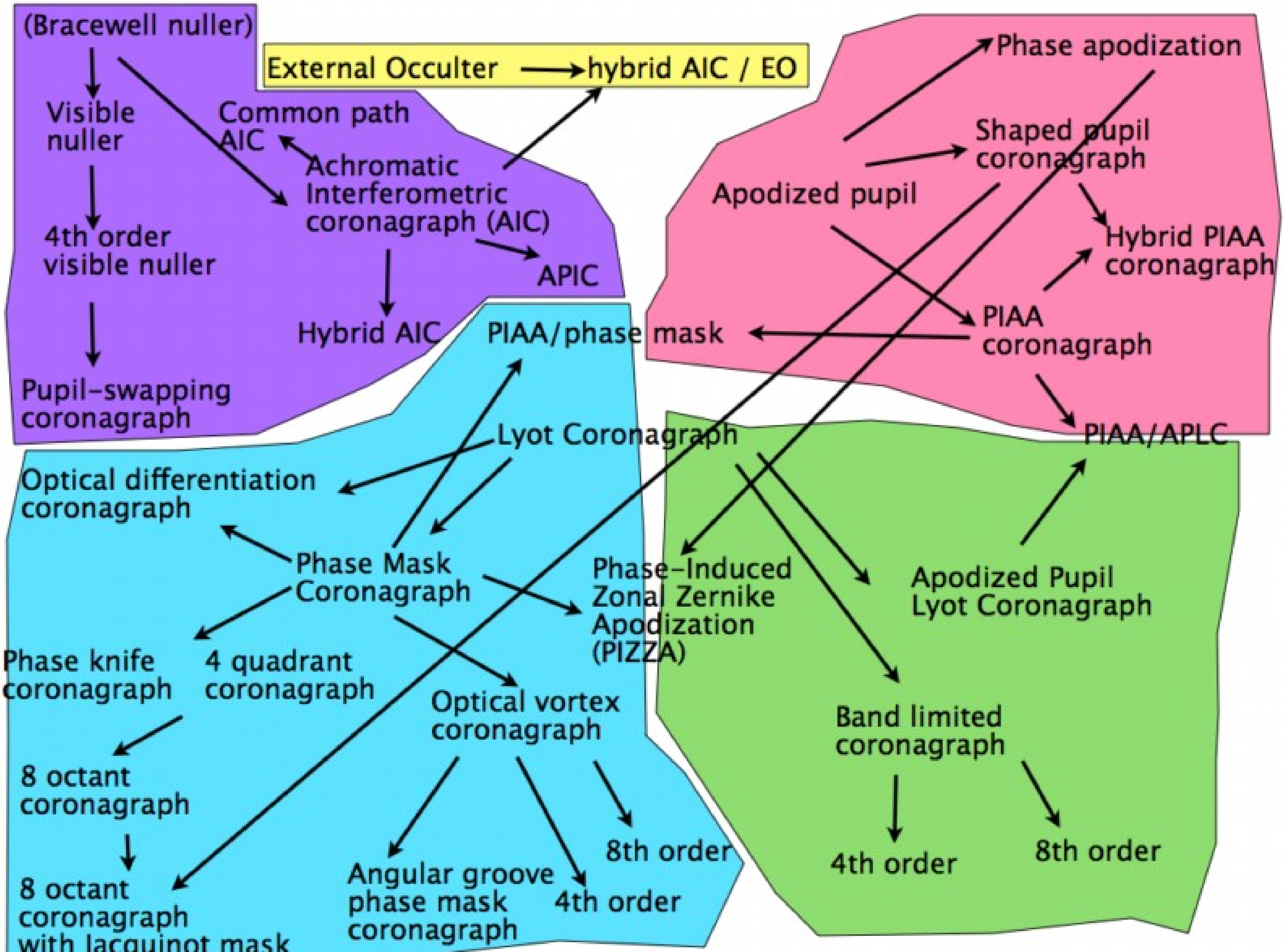
Coronagraph concepts & systems

Types of coronagraphs

Coronagraph systems & instruments


(Bracewell nuller)
External Occulter
hybrid AIC / EO
Visible nuller
Common path AIC
Achromatic Interferometric coronagraph (AIC)
4th order visible nuller
APIC
Hybrid AIC
Pupil-swapping coronagraph
Phase apodization
Shaped pupil coronagraph
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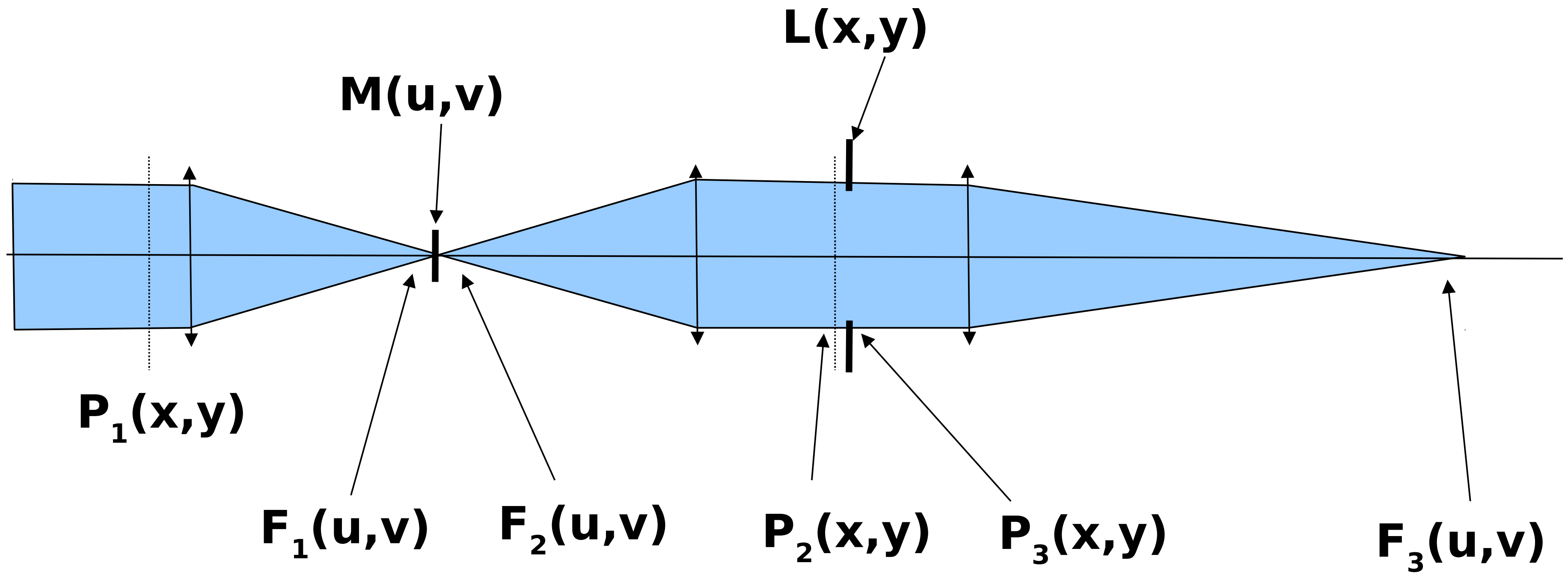
Angular groove phase mask coronagraph
4th order

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

Full set of equations (explained in next slides):

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

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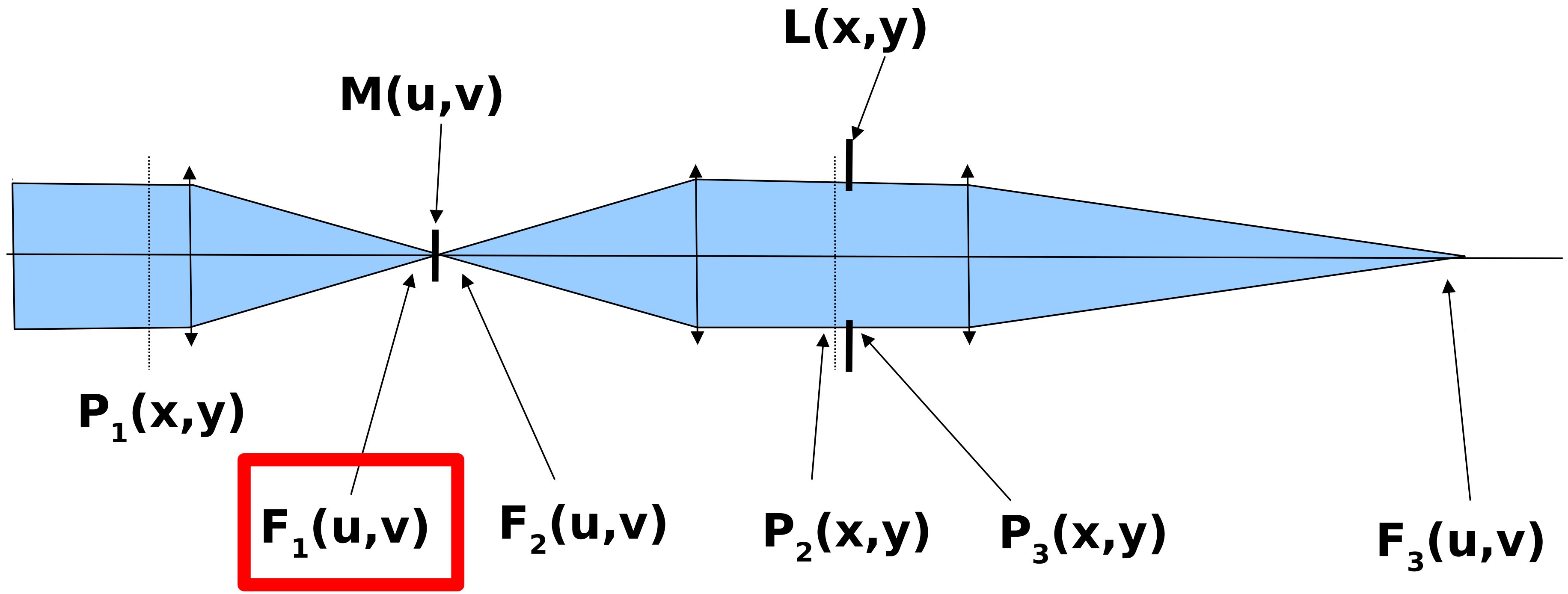
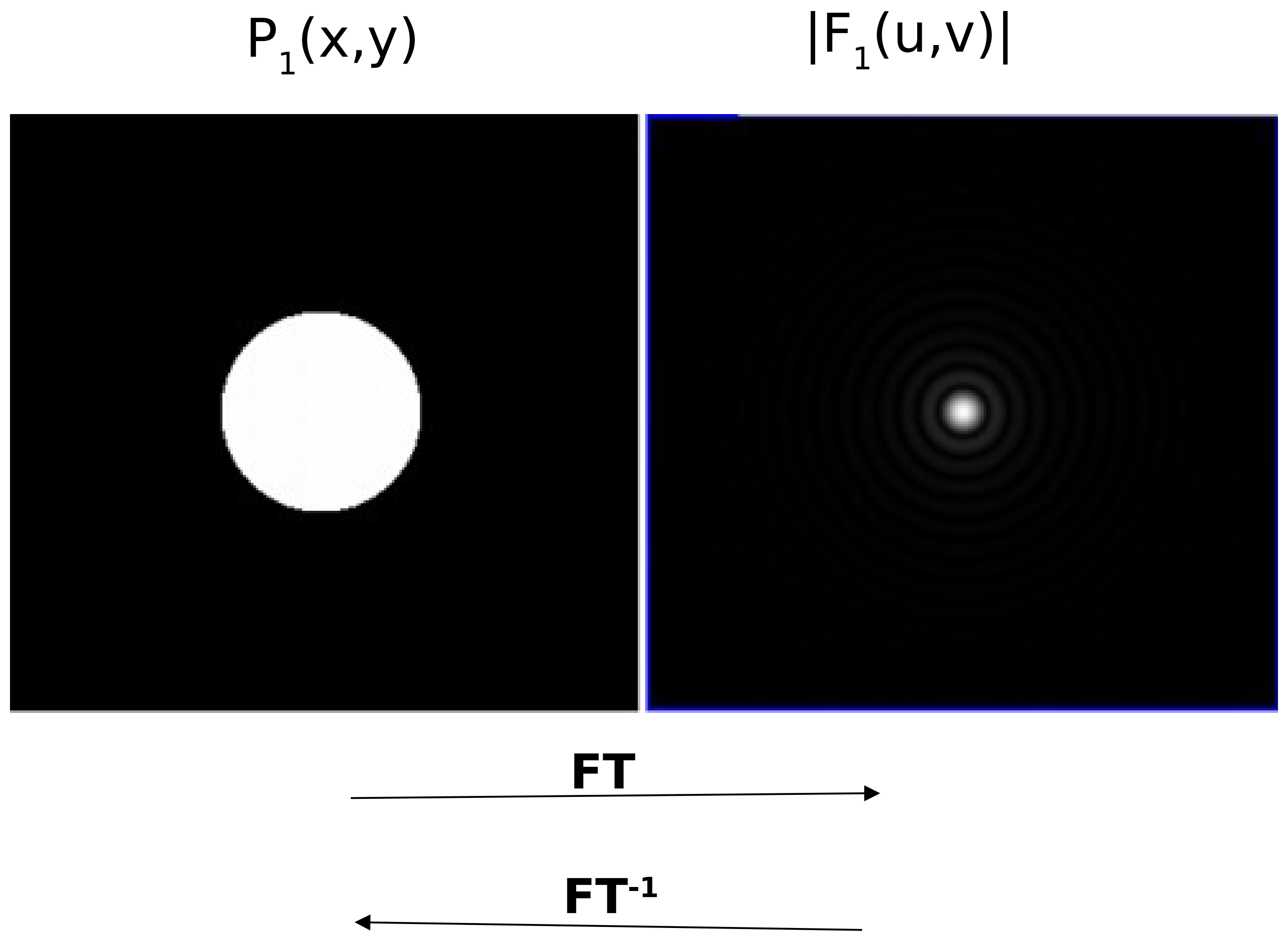


Focal plane image = FT of pupil complex amplitude

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

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→ Fourier transform
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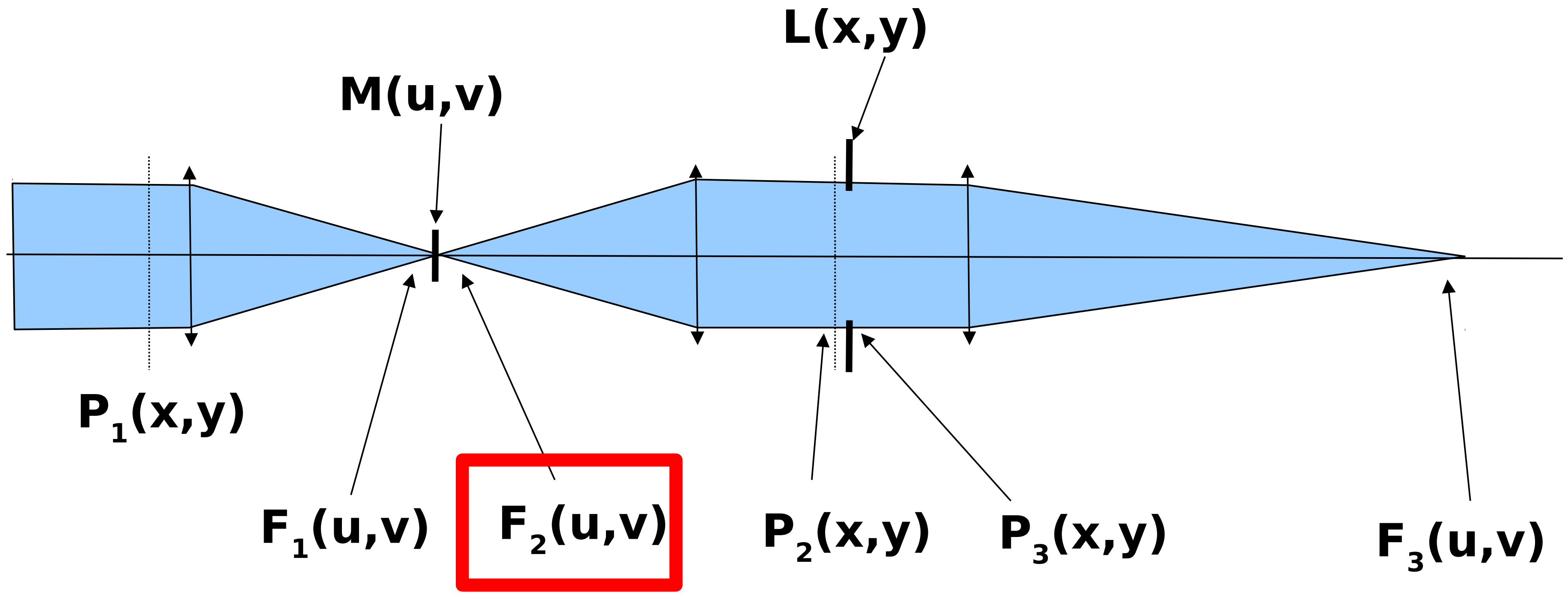
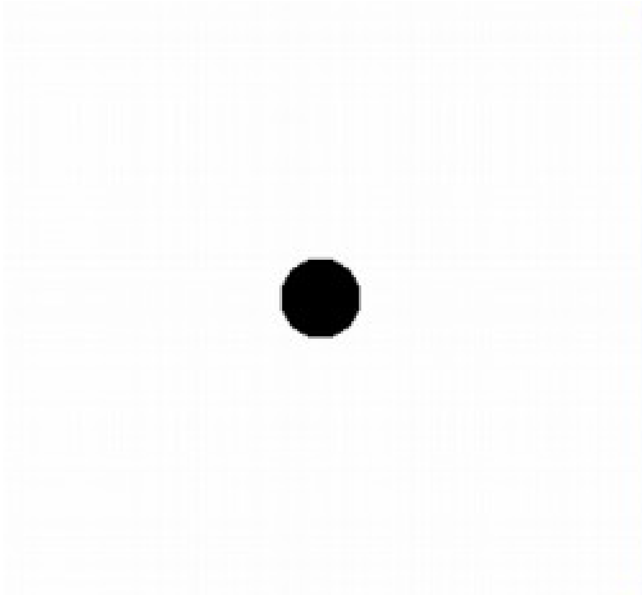


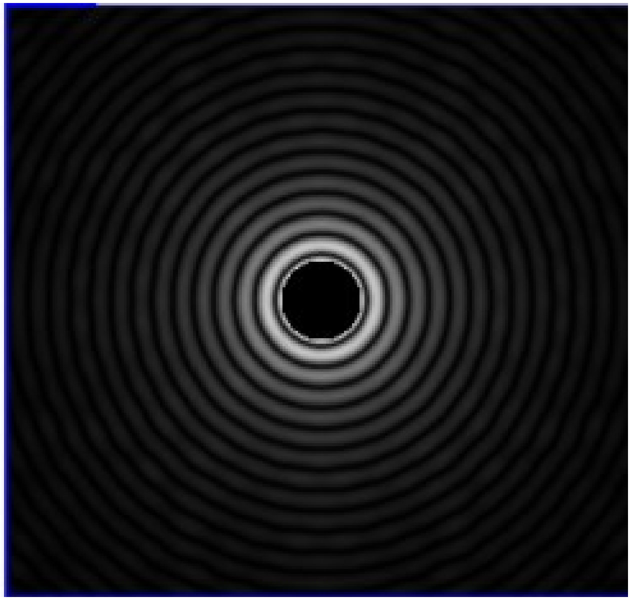
Inserting an opaque mask in the focal plane

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

Pupil plane complex amplitude ↔ focal plane complex amplitude

→ Fourier transform
← Inverse Fourier transform

Coordinates in pupil plane: x,y
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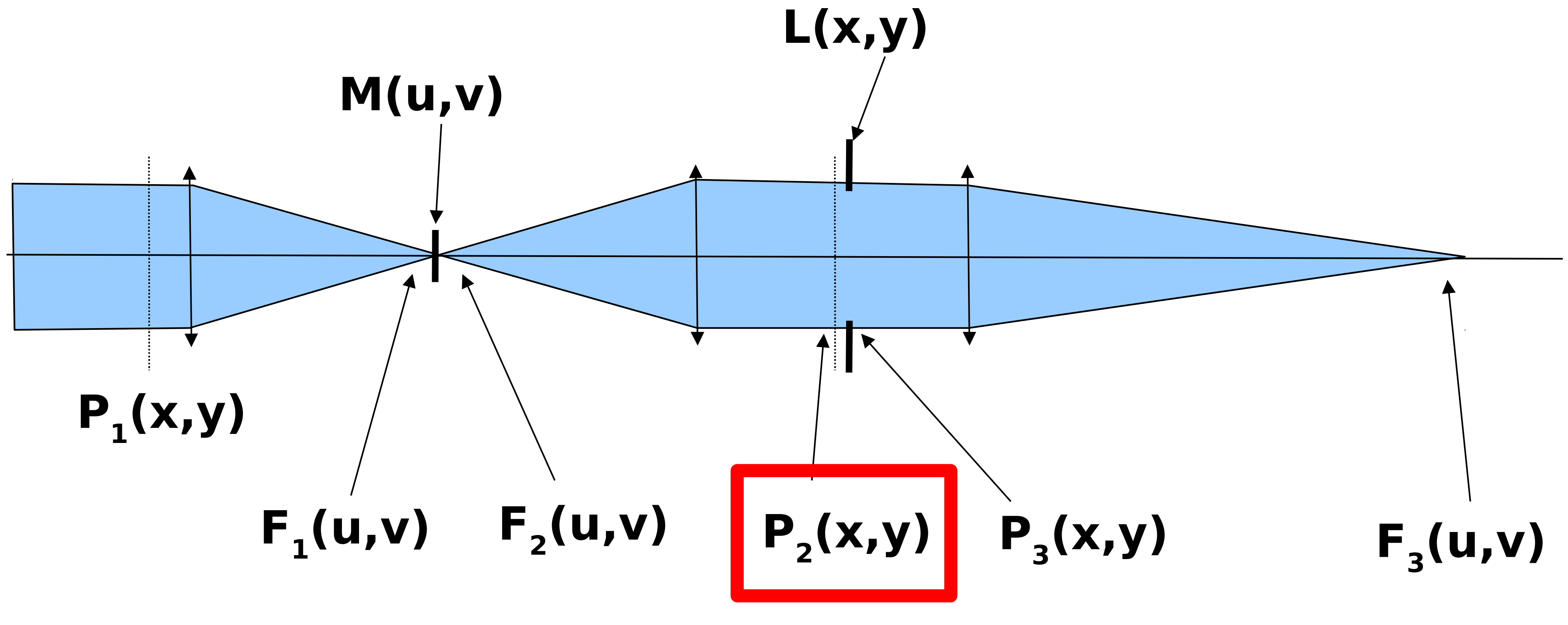


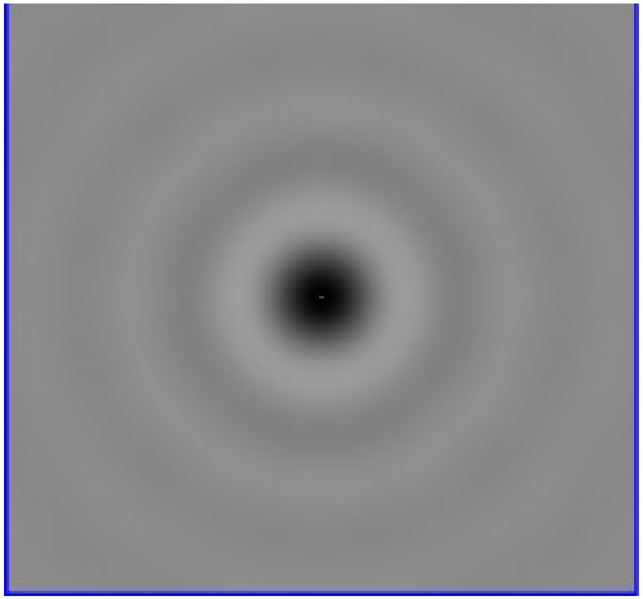
Lyot Coronagraph : light distribution in output pupil plane

Exit pupil plane:

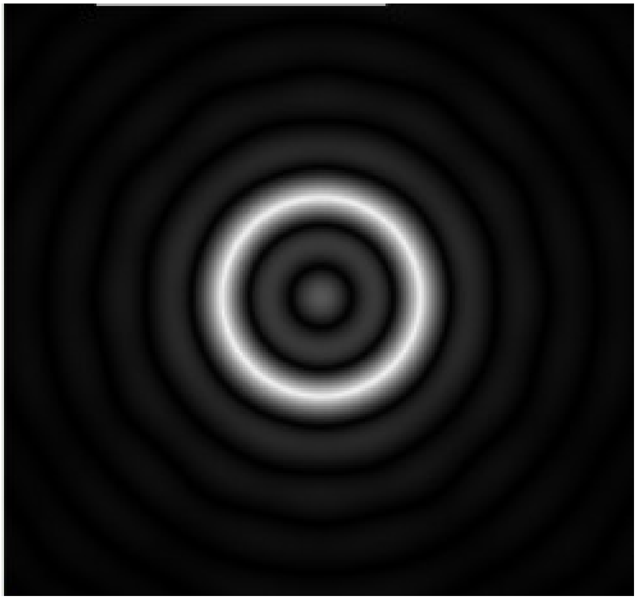
$P_2(x,y) = FT^{-1}(F_2(u,v))$

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

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



$|P_2(x,y)|$



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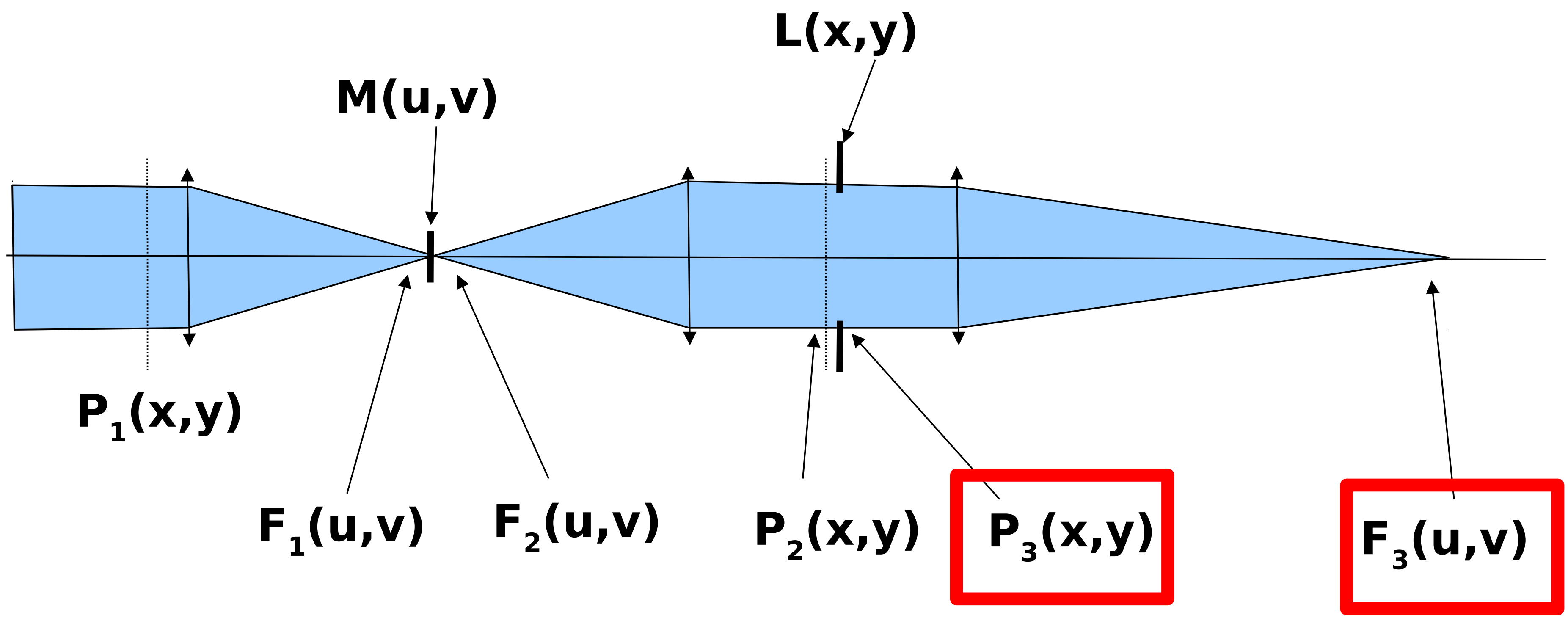


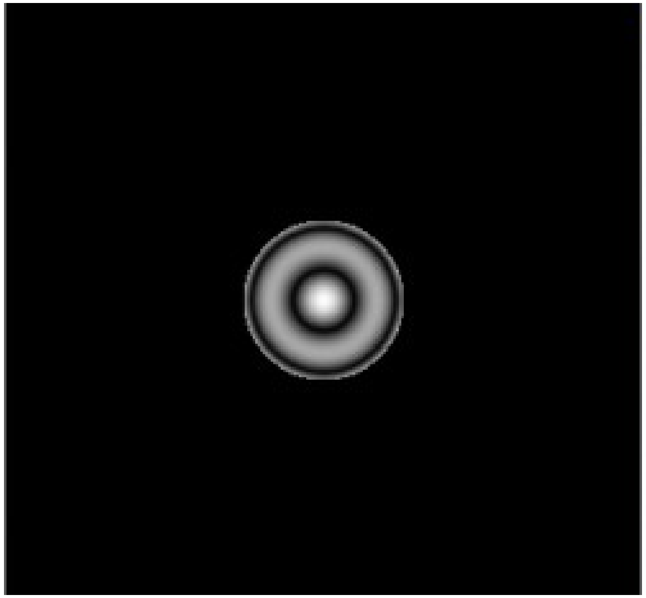
Lyot Coronagraph : Lyot stop (L)

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

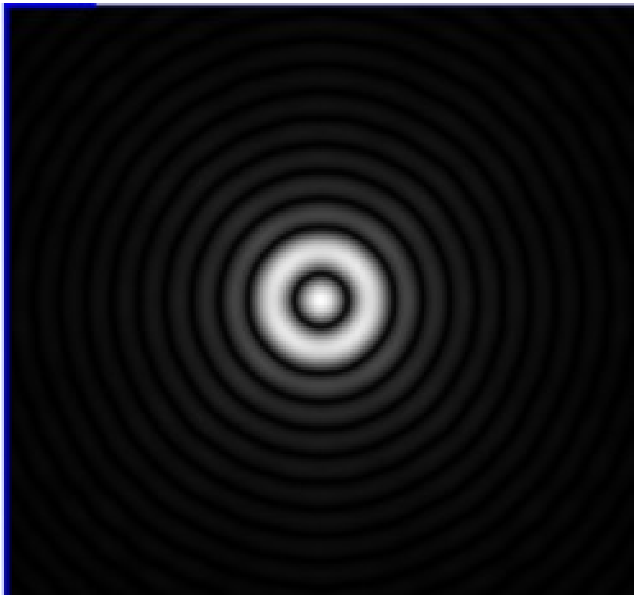
$\mathbf{P_3(x,y) = L(x,y) \times (P_1(x,y) * FT^{-1}(M(u,v)))}$

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

$|P_3(x,y)|$



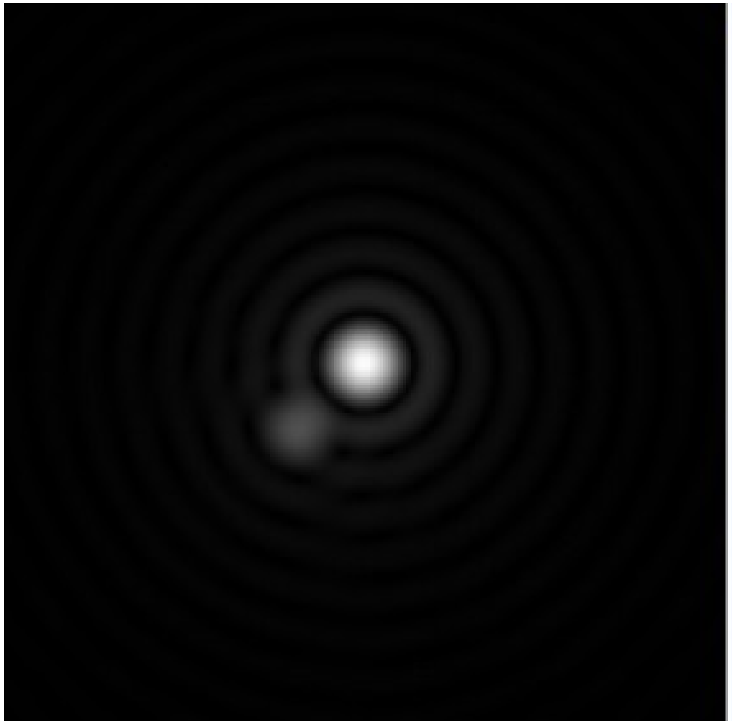
$|F_3(u,v)|$

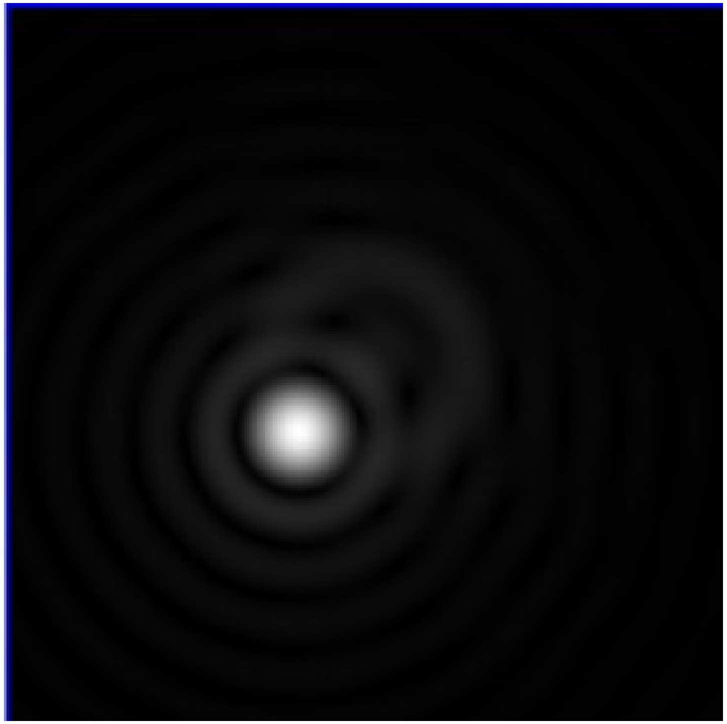


Numerical simulation of final image for 10:1 contrast

No coronagraph

With Lyot Coronagraph





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

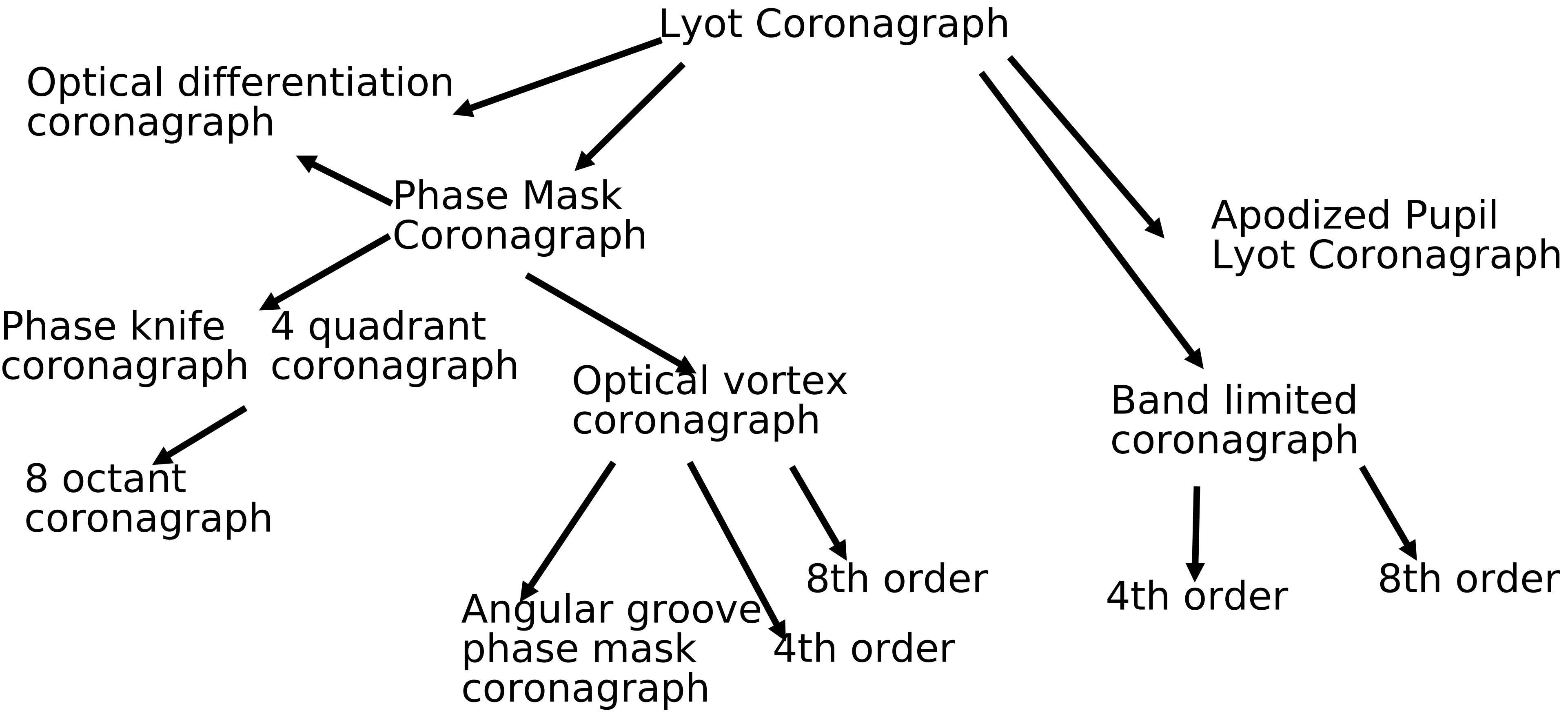
Optimization goal: make pupil dark inside Lyot mask

Possible optimizations include:

(1) Redesign of focal plane mask

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

(2) Apodize entrance aperture



Lyot Coronagraph
Optical differentiation coronagraph
Phase Mask Coronagraph
Apodized Pupil Lyot Coronagraph
Phase knife coronagraph
4 quadrant coronagraph
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Band limited coronagraph
8 octant coronagraph
8th order
4th order
8th order
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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

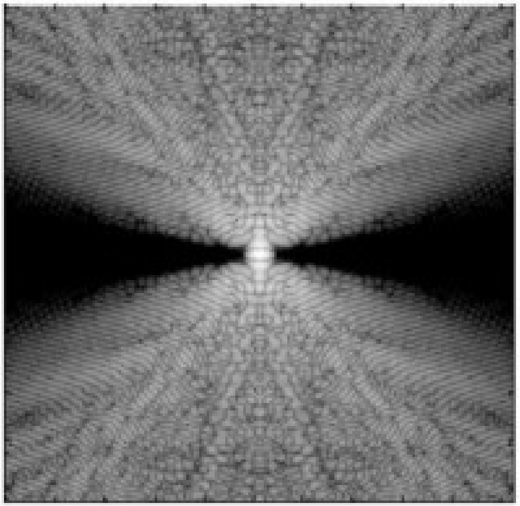
Conventional Pupil Apodization (CPA)

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



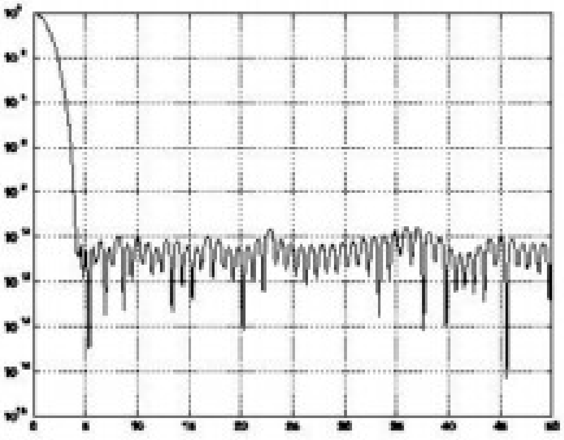


Fig. 9.—*Top*: Asymmetric multiopening mask designed to provide high-contrast, 10^{-10}, from $\lambda/D = 4$ to $\lambda/D = 100$ in two angular sectors centered on the x-axis. Ten integrations are required to cover all angles. Total throughput and pseudoarea are 24.4%. Airy throughput is 11.85%. *Bottom*: 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.

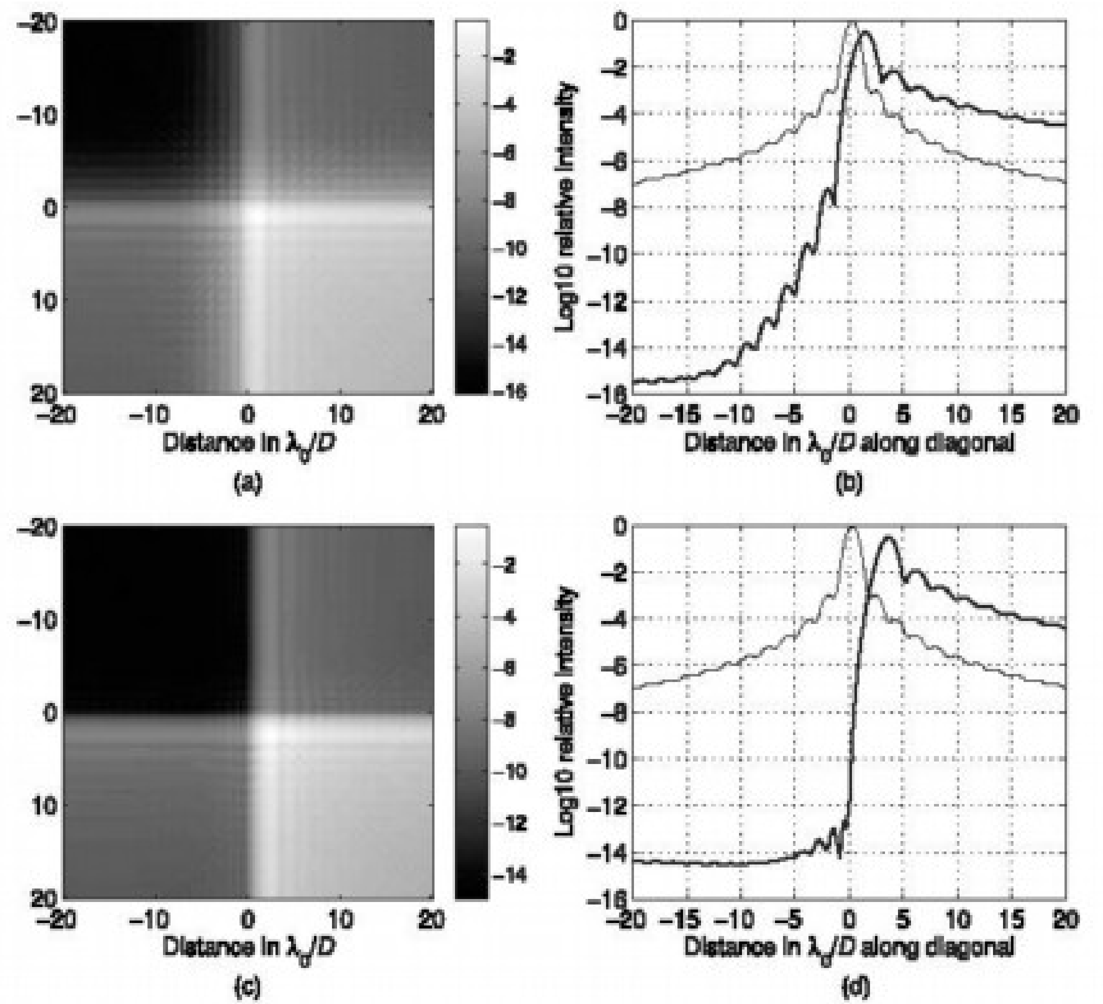
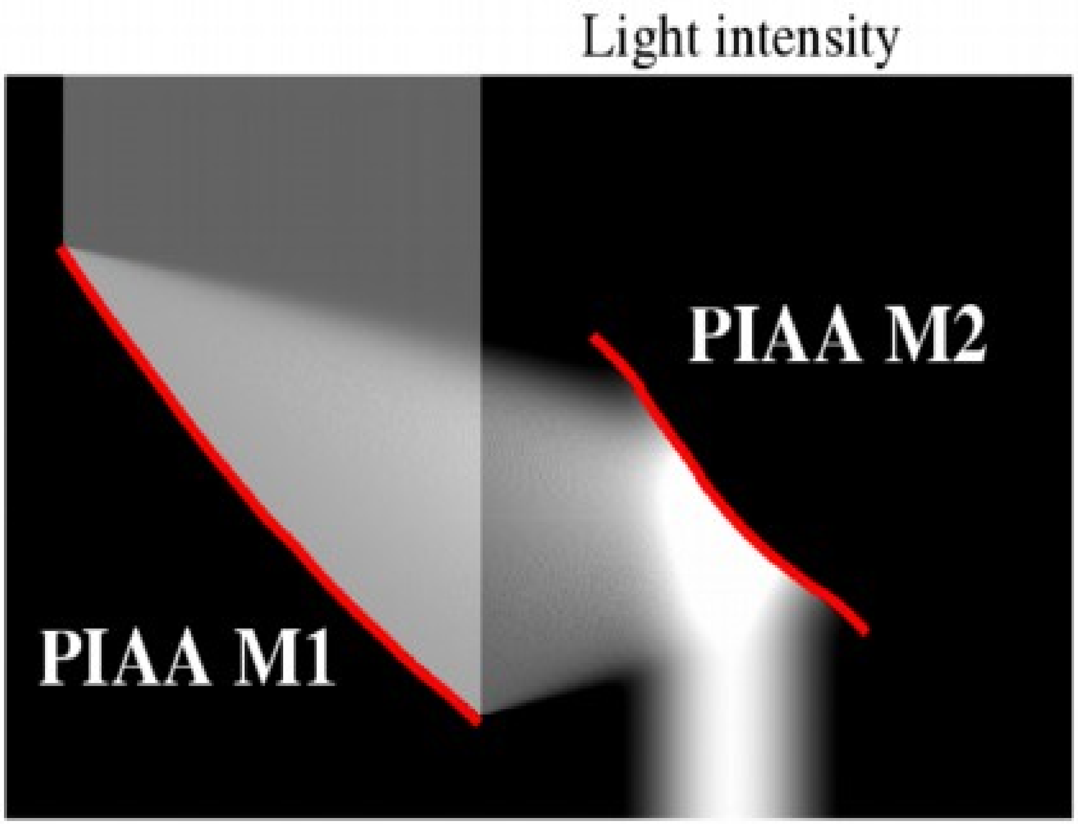


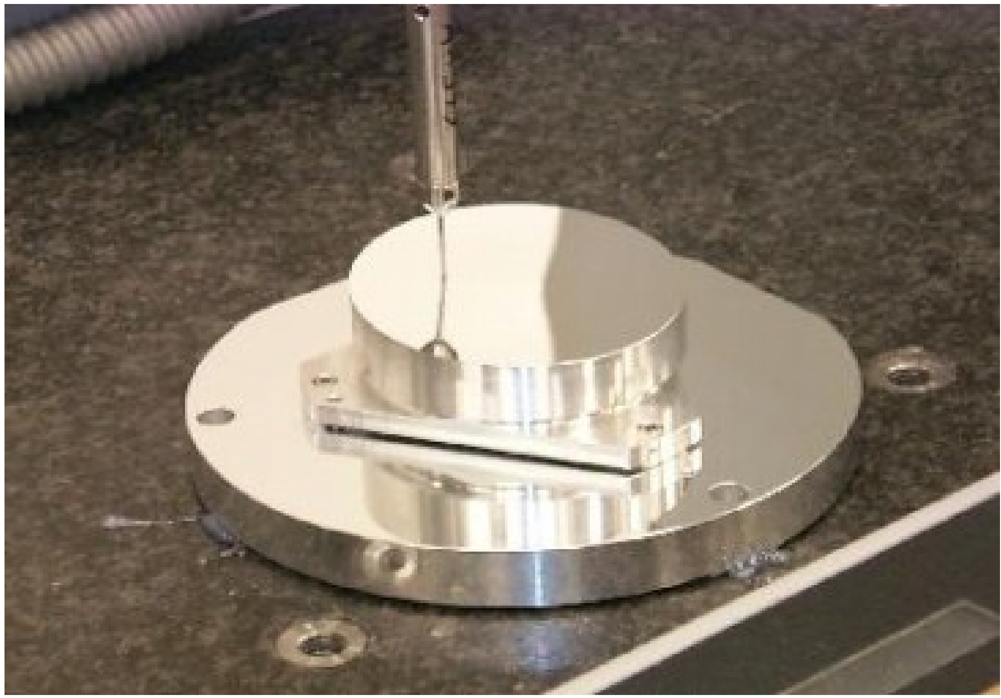
FIG. 9.—Broad-bandwidth light reduction effect on one quadrant of focal plane. The simulation is based on a rectangular spectrum distribution with total bandwidth of $0.6\lambda_0$. (*a*) $\log_{10}$ relative intensity image when phase $\phi(x, y) = a\tan[(0.5-\epsilon)2\pi x/D] + a\tan[(0.5-\epsilon)2\pi y/D]$, 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.

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

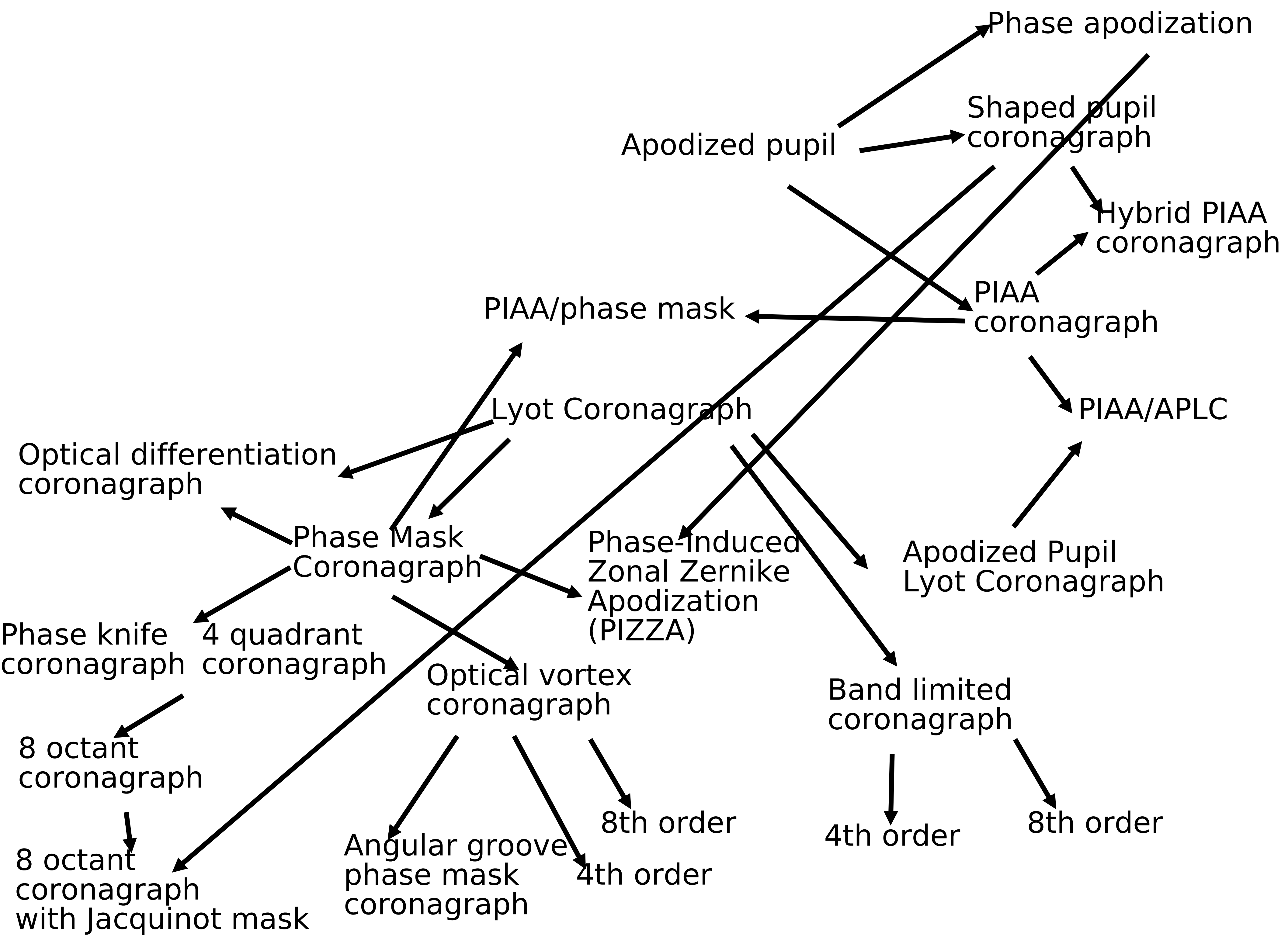
Phase-Induced Amplitude Apodization Coronagraph (PIAAC)

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
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PIAA/APLC
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8th order
4th order
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4th order

''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, 4^{th} order **VNC**

Shao et al., Menesson et al. 2003

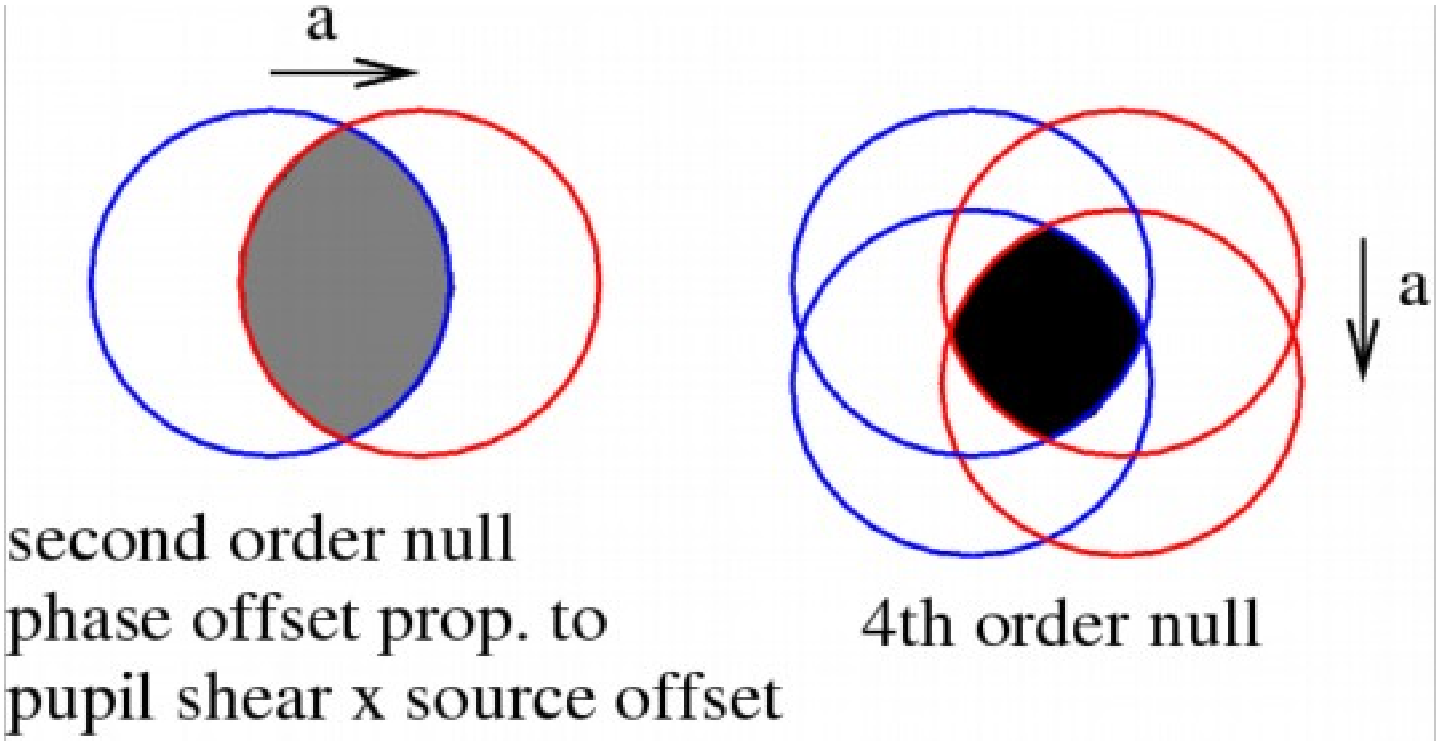
Destructive interference between 2 copies of the pupil, sheared by some distance.
4^{th} order null obtained by cascading 2 shear/null

Pupil Swapping Coronagraph **PSC**

Guyon & Shao, 2006

Destructive interference between pupil and a copy of the pupil where 4 quadrants have been swapped

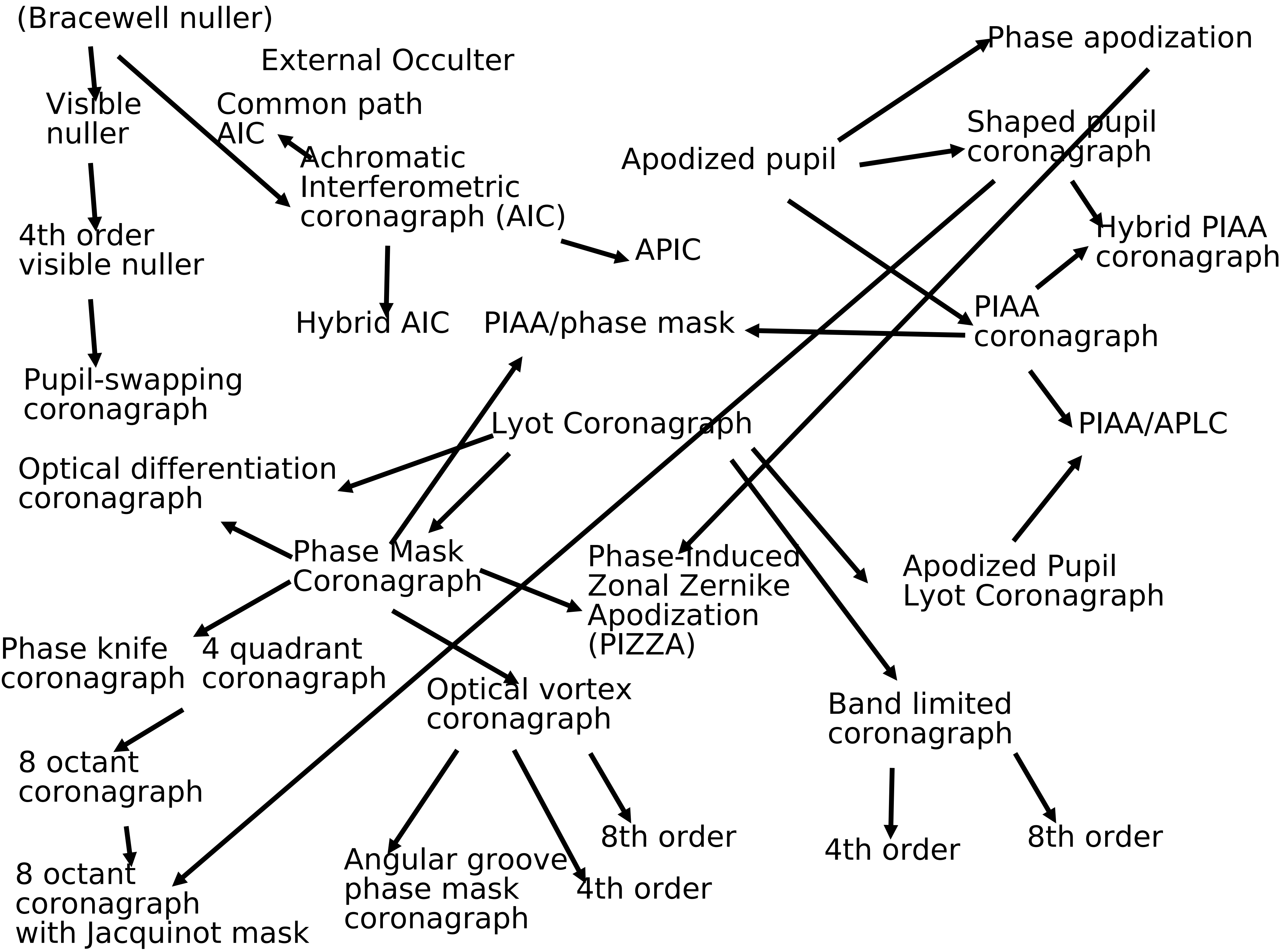
Visible Nuller Coron. (VNC)



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

Sounding rocket (PICTURE)

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



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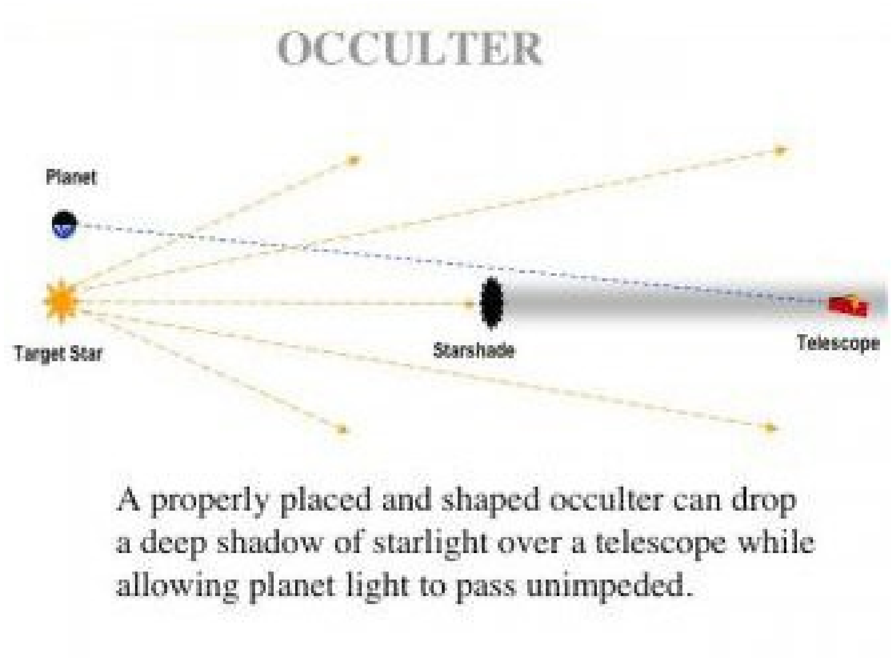
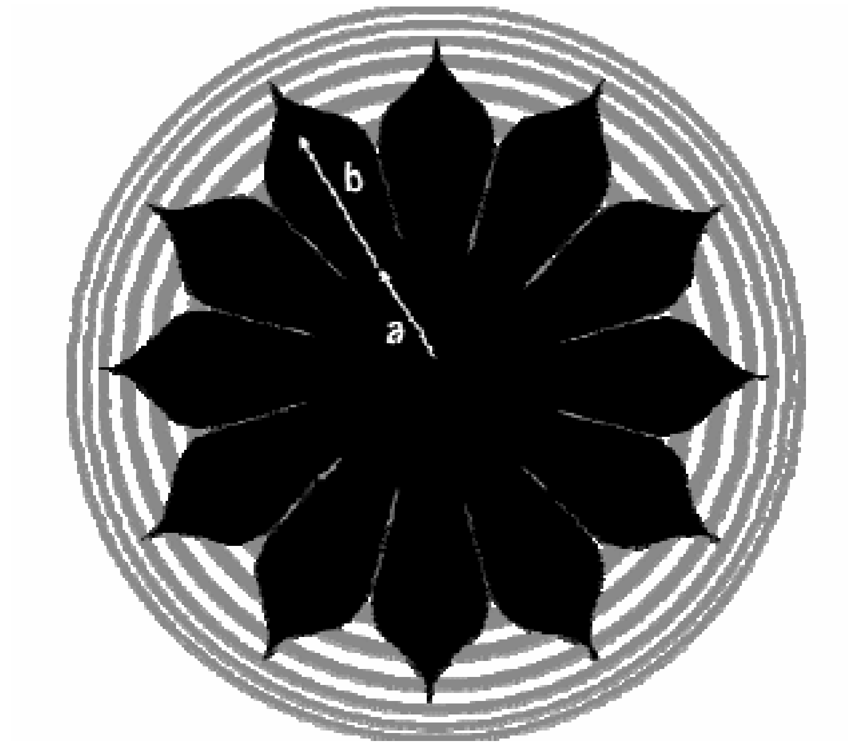
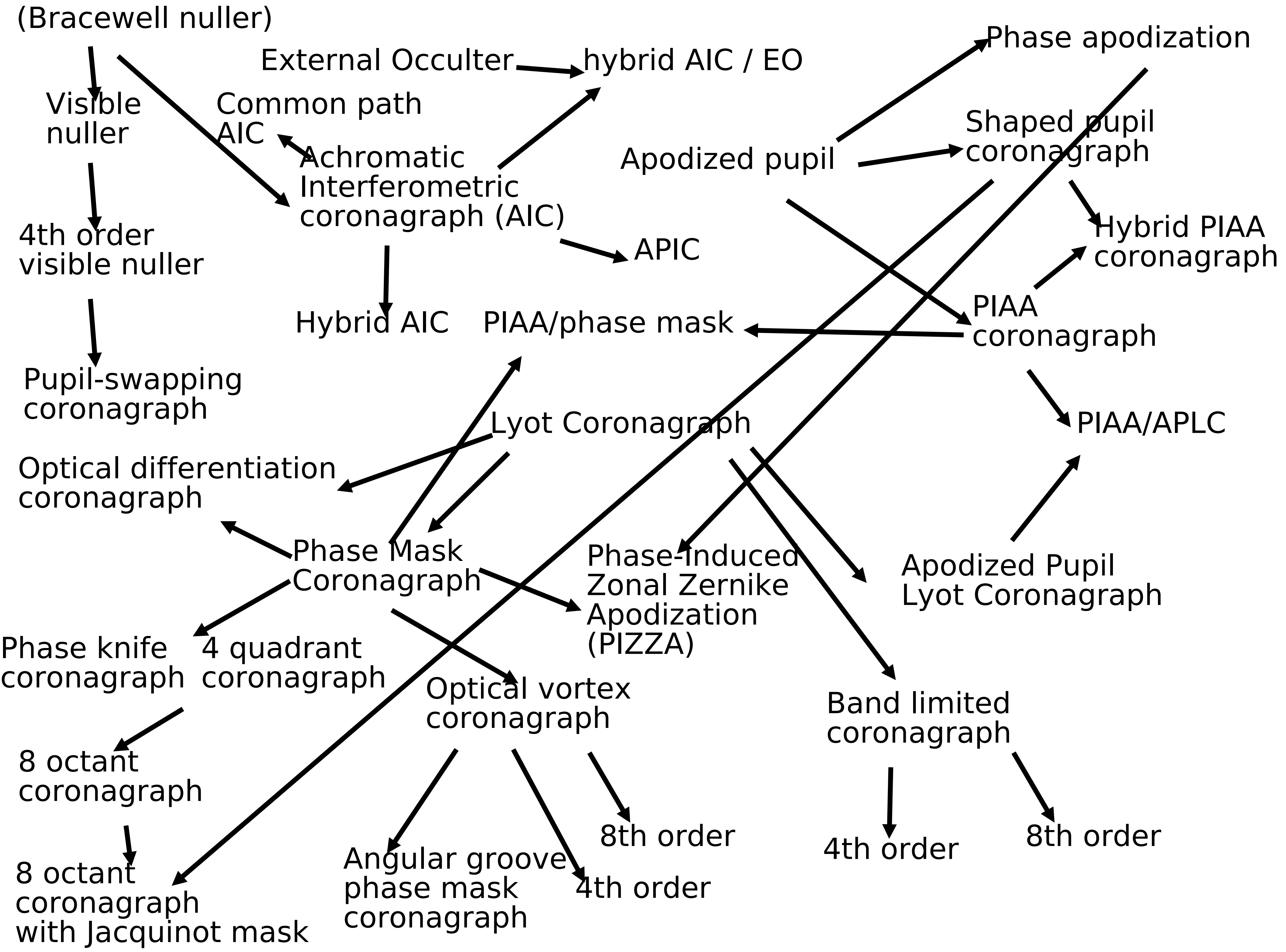
External Occulter



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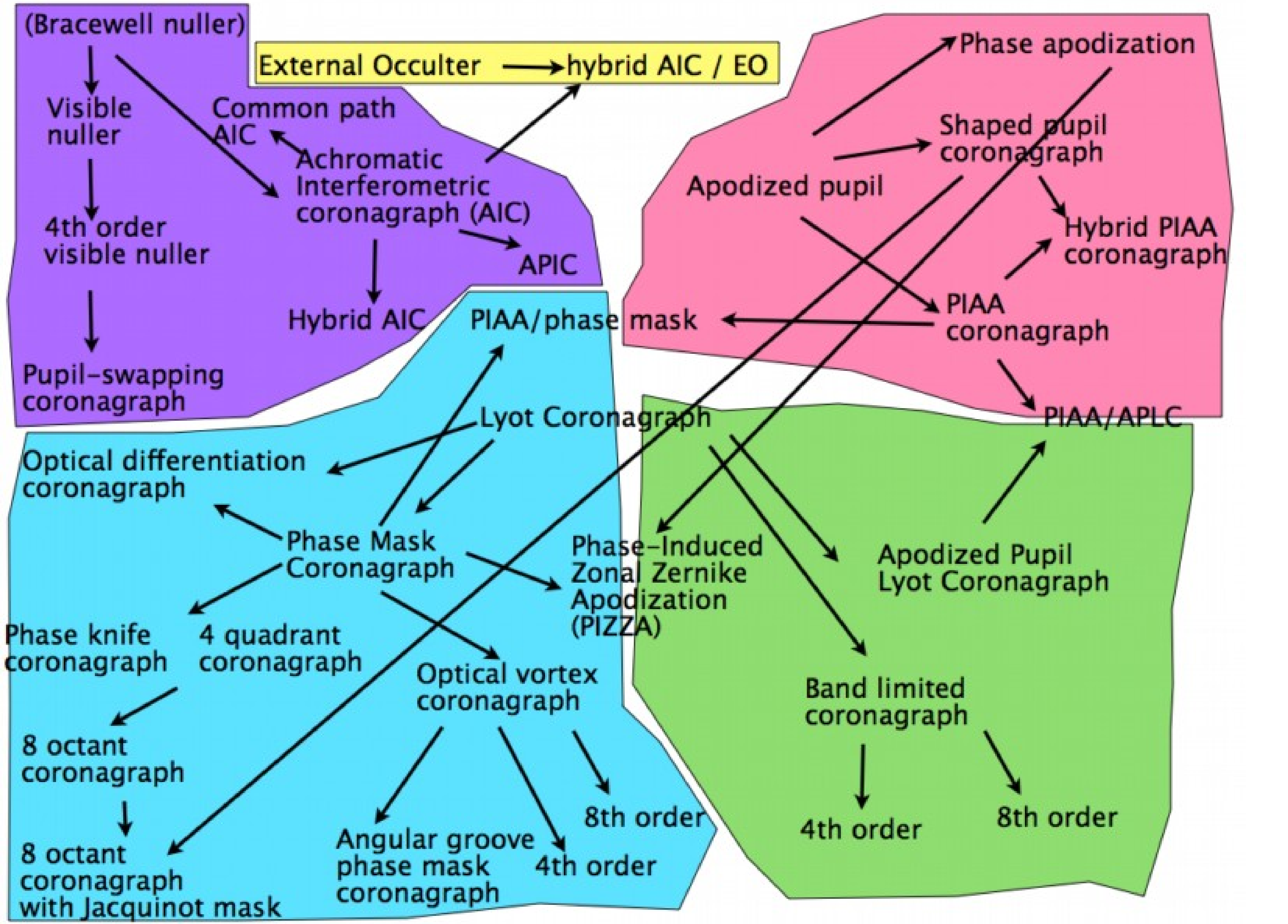
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Coronagraph systems

What is a high contrast imaging system (ground or space) ?

Imaging system optimized to provide high contrast at small angular separation.

Key elements:

- Coronagraph or nulling interferometer to optically remove starlight and isolate planet light (overcomes diffraction)

- Wavefront correction system to reduce and calibrate residual wavefront errors

For coronagraphs: Extreme-AO system to flatten wavefront

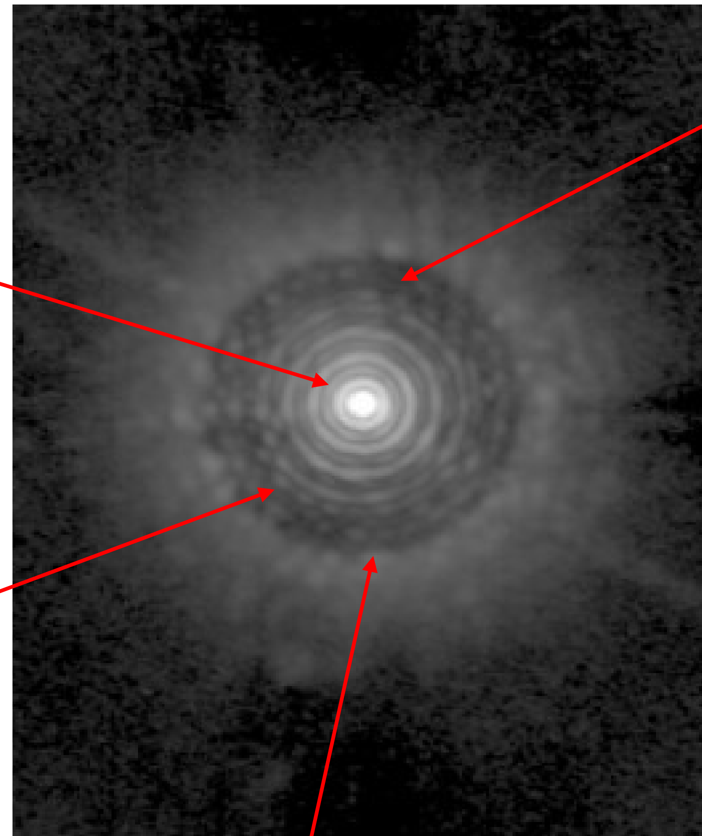
For interferometers: Optical pathlength sensing / correction (+ AO on individual apertures of the interferometer)

- Science detector (+ differential detection technique) for imaging, spectroscopy and polarimetry

(note: the science detector can be part of the wavefront control system, and measure residual scattered light to be removed)

From conventional AO to Coronagraphic Extreme-AO

We use a non-extreme AO system image as starting point
Example of a very good PSF with a current AO system: LBT AO image



Residual atmospheric speckle halo

REDUCED BY FAST, ACCURATE AND EFFICIENT AO SYSTEM

PSF diffraction (Airy rings, spiders)

REMOVED BY CORONAGRAPH

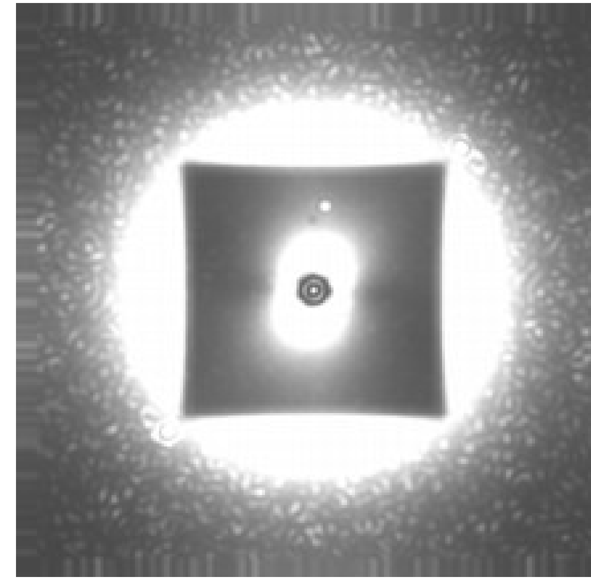
Static and slow speckles

MUST BE REMOVED BY CALIBRATION SYSTEM OR DIFFERENTIAL IMAGING (actively or in post processing)

Control radius of AO

DEFINED BY NUMBER OF ACTUATORS IN DM: MAY BE INCREASED WITH MORE ACTUATORS IF REQUIRED

Wavefront control for High contrast imaging



<u>Ground-based systems</u>

Residual speckle field is brighter than planets(s)

Systems often operate in **speckle noise limited regime**

→ calibrating speckles is extremely important

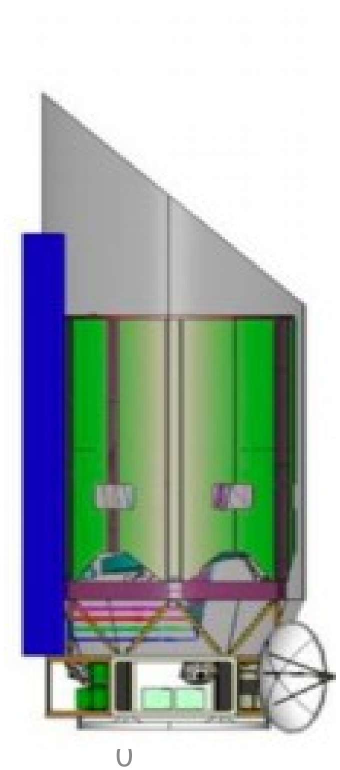
<u>Space-based ultra-high contrast systems</u>

Detection is close to the **photon noise limit** of the planet(s)

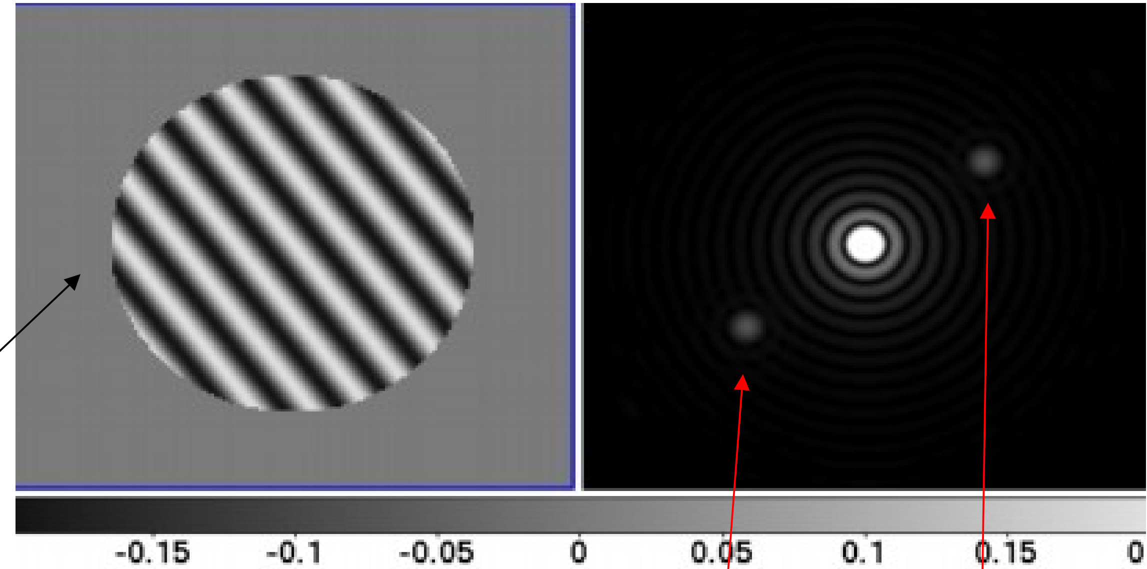
→ speckles need to be reduced at or below the planet image surface brightness level

Wavefront control is essential, and differential imaging/calibration will not work if speckle halo is brighter than planet

→ need to build extremely stable system



Relationship between speckle and wavefront errors



pupil plane complex amplitude

$$W(\vec{u}) = A(\vec{u})\, e^{i\phi(\vec{u})}$$

Cosine aberration in pupil phase

$$\phi(\vec{u}) = \frac{2\pi h}{\lambda} \cos\left(2\pi \vec{f}\vec{u} + \theta\right)$$

$$I(\vec{\alpha}) = PSF(\vec{\alpha}) + \left(\frac{\pi h}{\lambda}\right)^2 \left[PSF(\vec{\alpha}+\vec{f}\lambda) + PSF(\vec{\alpha}-\vec{f}\lambda)\right]$$

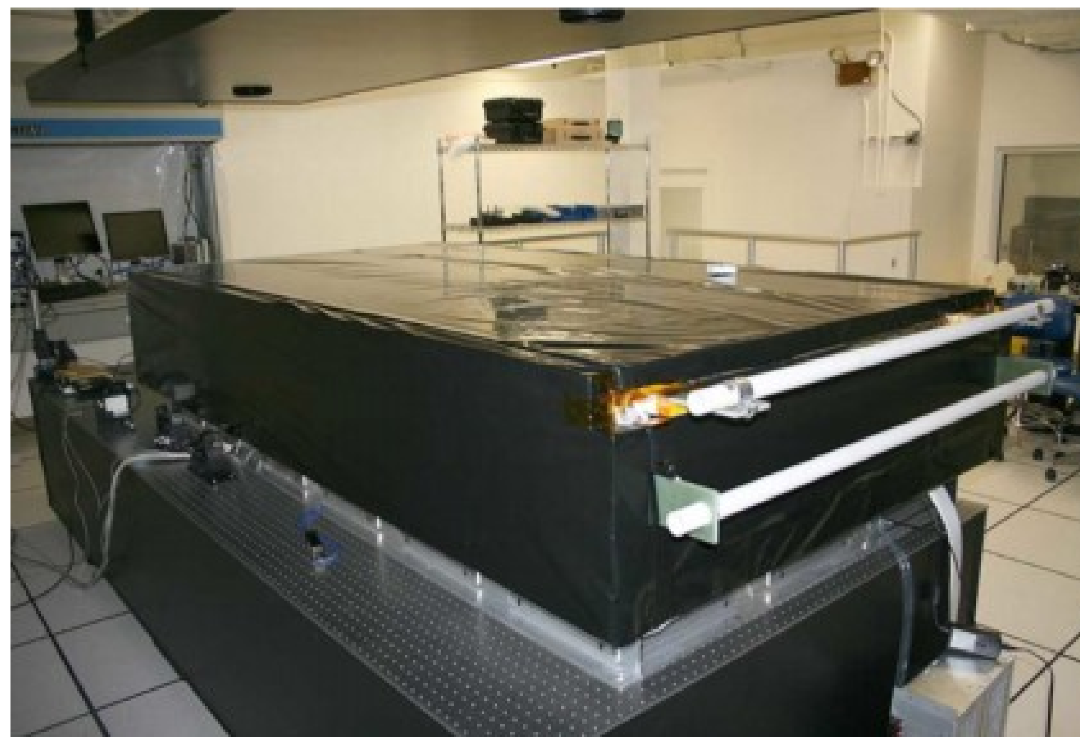
EXAMPLE:
Earth-like planet around Sun-like star is ~1e-10 contrast
In visible light, h=1.6e-12 m (0.0012 nm) = 1e-10 speckle

1e-10 speckle (or 1e-10 contrast planet) around Sun at 10pc = 0.1 ph/sec/m^2/um
On a 4-m telescope, with 10% efficiency and a 0.5 um spectral band:
Earth = 0.6 ph/sec
To measure phase and amplitude of speckle requires ~10 photon
10 photon = 16 sec
→ This spatial frequency needs to be stable to 1/1000 nm over ~ minute

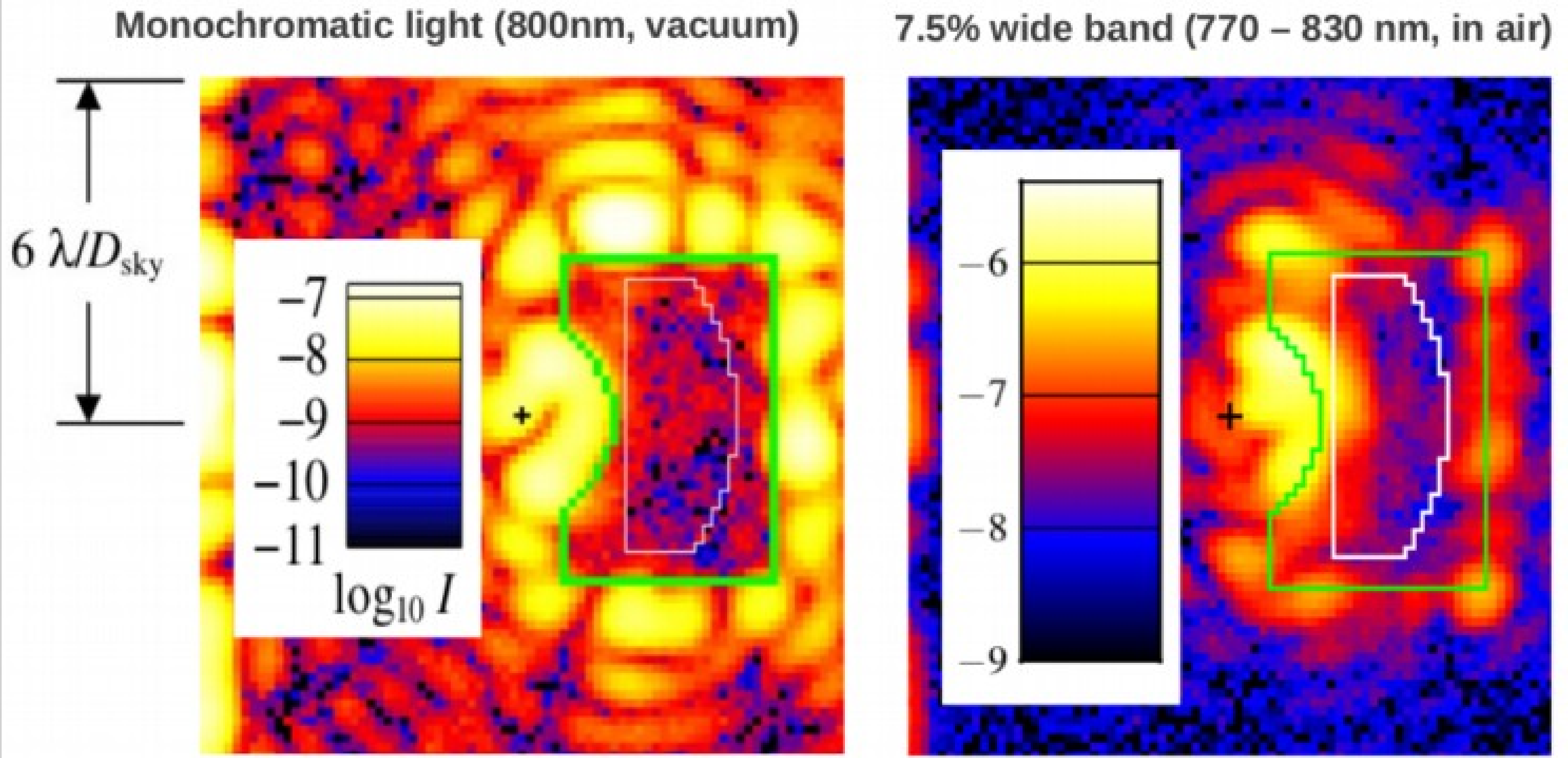
Coronagraphy testbeds for high contrast (< 1e-8) work need to achieve high stability

High Contrast Imaging Testbed (HCIT) is a vacuum facility at NASA JPL

NASA Ames testing PIAA coronagraph / WFC architectures & MEMs DMs.



High contrast images obtained in NASA labs
Example: PIAA coronagraph lab results



3 runs, contrast values averaged from 2 to 4 λ/D between 5.10^{-10} to 9.10^{-10} (figure shows $7.3.10^{-10}$ result)

5.10^{-8} contrast from 2 to 4 λ/D,
2.10^{-8} contrast from 3 to 4 λ/D
Contrast performance limited by wavefront instability (test in air)

Current and future high contrast systems - ground

NICI on Gemini South telescope – ongoing, large survey completed

- 85-element curvature AO system + Lyot coronagraph
- Differential imaging capability (methane absorption line)

HiCIAO on Subaru Telescope – ongoing survey

- 188-element curvature AO system + Lyot coronagraph
- Differential imaging capability (methane absorption line)

→ Subaru Coronagraphic Extreme AO (upgrade of HiCIAO) – on sky since 2012

- Small inner working angle PIAA coronagraph
- Pointing sensing and control with coronagraphic low order WFS
- Speckle control using focal plane image as sensor
- 32x32 MEMS deformable mirror (upgraded 2013 to 2000 elements)
- Includes Integral Field Spectrograph to help remove speckles and acquire spectra

P1640 + Palm300 on Palomar 5-m telescope – on sky since 2012

- 3000 element high order AO system + Lyot coronagraph
- Includes Integral Field Spectrograph to help remove speckles and acquire spectra

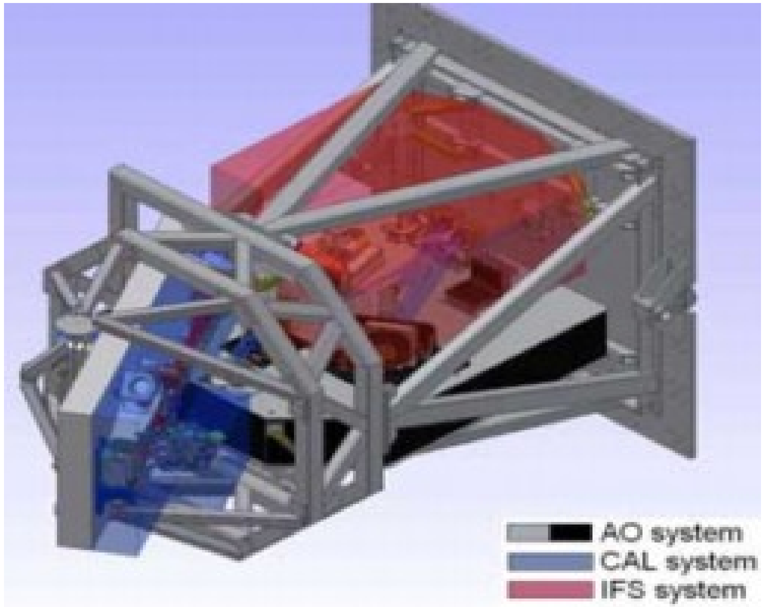
Gemini Planet Imager (GPI) – large survey will start observations in late 2013

- ExAO system using 64x64 MEMS DM + coronagraph
- Includes calibration interferometer to accurately measure residual speckles
- Includes Integral Field Spectrograph to help remove speckles and acquire spectra

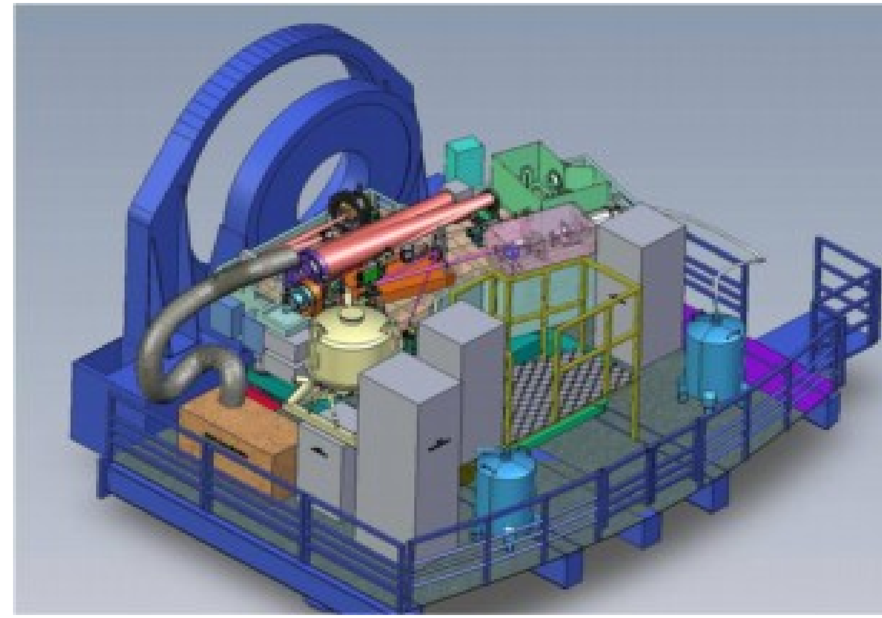
ESO's SPHERE on VLT – large survery will start observations in late 2013

- ExAO system + coronagraph
- Highly stable bench
- Includes Integral Field Spectrograph to help remove speckles and acquire spectra
- Includes differential polarimetric imager

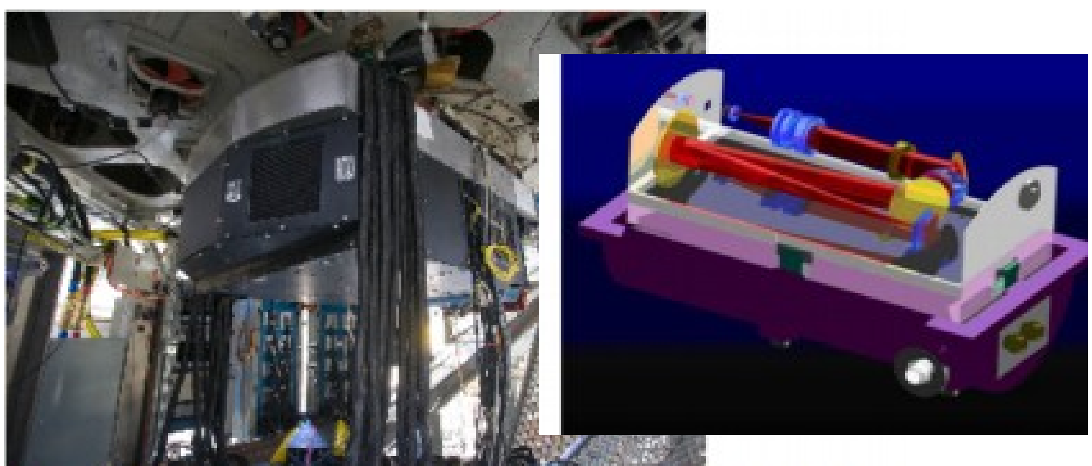
Current and future high contrast systems - ground



Gemini Planet Imager

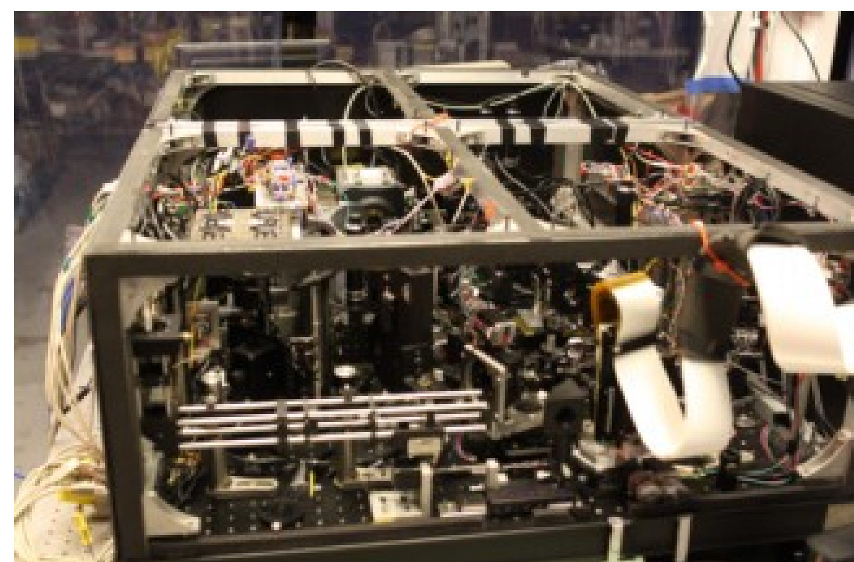


SPHERE (European Southern Observatory)



PALM-3000 installed at the Cass focus of the Hale Telescope at Palomar Mountain. Photo: Scott Kardel.

PALM3000/P1640 (Palomar 5-m Telescope)



Subaru Coronagraphic Extreme-AO