Coronagraph concepts & systems

Types of coronagraphs

Coronagraph systems & instruments

Olivier's thumb...
the slimplest coronagraph
Doesn't work well enough to
see planets around other stars

Coronagraphs for imaging exoplanets are based on diffractive optics, not geometrical optics

What is light: particle or wave ?

1807: Thomas Young publishes his double-slit experiment result
… cannot be explained by Newton's corpuscular theory of light

1818: French academy of science committee launches a competition
to explain nature of light

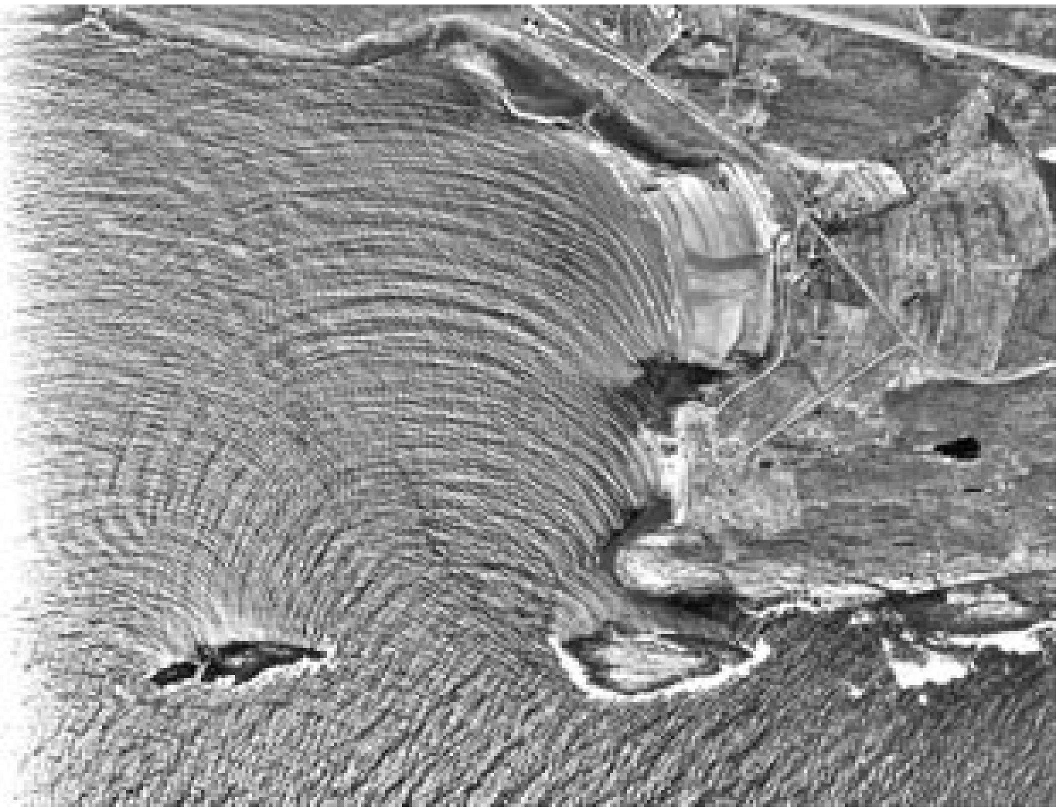
Augustin-Jean Fresnel
submits wave theory of light

Simeon-Denis Poisson finds a flaw in Fresnel's theory:
According to Fresnel's equations, a bright spot should appear in
the shadow of a circular obstacle → this absurd result disproves Fresnel's theory

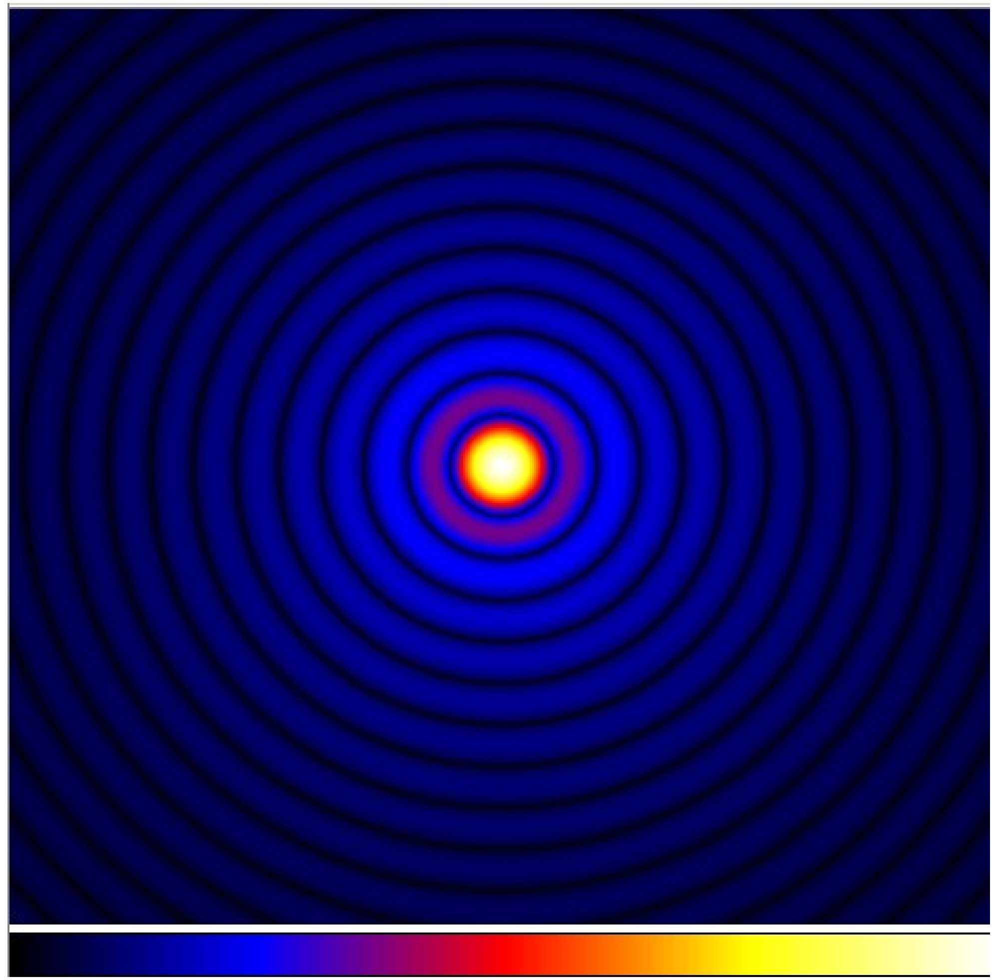
Dominique-Francois-Jean Arago, head of the committee, performs the experiment
He finds the predicted spot → Fresnel wins the competition

Water waves diffract around obstacles, edges, and so does light

→ designing a coronagraph is more complicated than simply putting an opaque mask at the star location in an image



Waves diffracted by coastline and islands



Ideal image of a distant star by a telescope
Diffraction rings around the image core

Types of Coronagraphs

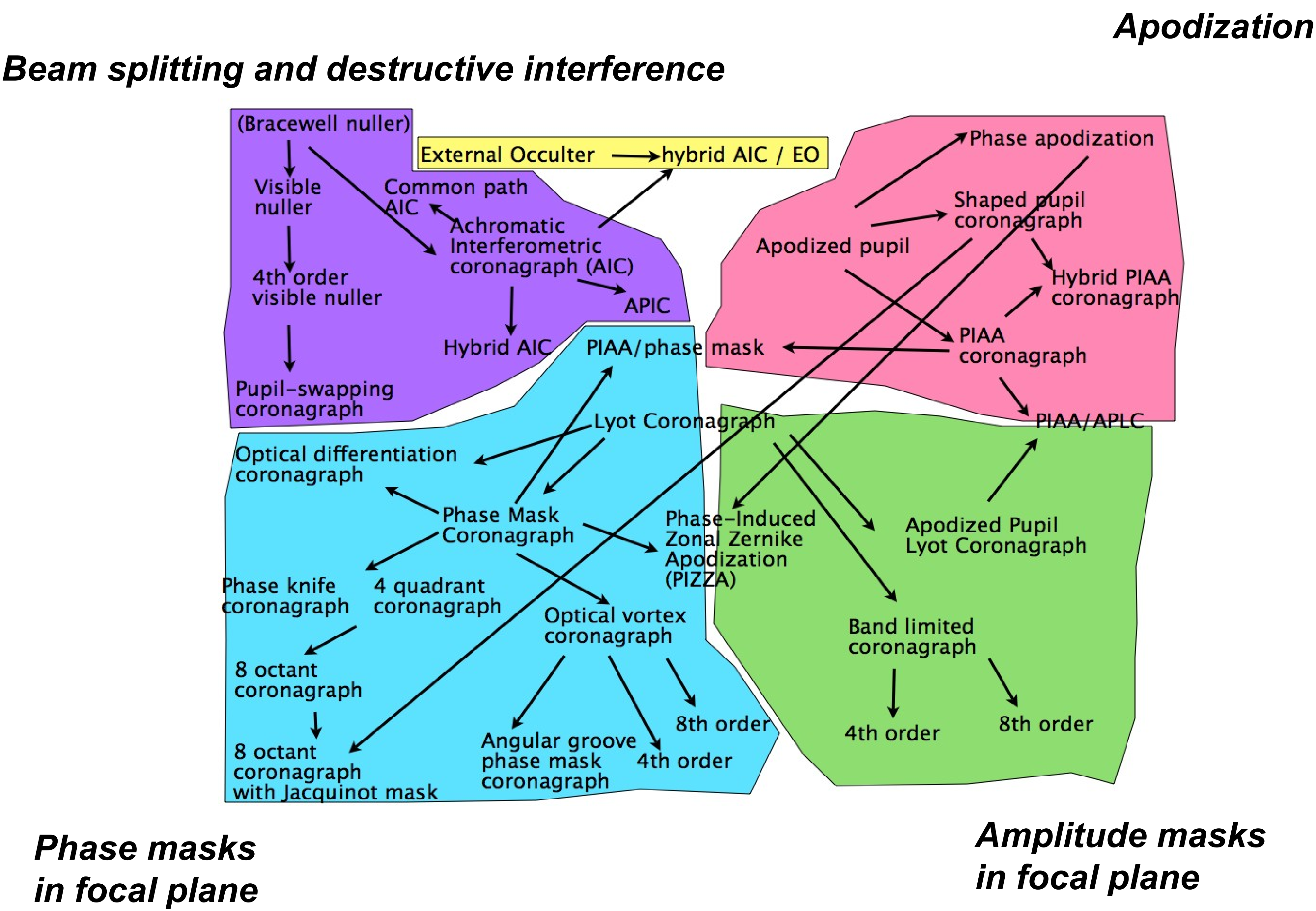
3 main approaches to remove starlight :

- Block starlight BEFORE it enters the telescope using a large ***external occulter*** ~50000 km in front of the telescope

- Design masks and optical components inside the telescope to induce starlight destructive interference at the expected location of a planet in the image: ***internal coronagraph (this lecture)***

- Induce destructive interference between beams of multiple telescopes: ***nulling interferometer***

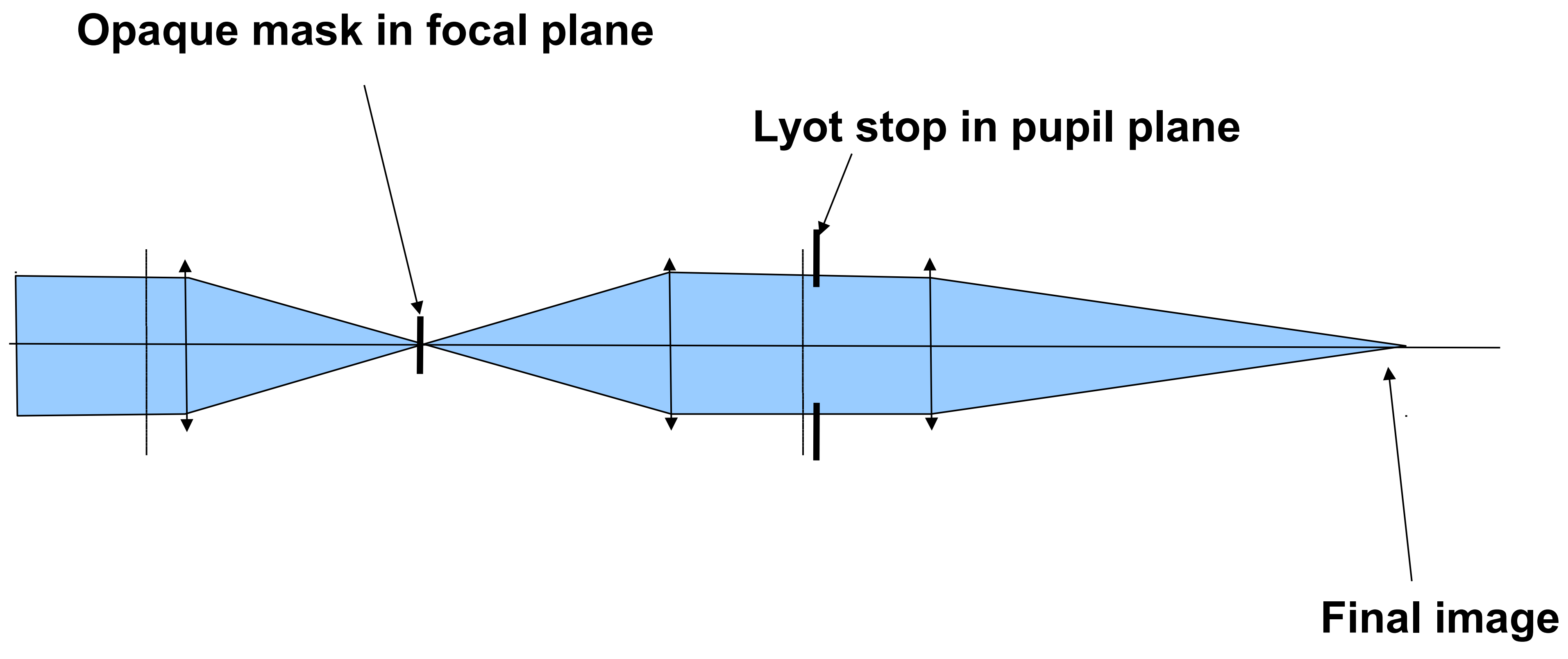
Internal Coronagraphs: main approaches



Lyot Coronagraph

Developped by Bernard Lyot in 1930 to observe the solar corona

It is the origin of many current high performance coronagraph designs

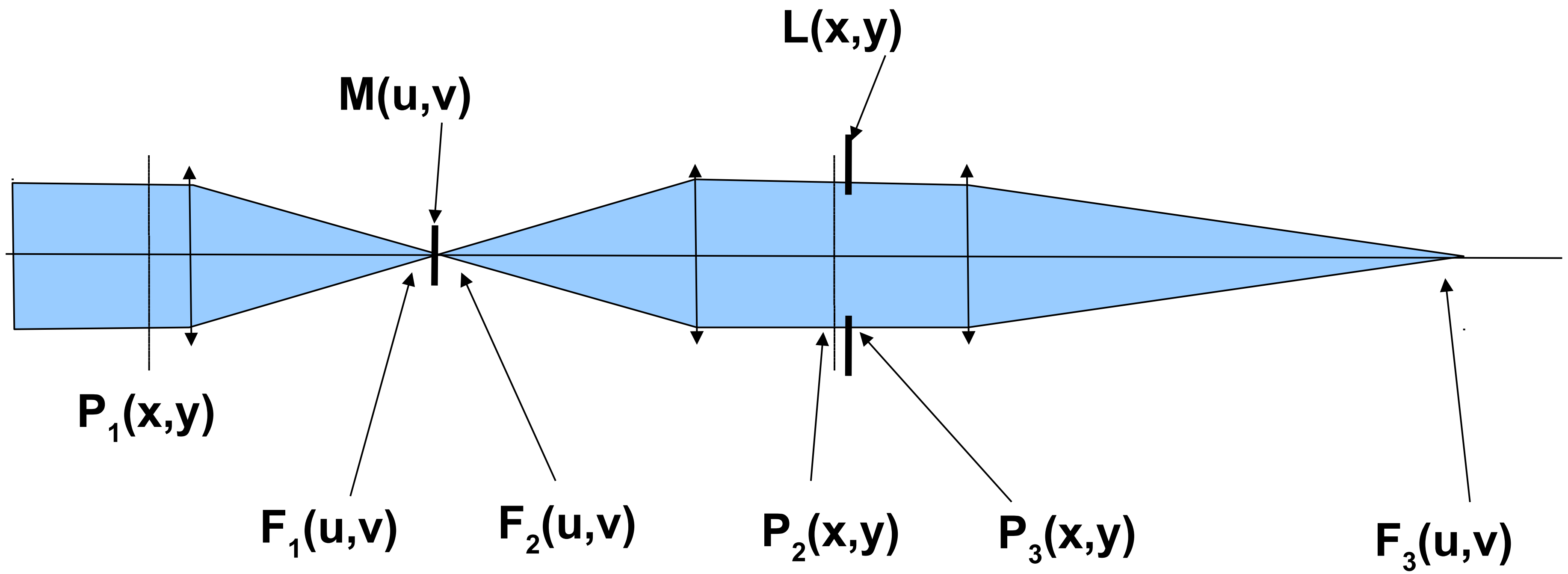


Lyot Coronagraph explained by Fourier transforms

Pupil plane complex amplitude ↔ focal plane complex amplitude

→ Fourier transform
← Inverse Fourier transform

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



Lyot Coronagraph explained by Fourier transforms

Full set of equations (explained in next slides):

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

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

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

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

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

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

Exit pupil plane:

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

With * denoting convolution

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

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

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

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

Lyot Coronagraph explained by Fourier transforms

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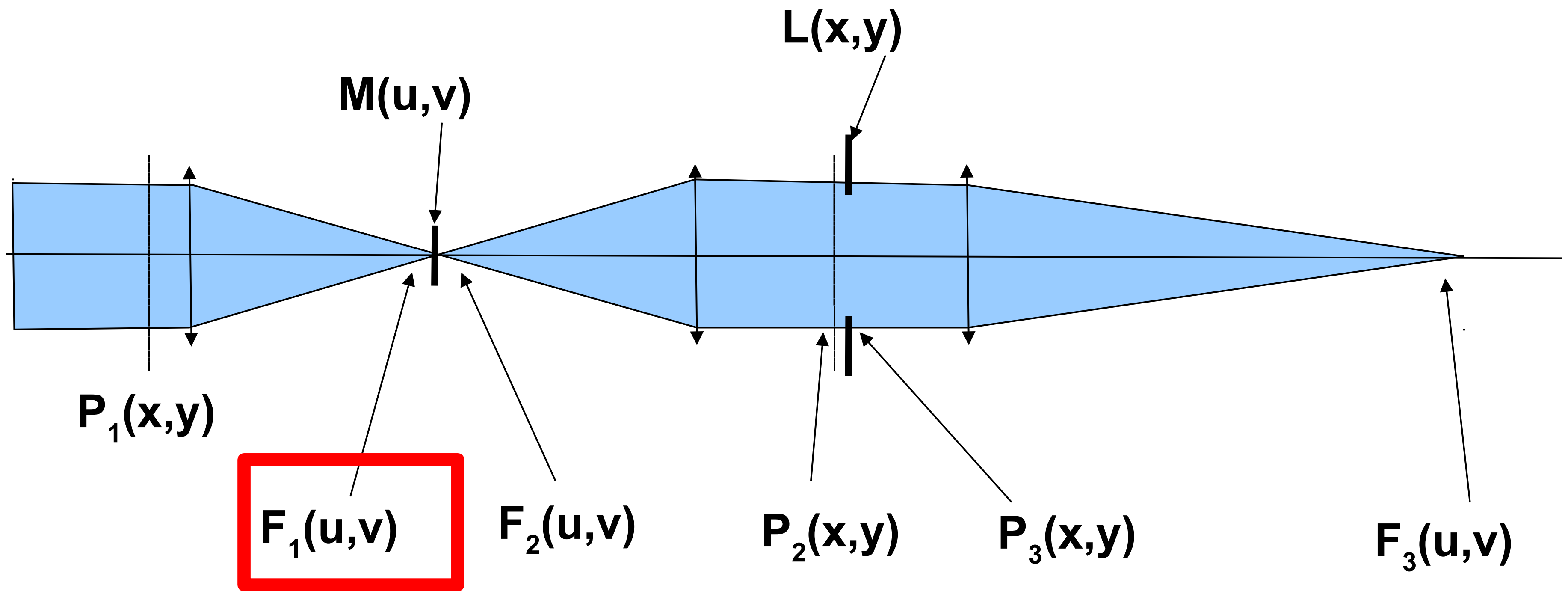
→ Fourier transform
← Inverse Fourier transform

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

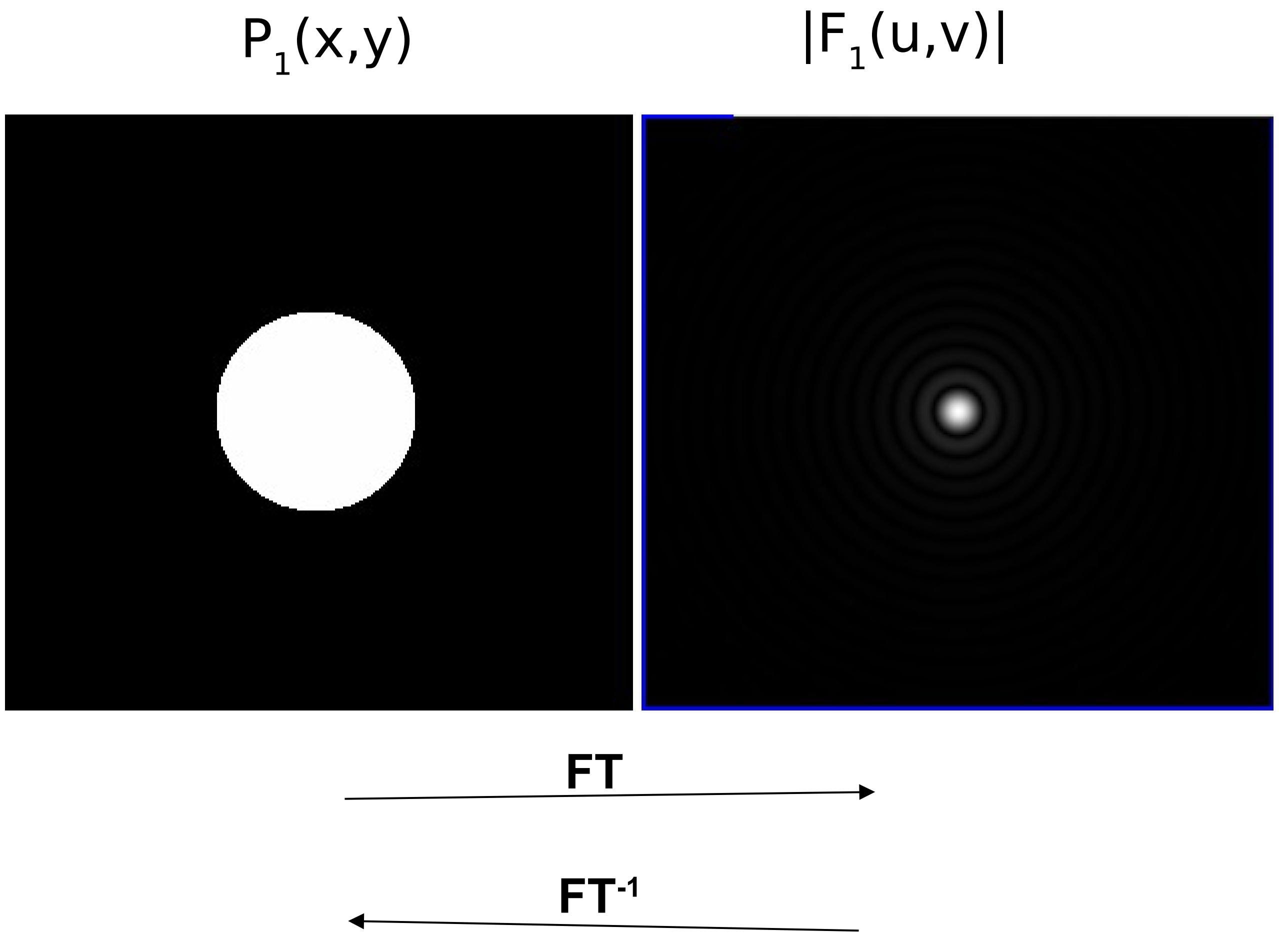


Focal plane image = FT of pupil complex amplitude

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

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

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



Lyot Coronagraph explained by Fourier transforms

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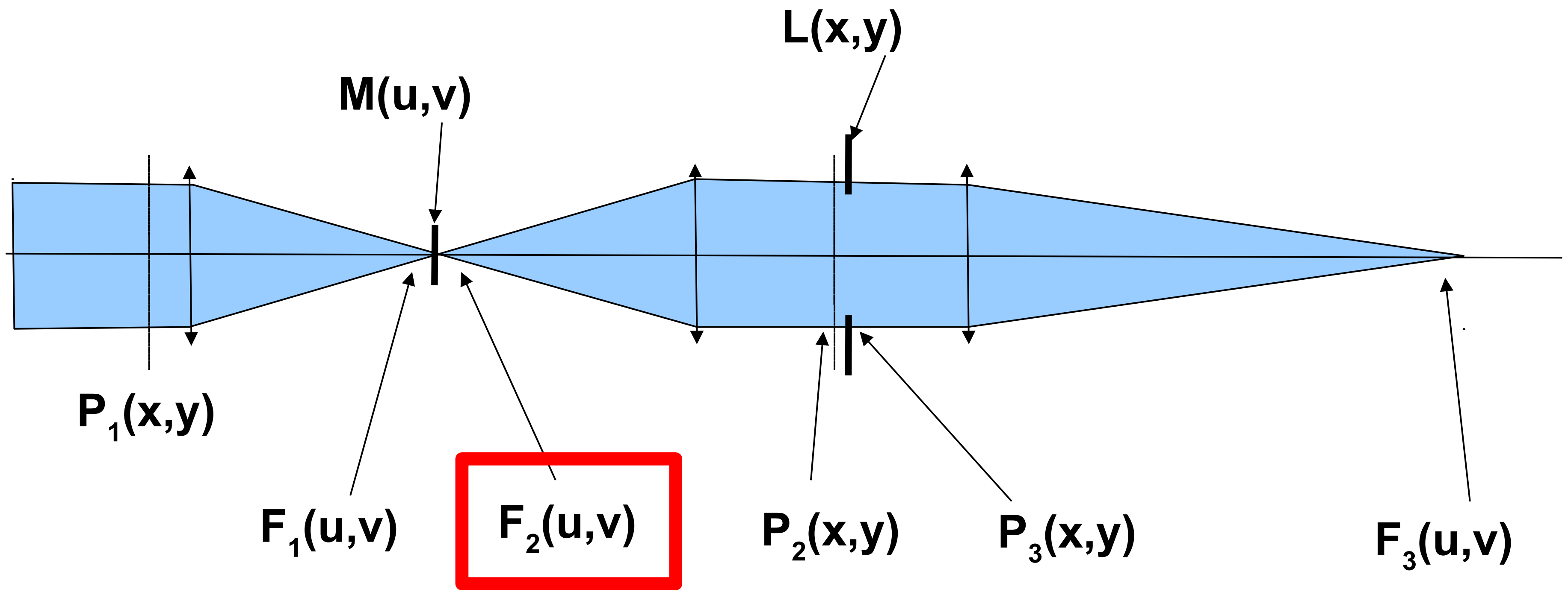
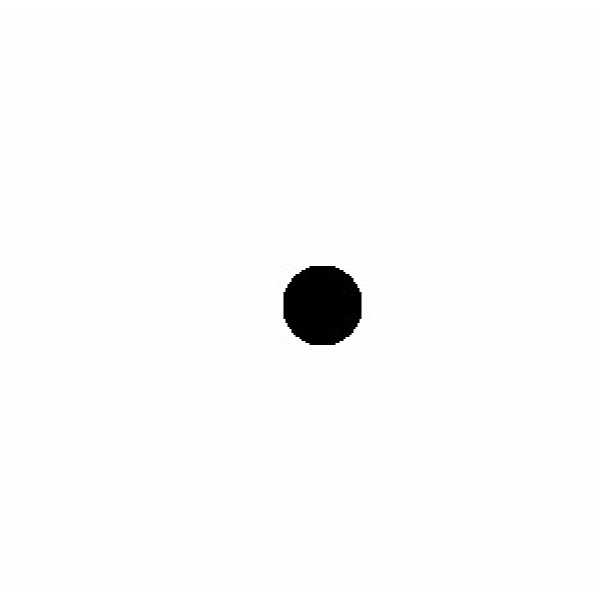


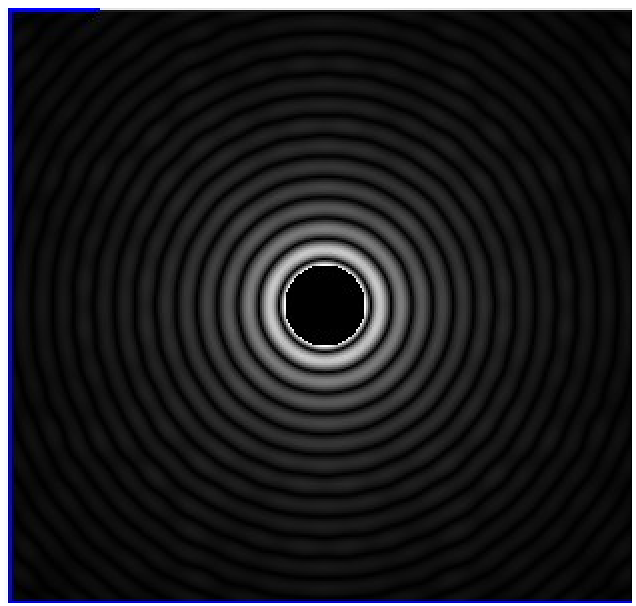
Inserting an opaque mask in the focal plane

Focal plane mask complex amplitude transmission: M(u,v)
Focal plane complex amplifude (after focal plane mask): $F_2(u,v)$
$F_2(u,v) = F_1(u,v) \times M(u,v) = FT(P_1(x,y)) \times M(u,v)$

M(u,v)



$|F_2(u,v)|$



Lyot Coronagraph explained by Fourier transforms

Pupil plane complex amplitude ↔ focal plane complex amplitude

→ Fourier transform
← Inverse Fourier transform

Coordinates in pupil plane: x,y
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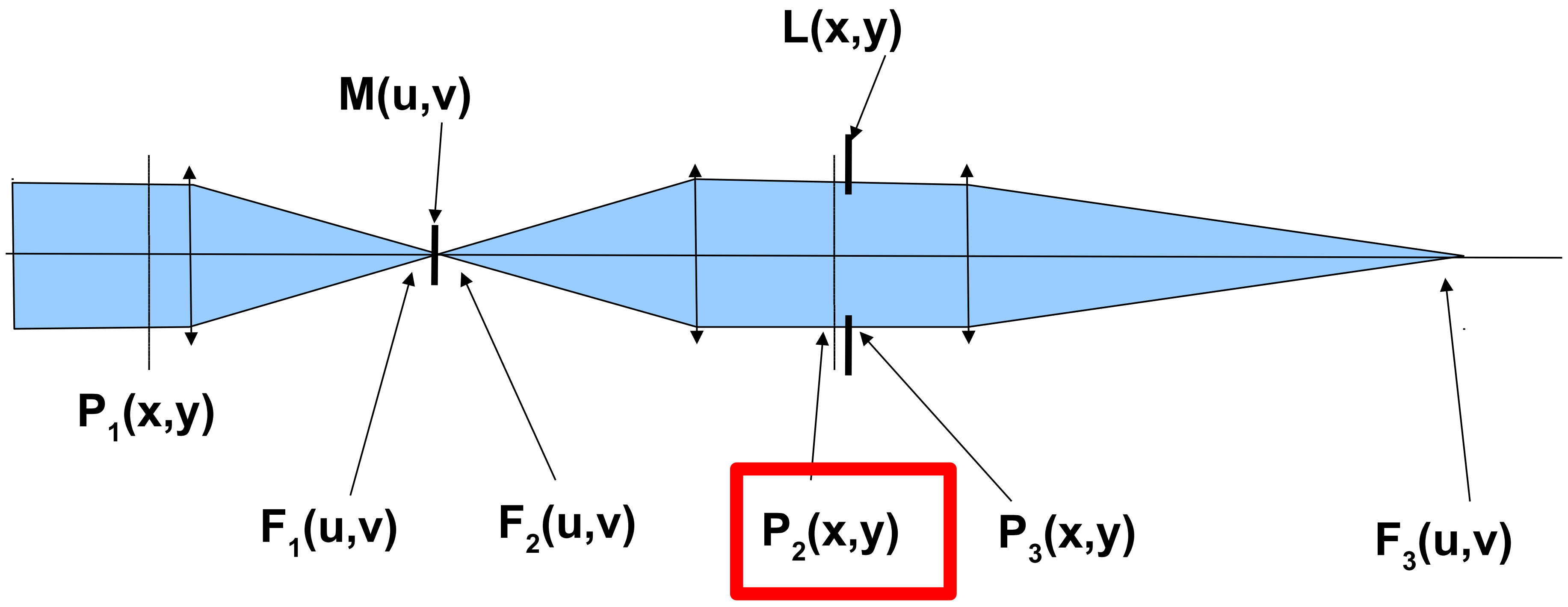


Lyot Coronagraph : light distribution in output pupil plane

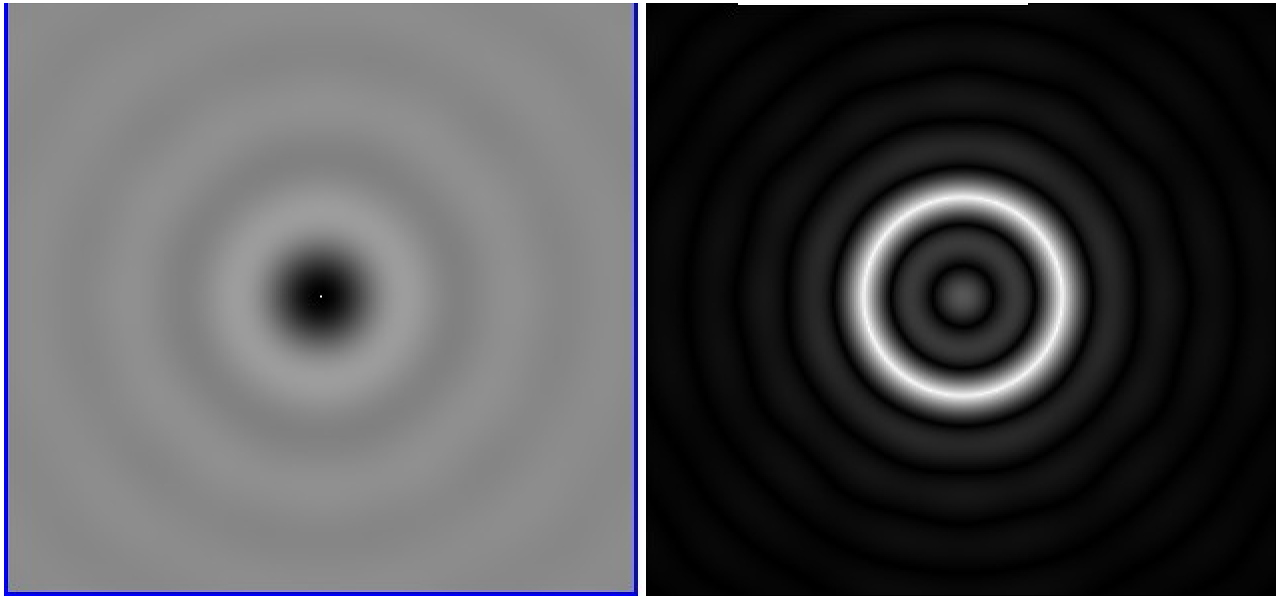
Exit pupil plane:

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

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

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

$|P_2(x,y)|$



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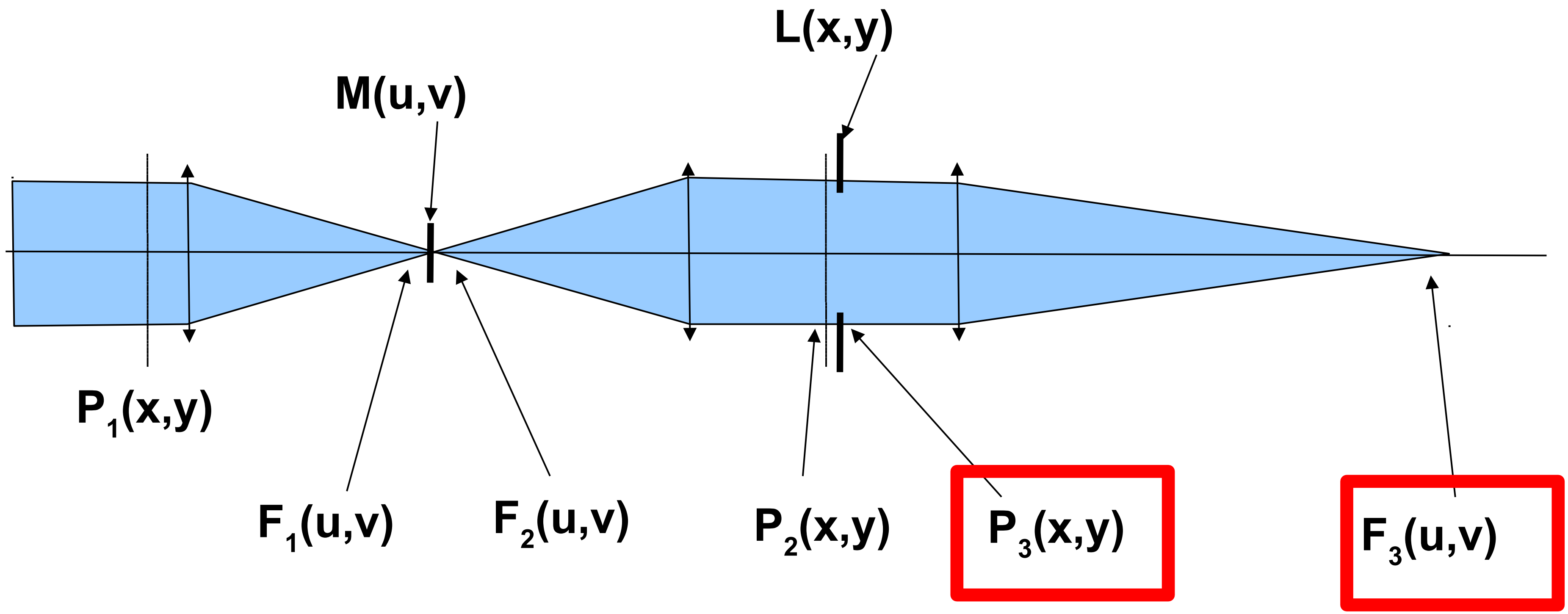


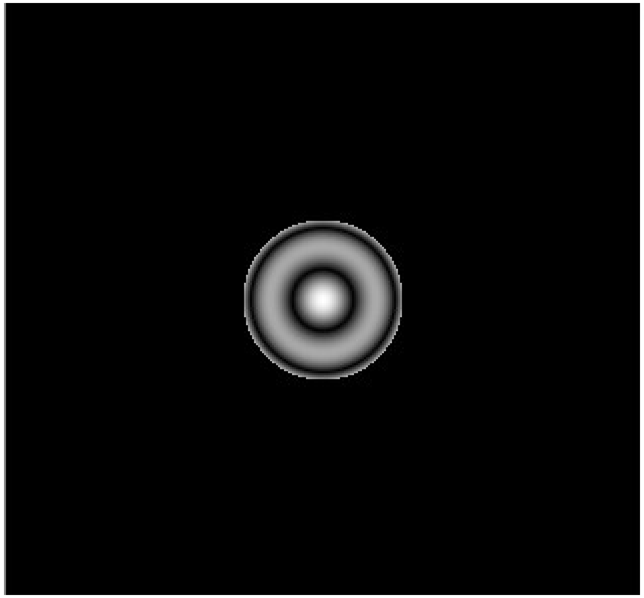
Lyot Coronagraph : Lyot stop (L)

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

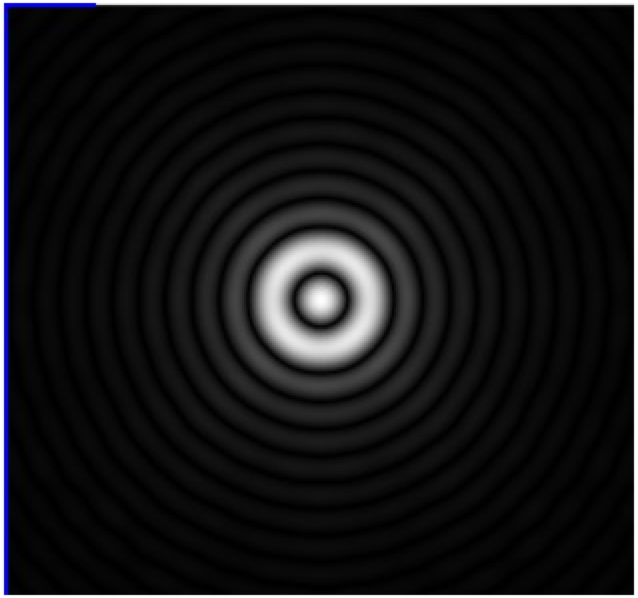
$\mathbf{P_3(x,y) = L(x,y) \times (P_1(x,y) * FT^{-1}(M(u,v)))}$

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

$|P_3(x,y)|$

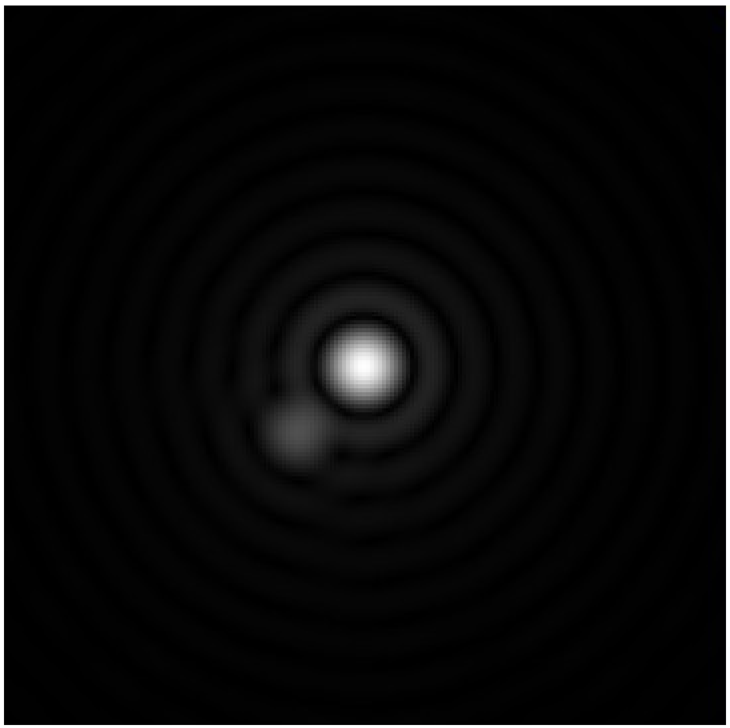


$|F_3(u,v)|$

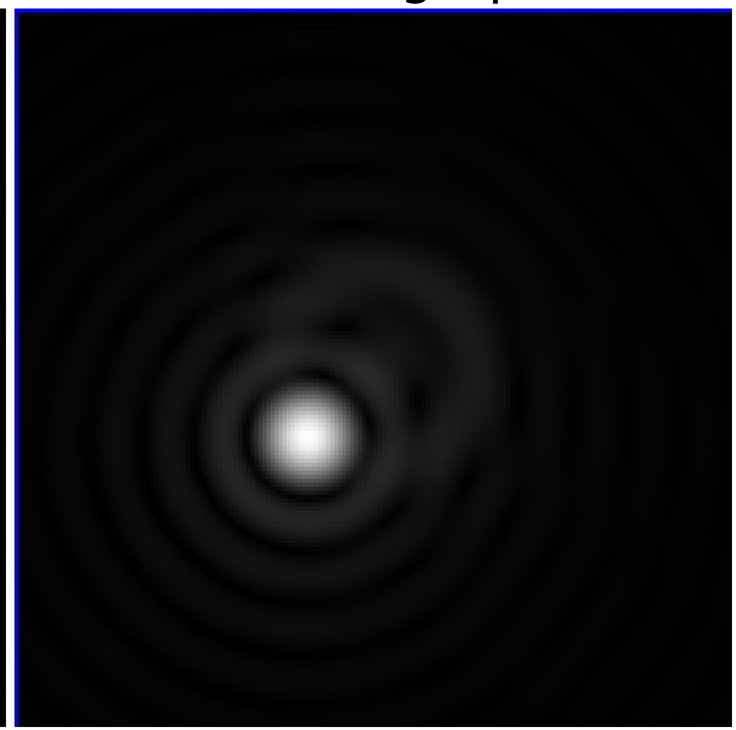


Numerical simulation of final image for 10:1 contrast

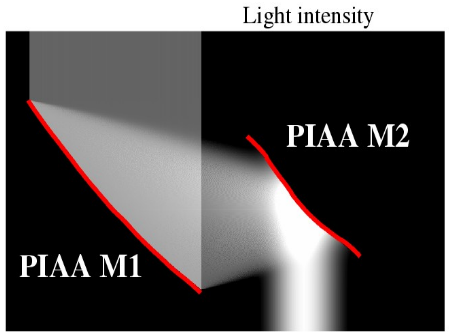
No coronagraph



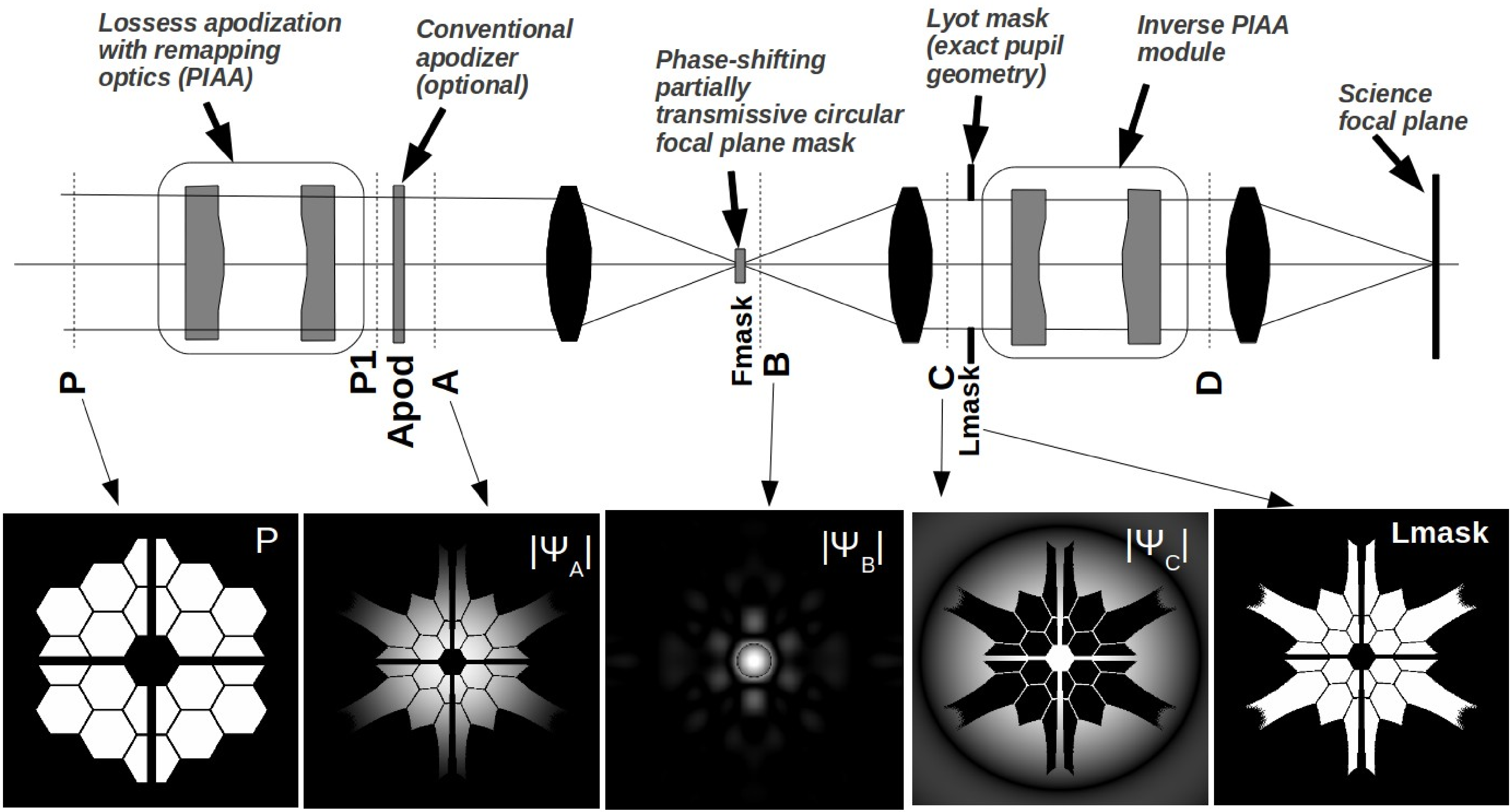
With Lyot Coronagraph



A more fancy coronagraph design



Phase Induced Amplitude Apodized Complex Mask Coronagraph (PIAACMC)



Lyot Coronagraph : optimizations

Conventional Lyot coronagraph is limited in performance:

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

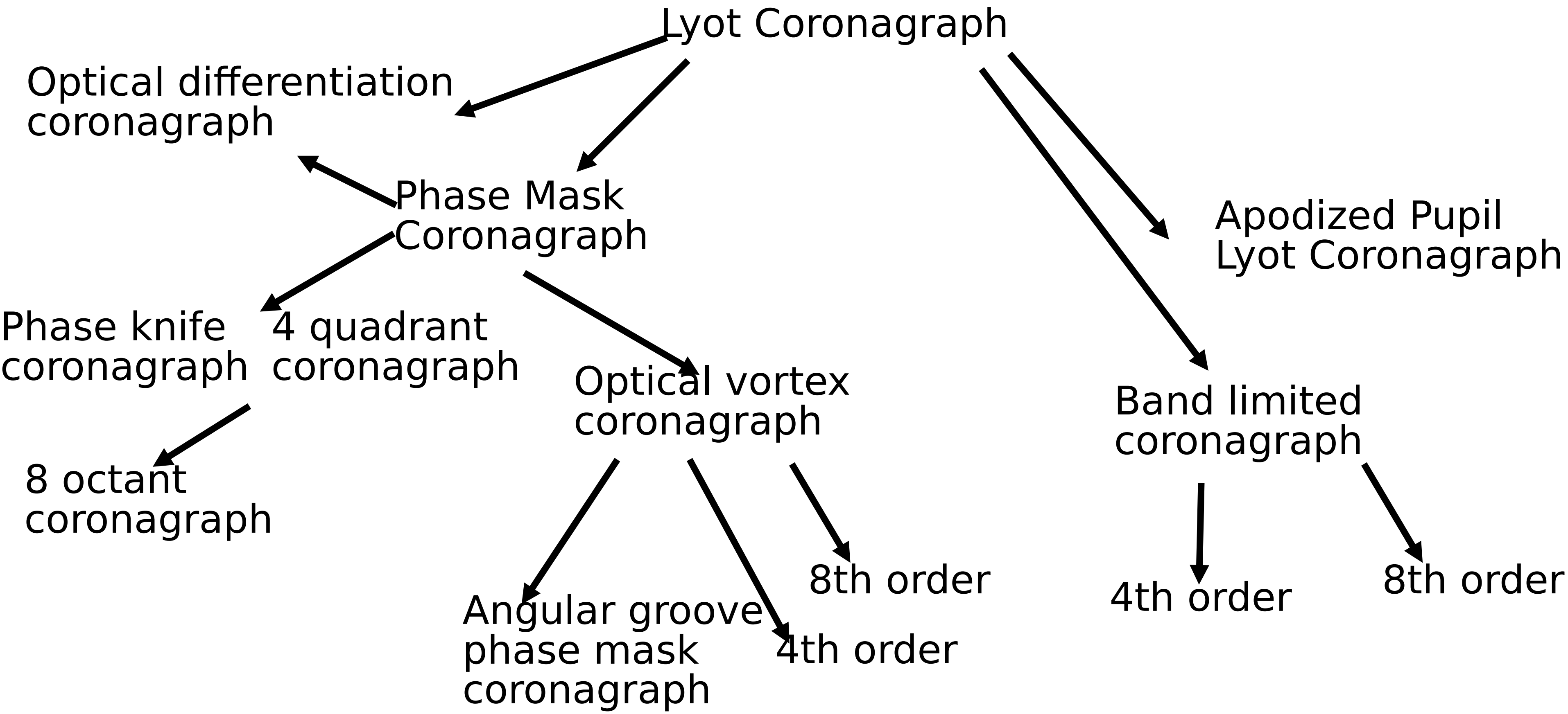
Optimization goal: make pupil dark inside Lyot mask

Possible optimizations include:

(1) Redesign of focal plane mask

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

(2) Apodize entrance aperture


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

Pupil Apodization

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

Conventional Pupil Apodization/ Shaped pupil CPA
Kasdin et al. 2003
Make the pupil edges fainter by absorbing light, either with a continuous or ''binary'' (shaped pupil) mask

Achromatic Pupil Phase Apodization PPA
Yang & Kostinski, 2004
Same as CPA, but achieved by a phase apodization rather than amplitude

Phase Induced Amplitude Apodization Coronagraph PIAAC
Guyon, 2003
Perform amplitude apodization by remapping of the pupil with aspheric optics

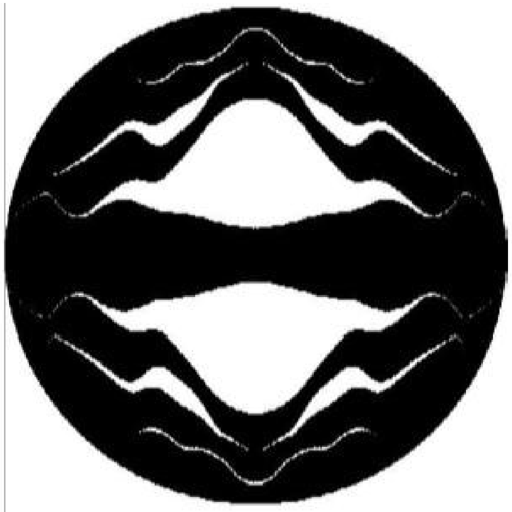
Phase Induced Zonal Zernike Apodization PIZZA
Martinache, 2003
Transform a pupil phase offset into an amplitude apodization thanks to a focal plane Zernike mask

Conventional Pupil Apodization (CPA)

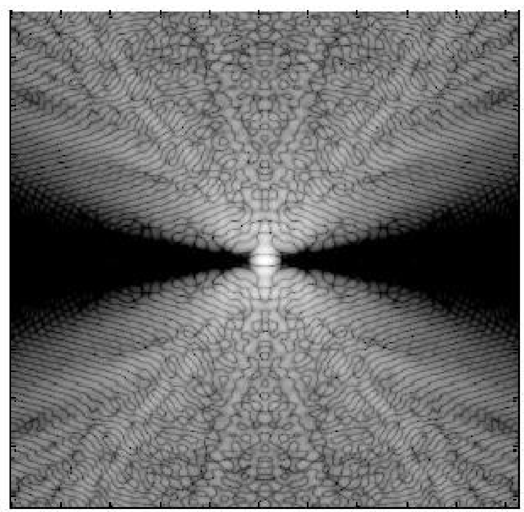
Many pupil apodizations have been proposed.

Apodization can be continuous or binary.

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



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



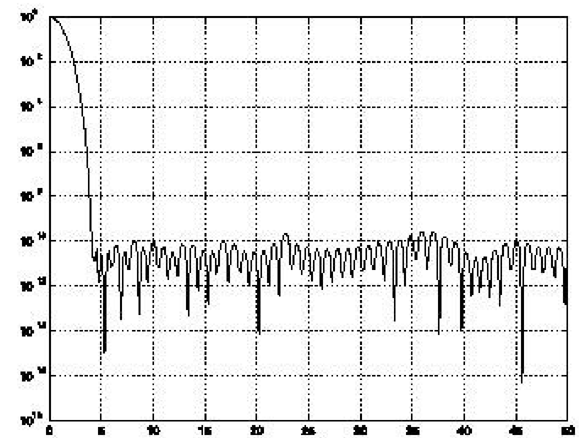


FIG. 9.—*Top*: Asymmetric multiopening mask designed to provide high-contrast, 10^{-10}, from $\lambda/D = 4$ to $\lambda/D = 100$ in two angular sectors centered on the x-axis. Ten integrations are required to cover all angles. Total throughput and pseudoarea are 24.4%. Airy throughput is 11.85%. *Bottom*: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

Pupil Phase Apodization (PPA)

Achromatic solutions exist.

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

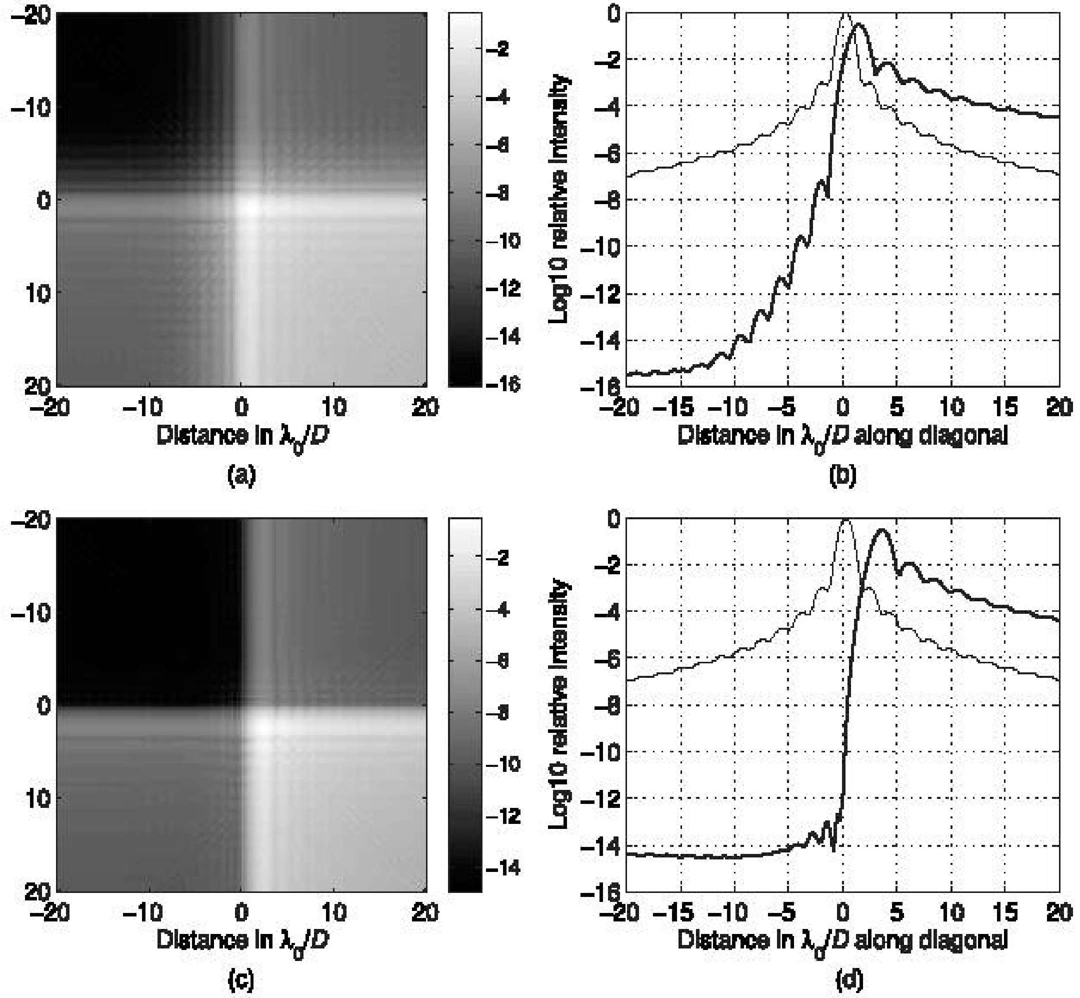
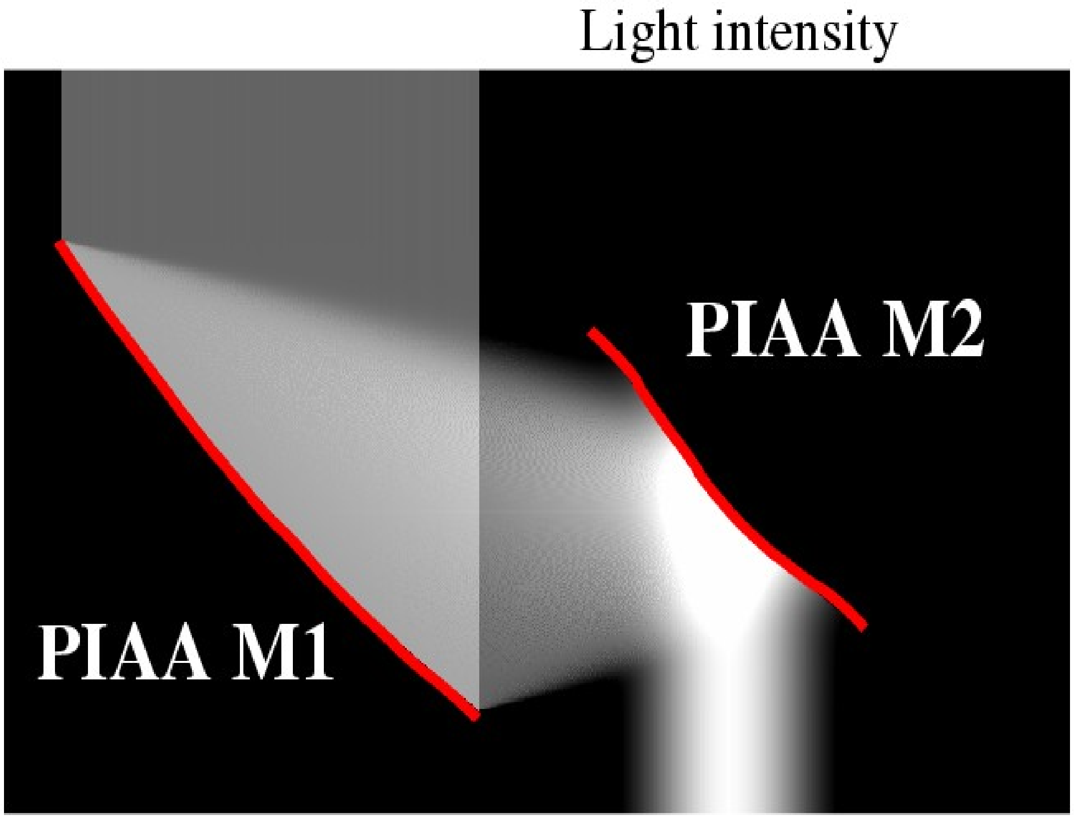
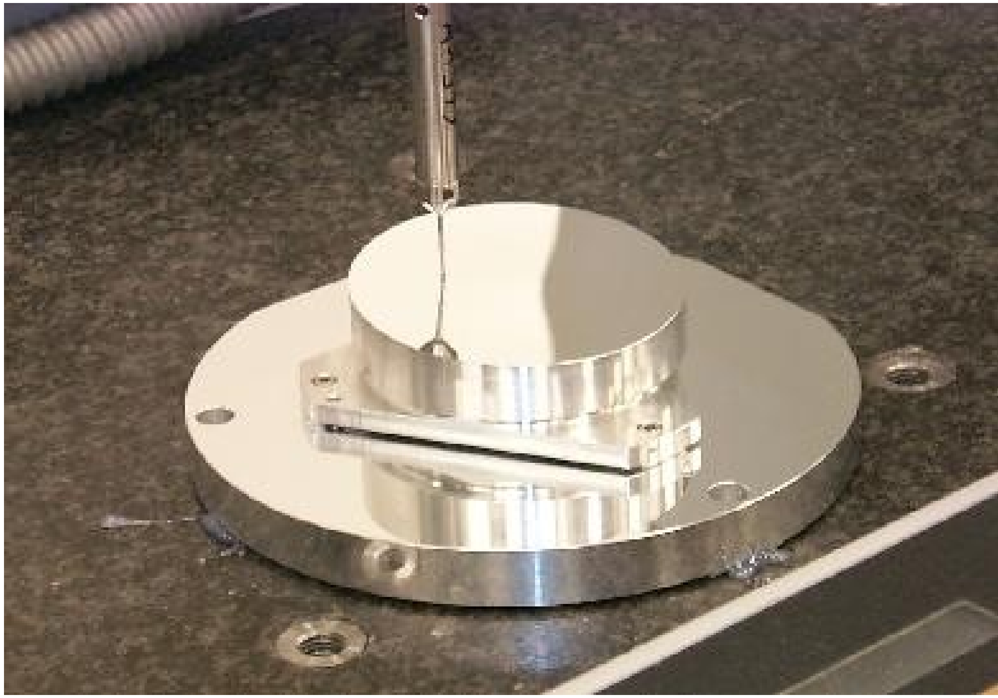


Fig. 9.—Broad-bandwidth light reduction effect on one quadrant of focal plane. The simulation is based on a rectangular spectrum distribution with total bandwidth of $0.6\lambda_0$. (*a*) $\log_{10}$ relative intensity image when phase $\phi(x, y) = a \tan[(0.5 - \epsilon)2\pi x/D] + a \tan[(0.5 - \epsilon)2\pi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

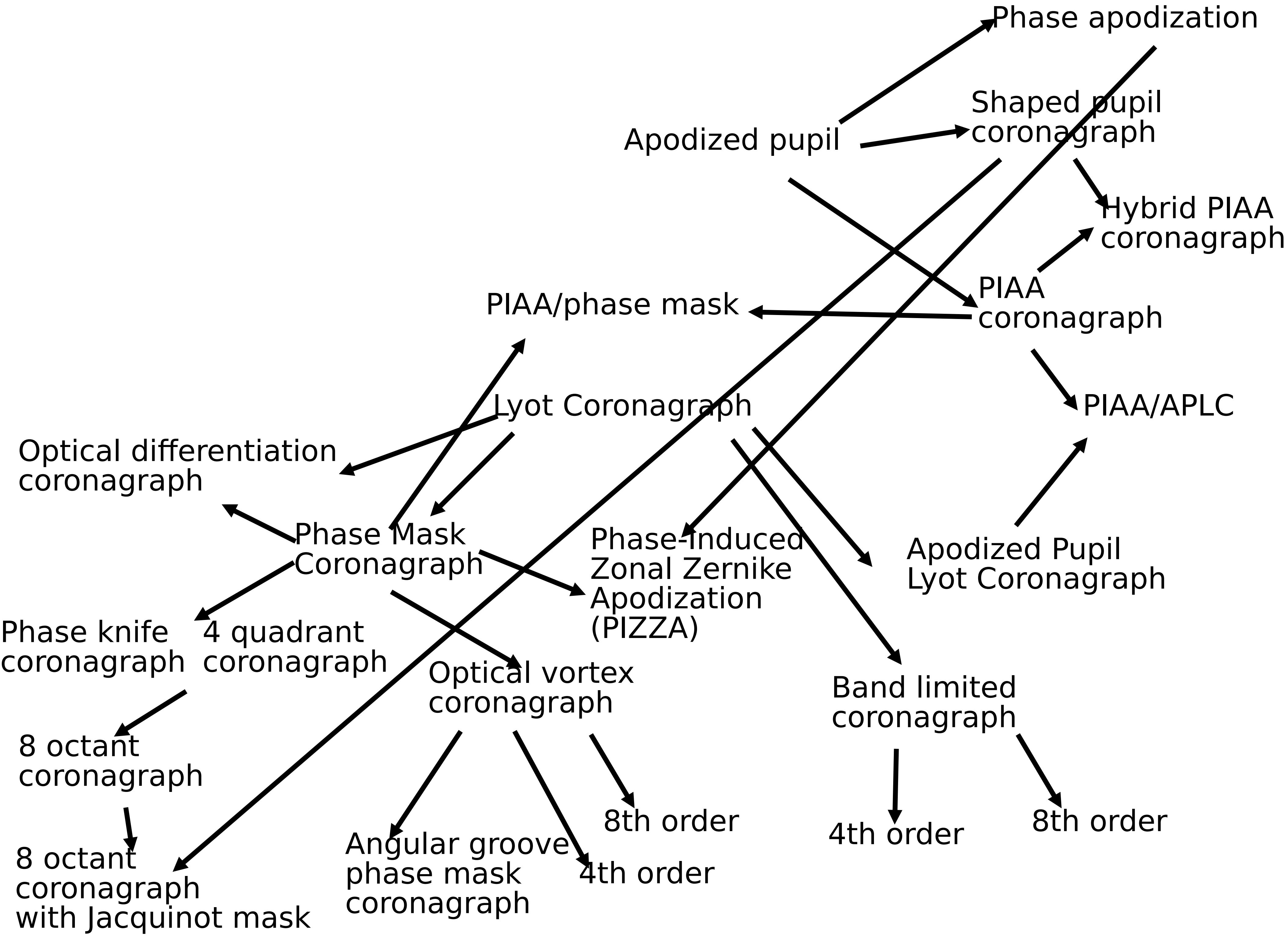
Phase-Induced Amplitude Apodization Coronagraph (PIAAC)

Lossless apodization by aspheric optics.





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


Phase apodization
Shaped pupil coronagraph
Apodized pupil
Hybrid PIAA coronagraph
PIAA coronagraph
PIAA/phase mask
Lyot Coronagraph
PIAA/APLC
Optical differentiation coronagraph
Phase Mask Coronagraph
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Band limited coronagraph
8 octant coronagraph
8th order
4th order
8th order
8 octant coronagraph with Jacquinot mask
Angular groove phase mask coronagraph
4th order

''Interferometric'' coronagraphs

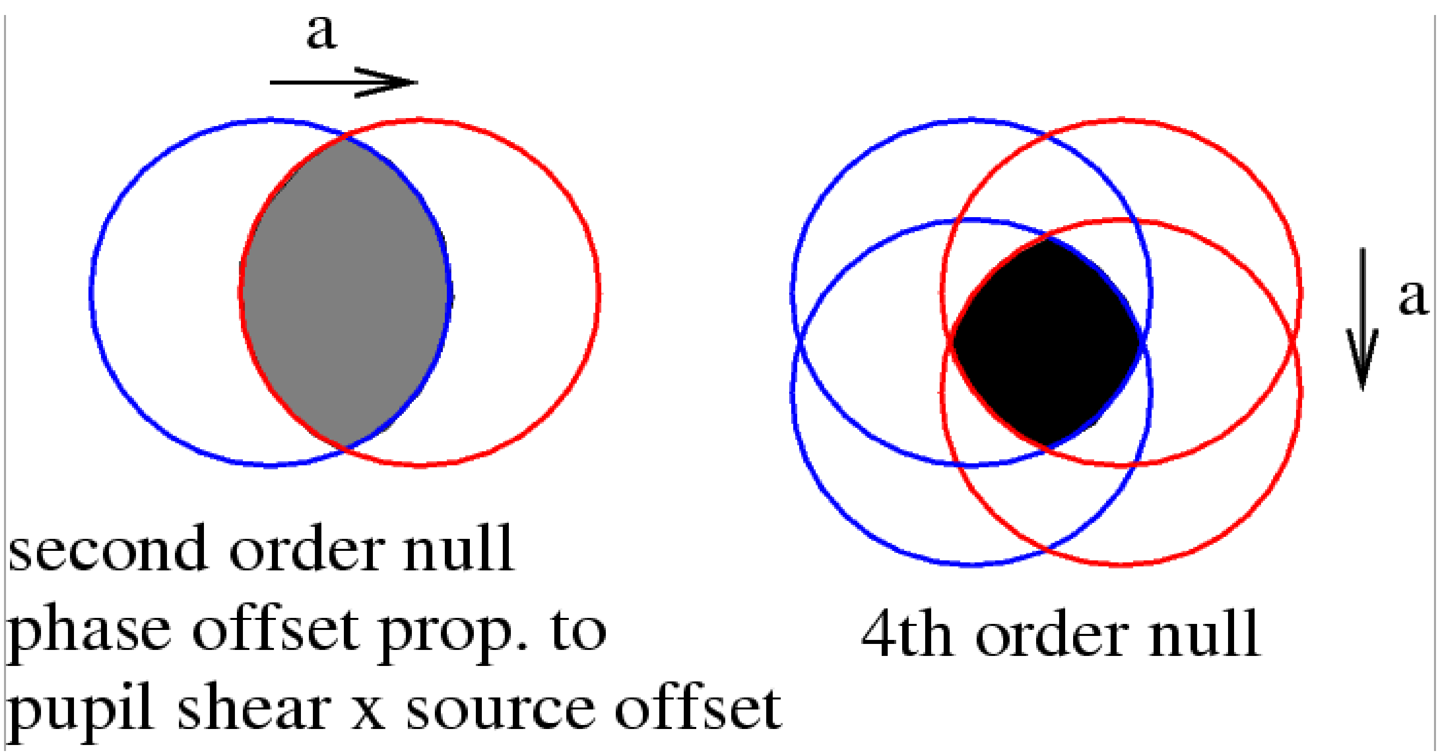
= Nulling interferometer on a single pupil telescope
- Creates multiple (at least 2) beams from a single telescope beam
- Combines them to produce a destructive interference on-axis and constructive interference off-axis

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

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

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

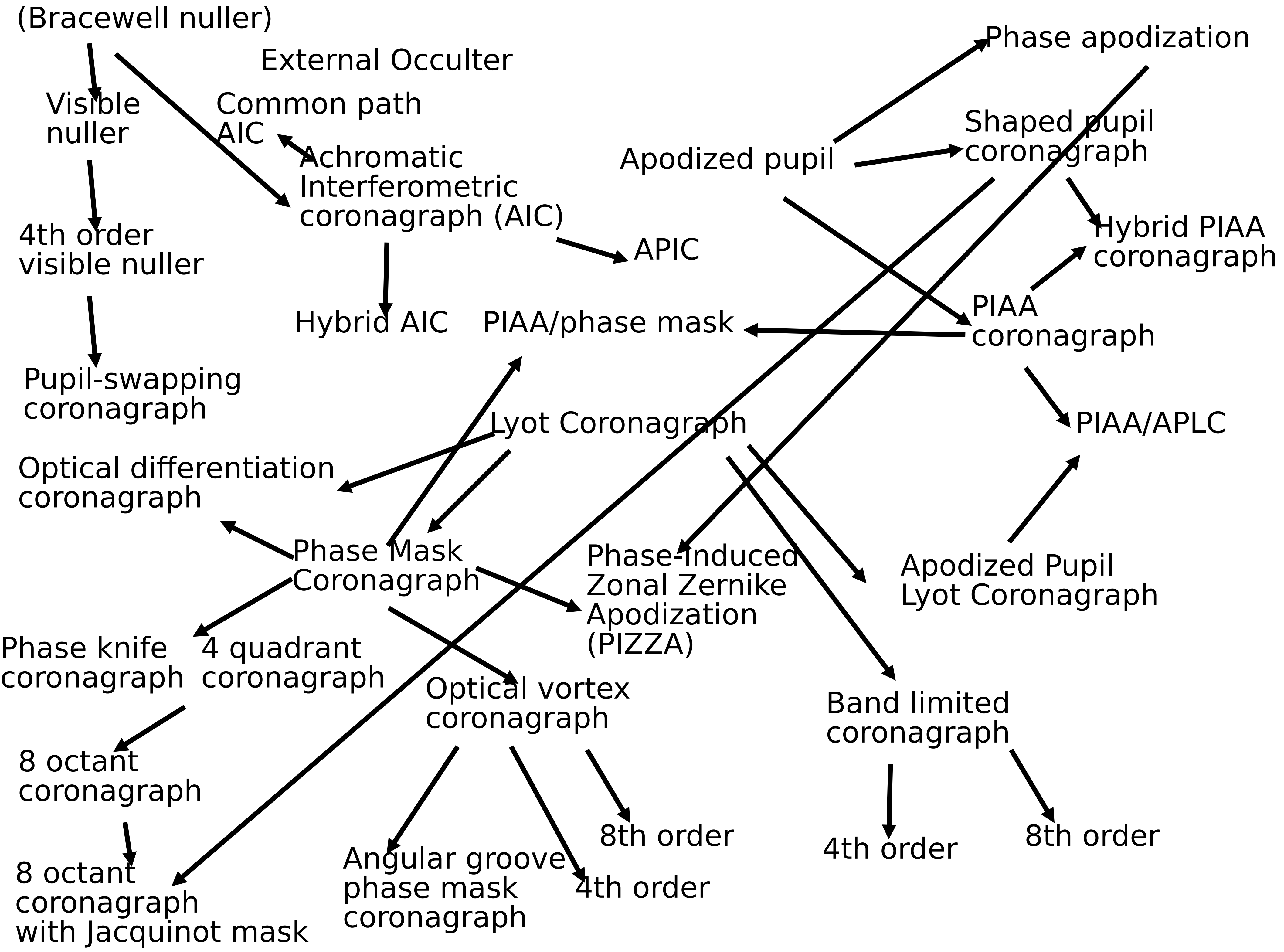
Visible Nuller Coron. (VNC)



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

Sounding rocket (PICTURE)

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


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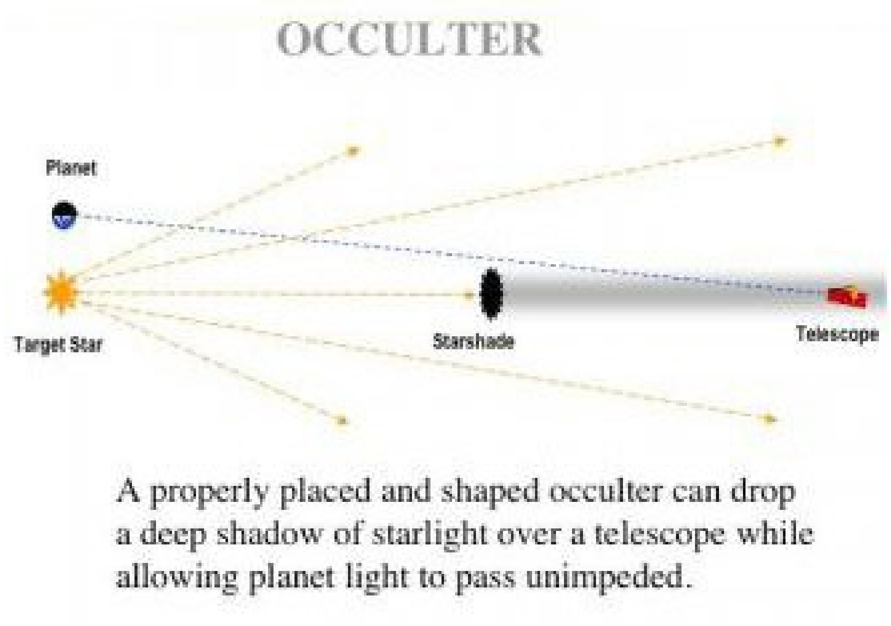
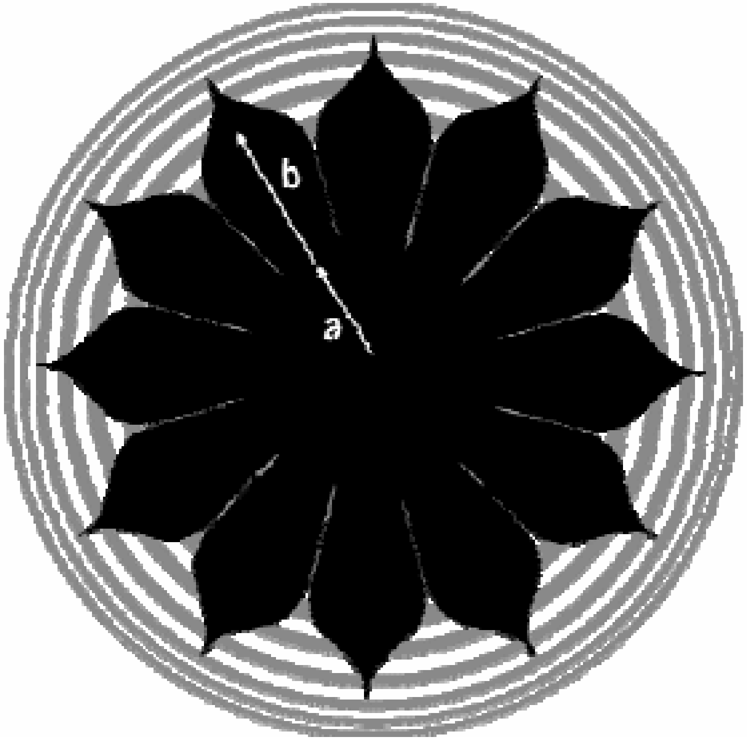
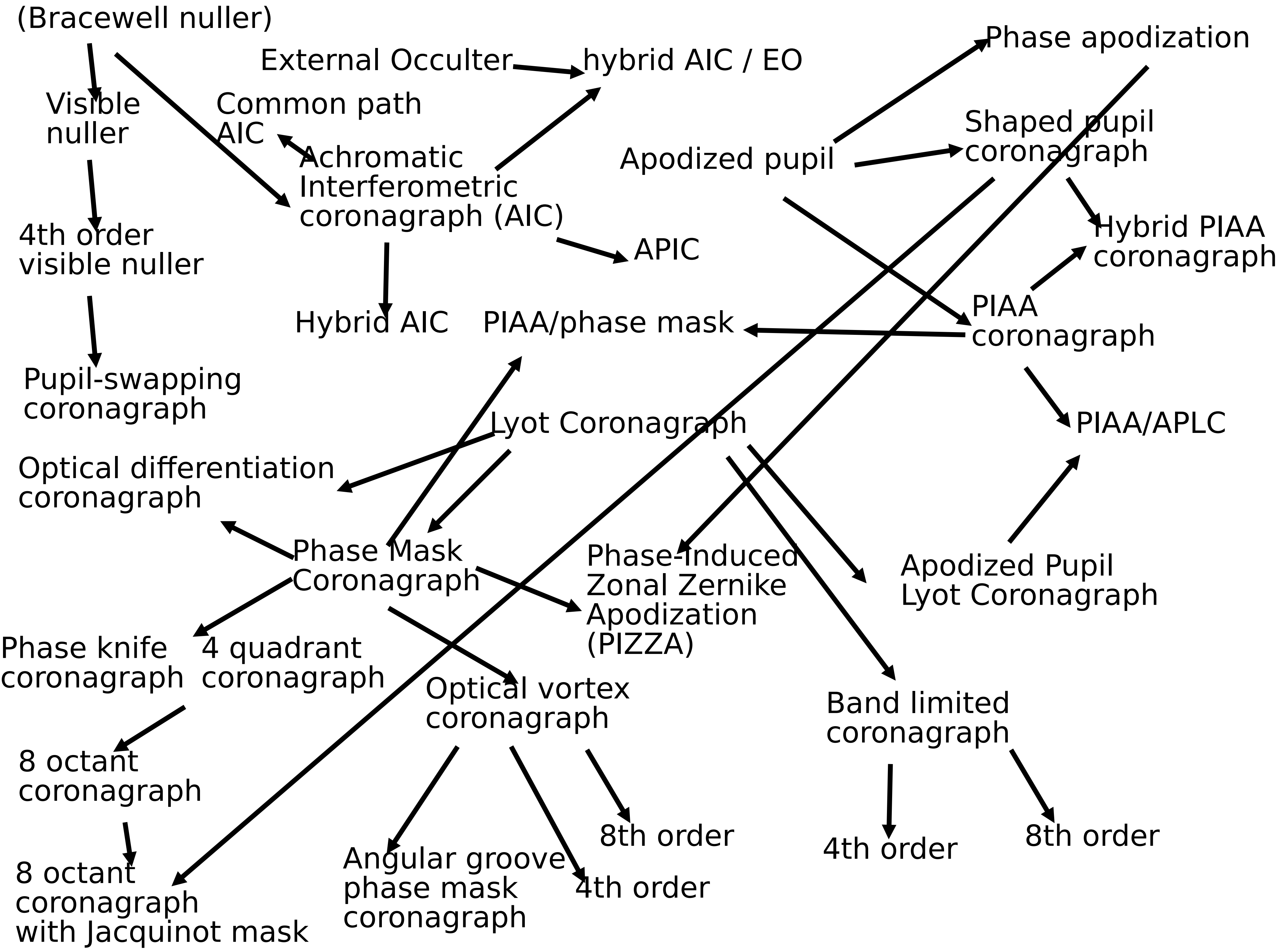
External Occulter



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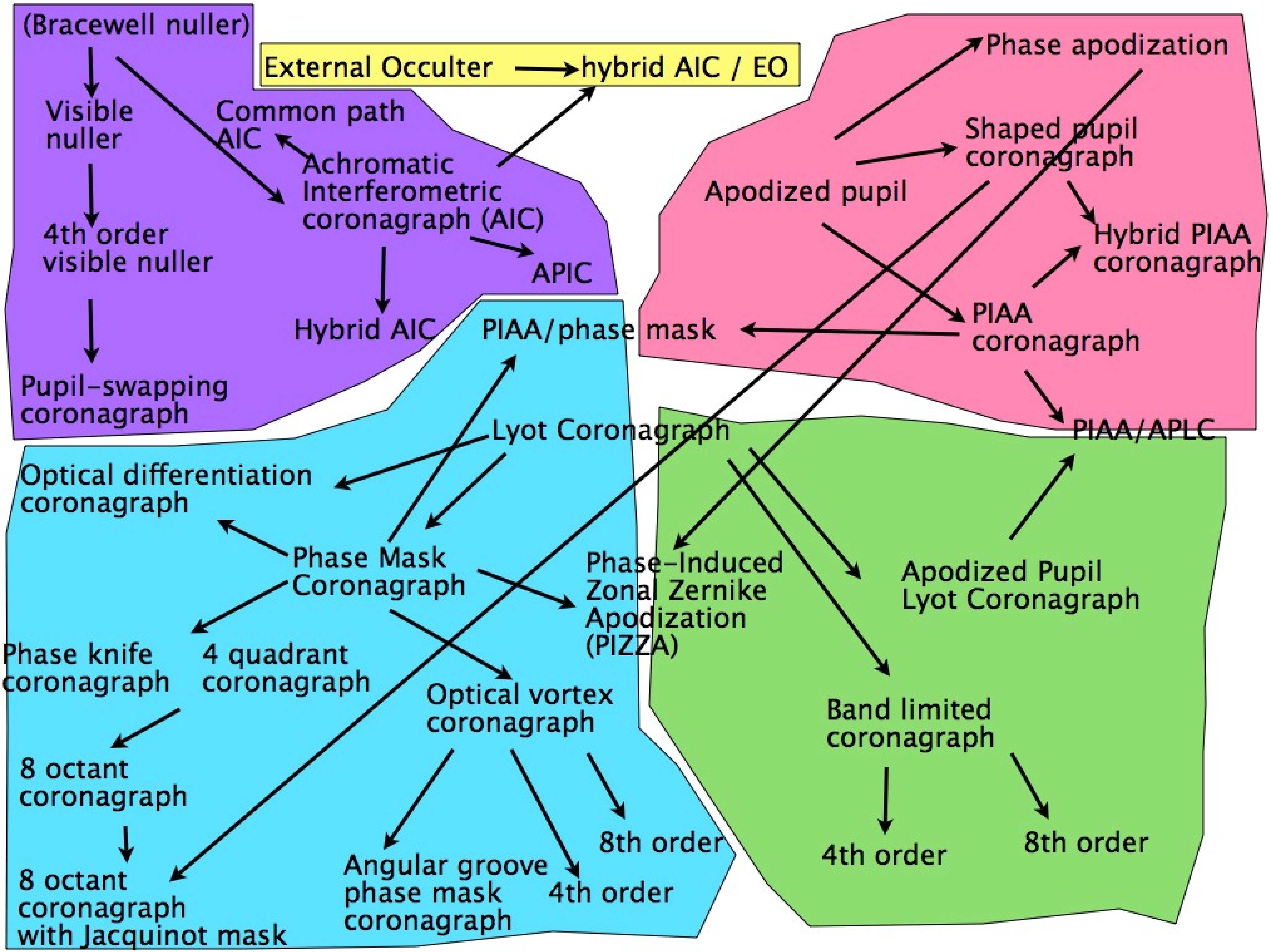

(Bracewell nuller)
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4th order visible nuller
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Coronagraph systems

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

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

Key elements:

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

- Wavefront correction system to reduce and calibrate residual wavefront errors

For coronagraphs: Extreme-AO system to flatten wavefront

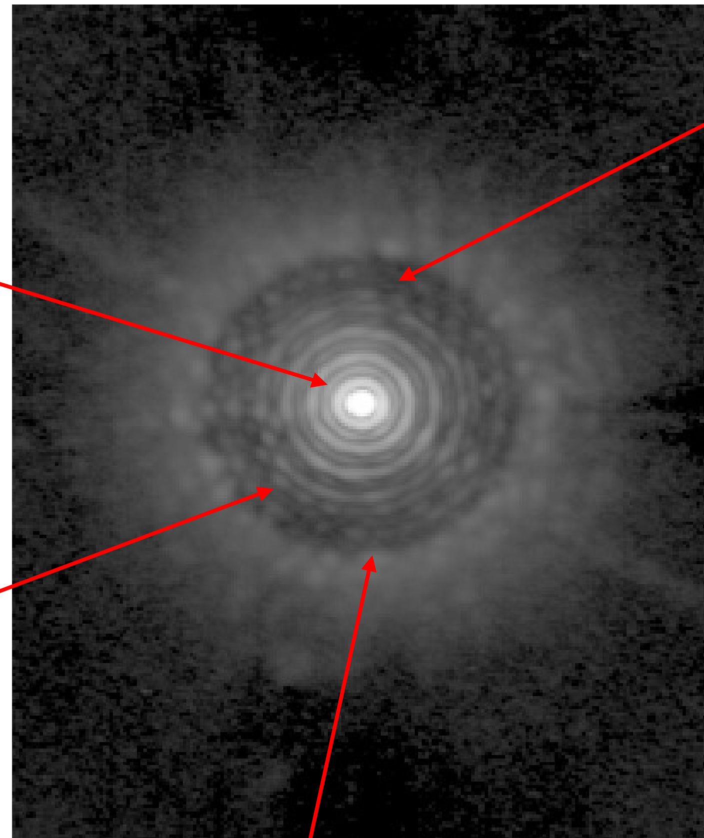
For interferometers: Optical pathlength sensing / correction (+ AO on individual apertures of the interferometer)

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

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

From conventional AO to Coronagraphic Extreme-AO

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



Residual atmospheric speckle halo

REDUCED BY FAST, ACCURATE AND EFFICIENT AO SYSTEM

PSF diffraction (Airy rings, spiders)

REMOVED BY CORONAGRAPH

Static and slow speckles

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

Control radius of AO

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

Current and future high contrast systems - ground

NICI on Gemini South telescope – ongoing, large survey completed
85-element curvature AO system + Lyot coronagraph
Differential imaging capability (methane absorption line)

HiCIAO on Subaru Telescope – ongoing survey
188-element curvature AO system + Lyot coronagraph
Differential imaging capability (methane absorption line)

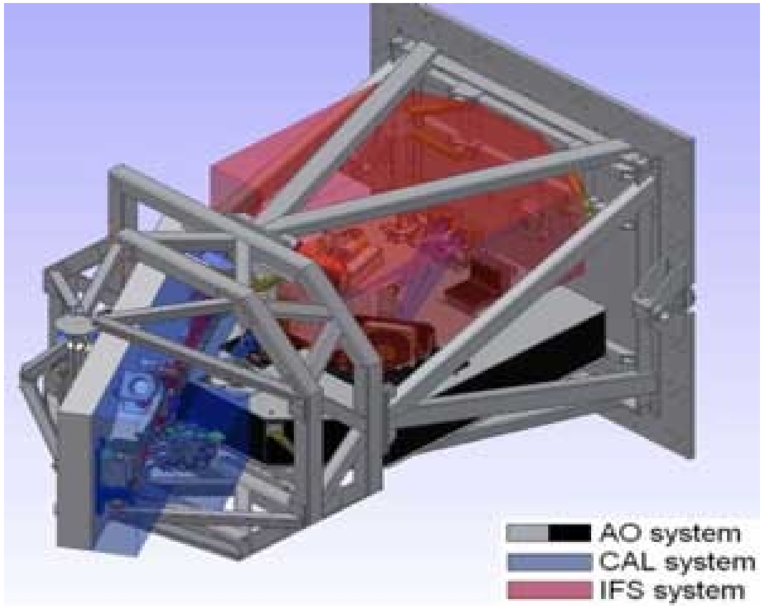
→ **Subaru Coronagraphic Extreme AO (upgrade of HiCIAO)** – on sky since 2012
Small inner working angle PIAA coronagraph
Pointing sensing and control with coronagraphic low order WFS
Speckle control using focal plane image as sensor
32x32 MEMS deformable mirror (upgraded 2013 to 2000 elements)
Includes Integral Field Spectrograph to help remove speckles and acquire spectra

P1640 + Palm300 on Palomar 5-m telescope – on sky since 2012
3000 element high order AO system + Lyot coronagraph
Includes Integral Field Spectrograph to help remove speckles and acquire spectra

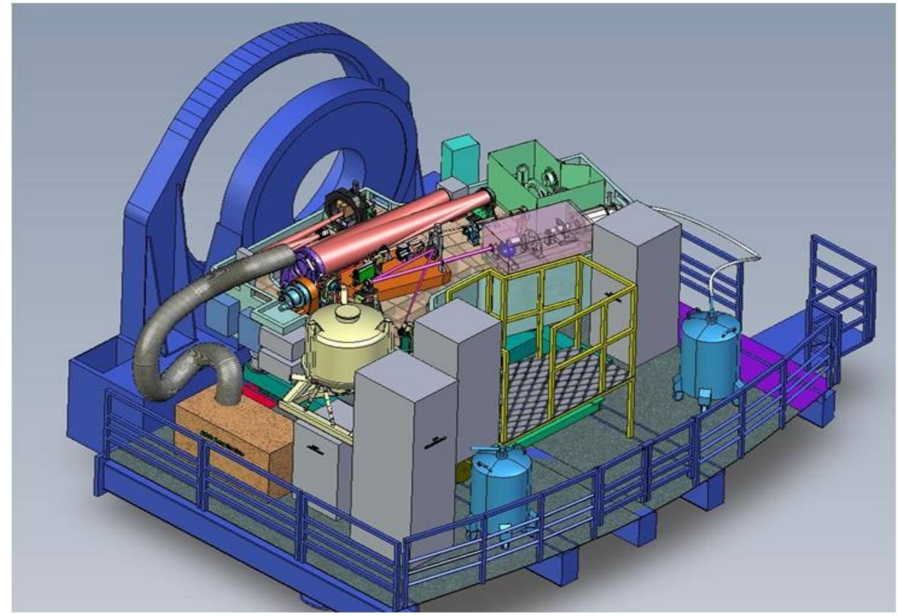
Gemini Planet Imager (GPI) – large survey starts observations in 2014
ExAO system using 64x64 MEMS DM + coronagraph
Includes calibration interferometer to accurately measure residual speckles
Includes Integral Field Spectrograph to help remove speckles and acquire spectra

ESO's SPHERE on VLT – large survery starts observations in 2014
ExAO system + coronagraph
Highly stable bench
Includes Integral Field Spectrograph to help remove speckles and acquire spectra
Includes differential polarimetric imager

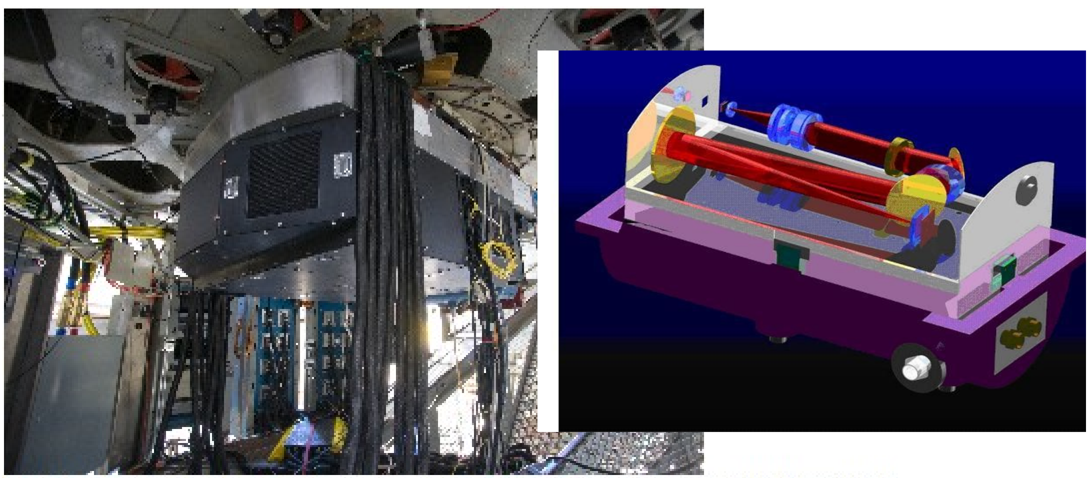
Current and future high contrast systems - ground



Gemini Planet Imager

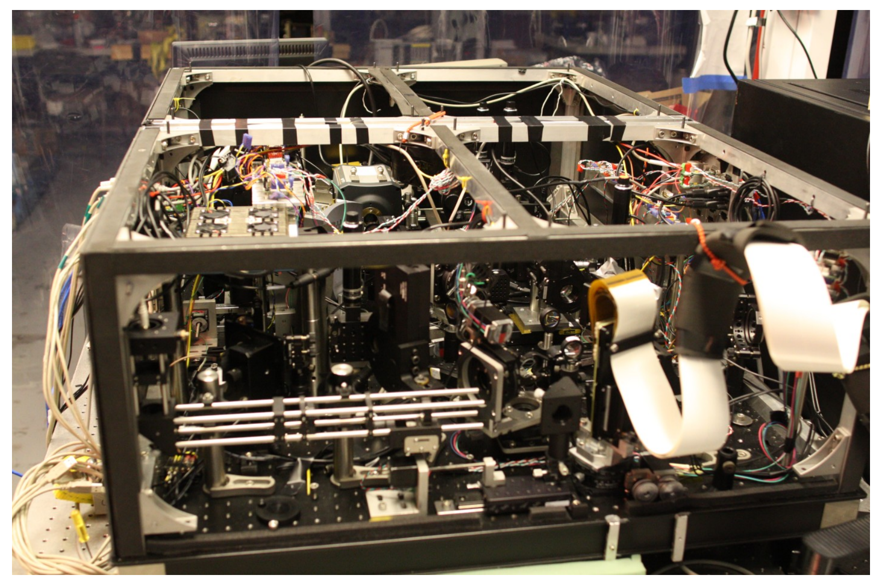


SPHERE (European Southern Observatory)



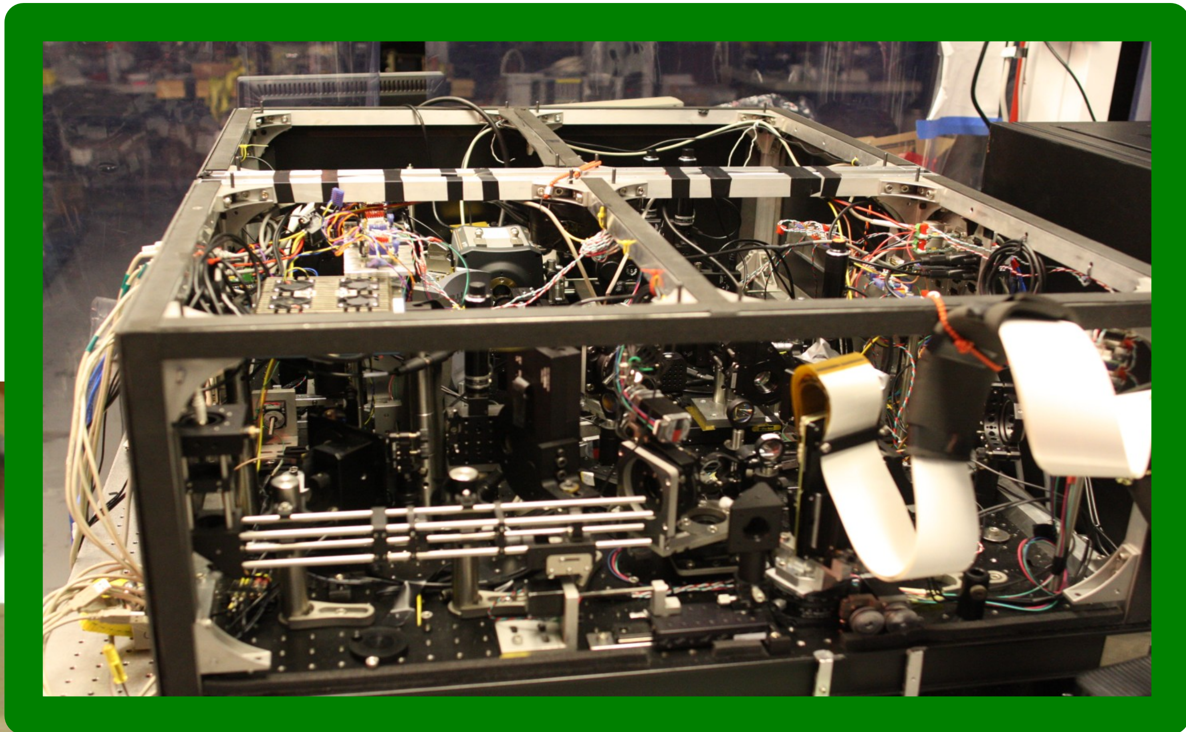
PALM-3000 installed at the Cass focus of the Hale Telescope at Palomar Mountain. Photo: Scott Kardel.

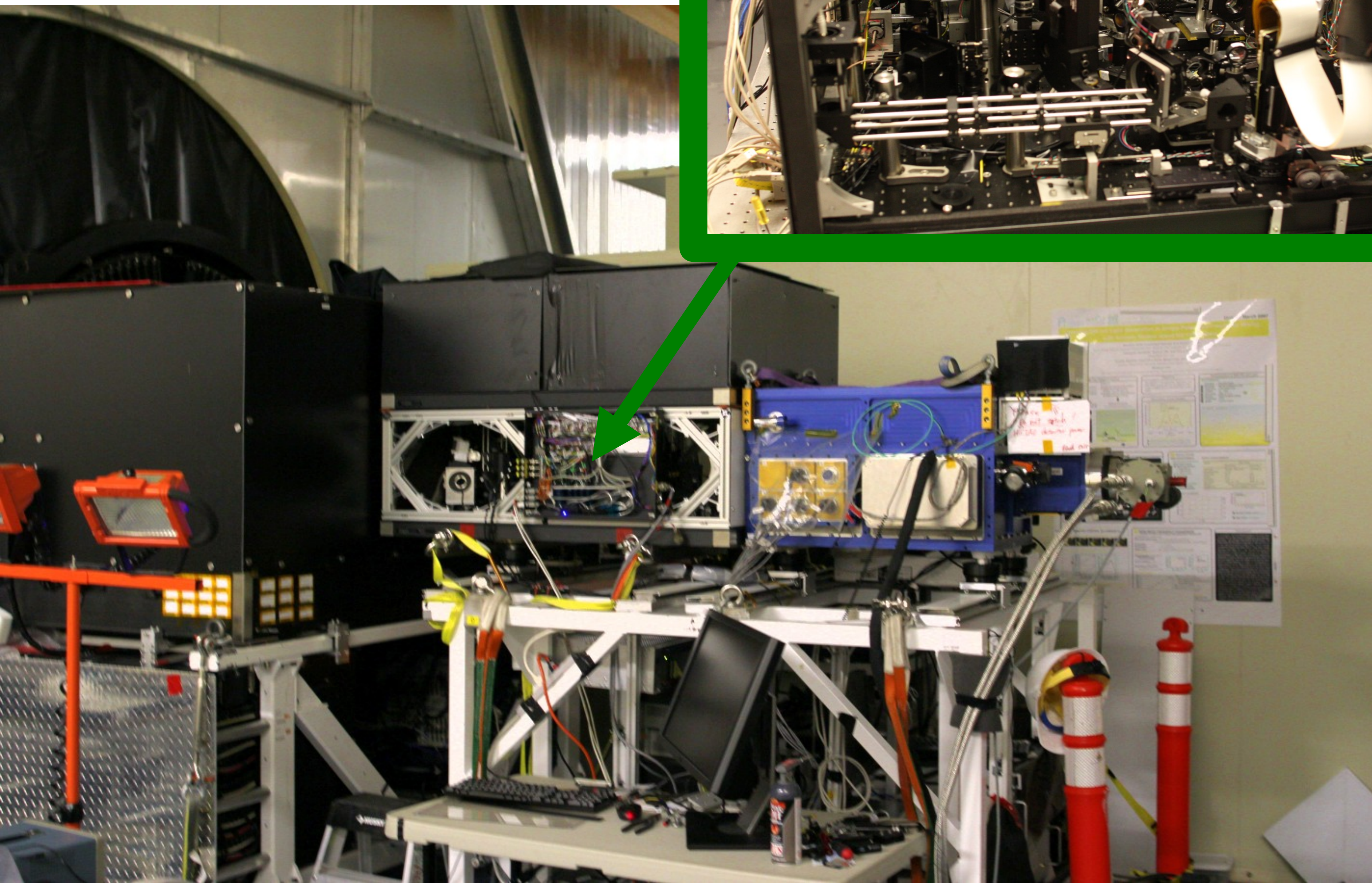
PALM3000/P1640 (Palomar 5-m Telescope)



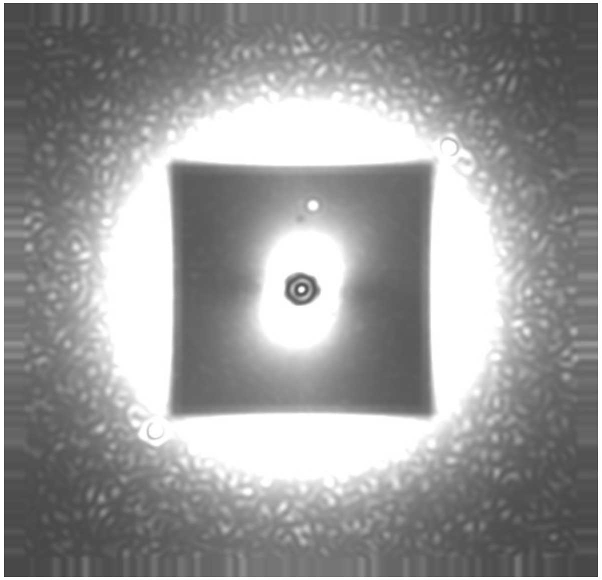
Subaru Coronagraphic Extreme-AO

The Subaru Coronagraphic Extreme Adaptive Optics (SCExAO) system





Wavefront control for High contrast imaging



Ground-based systems

Residual speckle field is brighter than planets(s)

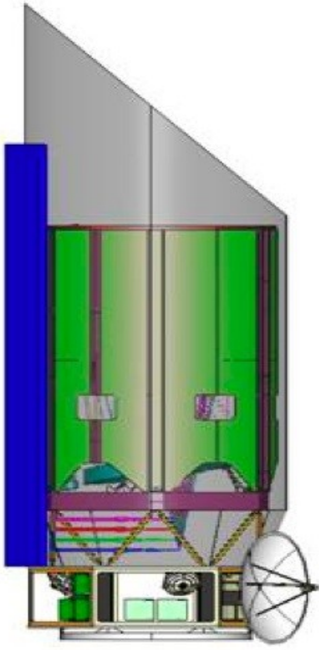
Systems often operate in **speckle noise limited regime**

→ calibrating speckles is extremely important

Space-based ultra-high contrast systems

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

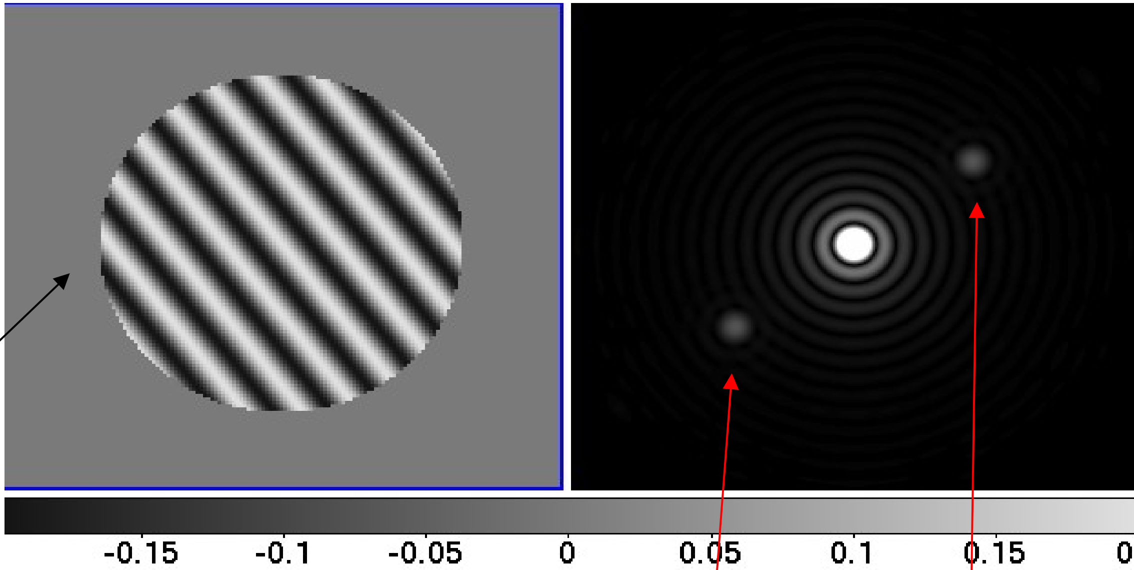
→ speckles need to be reduced at or below the planet image surface brightness level



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

→ need to build extremely stable system

Relationship between speckle and wavefront errors



pupil plane complex amplitude

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

Cosine aberration in pupil phase

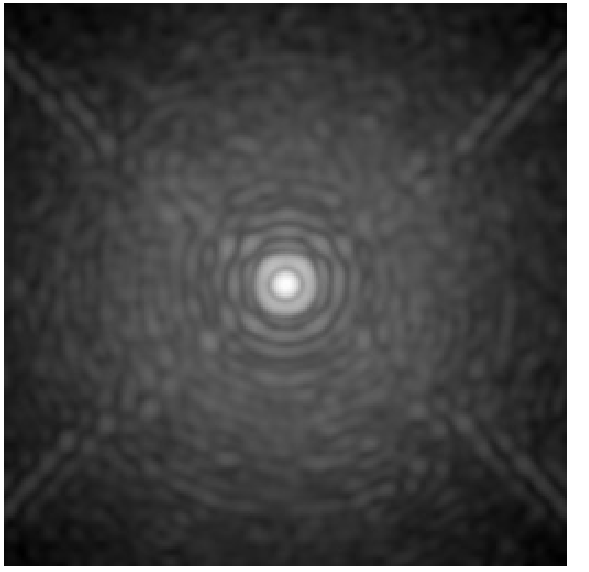
$$\phi(\vec{u}) = \frac{2\pi h}{\lambda} \cos\left(2\pi \vec{f}\vec{u} + \theta\right)$$

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

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

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

Focal plane AO and speckle calibration



Use Deformable Mirror (DM) to add speckles

SENSING: Put "test speckles" to measure speckles in the image, watch how they interfere

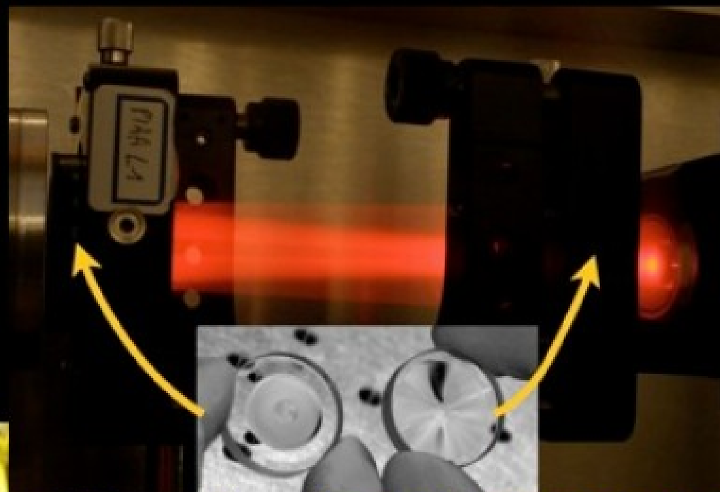
CORRECTION: Put "anti speckles" on top of "speckles" to have destructive interference between the two (Electric Field Conjugation, Give'on et al 2007)

CALIBRATION: If there is a real planet (and not a speckle) it will not interfere with the test speckles

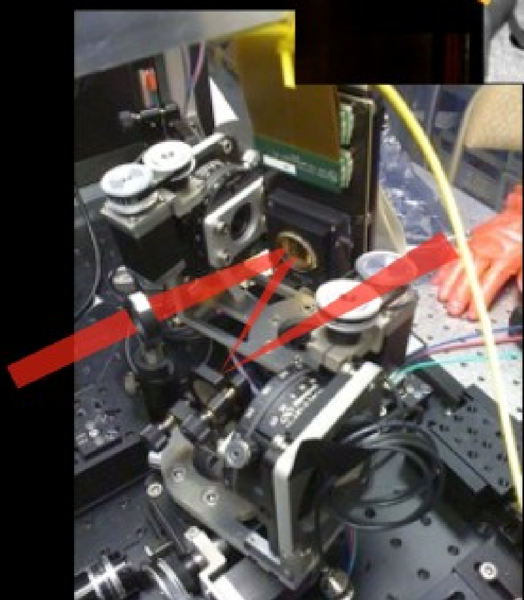
Fundamental advantage:
Uses science detector for wavefront sensing:
"What you see is EXACTLY what needs to be removed / calibrated"

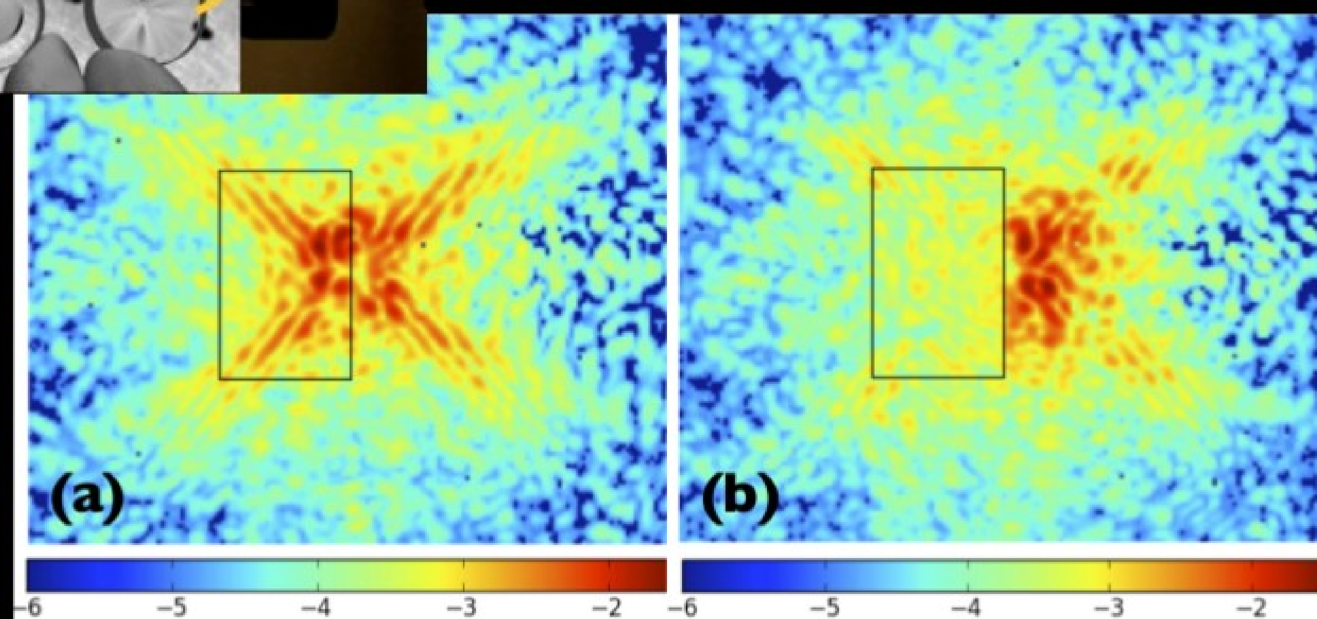
Active speckle control (Martinache et. al)

Active MEMS DM to replace a passive ADI approach at small angular separation



Taking advantage of the full PIAA - focal plane mask - PIAA^{-1} optical configuration





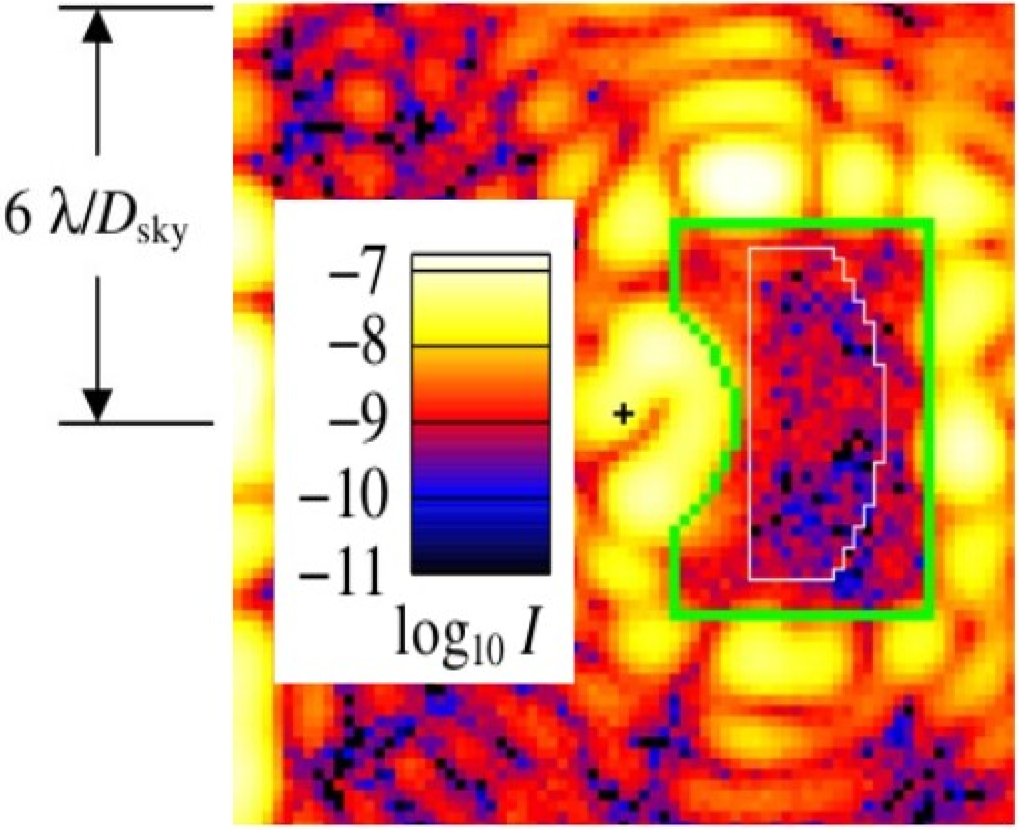
SCExAO's PIAA coronagraph permits speckle control from 1.5 to 14 λ/D

Raw contrast ~ 3e-4 inside the DM control region

Martinache et al, 2012, PASP, 124, 1288

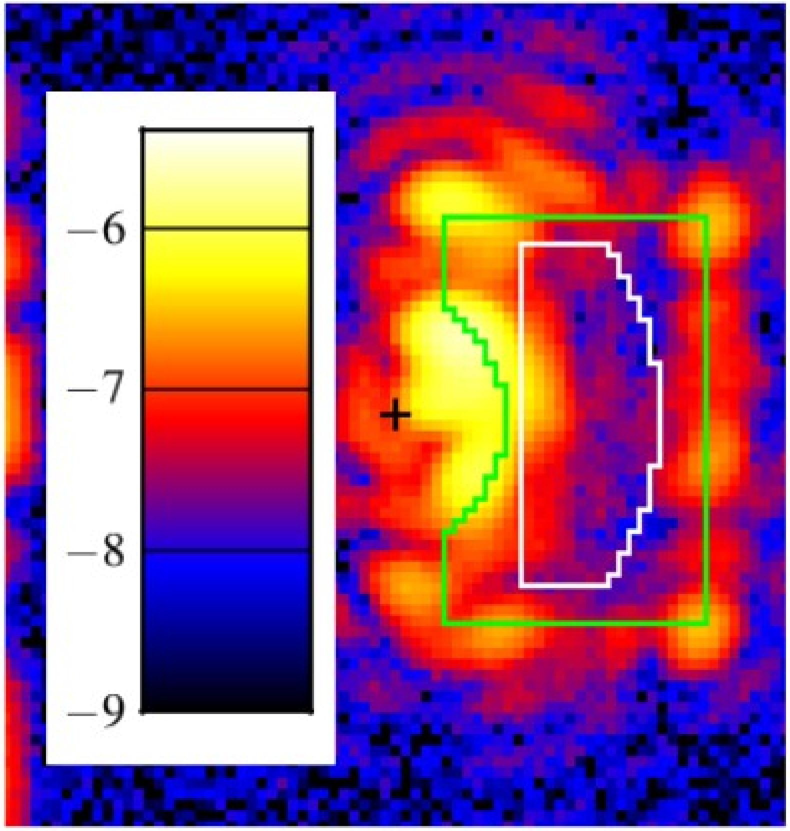
High contrast images obtained in NASA labs
Example: PIAA coronagraph lab results

Monochromatic light (800nm, vacuum)



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

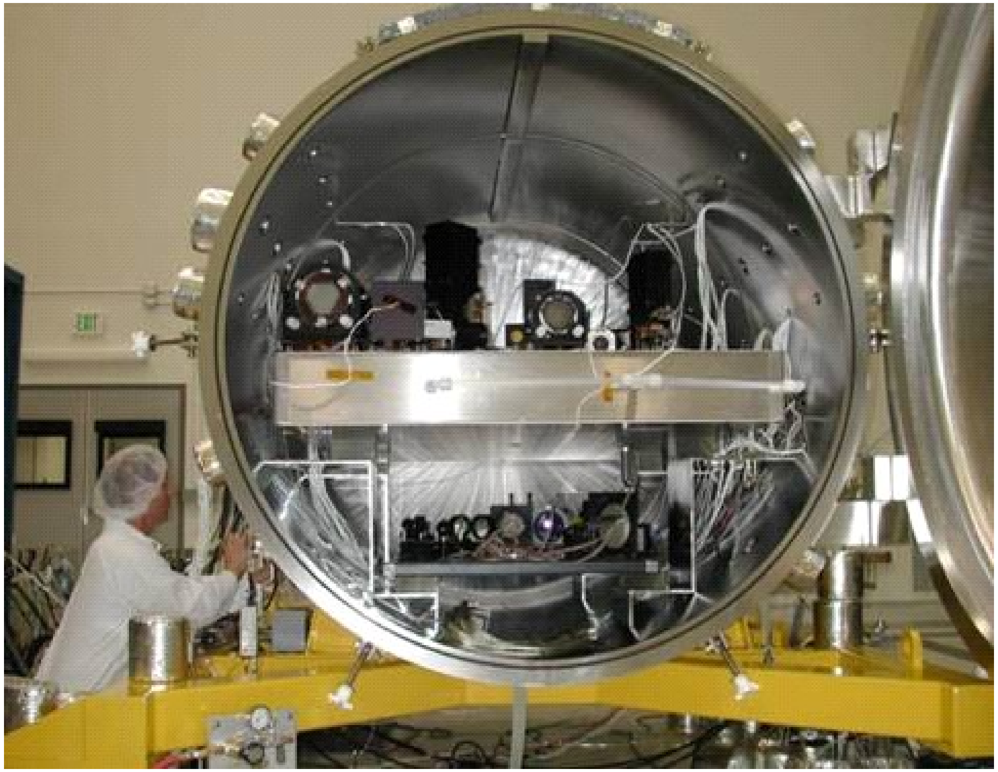
7.5% wide band (770 – 830 nm, in air)



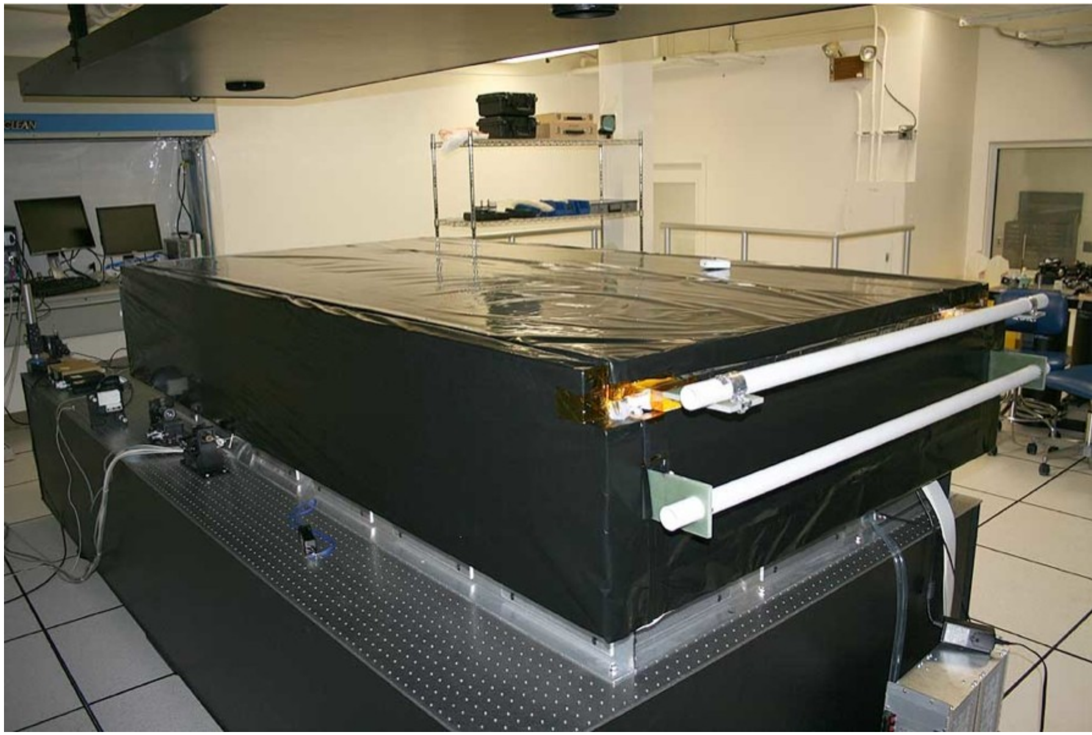
5.10^{-8} contrast from 2 to 4 λ/D,
2.10^{-8} contrast from 3 to 4 λ/D
Contrast performance limited by wavefront instability (test in air)

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

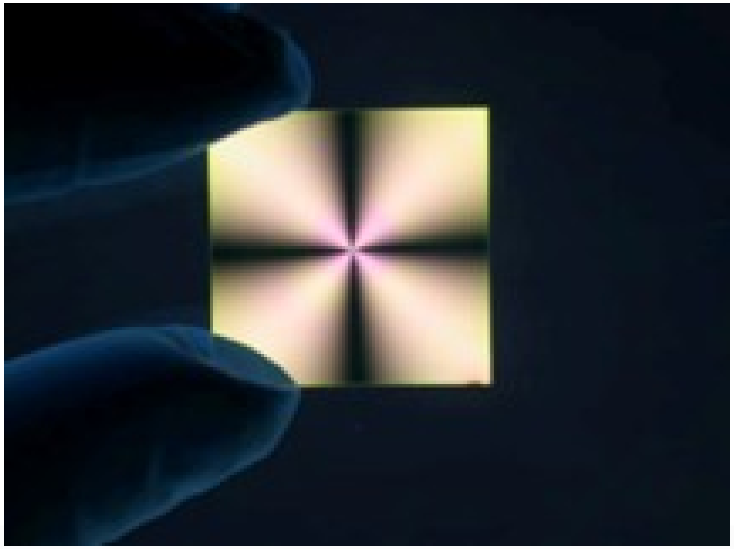
High Contrast Imaging Testbed (HCIT) is a vacuum facility at NASA JPL

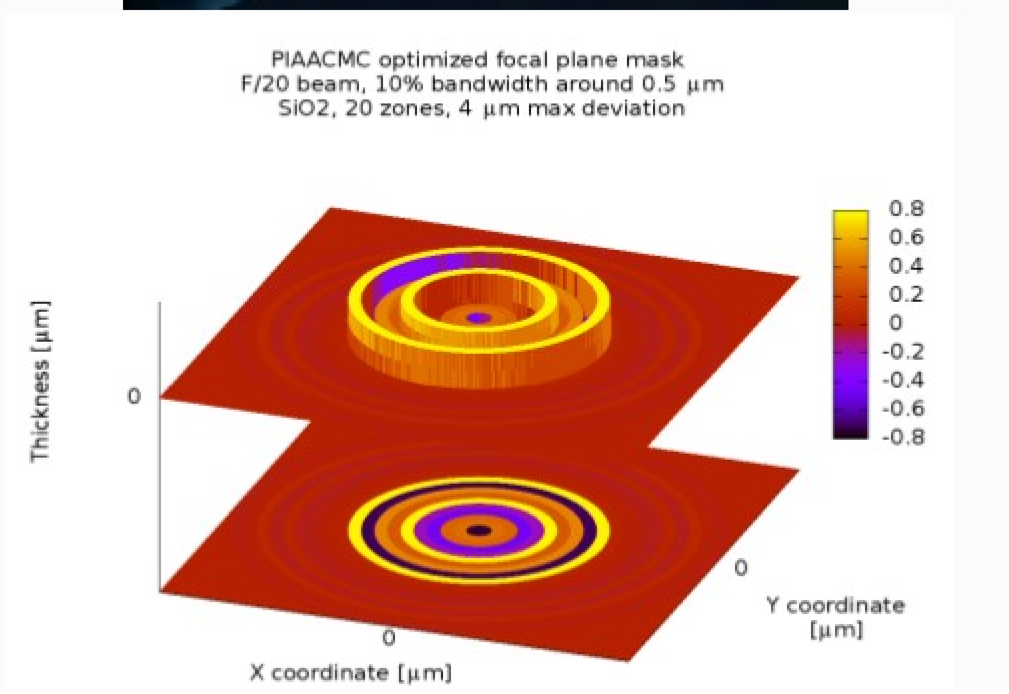


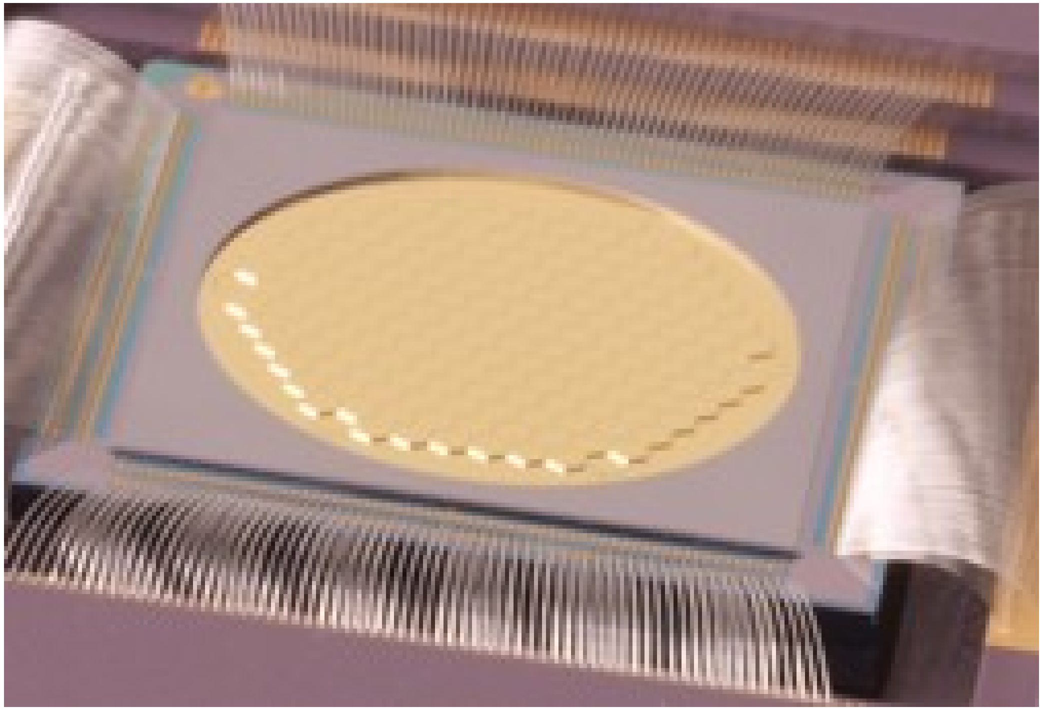
NASA Ames testing PIAA coronagraph / WFC architectures & MEMs DMs.



Technology: components







Habitable planet imaging: Scientific opportunities

Space allows access to very high contrast (no atmosphere), but aperture size is limited

Ground-based telescopes can be very large (~30m), but the contrast is limited due to atmosphere

Habitable planets

Potentially habitable planet :

- **Planet mass** sufficiently large to retain atmosphere, but sufficiently low to avoid becoming gaseous giant
- **Planet distance to star** allows surface temperature suitable for liquid water (habitable zone)

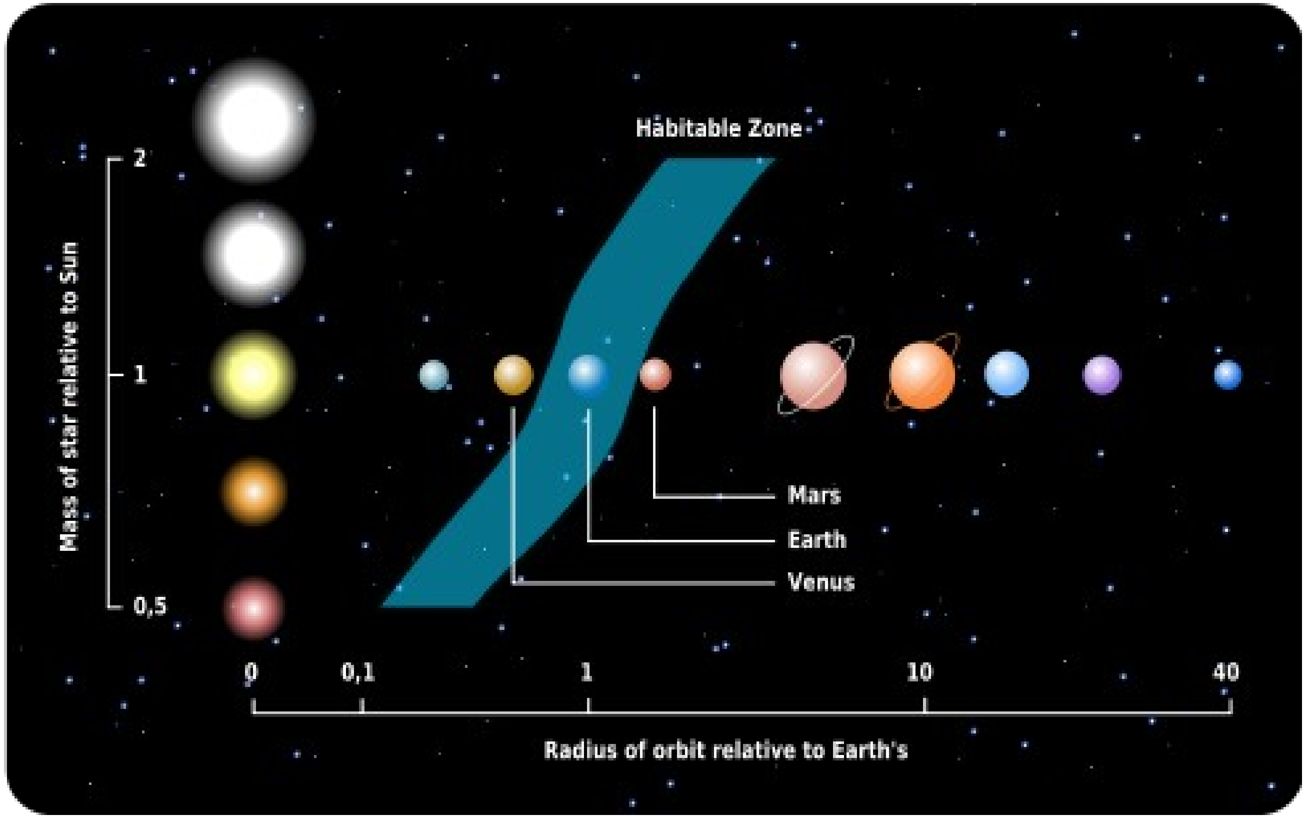
Habitable zone = zone within which Earth-like planet could harbor life
Location of habitable zone is function of star luminosity L. For constant stellar flux, distance to star scales as $L^{1/2}$

Examples:

Sun
→ habitable zone is at ~1 AU

Rigel (B type star)

Proxima Centauri (M type star)



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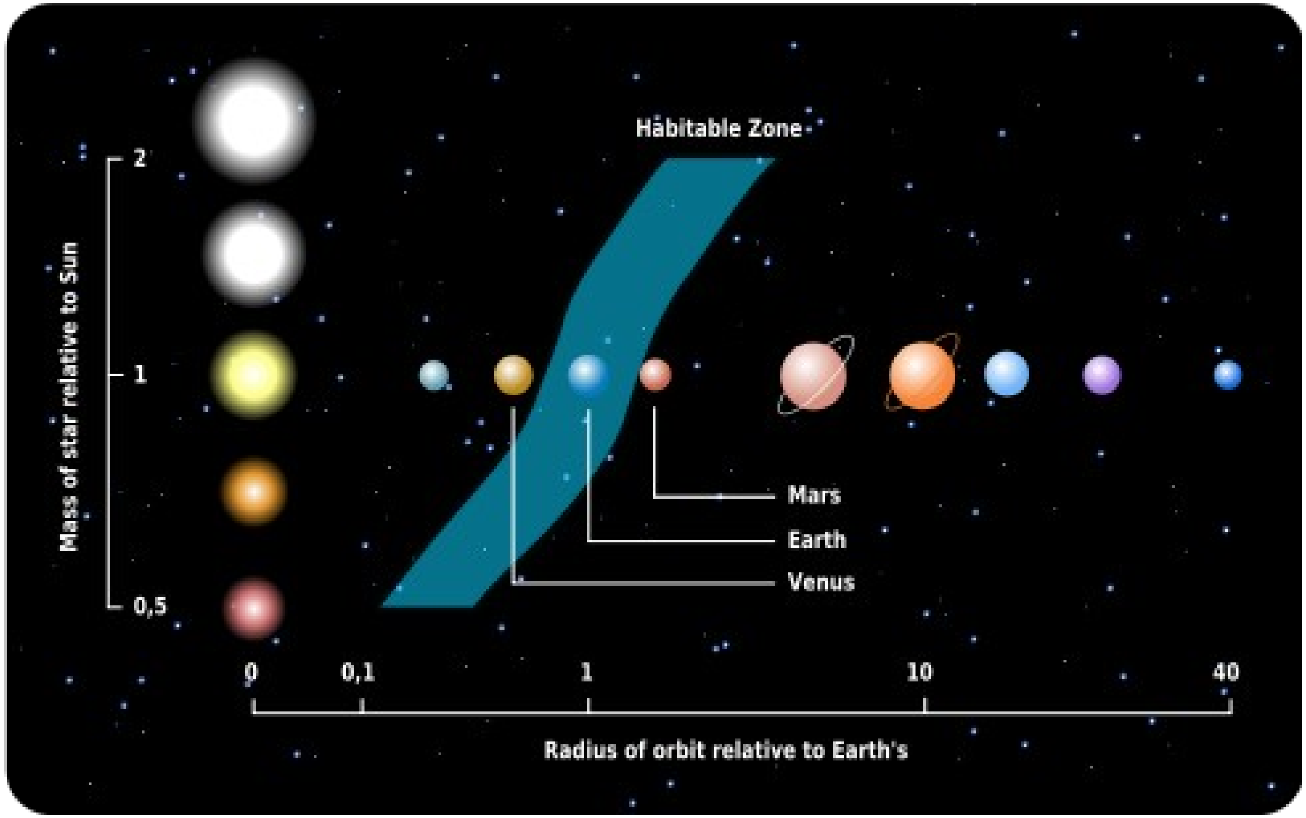
Rigel (B type star):
18 solar mass

Proxima Centauri (M type star):
0.123 solar mass



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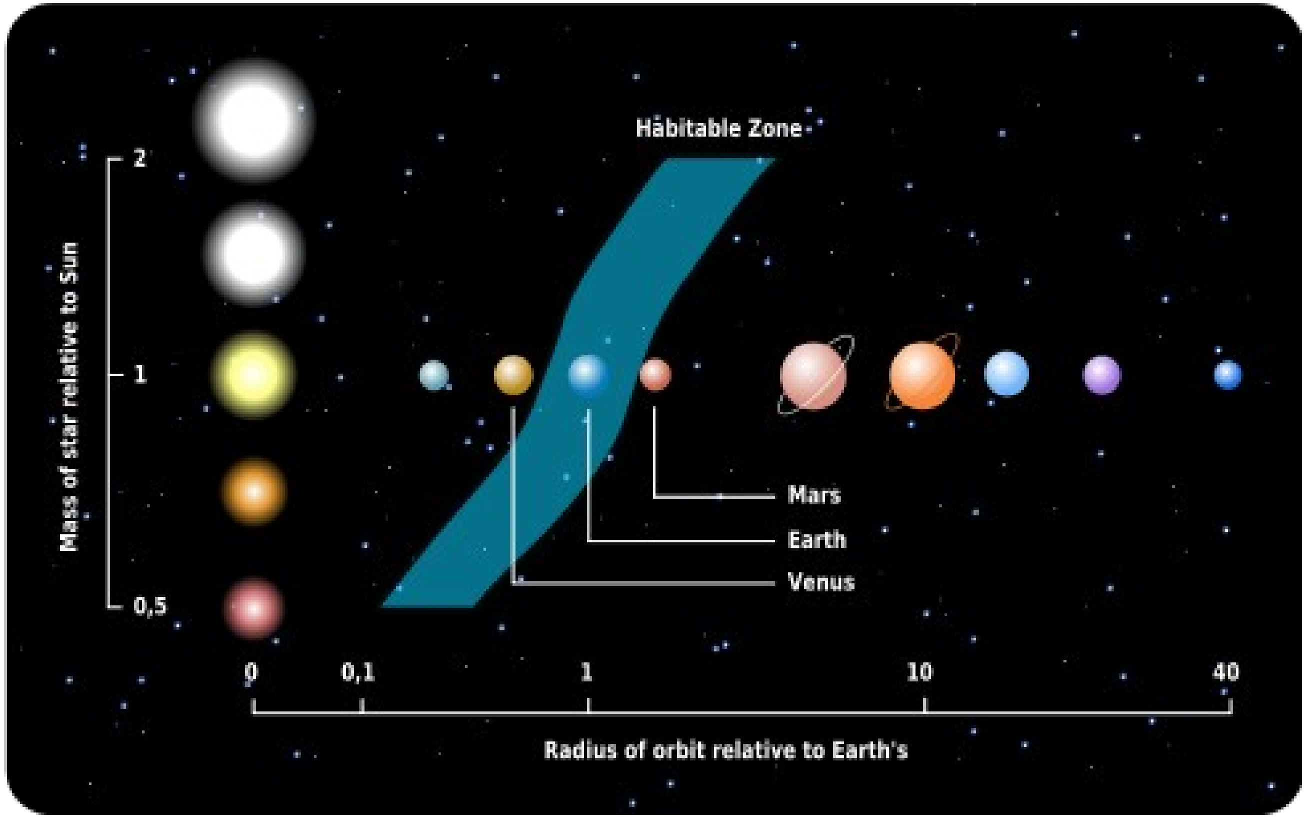
Examples:

Sun
→ habitable zone is at ~1 AU

Rigel (B type star):
18 solar mass
100000x Sun luminosity

Proxima Centauri (M type star):
0.123 solar mass
1/600 Sun luminosity



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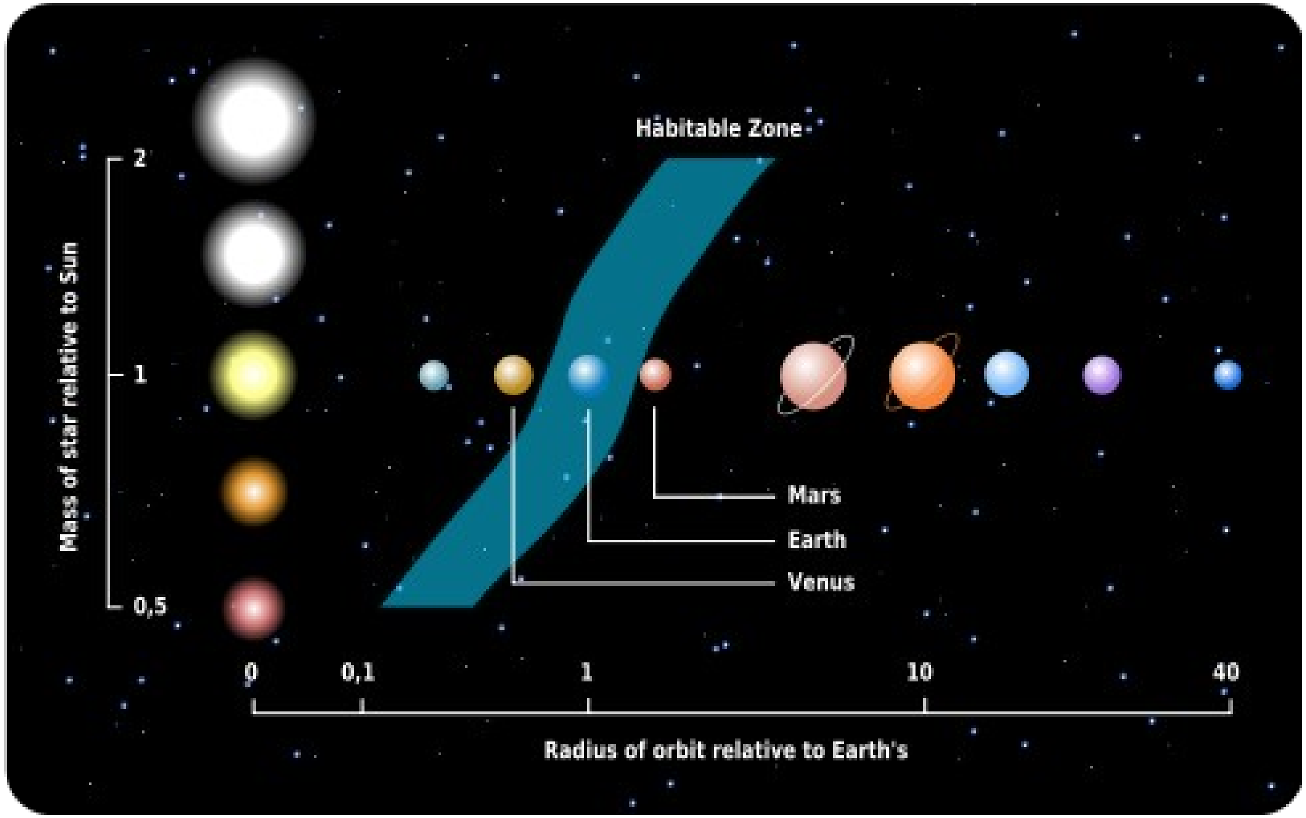
Examples:

Sun
→ habitable zone is at ~1 AU

Rigel (B type star):
18 solar mass
100000x Sun luminosity
→ habitable zone is at ~300 AU

Proxima Centauri (M type star):
0.123 solar mass
1/600 Sun luminosity
→ habitable zone is at ~0.04 AU



Habitable planets in reflected light: separation, contrast

total stellar luminosity: L (usually scaled to Sun)
Distance to Sun: d (in pc)

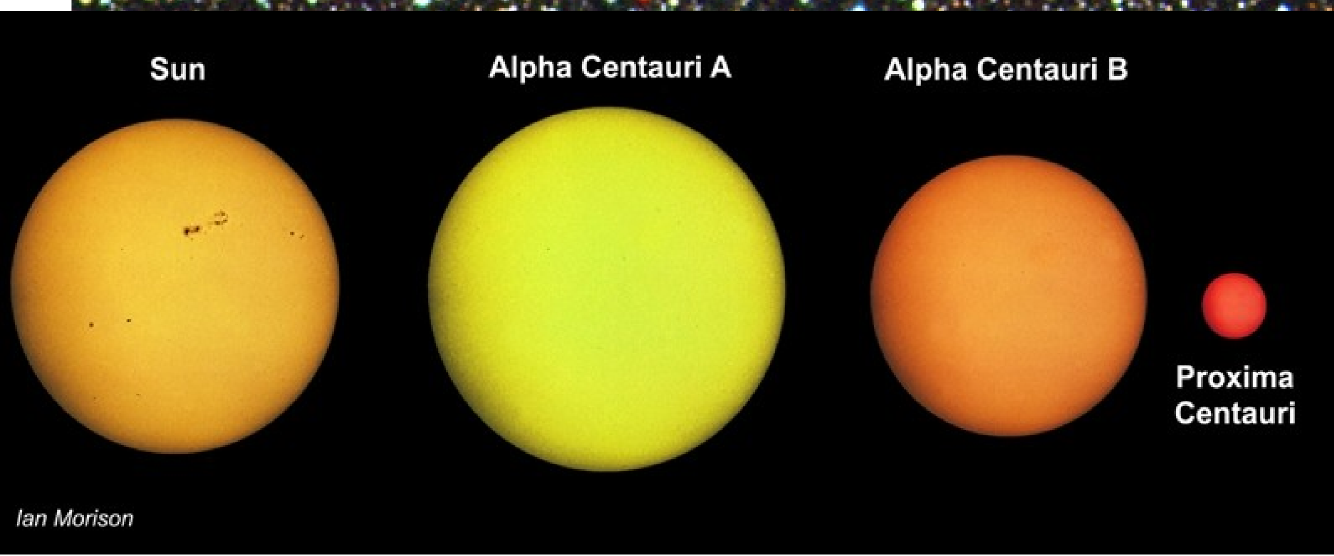
Physical distance to star scales as $a=L^{1/2}$
Angular distance (arcsec) = $L^{1/2}/d$
Example: d=10pc, L = 1 → 0.1"

Contrast ~ 2e-10 for Earth at maximum elongation

Contrast for Earth-like planets in habitable zone = 2e-10 / L
Example: L=0.01 (M type star) → contrast = 2e-8

Orbital period P = $\mathrm{sqrt}(a^3/M)$
Example: Proxima Centauri...
1/600 Sun luminosity, 0.123 Sun Mass, d=1.3 pc

Proxima Centauri



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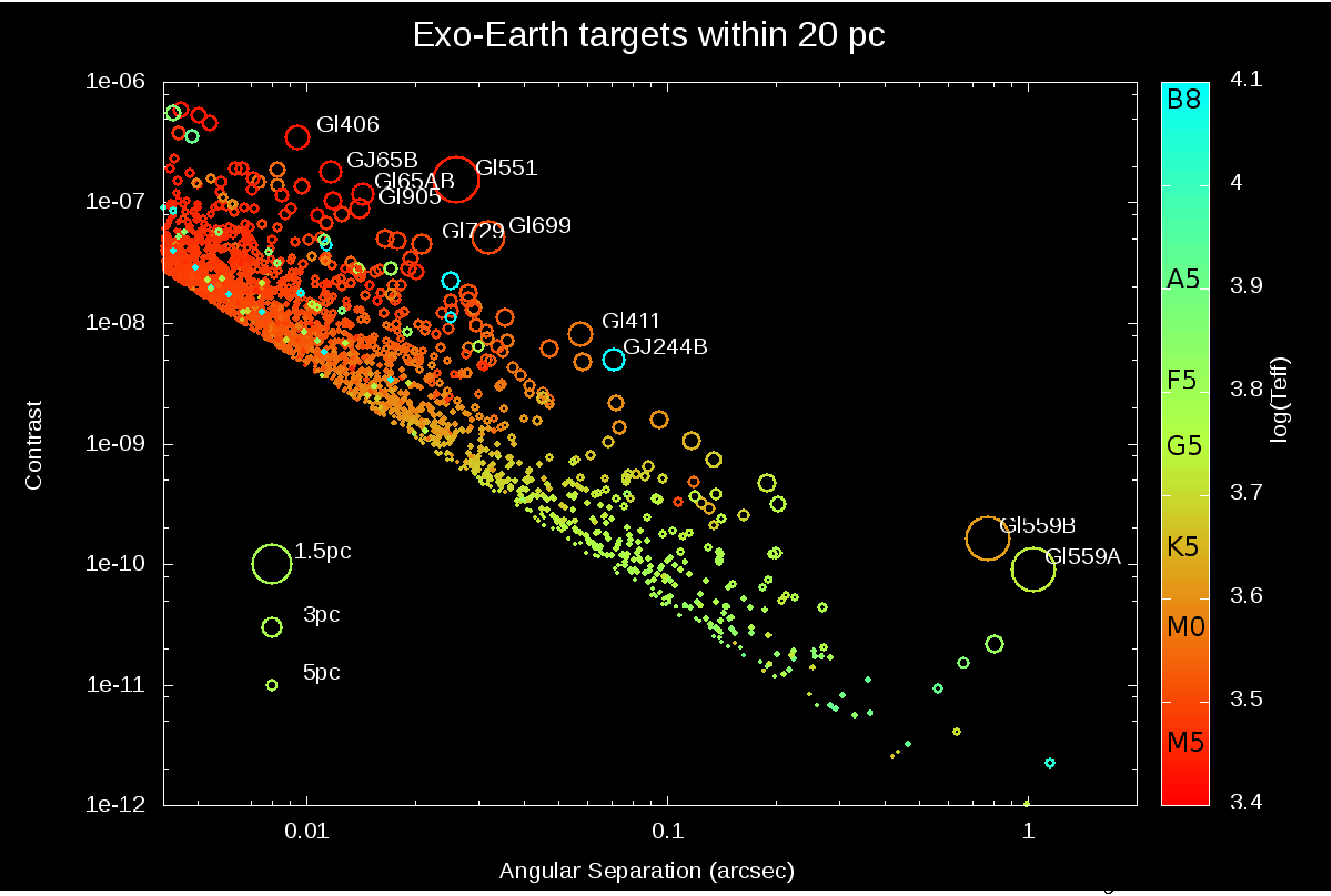
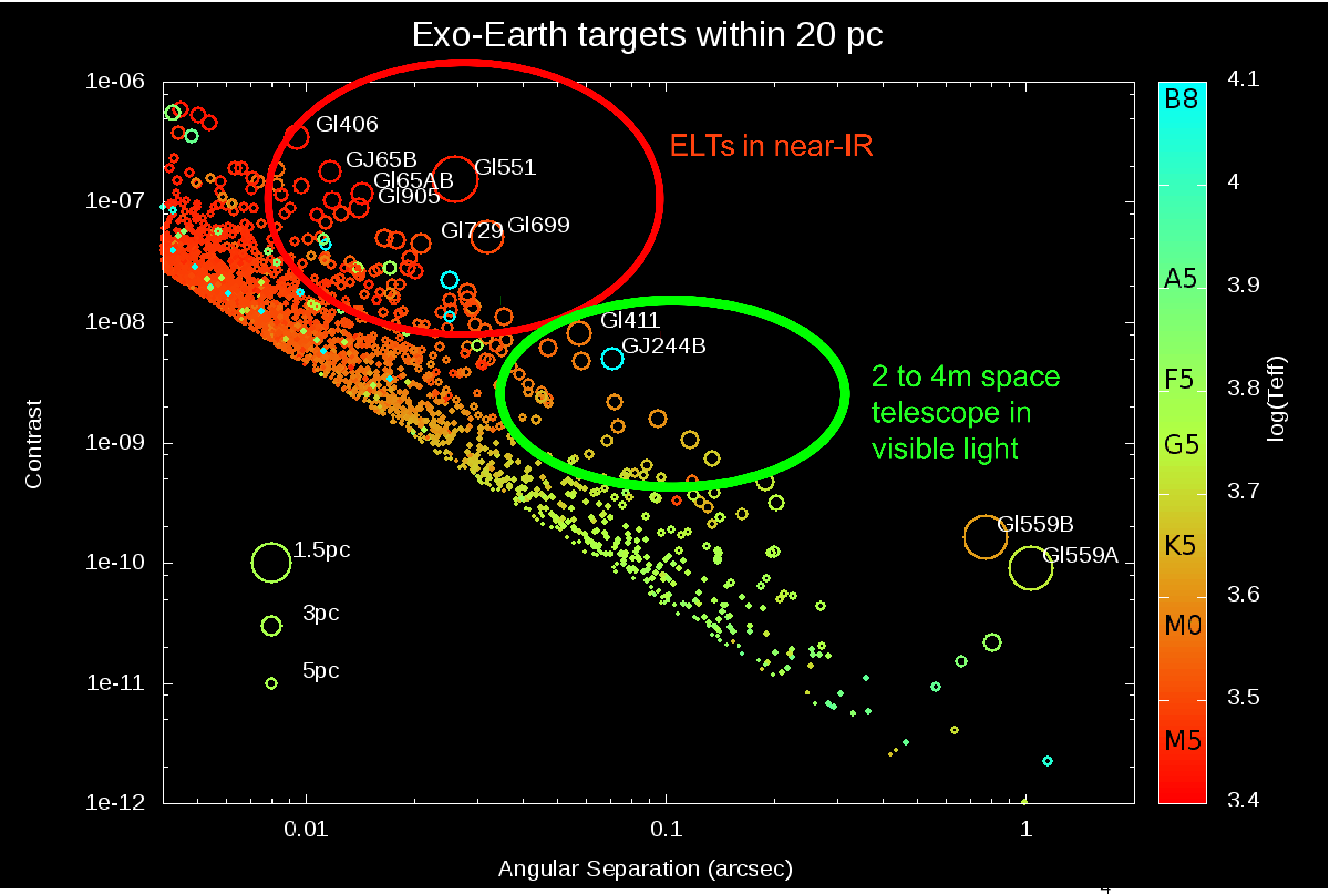
Example: L=0.01 (M type star) → contrast = 2e-8

Orbital period P = $\mathrm{sqrt}(a^3/M)$
Example: Proxima Centauri...
1/600 Sun luminosity, 0.123 Sun Mass, d=1.3 pc
Orbital radius : a=0.04 AU
Angular separation = a/d = 0.03 arcsec
Contrast = 1.2e-7
Orbital Period = 8 day

http://www.naoj.org/staff/guyon/04research.web/14hzplanetsELTs.web/catalog.web/exoplanetsDirectImaging.html

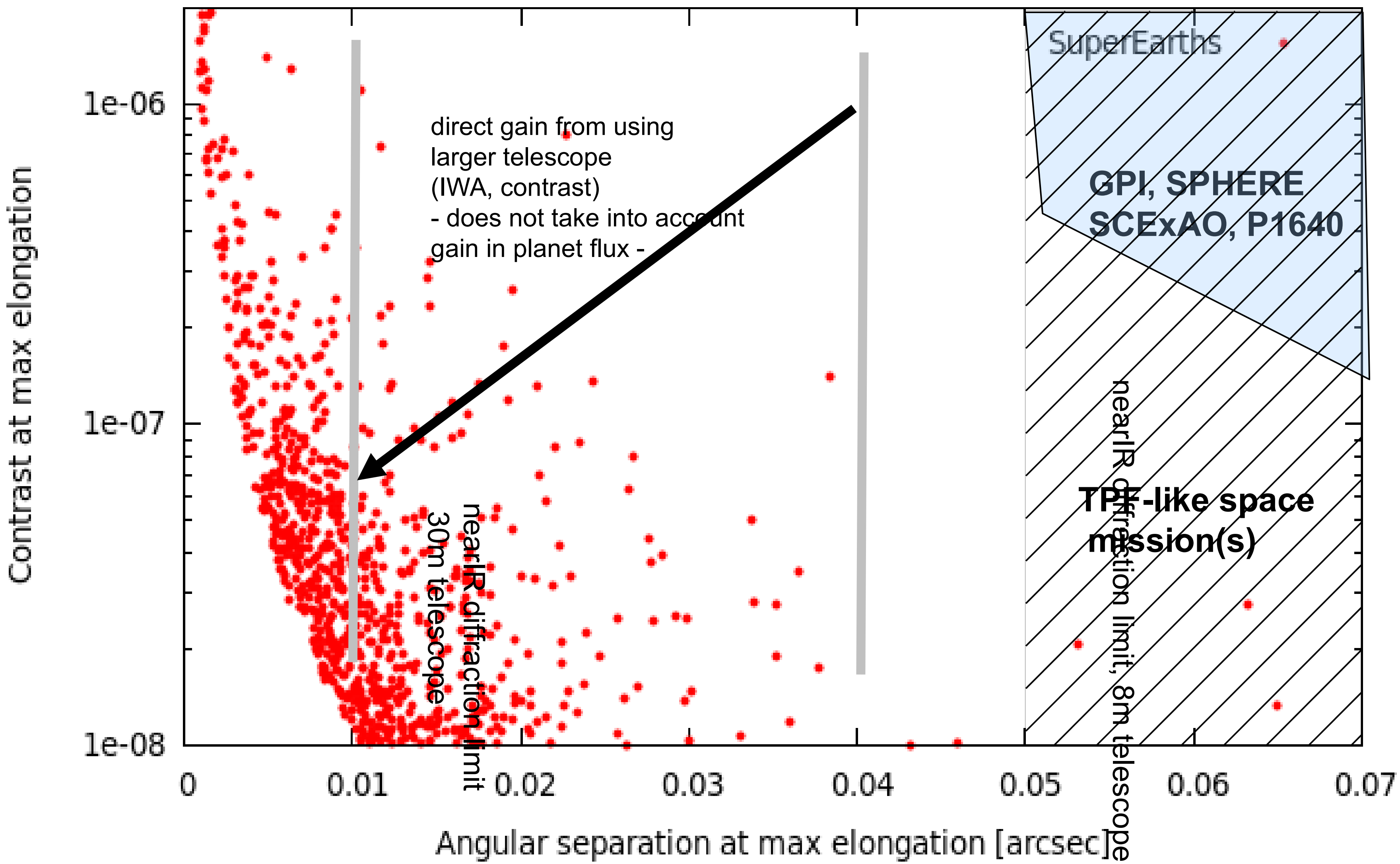

Exo-Earth targets within 20 pc
Contrast
Angular Separation (arcsec)
1e-06
1e-07
1e-08
1e-09
1e-10
1e-11
1e-12
0.01
0.1
1
Gl406
GJ65B
Gl551
Gl65AB
Gl905
Gl729
Gl699
Gl411
GJ244B
Gl559B
Gl559A
1.5pc
3pc
5pc
B8
A5
F5
G5
K5
M0
M5
4.1
4
3.9
3.8
3.7
3.6
3.5
3.4
log(Teff)


Exo-Earth targets within 20 pc
ELTs in near-IR
2 to 4m space telescope in visible light
Gl406
GJ65B
Gl65AB
Gl905
Gl551
Gl729
Gl699
Gl411
GJ244B
Gl559B
Gl559A
1.5pc
3pc
5pc
Contrast
Angular Separation (arcsec)
log(Teff)
1e-06
1e-07
1e-08
1e-09
1e-10
1e-11
1e-12
0.01
0.1
1
B8
A5
F5
G5
K5
M0
M5
4.1
4
3.9
3.8
3.7
3.6
3.5
3.4

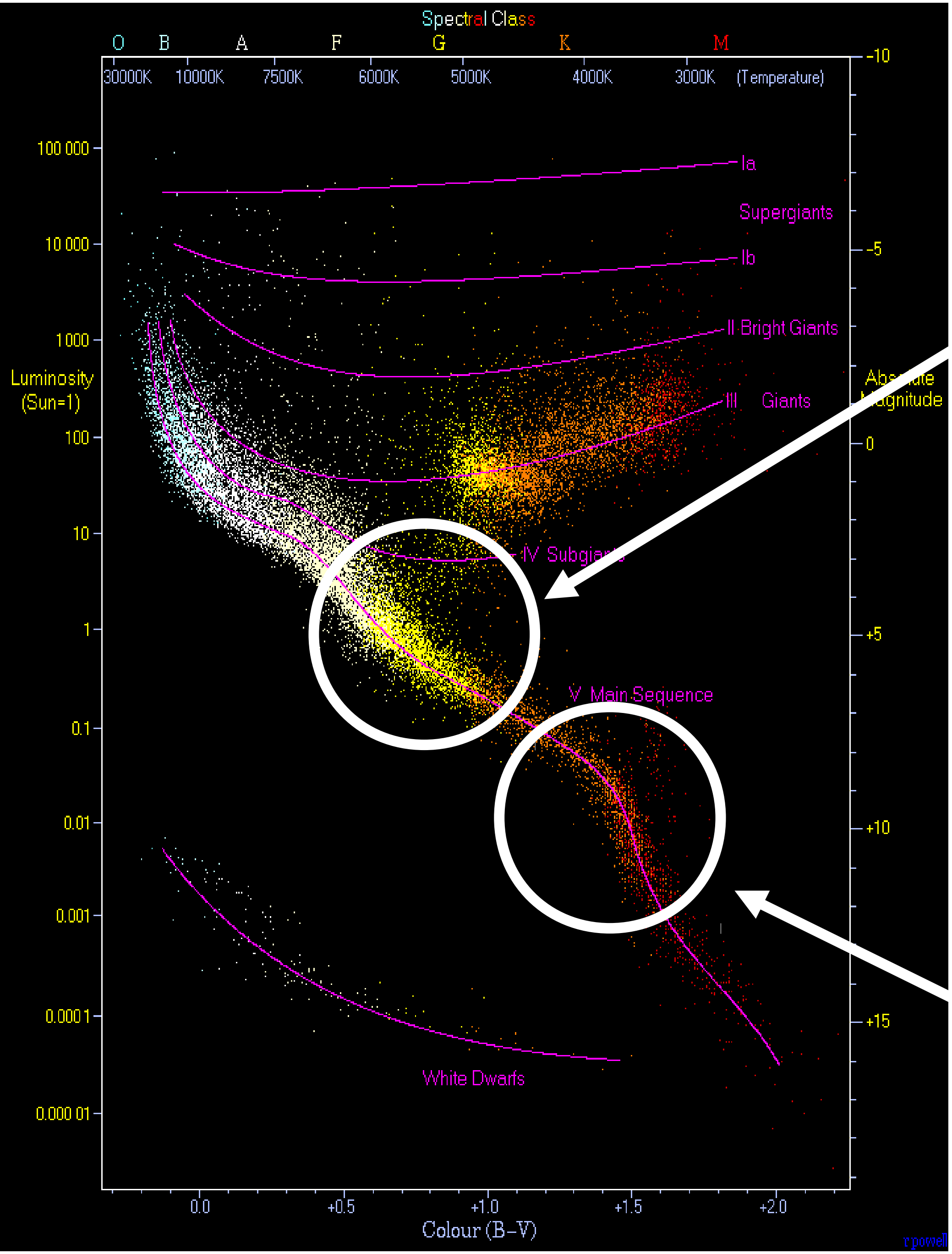
Reflected light planets

Assuming that each star has a SuperEarth (2x Earth diameter) at the 1AU equivalent HZ distance

(assumes Earth albedo, contrast and separation for max elongation)



Imaging habitable planets from space and ground



-------------- Space ----------------

Habitable planets can be imaged around nearby Sun-like stars with 2-4m telescope

---------- Ground ---------------

Next generation of 30-m telescopes will image habitable planets around nearby low-mass stars