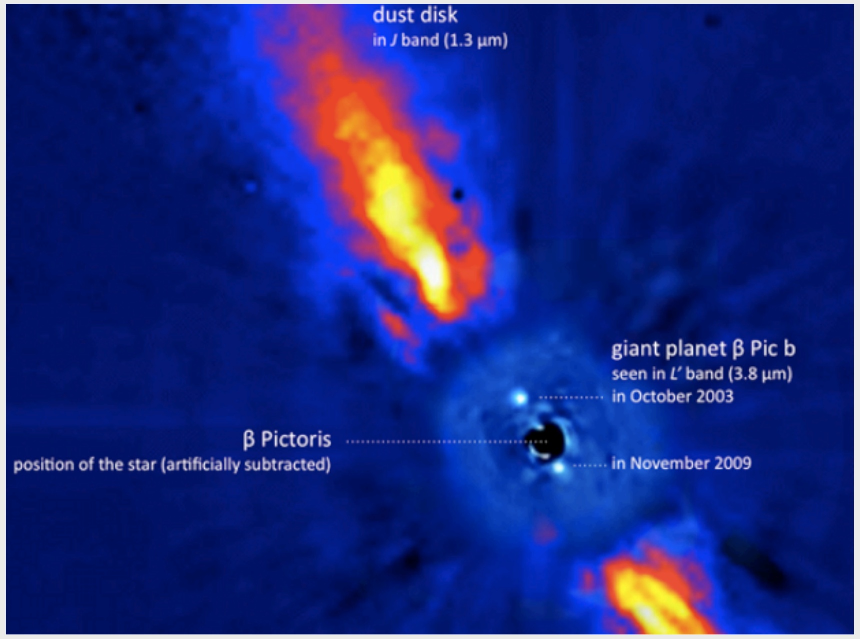
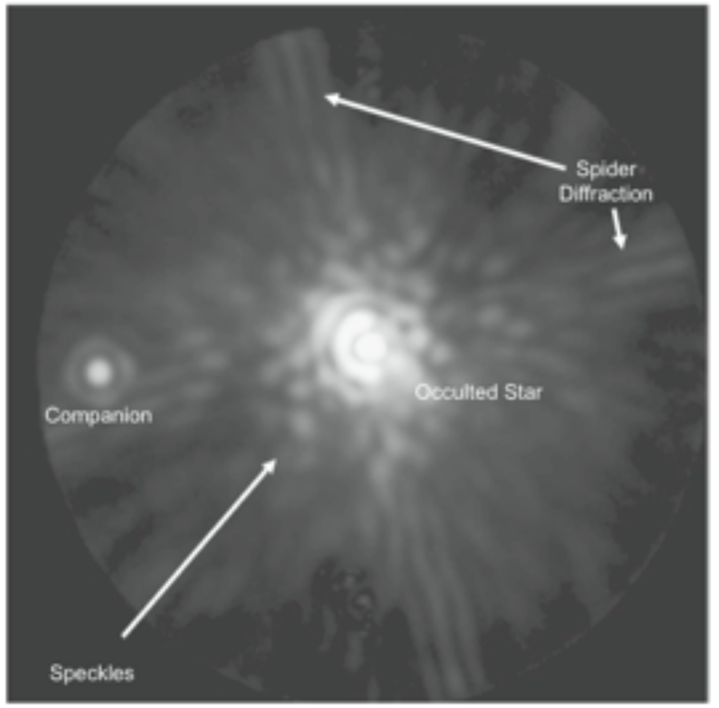


R. Claudi - INAF - Astronomical Observatory of Padova

DIRECT IMAGING OF EXTRASOLAR PLANETS

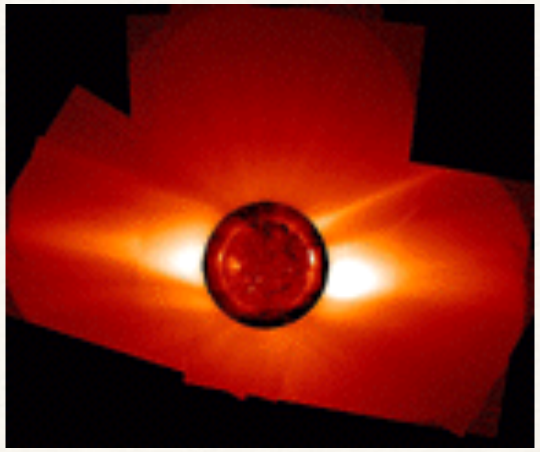
IV: CORONAGRAPHY

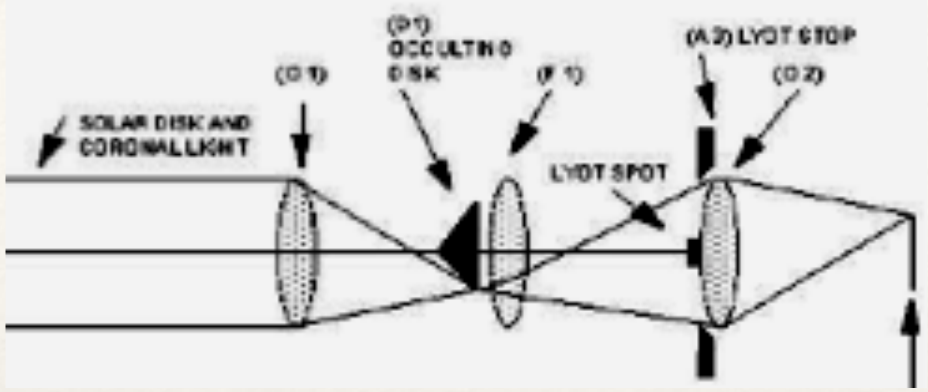


1st ADVANCED SCHOOL OF EXOPLANETARY SCIENCE
METHODS OF DETECTING EXOPLANETS
MAY 25-29, 2015 - VIETRI SUL MARE (SA)

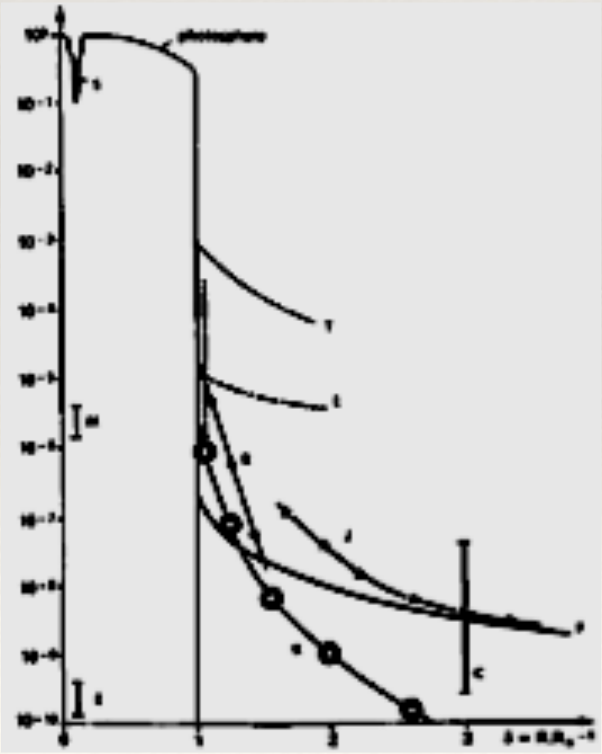
Coronography

Early solar coronagraphs

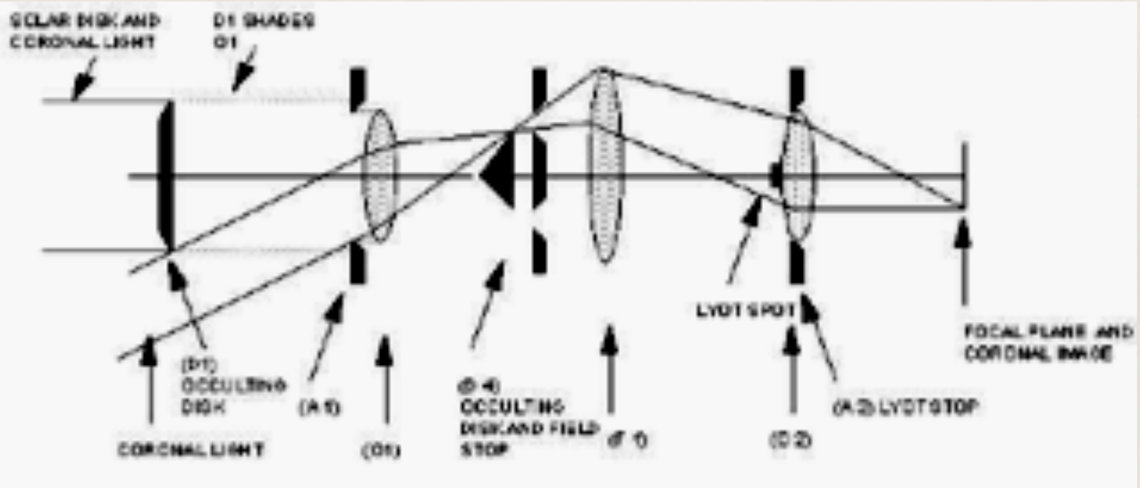




1932

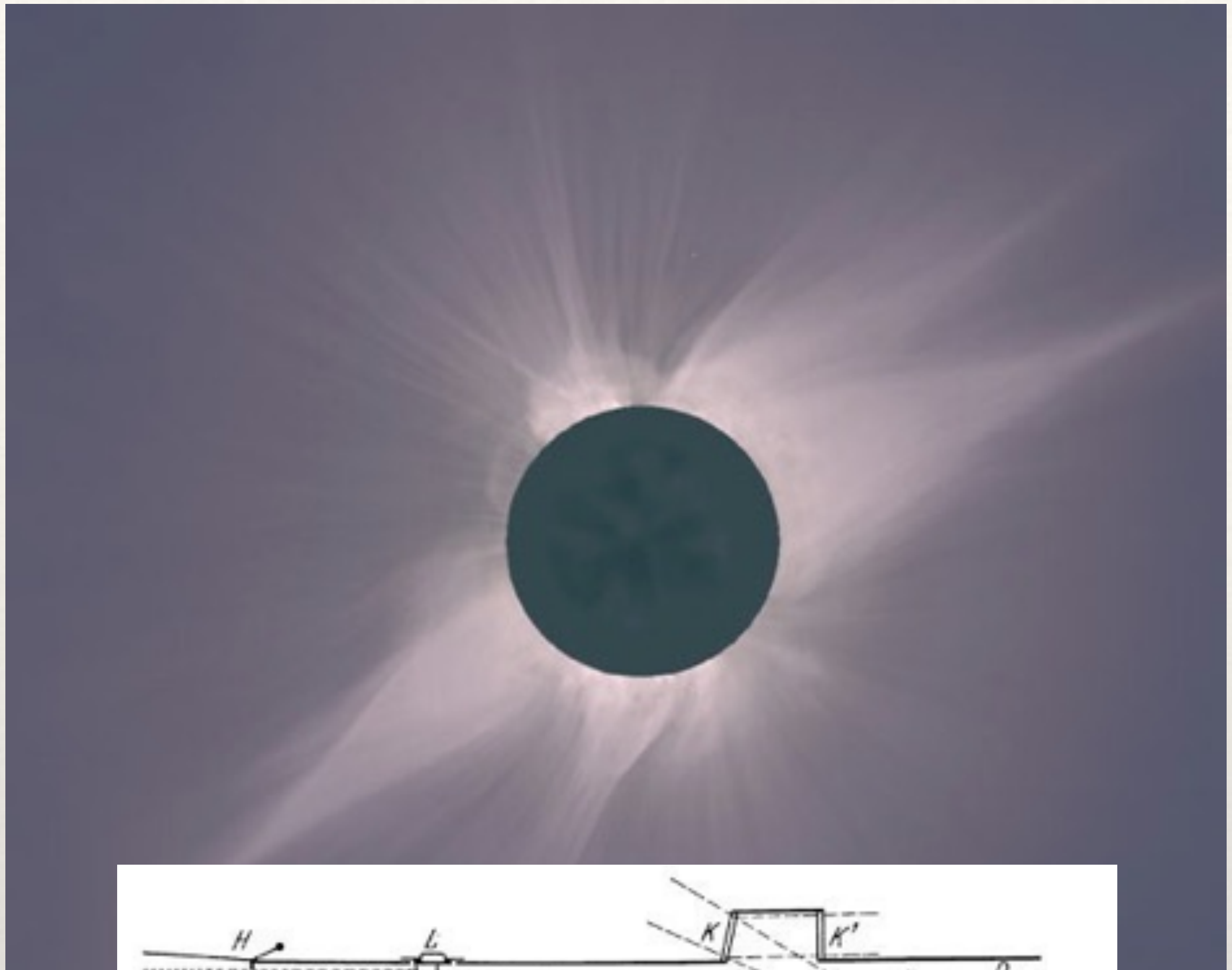


radial angle



1963

Solar Coronagraphy



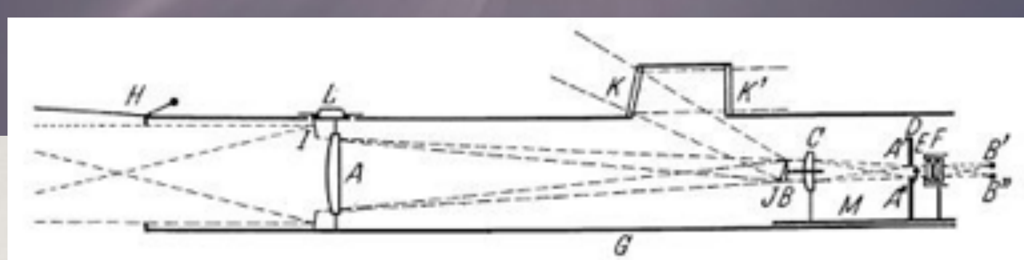
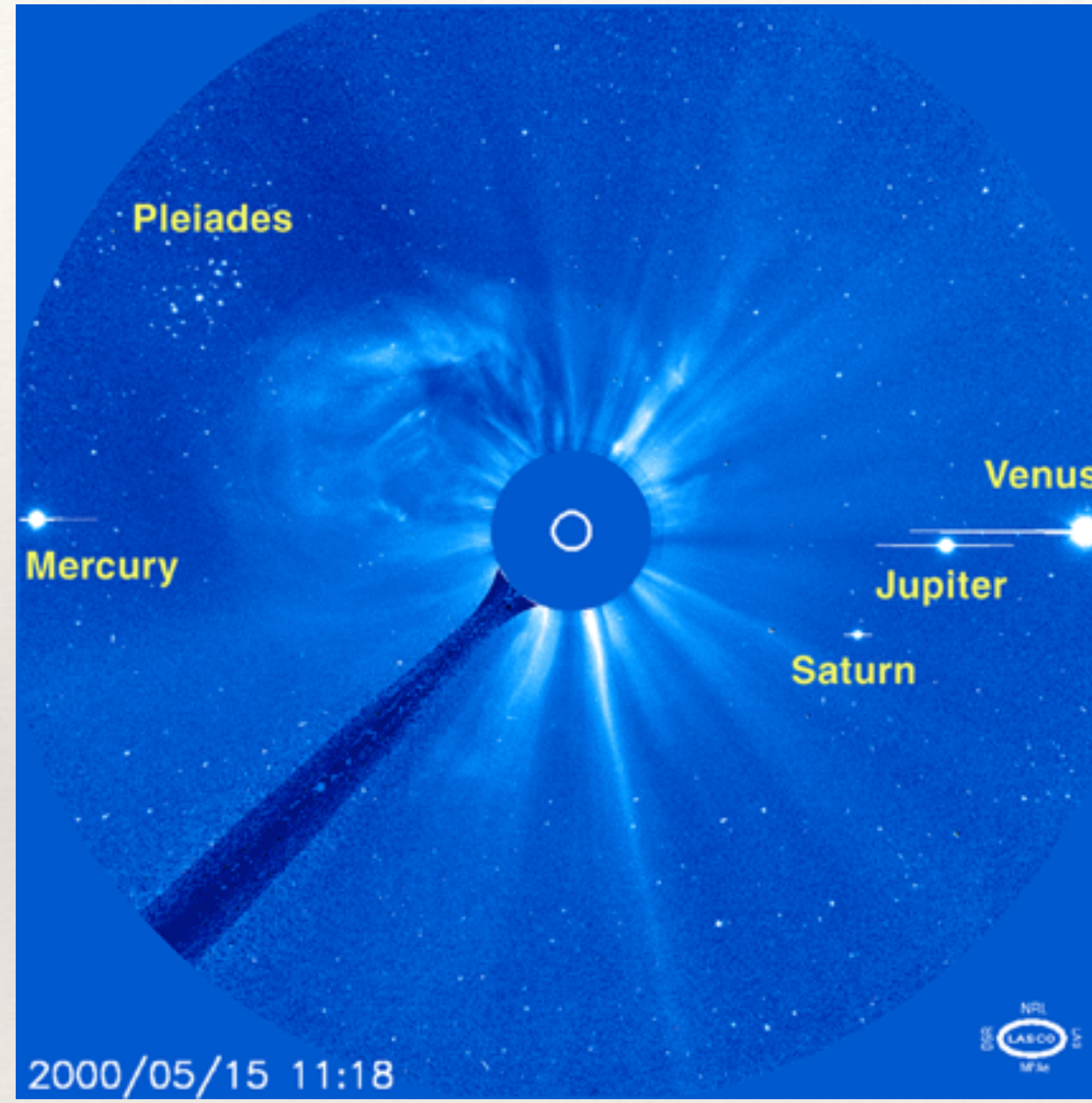


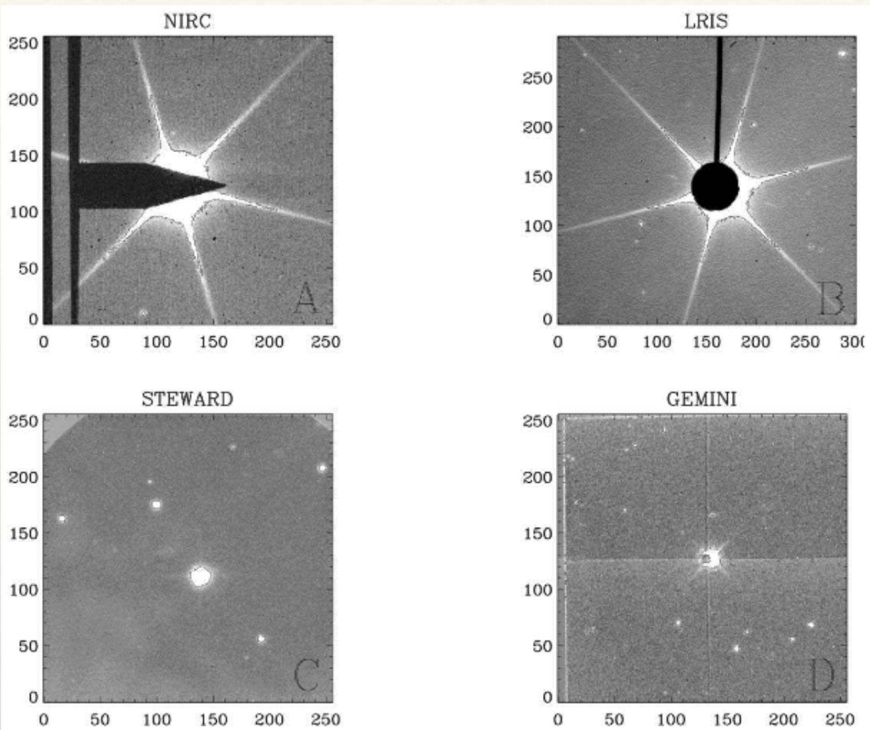
Schéma du coronographe.

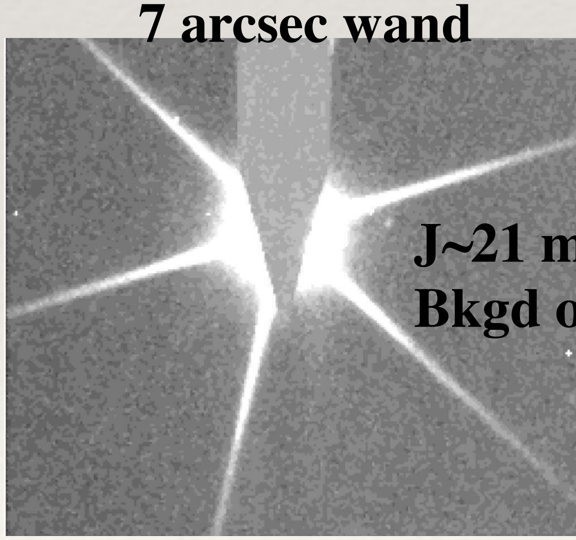
Lyot introduced this technique in 1930 in order to be able to observe the Solar Corona

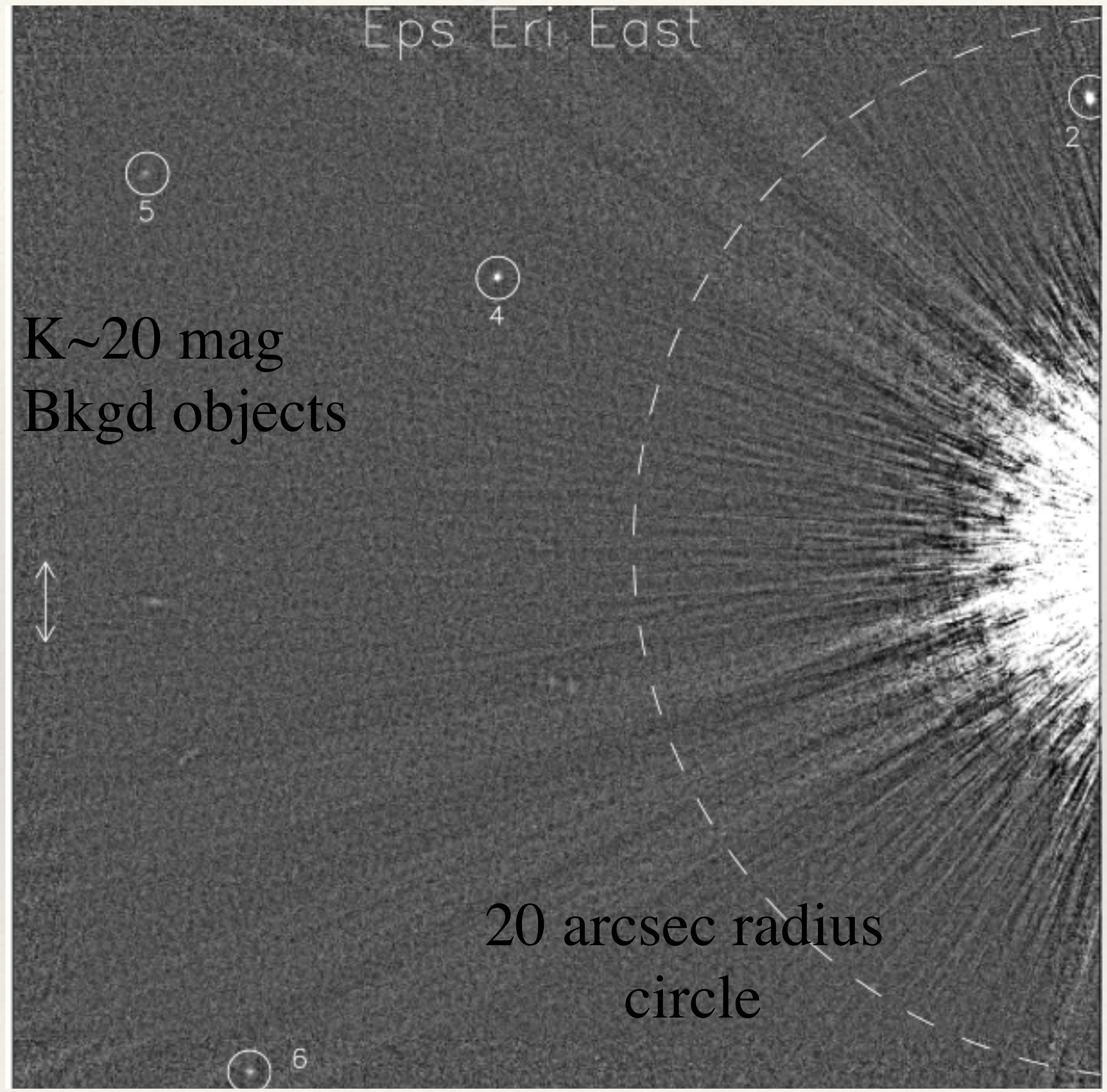
SOHO Image



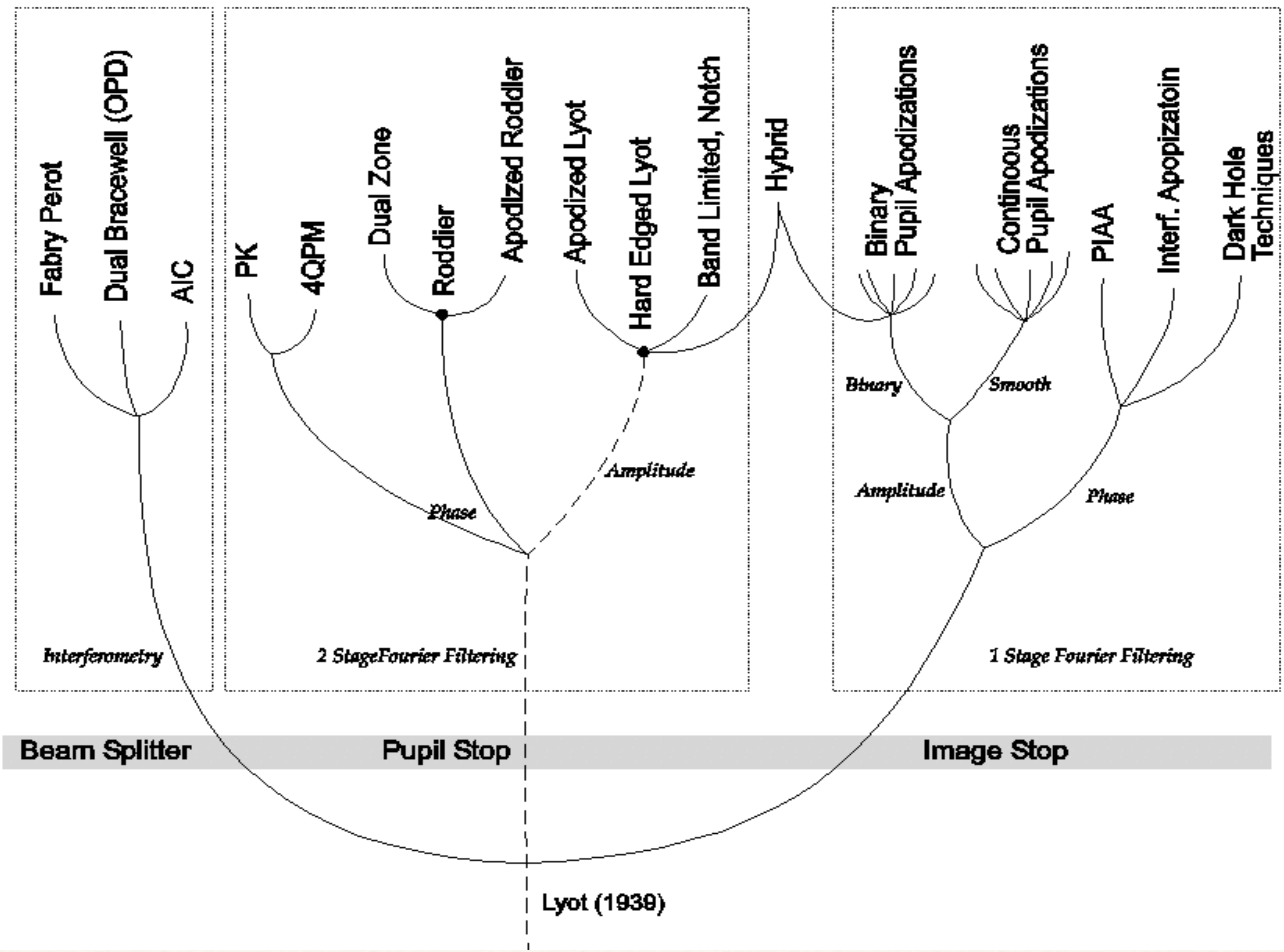
Stellar Coronagraphy







Ref: McCarthy & Zuckerman (2004); Macintosh et al (2003)

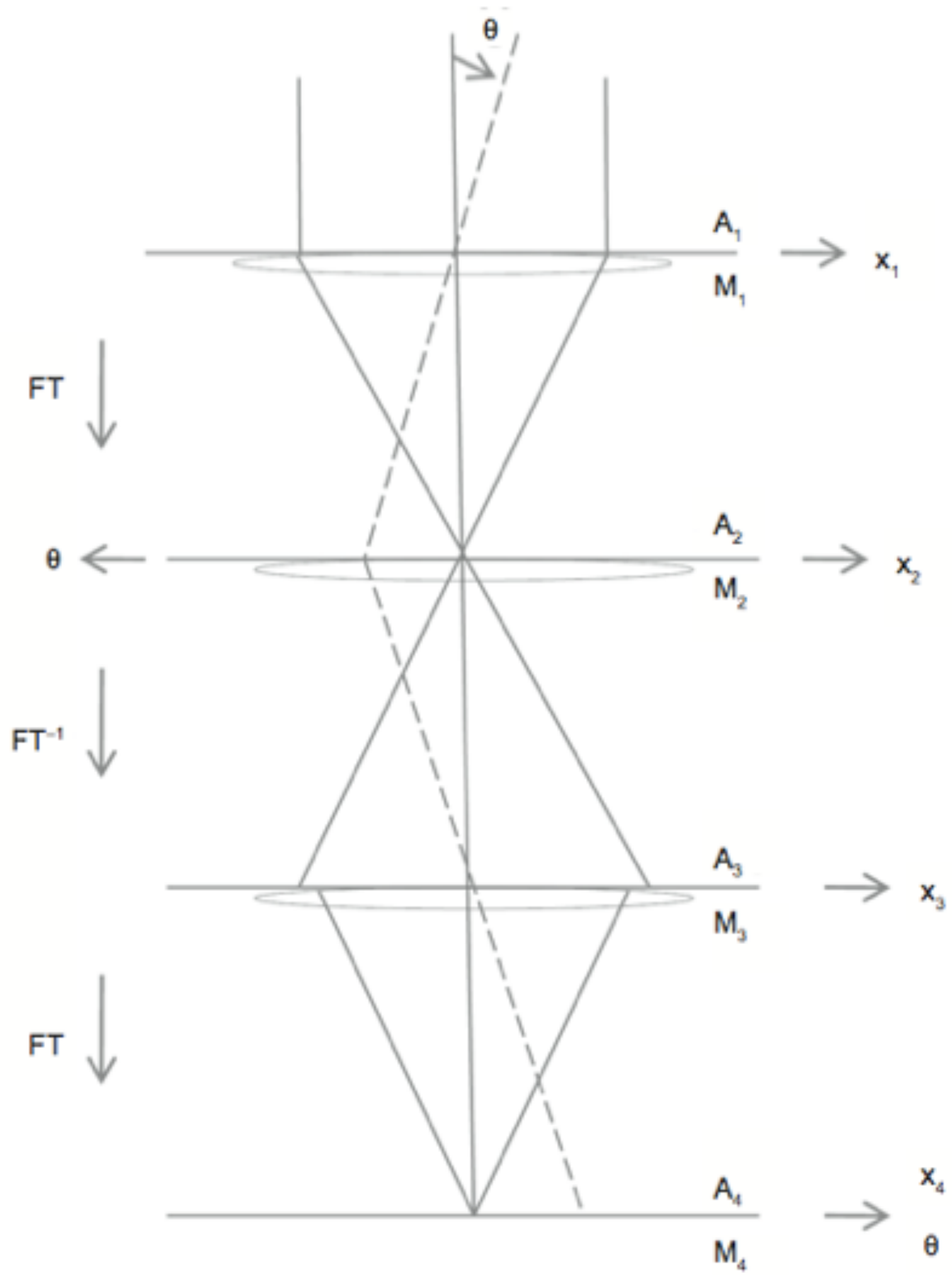

Fabry Perot
Dual Bracewell (OPD)
AIC
PK
4QPM
Dual Zone
Roddier
Apodized Roddier
Apodized Lyot
Hard Edged Lyot
Band Limited, Notch
Hybrid
Binary
Pupil Apodizations
Continous
Pupil Apodizations
PIAA
Interf. Apopizatoin
Dark Hole
Techniques
Binary
Smooth
Amplitude
Phase
Amplitude
Phase
Interferometry
2 StageFourier Filtering
1 Stage Fourier Filtering
Beam Splitter
Pupil Stop
Image Stop
Lyot (1939)

Fourier Optics vs Geometrical Optics

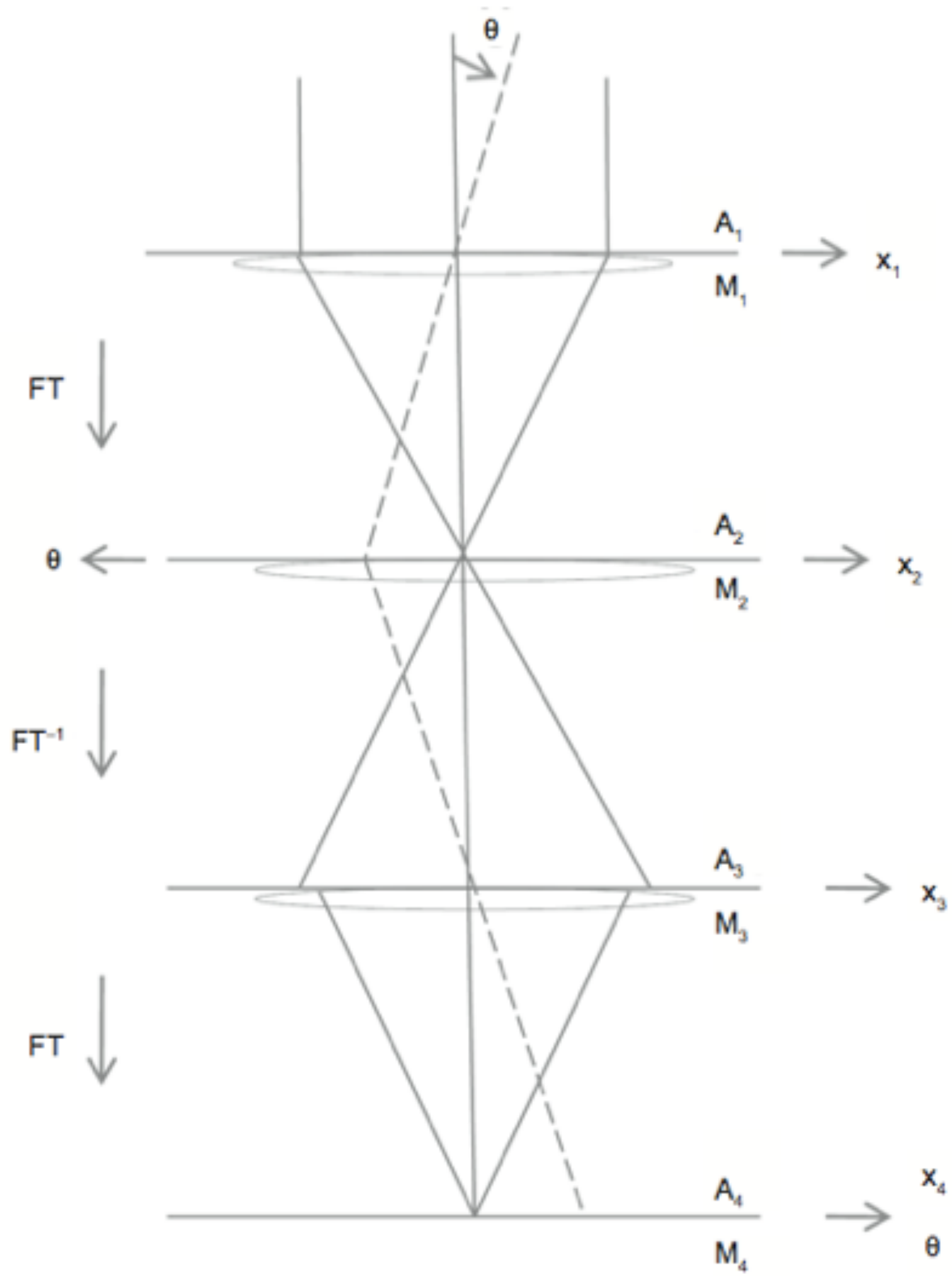
Fourier optics (or physical optics) describes ideal diffraction- limited optical situations (coronagraphs, interferometers, gratings, lenses, prisms, radio telescopes, eyes, etc.):
If the all photons start from the same atom, and follow the same many-fold path to the detectors, with the same amplitudes & phase shifts & polarizations, then we will see a diffraction-controlled interference pattern at the detectors. In other words, **waves** are needed to describe what you see.

Geometric optics describes the same situations but in the limit of zero wavelength, so no diffraction phenomena are seen. In other words, **rays** are all you need to describe what you see.

Pupils and Images …

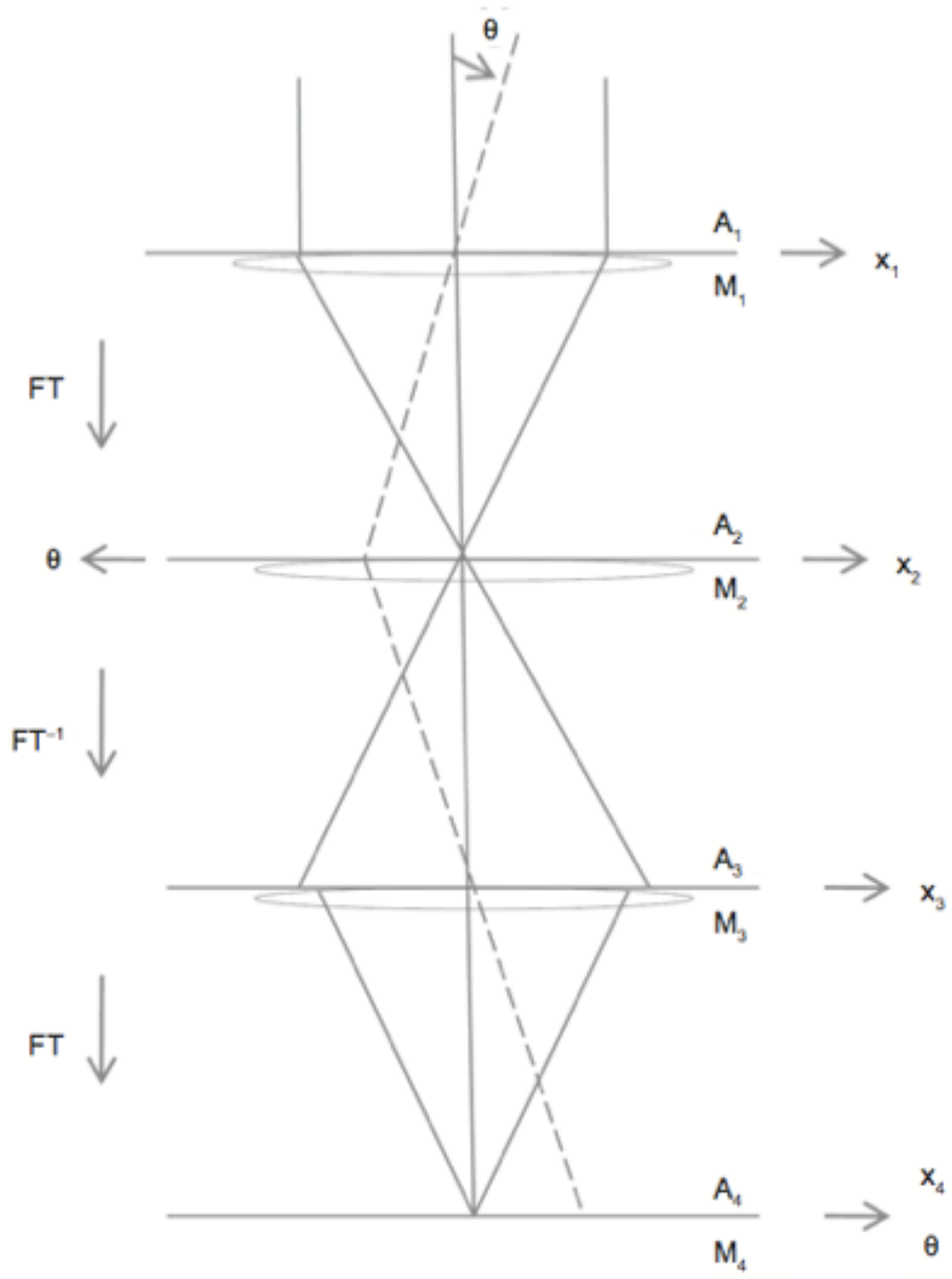


Pupils and Images …



We see that an ideal lens (or focussing mirror) acts on the amplitude in the **pupil plane**, with a **Fourier-transform** operation, to generate the amplitude in the **image plane**.

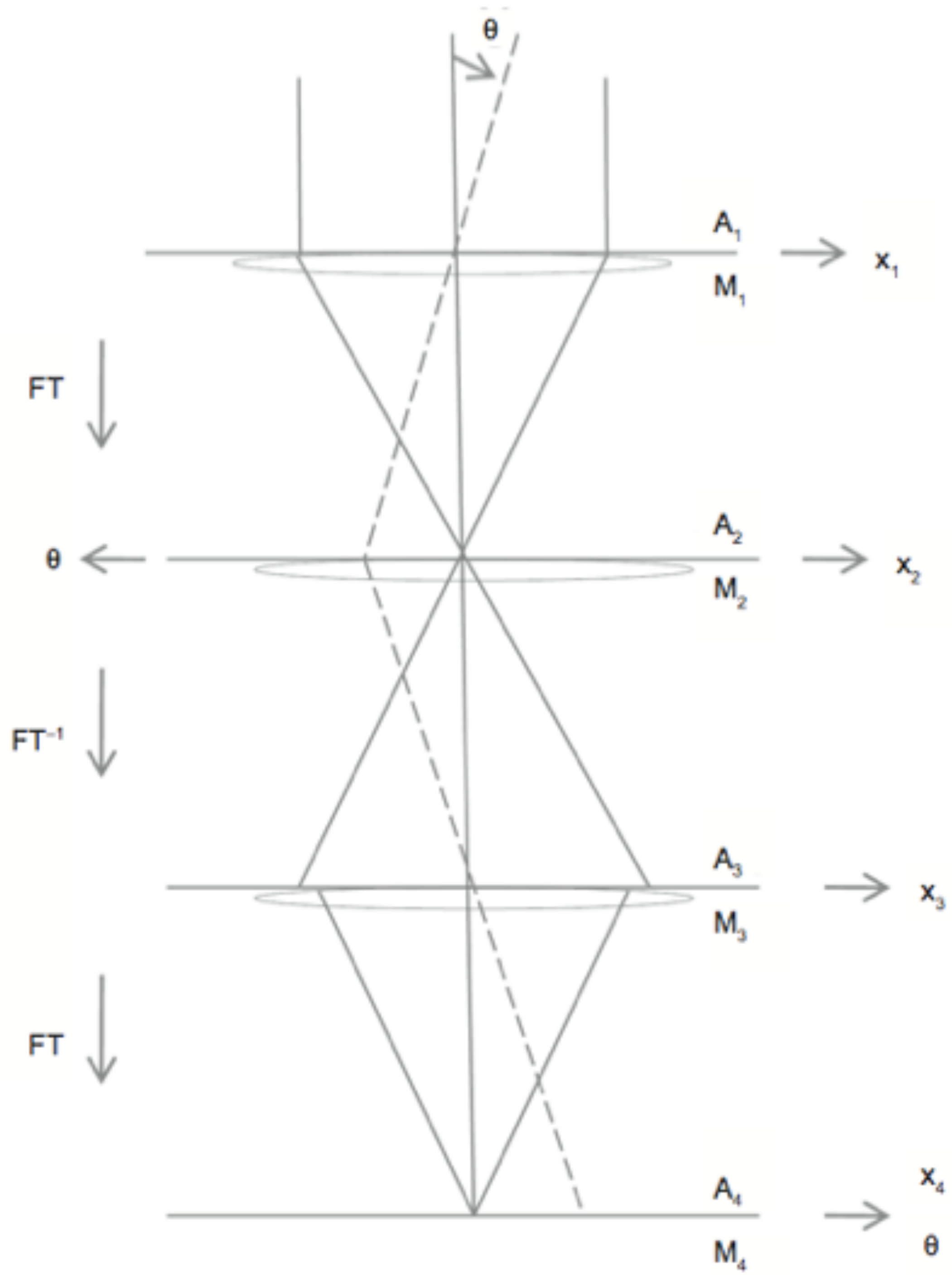
Pupils and Images …



We see that an ideal lens (or focussing mirror) acts on the amplitude in the **pupil plane**, with a **Fourier-transform** operation, to generate the amplitude in the **image plane**.

A second lens, after the image plane, would convert the **image-plane** amplitude, with a second **Fourier-transform**, to the plane where the initial **pupil is re-imaged**.

Pupils and Images …

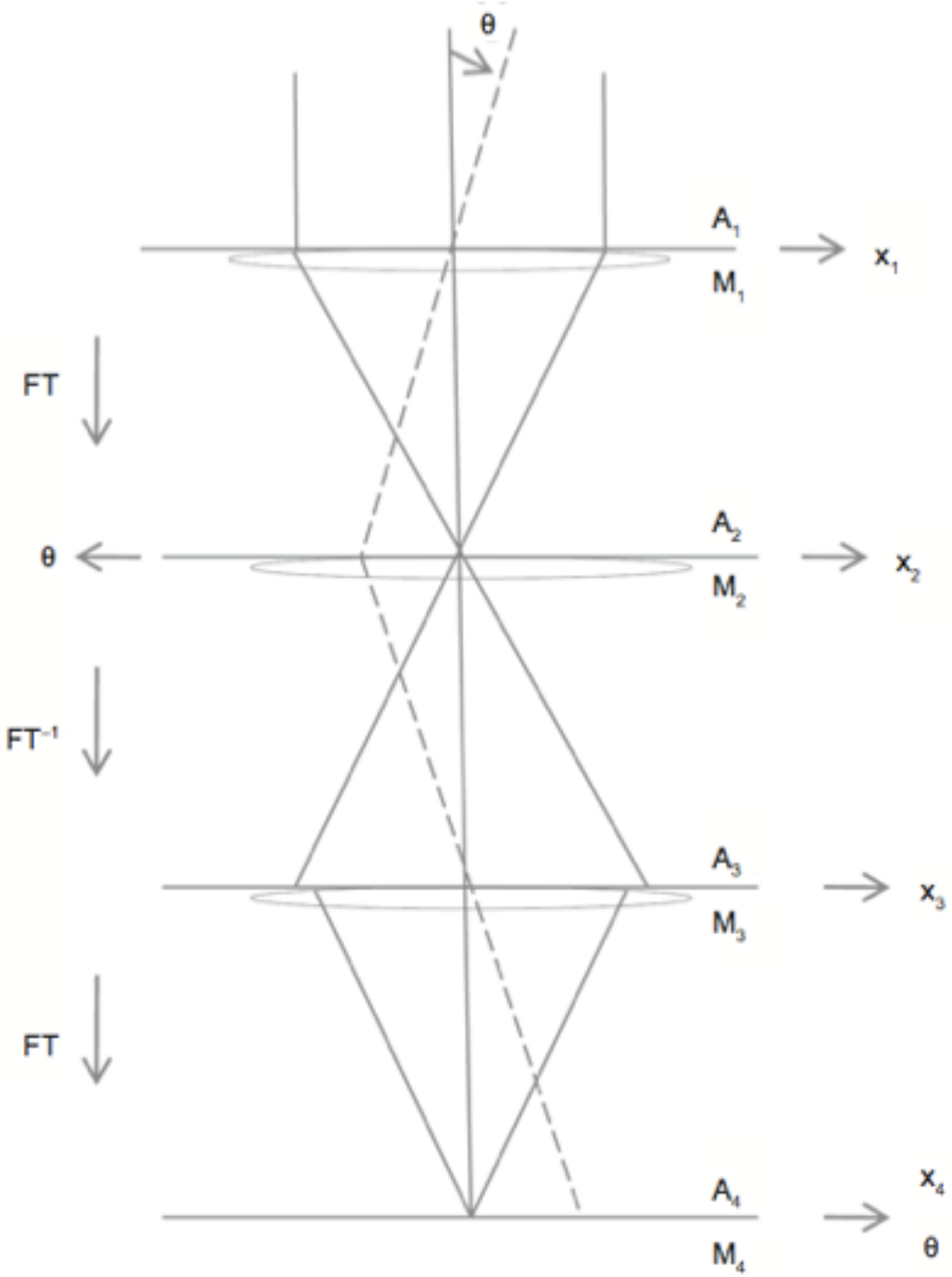


We see that an ideal lens (or focussing mirror) acts on the amplitude in the **pupil plane**, with a **Fourier-transform** operation, to generate the amplitude in the **image plane**.

A second lens, after the image plane, would convert the **image-plane** amplitude, with a second **Fourier-transform**, to the plane where the initial **pupil is re-imaged**.

A third lens after the **re-imaged pupil** would create a **re-imaged image** plane, via a third **FT**.

Pupils and Images ...

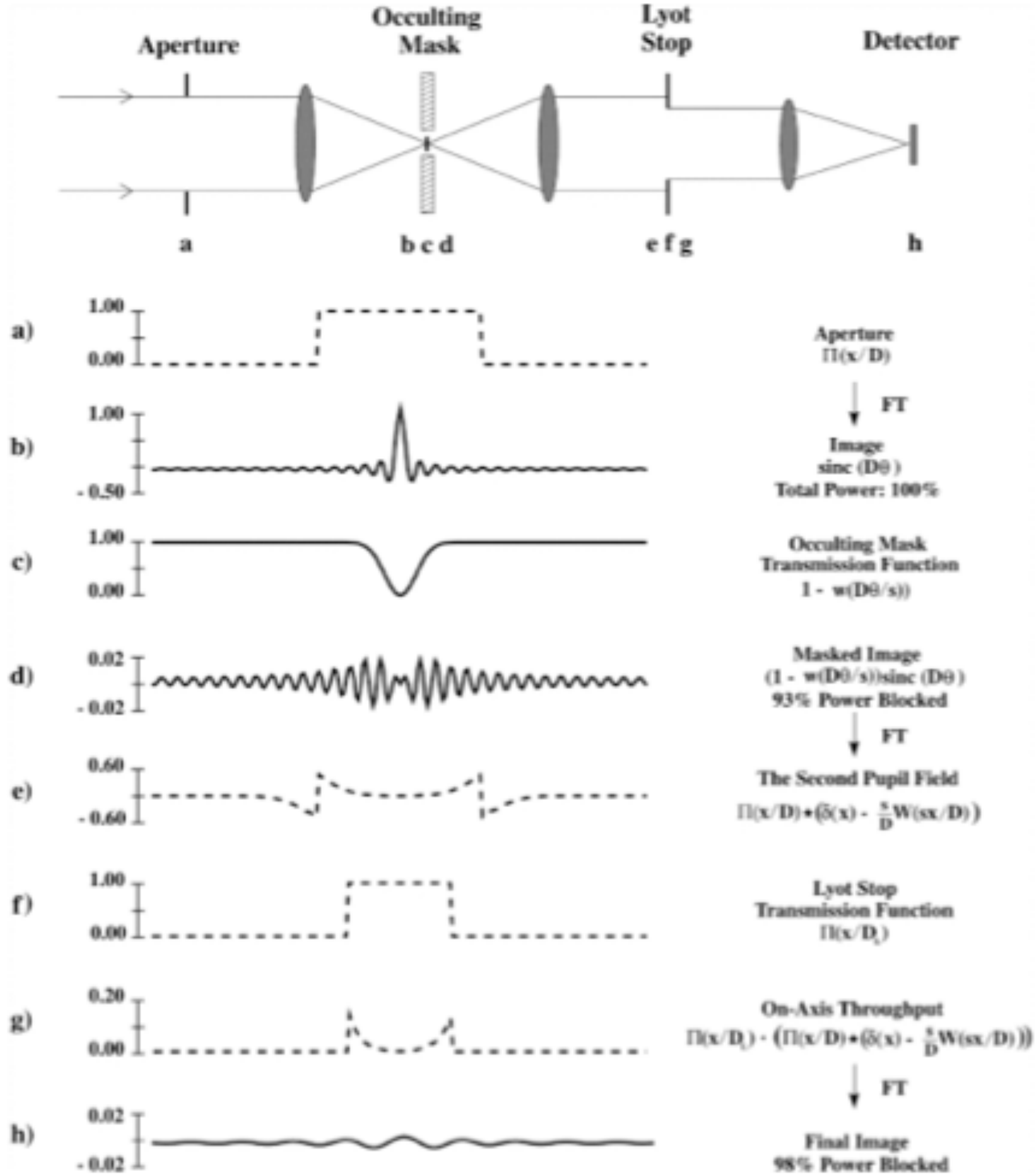


We see that an ideal lens (or focussing mirror) acts on the amplitude in the **pupil plane**, with a **Fourier-transform** operation, to generate the amplitude in the **image plane**.

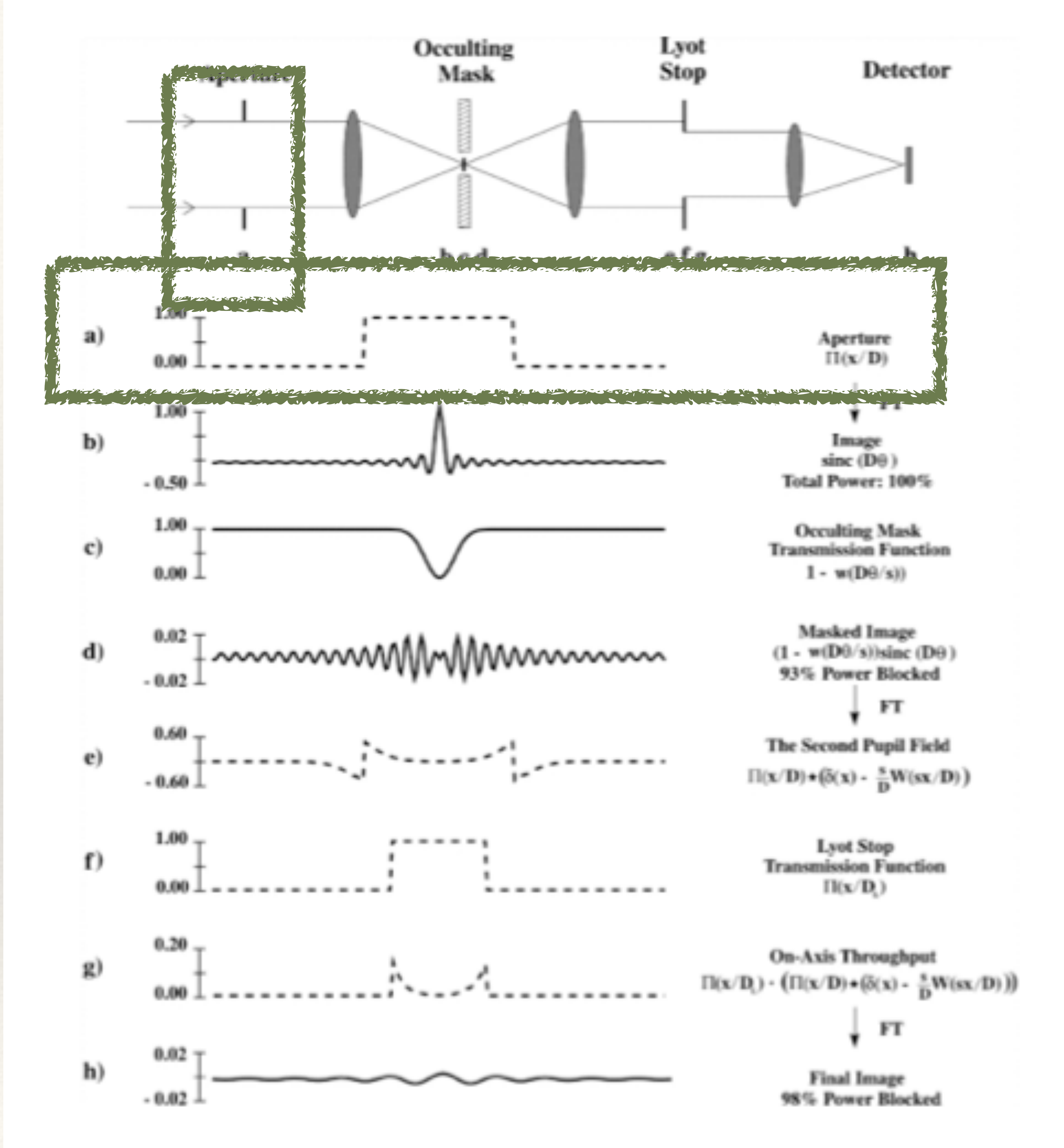
A second lens, after the image plane, would convert the **image-plane** amplitude, with a second **Fourier-transform**, to the plane where the initial **pupil is re-imaged**.

A third lens after the **re-imaged pupil** would create a **re-imaged image** plane, via a third **FT**.

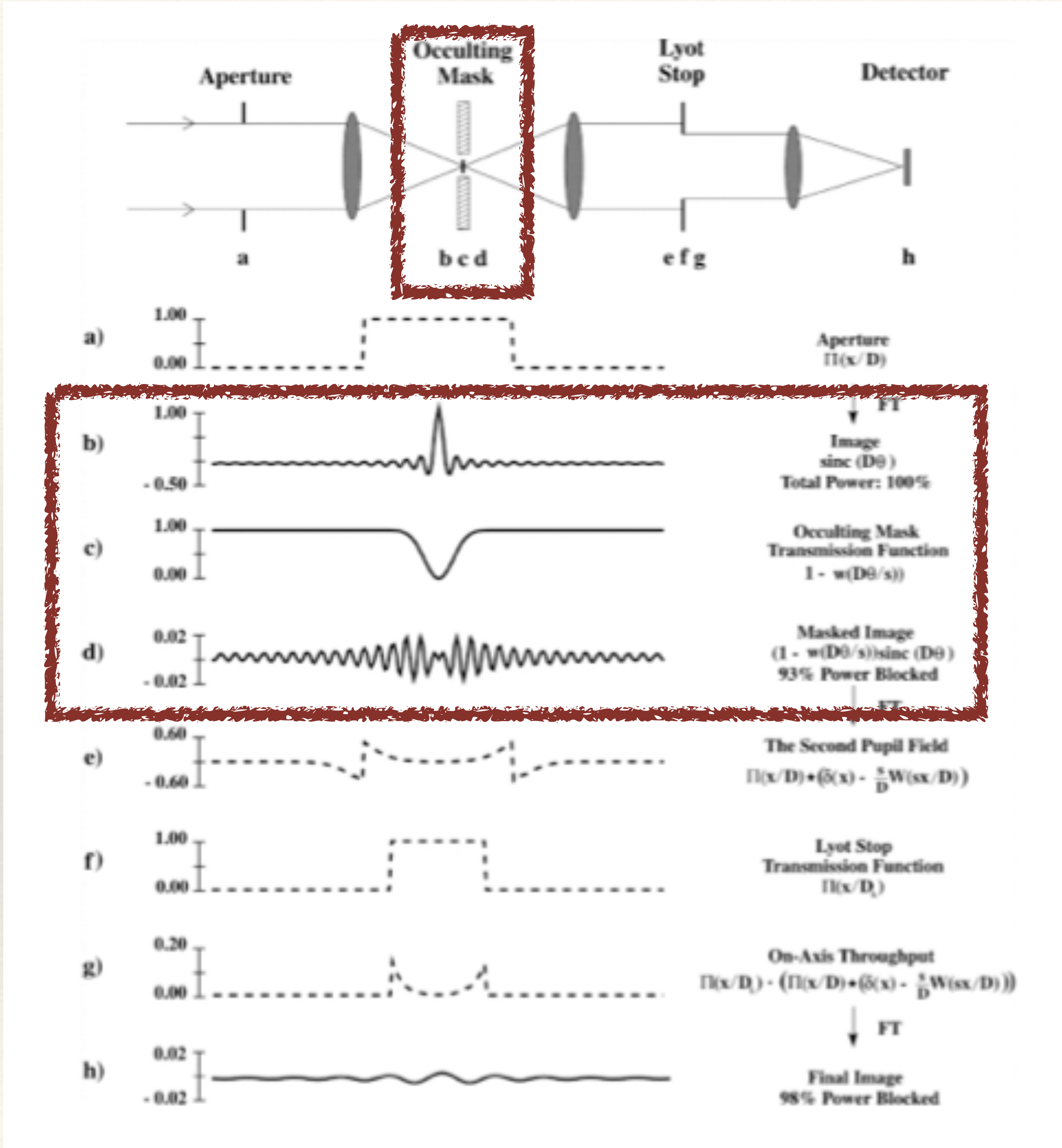
At each stage we can **modify the amplitude** with masks, stops, polarization shifts, and phase changes. These all go into the **net transmitted** amplitude, before the next FT operation.



Aperture
Occulting Mask
Lyot Stop
Detector
a
b c d
e f g
h
a)
b)
c)
d)
e)
f)
g)
h)
1.00
0.00
- 0.50
0.02
- 0.02
0.60
- 0.60
0.20
Aperture
Π(x/D)
FT
Image
sinc (Dθ)
Total Power: 100%
Occulting Mask
Transmission Function
1 - w(Dθ/s))
Masked Image
(1 - w(Dθ/s))sinc (Dθ)
93% Power Blocked
The Second Pupil Field
Lyot Stop
Transmission Function
On-Axis Throughput
Final Image
98% Power Blocked


Occulting Mask
Lyot Stop
Detector
a)
1.00
0.00
Aperture
Π(x/D)
b)
1.00
- 0.50
Image
sinc (Dθ)
Total Power: 100%
c)
1.00
0.00
Occulting Mask
Transmission Function
1 - w(Dθ/s))
d)
0.02
- 0.02
Masked Image
(1 - w(Dθ/s))sinc (Dθ)
93% Power Blocked
FT
e)
0.60
- 0.60
The Second Pupil Field
f)
1.00
0.00
Lyot Stop
Transmission Function
g)
0.20
0.00
On-Axis Throughput
FT
h)
0.02
- 0.02
Final Image
98% Power Blocked

A(u)

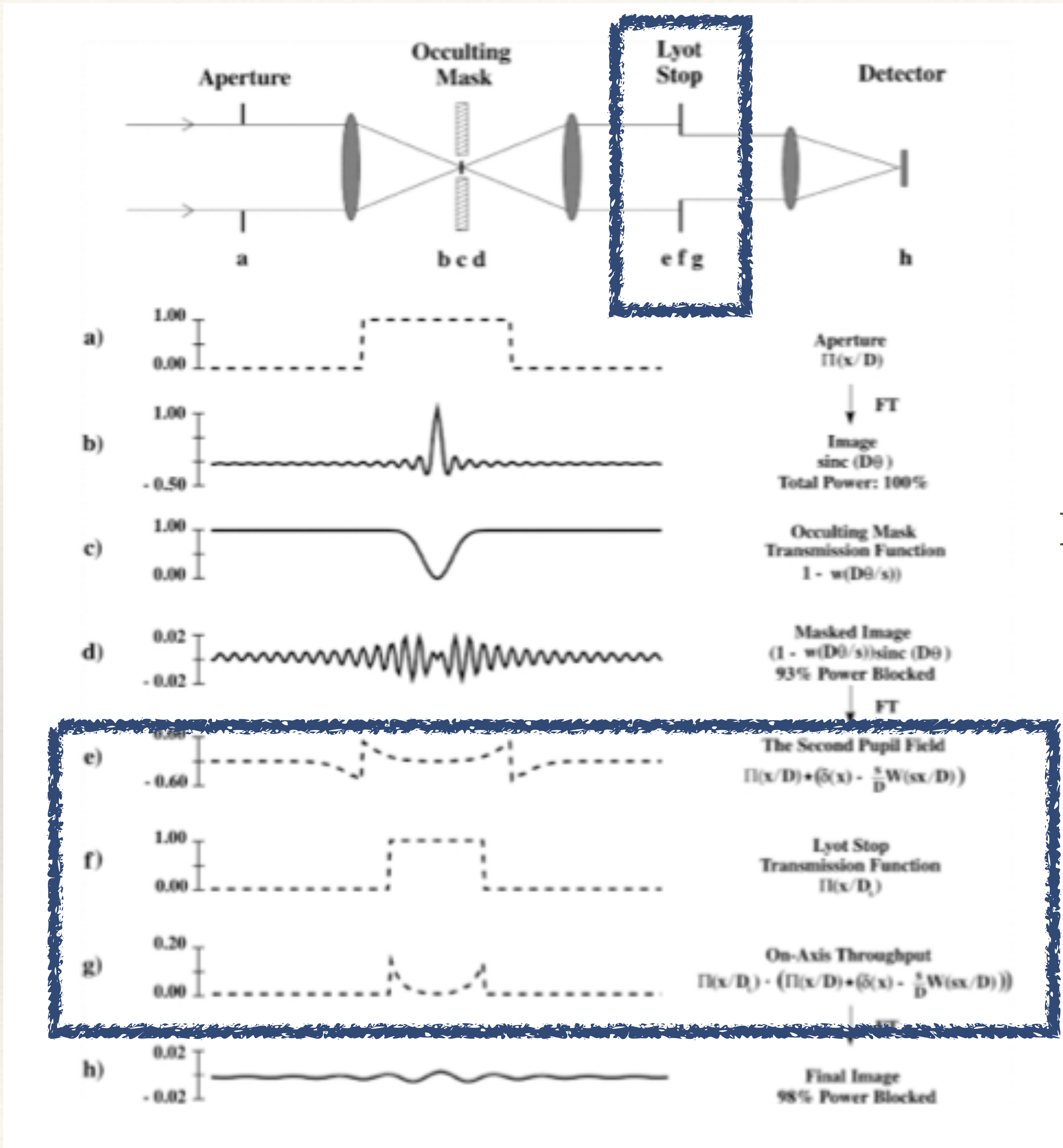

Aperture
Occulting Mask
Lyot Stop
Detector
a
b c d
e f g
h
a)
b)
c)
d)
e)
f)
g)
h)
Aperture
Π(x/D)
FT
Image
sinc (Dθ)
Total Power: 100%
Occulting Mask
Transmission Function
Masked Image
93% Power Blocked
FT
The Second Pupil Field
Lyot Stop
Transmission Function
On-Axis Throughput
FT
Final Image
98% Power Blocked

A(u)

A(x)

M(x)

AM



A(u)

A(x)

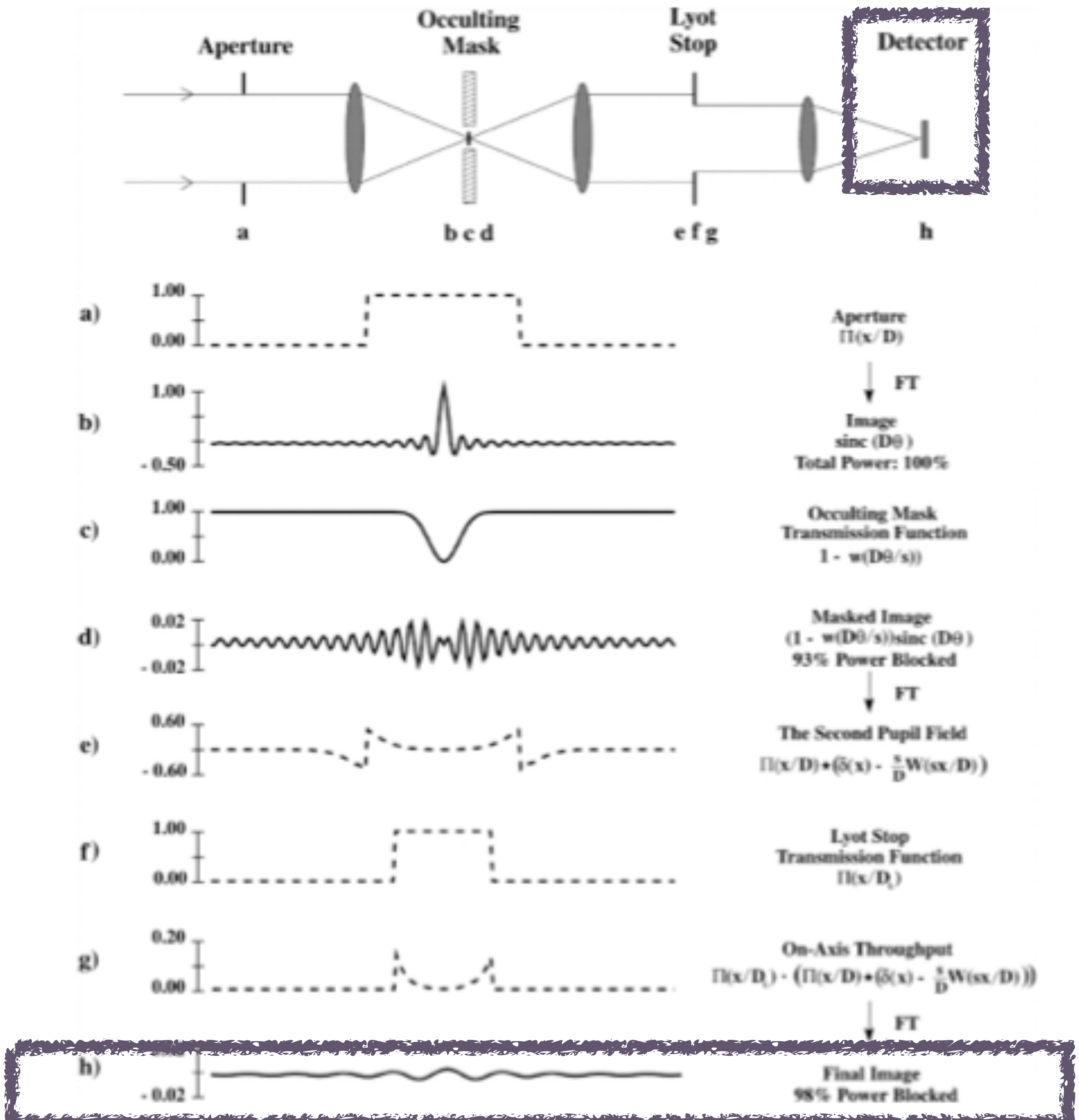
M(x)

AM

A*M

L(u)

L[M*A]



A(u)

A(x)

M(x)

AM

A*M

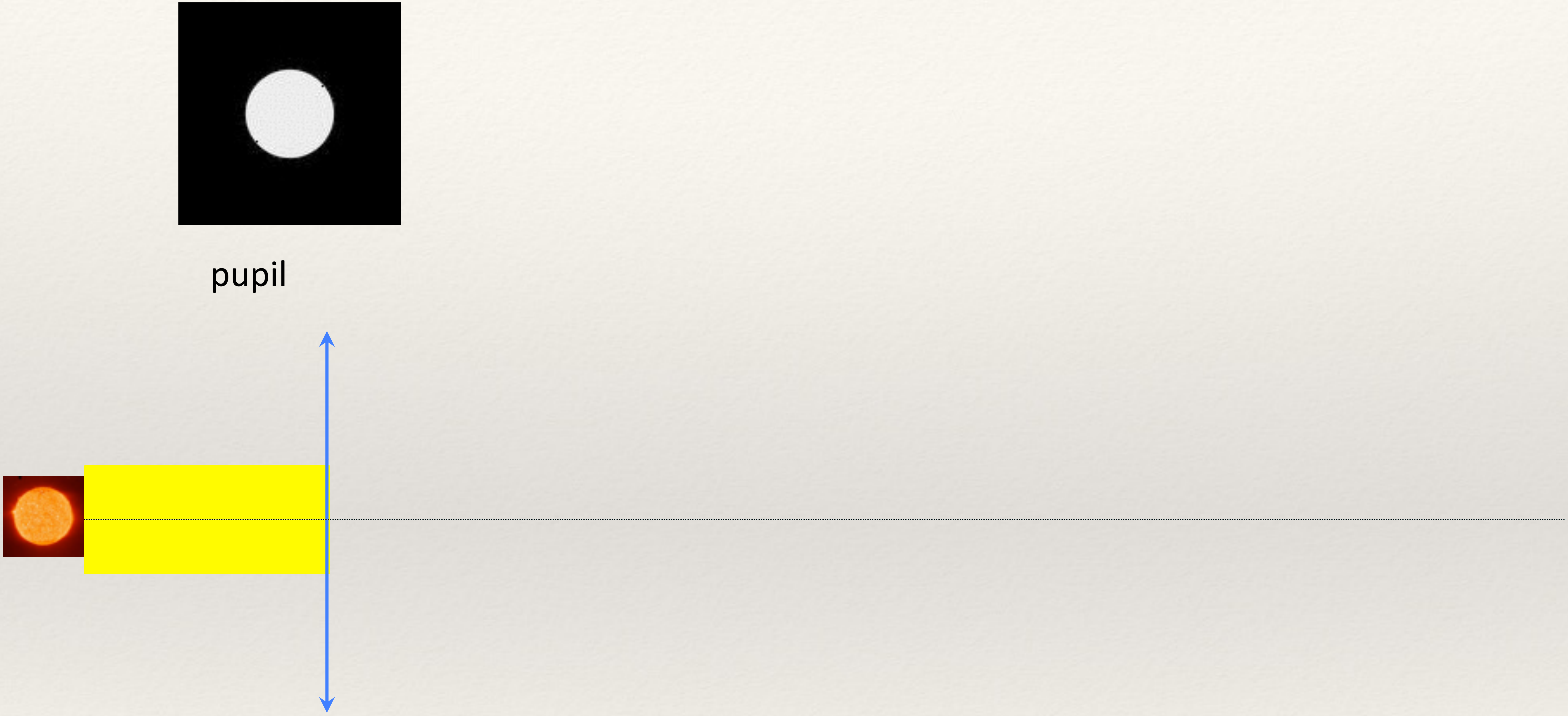
L(u)

L[M*A]

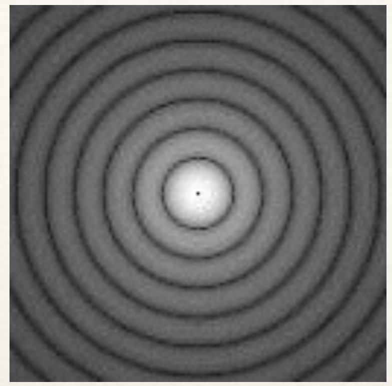
L*[MA]

Coronagraphy: principle

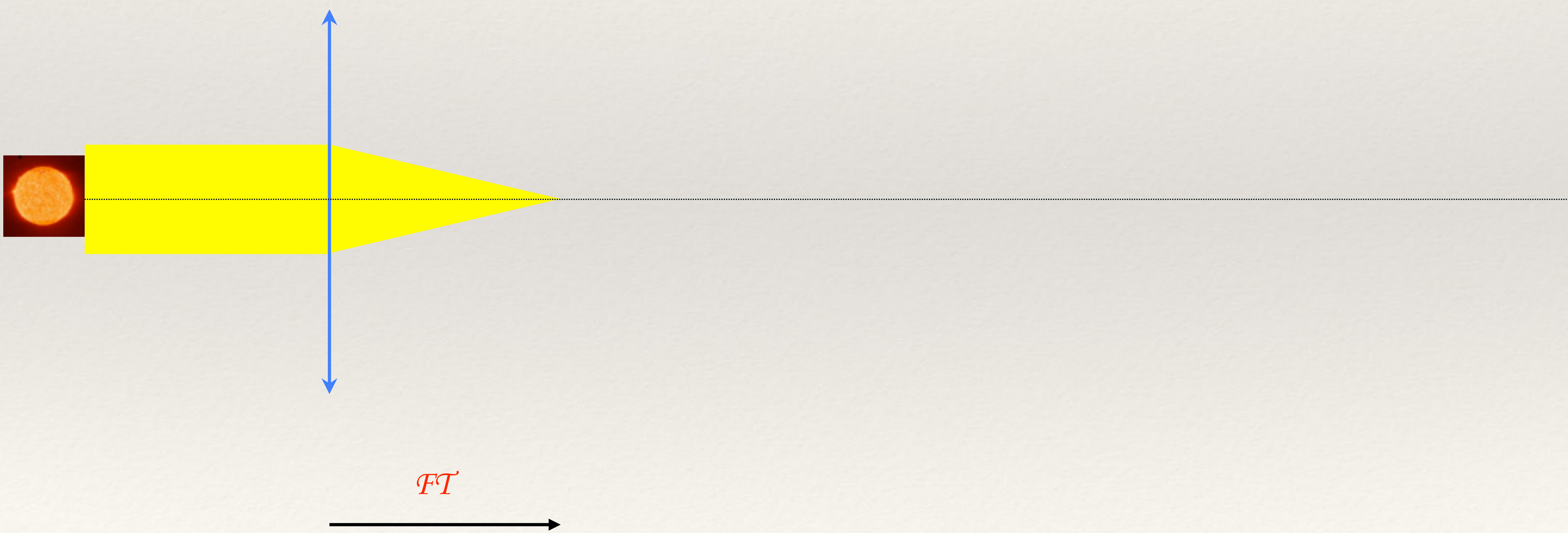
Coronagraphy: principle



Coronagraphy: principle

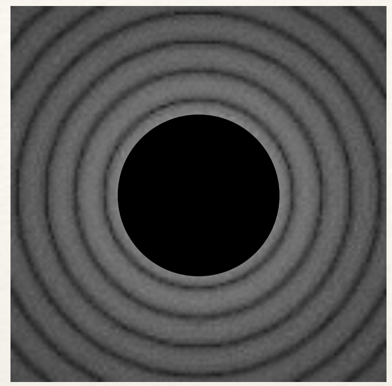


pupil

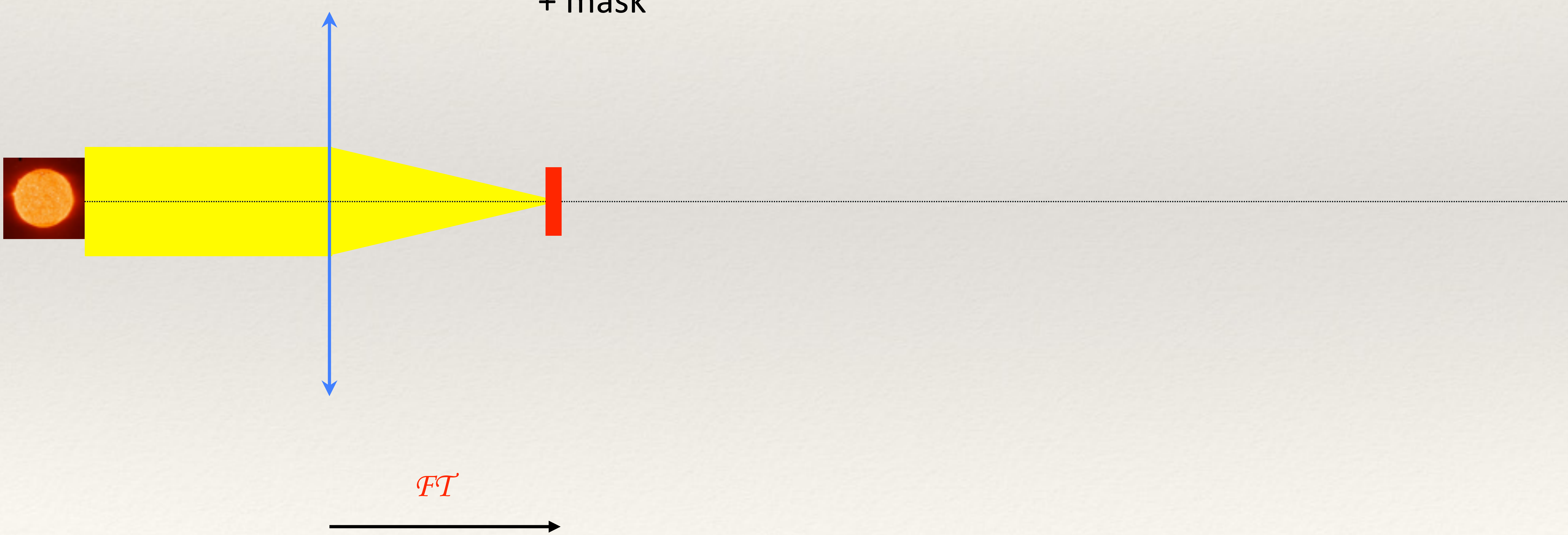


Coronagraphy: principle

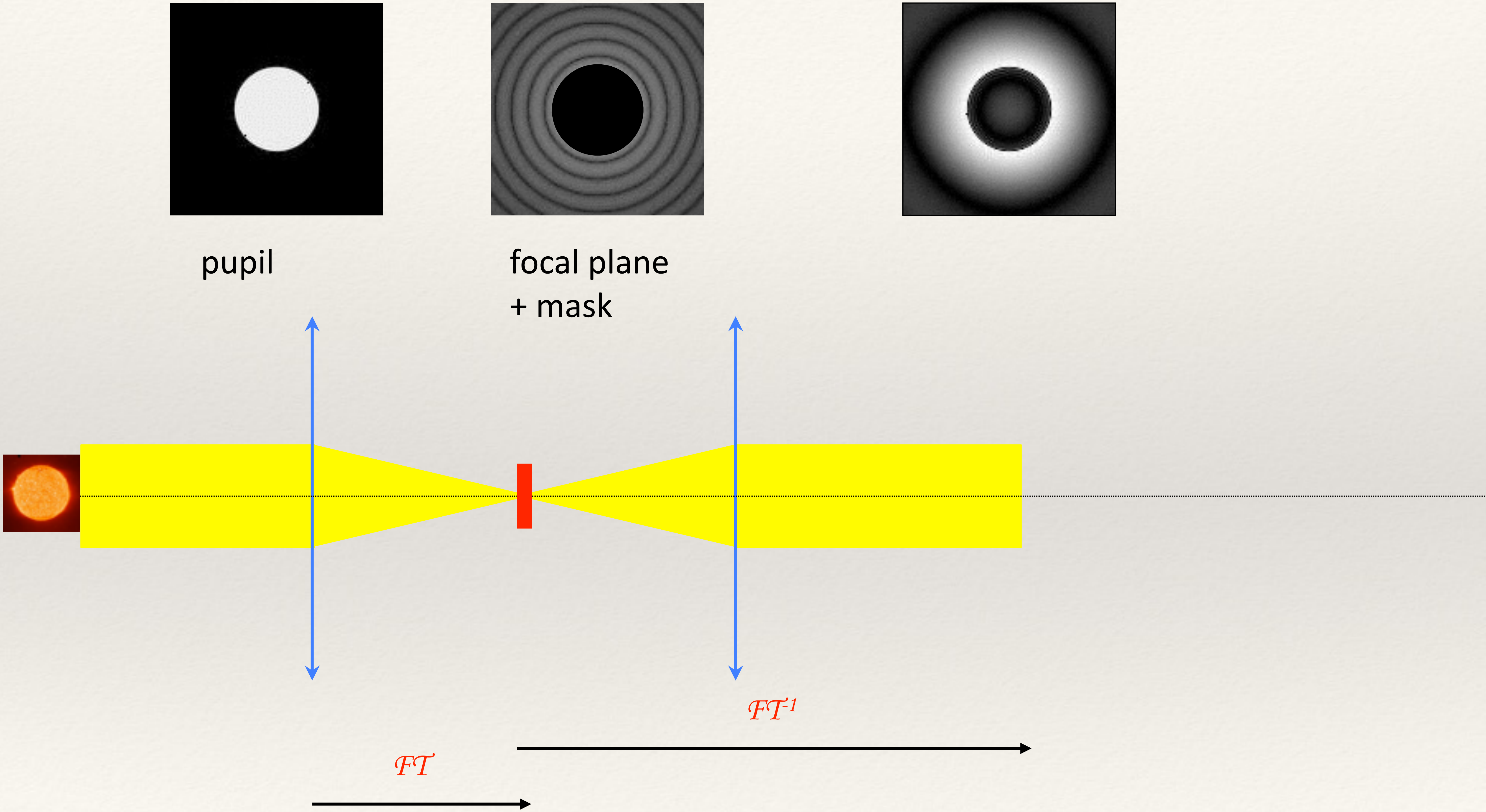
pupil



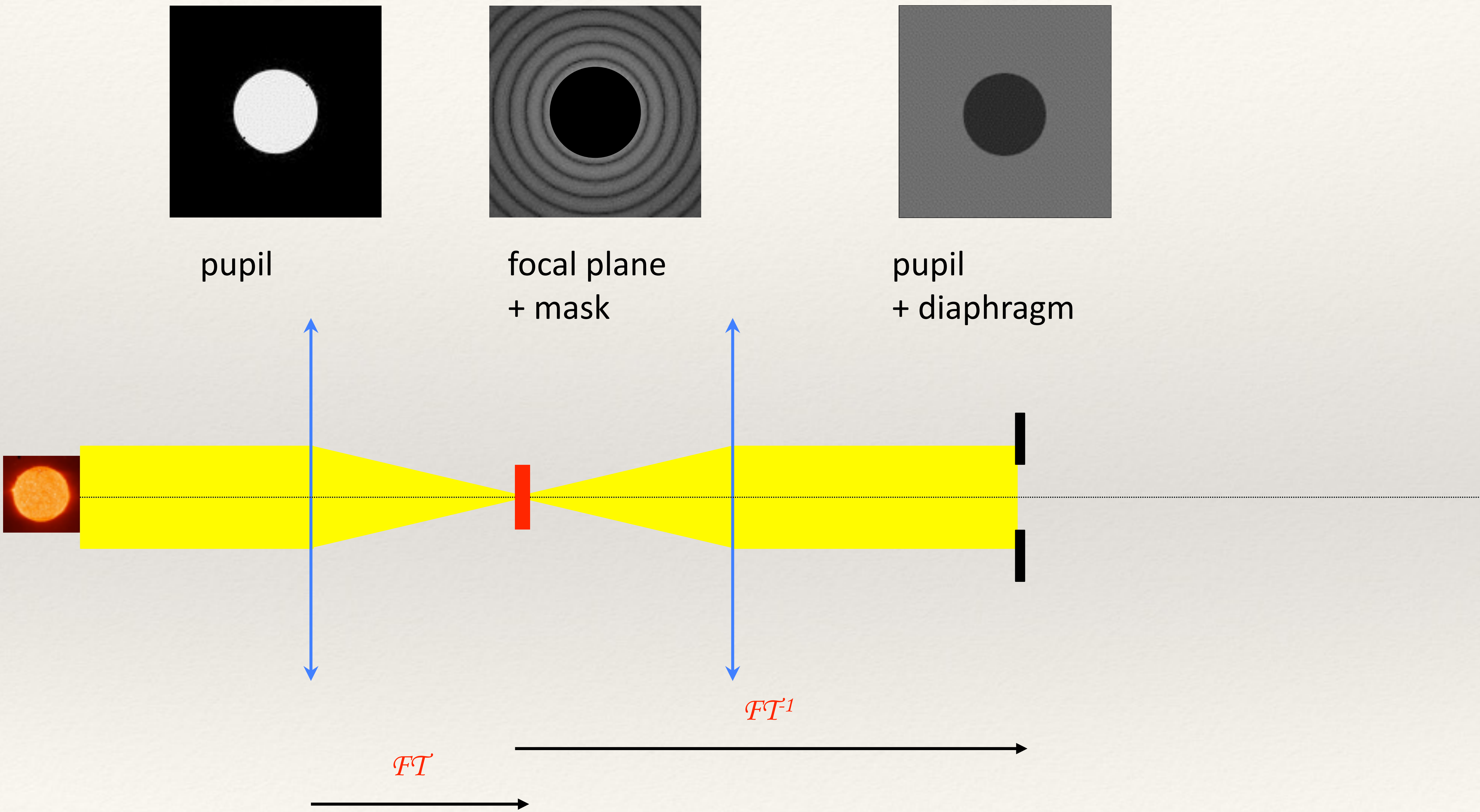
focal plane
+ mask



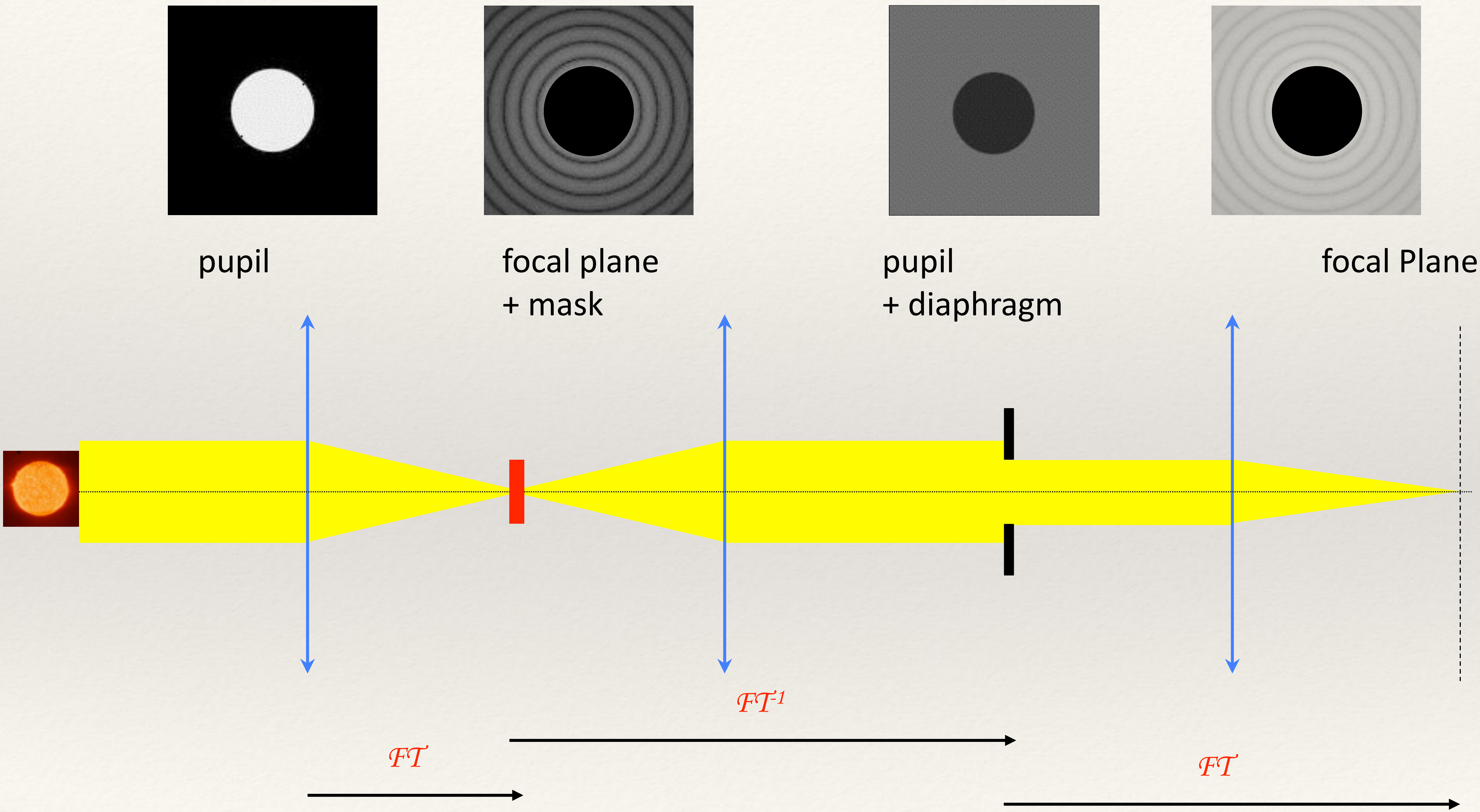
Coronagraphy: principle



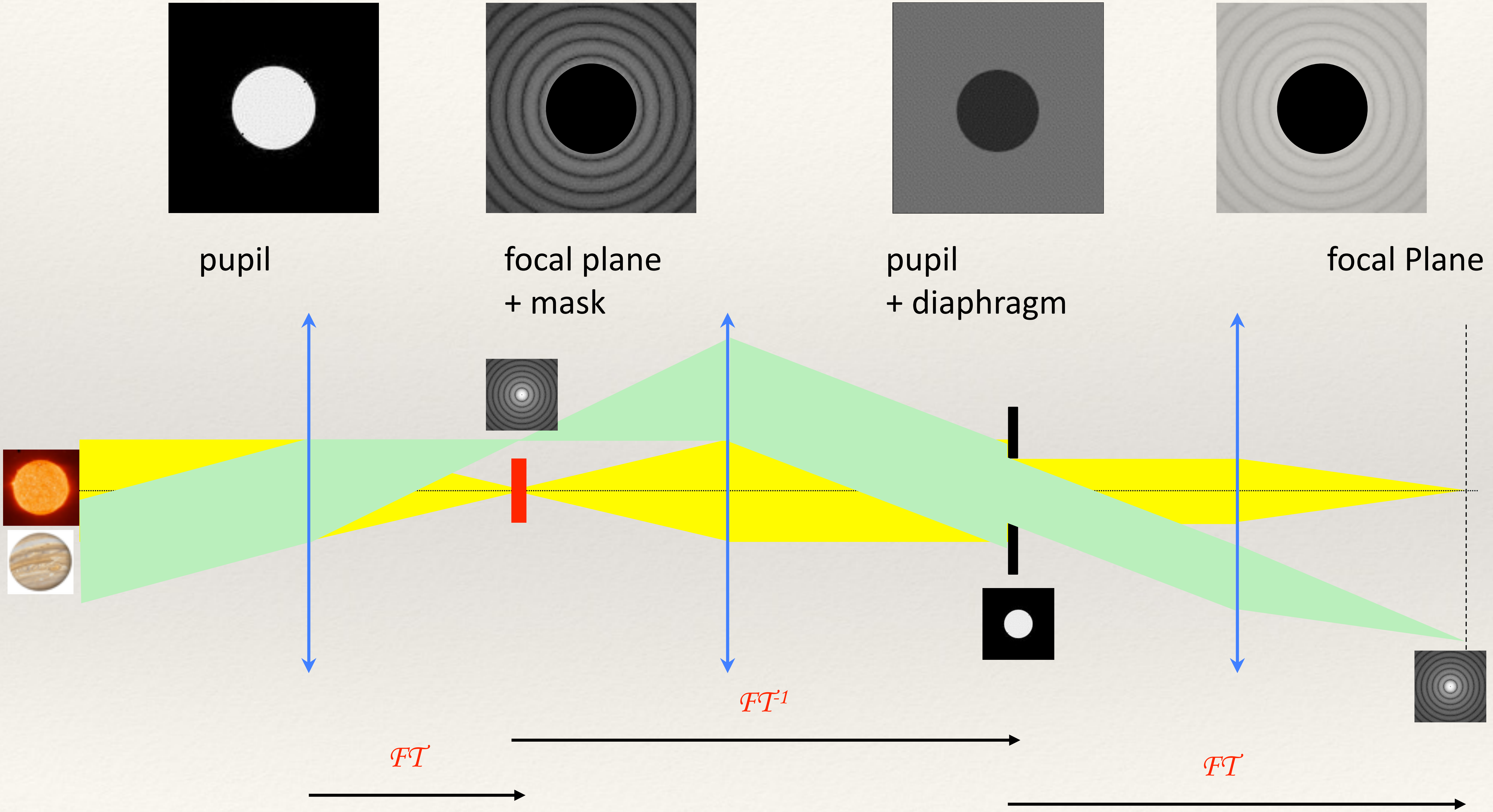
Coronagraphy: principle



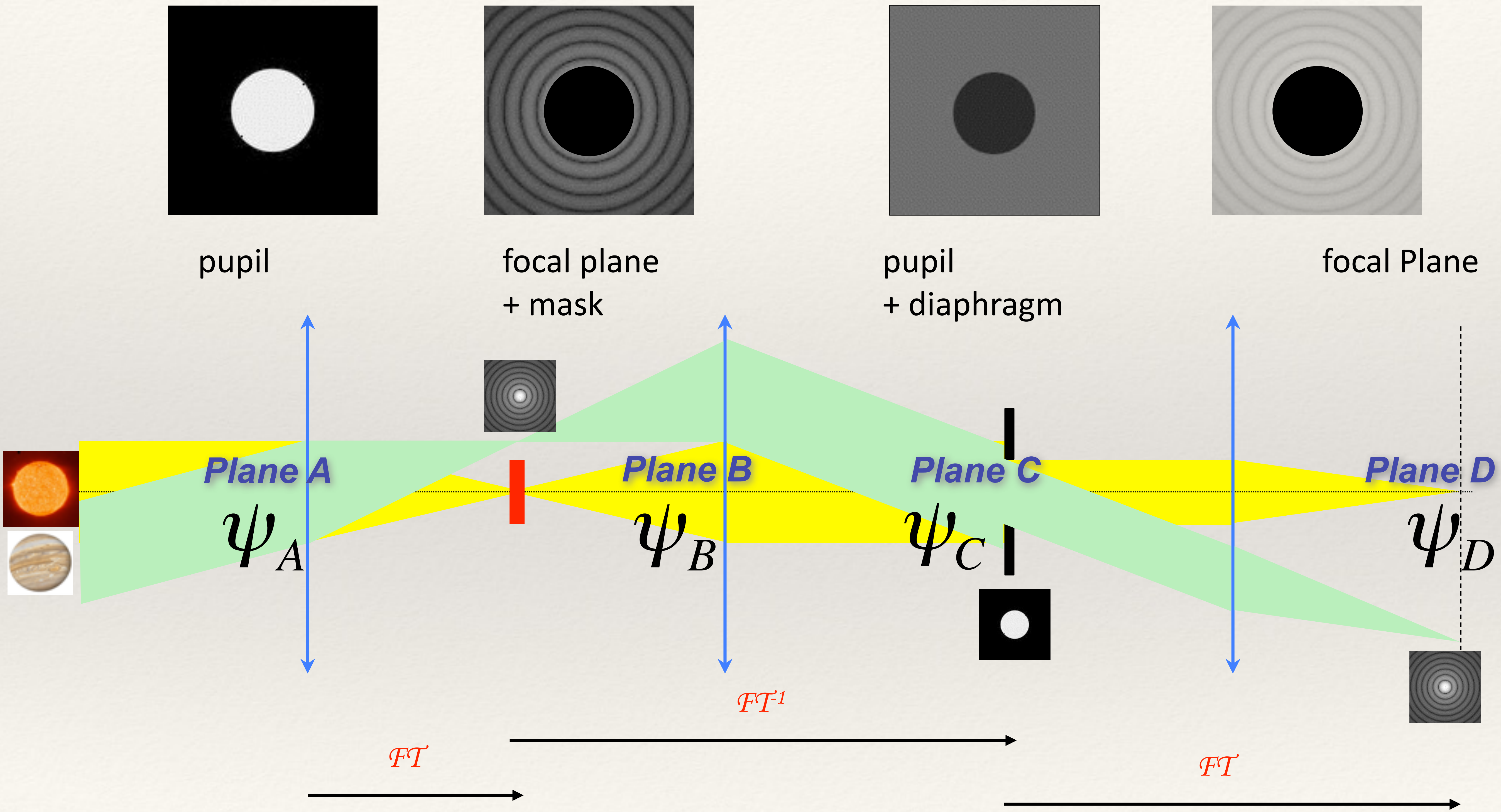
Coronagraphy: principle



Coronagraphy: principle



Coronagraphy: principle



Formation of a coronagraph image

Formation of a coronagraph image

Plane A: $\psi_A = A e^{i\varphi}$ $\qquad \psi_A = A$ if $\varphi = 0$

Formation of a coronagraph image

Plane A: $\psi_A = A e^{i\varphi}$ $\psi_A = A$ if $\varphi = 0$

Plane B: $\psi_B = \overline{\psi_A} \Rightarrow \overline{\psi_A} . M$

Formation of a coronagraph image

Plane A: $\psi_A = A e^{i\varphi}$ $\psi_A = A$ if $\varphi = 0$

Plane B: $\psi_B = \overline{\psi_A} \Rightarrow \overline{\psi_A} . M$

Plane C: $\psi_C = \overline{\psi_B} = \psi_A \otimes \overline{M} \Rightarrow \left(\psi_A \otimes \overline{M}\right) . D$

Formation of a coronagraph image

Plane A: $\psi_A = A e^{i\varphi}$ $\quad \psi_A = A$ if $\varphi = 0$

Plane B: $\psi_B = \overline{\psi_A} \Rightarrow \overline{\psi_A}.M$

Plane C: $\psi_C = \overline{\psi_B} = \psi_A \otimes \overline{M} \Rightarrow \left(\psi_A \otimes \overline{M}\right).D$

Plane D: $\psi_D = \overline{\psi_C} = \left(\overline{\psi_A}.M\right) \otimes \overline{D}$

Formation of a coronagraph image

Plane A: $\psi_A = A e^{i\varphi}$ $\quad \psi_A = A$ if $\varphi = 0$

Plane B: $\psi_B = \overline{\psi_A} \Rightarrow \overline{\psi_A}.M$

Plane C: $\psi_C = \overline{\psi_B} = \psi_A \otimes \overline{M} \Rightarrow \left(\psi_A \otimes \overline{M}\right).D$

Plane D: $\psi_D = \overline{\psi_C} = \left(\overline{\psi_A}.M\right) \otimes \overline{D}$

Formation of a coronagraph image

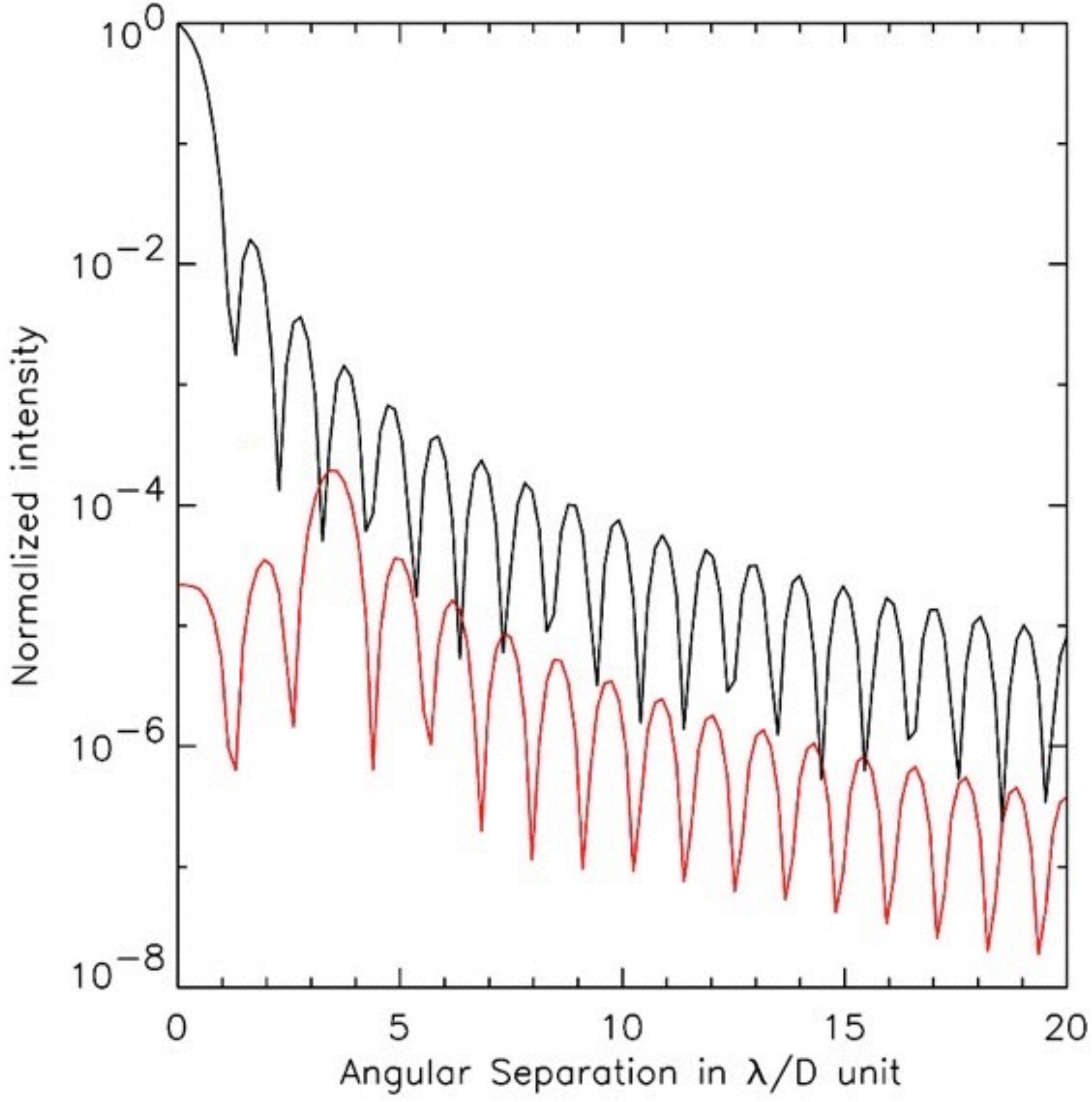
Plane A: $\psi_A = A\,e^{i\varphi}$ $\quad \psi_A = A$ if $\varphi = 0$

Plane B: $\psi_B = \overline{\psi_A} \Rightarrow \overline{\psi_A}\,.M$

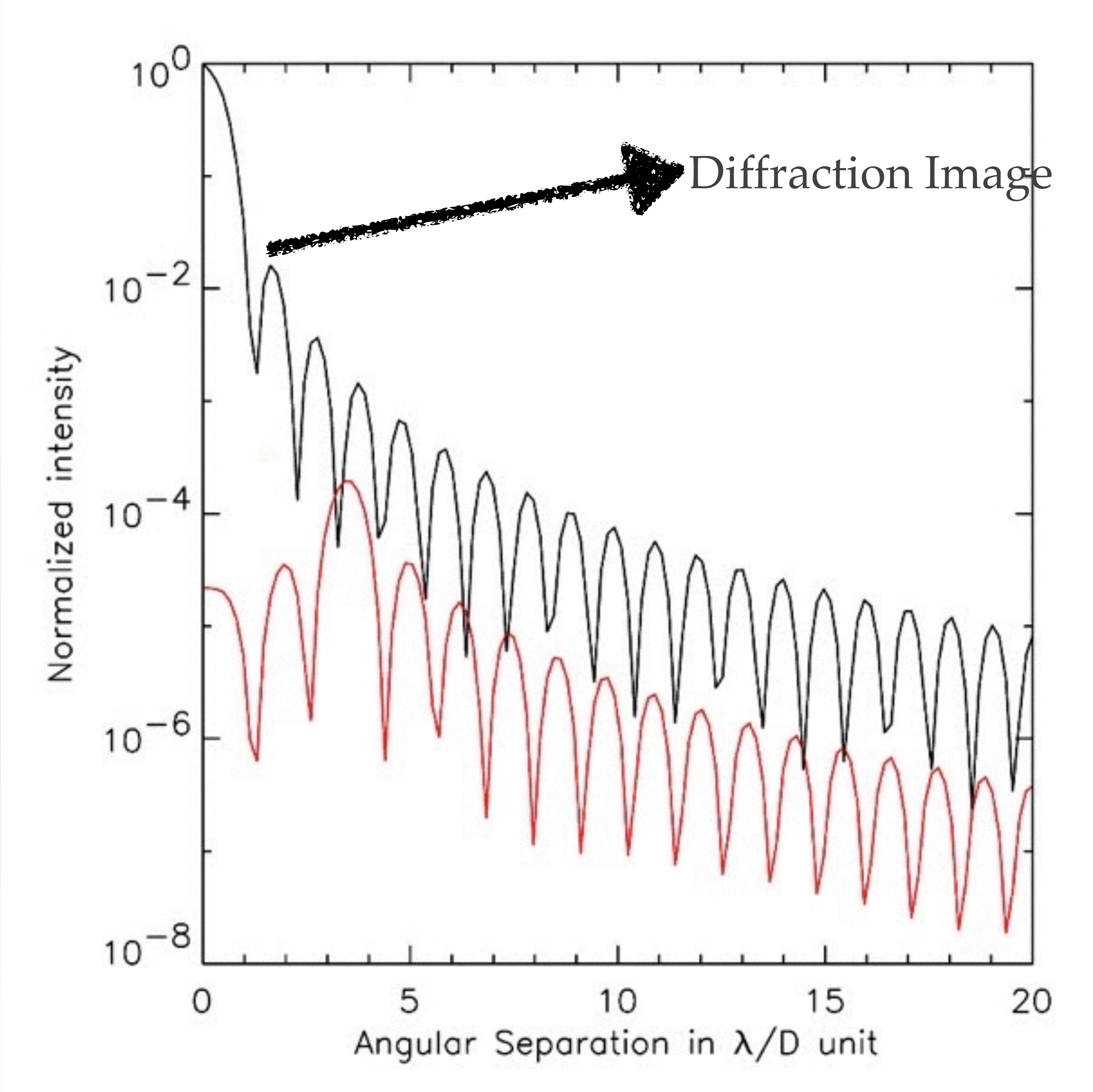
This is a Coronagraph

Plane C: $\psi_C = \overline{\psi_B} = \psi_A \otimes \overline{M} \Rightarrow \left(\psi_A \otimes \overline{M}\right).D$

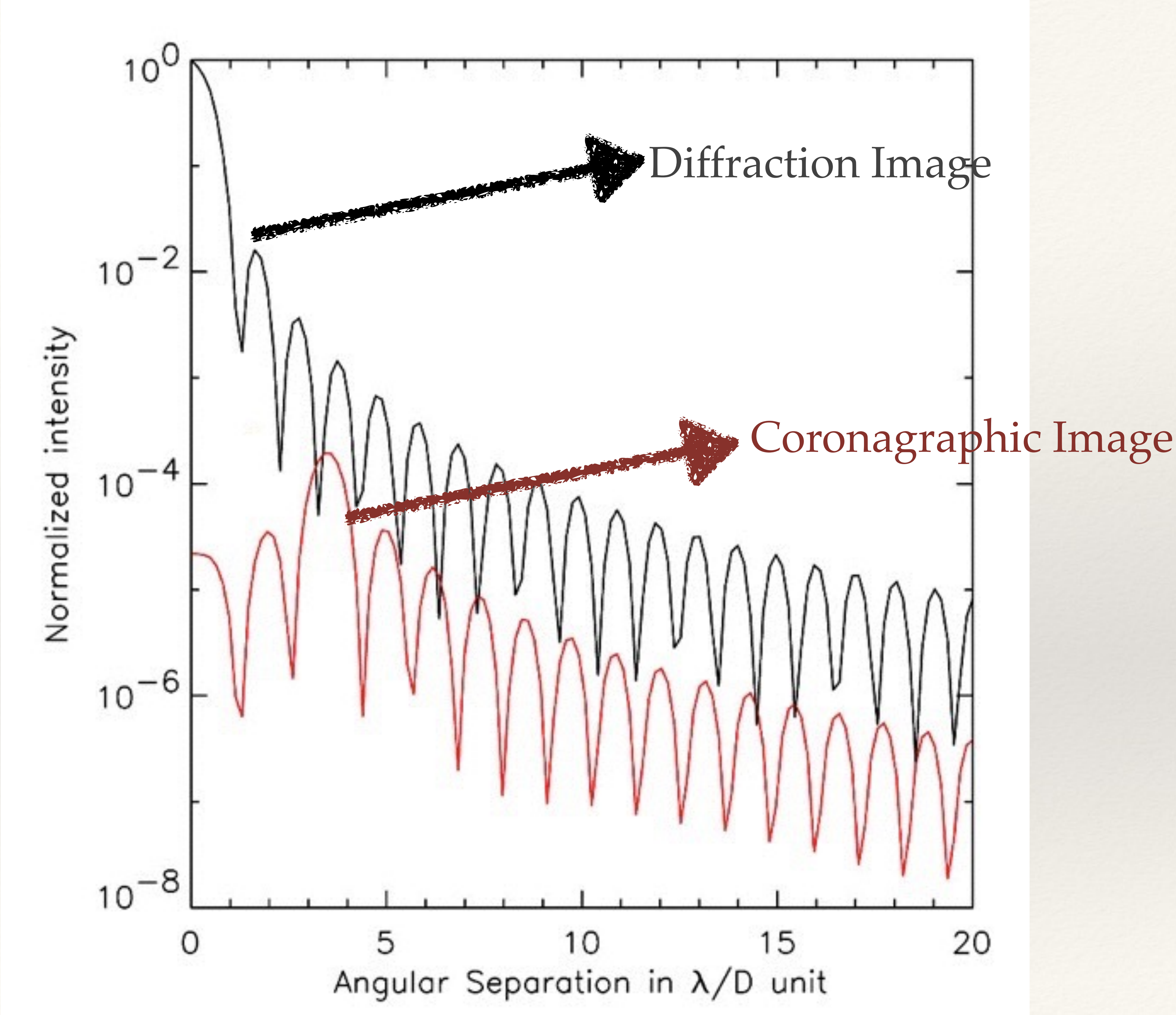
Plane D: $\psi_D = \overline{\psi_C} = \left(\overline{\psi_A}\,.M\right) \otimes \overline{D}$



10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
Normalized intensity
0
5
10
15
20
Angular Separation in λ/D unit



Diffraction Image
Normalized intensity
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
0
5
10
15
20
Angular Separation in λ/D unit



Diffraction Image
Coronagraphic Image
Normalized intensity
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
0
5
10
15
20
Angular Separation in λ/D unit

Important parameters I

Contrast C: The ratio dark/bright parts of image. Specifically, the average background brightness in the search area, divided by the central star brightness. Speckle/star.

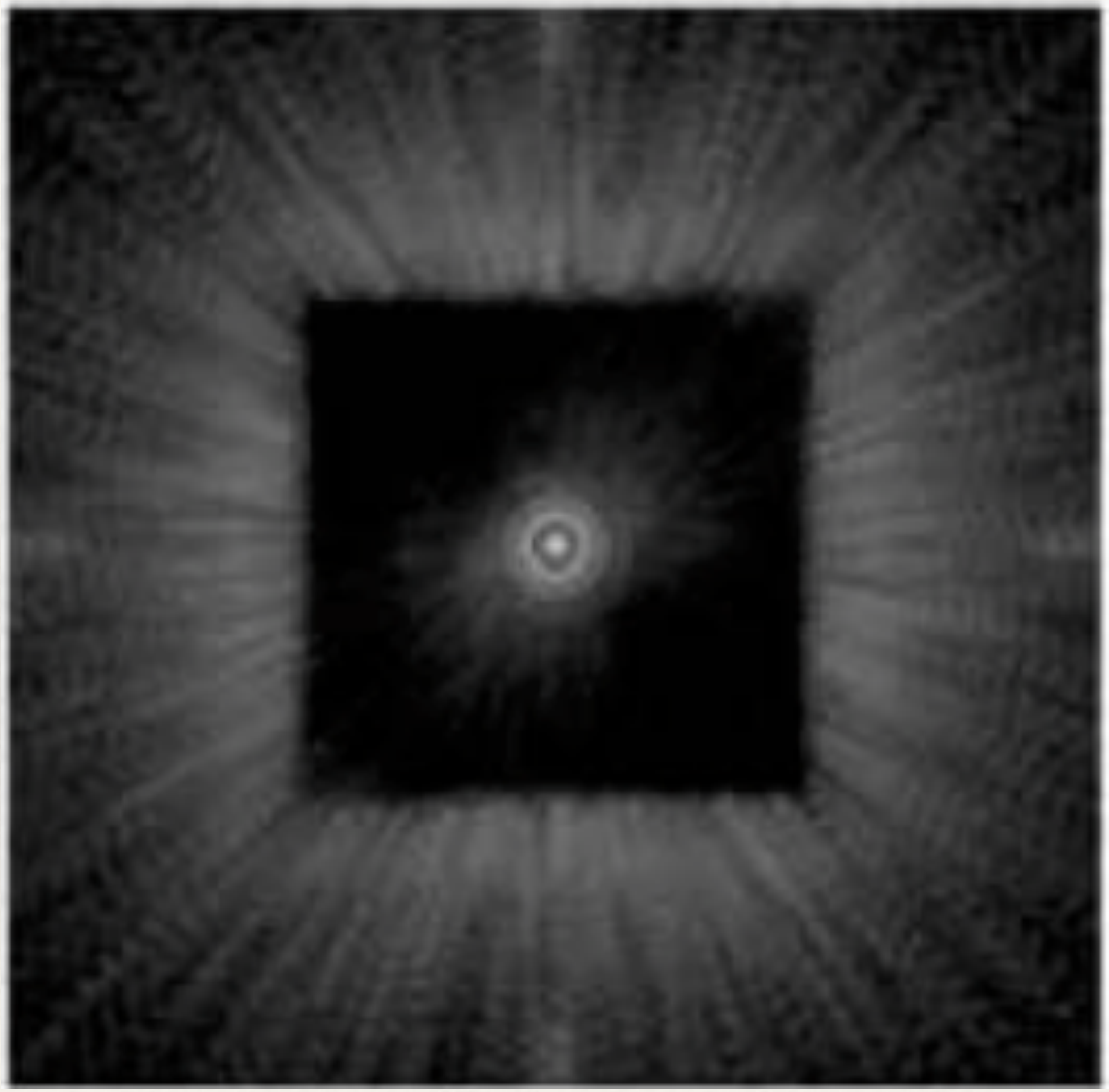
Example: C = 10^{-10} driven by Earth/Sun = $2x10^{-10}$.

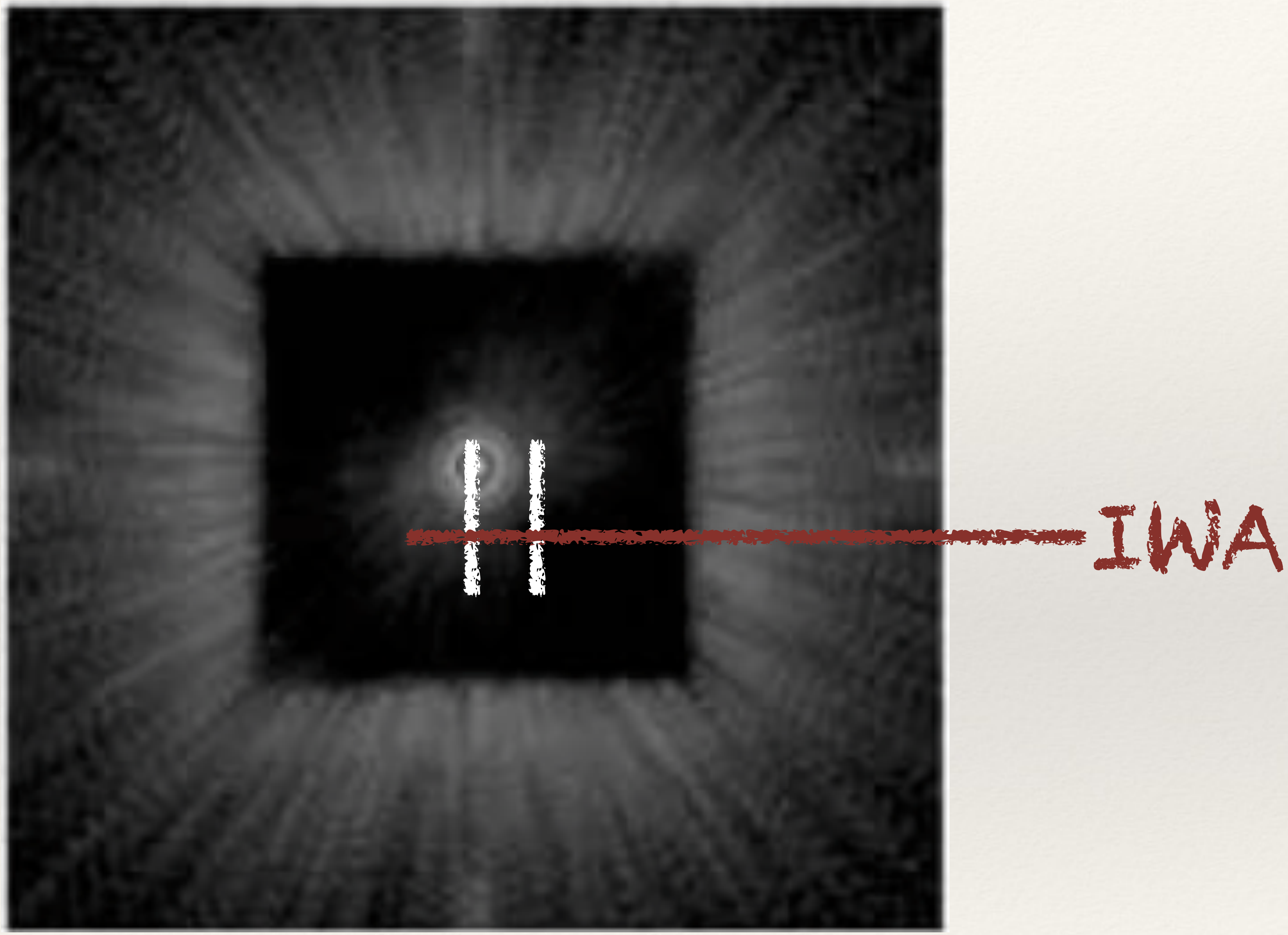
Inner working angle IWA: Smallest angle at which a planet can be detected. Inner boundary of high-contrast search area.

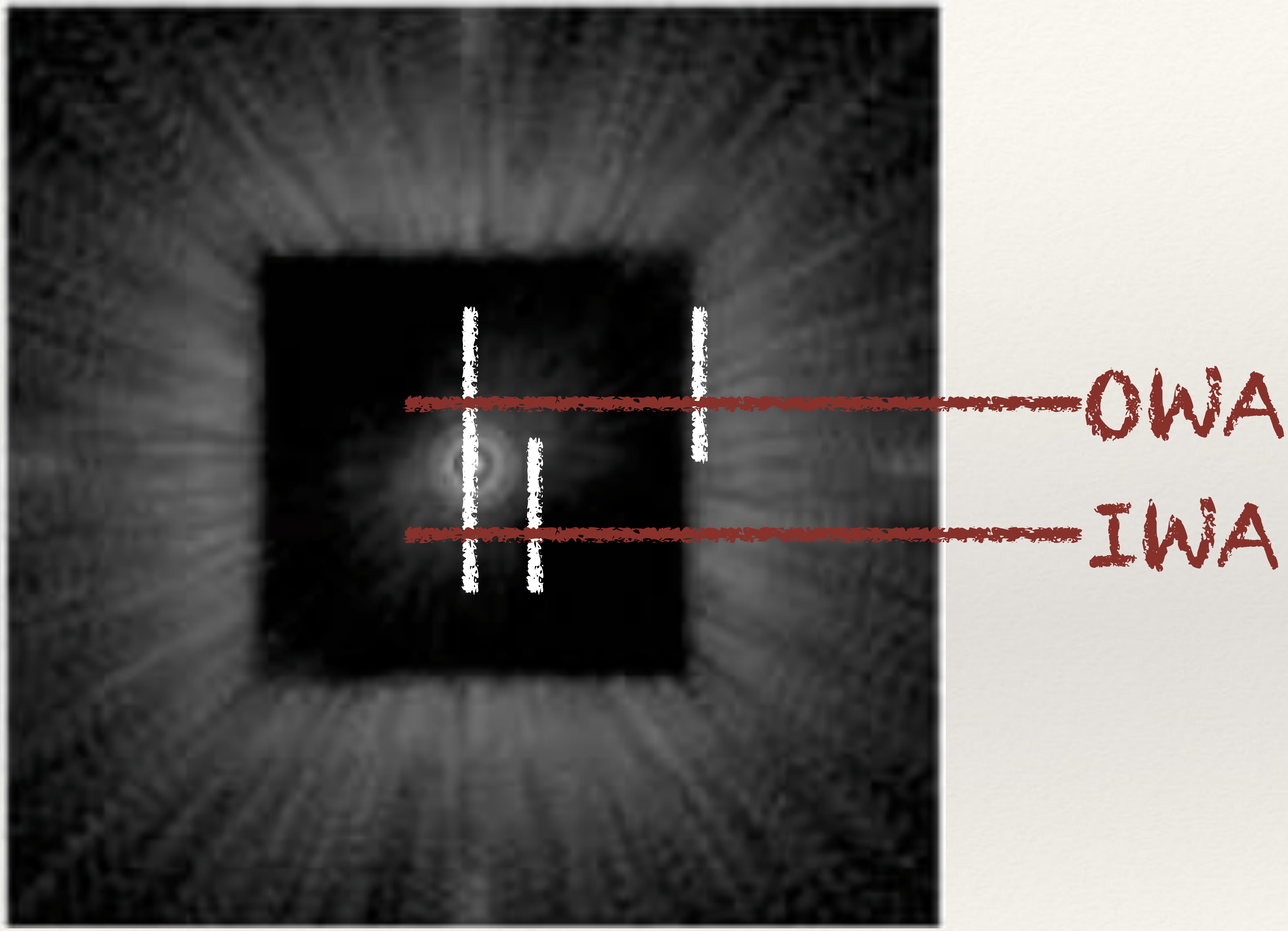
Example: IWA = 3 /D driven by 1 AU/10pc = 0.100 arcsec.

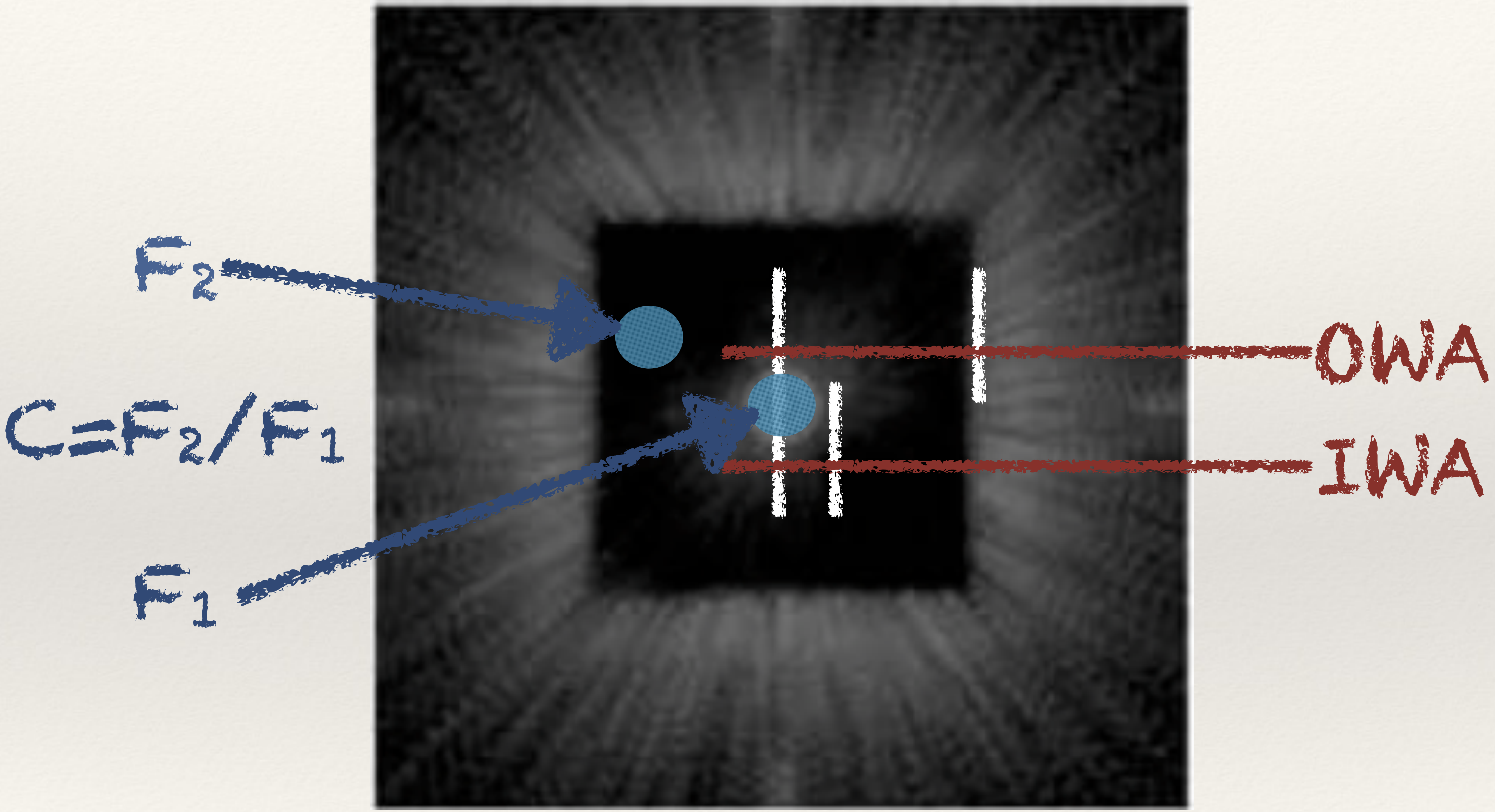
Outer working angle OWA: Largest angle at which a planet can be detected. Outer boundary of high-contrast search area.

Example: OWA = 48 /D driven by N = 96 actuator DM.



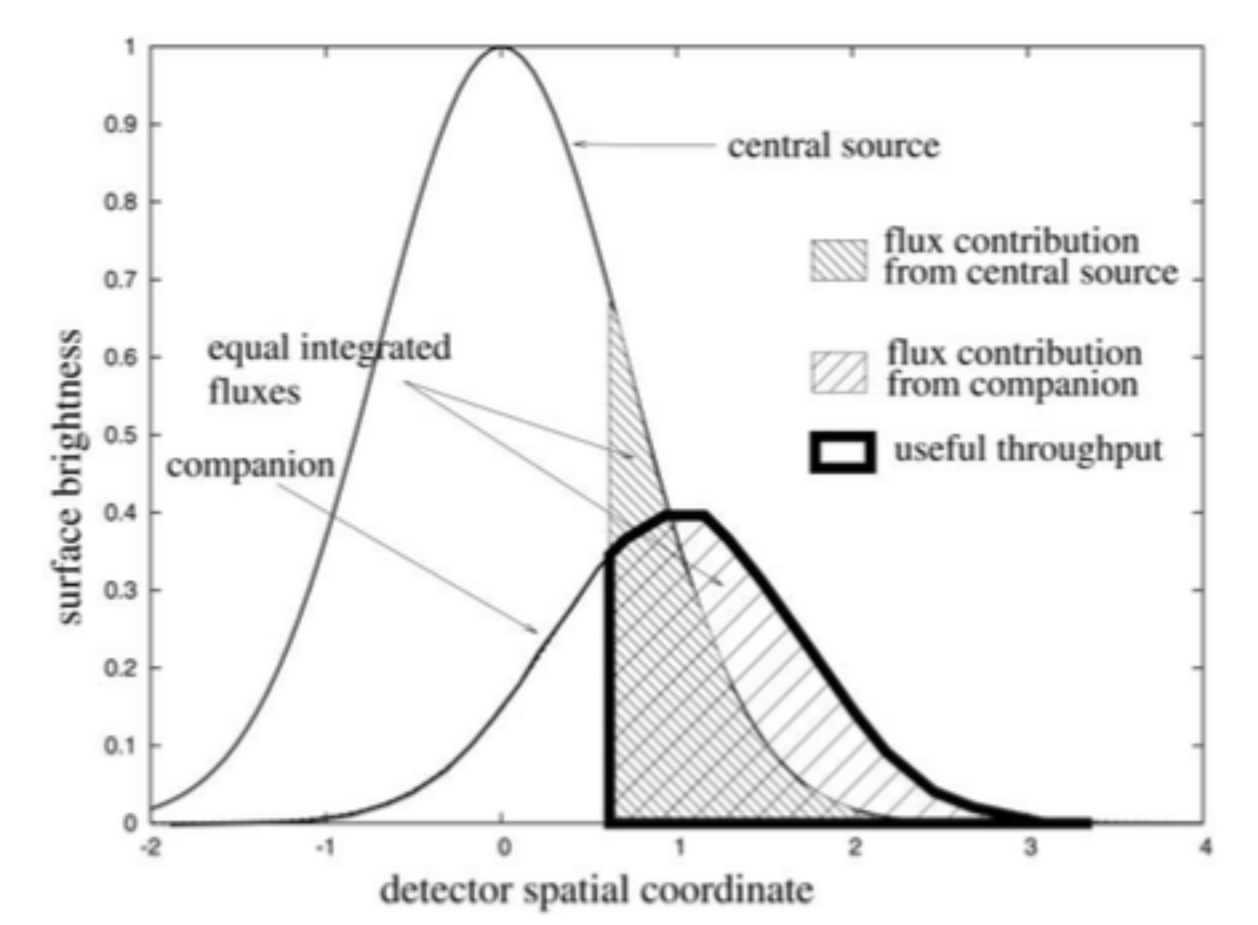

IWA


OWA
IWA


F2
C=F2/F1
F1
OWA
IWA

Important parameters II

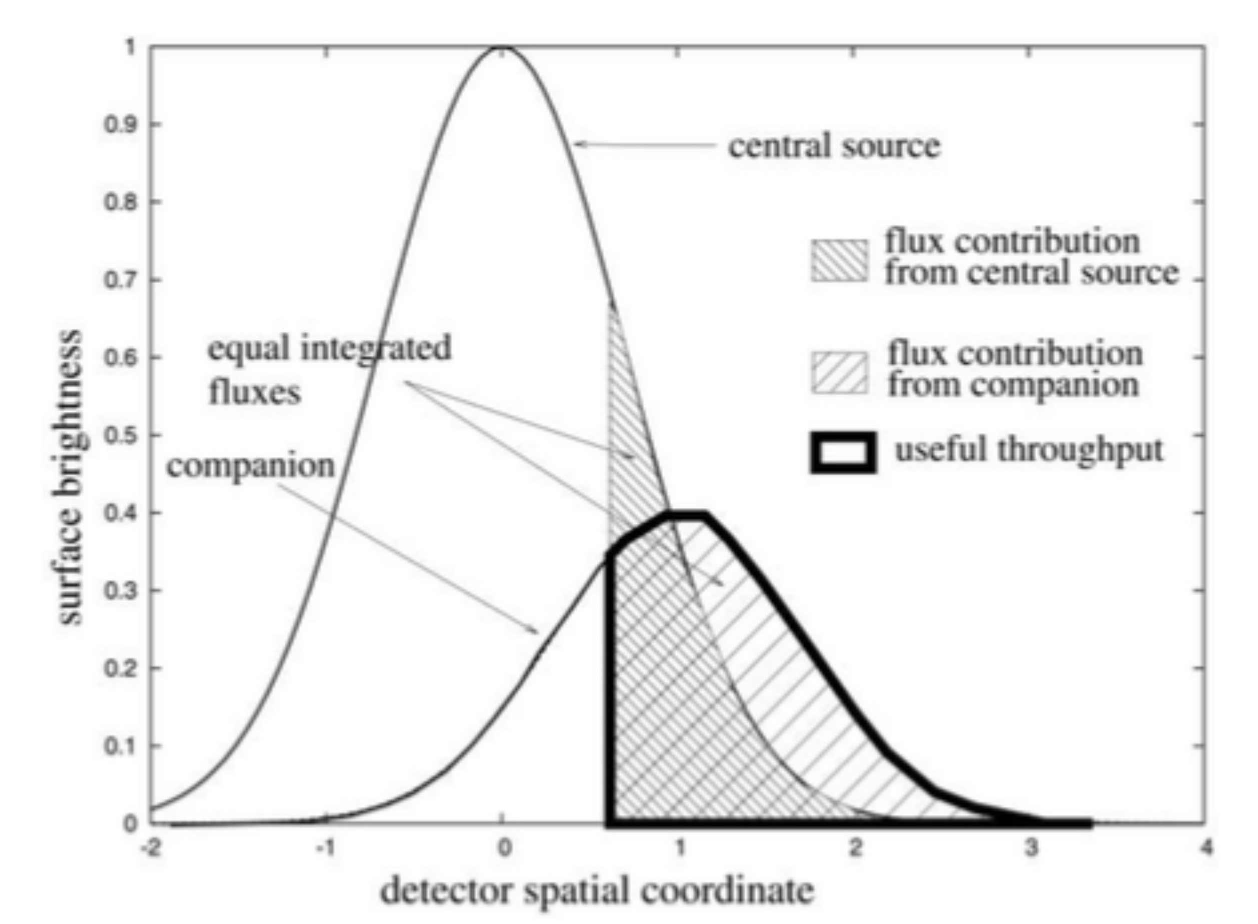
Planet Throughput: Fraction of the light of the planet that survive to the suppression due to the coronagraph.



Guyon et al., 2006

Important parameters II

Planet Throughput: Fraction of the light of the planet that survive to the suppression due to the coronagraph.



Guyon et al., 2006

Chromaticity: Capacity of the coronagraph to suppress light on a large range of wavelength.

Low chromaticity is better.

Coronagraphic Zoo …

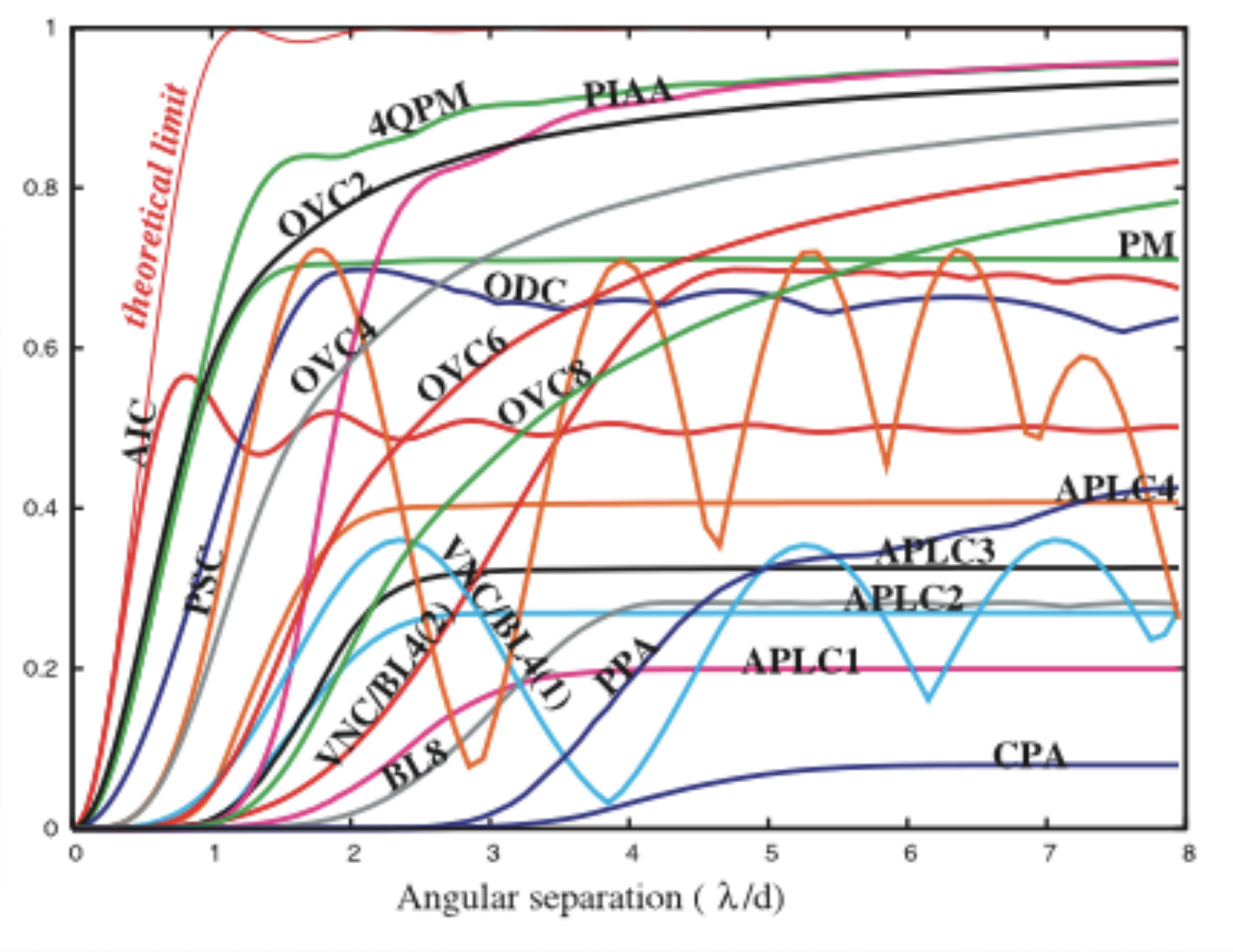
TABLE 1

Coronagraphs Able to Achieve 10^{10} PSF Contrast within $5\lambda/d$

Coronagraph	Abbreviation	Reference	Design(s) Adopted
"Interferometric" Coronagraphs			
Achromatic Interferometric Coronagraph	AIC	Baudoz et al. (2000)	
Common-Path Achromatic Interferometer-Coronagraph	CPAIC	Tavrov et al. (2005)	(=AIC)
Visible Nulling Coronagraph, X-Y shear (fourth-order null)[a]	VNC	Mennesson et al. (2003)	Shear distance $=\pm 0.3$ pupil radius
Pupil Swapping Coronagraph	PSC	Guyon & Shao (2006)	Shear distance $=0.4$ pupil diameter
Pupil Apodization			
Conventional Pupil Apodization and Shaped-Pupil[b]	CPA	Kasdin et al. (2003)	Prolate[c] ($r = 4.2\lambda/d$, 8% throughput)
Achromatic Pupil Phase Apodization	PPA	Yang & Kostinski (2004)	$\phi = \phi_2(x) + \phi_2(y)$; $a = 2$; $\epsilon = 0.01$
Phase Induced Amplitude Apodization Coronagraph	PIAAC	Guyon (2003)	Prolate apodization
Phase Induced Zonal Zernike Apodization	PIZZA	Martinache (2004)	Not simulated
Improvement on the Lyot Concept with Amplitude Masks			
Apodized Pupil Lyot Coronagraph	APLC	Soummer et al. (2003a, 2003b)	$r = 1.8\lambda/d$
Apodized Pupil Lyot Coronagraph, *N* steps	APLC*N*	Aime & Soummer (2004)	$(N, r) = (2, 1.4); (3, 1.2); (4, 1.0)$
Band-limited, fourth-order[a]	BL4	Kuchner & Traub (2002)	$\sin^4$ intensity mask, $\epsilon = 0.21$
Band-limited, eighth-order	BL8	Kuchner et al. (2005)	$m = 1$, $l = 3$, $\epsilon = 0.6$
Improvement on the Lyot Concept with Phase Masks			
Phase Mask	PM	Roddier & Roddier (1997)	With mild prolate pupil apod.
4 Quadrant Phase Mask	4QPM	Rouan et al. (2000)	
Achromatic Phase Knife Coronagraph	APKC	Abe et al. (2001)	(=4QPM)
Optical Vortex Coronagraph, topological charge *m*	OVC*m*	Palacios (2005)	$m = 2, 4, 6, 8$
Angular Groove Phase Mask Coronagraph	AGPMC	Mawet et al. (2005)	(=OVC)
Optical Differentiation	ODC	Oti et al. (2005)	Mask: $x \times \exp^{-(x/10)^2 d}$

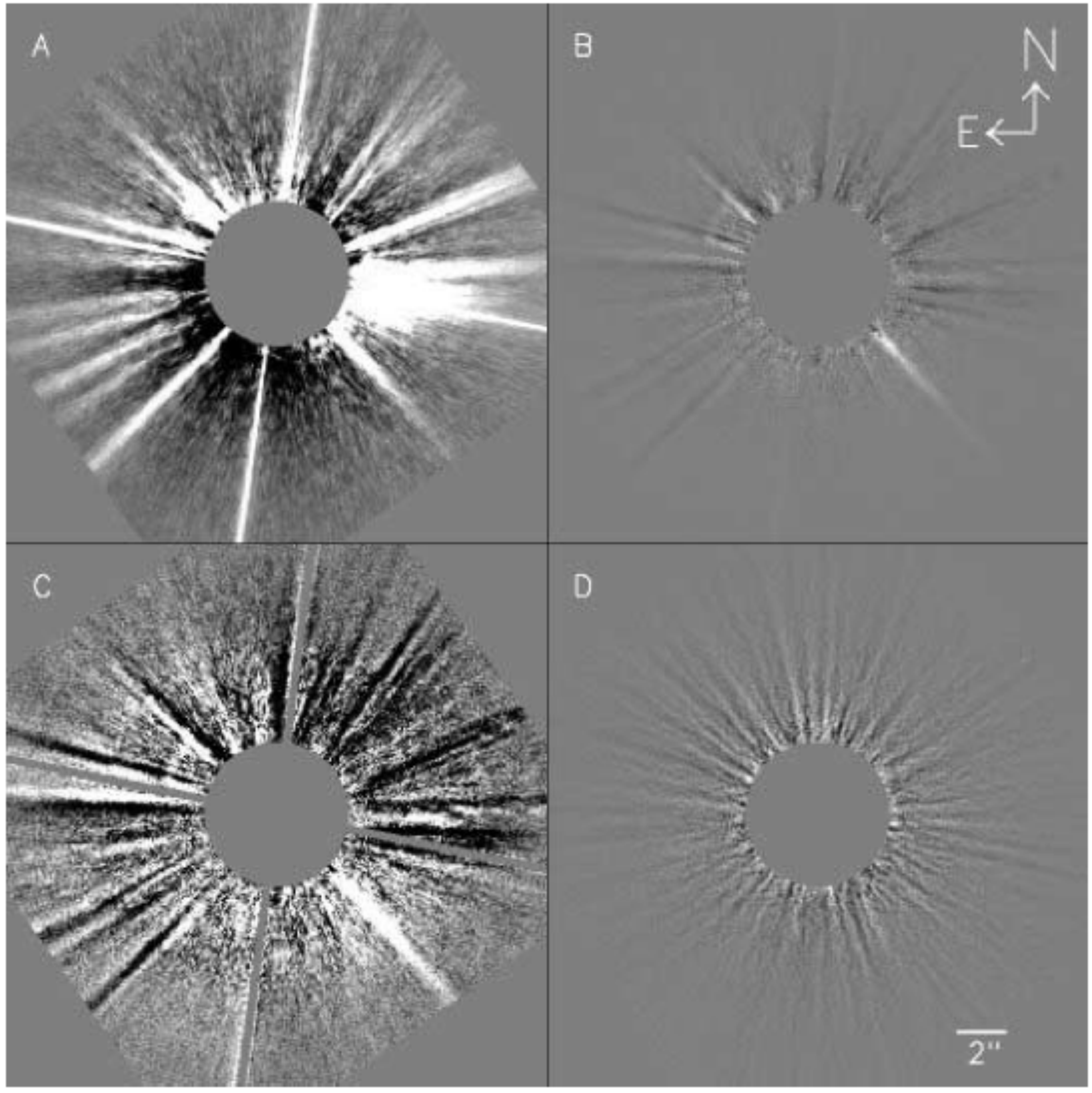
Guyon et al., 2006, ApJ Suppl, 167, 81

Peak Throughput

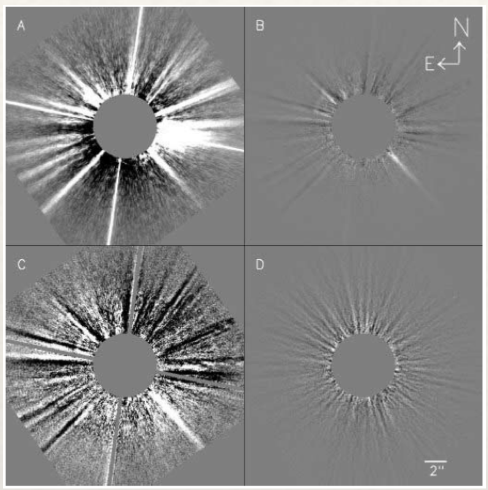


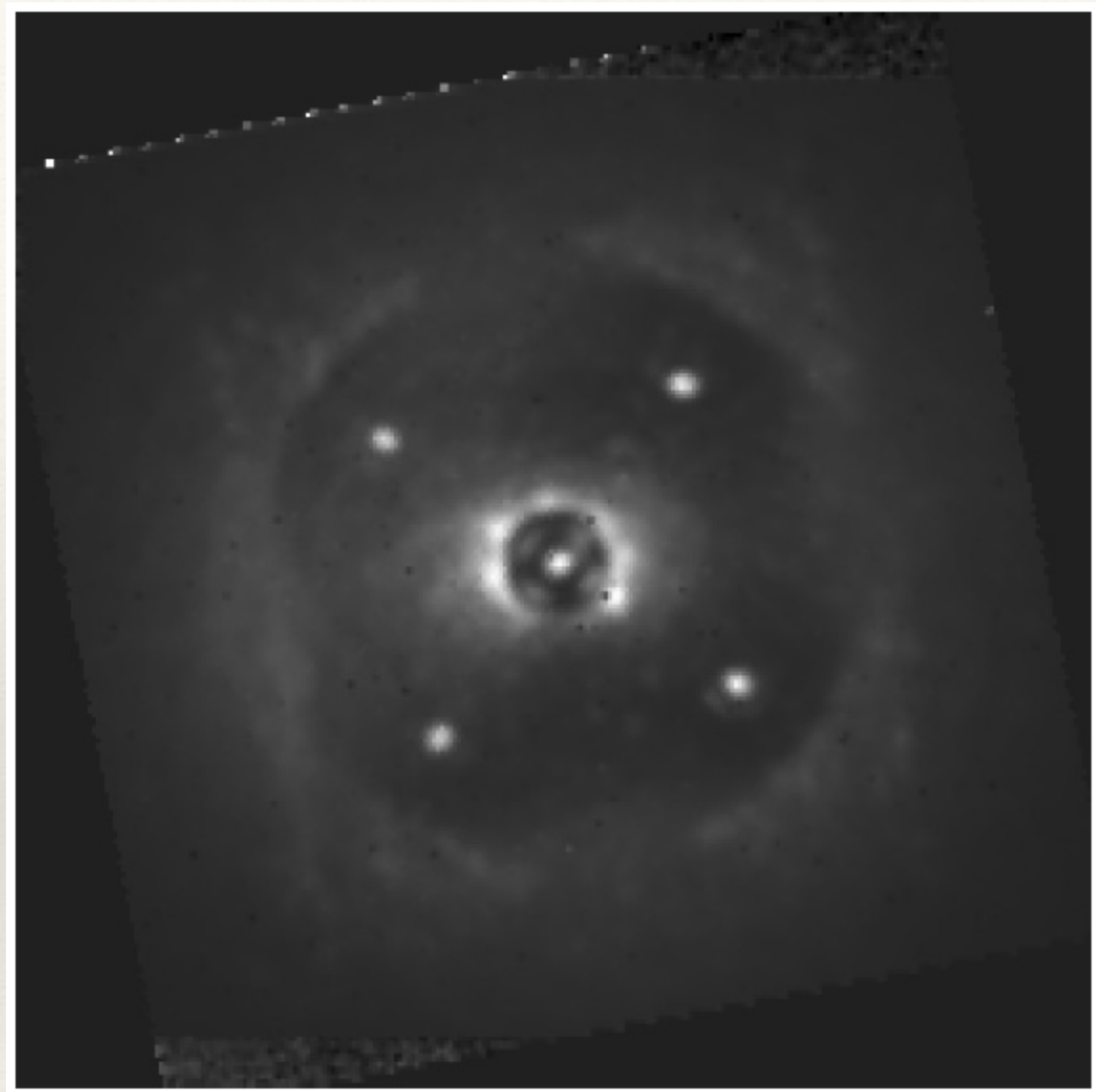
Guyon et al., 2006, ApJ Suppl, 167, 81

Coronagraphy and Astrometry...



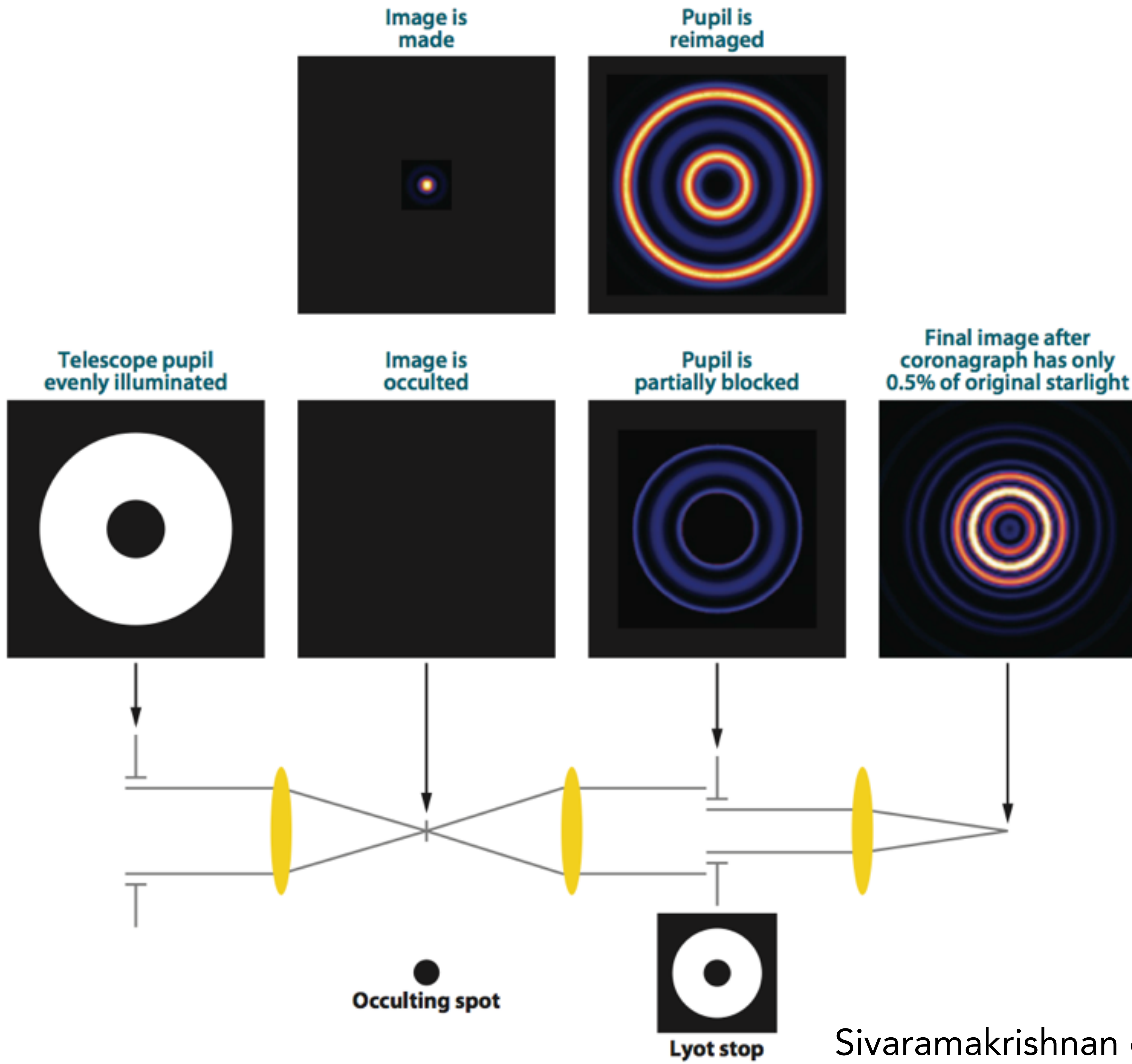
Coronagraphy and Astrometry…





Setting a sinusoidal pattern on the DM yields four bright speckles that can be used center

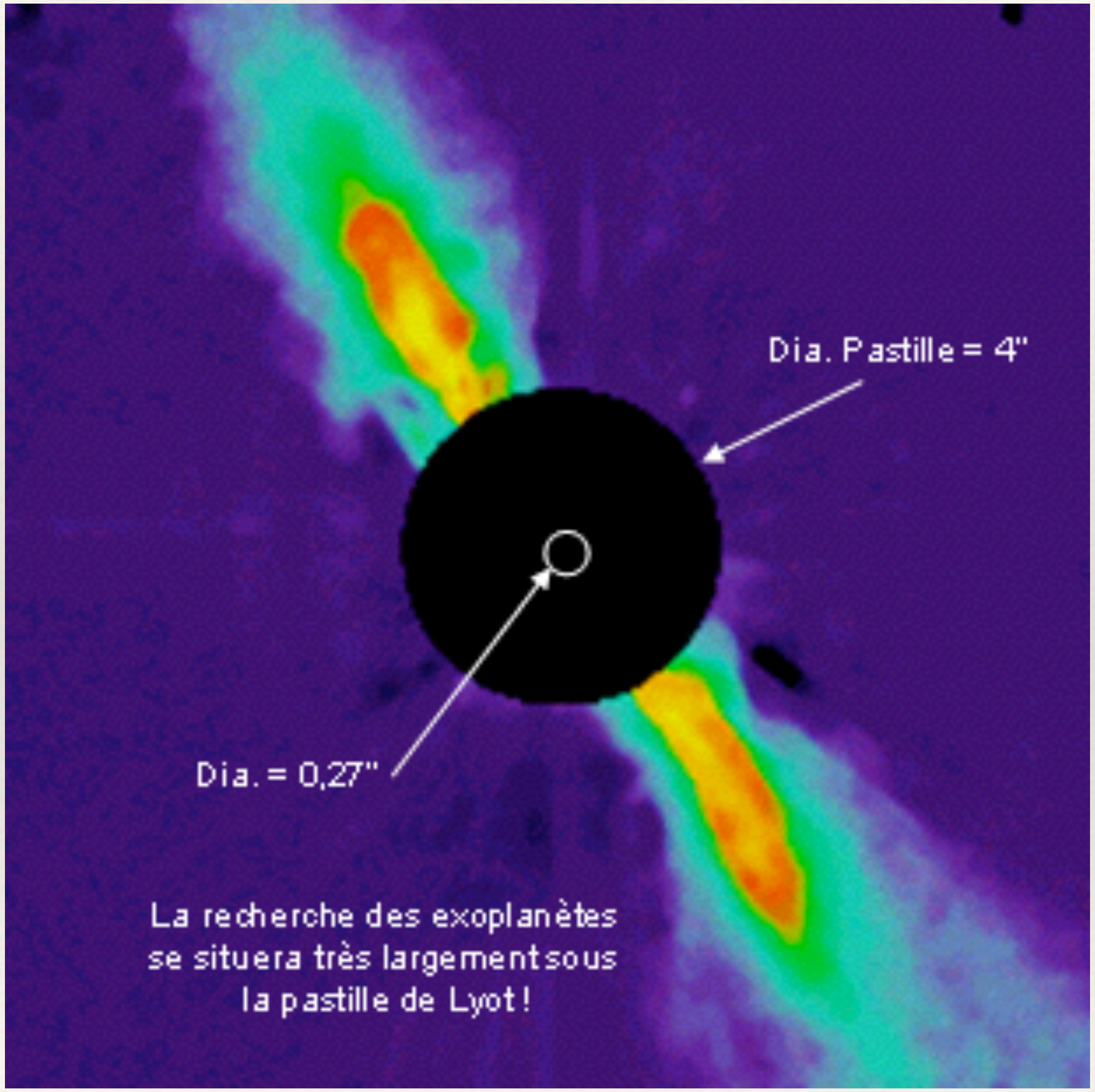
AMPLITUDE BASED CORONAGRAPH



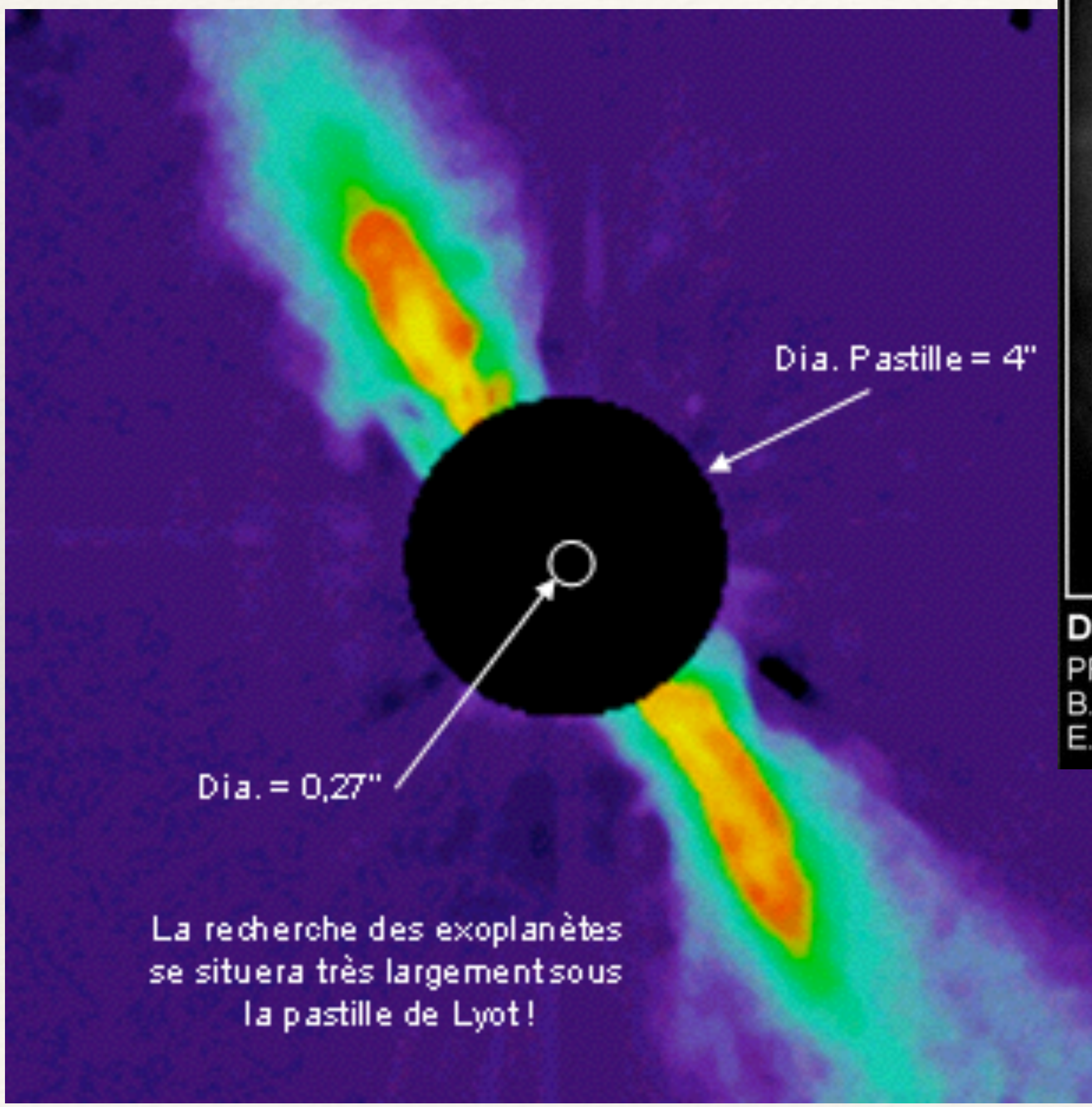
Sivaramakrishnan et al. (2001)

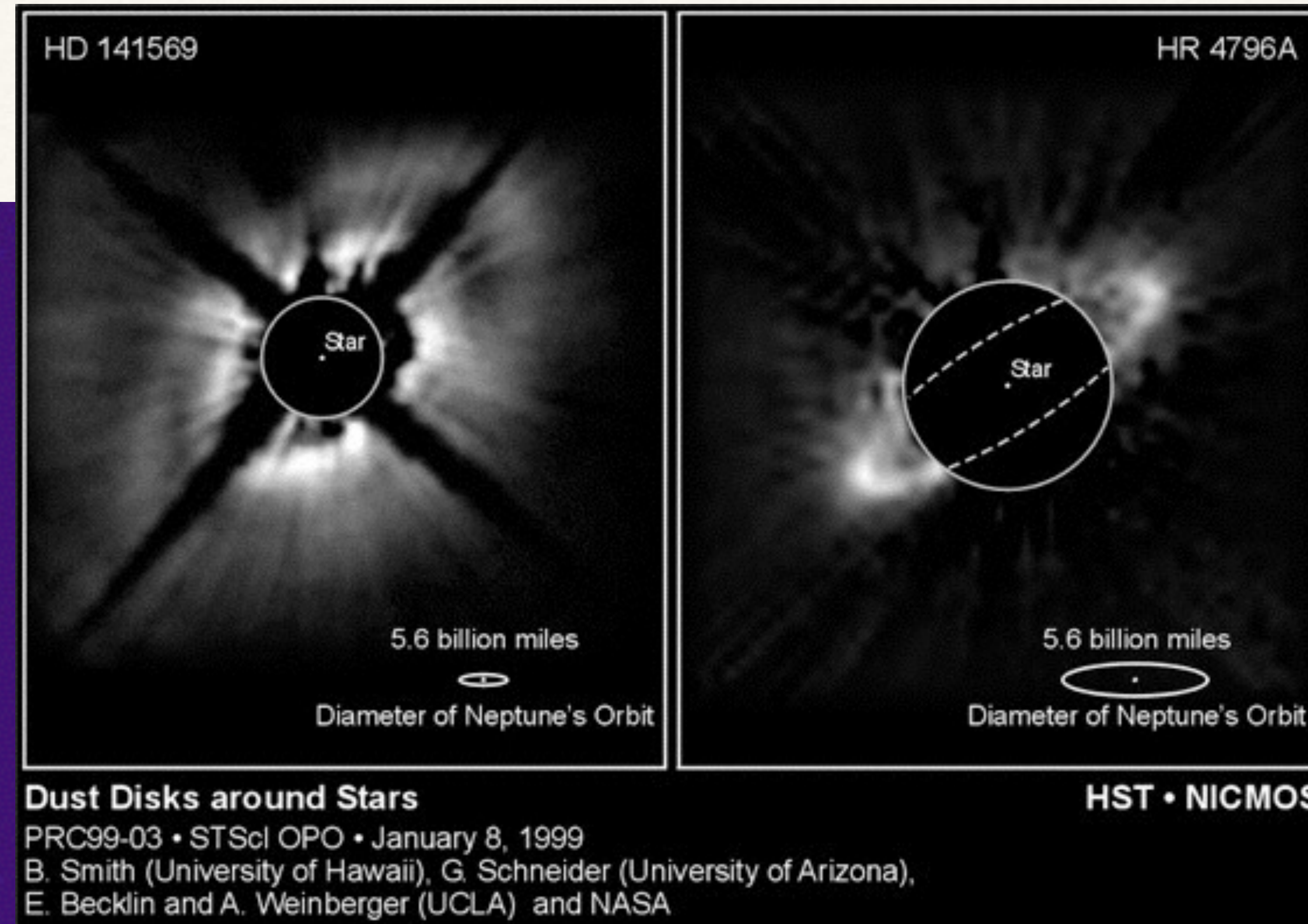
With a Lyot Coronagraph

With a Lyot Coronagraph

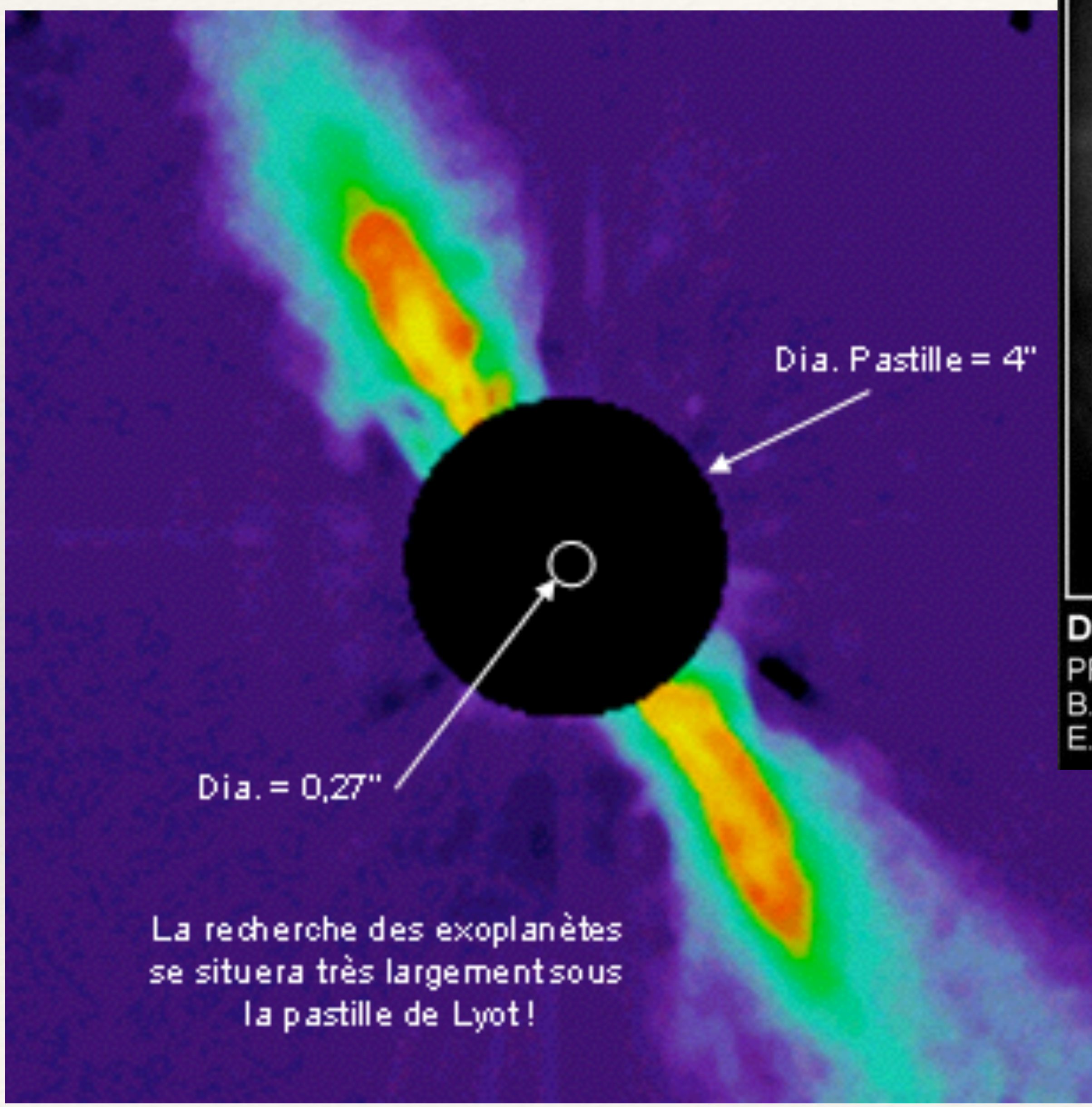


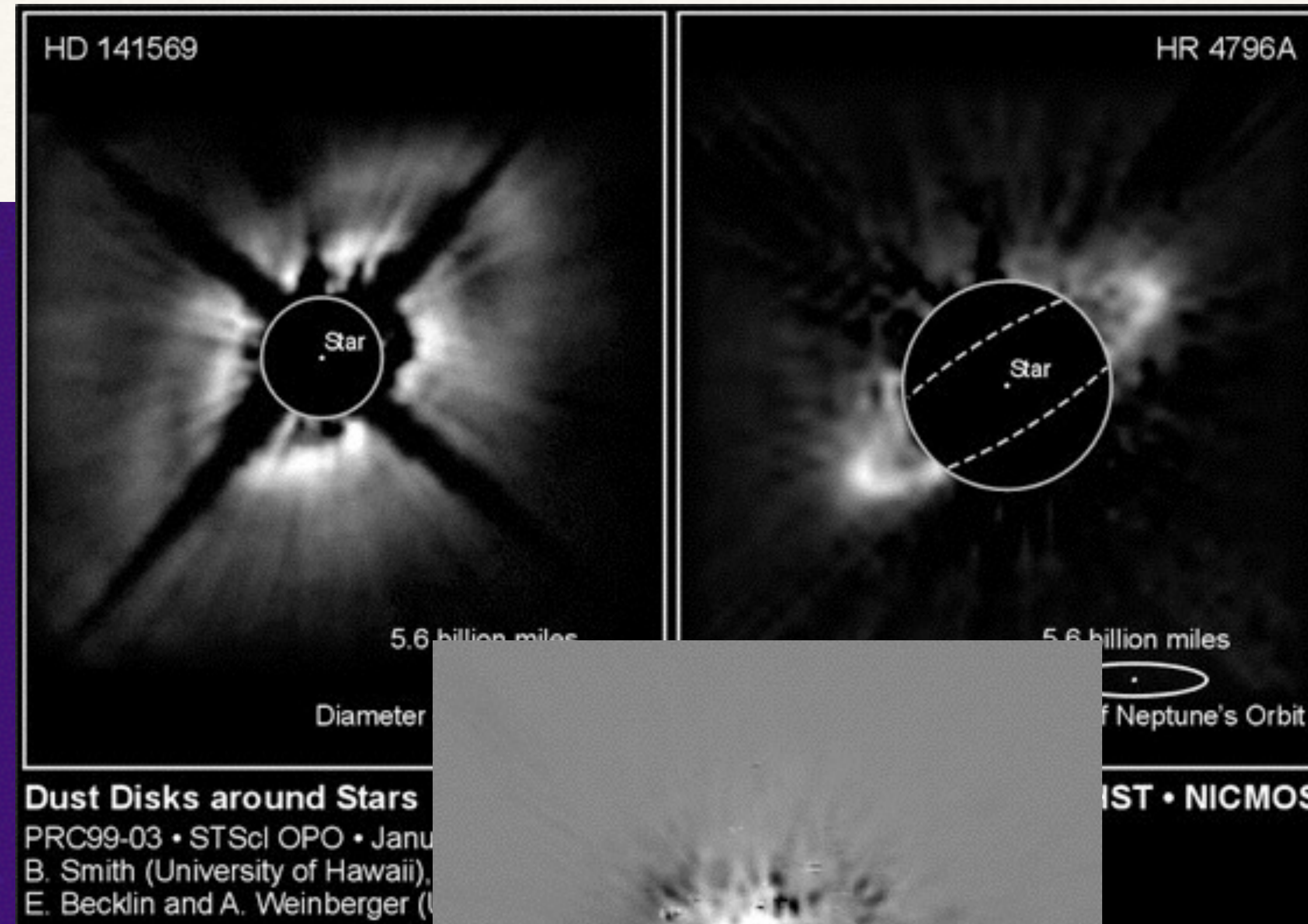
With a Lyot Coronagraph

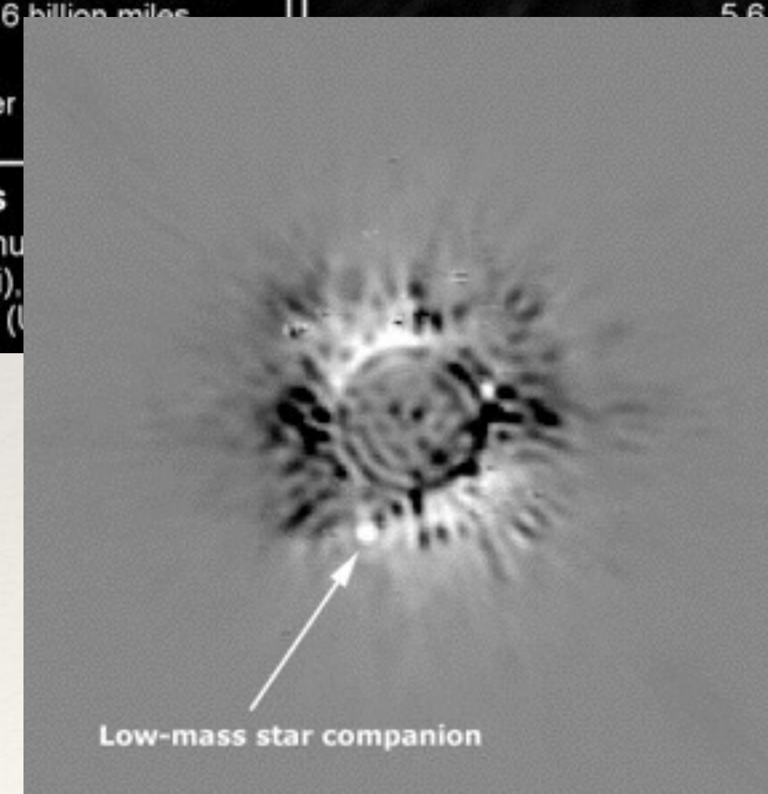




With a Lyot Coronagraph



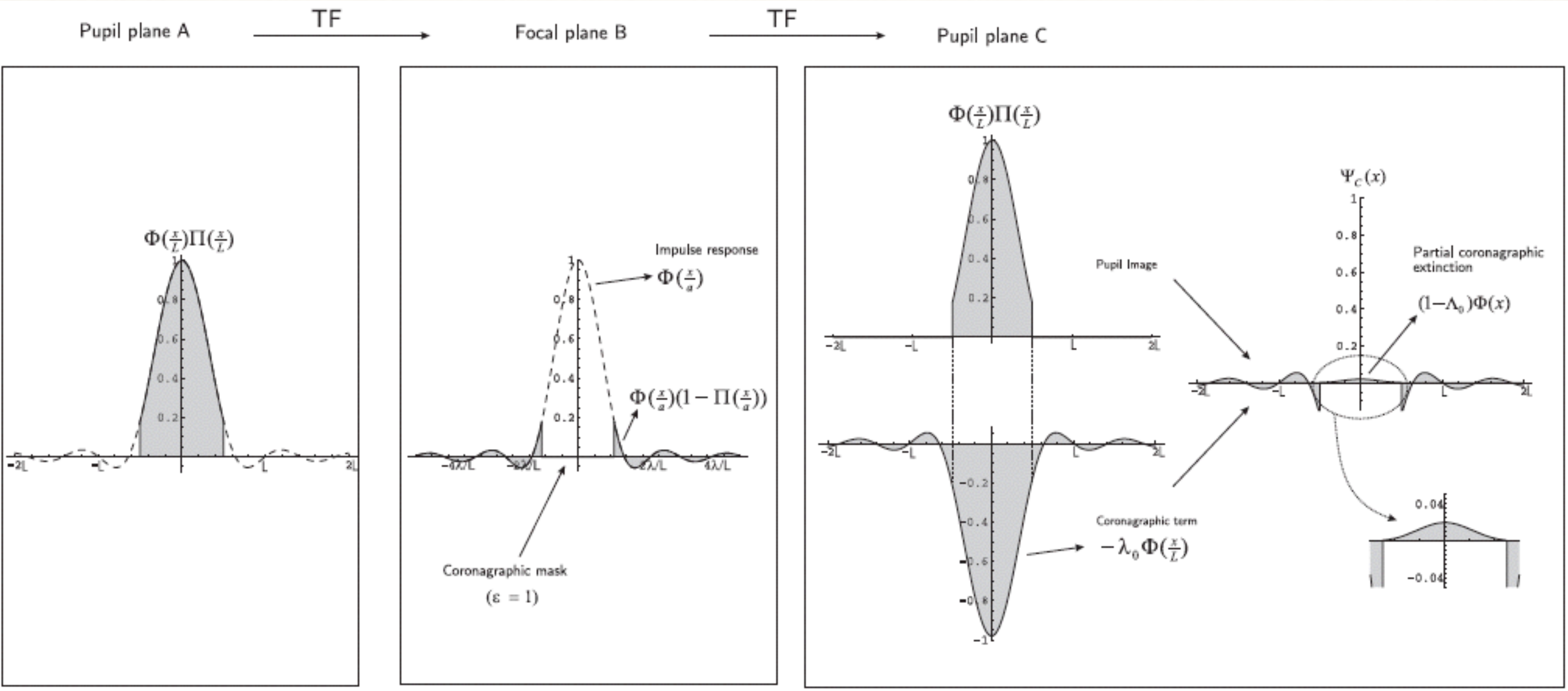




Apodization

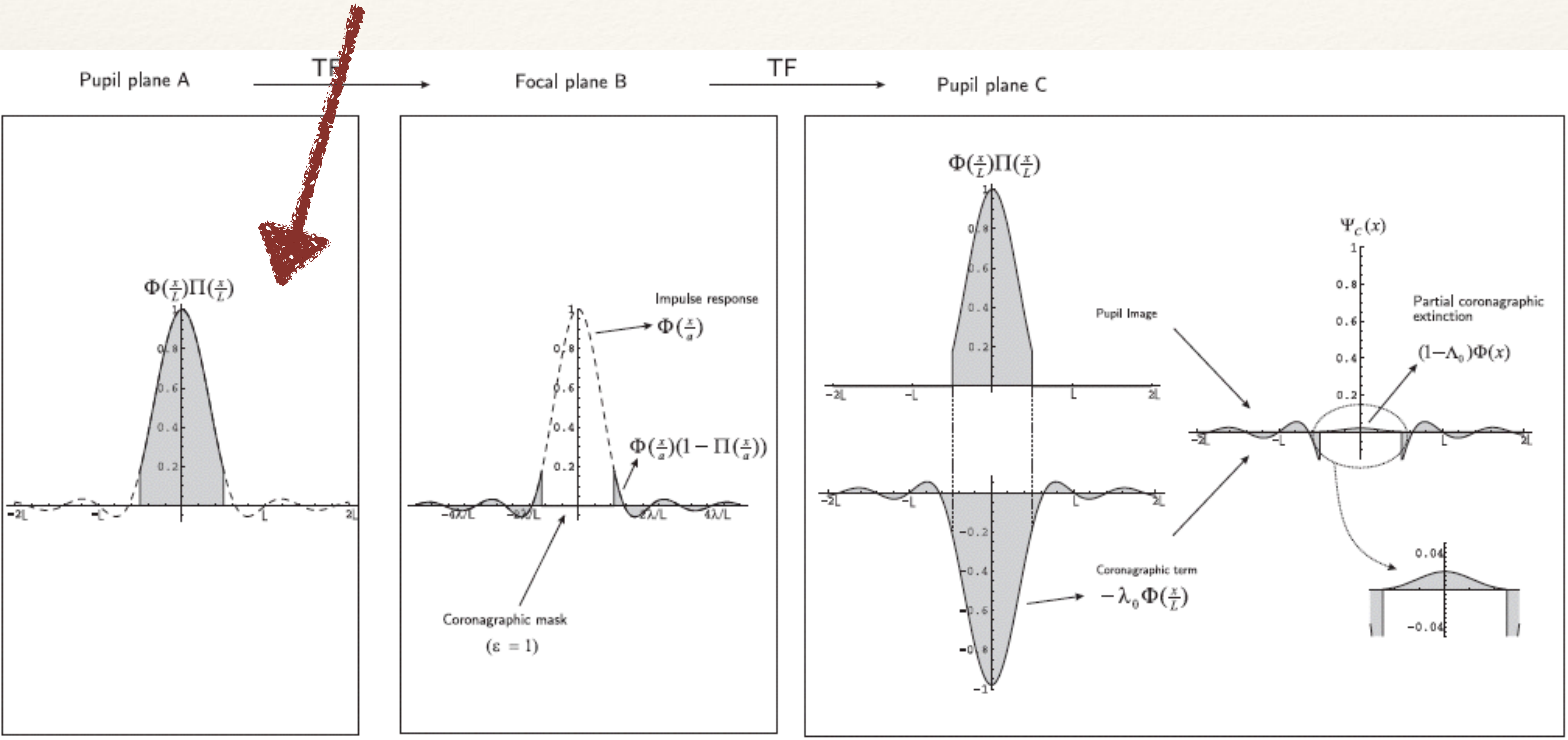
- Apodizer = Remove the PSF foot
- Apodization of the entrance pupil to improve the extinction of Lyot and Roddier Masks
- Aime et al (2000): a prolate spheroid function (cos^2) together with a square or circular pupil
- Apodized Roddier: Total Extintion
- Apodized Lyot: Partial extintion but smaller occulter
- Loss of angular resolution

Apodization



Apodization

Put an apodized mask in the pupil plane …



Apodized Lyot coronagraph

The Lyot coronagraph has sharp edges on the pupil. The PSF is then characterized by a considerable amount of light at large separation because pupil and focal planes are conjugated and power at high frequencies (large separation from center) are required to reproduce the sharp edges on the pupil. Smoothing edges on the pupil reduce power at high frequencies, resulting in a sharper PSF. This is obtained by inserting an apodizer on the pupil. This allows to reduce the size of the PSF even wrt not-coronagraphic images (the telescope pupil itself has sharp edges).

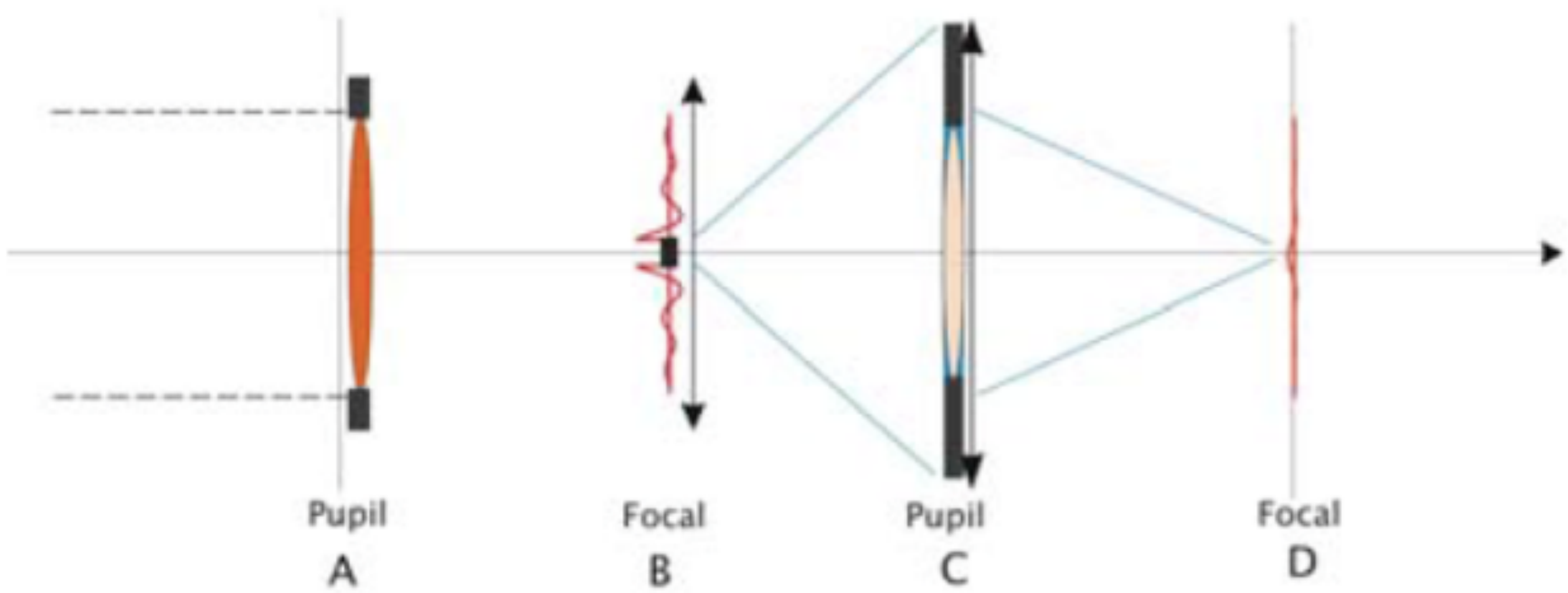
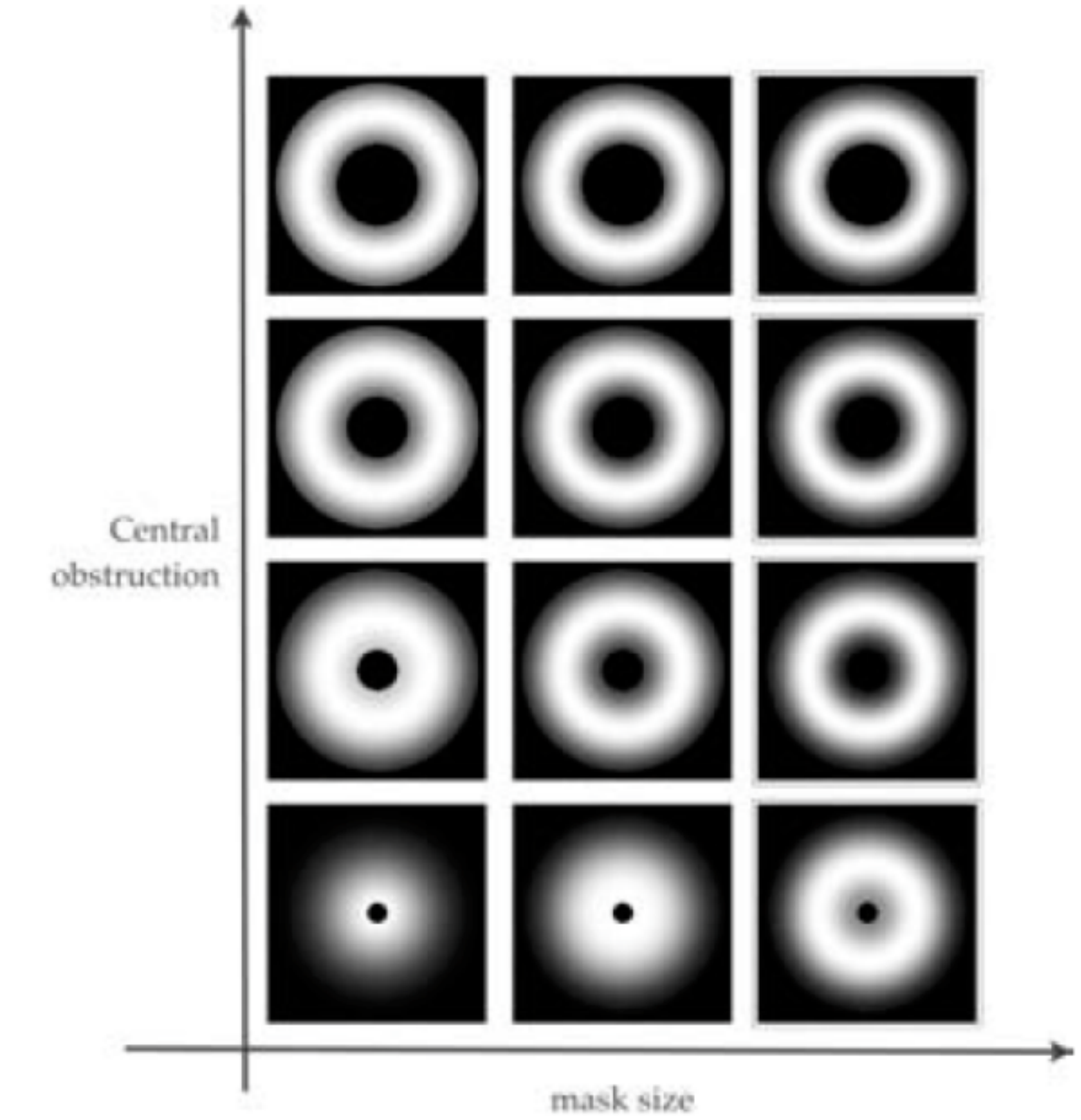
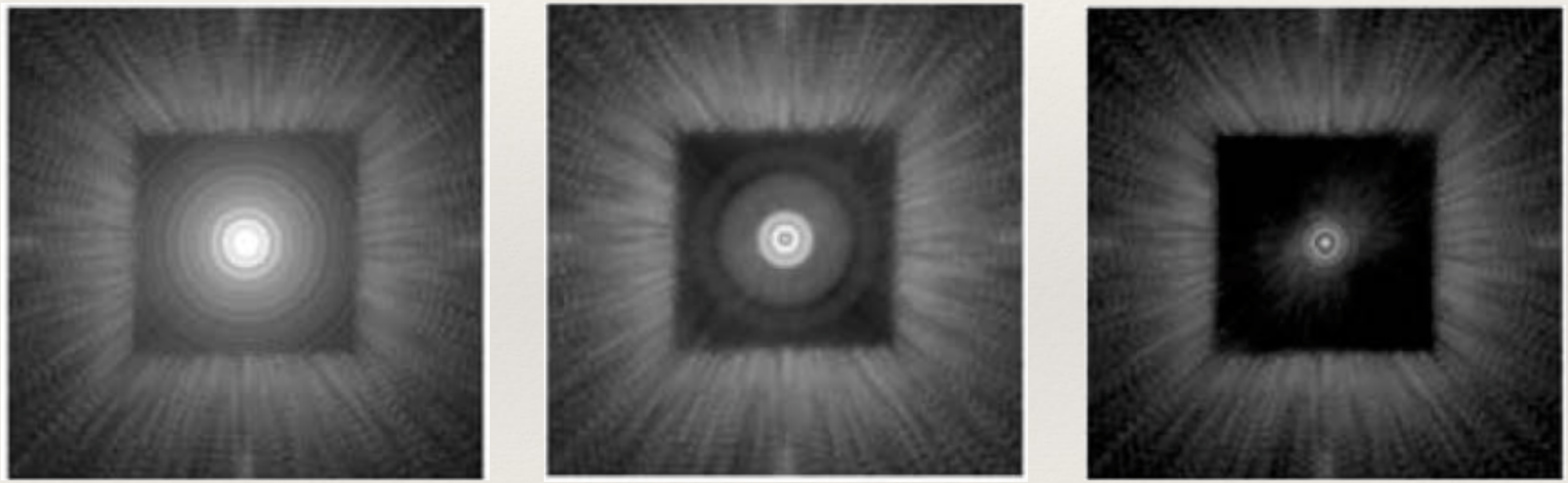


Figure 1. The basic layout of an APLC is similar to a classical Lyot coronagraph, but adding an upstream apodized pupil in Plane A. A hard hedged focal maks is set in the focal plane B, and a Lyot stop *identical* to the entrance pupil shape in plane C. A remarquable difference between APLC and classical Lyot is that APLCs don't require to undersize the Lyot stop.

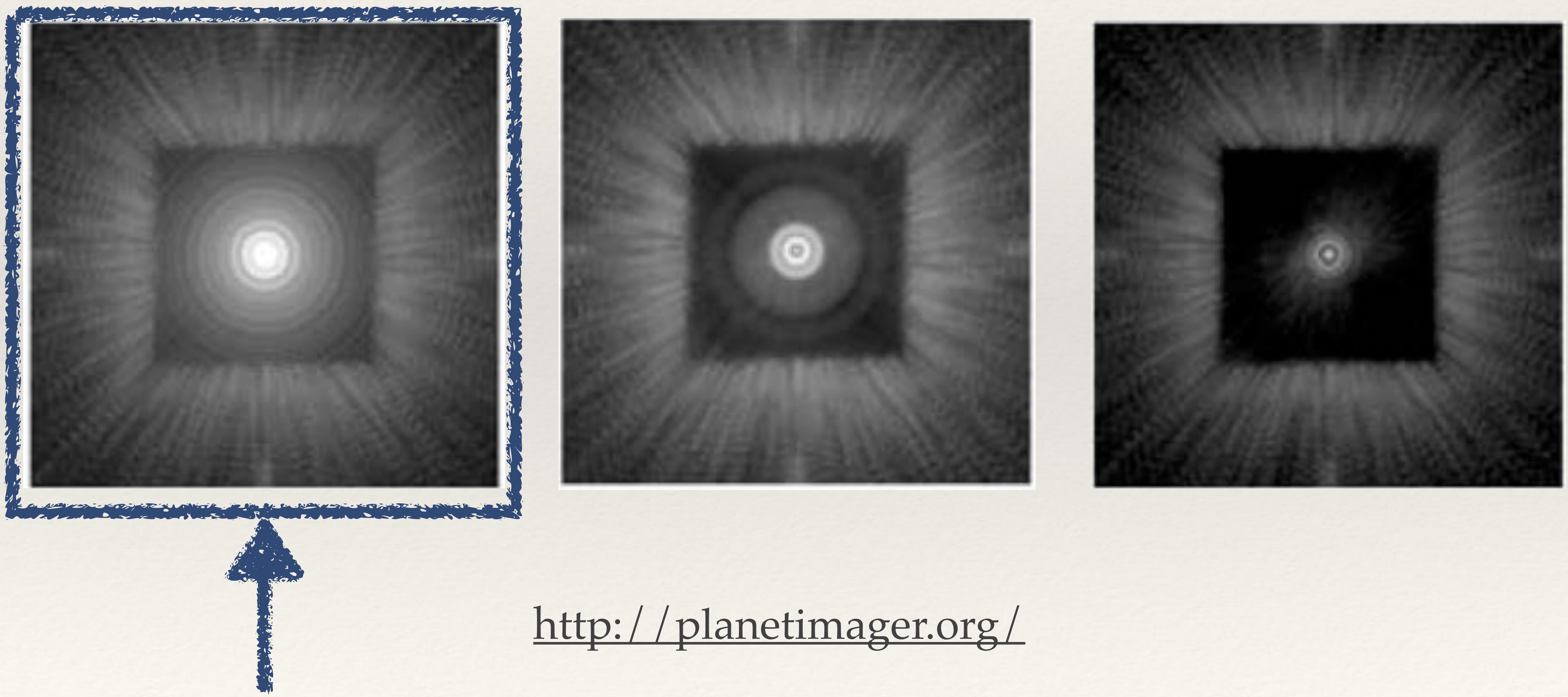

Central
obstruction
mask size

An Apodized Lyot for the GPI Project



http://planetimager.org/

An Apodized Lyot for the GPI Project

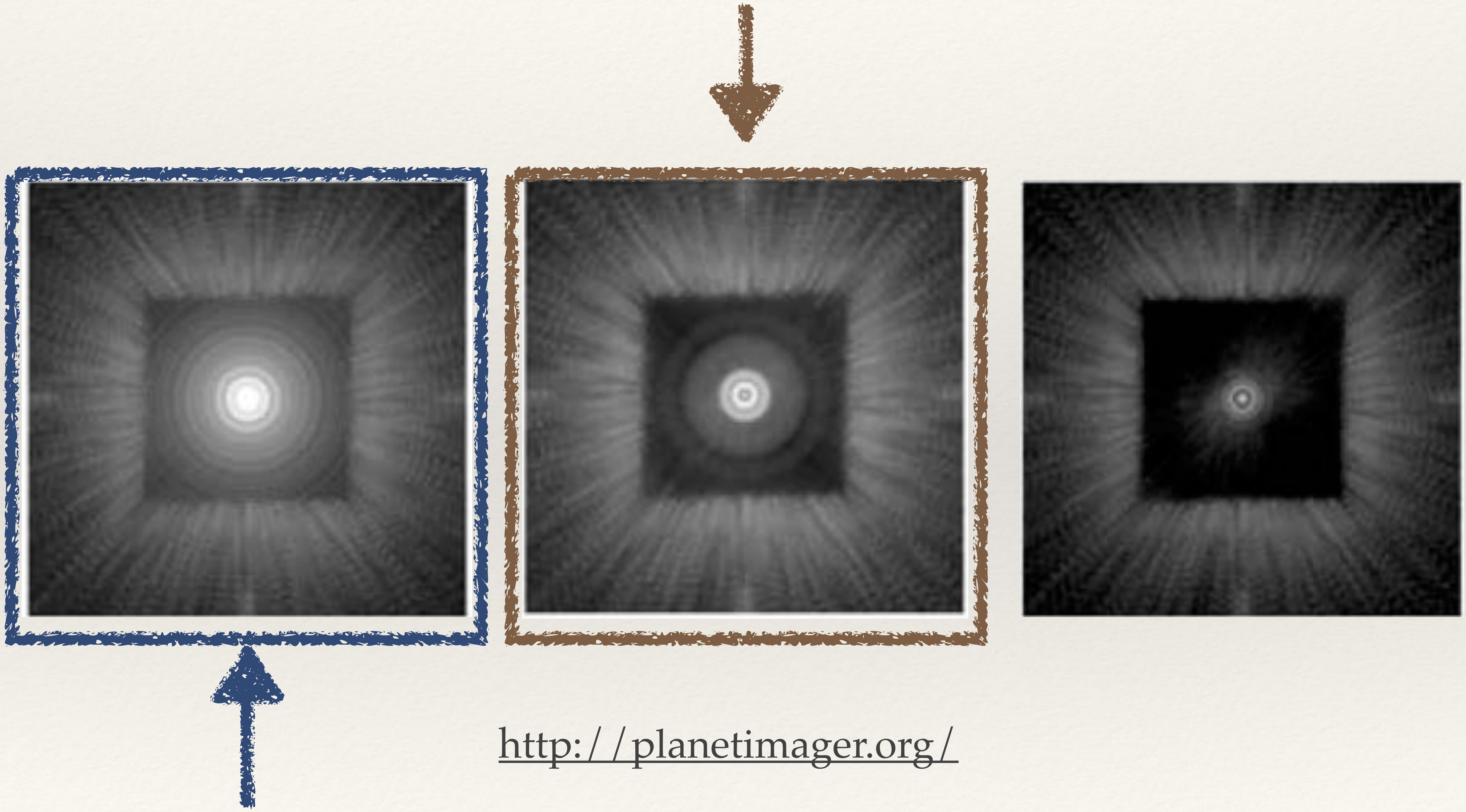


AO Corrected PSF

http://planetimager.org/

An Apodized Lyot for the GPI Project

Lyot Coronagraphic PSF

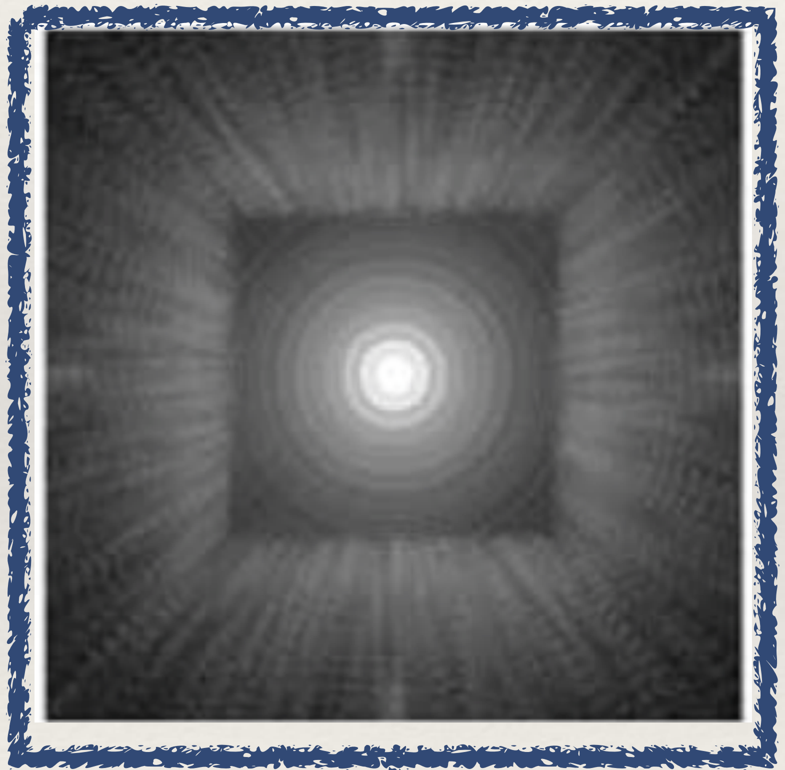


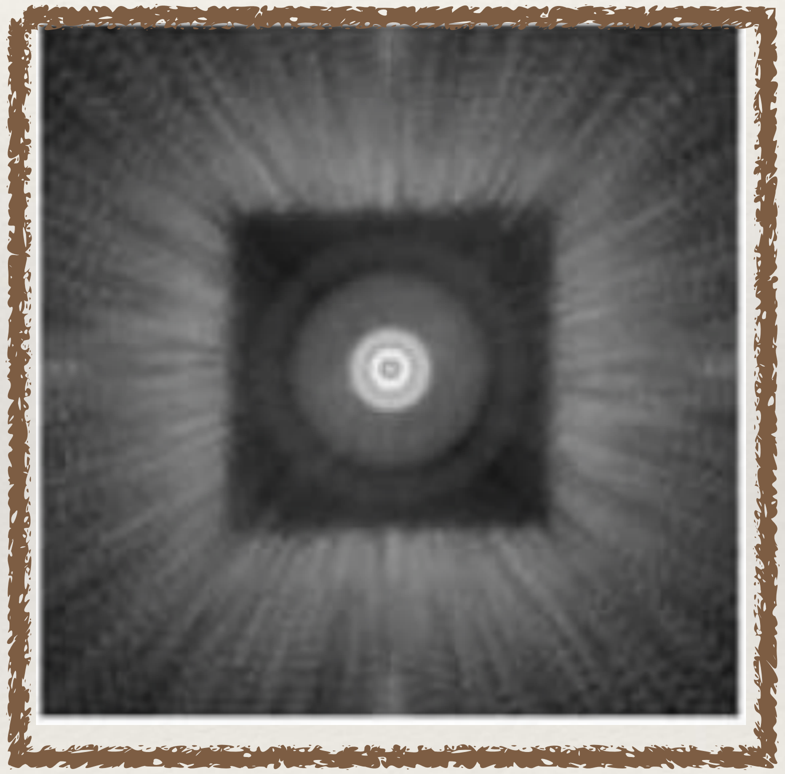
AO Corrected PSF

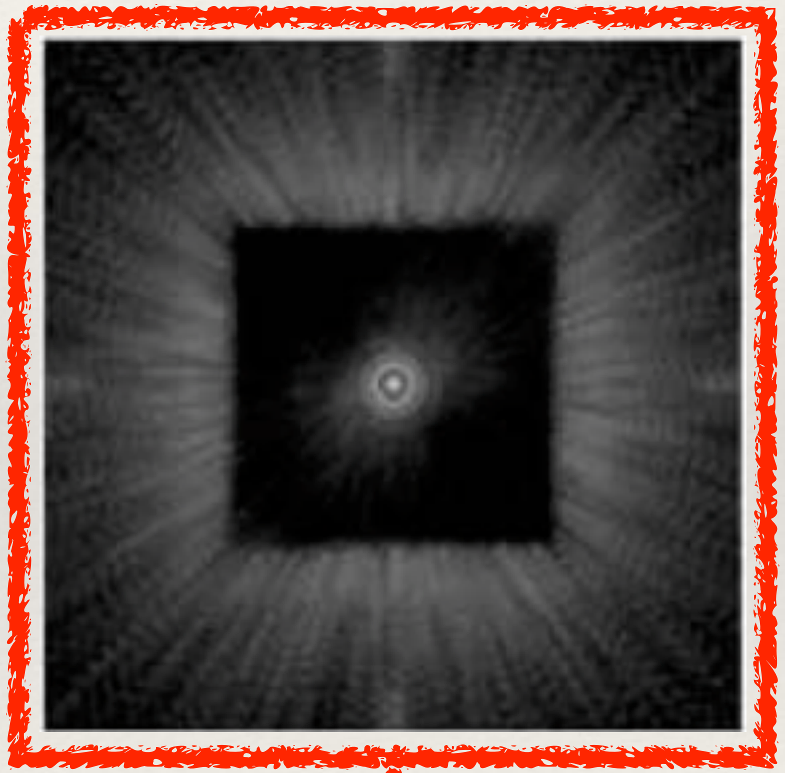
http://planetimager.org/

An Apodized Lyot for the GPI Project

Lyot Coronagraphic PSF







http://planetimager.org/

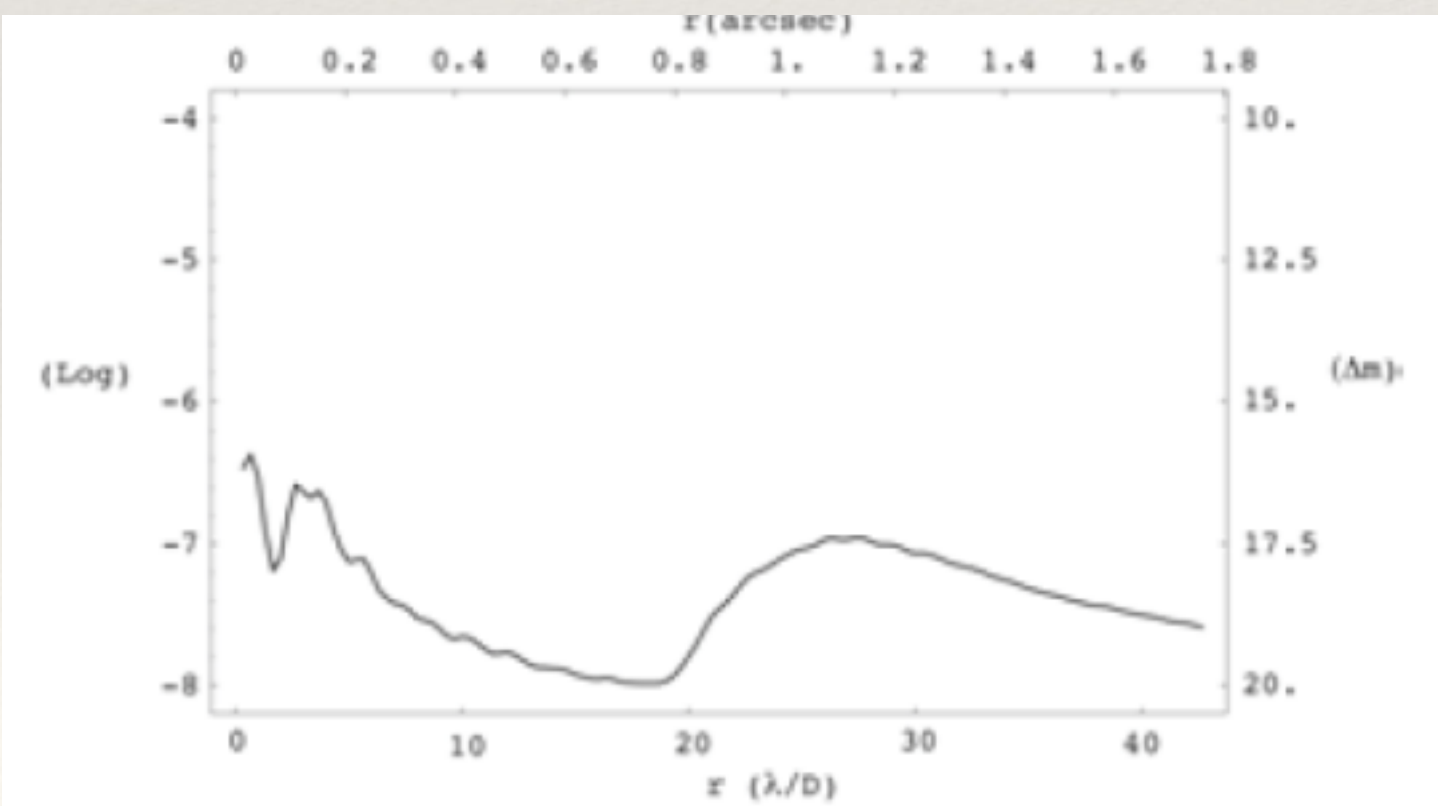
AO Corrected PSF

APLC coronagraphic PSF

Expected gain in contrast

Problems:

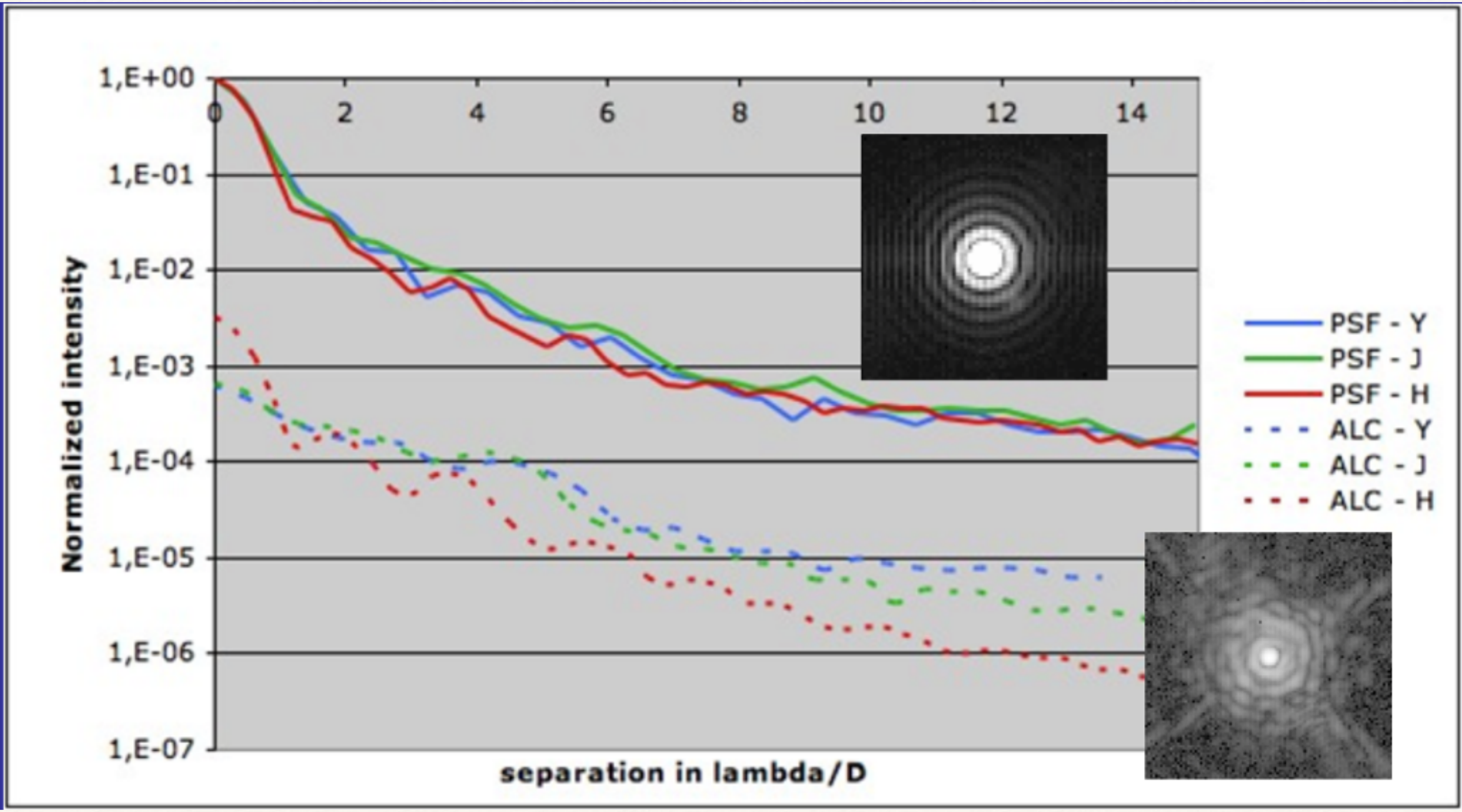
- ☑ Coronagraphs are based on diffraction properties gain is wavelength dependent (more efficient coro's works on a narrow range)
- ☑ A balance should be found between Inner Working Angle (central obscuration), off-axis transmission and diffraction suppression
- ☑ For apodized Lyot coro, typical values are : IWA~4-5 /D, transmission ~50%, and gain in contrast a few tens



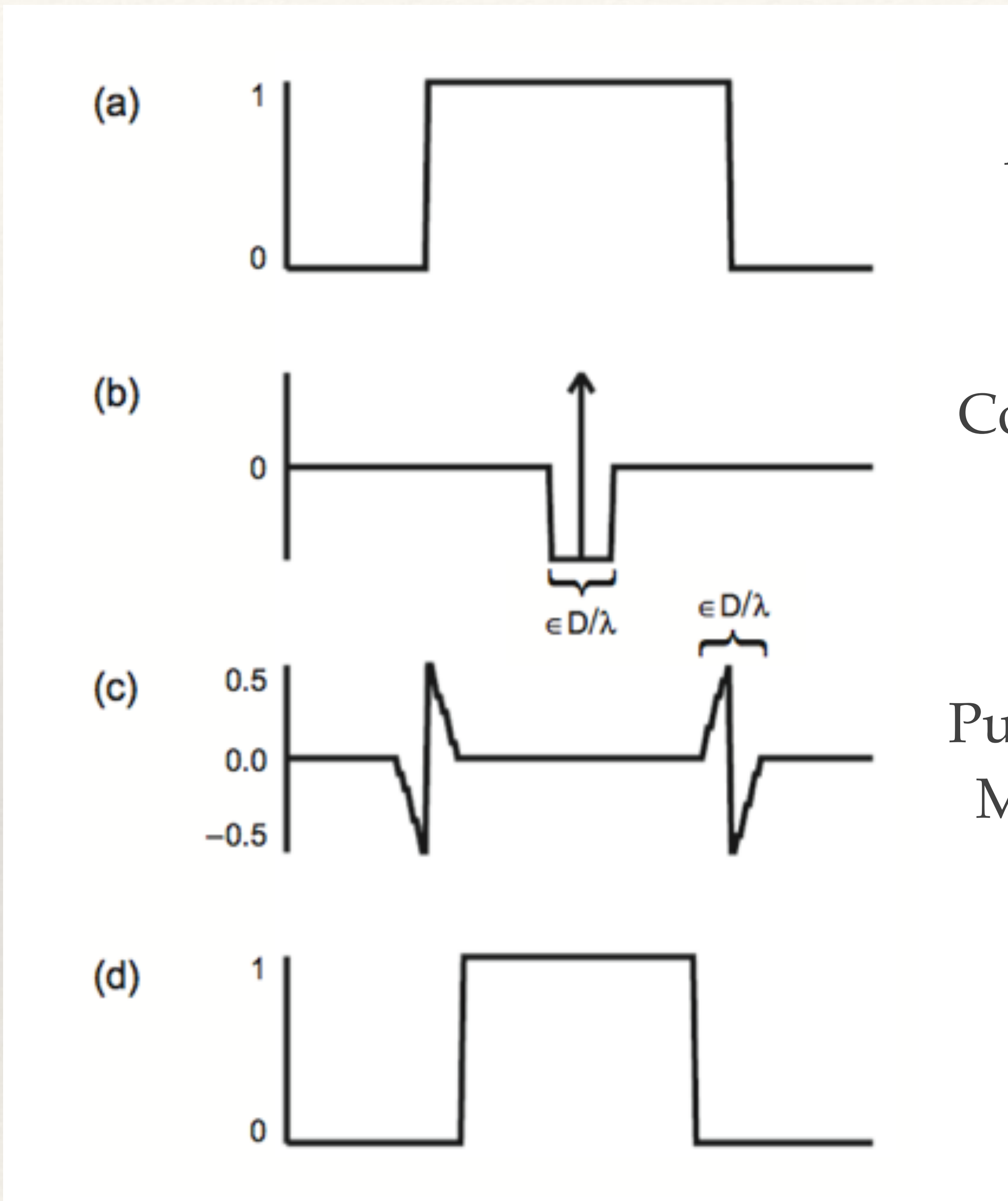
Simulation for GPI:

dynamic range including speckle and photon noise for a 7th mag star (1000s in H)

Results with ALC on SPHERE



Band Limited Coronograph



Aperture
$A(u)$

Amplitude of on-axis star = *1* e^{i0}

Conjugate of
mask FT
$M(u)$

FT(*1* - *sin x/x*) = *rect(u)* + *delta(u)*

Pupil Field of
$M(u) \otimes A(u)$

Convolution

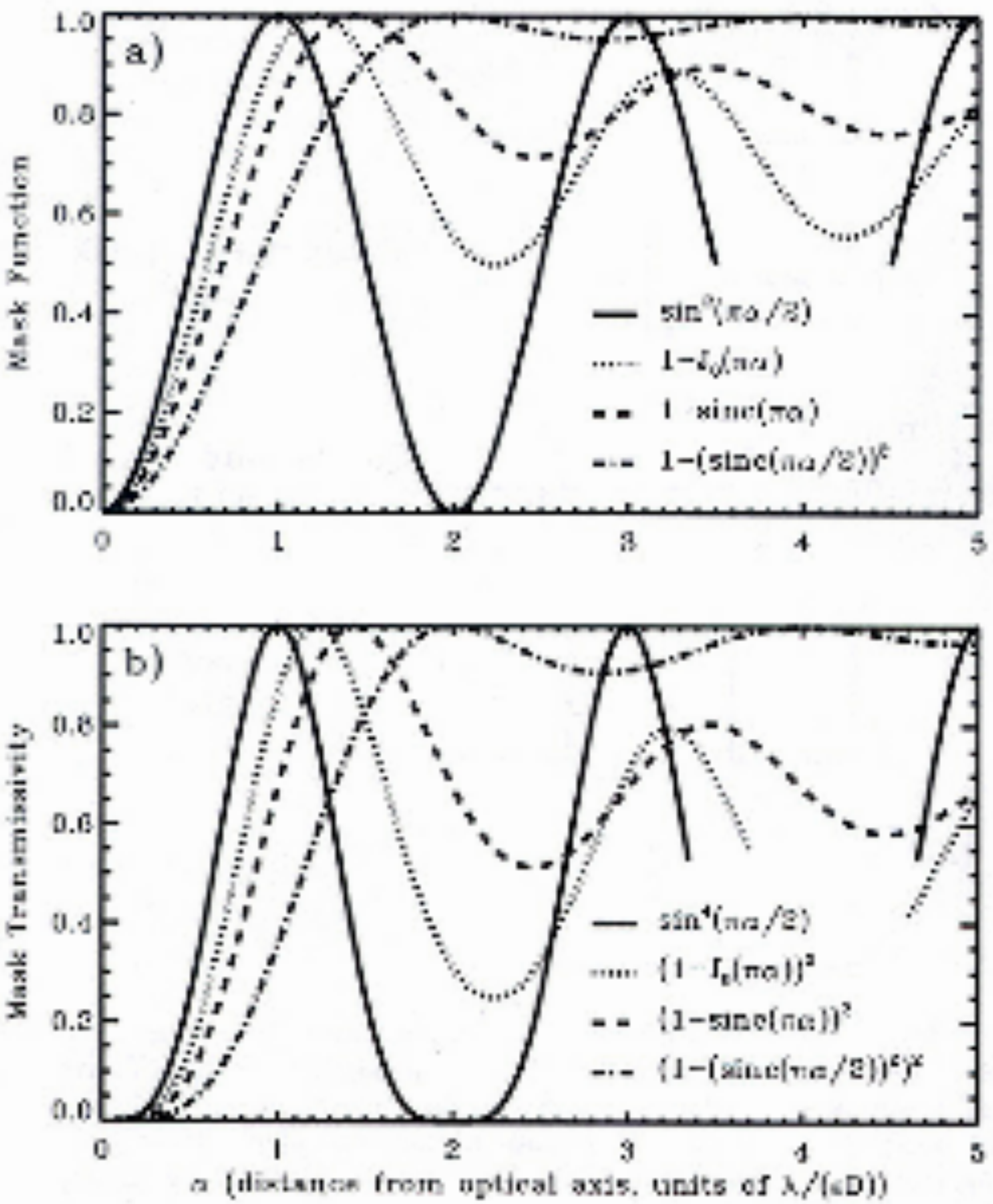
Lyot Stop
$L(u)$

Lyot stop blocks bright edges

Final Field
$L(u)(M(u) \otimes A(u))$

Zero transmission of on-axis star

Kuchner & Traub,2002



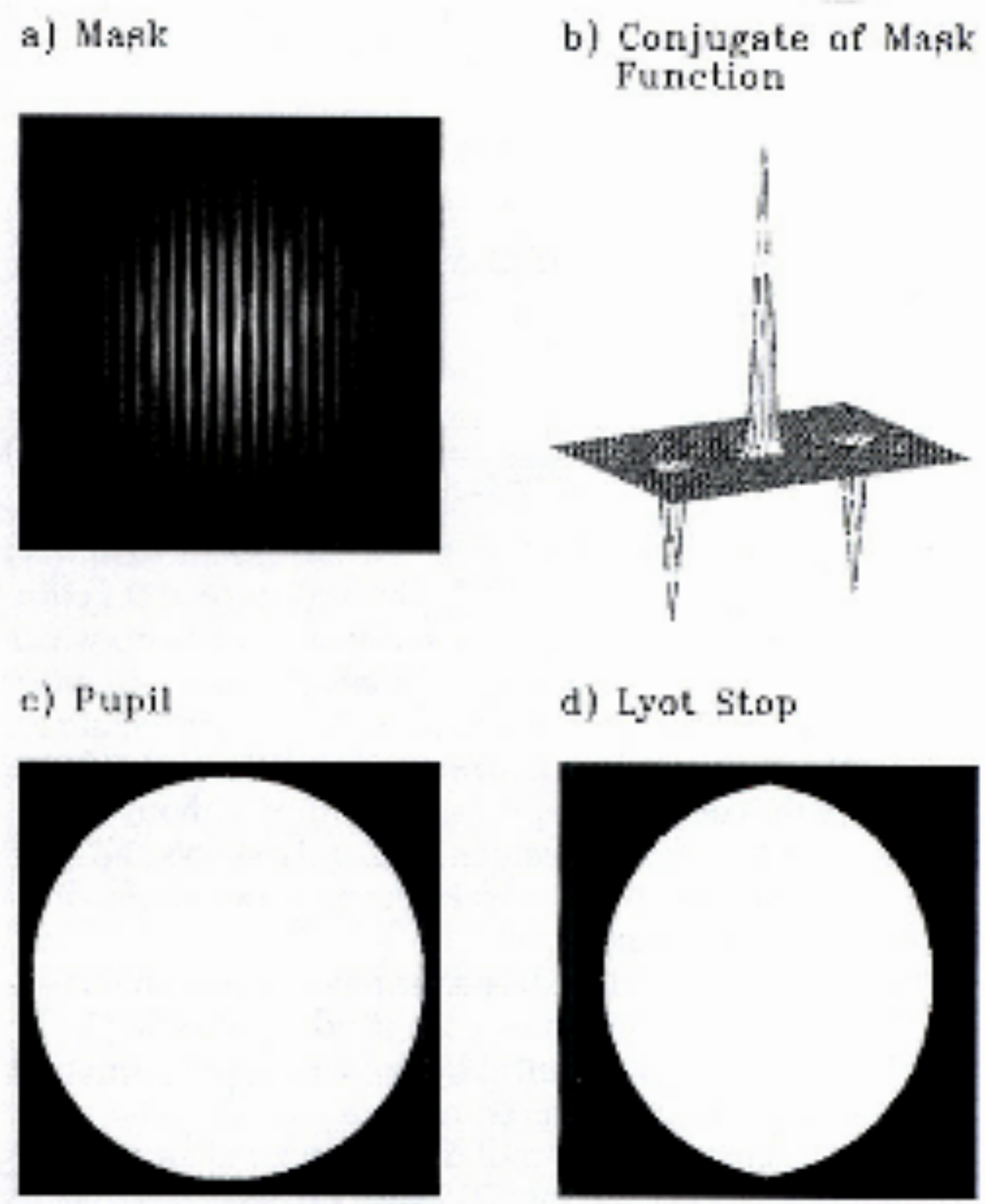


FIG. 3.—Examples of band-limited functions that can be used as mask

PHASE BASED

CORONAGRAPH

Phase Mask

- Introduced by F Roddier (1997)
- Concept: Phase Difference of π -> destructive interference
- Transparent mask
- Thickness $\Delta\phi = 2\pi\delta/\lambda = 2\pi(n-1)e/\lambda = \pi$ -> $e = \lambda(n-1)/2$
- Mask manufacturing: Equilibre between phased and out of phase beams
- Gain in dynamics and angular separation
- Really chromatic!

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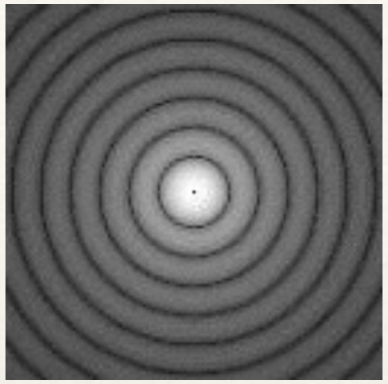
- Really chromatic!

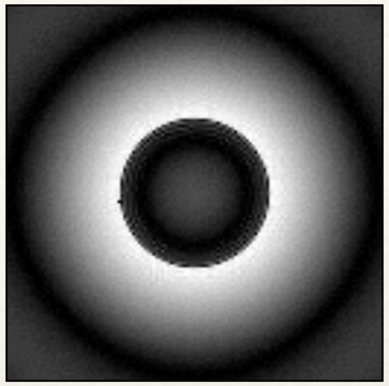
e.g.:
$n_{GLASS}=1.4$
lambda=636 nm -> e=127 nm
lambda=2μm -> 400 nm

Disk Phase Mask

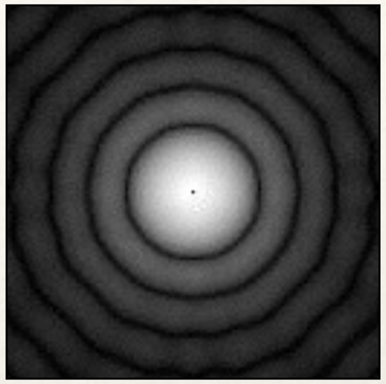
pupil



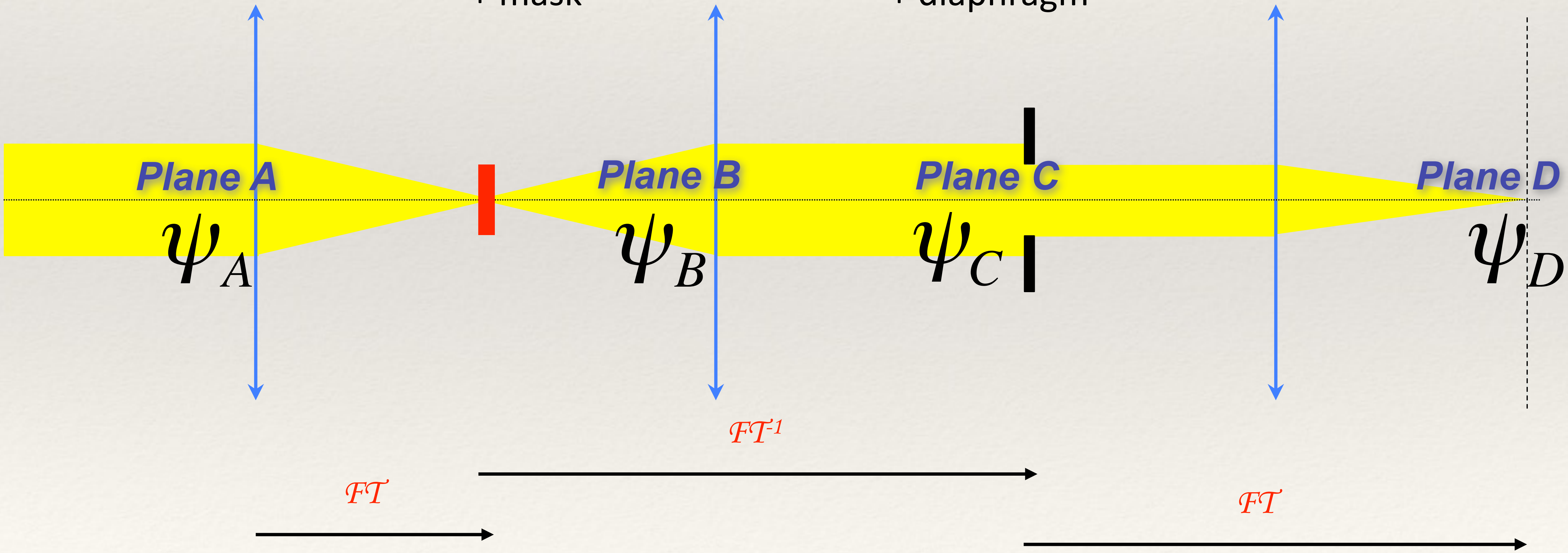
focal Plane
+ mask



pupil
+ diaphragm

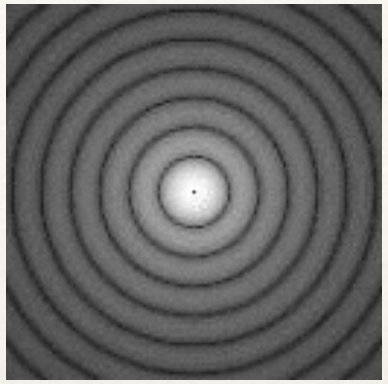


focal Plane



Disk Phase Mask

pupil



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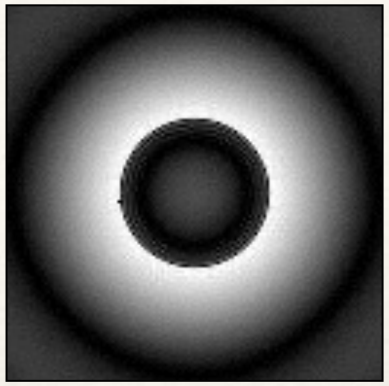
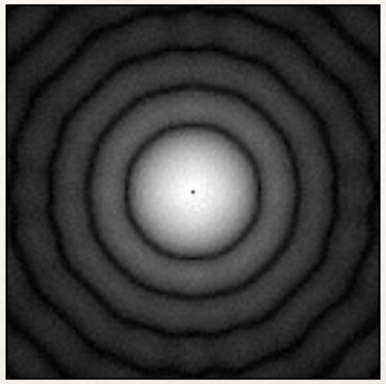
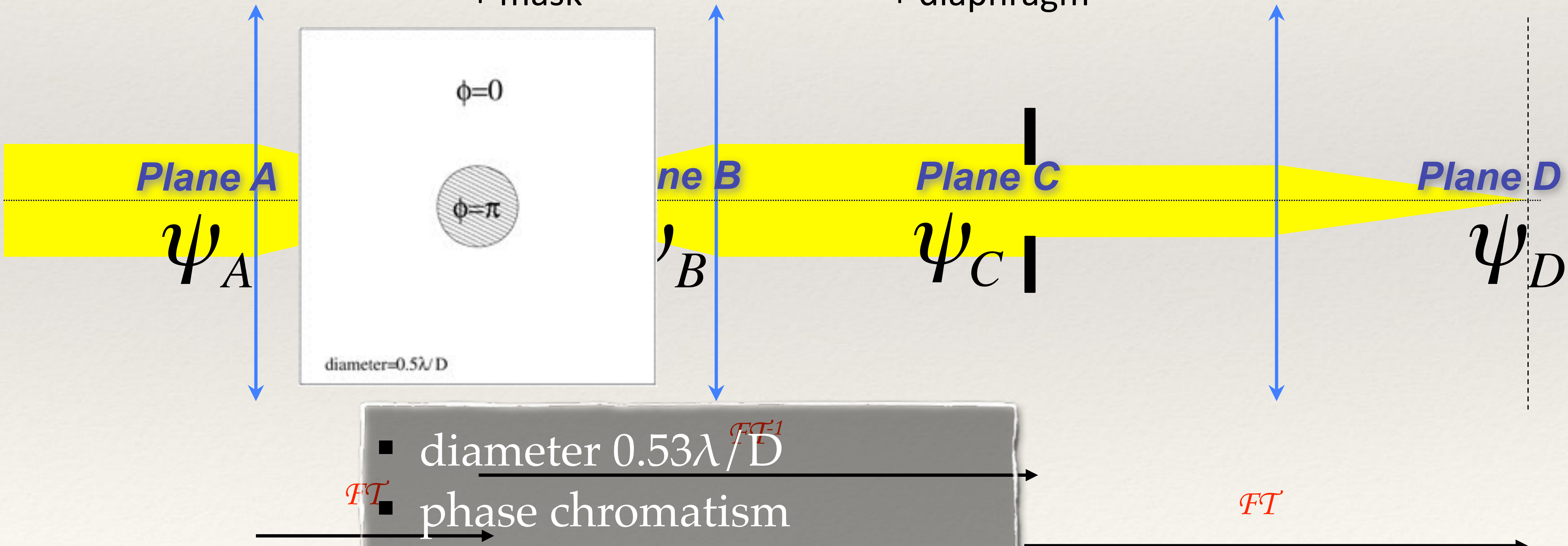
+ mask



pupil
+ diaphragm

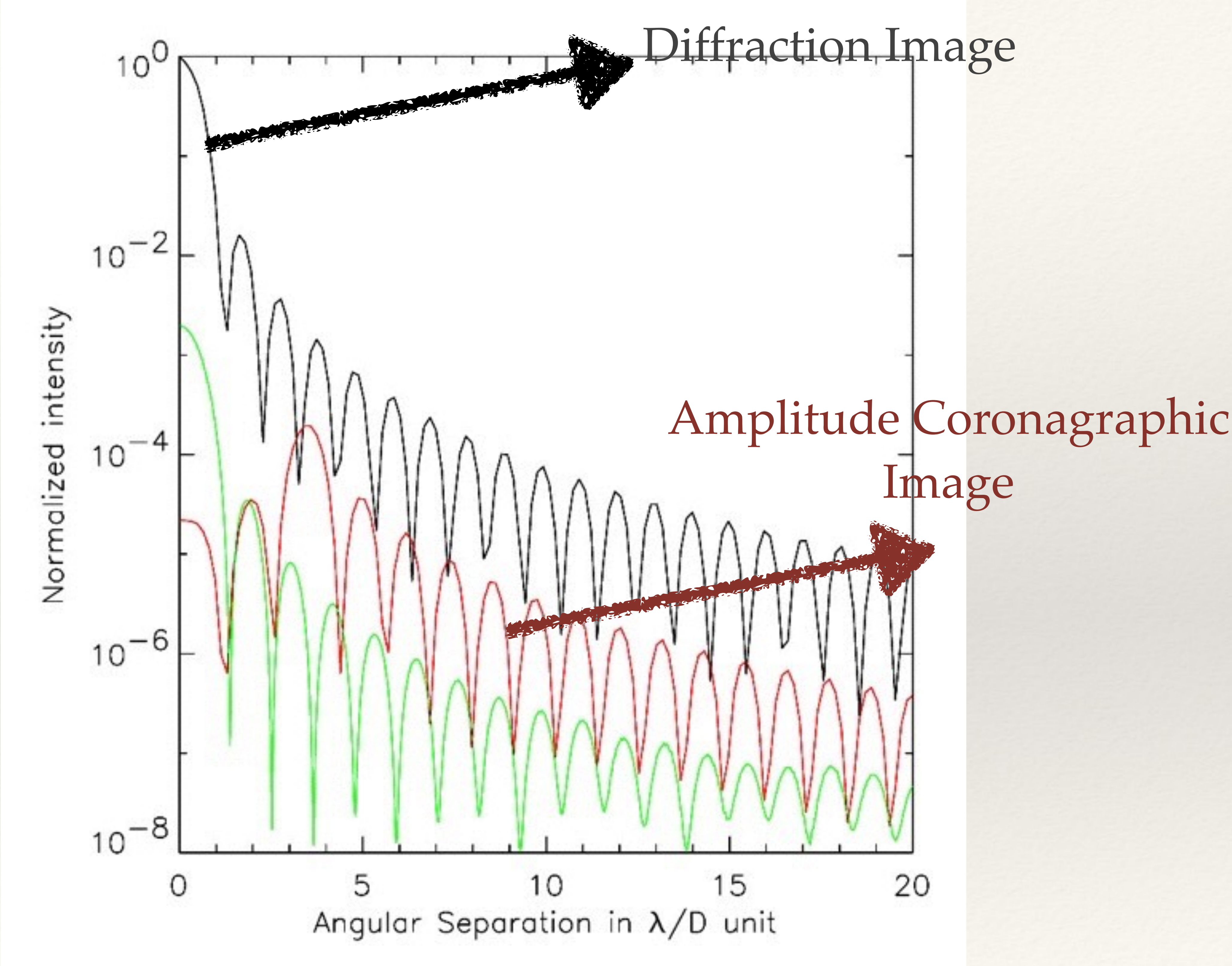


focal Plane

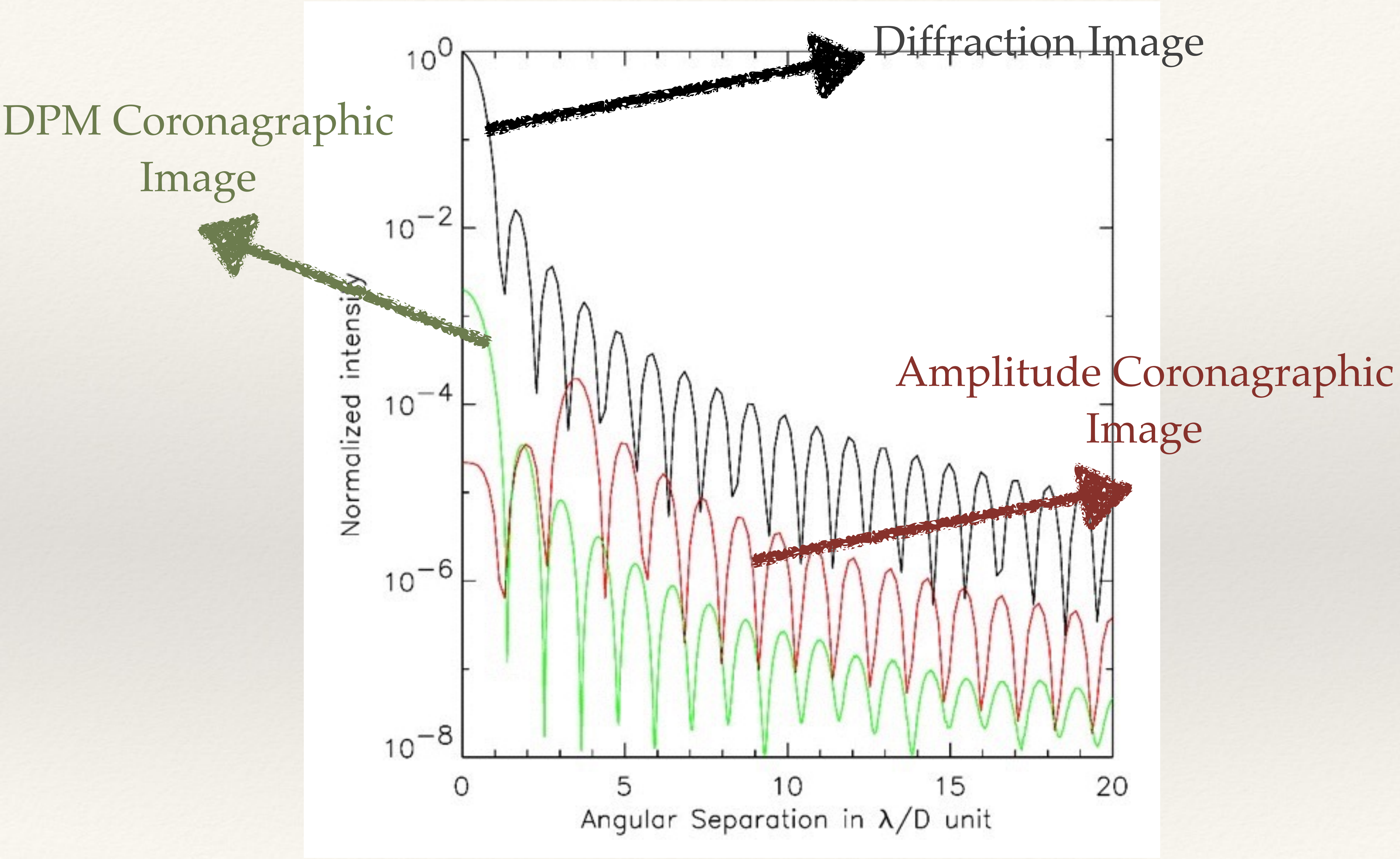


- diameter 0.53λ/D
- phase chromatism
- Geometric chromatism

Disk Phase Mask



Disk Phase Mask



4 Quadrant Phase Mask

Star image is centered on mask which transmits half of image shifted by 1/2 wavelength, and 1/2 unshifted, so symmetric parts cancel.

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Rouan et al. (2000) proposed the 4QPM to avoid the Geometric chromaticism

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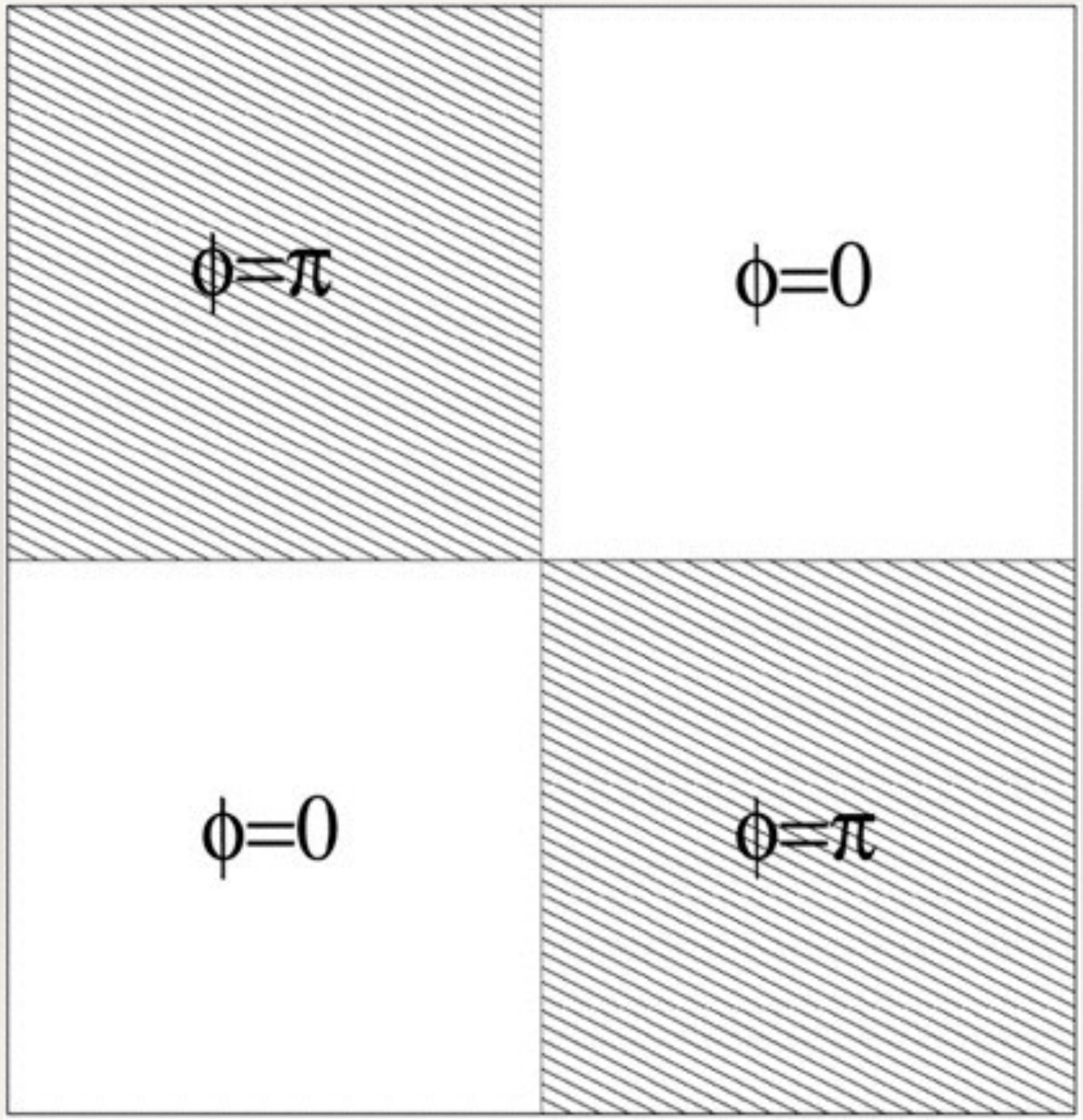

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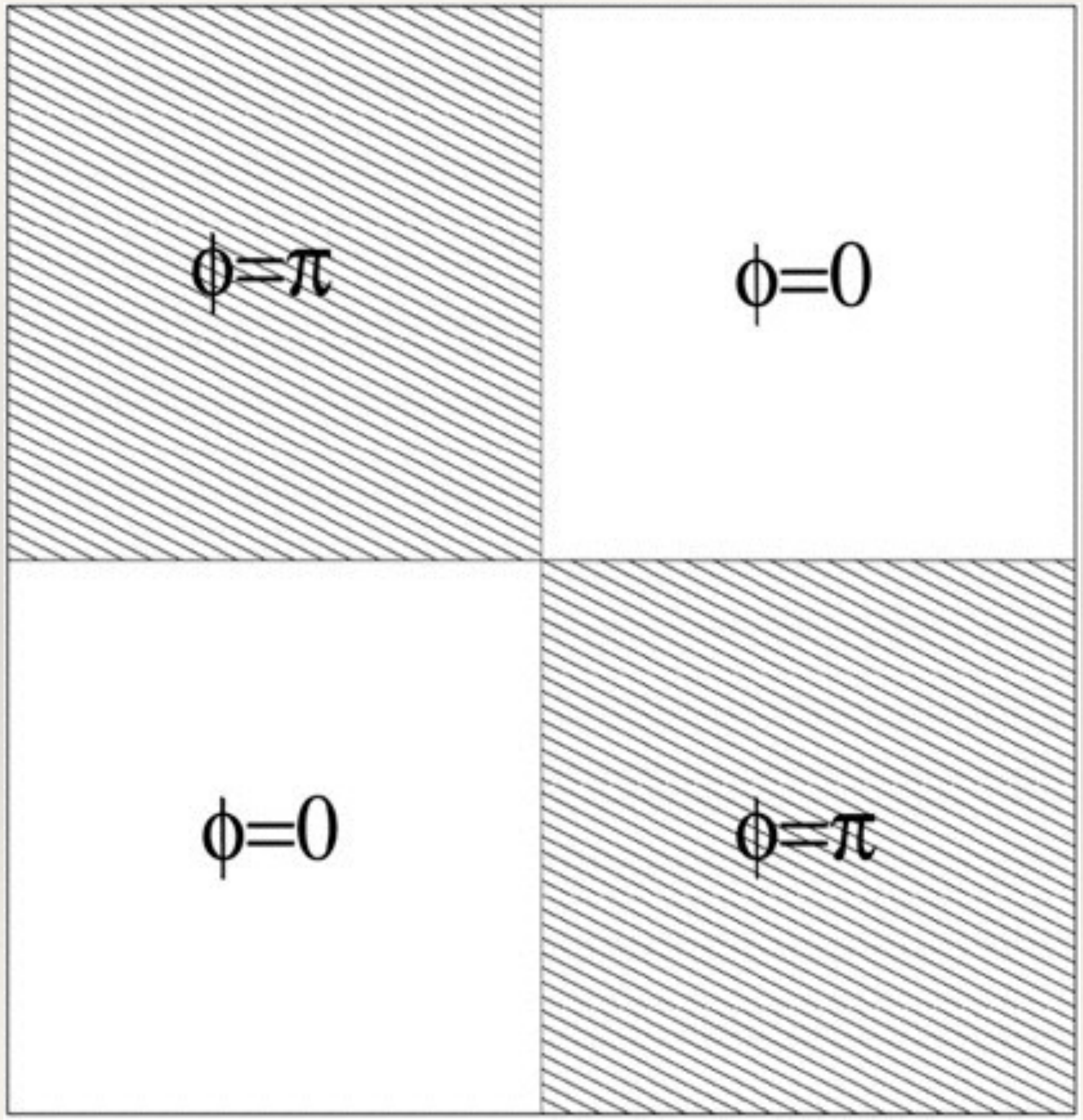

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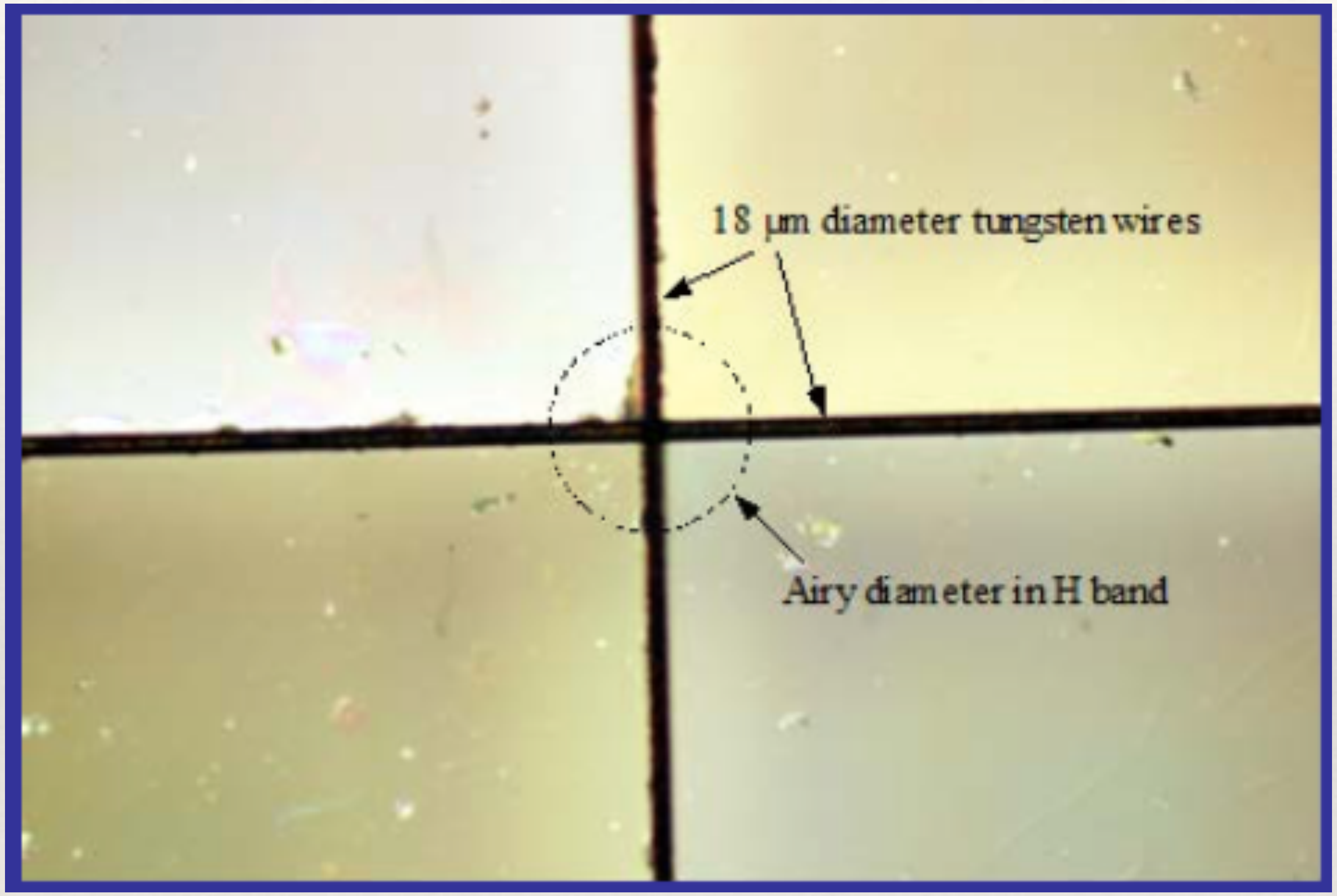
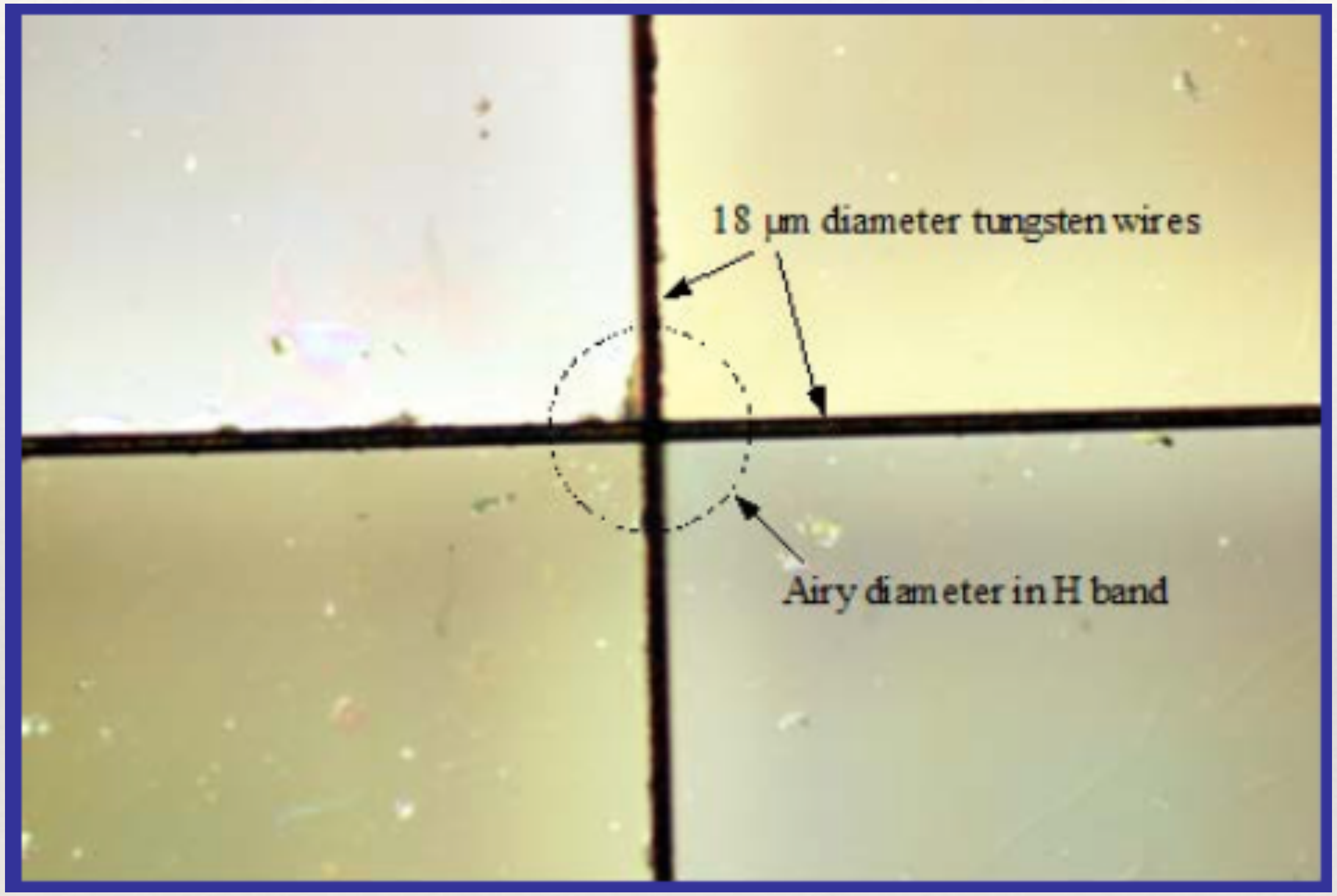
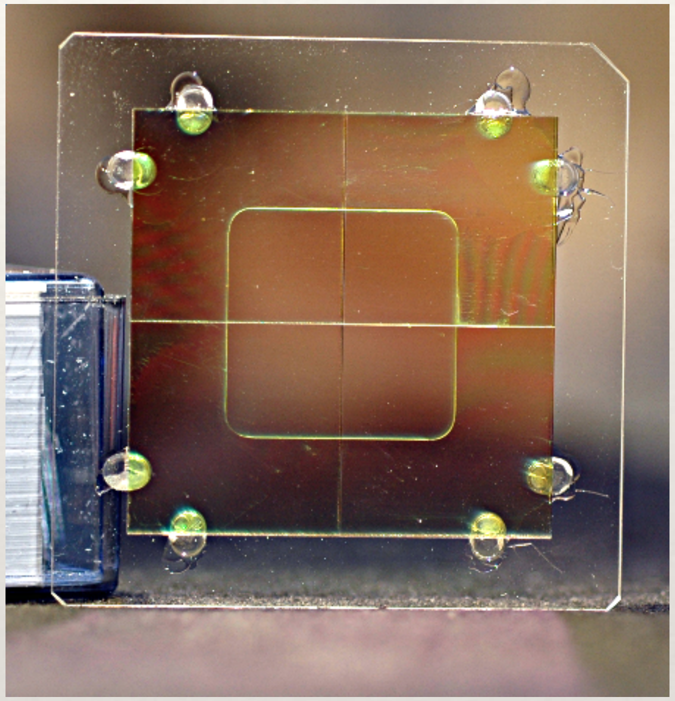
4QPM Manufacturing



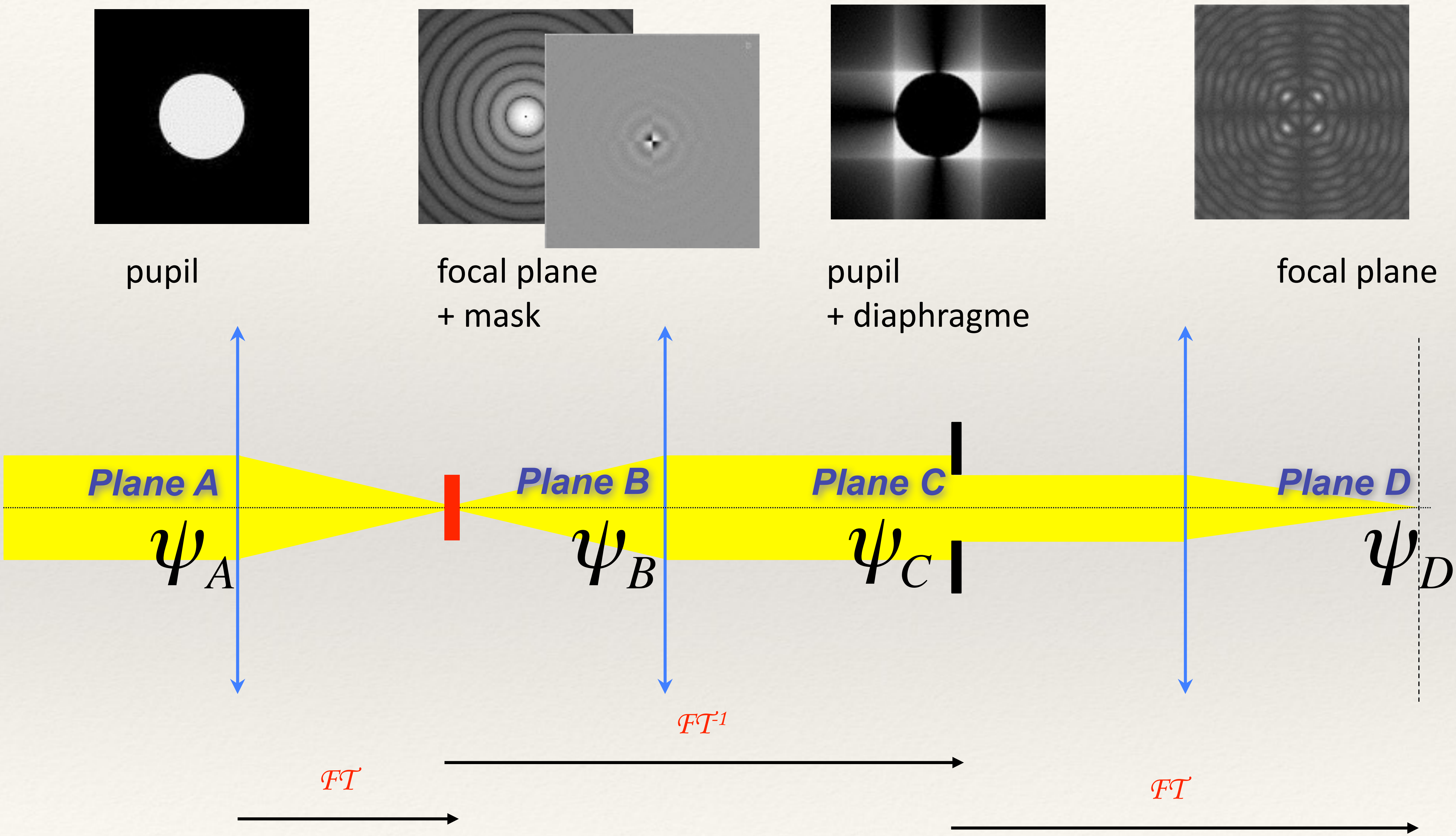
4QPM Manufacturing



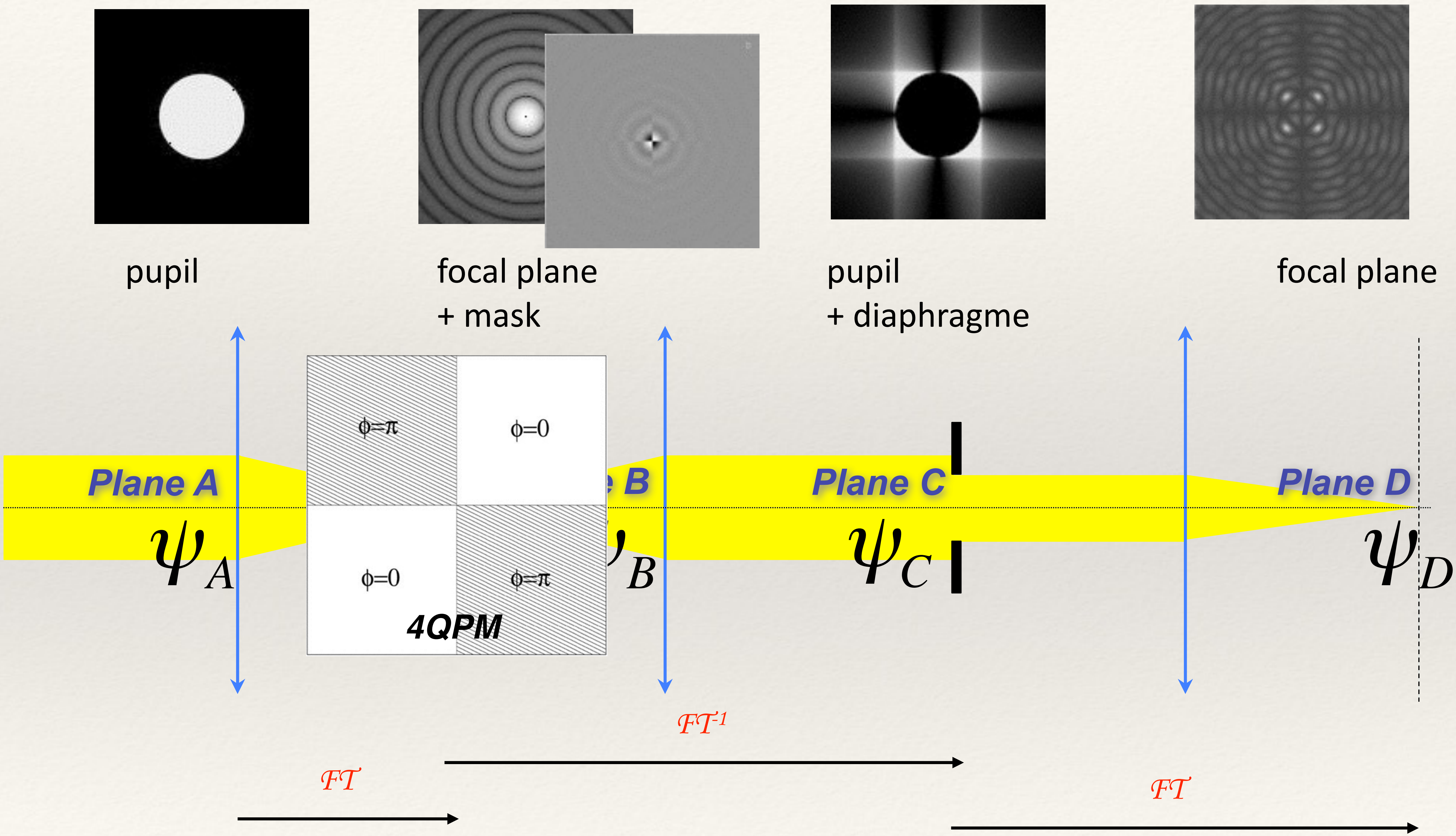


Masque de Phase 4 quadrants

4 Quadrant Phase Mask



4 Quadrant Phase Mask



4 Quadrant Phase Mask

4QPMC PROs:

- With respect to the apodized Lyot coronagraph, 4- quadrant have a smaller IWA (down to ~2-3 /D)
- Higher off-axis transmission possible

4QPMC CONs:

- Cancelation is wavelength dependent (narrow useful spectral band)
- Alignment is very critical
  - Accurate manufacturing (edge effects should be minimized)
  - Centering of the star image must be at sub-mas accuracy

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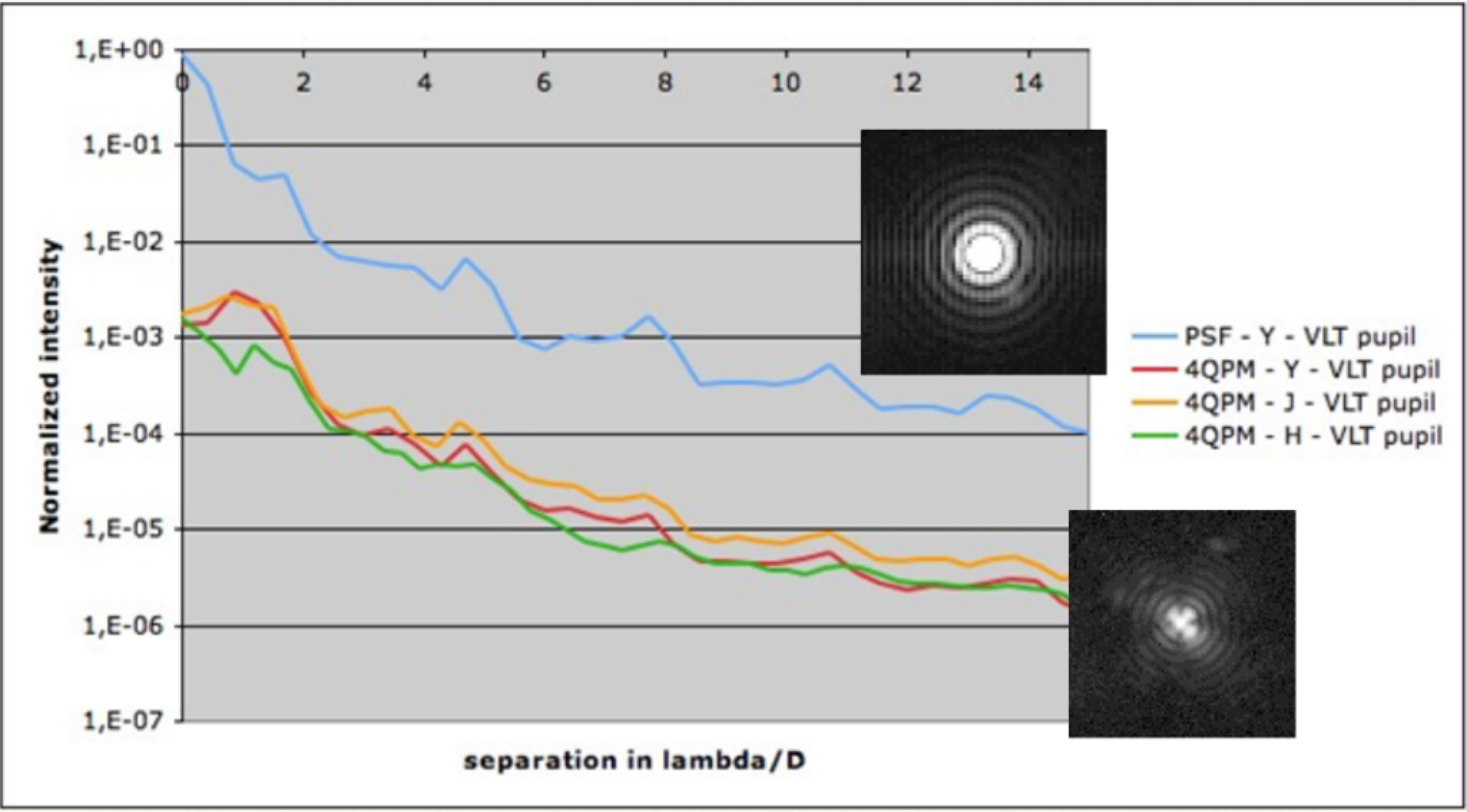
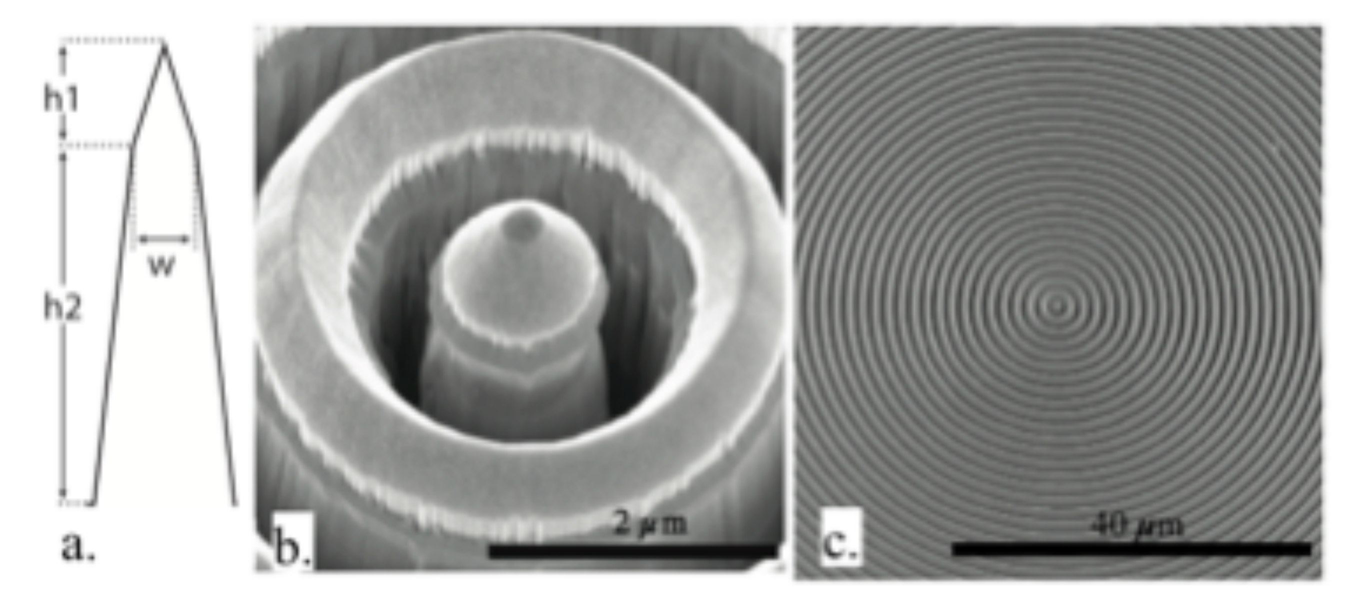
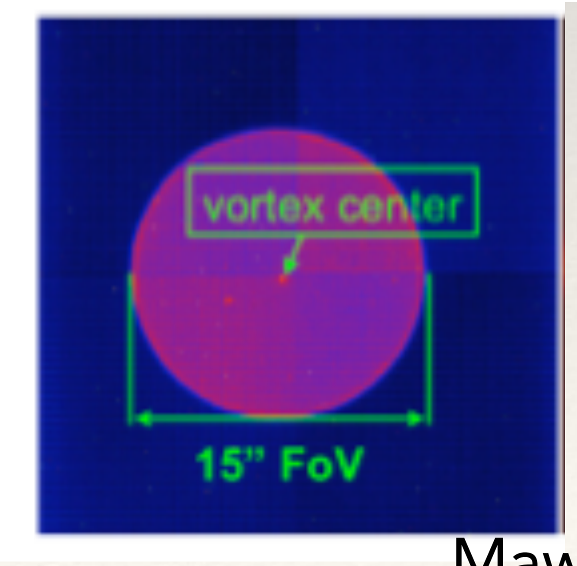
Results with 4QPM on SPHERE



Optical Vortex

An optical vortex may be characterized as a dark core of destructive interference in a beam of spatially coherent light. This dark core may be used as a filter to attenuate a coherent beam of light so an incoherent background signal may be detected





Mawet et al., 2013 A&A L13

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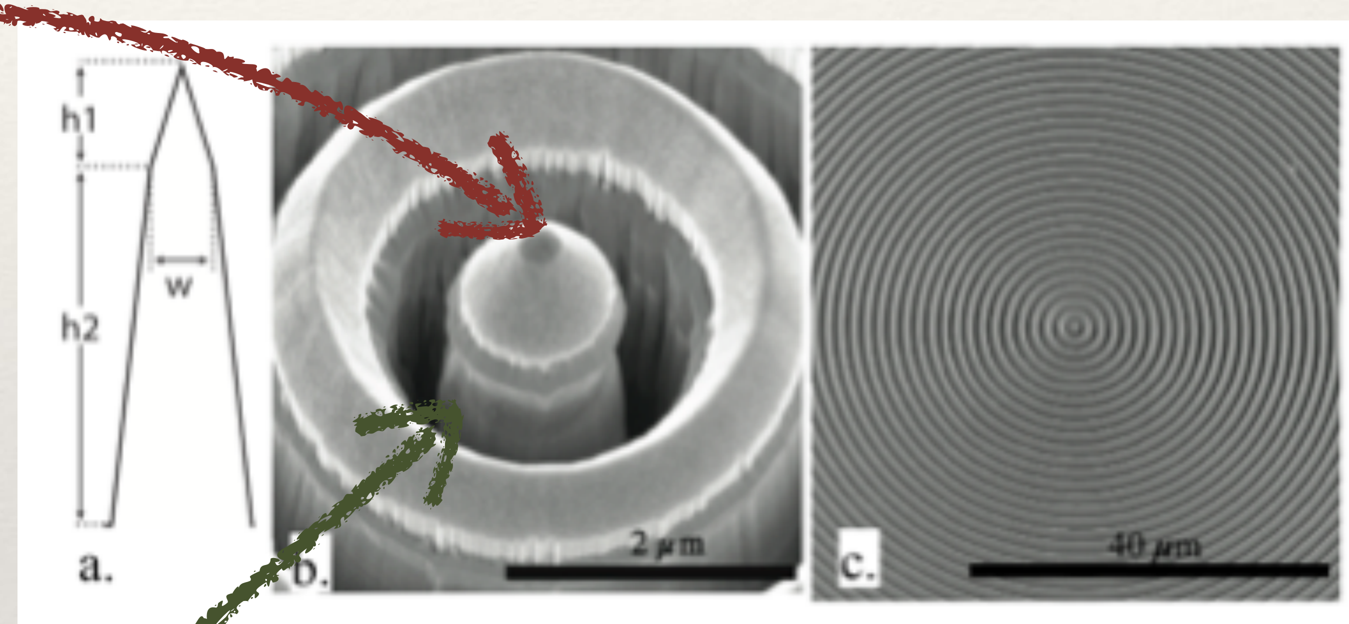
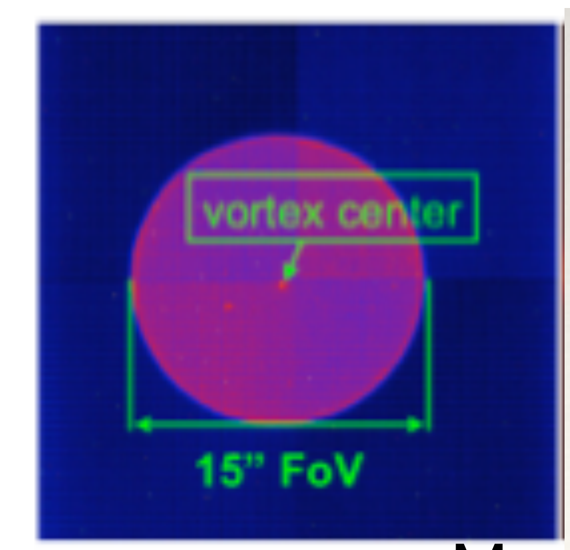
CENTER: Phase singularity generating a point of zero intensity

HELICAL PHASE RAMP: Longitudinal Phase dalay operating on both polarisation





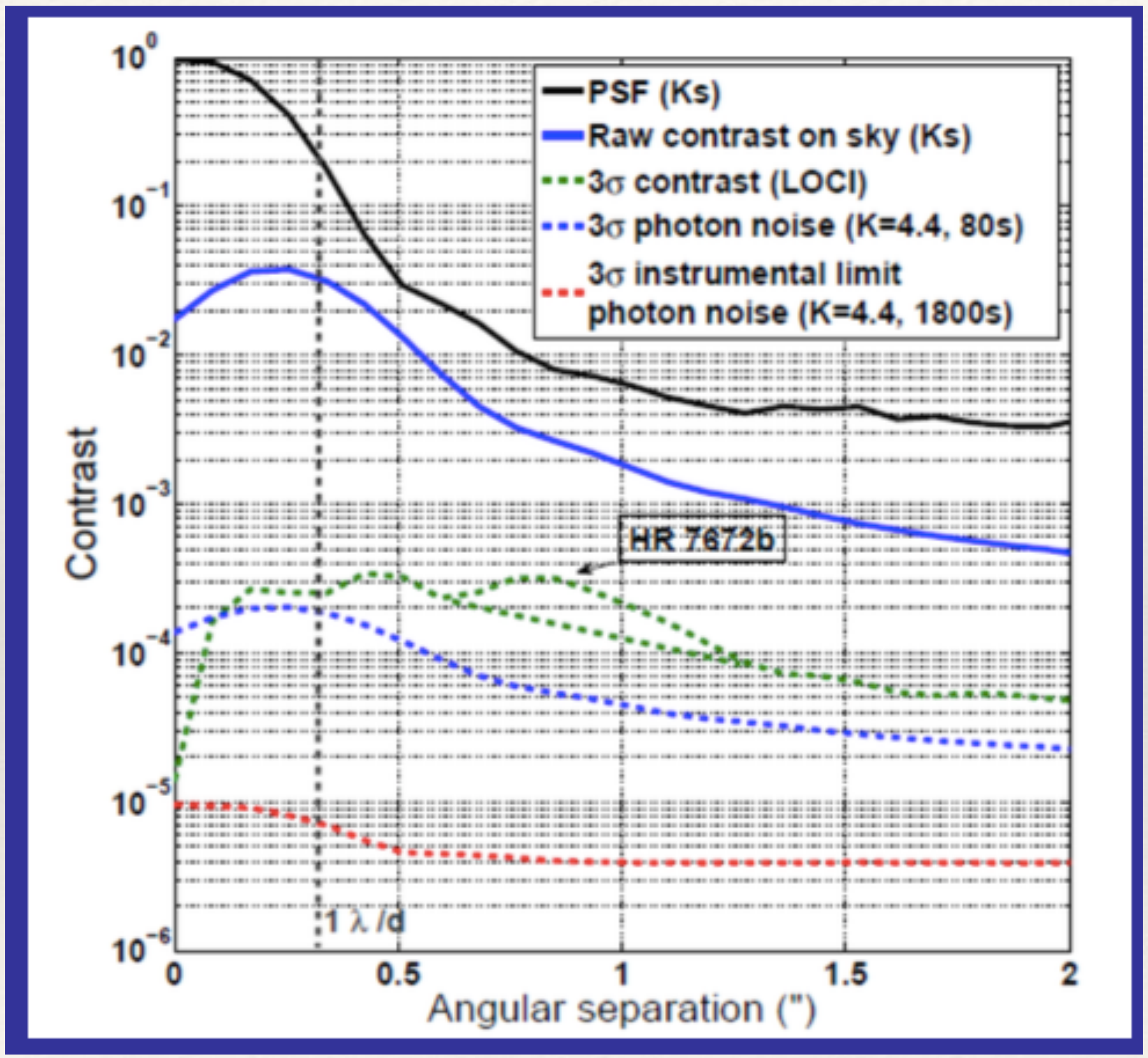
Mawet et al., 2013 A&A L13

Optical Vortex

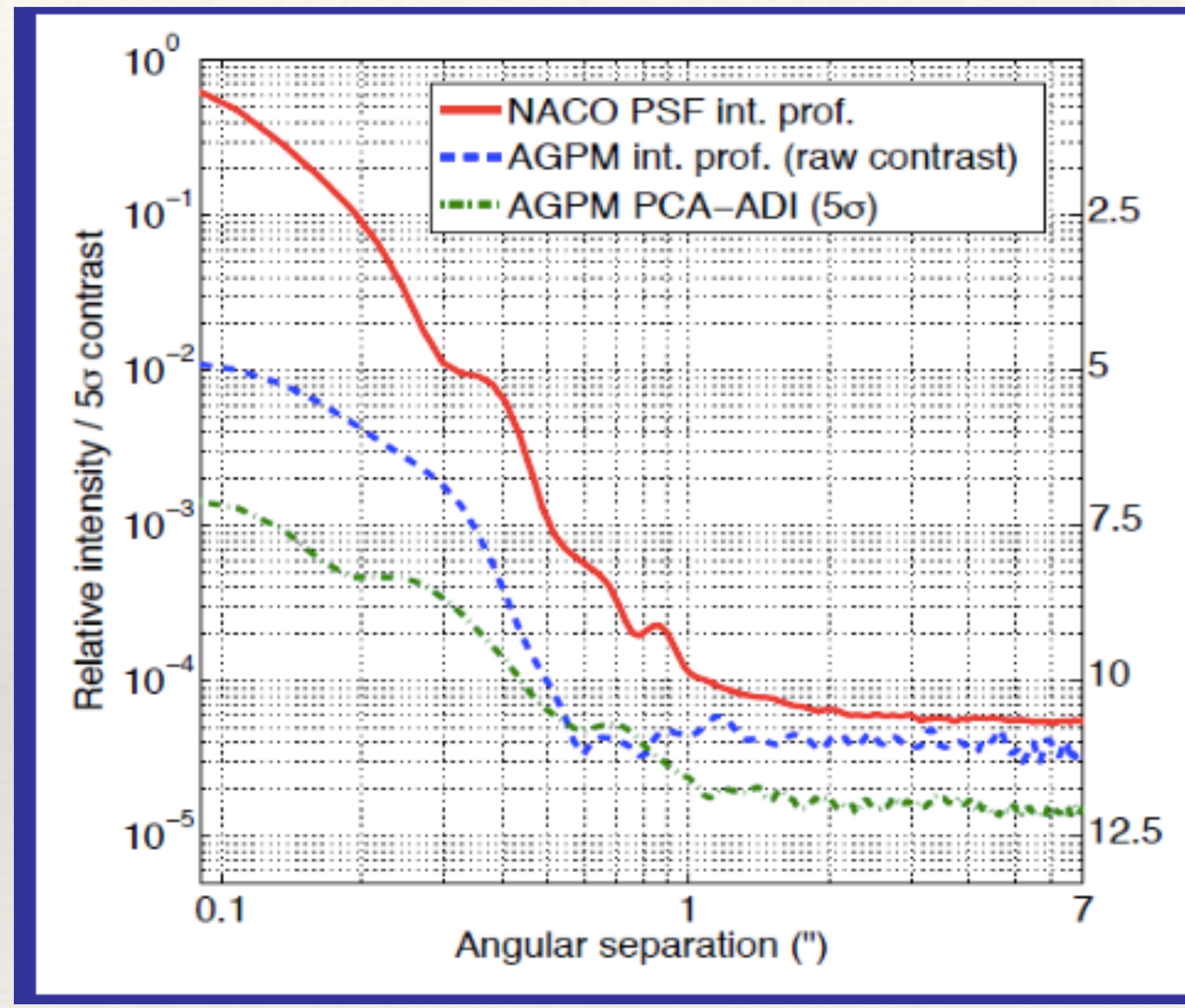
- Many coro's concepts have been developed
- Some of them achieve high cancellation
- However, at expense of low throughput, narrow wavelength range and critical alignment
- The optical vortex is truly close to ideal: – small inner working angle
  – high throughput
  – completely clear off-axis discovery space
- Vortex is a phase mask coronagraph (like the 4- quadrant)

Contrast with Optical Vortex

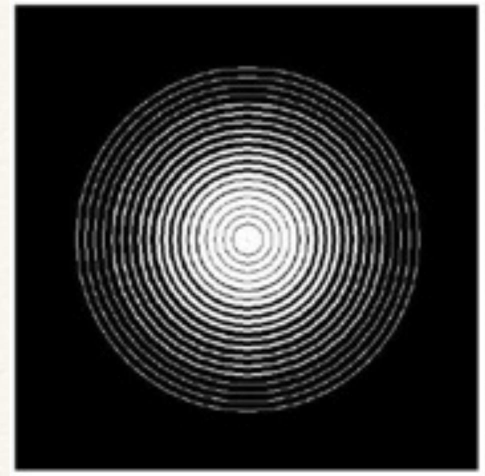
Palomar - K-Band
(Nawet et al., 2009

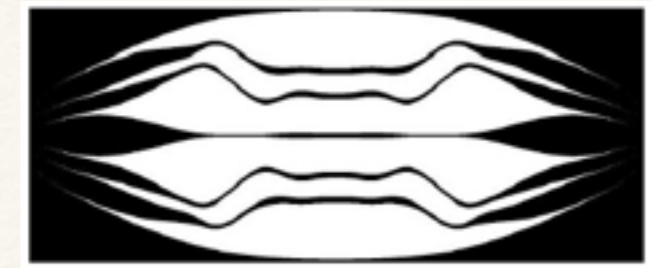


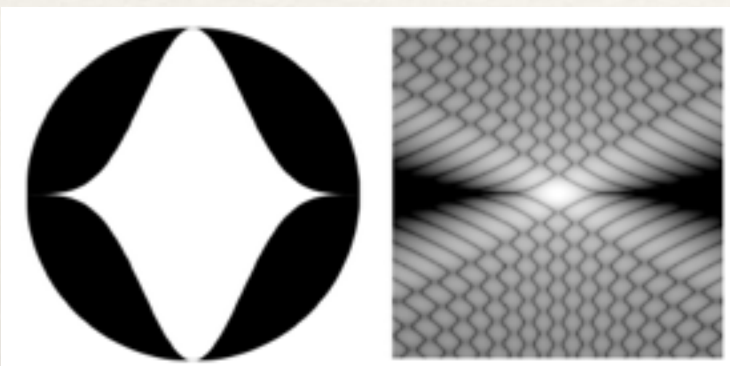
NACO - L′-Band
(Nawet et al., 2013

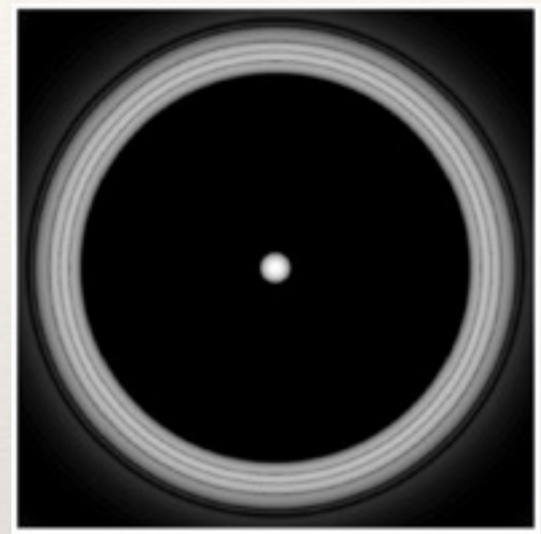


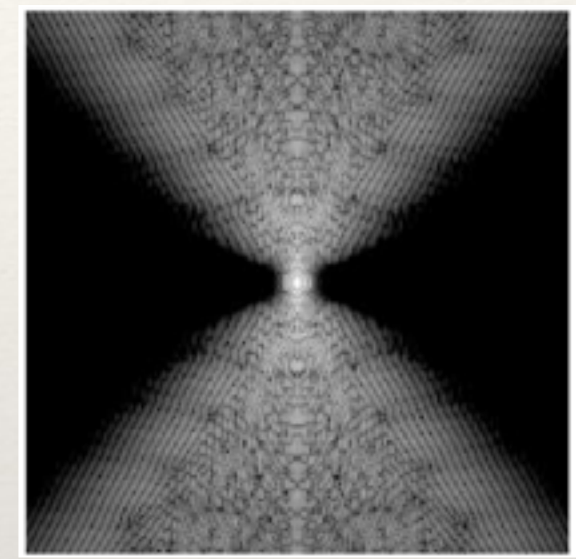
Shaped Pupil

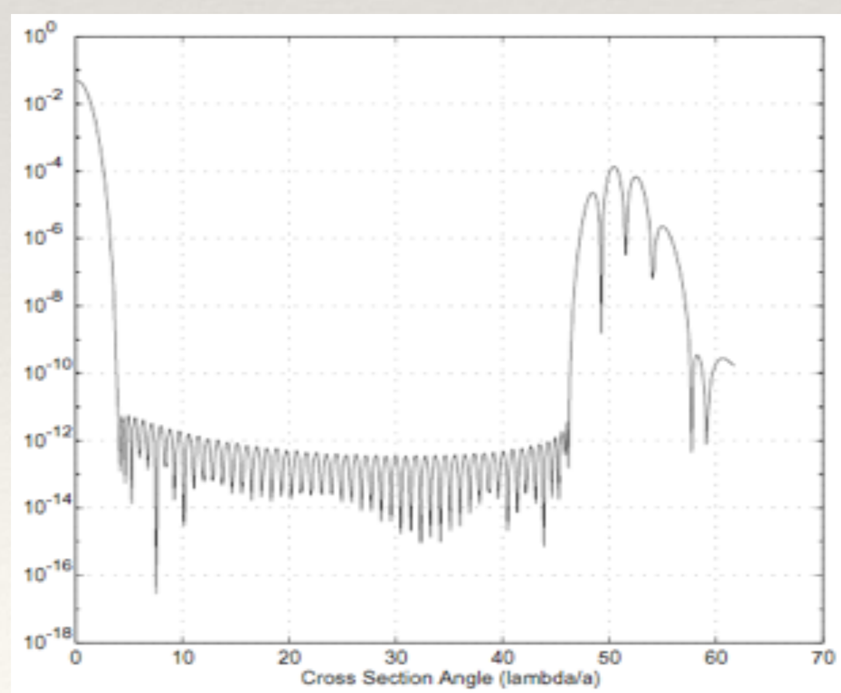


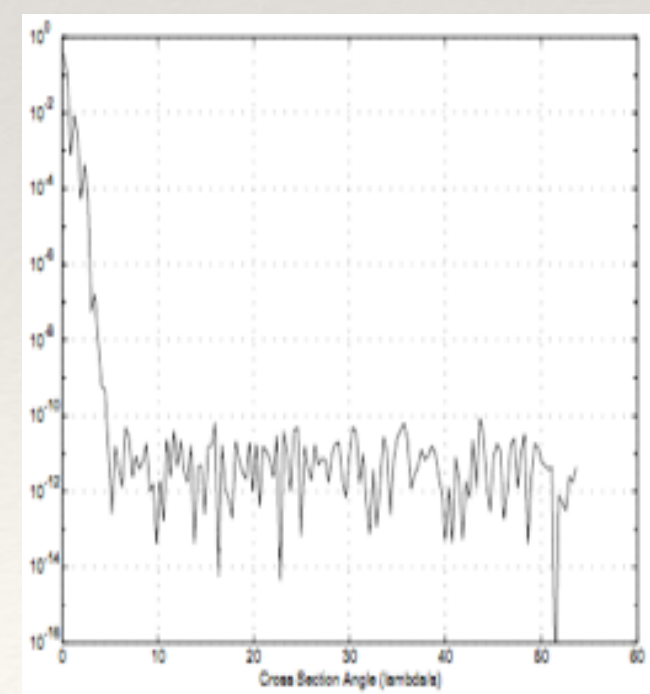




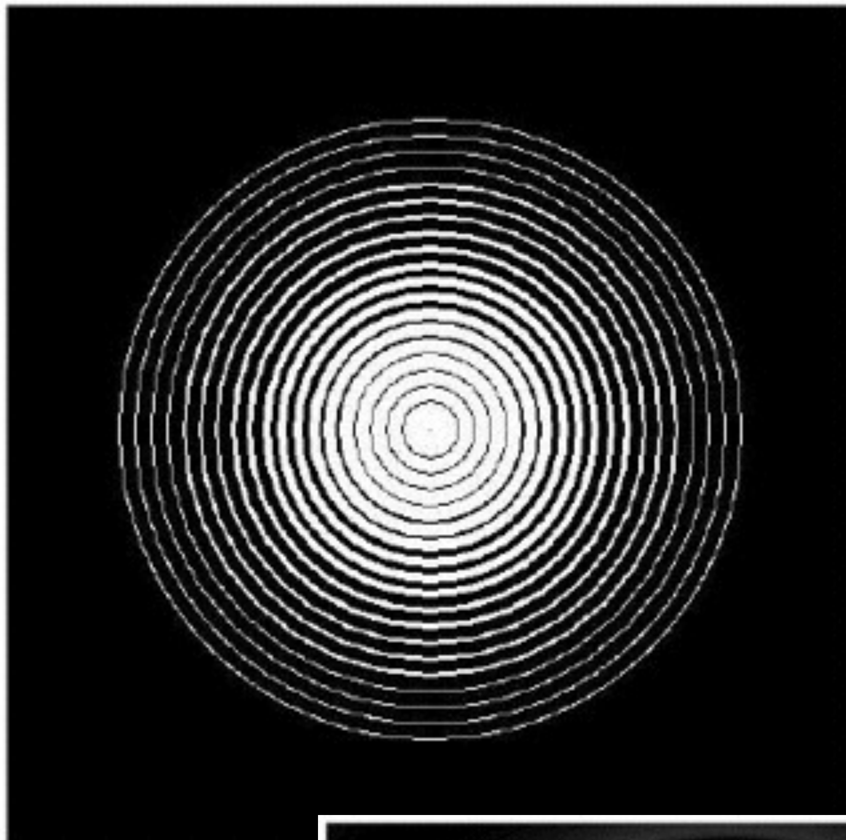


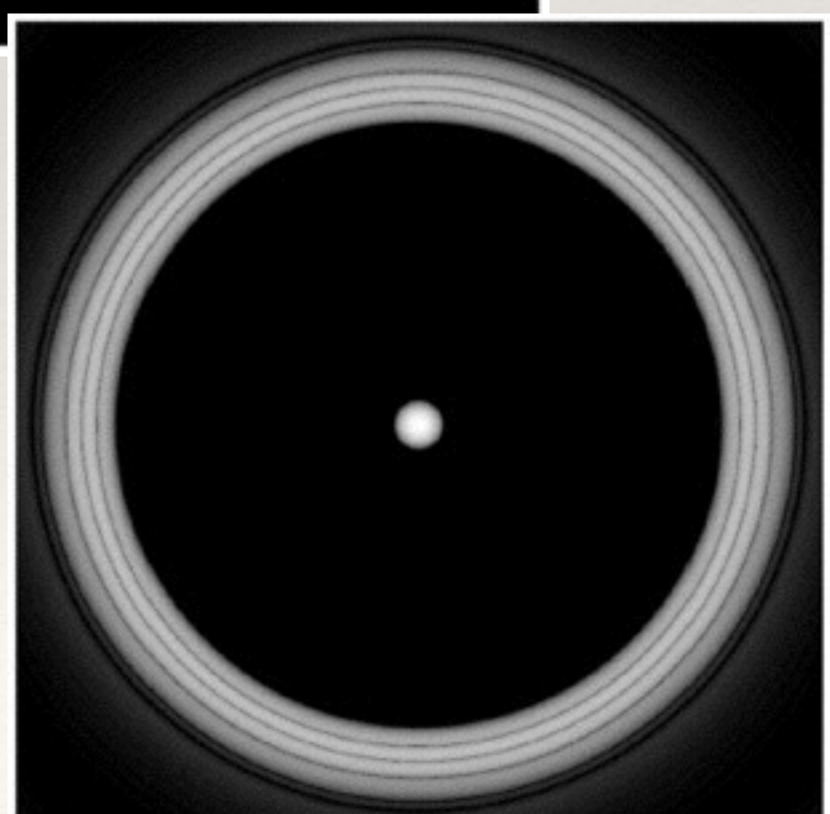


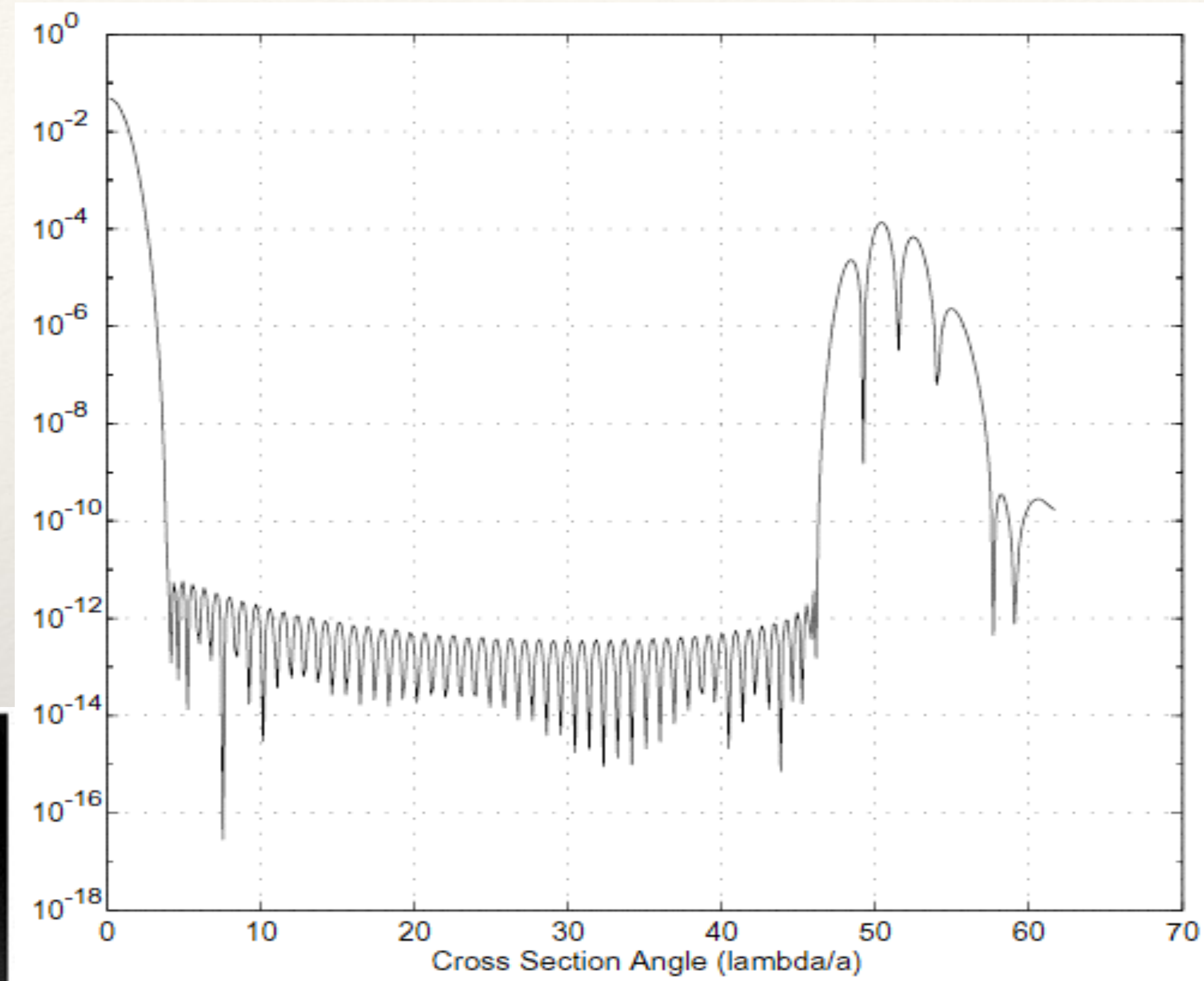




Shaped Pupil



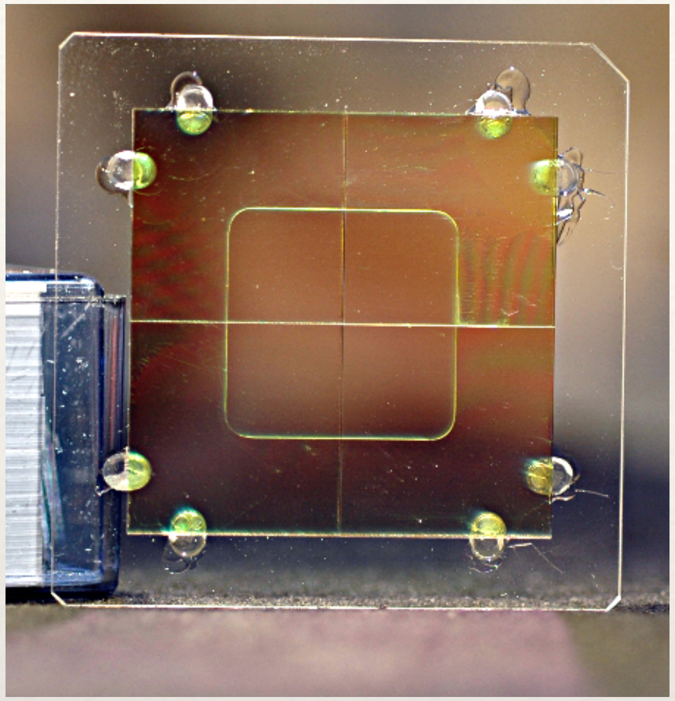




Some Examples

shaped pupil

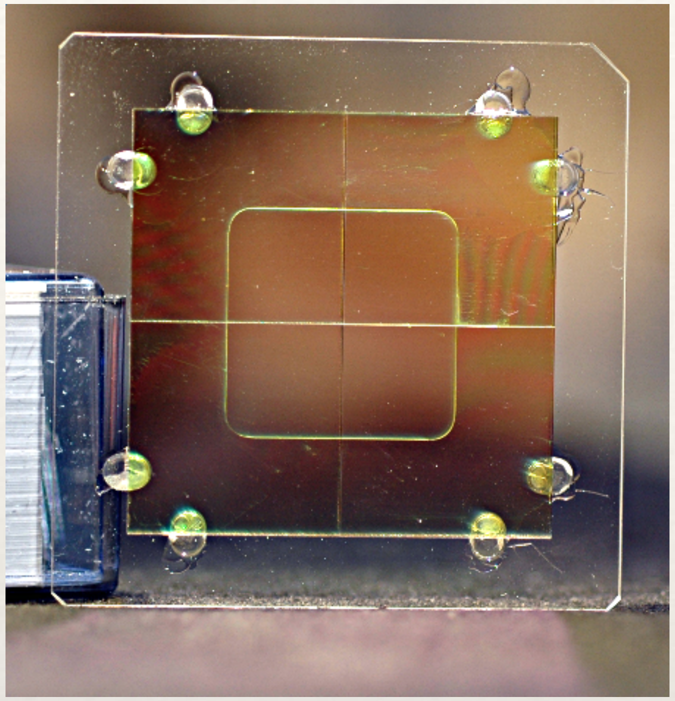
Some Examples



Masque de Phase 4 quadrants

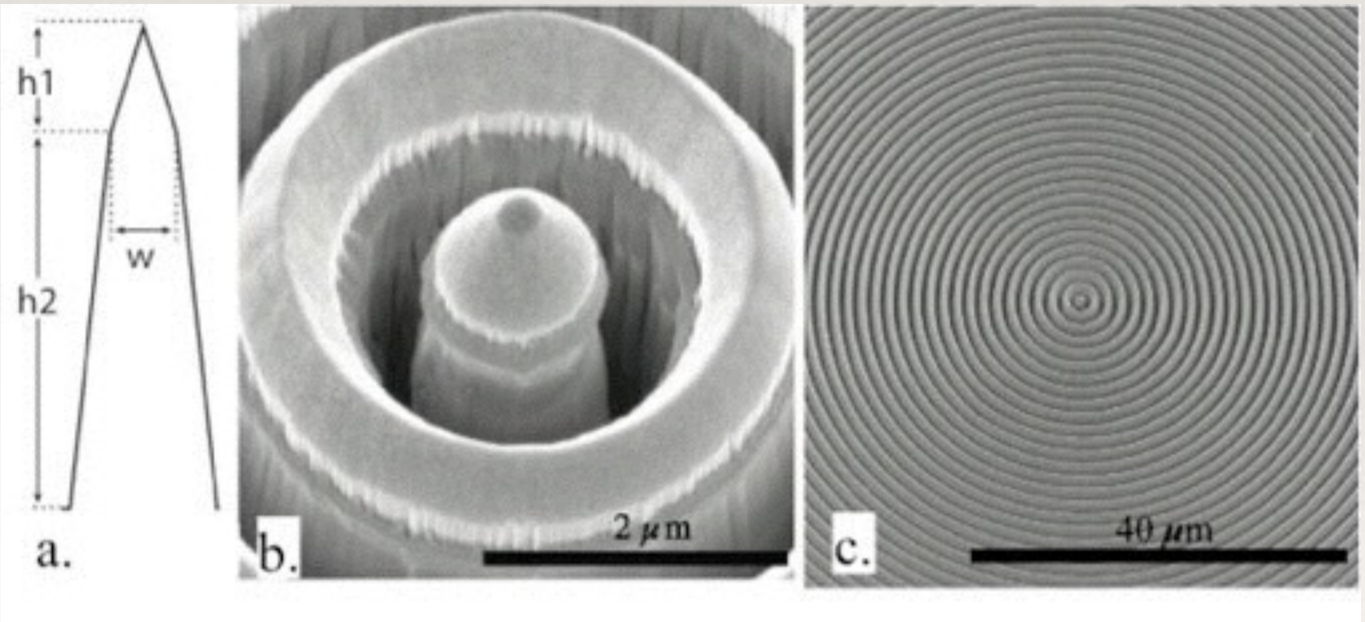
shaped pupil

Some Examples



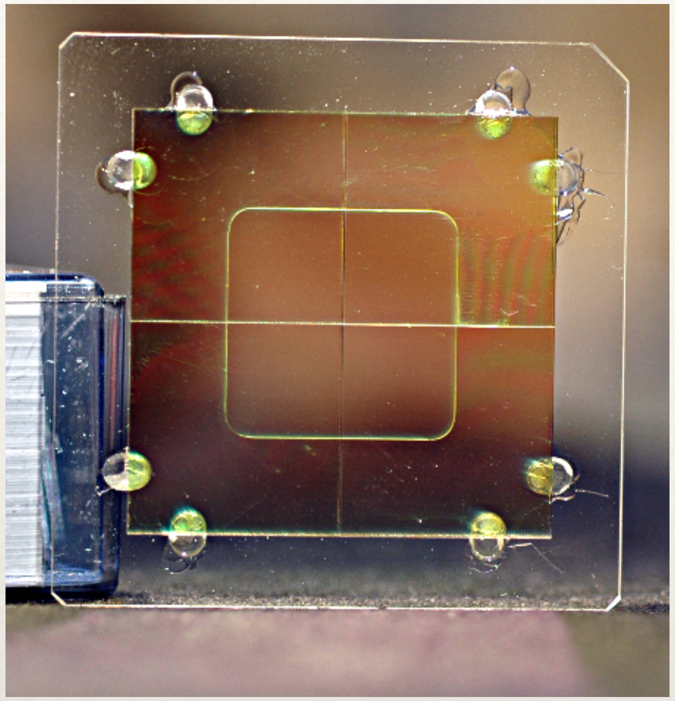
Masque de Phase 4 quadrants

shaped pupil



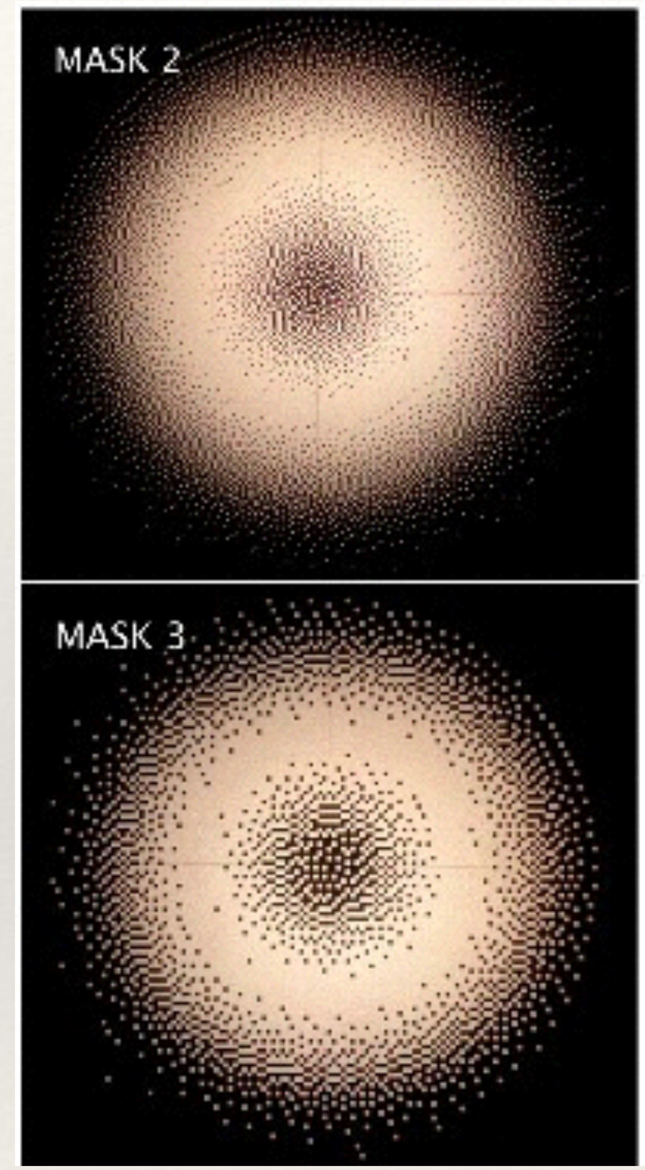
Masque de Phase Vortex réalisé en diamant

Some Examples

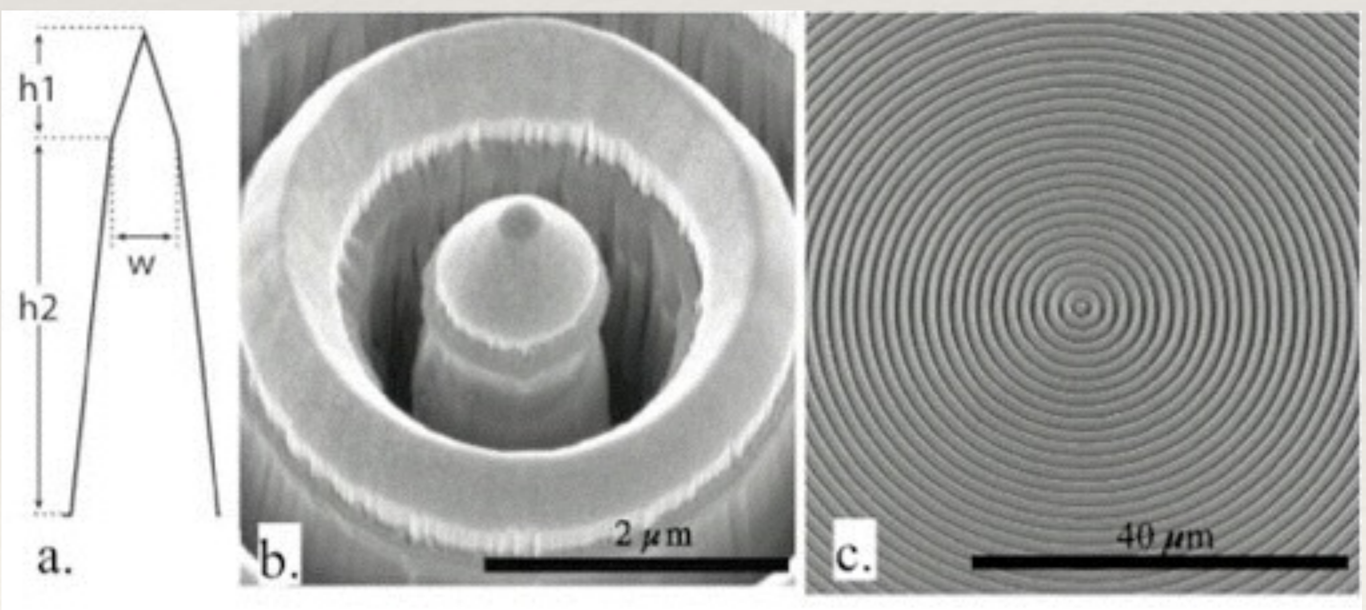


Masque de Phase 4 quadrants

shaped pupil



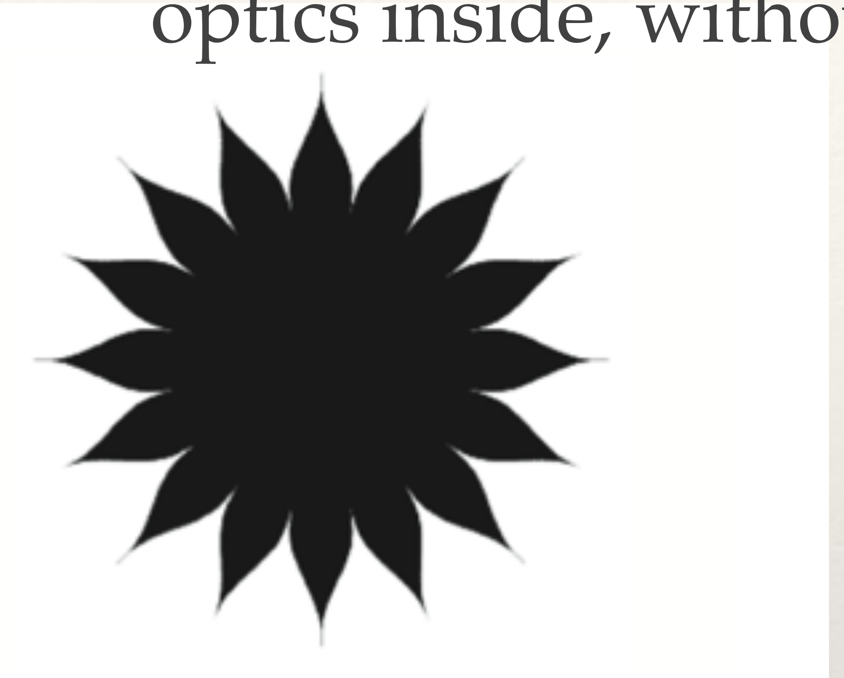
Apodisation

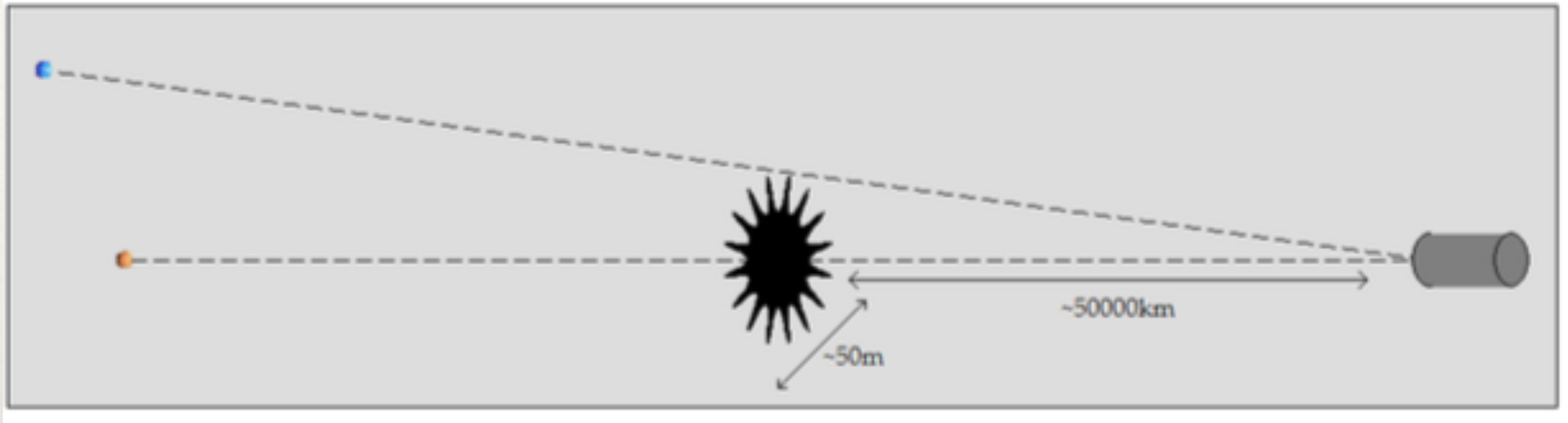


Masque de Phase Vortex réalisé en diamant

Occulters...

An occulter is an optical element which is placed in front of the telescope to block most of the light from a star before it reaches the optics inside, without blocking the planet.





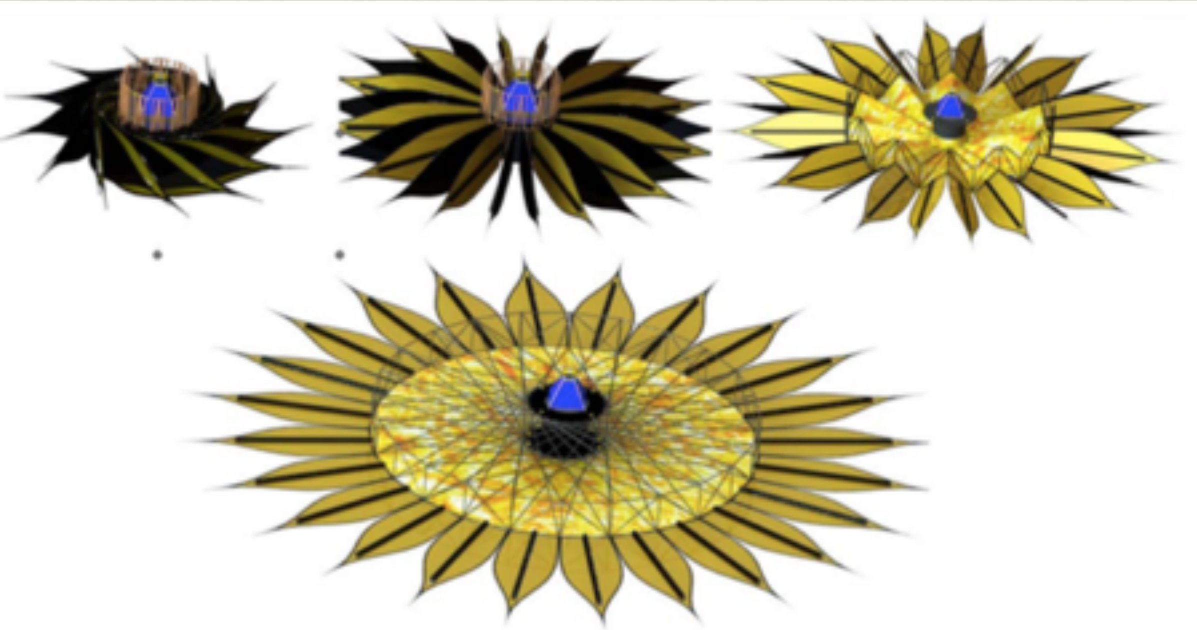


TABLE 6. Occulter examples.

D_{occ} (m)	z (km)	D_{tel} (m)	θ_{IWA}
70	140,000	6.5	50
50	72,000	4.0	72
37	39,000	2.4	98

Traub & Oppenheimer, 2010

Credits: E. Cady JPL