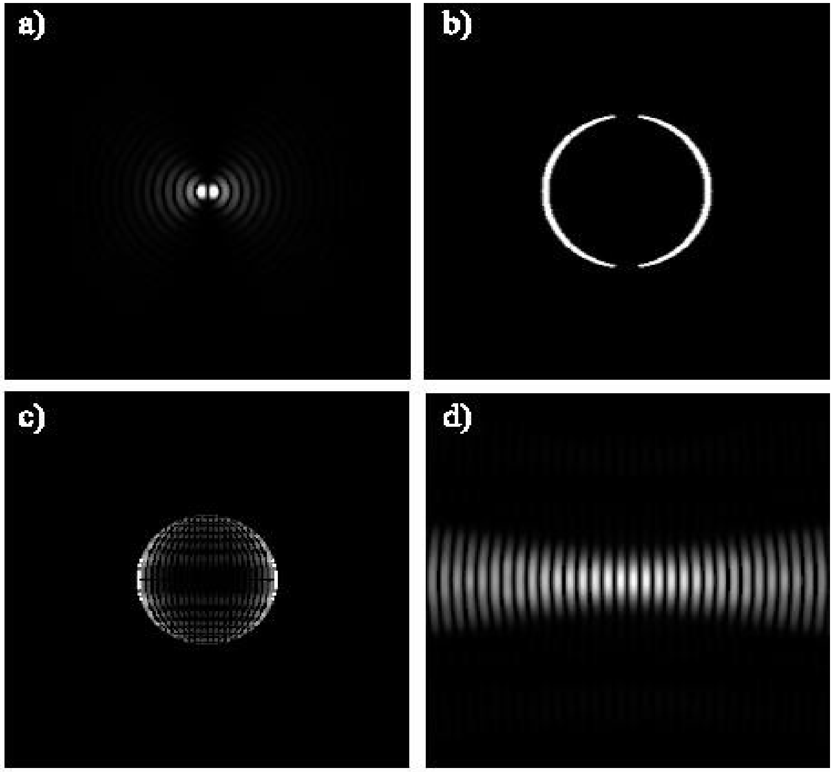
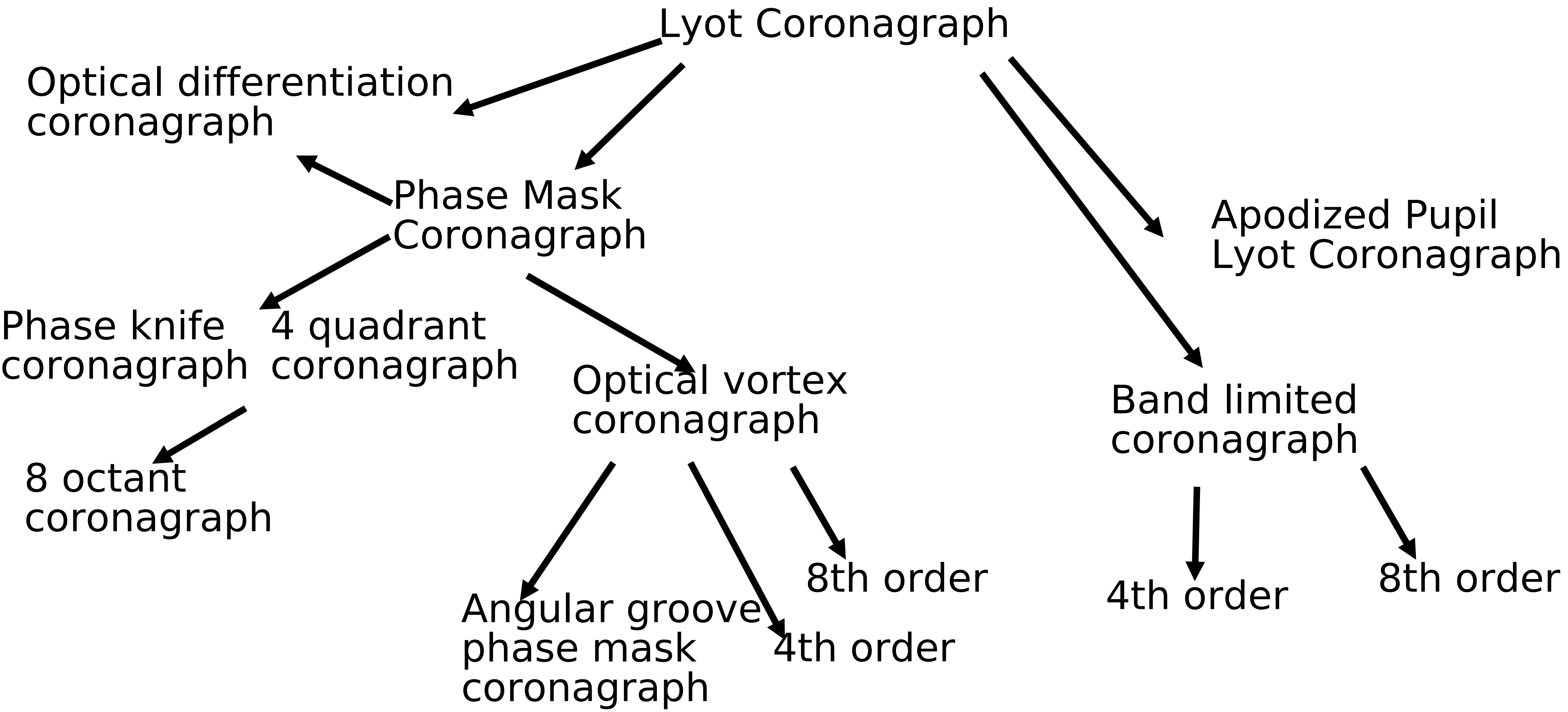


FIG. 3.—Simulated images at different planes in the optical differentiation coronagraph illustrating its principle of operation. (*a*) Image of the star PSF multiplied by the modified differentiation mask. (*b*) Intensity distribution just before (*b*) and after (*c*) the Lyot stop plane. (*d*) Final image detected at the CCD plane. Images are displayed in different intensity scales.

Oti et al., 2005, ApJ, 630, 631


Lyot Coronagraph
Optical differentiation coronagraph
Phase Mask Coronagraph
Apodized Pupil Lyot Coronagraph
Phase knife coronagraph
4 quadrant coronagraph
Optical vortex coronagraph
Band limited coronagraph
8 octant coronagraph
8th order
4th order
8th order
Angular groove phase mask coronagraph
4th order

Pupil Apodization

Since Airy rings originate from sharp edges of the pupil, why not change the pupil ?

Conventional Pupil Apodization/ Shaped pupil CPA

Kasdin et al. 2003

Make the pupil edges fainter by absorbing light, either with a continuous or ''binary'' (shaped pupil) mask

Achromatic Pupil Phase Apodization PPA

Yang & Kostinski, 2004

Same as CPA, but achieved by a phase apodization rather than amplitude

Phase Induced Amplitude Apodization Coronagraph PIAAC

Guyon, 2003

Perform amplitude apodization by remapping of the pupil with aspheric optics

Phase Induced Zonal Zernike Apodization PIZZA

Martinache, 2003

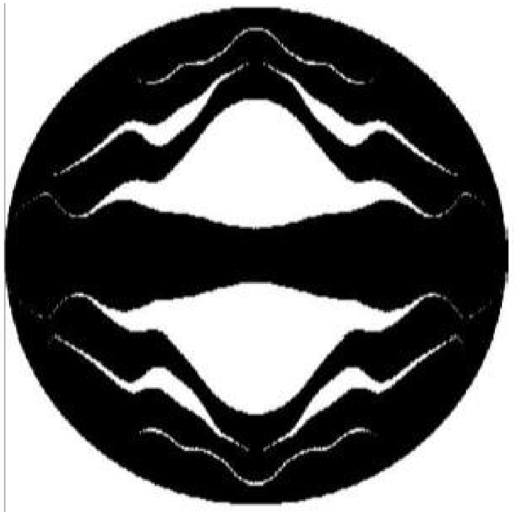
Transform a pupil phase offset into an amplitude apodization thanks to a focal plane Zernike mask

Conventional Pupil Apodization (CPA)

Many pupil apodizations have been proposed.

Apodization can be continuous or binary.

\+ Simple, robust, achromatic
\- low efficiency for high contrast



Jacquinot & Roisin-Dossier 1964
Kasdin et al. 2003, ApJ, 582, 1147
Vanderbei et al. 2003, ApJ, 590, 593
Vanderbei et al. 2003, ApJ, 599, 686
Vanderbei et al. 2004, ApJ, 615, 555

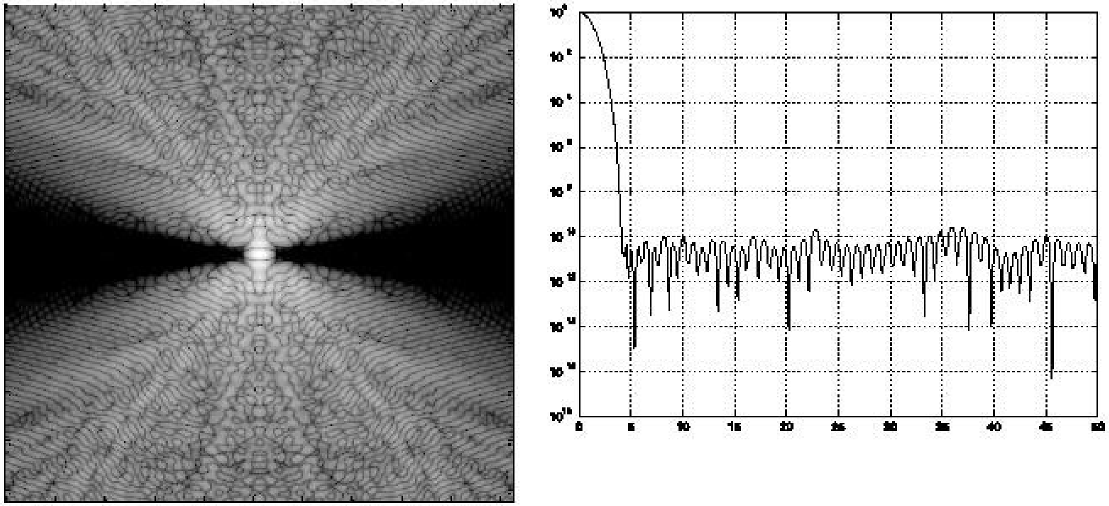


FIG. 9.—*Top*: Asymmetric multiopening mask designed to provide high-contrast, 10^{-10}, from $\lambda/D = 4$ to $\lambda/D = 100$ in two angular sectors centered on the x-axis. Ten integrations are required to cover all angles. Total throughput and pseudoarea are 24.4%. Airy throughput is 11.85%. *Bottom*: Associated PSF. (Note that this mask was originally designed for an elliptical mirror. It has been rescaled to fit a circular aperture.)

Pupil Phase Apodization (PPA)

Achromatic solutions exist.

Yang & Kostinski 2004, ApJ, 605, 892
Codona & Angel 2004, ApJ, 604, L117

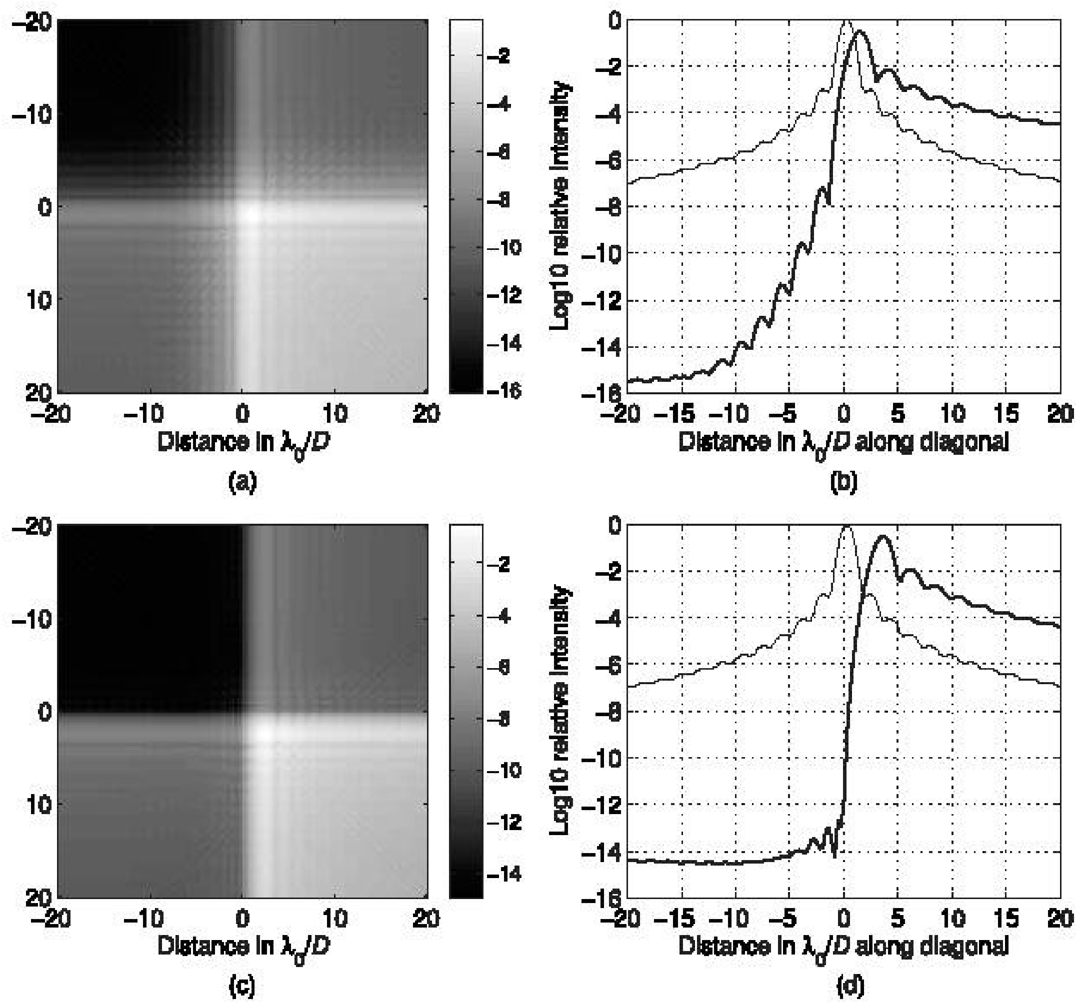
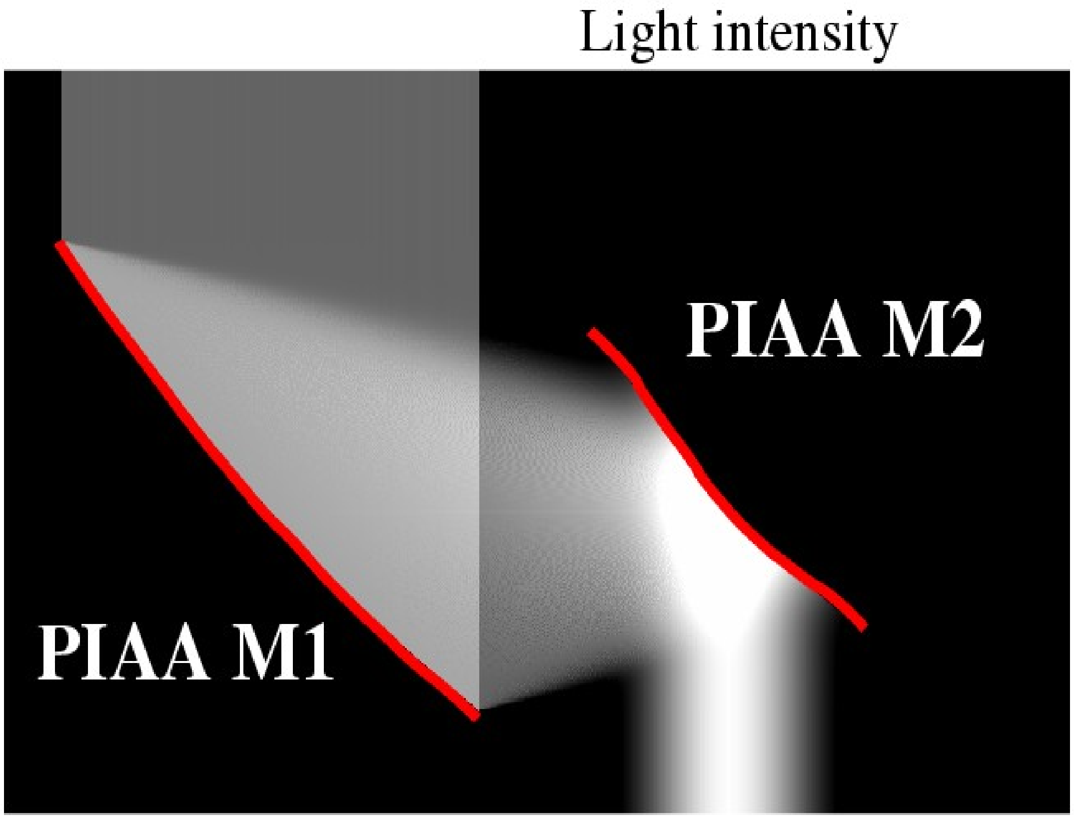


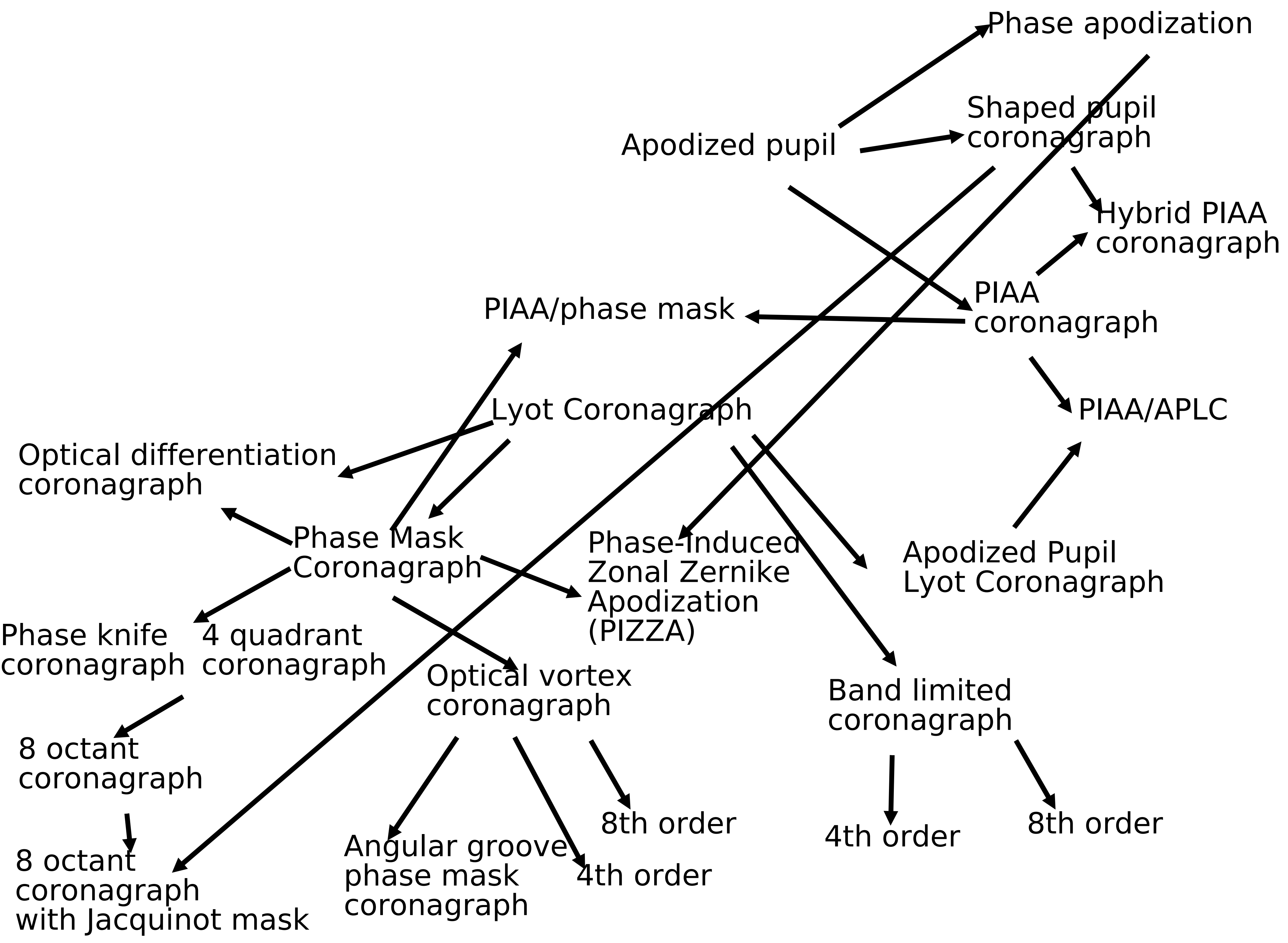
FIG. 9.—Broad-bandwidth light reduction effect on one quadrant of focal plane. The simulation is based on a rectangular spectrum distribution with total bandwidth of $0.6\lambda_0$. (*a*) $\log_{10}$ relative intensity image when phase $\phi(x, y) = a \tan[(0.5 - \epsilon)2\pi x/D] + a \tan[(0.5 - \epsilon)2\pi y/D]$, with $a = 1$ and $\epsilon = 0.005$, is applied to a square pupil. (*b*) The thicker line represents the $\log_{10}$ relative intensity along the diagonal line crossing the second and the fourth quadrants in (*a*). The thinner line represents the one without phase modulation. (*c*) Same as (*a*), but with phase $\phi(x, y)$ from eq. (11), with $a = 3$ and $\epsilon = 0.001$, applied to a square pupil. (*d*) Same as (*b*), but for the quadrants in (*c*). One can see that the reduction level of 10^{-12}, with an inner working distance of about $3.5\lambda_0/D$, can still be kept with a broad bandwidth of $0.6\lambda_0$ in the second quadrant.

Phase-Induced Amplitude Apodization Coronagraph (PIAAC)

Lossless apodization by aspheric optics.



Guyon, Belikov, Pluzhnik, Vanderbei, Traub, Martinache ... 2003-present


Phase apodization
Shaped pupil coronagraph
Apodized pupil
Hybrid PIAA coronagraph
PIAA coronagraph
PIAA/phase mask
Lyot Coronagraph
PIAA/APLC
Optical differentiation coronagraph
Phase Mask Coronagraph
Phase-Induced Zonal Zernike Apodization (PIZZA)
Apodized Pupil Lyot Coronagraph
Phase knife coronagraph
4 quadrant coronagraph
Optical vortex coronagraph
Band limited coronagraph
8 octant coronagraph
8th order
4th order
8th order
Angular groove phase mask coronagraph
4th order
8 octant coronagraph with Jacquinot mask

''Interferometric'' coronagraphs

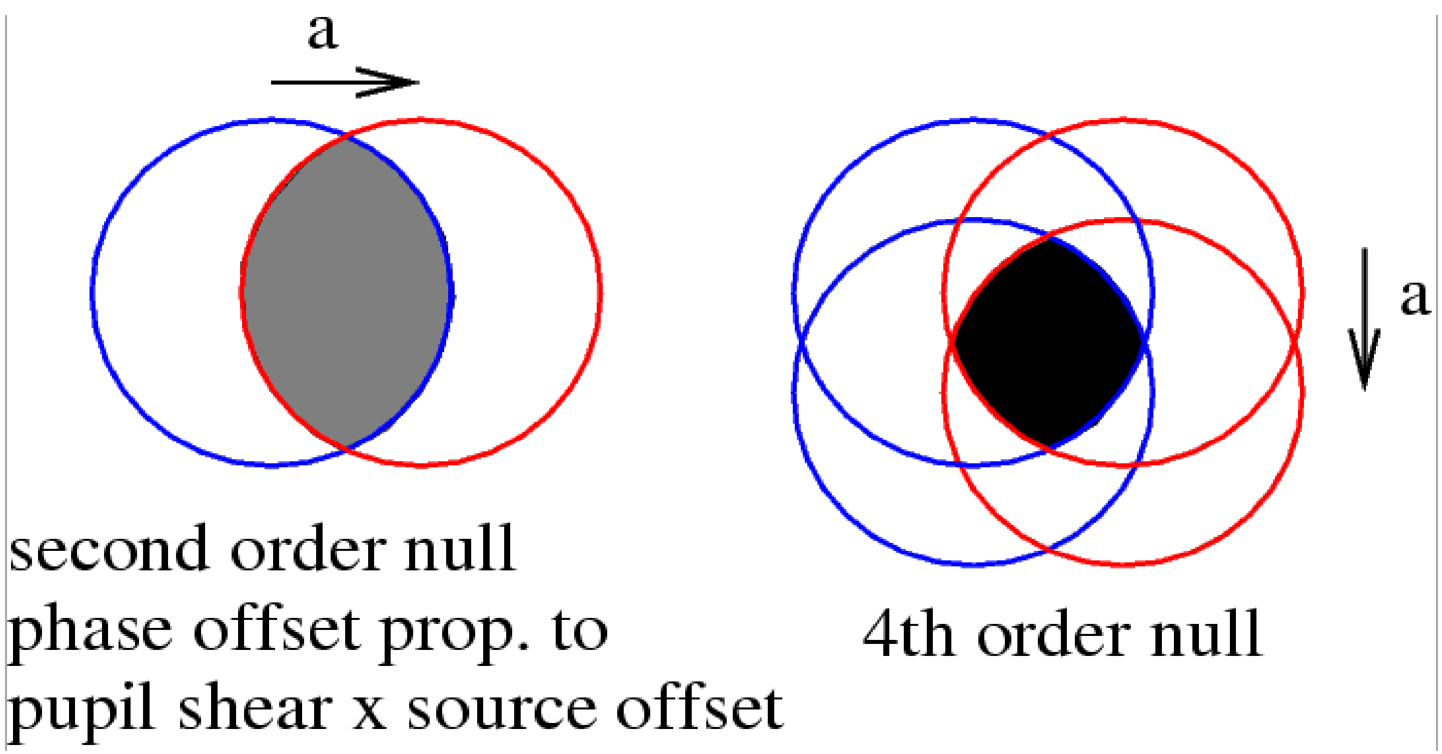
= Nulling interferometer on a single pupil telescope
- Creates multiple (at least 2) beams from a single telescope beam
- Combines them to produce a destructive interference on-axis and constructive interference off-axis

Achromatic Interferometric Coronagraph **AIC**
Common Path AIC **CPAIC**
Baudoz et al. 2000, Tavrov et al. 2005
Destructive interference between pupil and flipped copy of the pupil
Achromatic PI phase shift and geometrical flip performed by going through focus

Visible Nulling Coronagraph, X & Y shear, 4th order **VNC**
Shao et al., Menesson et al. 2003
Destructive interference between 2 copies of the pupil, sheared by some distance.
4th order null obtained by cascading 2 shear/null

Pupil Swapping Coronagraph **PSC**
Guyon & Shao, 2006
Destructive interference between pupil and a copy of the pupil where 4 quadrants have been swapped

Visible Nuller Coron. (VNC)



Small shear : high throughput, low IWA
Large shear : low throughput, small IWA
The 2 shears can also be colinear

Will fly soon on sounding rocket (PICTURE)

Mennesson, Shao ... 2003, SPIE 4860, 32

tic interfero coronagraphy. I.

Achromatic Interferometric Coronagraph (AIC)

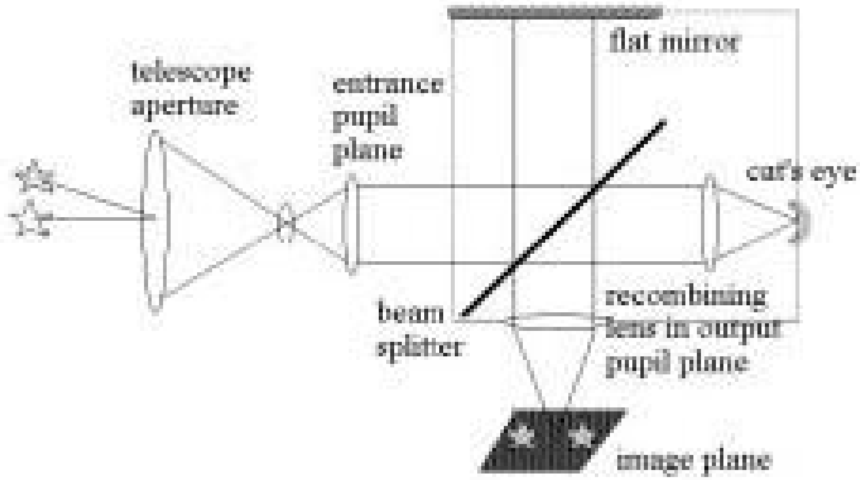


Fig. 1. Schematic of the Generic Set-up of our coronagraph

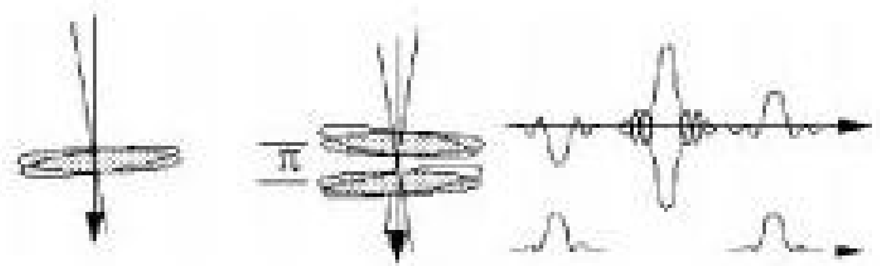


Fig. 2. Left: collected wavefronts, one from the central source the other (tilted) from a companion. Center: wavefronts on the recombiner lens. Right: amplitudes and resulting intensity in image plane

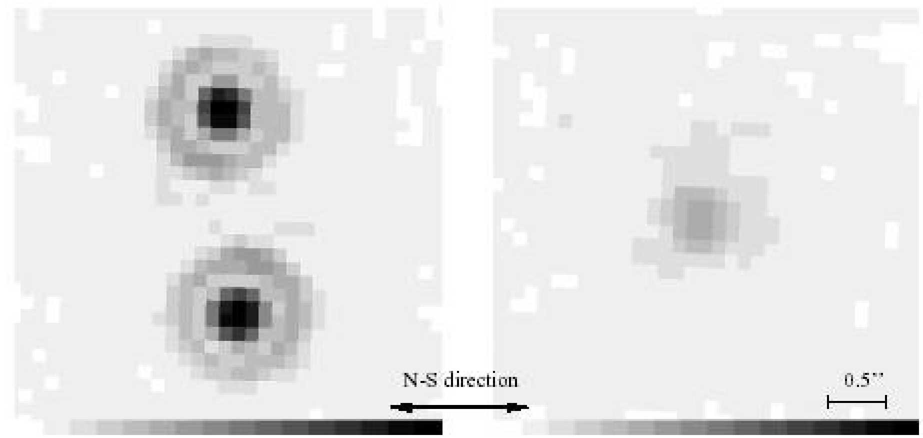
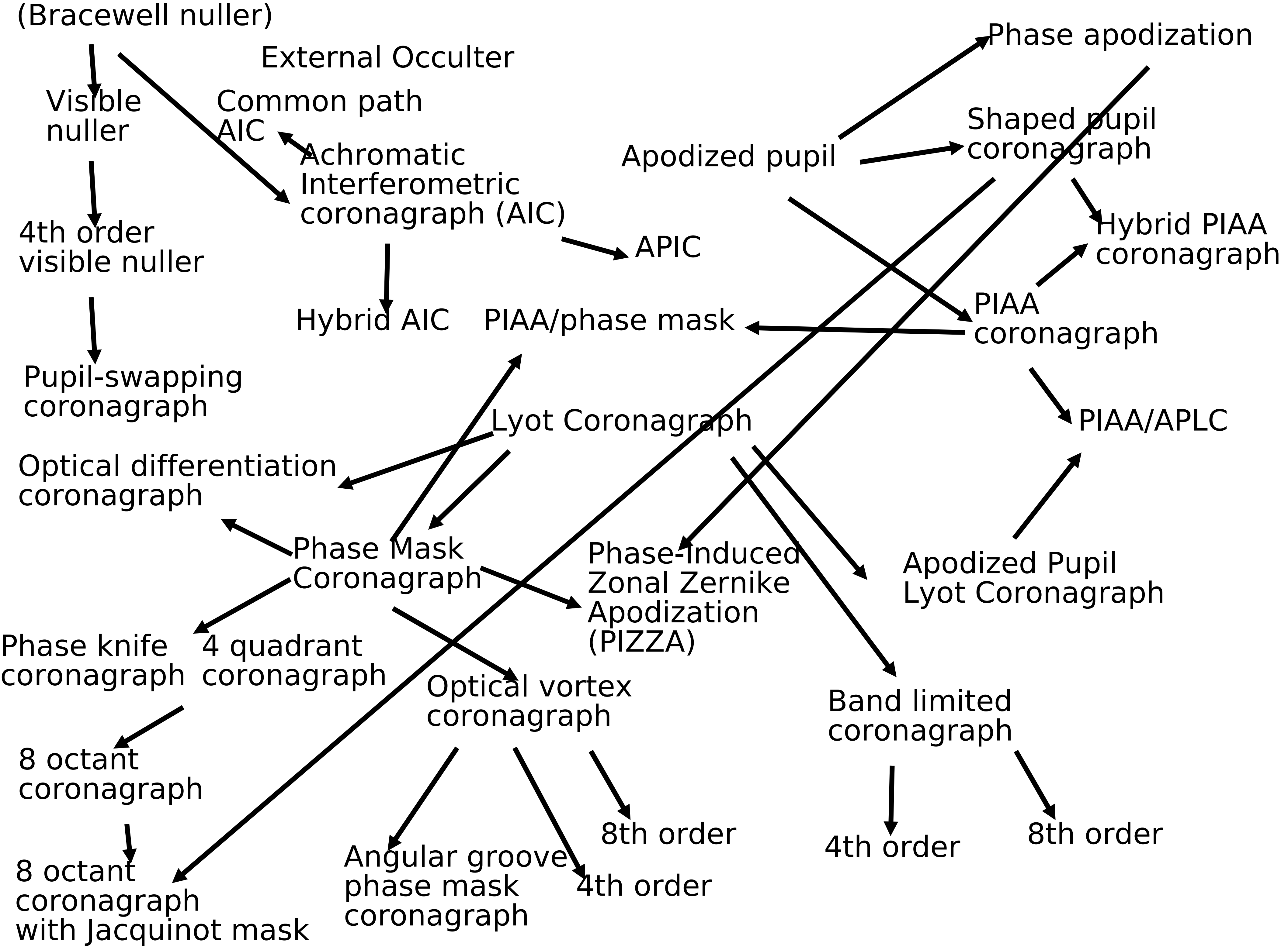


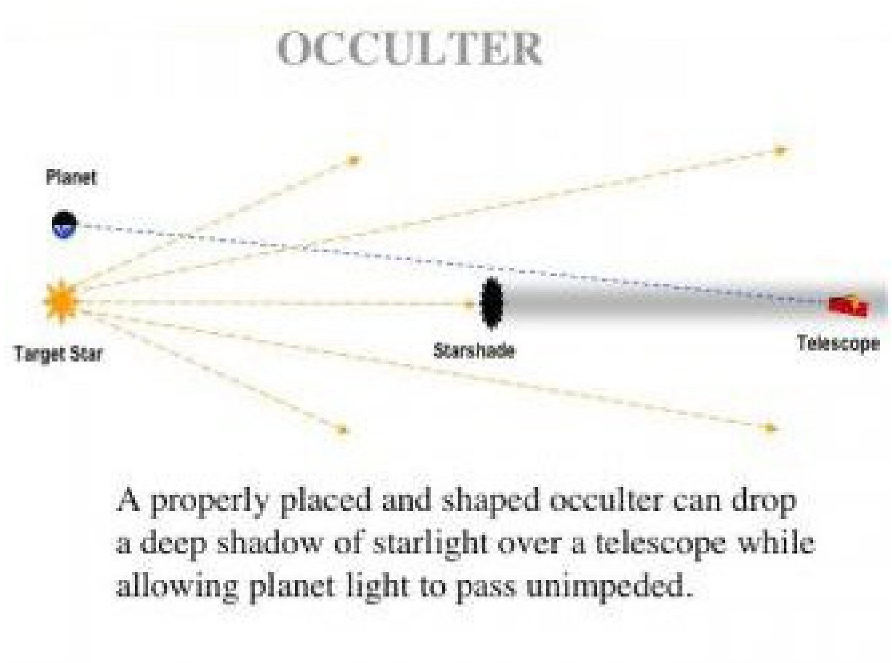
Fig. 3. Image of a star off-axis and on-axis. The scale is linear and is the same for the 2 images

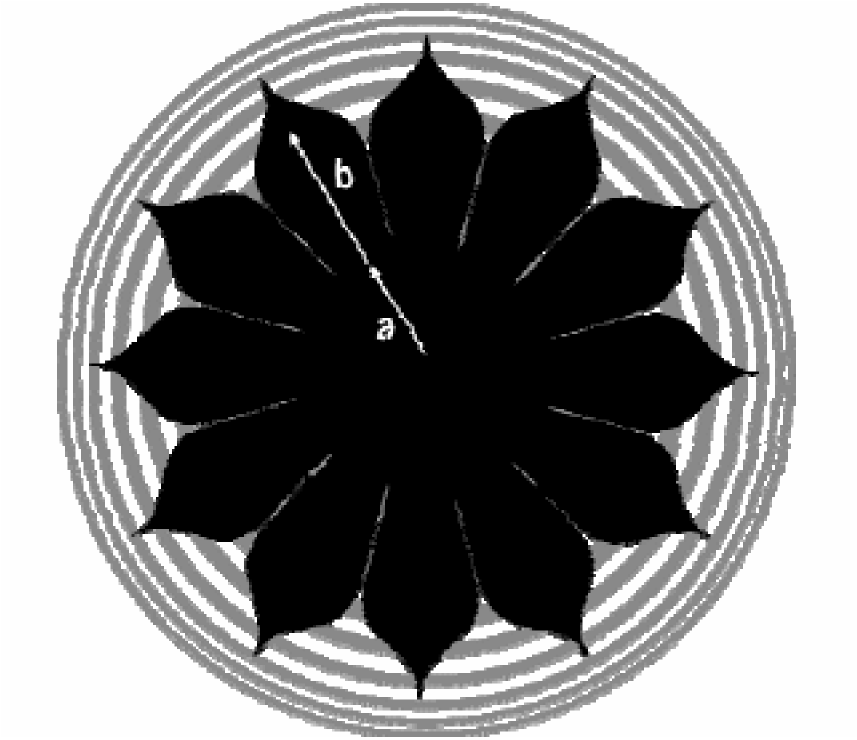
Used on sky (CFHT)

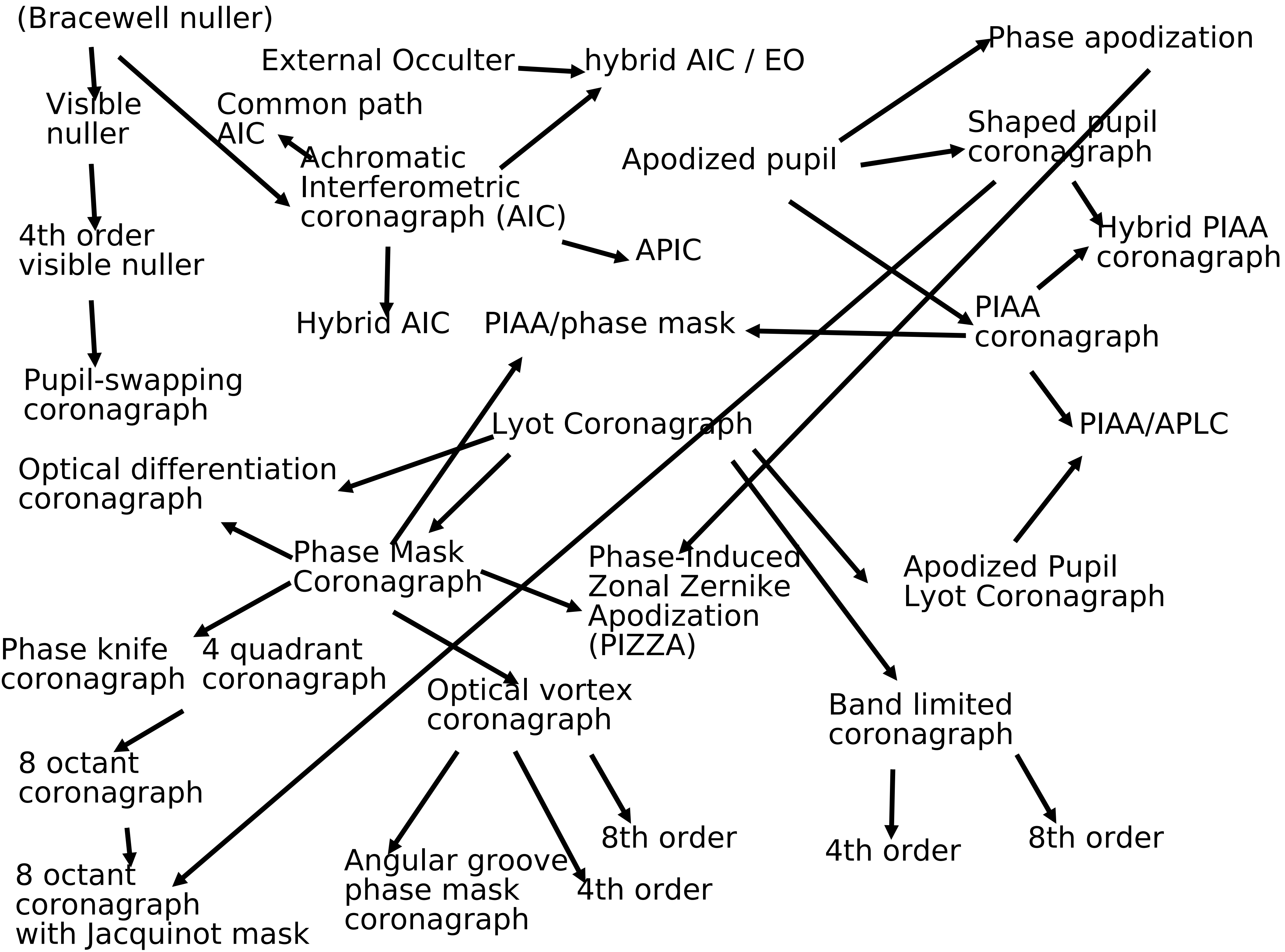
Gay & Rabbia 1996, C.R. Acad. Sci. Paris 322, 265
Baudoz et al. 2000, A&AS, 141, 319
Baudoz et al. 2005, PASP, 117, 1004 (Hybrid AIC, no 180 deg ambiguity)
Tavrov et al. 2005, Opt. Letters, 30, 2224 (Common path AIC)

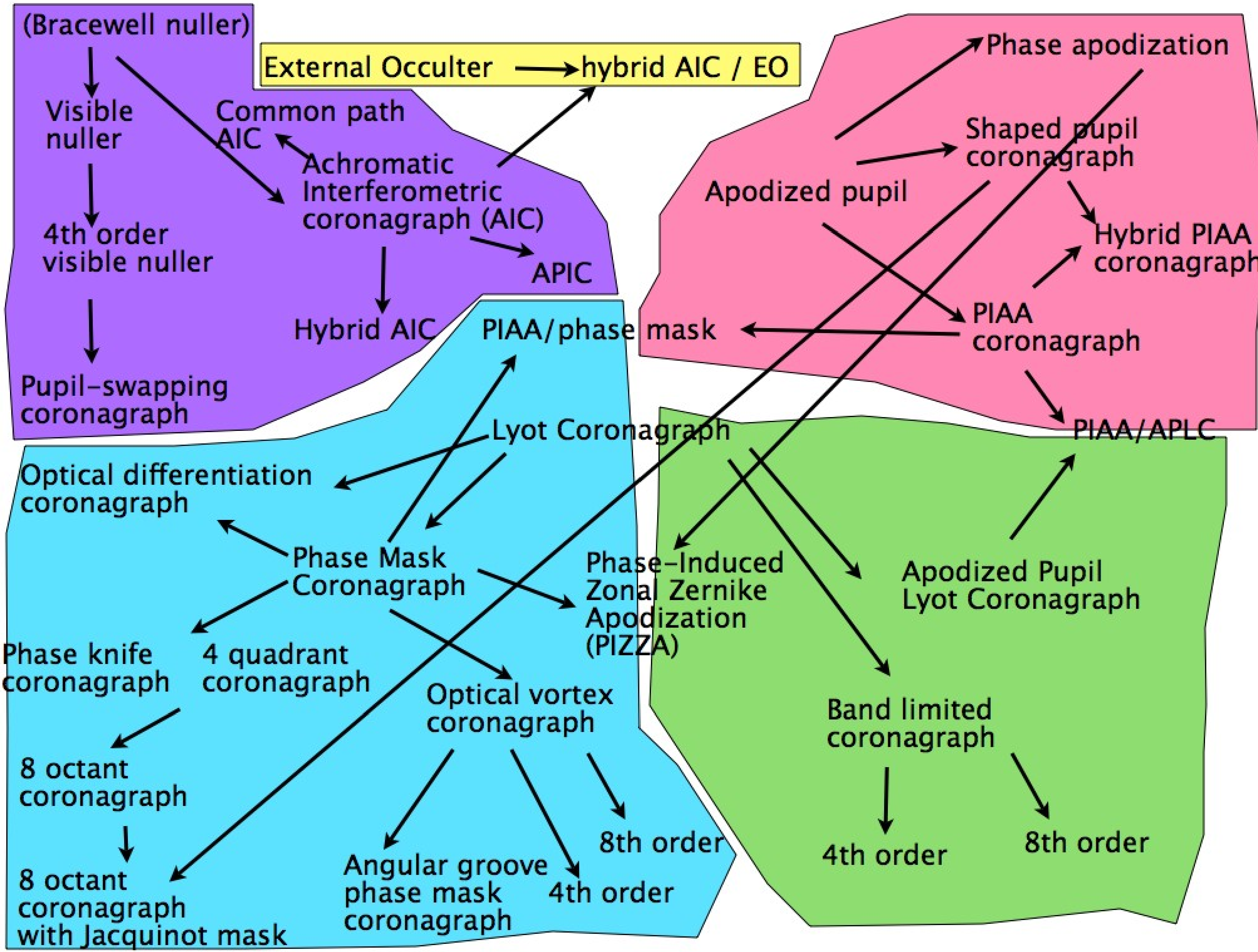

(Bracewell nuller)
External Occulter
Phase apodization
Visible nuller
Common path AIC
Shaped pupil coronagraph
Apodized pupil
Achromatic Interferometric coronagraph (AIC)
Hybrid PIAA coronagraph
4th order visible nuller
APIC
PIAA coronagraph
Hybrid AIC
PIAA/phase mask
Pupil-swapping coronagraph
Lyot Coronagraph
PIAA/APLC
Optical differentiation coronagraph
Phase Mask Coronagraph
Phase-Induced Zonal Zernike Apodization (PIZZA)
Apodized Pupil Lyot Coronagraph
Phase knife coronagraph
4 quadrant coronagraph
Optical vortex coronagraph
Band limited coronagraph
8 octant coronagraph
8th order
4th order
8th order
8 octant coronagraph with Jacquinot mask
Angular groove phase mask coronagraph
4th order

External Occulter






(Bracewell nuller)
External Occulter
hybrid AIC / EO
Phase apodization
Visible nuller
Common path AIC
Achromatic Interferometric coronagraph (AIC)
Apodized pupil
Shaped pupil coronagraph
4th order visible nuller
APIC
Hybrid PIAA coronagraph
Hybrid AIC
PIAA/phase mask
PIAA coronagraph
Pupil-swapping coronagraph
Lyot Coronagraph
PIAA/APLC
Optical differentiation coronagraph
Phase Mask Coronagraph
Phase-Induced Zonal Zernike Apodization (PIZZA)
Apodized Pupil Lyot Coronagraph
Phase knife coronagraph
4 quadrant coronagraph
Optical vortex coronagraph
Band limited coronagraph
8 octant coronagraph
8th order
4th order
8th order
8 octant coronagraph with Jacquinot mask
Angular groove phase mask coronagraph
4th order


(Bracewell nuller)
Visible nuller
4th order visible nuller
Pupil-swapping coronagraph
Common path AIC
Achromatic Interferometric coronagraph (AIC)
APIC
Hybrid AIC
External Occulter
hybrid AIC / EO
Phase apodization
Shaped pupil coronagraph
Apodized pupil
Hybrid PIAA coronagraph
PIAA coronagraph
PIAA/phase mask
PIAA/APLC
Lyot Coronagraph
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Phase Mask Coronagraph
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Apodized Pupil Lyot Coronagraph
Phase knife coronagraph
4 quadrant coronagraph
Optical vortex coronagraph
Band limited coronagraph
8 octant coronagraph
8 octant coronagraph with Jacquinot mask
Angular groove phase mask coronagraph
8th order
4th order
4th order
8th order