A bright future for direct imaging of extrasolar planets

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- **Science case**
  - Are we alone ? Is complex life an unlucky accident ?
- **Tools**
  - Coronagraphy
  - Wavefront control
  - PSF / speckles Calibration
- **Projects**
  - PECO
  - Subaru Coronagraphic Extreme-AO (SCExAO)

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! :-)”**

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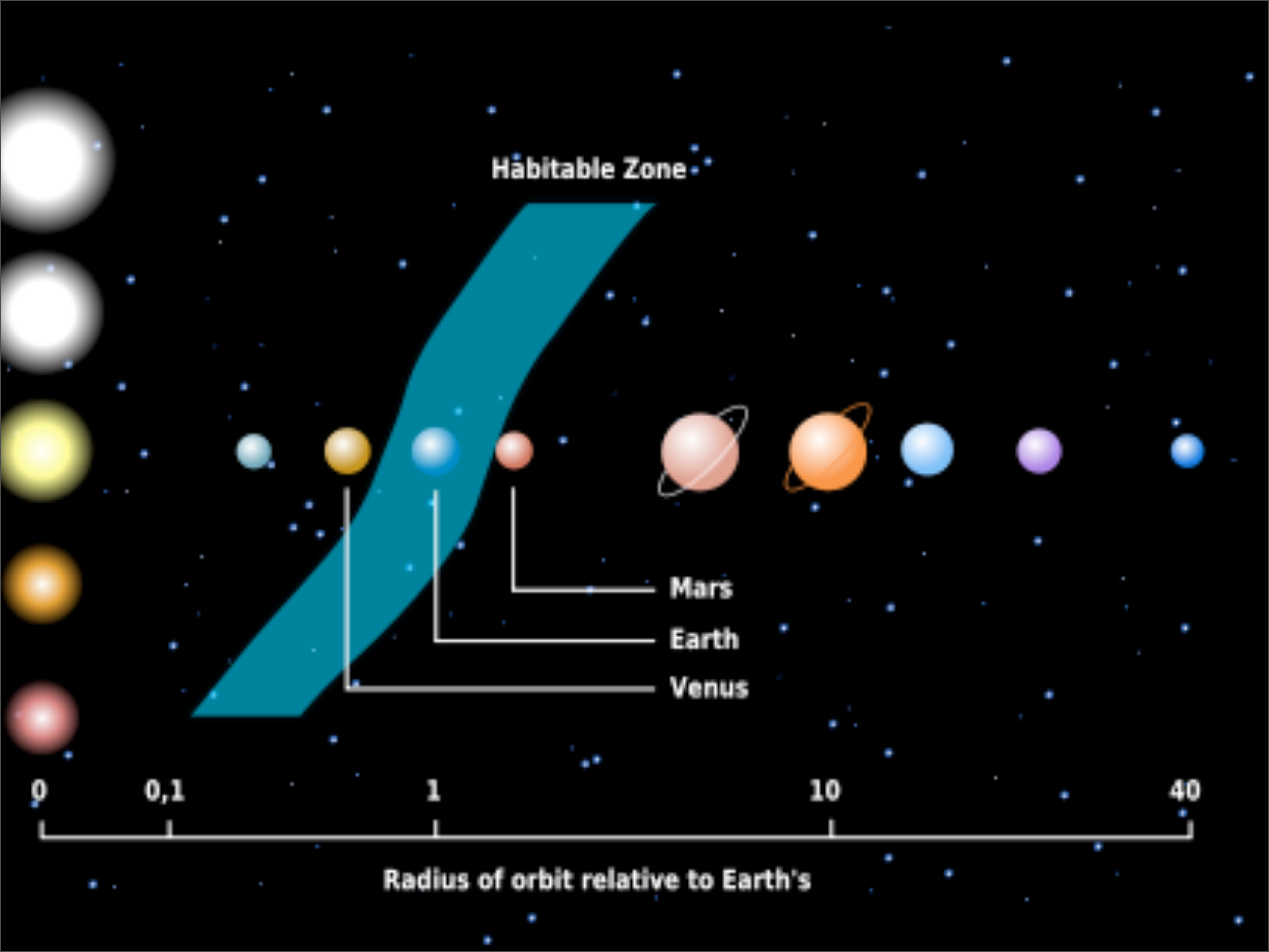
“Maybe, we could stop wasting money on project like this, and spend it on more important issues?

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


Habitable Zone
Mars
Earth
Venus
0
0,1
1
10
40
Radius of orbit relative to Earth's

When is a planet habitable ?

- Too many collisions in the first few 100 Myr
- Stellar activity decreases with time -> challenge for life around young stars
- Stars get brighter with time -> HZ moves out !

We have ~400 Myr left before CO_2 cycle fails to regulate Earth’s temperature

- Magnetic field is a good thing, but WILL “freeze away” with time

Water...

Mars & Venus lost their oceans

$H2O$ -> Hydrogen + Oxygen

Oxygen oxydizes rocks (Mars is red),
Hydrogen escapes in space

Why not Earth ??? Right size, right spot.

~2 billion years ago Oxygen concentration went up (bacteria) -> recaptures Hydrogen, stops H2O loss.

Carbon cycle regulates temperature on Earth

- Production:

Volcanos & direct emission from Earth's crust (~0.5 Gt/yr)

Humans burning fossil fuels (~6 Gt/yr)

- Removal (depletion in 10 000 yrs for atmosphere, 500 000 yrs for atm+oceans):

Silicate wheathering

Carbonate deposition

Burial of organic matter

What kind of life ?

ASM Biofilms Collection. Kobayashi

- On Earth, bacteria got an early start and ruled Earth for the first 2 billion yrs
- bacteria live in many environments (extremophiles)
- Complex life started with unlikely merging of Bacteria + Archaea -> Eukaryote
- Complex life may be rare event ...

How much time needed to have complex life ?

Life on Earth does not evolve at a constant pace

BIG jumps forward :

~2 Gy ago: Eukaryotes appear

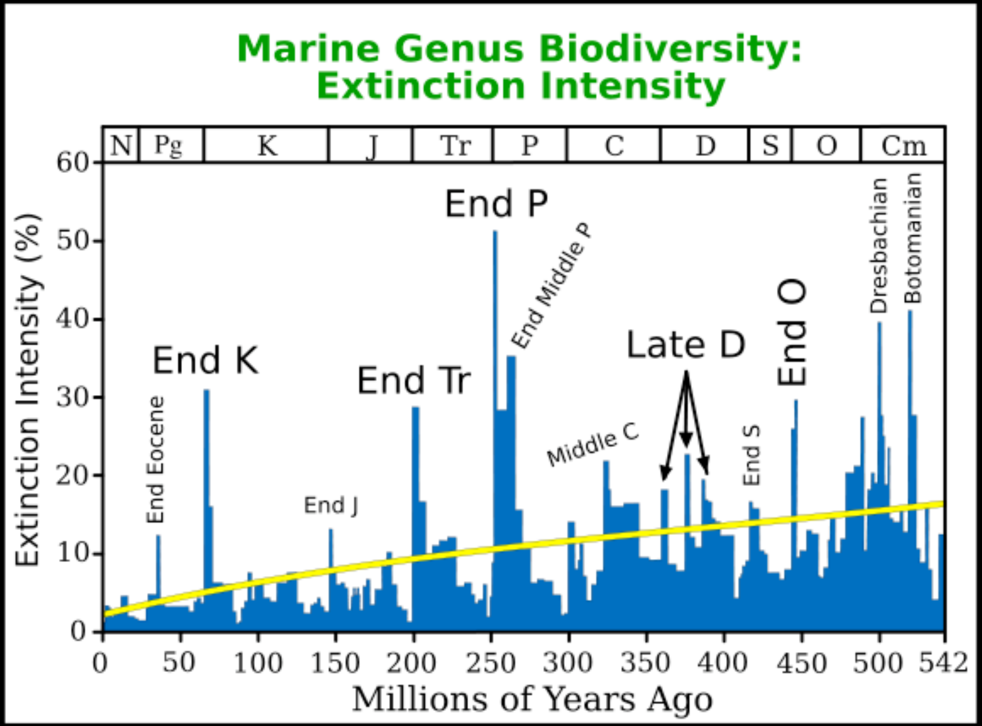
560 Myr ago: Cambrian explosion

But also...

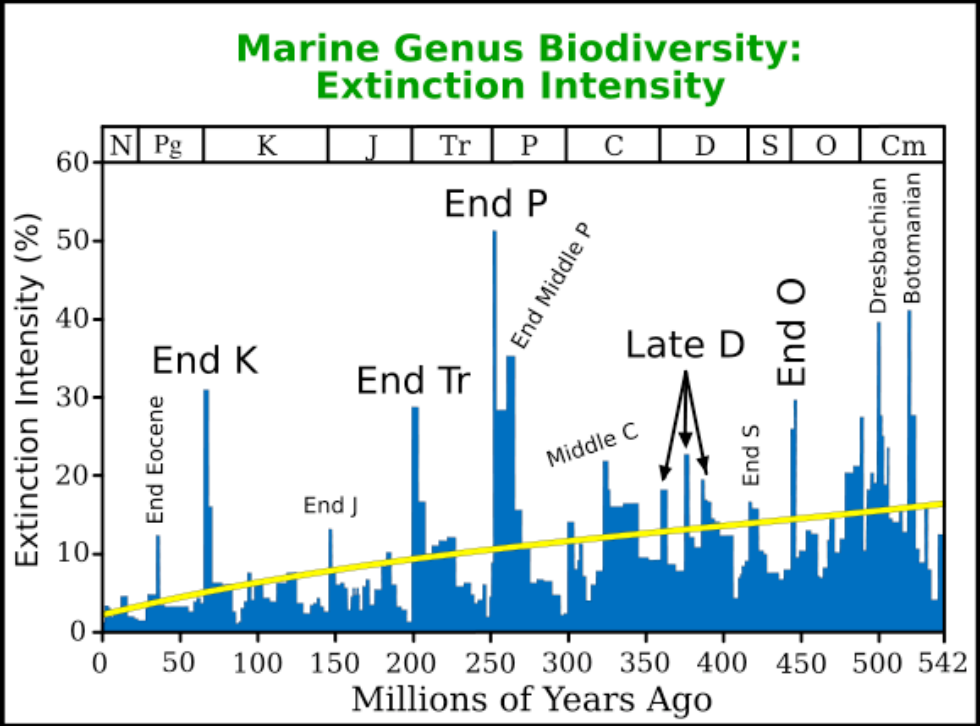
“Snowball Earth” episodes 2.3 Myr and 790 to 630 Myr ago

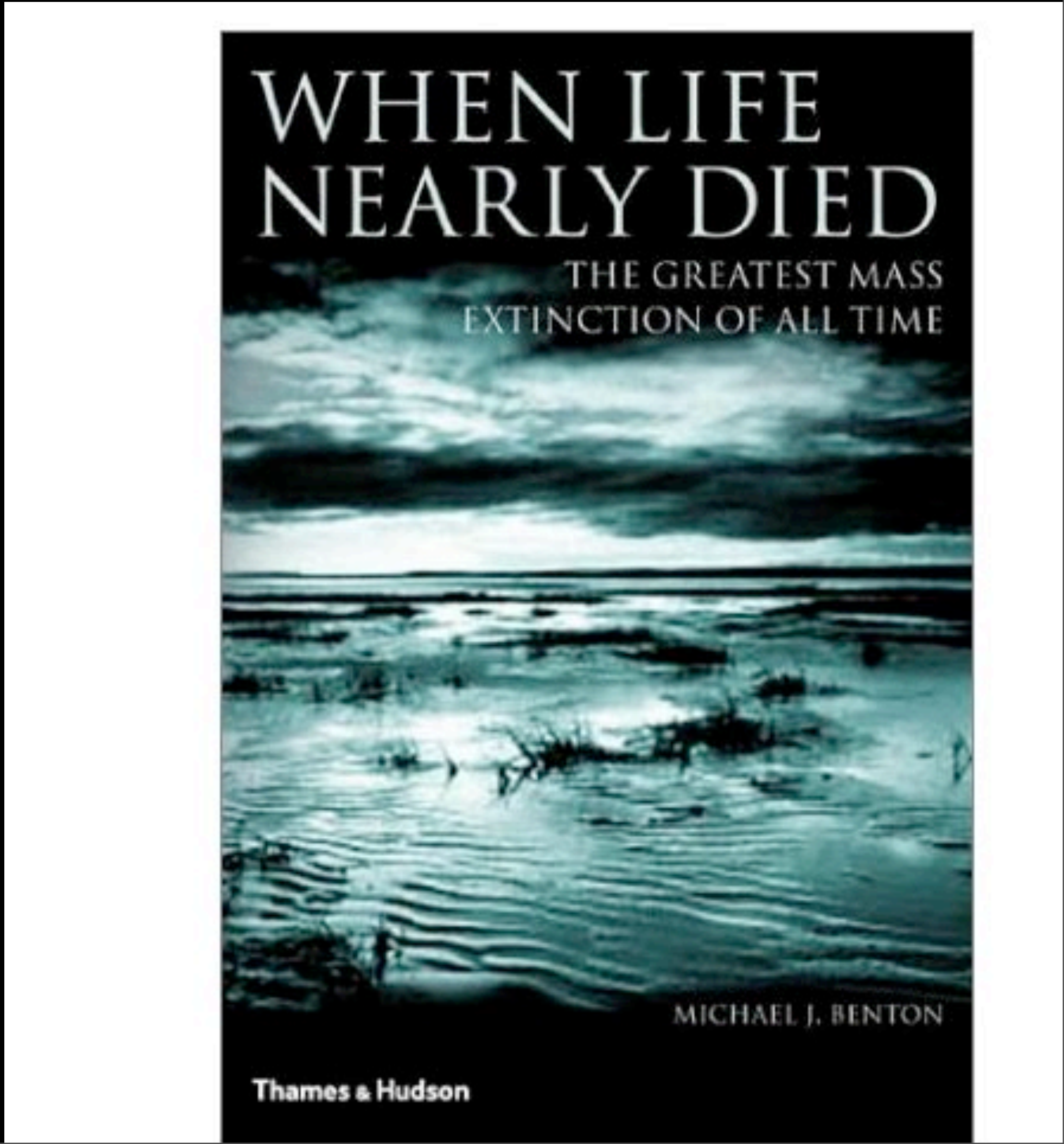
Several mass extinctions since Cambrian explosion

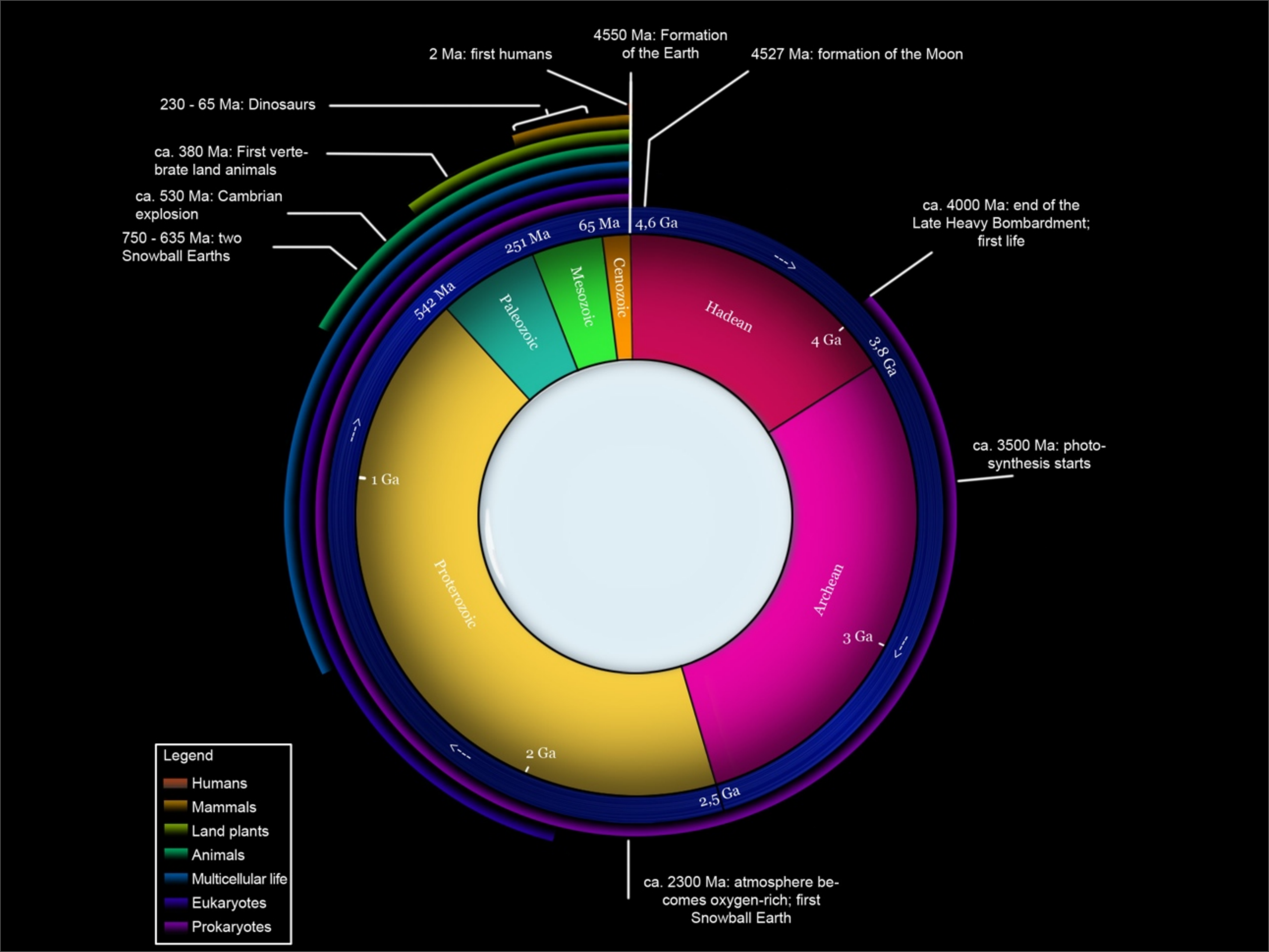
(large impact, massive volcanic eruption...)



Extinctions still very poorly understood







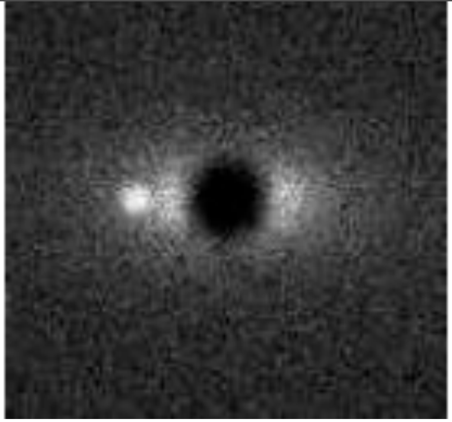
4550 Ma: Formation of the Earth
2 Ma: first humans
4527 Ma: formation of the Moon
230 - 65 Ma: Dinosaurs
ca. 380 Ma: First vertebrate land animals
ca. 530 Ma: Cambrian explosion
750 - 635 Ma: two Snowball Earths
ca. 4000 Ma: end of the Late Heavy Bombardment; first life
ca. 3500 Ma: photosynthesis starts
ca. 2300 Ma: atmosphere becomes oxygen-rich; first Snowball Earth
65 Ma
4,6 Ga
251 Ma
542 Ma
Cenozoic
Mesozoic
Paleozoic
Hadean
4 Ga
3,8 Ga
Archean
3 Ga
2,5 Ga
2 Ga
Proterozoic
1 Ga
Legend
Humans
Mammals
Land plants
Animals
Multicellular life
Eukaryotes
Prokaryotes

COMPLEX life, AS WE KNOW IT requires special conditions on planet

- simple life forms (bacteria / Archaea) might be much more common

BUT many many "suitable" planets in our galaxy, and many many galaxies... (Drake equation)

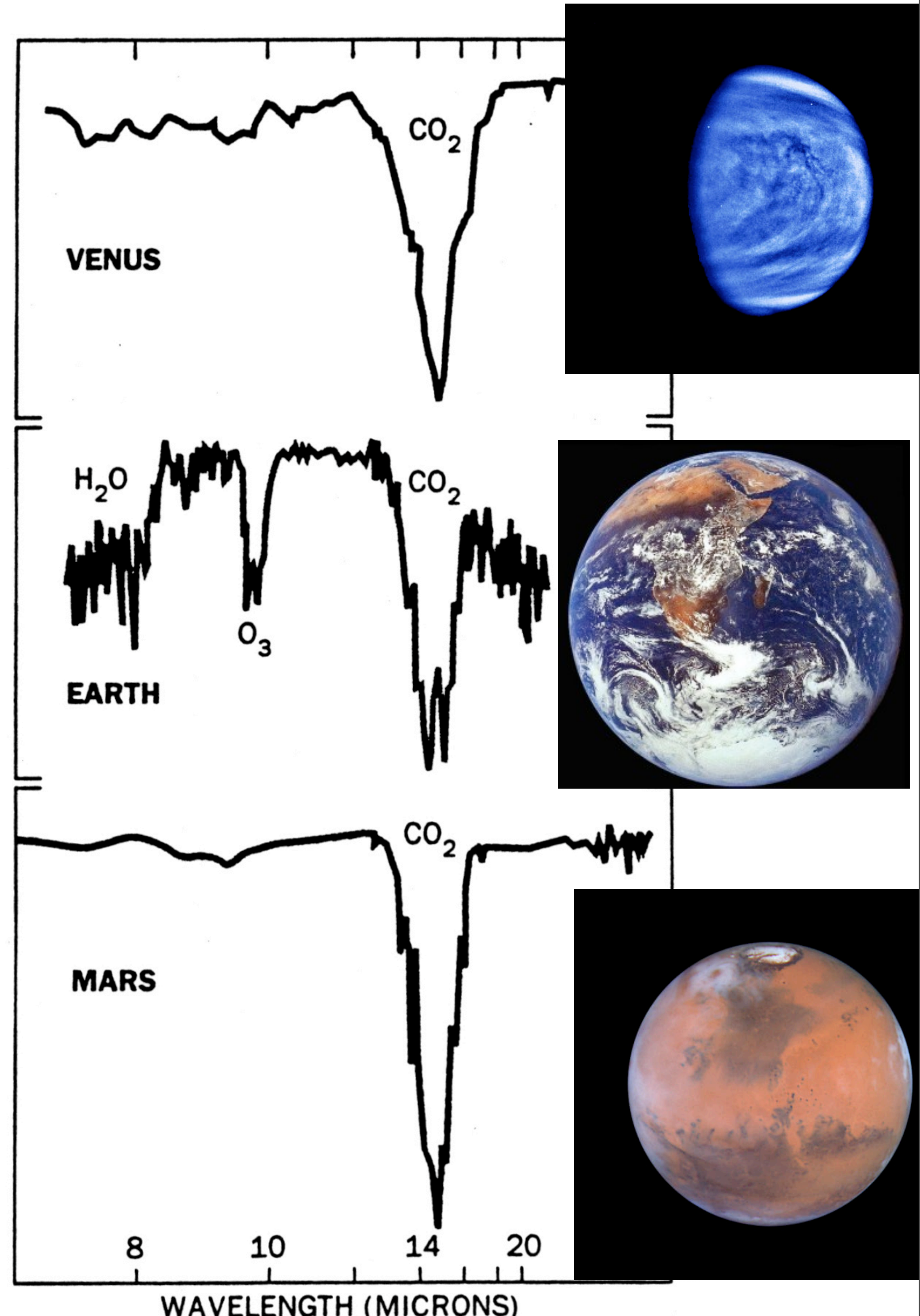
Within next decades, we will finally be able to probe for life on exoplanets not too different from Earth

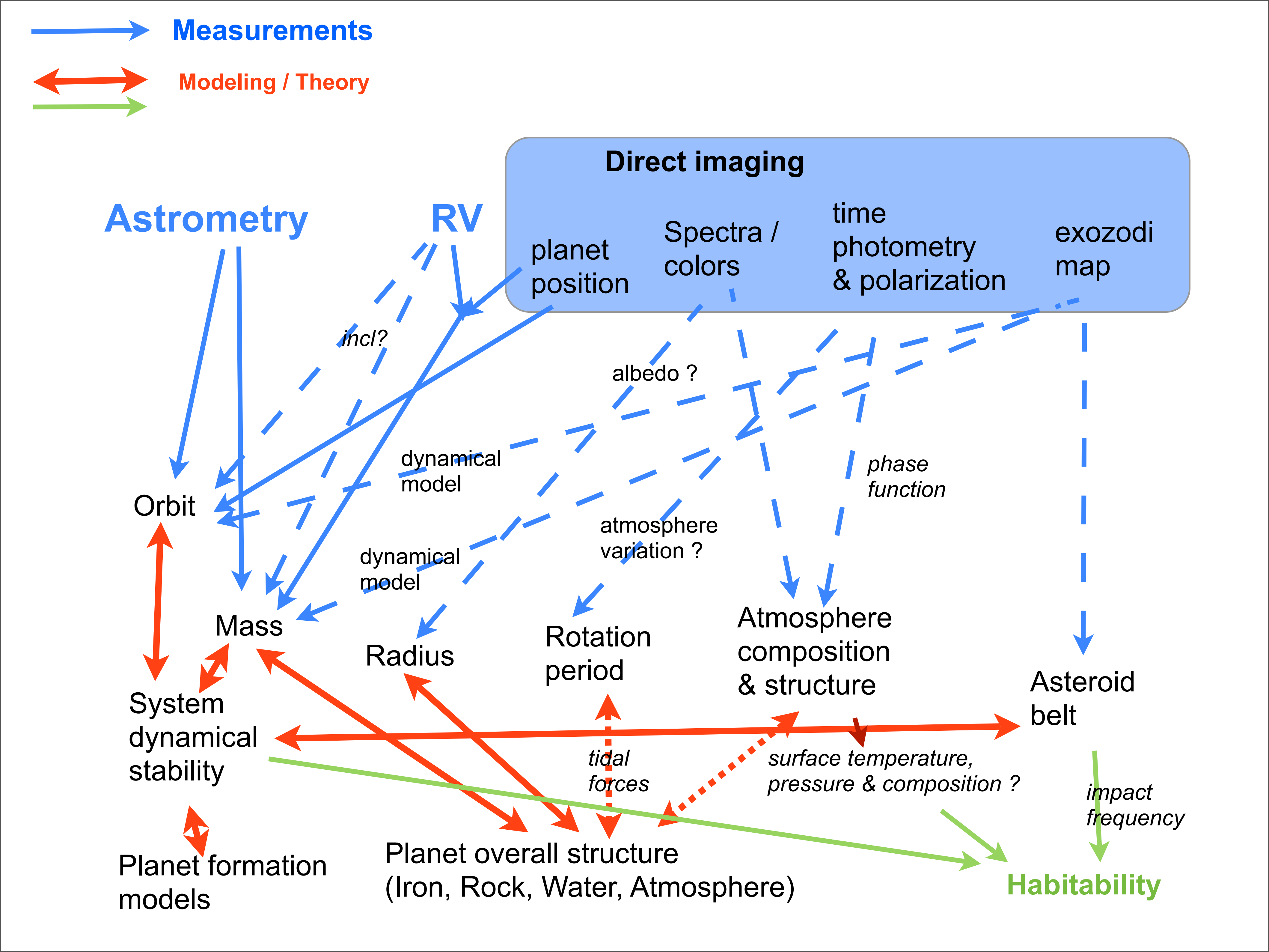


Imaging

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

  Planets + dust





Measurements
Modeling / Theory
Direct imaging
Astrometry
RV
planet position
Spectra / colors
time photometry & polarization
exozodi map
incl?
albedo ?
dynamical model
phase function
atmosphere variation ?
dynamical model
Orbit
Mass
Radius
Rotation period
Atmosphere composition & structure
Asteroid belt
System dynamical stability
tidal forces
surface temperature, pressure & composition ?
impact frequency
Planet formation models
Planet overall structure (Iron, Rock, Water, Atmosphere)
Habitability

Challenges

- **Contrast**
  - Visible:
    - 1e10 for Earth/Sun -> space
    - 1e9 for Jupiter/Sun -> space / ELTs ?
    - ~1e8 for close-in planets -> ground ExAO ?
  - Near-IR (~1.6 micron)
    - 1e10 for Earth/Sun
    - ~1e12 for Jupiter/Sun
    - ~1e7 for young giant planet / Sun -> Ground ExAO
  - Thermal IR (~10 micron)
    - 1e6 for Earth/Sun
    - 1e7 for Jupiter/Sun
- **Angular separation** (HZs at ~0.1”)

Coronagraphy

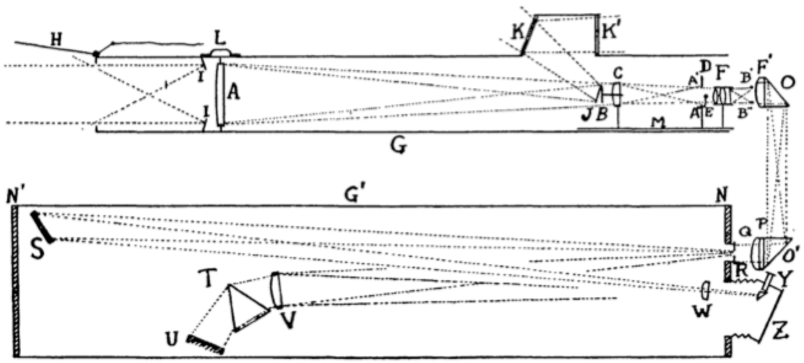
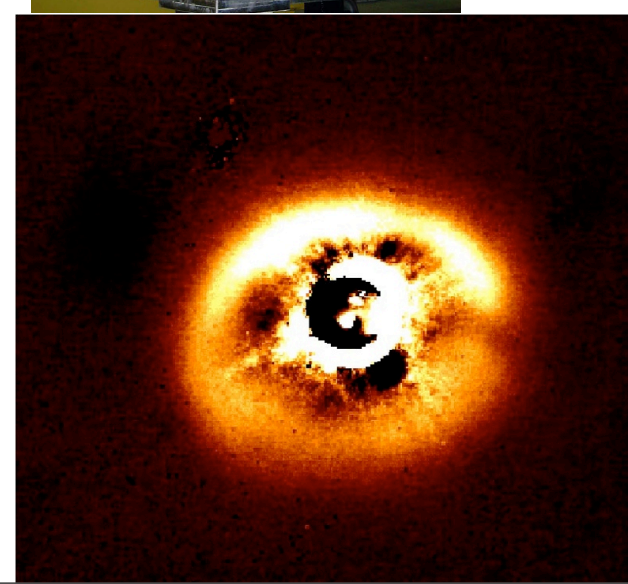


Fig. 4. Plan of the mounting of the coronograph (above) and the spectrograph.



?

A quick history of coronagraphy ...

Lyot Coronagraph

Lyot Coronagraph

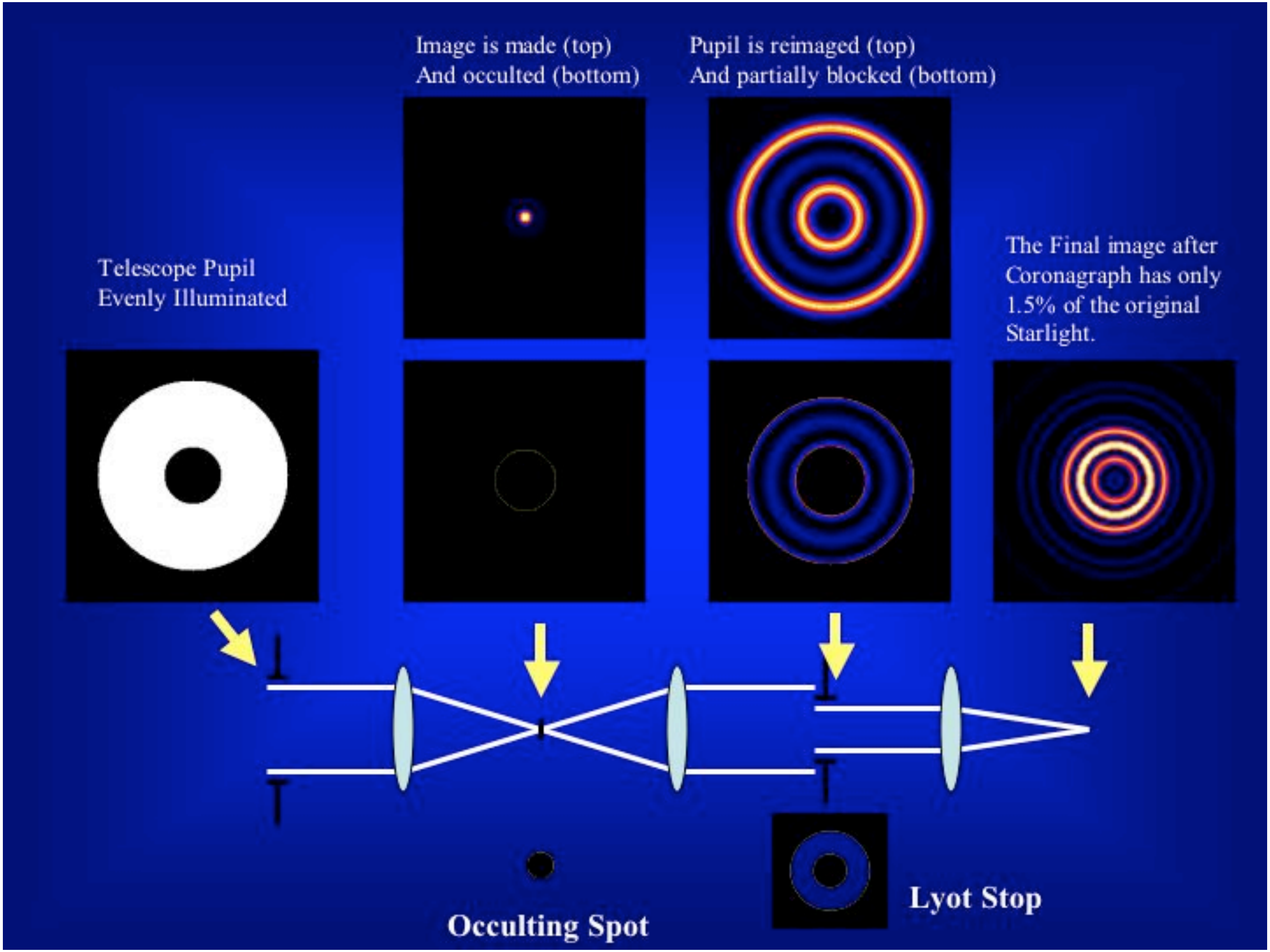
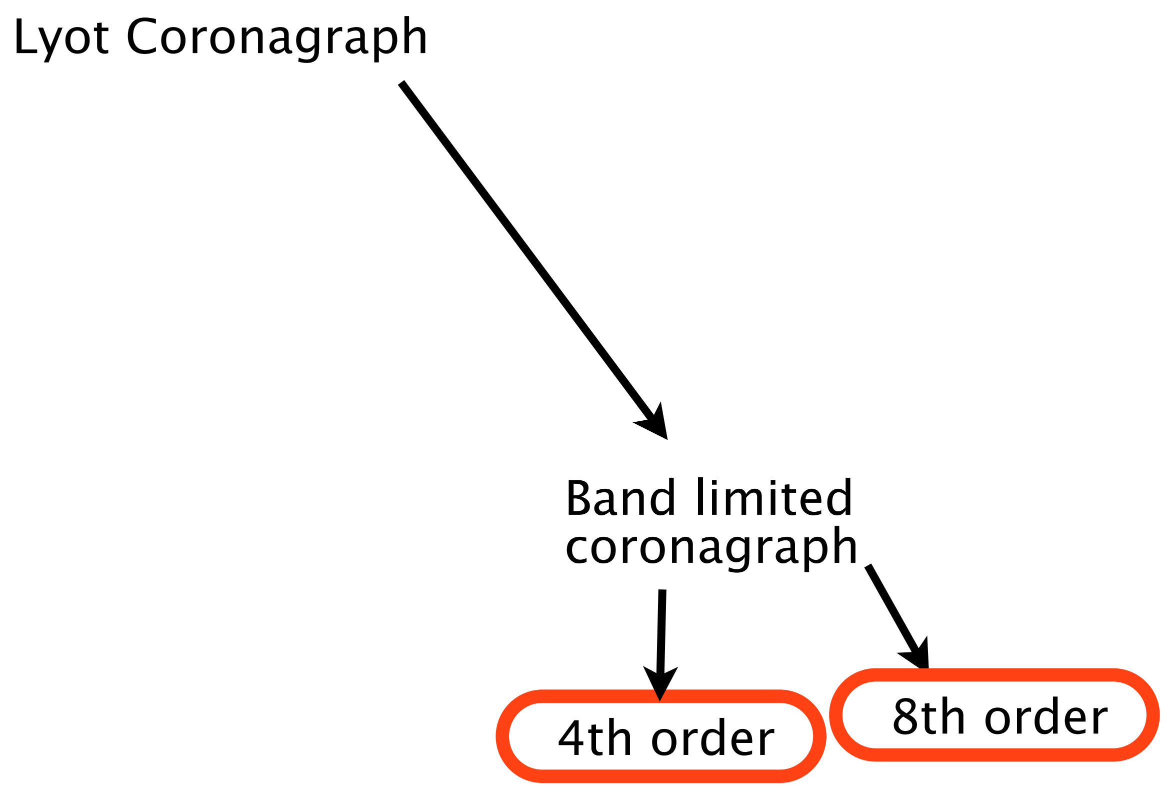


figure from Lyot project website

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

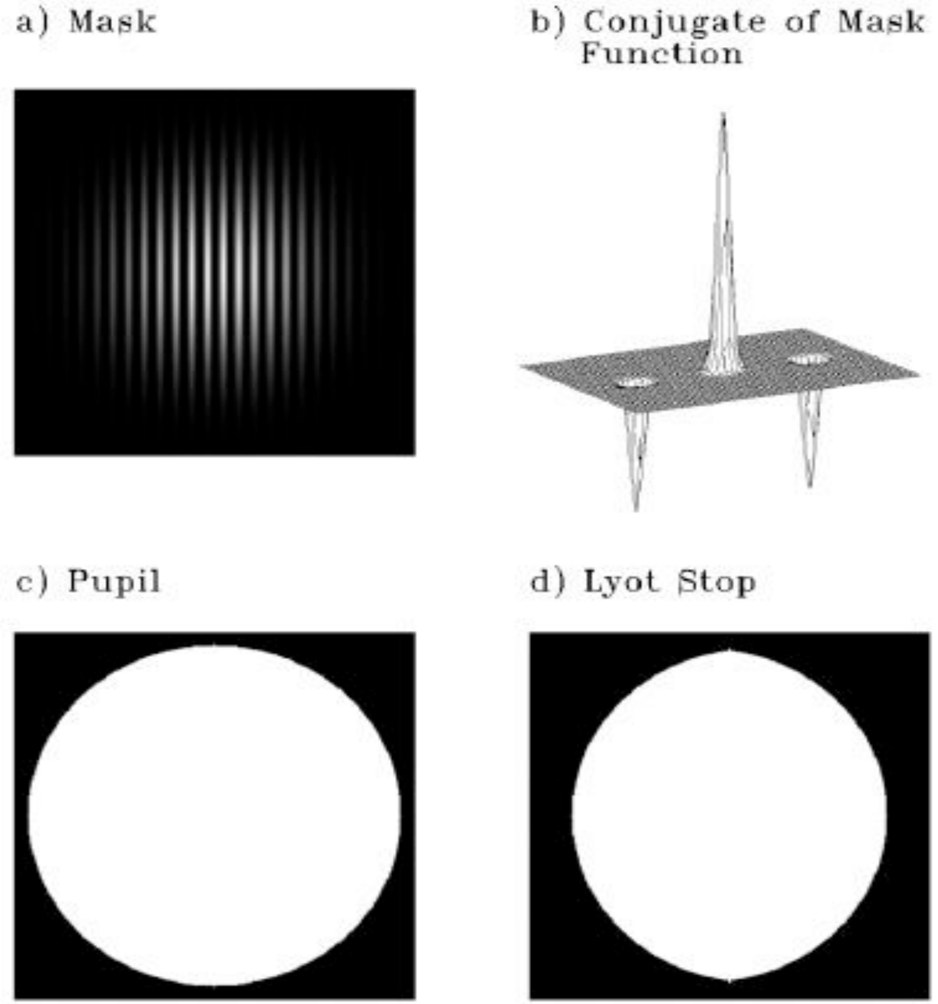


FIG. 4.—Simplest band-limited mask, analogous to a single-baseline nulling interferometer. (*a*) Mask ITF $\sin^4(x)$ multiplied by a slow taper. Dark areas are opaque. (*b*) Conjugate of the mask ATF (eq. [13]). This occulting mask can be used with any aperture shape, but for the circular aperture shown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

Lyot Coronagraph

Apodized Pupil
Lyot Coronagraph

Band limited
coronagraph

4th order

8th order

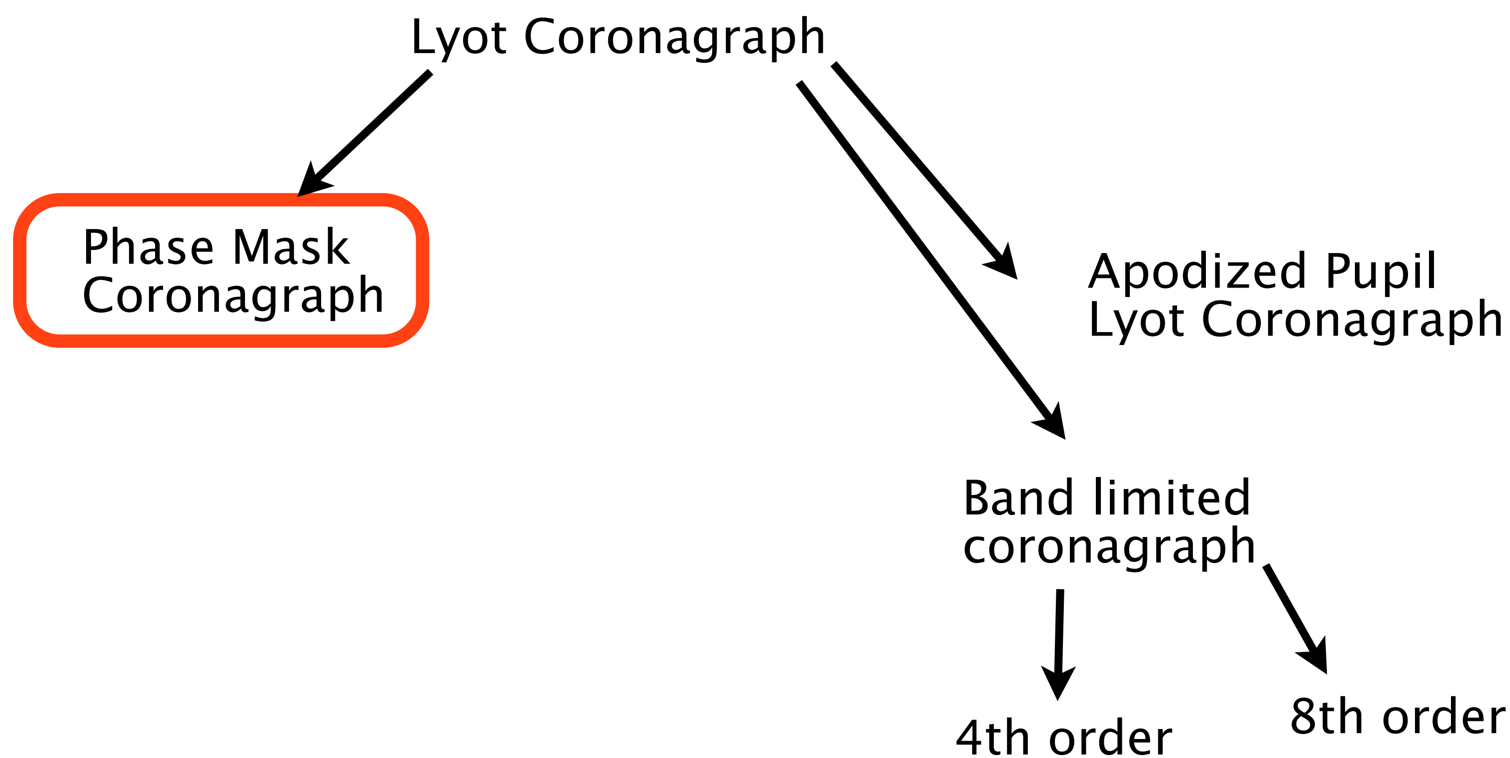
Apodized Pupil Lyot Coronagraph (APLC)
= Prolate Apodized Lyot Coronagraph (PALC)

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 APLC.

Adopted for Gemini Planet Imager (GPI).

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


Lyot Coronagraph
Phase Mask
Coronagraph
Apodized Pupil
Lyot Coronagraph
Band limited
coronagraph
4th order
8th order

Phase Mask Coronagraph (PM)

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

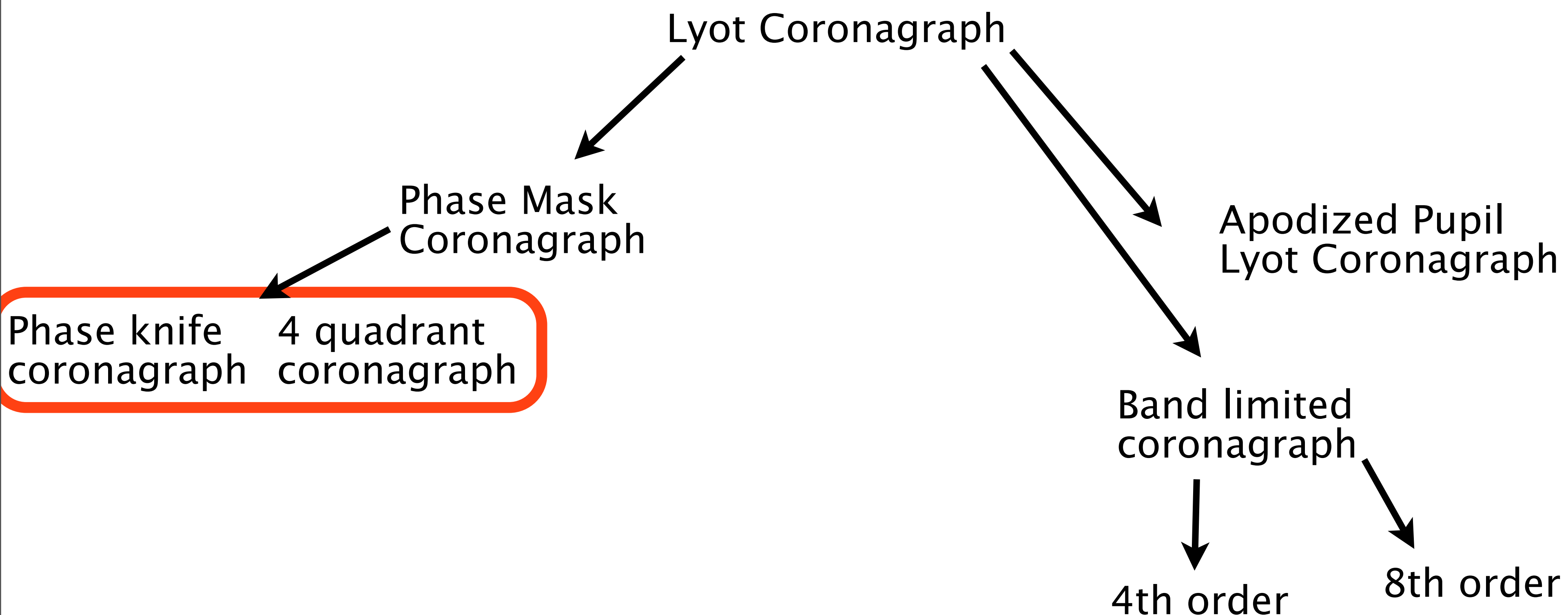
- smaller mask
- smaller IWA

Requires mild prolate pupil apodization.

Phase shift needs to be achromatic
Mask size should be wavelength dependant
Dual zone PM coronagraph mitigates chromaticity

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)


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

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

2^{nd} order null only.

Used on VLT for science obs.

Rouan et al. 2000, PASP, 112, 1479

PHASE CORONAGRAPH WITH FOUR QUADRANTS. I. 1481

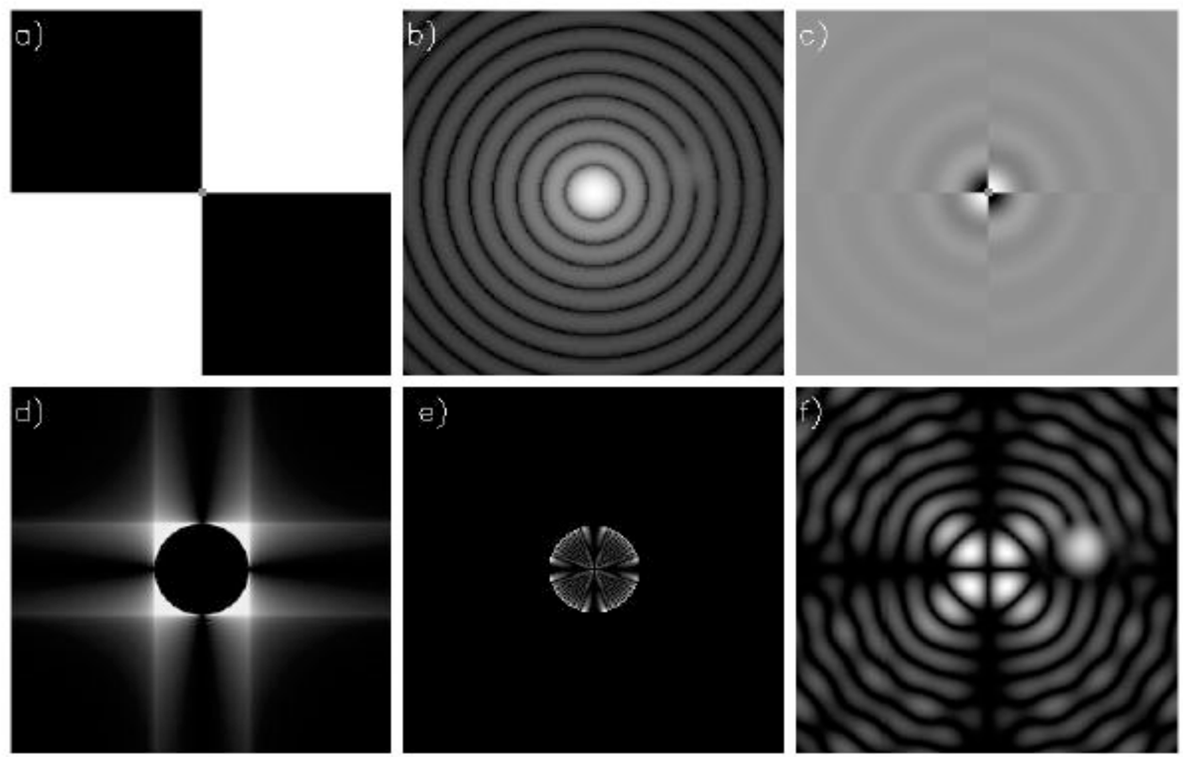


FIG. 2.—Numerical simulation illustrating the principle of the four-quadrant coronagraph. A companion 15 mag fainter (flux ratio of 10^6) is located $2.1\lambda/D$ away from the star. The individual images show (*a*) the shape of the phase mask (white for 0 phase shift, black for π phase shift), (*b*)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

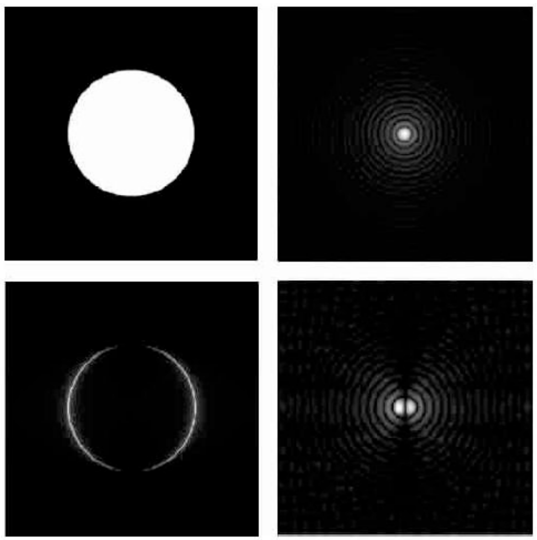


Fig. 1. Pupil intensity with perfect wavefront and its corresponding Airy pattern (*top left and right*). Intensity distribution after the Phase Knife Coronagraph has been applied (*bottom-left*): the two thin crescents encircle the pupil area perpendicular to the Knife-Edge direction. "Butterfly shape"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

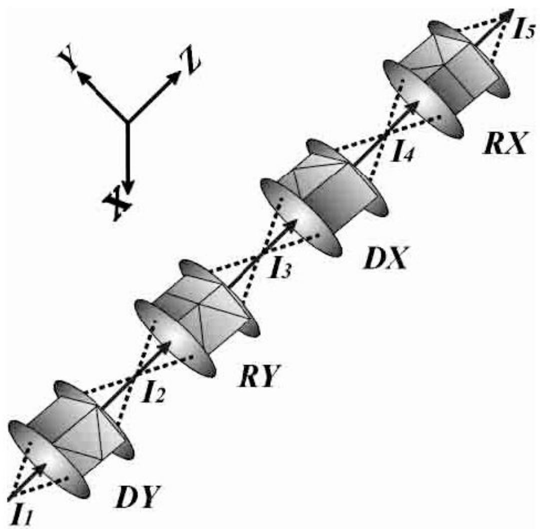


Fig. 2. Generic 3D optical scheme of the PKC. I1 is the input Airy pattern, DY is a direct vision dispersing prism in the Y direction, I2 corresponds to the first chromatic phase-knife parallel to Y. RY is a second direct-vision prism rotated by 180 degrees with respect to DY which superimposes the dispersed 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.

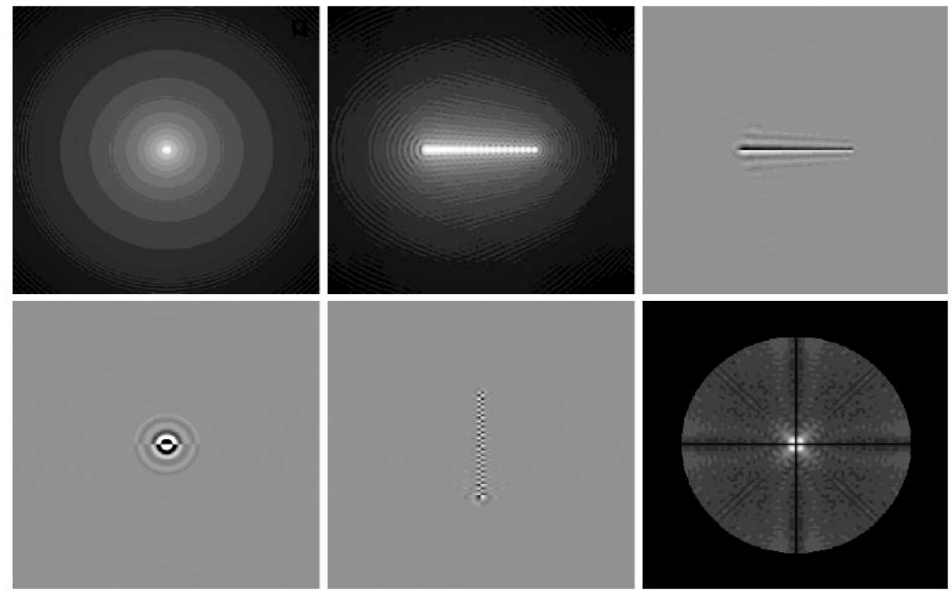
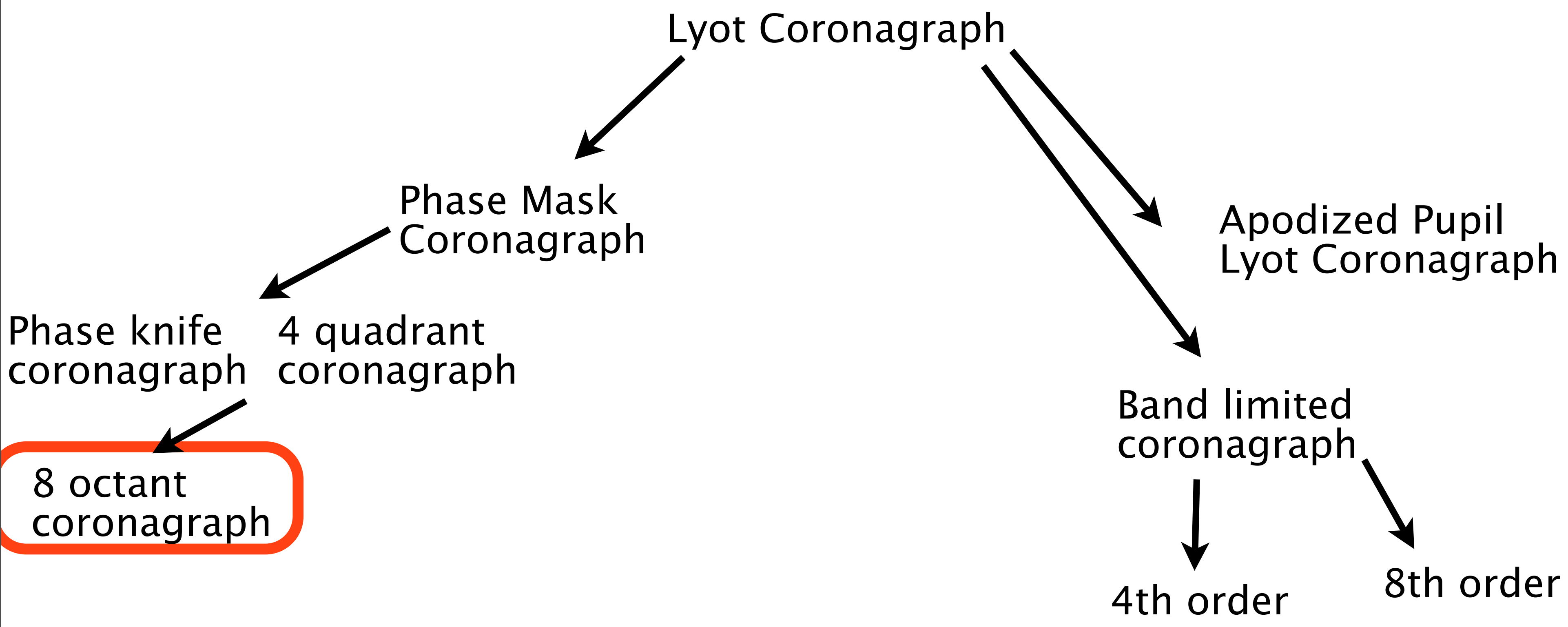
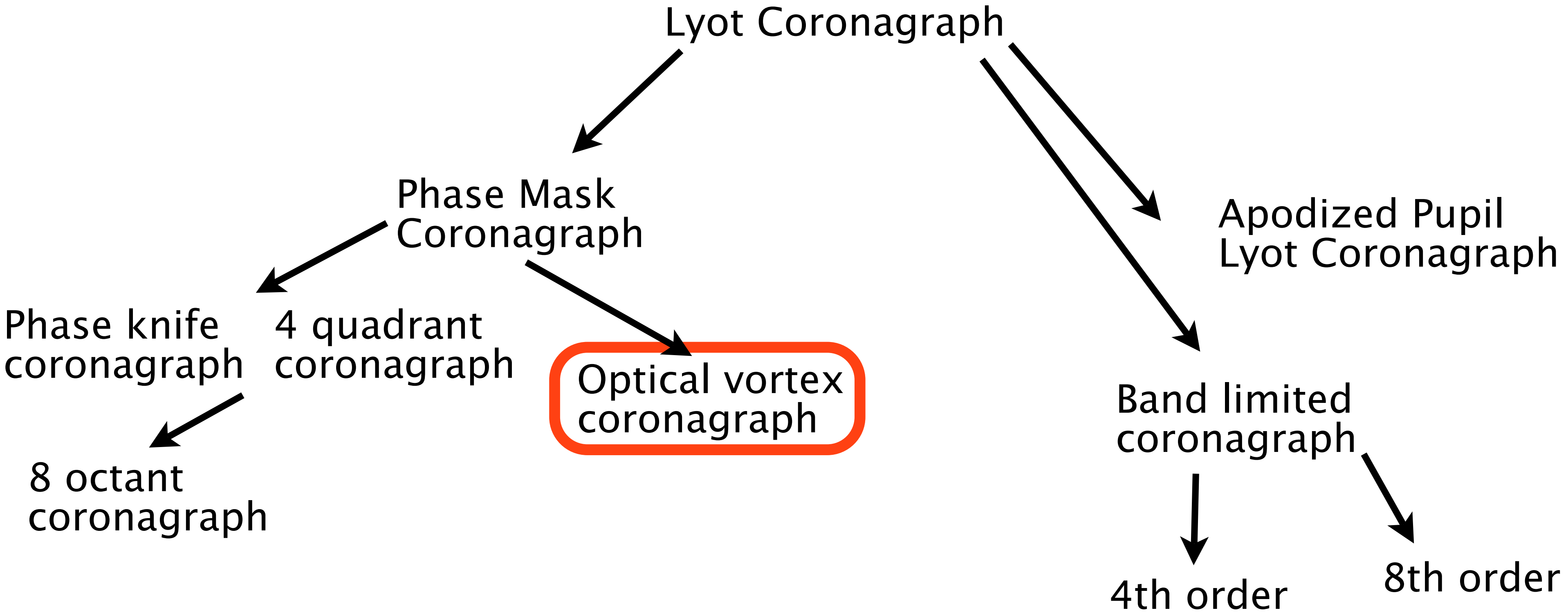


Fig. 3. Different steps of the phase-knife screen effect: (*top-left*) polychromatic Airy pattern (bandwidth: 400–800 nm) (corresponding to step I1 in Fig. 2), (*top-middle*) dispersed Airy disc, (*top-right*) the polychromatic phase-knife where the optical retardation follows the dispersion law (step 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

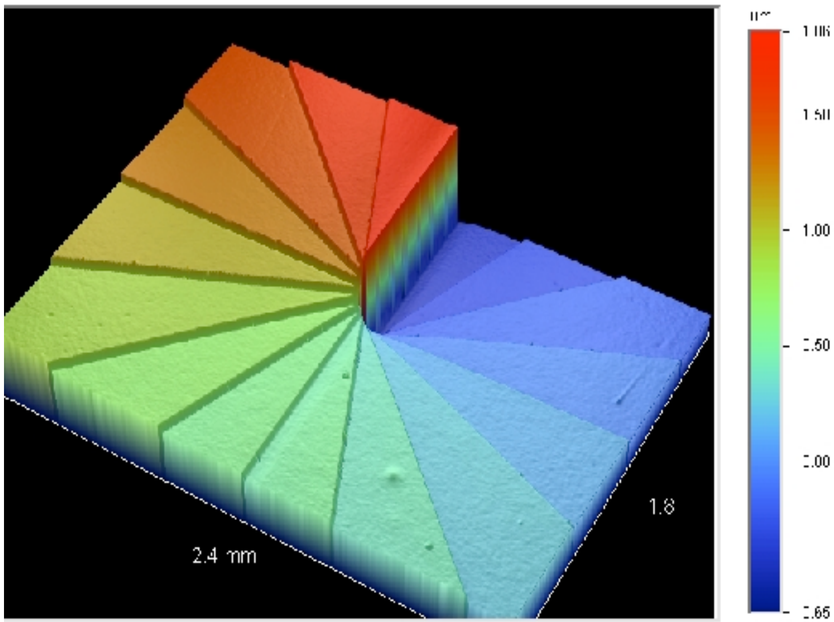


Lyot Coronagraph
Phase Mask
Coronagraph
Apodized Pupil
Lyot Coronagraph
Phase knife
coronagraph
4 quadrant
coronagraph
8 octant
coronagraph
Band limited
coronagraph
4th order
8th order


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

Optical Vortex Coronagraph (OVC)

Phase in focal plane mask = Cst x PA



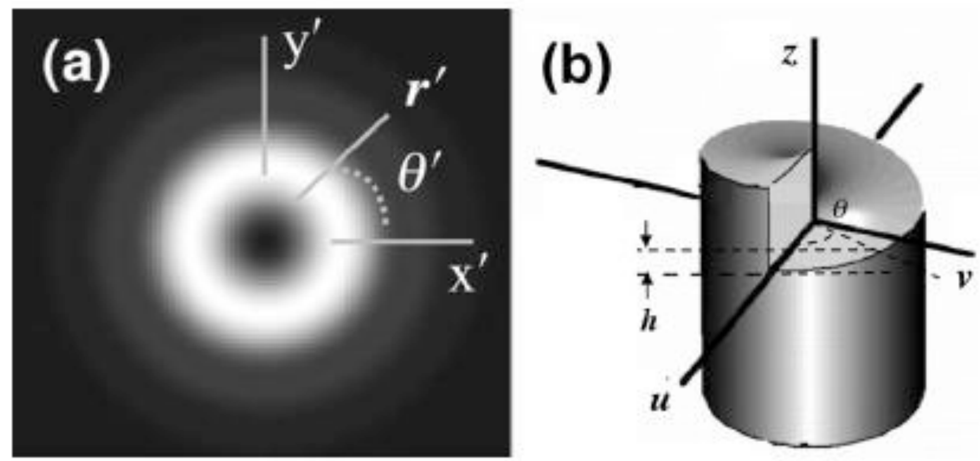


Fig. 2. (a) Intensity profile, $|U(x',y')|^2$ of a beam containing an optical vortex. (b) Surface profile of a VPM.

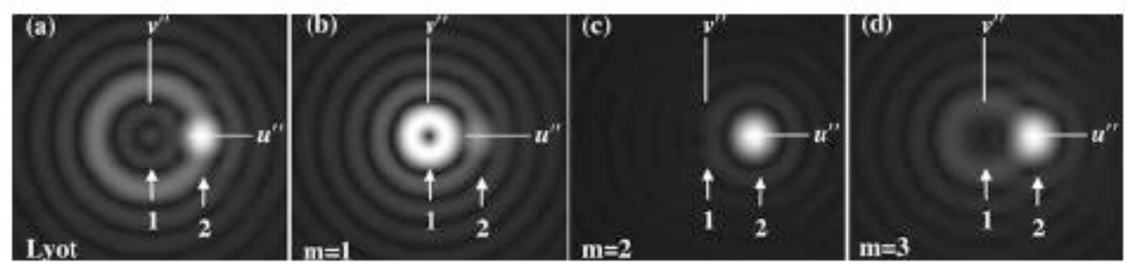
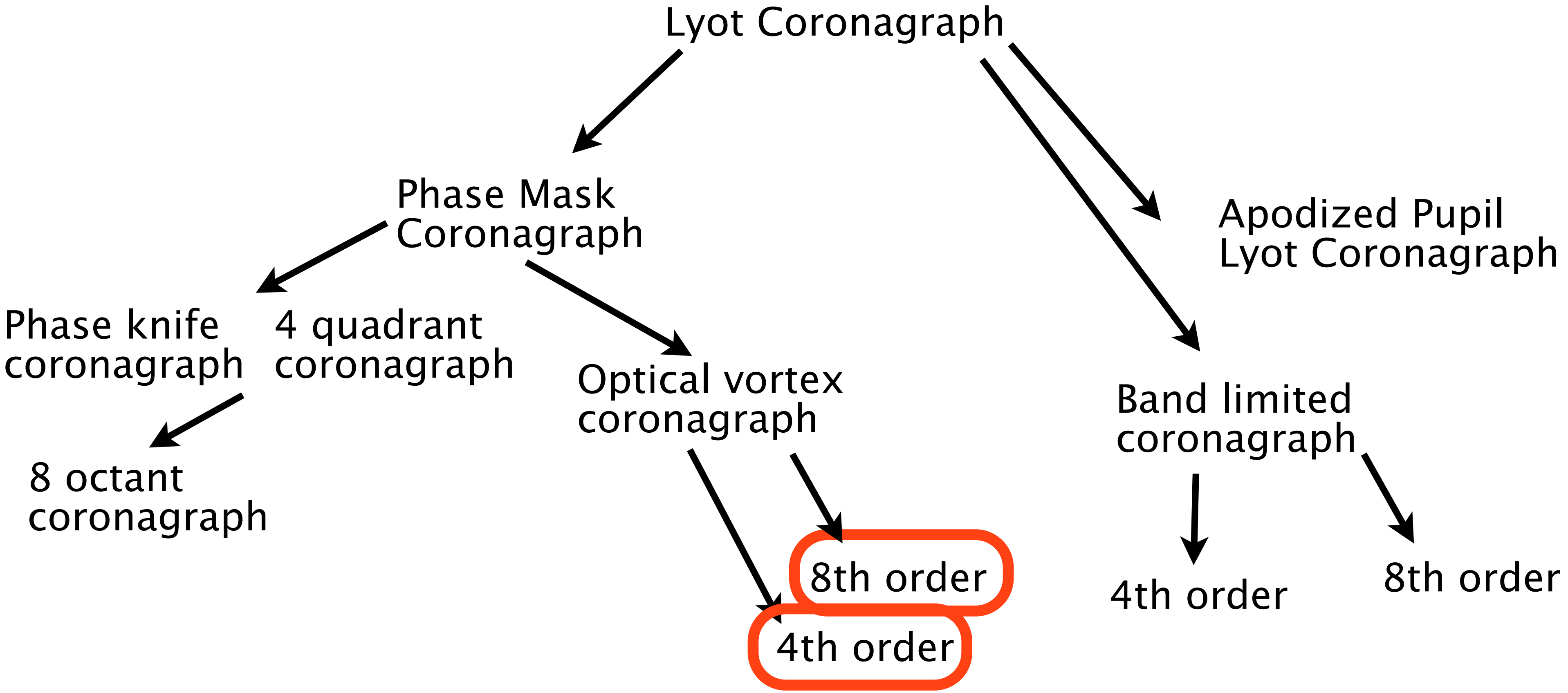
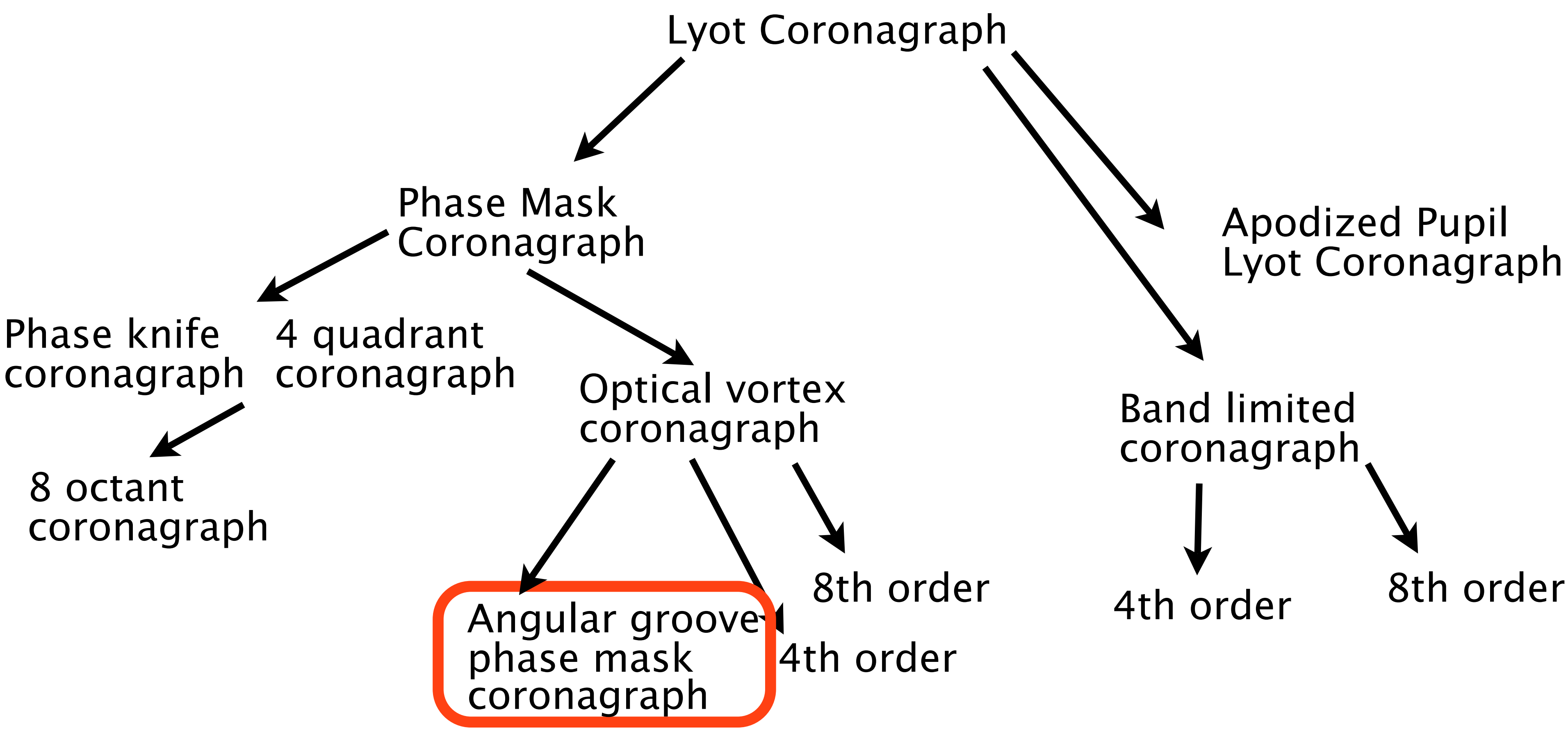


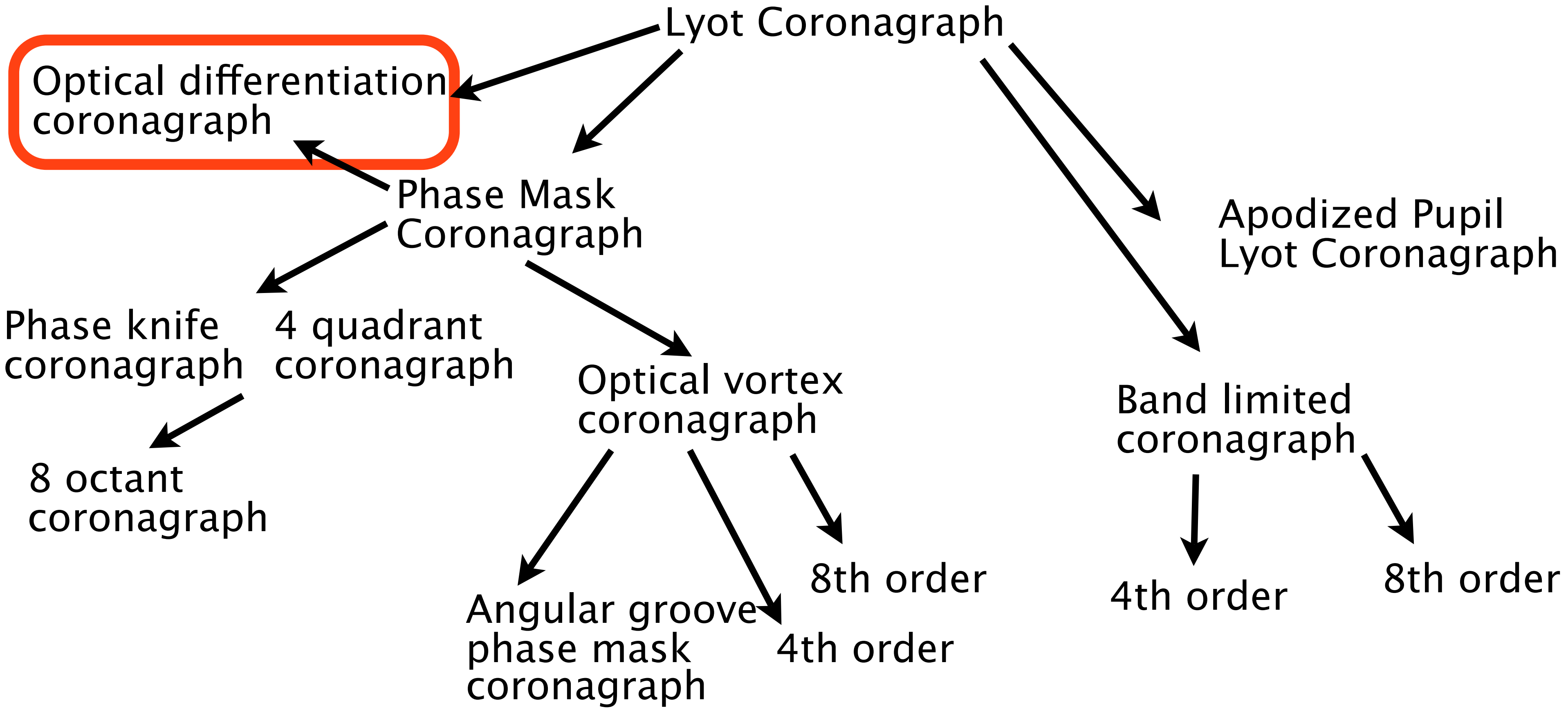
Fig. 3. Comparisons for $\alpha_2 = \alpha_{\mathrm{diff}}$ and $A_1{}^2/A_2{}^2 = 100$. (a) Lyot coronagraph where $R_{\mathrm{OM}} = r_{\mathrm{diff}}$. (b), (c), (d) Vortex coronagraphs where $m=1$, $m=2$, $m=3$, respectively. In (c) the starlight is essentially eliminated, revealing a high-contrast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

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

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


Lyot 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
4th order
8th order

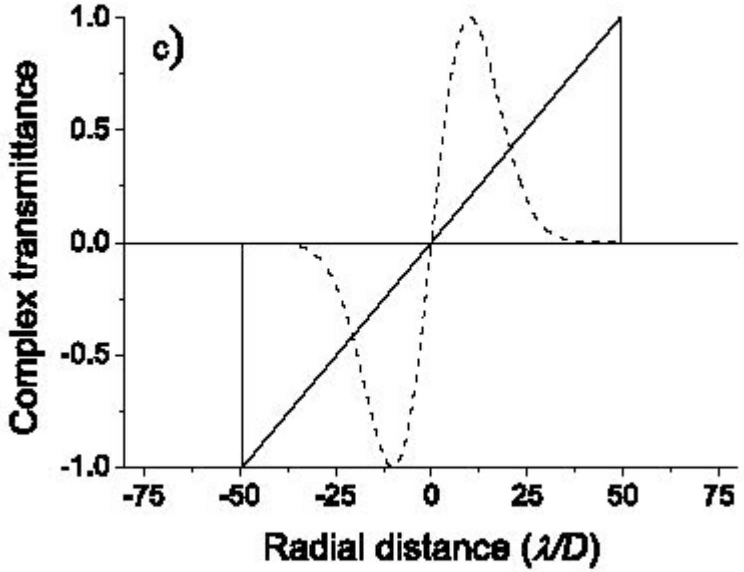

Lyot Coronagraph
Phase Mask Coronagraph
Apodized Pupil Lyot Coronagraph
Phase knife coronagraph
4 quadrant coronagraph
Optical vortex coronagraph
Band limited coronagraph
8 octant coronagraph
8th order
4th order
8th order
Angular groove phase mask coronagraph
4th order



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
Angular groove phase mask coronagraph
4th order
8th order
4th order
8th order

Optical Differentiation Coronagraph (ODC)

Optimized version of a single axis phase knife coronagraph.



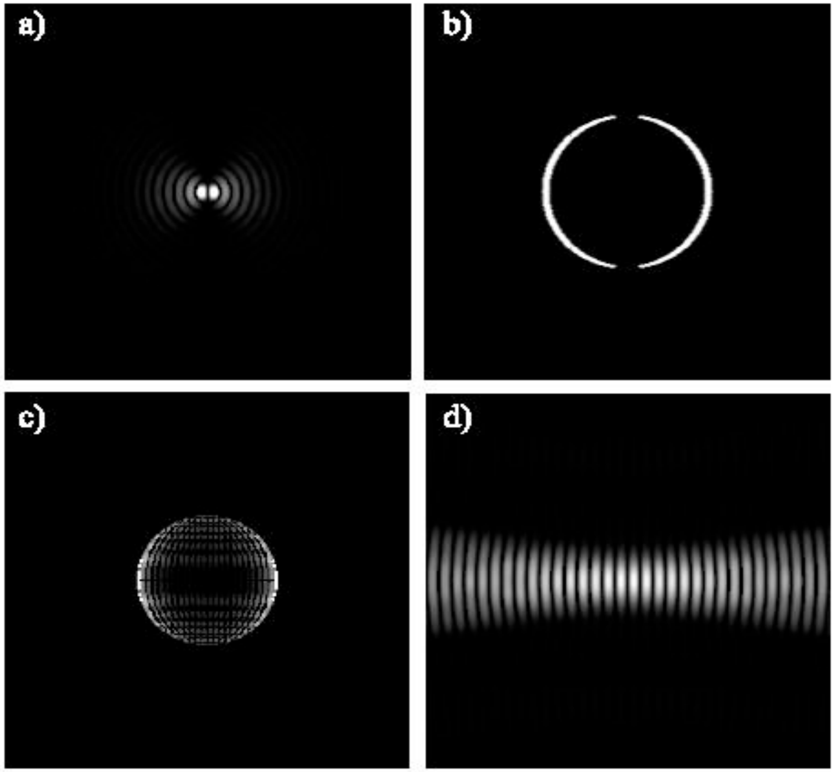
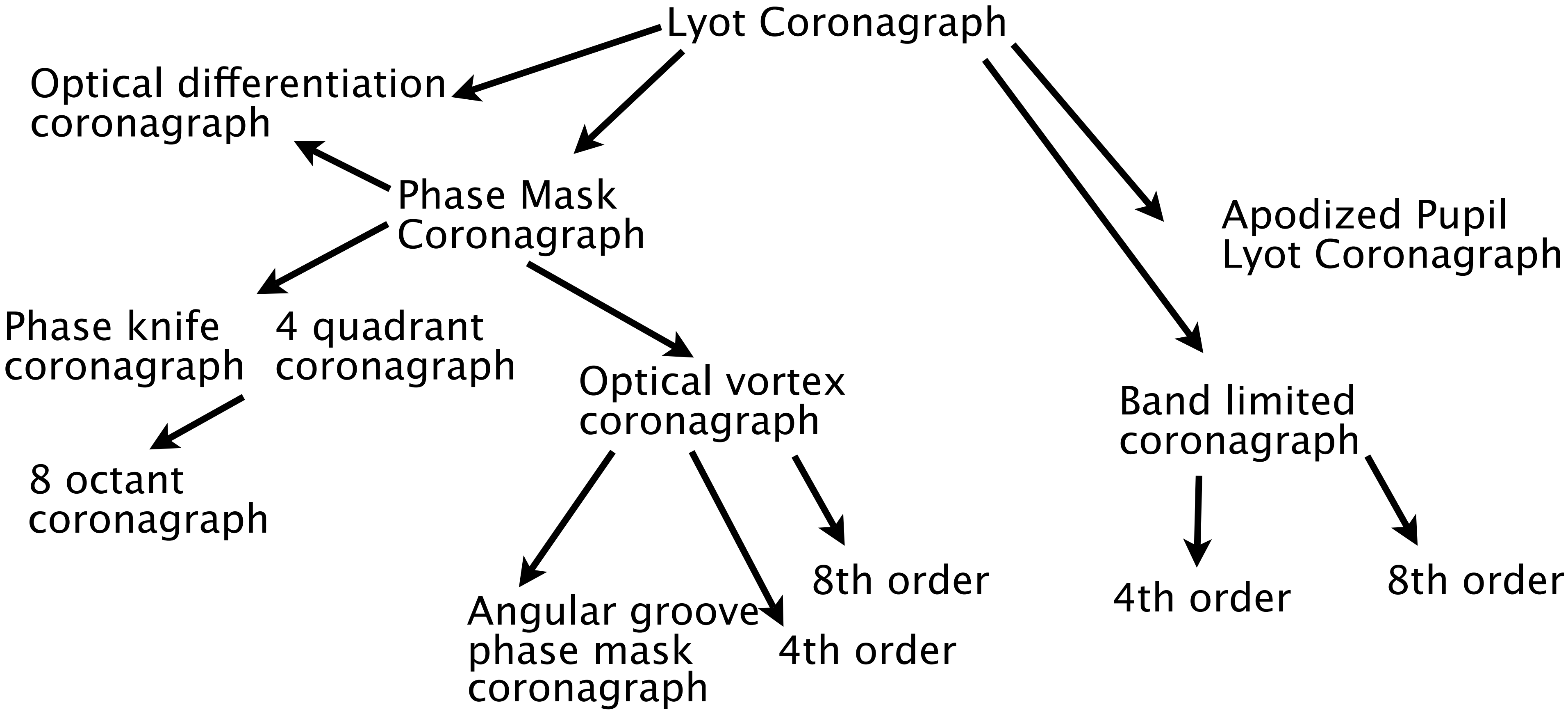


Fig. 3.—Simulated images at different planes in the optical differentiation coronagraph illustrating its principle of operation. (*a*) Image of the star PSF multiplied by the modified differentiation mask. (*b*) Intensity distribution just before (*b*) and after (*c*) the Lyot stop plane. (*d*) Final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

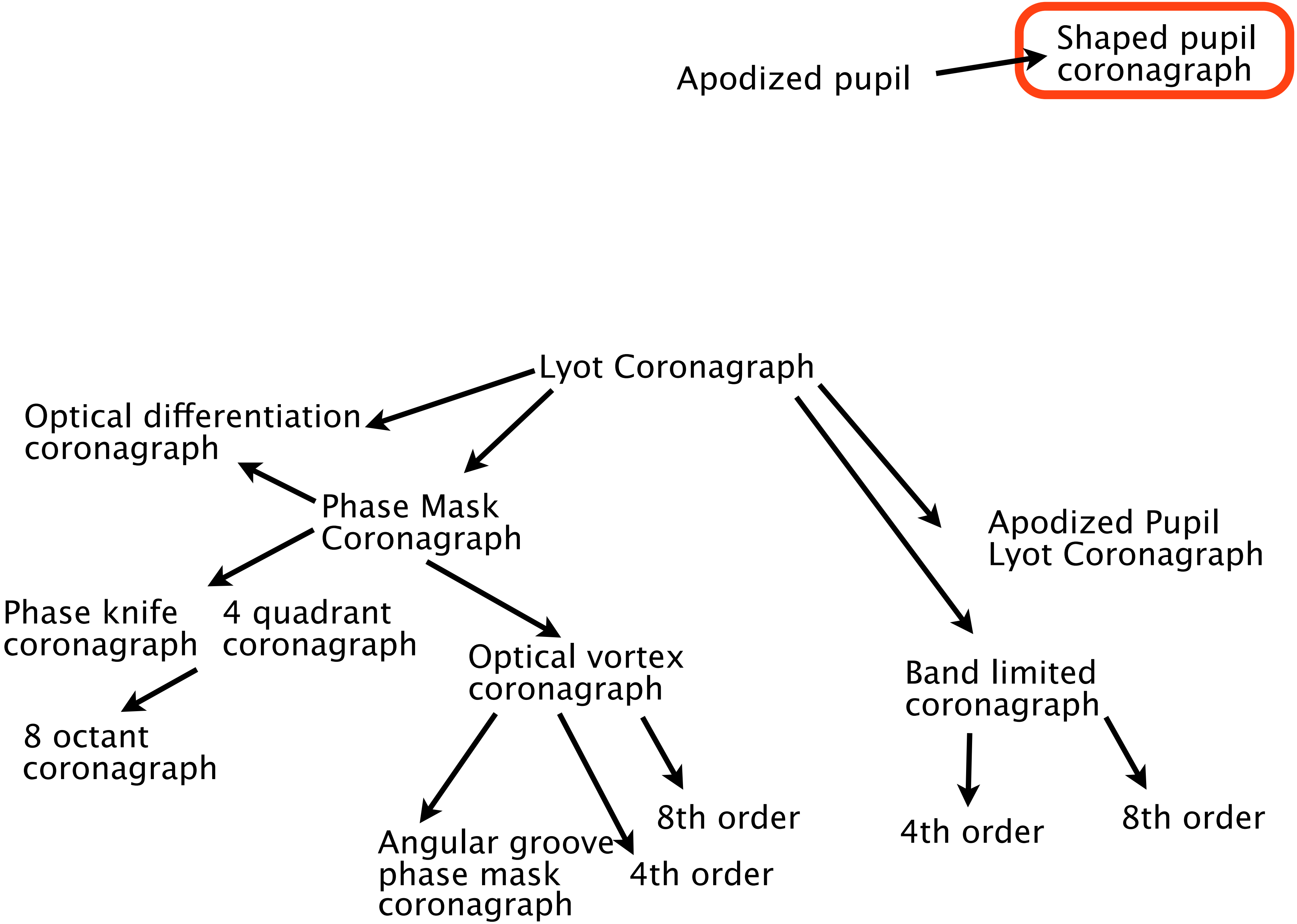
Guyon, 2003

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

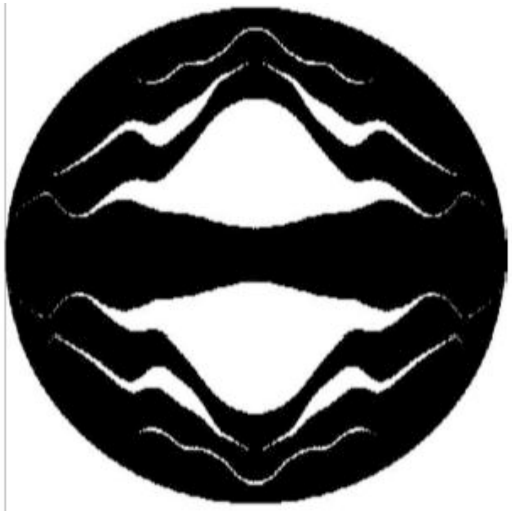

Shaped pupil coronagraph
Apodized pupil
Lyot Coronagraph
Optical differentiation coronagraph
Phase Mask Coronagraph
Apodized Pupil Lyot Coronagraph
Phase knife coronagraph
4 quadrant coronagraph
Optical vortex coronagraph
Band limited coronagraph
8 octant coronagraph
8th order
4th order
8th order
Angular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

Conventional Pupil Apodization (CPA)

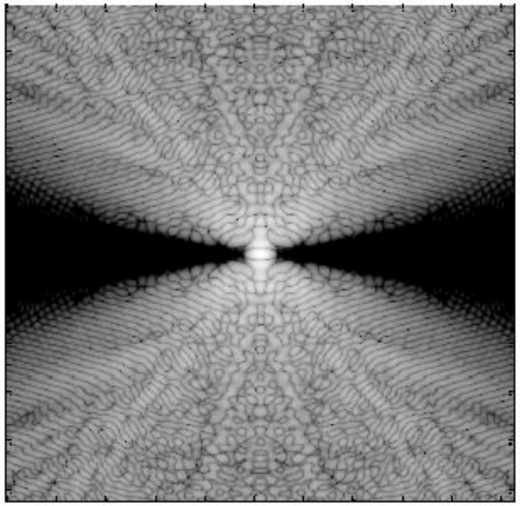
Many pupil apodizations have been proposed.

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



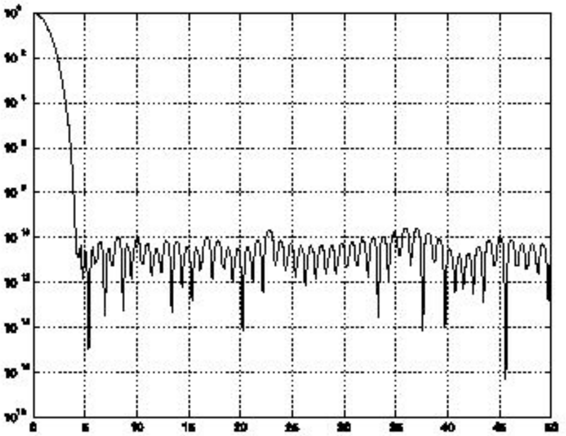
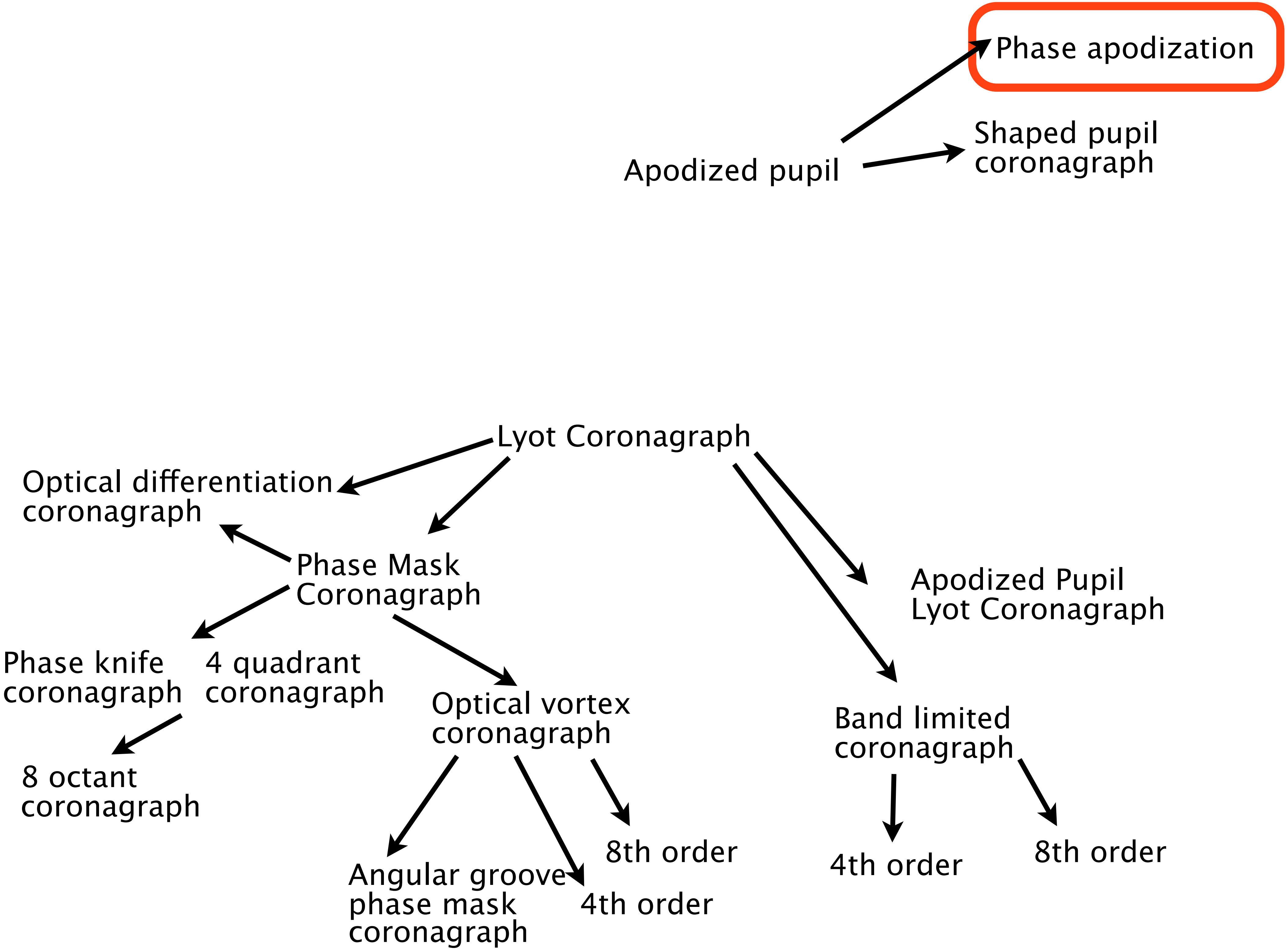


FIG. 9.—*Top*: Asymmetric multiopening mask designed to provide high-contrast, 10^{-10}, from $\lambda/D = 4$ to $\lambda/D = 100$ in two angular sectors centered on the x-axis. Ten integrations are required to cover all angles. Total throughput and pseudoarea are 24.4%. Airy throughput is 11.85%. *Bottom*: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



Phase apodization
Apodized pupil
Shaped pupil coronagraph
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 Phase Apodization (PPA)

Achromatic solutions exist.

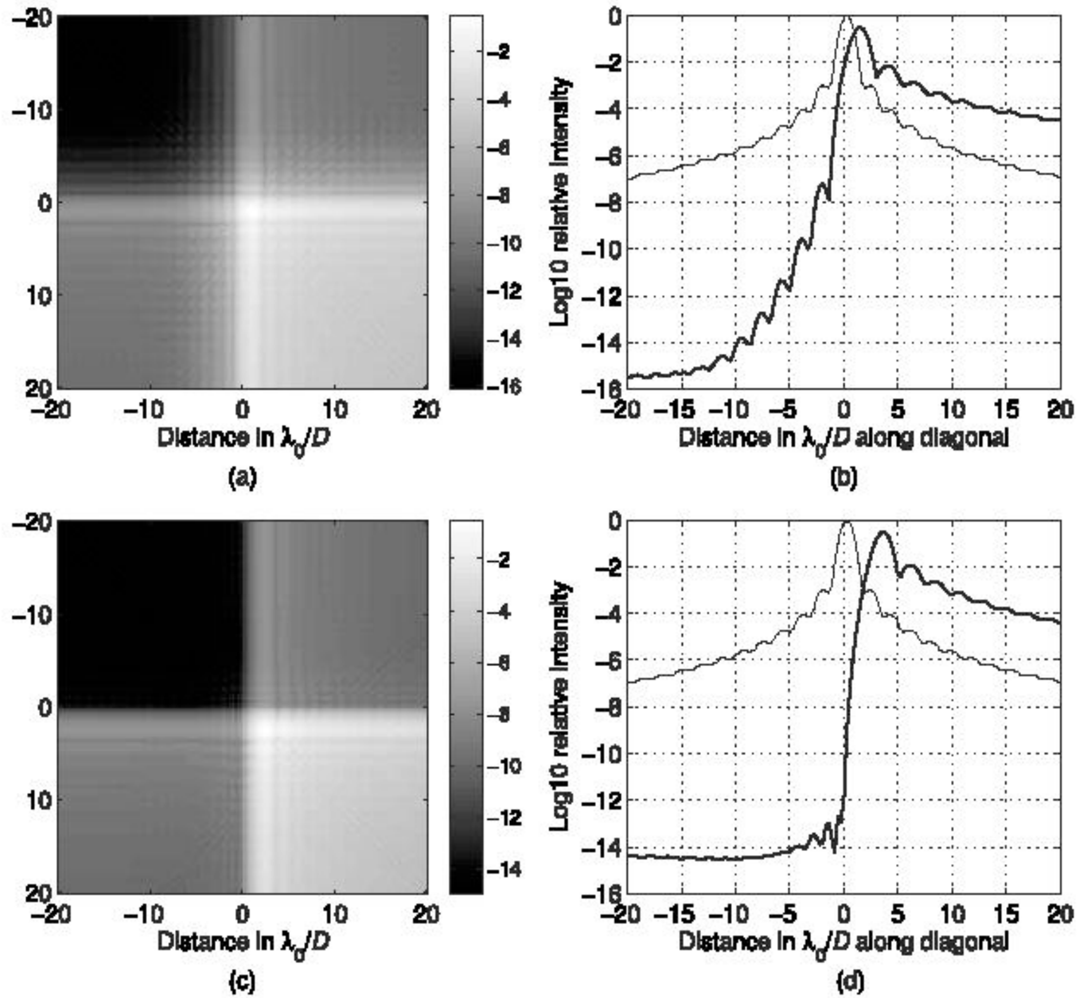
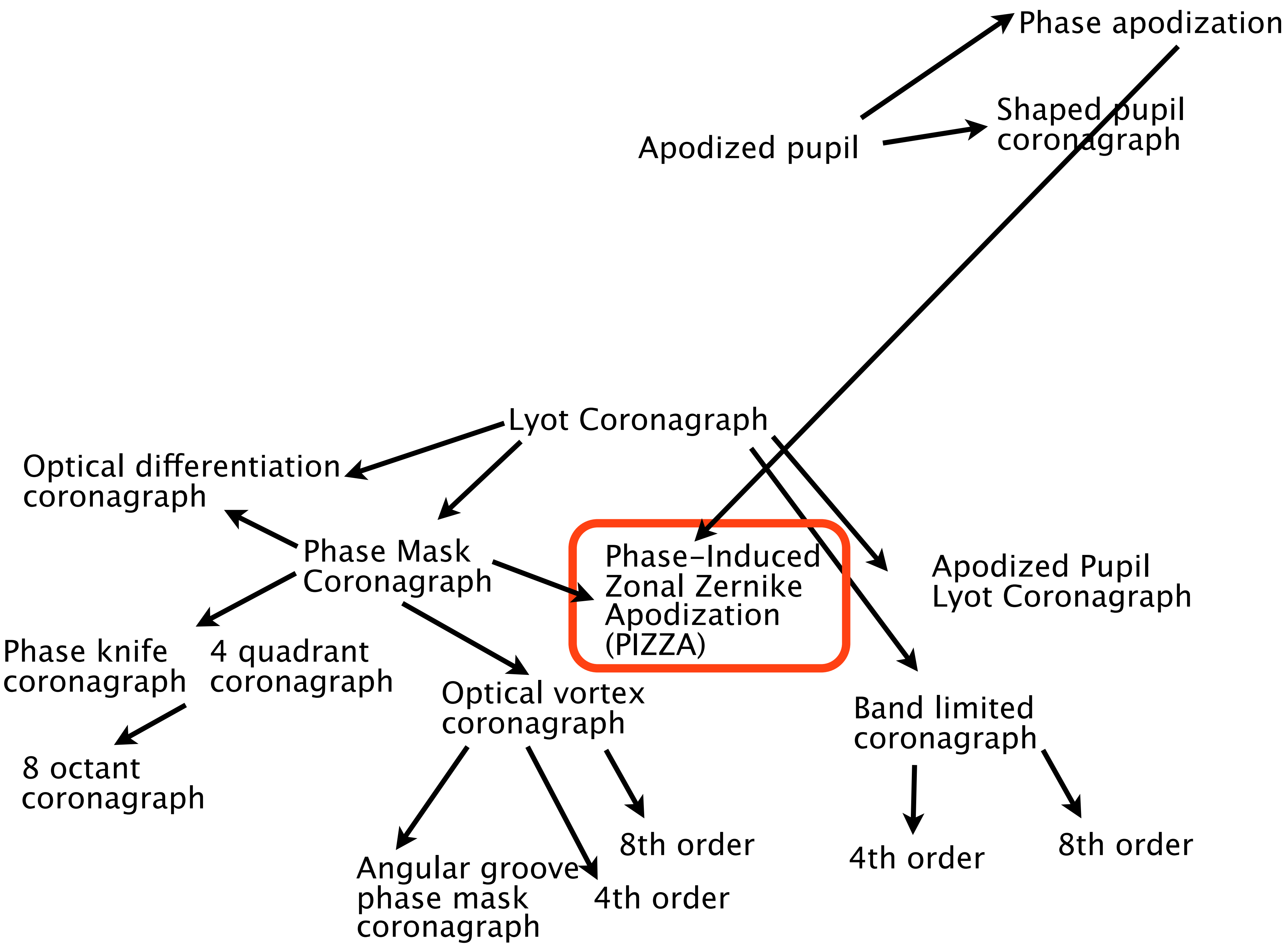


Fig. 9.—Broad-bandwidth light reduction effect on one quadrant of focal plane. The simulation is based on a rectangular spectrum distribution with total bandwidth of $0.6\lambda_0$. (*a*) $\log_{10}$ relative intensity image when phase $\phi(x, y) = a \tan[(0.5 - \epsilon)2\pi x/D] + a \tan[(0.5 - \epsilon)2\pi y/D]$, 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 apodization
Shaped pupil coronagraph
Apodized pupil
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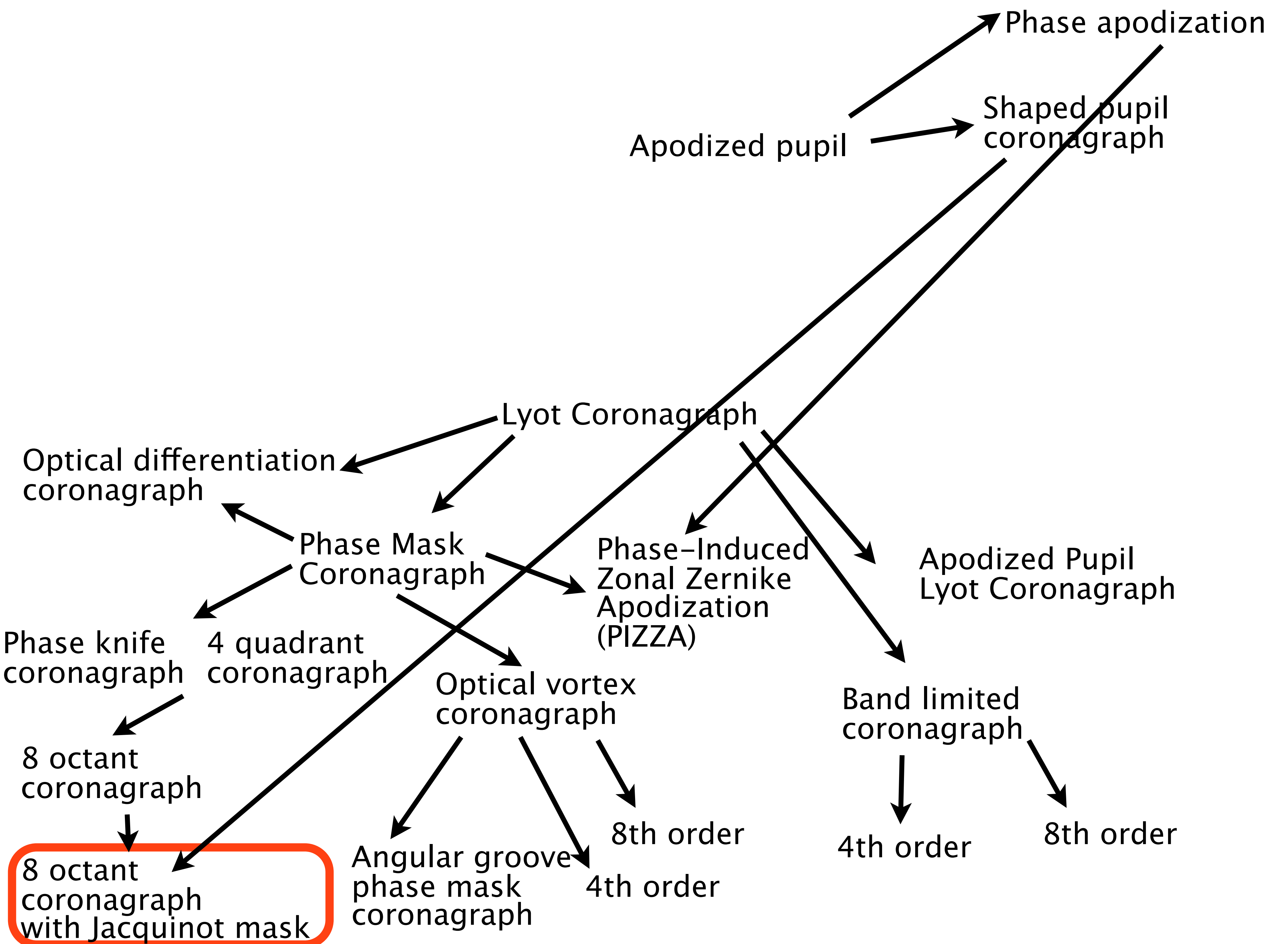
Angular groove phase mask coronagraph
4th order

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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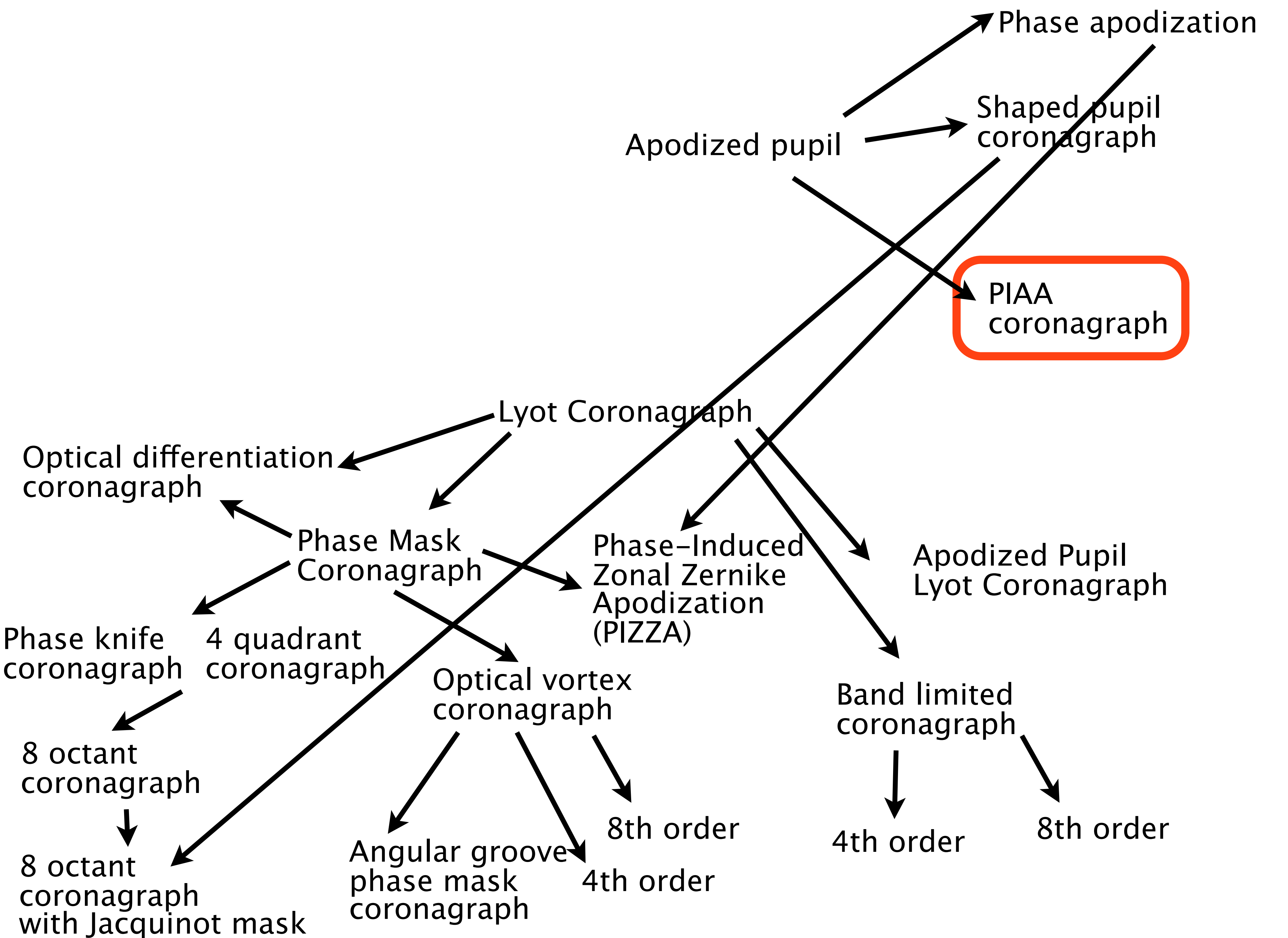
8 octant coronagraph with Jacquinot mask
Angular groove phase mask coronagraph
8th order
4th order
4th order
8th order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Lyot Coronagraph
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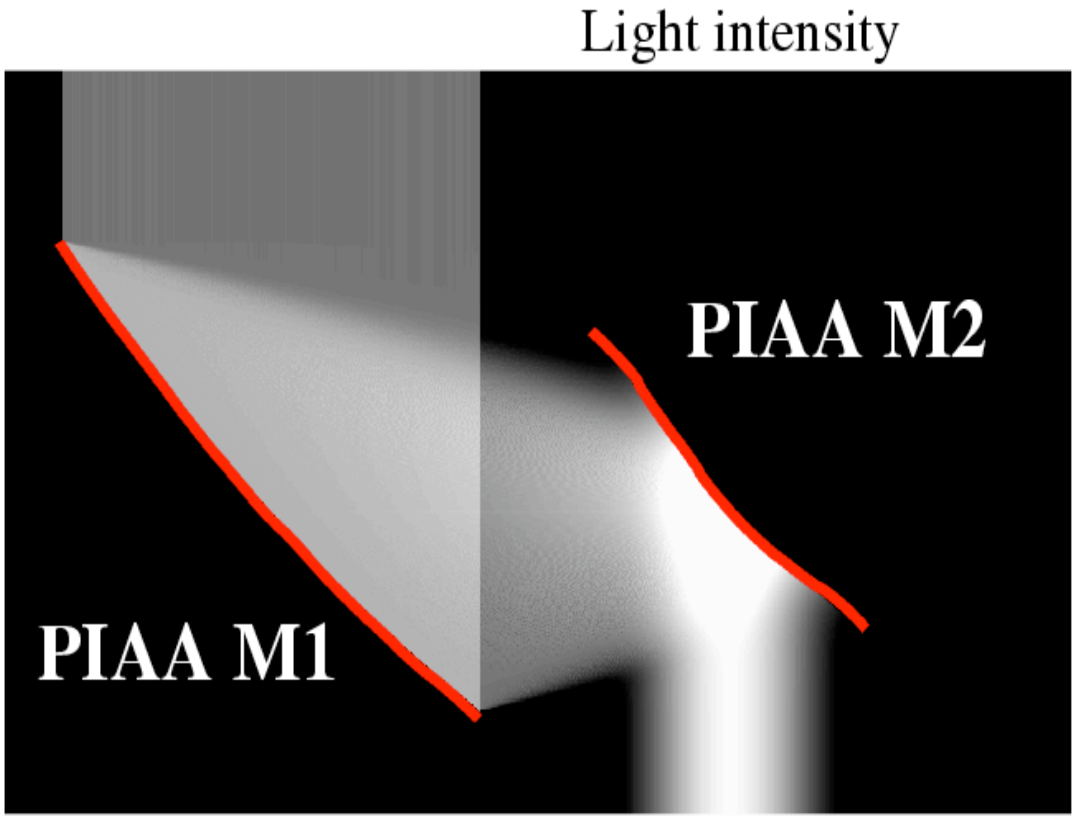
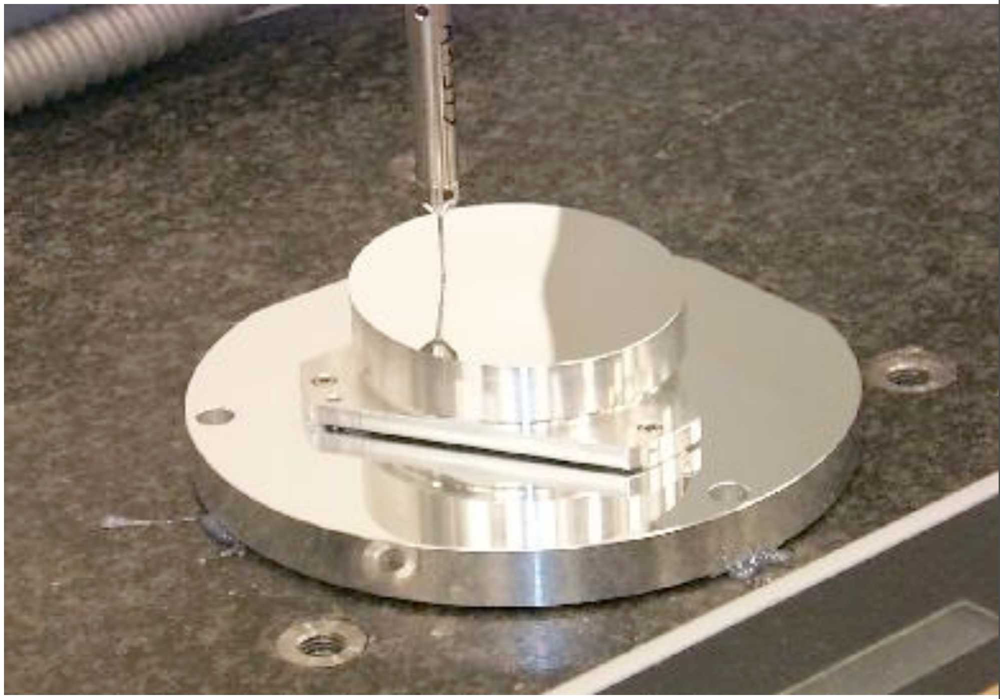
Angular groove phase mask coronagraph
8th order
4th order
4th order
8th order

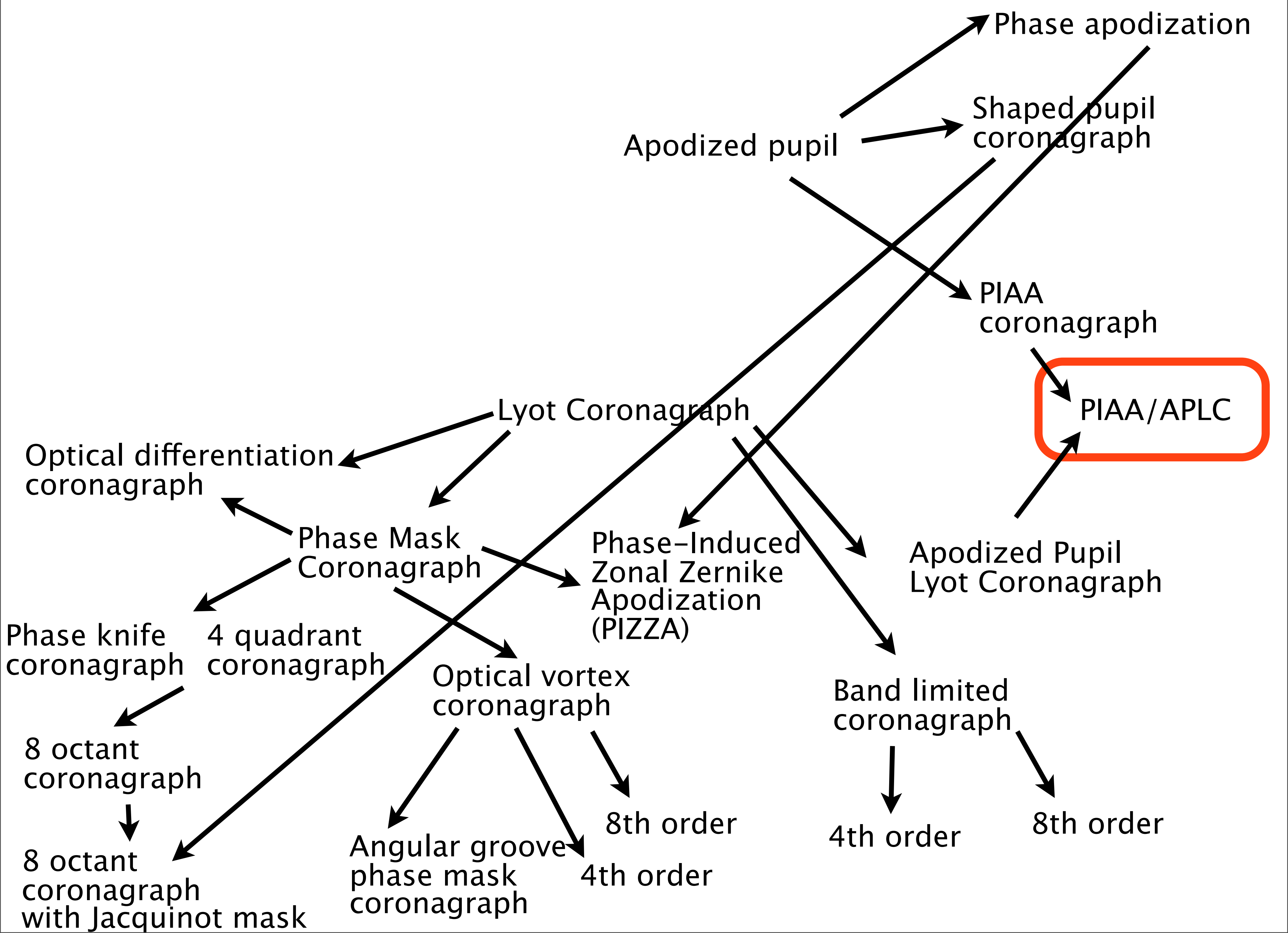
Phase-Induced Amplitude Apodization Coronagraph (PIAAC)

Lossless apodization by aspheric optics.





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



Phase apodization
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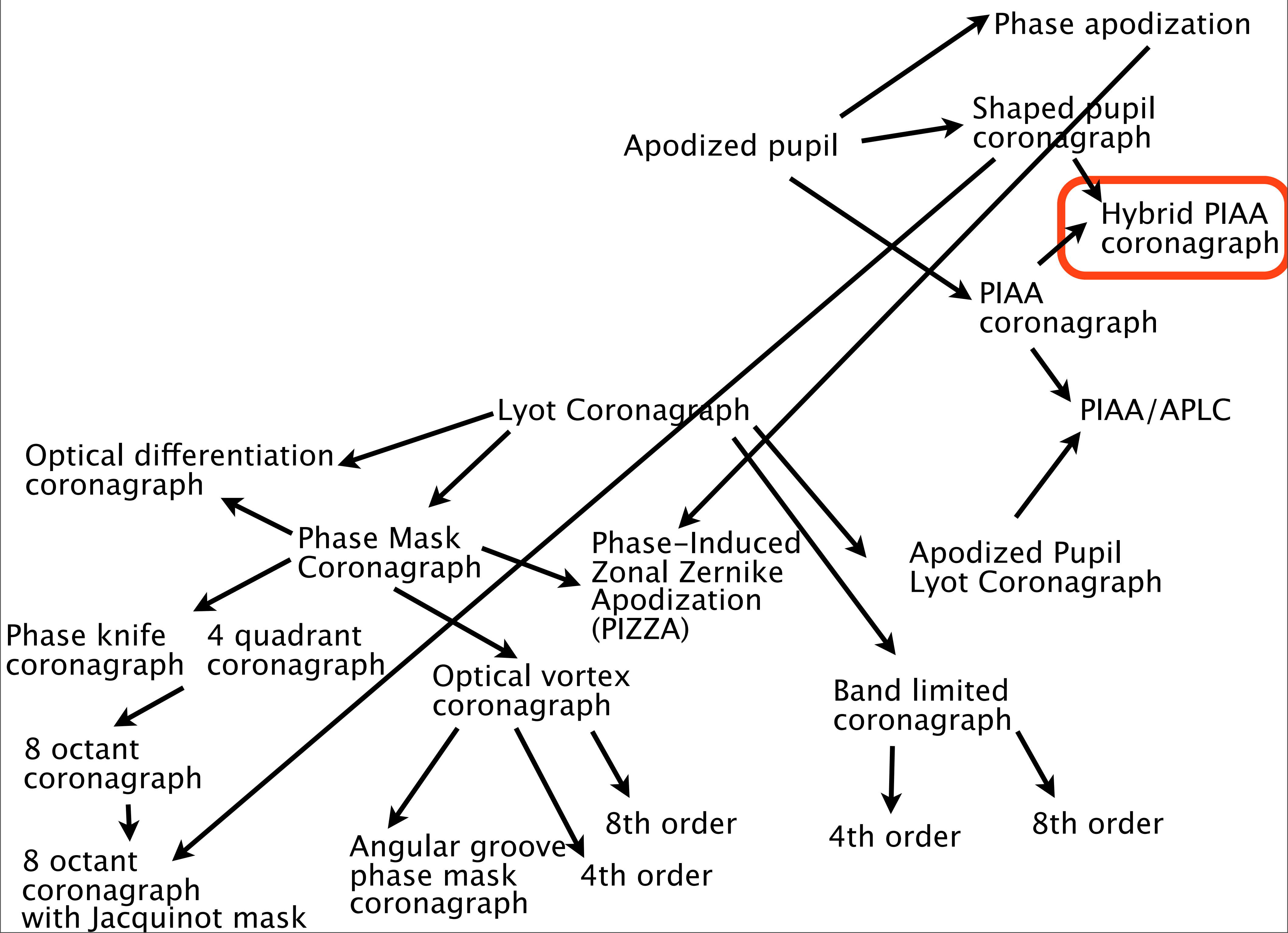
8th order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coronagraph
Apodized pupil
Hybrid PIAA
coronagraph
PIAA
coronagraph
PIAA/APLC
Lyot Coronagraph
Optical differentiation
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Zonal Zernike
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4 quadrant
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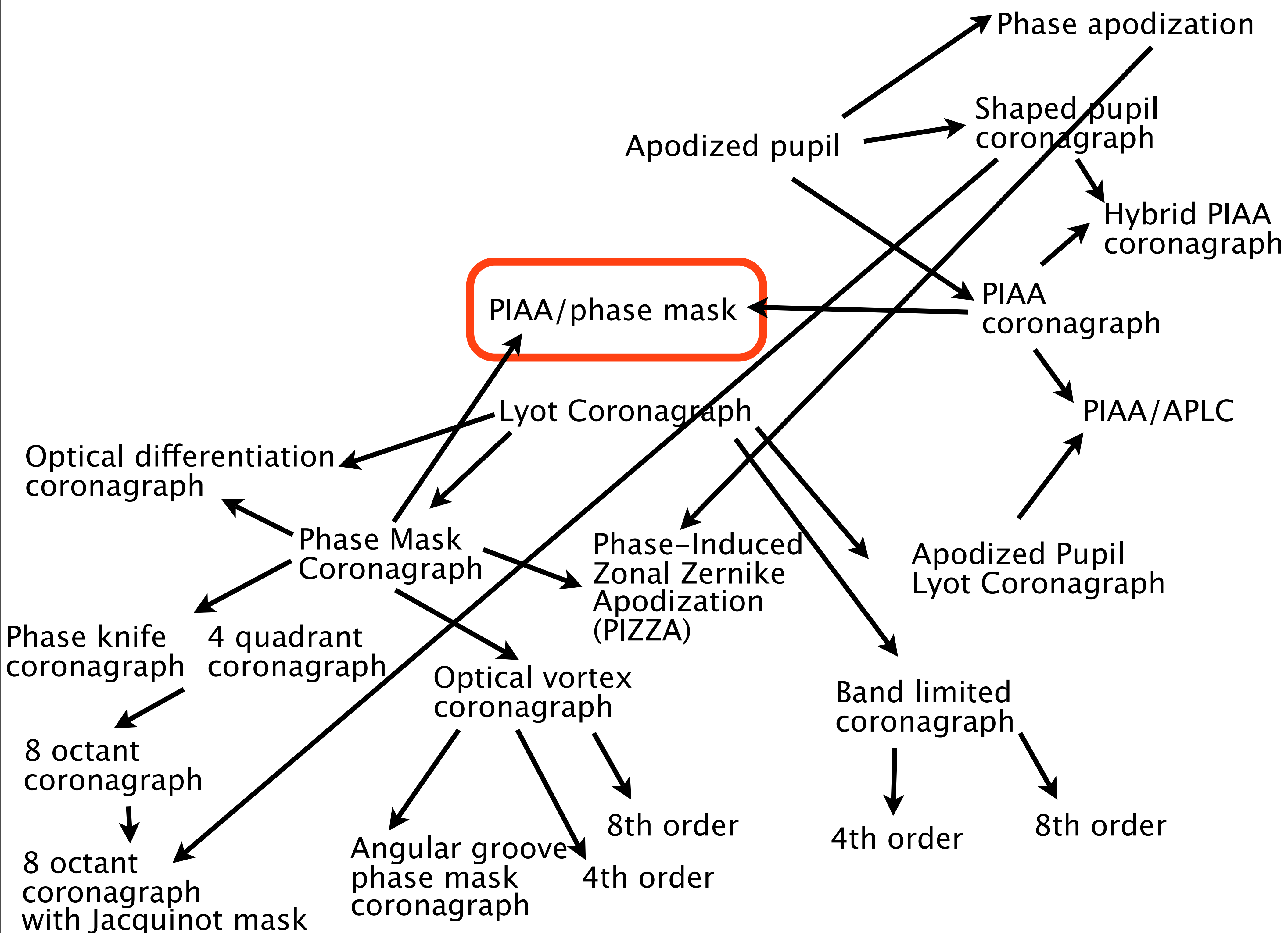
coronagraph
with Jacquinot mask



Phase apodization
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8th order
4th order
8th order
Angular groove phase mask coronagraph
4th order
8 octant coronagraph with Jacquinot mask

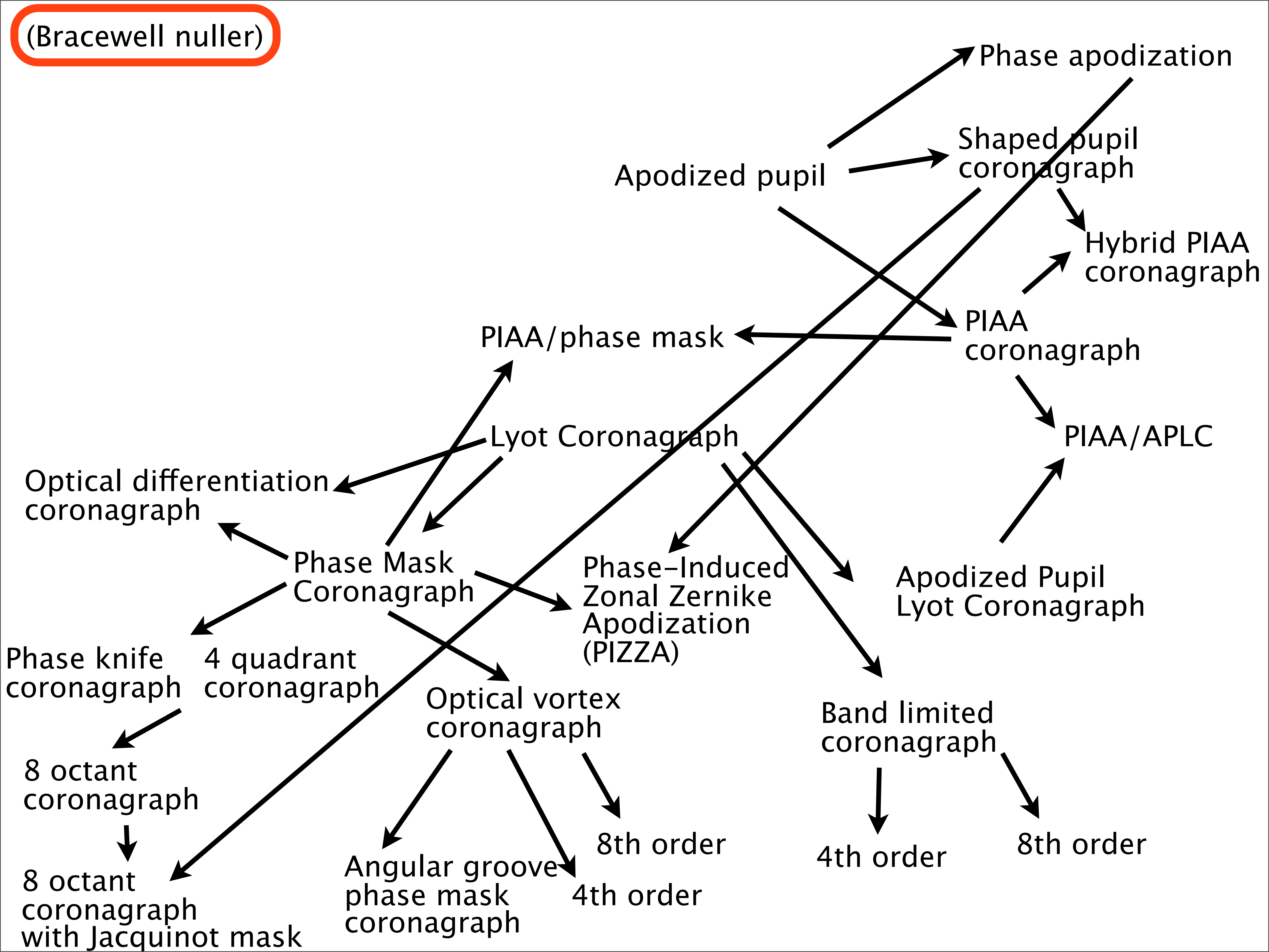
"Interferometric" coronagraphs

= 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



(Bracewell nuller)
Phase apodization
Apodized pupil
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PIAA coronagraph
PIAA/phase mask
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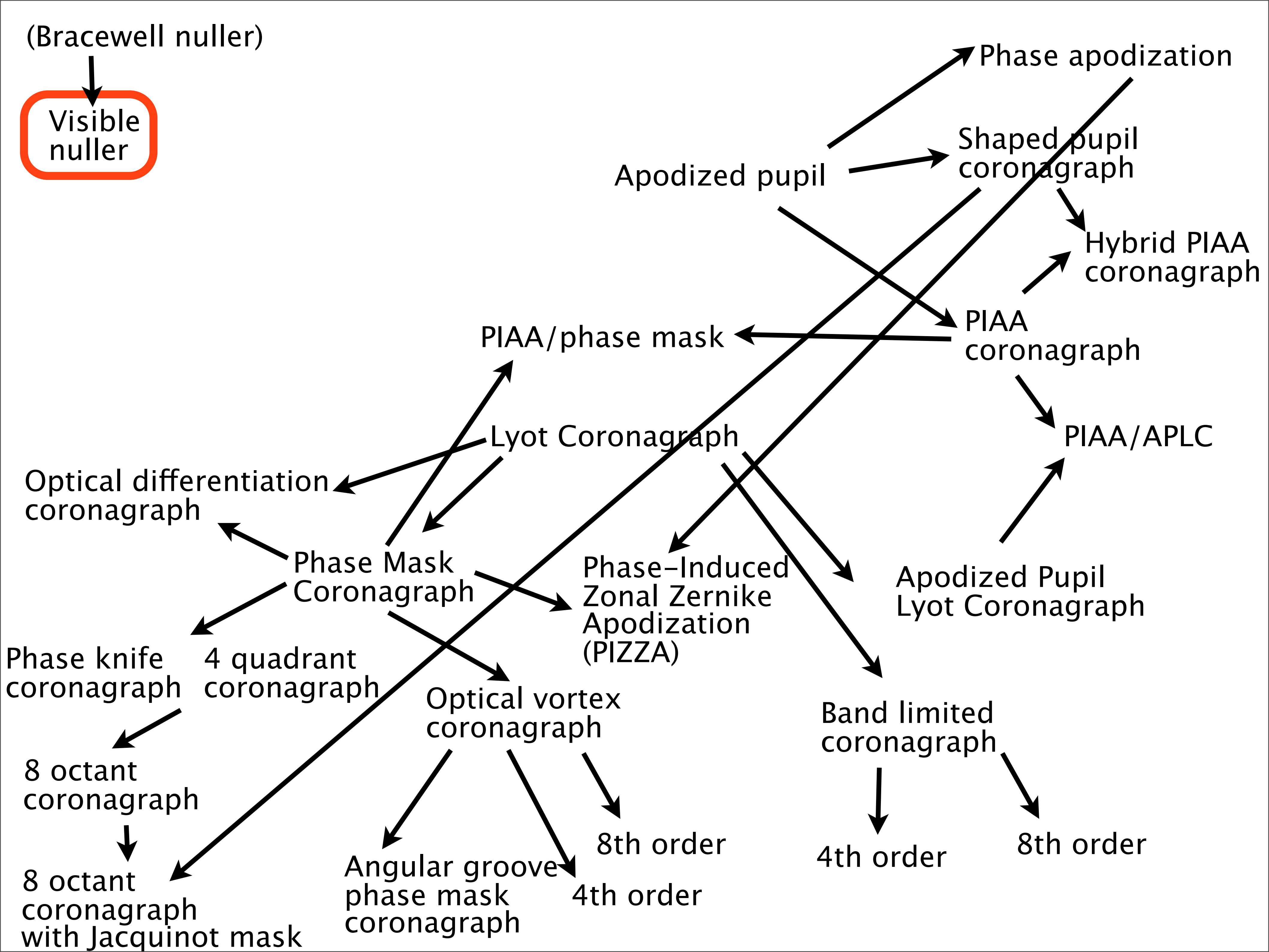

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Visible nuller
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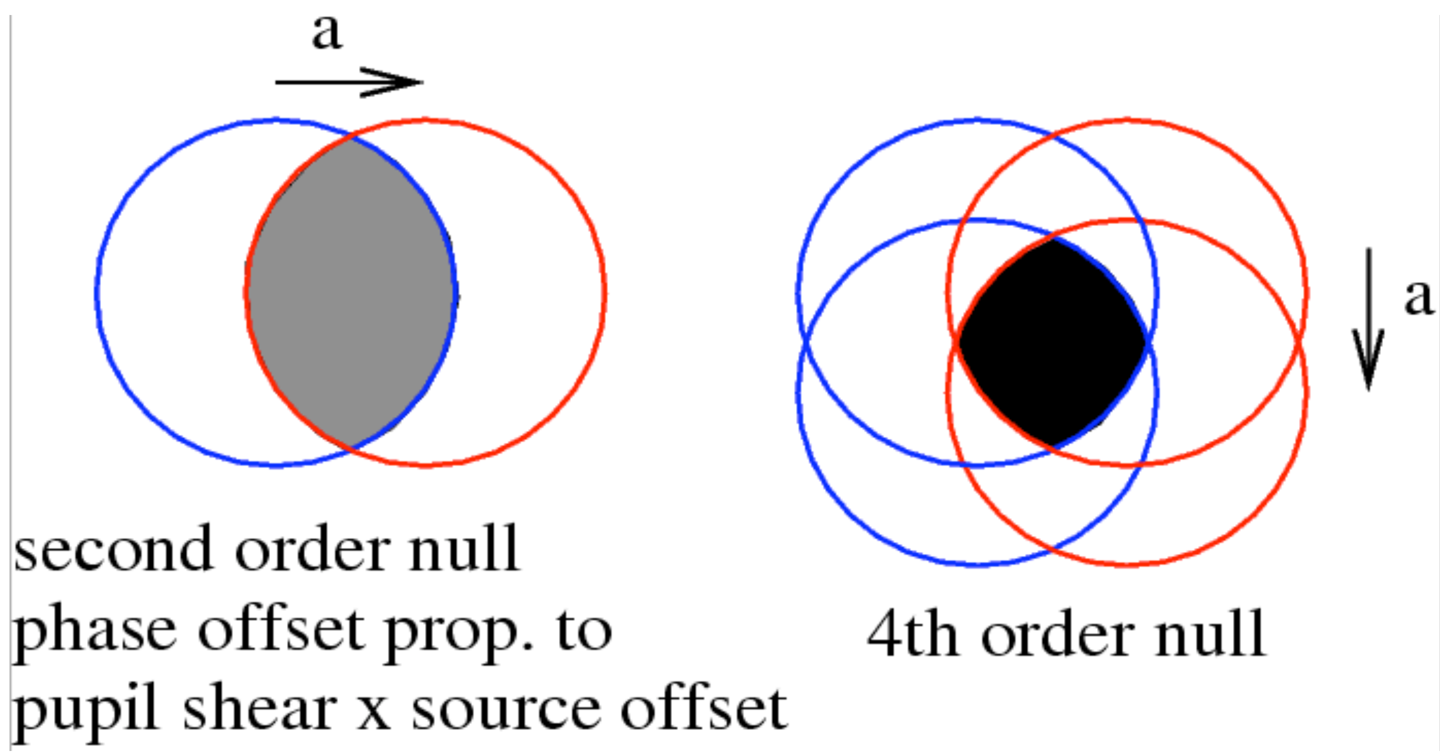
8th order
4th order
4th order
8th order

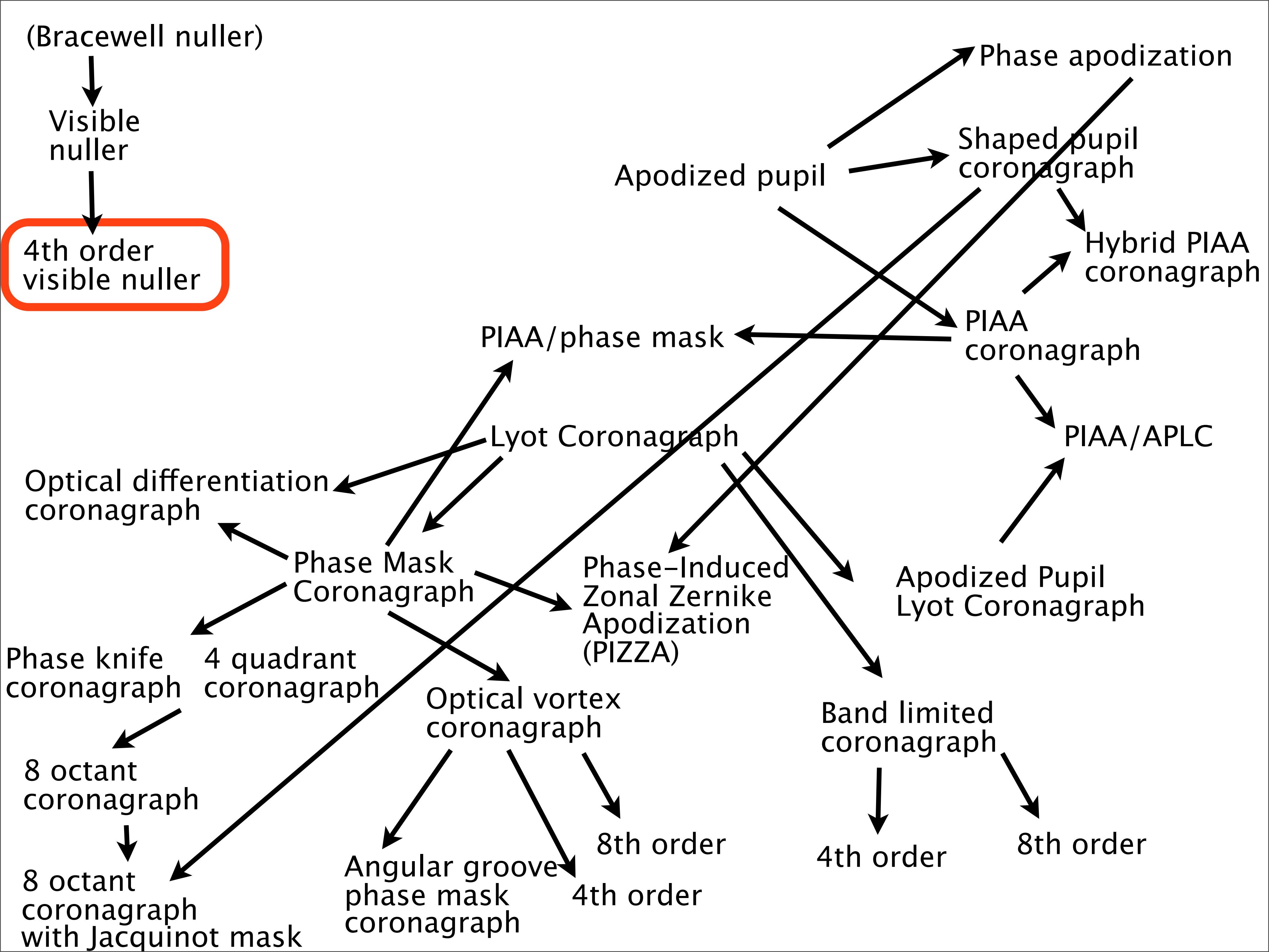
Visible Nuller Coron. (VNC)



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


(Bracewell nuller)
Visible nuller
4th order visible nuller
Phase apodization
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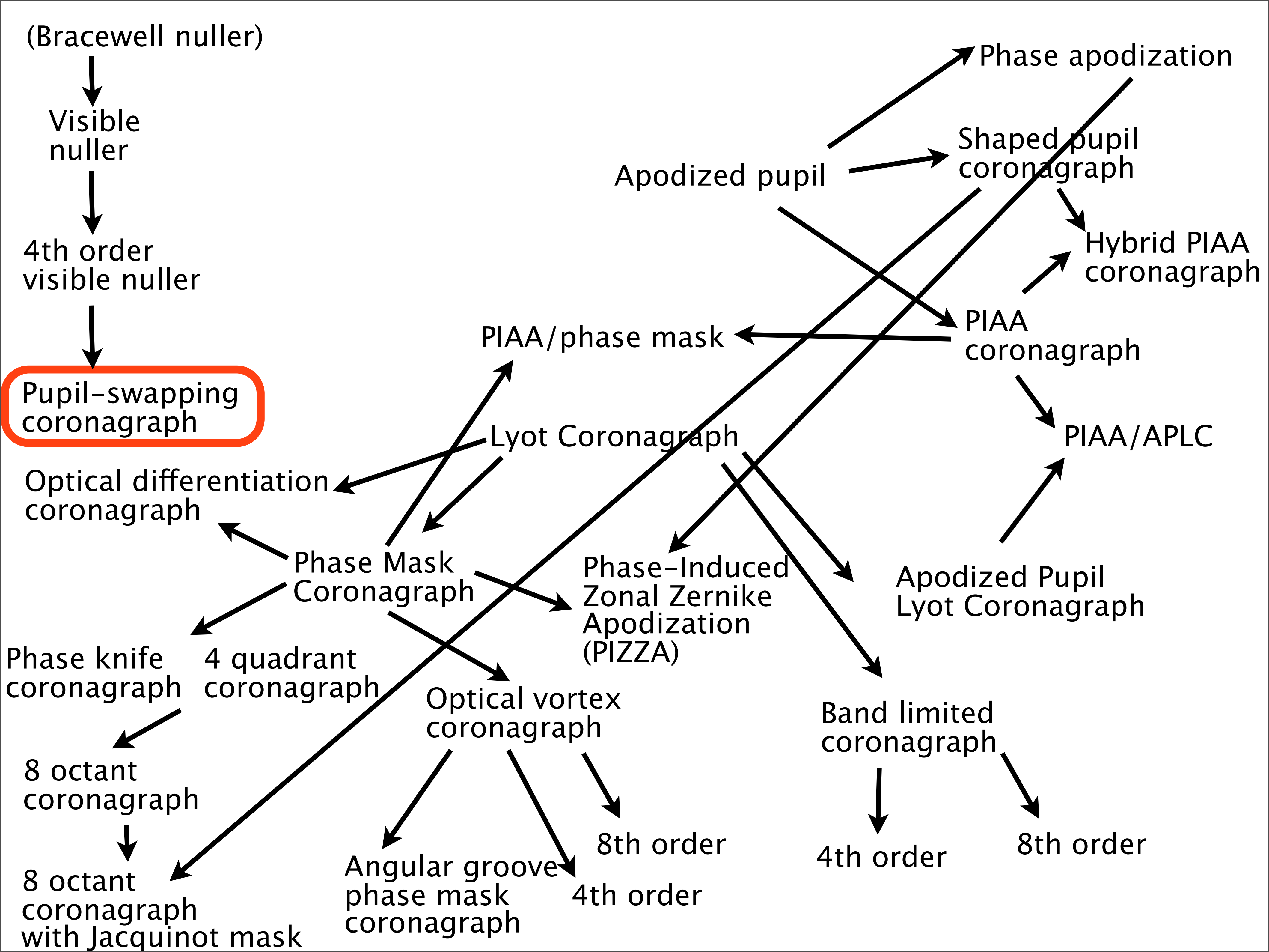
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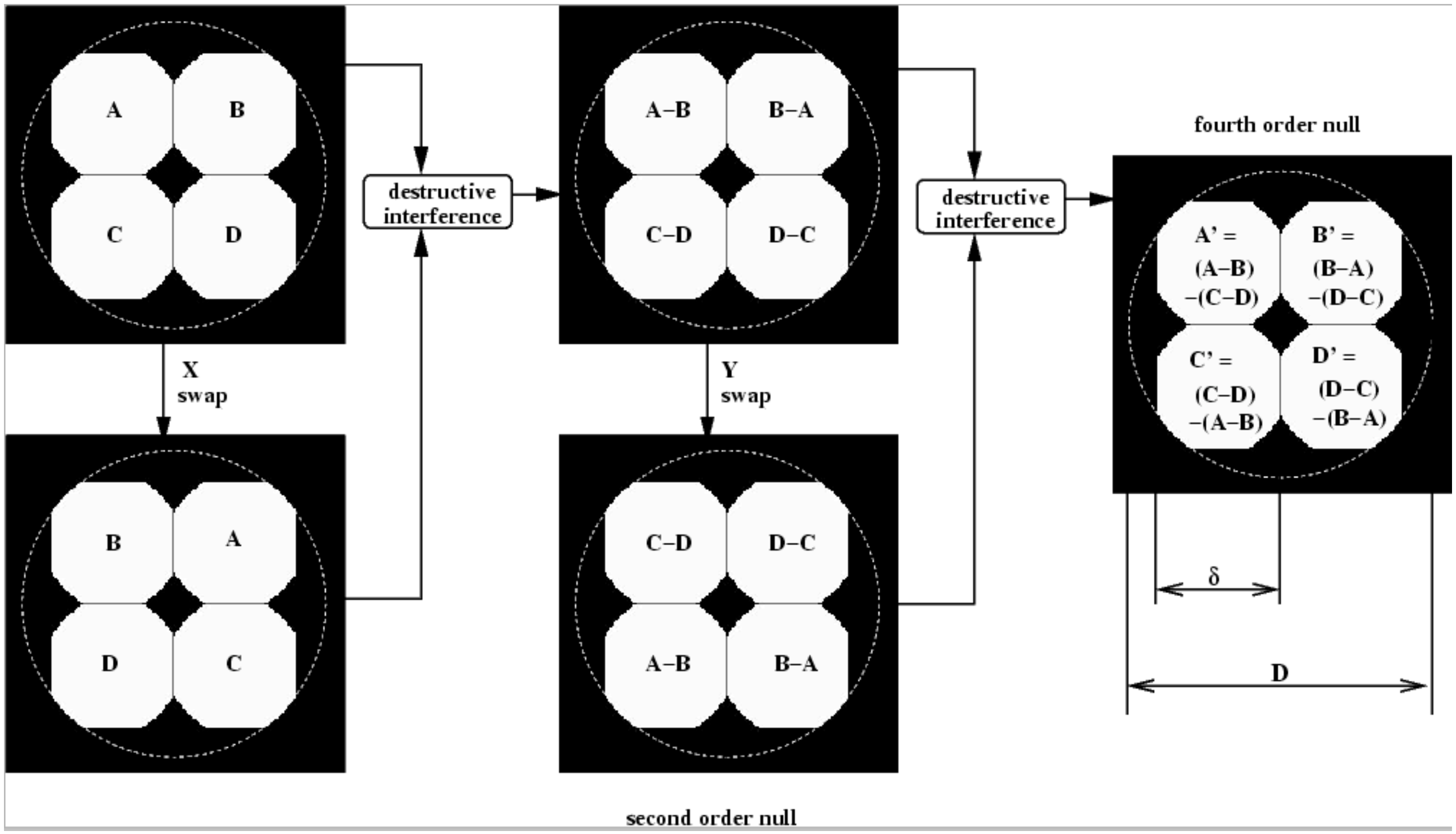
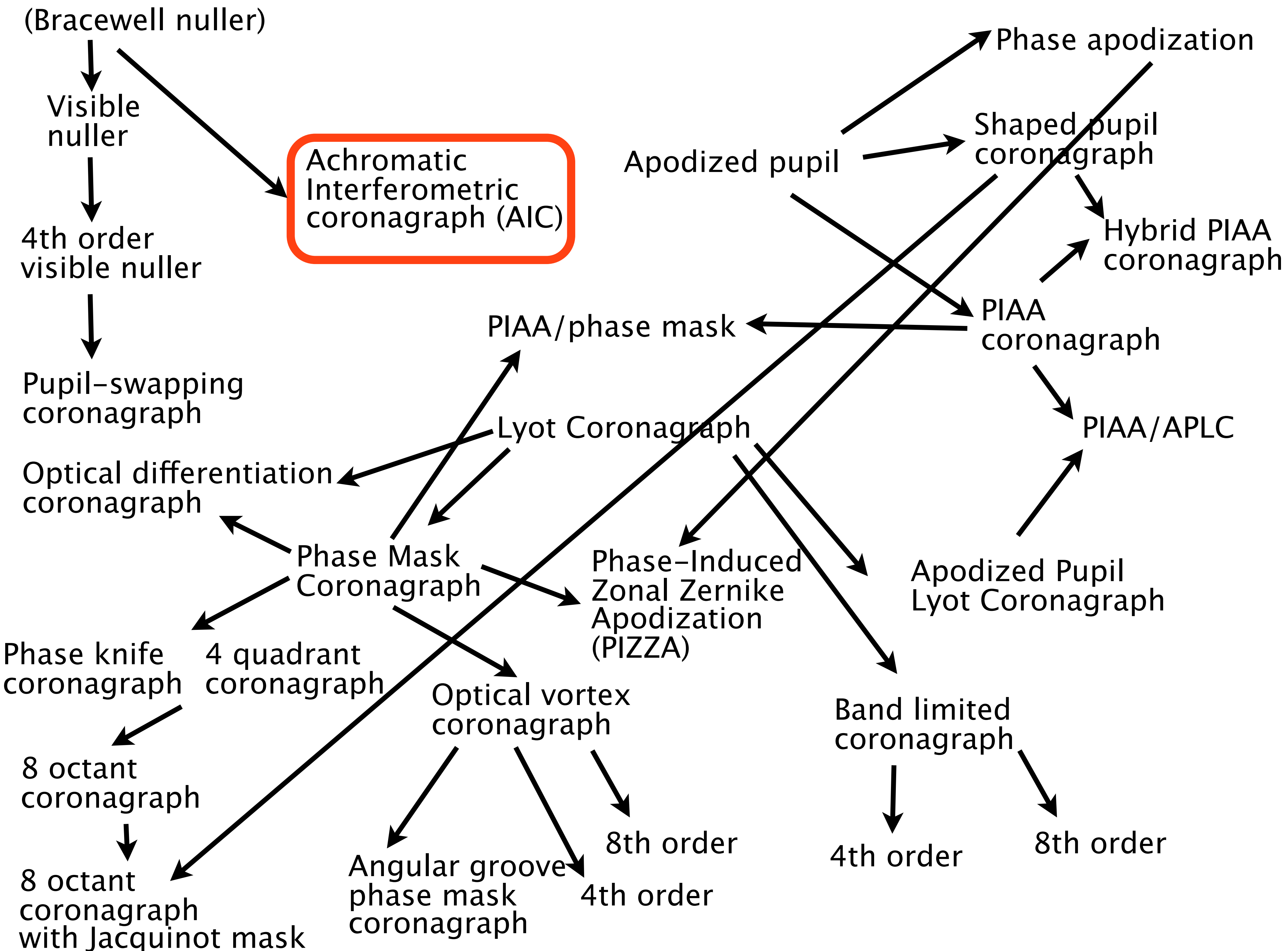
Pupil Swapping Coronagraph (PSC)



Same basic principle as VNC, higher throughput

Guyon & Shao, 2006, PASP


(Bracewell nuller)
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Pupil-swapping coronagraph
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8th order
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Achromatic Interferometric Coronagraph (AIC)

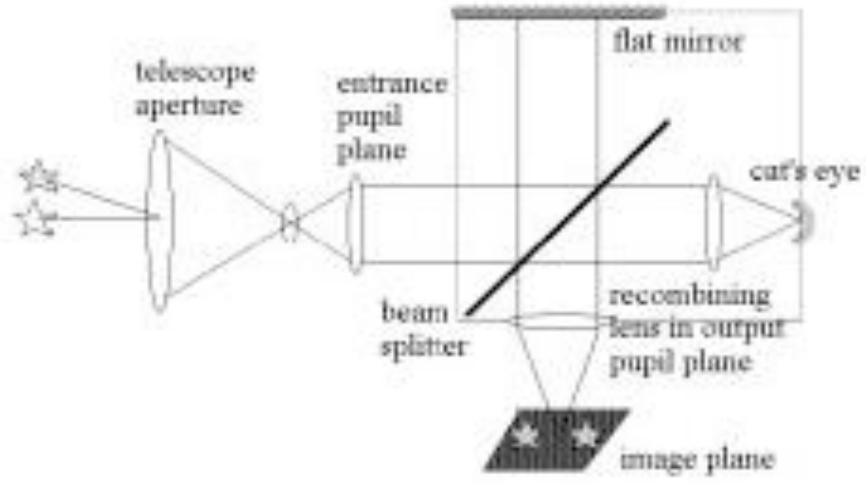


Fig. 1. Schematic of the Generic Set-up of our coronagraph

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

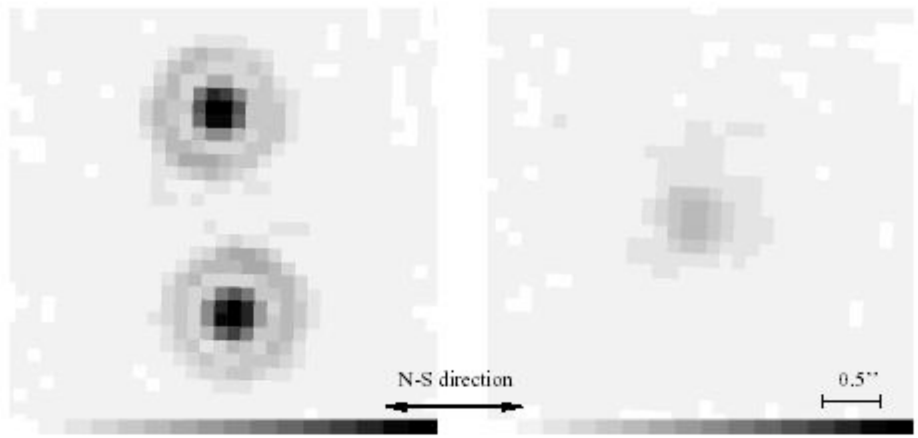
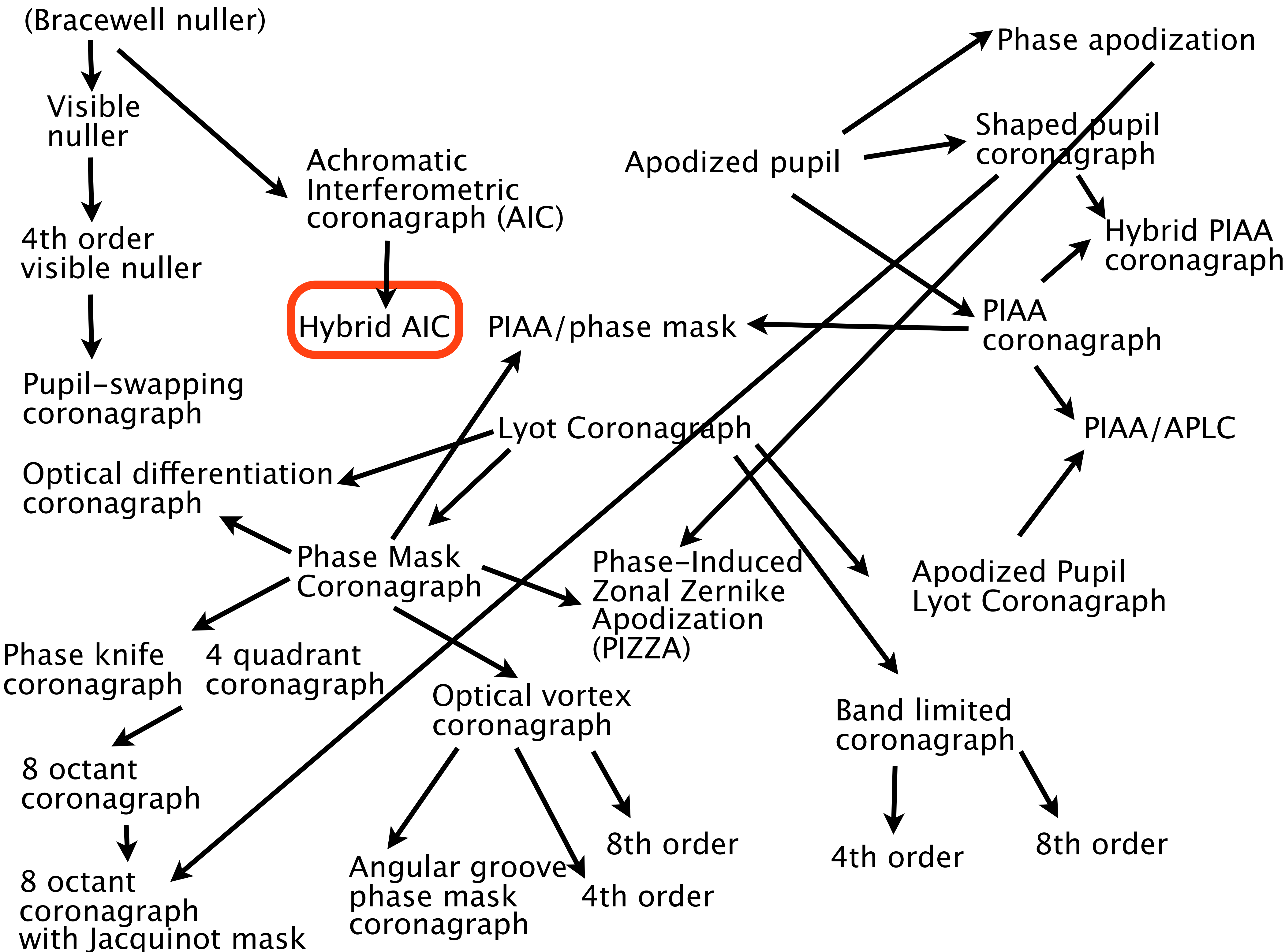


Fig. 3. Image of a star off-axis and on-axis. The scale is linear and is the same for the 2 images

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)
Visible nuller
4th order visible nuller
Pupil-swapping coronagraph
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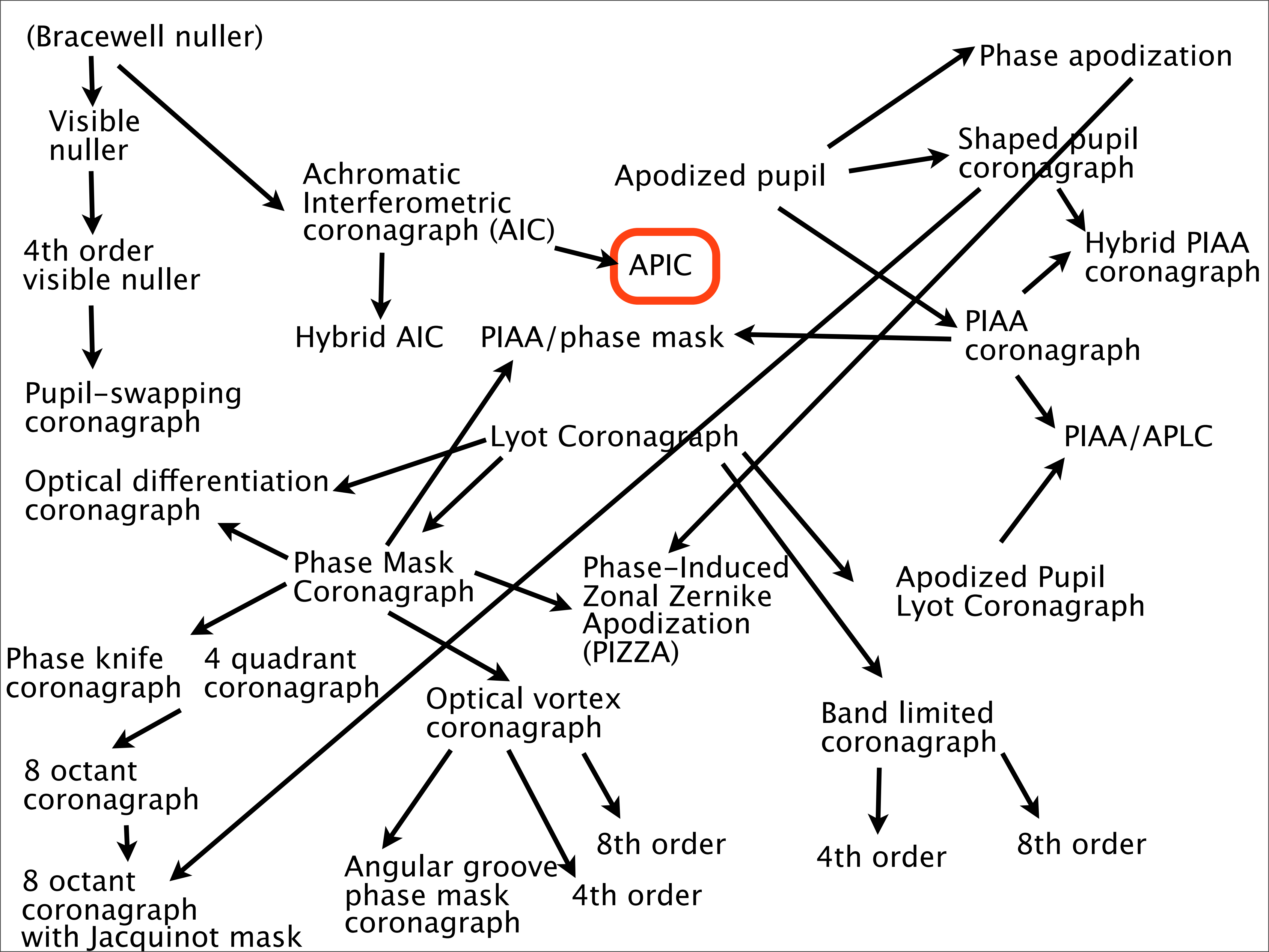
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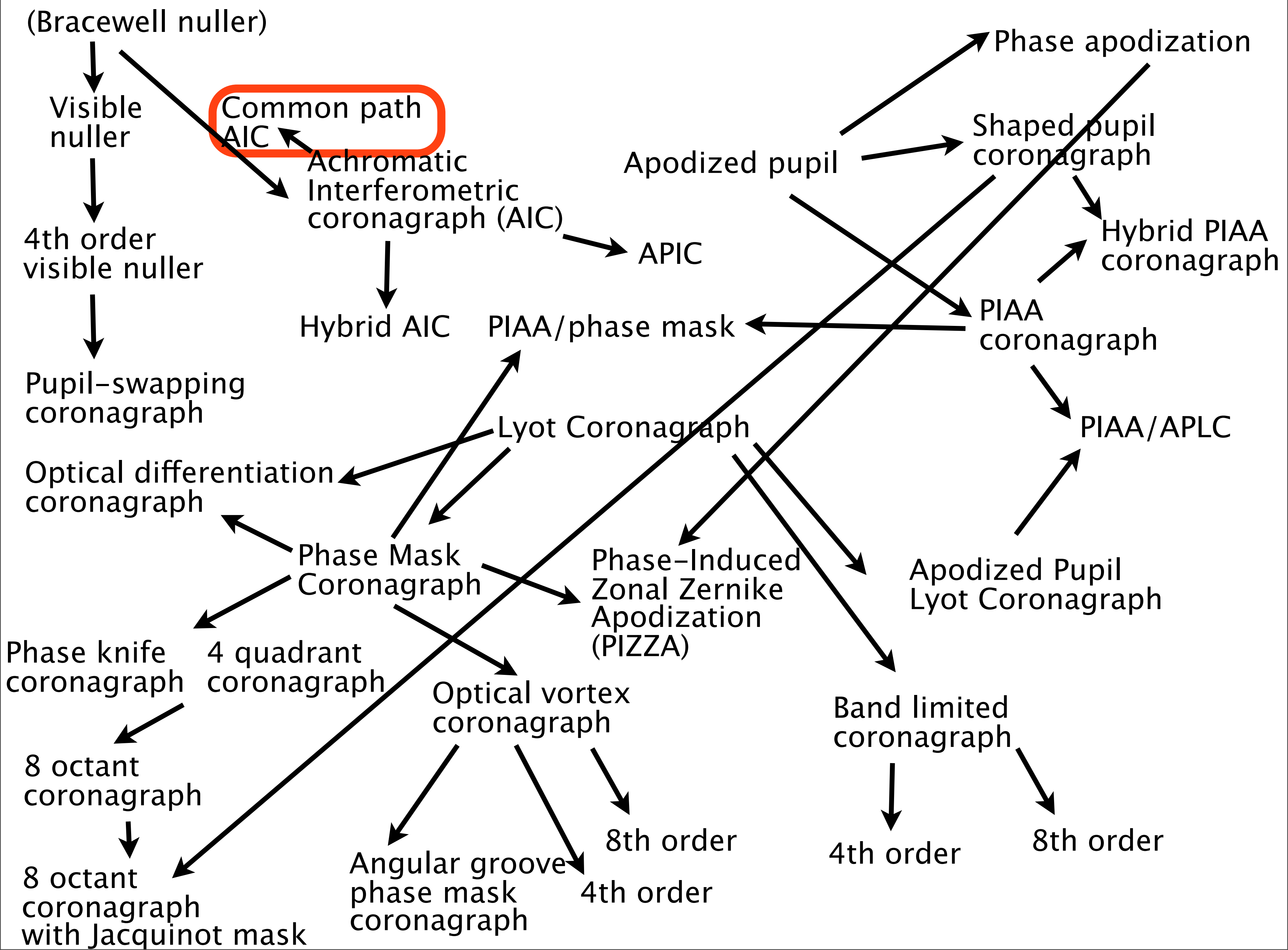

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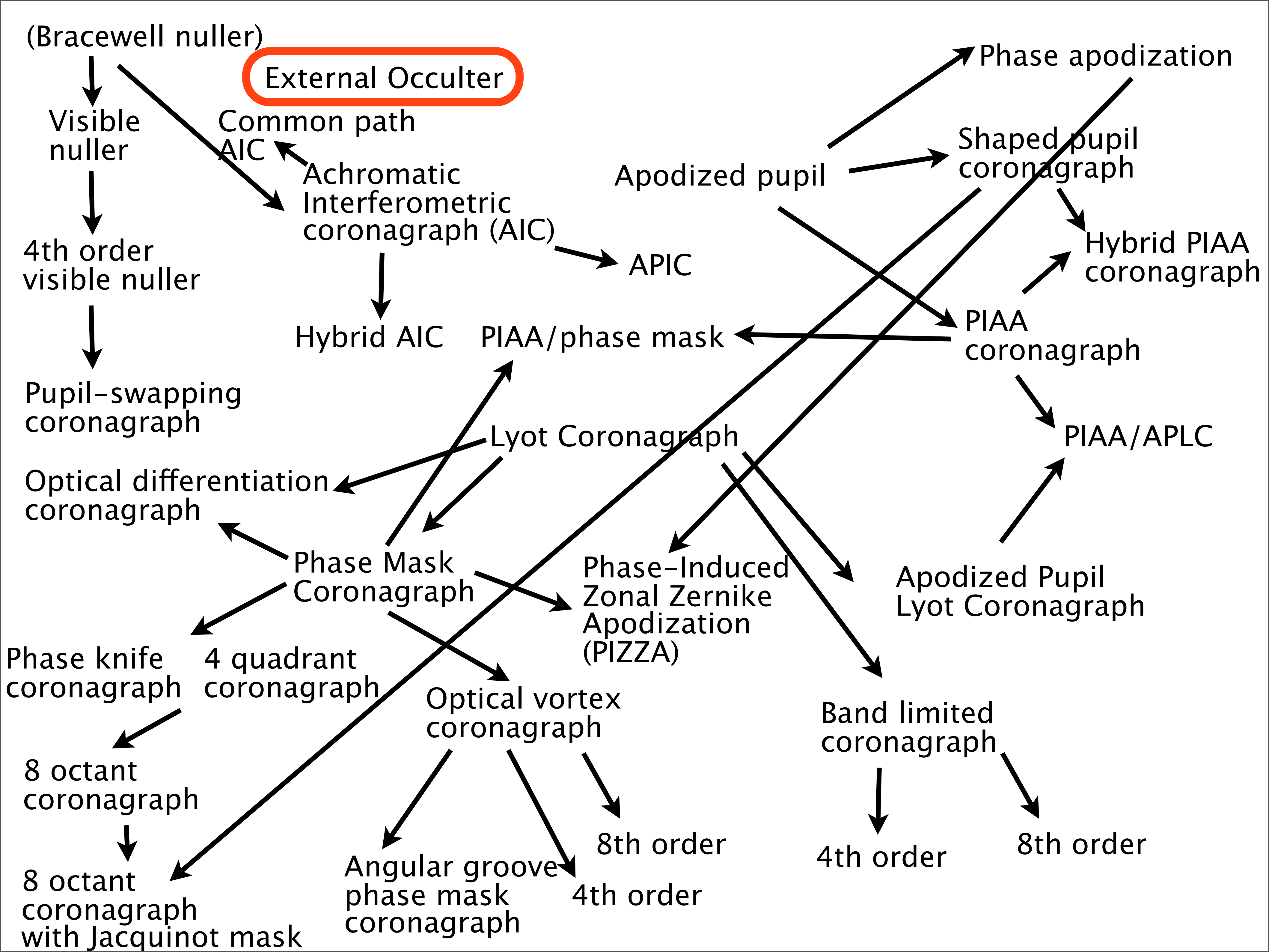
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External Occulter
Visible nuller
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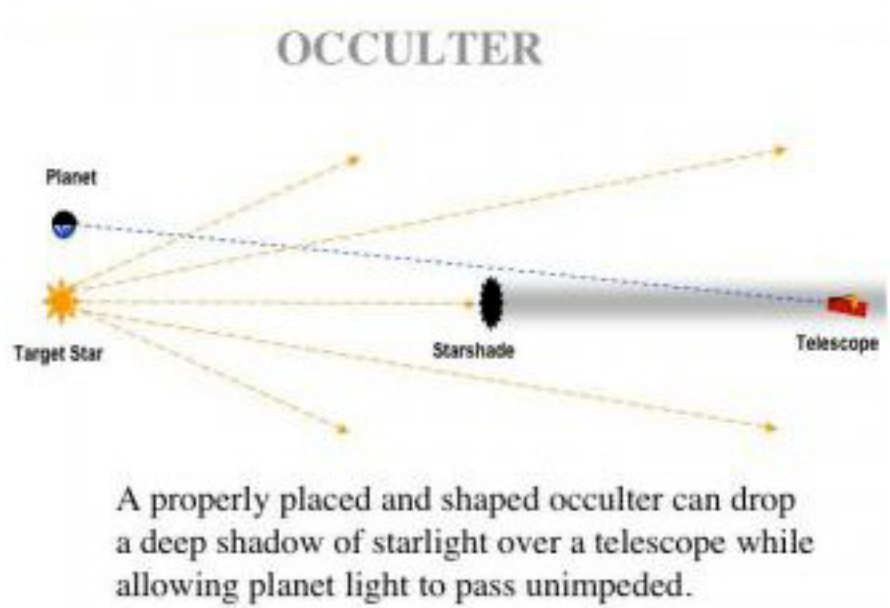
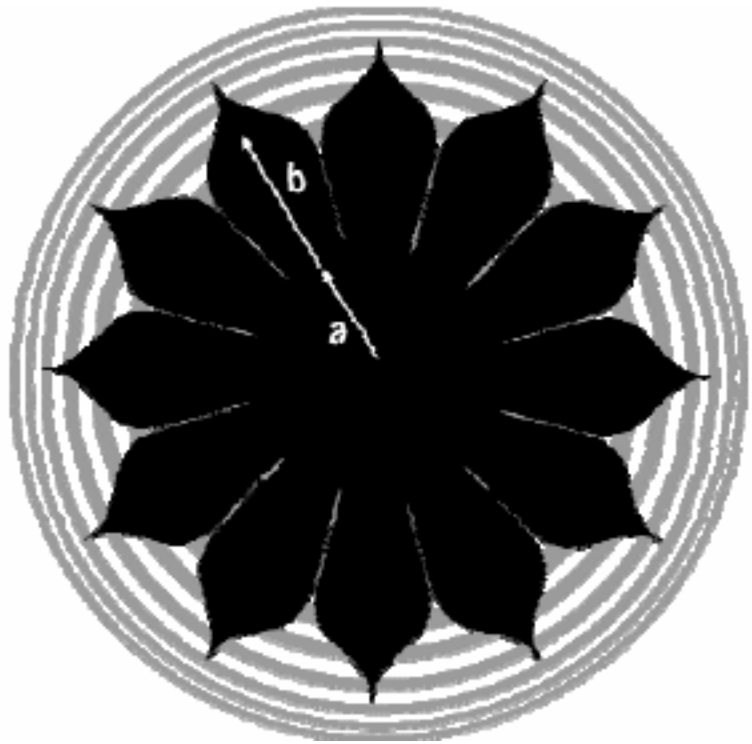
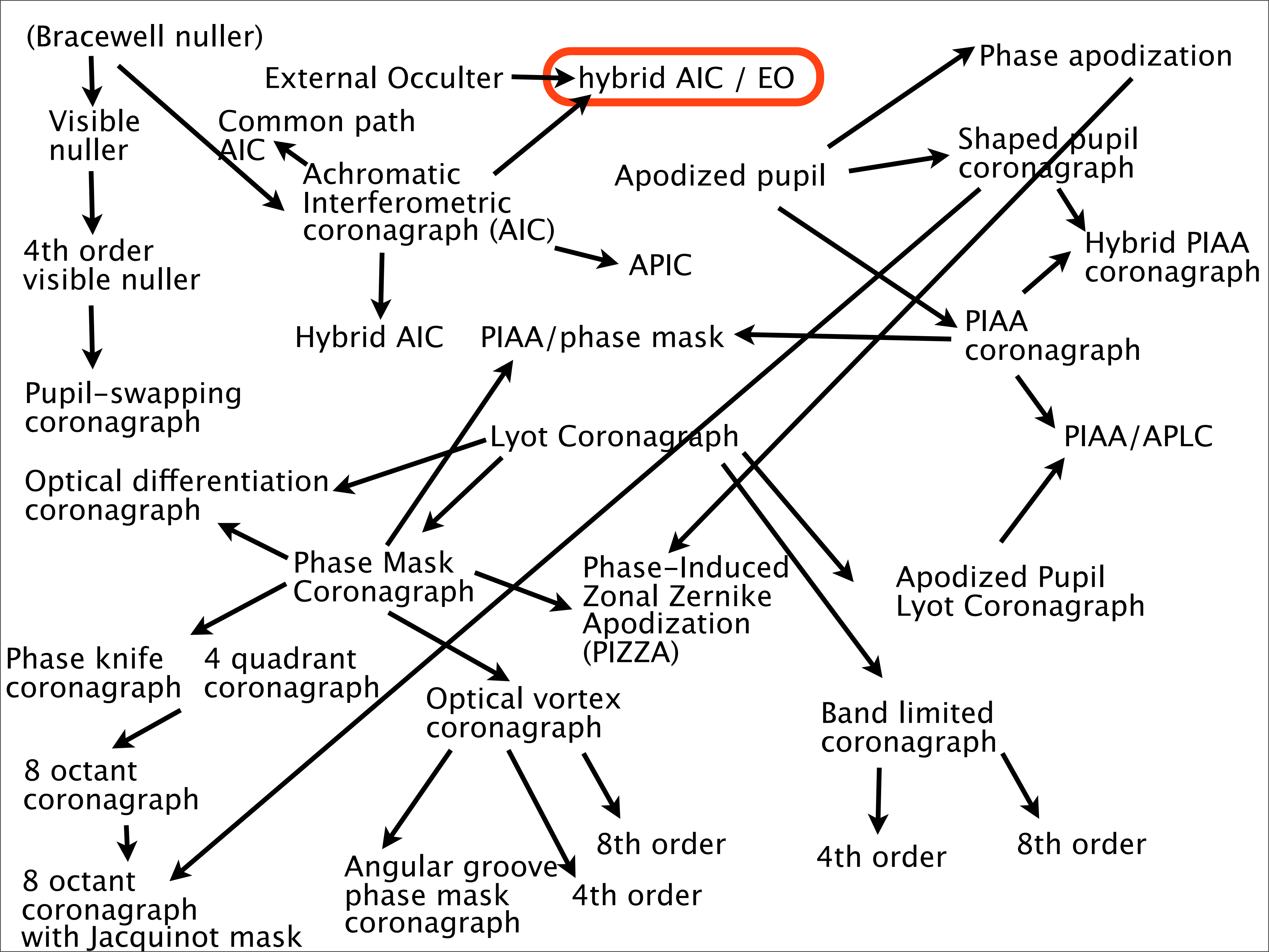
External Occulter






(Bracewell nuller)
External Occulter
hybrid AIC / EO
Phase apodization
Visible nuller
Common path AIC
Achromatic Interferometric coronagraph (AIC)
Apodized pupil
Shaped pupil coronagraph
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APIC
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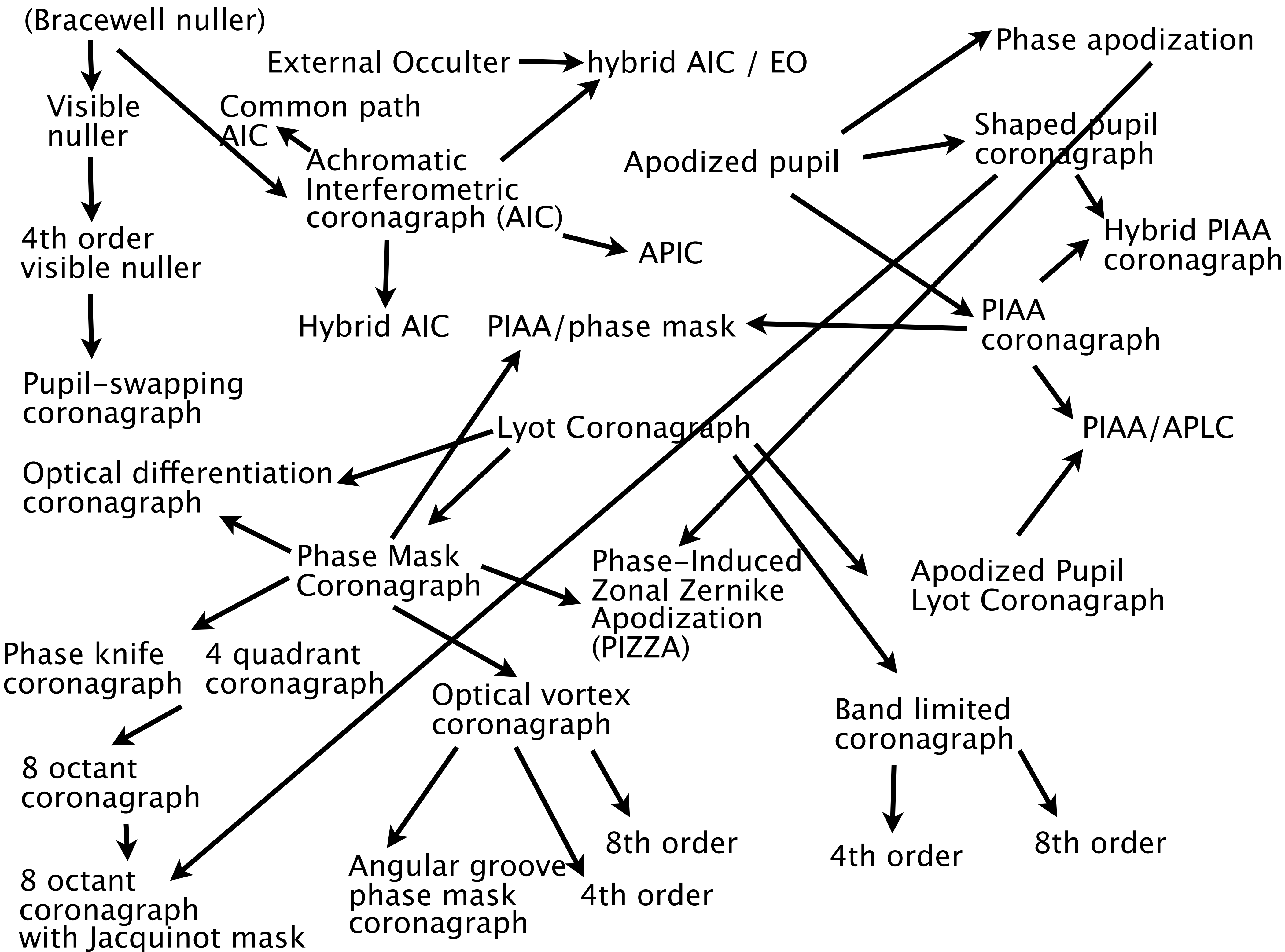
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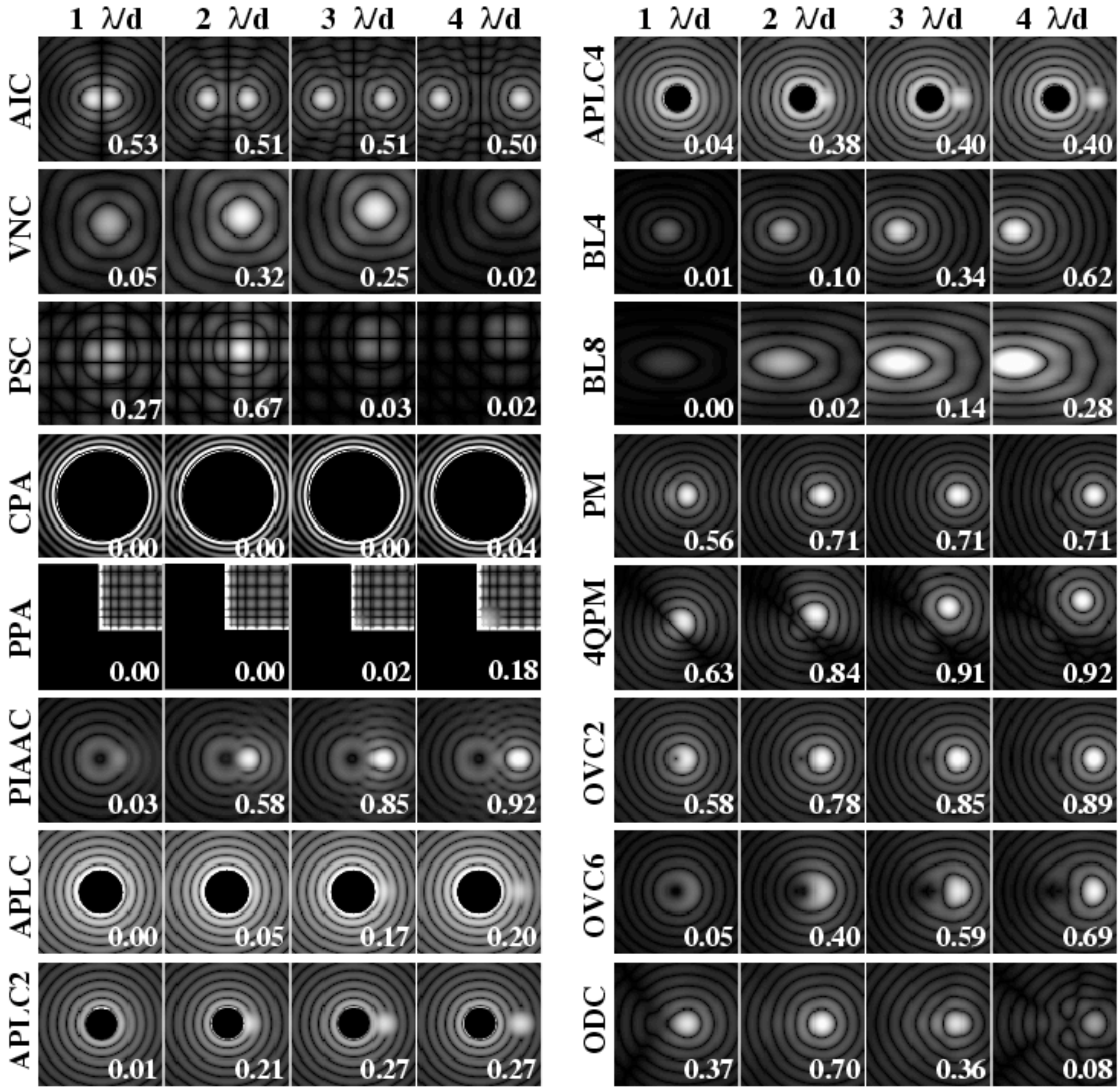
Coronagraph Performance

Every coronagraph in the previous chart except the classical Lyot can theoretically deliver 1e10 contrast at 4 l/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 ?



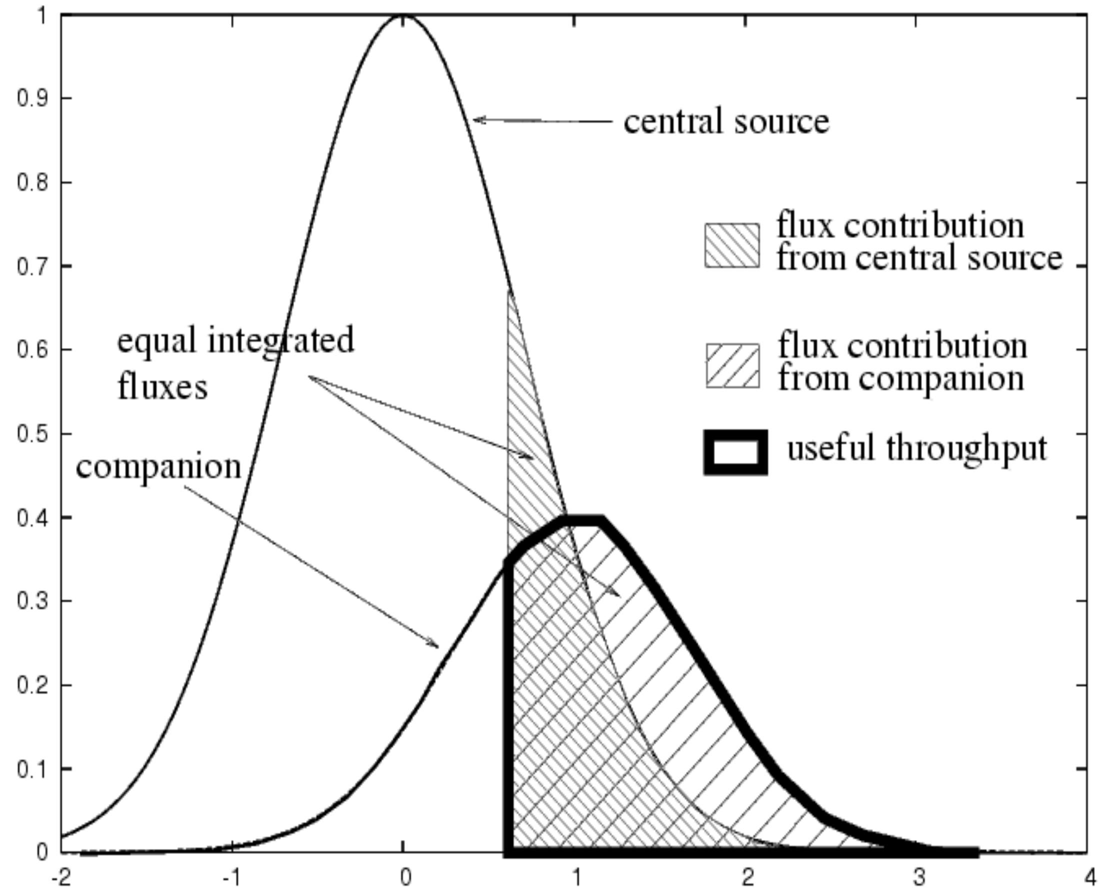
1 λ/d
2 λ/d
3 λ/d
4 λ/d
AIC 0.53 0.51 0.51 0.50
VNC 0.05 0.32 0.25 0.02
PSC 0.27 0.67 0.03 0.02
CPA 0.00 0.00 0.00 0.04
PPA 0.00 0.00 0.02 0.18
PIAAC 0.03 0.58 0.85 0.92
APLC 0.00 0.05 0.17 0.20
APLC2 0.01 0.21 0.27 0.27
APLC4 0.04 0.38 0.40 0.40
BL4 0.01 0.10 0.34 0.62
BL8 0.00 0.02 0.14 0.28
PM 0.56 0.71 0.71 0.71
4QPM 0.63 0.84 0.91 0.92
OVC2 0.58 0.78 0.85 0.89
OVC6 0.05 0.40 0.59 0.69
ODC 0.37 0.70 0.36 0.08

Useful throughput as a metric independent of coronagraph design

Commonly used metrics: **IWA, throughput, discovery space**

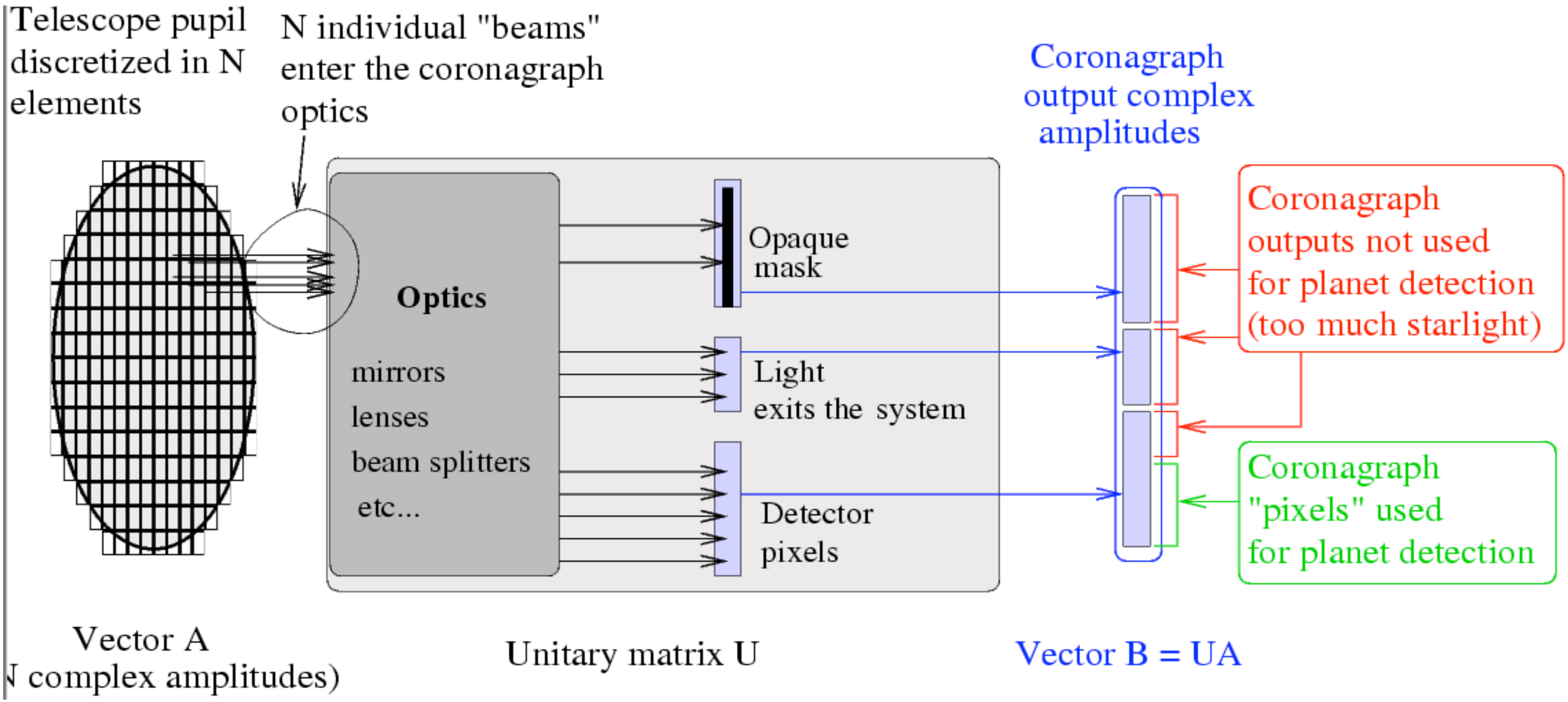
Useful throughput

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 independant 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

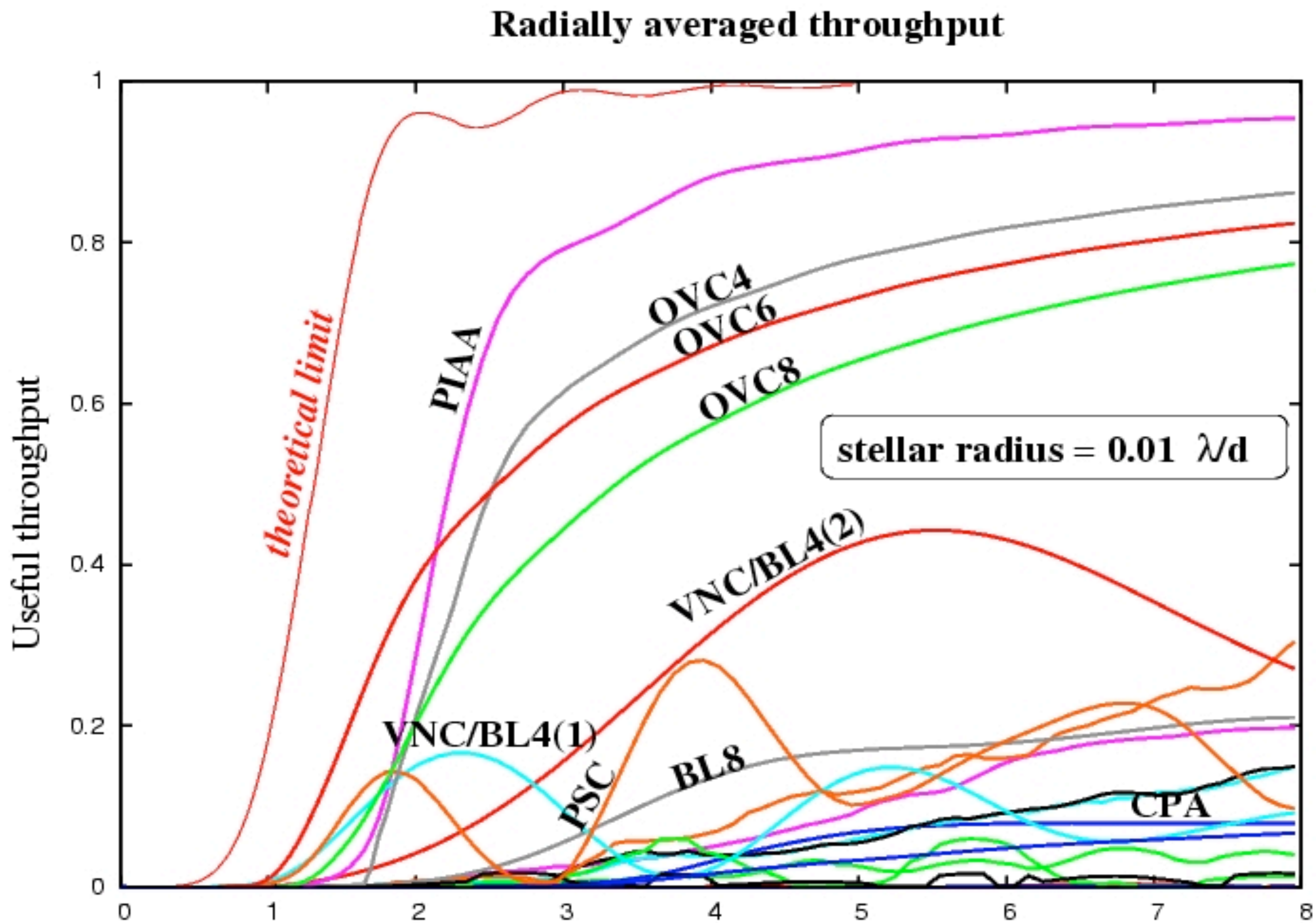
What is the vector C that maximizes C.A(planet) but keeps C.A(star position) < C.A(planet position)*sqrt(1e-10) ?

Fundamental physics tells us limits of coronagraphy

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

Problem: stars are not points !
Sun diameter ~1% of 1 AU
If 1AU=2 l/d, Stellar radius ~ 0.01 l/d

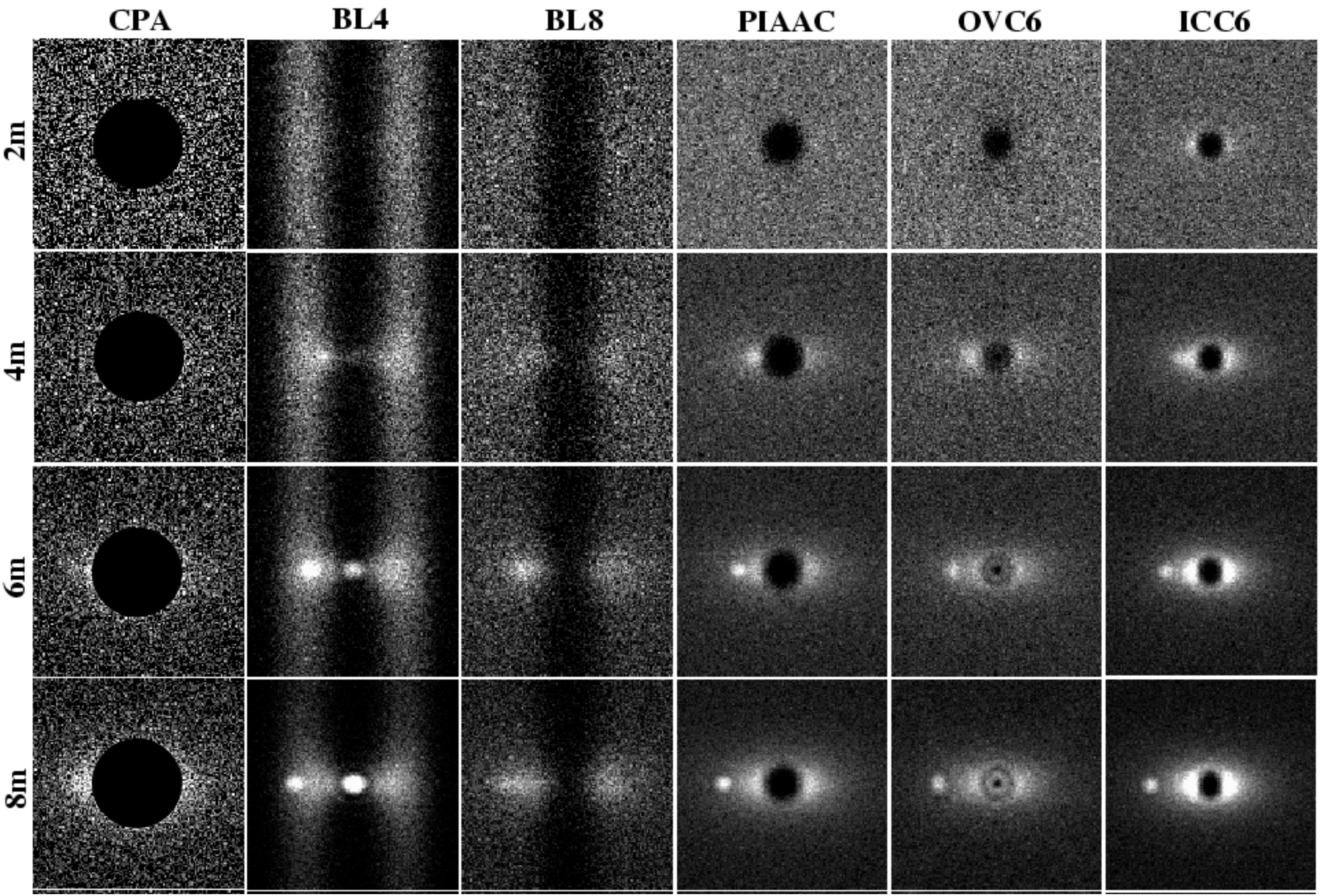
<u>Wavefront control cannot solve it</u>



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 20x20 lambda/d



CPA
BL4
BL8
PIAAC
OVC6
ICC6
2m
4m
6m
8m

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

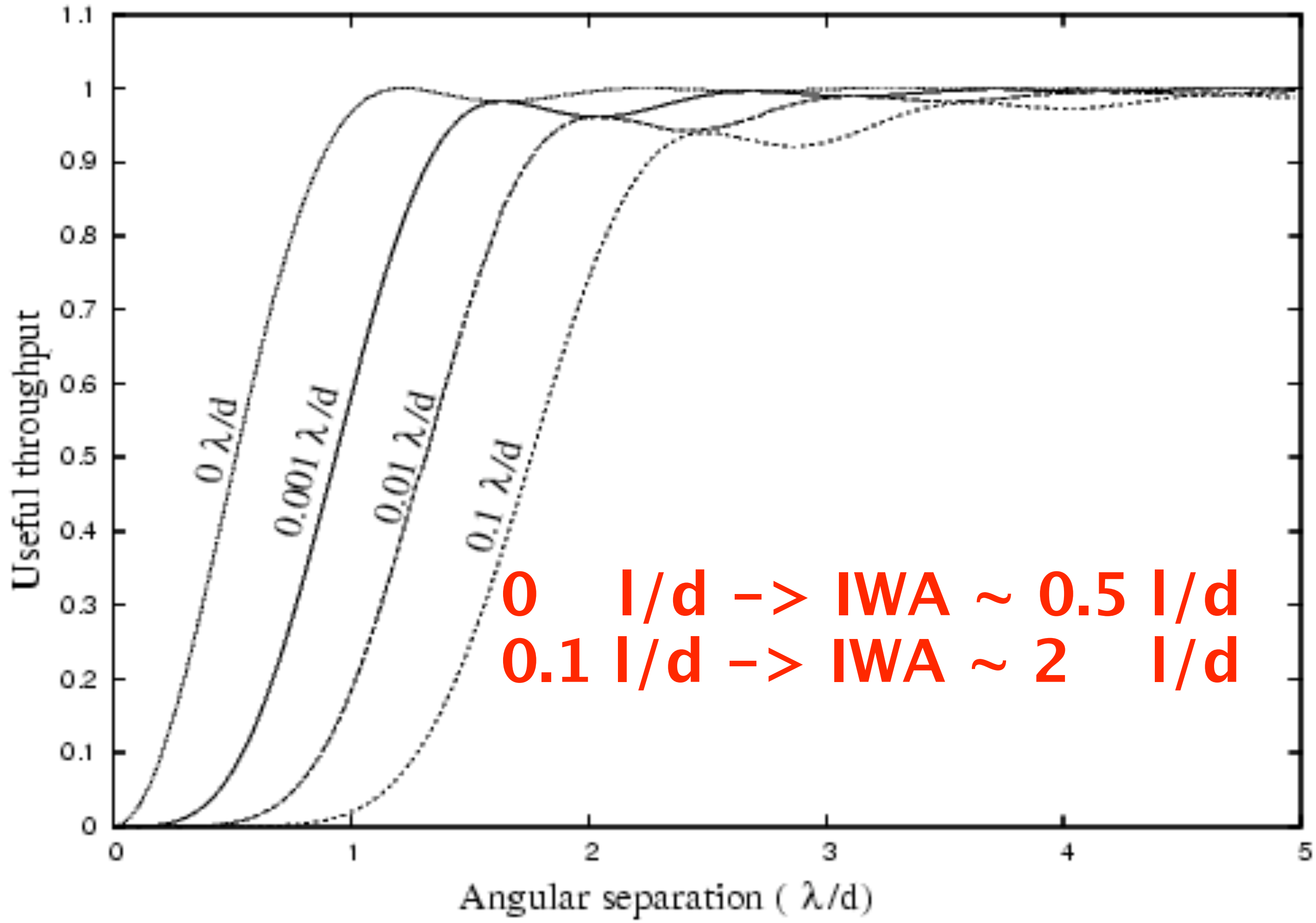


Fig. 5.— Upper limit on the off-axis throughput of a coronagraph for different stellar radii.

Pointing control demonstrated to 1e-3 l/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 l/D ~ 0.1 mas on 1.4m PECO.
ref: Guyon, Matsuo, Angel 2009

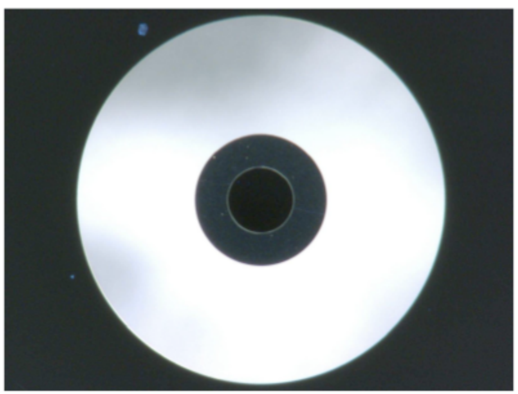


Fig. 9.— CLOWFS focal plane mask used in the PIAA coronagraph laboratory testbed at Subaru Telescope. The 100 micron radius mask center is opaque (low reflectivity), and is surrounded by a 100 micron wide highly reflective annulus. The science field, transmiting light to the science camera, extends from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

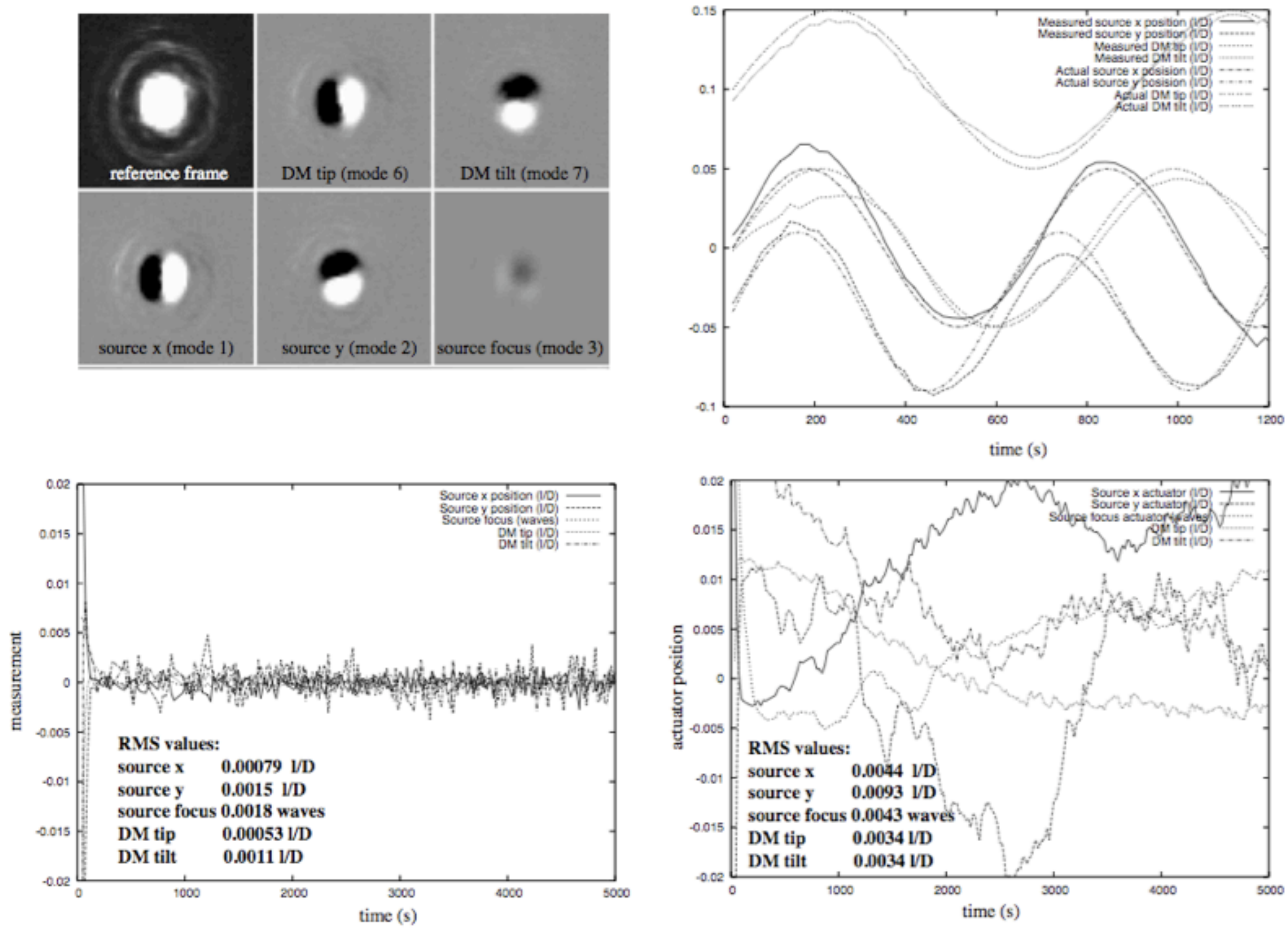


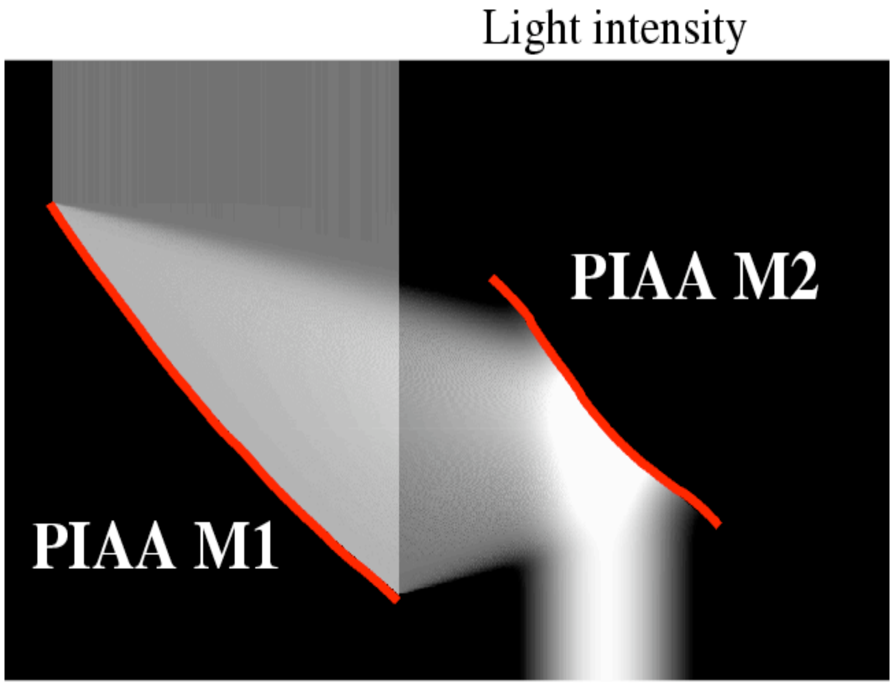
Fig. 10.— Laboratory performance for the CLOWFS. Upper left: Measured CLOWFS reference frame and influence functions for the 5 axis controlled in the experiment. Pre-PIAA and post-PIAA modes look extremely similar, as expected. Top right: Open loop simultaneous measurement of pre and post-PIAA modes. 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} λ/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).

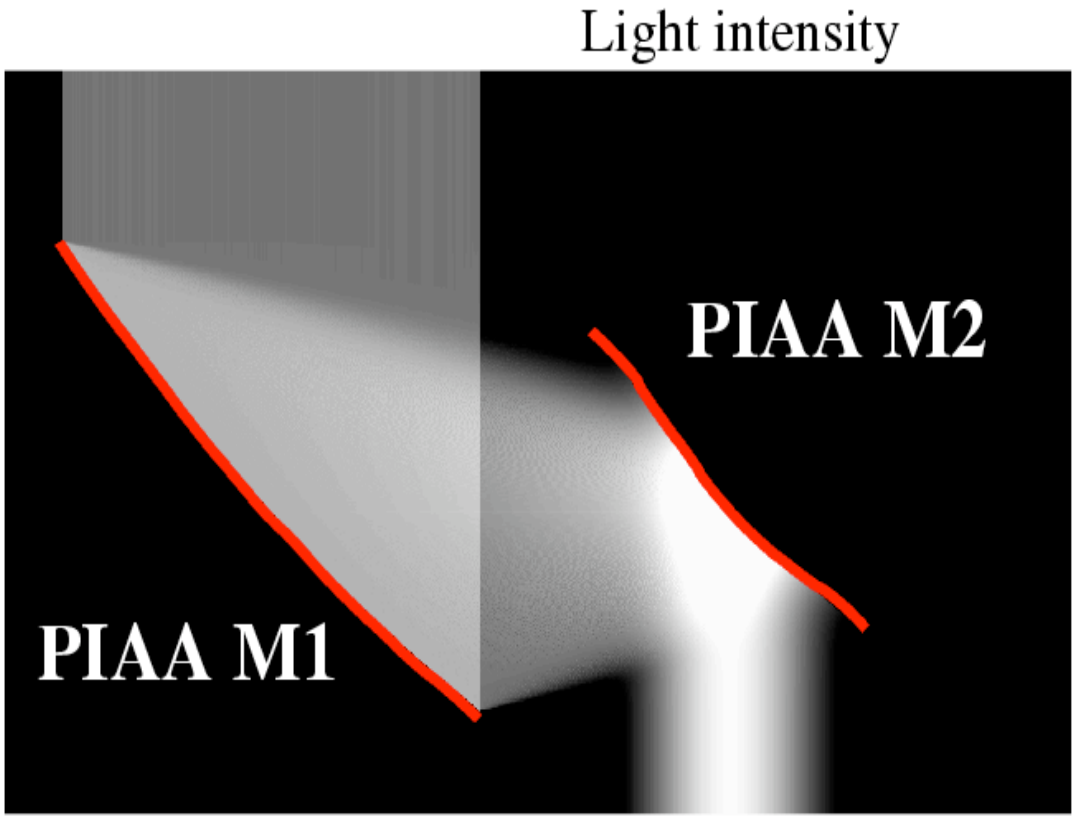
- high contrast
- Nearly 100% throughput
- IWA ~1 l/D to 2 l/D
- 100% search area
- no loss in angular resol.
- can remove central obsc. and spiders
- achromatic (with mirrors)

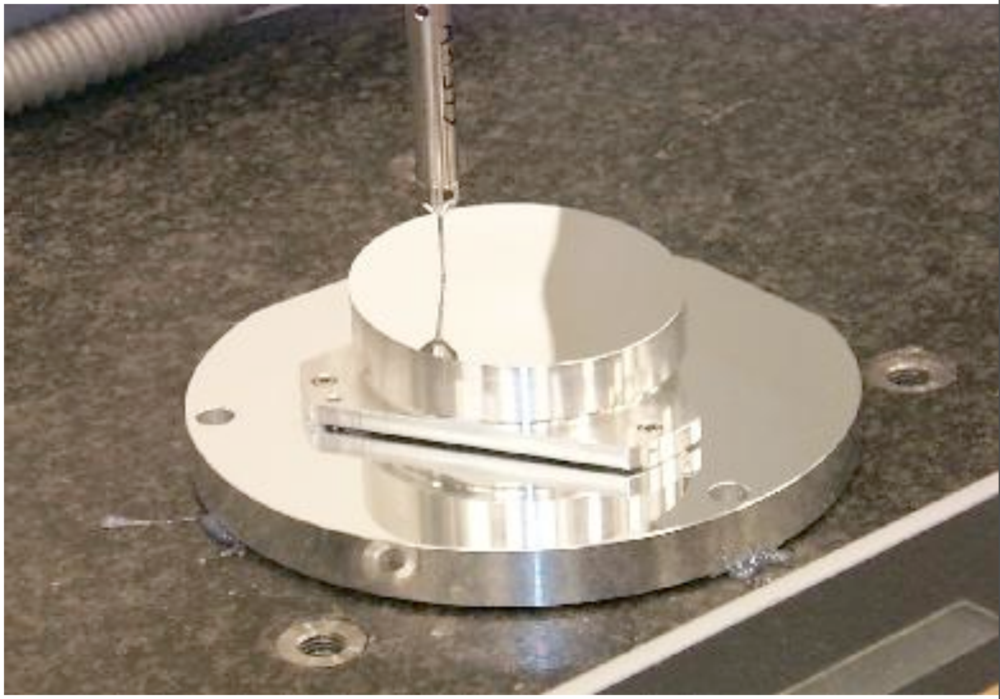


For Subaru, Lyot Coronagraph with PIAA- apodized input pupil. IWA ~ 1 lambda/d

Phase-Induced Amplitude Apodization Coronagraph (PIAAC)

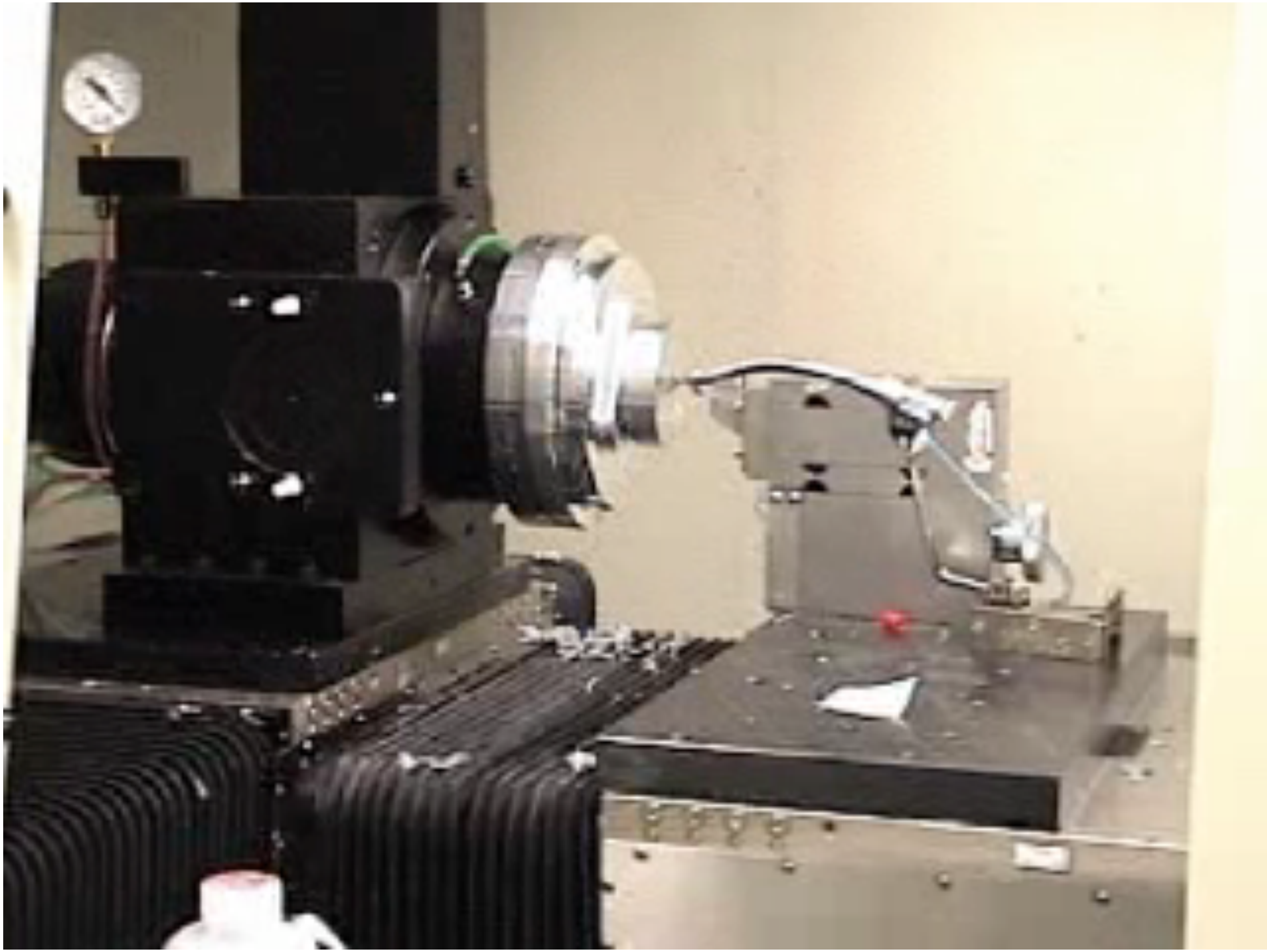
Lossless apodization by aspheric optics.

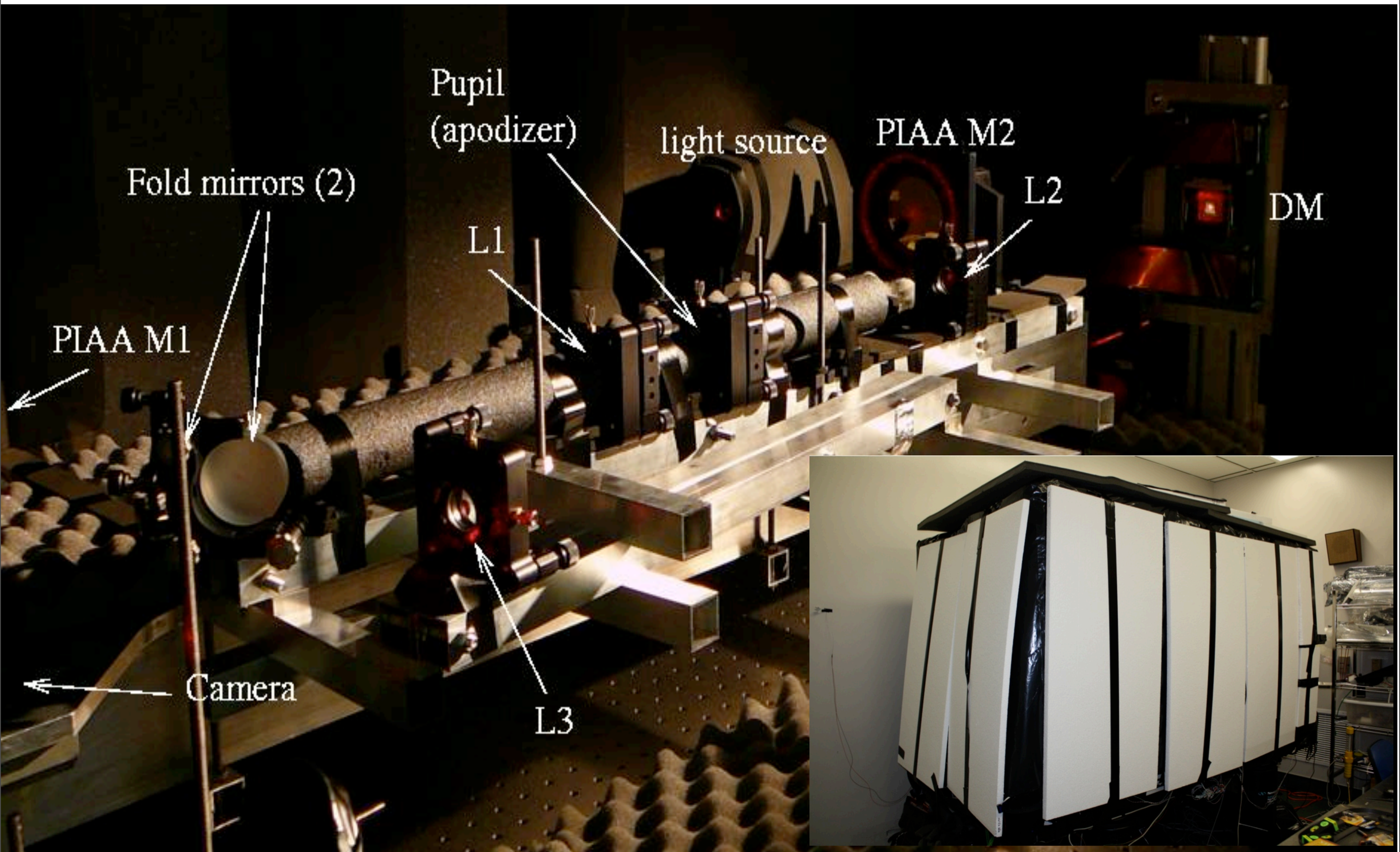




Guyon, Pluzhnik, Vanderbei, Traub, Martinache ... 2003-2006

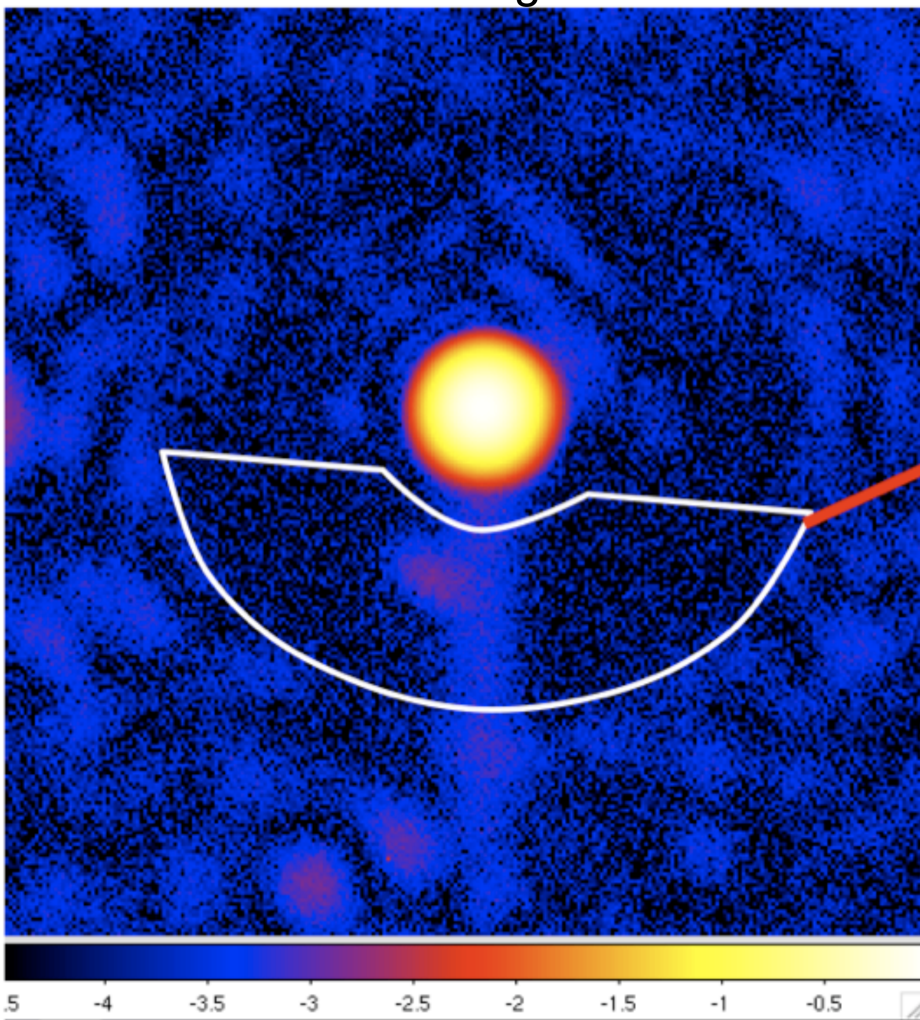
PIAA optics - Diamond turning



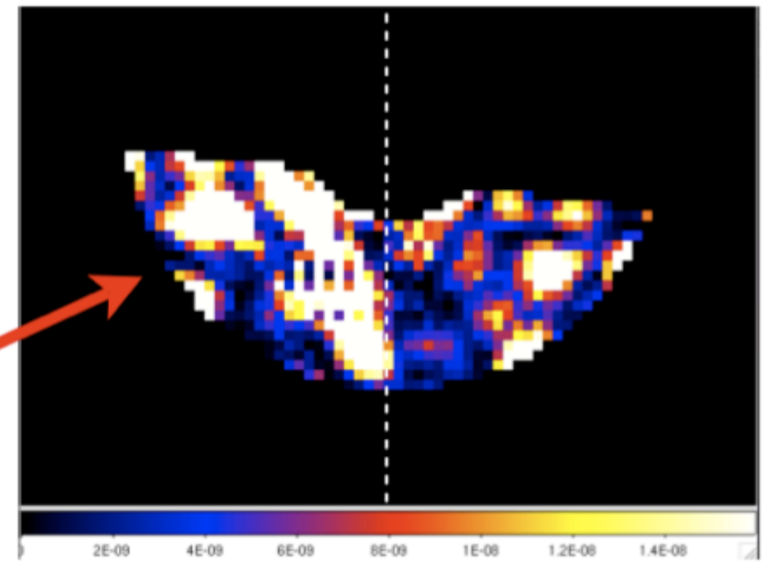

Pupil
(apodizer)
light source
PIAA M2
Fold mirrors (2)
L2
DM
L1
PIAA M1
Camera
L3

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

Raw image



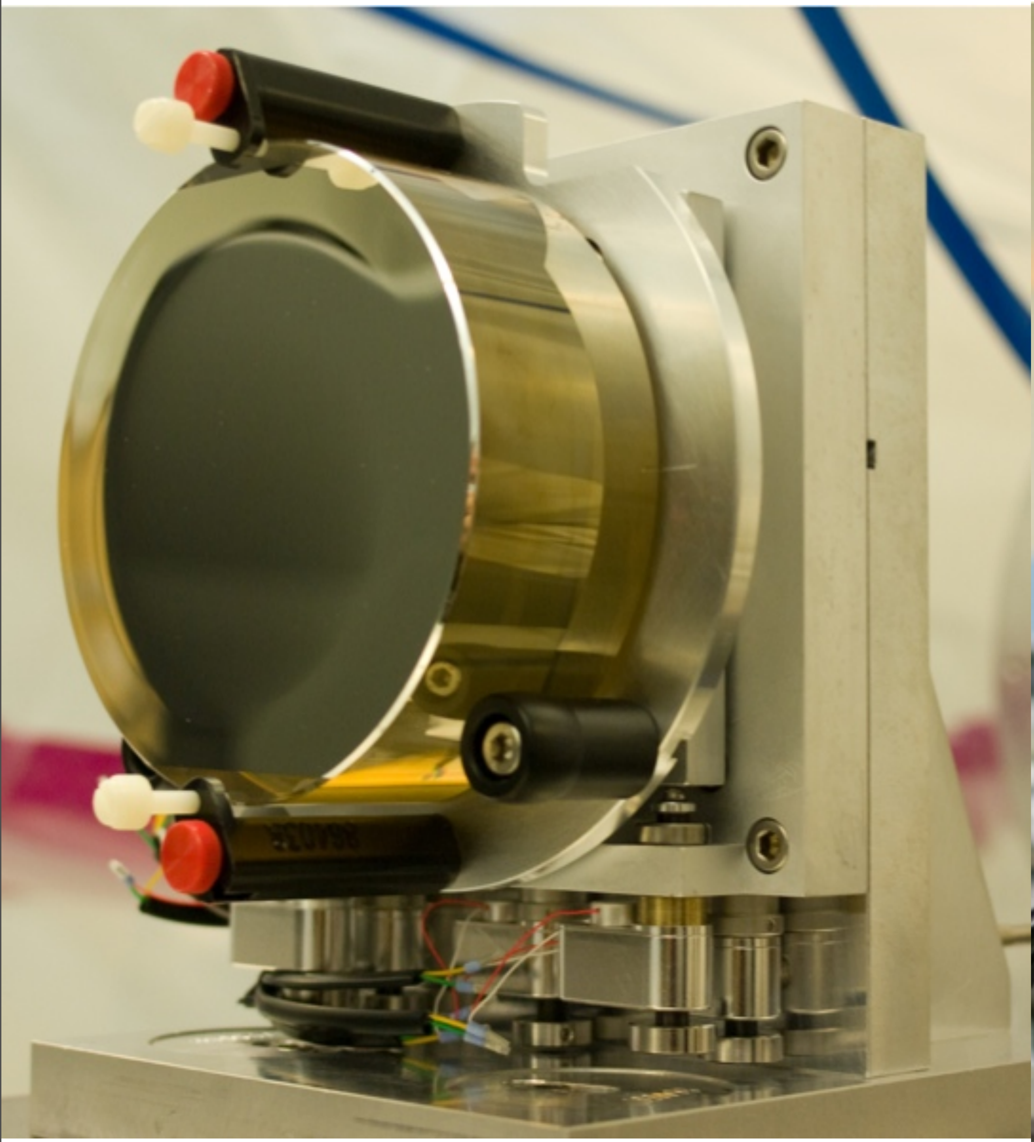
Coherent starlight

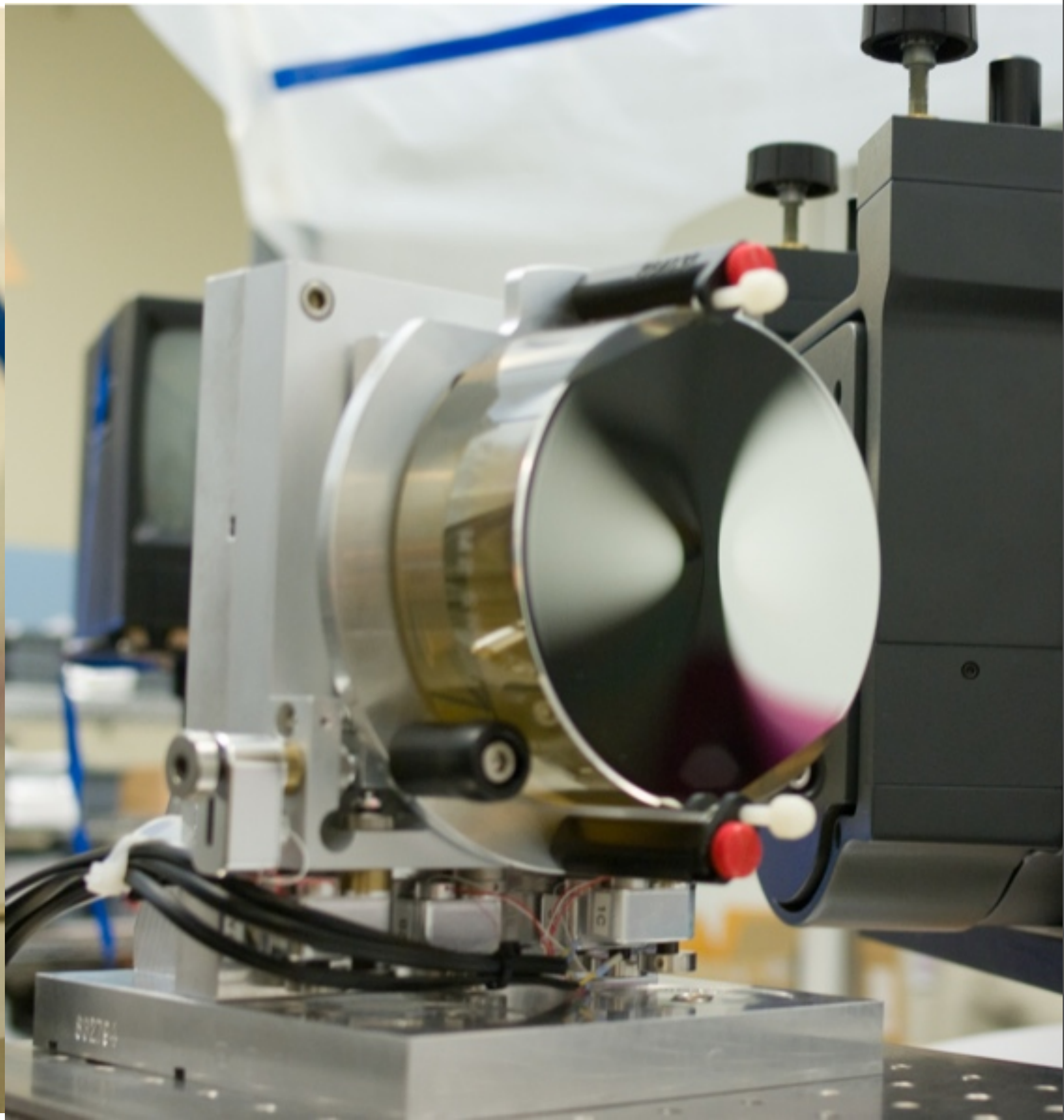


Average contrast in right half of the science field shown above (excludes the ghost on the left) = 7e-9

Contrast achieved in 1.6 to 4.5 l/D zone:
1.5e-7 incoherent halo ghost (equivalent to exozodi)
7e-9 coherent starlight speckles (turbulence, vibrations)

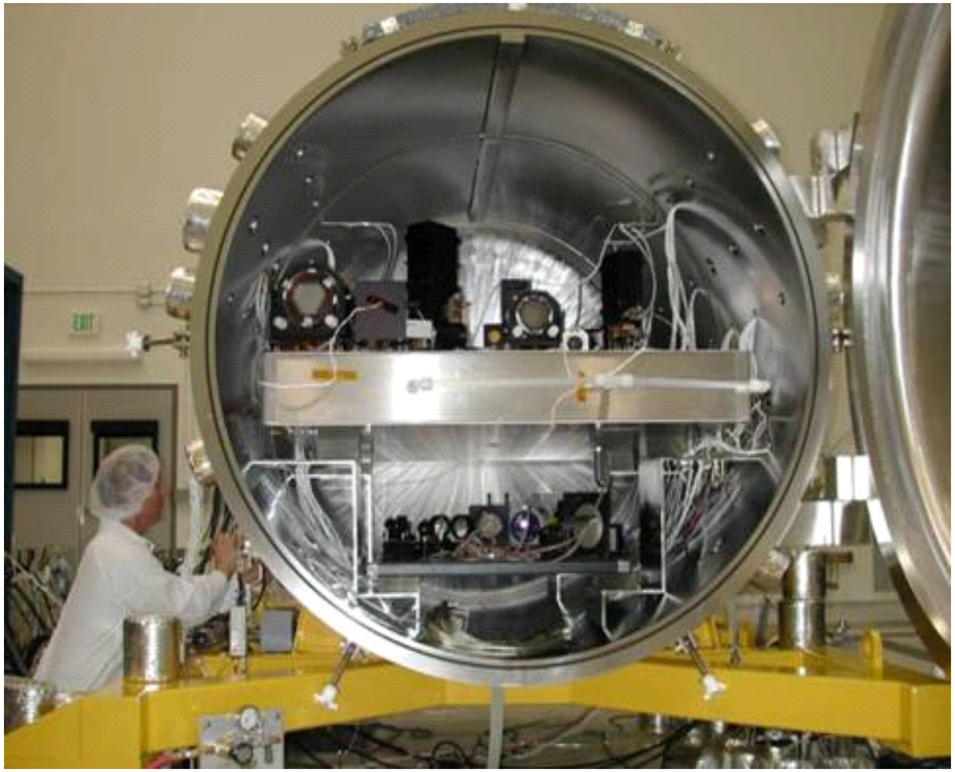
High contrast polychromatic PIAA demonstration in preparation (NASA Ames / NASA JPL)

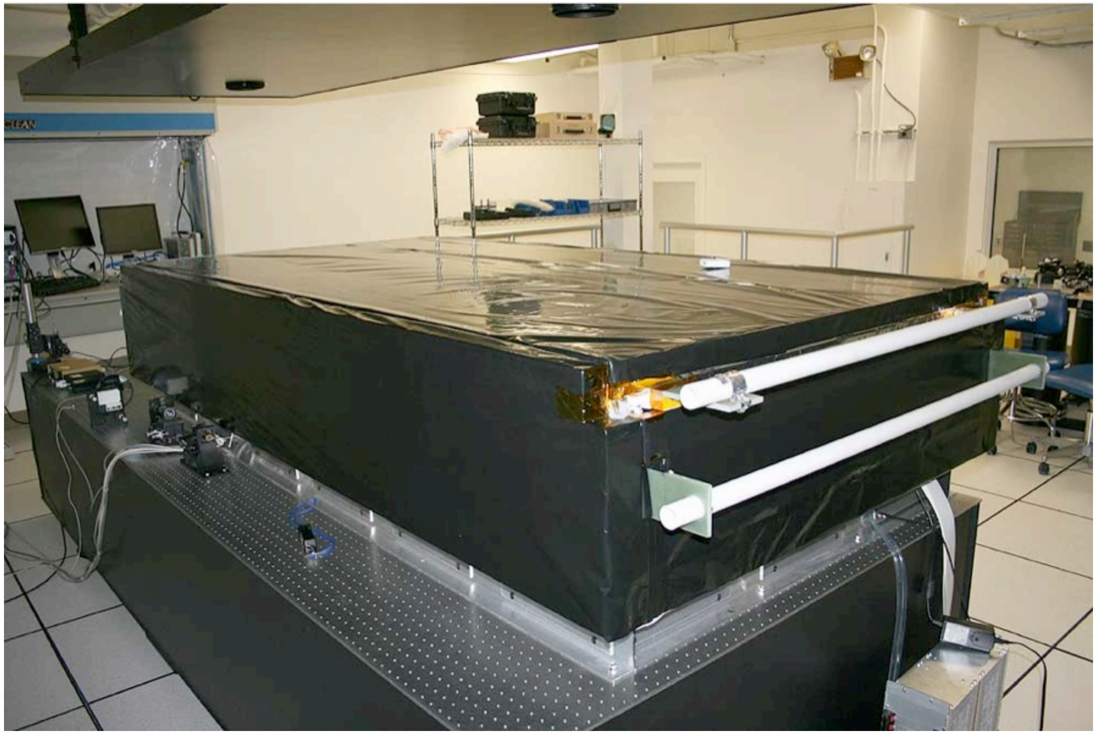




2nd generation PIAA optics manufacturing completed by Tinsley on Jan 5, 2009 (better surface accuracy, better achromatic design than PIAAgen1)

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

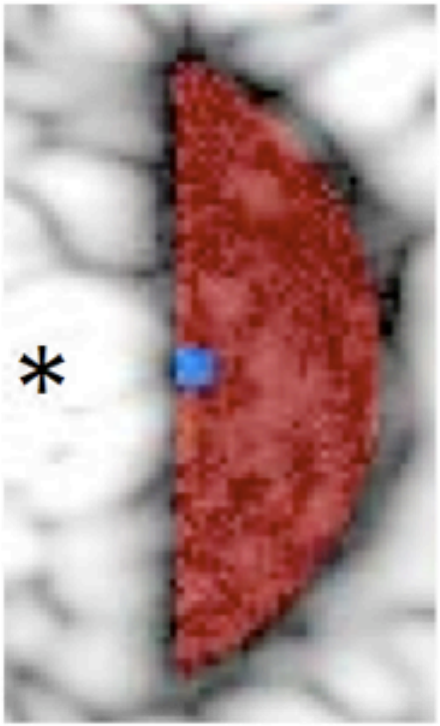


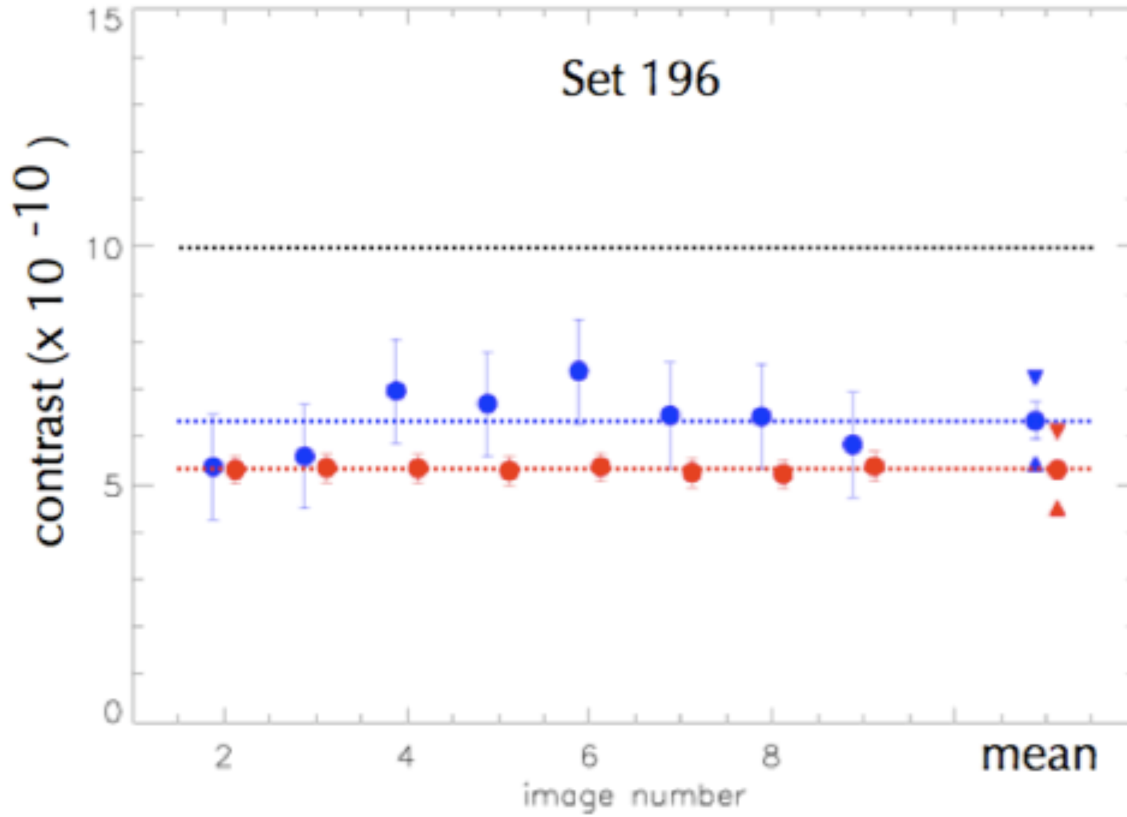


Coronagraph labs in:
- NASA JPL (vacuum)
- NASA Ames
- Princeton Univ.
- Subaru Telescope
- Japan/ISAS (vacuum)

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

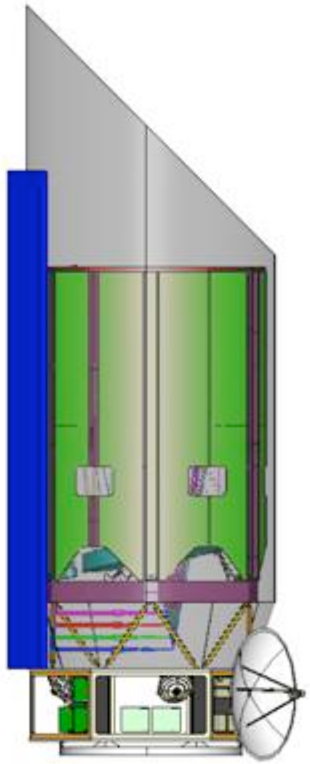
"Classical" speckle nulling with the HCIT





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) *(caao.as.arizona.edu/PECO)*



- 1.4m diameter off-axis telescope
- Uses high efficiency low IWA PIAA coronagraph
- 0.4 - 0.9 micron spectral coverage / R~20

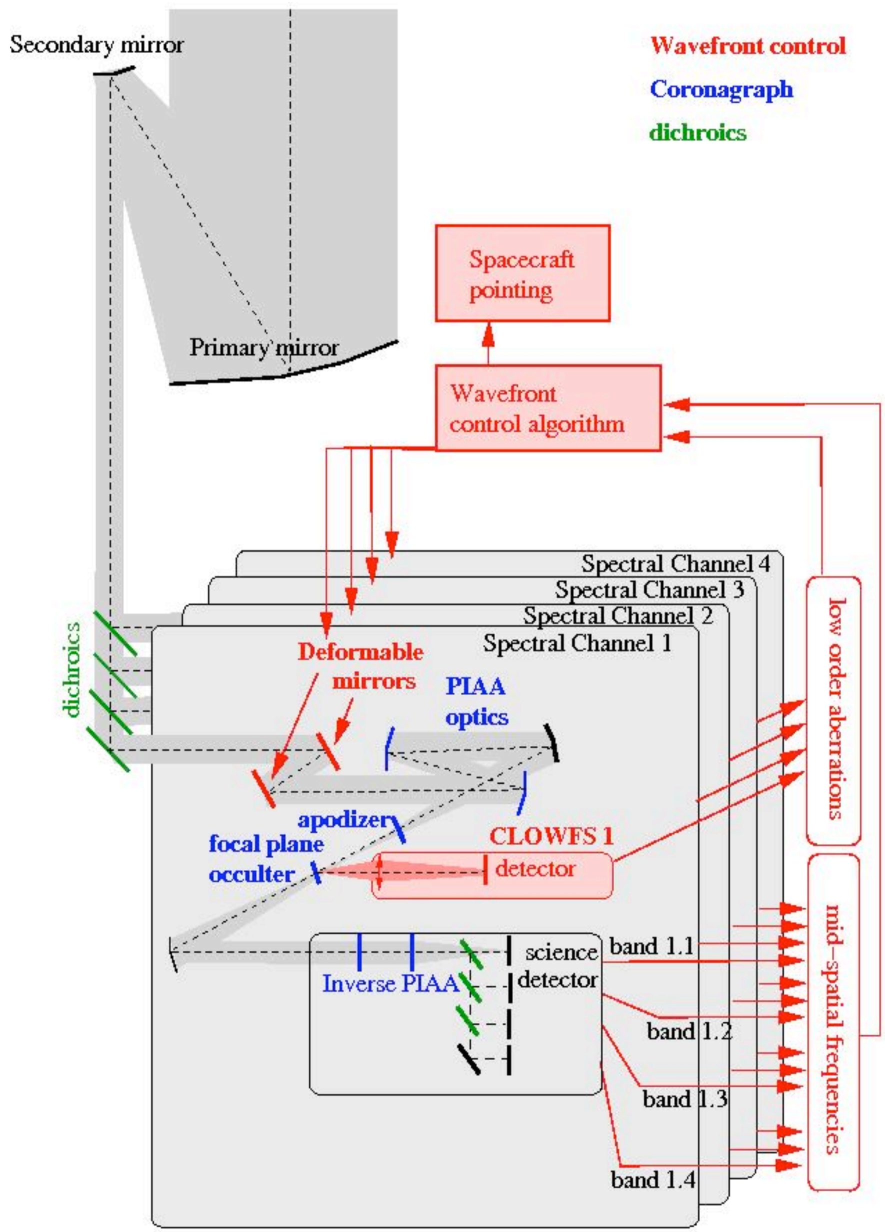
- **Conduct a "Grand Tour" of 10 nearby stars searching for small (Earth & Super-Earth) planets in their habitable zones.**
- **Study known RV planets, observing them at maximum elongation**
- **Snapshot survey of ~100 other nearby stars to study diversity of exozodiacal disks and search for / characterize gas giant planets.**

Earth/SuperEarths with a medium-class mission ?

Yes, if:

- **High throughput** instrument & good detector
  - high throughput coronagraph
  - no photon lost, use dichroics instead of filters
  - combined imaging & spectroscopy
  - photon counting (no readout noise allowed)
- Small **Inner Working Angle** AND full telescope **angular resolution**
  - good coronagraph
  - use blue light for discovery & orbit determination
- Large amount of **observation time** on few targets
  - small sample of the easiest 10 to 20 targets
  - long exposure times & many revisits
- Accept risk of high exozodi & low Earth frequency
  - broader science case:
    - exoplanetary systems architecture
    - extrasolar giant planets characterization
    - exozodi disks imaging

PECO approaches theoretically optimum coronagraph performance



High performance PIAA coronagraph

- IWA = 2 λ/D
- 90% coronagraph throughput
- No loss in telescope angular resolution: max sensitivity in background-limited case
- Full 360 deg field probed

Simultaneous acquisition of all photons from 0.4 to 0.9 µm in 16 spectral bands, combining detection & characterization

- High sensitivity for science and wavefront sensing
- polarization splitting just before detector (helps with exozodi & characterization)

Wavefront control and coronagraph perform in 4 parallel channels

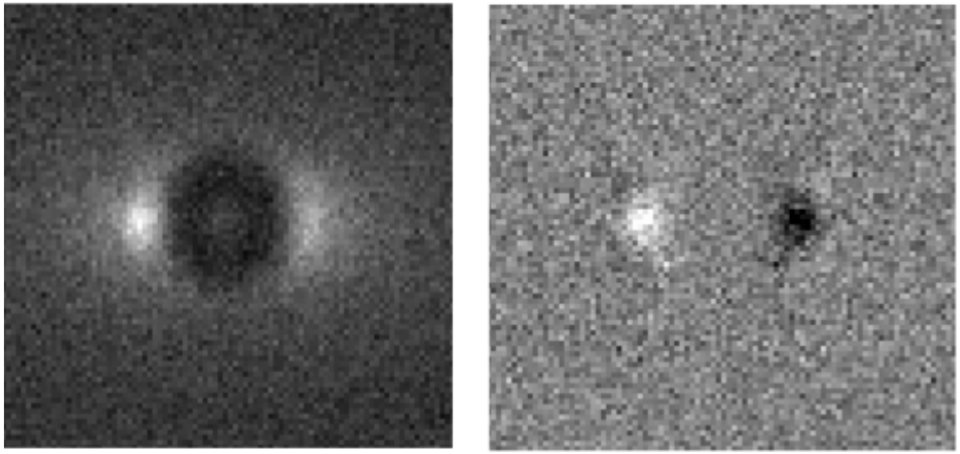
- Allows scaling of IWA with lambda
- Allows high contrast to be maintained across full wavelength coverage

Number of Earths & Super 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

Earths still detectable at shorter wavelengths and smaller D

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



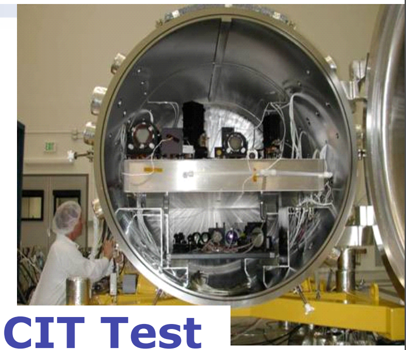
Left: a simulation of 24 hr of PECO data showing an Earth-like planet (a=0.2) around Tau Ceti with 1 zodi of exododi dust in a uniform density disk inclined 59 degrees. This is a simulation of λ= 550 nm light in a 100 nm bandpass PECO (1.4-m aperture). Photon noise and 16 electrons total detector noise 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.

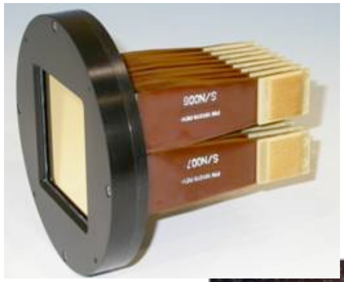
- Trade study shows number of Earths detected for different telescope diameters
- PECO simulation of Earth-radius planet with Earth albedo in habitable zone of candidate star
- Assumes detection in < 5 attempts of < 12 hr integration
- IWA of 2 lambda/D

PECO top 5 key technologies are identified and under study

- **PIAA Coronagraph System Path to TRL6**
  - PIAA mirror fabrication
  - Performance demonstrations in JPL HCIT
  - Brassboard component qualification
    - Note that existing PIAA coronagraph bench is the same scale as flight components
- **Broadband Wavefront Control**
  - Baseline Xinetics DM near TRL 6
  - MEMs DM technology in progress as potential cheaper alternative (NASA Ames Funding)
  - Algorithms tested in HCIT
- **Pointing Control Demonstration**
  - LOWFS provides fine guidance, to be tested in HCIT
  - Models predict 0.5 mas possible with existing technology (1 mas demonstrated with PIAA in the lab in air)
- **Thermal-Structural-Optical modeling**
  - Needed for final system verification
  - HCIT will validate optical models
  - SIM TOM testbed demonstrated thermo-structural
- **Photon-counting EMCCD Detectors**



JPL HCIT Test Facility



Xinetics 64x64 DM

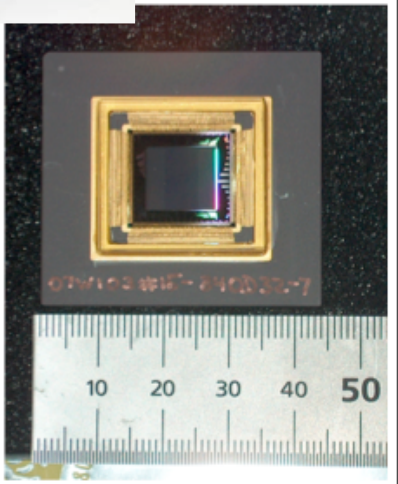
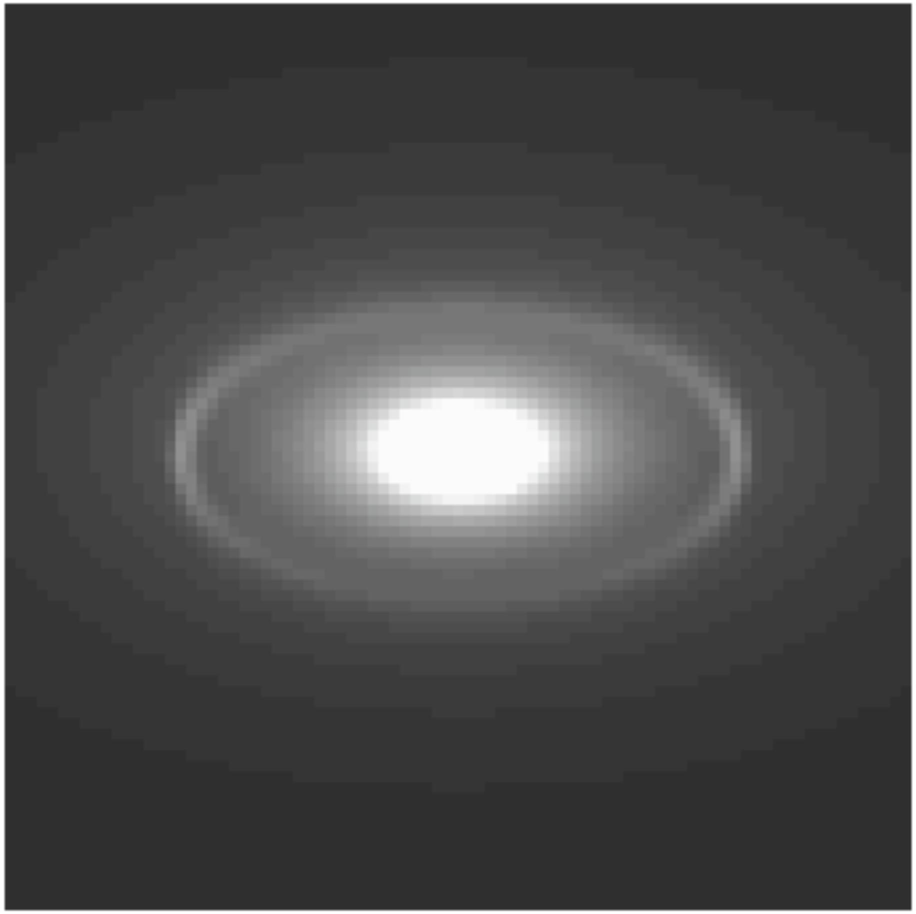


Figure 1: 1024 actuator (32x32) MEMs DM commercially available from Boston Micromachines (mm scale).

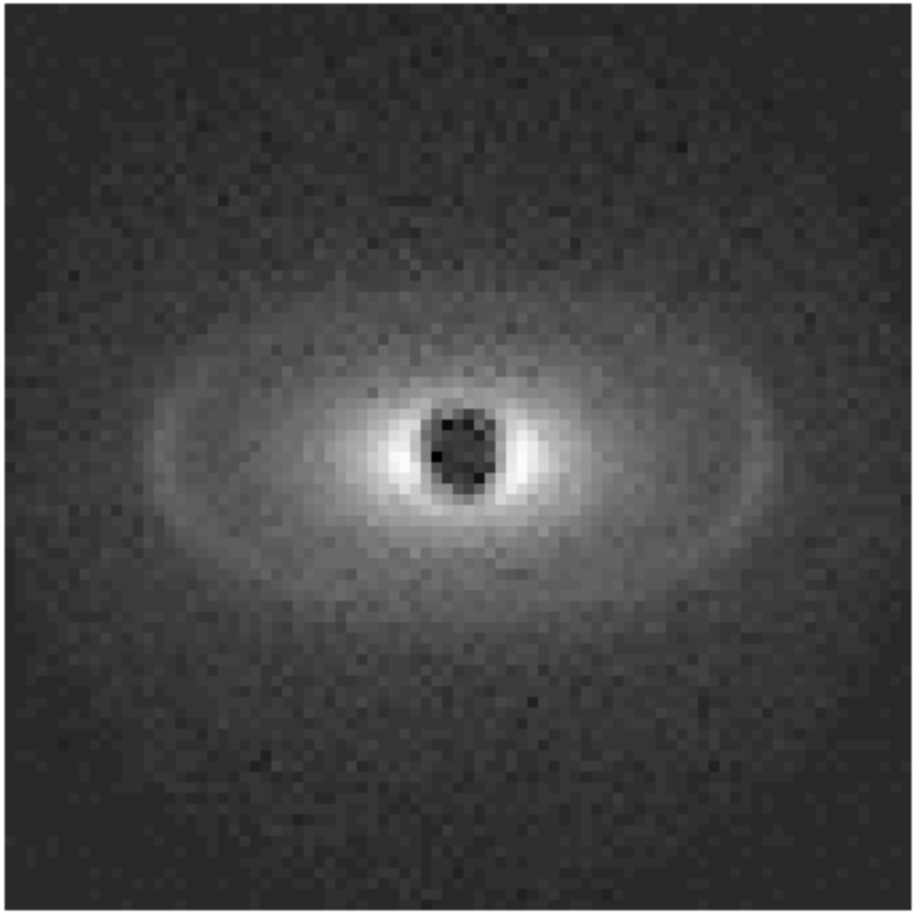
PECO exozodi imaging

Univ. of Arizona
Jet Propulsion Laboratory
California Institute of Technology
LOCKHEED MARTIN
Ames Research Center
ITT

- Simulated PECO imaging of Alpha Cent exozodi



Model
1 zodi
enhancement at 1AU



PECO image
3 hr exposure
400 nm, 20% band

PECO Pupil mapping Exoplanet Coronagraph Observer

Wavefront control
(& coronagraphy)

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 -> speckles are amplified by the PSF diffraction.

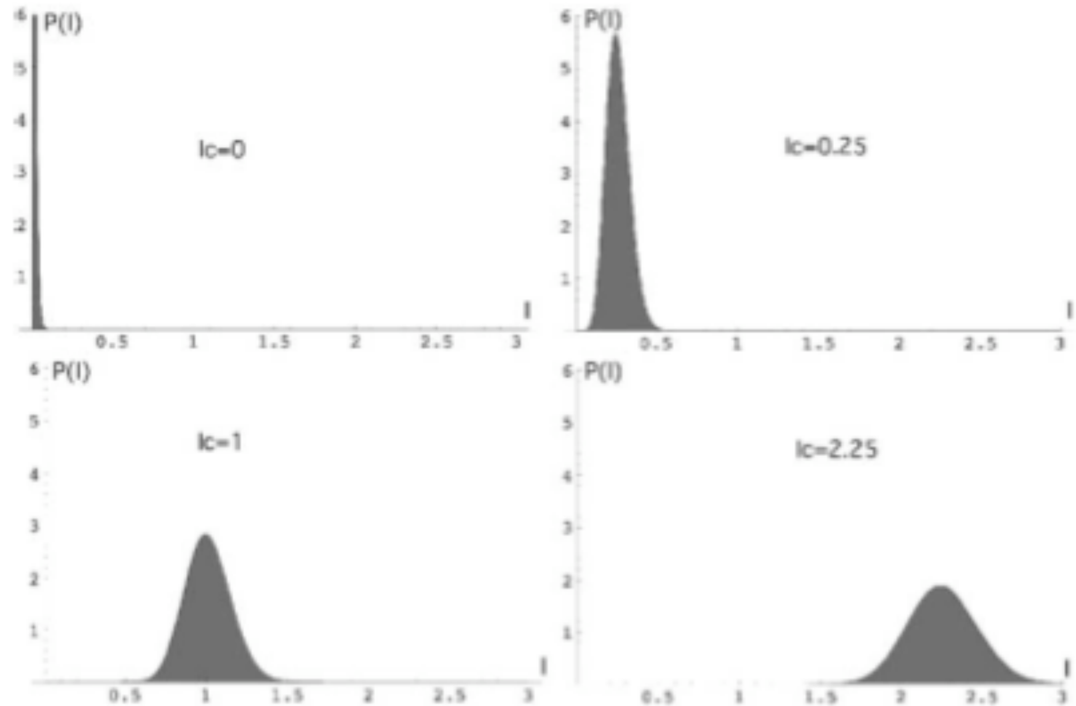


FIG. 3.—PDF of the light intensity at four different constant background intensity levels I_c and a single value of $I_s = 0.1$. High values of I_c correspond to locations near the perfect PSF maxima (rings), and low values of I_c correspond to locations near the zeros of the perfect PSF or far from 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.

Aime & Soummer 2004

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)

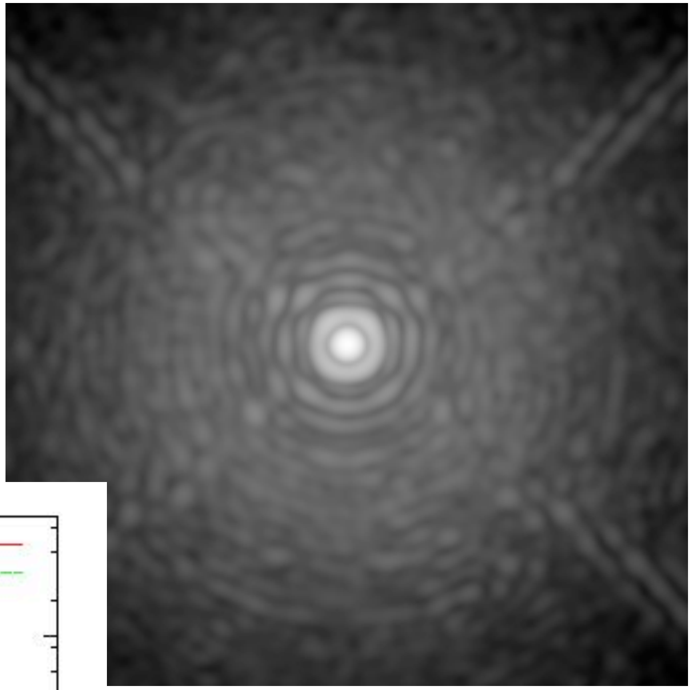
"Side effects" of coronagraphs :

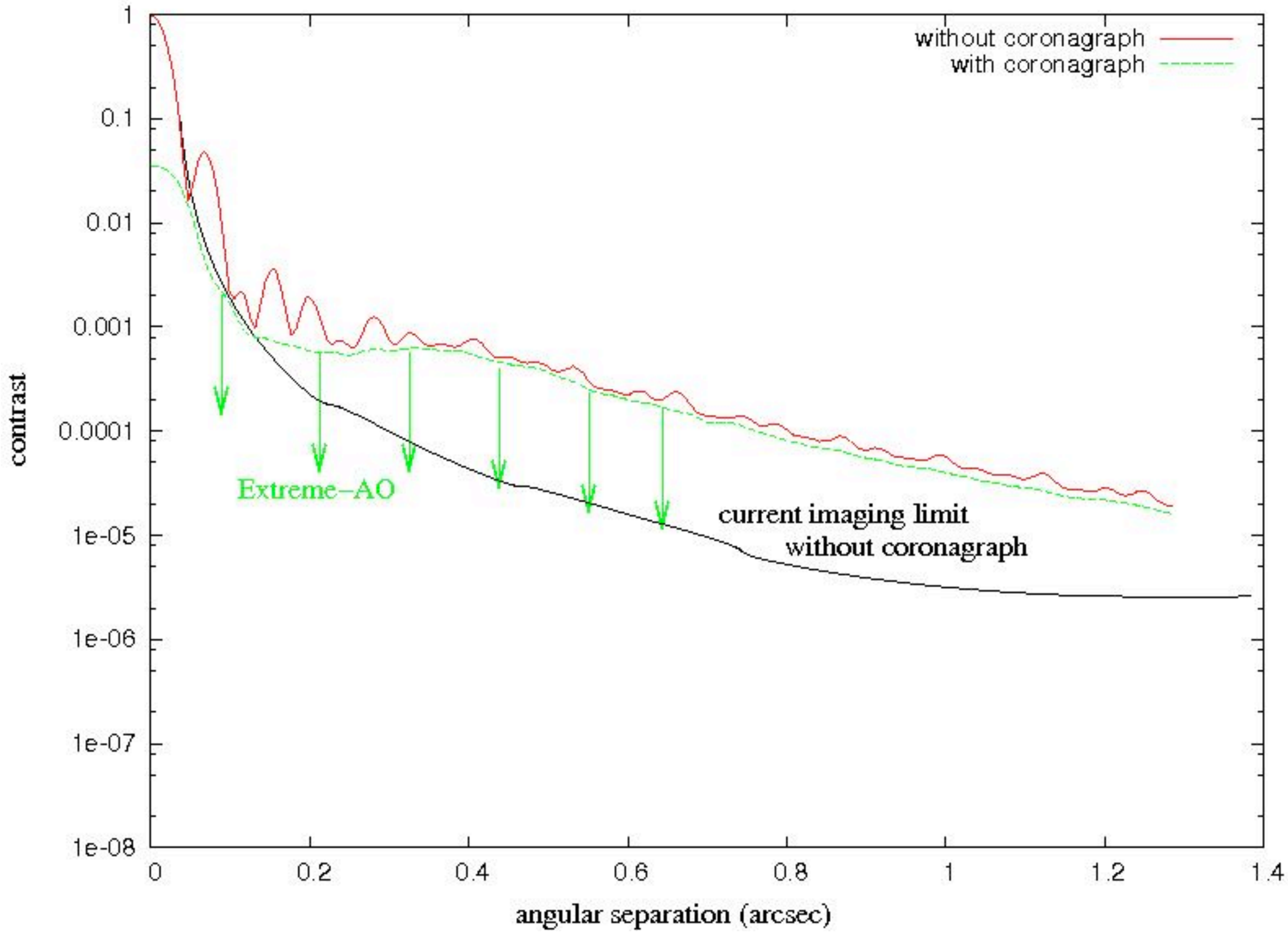
- (Usually) requires very good pointing. Risk of low order aberrations (for example pointing) creating additional scattered light in the region of interest

- 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 ~0.3" in H band
- PSF calibration with coronagraphs is more complicated





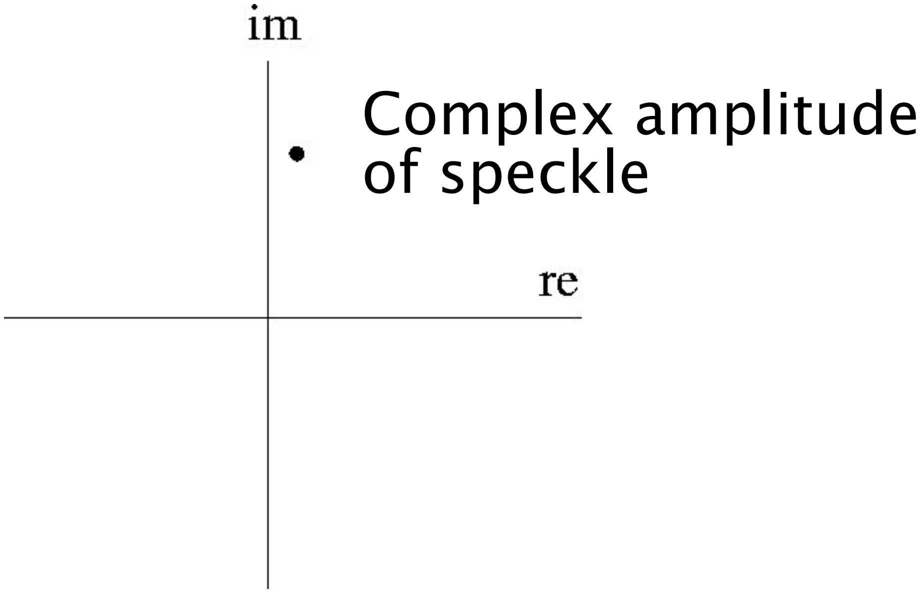
ExAO systems currently under construction improve contrast with AO + coronagraphy

Speckles vs. planet

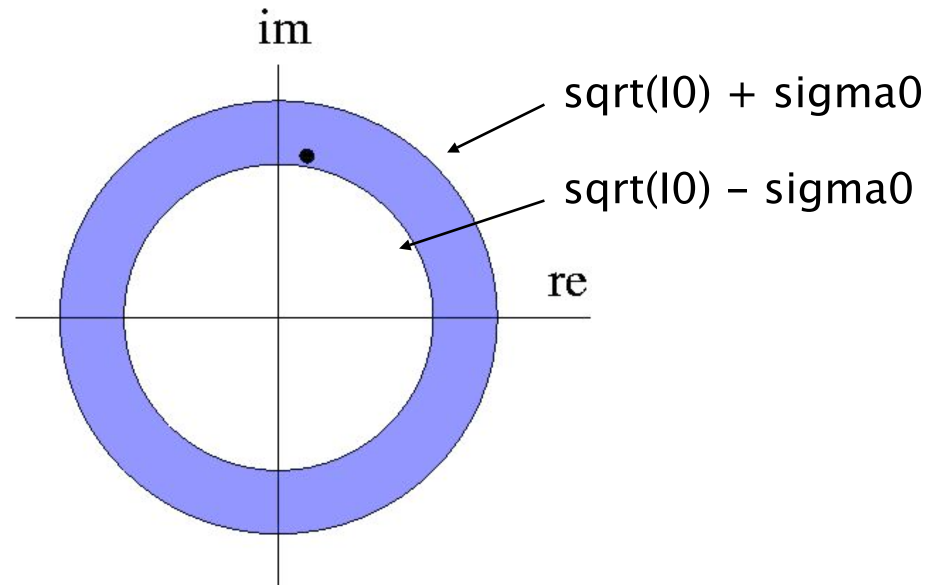
Spectra differential imaging (SDI)
Optimized for methane-bearing giant planets
Will only detect planets with a given spectral feature
Polarization differential imaging (PDI)
Degree of polarization may be low (few %)
Only works on reflected light
Angular differential imaging (ADI)
Performs well if static speckles are strong
Does not work well at small angular separations

Coherent differential imaging (CDI)
Use DM to introduce a know variation in the WF to modulate speckle intensity
Can reach photon noise limit if system is very well calibrated and CDI is performed quickly (or simultaneously)

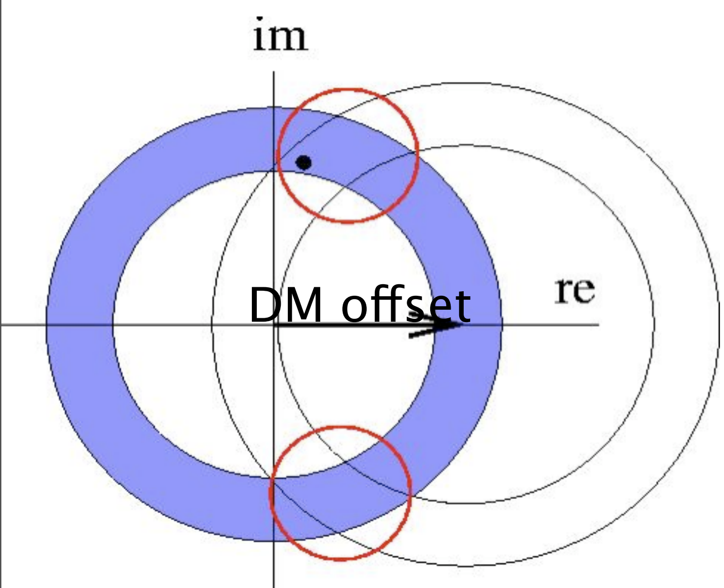
Initial problem

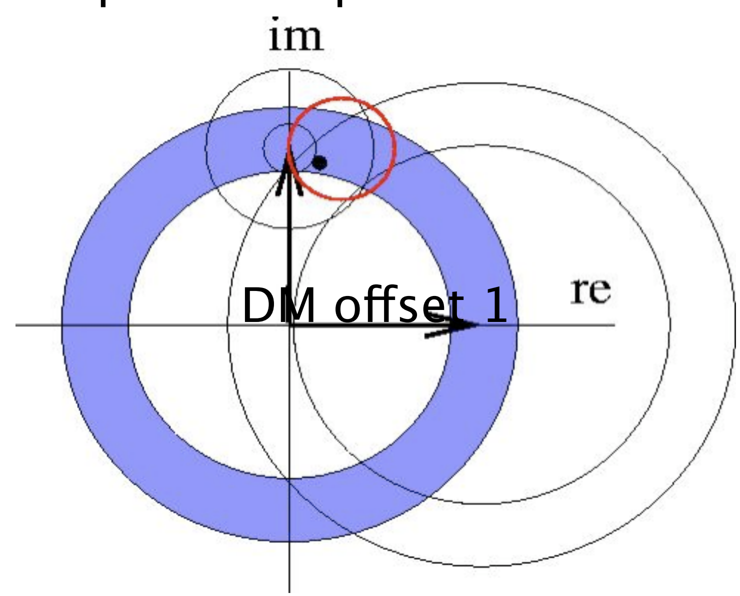


Take a frame -> measured speckle intensity = I0

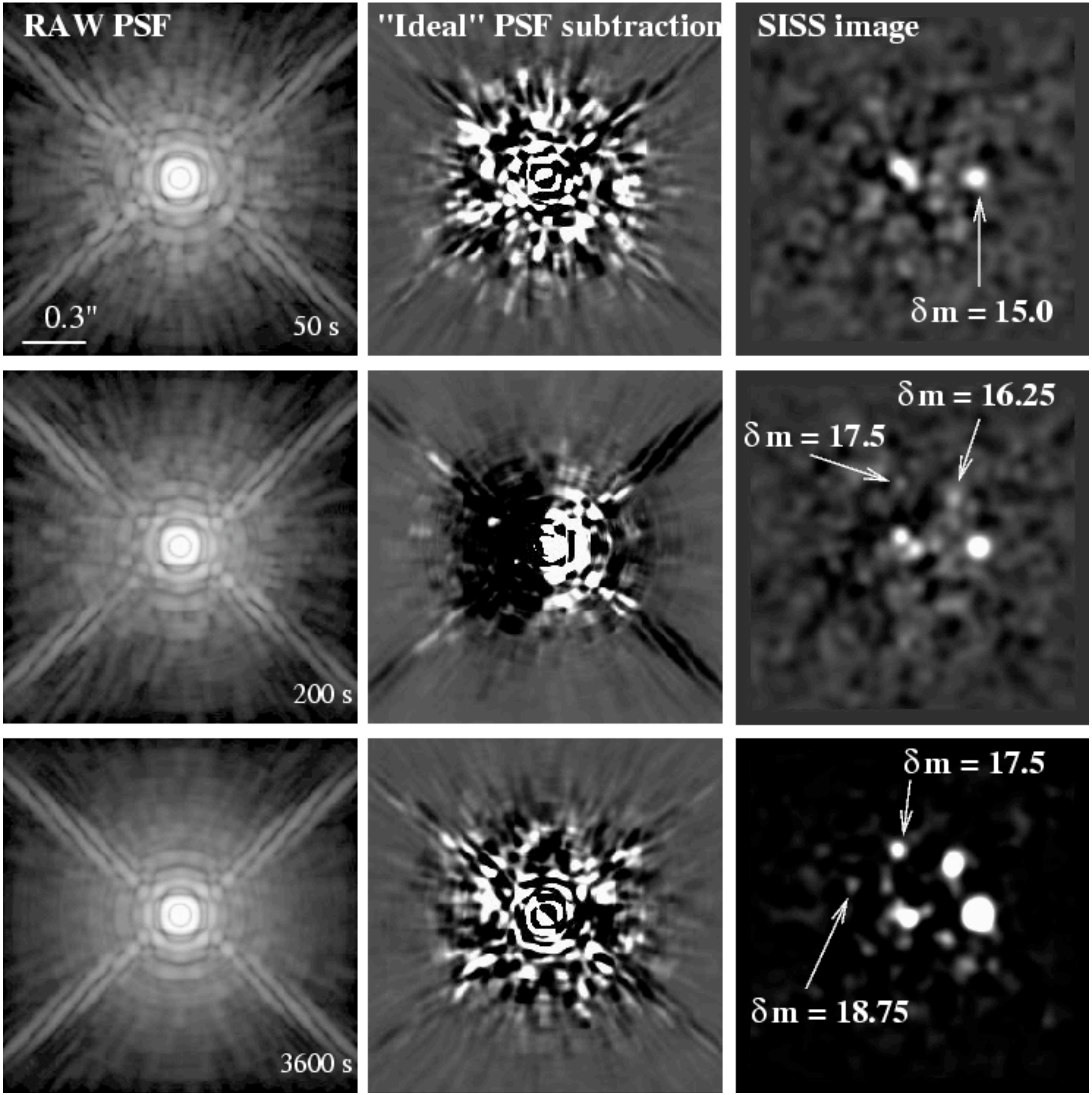


DM offset chosen to be ~ equal to speckle amplitude



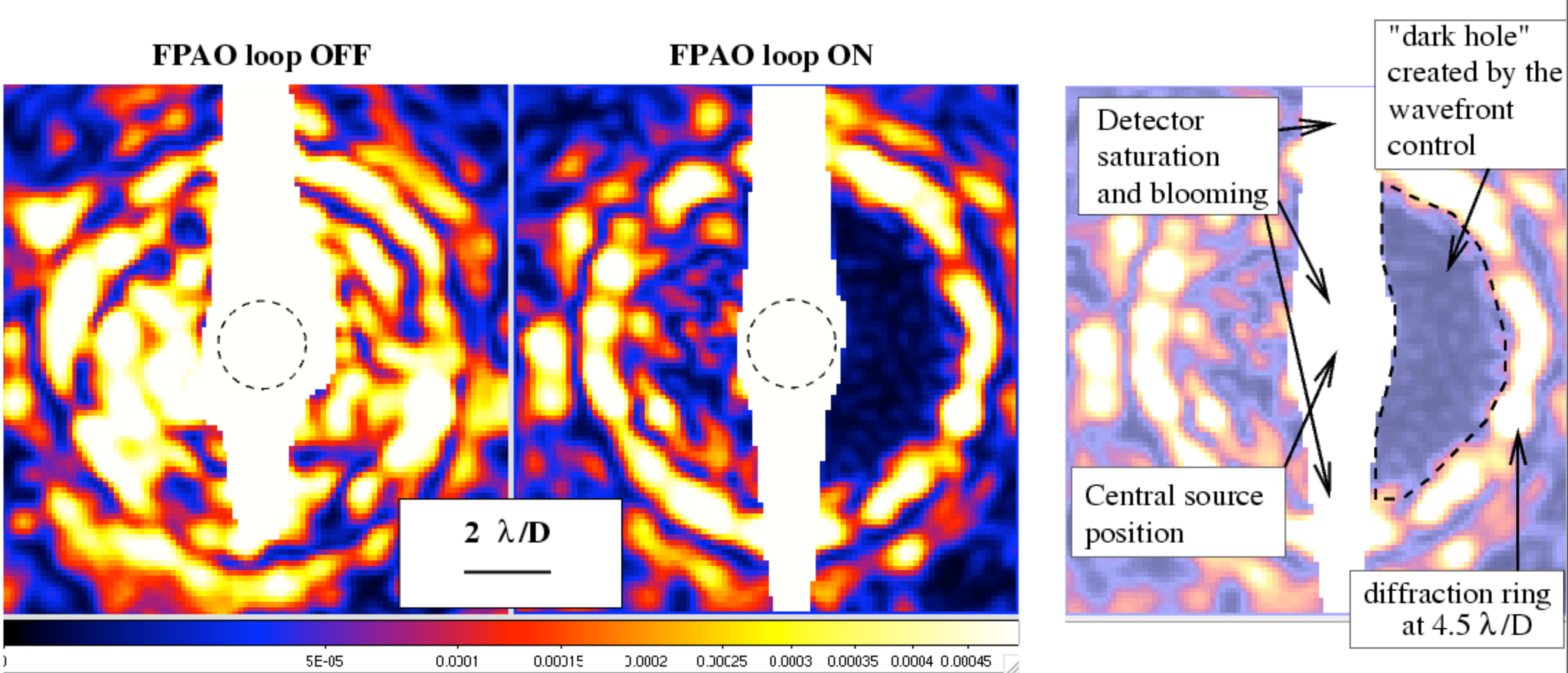


Speckle calibration with active coherent modulation



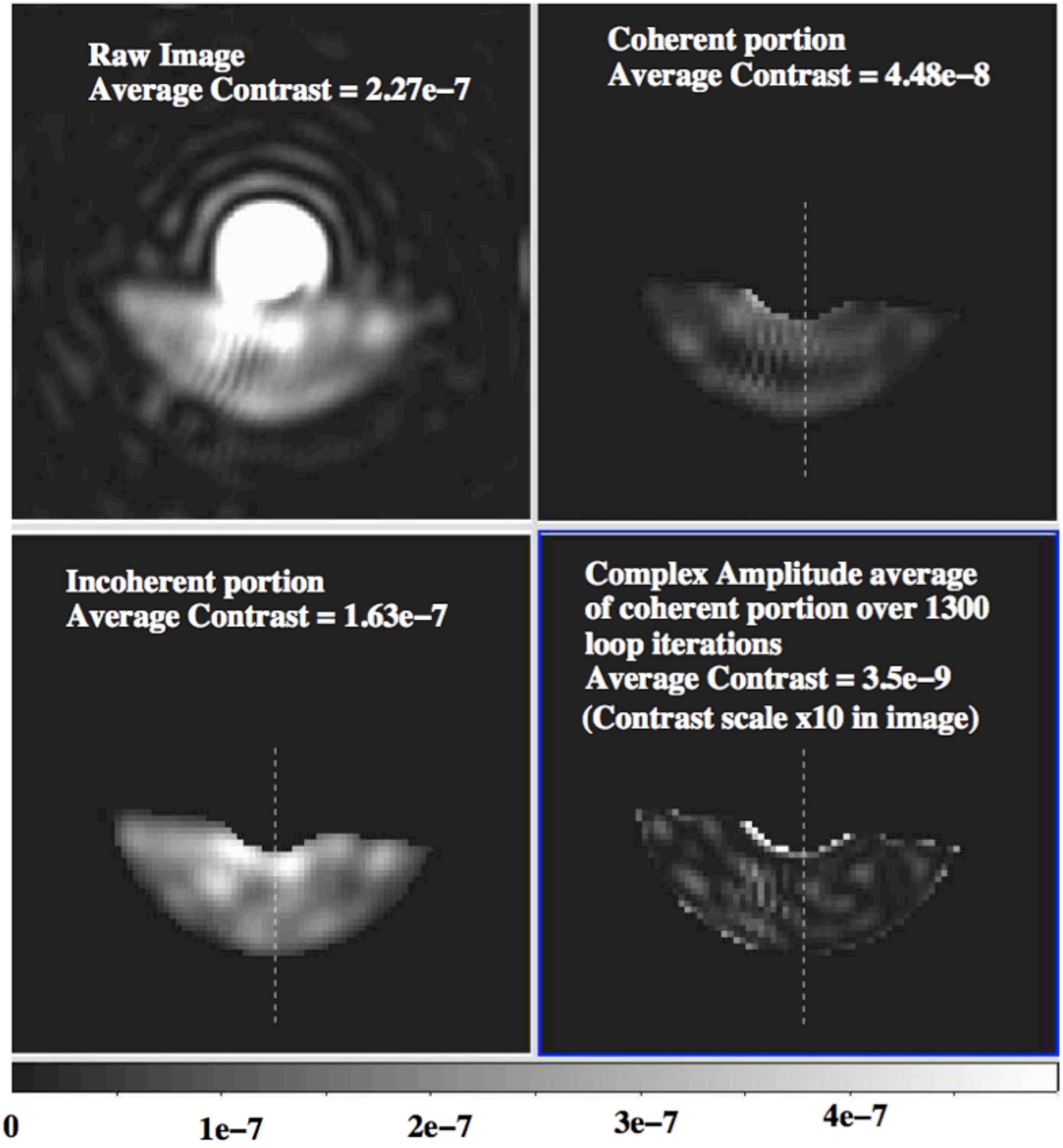
Focal plane wavefront sensing and CDI use the same modulation: if something is a speckle, we can kill it with the DM !

With FPAO, separation between coronagraph and wavefront control becomes blurry



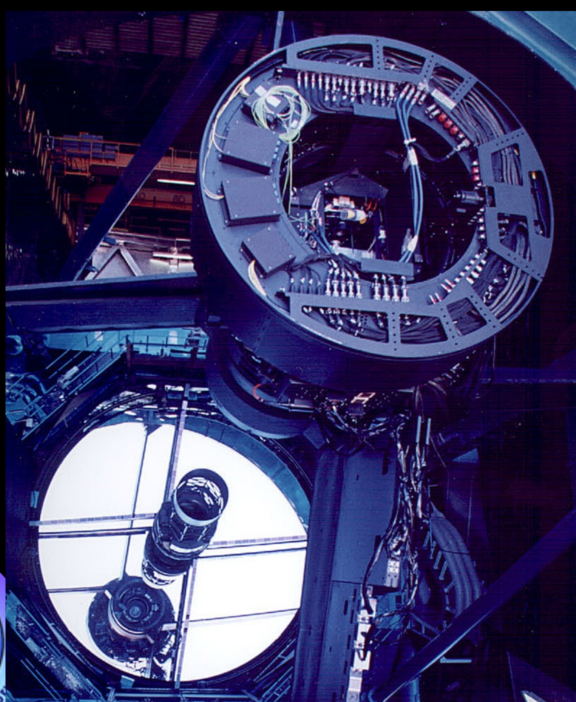
Coherent detection works in the lab alongside FPAO

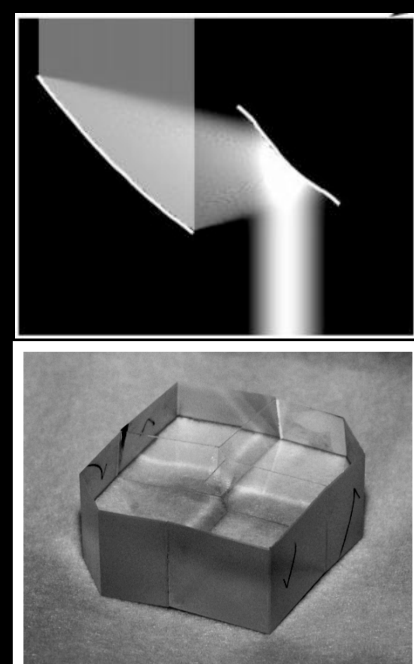
Extremely powerful for ExAO:
- Optically simple
- Non NCPE
- on-the fly diagnostics
- CDI post-processing

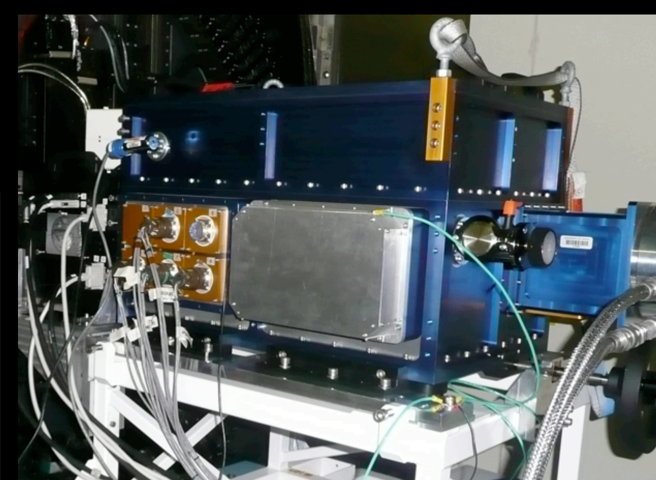


The Subaru Coronagraphic Extreme AO Project (SCExAO)

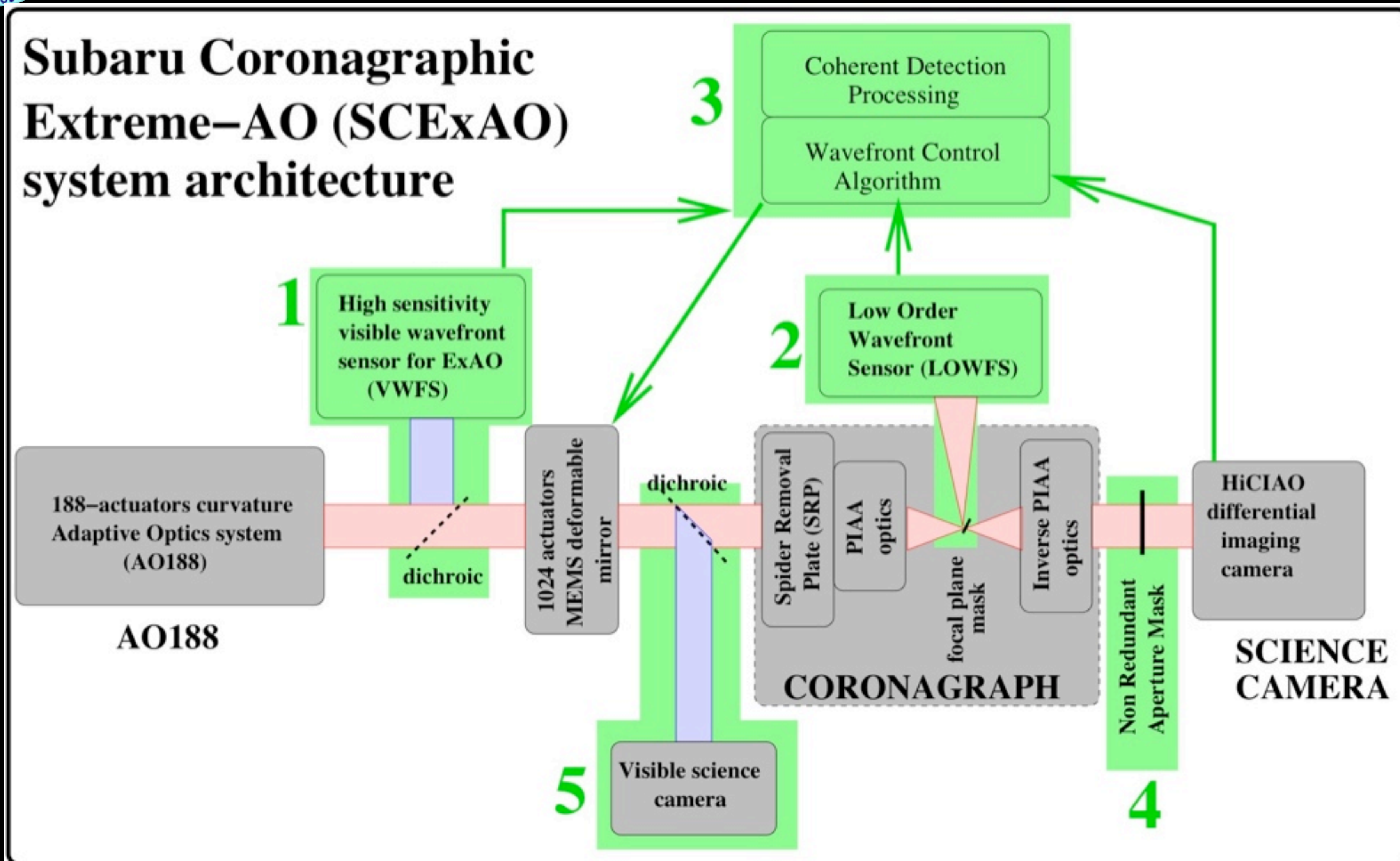
Olivier Guyon, Frantz Martinache,
Julien Lozi, Vincent Garrel



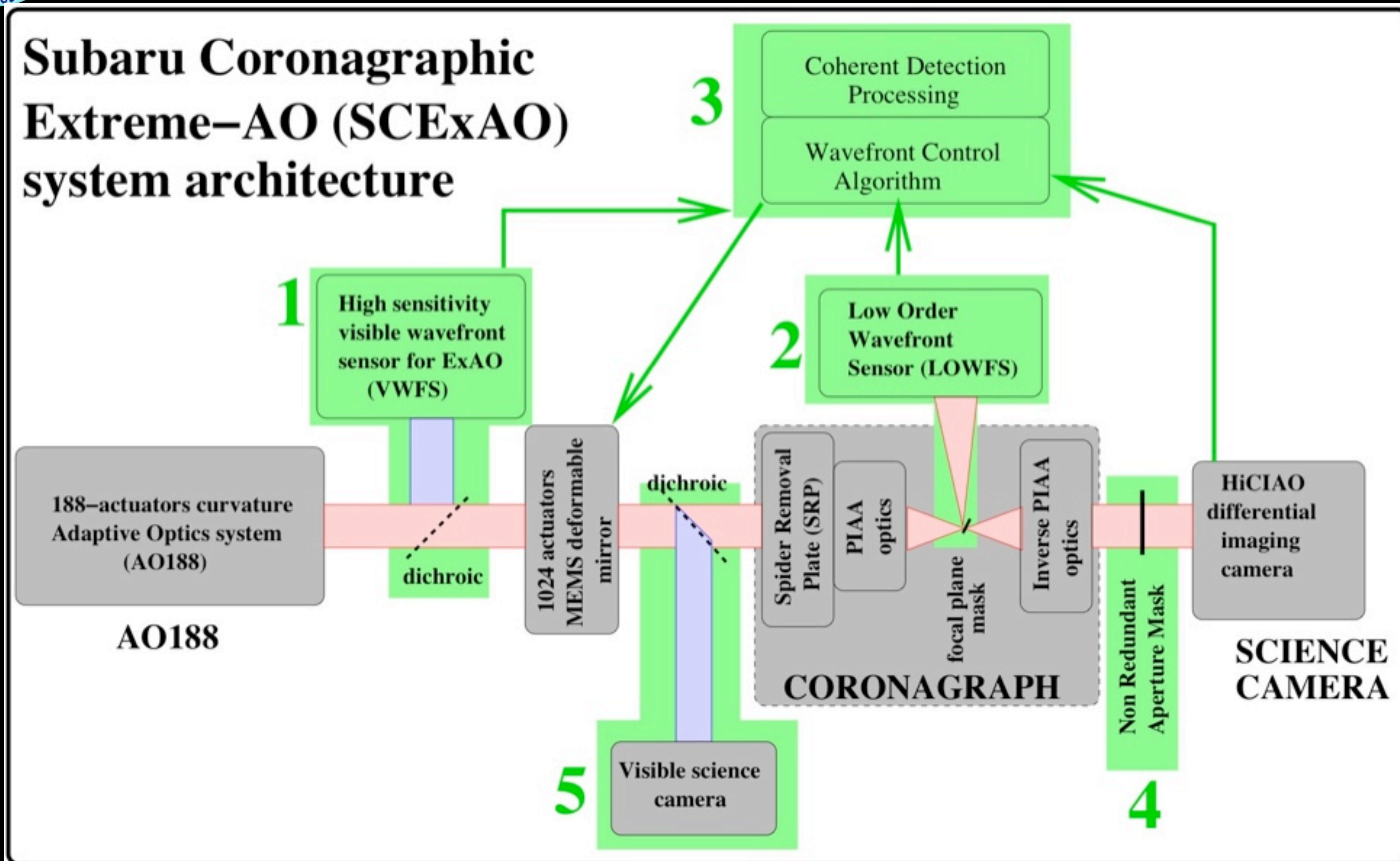




System architecture

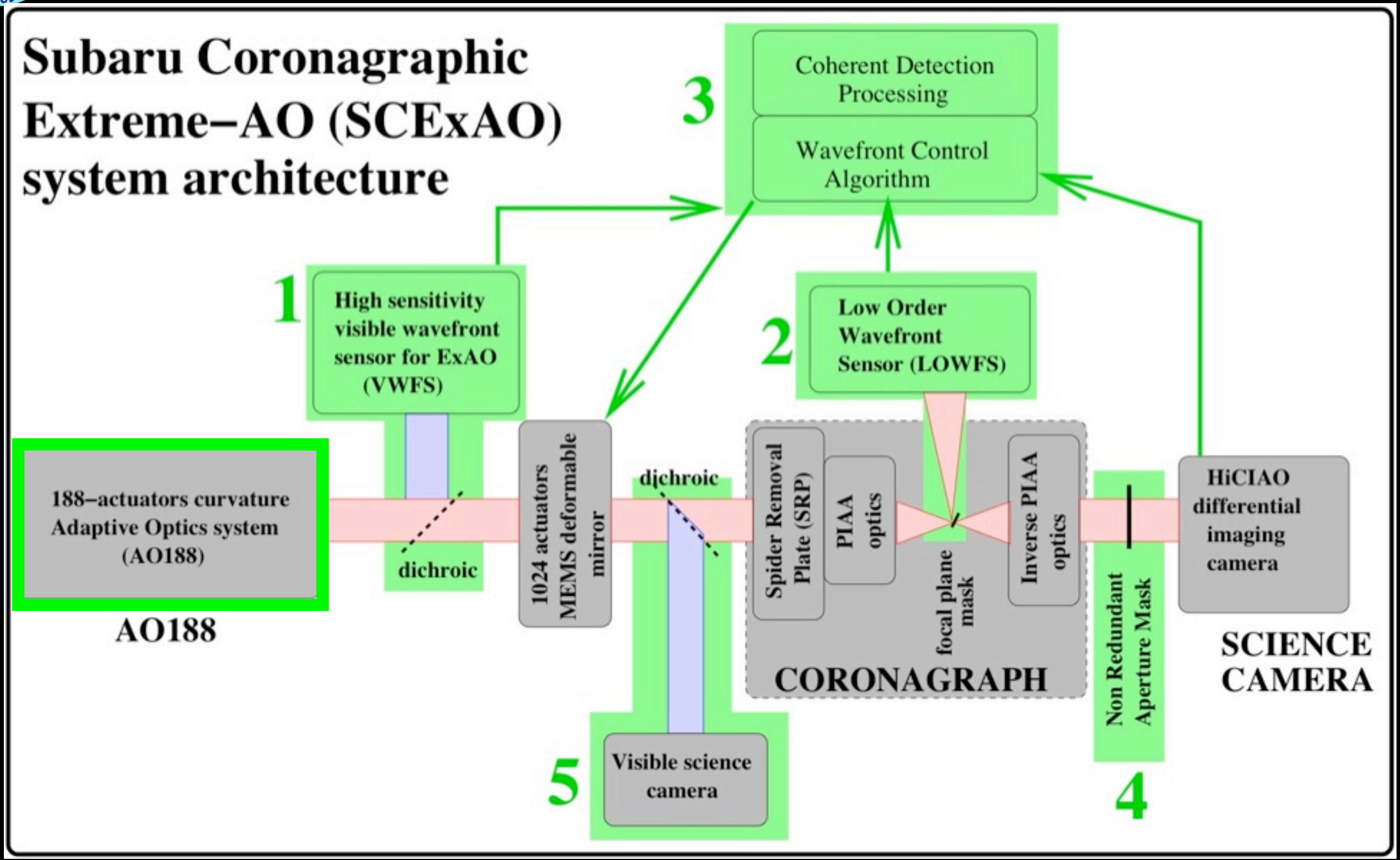


System architecture



Designed as a highly flexible, evolvable platform
Efficient use of AO188 system & HiCIAO camera

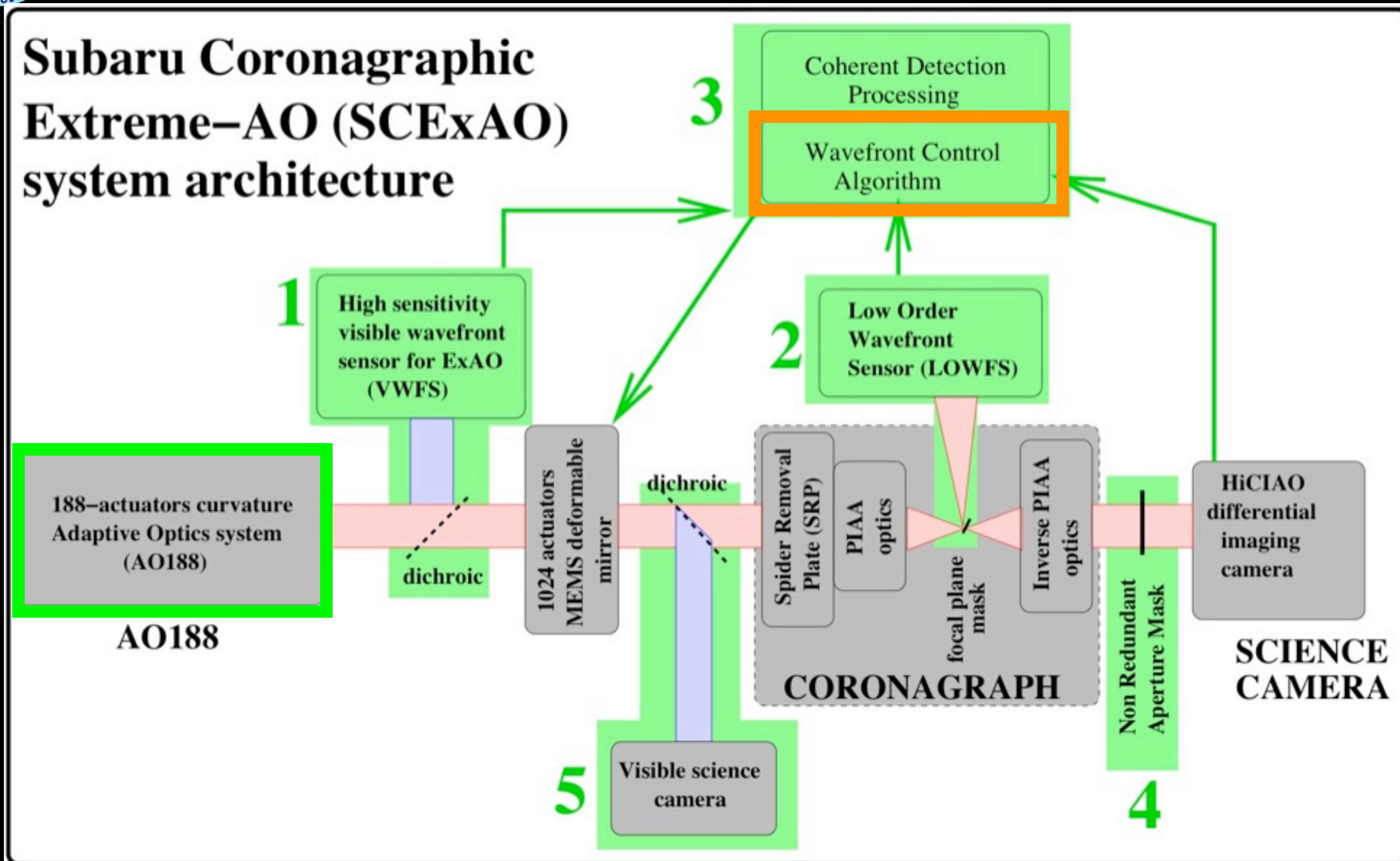
System architecture



Designed as a highly flexible, evolvable platform

Efficient use of AO188 system & HiCIAO camera

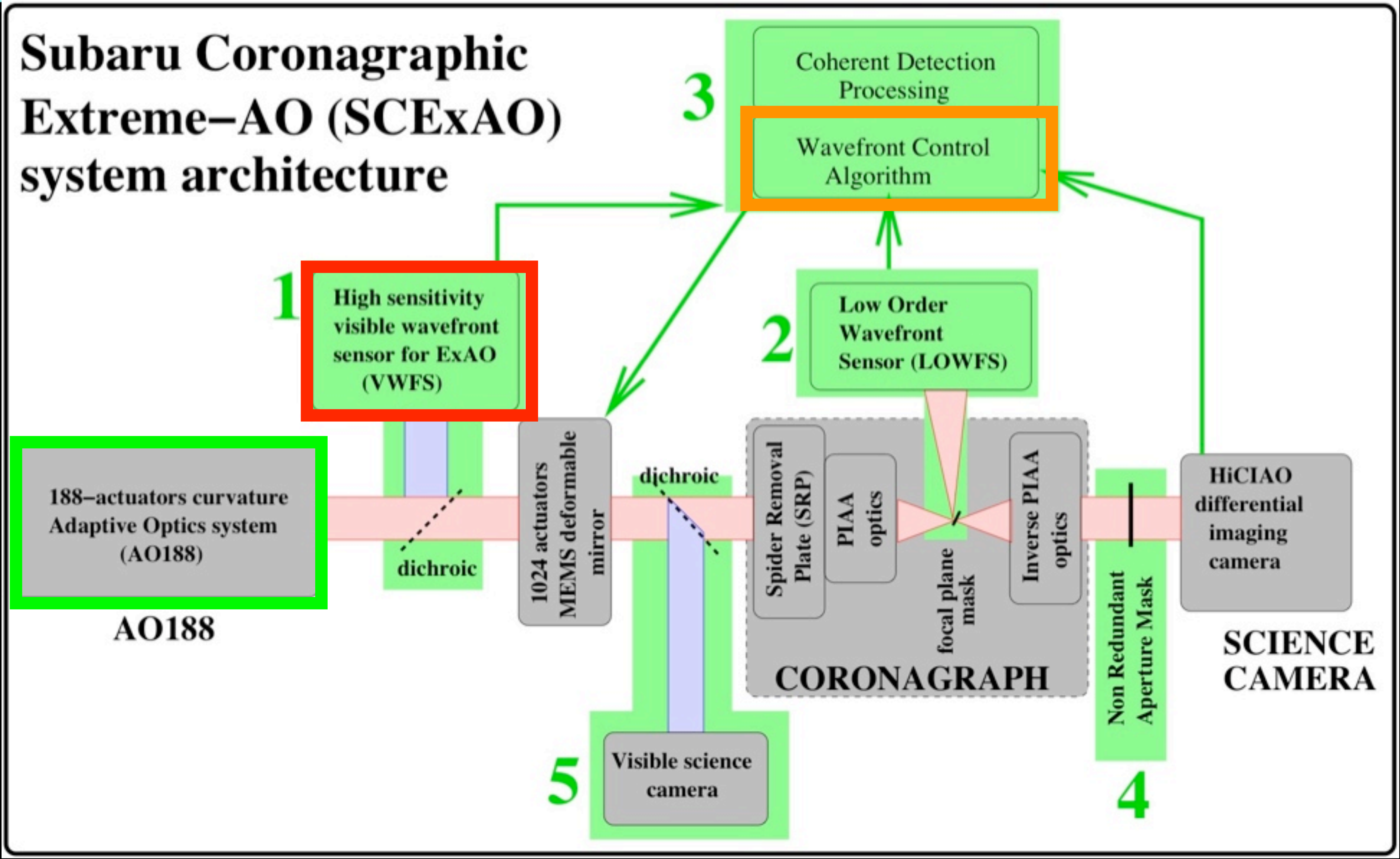
System architecture



Designed as a highly flexible, evolvable platform

Efficient use of AO188 system & HiCIAO camera

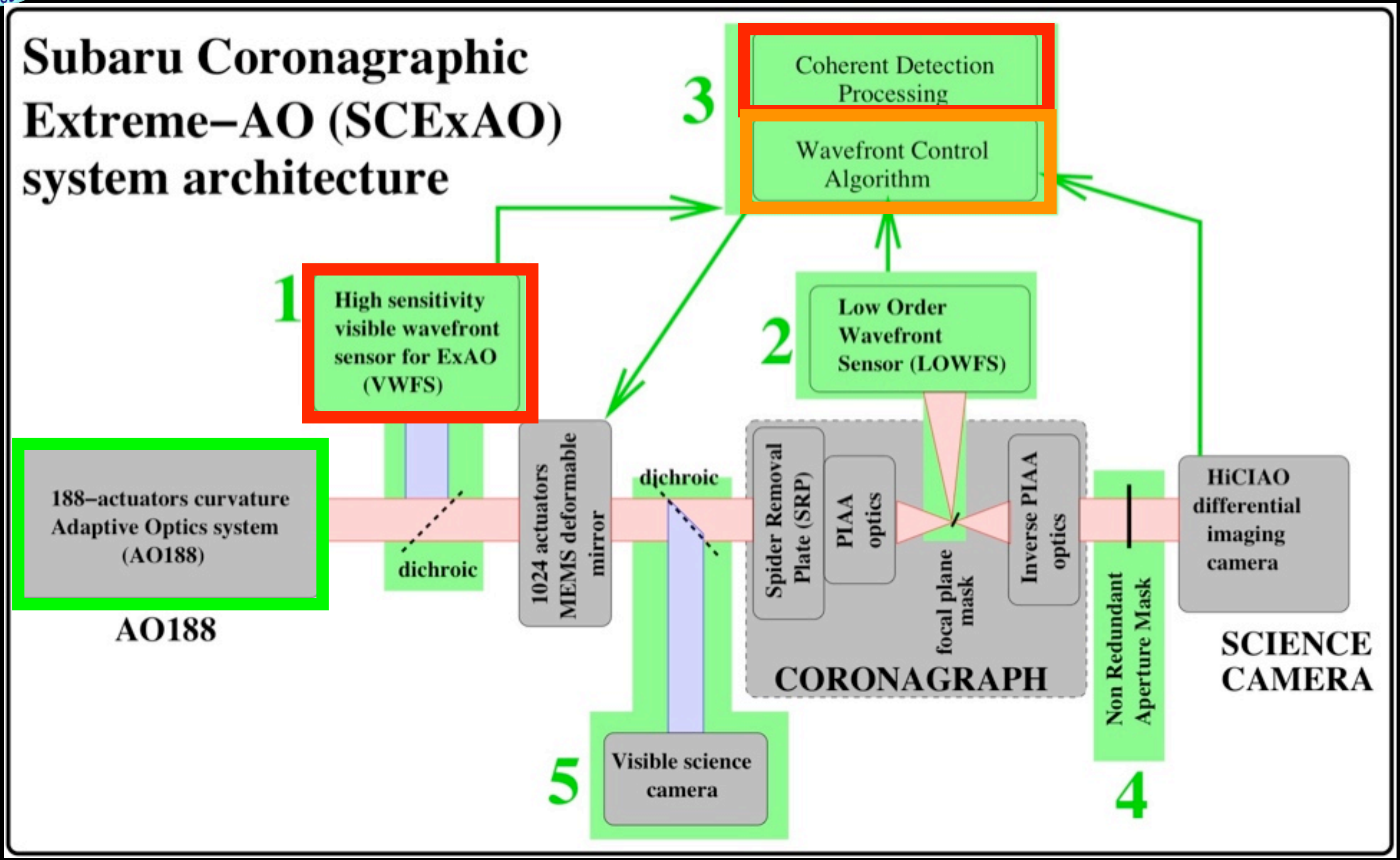
System architecture



Designed as a highly flexible, evolvable platform

Efficient use of AO188 system & HiCIAO camera

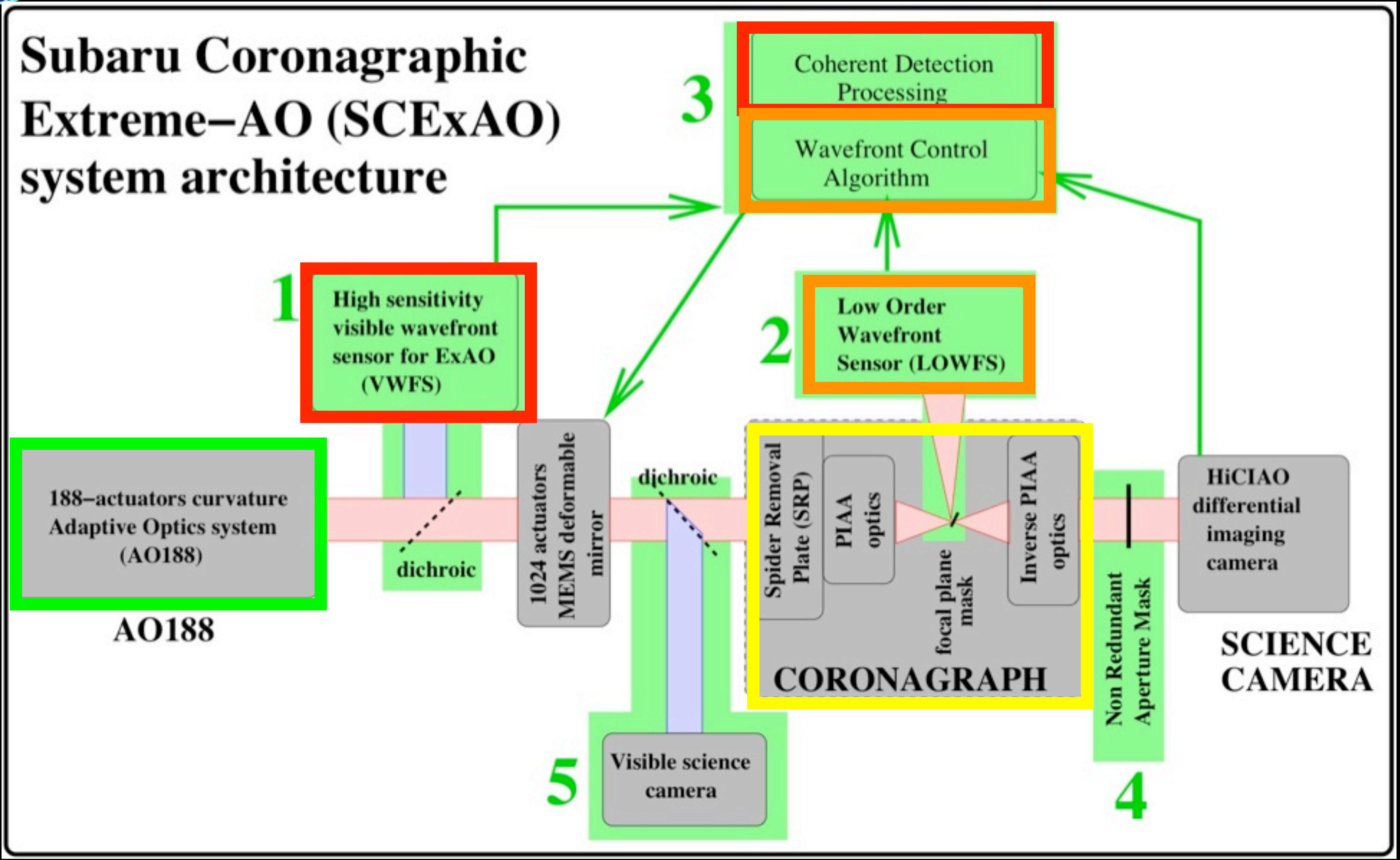
System architecture



Designed as a highly flexible, evolvable platform

Efficient use of AO188 system & HiCIAO camera

System architecture



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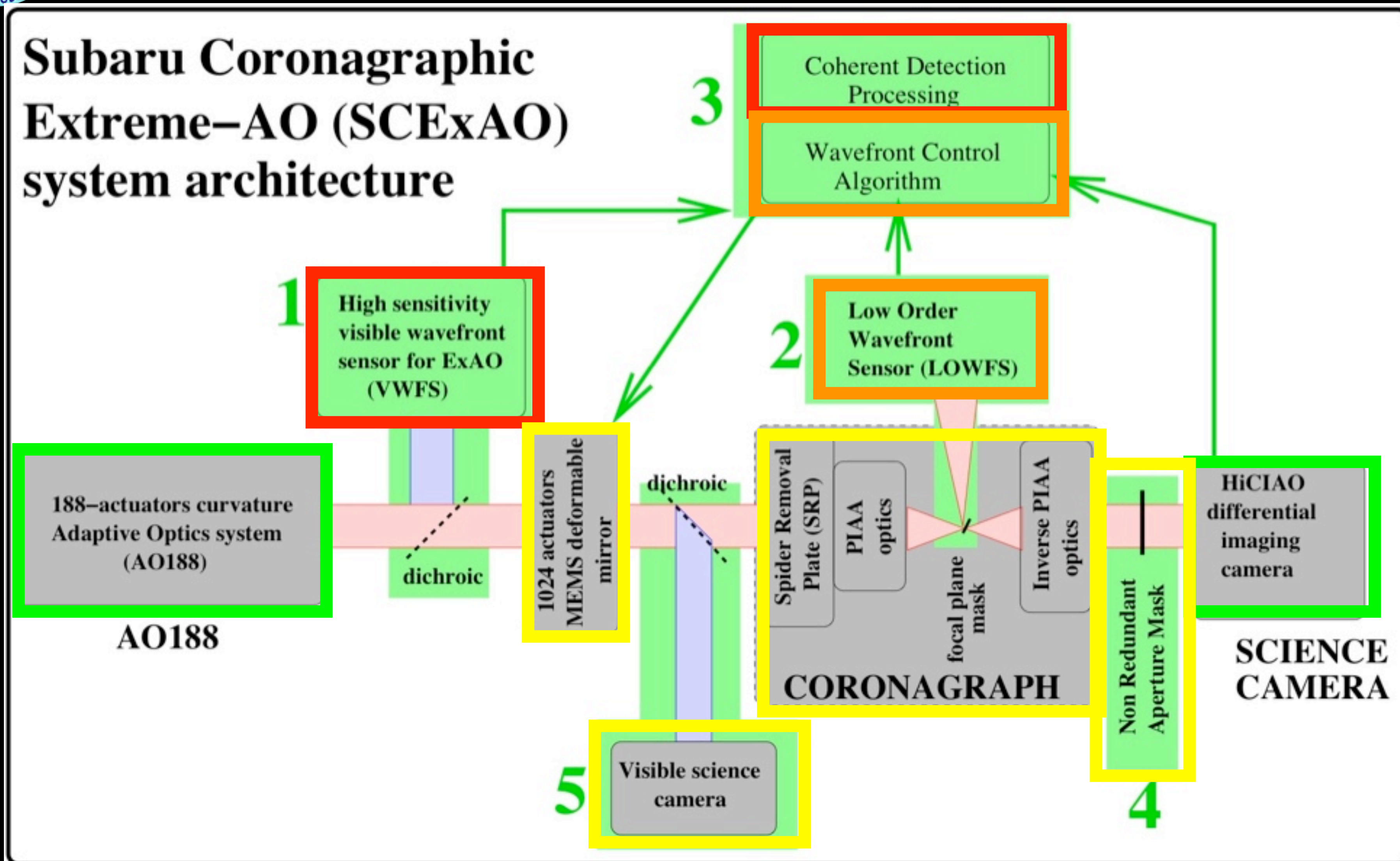

Designed as a highly flexible, evolvable platform

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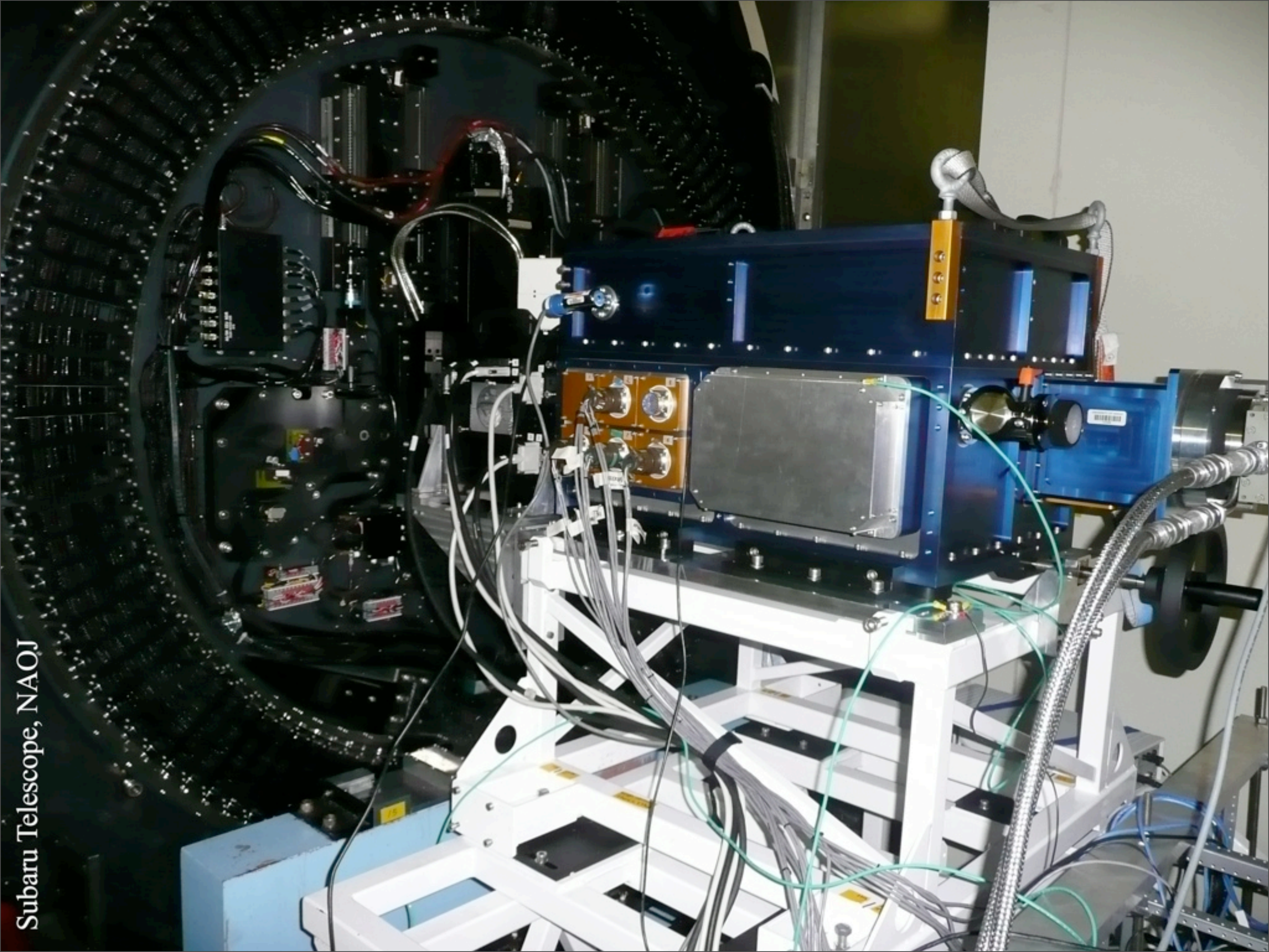
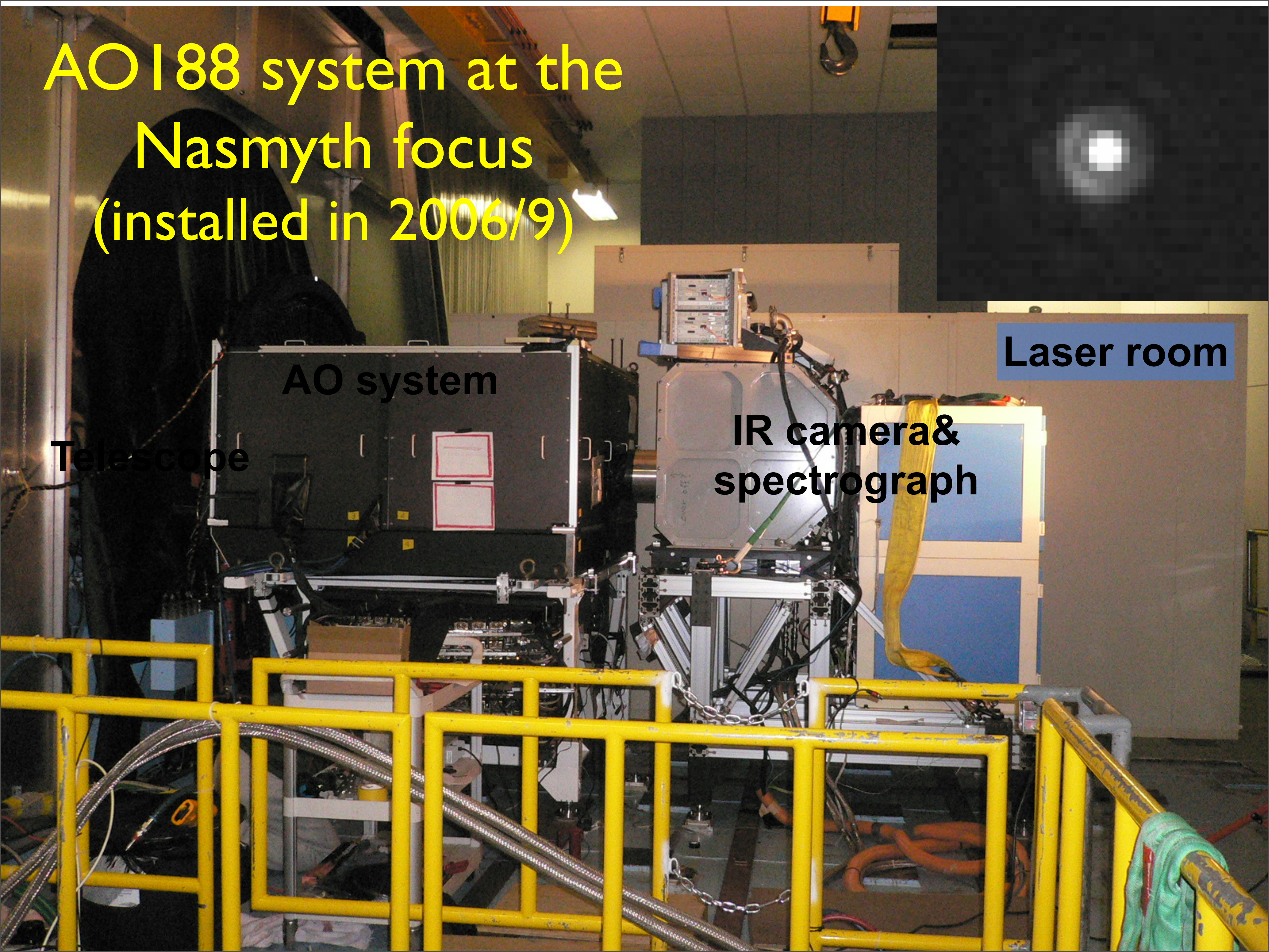
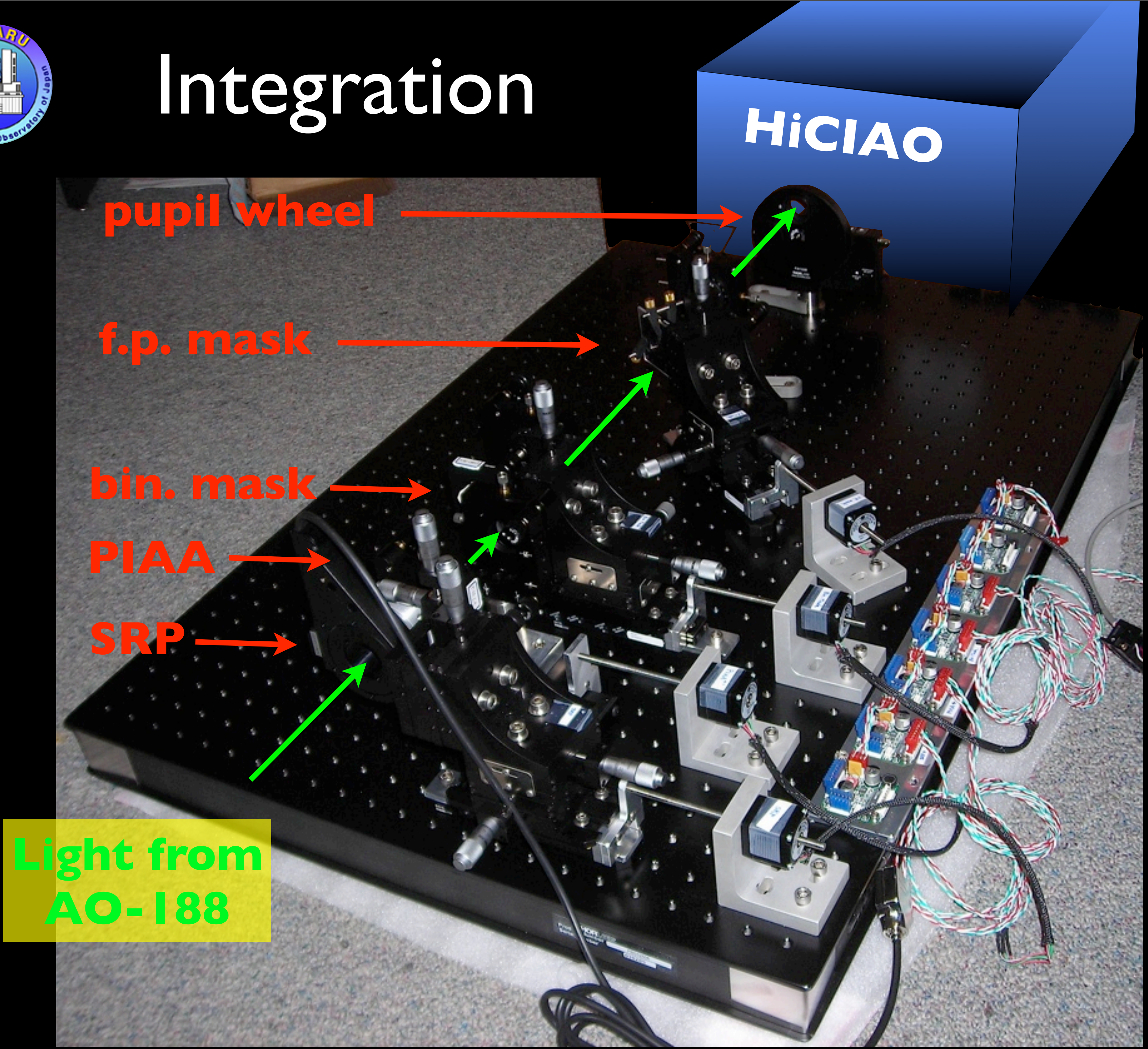

Subaru Telescope, NAOJ

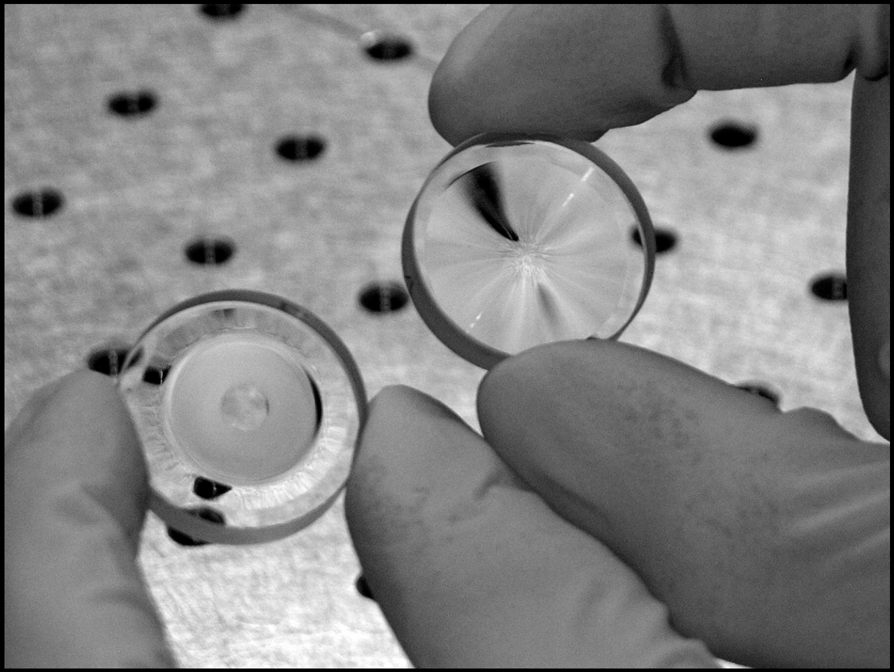
AO188 system at the Nasmyth focus (installed in 2006/9)



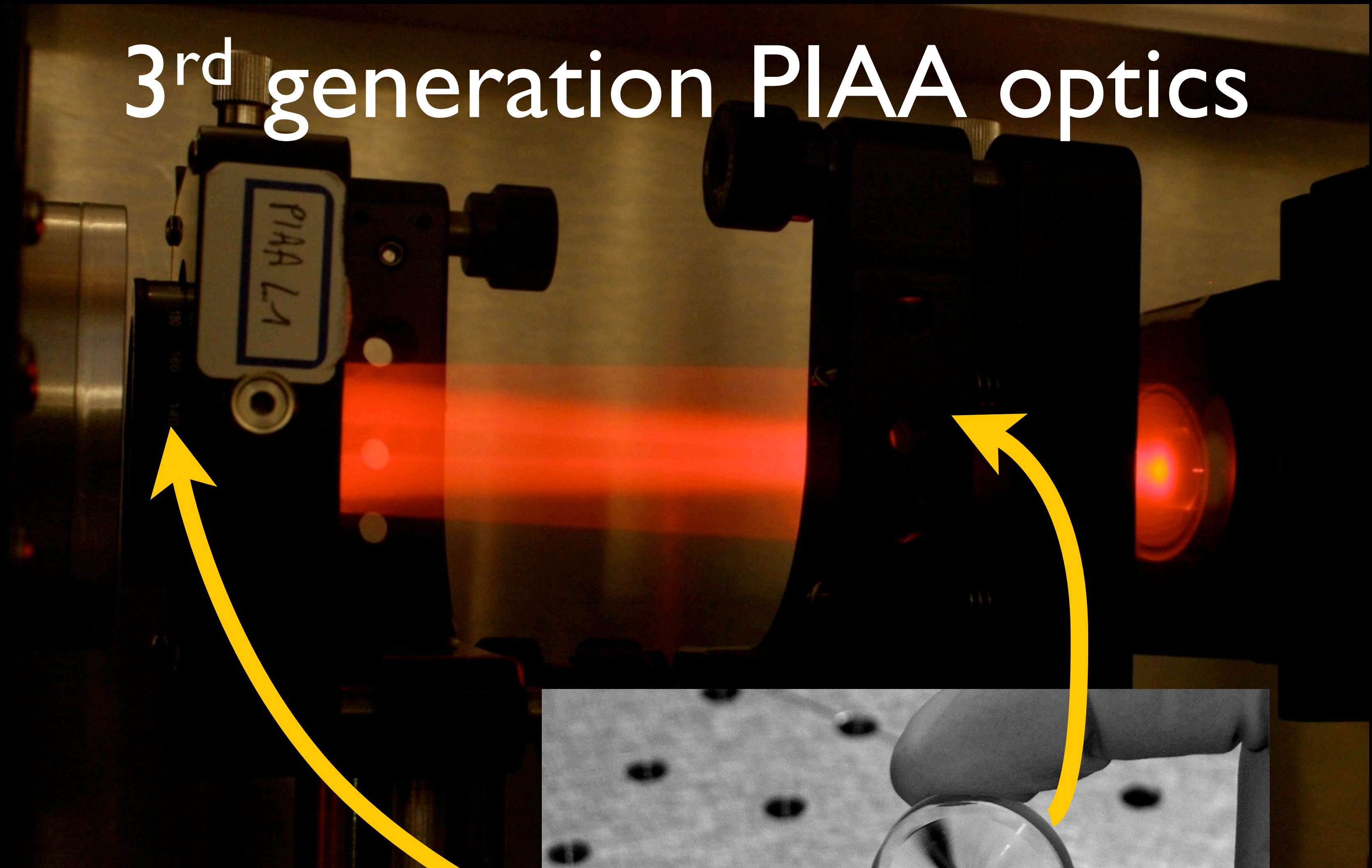
Integration

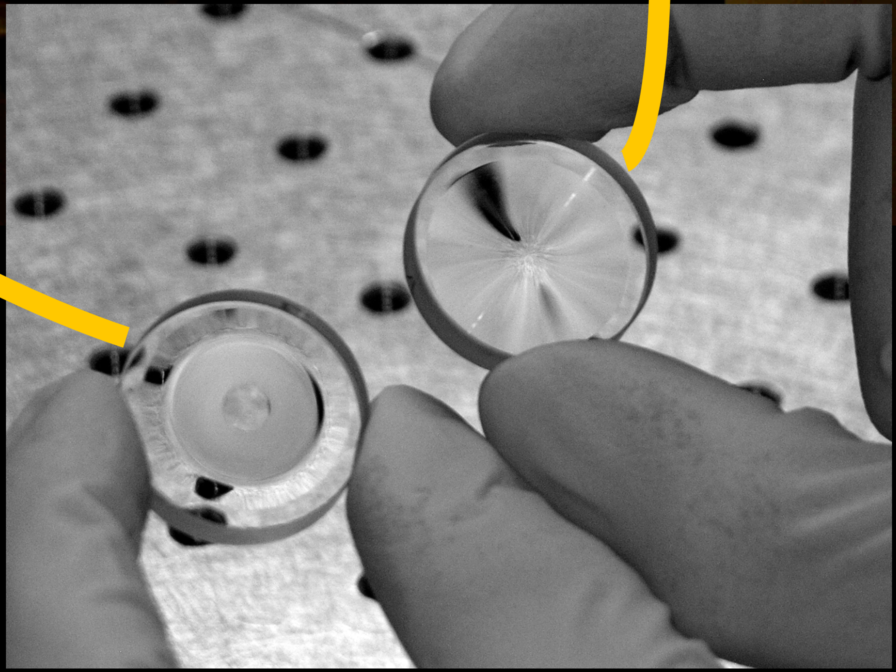


3rd generation PIAA optics



3rd generation PIAA optics

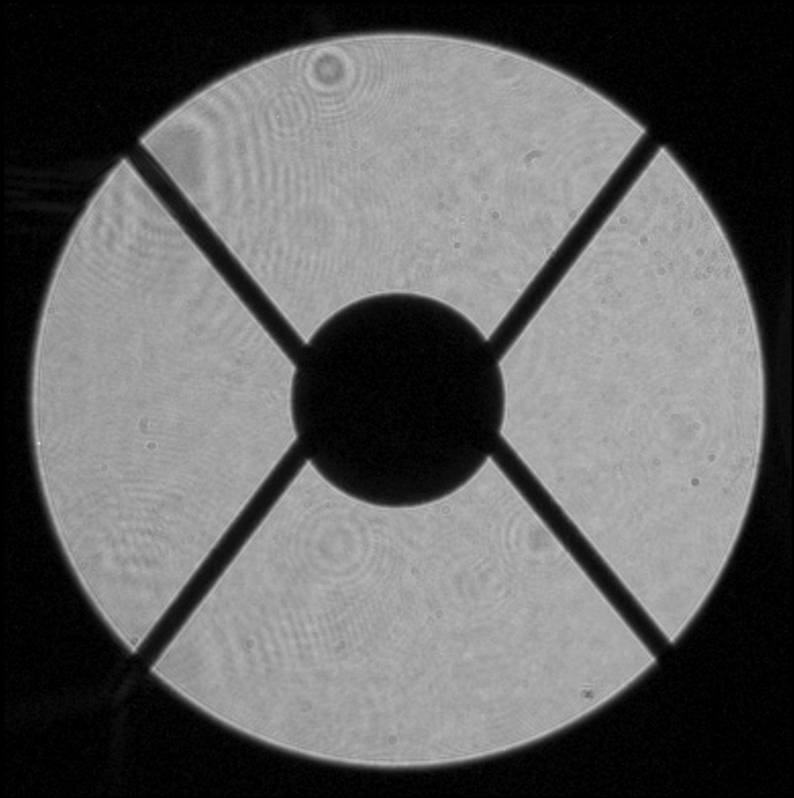




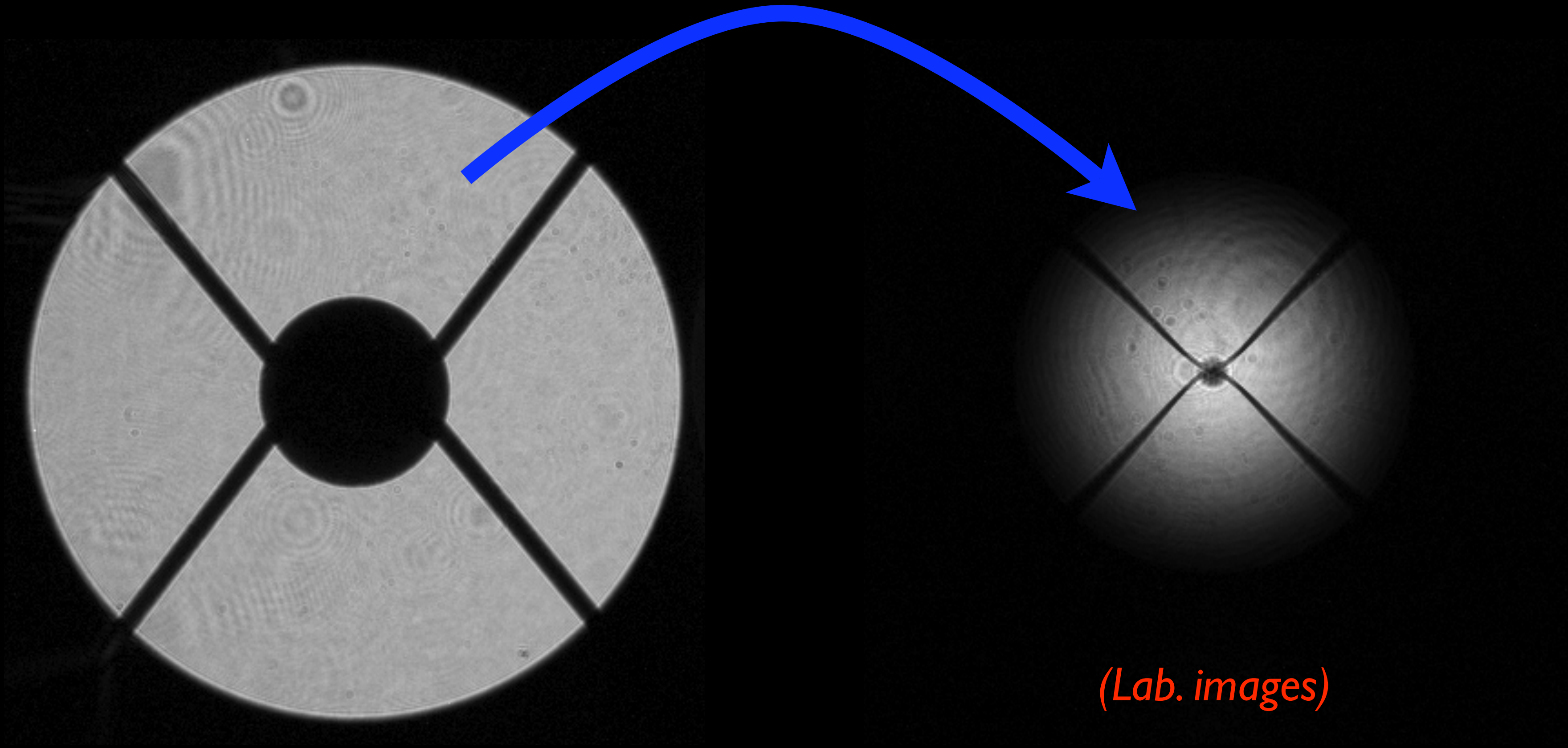
- On-axis lenses
- Lenses are 96 mm apart
- Apodize the beam
- Remove the central obscuration

Optics tested, and good to go!

Apodized beam



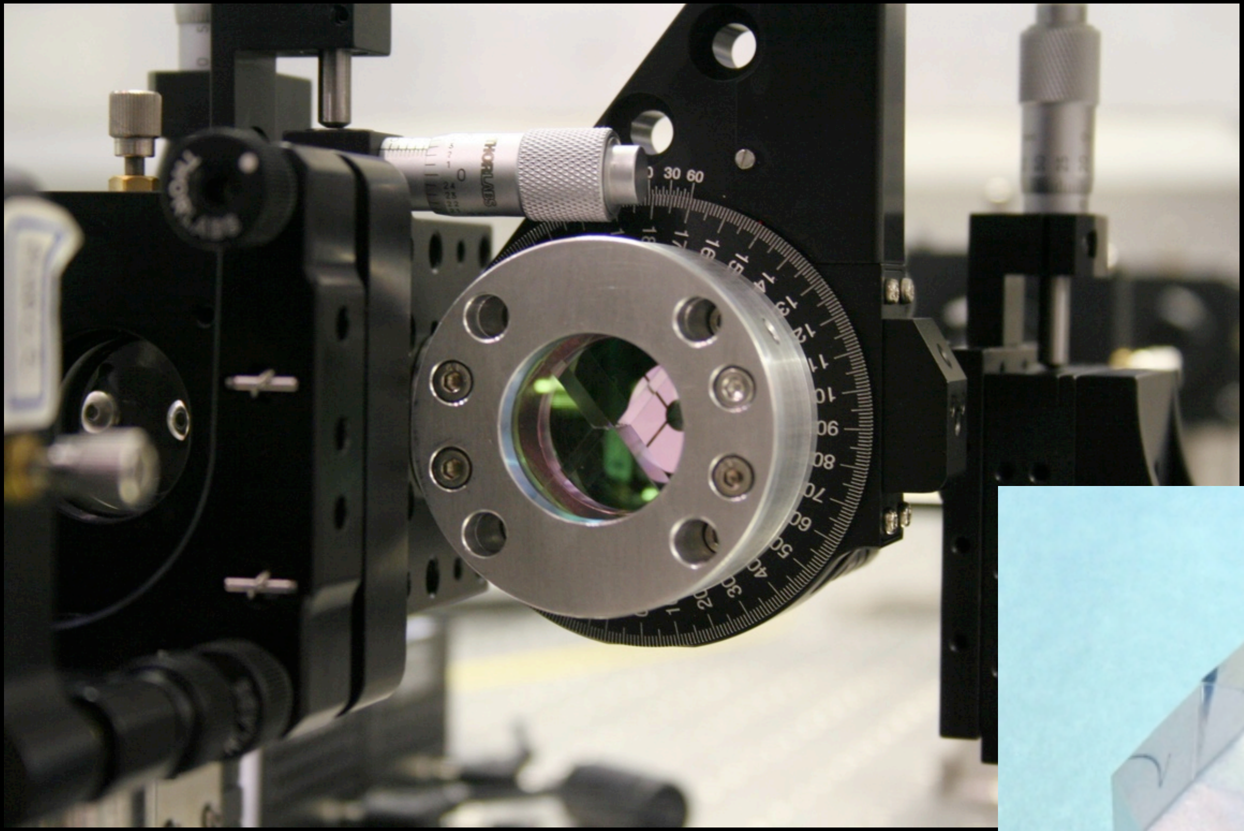
Apodized beam

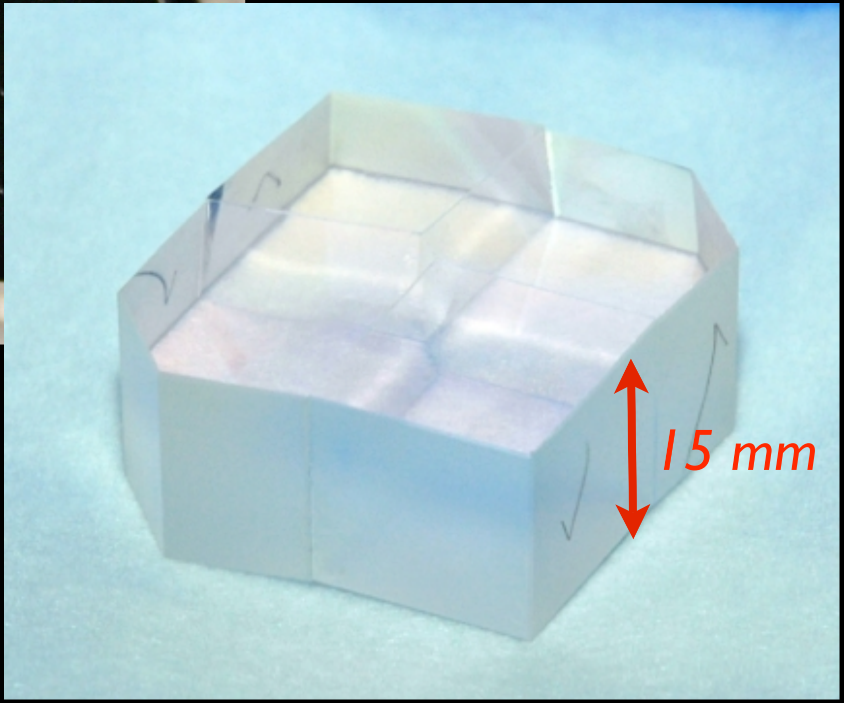


(Lab. images)

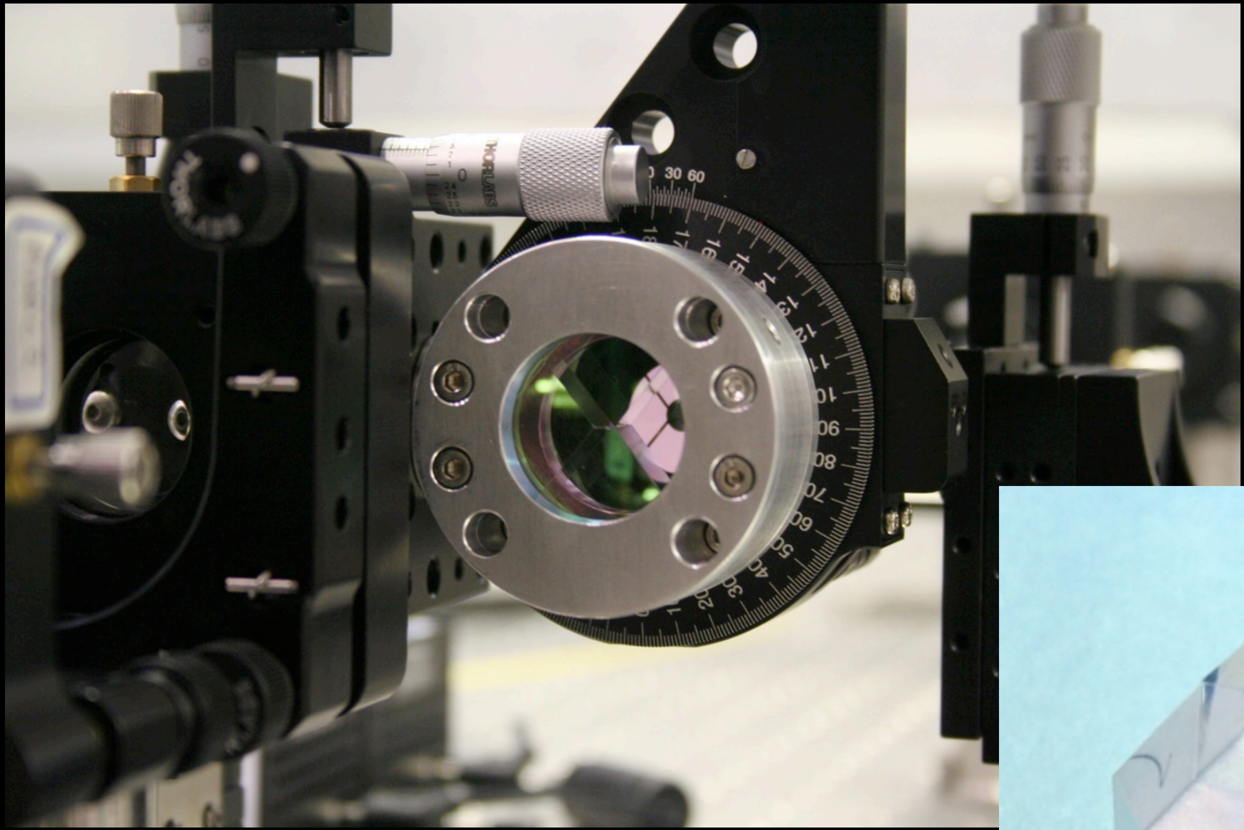
The PIAA does its job but spider vanes remain...

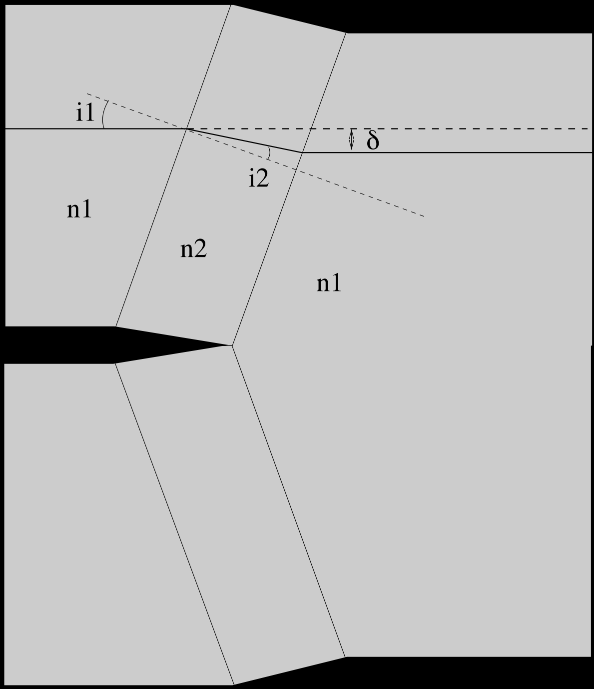
Spider Removal Plate

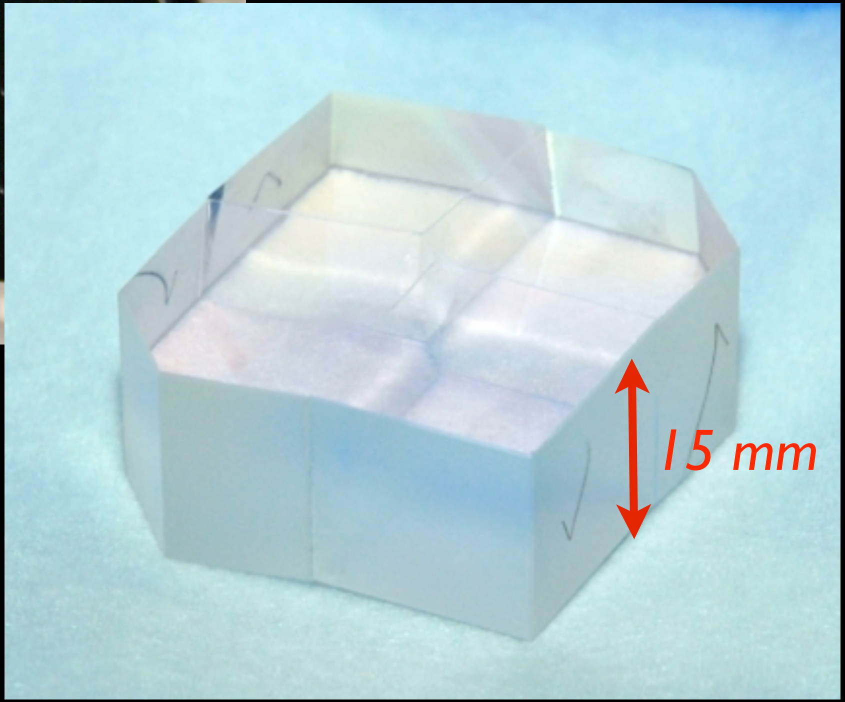




Spider Removal Plate







- 15 mm thick precision window
- Fused Silica
- Tilt angle: 5 +/- 0.02°

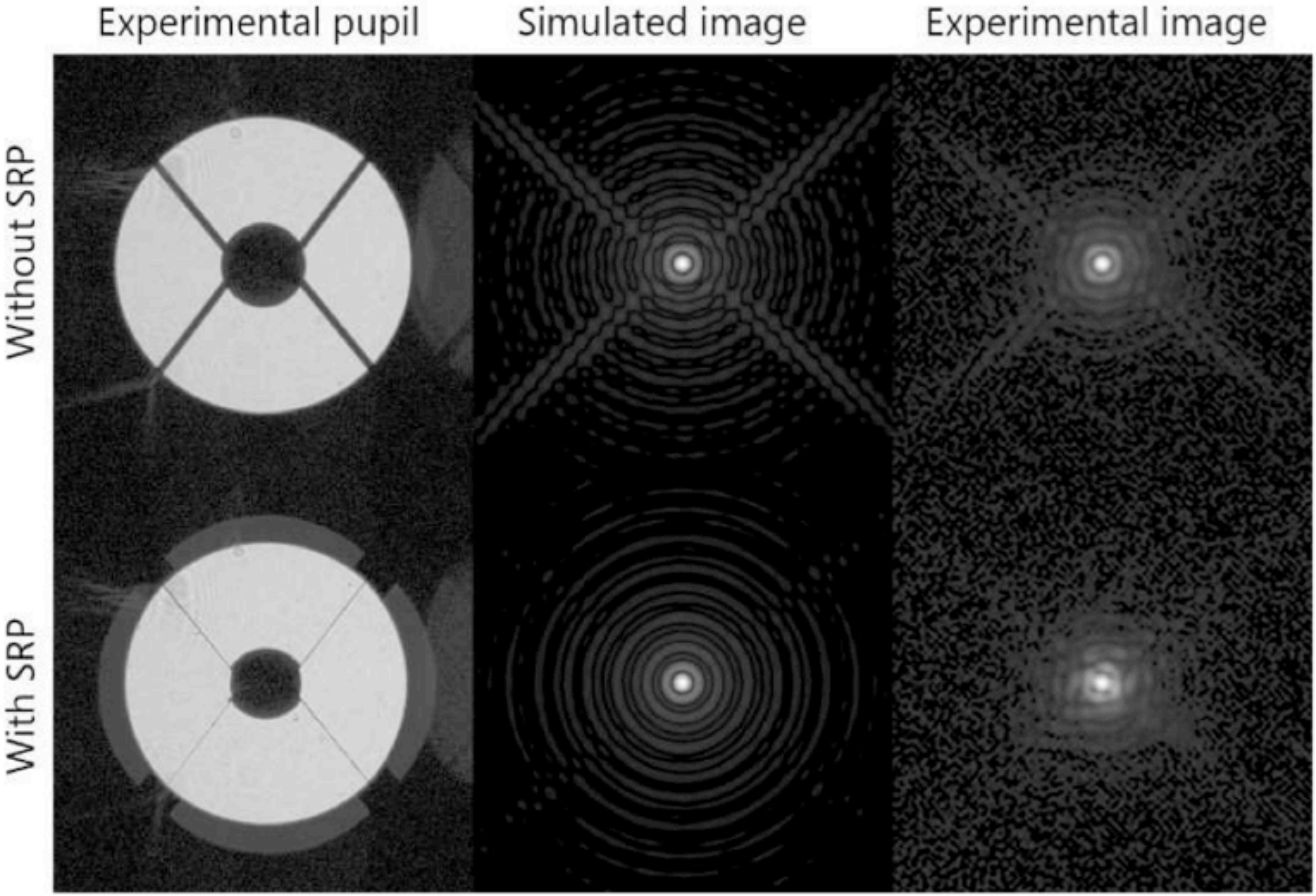


Fig. 8.— Effect of the SRP on the pupil. The three top panels show (from left to right): an image taken with the camera in a location conjugated with the pupil plane, showing the mask simulating the Subaru telescope pupil, as well as the corresponding simulated and experimental images. The three bottom panels show the same images when the SRP is inserted into the beam (cf. Sec. 3.3 for details).

Putting things together: SRP+PIAA

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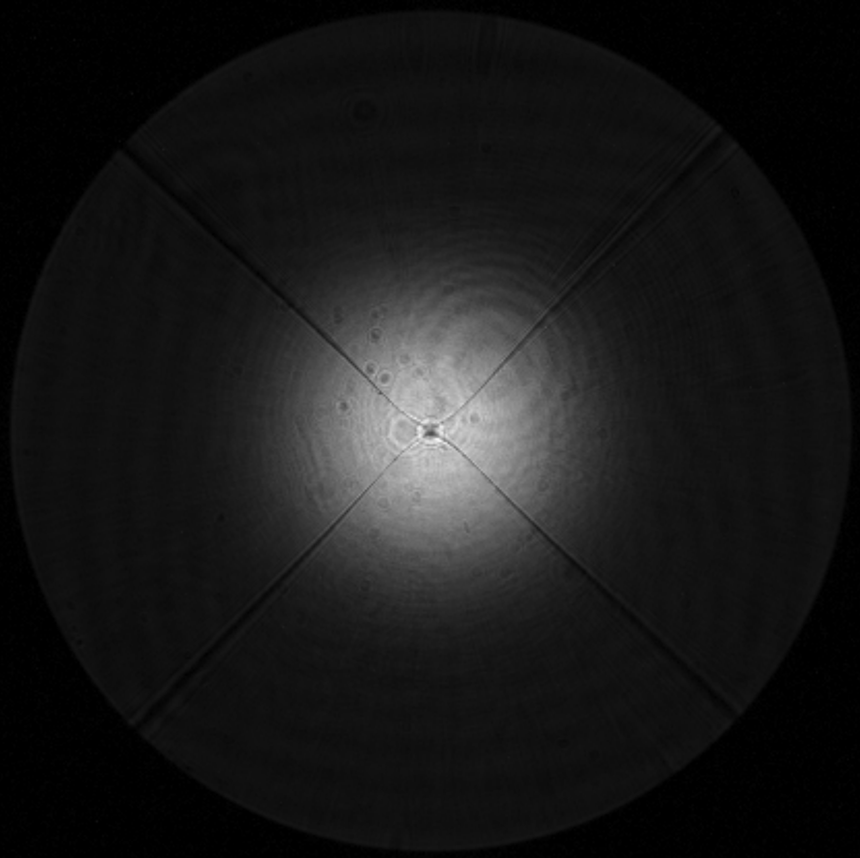
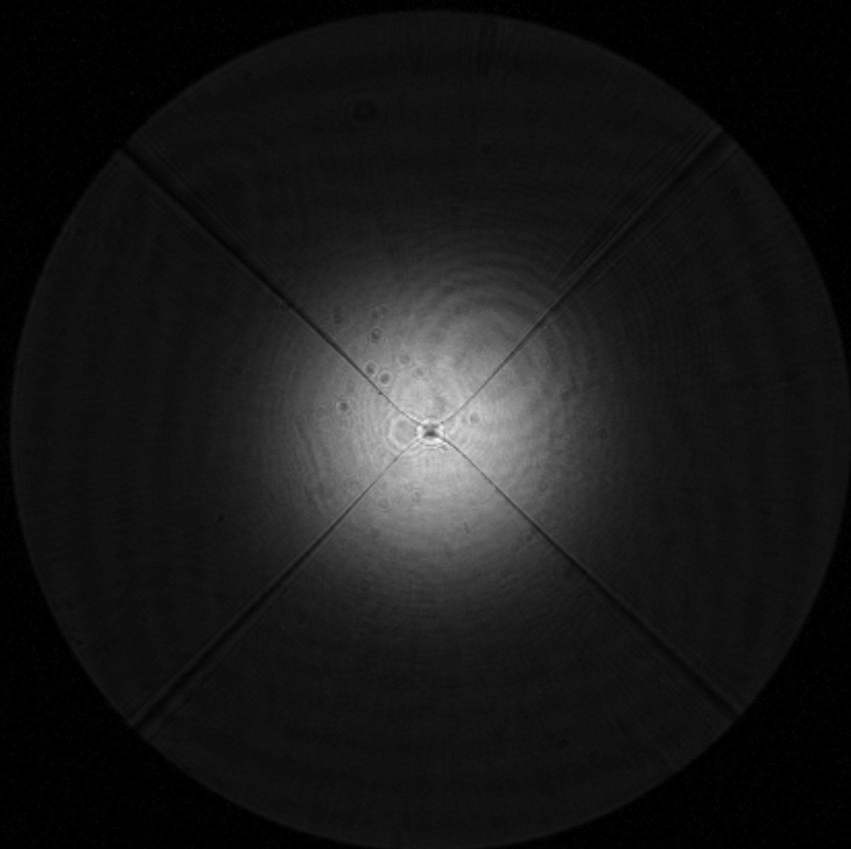


(Lab. image)

Putting things together: SRP+PIAA



(Lab. image)

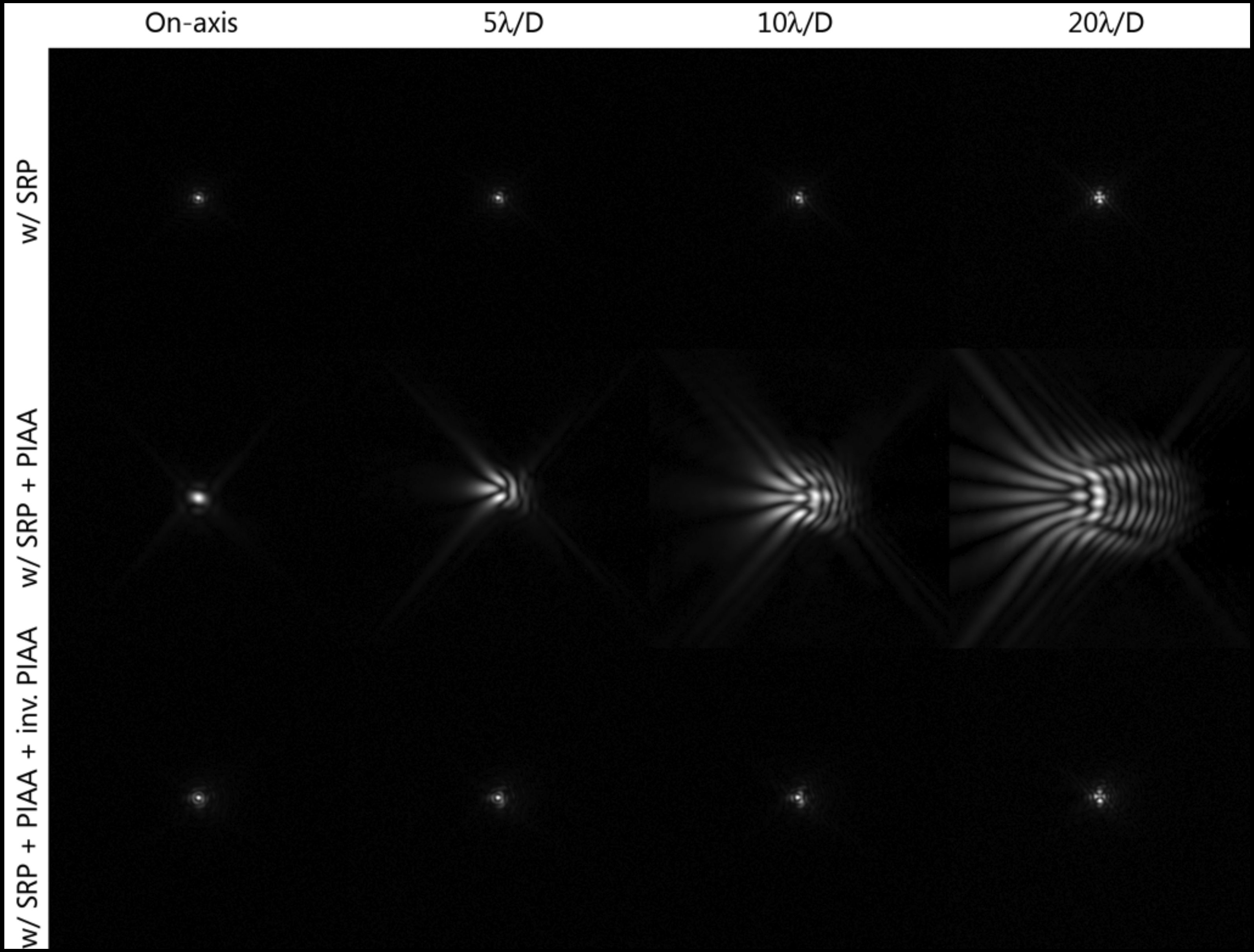
✓ Spider vanes gone

✓ Cent. obscur. gone

✓ Pupil apodized

-> coronagraphy with no losses with with inner working angle = 1 lambda/D

Recover the Field of view with "inverse PIAA" optics



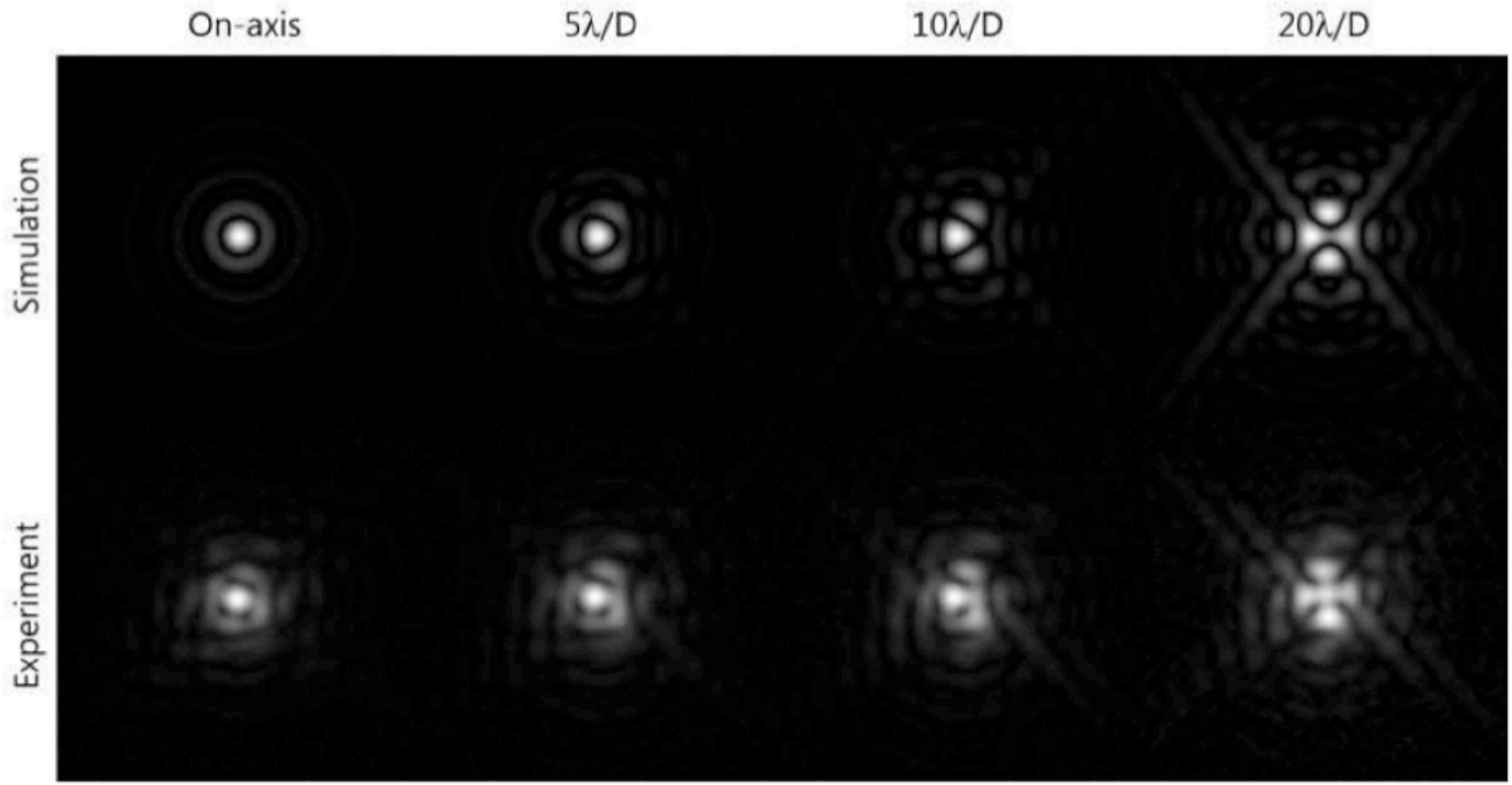
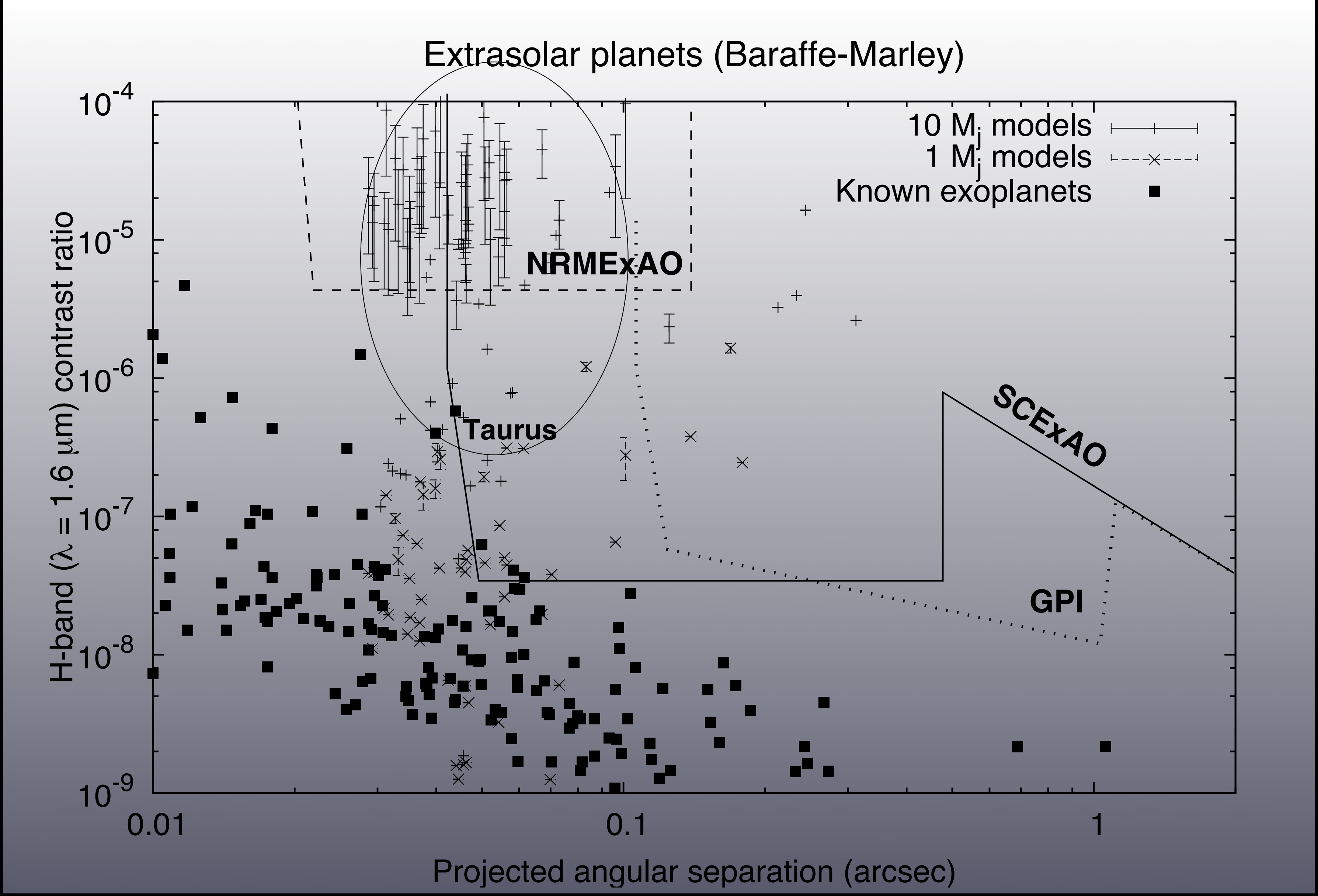


Fig. 12.— Comparison between simulated and experimental images of an off-axis source, from 0 to 20 λ/D with a 5 λ/D step. The field of view of each image is $\pm 12\lambda/D$.

Expected performance?

Expected performance?



Summary

- Coronagraphy: Many high performance coronagraph concepts. Recent advances are 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 x100 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
  - Potential to detect reflected light -> older planets closer to us
- **Space-based coronagraphy**
  - Direct imaging of Earths possible around the ~ 10 most favorable stars with a 1.4-m telescope and advanced coronagraph
  - A 4-m would allow atmosphere characterization for habitable planets