

Coronagraphy

Olivier Guyon

Subaru Telescope / University of Arizona

guyon@naoj.org



Text

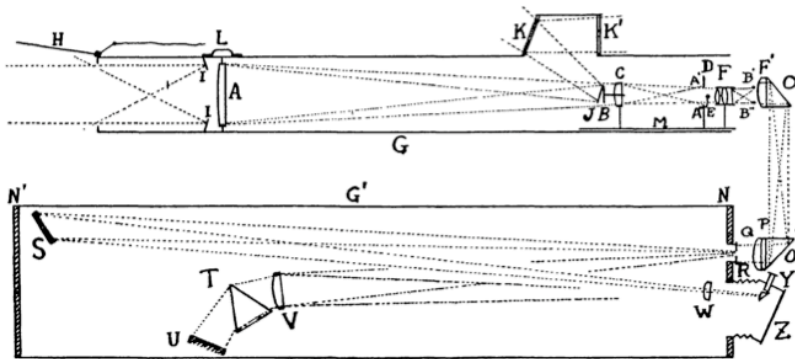
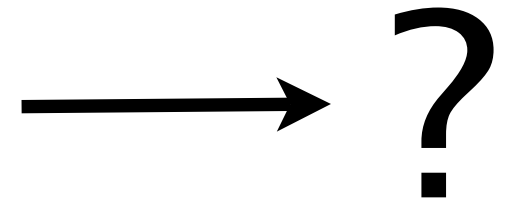
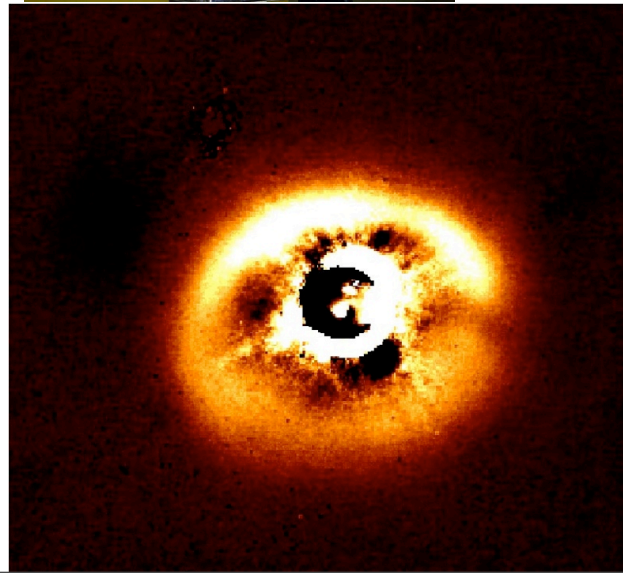


Fig. 4. Plan of the mounting of the coronagraph (above) and the spectrograph.



What does the general public think about imaging exoplanets ?

(quotes from http://www.dailygalaxy.com/my_weblog/2008/02/nasas-new-world.html)

“What an amazing idea - to stay at the fuzzy image of another world with oceans and continents and perhaps even clouds! And what if it did discover O₂, methane or another bio marker? How would this world be changed to have proof - **visual proof at that (best kind for a visual-oriented primate)** - that there is other life in the universe? **Well worth \$3bill. Maybe Bill Gates or another billionaire could be convinced to pay up some! :-)**”

What does the general public think about imaging exoplanets ?

(quotes from http://www.dailygalaxy.com/my_weblog/2008/02/nasas-new-world.html)

“What an amazing idea - to stay at the fuzzy image of another world with oceans and continents and perhaps even clouds! And what if it did discover O₂, methane or another bio marker? How would this world be changed to have proof - **visual proof at that (best kind for a visual-oriented primate)** - that there is other life in the universe? **Well worth \$3bill. Maybe Bill Gates or another billionaire could be convinced to pay up some! :-)**”

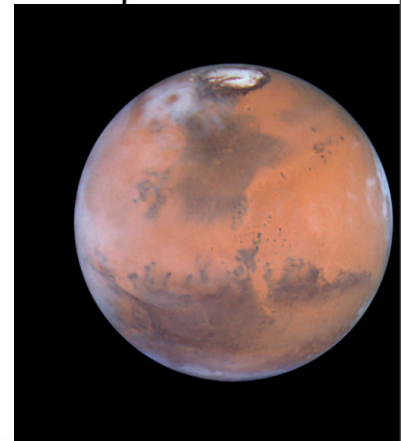
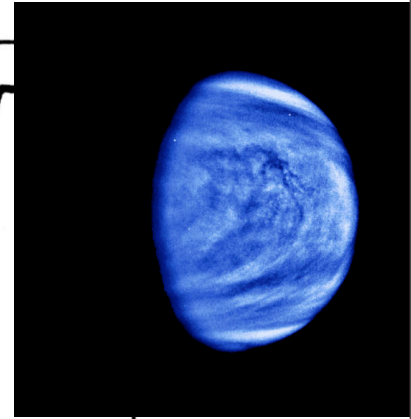
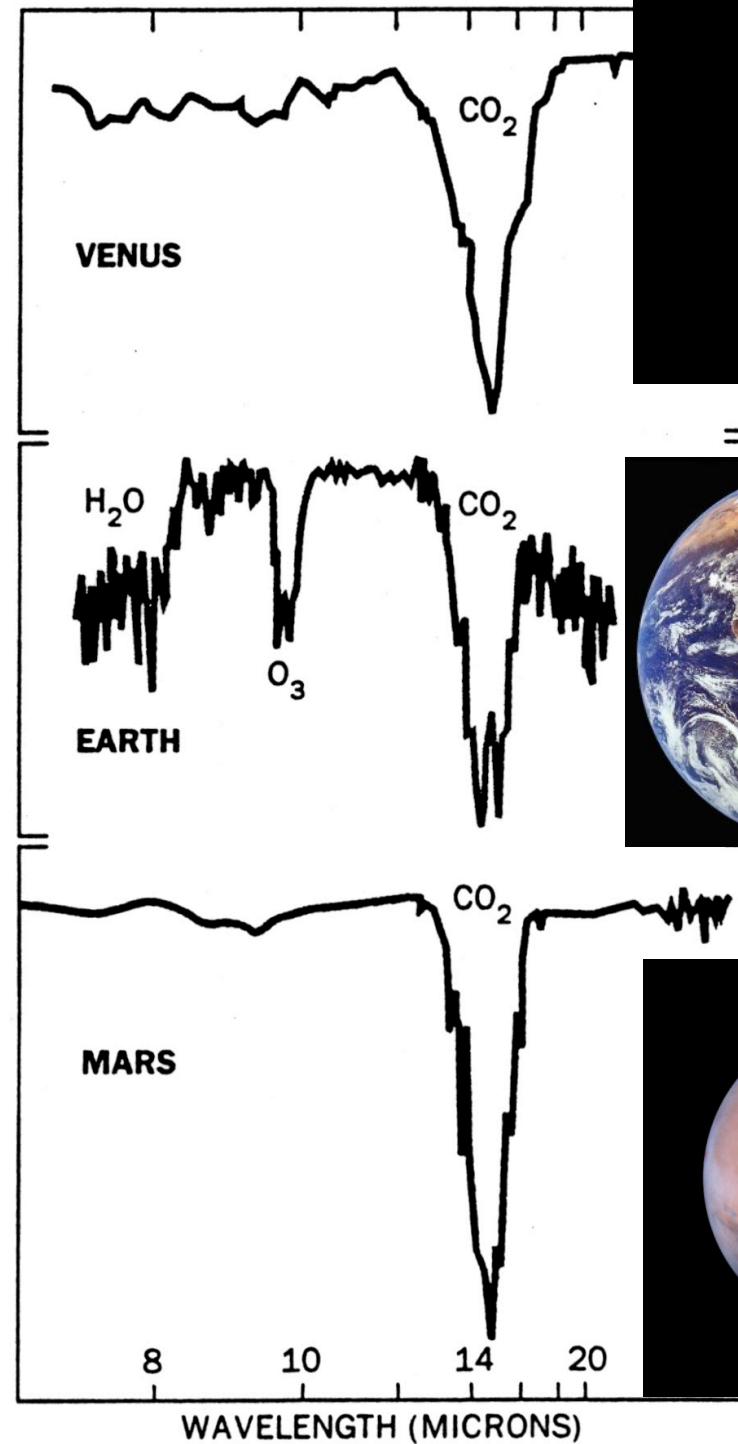
“Maybe, we could stop wasting money on project like this, and spend it on more important issues?

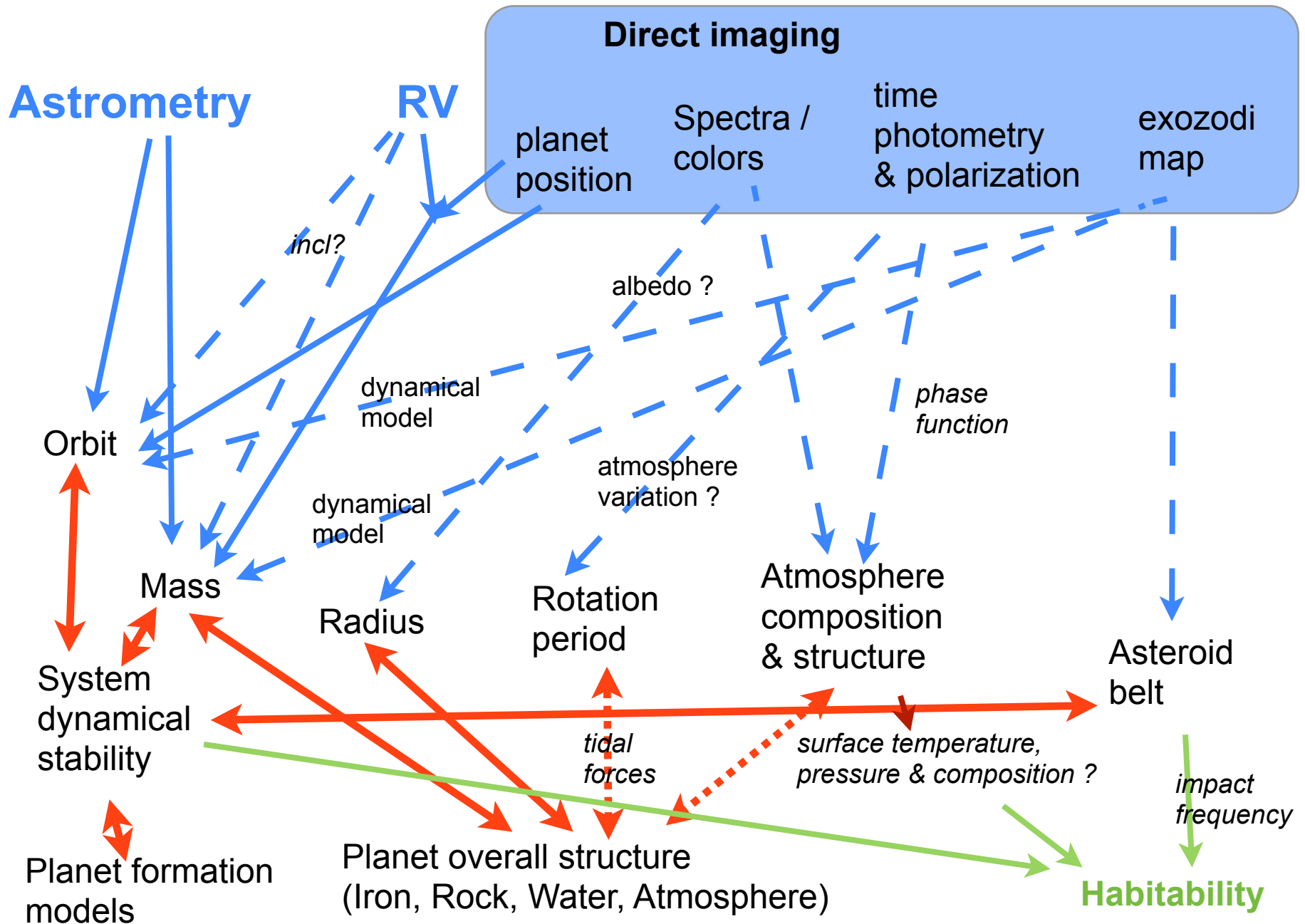
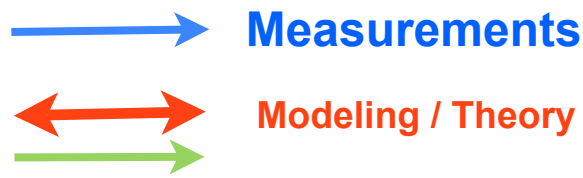
We have already discovered other life forms, countless of documents explain they came and landed, and were shot at, and downed and retrieved...”

Imaging

- Orbit
- Atmosphere composition
- Continents vs. Oceans ?
- Rotation period
- Weather patterns
- Planetary environment :

Planets + dust





Challenges

- **Contrast**
 - Visible:
 - 10^{10} for Earth/Sun \rightarrow space
 - 10^9 for Jupiter/Sun \rightarrow space / ELTs ?
 - $\sim 10^8$ for close-in planets \rightarrow ground ExAO ?
 - Near-IR (~ 1.6 micron)
 - 10^{10} for Earth/Sun
 - $\sim 10^{12}$ for Jupiter/Sun
 - $\sim 10^7$ for young giant planet / Sun \rightarrow Ground ExAO
 - Thermal IR (~ 10 micron)
 - 10^6 for Earth/Sun
 - 10^7 for Jupiter/Sun
- **Angular separation** (HZs at $\sim 0.1''$)

Why do we need coronagraphs ?

Coronagraph can only remove known & static diffraction pattern

BUT:

- static & known diffraction can be removed in the computer
- coronagraphs don't remove speckles due to WF errors

Fundamental reasons:

- (1) Photon Noise
- (2) Coherent amplification between speckles and diffraction pattern

Practical reasons:

- (3) Avoid detector saturation / bleeding
- (4) Limit scattering in optics → “stop light as soon as you can”

Coherent amplification between speckles and diffraction pattern

Final image = PSF diffraction (Airy) + speckle halo

This equation is true in complex amplitude, not in intensity. Intensity image will have product term \rightarrow speckles are amplified by the PSF diffraction.

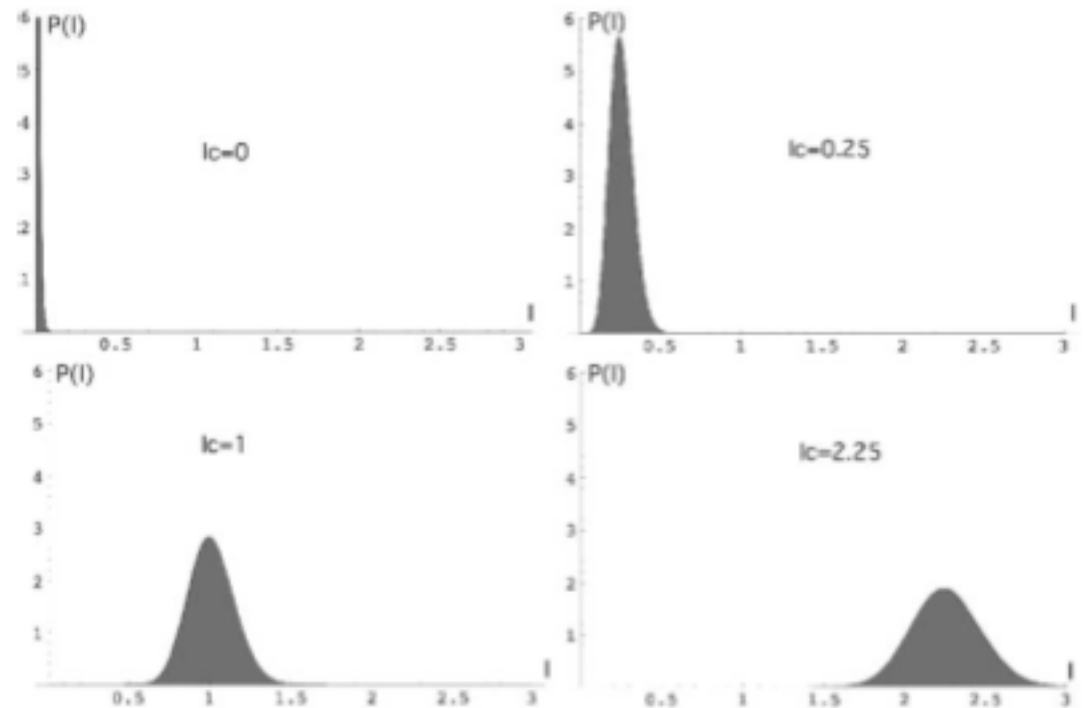


FIG. 3.—PDF of the light intensity at four different constant background intensity levels I_c and a single value of $I_s = 0.1$. High values of I_c correspond to locations near the perfect PSF maxima (rings), and low values of I_c correspond to locations near the zeros of the perfect PSF or far from the core. For $I_c = 0$ we have the pure speckle exponential statistics. The width of the distribution increases with an increase in the level of I_c . This explains speckle pinning; speckle fluctuations are amplified by the coherent addition of the perfect part of the wave.

When do we need coronagraphs ?

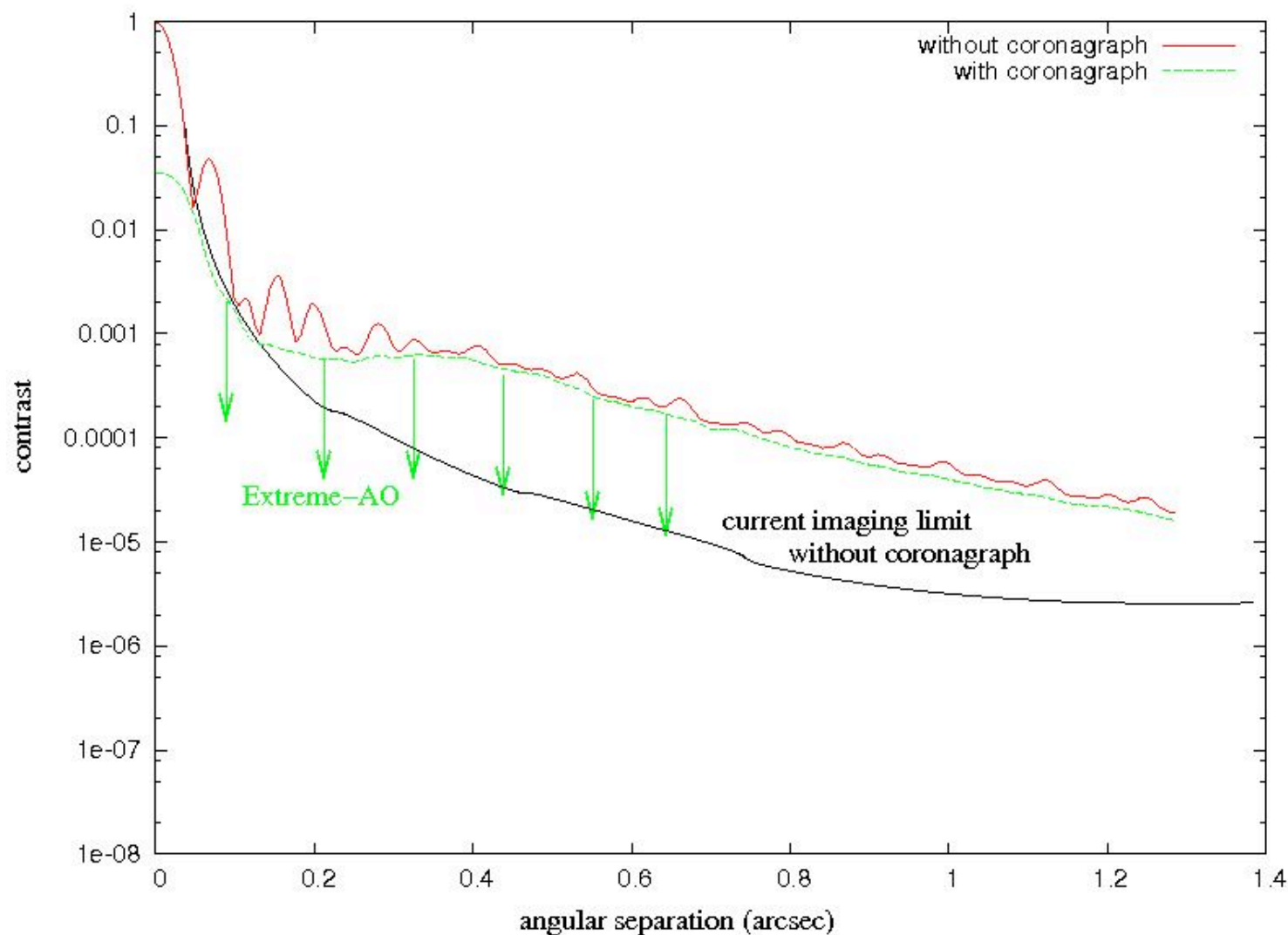
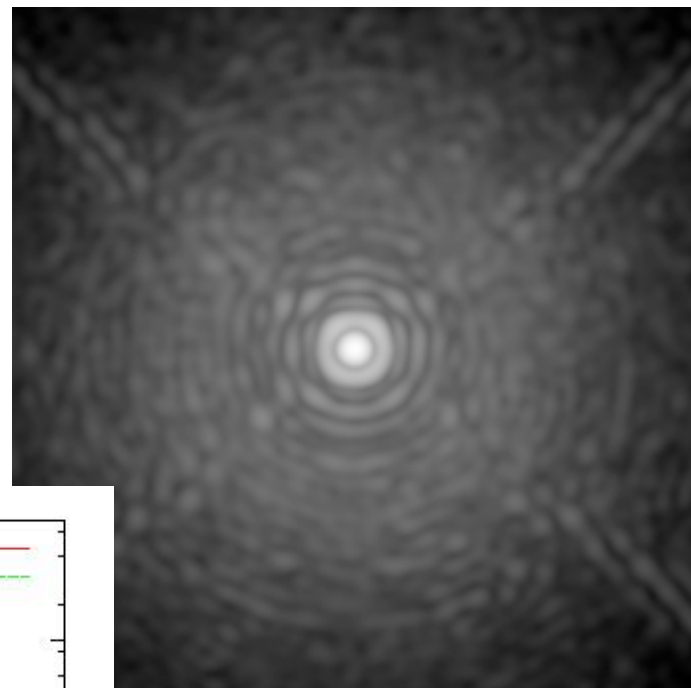
Coronagraphs serve no purpose if dynamic speckle halo is $>$ diffraction

–> Very important to keep in mind to **avoid over-designing the coronagraph**, as this usually would mean giving up something (usually throughput)

“Side effects” of coronagraphs :

- (Usually) requires very good pointing. Risk of low order aberrations (for example pointing) creating additional scattered light in the region of interest
- data interpretation & analysis can be challenging (especially at inner working angle)
- Astrometry more difficult (solutions exist)

- None of the recent ground-based planet discoveries has been done with coronagraph
- With current Telescopes+AO systems, coronagraphs offer almost no help beyond $\sim 0.3''$ in H band
- PSF calibration with coronagraphs is more complicated



ExAO systems currently under construction improve contrast with AO + coronagraphy

PSF calibration strategies

- **“classical” PSF subtraction**
- **Angular Differential Imaging**
 - works well at large angular separations, where aberrations have large static component
 - poor performance close in to the star
- **Spectral / Polarimetric differential imaging**
 - works great IF source has expected spectral signature or is polarized
- **Coherent differential imaging**
 - highly flexible, does not make any assumption about source
 - combined wavefront sensing / PSF calibration
 - works within control radius of DM

A quick history of coronagraphy ...



Lyot Coronagraph

Lyot Coronagraph

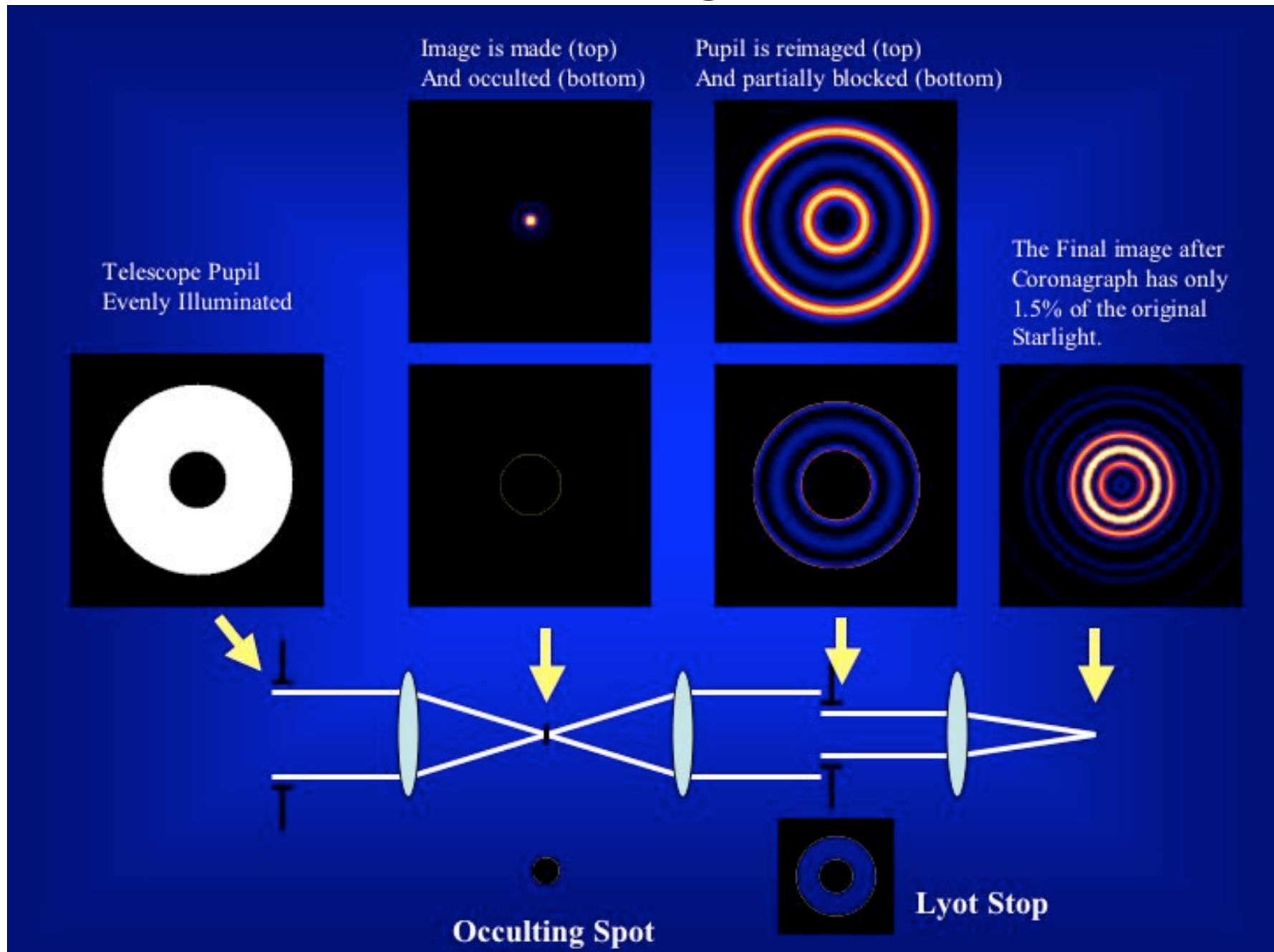
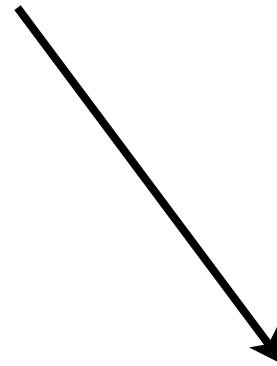


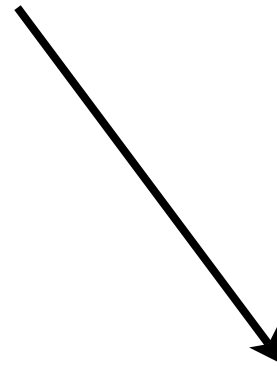
figure from Lyot project website

Lyot Coronagraph



Band limited
coronagraph

Lyot Coronagraph



Band limited
coronagraph



4th order



8th order

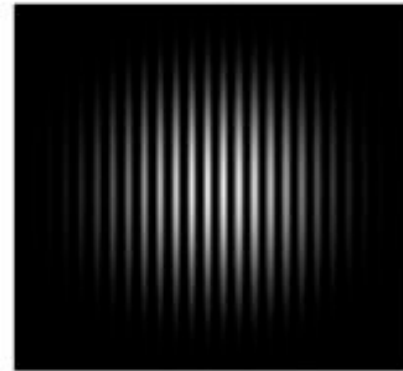
Band-Limited mask Coronagraph (BL4, BL8)

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

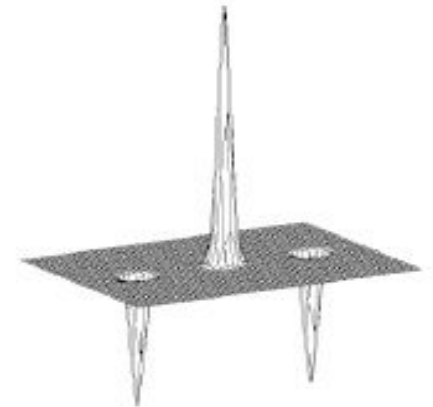
4th or 8th order extinction.

Kuchner & Traub 2002
Kuchner 2005

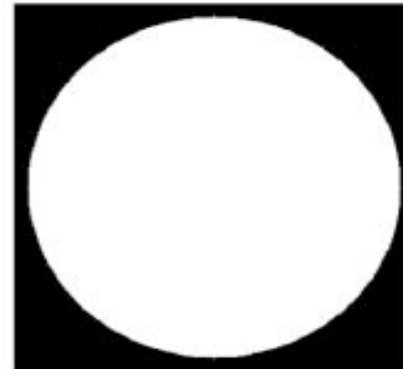
a) Mask



b) Conjugate of Mask Function



c) Pupil



d) Lyot Stop

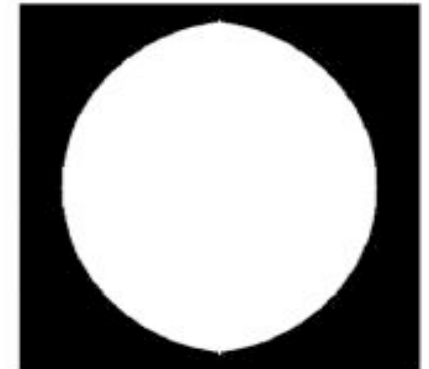
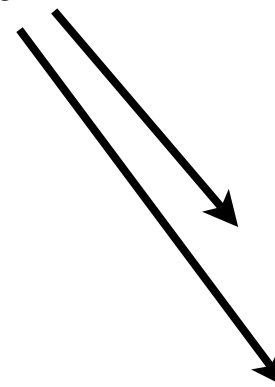


FIG. 4.—Simplest band-limited mask, analogous to a single-baseline nulling interferometer. (a) Mask ITF $\sin^4(x)$ multiplied by a slow taper. Dark areas are opaque. (b) Conjugate of the mask ATF (eq. [13]). This occulting mask can be used with any aperture shape, but for the circular aperture shown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

Lyot Coronagraph



Apodized Pupil
Lyot Coronagraph

Band limited
coronagraph

4th order

8th order

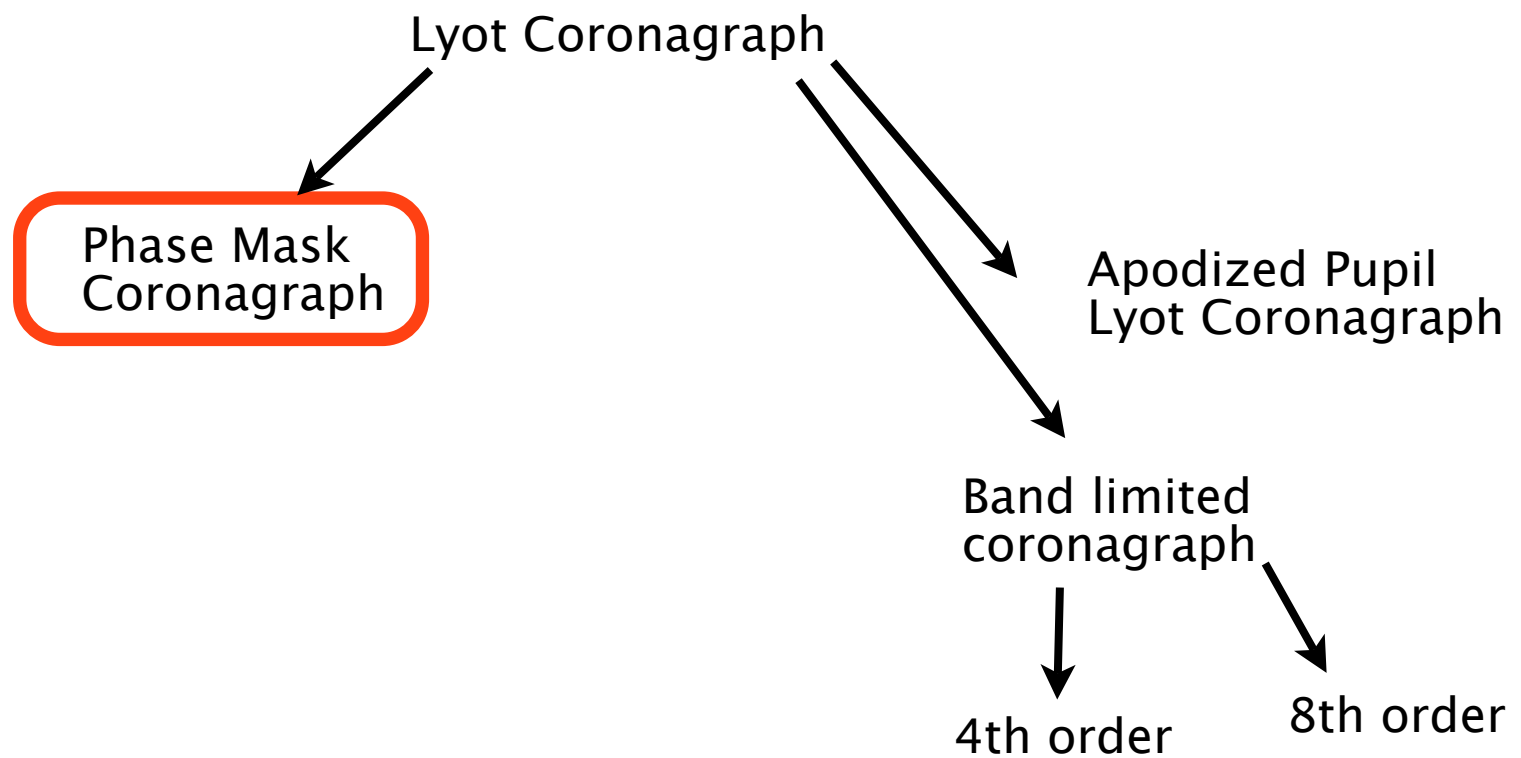
Apodized Pupil Lyot Coronagraph (APLC) = Prolate Apodized Lyot Coronagraph (PALC)

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 AP LC.

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-shifting (-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

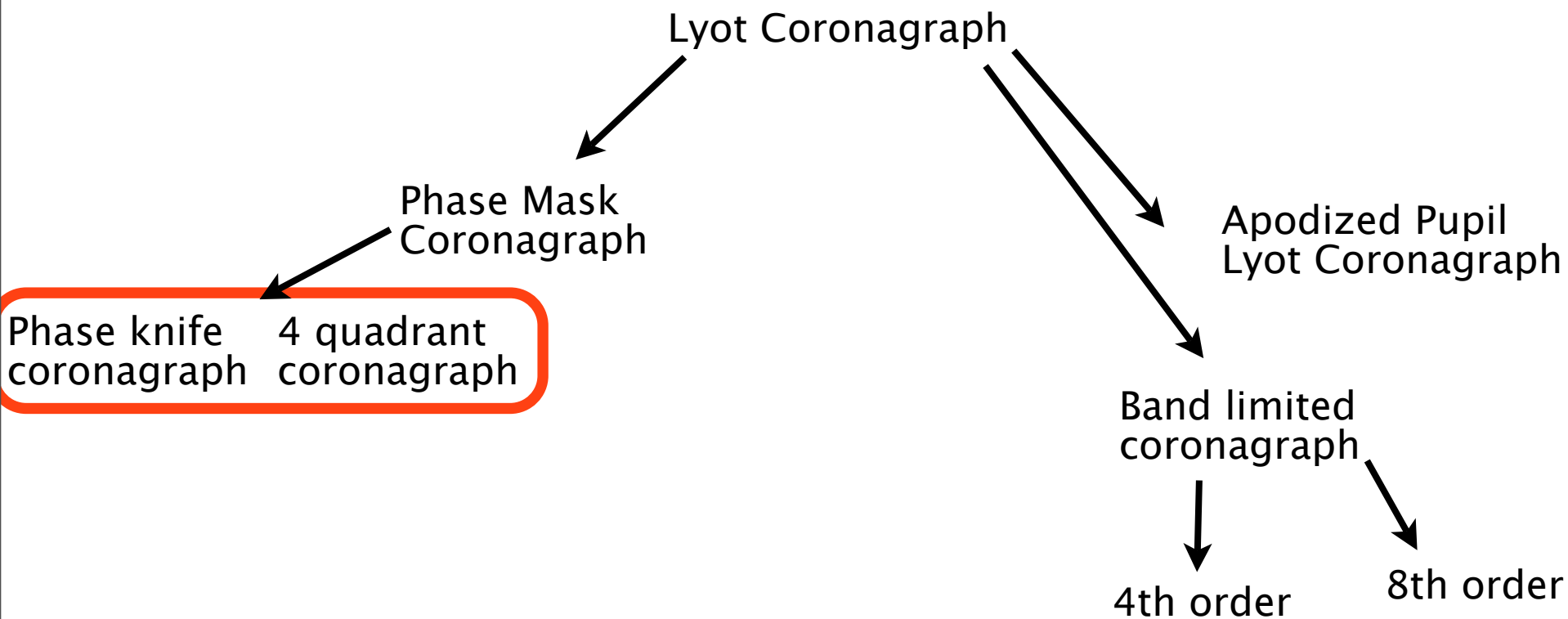
Dual zone PM coronagraph mitigates chromaticity

2nd 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)



4 Quadrant Phase Mask (4QPM)

Lyot-like design with PI-shifting (-1 amplitude) of 2 opposite 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

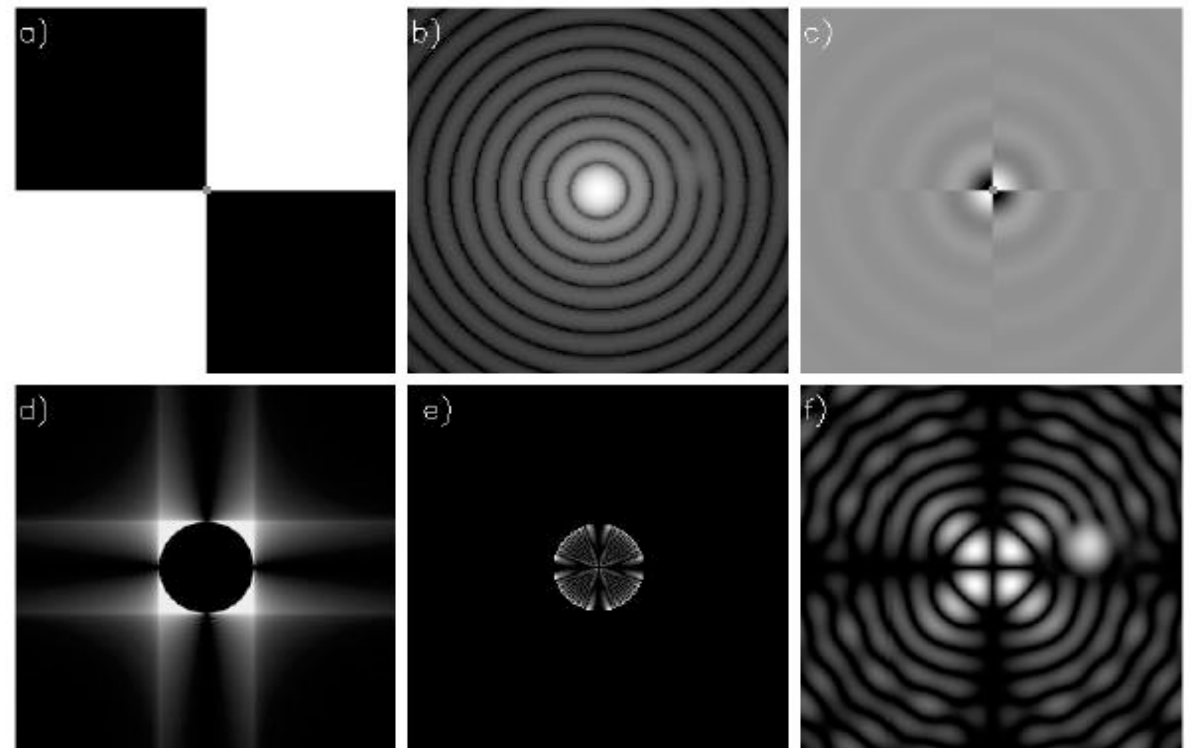


FIG. 2.—Numerical simulation illustrating the principle of the four-quadrant coronagraph. A companion 15 mag fainter (flux ratio of 10^{-6}) is located $2.1\lambda/D$ away from the star. The individual images show (a) the shape of the phase mask (white for 0 phase shift, black for π phase shift), (b) 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.

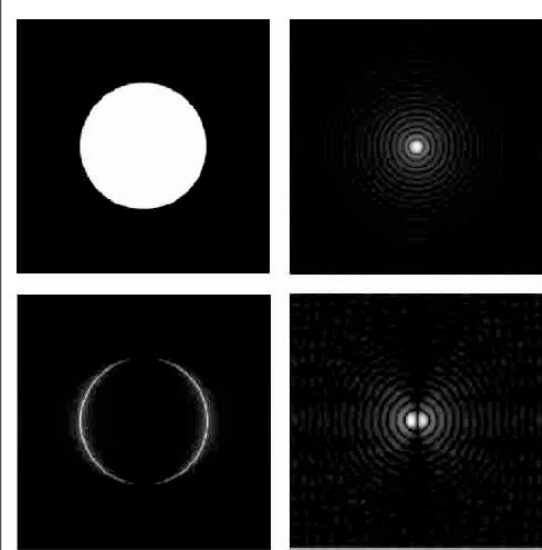


Fig. 1. Pupil intensity with perfect wavefront and its corresponding Airy pattern (*top left and right*). Intensity distribution after the Phase Knife Coronagraph has been applied (*bottom-left*): the two thin crescents encircle the pupil area perpendicular to the Knife-Edge direction. “Butterfly shape” 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).

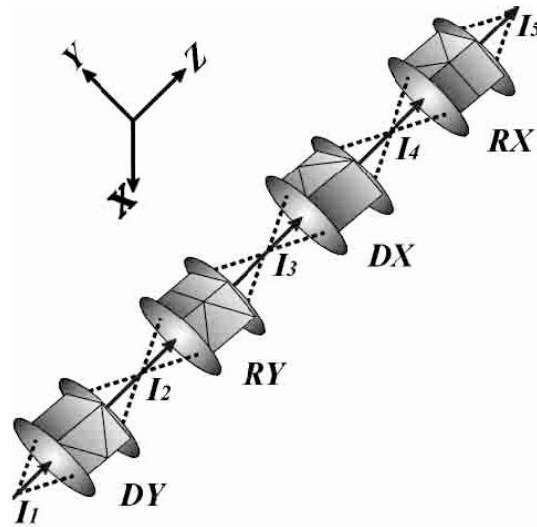


Fig. 2. Generic 3D optical scheme of the PKC. I_1 is the input Airy pattern, DY is a direct vision dispersing prism in the Y direction, I_2 corresponds to the first chromatic phase-knife parallel to Y . RY is a second direct-vision prism rotated by 180 degrees with respect to DY which superimposes the 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.

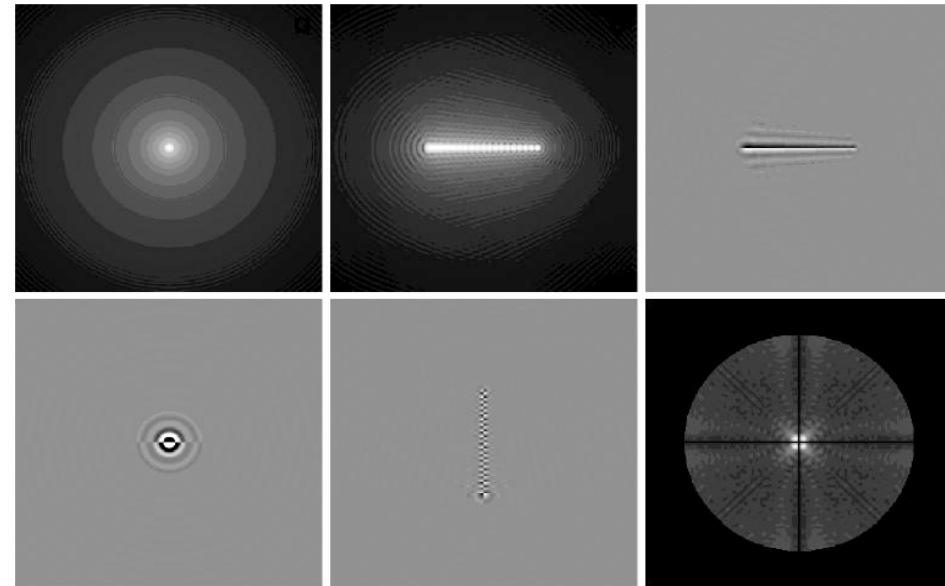
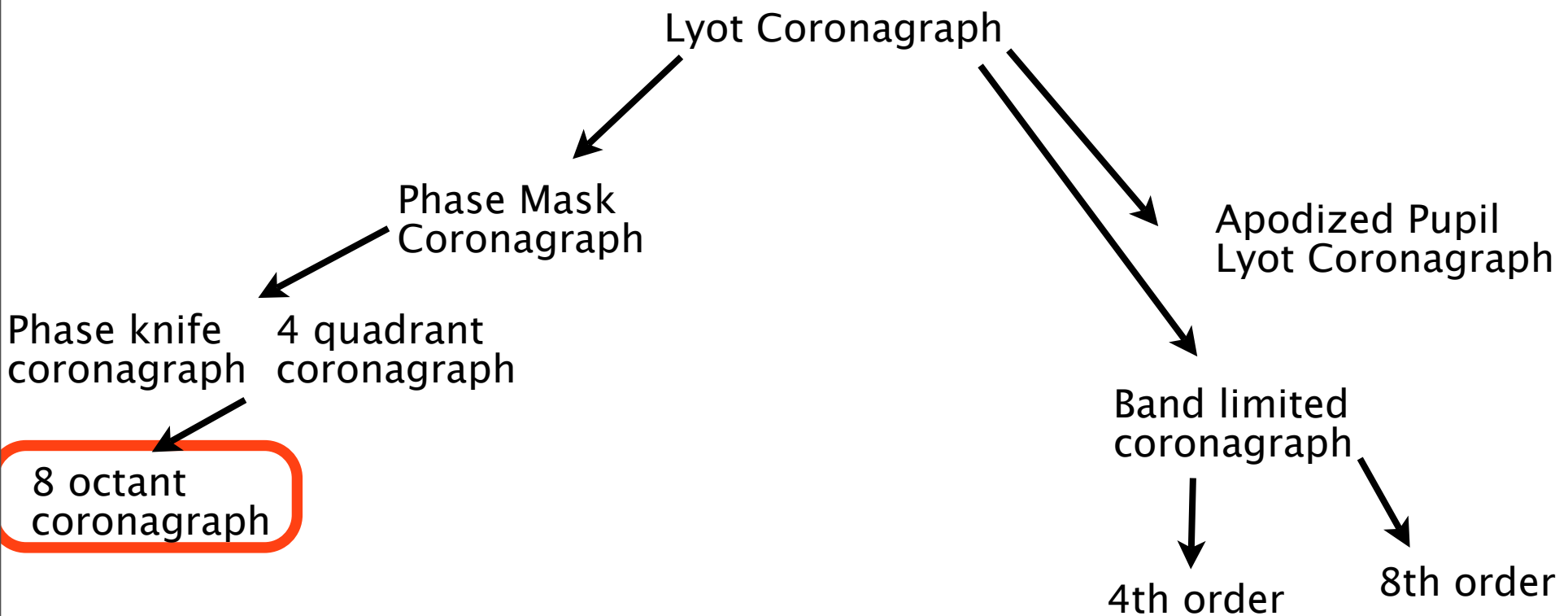
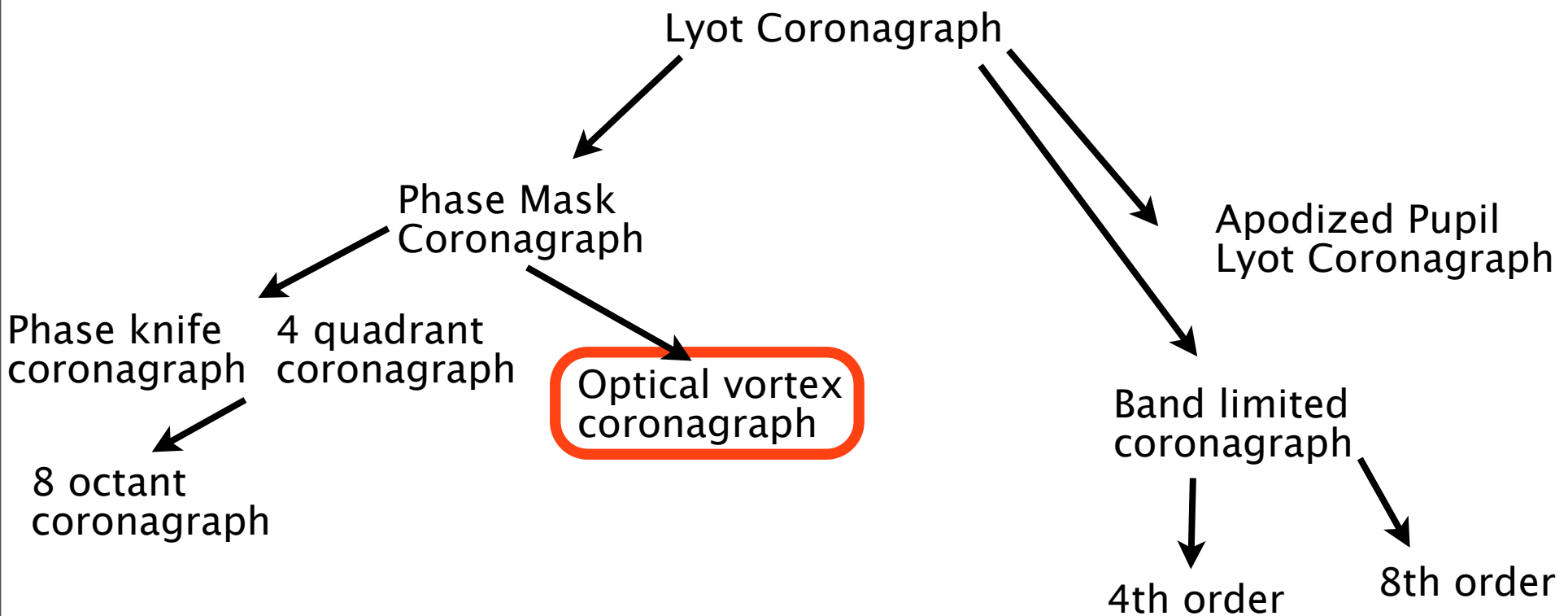


Fig. 3. Different steps of the phase-knife screen effect: (*top-left*) polychromatic Airy pattern (bandwidth: 400–800 nm) (corresponding to step I_1 in Fig. 2), (*top-middle*) dispersed Airy disc, (*top-right*) the polychromatic phase-knife where the optical retardation follows the dispersion law (step I_2), (*bottom-left*) an intermediate image plane where the Airy discs are de-dispersed (step I_3), (*bottom-middle*) the polychromatic phase-knife applied in the perpendicular direction (step I_4), (*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 = $Cst \times PA$

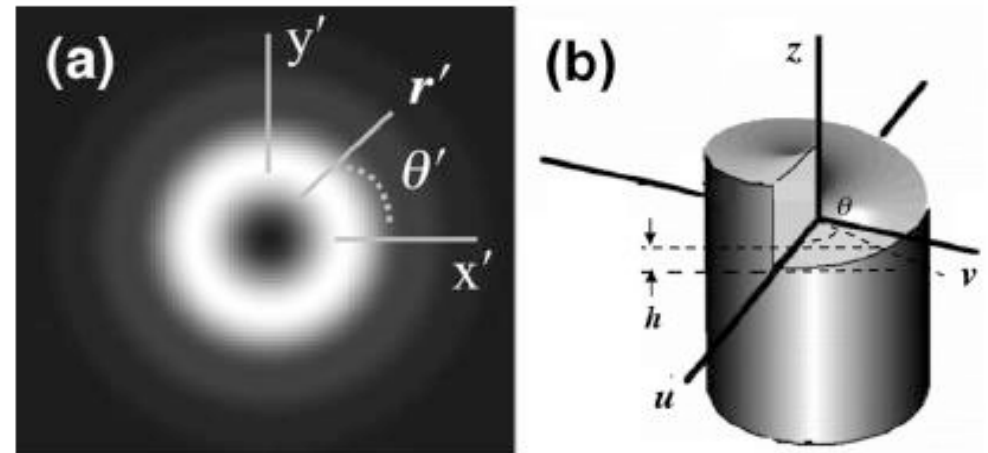
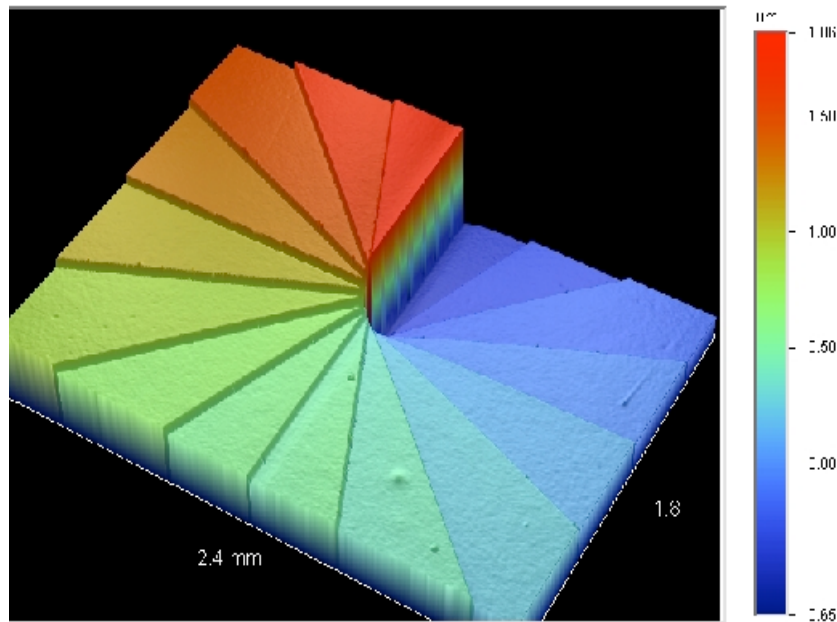


Fig. 2. (a) Intensity profile, $|U(x', y')|^2$ of a beam containing an optical vortex. (b) Surface profile of a VPM.

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

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

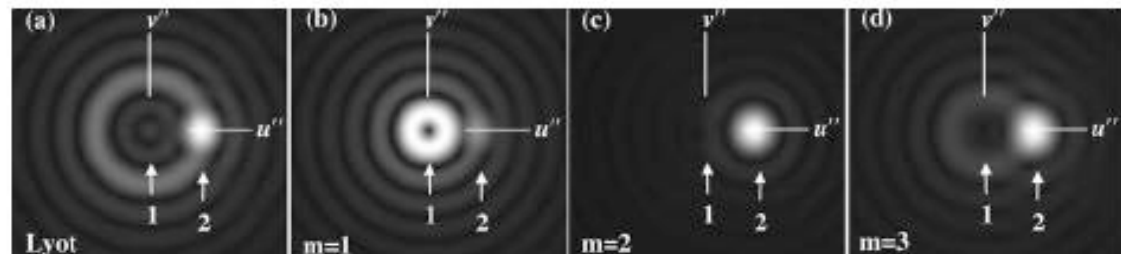
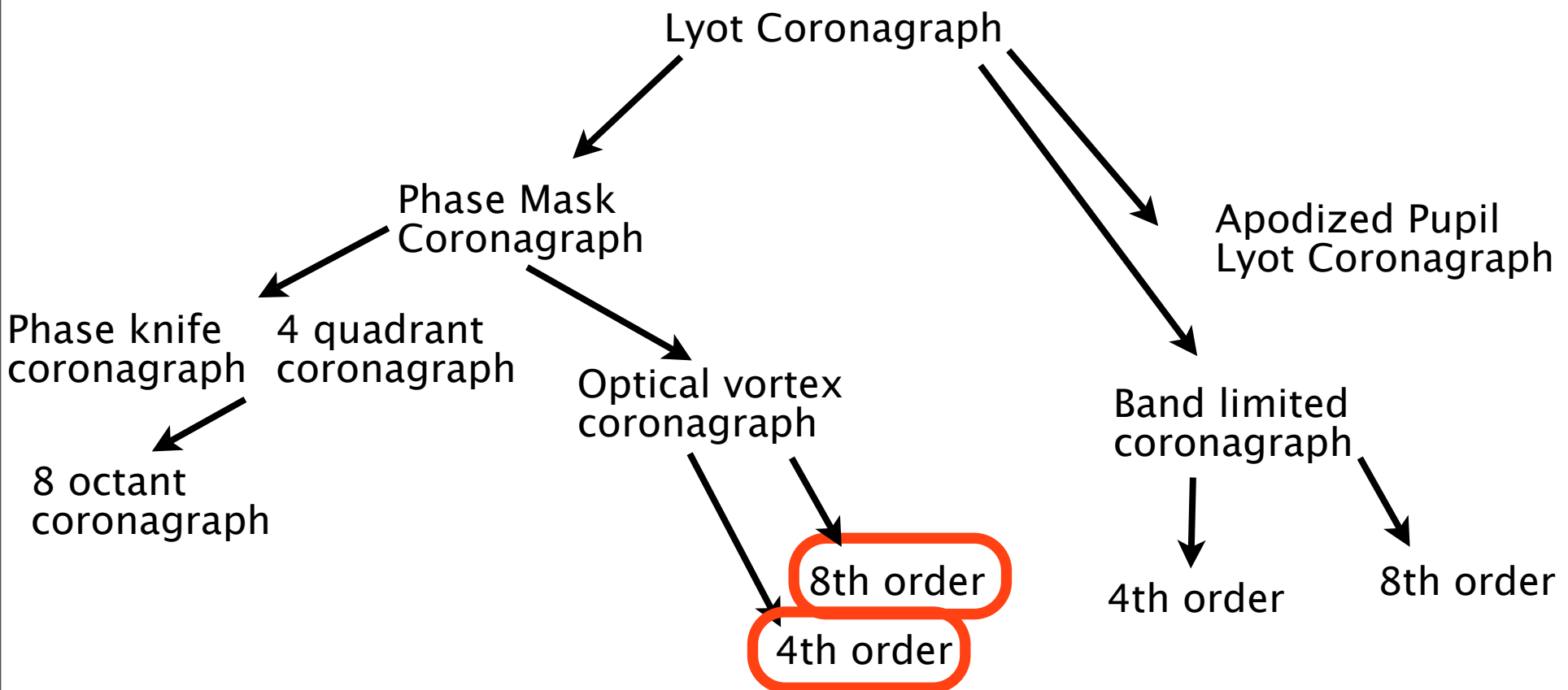
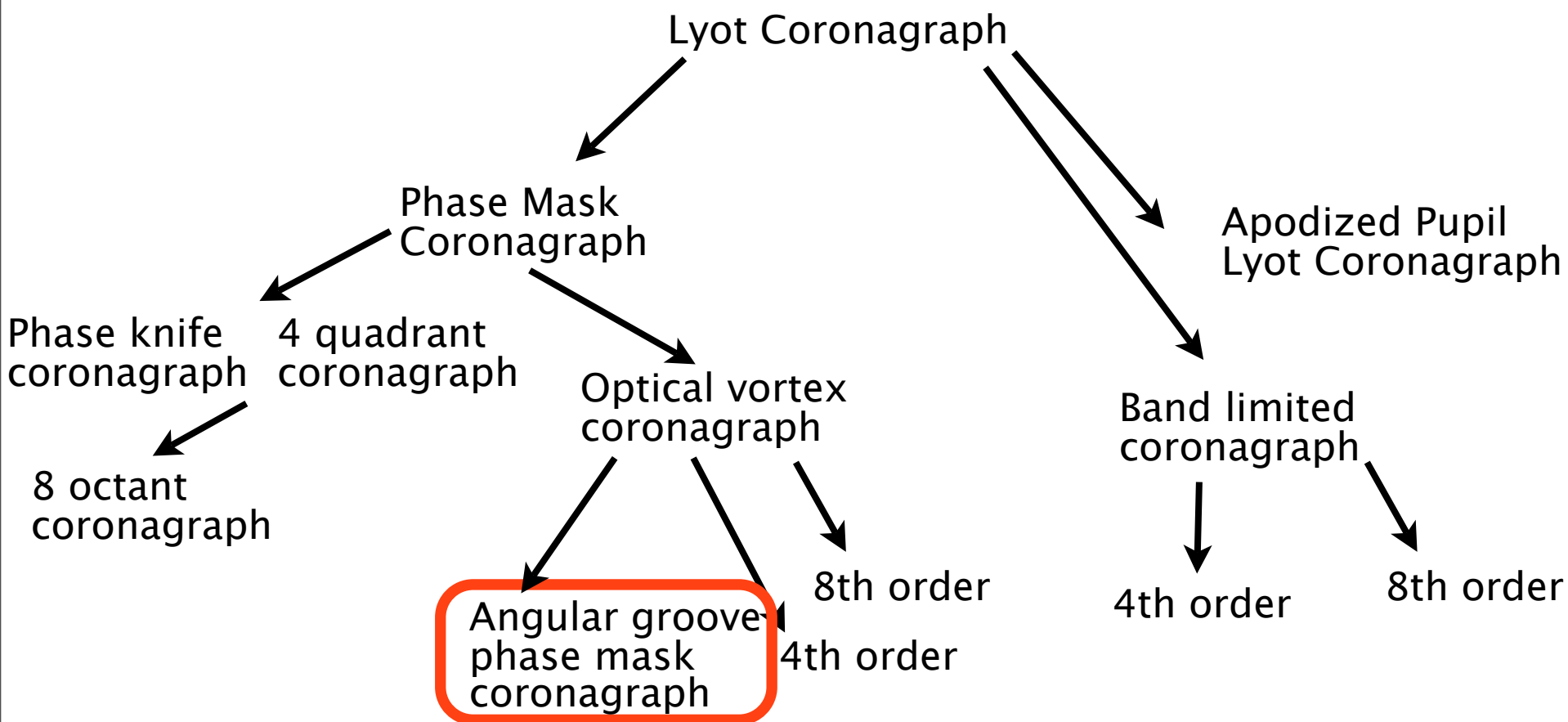
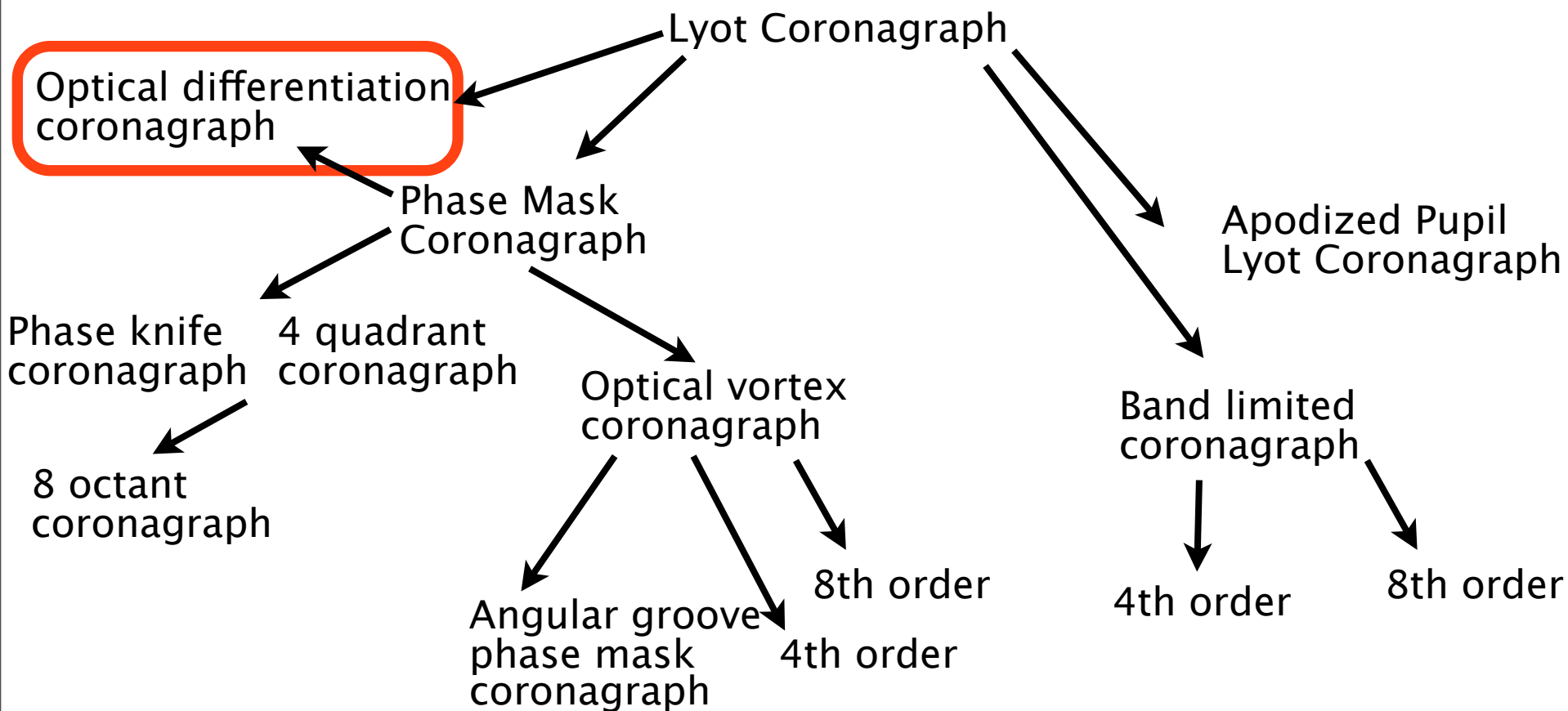


Fig. 3. Comparisons for $\alpha_2 = \alpha_{\text{diff}}$ and $A_1^2/A_2^2 = 100$. (a) Lyot coronagraph where $R_{\text{OM}} = r_{\text{diff}}$. (b), (c), (d) Vortex coronagraphs where $m=1$, $m=2$, $m=3$, respectively. In (c) the starlight is essentially eliminated, revealing a high-contrast image of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







Optical Differentiation Coronagraph (ODC)

Optimized version of a single axis phase knife coronagraph.

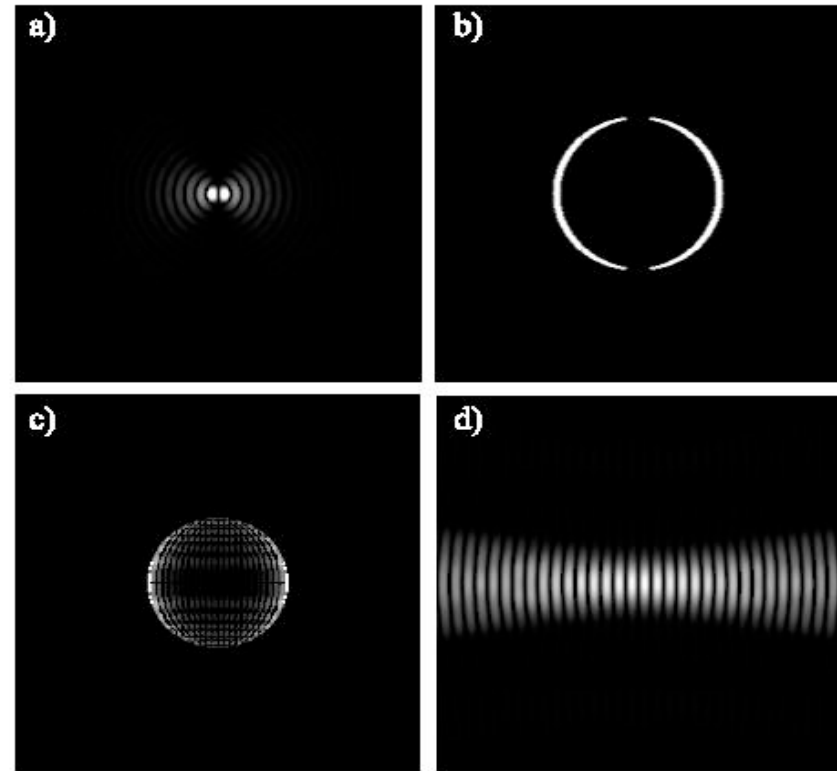
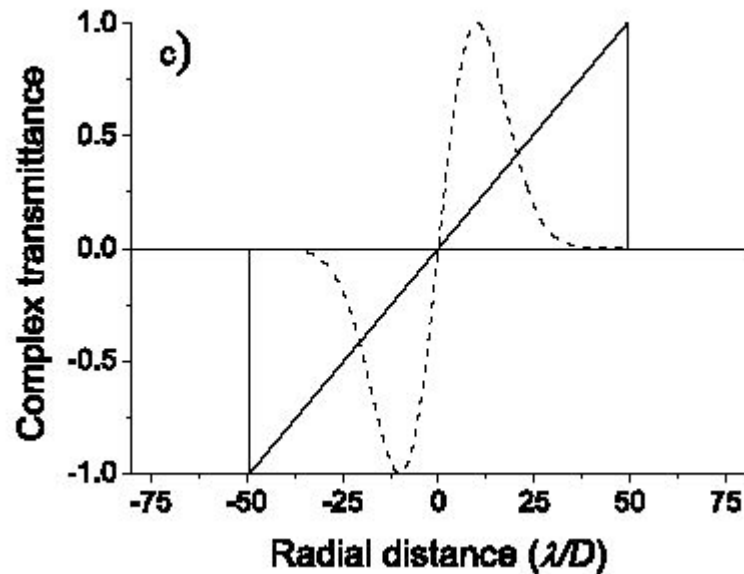
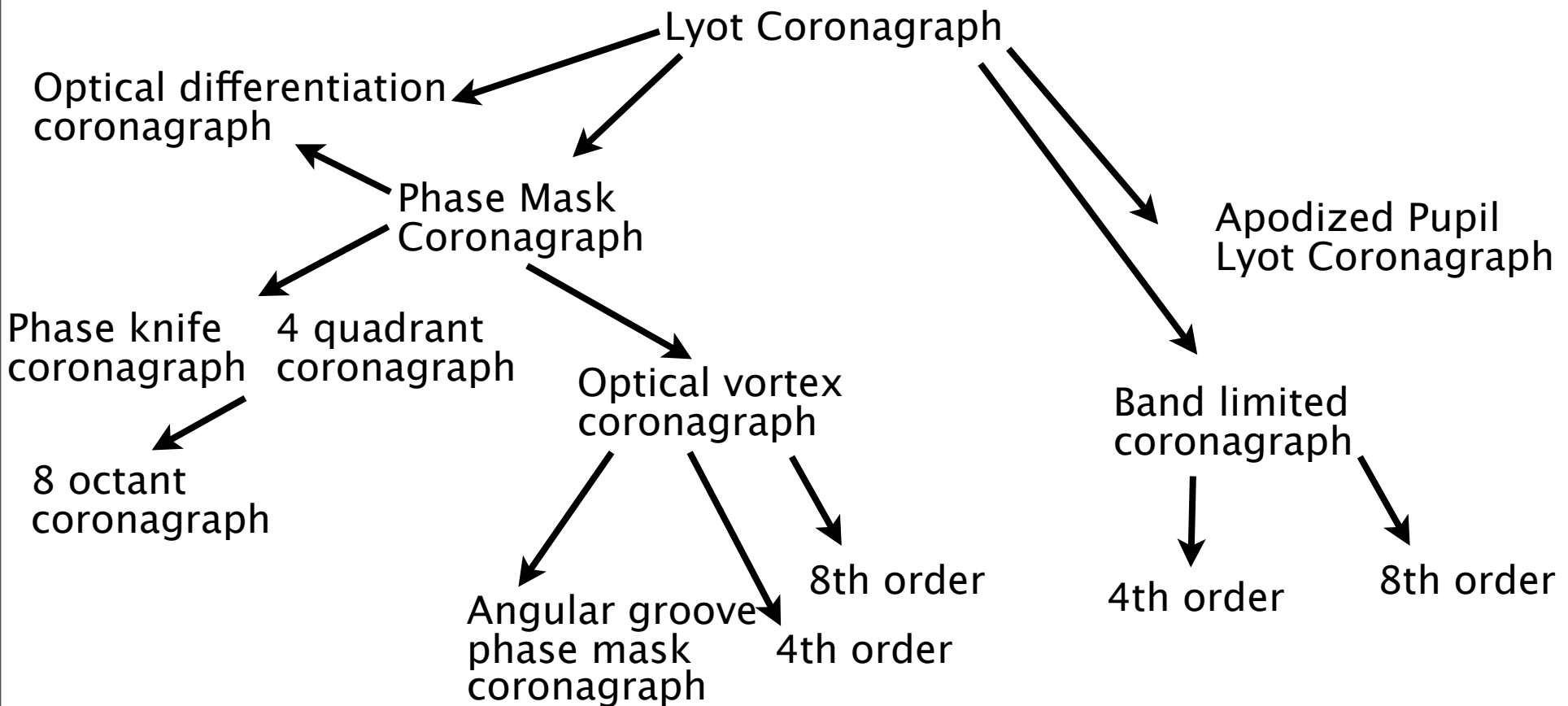


FIG. 3.—Simulated images at different planes in the optical differentiation coronagraph illustrating its principle of operation. (a) Image of the star PSF multiplied by the modified differentiation mask. (b) Intensity distribution just before (b) and after (c) the Lyot stop plane. (d) Final image detected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

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

Apodized pupil



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

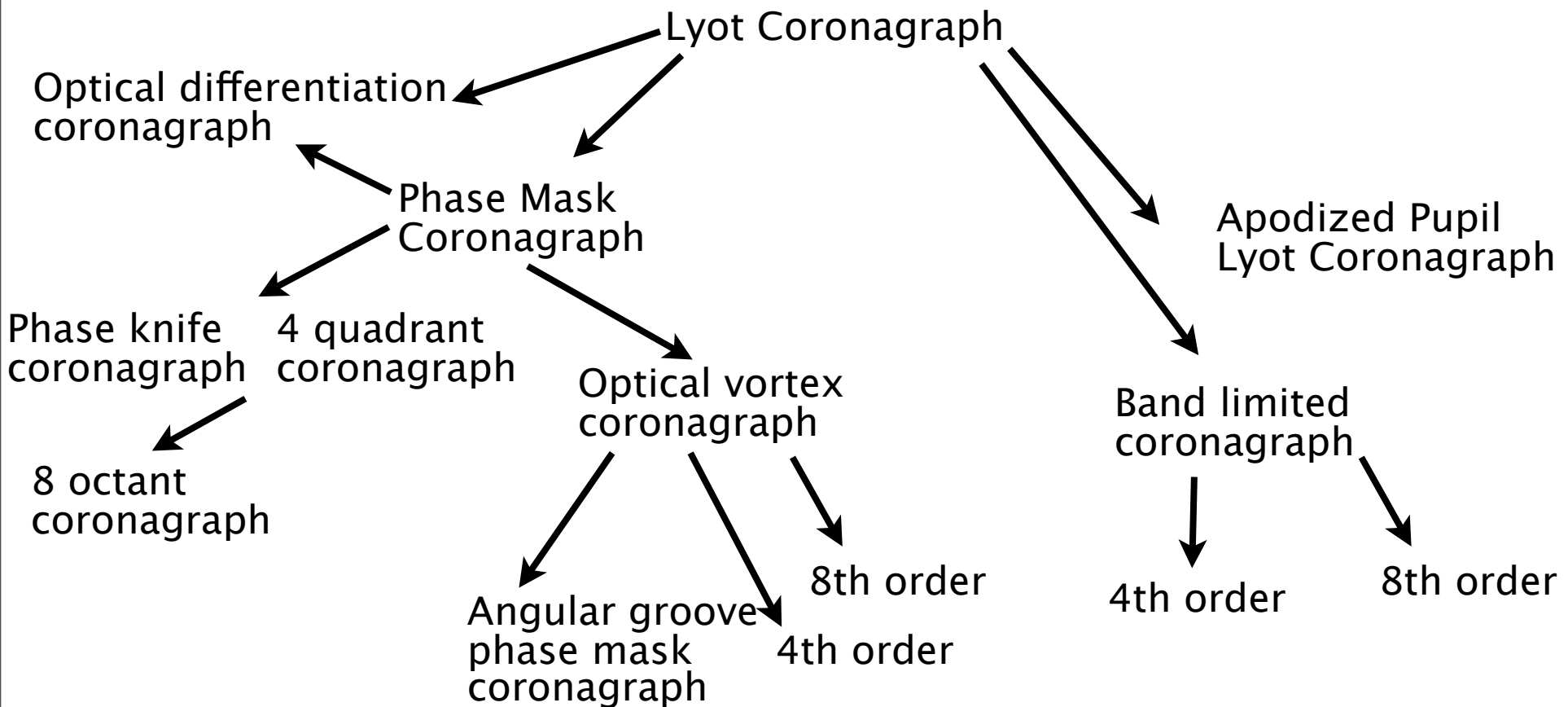
PIZZA

[Martinache, 2003](#)

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

Apodized pupil

Shaped pupil
coronagraph



Conventional Pupil Apodization (CPA)

Many pupil apodizations have been proposed.

Apodization can be continuous or binary.

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



Jacquinet & 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

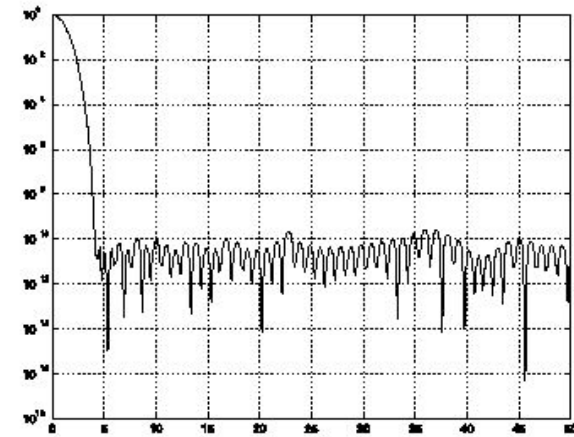
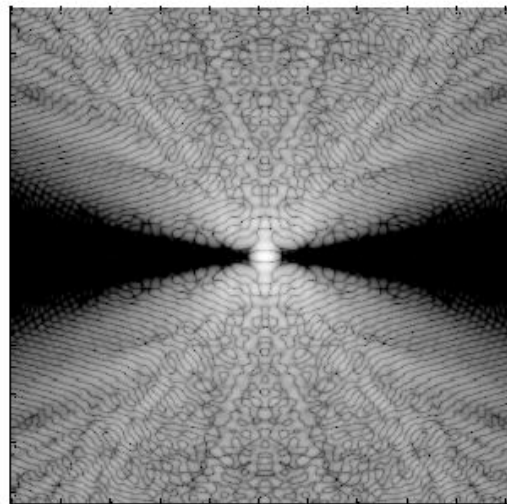
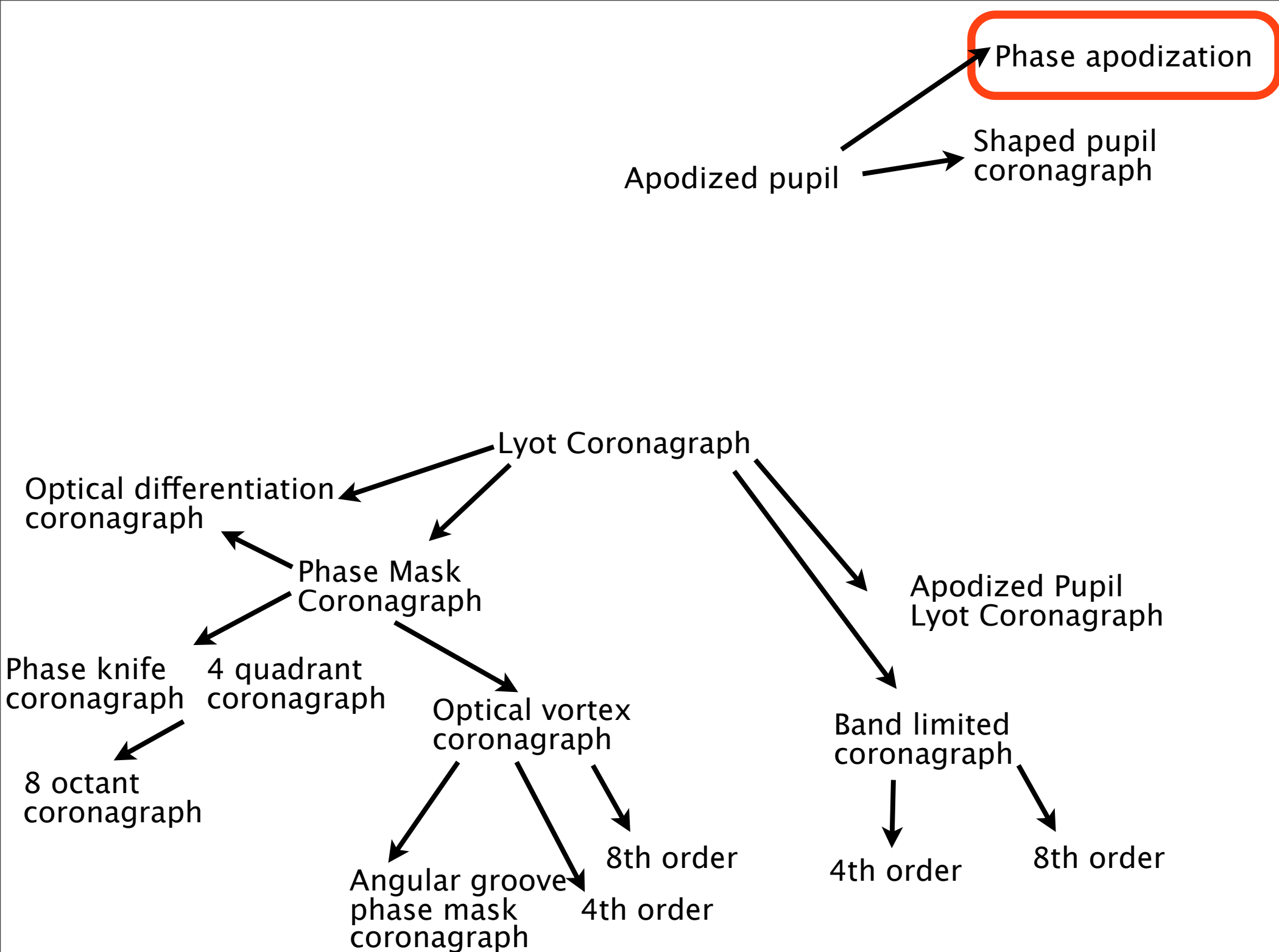
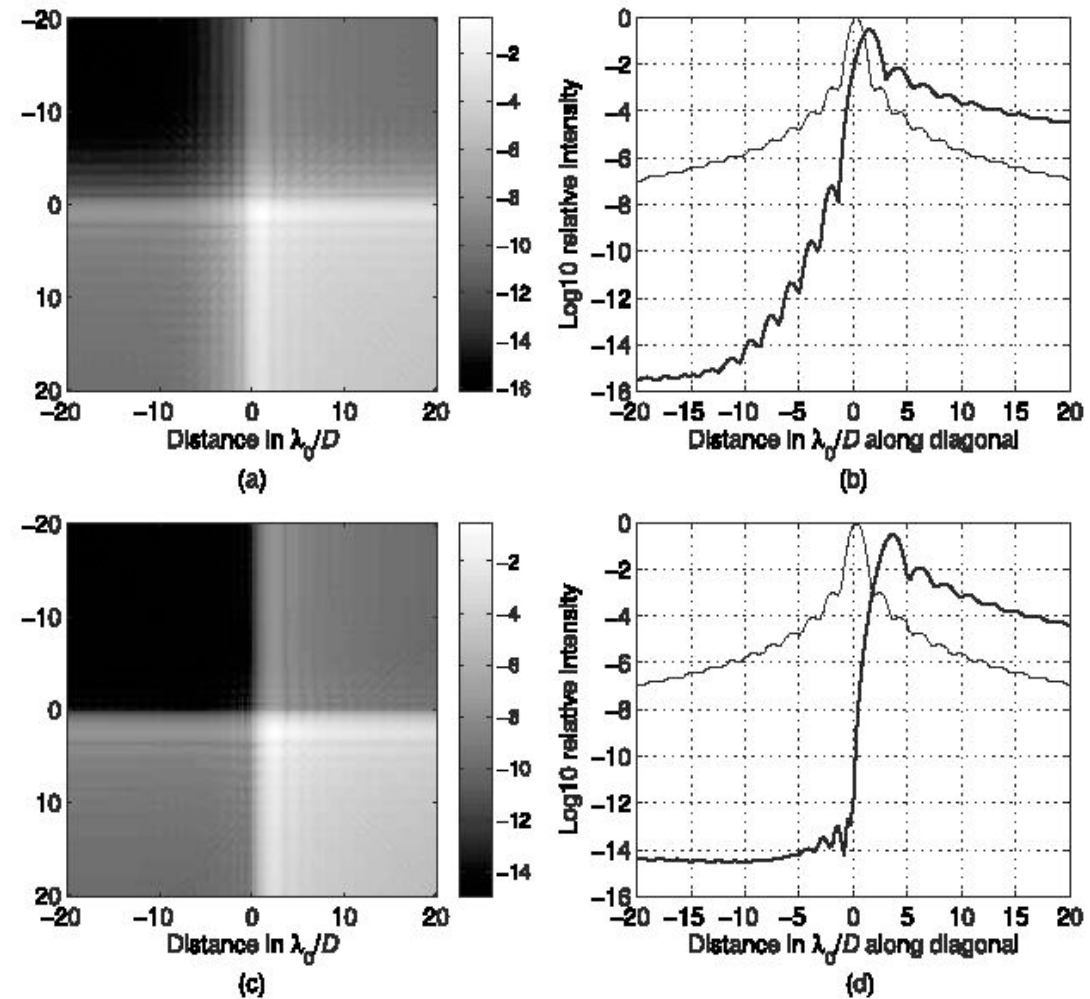


FIG. 9.—*Top*: Asymmetric multiopening mask designed to provide high-contrast, 10^{-10} , from $\lambda/D = 4$ to $\lambda/D = 100$ in two angular sectors centered on the x -axis. Ten integrations are required to cover all angles. Total throughput and pseudoarea are 24.4%. Airy throughput is 11.85%.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



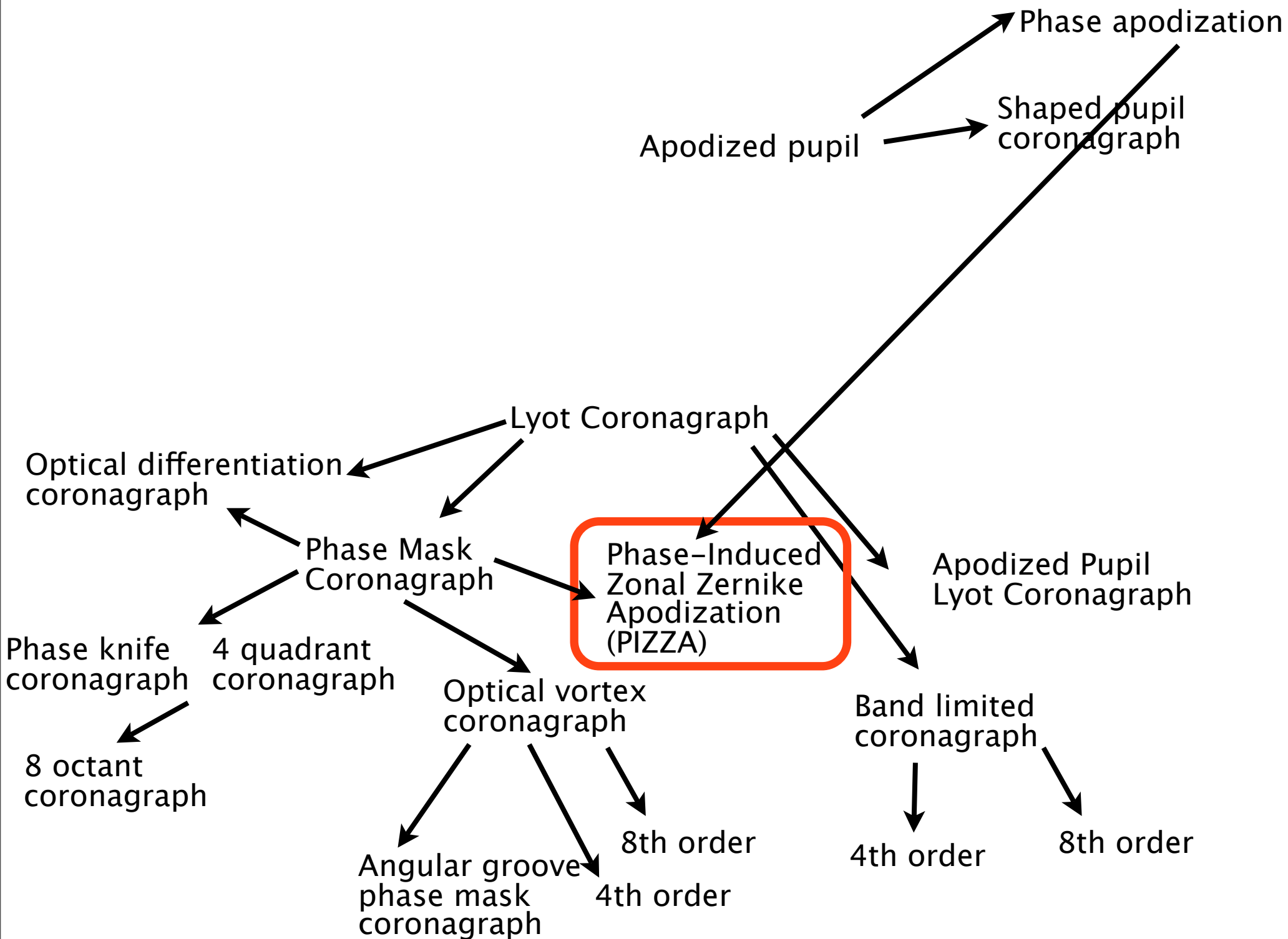
Pupil Phase Apodization (PPA)

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.

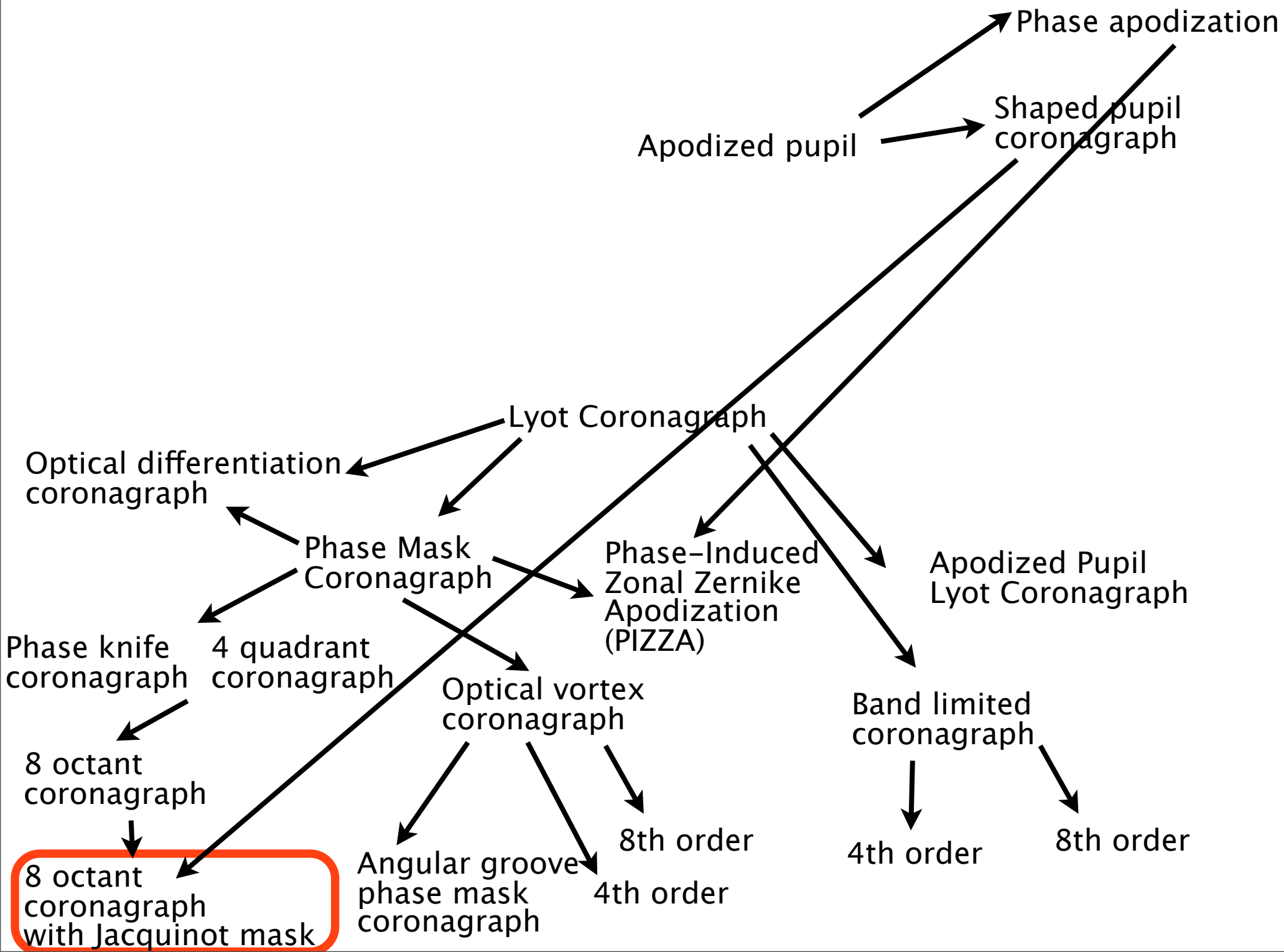


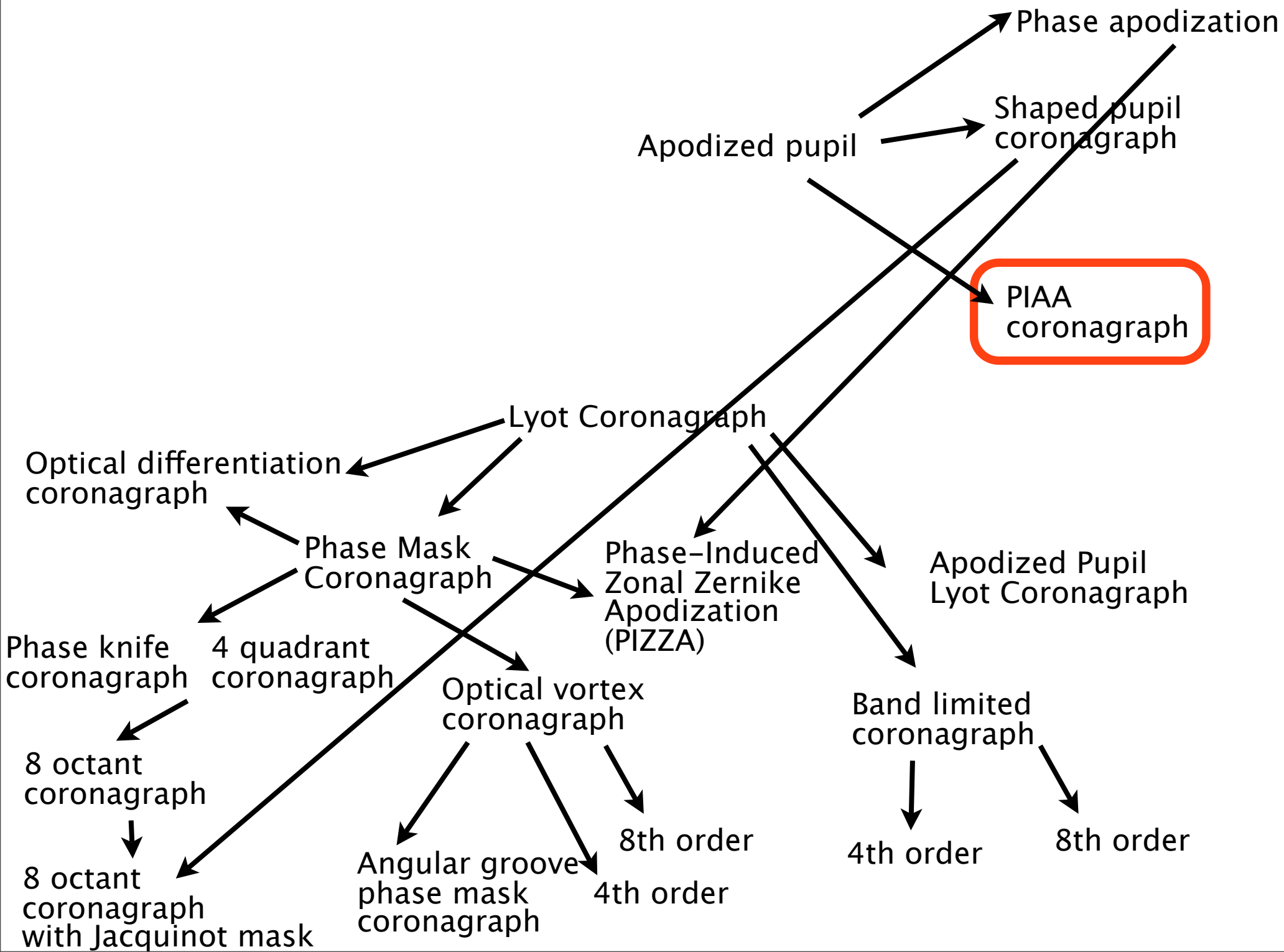
Phase-Induced Zernike Zonal Apodization (PIZZA)

Zernike phase contrast transforms pupil phase aberration into pupil amplitude modulation.

This property is used to produce an amplitude apodization.

Martinache, 2004, J. of Opt. A, 6, 809

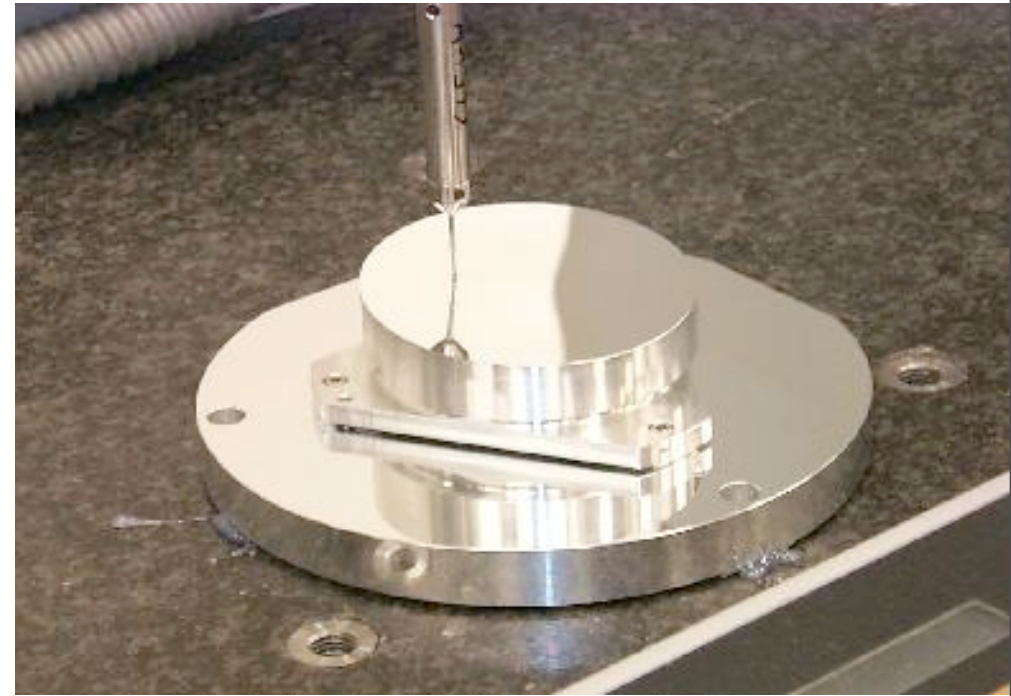
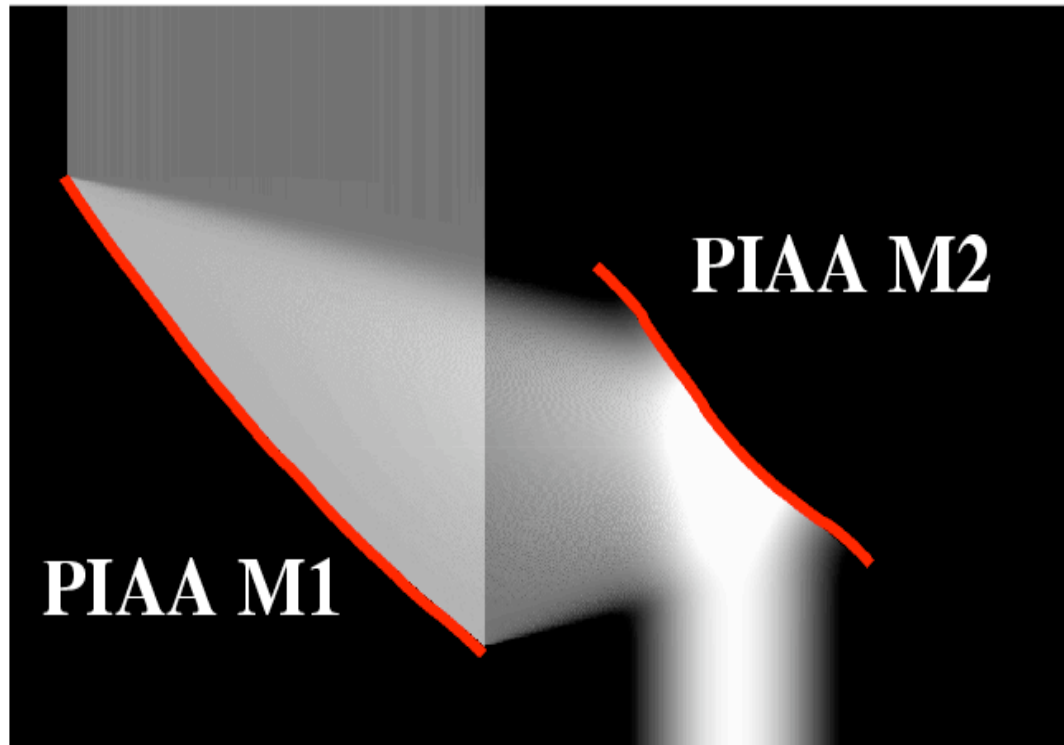




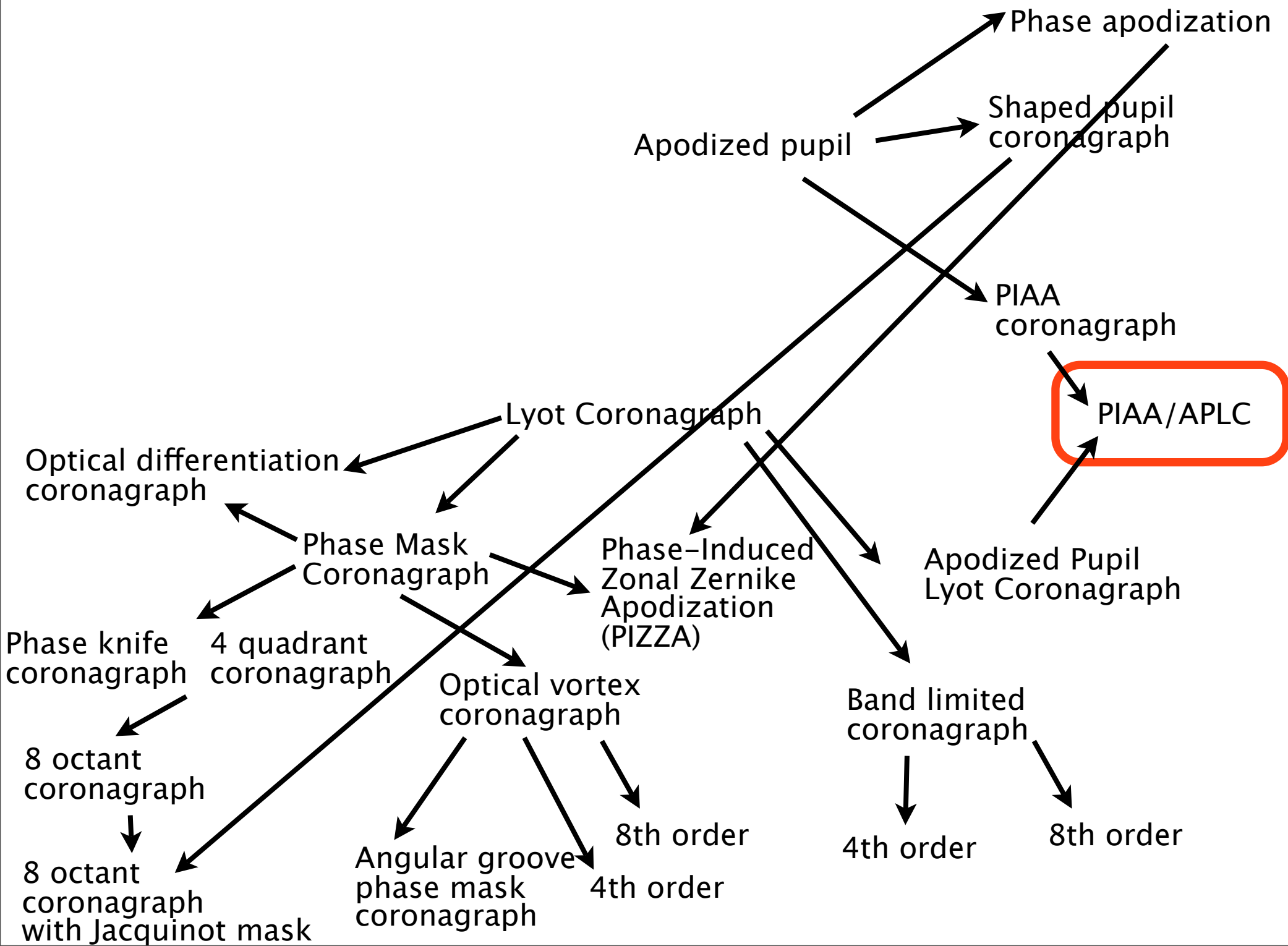
Phase-Induced Amplitude Apodization Coronagraph (PIAAC)

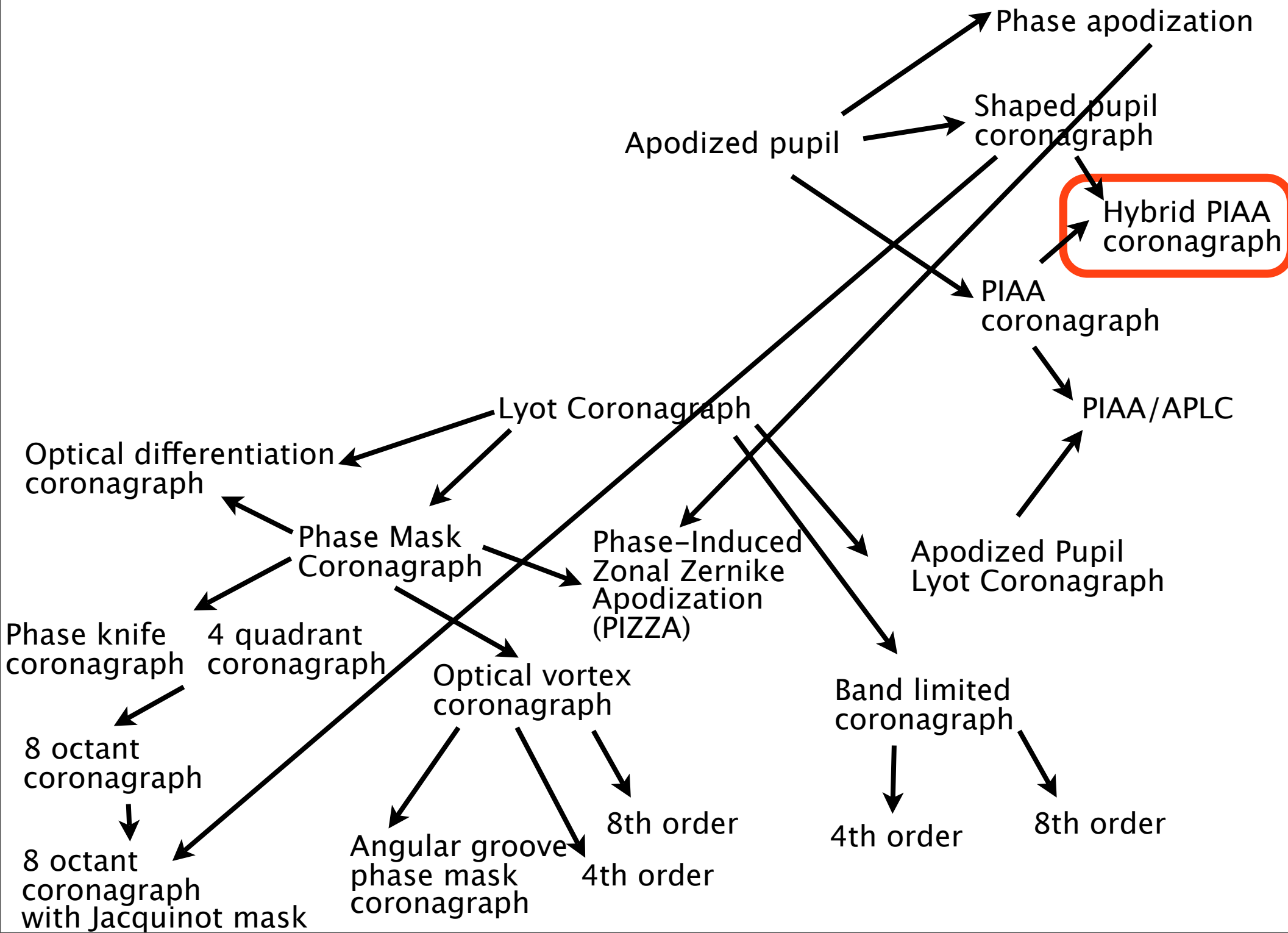
Lossless apodization by aspheric optics.

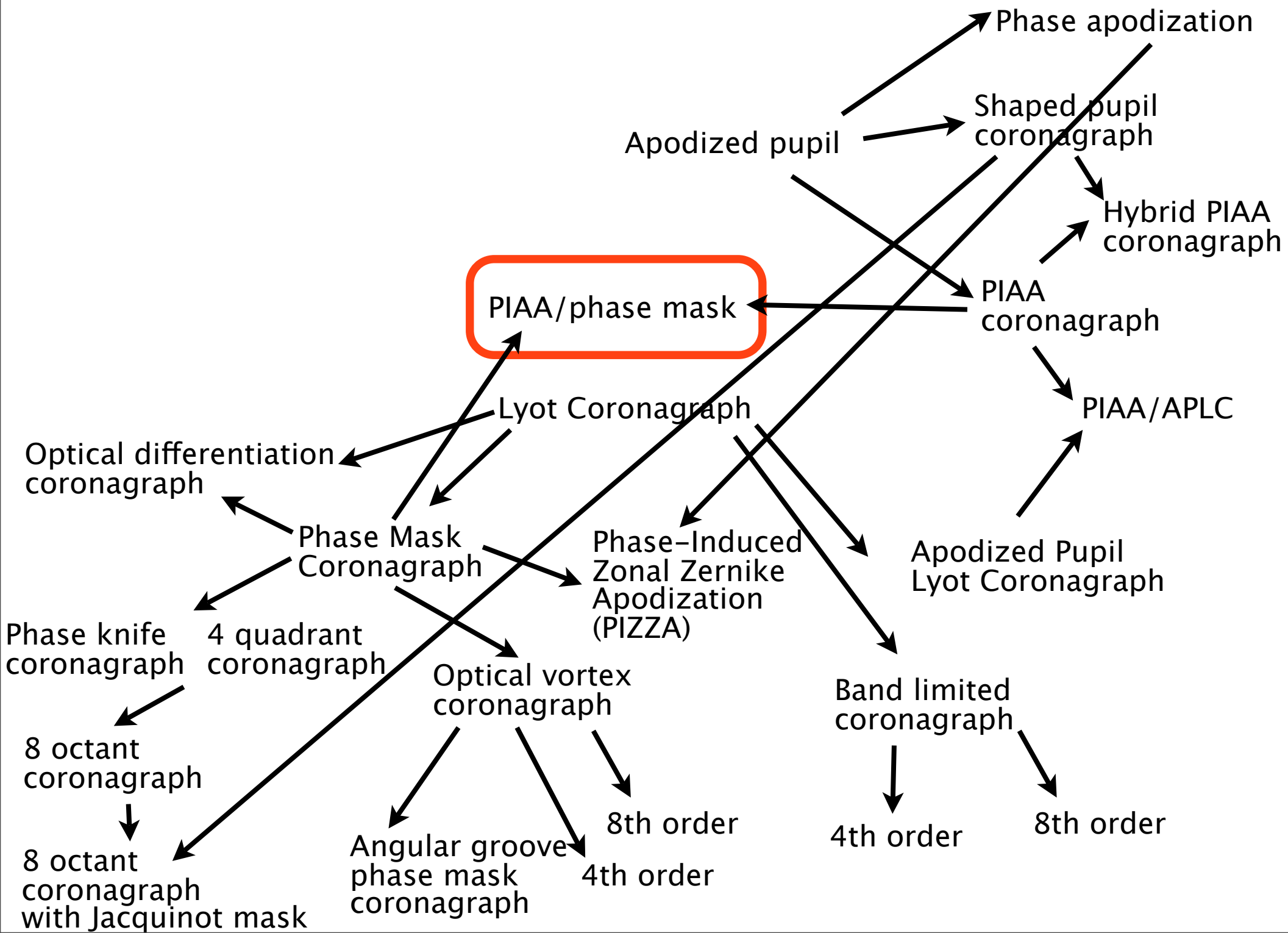
Light intensity



Guyon, Pluzhnik, Vanderbei, Traub, Martinache ... 2003–2006







"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
Common Path AIC

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

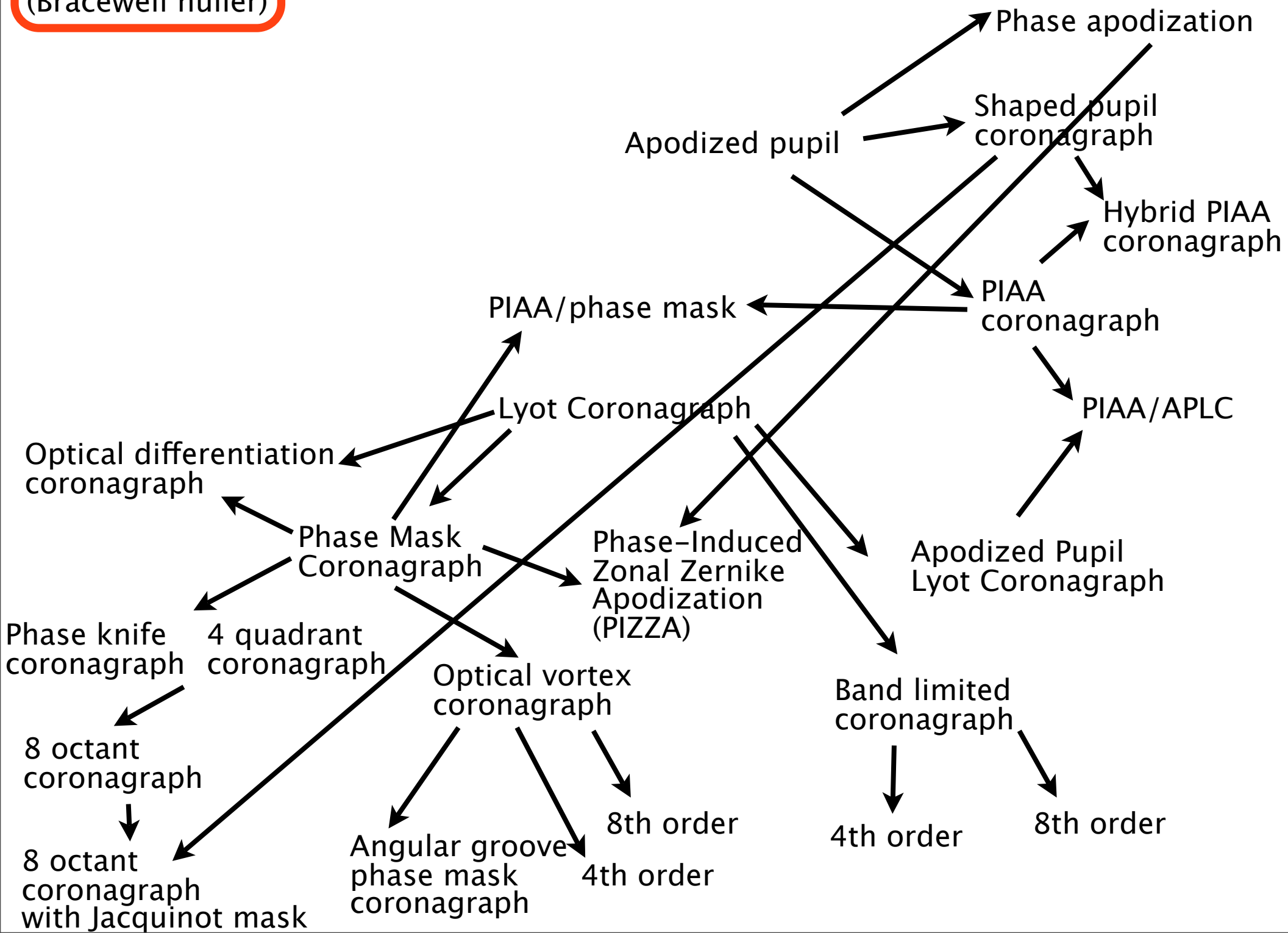
Pupil Swapping Coronagraph

PSC

[Guyon & Shao, 2006](#)

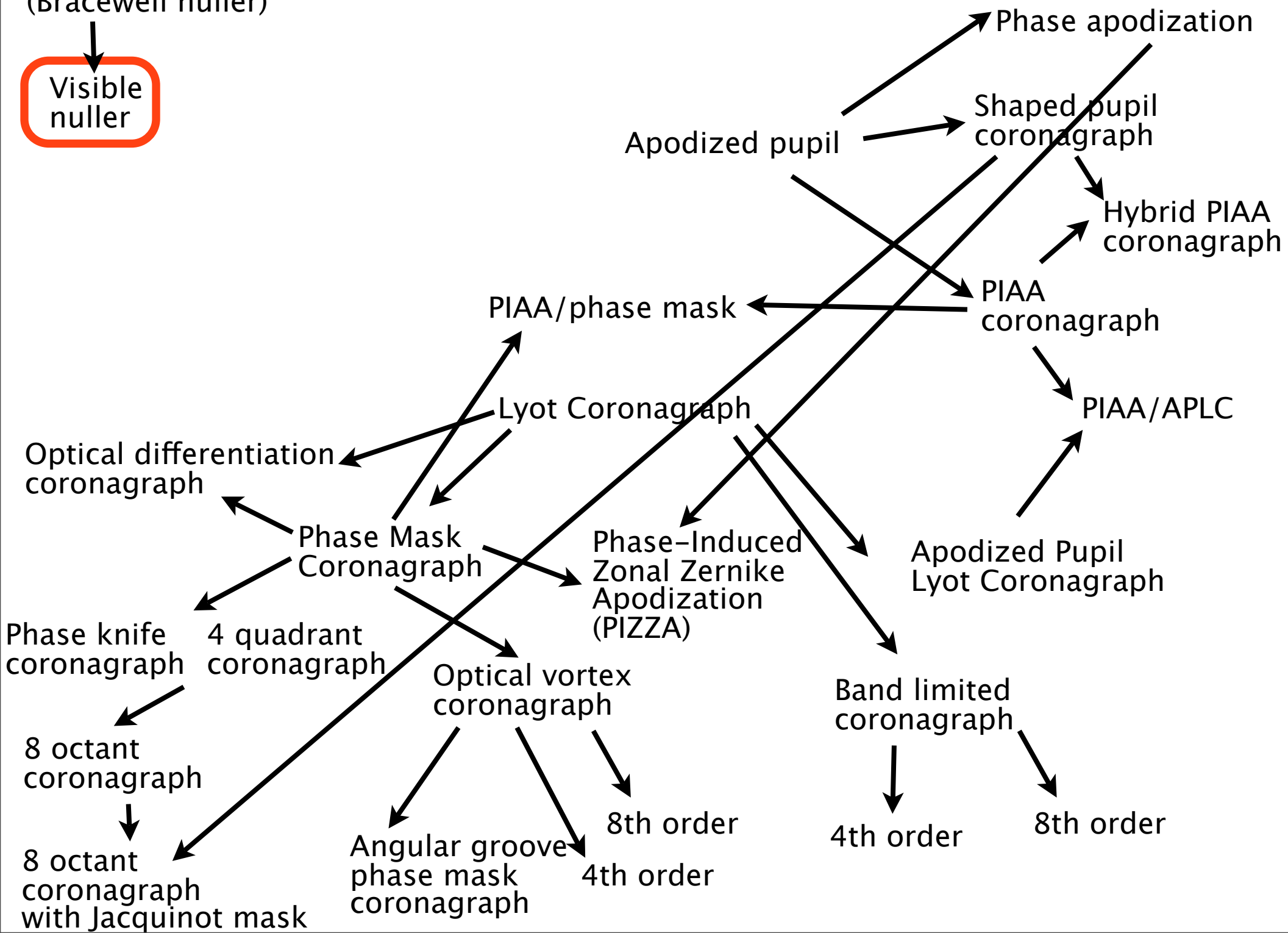
Destructive interference between pupil and a copy of the pupil where 4 quadrants have been swapped

(Bracewell nuller)

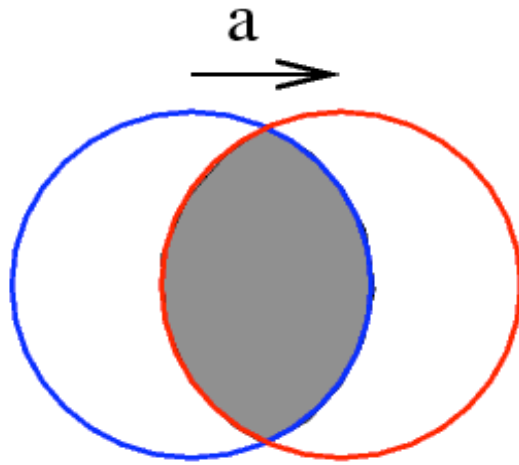


(Bracewell nuller)

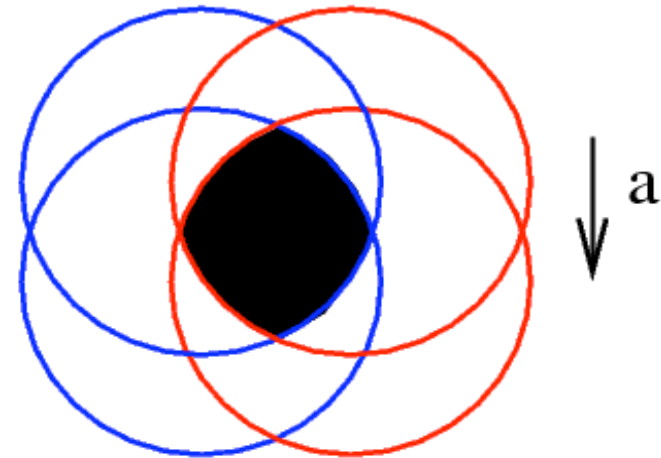
Visible
nuller



Visible Nuller Coron. (VNC)



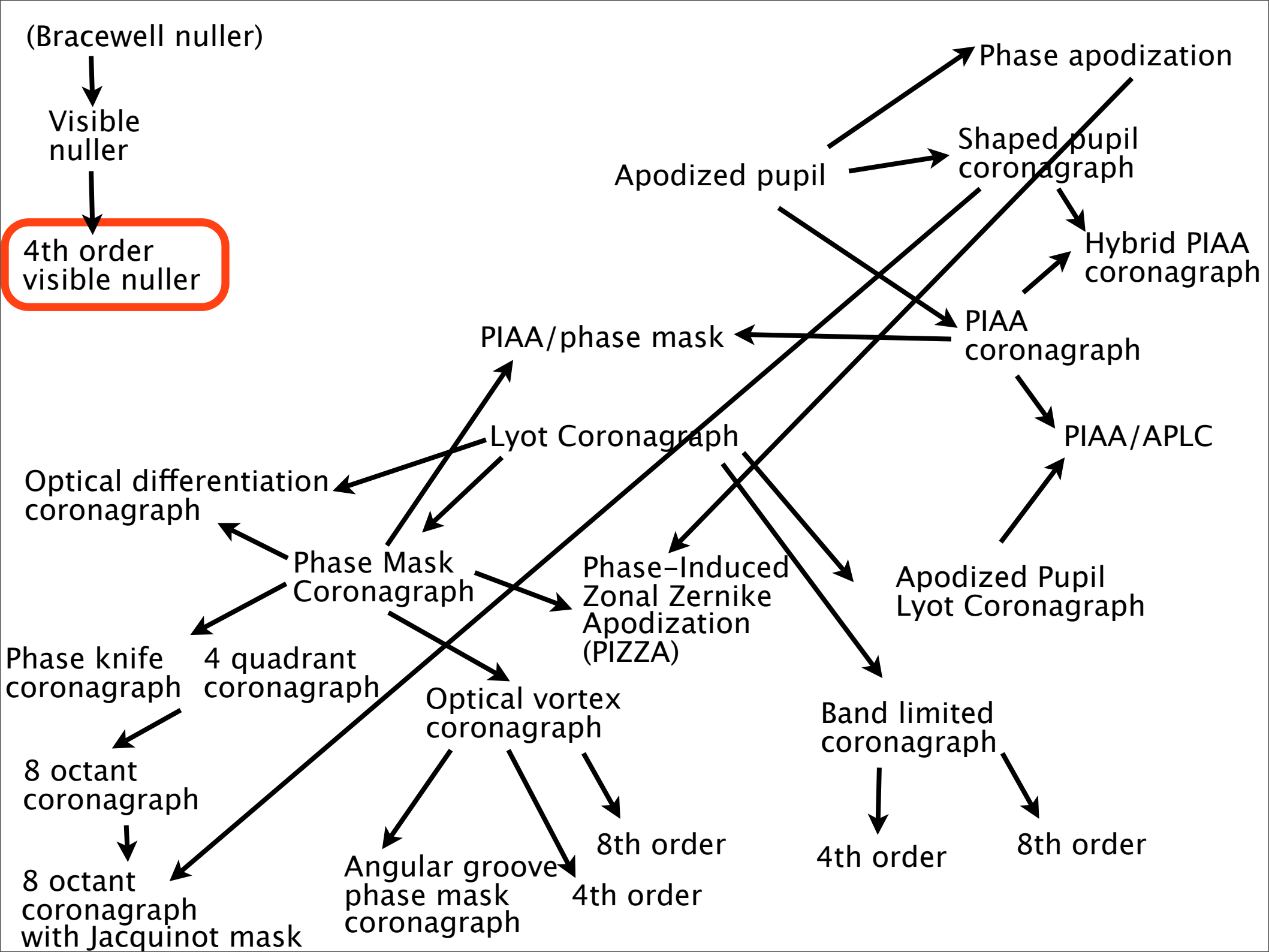
second order null
phase offset prop. to
pupil shear x source offset

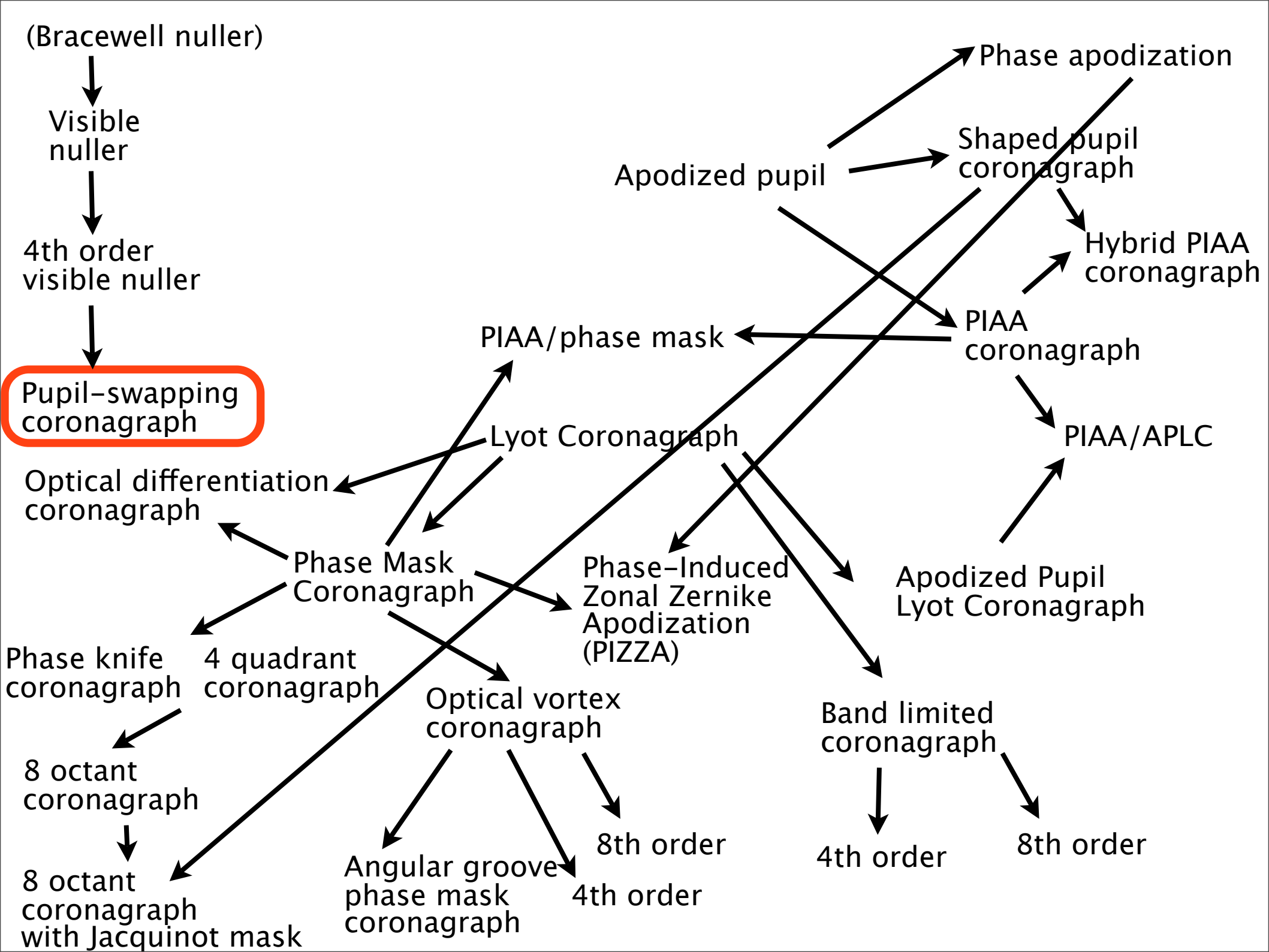


4th order null

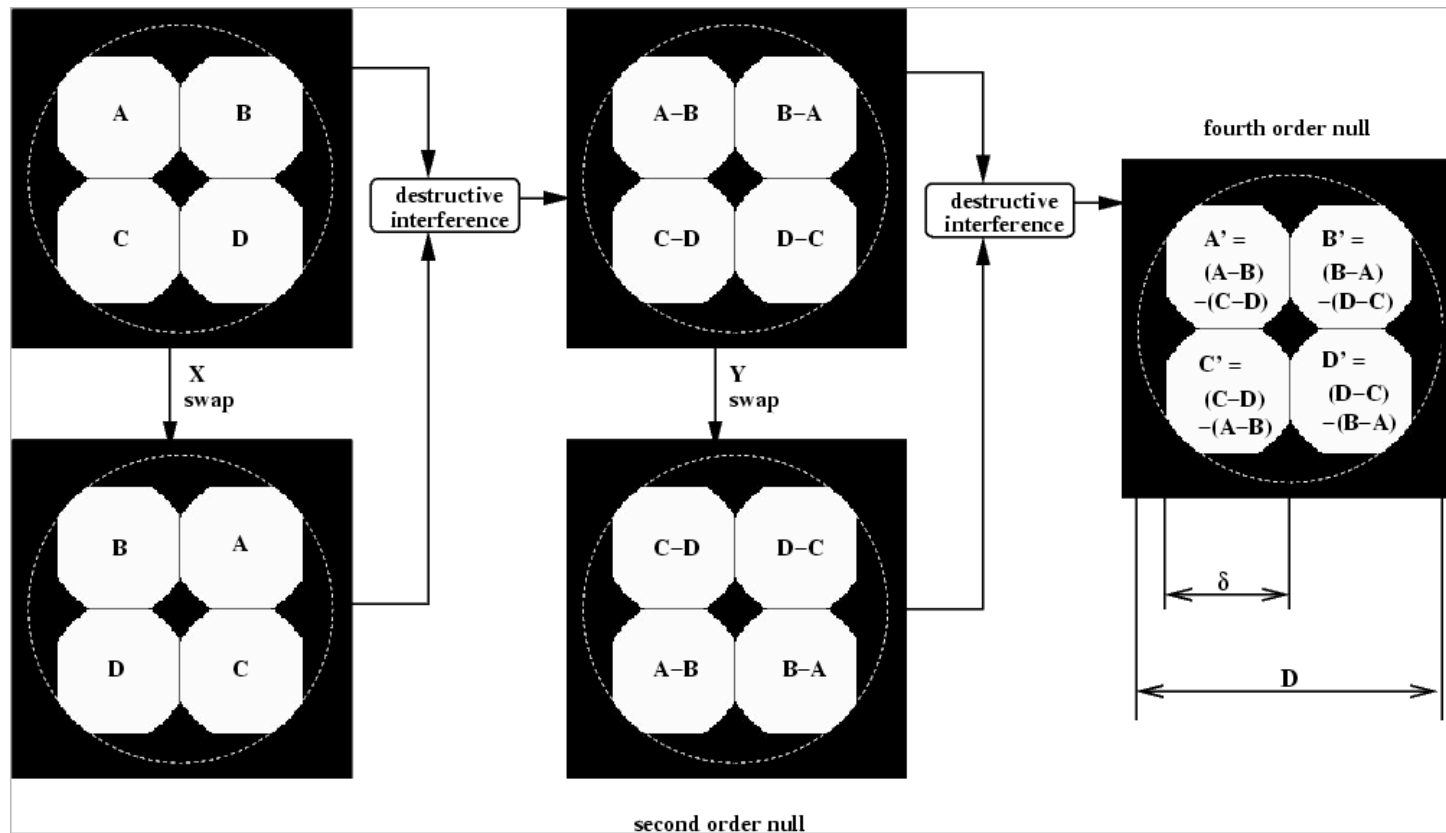
Small shear : high throughput, low IWA
Large shear : low throughput, small IWA
The 2 shears can also be colinear

**Will fly soon
on sounding rocket
(PICTURE)**



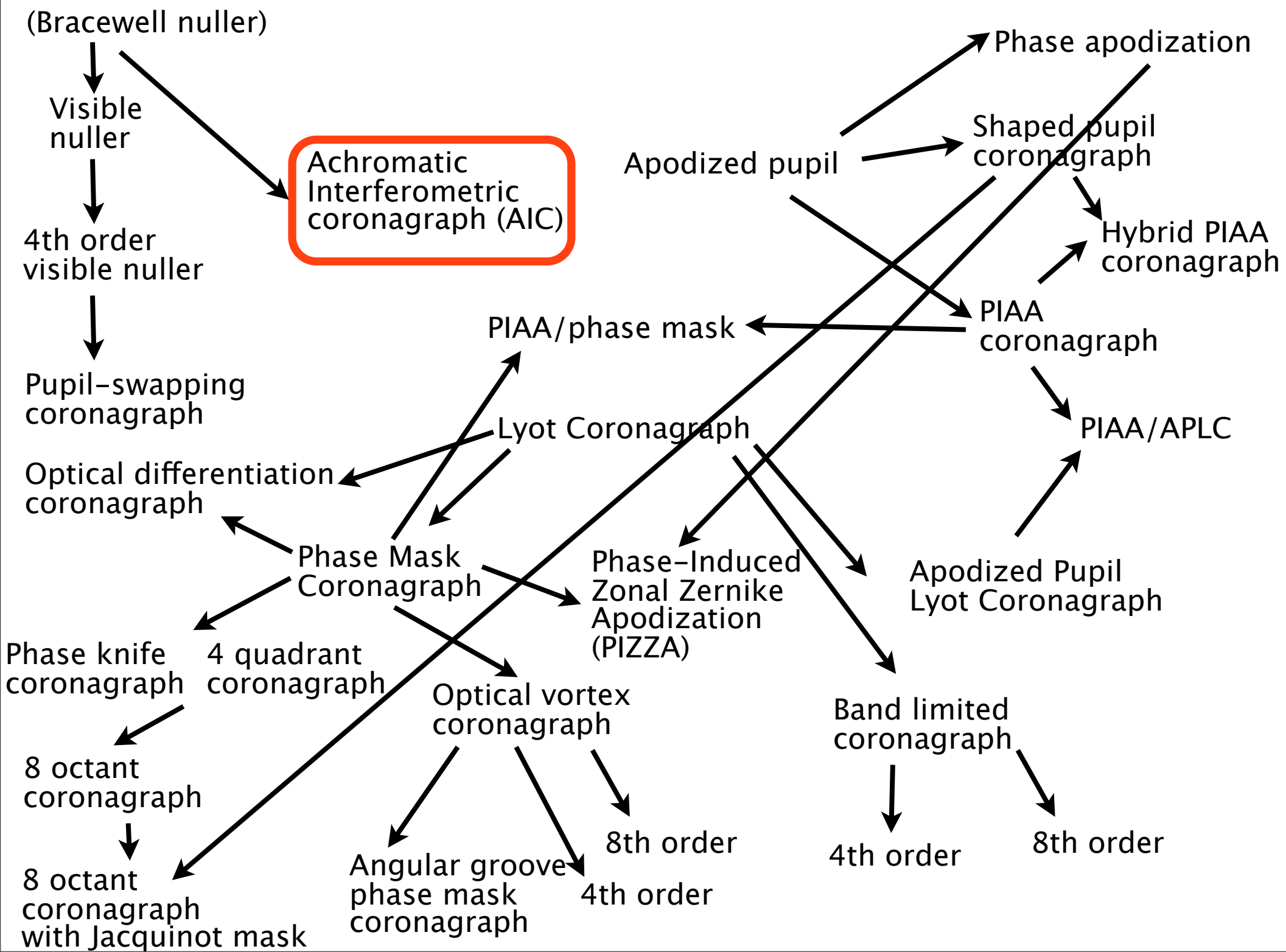


Pupil Swapping Coronagraph (PSC)



Same basic principle as VNC, higher throughput

Guyon & Shao, 2006, PASP



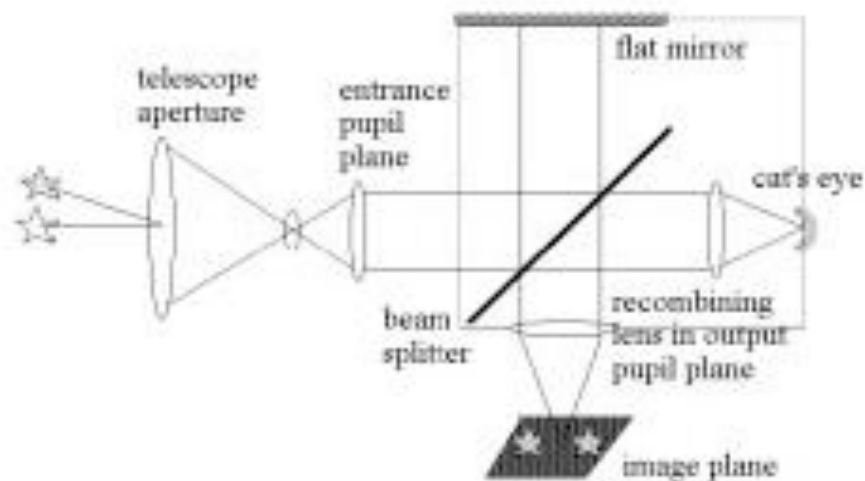


Fig. 1. Schematic of the Generic Set-up of our coronagraph



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

Achromatic Interferometric Coronagraph (AIC)

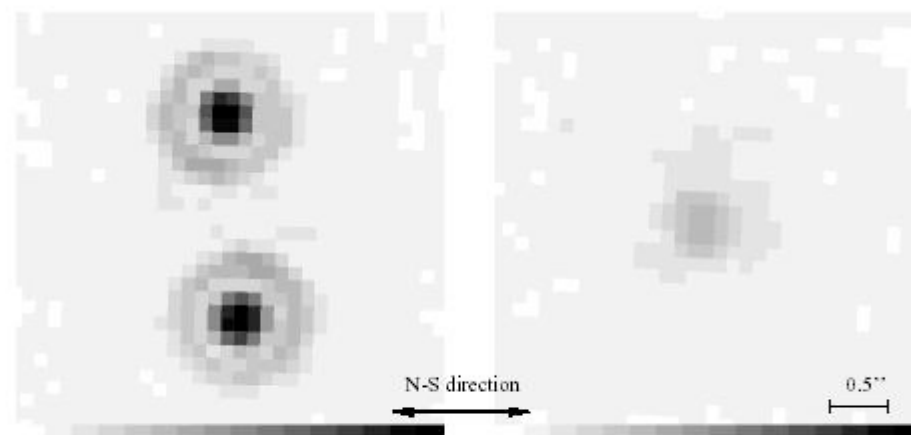


Fig. 3. Image of a star off-axis and on-axis. The scale is linear and is the same for the 2 images

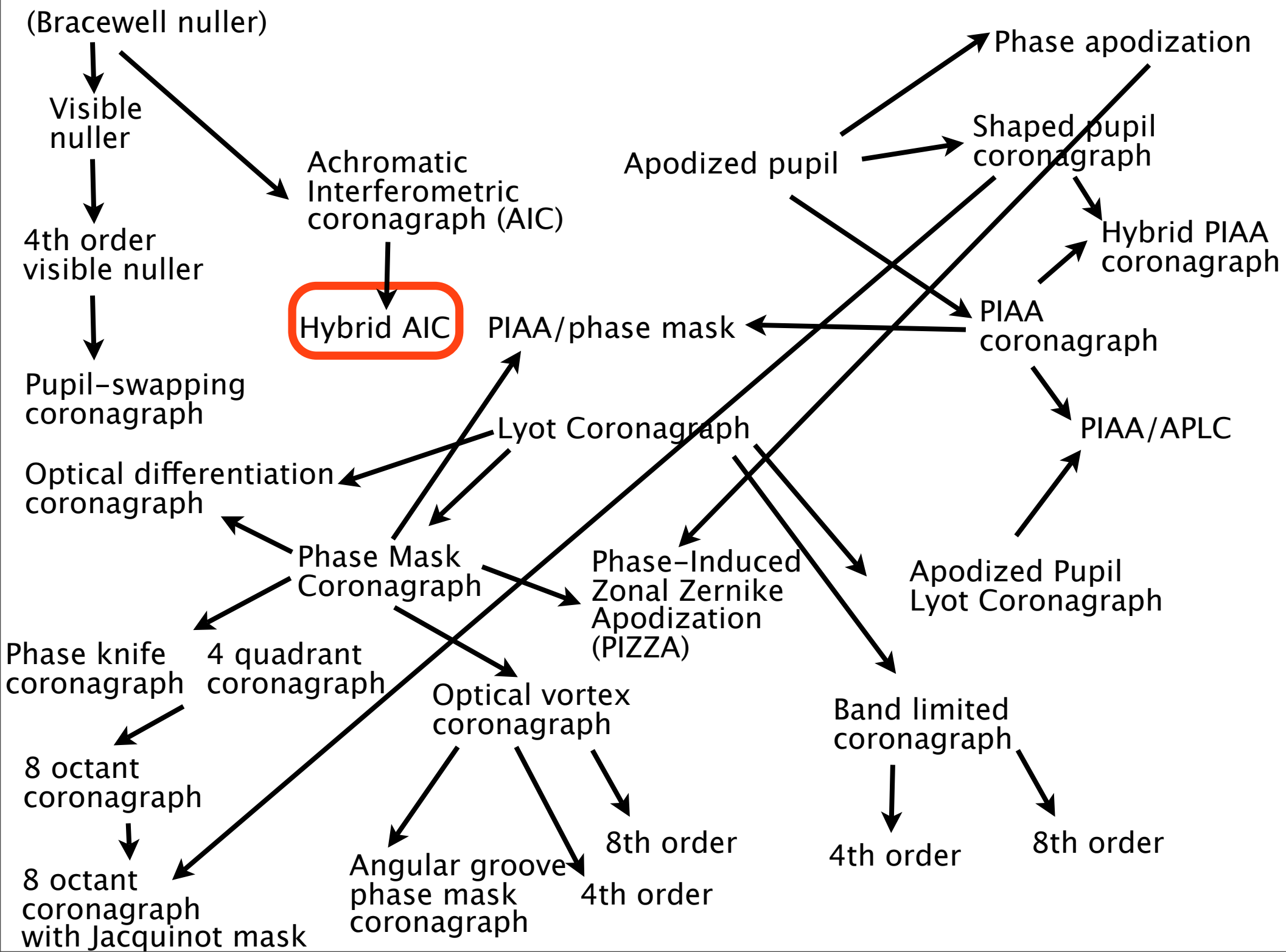
Used on sky (CFHT)

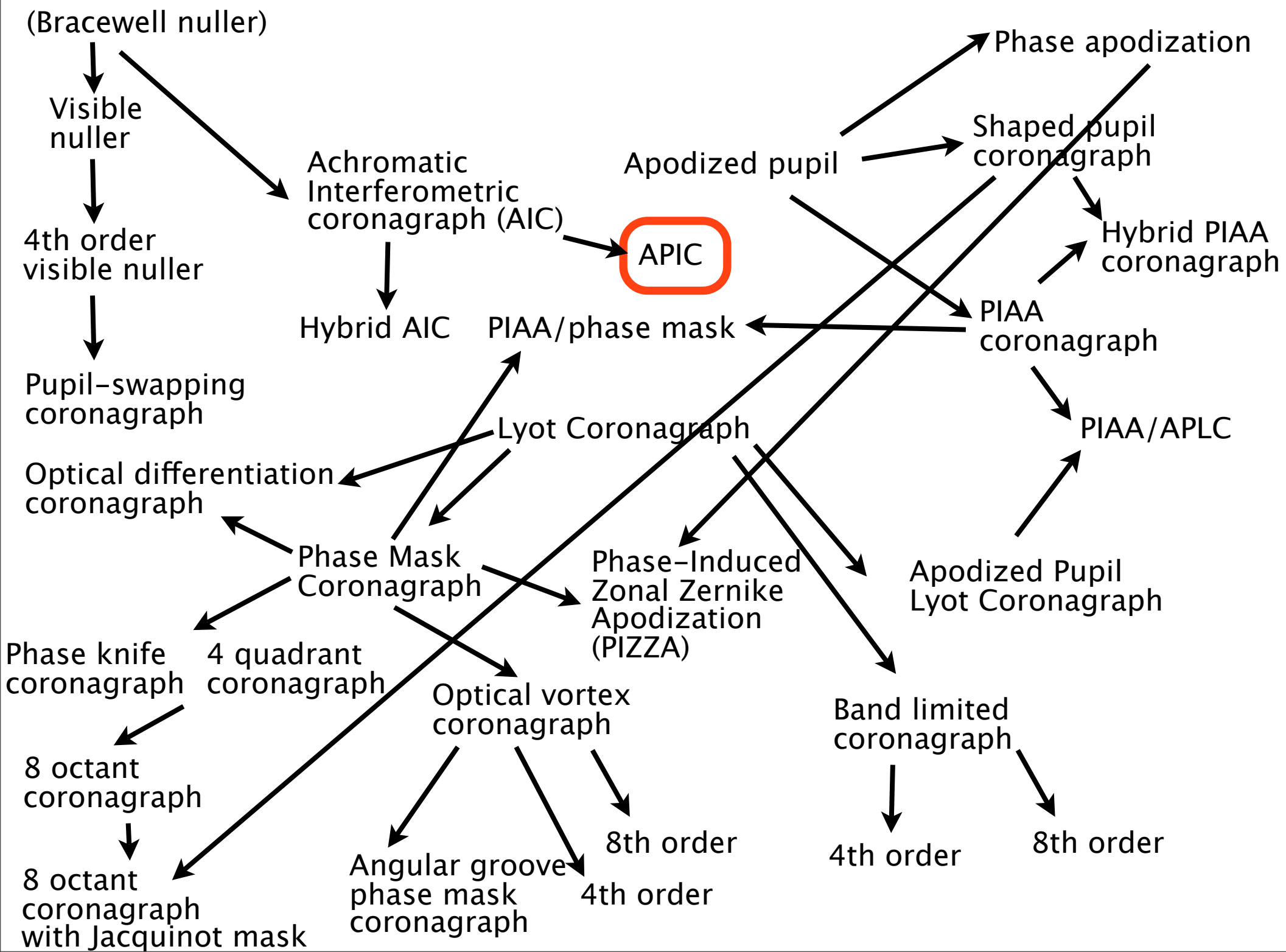
Gay & Rabbia 1996, C.R. Acad. Sci. Paris 322, 265

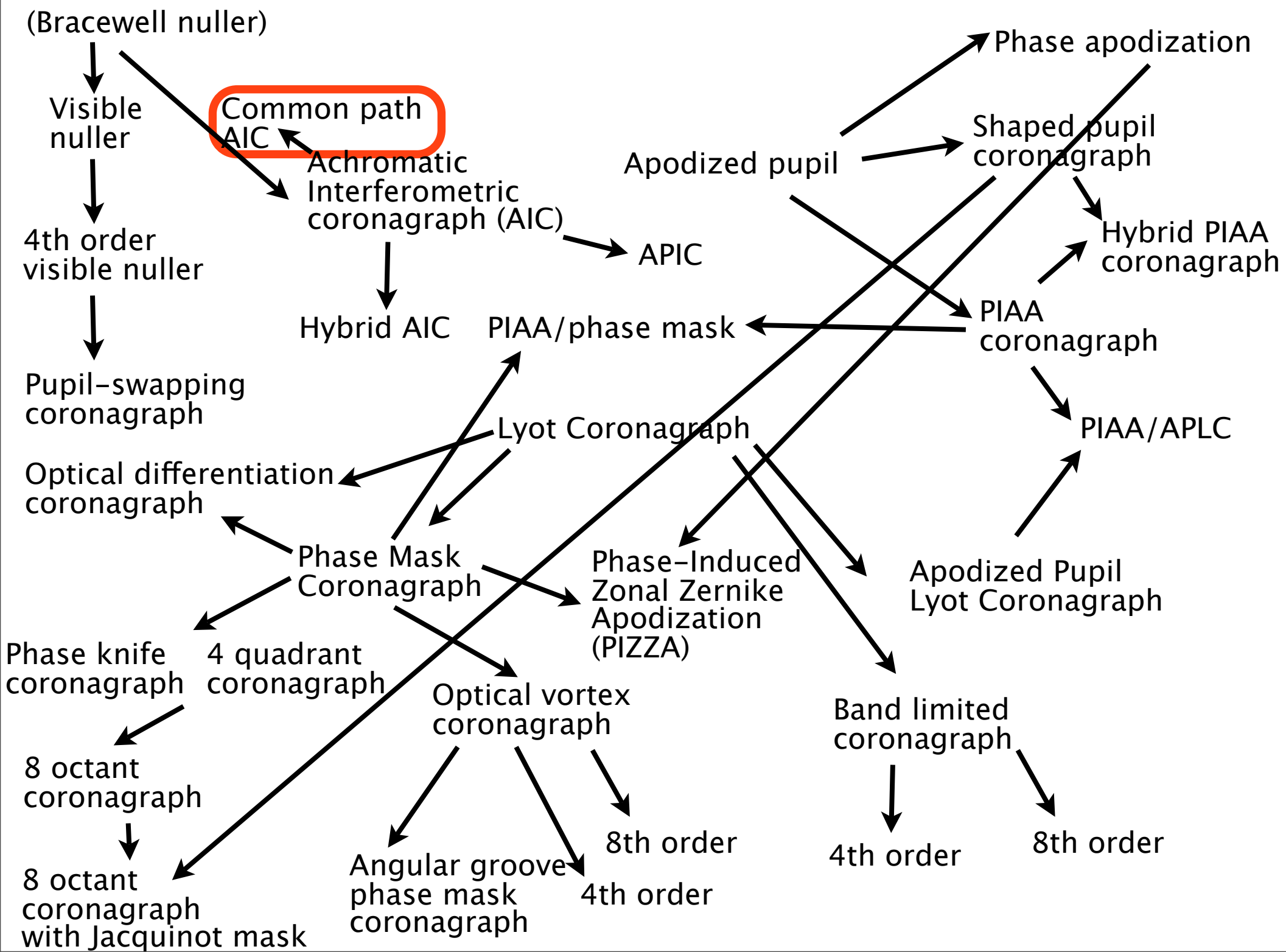
Baudoz et al. 2000, A&AS, 141, 319

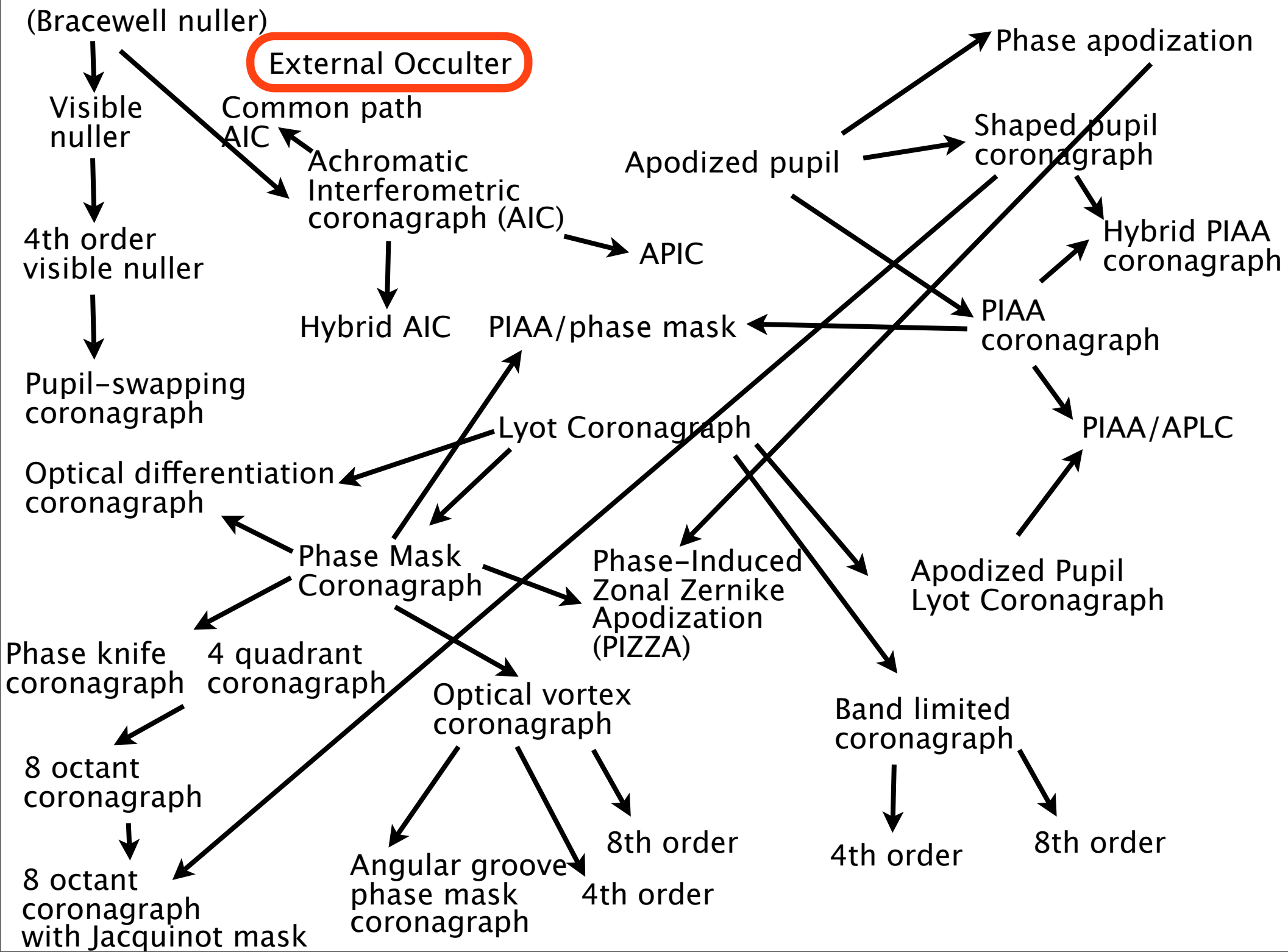
Baudoz et al. 2005, PASP, 117, 1004 (Hybrid AIC, no 180 deg ambiguity)

Tavrov et al. 2005, Opt. Letters, 30, 2224 (Common path AIC)

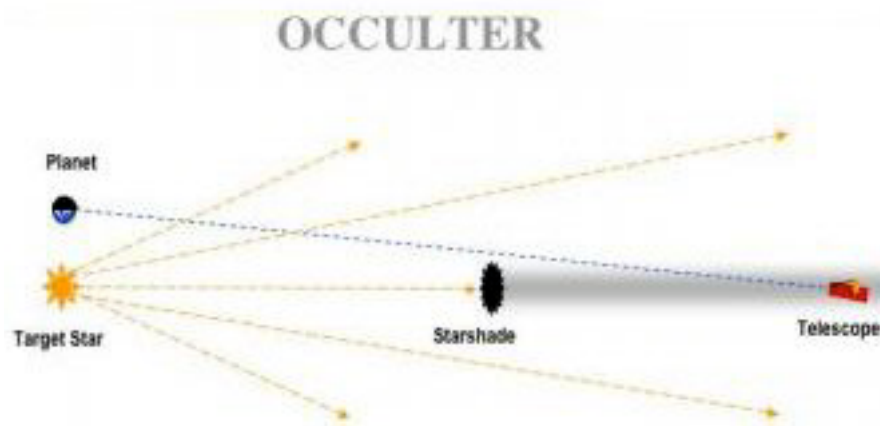




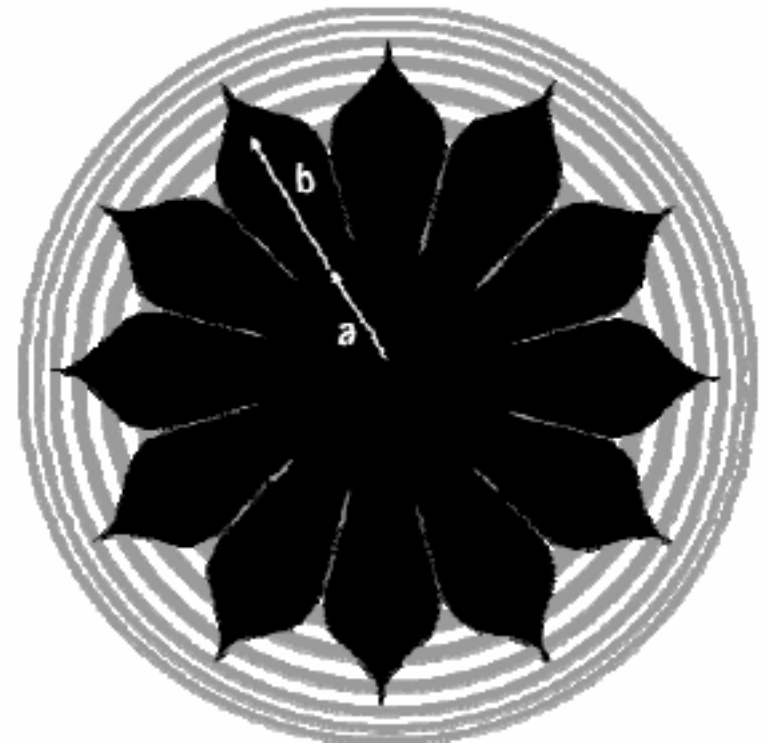


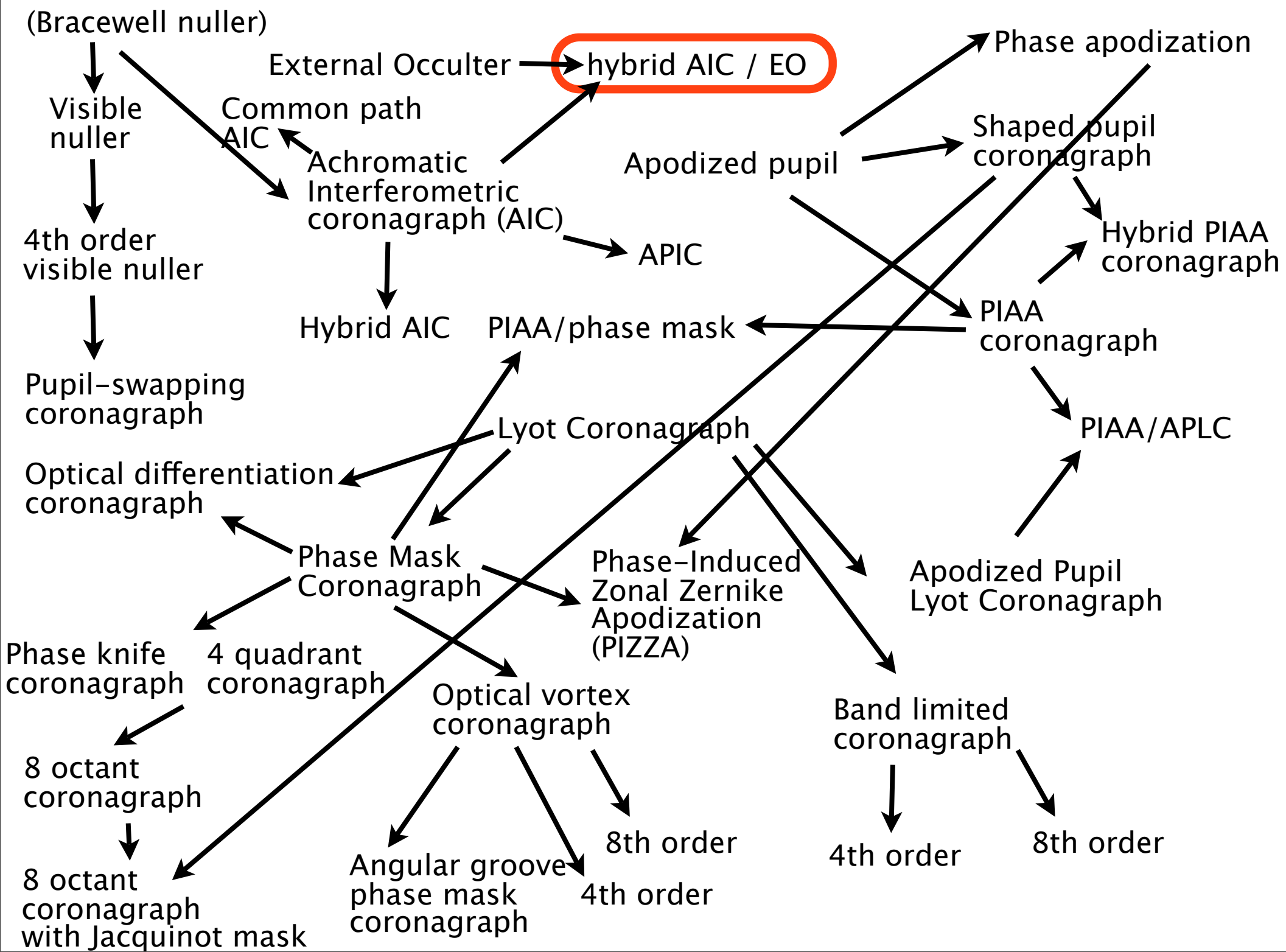


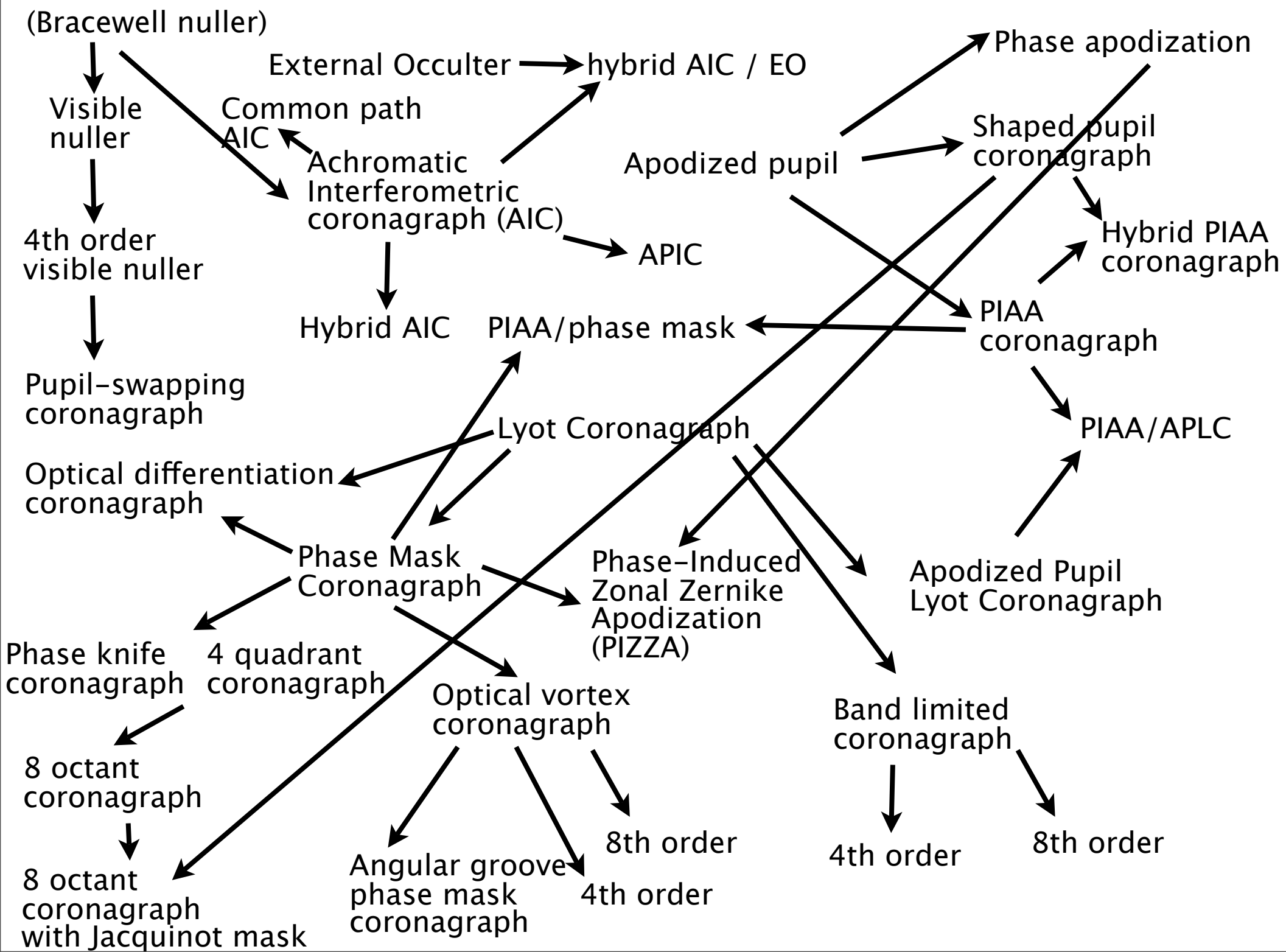
External Occulter



A properly placed and shaped occulter can drop a deep shadow of starlight over a telescope while allowing planet light to pass unimpeded.







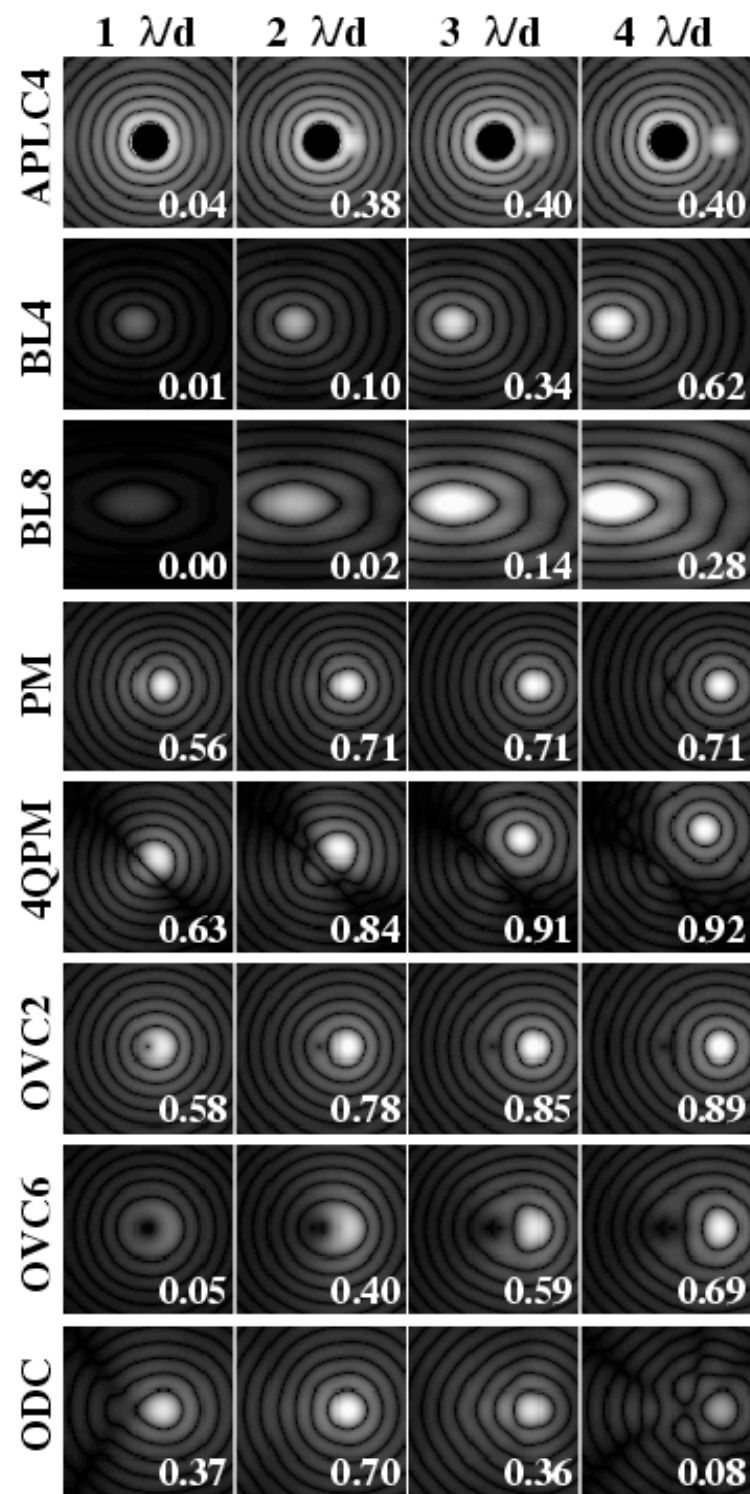
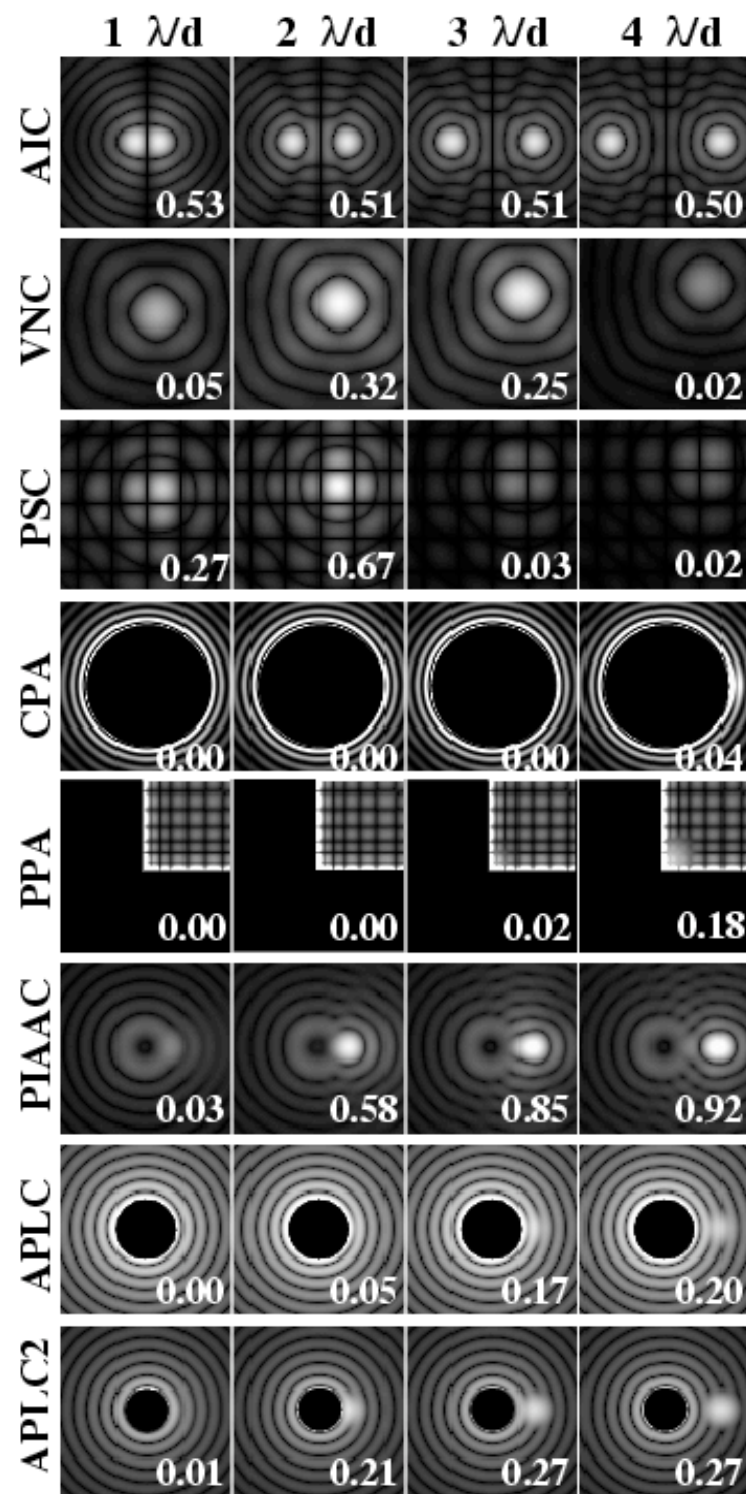
Coronagraph Performance

Every coronagraph in the previous chart except the classical Lyot can theoretically deliver $1e10$ contrast at 4 I/D

Newer coronagraphs tend to be better than older ones, not in contrast, but : smaller inner working angle, higher throughput

New coronagraphs continuously appear

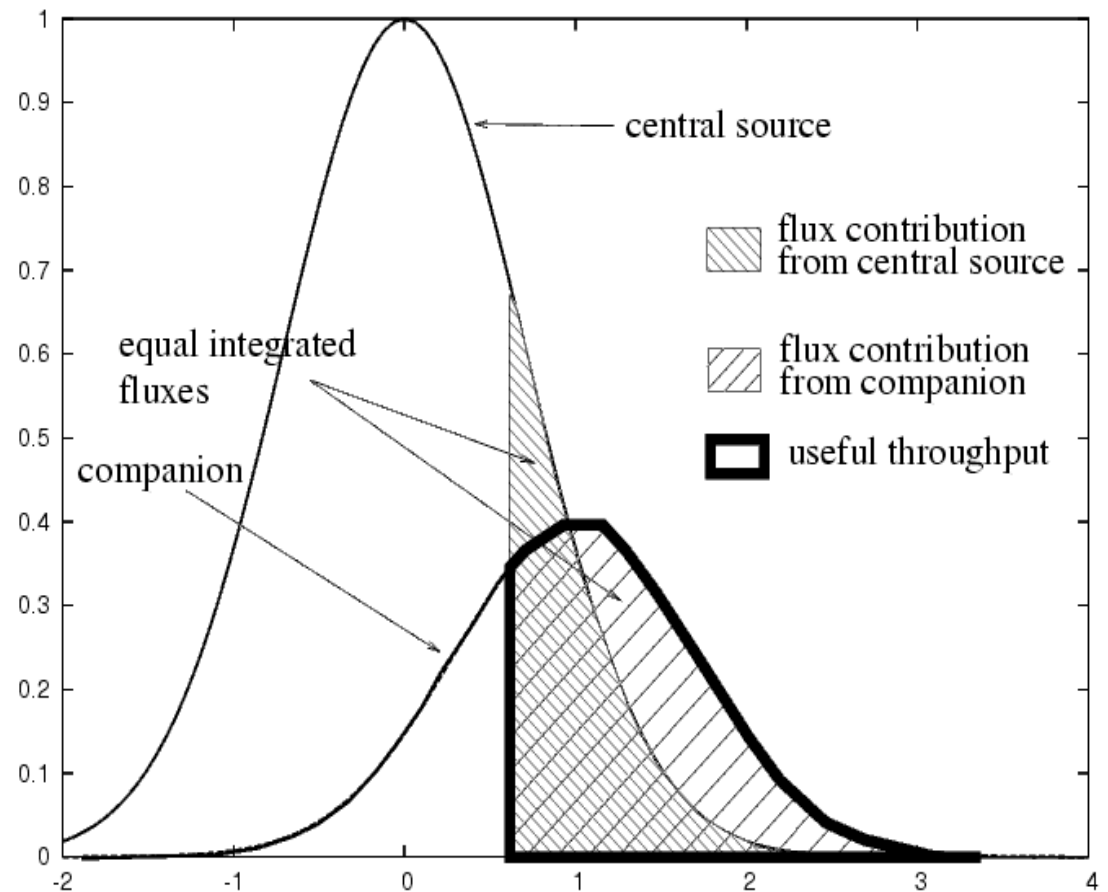
- > Is there a theoretical performance limit ?
If yes, where is it & what sets it ?
Have we reached / approached it yet ?



Useful throughput as a metric independent of coronagraph design

Commonly used metrics: IWA, throughput, discovery space

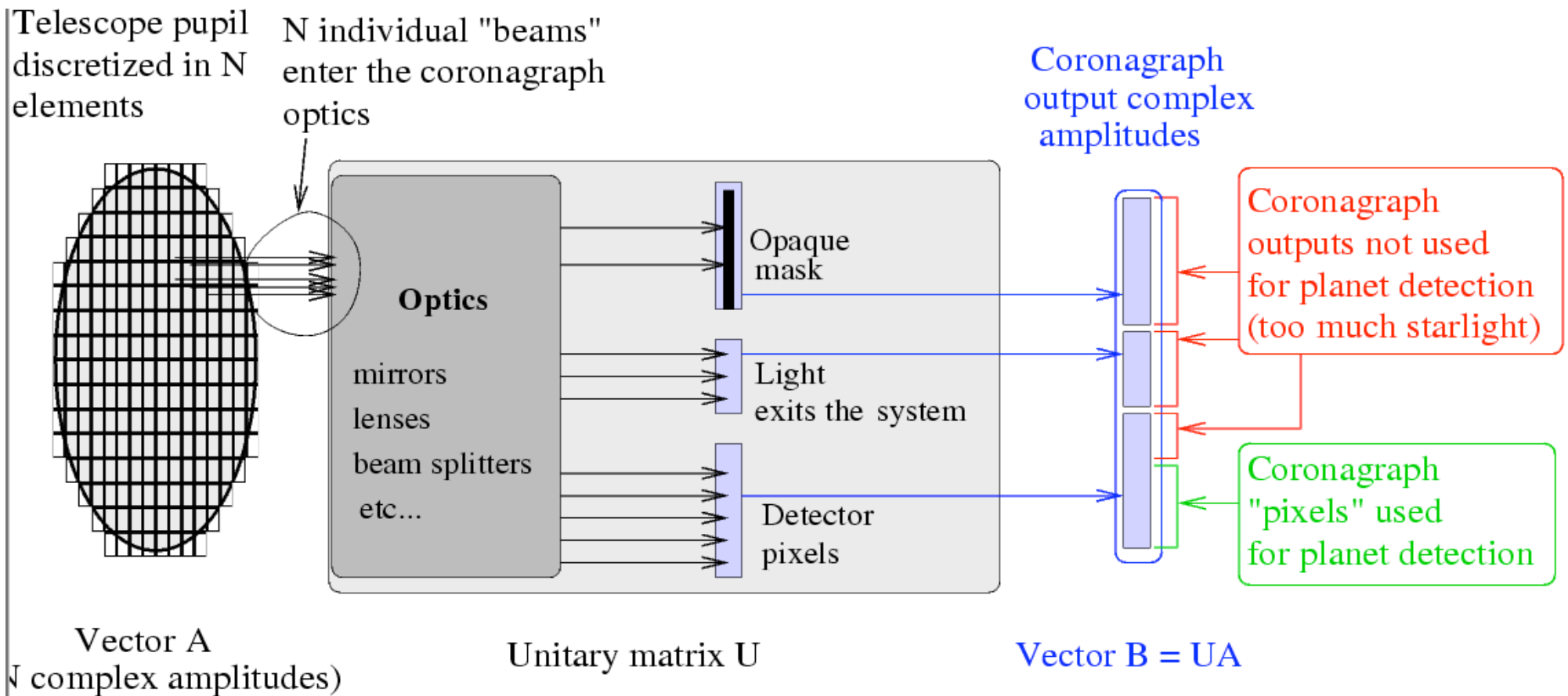
Useful throughput
fraction of the planet's
light that can be isolated
from the stellar light



Coronagraph model

Linear system in complex amplitude

Fourier transforms, Fresnel propagation, interferences, every wavefront control schemes: **all are linear**



U is fixed by optical configuration, and is independent of the source position on the sky.

Coronagraph model

What is the theoretical performance limit of coronagraphy ?

Coronagraph is a linear filter which removes starlight.

If :

planet = 0.2 x starlight wavefront + 0.8 x something else

then:

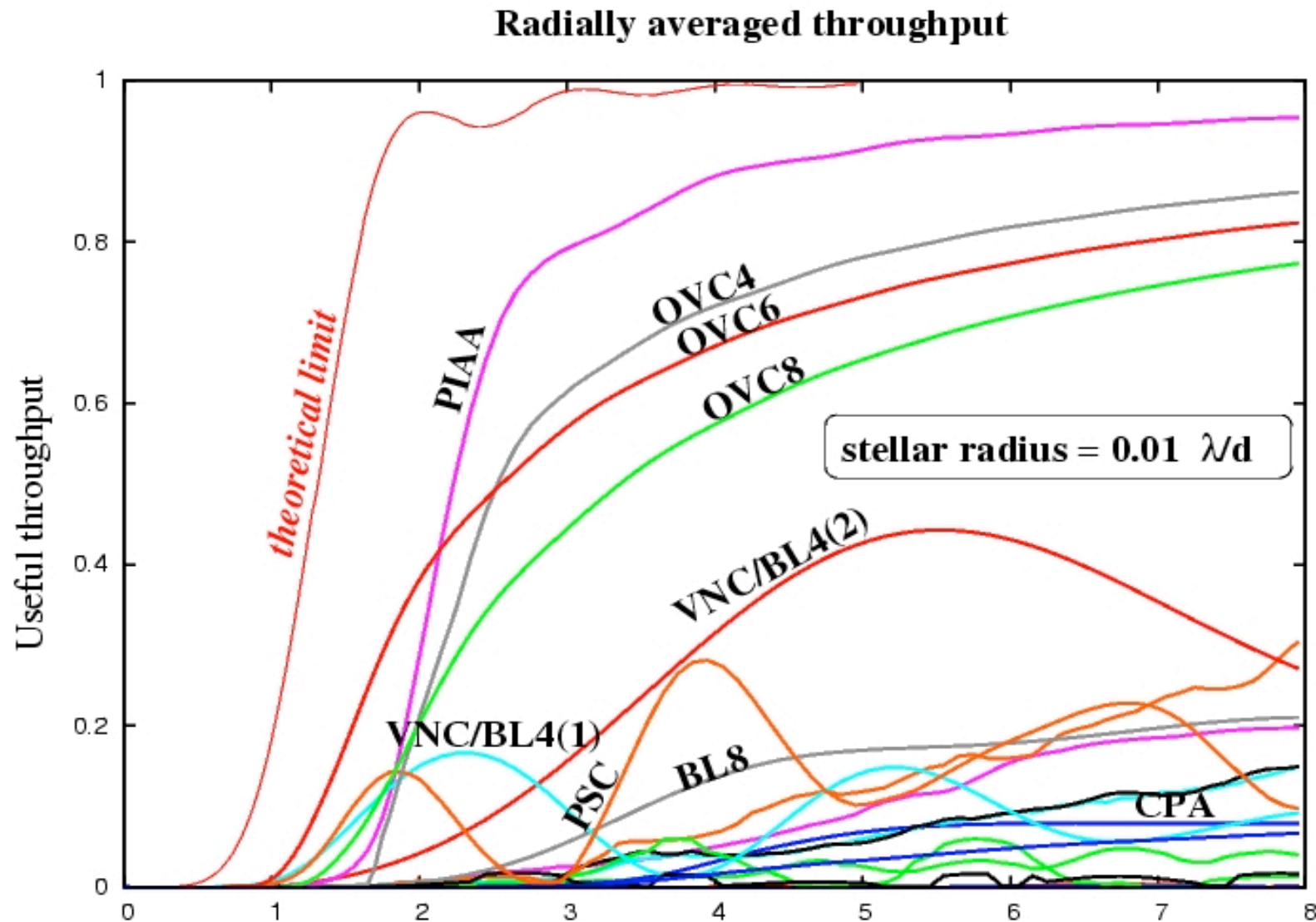
coronagraph throughput for planet < 0.8

What is the vector C that maximizes $C.A(\text{planet})$ but keeps $C.A(\text{star position}) < C.A(\text{planet position}) \cdot \sqrt{1e-10}$?

Fundamental physics
tells us limits of
coronagraphy

Problem: stars are not points !
Sun diameter $\sim 1\%$ of 1 AU
If $1\text{AU} = 2 \lambda/d$, Stellar radius $\sim 0.01 \lambda/d$
Wavefront control cannot solve it

Guyon, Pluzhnik, Kuchner, Collins & Ridgway 2006, ApJS 167, 81



Example:

HIP 56997 (G8 star at 9.54pc)

0.55 micron, 0.1 micron band

Planet at maximum elongation (80 mas)

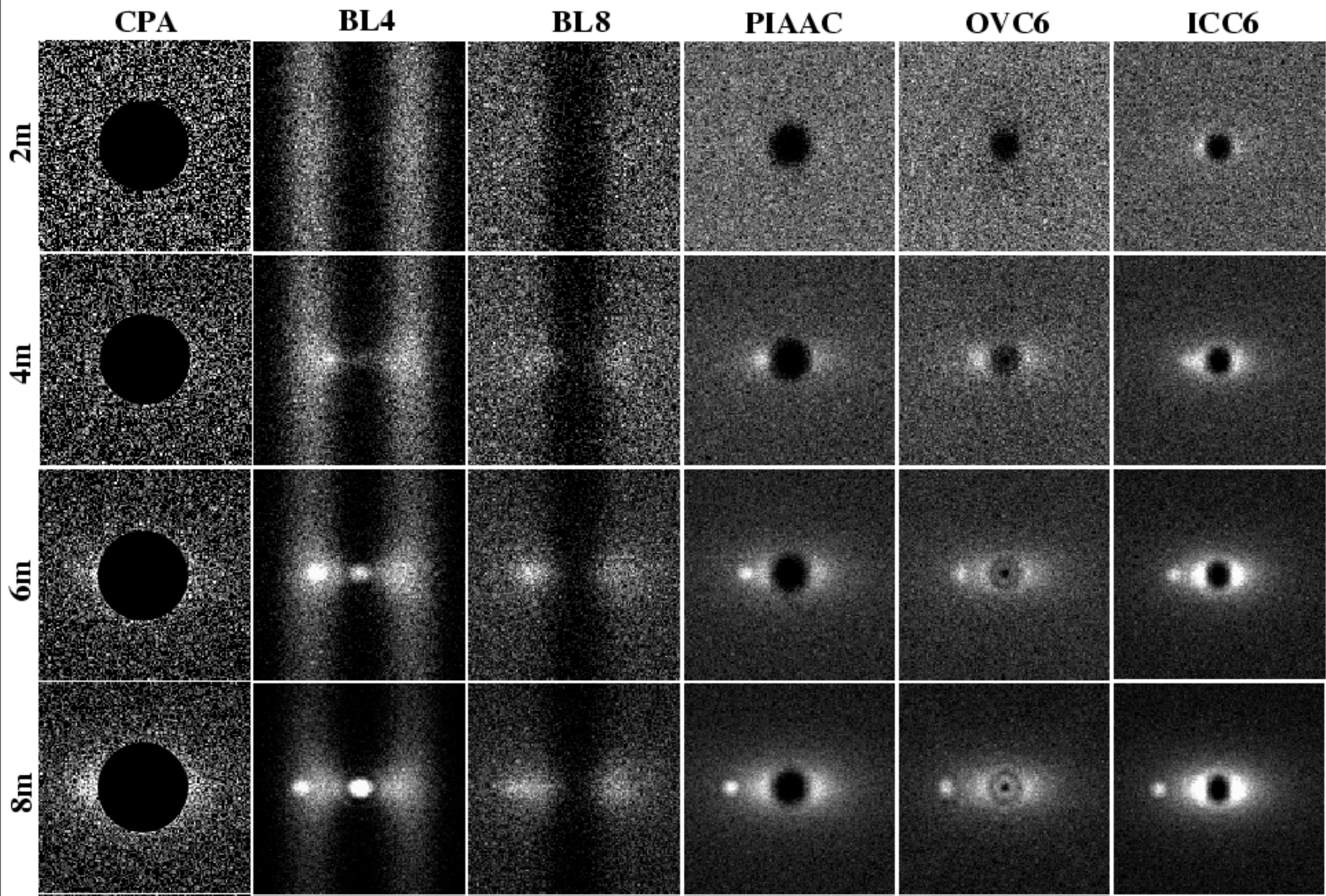
Earth albedo = 0.3 ($C=6e9$)

4h exposure, 0.25 throughput, perfect detector

Exozodi : 1 zodi

System observed at time when zodi is minimal

Each image is $20 \times 20 \lambda/d$



Theoretical limit with increasing stellar radius (monochromatic light, $1e10$ contrast)

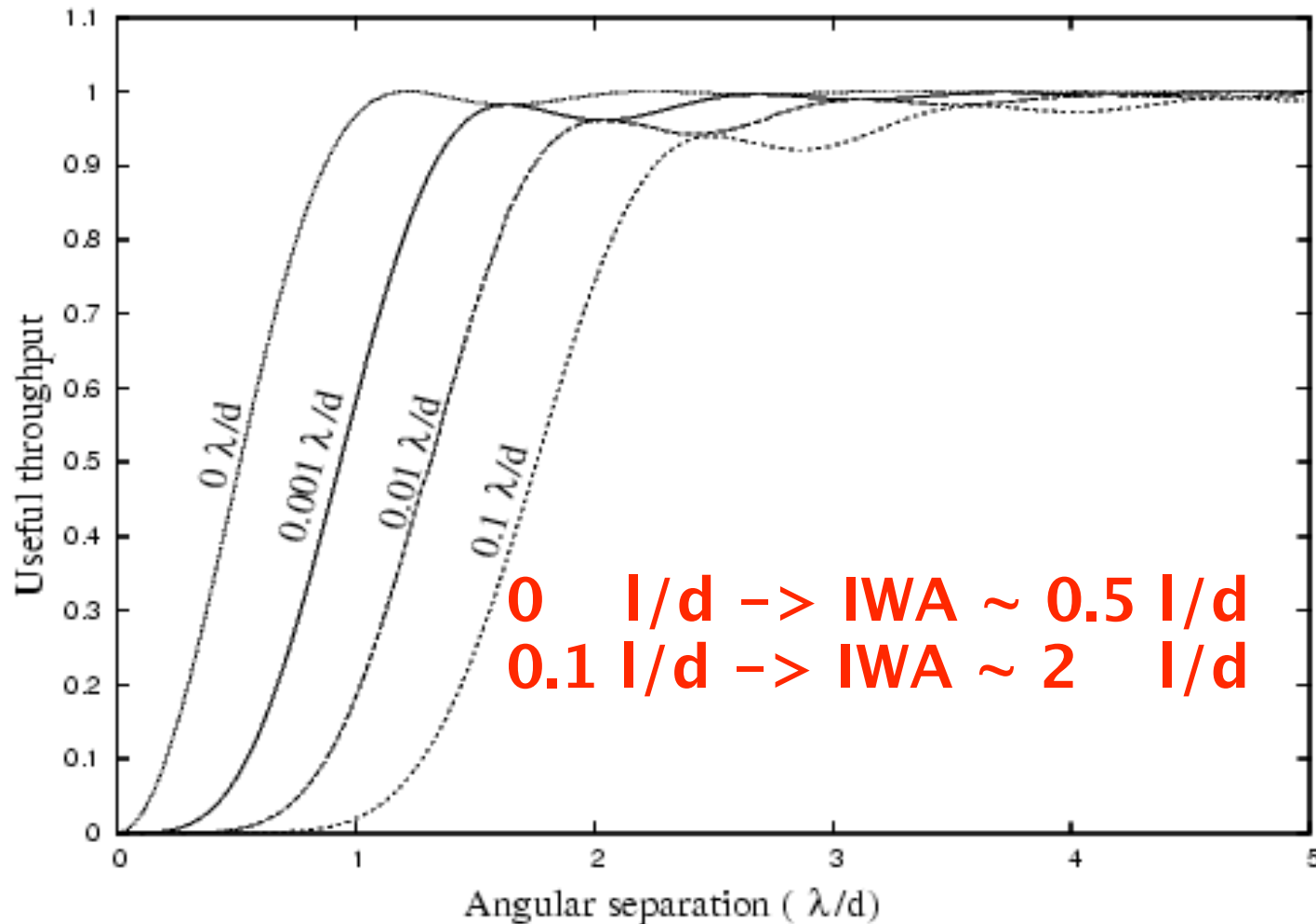


Fig. 5.— Upper limit on the off-axis throughput of a coronagraph for different stellar radii.

Pointing control demonstrated to $1e-3$ I/D at Subaru PIAA testbed

LOWFS efficiently uses starlight to measure tip tilt and a few other low order modes.

Subaru Testbed has demonstrated closed loop pointing control to $1e-3$ I/D ~ 0.1 mas on 1.4m PECO. ref: Guyon, Matsuo, Angel 2009

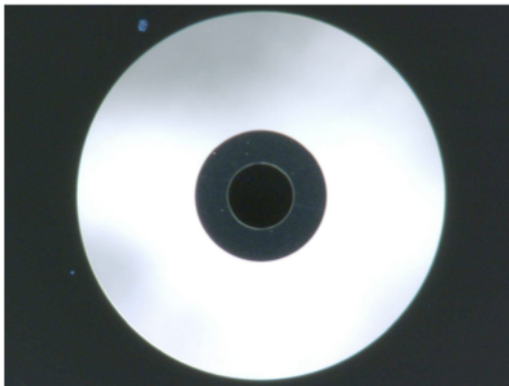


Fig. 9.— CLOWFS focal plane mask used in the PIAA coronagraph laboratory testbed at Subaru Telescope. The 100 micron radius mask center is opaque (low reflectivity), and is surrounded by a 100 micron wide highly reflective annulus. The science field, transmitting light to the science camera, extends from 200 micron to 550 micron radius.

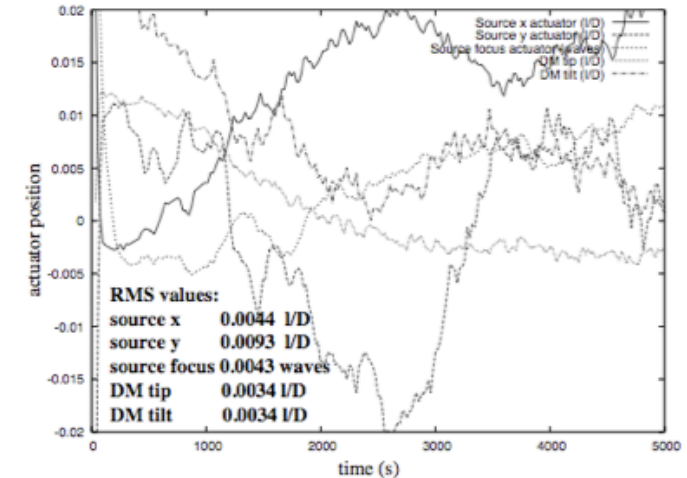
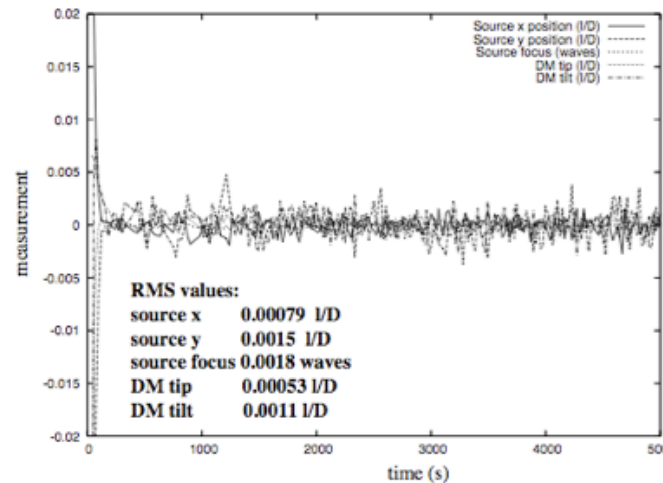
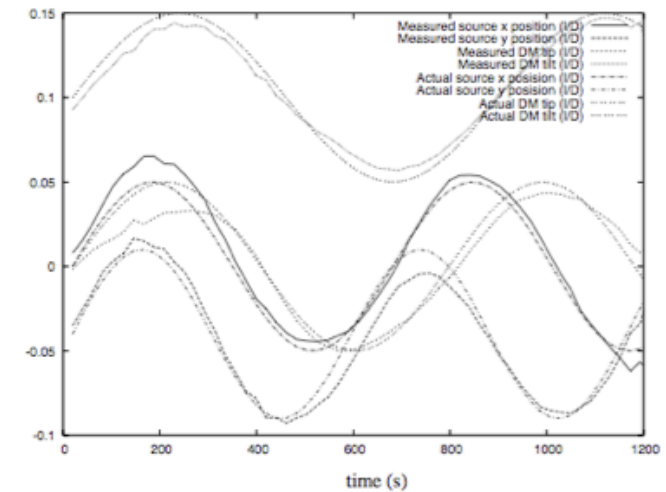
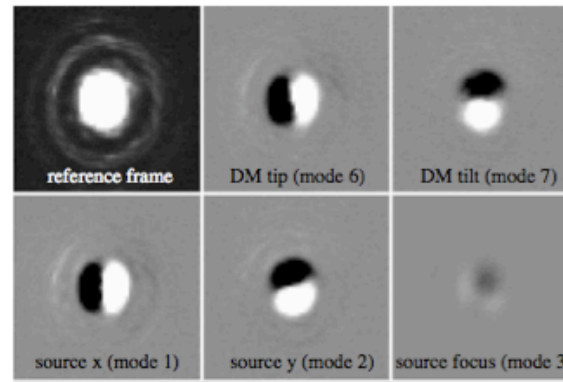


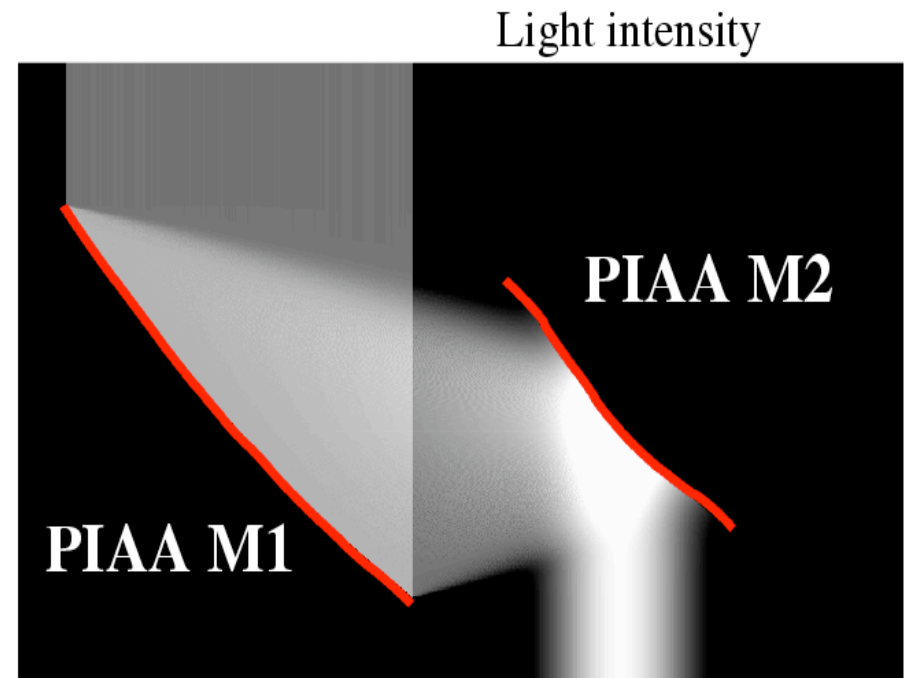
Fig. 10.— Laboratory performance for the CLOWFS. Upper left: Measured CLOWFS reference frame and influence functions for the 5 axis controlled in the experiment. Pre-PIAA and post-PIAA modes look extremely similar, as expected. Top right: Open loop simultaneous measurement of pre and post-PIAA modes. The measured amplitudes match very well the sine-wave signals sent to the actuators, and the CLOWFS is able to accurately measure all 4 modes shown here with little cross-talk. Since this measurement was performed in open loop, the measurement also include unknown drifts due to the limited stability of the testbed. Bottom left: Closed loop measurement of the residual error for the 5 modes controlled. The achieved pointing stability is about $10^{-3} \lambda/D$ for both the pre-PIAA and post-PIAA tip/tilt. Bottom right: Position of the actuators during the same closed loop test.

PIAA coronagraph development at Subaru

co-funded by Subaru/NAOJ, NASA JPL & NASA Ames

Utilizes lossless beam apodization with aspheric optics (mirrors or lenses) to concentrate starlight in single diffraction peak (no Airy rings).

- high contrast
- Nearly 100% throughput
- IWA $\sim 1 \lambda/D$ to $2 \lambda/D$
- 100% search area
- no loss in angular resol.
- can remove central obsc. and spiders
- achromatic (with mirrors)

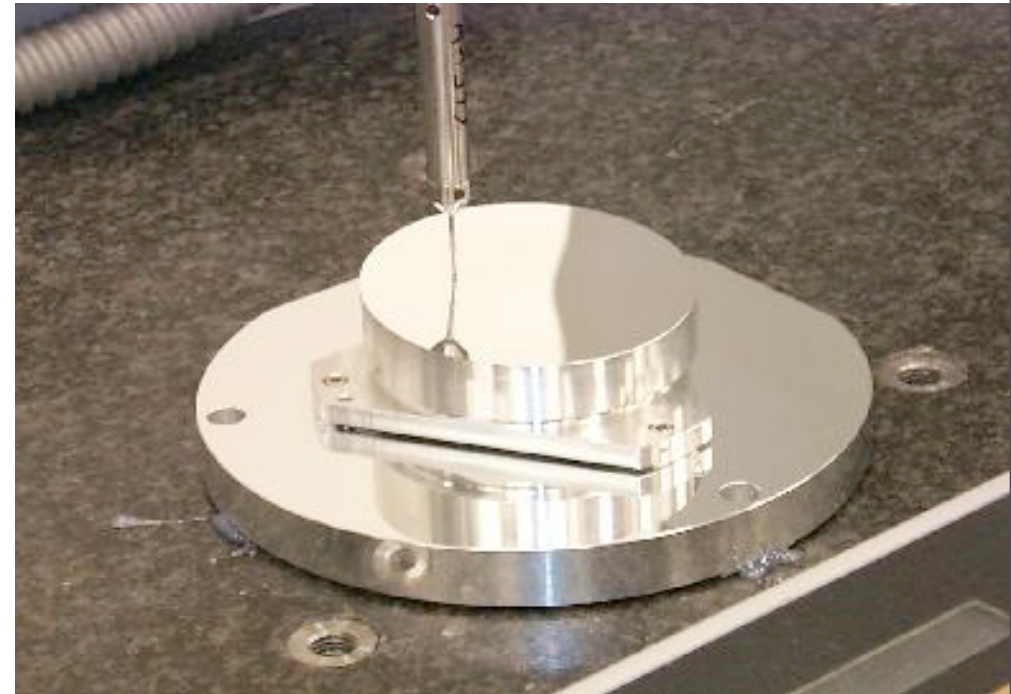
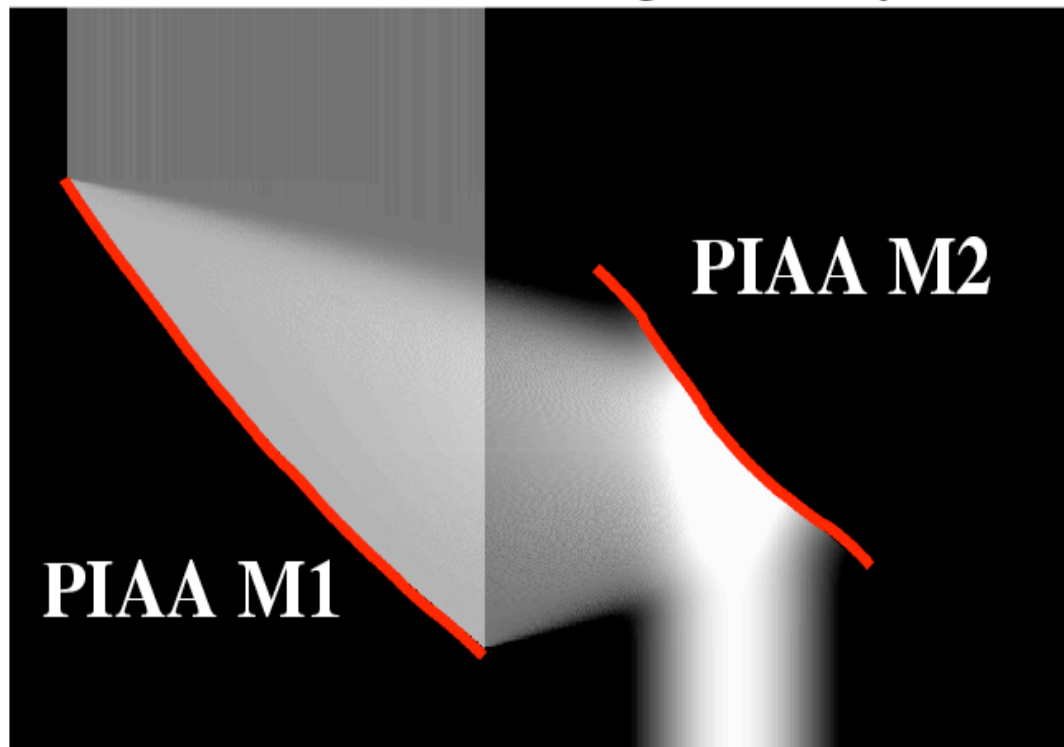


For Subaru, Lyot Coronagraph with PIAA– apodized input pupil. IWA $\sim 1 \lambda/d$

Phase-Induced Amplitude Apodization Coronagraph (PIAAC)

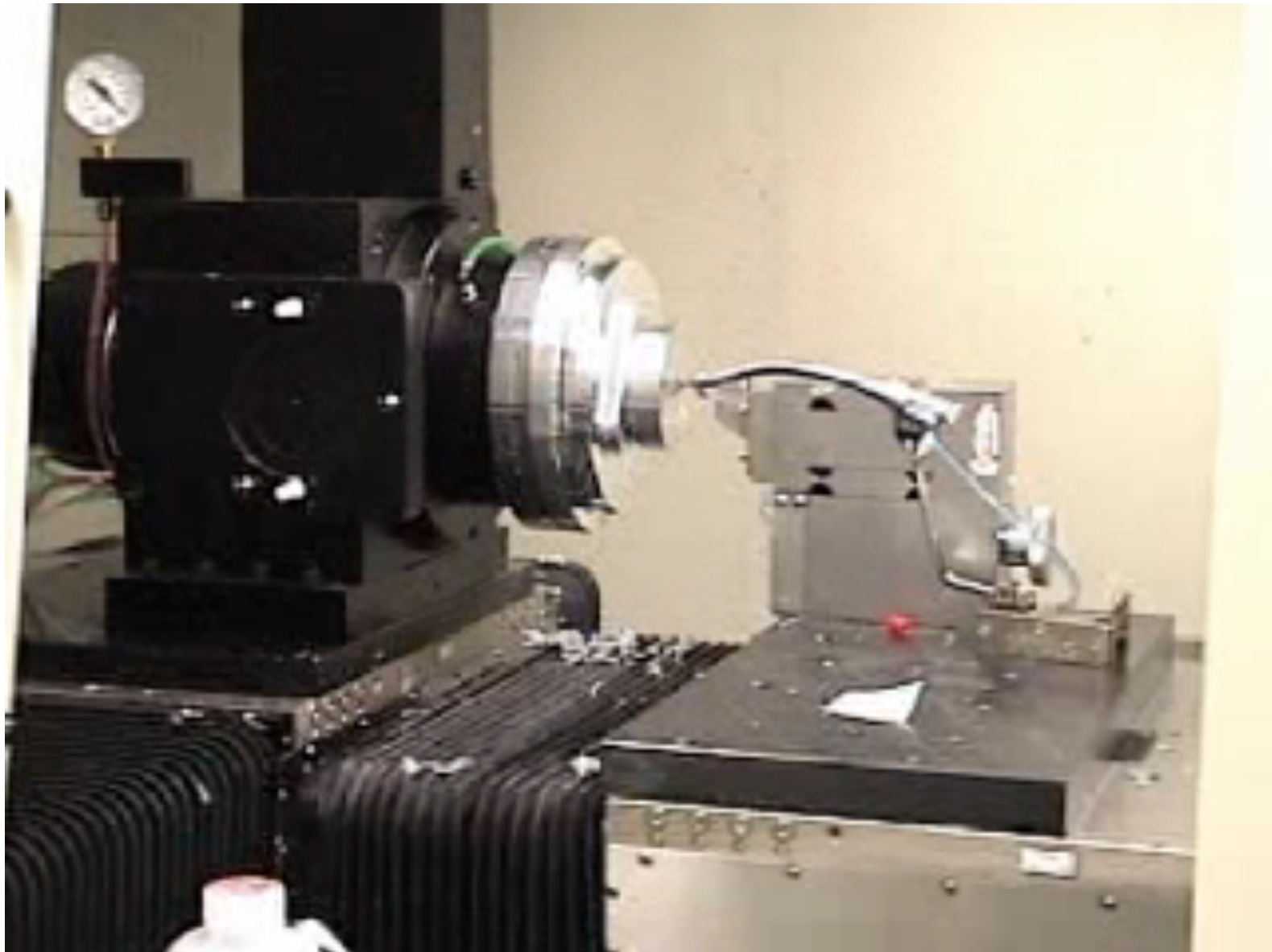
Lossless apodization by aspheric optics.

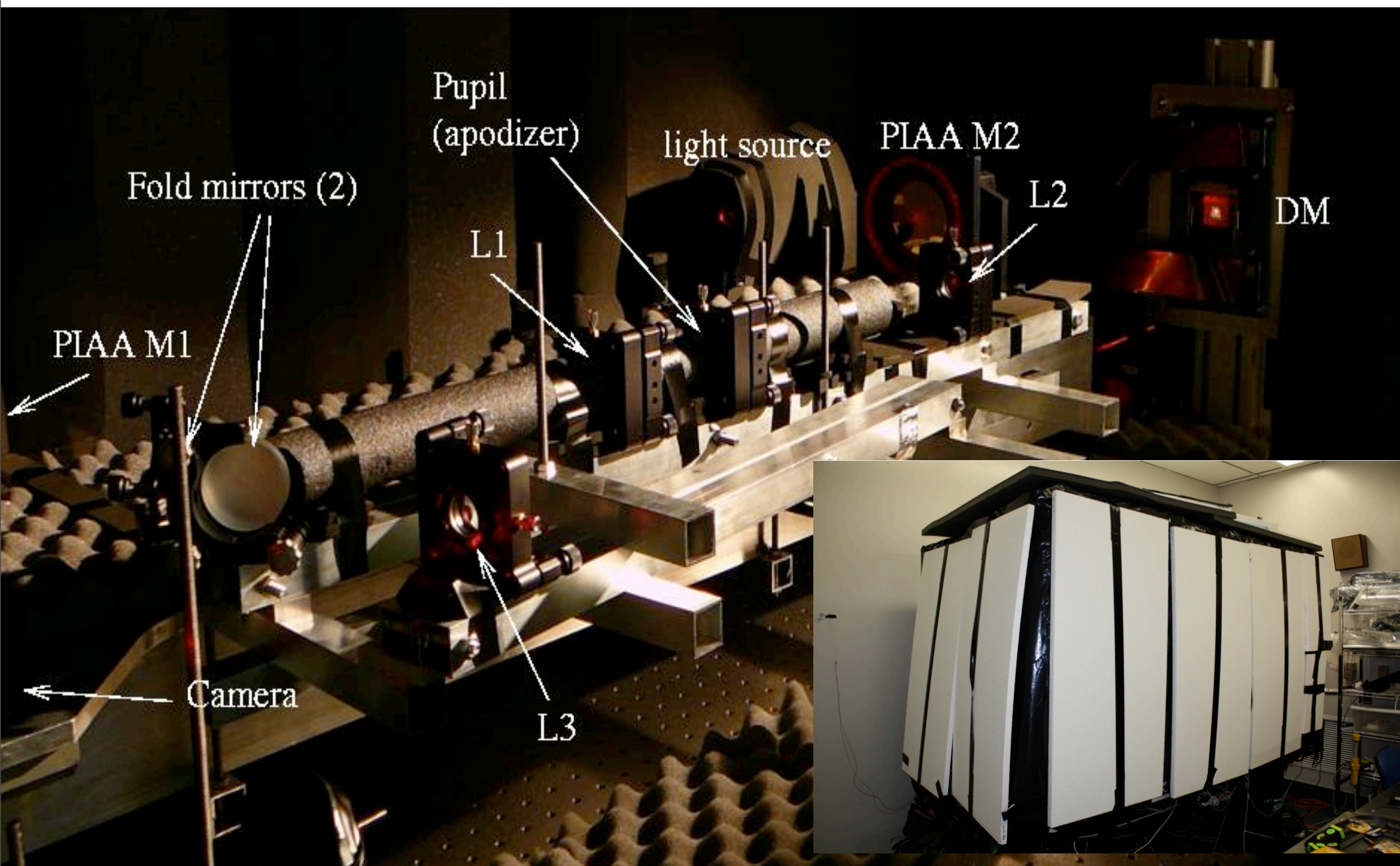
Light intensity



Guyon, Pluzhnik, Vanderbei, Traub, Martinache ... 2003–2006

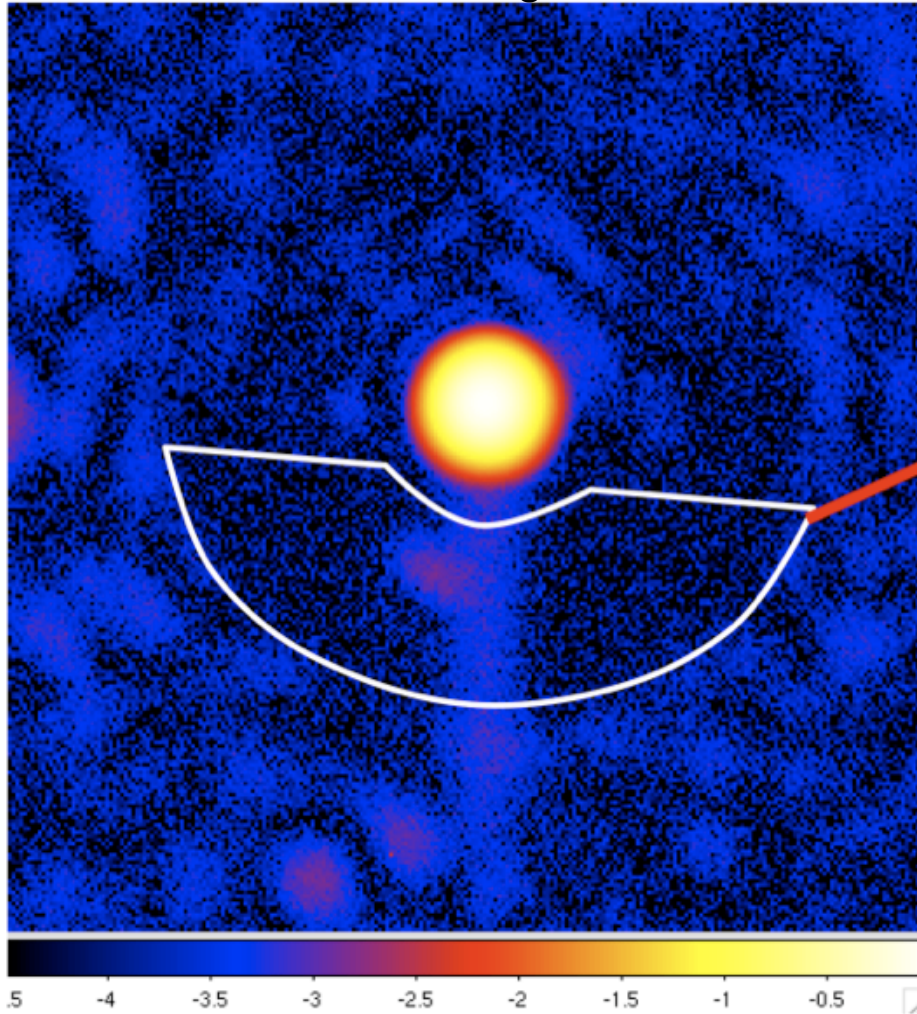
PIAA optics – Diamond turning



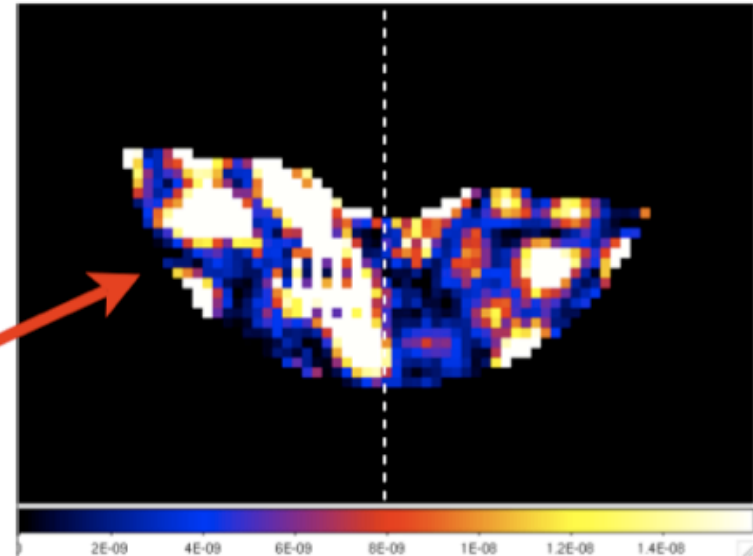


Recent lab results demonstrate PIAA coronagraph + Focal plane AO + coherent differential imaging

Raw image



Coherent starlight



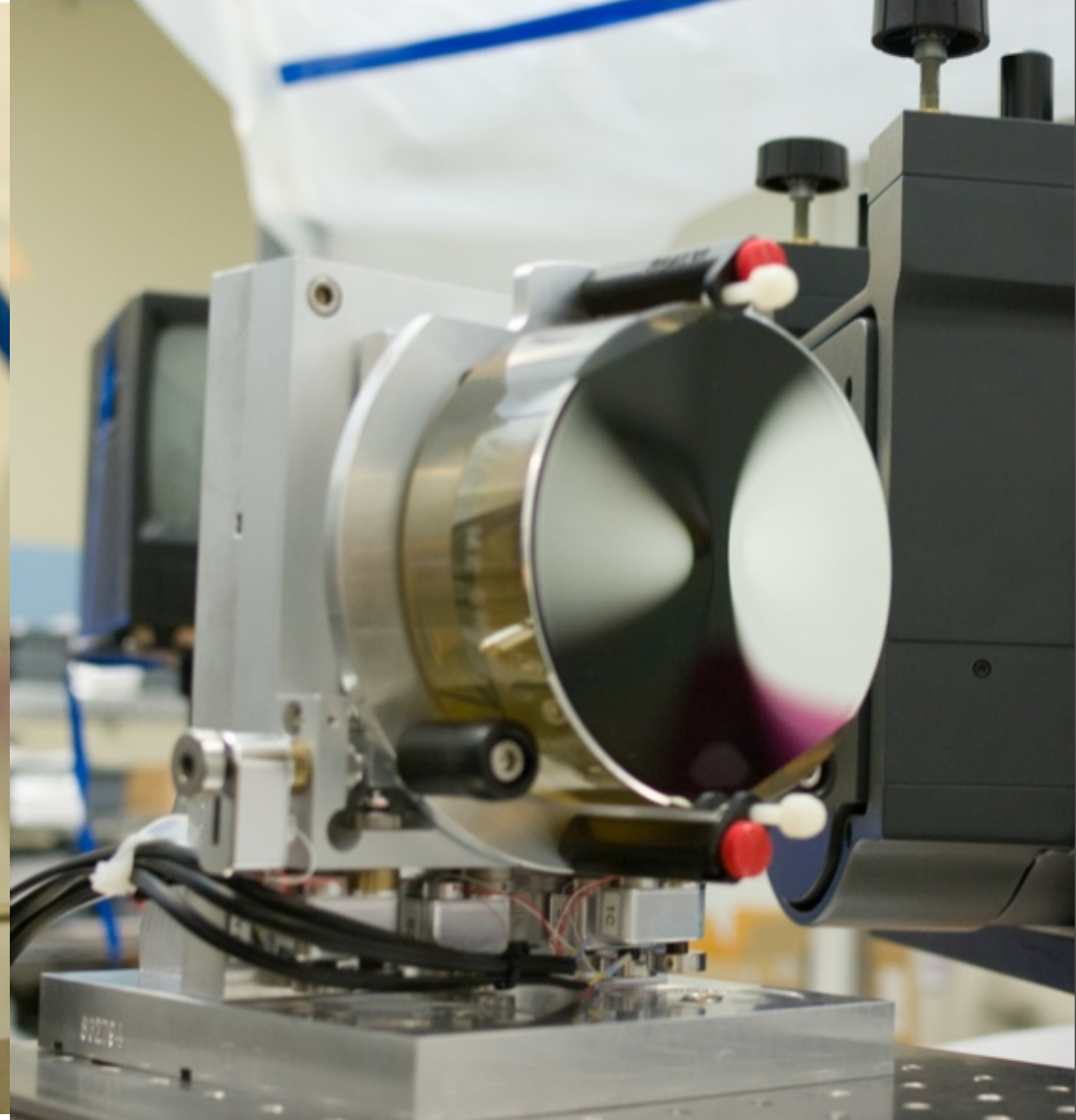
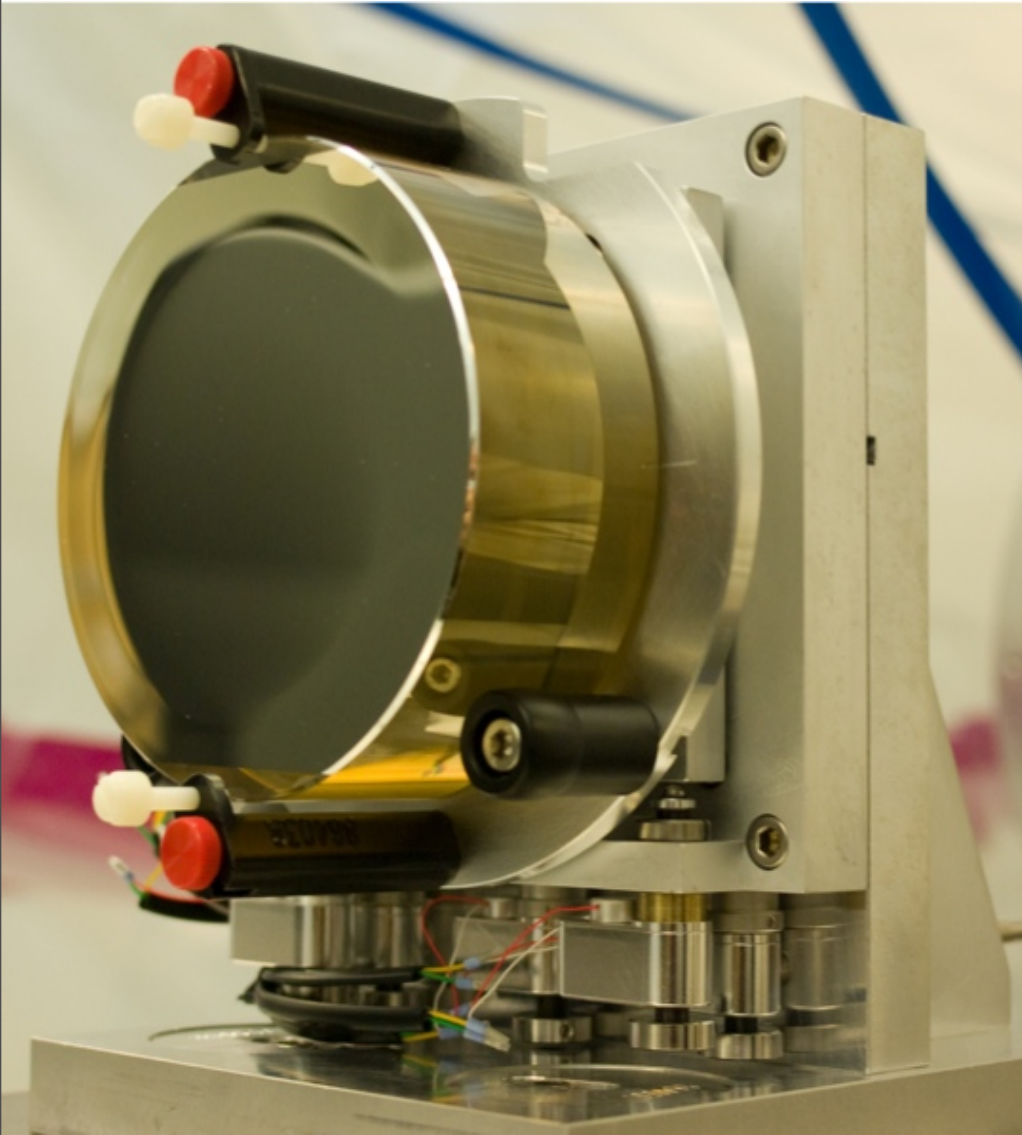
Average contrast in right half of the science field shown above (excludes the ghost on the left)
 $= 7e-9$

Contrast achieved in 1.6 to 4.5 I/D zone:

$1.5e-7$ incoherent halo ghost (equivalent to exozodi)

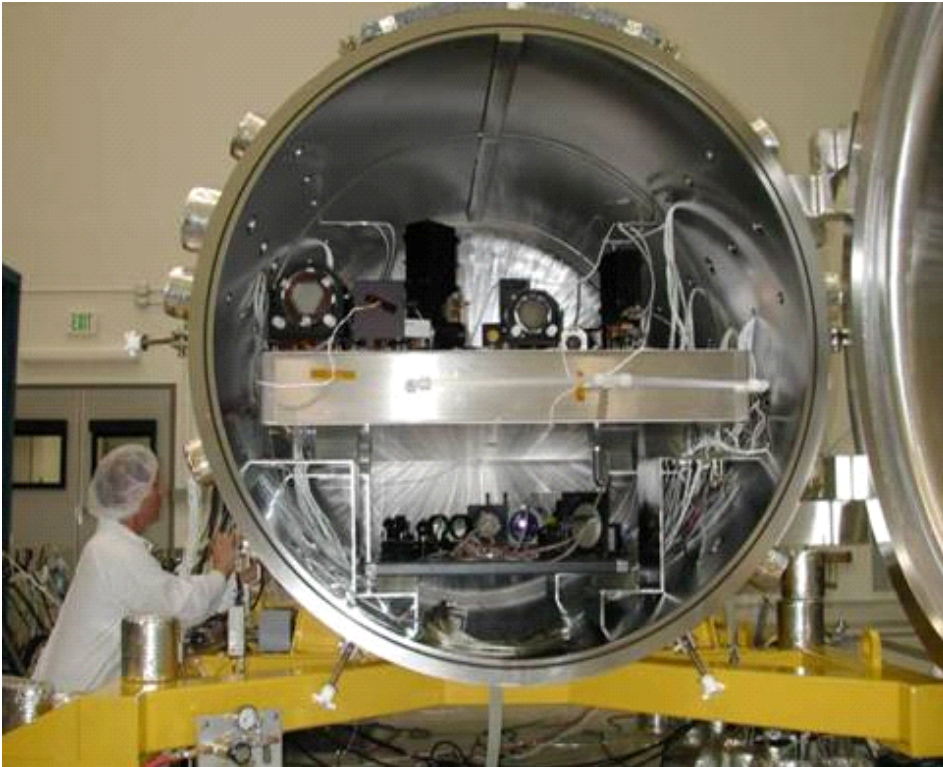
$7e-9$ coherent starlight speckles (turbulence, vibrations)

High contrast polychromatic PIAA demonstration in preparation (NASA Ames / NASA JPL)



2nd generation PIAA optics manufacturing completed by Tinsley on Jan 5, 2009 (better surface accuracy, better achromatic design than PIAAgen1)

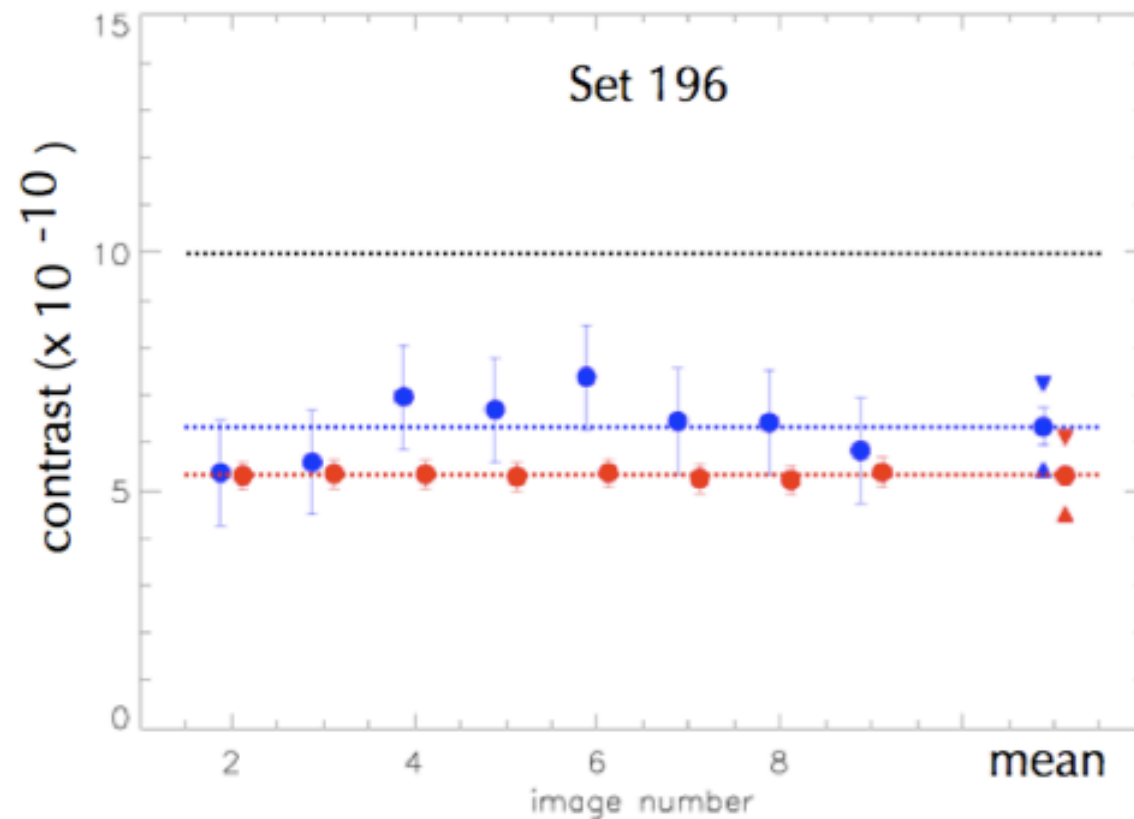
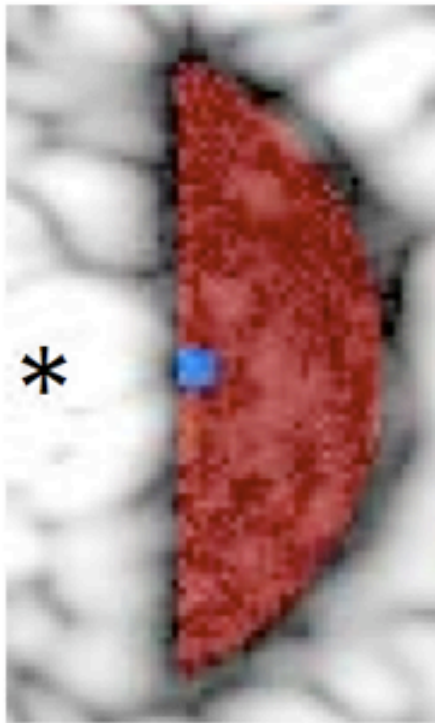
PIAA-dedicated testbed at NASA Ames testing
WFC architectures & MEMs DMs.



Coronagraph labs in:
NASA JPL (vacuum)
NASA Ames
Princeton Univ.
Subaru Telescope
Japan/ISAS (vacuum)

Vacuum tests at NASA JPL have reached close to $1e-10$ contrast at 4 I/D with band-limited masks

“Classical” speckle nulling with the HCIT

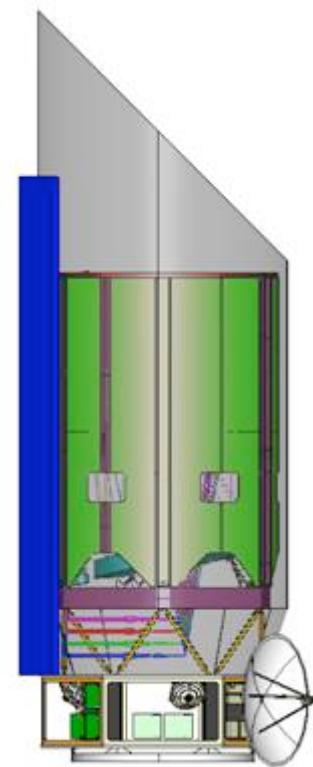


Contrast obtained in a sequence of images over a representative one-hour period. At left is the high contrast field: the inner and outer target areas are highlighted in blue and red respectively; an asterisk marks the location of the occulted “star”. Plotted at right are contrast values averaged over the inner and outer areas (again in blue and red respectively) for each image in the sequence. 1- σ error bars indicate the measurement noise estimated from pairwise data.



Pupil mapping Exoplanet Coronagraph Observer (PECO)

- 1.4m diameter off-axis telescope
- Uses high efficiency low IWA PIAA coronagraph
- 0.4 – 0.9 micron spectral coverage / $R \sim 20$
- **Conduct a “Grand Tour” of 10 nearby stars searching for small (Earth & Super-Earth) planets in their habitable zones.**
- **Study known RV planets, observing them at maximum elongation**
- **Snapshot survey of ~ 100 other nearby stars to study diversity of exozodiacal disks and search for / characterize gas giant planets.**



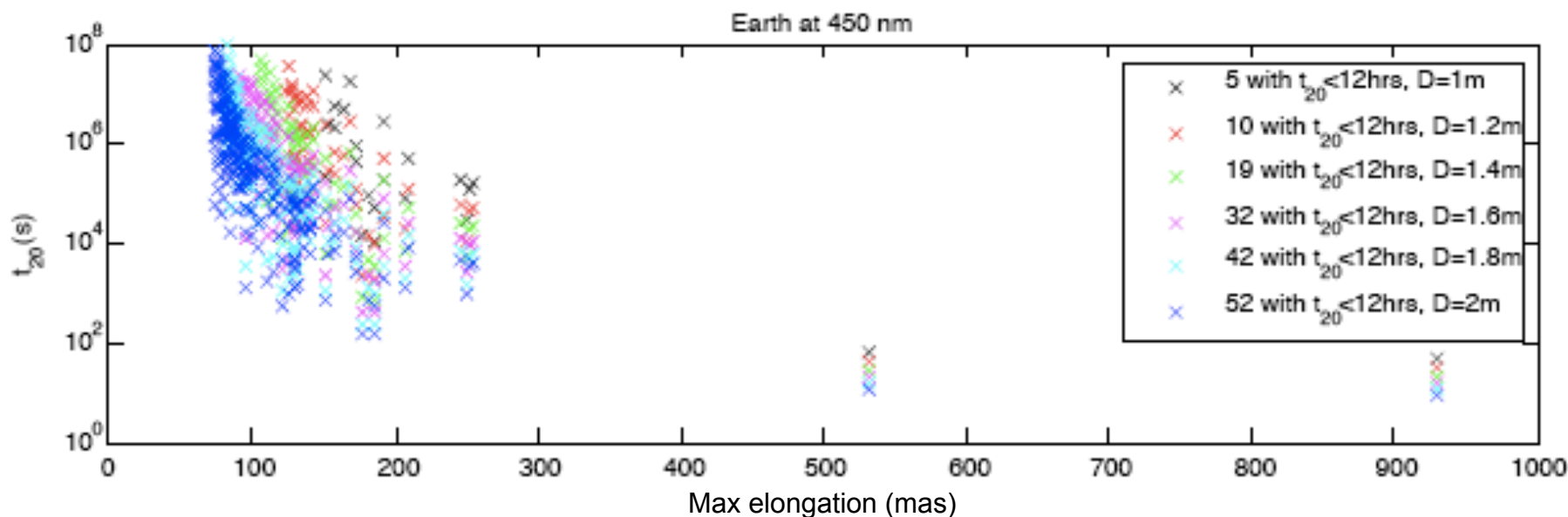
Number of Earths detected with PECO scales gracefully with aperture



Telescope D(m)	# Earths, 450 nm	# Earths, 672 nm
1.0	5	2
1.2	10	5
1.4	19	8
1.6	32	14
1.8	42	20
2.0	52	30

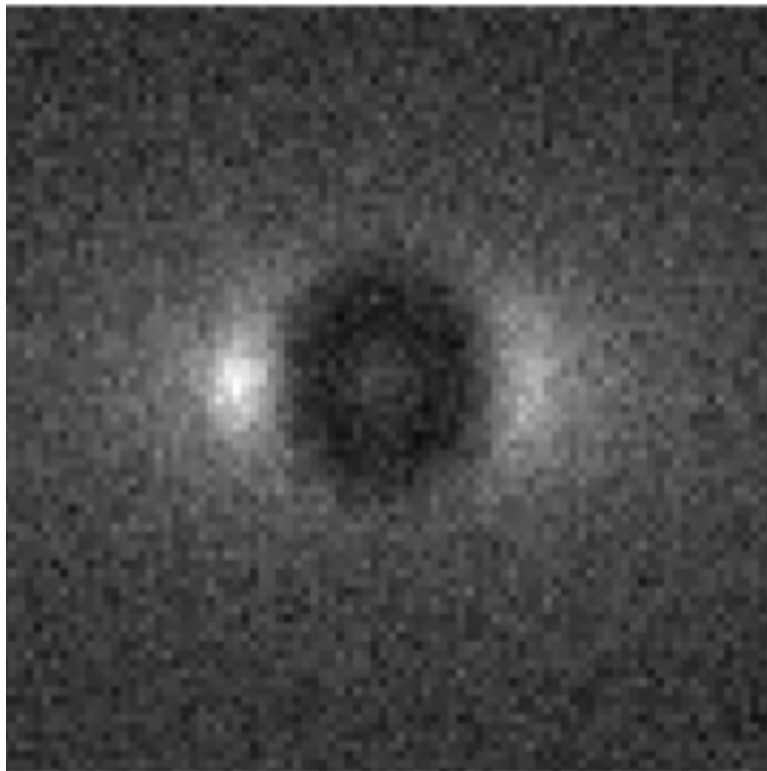
- Trade study shows number of Earths detected for different telescope diameters
- PECO simulation of Earth-radius planet with Earth albedo in habitable zone of candidate star
- Assumes detection in < 5 attempts of < 12 hr integration
- IWA of 2 λ/D

Earths still detectable at shorter wavelengths and smaller D

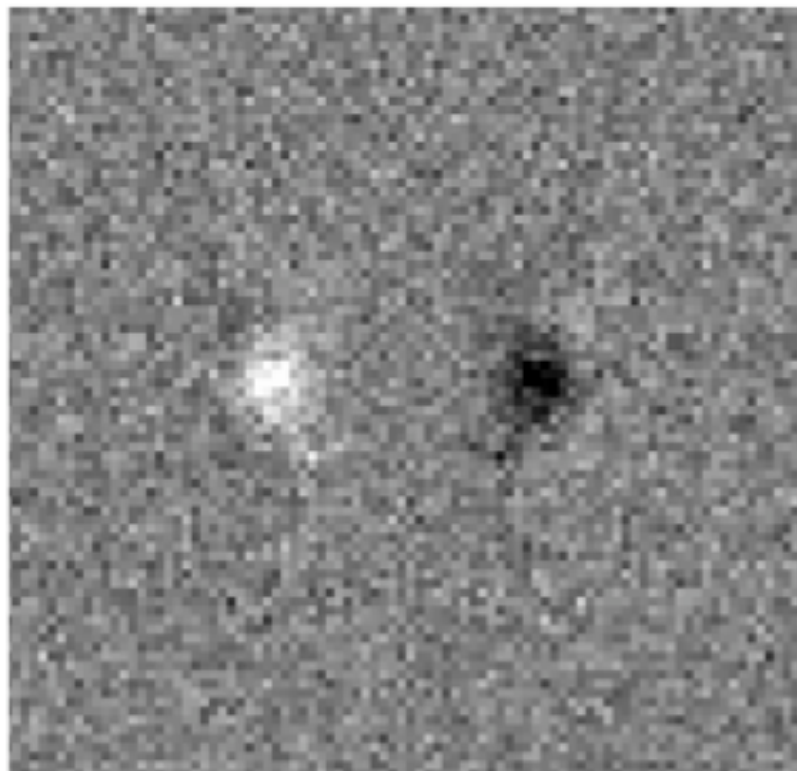


PECO can observe an Earth at distance of Tau Ceti

Initial image



After Symmetric Dust Subtraction



Left: a simulation of 24 hr of PECO data showing an Earth-like planet ($a=0.2$) around Tau Ceti with 1 zodi of exozodi dust in a uniform density disk inclined 59 degrees. This is a simulation of $\lambda=550$ nm light in a 100 nm bandpass PECO (1.4-m aperture). Photon noise and 16 electrons total detector noise for an electron multiplying CCD have been added.

Right: the PECO image after subtracting the right half from the left half, effectively removing the exozodiacal dust and other circularly symmetric extended emission or scattered light. The Earth-like planet is obvious as the white region on the left, and the dark region on the right is its mirror image artifact.

PECO can easily detect Super-Earths

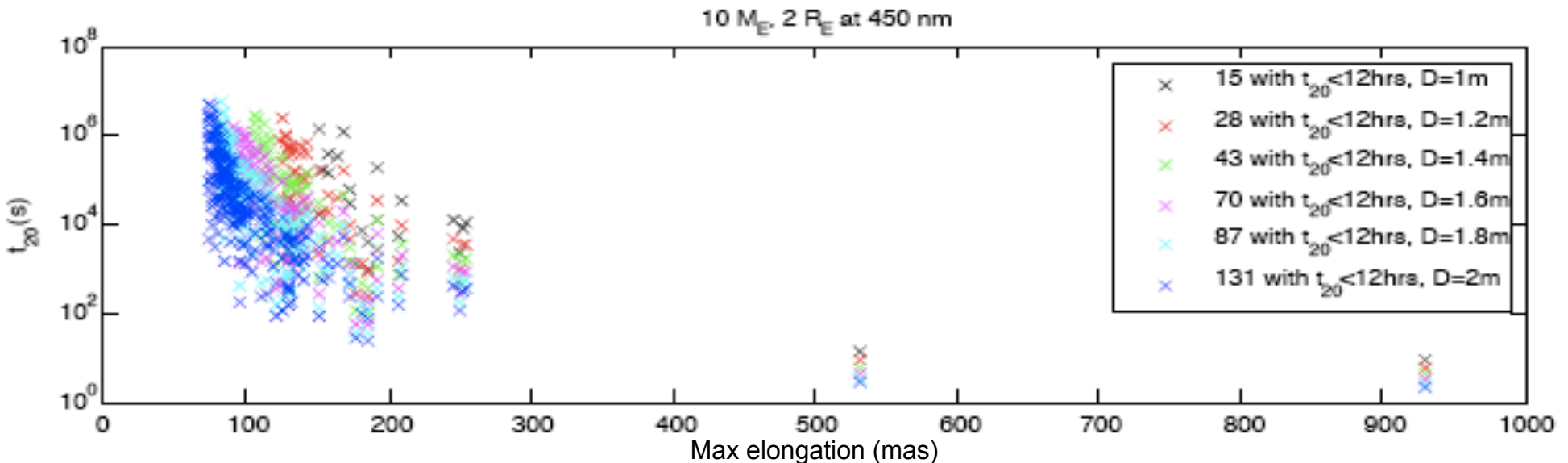


Telescope D (m)	# S-Earths, 450 nm	# S-Earths, 672 nm
1.0	15	5
1.2	28	13
1.4	43	20
1.6	70	33
1.8	87	44
2.0	131	61

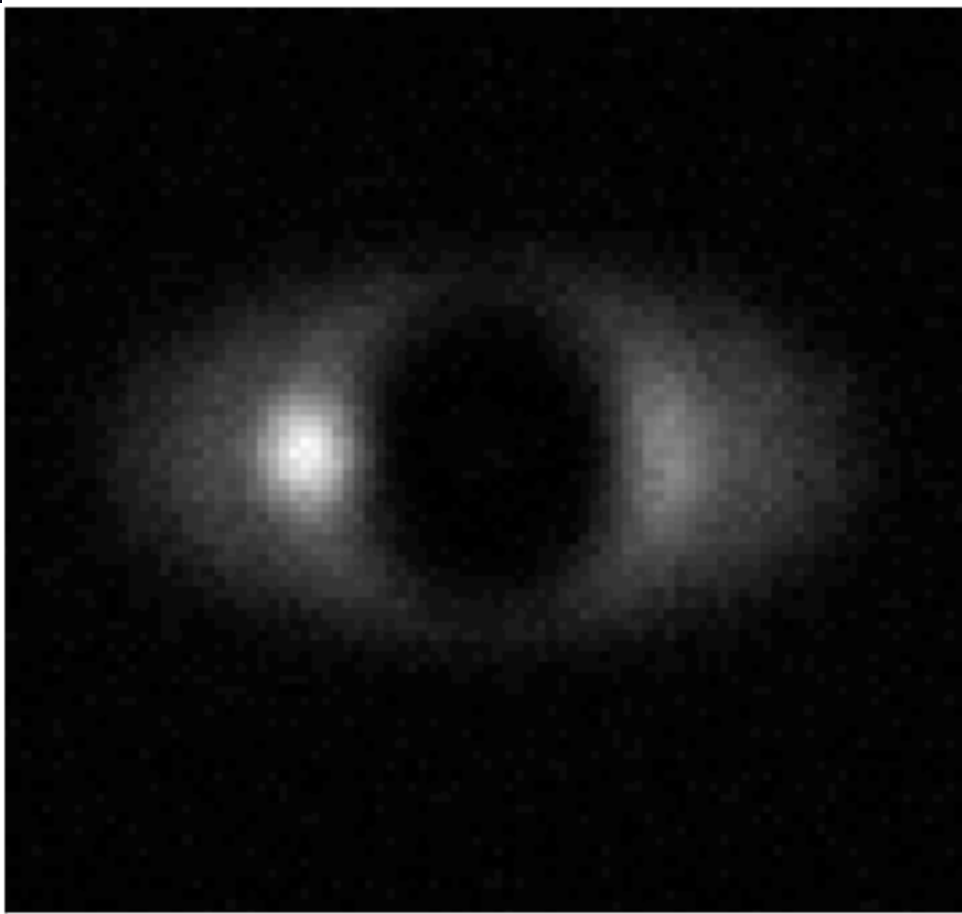
Trade study shows number of Super-Earths detected for different telescope diameters

- PECO simulation of 2 x Earth-radius planet with 10 x Earth-mass and Earth-like albedo in habitable zone of candidate star
- Assumes detection in ≤ 5 attempts of < 12 hr integration
- IWA of 2 λ/D

Can see more targets at shorter wavelengths and larger diameters



PECO easily observes Jupiters



Simulated PECO observation of 47 Uma b

Shown is a simulation of 24 hrs of PECO data showing the Jovian planet 47 Uma b with 3 zodis of exozodi dust in a uniform density disk inclined 59 deg.

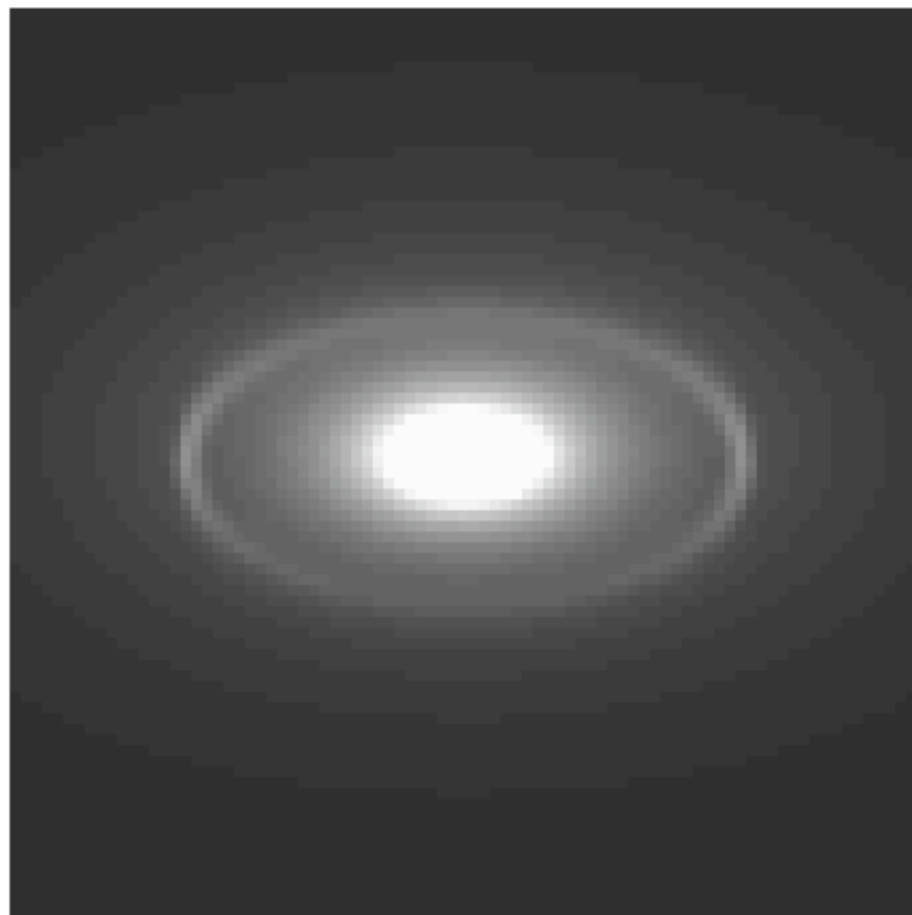
This is a simulation of 550 nm light in a 100 nm bandpass with predicted PIAA performance in the PECO observatory (1.4-m aperture).

Photon noise and 16 electrons total detector noise (for an electron-multiplying CCD) have been added.

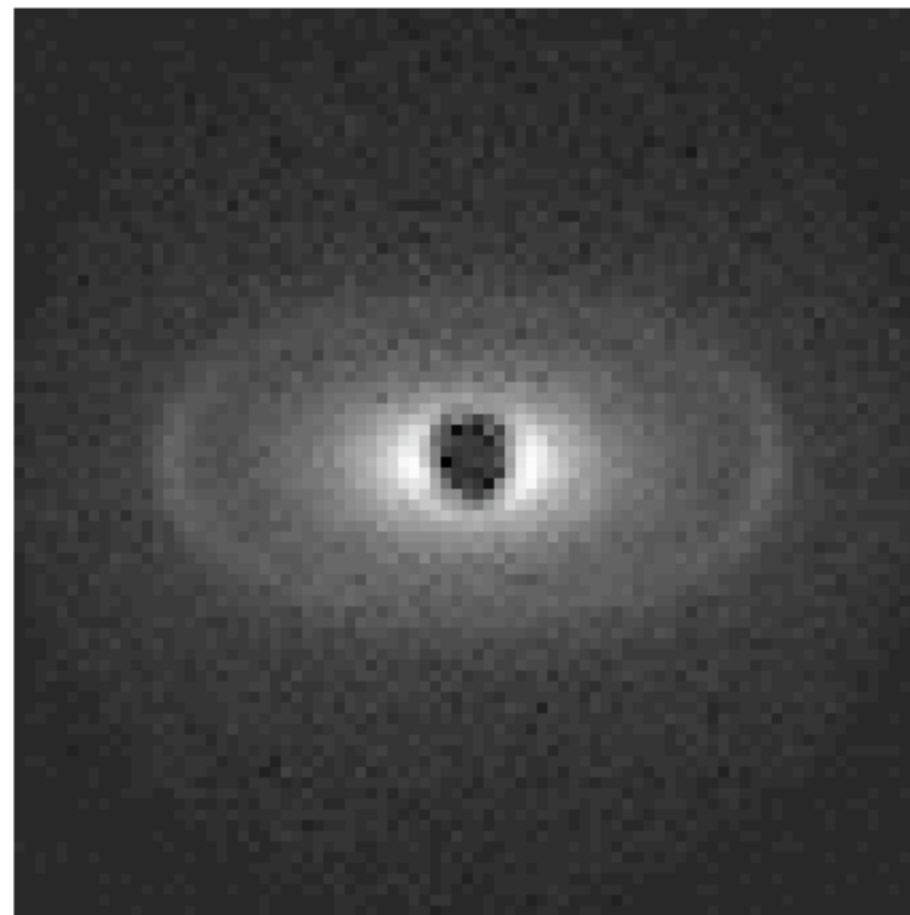
This and other RV planets are very easy detections for PECO even in the presence of significant exozodiacal dust, demonstrating that PECO will likely obtain high S/N data on numerous radial velocity EGPs.

PECO exozodi imaging

- Simulated PECO imaging of Alpha Cent exozodi



Model
 1 zodi
 enhancement at 1AU



PECO image
 3 hr exposure
 400 nm, 20% band

Summary

- Many high performance coronagraph concepts. Recent advances: Improved IWA, throughput, PSF calibration. Some coronagraph concepts now approach theoretical limit imposed by fundamental physics.
- **Ground-based coronagraphy**
 - Lab results now exceed requirements even with the highest performance coronagraphs (see for example lab PIAA results)
 - Performance will be driven by wavefront control & PSF calibration
 - Coherence-based PSF calibration & focal plane AO attractive
 - Conventional wavefront sensors are terribly inefficient. Higher performance WFS exist and should be used (Pyramid, FPWFS...)
 - Very efficient, fast AO (~ 10 kHz) system with few $\times 100$ actuators
 - tip-tilt control is very important to get close to the optical axis
 - Subaru Coronagraphic ExAO system plans to take advantage of these recent advances with flexible architecture (See talk by F. Martinache)
 - Potential to detect reflected light \rightarrow older planets closer to us
- **Space-based coronagraphy**
 - Direct imaging of Earths possible around the ~ 10 most favorable stars with a ~ 1.5 -m telescope and advanced coronagraph
 - A 4-m would allow atmosphere characterization for habitable planets