Directly imaging habitable exoplanets

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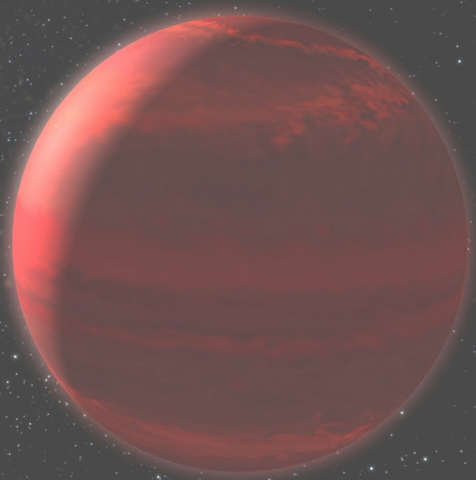

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Outline

Introduction & fundamentals

- Scientific motivation
- Fundamentals: contrast, separation, visible & IR
- Current exoplanet imaging

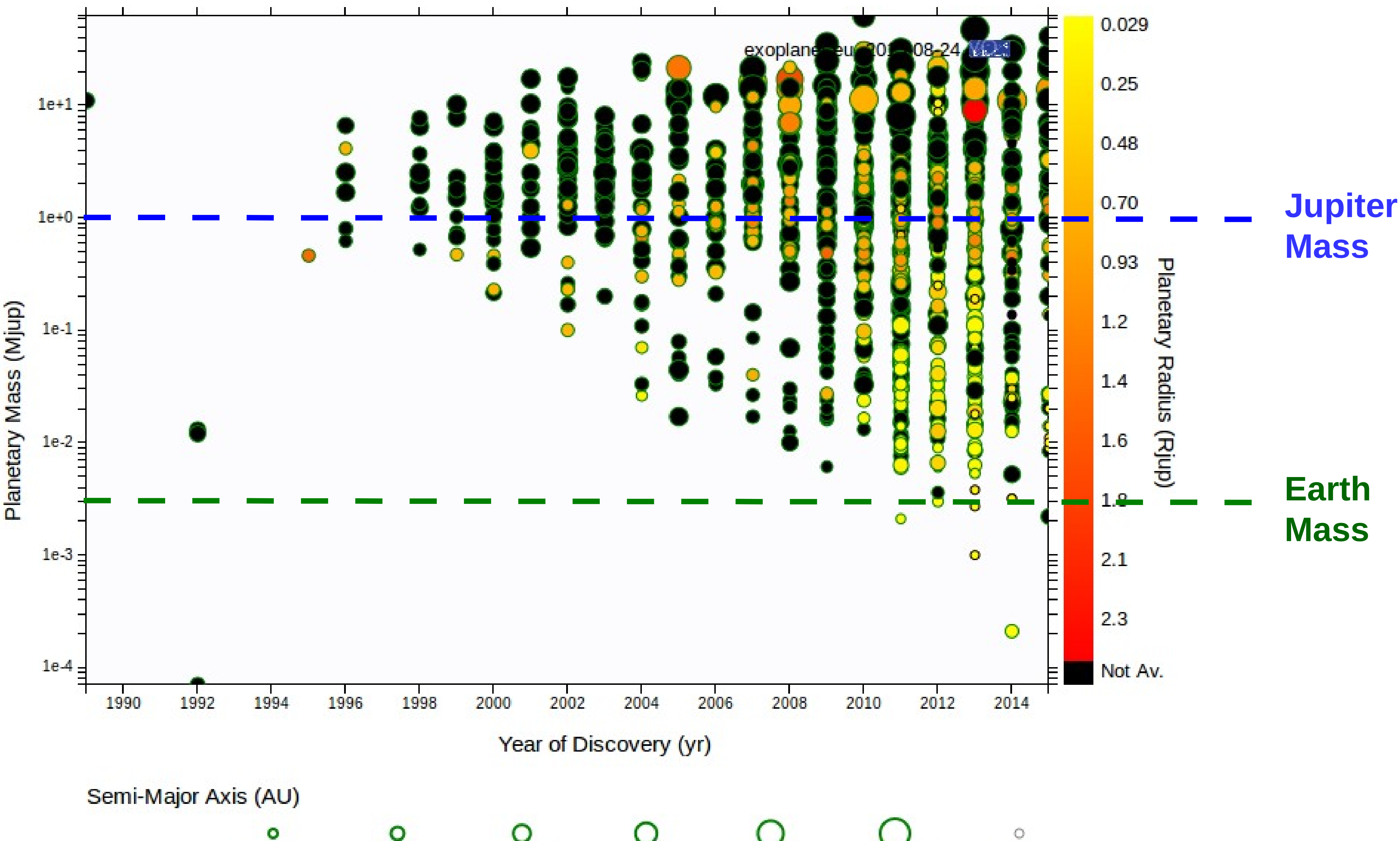
Technology

- Overcoming diffraction
- Coronagraphy
- Wavefront control

Habitable planets: Scientific Opportunities

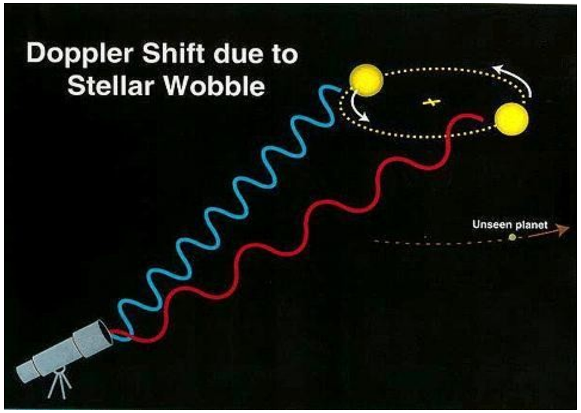
- SPACE: Direct imaging of Earth-like planets around Sun-like stars
- GROUND: Imaging habitable planets around M-type stars with ELTs

Planets identified – we are now starting to identify Earth-size planets



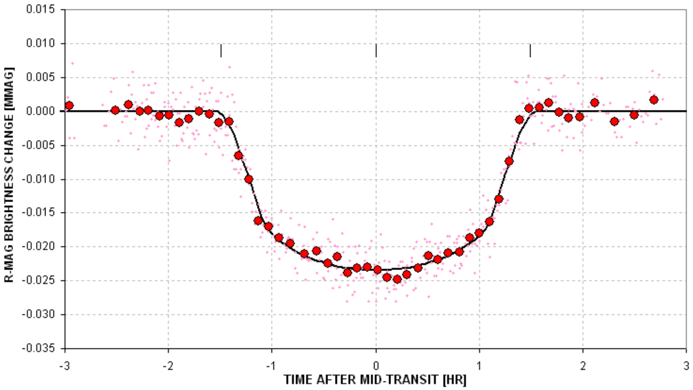
Observation techniques

Techniques to detect exoplanets around main sequence stars (many of them covered in this course):



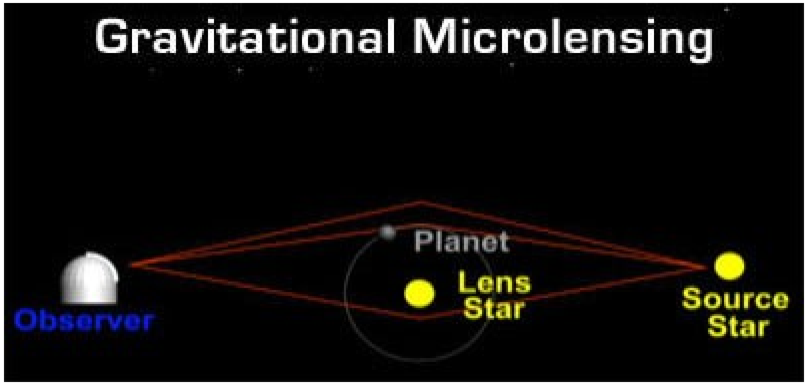
Radial velocity: measure small shift in star's spectra to compute its speed along line of sight.

Astrometry: measure accurate position of star on sky to identify if a planet is pulling the star in a small periodic orbit around the center of mass



Transit photometry: if planet passes in front of its star, the star apparent luminosity is reduced

Microlensing: planet can bend light, and amplify background starlight through gravitational lensing



Direct imaging (with telescope or interferometer): capture high contrast image of the immediate surrounding of a star

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)

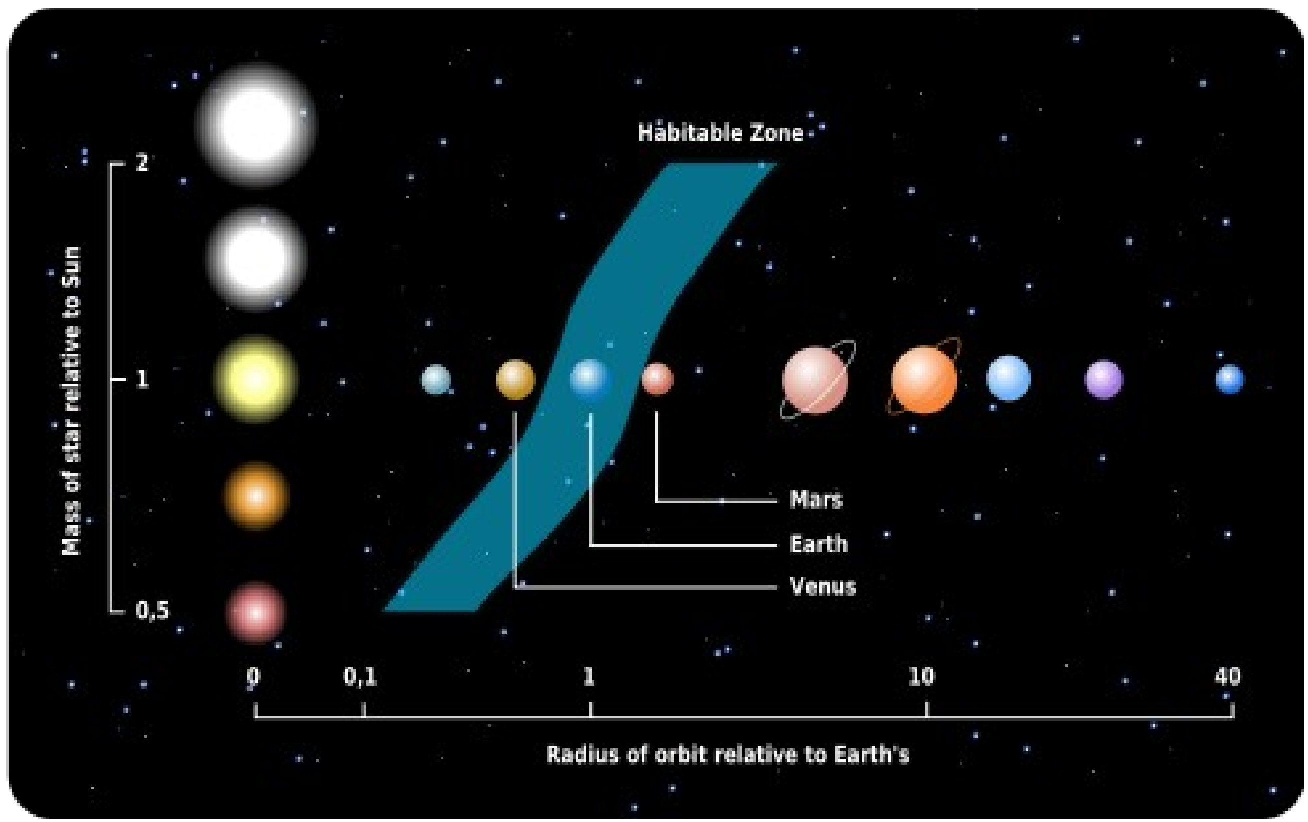
Habitable zone = zone within which Earth-like planet could harbor life
Location of habitable zone is function of star luminosity L. For constant stellar flux, distance to star scales as $L^{1/2}$

Examples:

Sun
→ habitable zone is at ~1 AU

Rigel (B type star)

Proxima Centauri (M type star)



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Examples:

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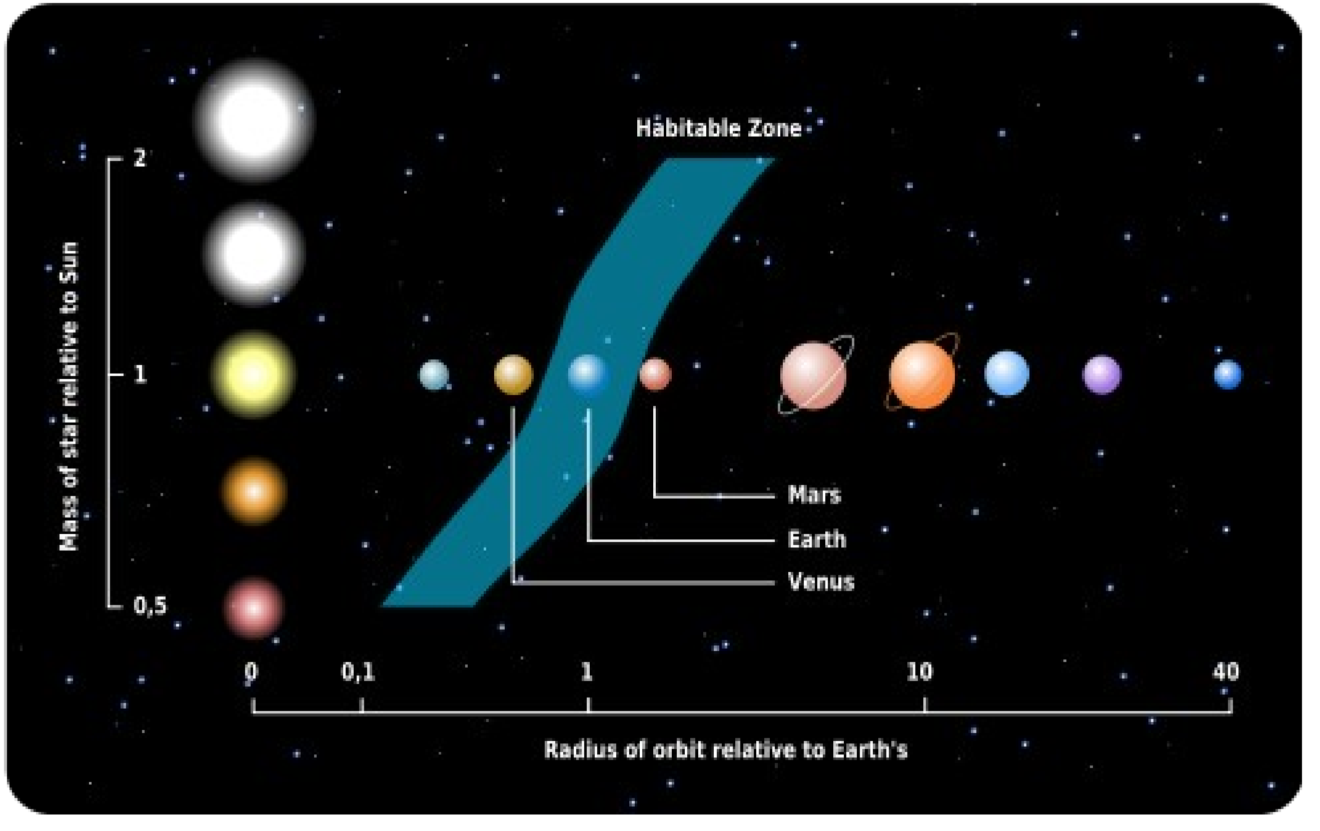
Rigel (B type star):
18 solar mass

Proxima Centauri (M type star):
0.123 solar mass



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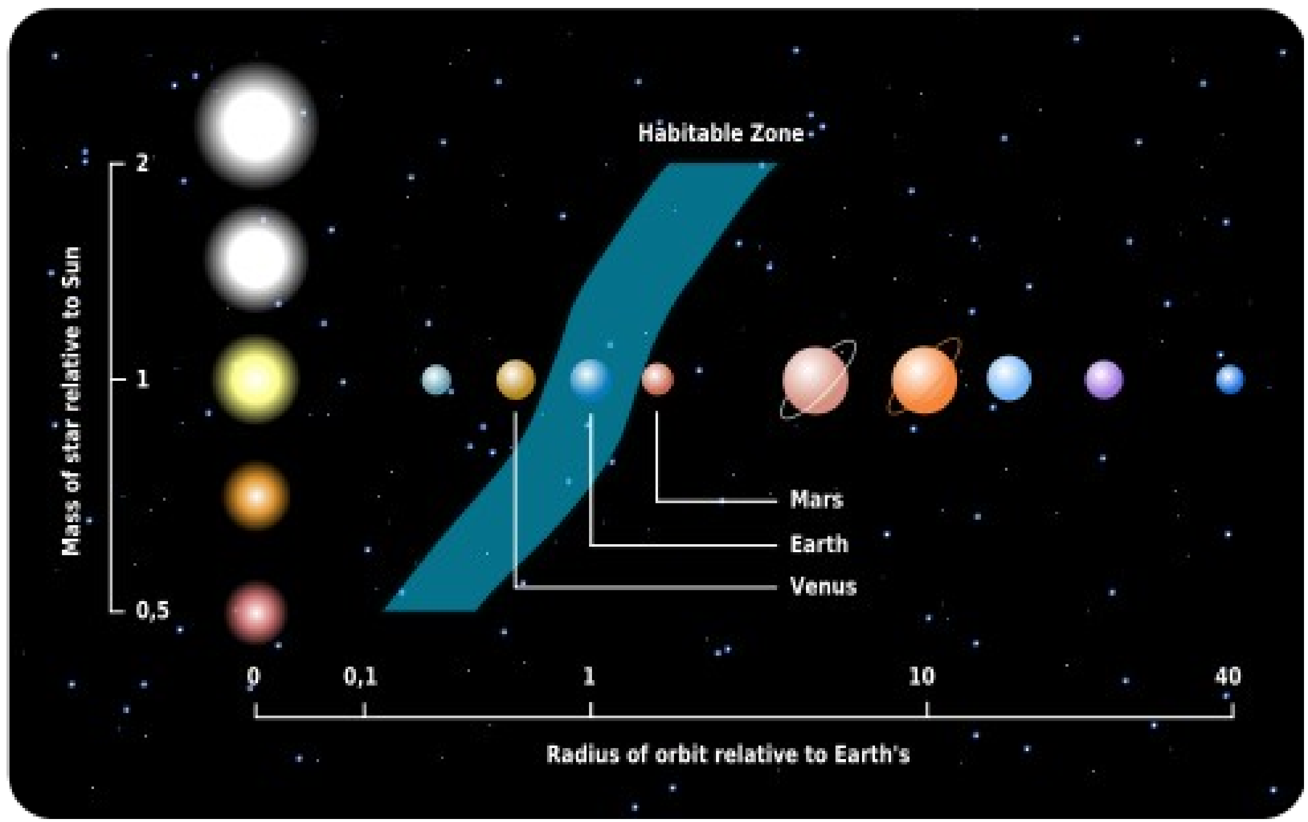
Examples:

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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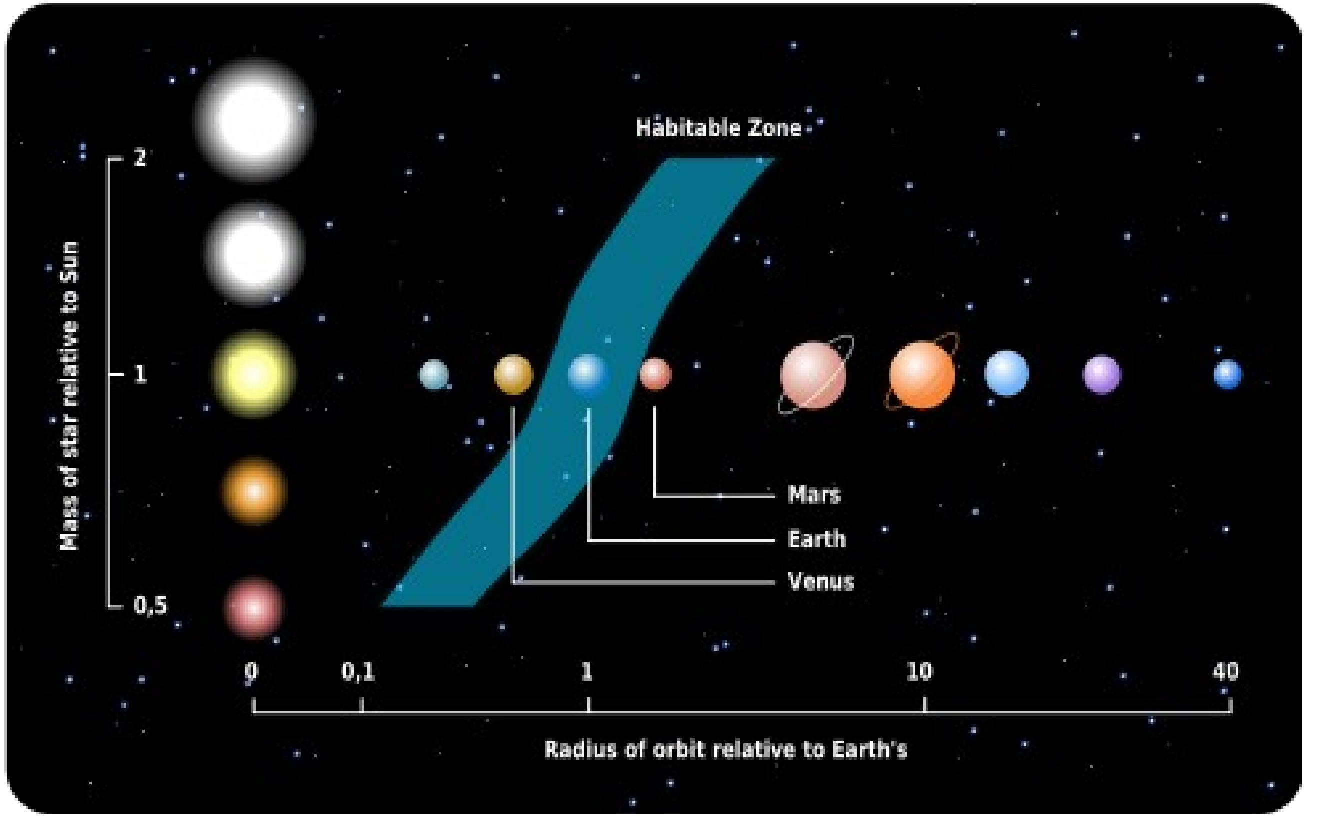
Examples:

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



Direct imaging of Exoplanets (incl. Habitable planets) allows …

Orbit

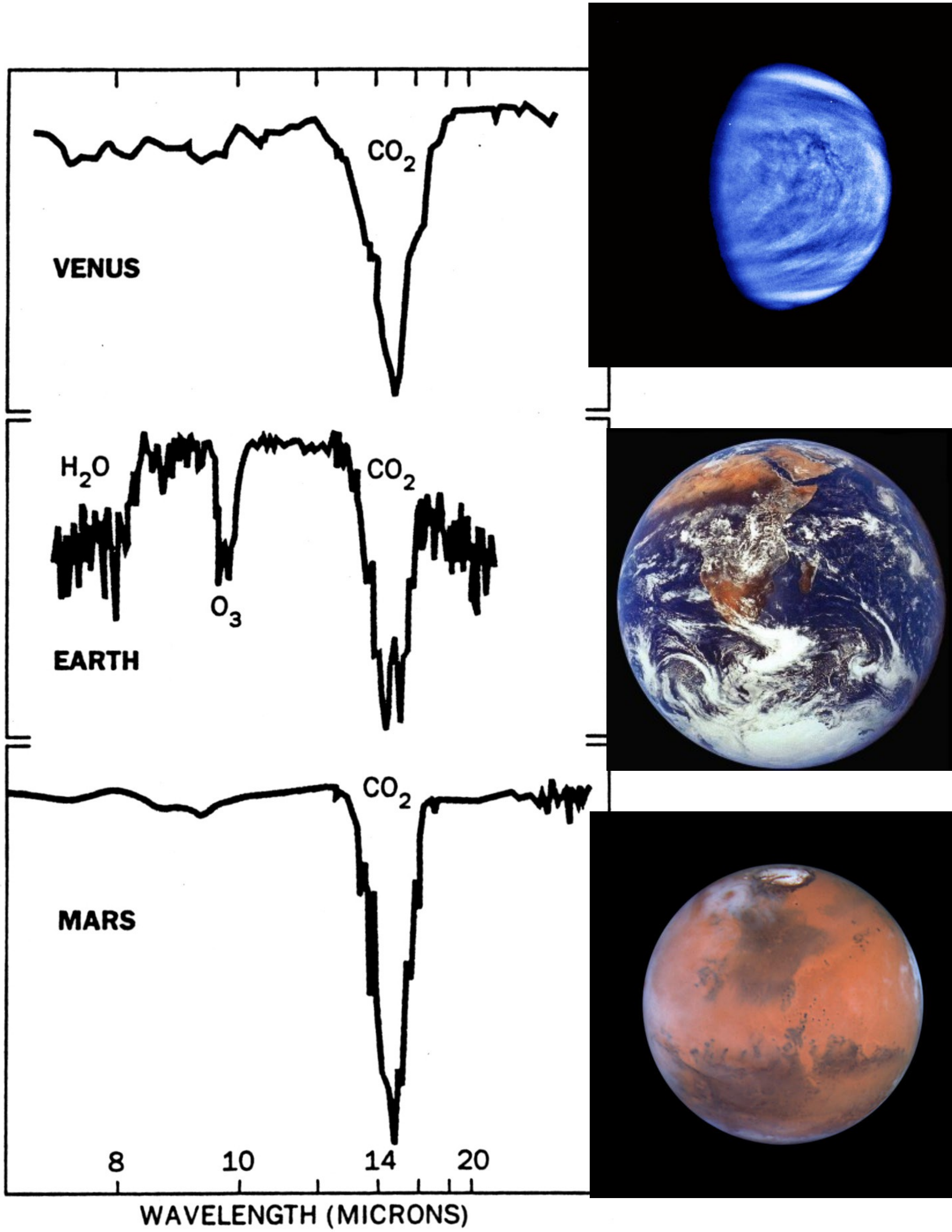
Atmosphere composition

Continents vs. Oceans ?

Rotation period

Weather patterns

Planetary environment : Planets + dust



Spectroscopy of Earth-like planets
… may allow detection of life

Spectroscopy can identify biomarkers: molecular species, or combinations of species that can only be explained by biological activity

On Earth: water + O_2 + O_3 + CH_4

Spectra of Earth obtained through Earthshine observation also reveals vegetation's red edge !

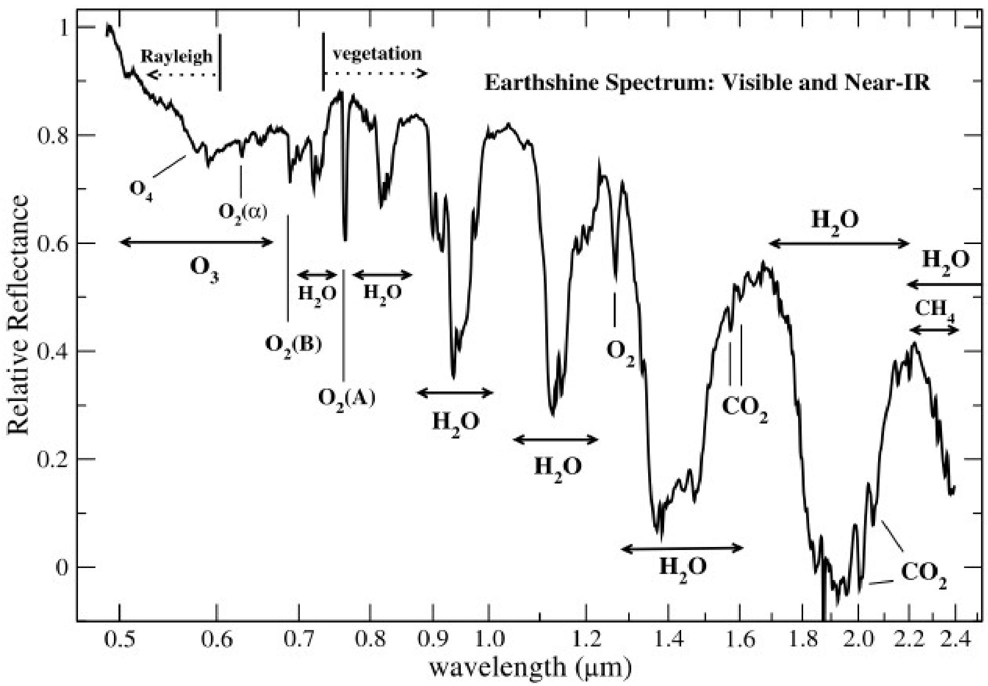
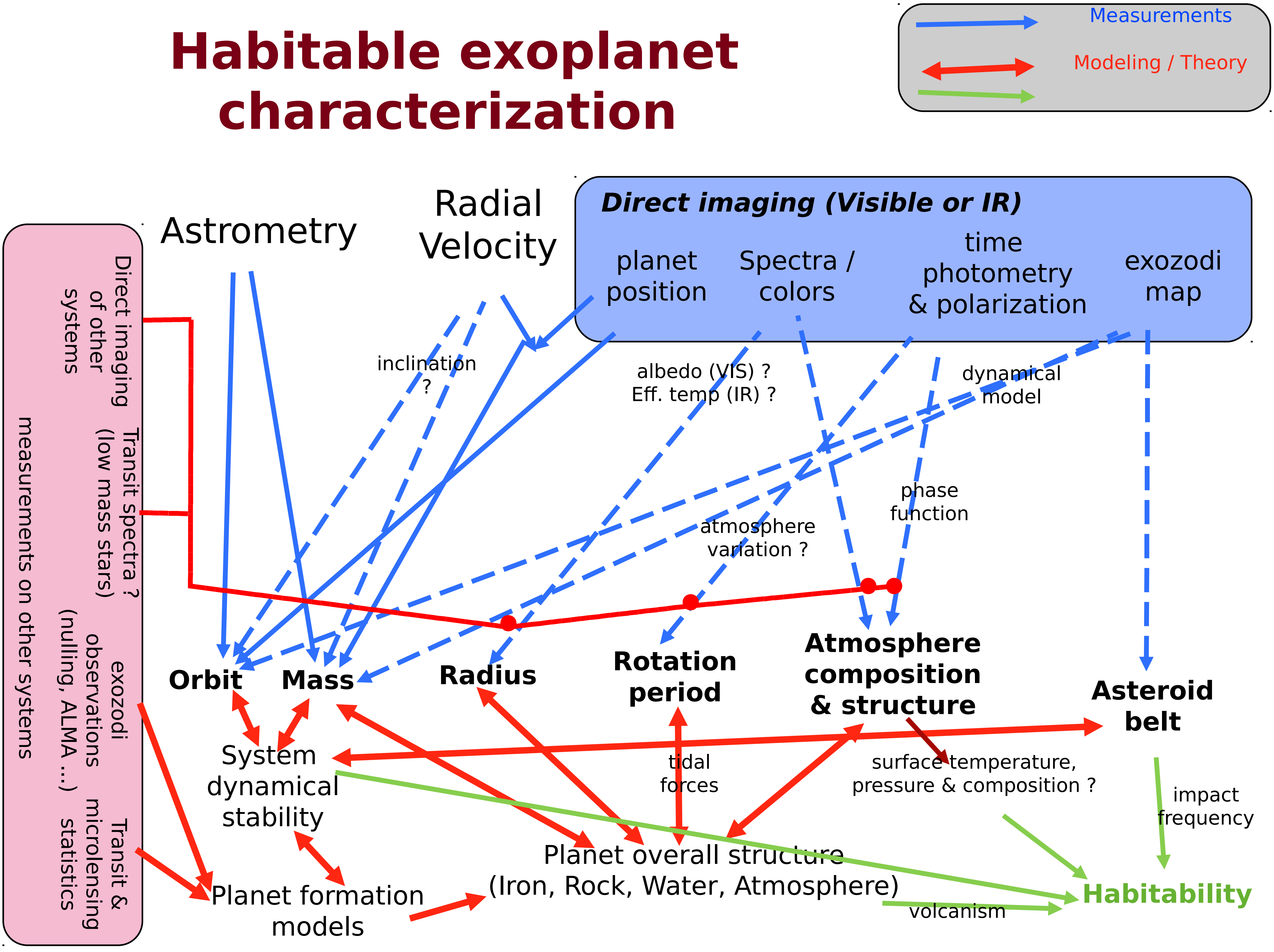


FIG. 7.—Earth's observed reflectance spectrum, at visible and near-infrared wavelengths, created from a composite of the data in this paper (0.8–2.4 μm) and the data presented in Paper I (0.5–0.8 μm). The strongest molecular signatures are indicated, as are the wavelengths where Rayleigh scattering and vegetation reflection are most significant.

Turnbull et al. 2006

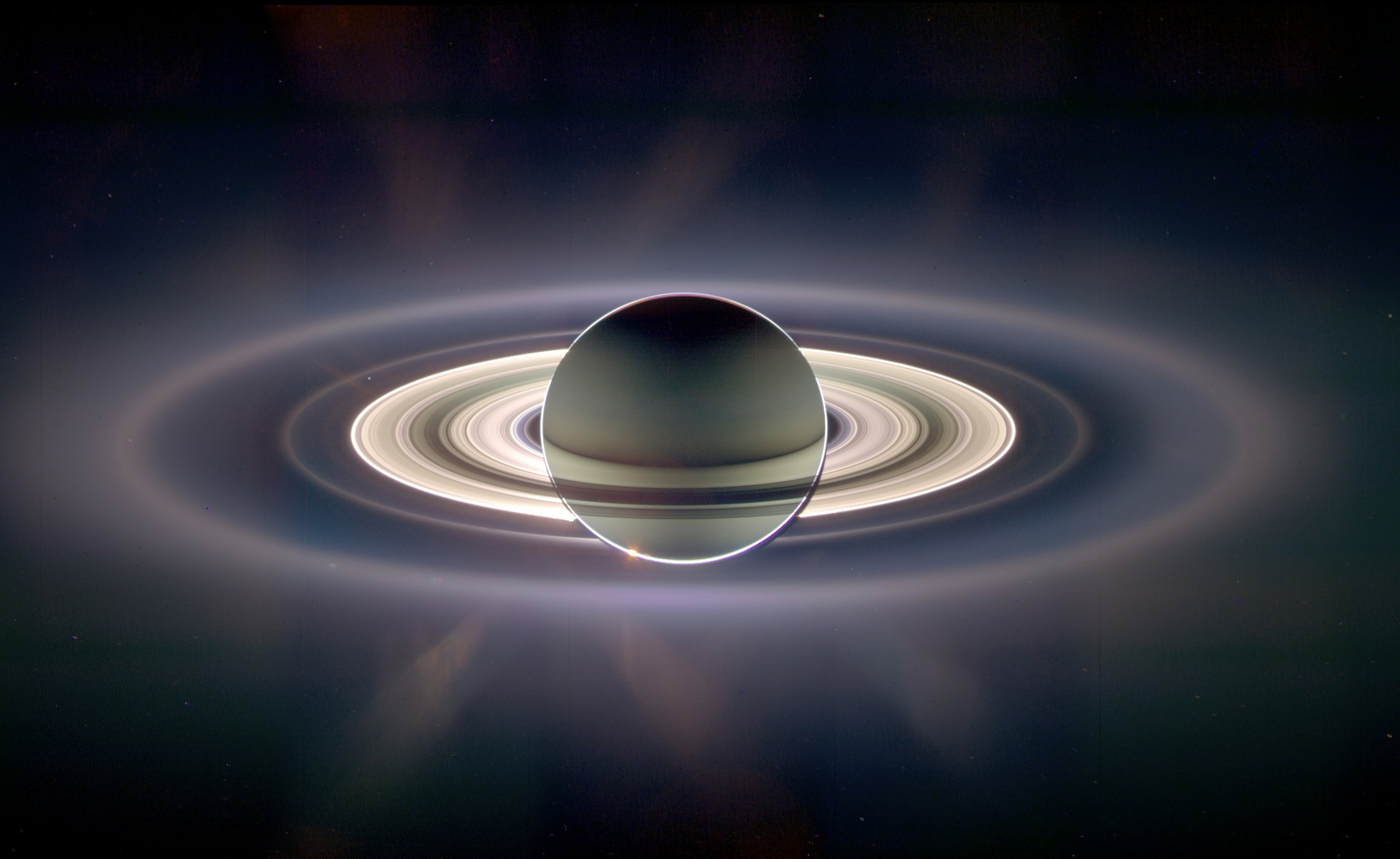
Habitable exoplanet characterization

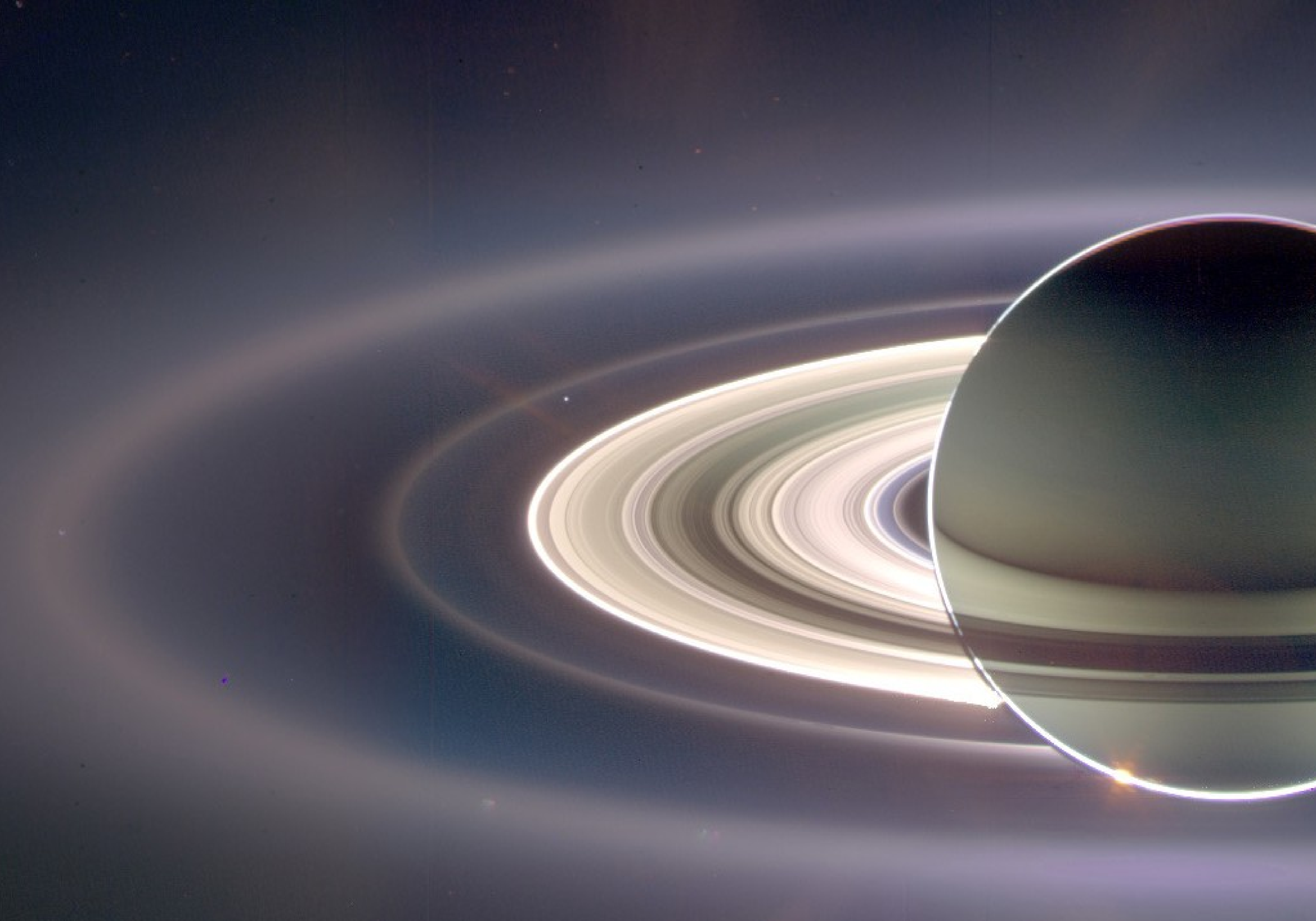


Exoplanets imaging
angular separation, contrast: why is it difficult ?

What would our solar system look like from 10pc away ?

- Sun would be m_V = 4.8 star (faint naked-eye star)
- Sun diameter would be 0.001” (diffraction limit of a 200m telescope in the near-IR, or 100m in visible)
- Sun-Earth separation would be 0.1” (diffraction limit of a 2-3m telescope in the near-IR, or 1m in visible)
- Earth diameter = 0.00001” (diffraction limit of a 20km diameter telescope in near-IR, or 10km in visible)
- In the visible:
  - Earth at 1e-10 contrast would be m_V~ 30 sources (very faint, would be challenging even for Hubble without the host star)
  - Jupiter in the visible would be ~10x brighter than Earth, at 0.5”
  - Zodiacal light would be several 100x brighter than Earth when integrated, and brightest near Sun
- In the near IR (~2 um): similar contrasts
- In the thermal IR (~10 um):
  - Contrasts are much more favorable
  - Earth is brightest planet, at ~1e-6 contrast





Exoplanets: Contrast ratio, visible vs. infrared, giant vs rocky

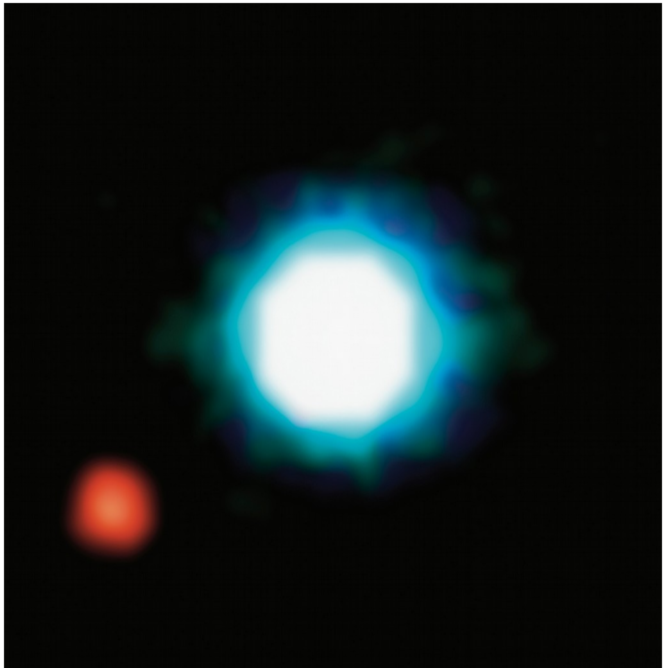
In the visible, planets are very faint unless they are very close to their star (luminosity goes as d^{-2})
Planets in or near habitable zone cannot be imaged from the ground, and would require dedicated space telescope+instrument.

In the near-IR, giant and young planets (“young Jupiters”) can be imaged:

- AO systems work well in the near-IR
- Giant planets emit their own light (thermal emission)
- Young planets are still very hot, and slowly cool after formation

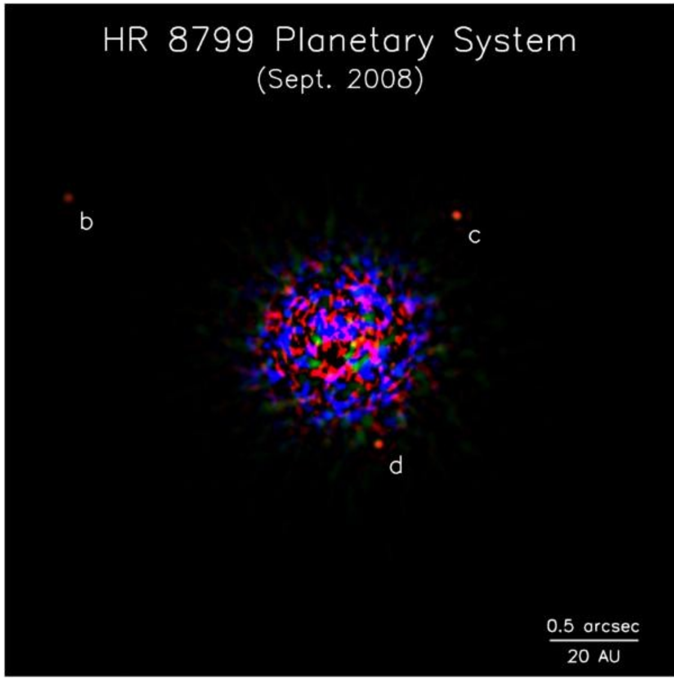
But, habitable planets are not bright in near-IR

In the Thermal IR (~10 um & longer), contrast is more favorable.
Older giant planets can be imaged (this is one of the key science goals of JWST), and habitable planets are near their thermal emission peak



2M1207 exoplanet (Chauvin et al., ESO, 2004)
Probably the first direct image of an exoplanet

HR8799: first image of exoplanetary sytem with multiple planets (Marois et al. 2009)

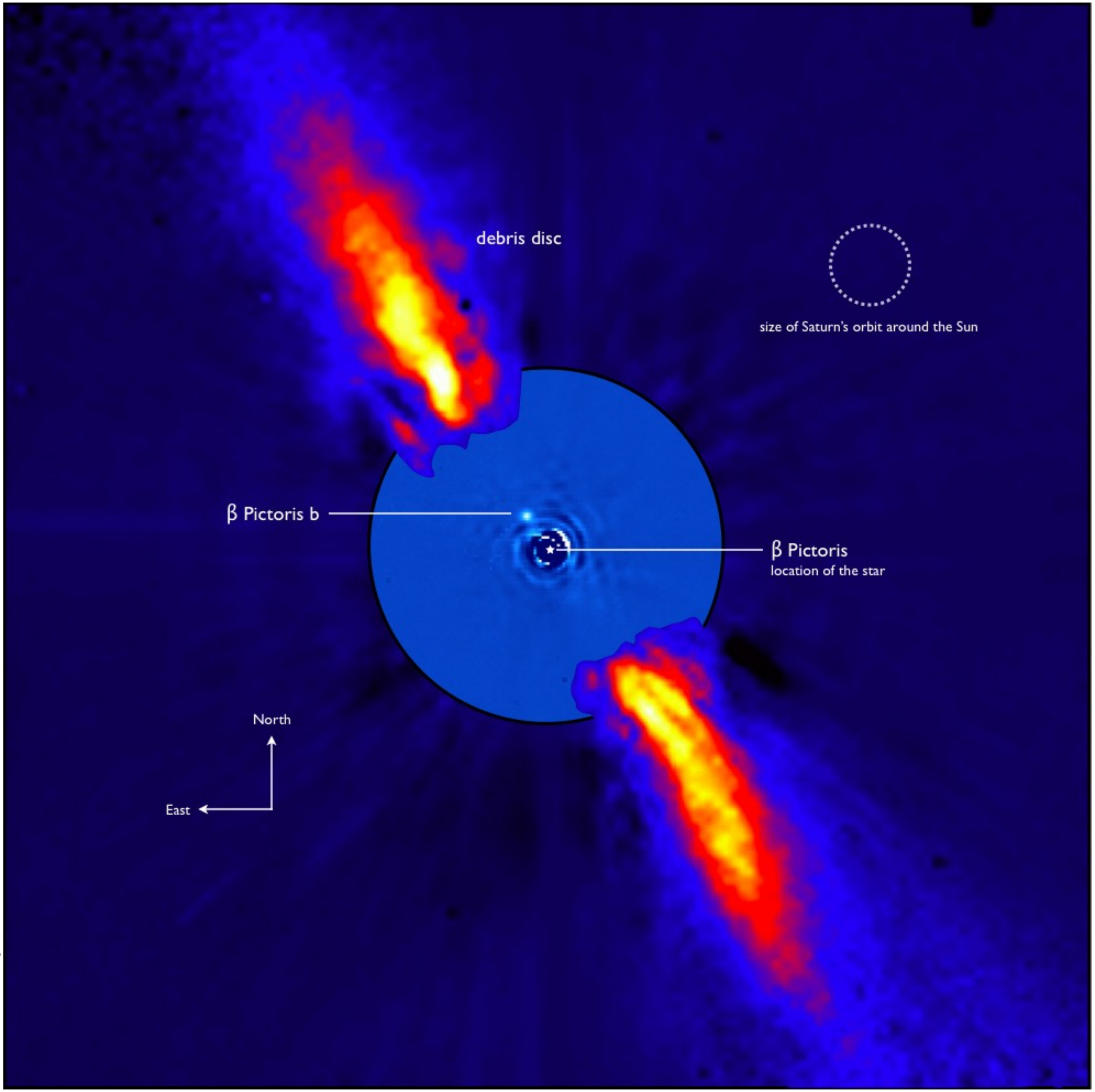


Exoplanets & dust disks

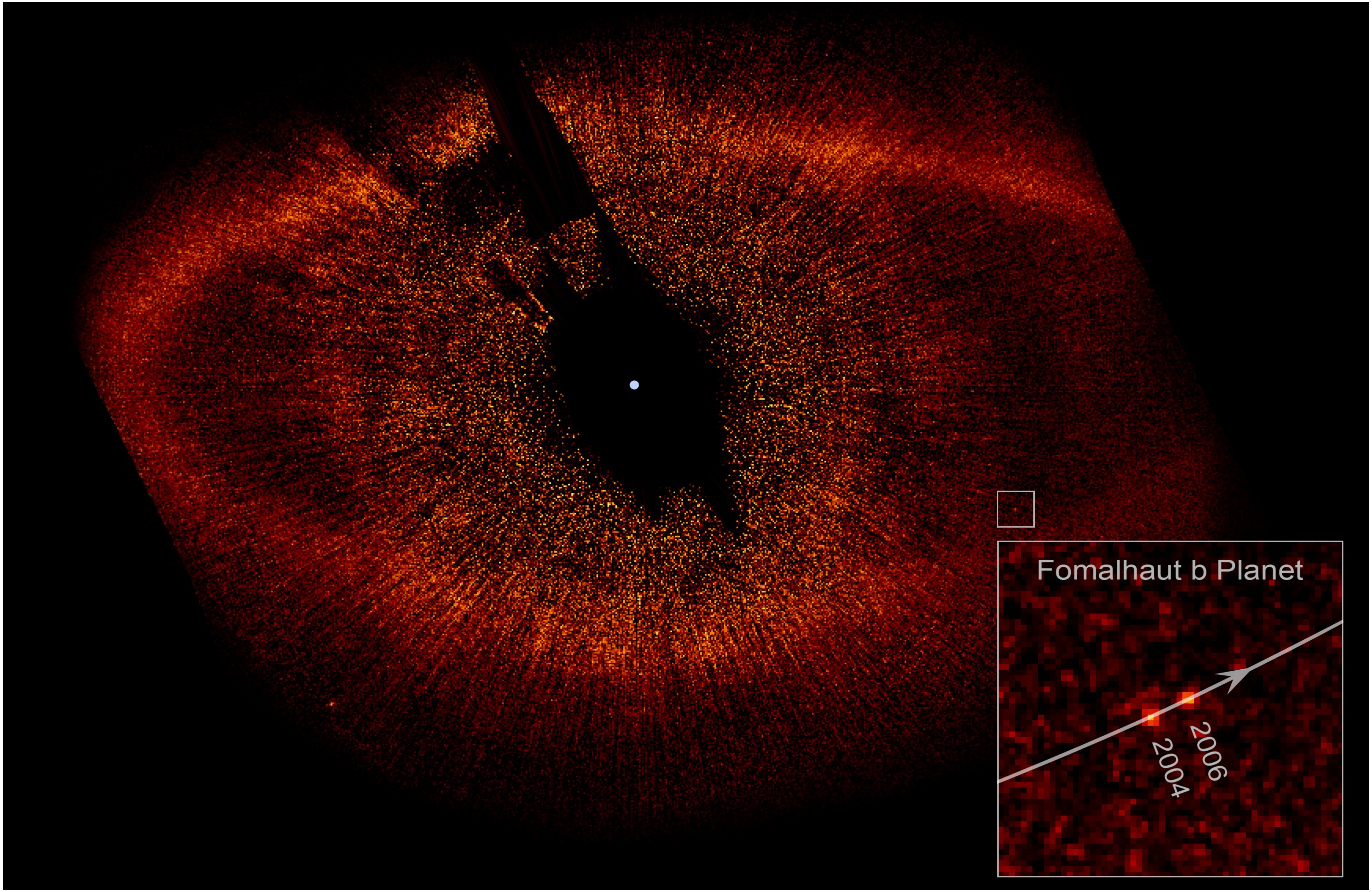
Protoplanetary disk:
Disk in the process of forming planets

Debris disk:
Disk generated by collision between small bodies

Ability to image planets and disks → study planetary formation and evolution of planetary systems



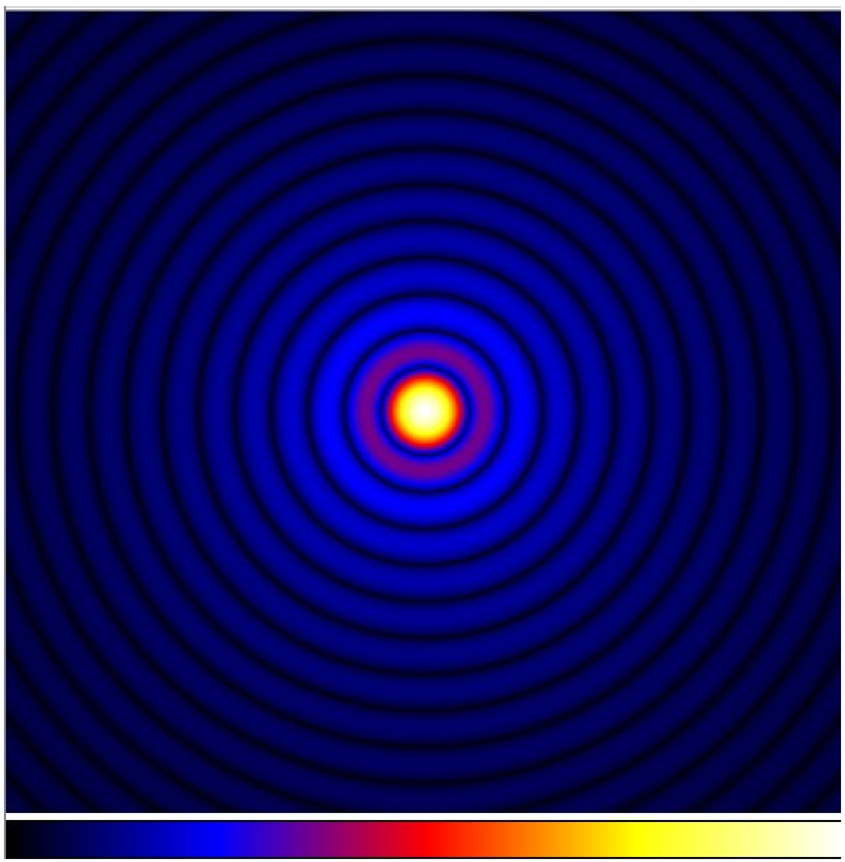
Beta Pic exoplanet and dust disk (Lagrange et al. 2009)

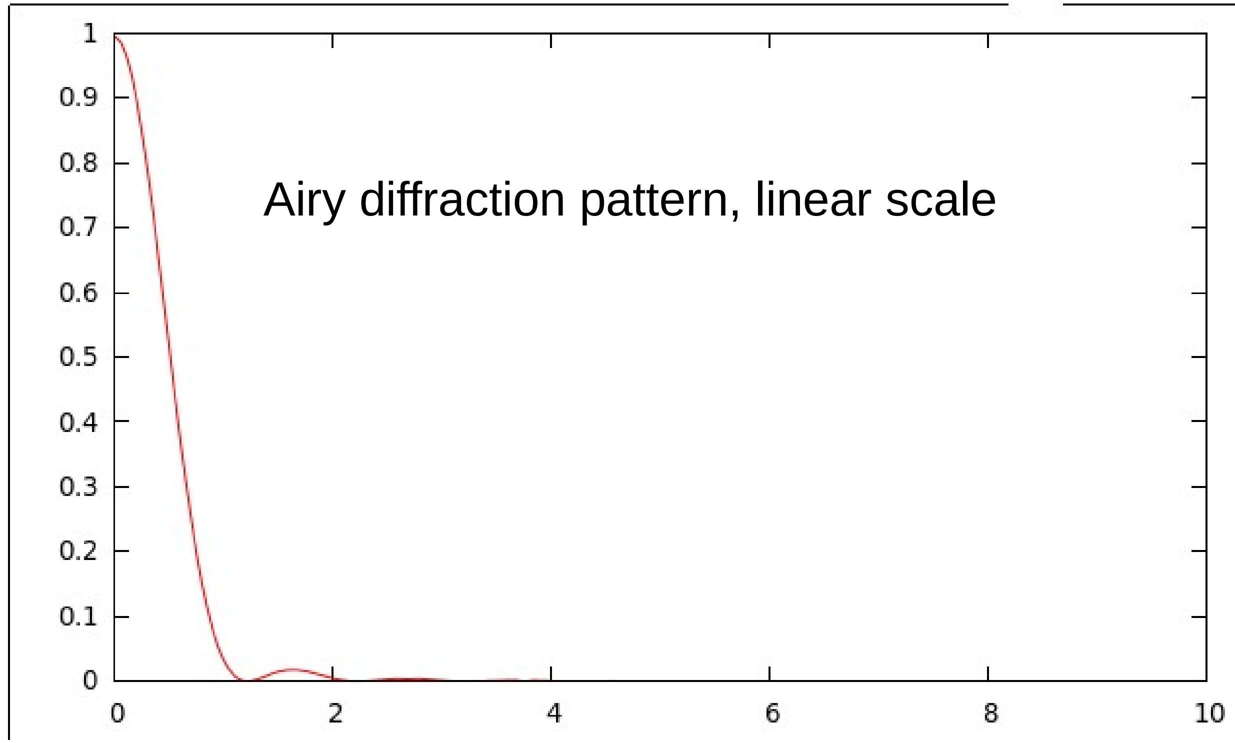


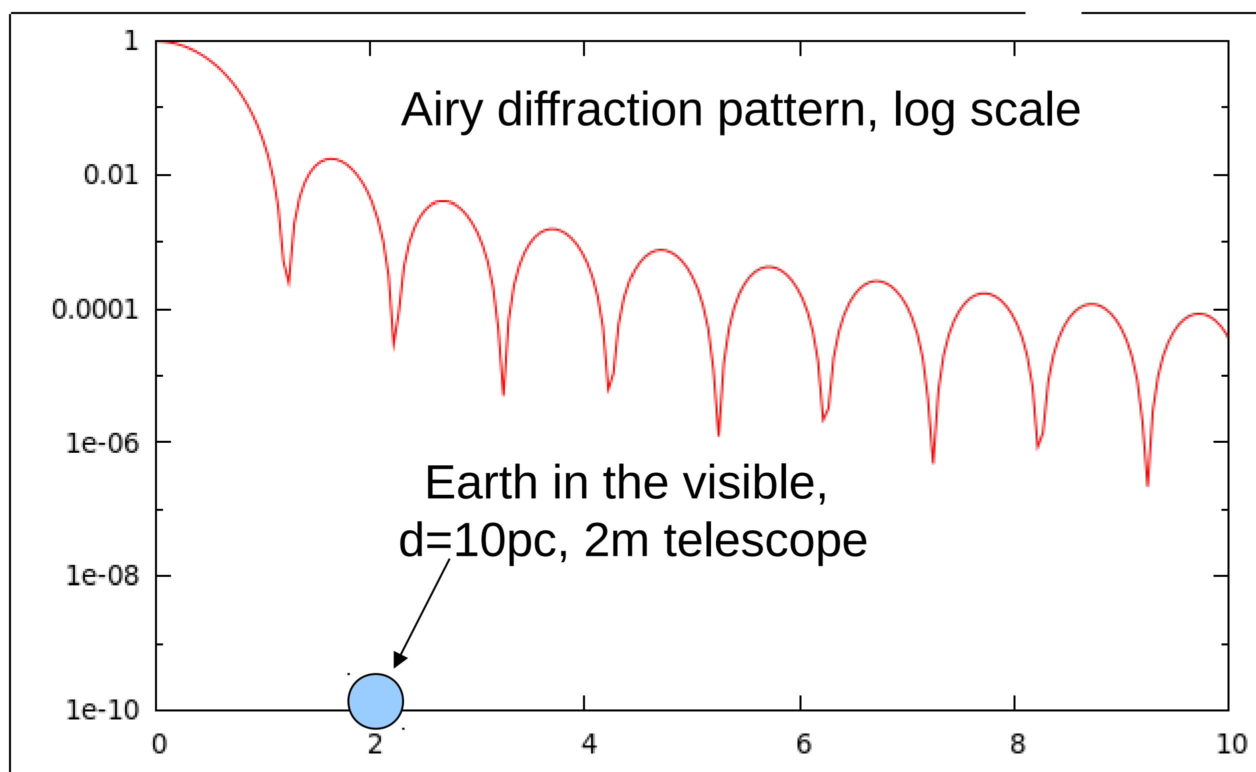
Kalas et al., HST image

Why coronagraphy ?

Conventional imaging systems are not suitable for high contrast (even if perfect) due to diffraction







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.

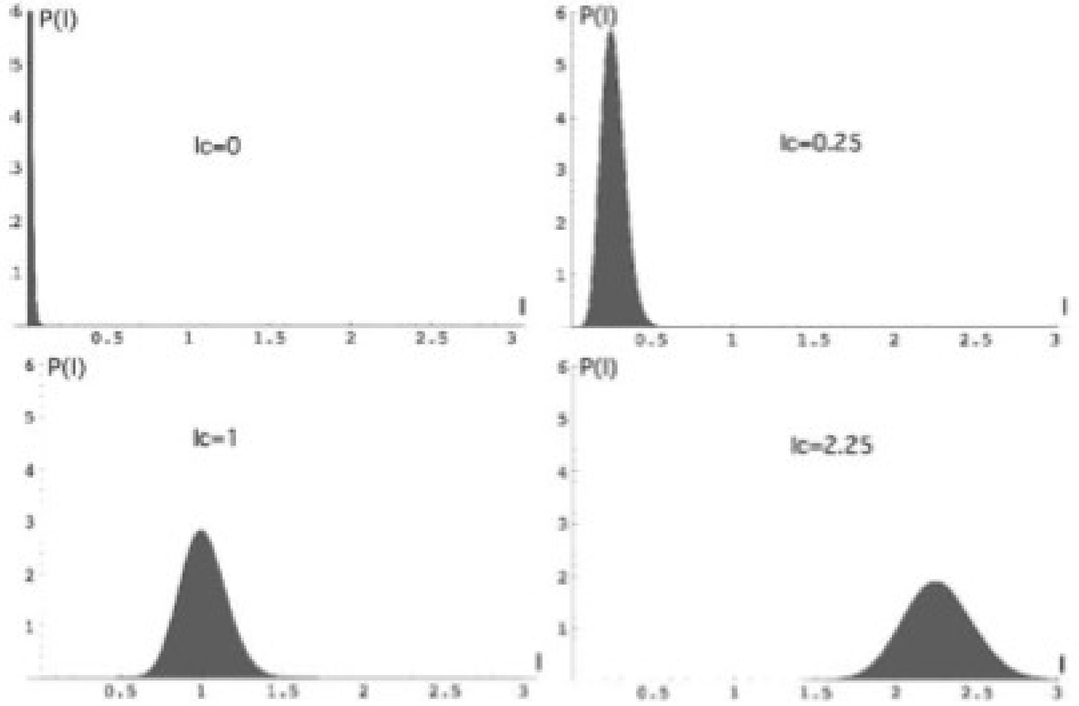


FIG. 3.—PDF of the light intensity at four different constant background intensity levels I_c and a single value of $I_s = 0.1$. High values of I_c correspond to locations near the perfect PSF maxima (rings), and low values of I_c correspond to locations near the zeros of the perfect PSF or far from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

Coherent amplification between speckles and diffraction pattern

Final image = PSF diffraction (Airy) + speckle halo

$$\text{Image} = |A_{PSF} + A_{speckles}|^2$$

$$= |A_{PSF}|^2 + |A_{speckles}|^2 + 2\,|A_{PSF}|\,|A_{speckle}|\cos(\theta)$$

With PSF >> Speckles, this term dominates speckles

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

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

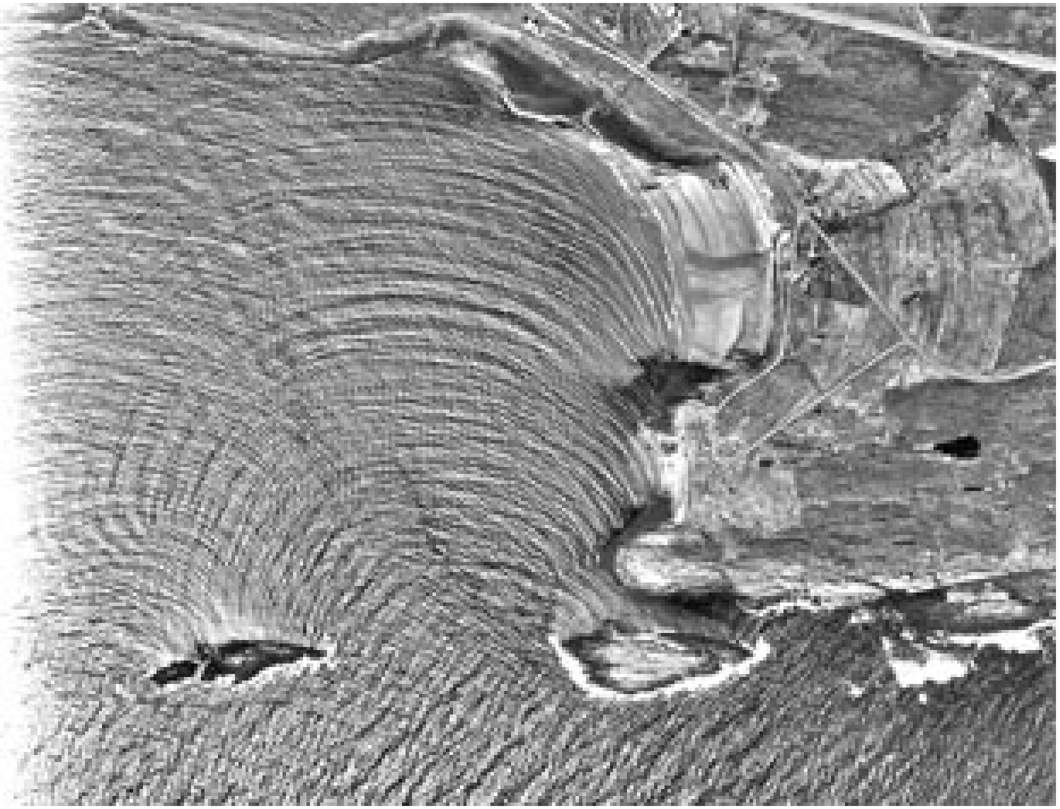
1818: French academy of science committee launches a competition
to explain nature of light

Augustin-Jean Fresnel
submits wave theory of light

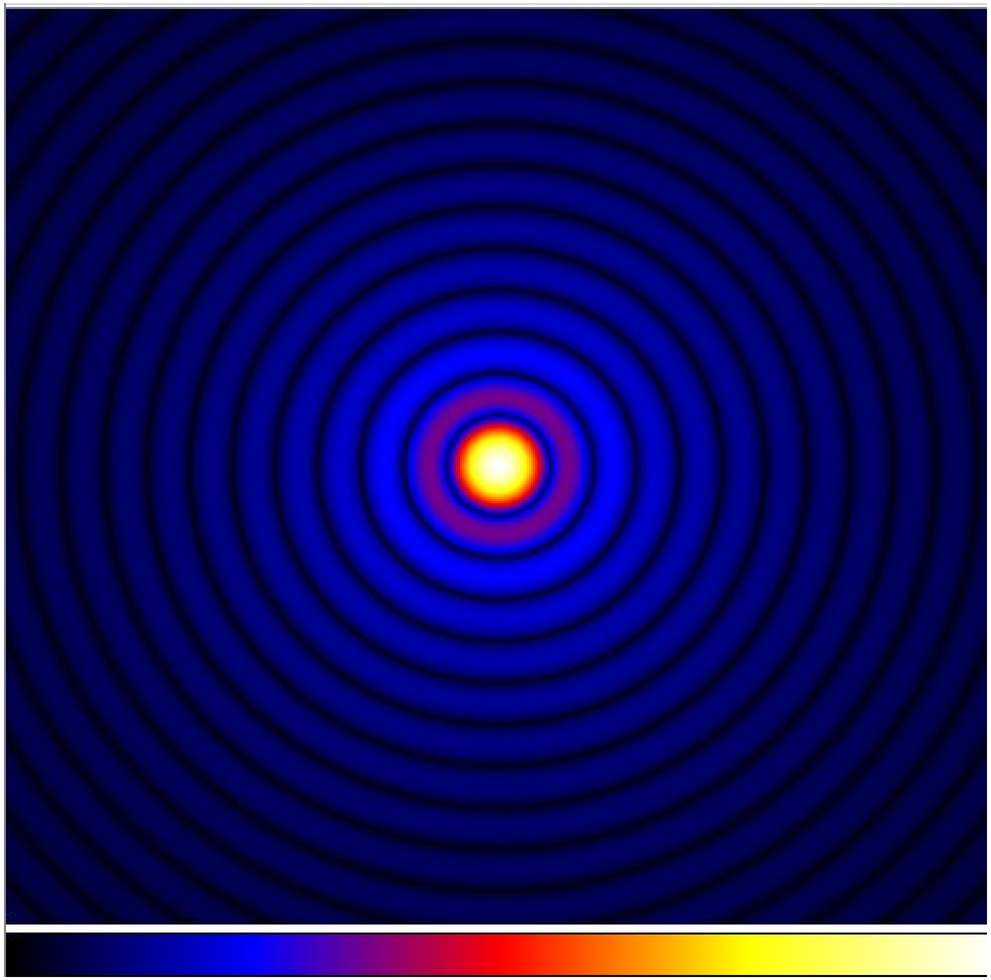
Simeon-Denis Poisson finds a flaw in Fresnel's theory:
According to Fresnel's equations, a bright spot should appear in
the shadow of a circular obstacle → this absurd result disproves Fresnel's theory

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

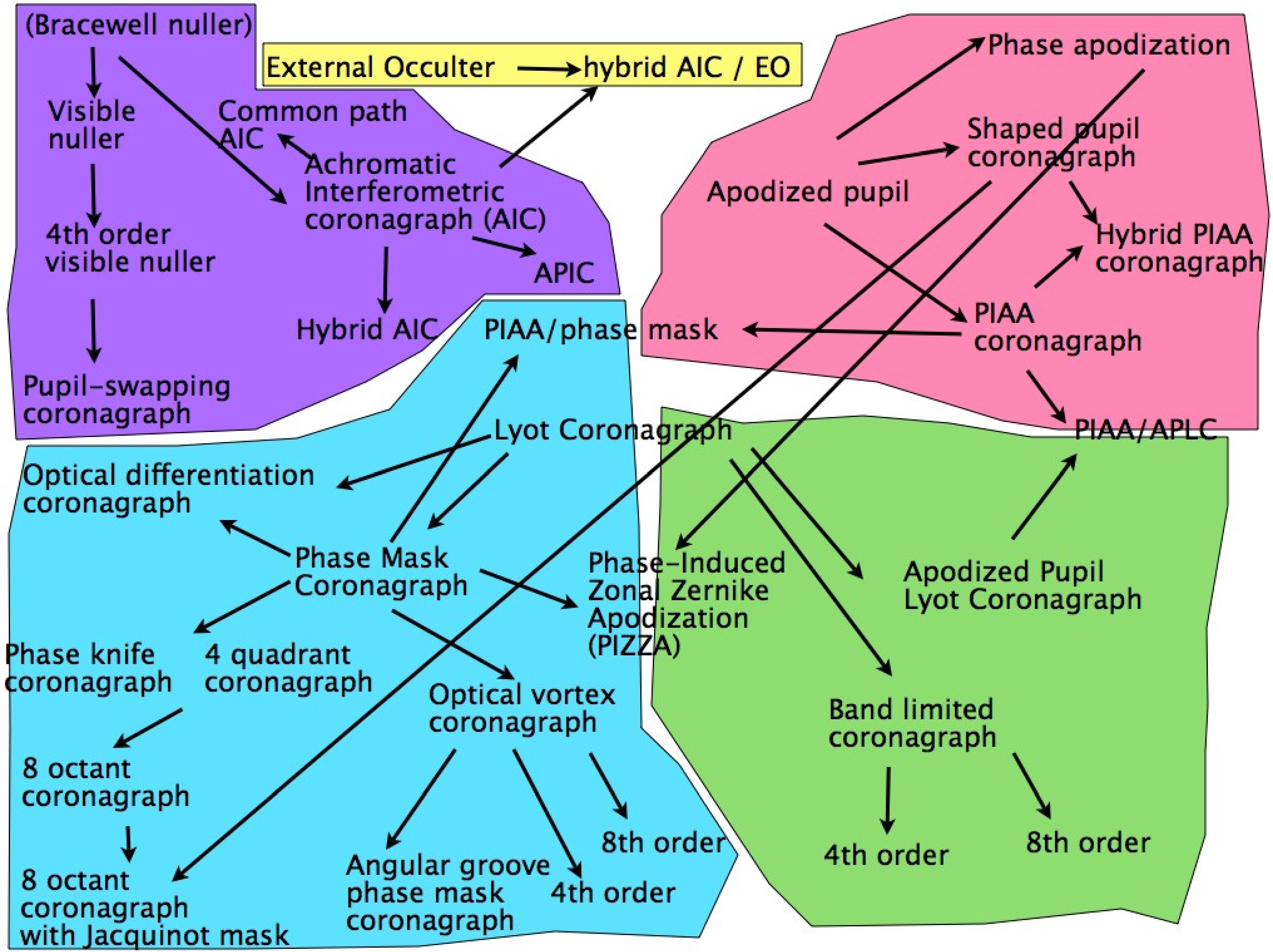
Water waves diffract around obstacles, edges, and so does light



Waves diffracted by coastline and islands



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

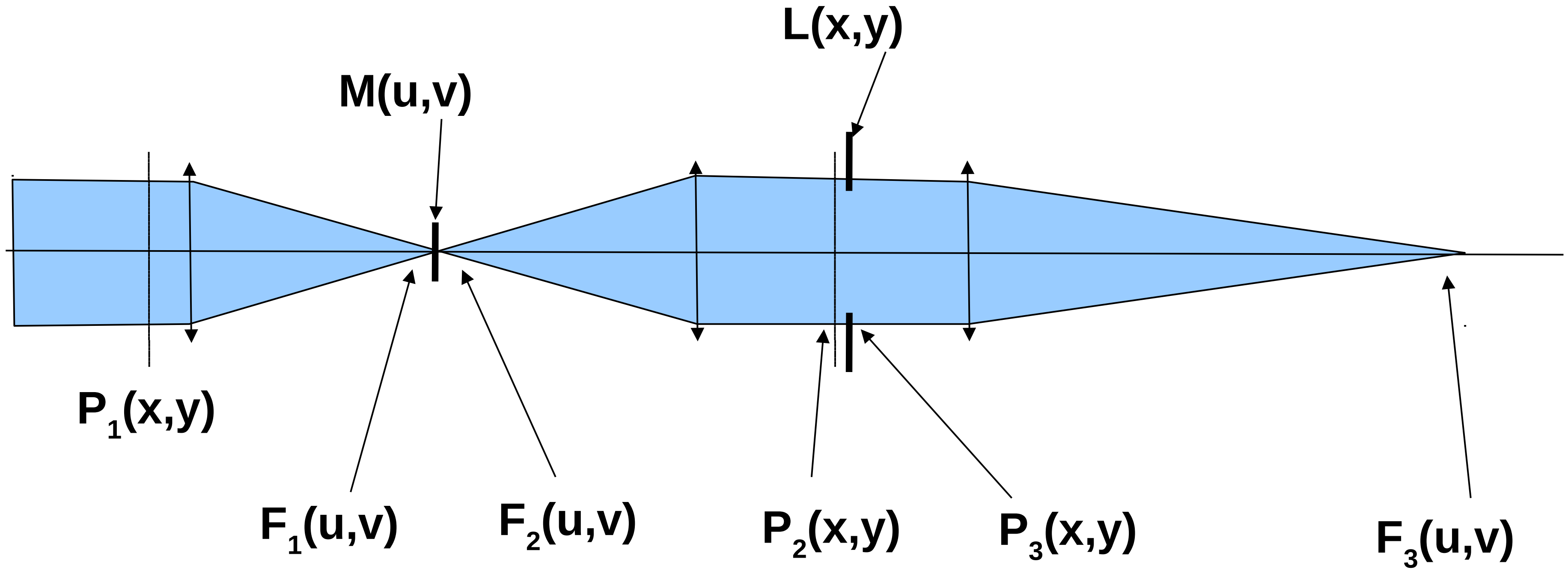

(Bracewell nuller)
External Occulter
hybrid AIC / EO
Phase apodization
Visible nuller
Common path AIC
Achromatic Interferometric coronagraph (AIC)
Shaped pupil coronagraph
Apodized pupil
4th order visible nuller
APIC
Hybrid PIAA coronagraph
Hybrid AIC
PIAA/phase mask
PIAA coronagraph
Pupil-swapping coronagraph
Lyot Coronagraph
PIAA/APLC
Optical differentiation coronagraph
Phase Mask Coronagraph
Phase-Induced Zonal Zernike Apodization (PIZZA)
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
8 octant coronagraph with Jacquinot mask

Lyot Coronagraph explained by Fourier transforms

Pupil plane complex amplitude ↔ focal plane complex amplitude

→ Fourier transform
← Inverse Fourier transform

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



Lyot Coronagraph explained by Fourier transforms

Full set of equations (explained in next slides):

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

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

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

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

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

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

Exit pupil plane:

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

With * denoting convolution

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

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

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

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

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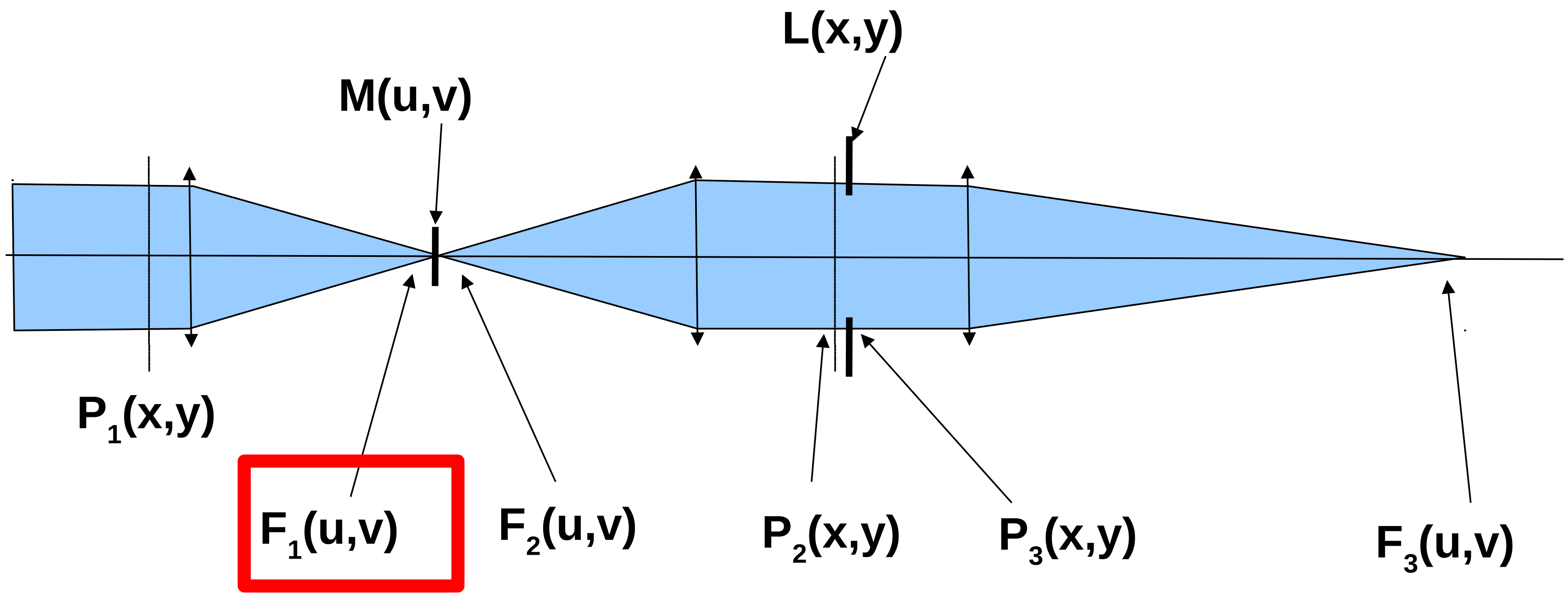
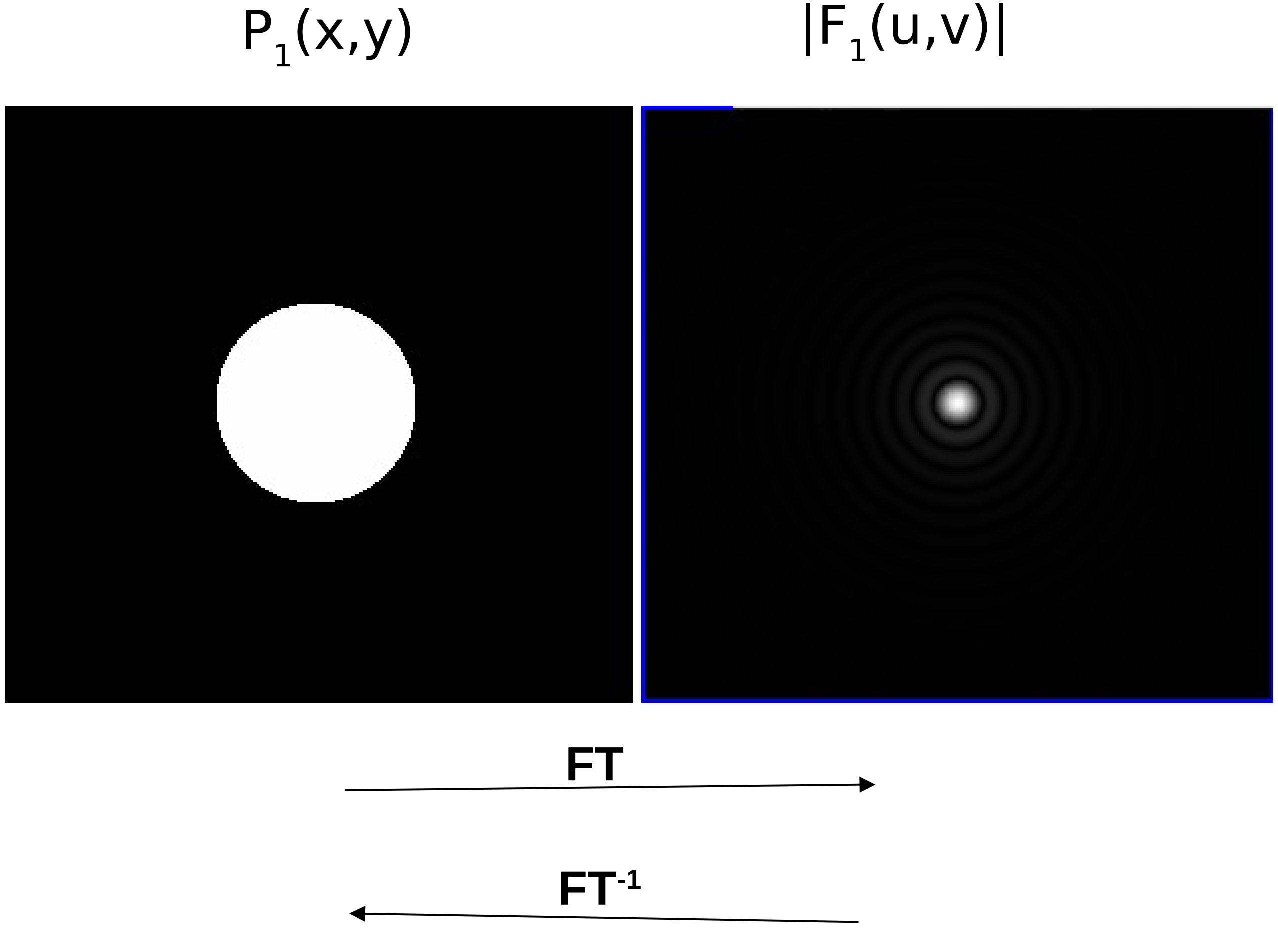


Focal plane image = FT of pupil complex amplitude

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

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

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



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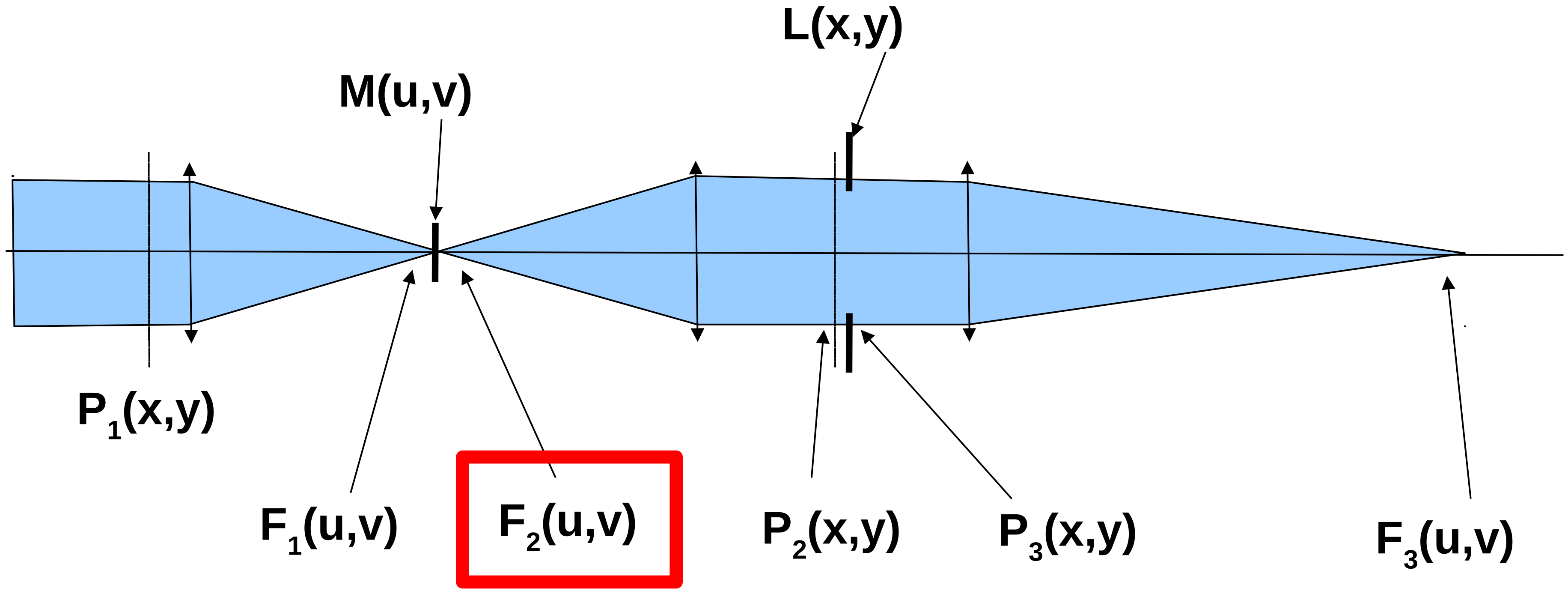


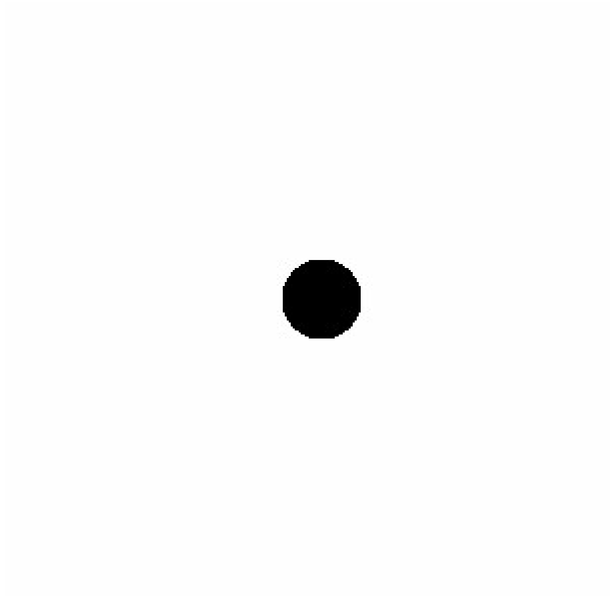
Inserting an opaque mask in the focal plane

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

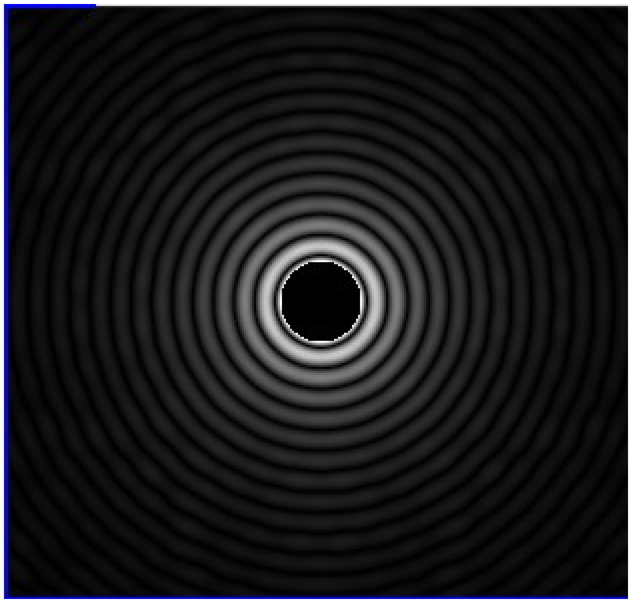
Focal plane complex amplifude (after focal plane mask): $F_2(u,v)$

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

M(u,v)



$|F_2(u,v)|$



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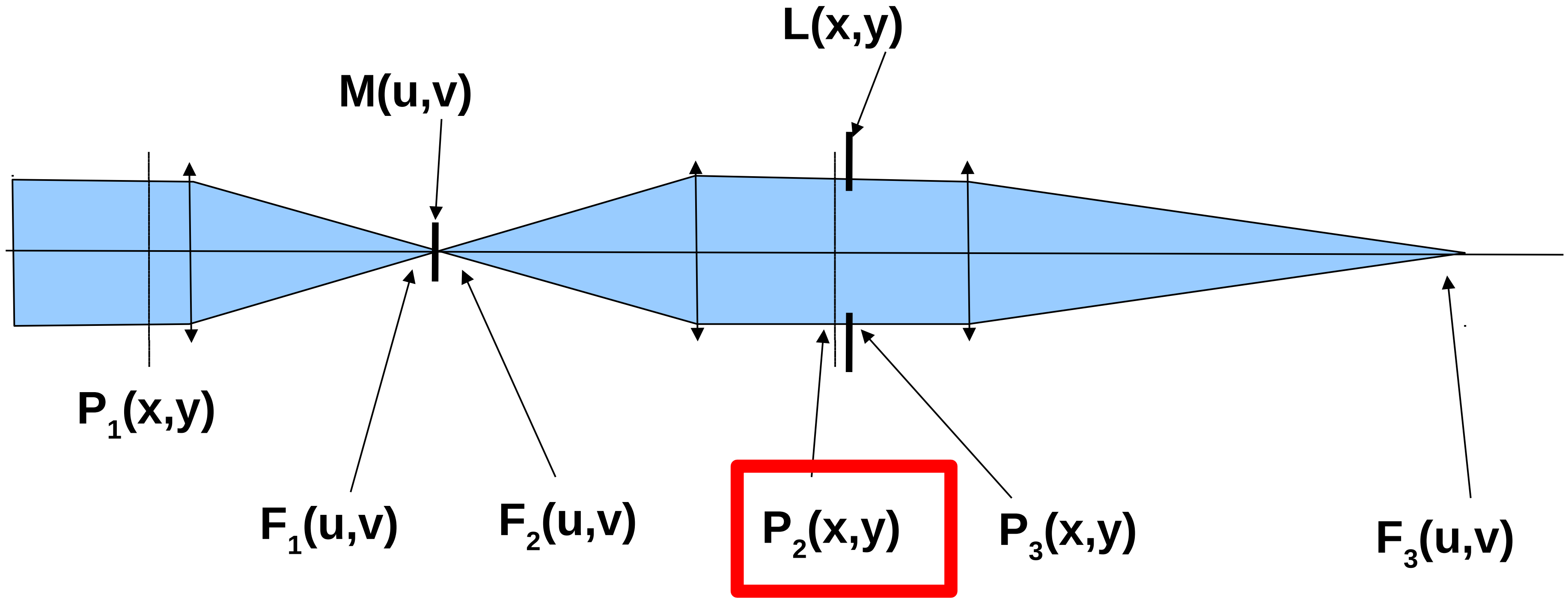


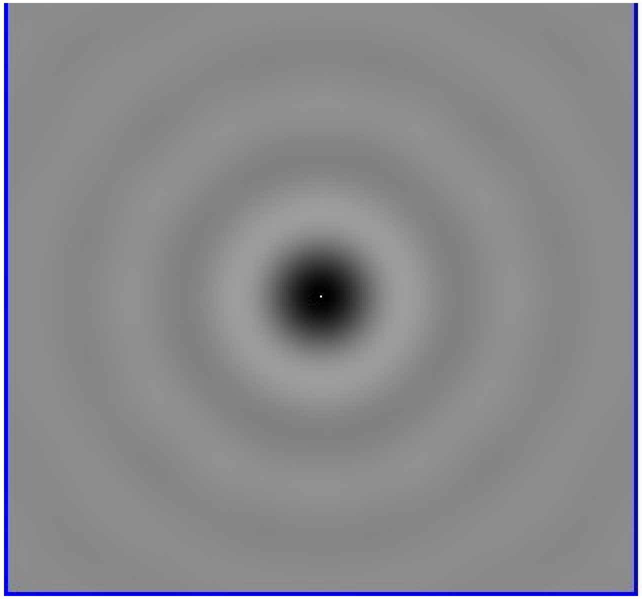
Lyot Coronagraph : light distribution in output pupil plane

Exit pupil plane:

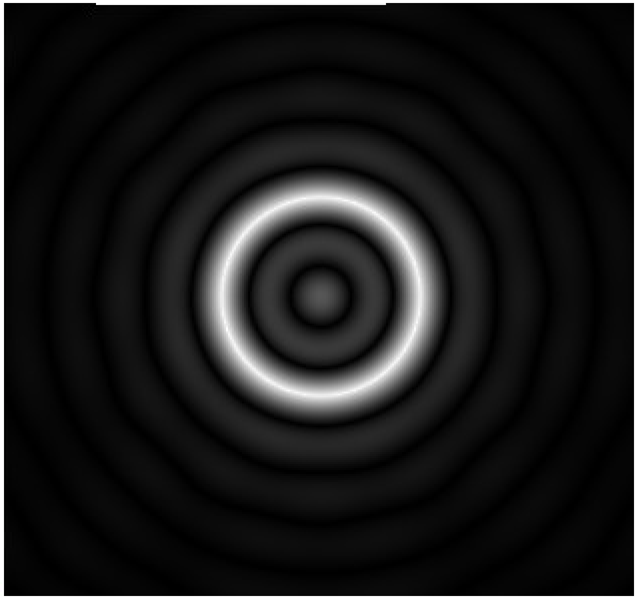
$$P_2(x,y) = FT^{-1}(\, F_2(u,v)\,)$$

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

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



$|P_2(x,y)|$



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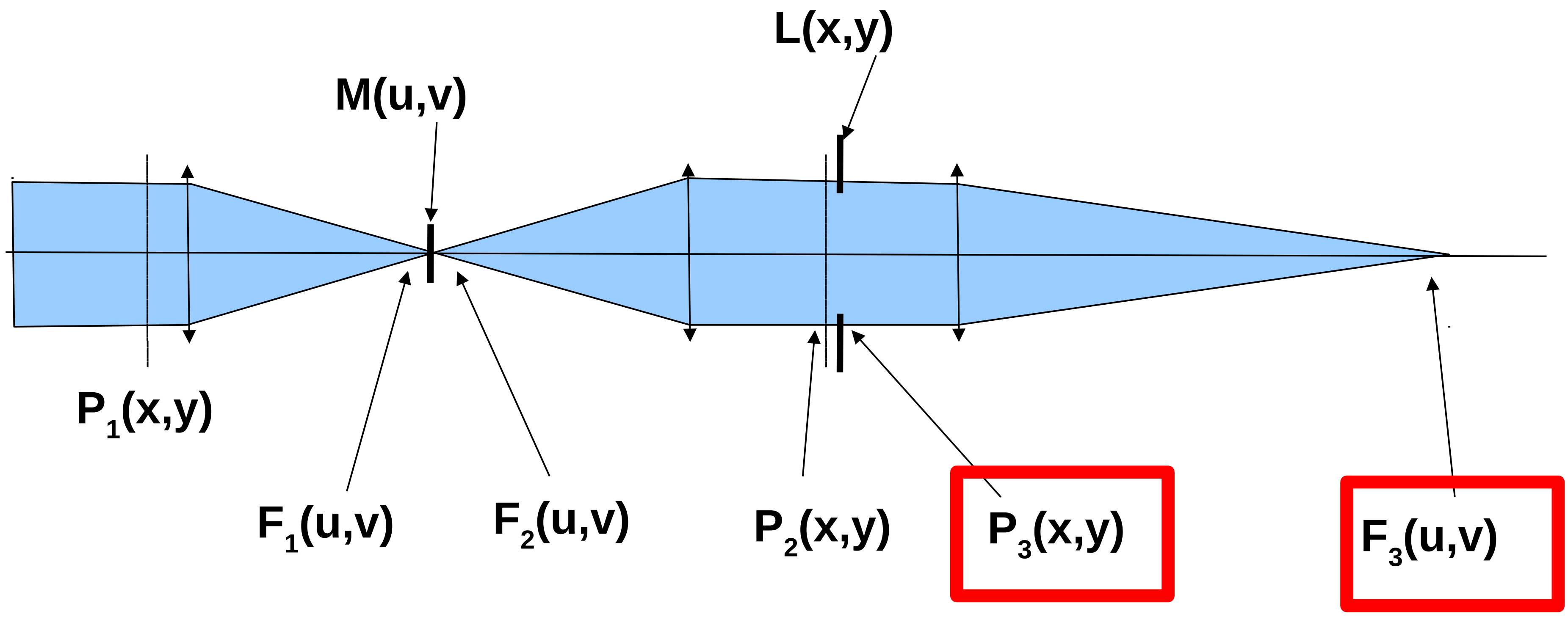


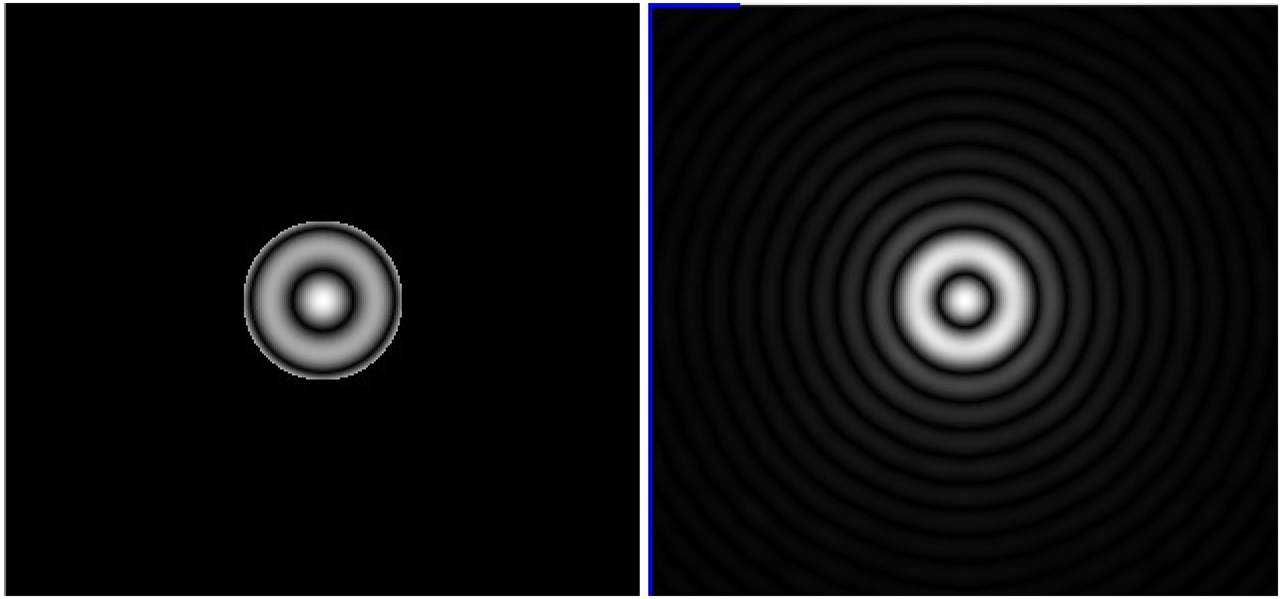
Lyot Coronagraph : Lyot stop (L)

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

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

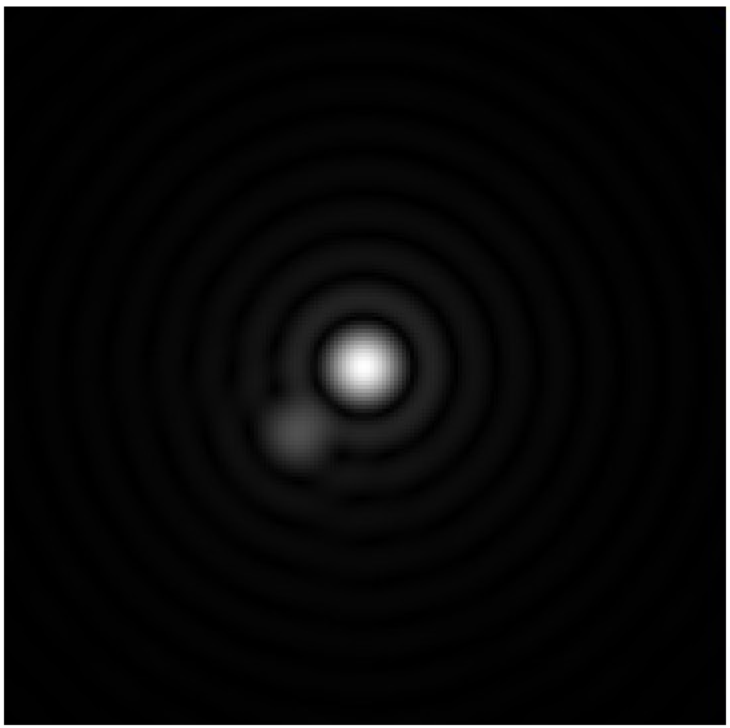
$F_3(u,v) = FT(L(x,y)) * (F_1(u,v) \times M(u,v))$

$|P_3(x,y)|$ $|F_3(u,v)|$

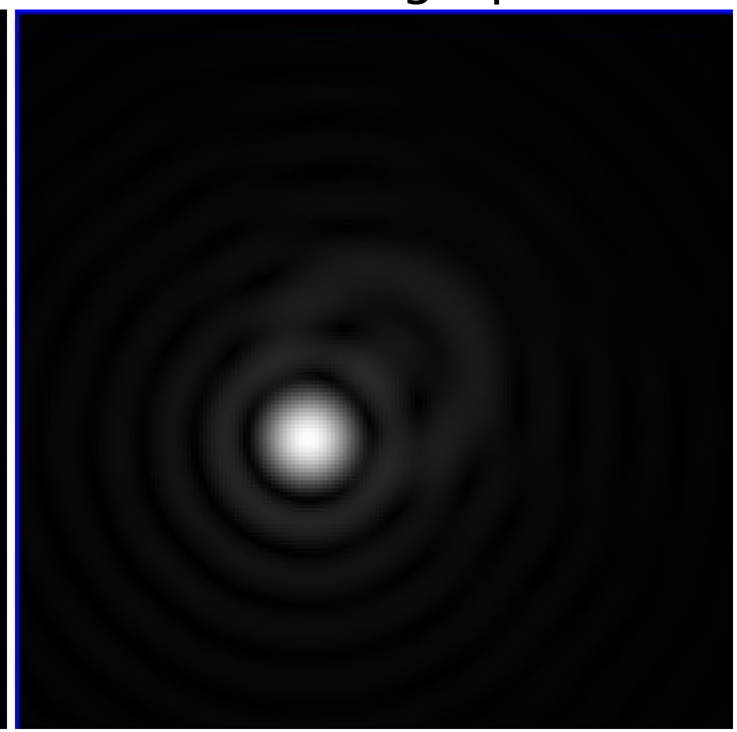


Numerical simulation of final image for 10:1 contrast

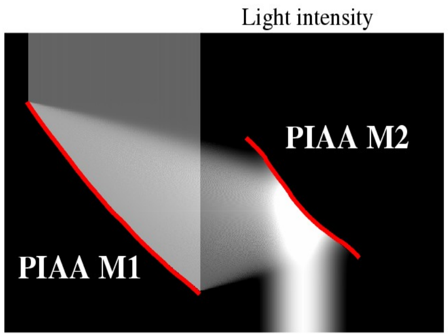
No coronagraph



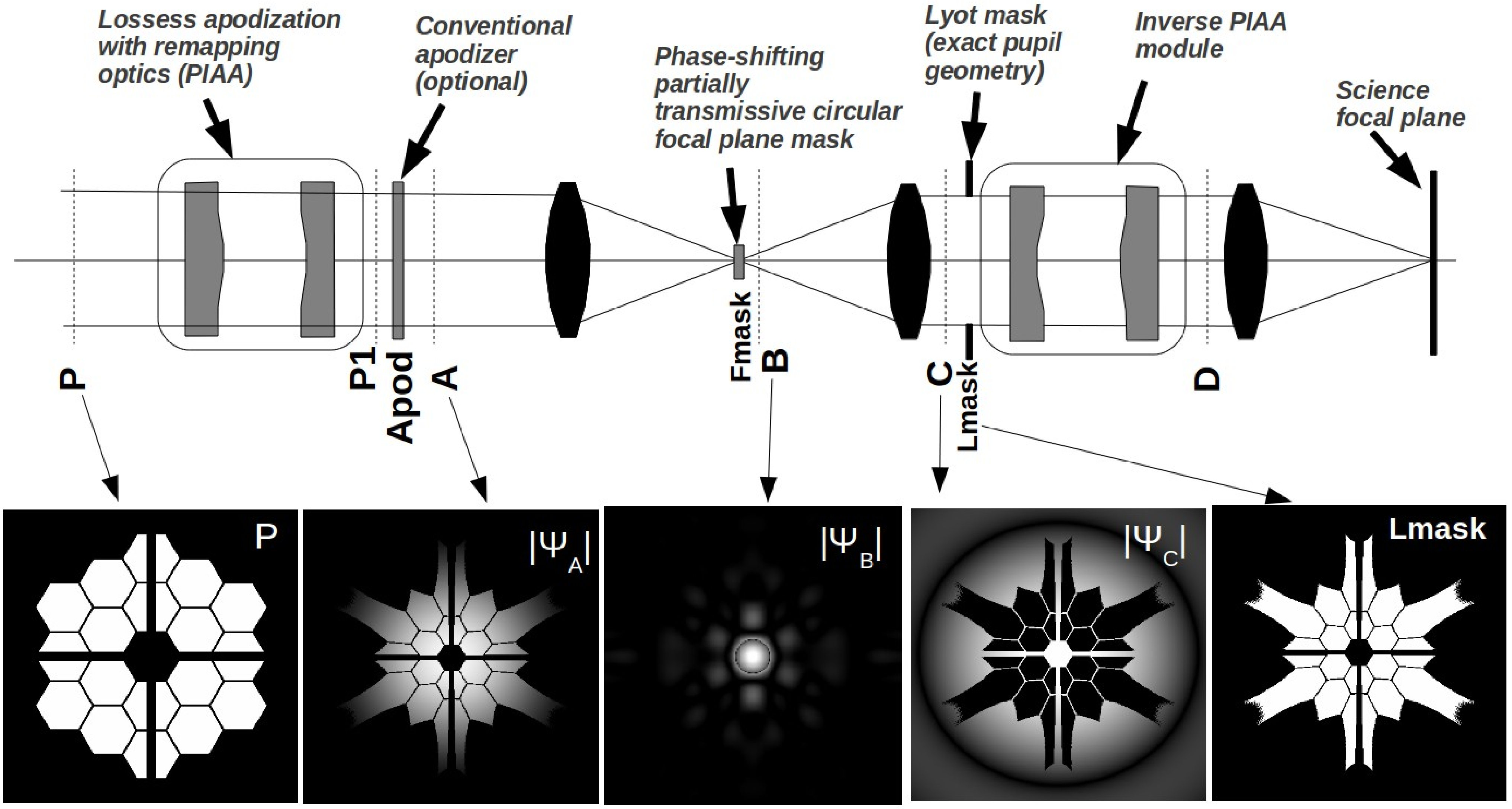
With Lyot Coronagraph



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

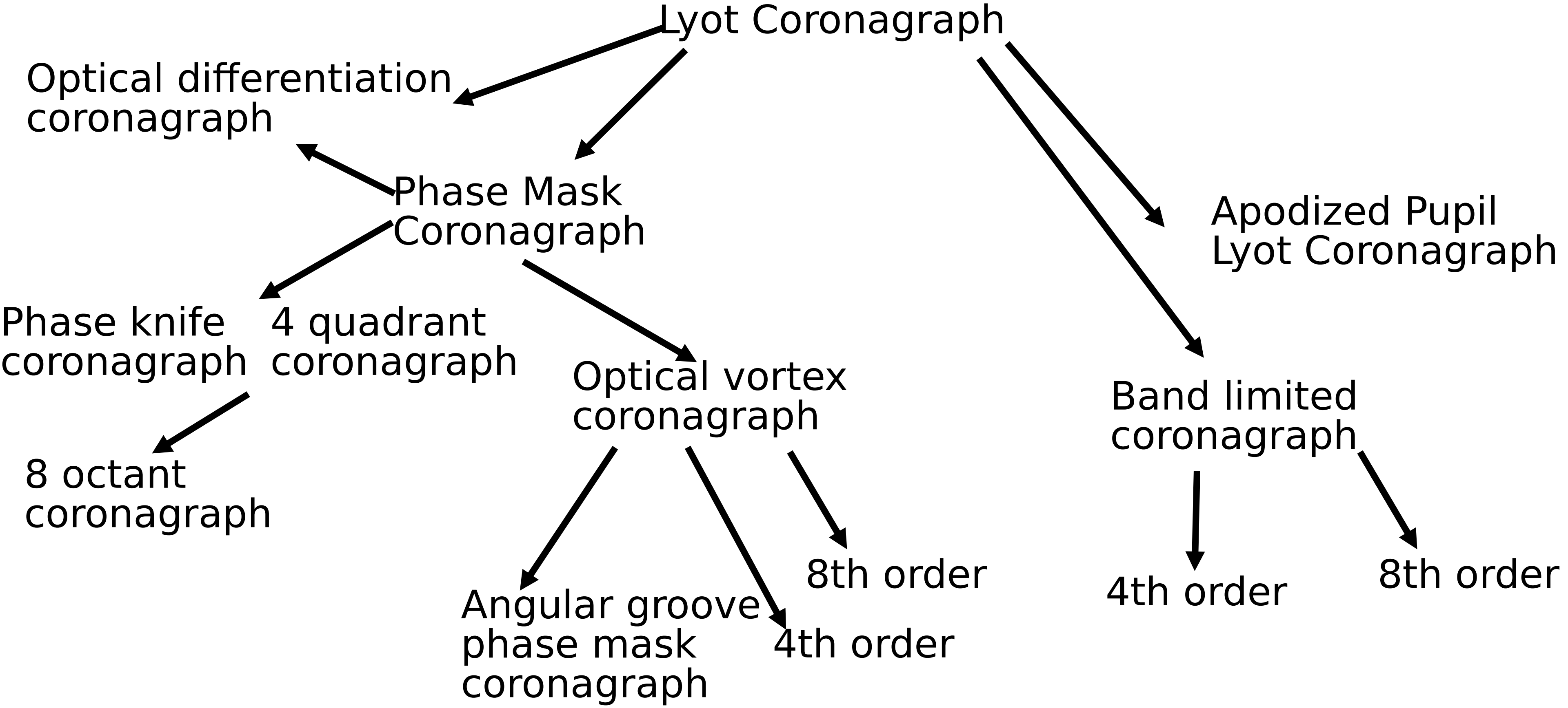
Optimization goal: make pupil dark inside Lyot mask

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

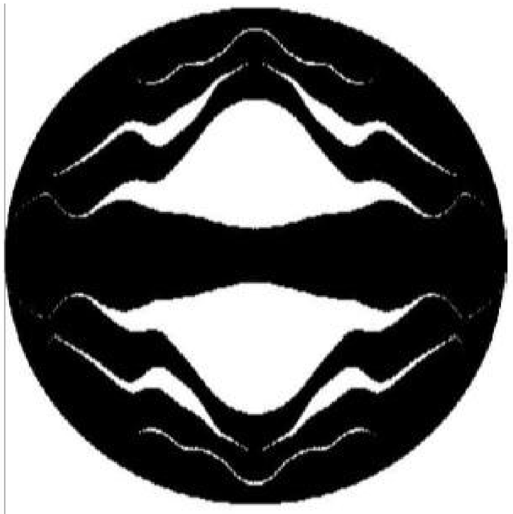
Transform a pupil phase offset into an amplitude apodization thanks to a focal plane Zernike mask

Conventional Pupil Apodization (CPA)

Many pupil apodizations have been proposed.

Apodization can be continuous or binary.

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



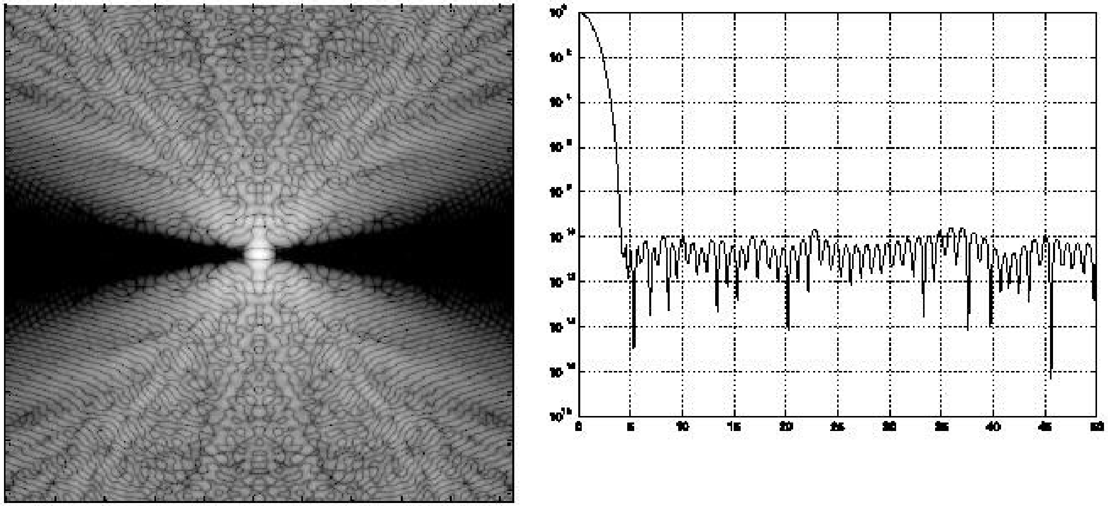


FIG. 9.—*Top*: Asymmetric multiopening mask designed to provide high-contrast, 10^{-10}, from $\lambda/D = 4$ to $\lambda/D = 100$ in two angular sectors centered on the x-axis. Ten integrations are required to cover all angles. Total throughput and pseudoarea are 24.4%. Airy throughput is 11.85%. *Bottom*: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

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

Pupil Phase Apodization (PPA)

Achromatic solutions exist.

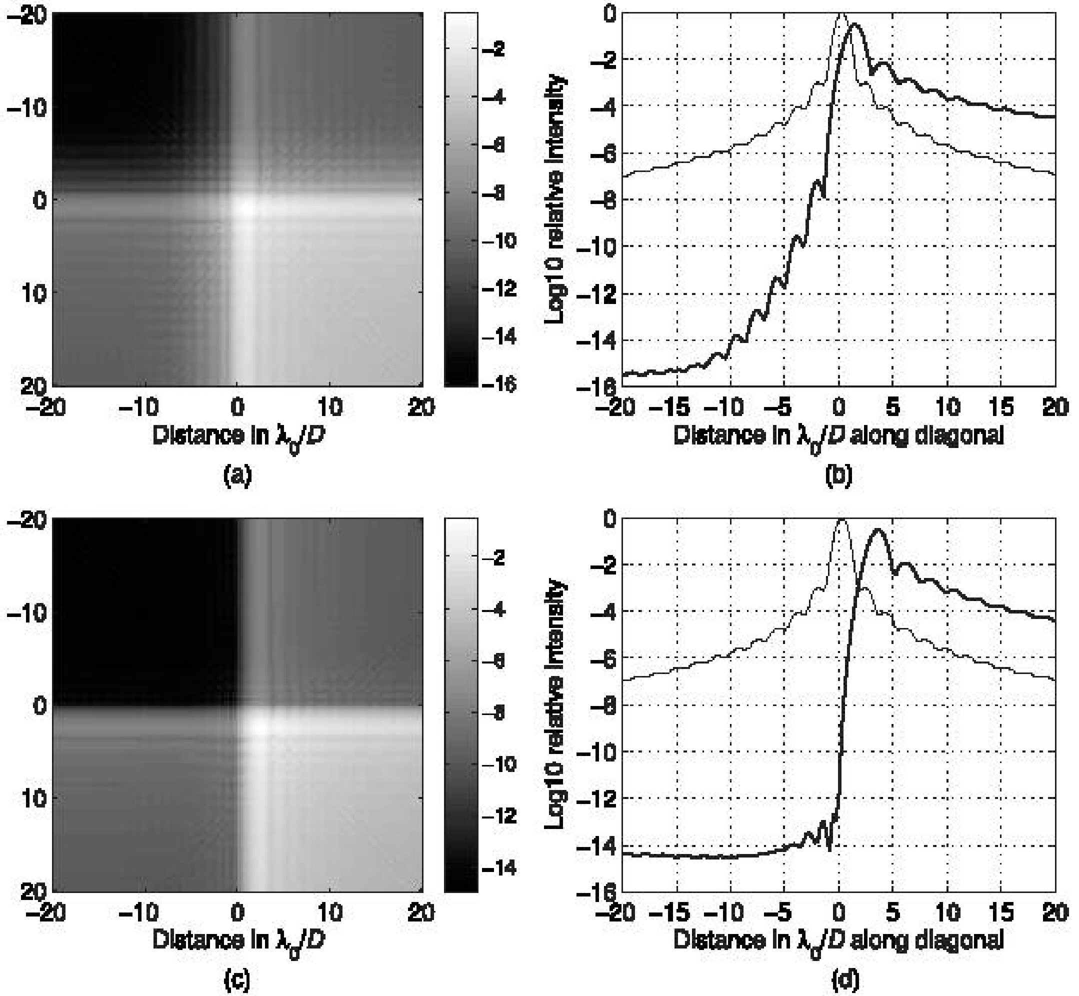
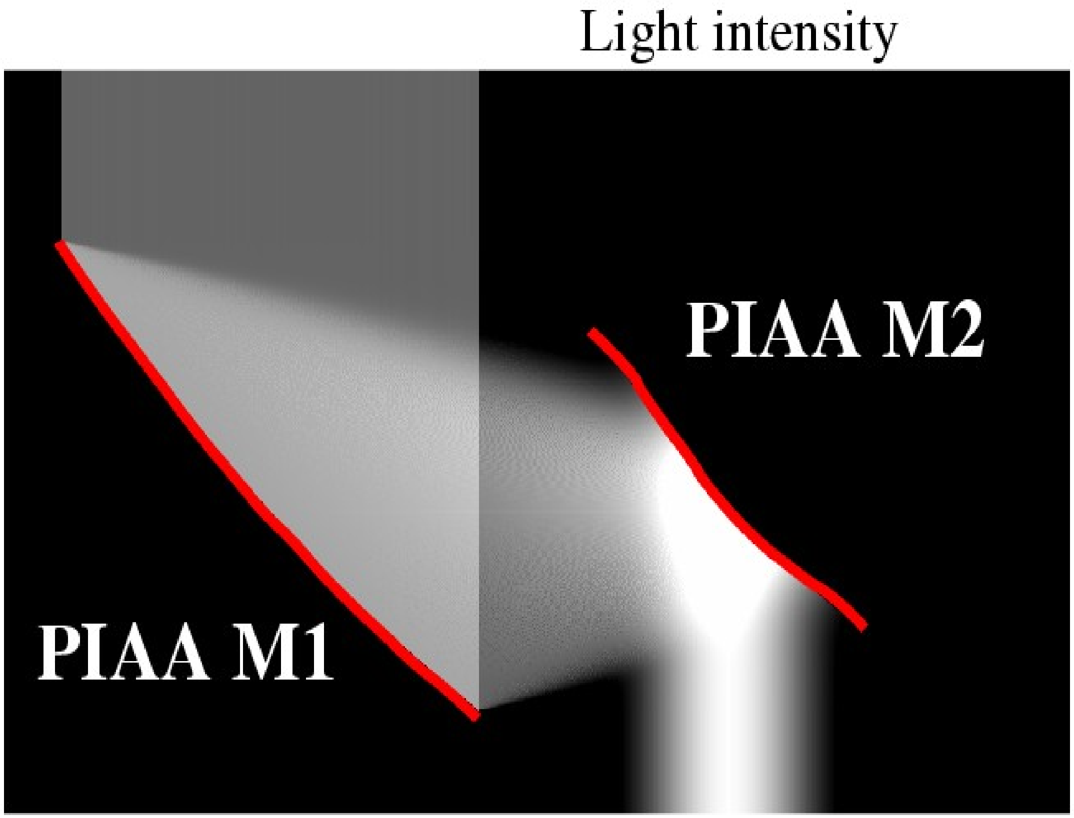


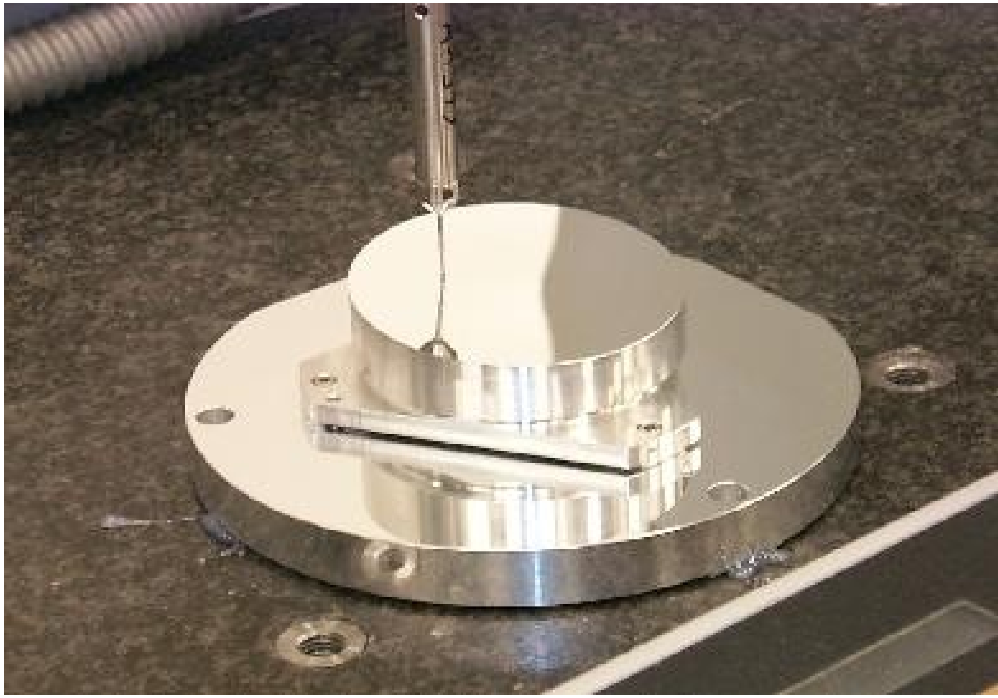
FIG. 9.—Broad-bandwidth light reduction effect on one quadrant of focal plane. The simulation is based on a rectangular spectrum distribution with total bandwidth of $0.6\lambda_0$. (*a*) $\log_{10}$ relative intensity image when phase $\phi(x, y) = a\tan[(0.5-\epsilon)2\pi x/D] + a\tan[(0.5-\epsilon)2\pi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

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

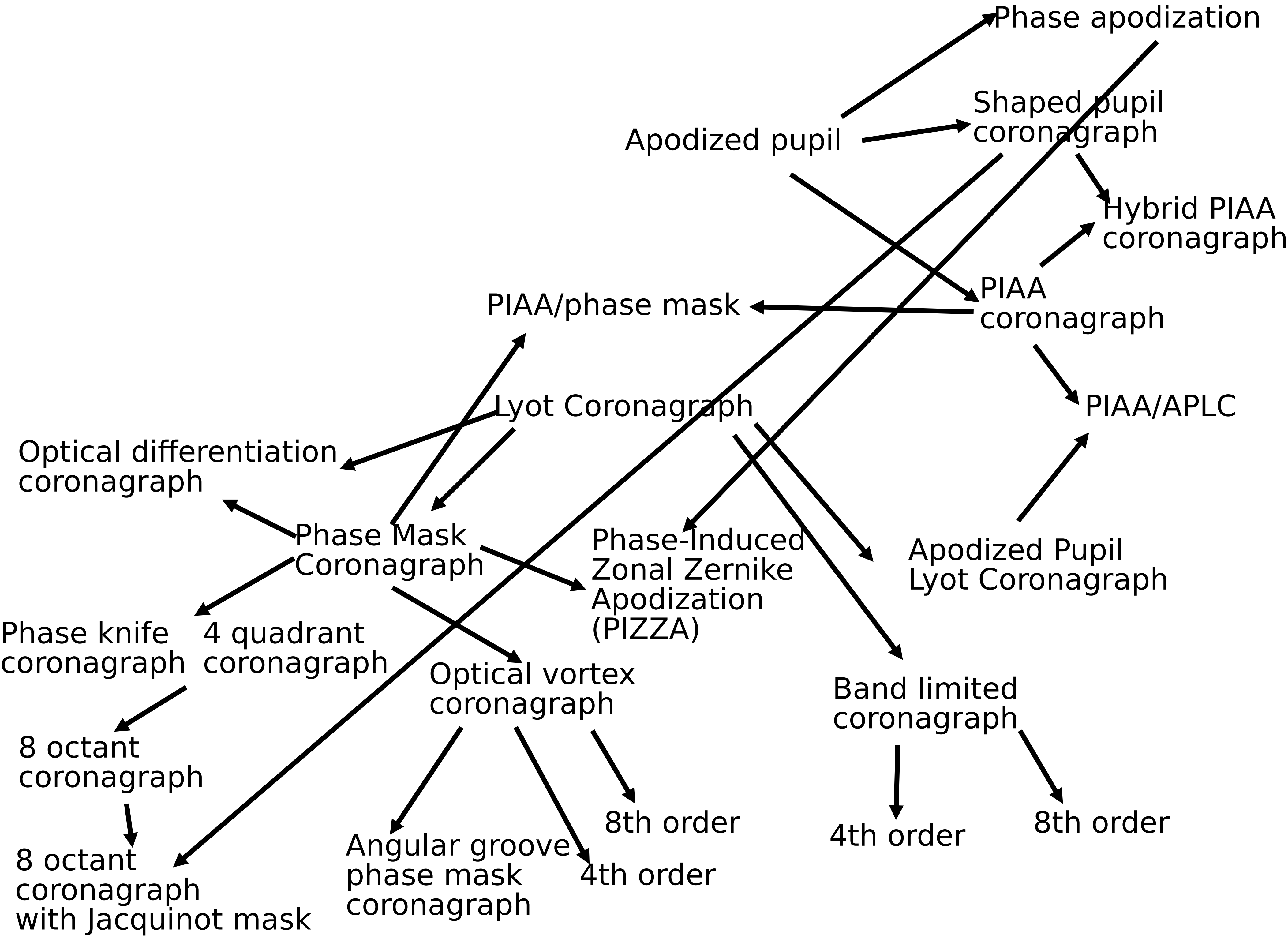
Phase-Induced Amplitude Apodization Coronagraph (PIAAC)

Lossless apodization by aspheric optics.





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


Phase apodization
Shaped pupil coronagraph
Apodized pupil
Hybrid PIAA coronagraph
PIAA coronagraph
PIAA/phase mask
Lyot Coronagraph
PIAA/APLC
Optical differentiation coronagraph
Phase Mask Coronagraph
Phase-Induced Zonal Zernike Apodization (PIZZA)
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
8 octant coronagraph with Jacquinot mask

''Interferometric'' coronagraphs

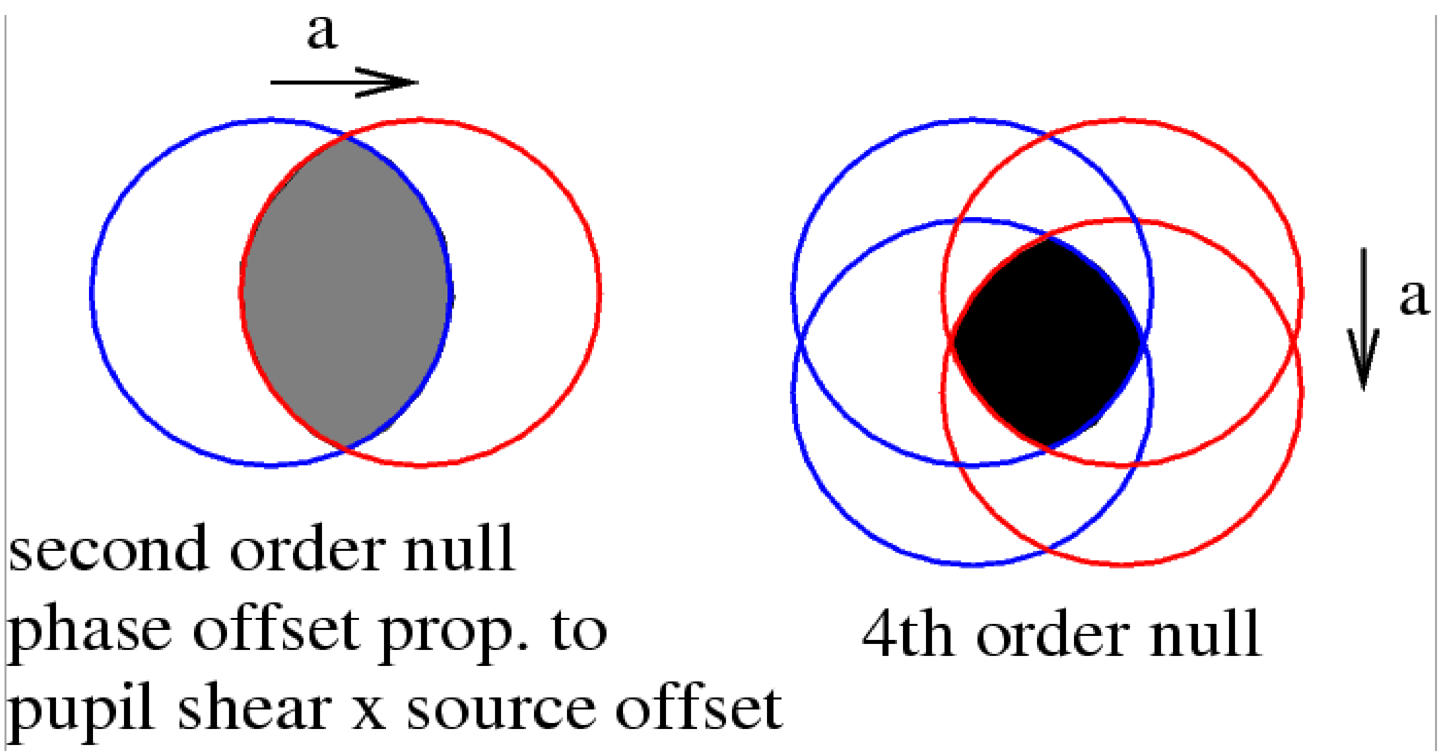
= Nulling interferometer on a single pupil telescope
- Creates multiple (at least 2) beams from a single telescope beam
- Combines them to produce a destructive interference on-axis and constructive interference off-axis

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

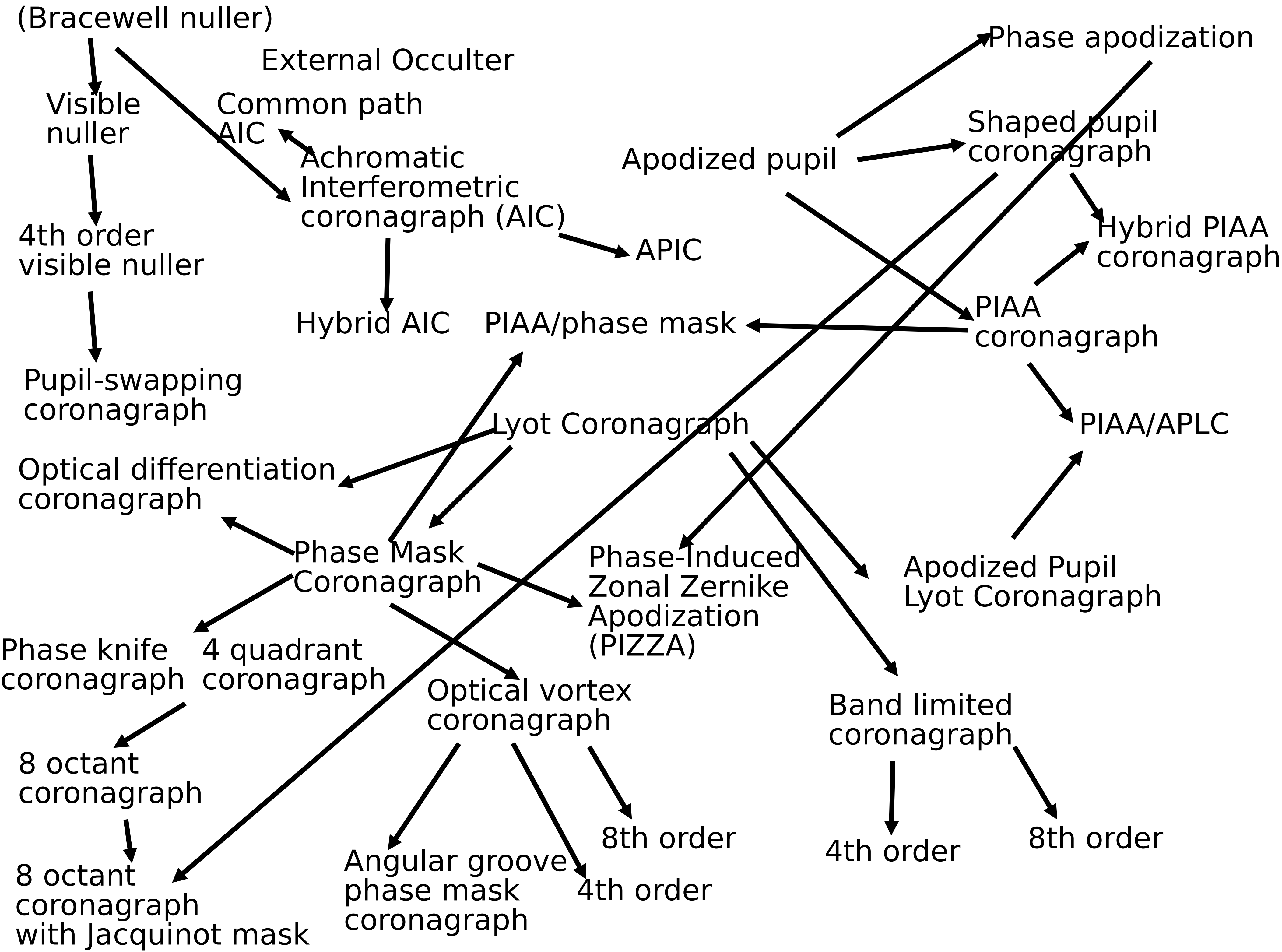
Visible Nuller Coron. (VNC)



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

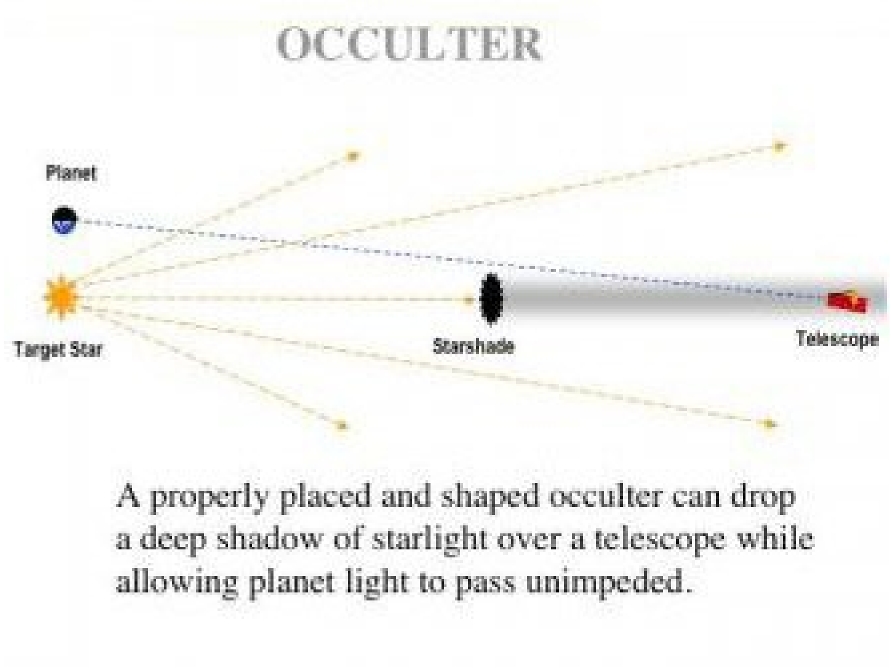
Sounding rocket (PICTURE)

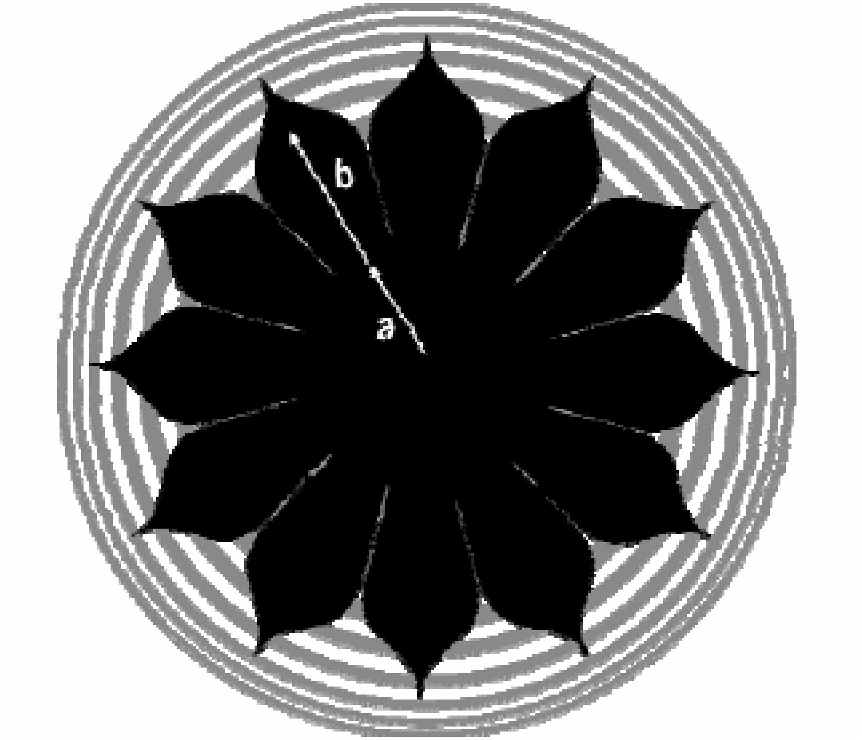
Mennesson, Shao ... 2003, SPIE 4860, 32

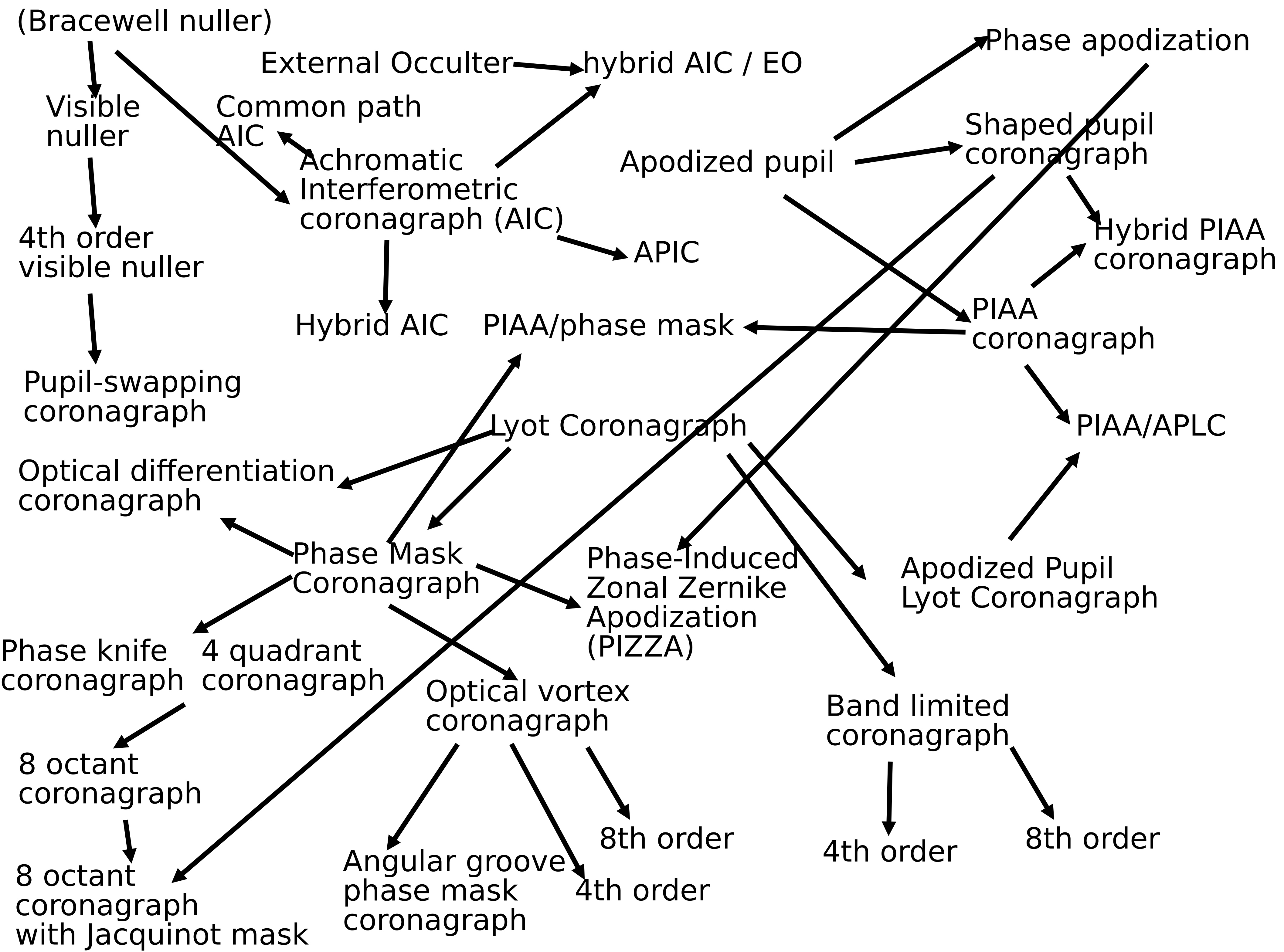


(Bracewell nuller)
External Occulter
Visible nuller
Common path AIC
Achromatic Interferometric coronagraph (AIC)
Apodized pupil
Phase apodization
Shaped pupil coronagraph
Hybrid PIAA coronagraph
4th order visible nuller
APIC
Hybrid AIC
PIAA/phase mask
PIAA coronagraph
Pupil-swapping coronagraph
Lyot Coronagraph
PIAA/APLC
Optical differentiation coronagraph
Phase Mask Coronagraph
Phase-Induced Zonal Zernike Apodization (PIZZA)
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
8 octant coronagraph with Jacquinot mask
Angular groove phase mask coronagraph
4th order

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
4th order visible nuller
APIC
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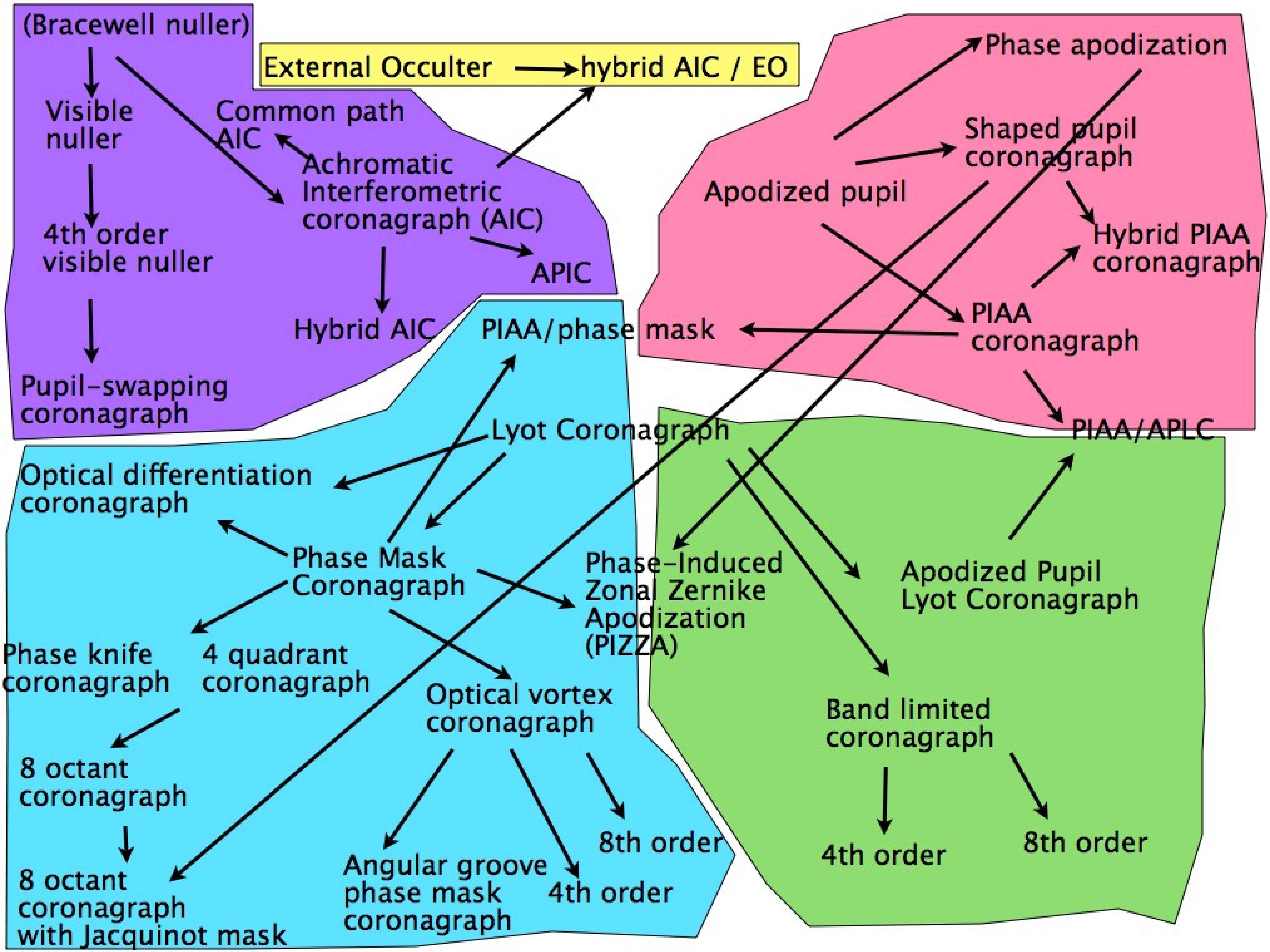
Angular groove phase mask coronagraph
4th order


(Bracewell nuller)
External Occulter
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Achromatic Interferometric coronagraph (AIC)
4th order visible nuller
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8th order
4th order
8th order

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:

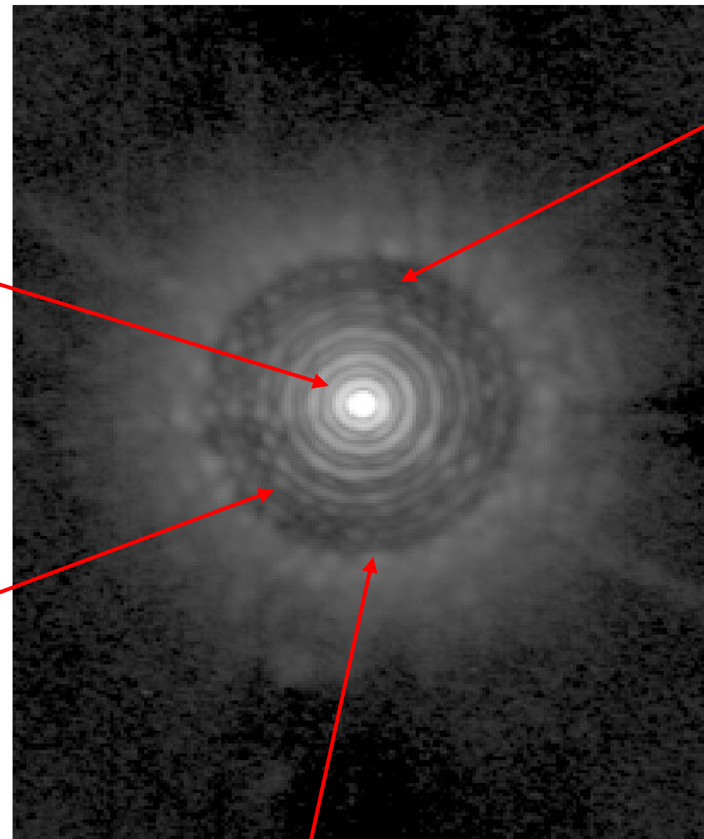
- Coronagraph or nulling interferometer to optically remove starlight and isolate planet light (overcomes diffraction)

- 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)

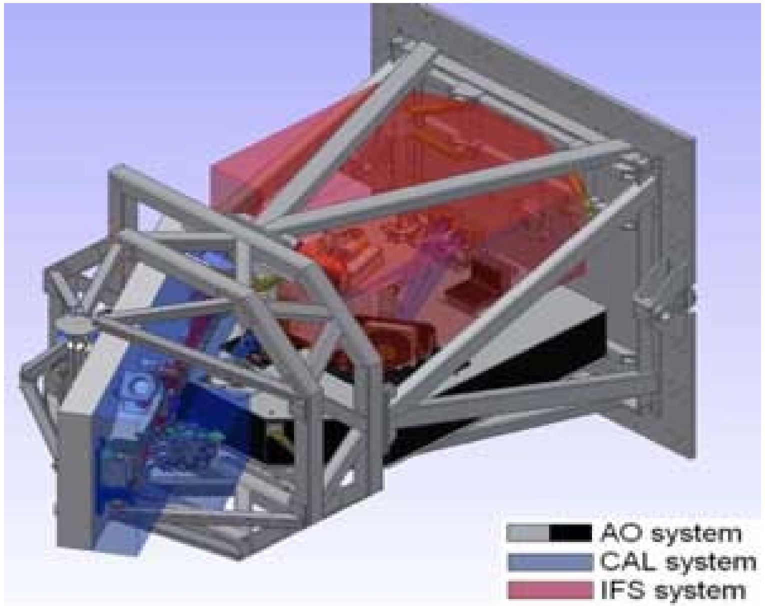
Control radius of AO

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

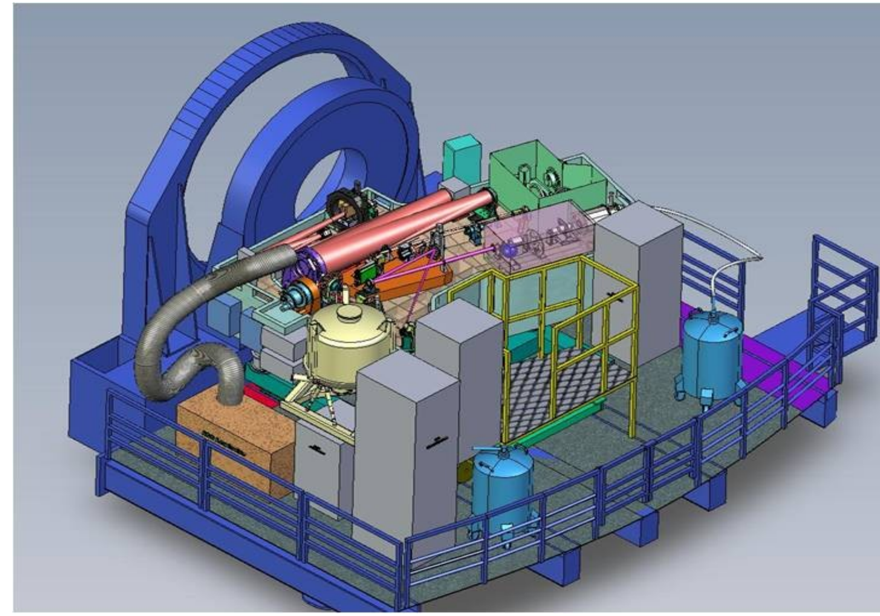
Current and future high contrast systems - ground

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
  2000 element MEMS deformable mirror
  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 started 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 started observations in 2014
  ExAO system + coronagraph
  Highly stable bench
  Includes Integral Field Spectrograph to help remove speckles and acquire spectra
  Includes differential polarimetric imager

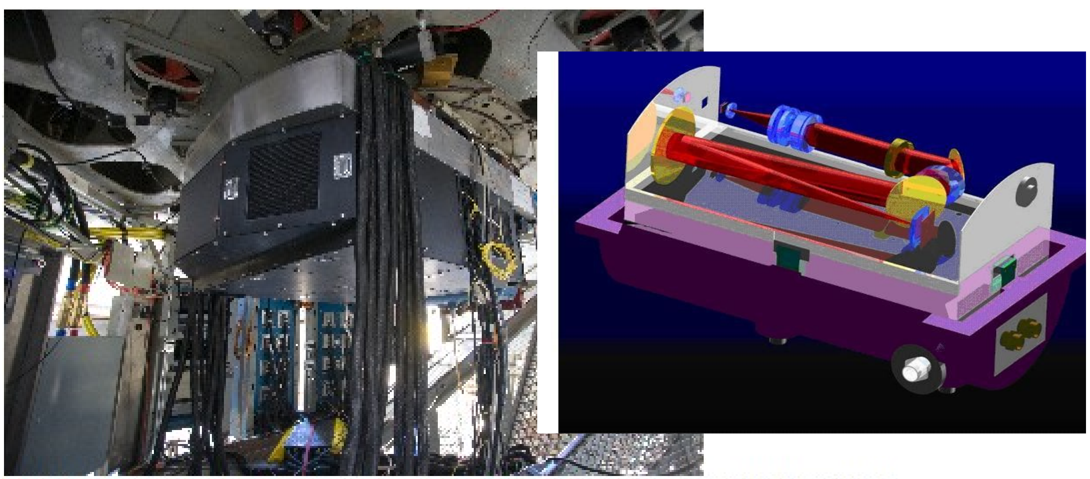
Current and future high contrast systems - ground



Gemini Planet Imager

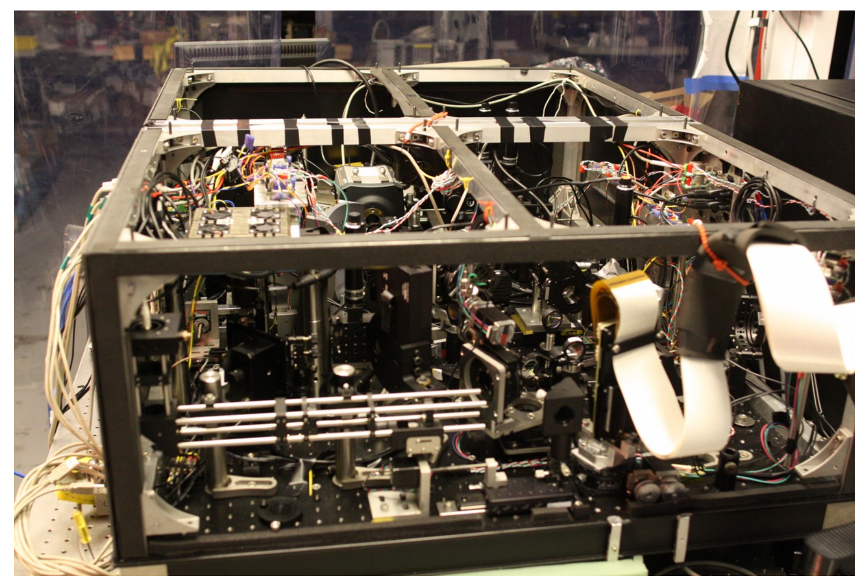


SPHERE (European Southern Observatory)



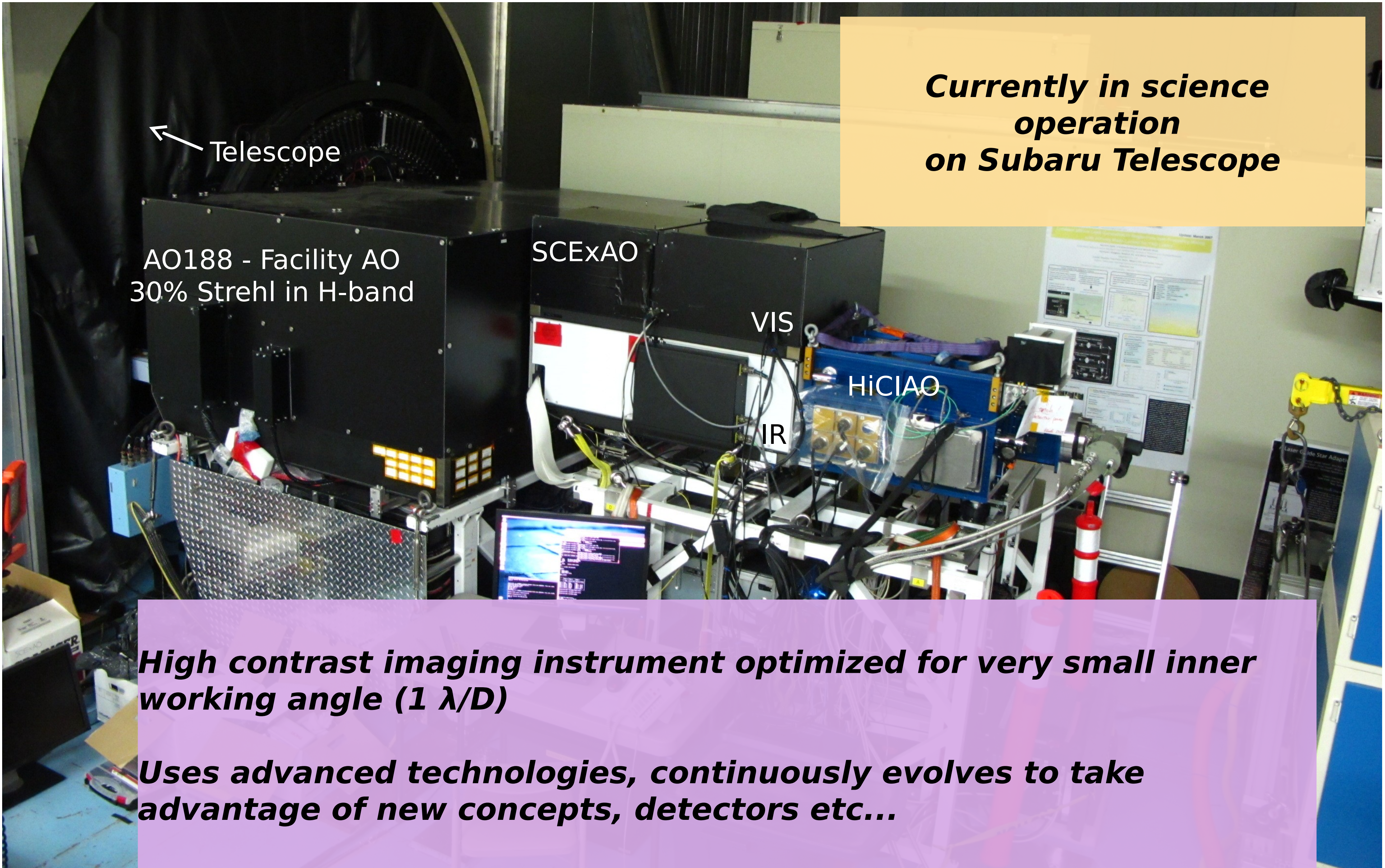
PALM-3000 installed at the Cass focus of the Hale Telescope at Palomar Mountain. Photo: Scott Kardel.

PALM3000/P1640 (Palomar 5-m Telescope)



Subaru Coronagraphic Extreme-AO

Subaru Coronagraphic Extreme AO (SCExAO)



Currently in science operation on Subaru Telescope

High contrast imaging instrument optimized for very small inner working angle (1 λ/D)

Uses advanced technologies, continuously evolves to take advantage of new concepts, detectors etc...

Plans for SCExAO to become visitor instrument on TMT under study → will submit to TMT technical and scientific proposal

Wavefront sensing:

- Non-modulated pyramid WFS (VIS)
- Coronagraphic low order wavefront sensor (IR) for non-common tip/tilt errors
- Near-IR speckle control

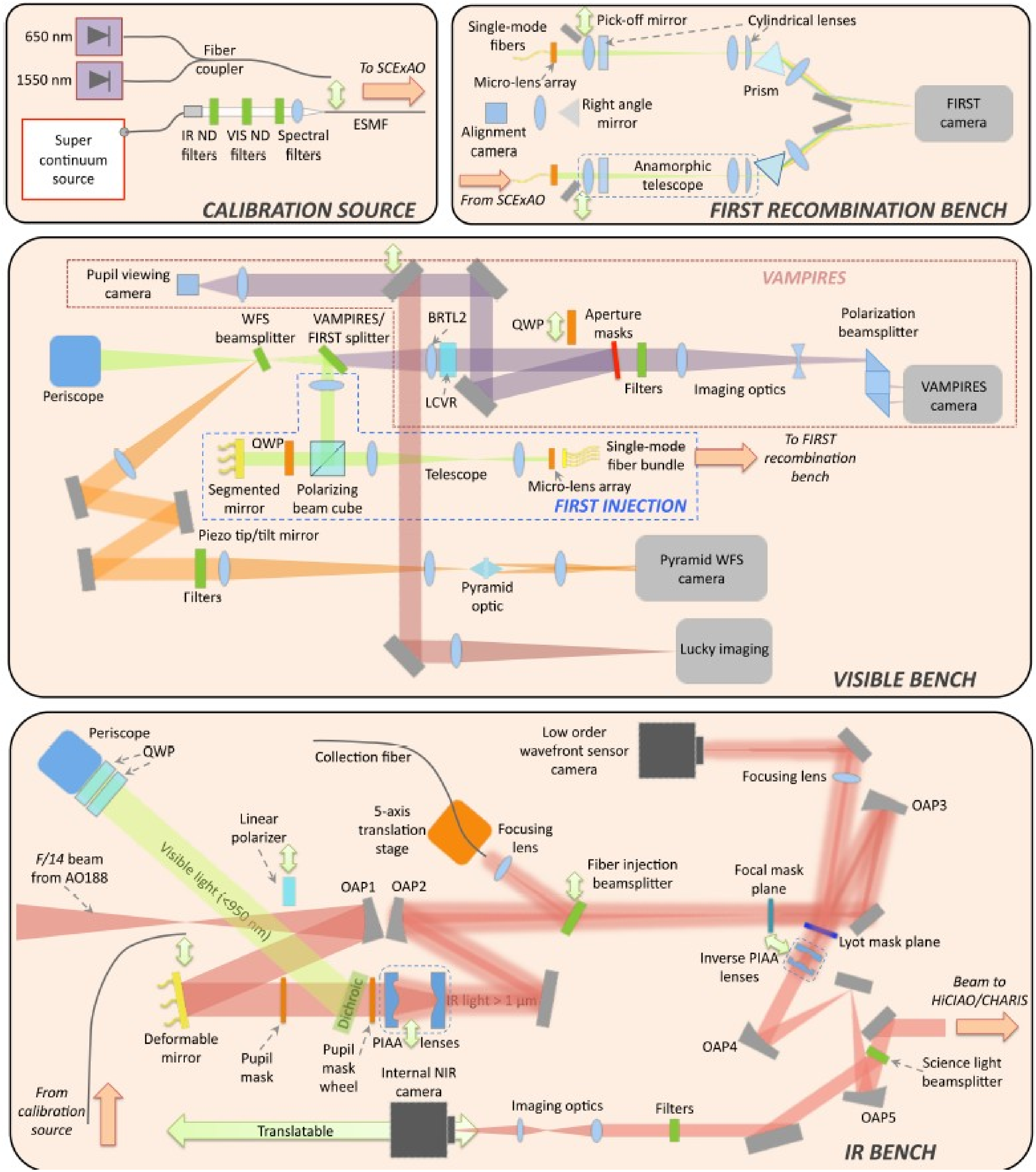
2k MEMS DM

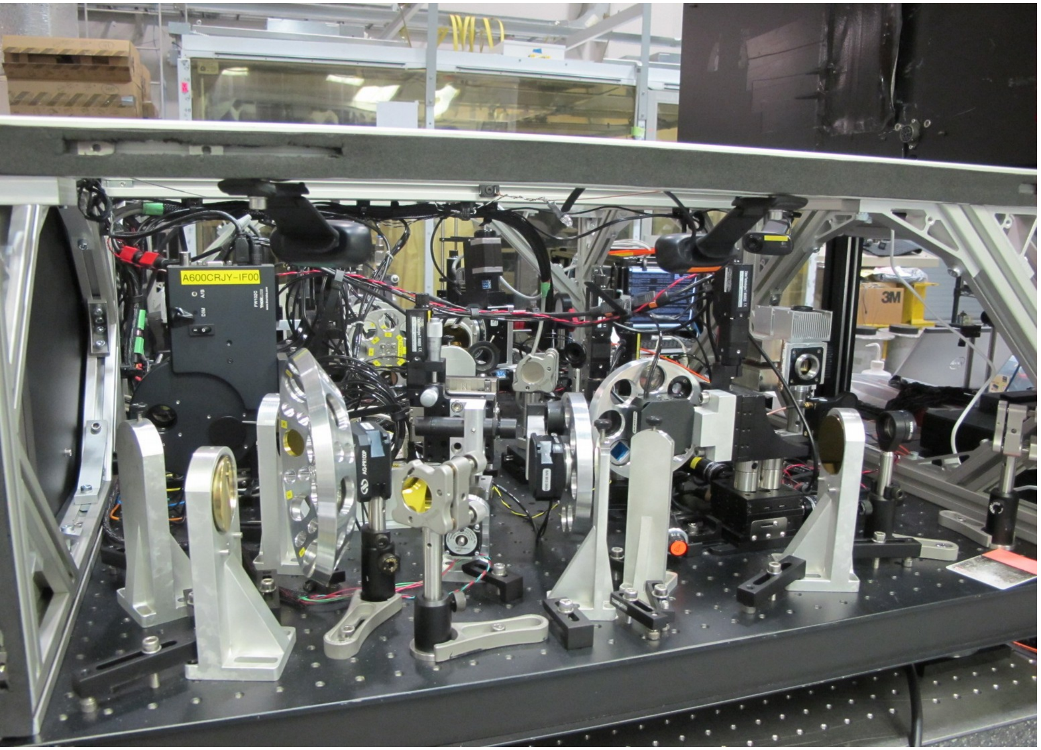
Numerous **coronagraphs** – PIAA, Vector Vortex, 4QPM, 8OPM, shaped pupil (IR)

Visible Aperture Masking Polarimetric Interferometer for Resolving Exoplanetory Signatures (VAMPIRES) (VIS)

Fibered Imager for a Single Telescope (FIRST) (VIS)
Fourier Lucky imaging (VIS)

Broadband diffraction limited internal cal. Source + phase turbulence simulator

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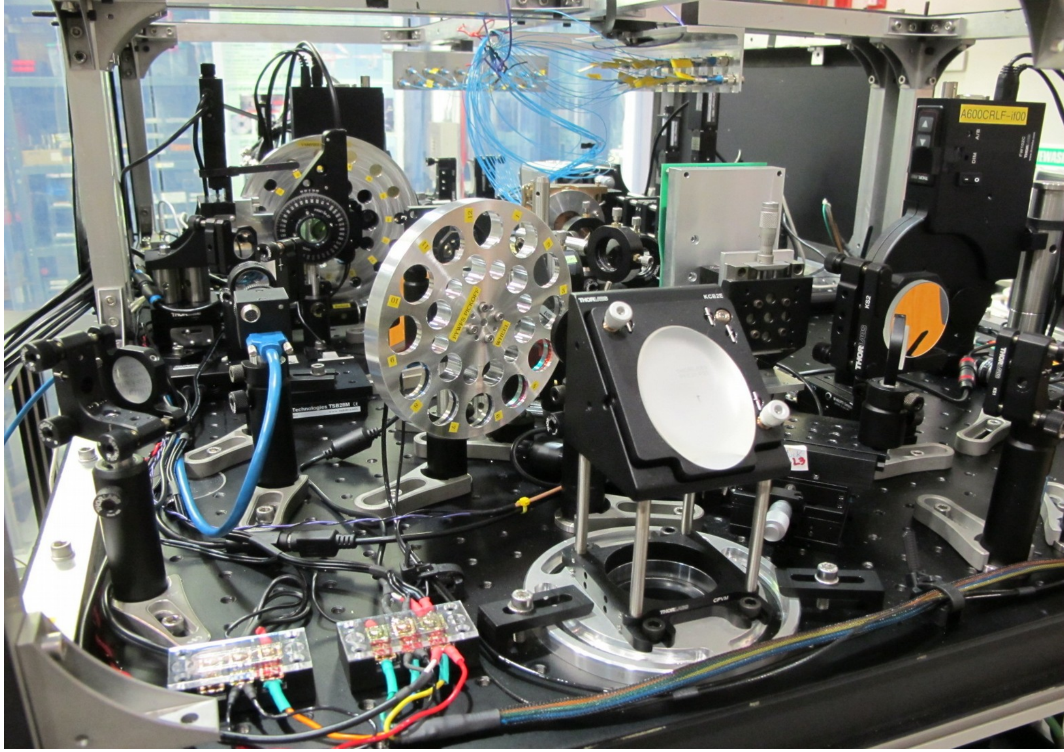
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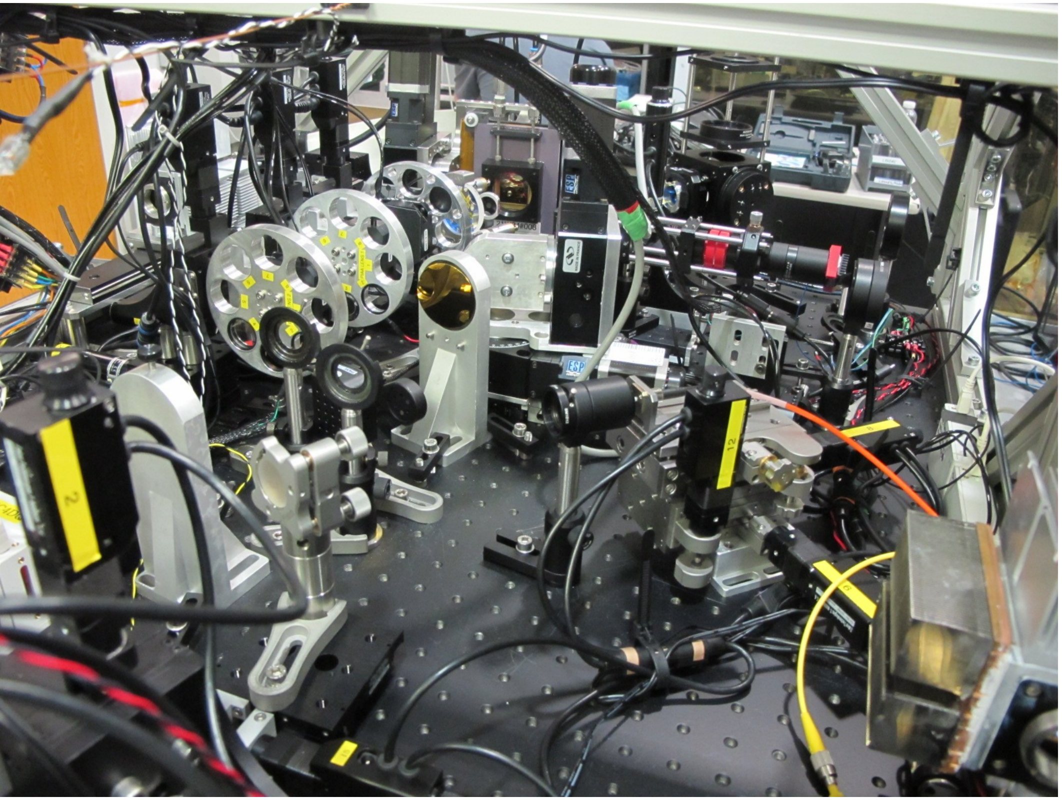
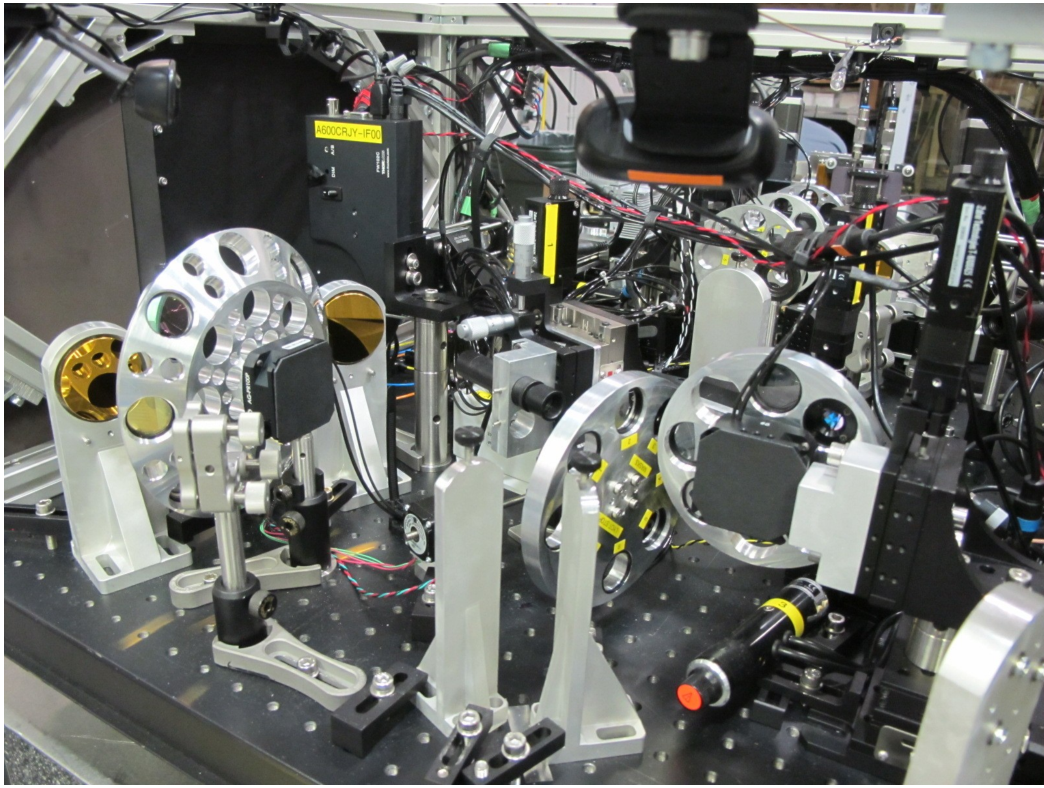


A600CRJY-IF00

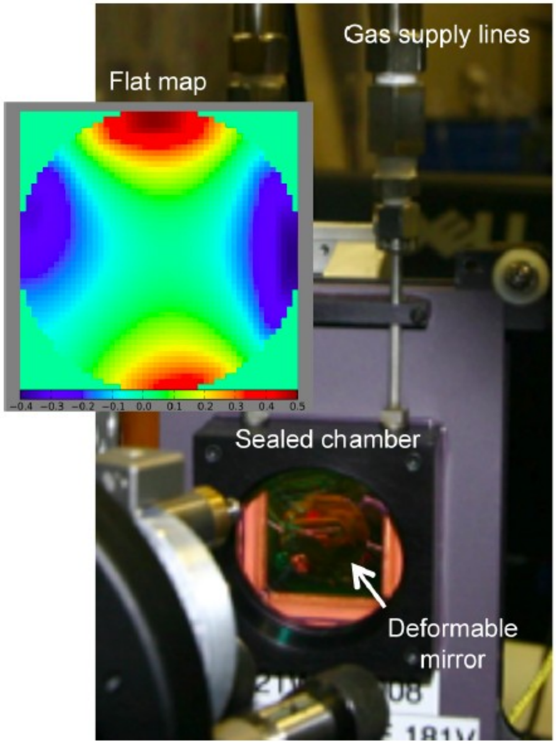
How SCExAO achieves high contrast

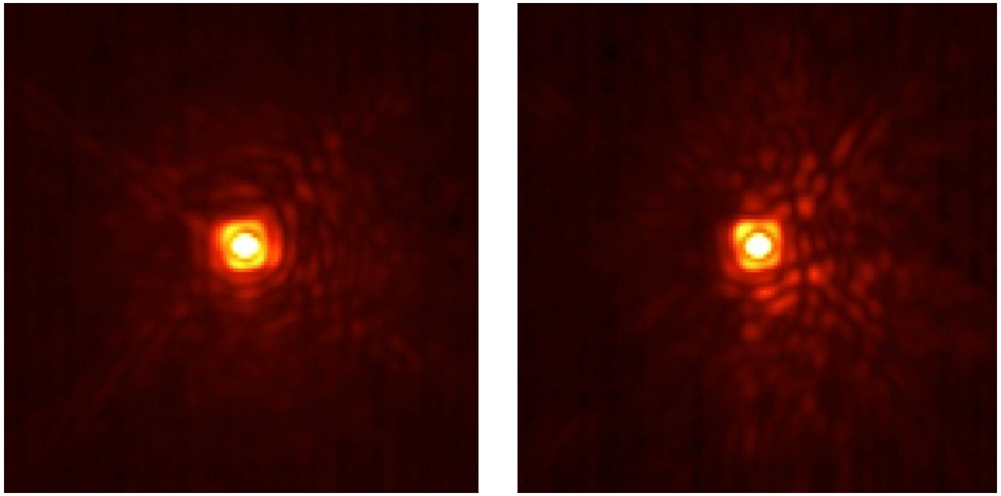
(1) Small IWA, high throughput Coronagraphy
→ removes diffraction (Airy rings), transmits r>1 l/D region

(2) Extreme-AO with fast diffraction-limited WFS
→ removes wavefront errors

(3) Near-IR LOWFS
→ keeps star centered on coronagraph and controls Focus, Astig, etc..
→ records residual WF errors to help process data

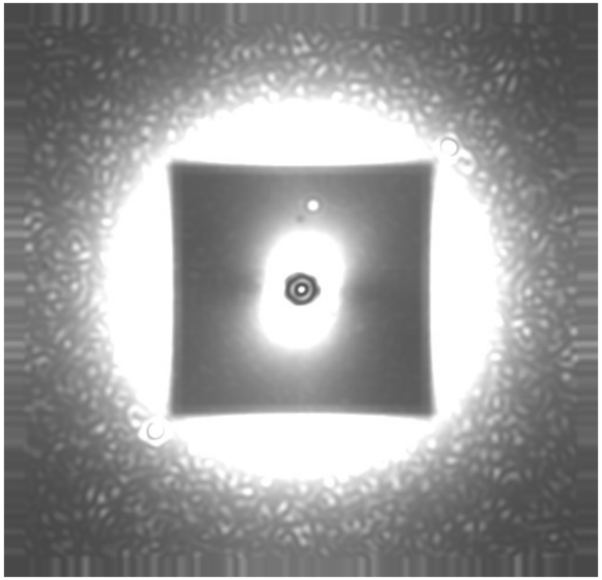
(4) Fast Near-IR Speckle control
→ modulates, removes and calibrates residual speckles





Speckle nulling on-sky

Wavefront control for High contrast imaging



<u>Ground-based systems</u>

Residual speckle field is brighter than planets(s)

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

→ calibrating speckles is extremely important

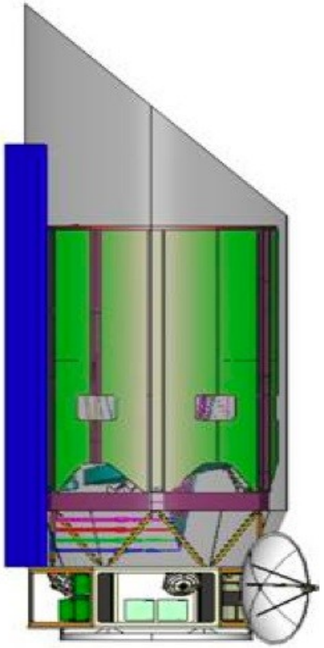
<u>Space-based ultra-high contrast systems</u>

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

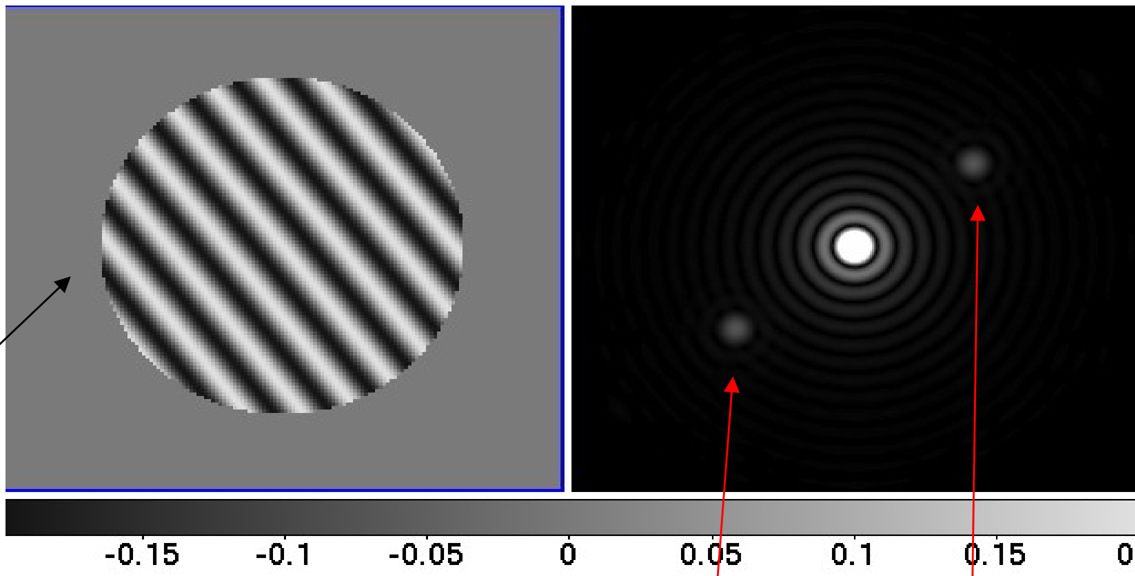
→ speckles need to be reduced at or below the planet image surface brightness level

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

→ need to build extremely stable system



Relationship between speckle and wavefront errors



pupil plane complex amplitude

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

Cosine aberration in pupil phase

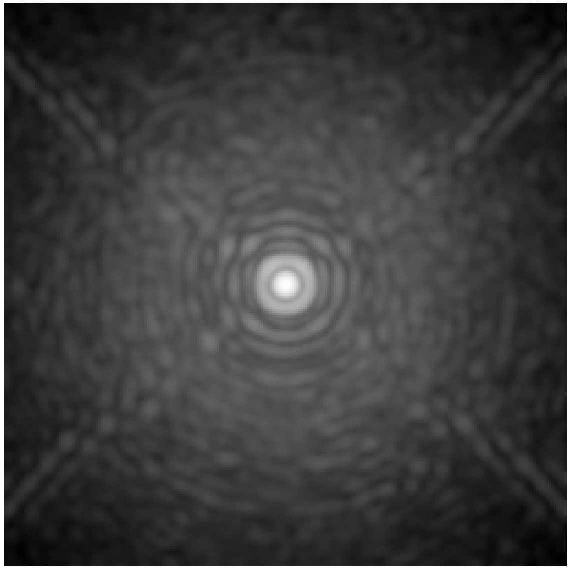
$$\phi(\vec{u}) = \frac{2\pi h}{\lambda} \cos\left(2\pi \vec{f}\vec{u} + \theta\right)$$

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

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

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

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

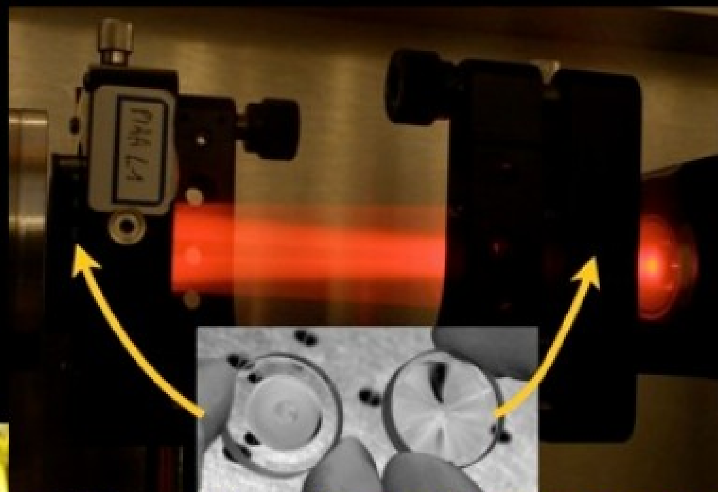
CORRECTION: Put "anti speckles" on top of "speckles" to have destructive interference between the two (Electric Field Conjugation, Give'on et al 2007)

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

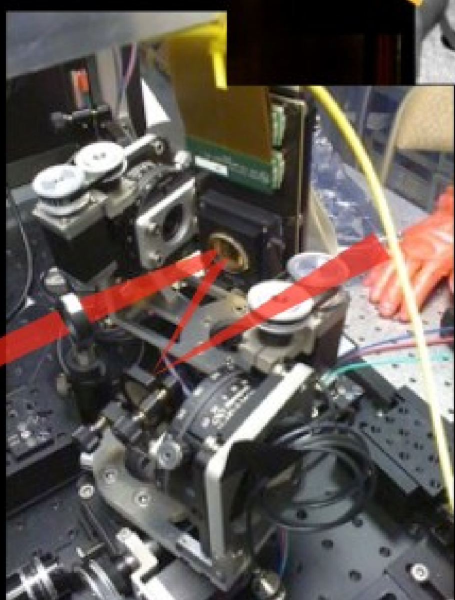
Fundamental advantage:
Uses science detector for wavefront sensing:
"What you see is EXACTLY what needs to be removed / calibrated"

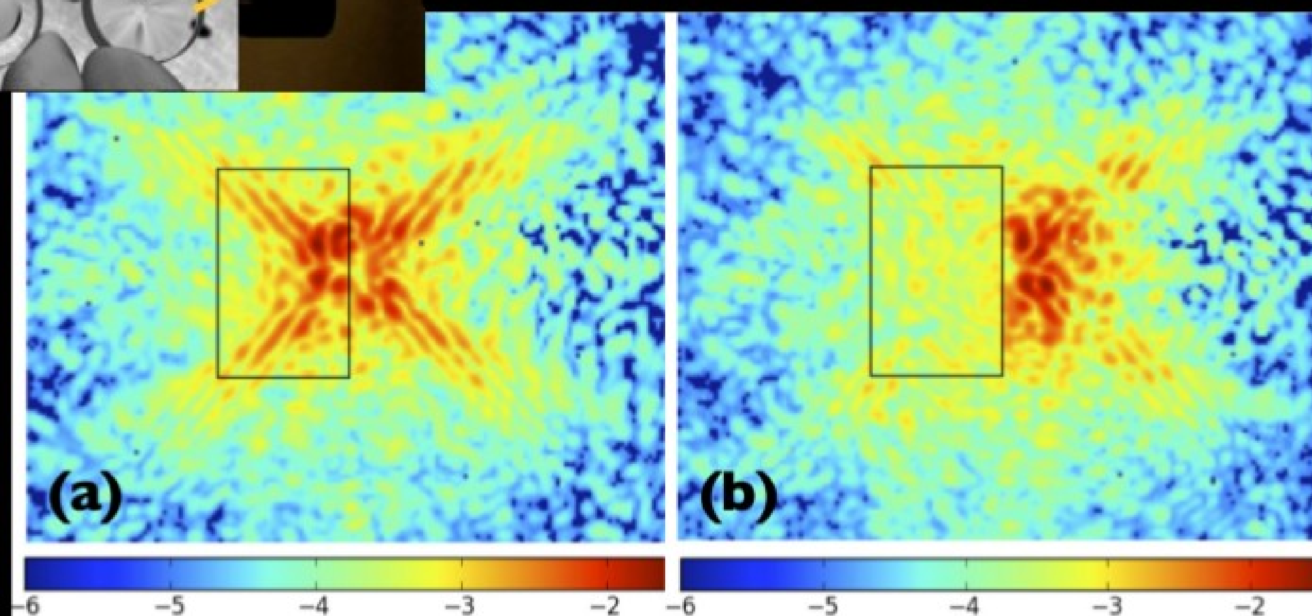
Active speckle control (Martinache et. al)

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





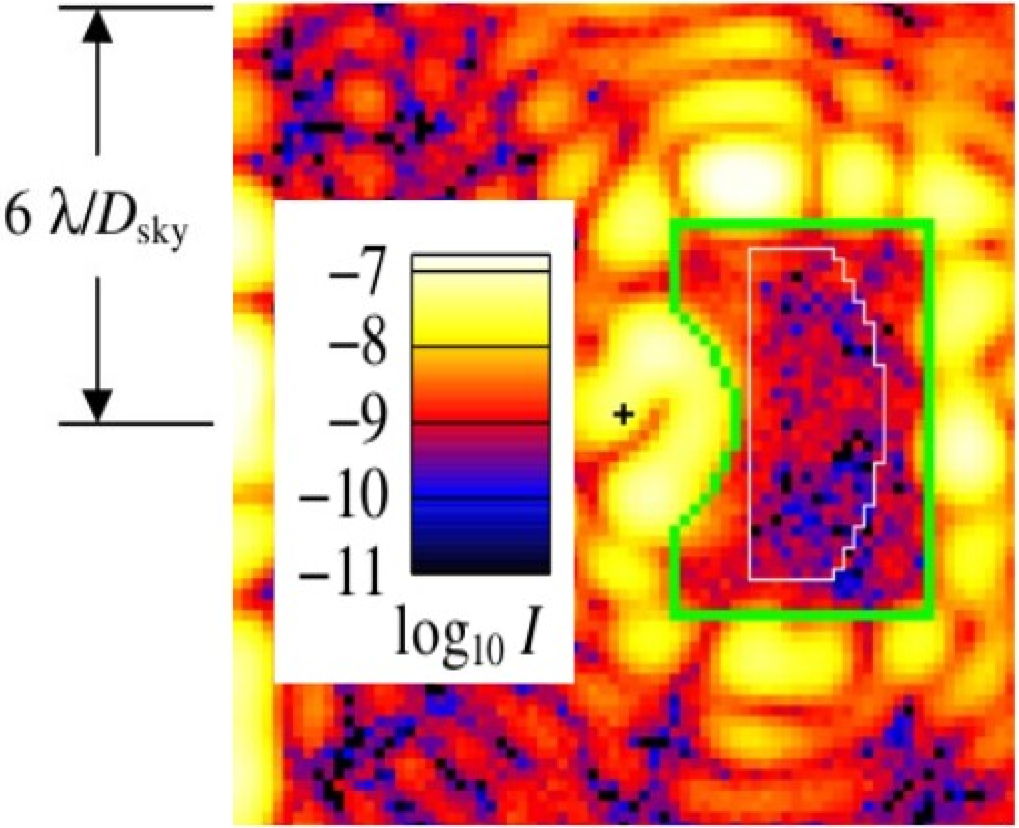
SCExAO's PIAA coronagraph permits speckle control from 1.5 to 14 λ/D

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

Martinache et al, 2012, PASP, 124, 1288

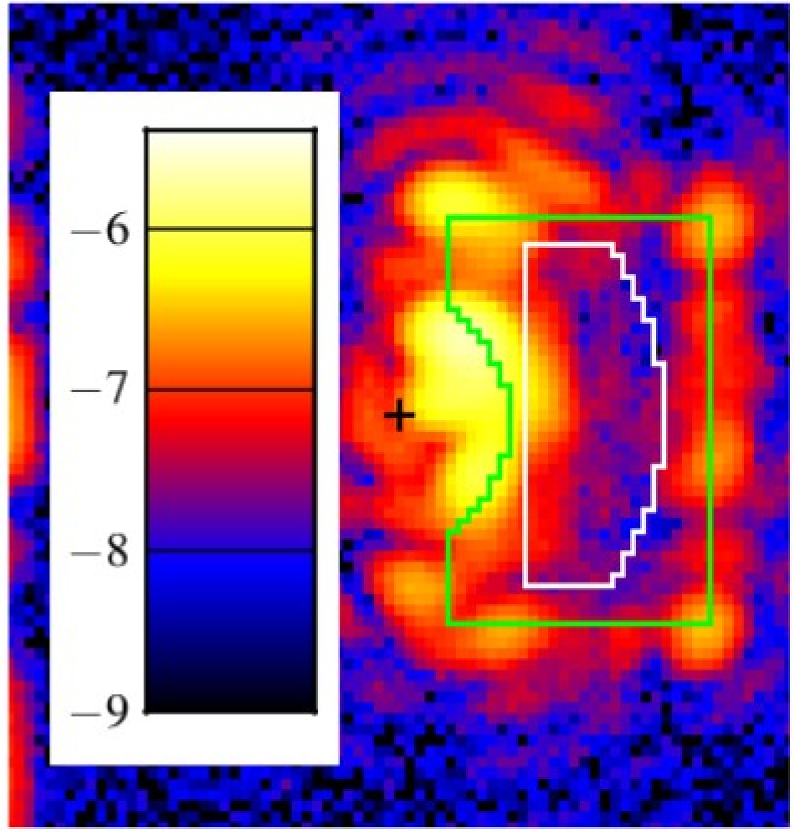
High contrast images obtained in NASA labs
Example: PIAA coronagraph lab results

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)

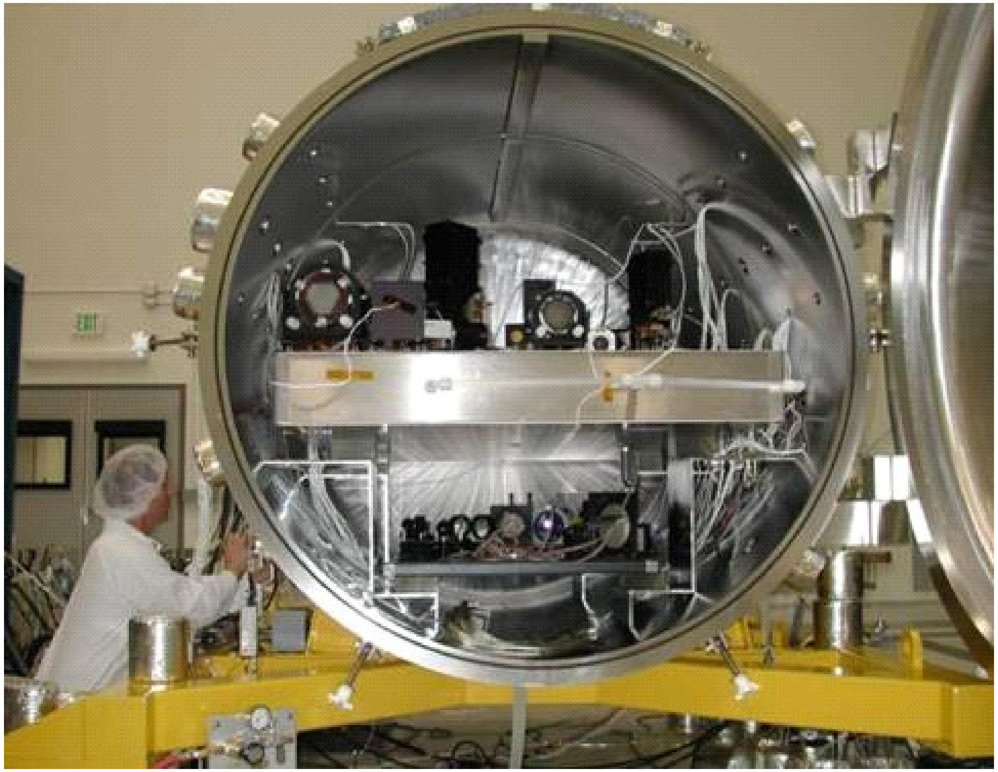
7.5% wide band (770 – 830 nm, in air)



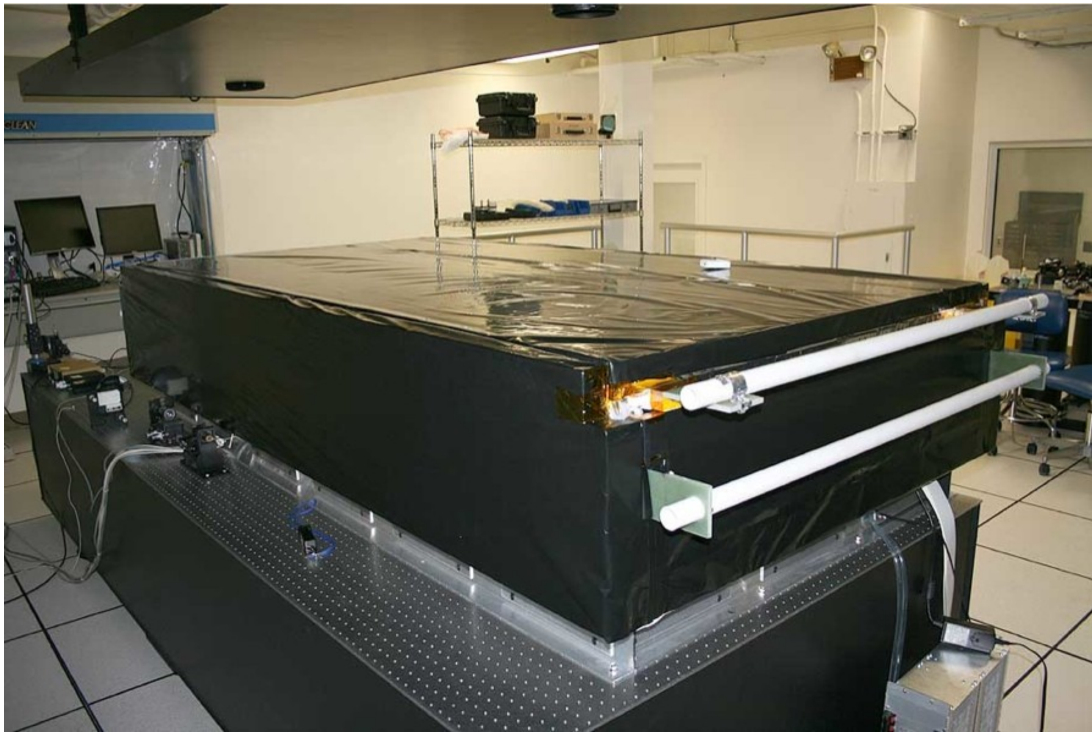
5.10^{-8} contrast from 2 to 4 λ/D,
2.10^{-8} contrast from 3 to 4 λ/D
Contrast performance limited by wavefront instability (test in air)

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

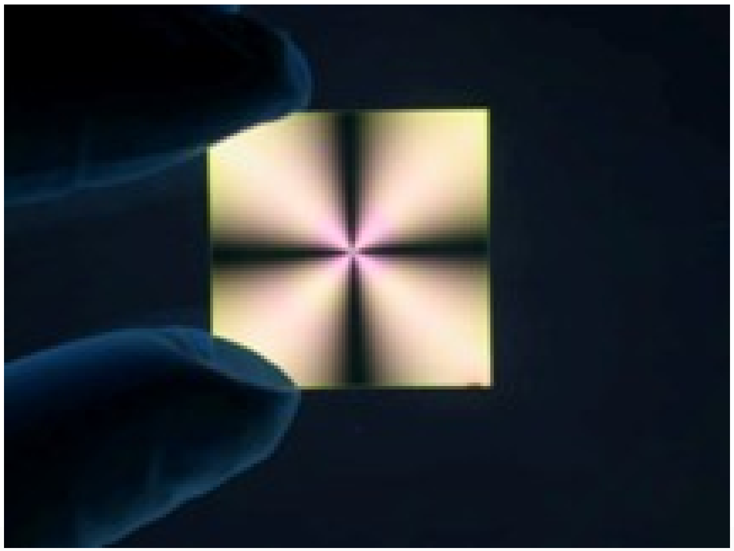
High Contrast Imaging Testbed (HCIT) is a vacuum facility at NASA JPL

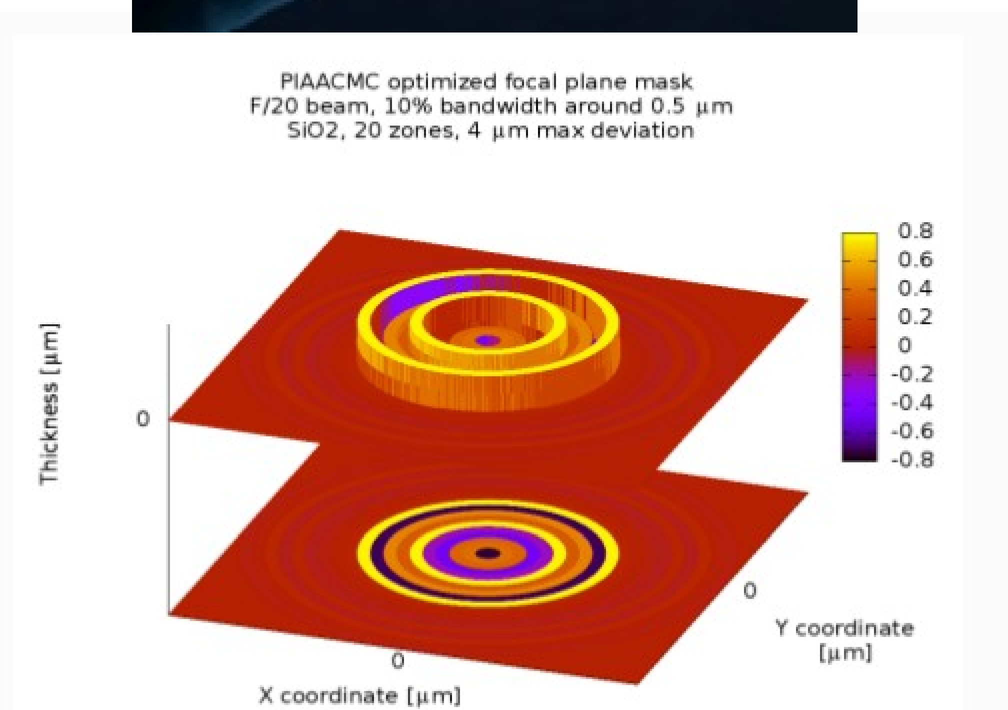


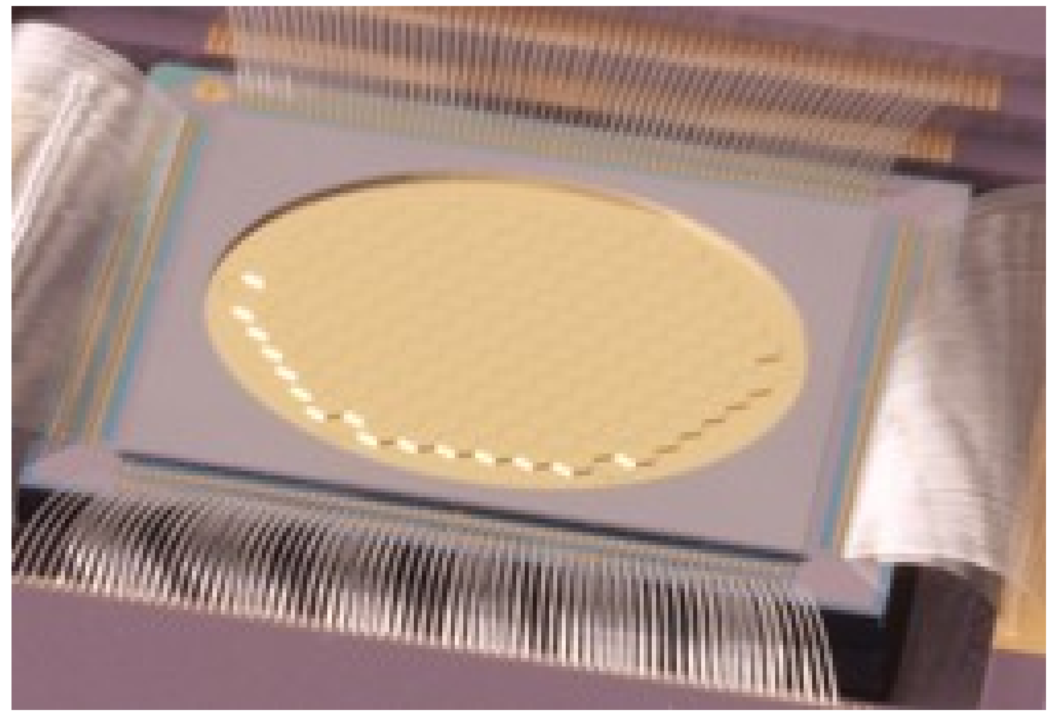
NASA Ames testing PIAA coronagraph / WFC architectures & MEMs DMs.



Technology: components



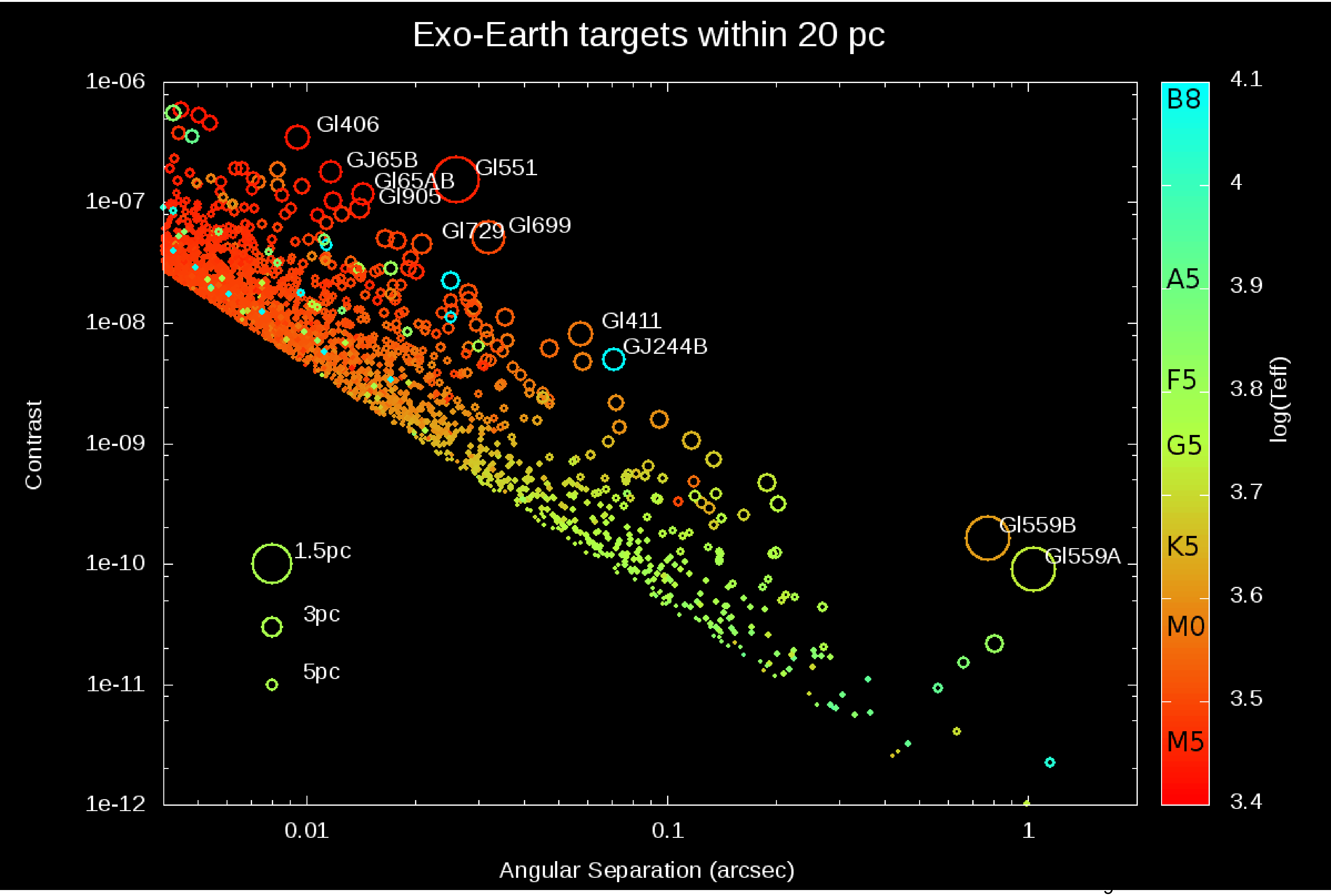


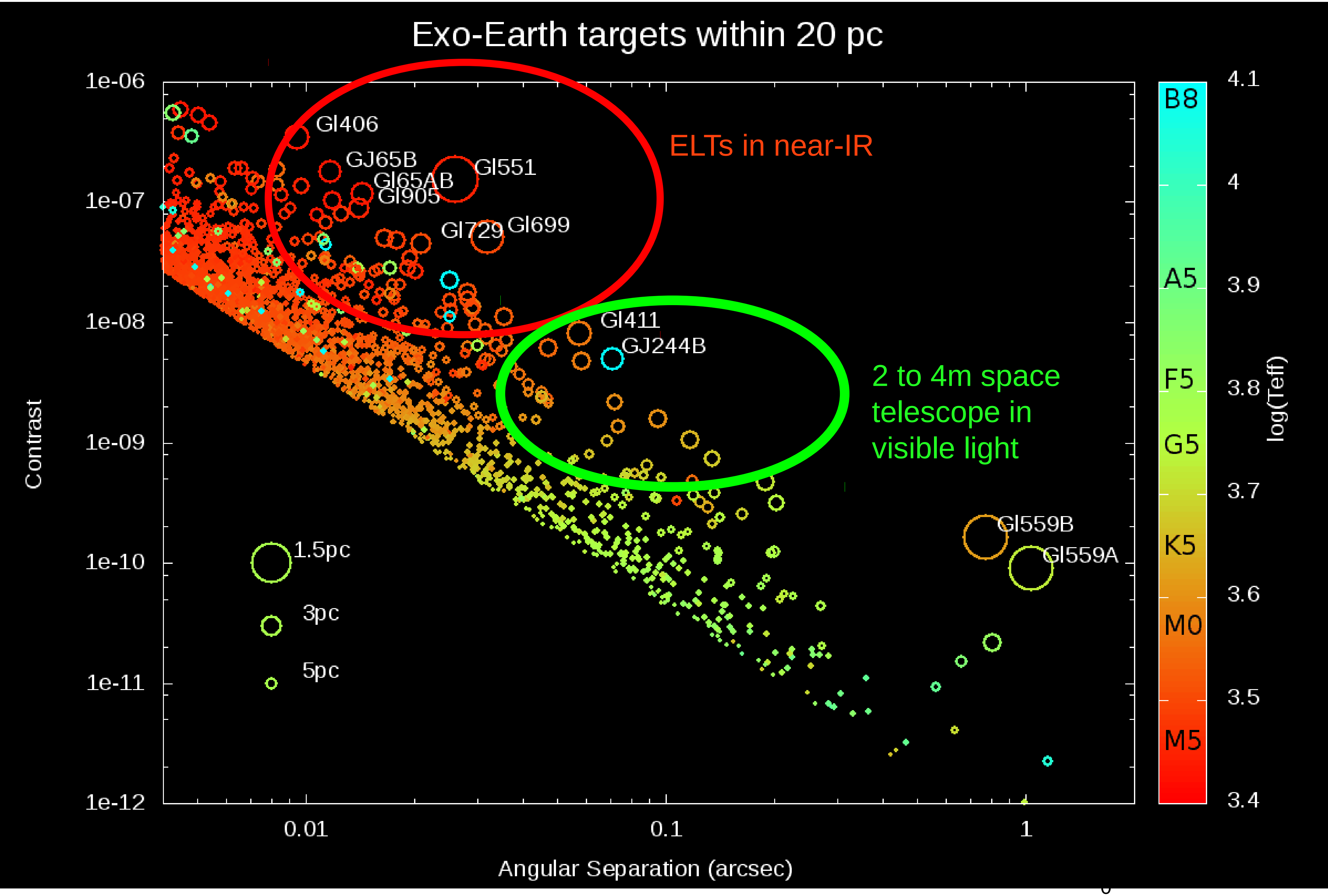


Habitable planet imaging: Scientific opportunities

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

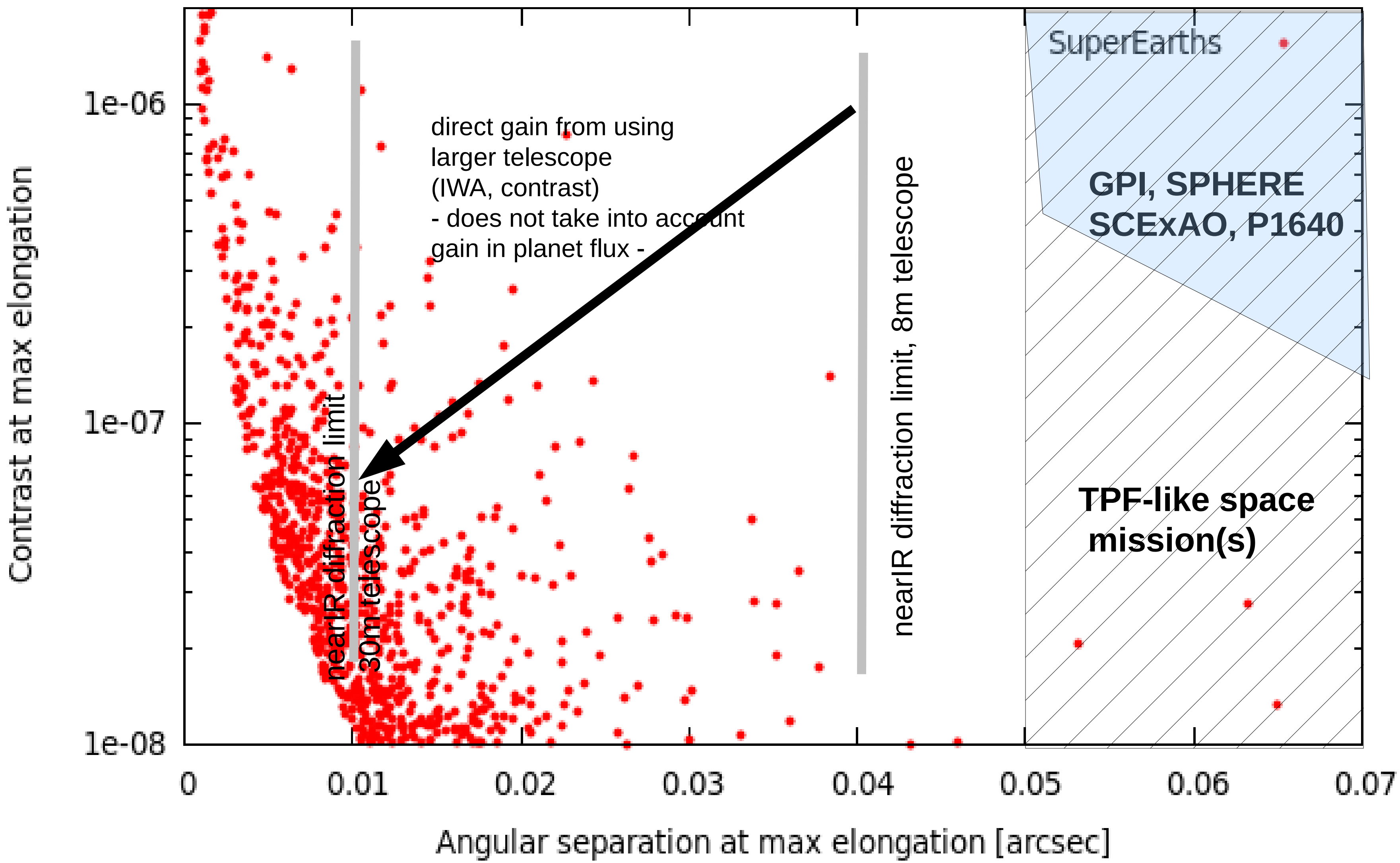

Exo-Earth targets within 20 pc
Contrast
1e-06
1e-07
1e-08
1e-09
1e-10
1e-11
1e-12
0.01
0.1
1
Angular Separation (arcsec)
Gl406
GJ65B
Gl551
Gl65AB
Gl905
Gl729
Gl699
Gl411
GJ244B
Gl559B
Gl559A
1.5pc
3pc
5pc
B8
A5
F5
G5
K5
M0
M5
4.1
4
3.9
3.8
3.7
3.6
3.5
3.4
log(Teff)


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

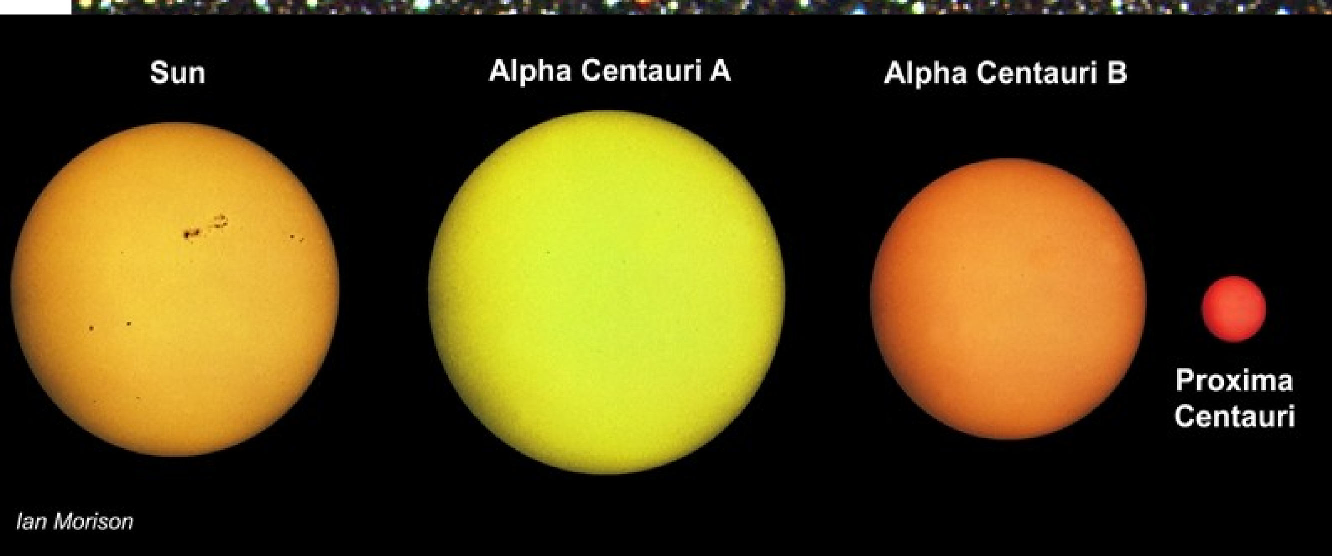
Reflected light planets

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

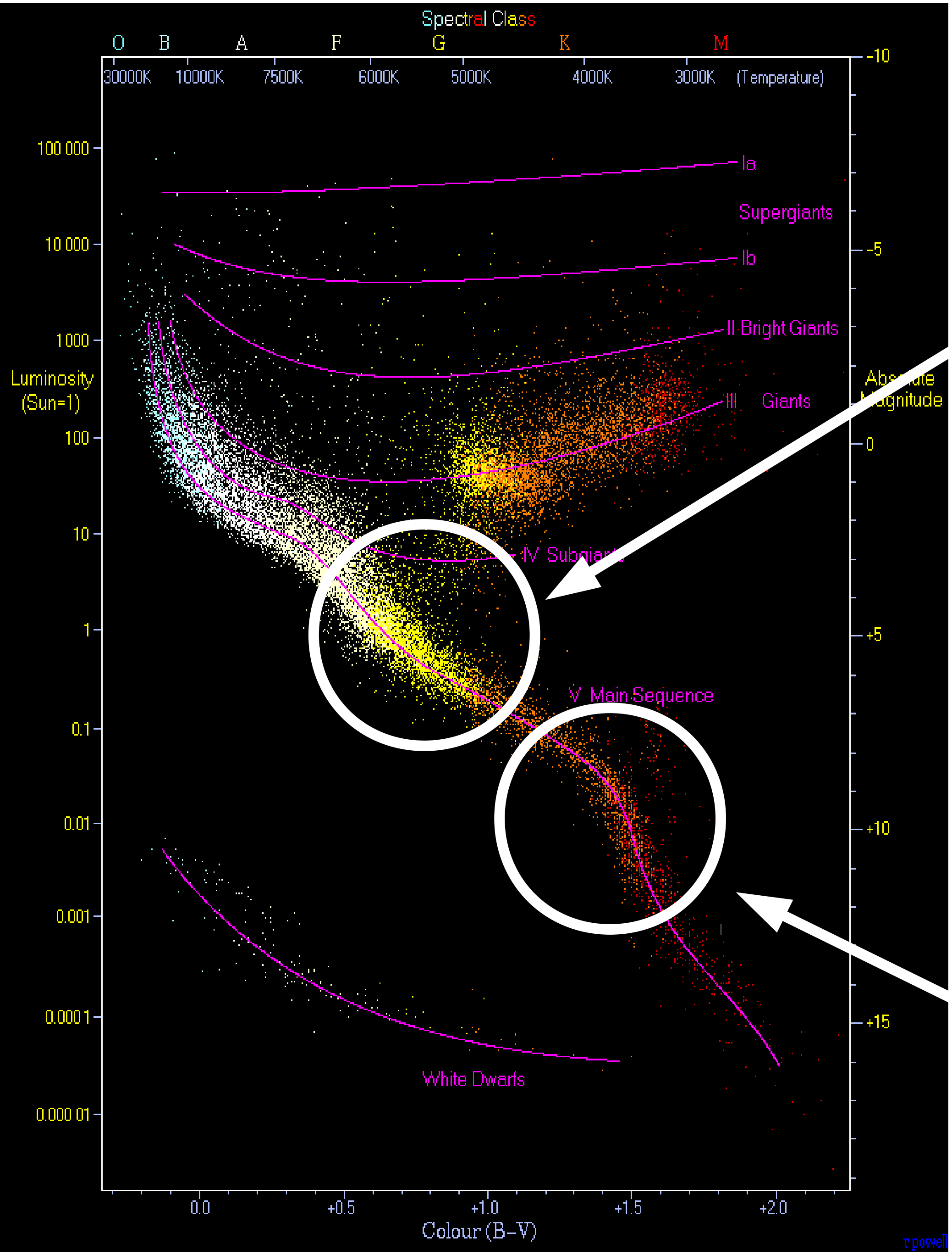
(assumes Earth albedo, contrast and separation for max elongation)



Proxima Centauri



Imaging habitable planets from space and ground



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

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

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

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