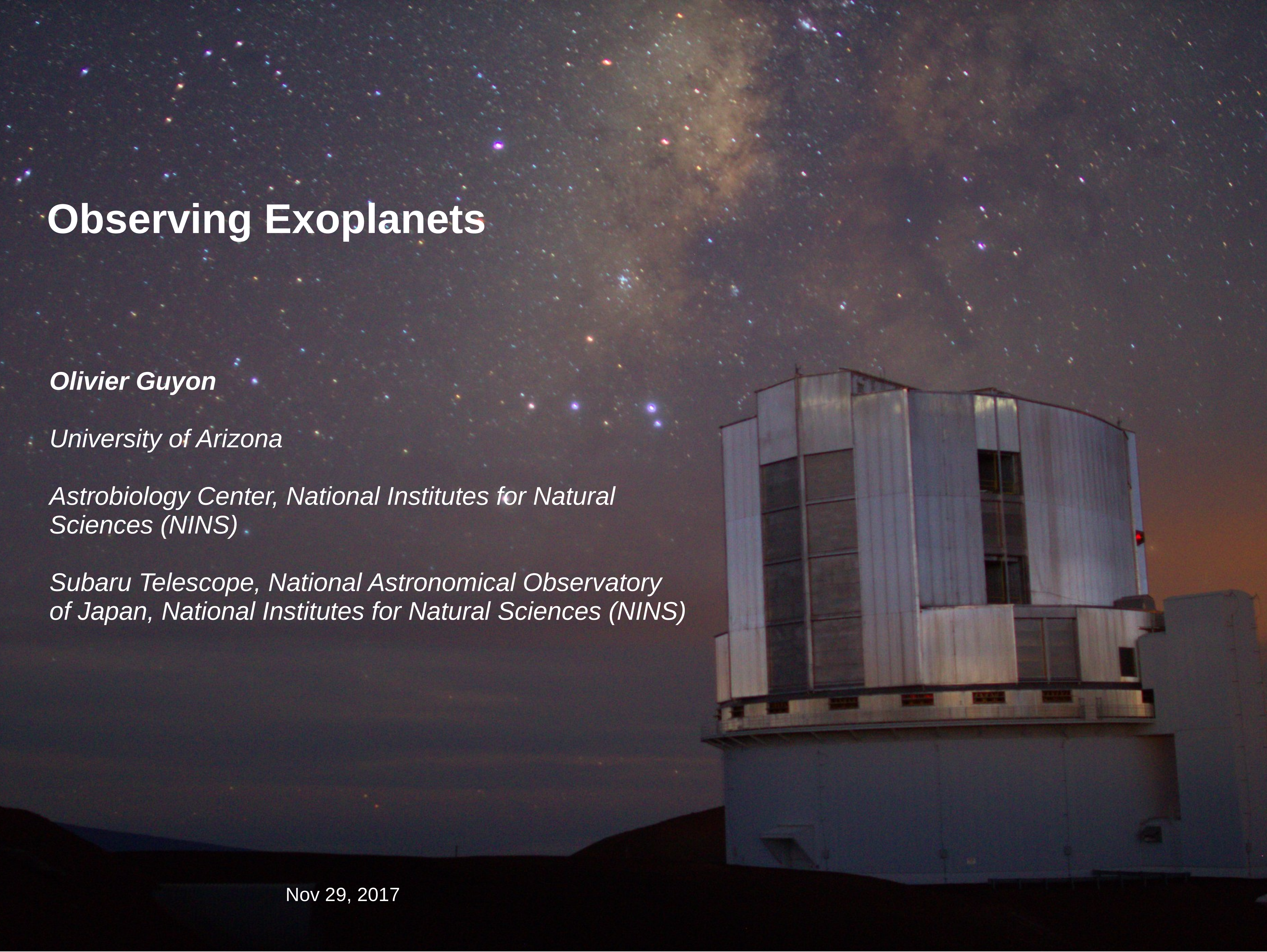


Observing Exoplanets

Olivier Guyon

University of Arizona

Astrobiology Center, National Institutes for Natural Sciences (NINS)

Subaru Telescope, National Astronomical Observatory of Japan, National Institutes for Natural Sciences (NINS)

Nov 29, 2017

My Background

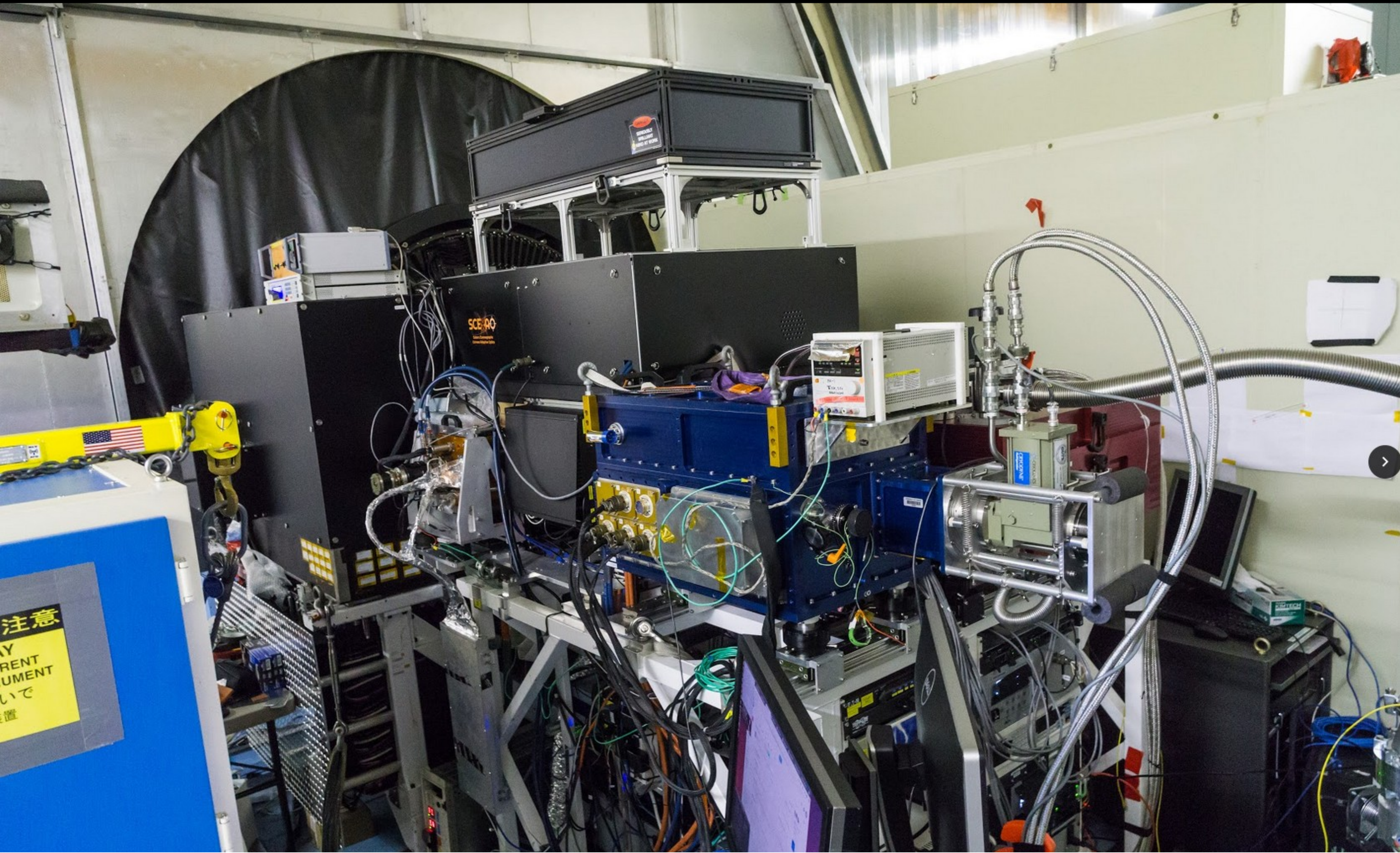
Astronomer / Optical scientist at University of Arizona and Subaru Telescope (National Astronomical Observatory of Japan, Telescope located in Hawaii)

I develop instrumentation to find and study exoplanet, for ground-based telescopes and space missions

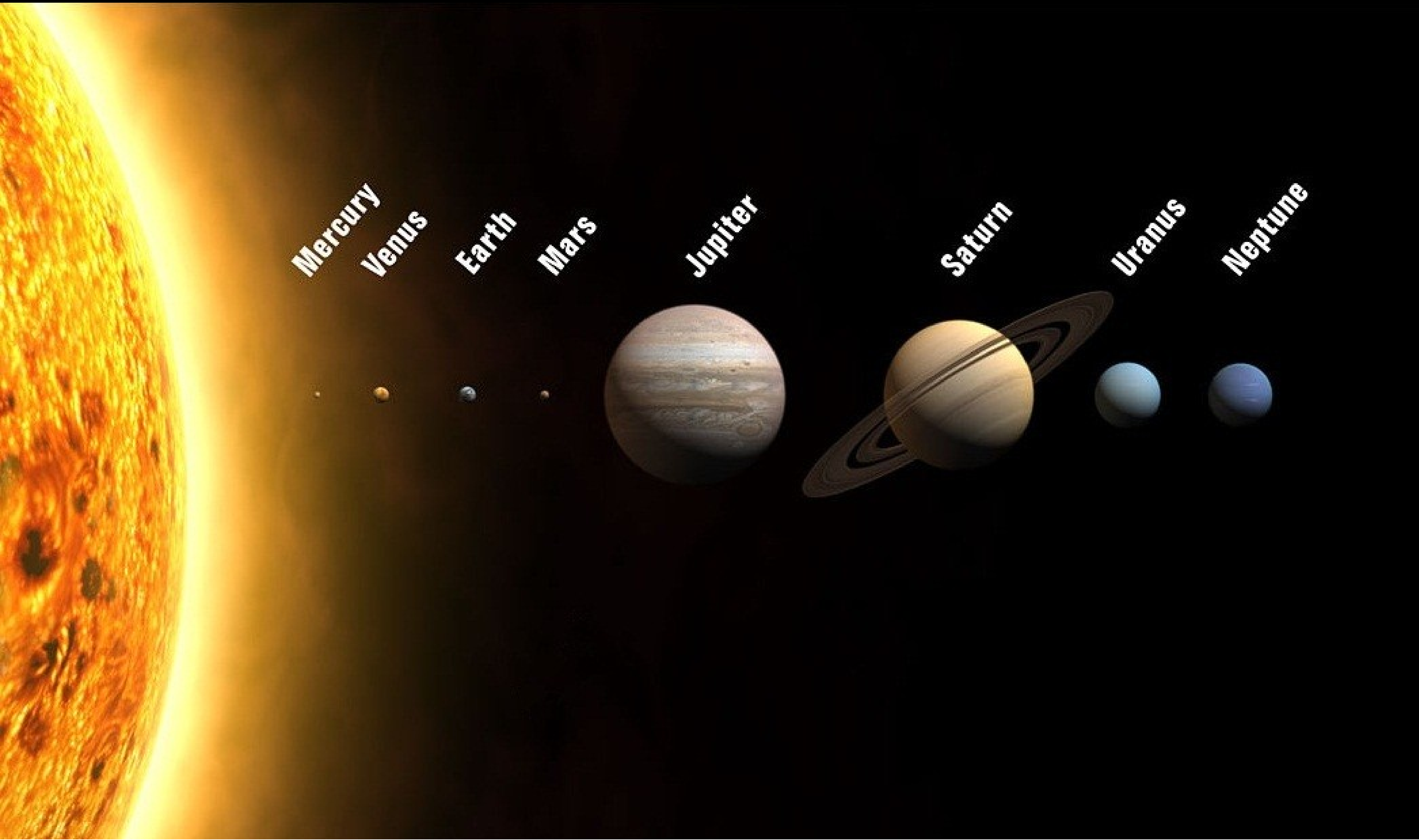
My interest is focused on habitable planets and search for life outside our solar system

At Subaru Telescope, I lead the Subaru Coronagraphic Extreme Adaptive Optics (SCExAO) instrument.

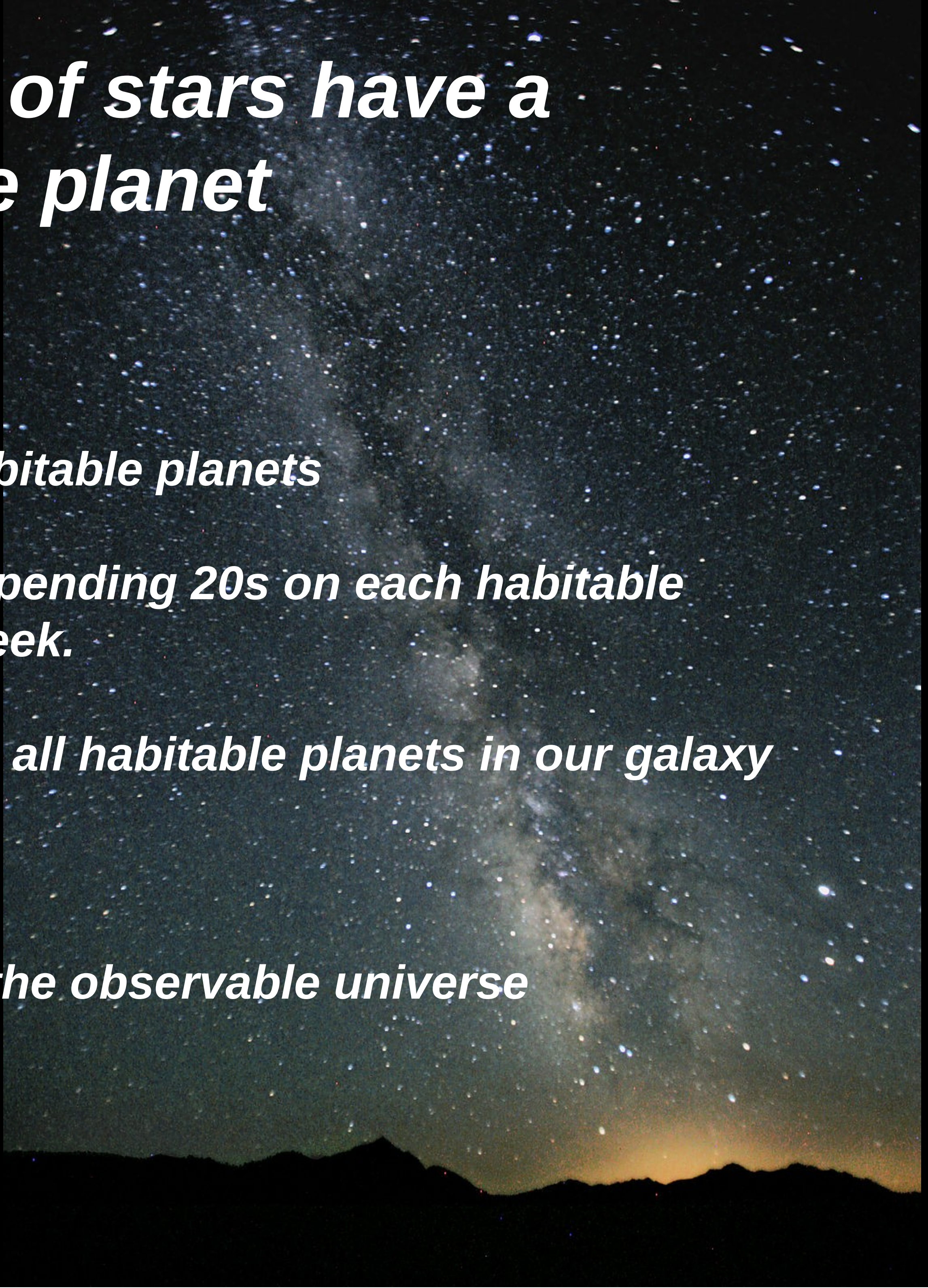
Subaru Coronagraphic Extreme Adaptive Optics



ALL known Planets until 1989



Approximately 10% of stars have a potentially habitable planet



200 billion stars in our galaxy

→ approximately 20 billion habitable planets

Imagine 200 explorers, each spending 20s on each habitable planet, 24hr a day, 7 days a week.

It would take >60yr to explore all habitable planets in our galaxy alone.

x 100,000,000,000 galaxies in the observable universe

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

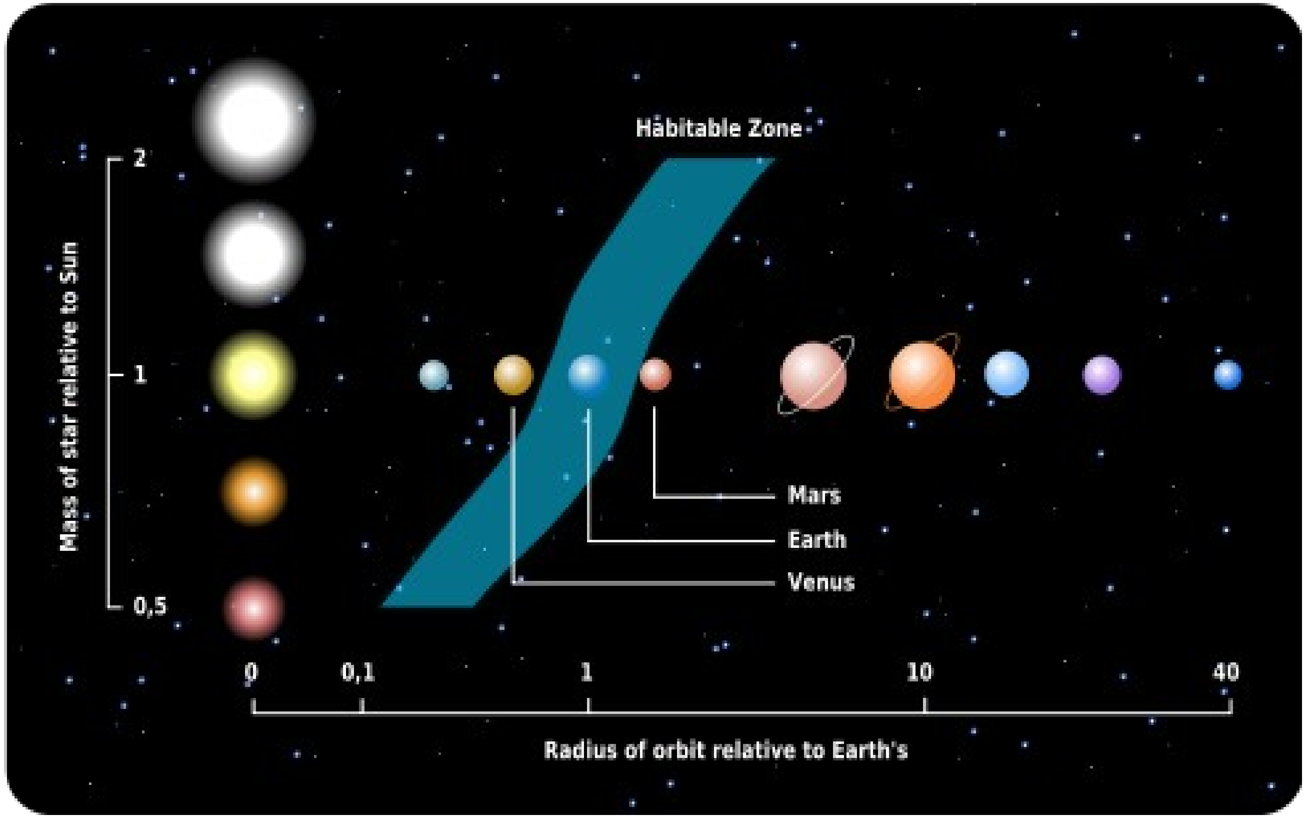
Location of habitable zone is function of star luminosity L. For constant stellar flux, distance to star scales as $L^{1/2}$

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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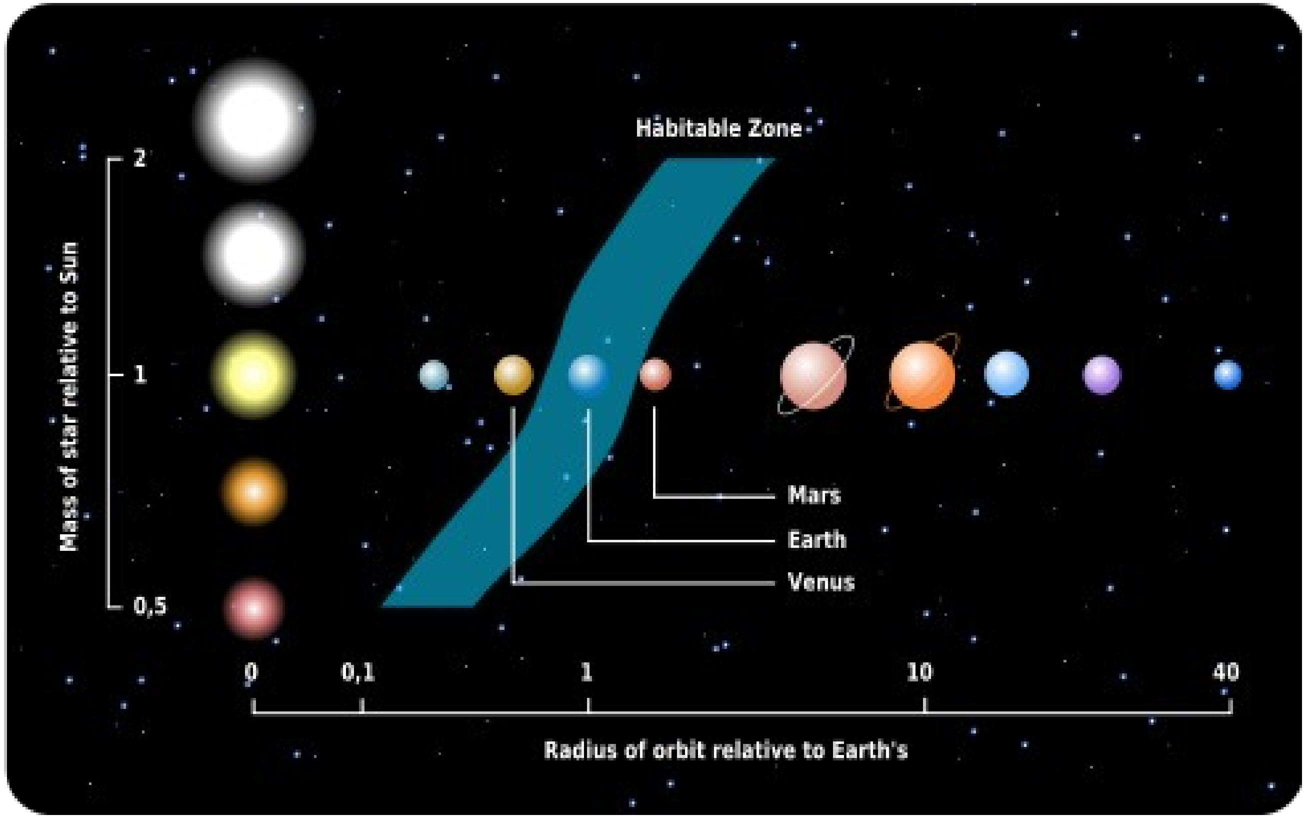
Rigel (B type star):
18 solar mass

Proxima Centauri (M type star):
0.123 solar mass



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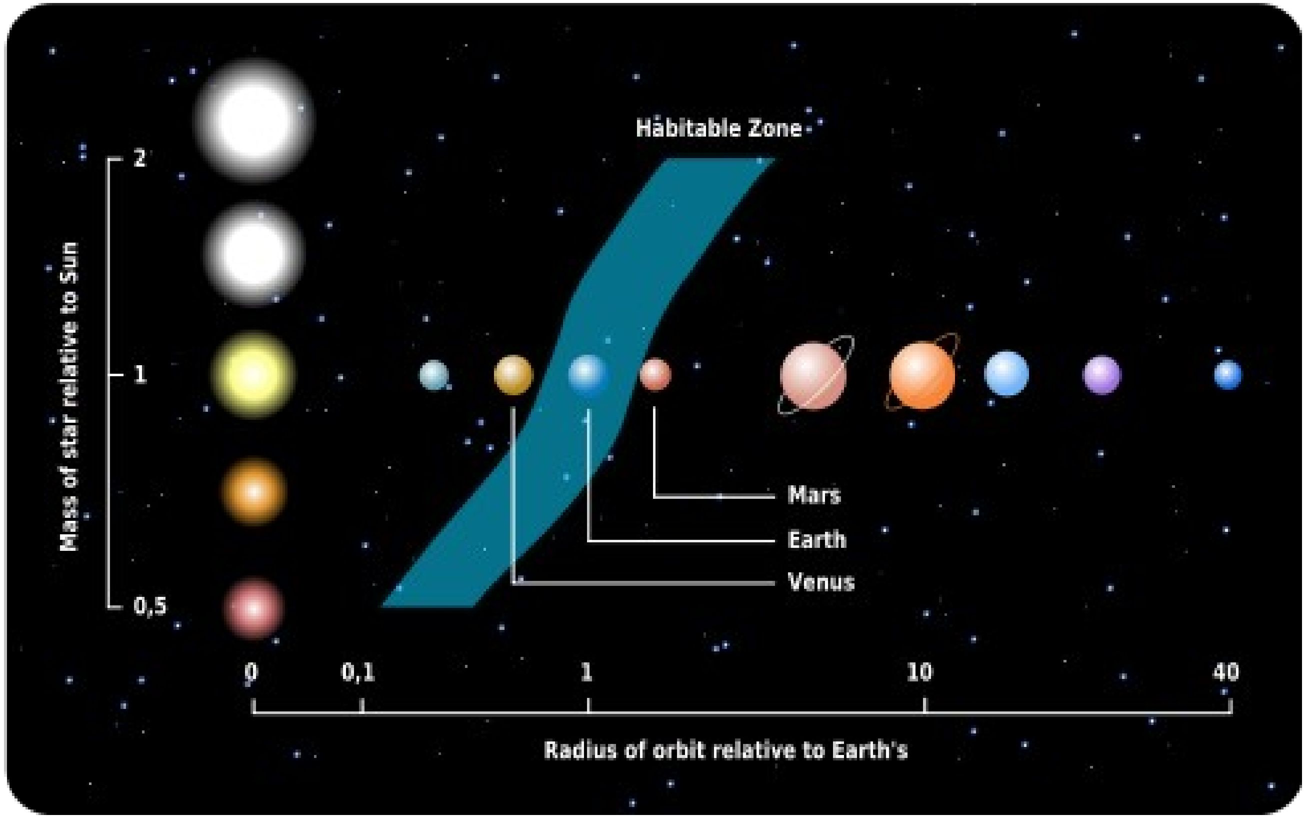
Examples:

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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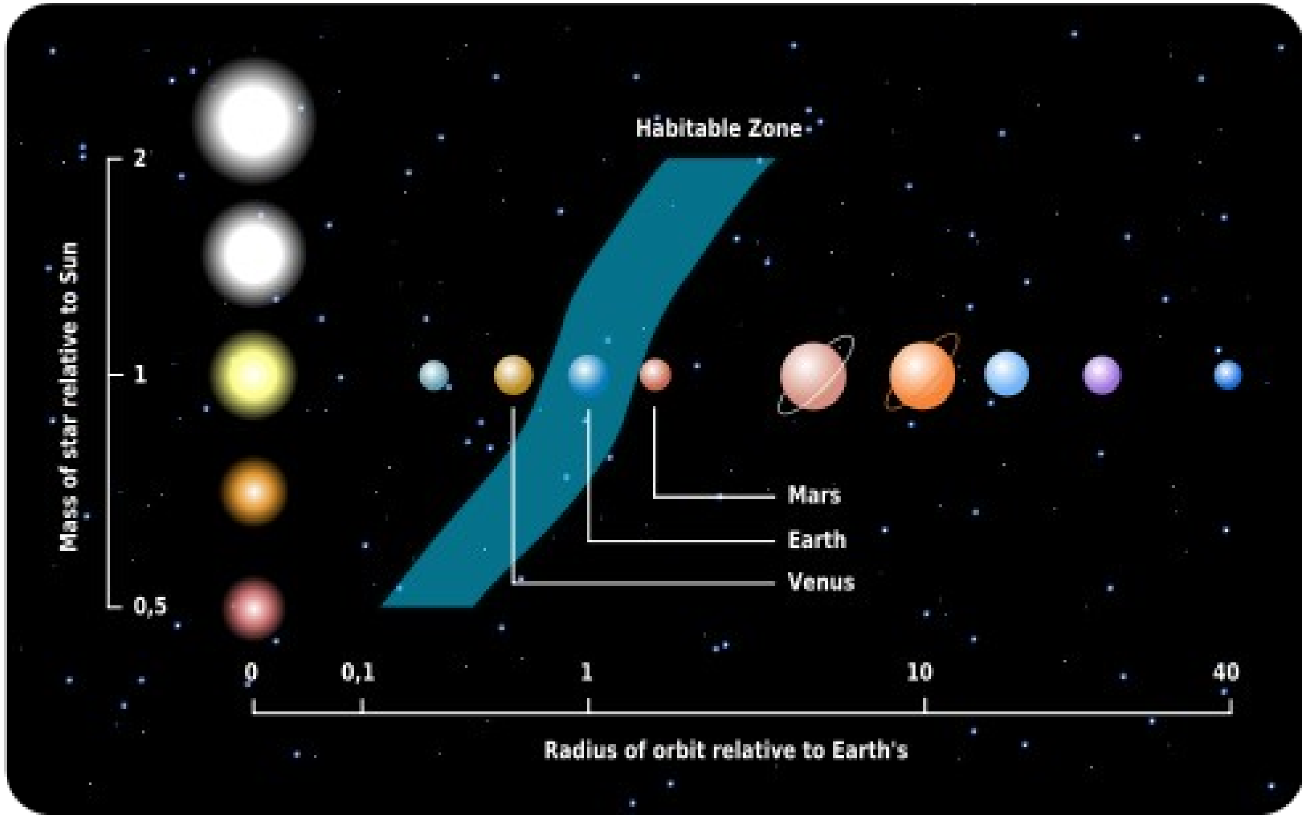
Location of habitable zone is function of star luminosity L. For constant stellar flux, distance to star scales as $L^{1/2}$

Examples:

Sun
→ habitable zone is at ~1 AU

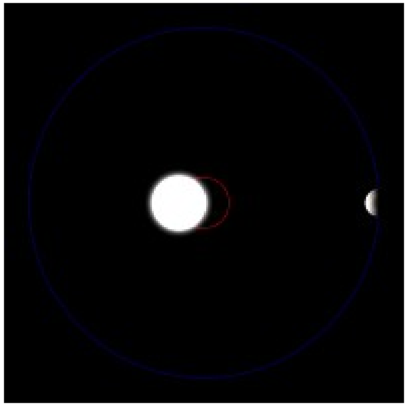
Rigel (B type star):
18 solar mass
100000x Sun luminosity
→ habitable zone is at ~300 AU

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



How to identify exoplanets ?

HIGH PRECISION OPTICAL MEASUREMENTS OF STARLIGHT (<u>indirect</u> techniques)



Earth around Sun at ~30 light year

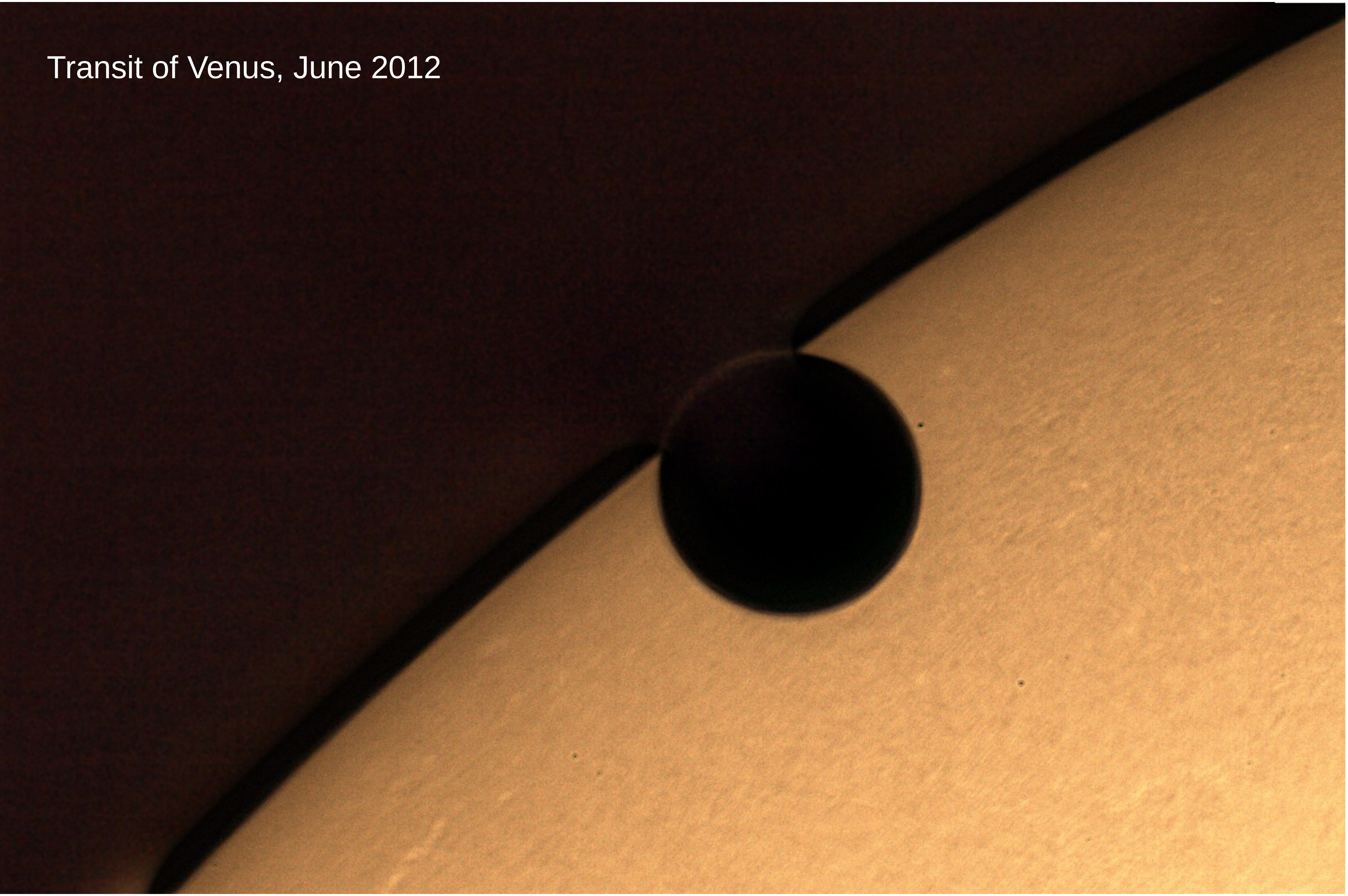
→ ***<u>Astrometry</u>:*** *measure star position moves by 0.3 micro arcsecond*
(thickness of a human hair at 20,000 miles)

→ ***<u>Radial velocity</u>:*** *measure speed along line of sight*
Star velocity is modulated by 10cm / sec
(changes light frequency by 1 part in 3,000,000,000)

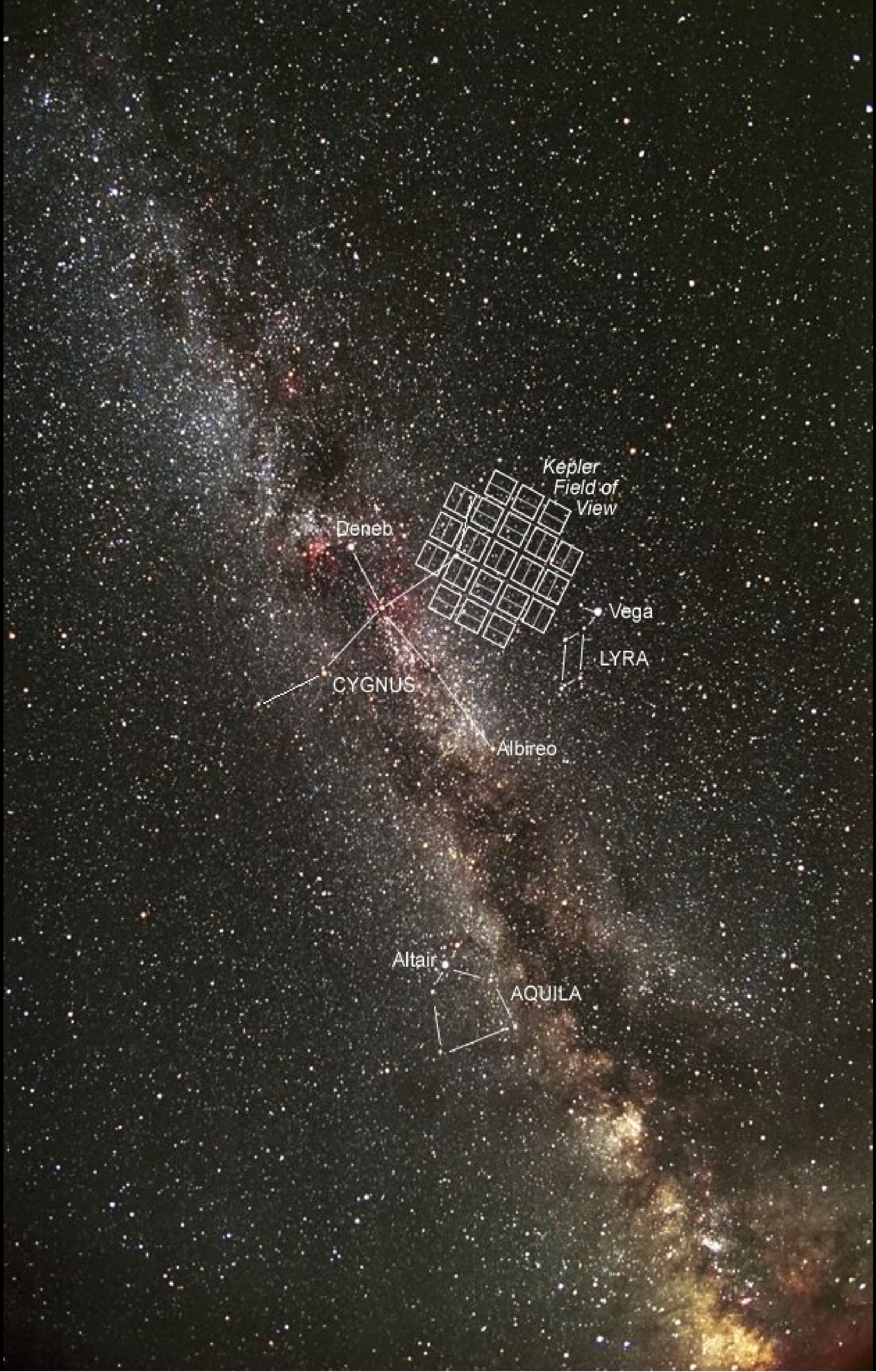
<u>Transit</u>: *measure star brightness*
If Earth-like planet passes in front of Sun-like star, star dims by 70 parts per million
(12x12 pixel going dark on a HD TV screen 70 miles away)

Exoplanet transit

If the planet passes in front of its star, we see the star dimming slightly

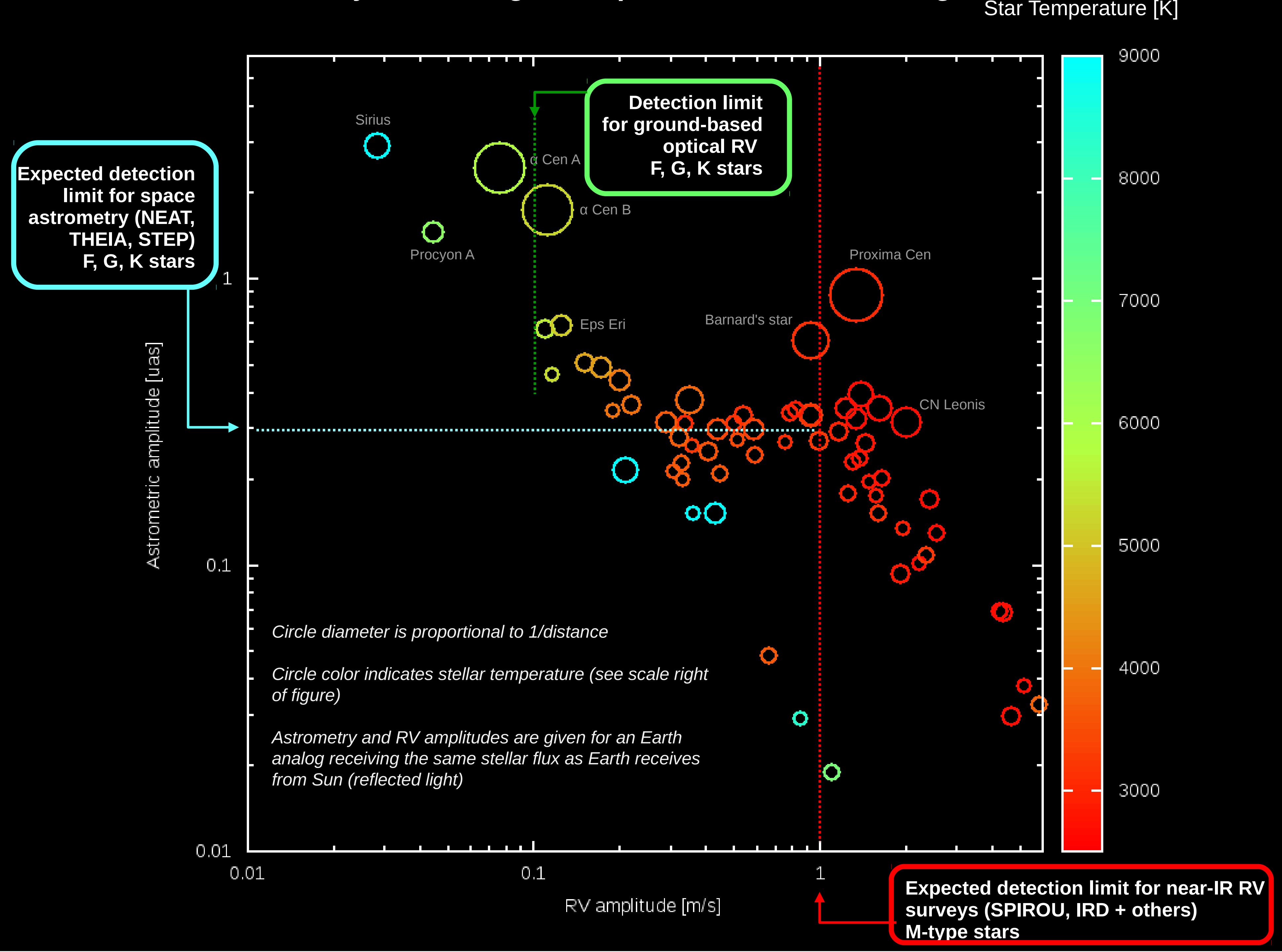


Kepler (NASA)



Kepler
Field of
View
Deneb
Vega
LYRA
CYGNUS
Albireo
Altair
AQUILA

Habitable Zones within 5 pc (16 ly): Astrometry and RV Signal Amplitudes for Earth Analogs



Spectroscopy of Earth-like planets
… allows detection of biomarkers

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 !

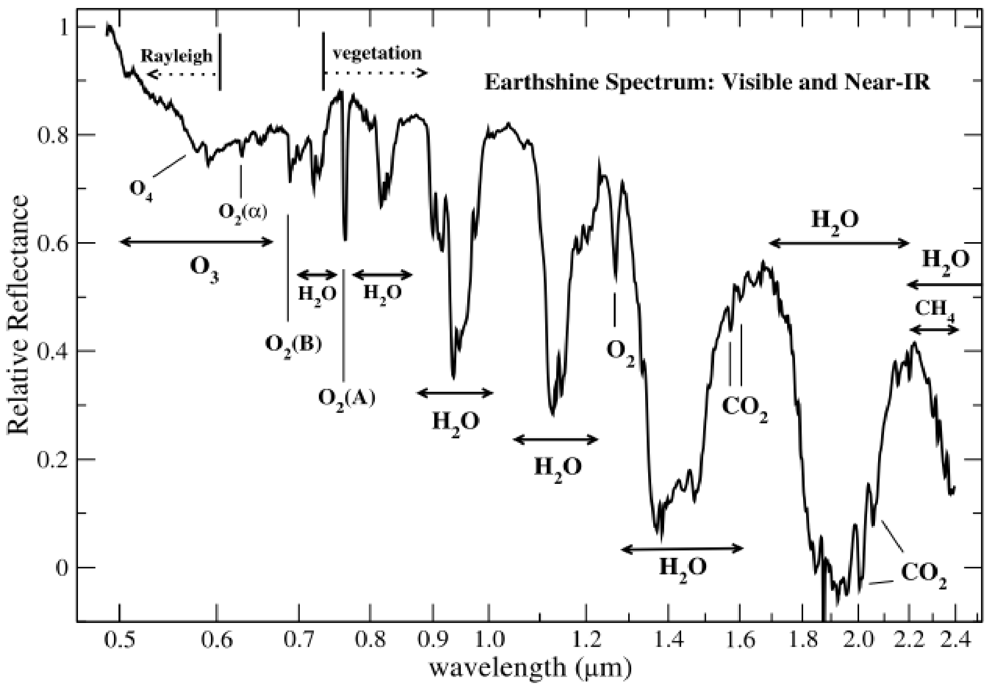


FIG. 7.—Earth's observed reflectance spectrum, at visible and near-infrared wavelengths, created from a composite of the data in this paper (0.8–2.4 μm) and the data presented in Paper I (0.5–0.8 μm). The strongest molecular signatures are indicated, as are the wavelengths where Rayleigh scattering and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

Turnbull et al. 2006

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

Orbit

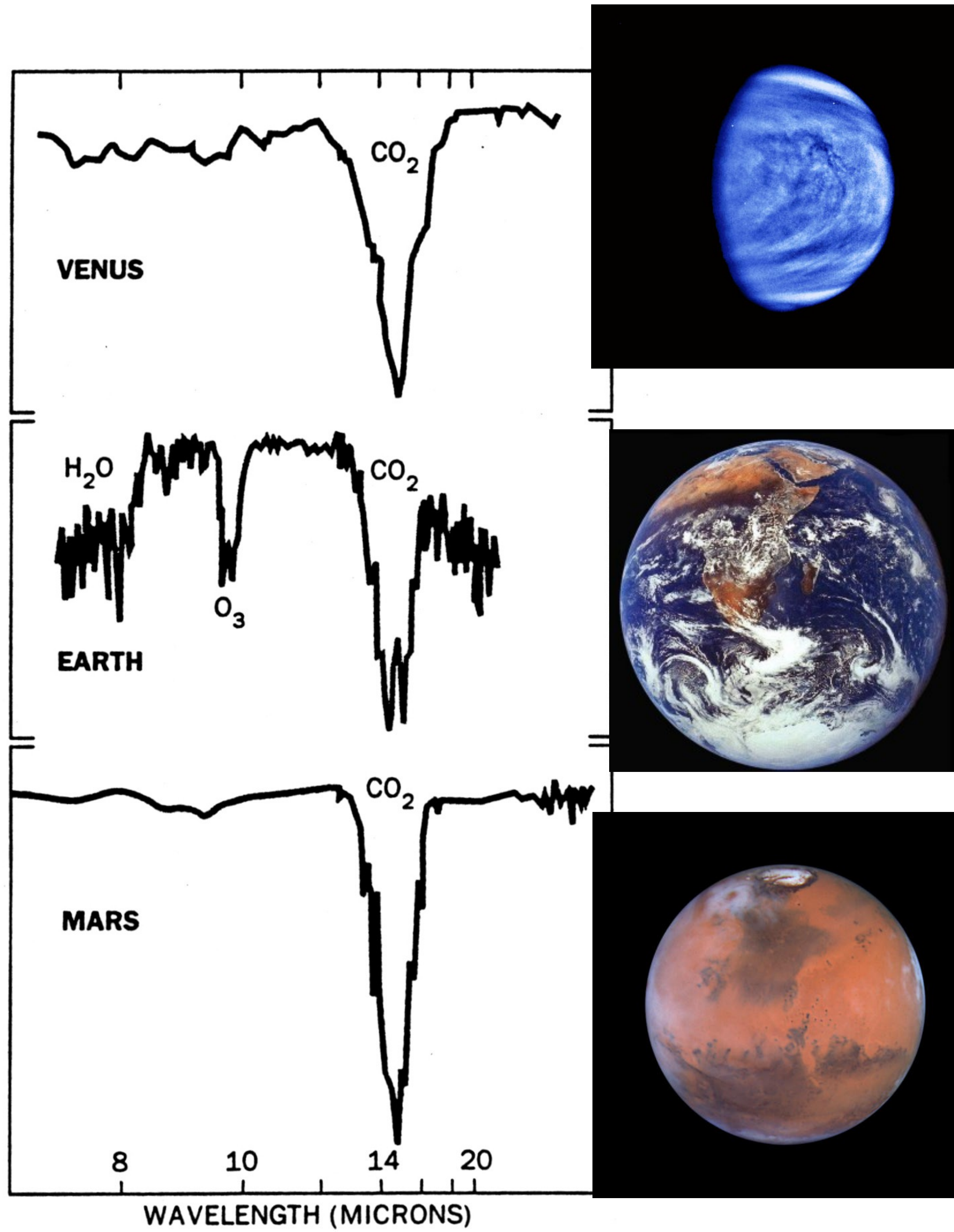
Atmosphere composition

Continents vs. Oceans ?

Rotation period

Weather patterns

Planetary environment :
Planets + dust

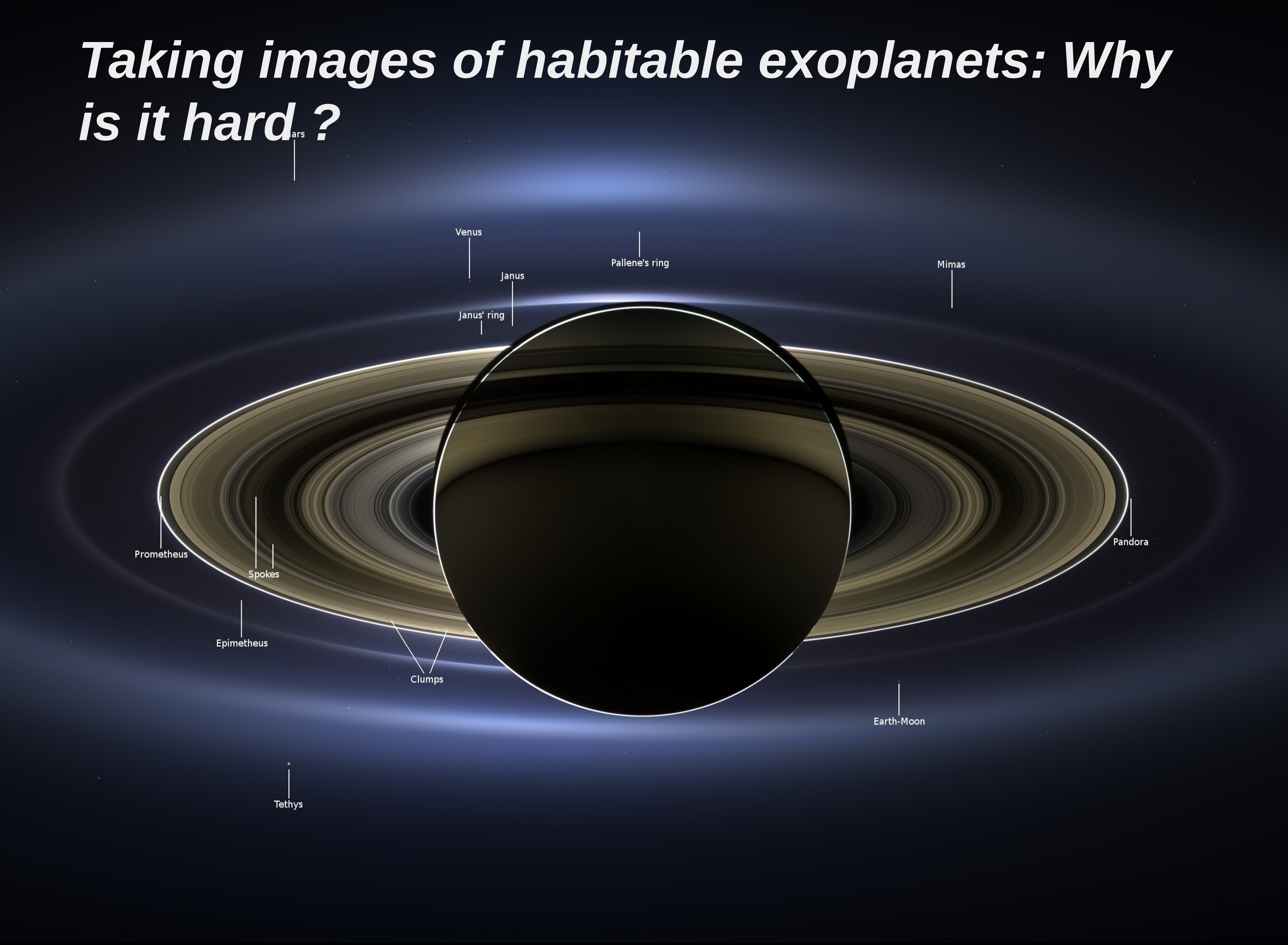


Exoplanets imaging
angular separation, contrast: why is it difficult ?

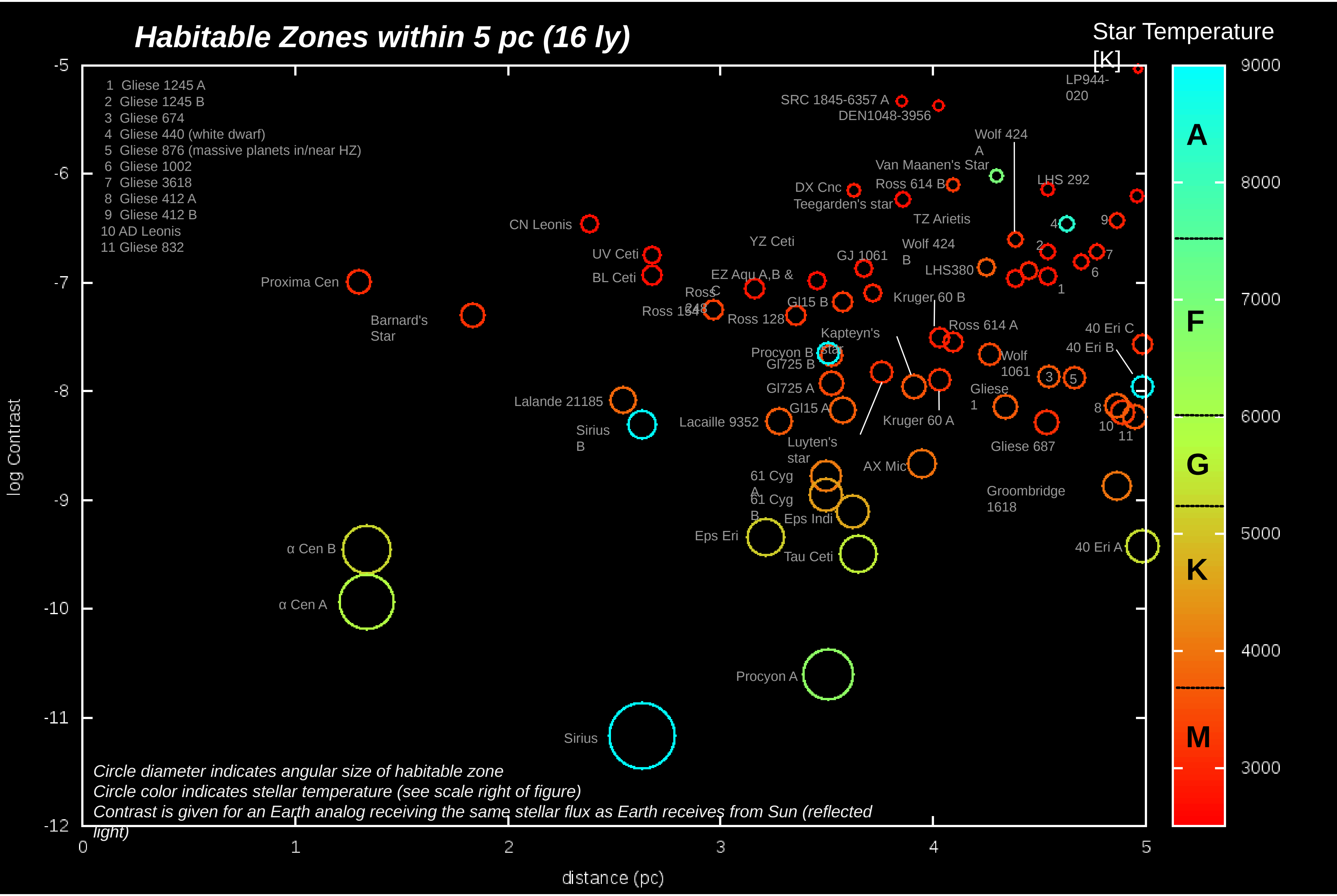
What would our solar system look like from 10pc away ?

- 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)
- Sun-Earth separation would be 0.1” (diffraction limit of a 2-3m telescope in the near-IR)
- Earth diameter = 0.00001” (diffraction limit of a 20km diameter telescope in near-IR)
- 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

Taking images of habitable exoplanets: Why is it hard ?




Saturn
Earth



Habitable Zones within 5 pc (16 ly)
Star Temperature [K]
1 Gliese 1245 A
2 Gliese 1245 B
3 Gliese 674
4 Gliese 440 (white dwarf)
5 Gliese 876 (massive planets in/near HZ)
6 Gliese 1002
7 Gliese 3618
8 Gliese 412 A
9 Gliese 412 B
10 AD Leonis
11 Gliese 832
Proxima Cen
Barnard's Star
CN Leonis
UV Ceti
BL Ceti
Lalande 21185
Sirius B
Lacaille 9352
Ross 154
Ross 248
Ross 128
EZ Aqu A,B & C
YZ Ceti
GJ 1061
Gl15 B
Gl15 A
Gl725 A
Gl725 B
Procyon B
Kapteyn's star
Luyten's star
61 Cyg A
61 Cyg B
Eps Indi
Eps Eri
Tau Ceti
AX Mic
Kruger 60 A
Kruger 60 B
Ross 614 A
Ross 614 B
Teegarden's star
DX Cnc
Van Maanen's Star
SRC 1845-6357 A
DEN1048-3956
Wolf 424 A
Wolf 424 B
TZ Arietis
LHS380
LHS 292
LP944-020
Wolf 1061
Gliese 1
Gliese 687
Groombridge 1618
40 Eri A
40 Eri B
40 Eri C
α Cen A
α Cen B
Procyon A
Sirius
A
F
G
K
M
9000
8000
7000
6000
5000
4000
3000
log Contrast
distance (pc)
Circle diameter indicates angular size of habitable zone
Circle color indicates stellar temperature (see scale right of figure)
Contrast is given for an Earth analog receiving the same stellar flux as Earth receives from Sun (reflected light)

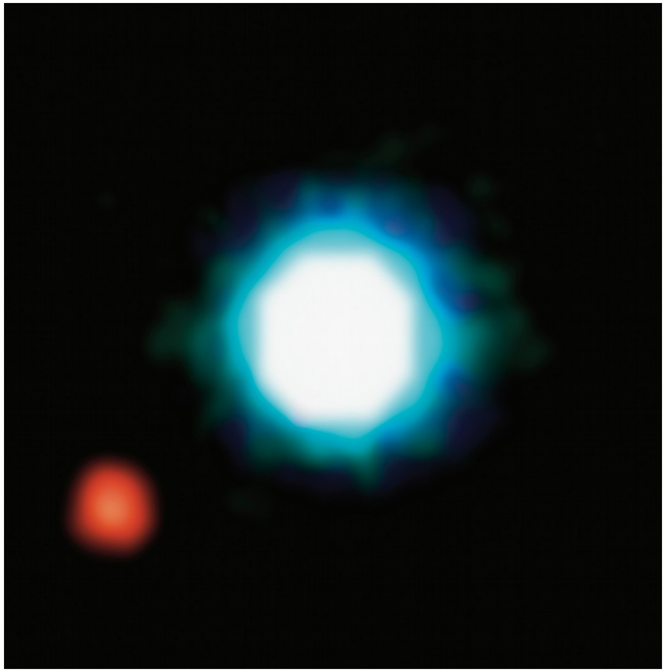
Exoplanets: Contrast ratio, visible vs. infrared

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.

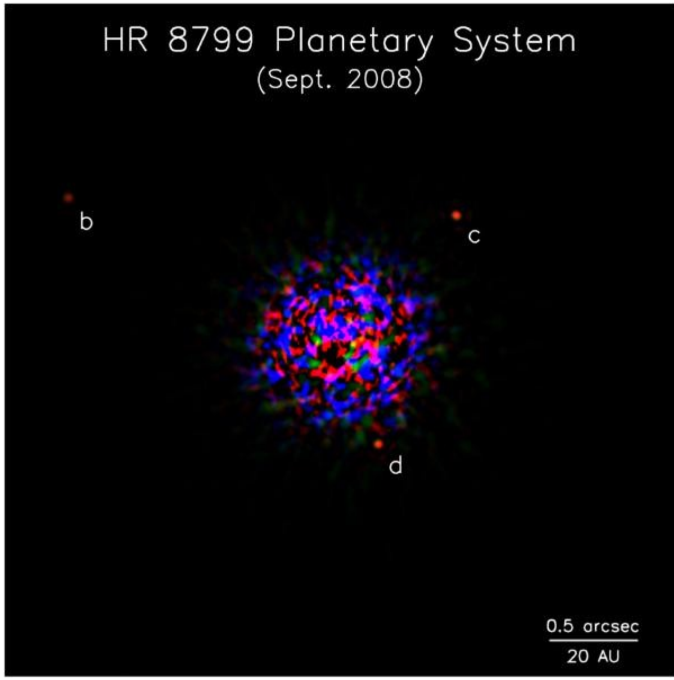
In the near-IR, giant and young planets ("young Jupiters") can be imaged:

- 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

In the Thermal IR (~10 um & longer), contrast is even more favorable, and older giant planets can be imaged (this is one of the key science goals of JWST)



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



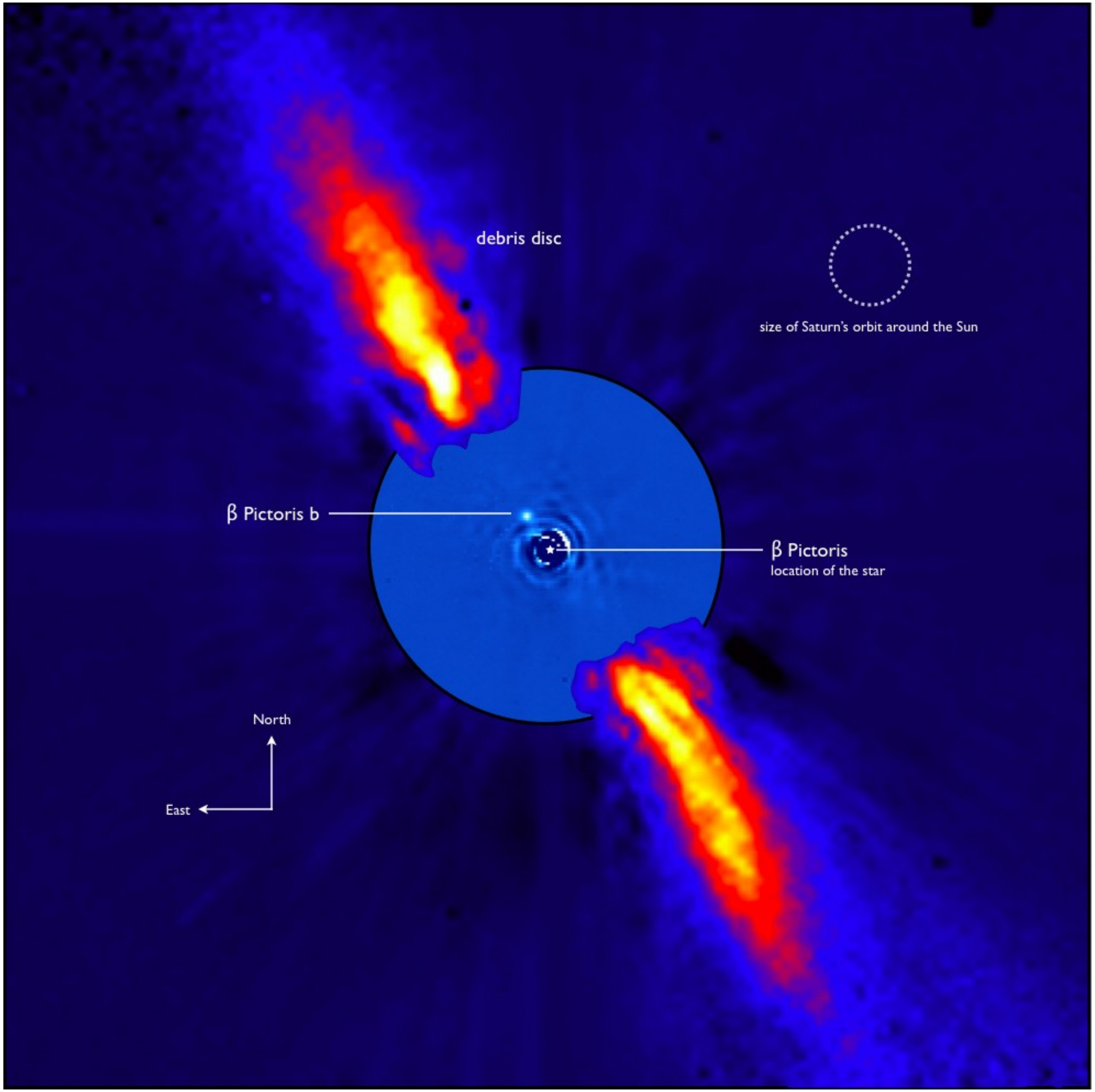
HR8799: first image of exoplanetary sytem with multiple planets
(Marois et al. 2009)

Exoplanets & dust disks

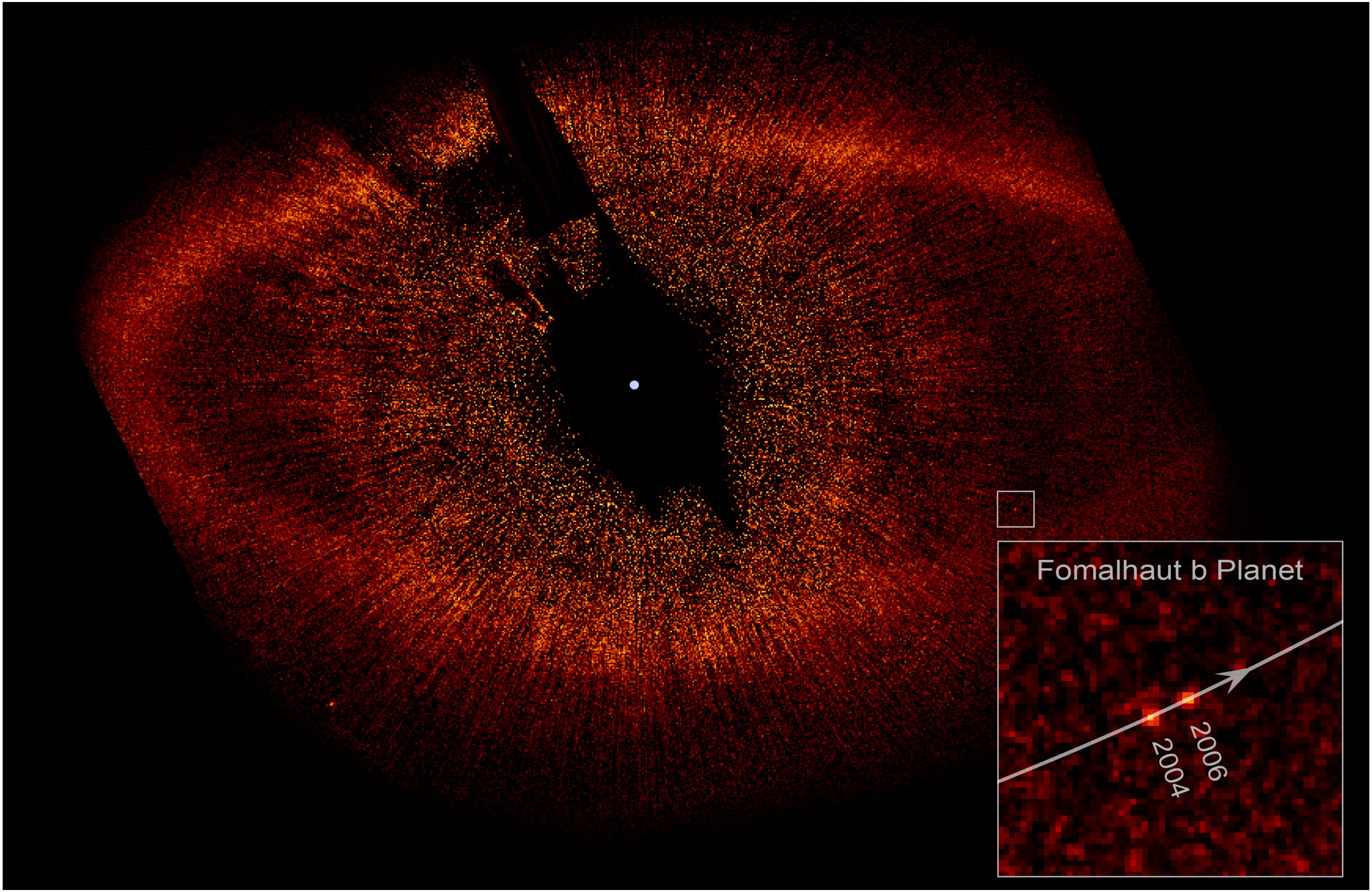
Protoplanetary disk:
Disk in the process of forming planets

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)

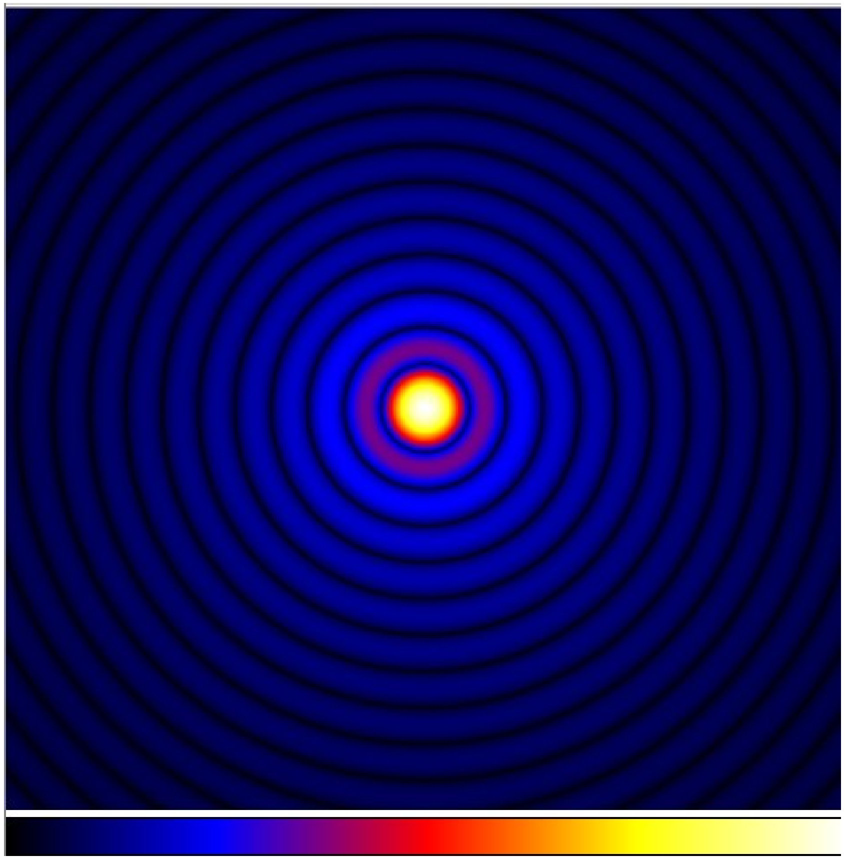


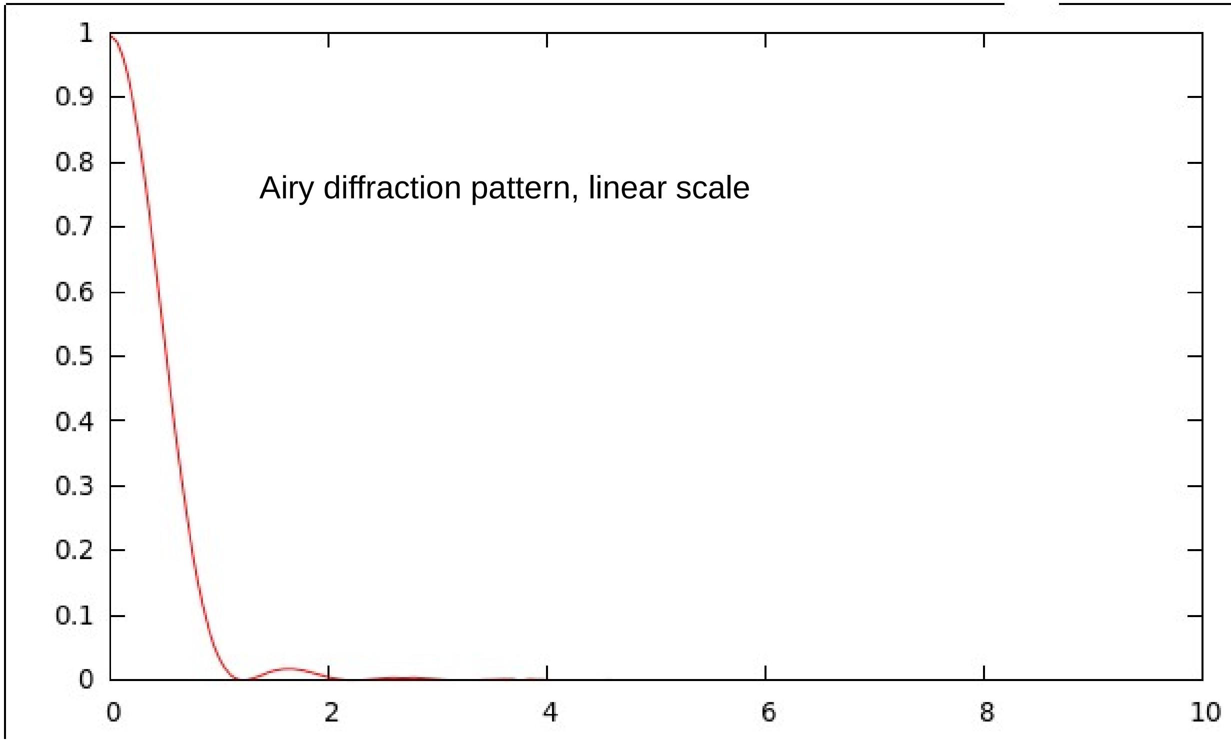
Kalas et al., HST image

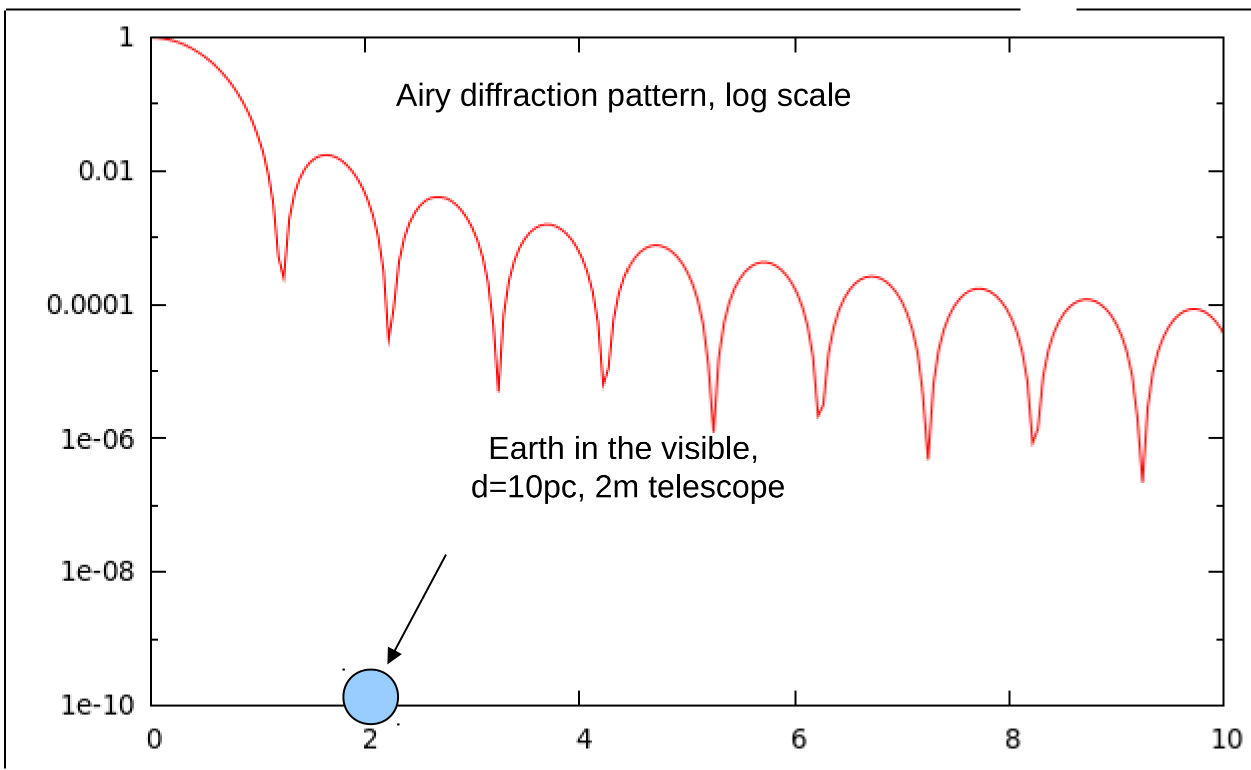
Coronagraphy

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.

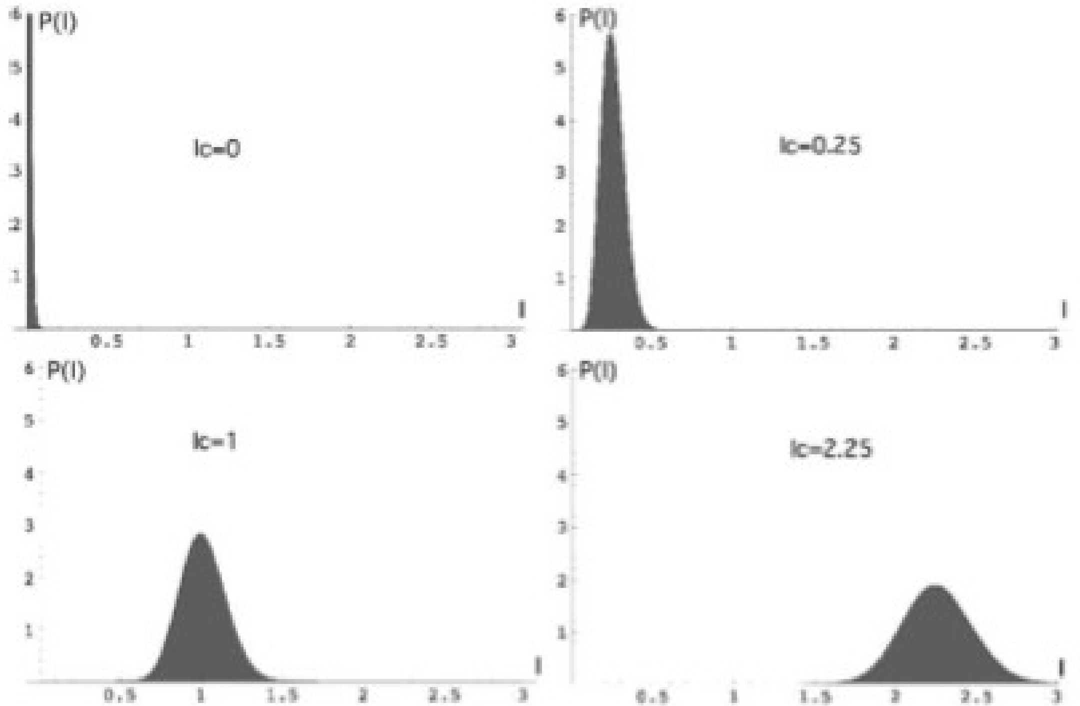


FIG. 3.—PDF of the light intensity at four different constant background intensity levels I_c and a single value of $I_s = 0.1$. High values of I_c correspond to locations near the perfect PSF maxima (rings), and low values of I_c correspond to locations near the zeros of the perfect PSF or far from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

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

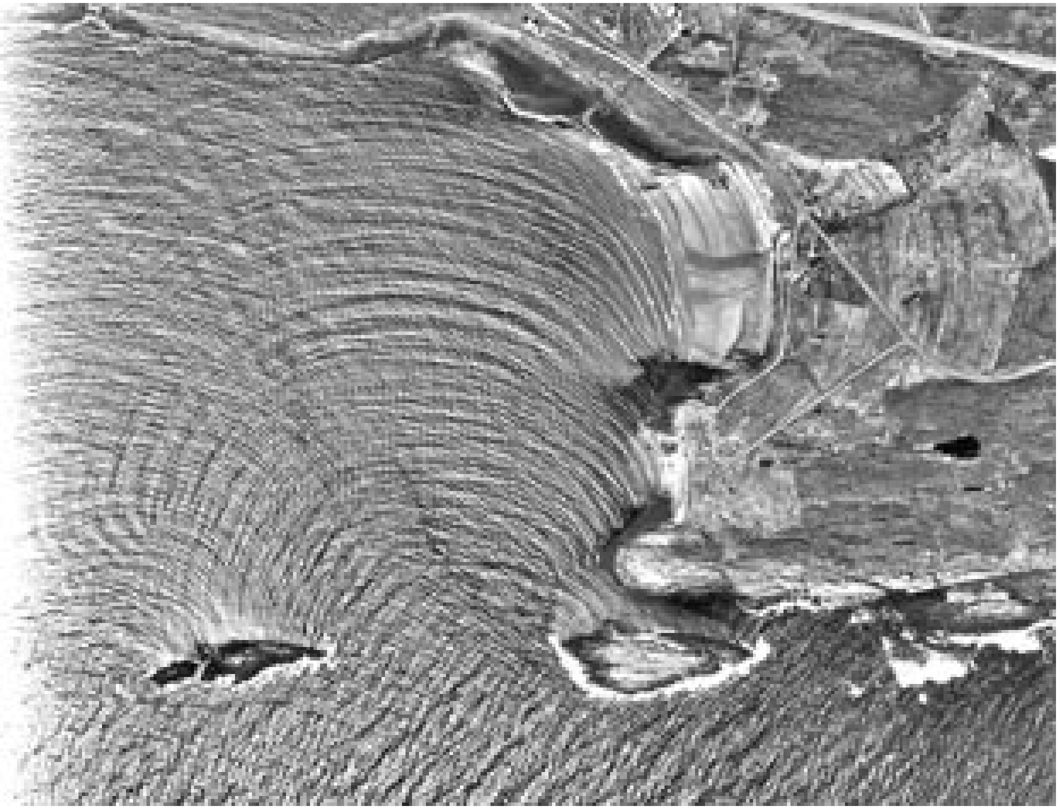
Augustin-Jean Fresnel
submits wave theory of light

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

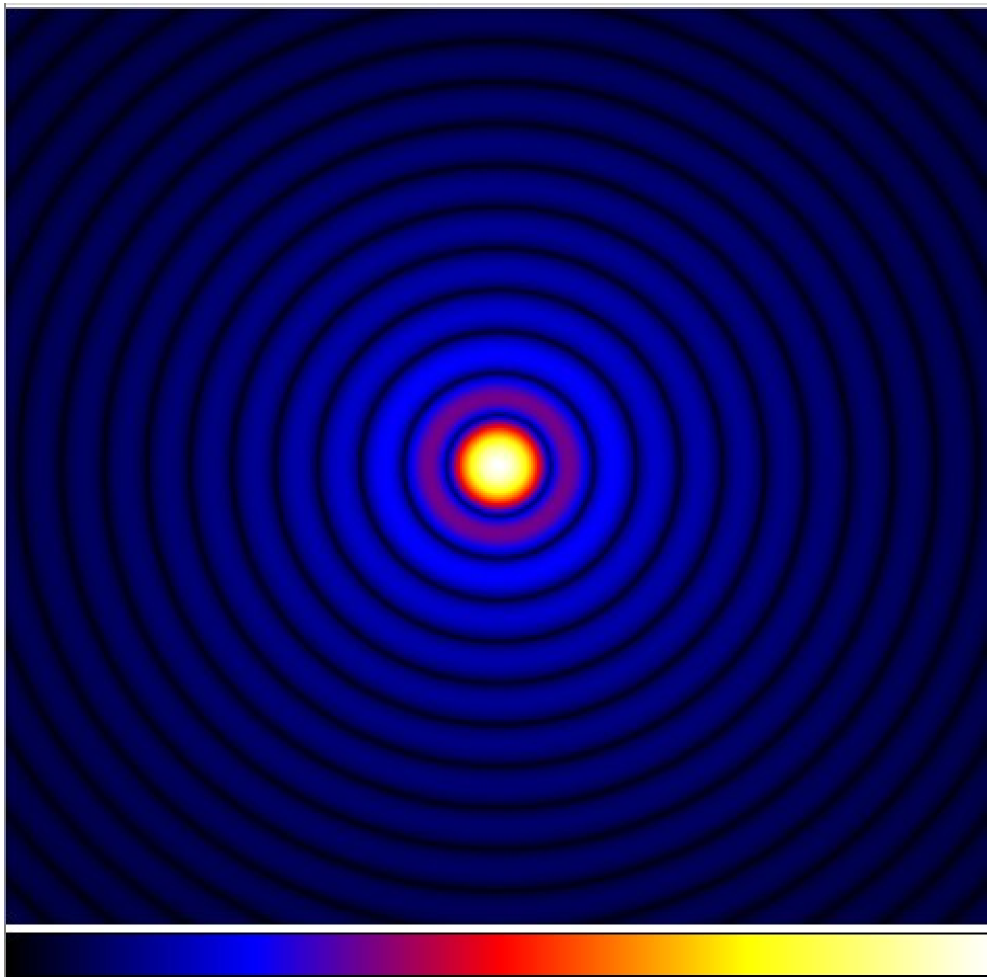
Dominique-Francois-Jean Arago, head of the committee, performs the experiment
He finds the predicted spot → Fresnel wins the competition

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

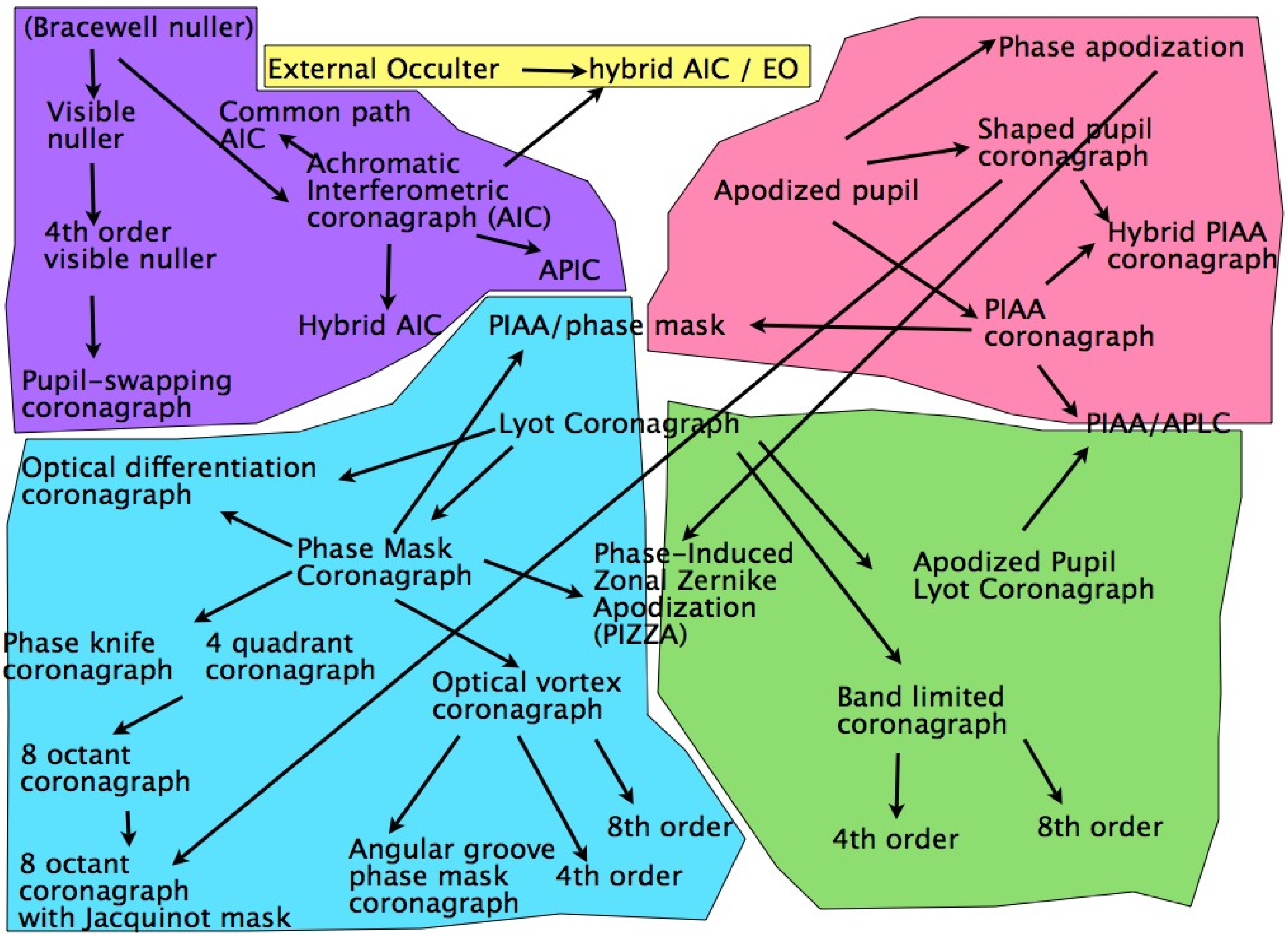
- Design masks and optical components inside the telescope to induce starlight destructive interference at the expected location of a planet in the image: ***internal coronagraph***

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

Internal Coronagraphs: main approaches

Apodization

Beam splitting and destructive interference



Phase masks in focal plane

Amplitude masks in focal plane

High Contrast Imaging systems

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

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

Key elements:

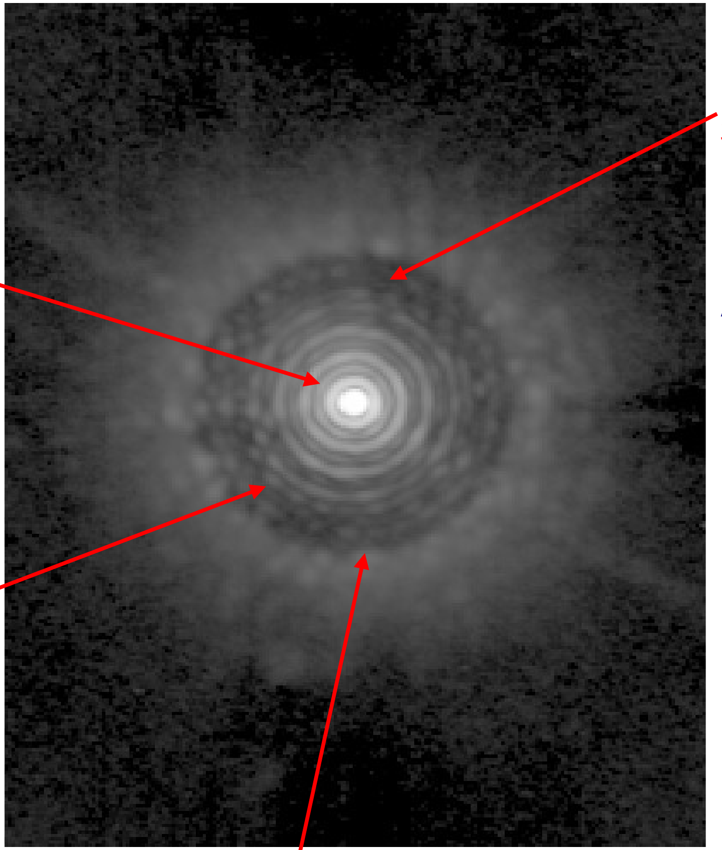
- Coronagraph or nulling interferometer to optically remove starlight and isolate planet light (overcomes diffraction)

- 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



PSF diffraction
(Airy rings, spiders)

REMOVED BY CORONAGRAPH

Residual atmospheric speckle halo

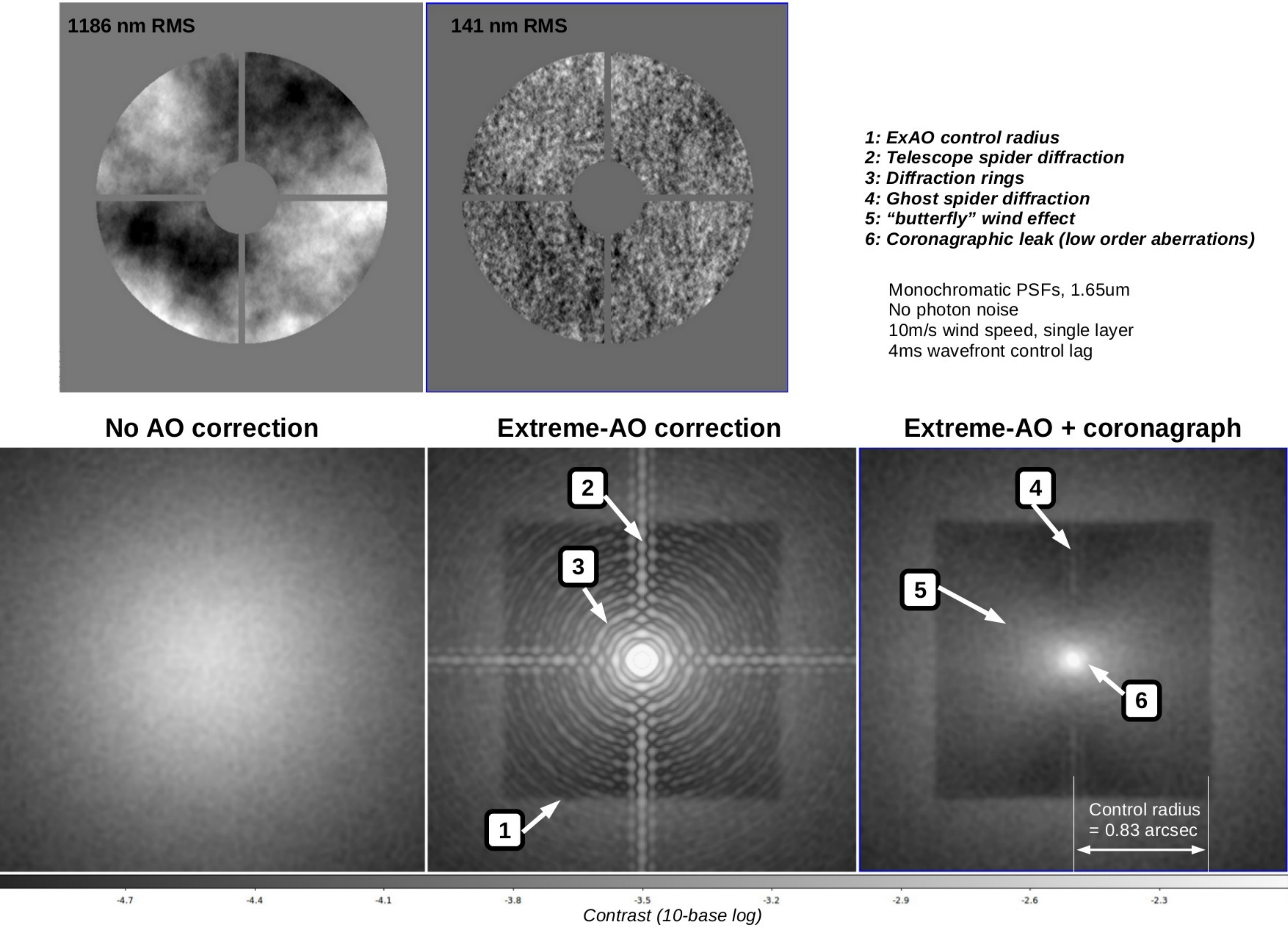
REDUCED BY FAST, ACCURATE AND EFFICIENT AO SYSTEM

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

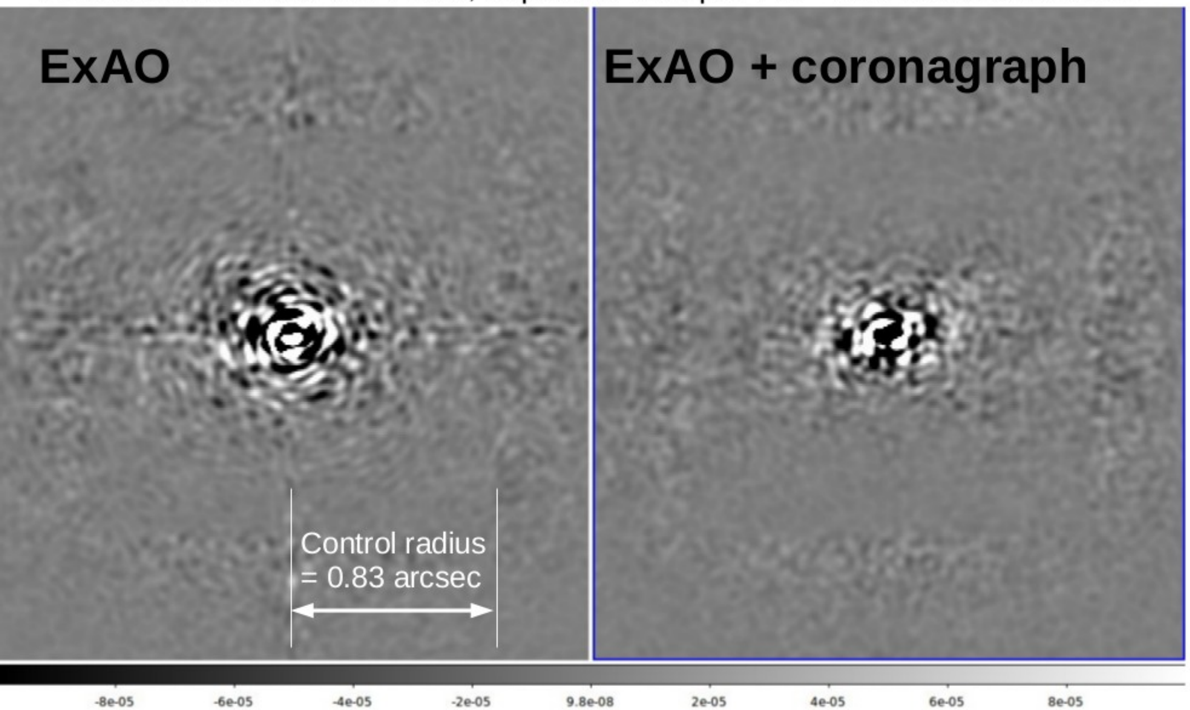

1186 nm RMS
141 nm RMS
1: ExAO control radius
2: Telescope spider diffraction
3: Diffraction rings
4: Ghost spider diffraction
5: “butterfly” wind effect
6: Coronagraphic leak (low order aberrations)
Monochromatic PSFs, 1.65um
No photon noise
10m/s wind speed, single layer
4ms wavefront control lag
No AO correction
Extreme-AO correction
Extreme-AO + coronagraph
1
2
3
4
5
6
Control radius
= 0.83 arcsec
-4.7
-4.4
-4.1
-3.8
-3.5
-3.2
-2.9
-2.6
-2.3
Contrast (10-base log)

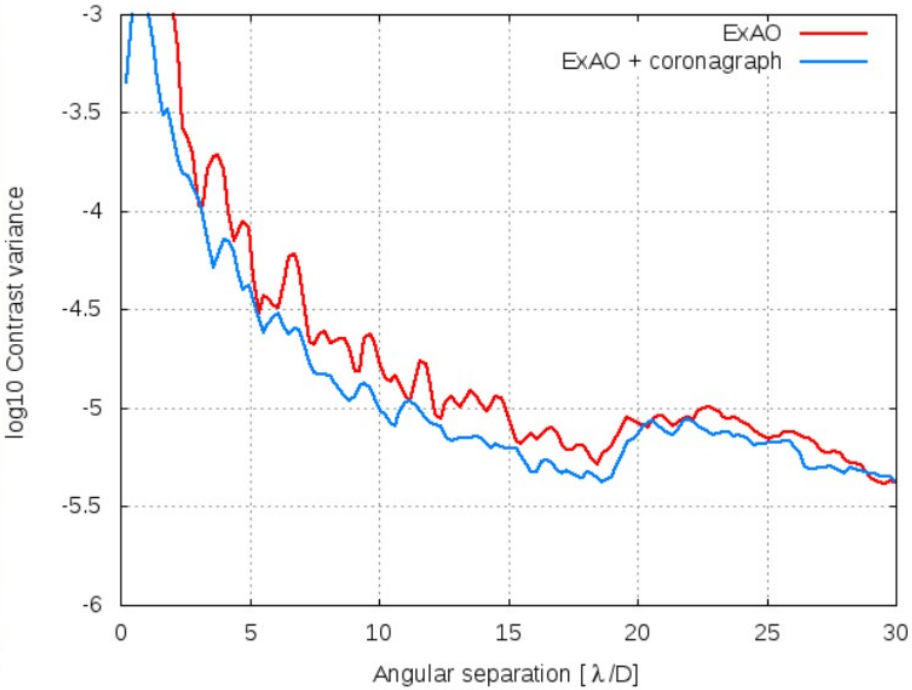
Coronagraphs reduce speckle noise

“speckle pinning” effect
See: Bloemhof et al. 2001, Aime & Soummer 2004, Soummer et al. 2007

PSF subtraction residual (no photon noise)

Difference between two PSFs, exposure time per PSF=100 coherence times





Current and future high contrast systems - ground

Subaru Coronagraphic Extreme AO – under operation and development

- 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 deformable mirror
- 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

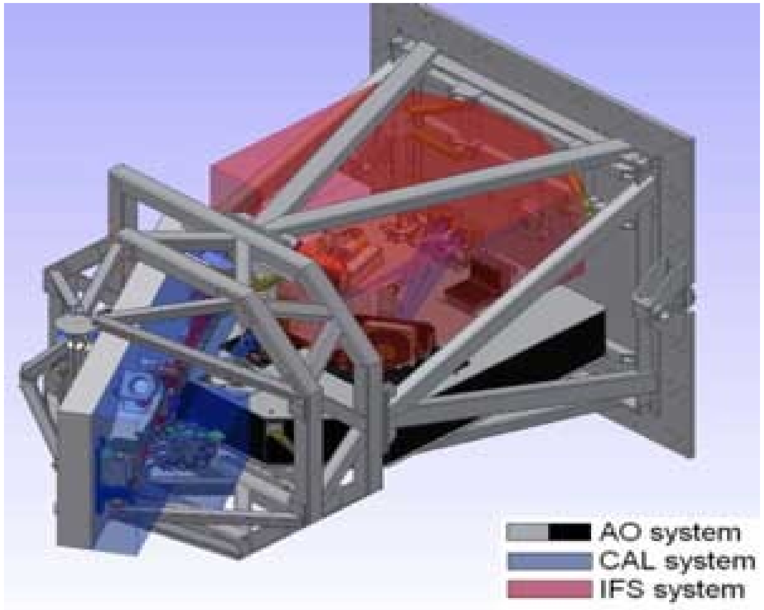
ESO's SPHERE on VLT – large survery starts observations in 2014

- ExAO system + coronagraph
- Highly stable bench
- Includes Integral Field Spectrograph to help remove speckles and acquire spectra
- Includes differential polarimetric imager

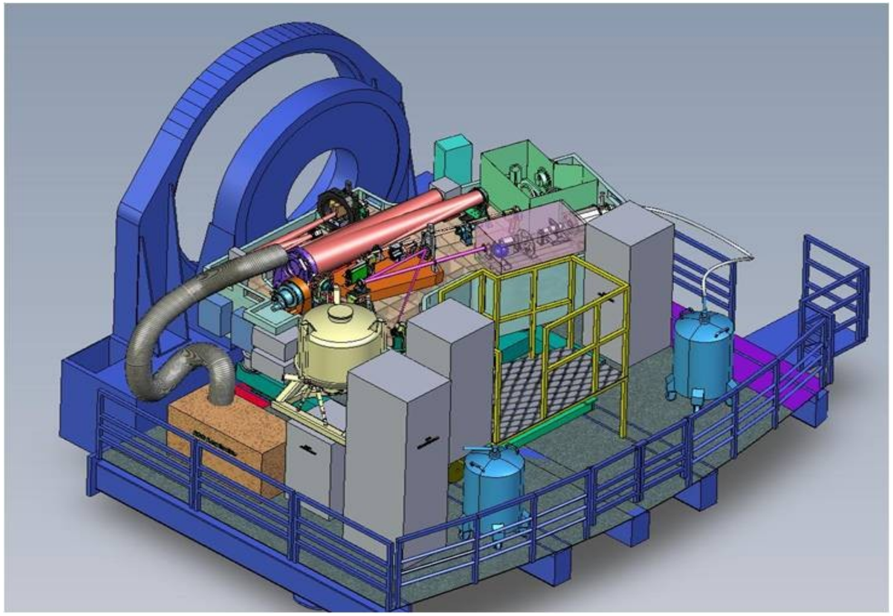
MagAO-X – under development for 6.5m Magellan Telescope

- High speed, high efficiency ExAO system, visible light optimized, 2000 elements
- Small IWA coronagraph (PIAACMC + other modes)

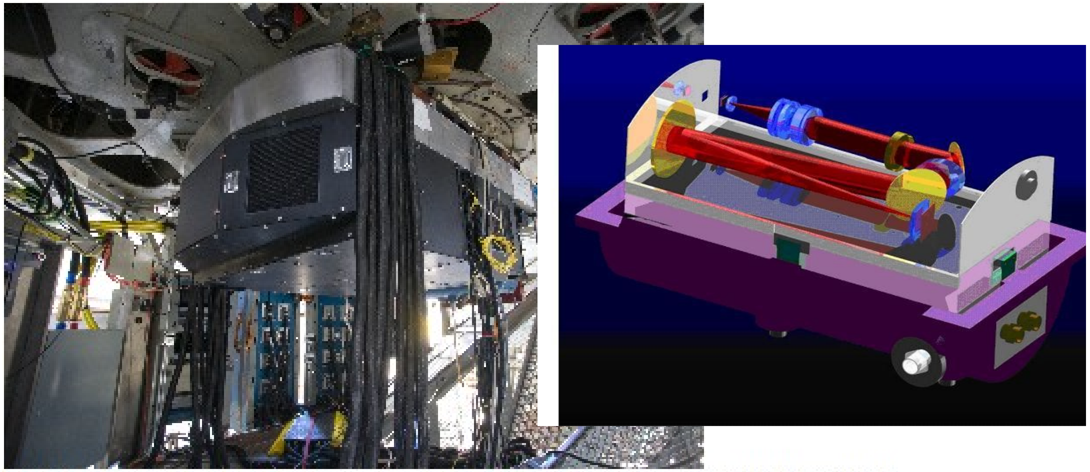
Current and future high contrast systems - ground



Gemini Planet Imager

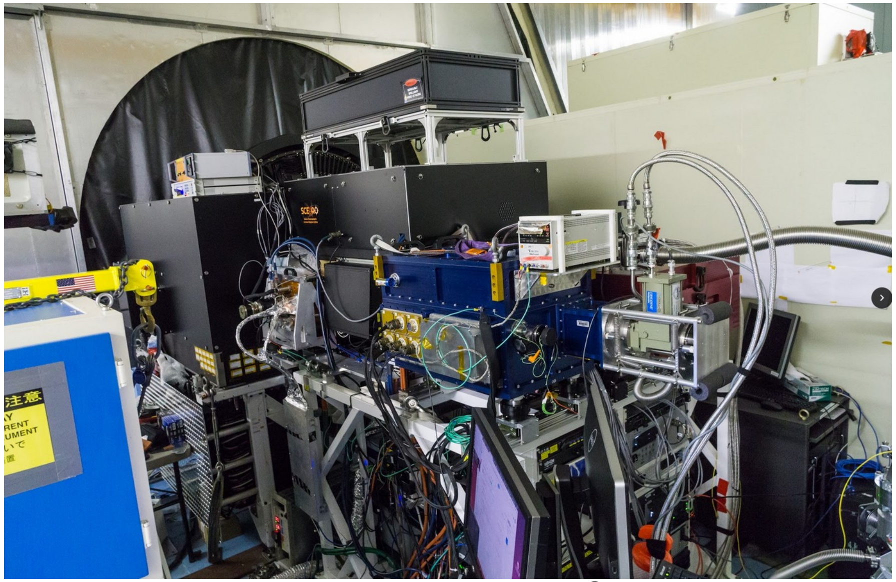


SPHERE (European Southern Observatory)



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

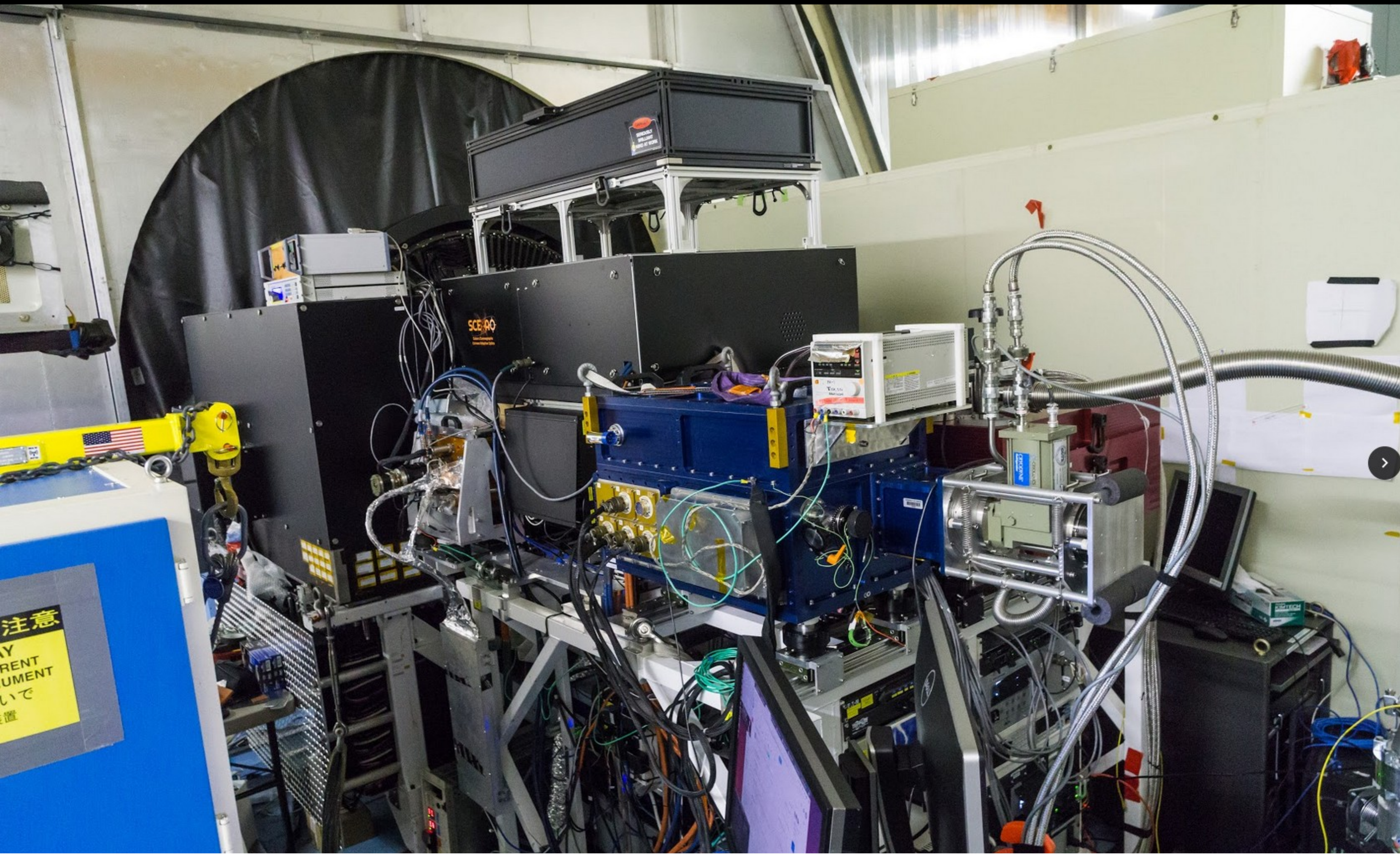
PALM3000/P1640 (Palomar 5-m Telescope)



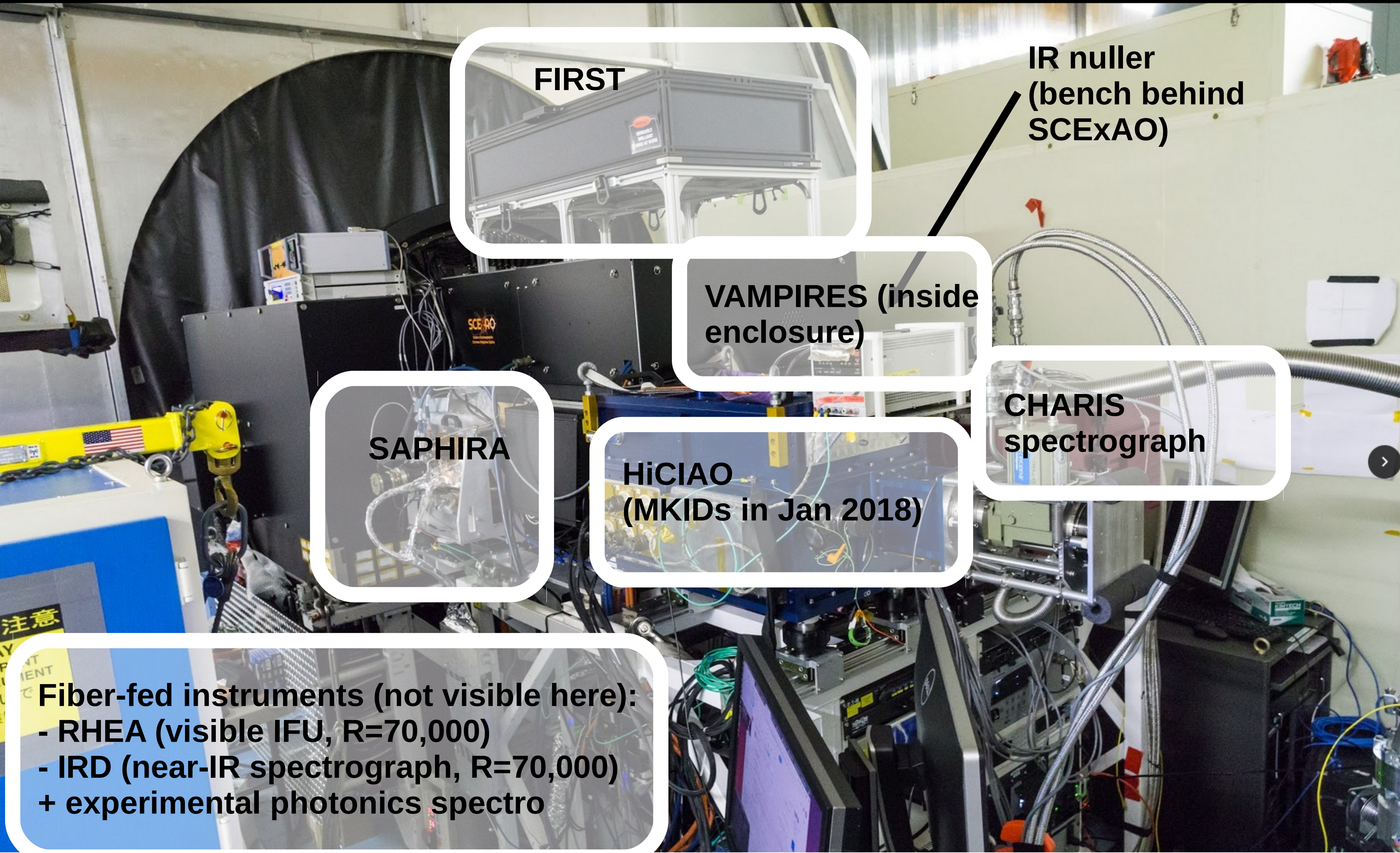
Subaru Coronagraphic Extreme-AO

SCExAO

Subaru Coronagraphic Extreme Adaptive Optics

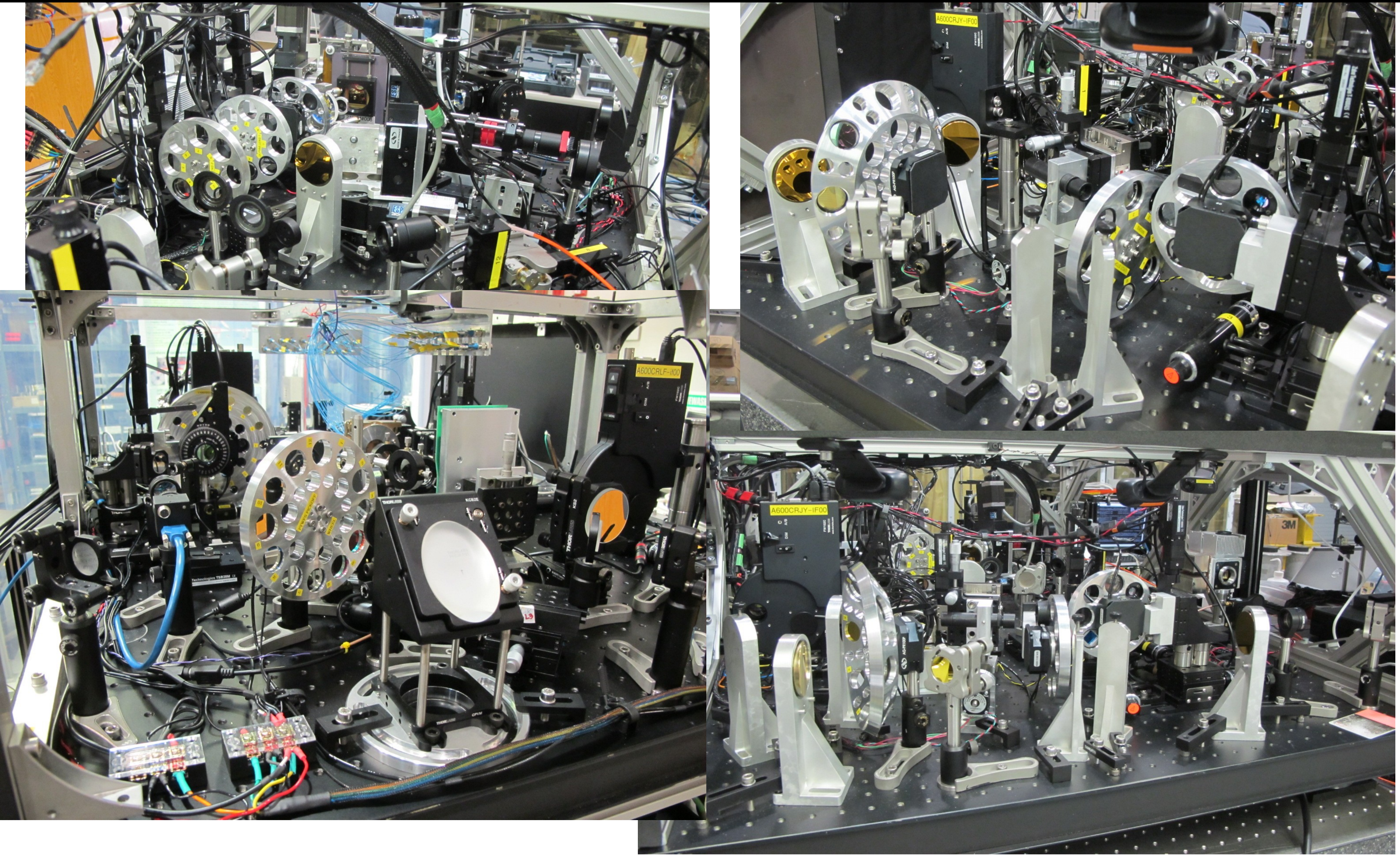


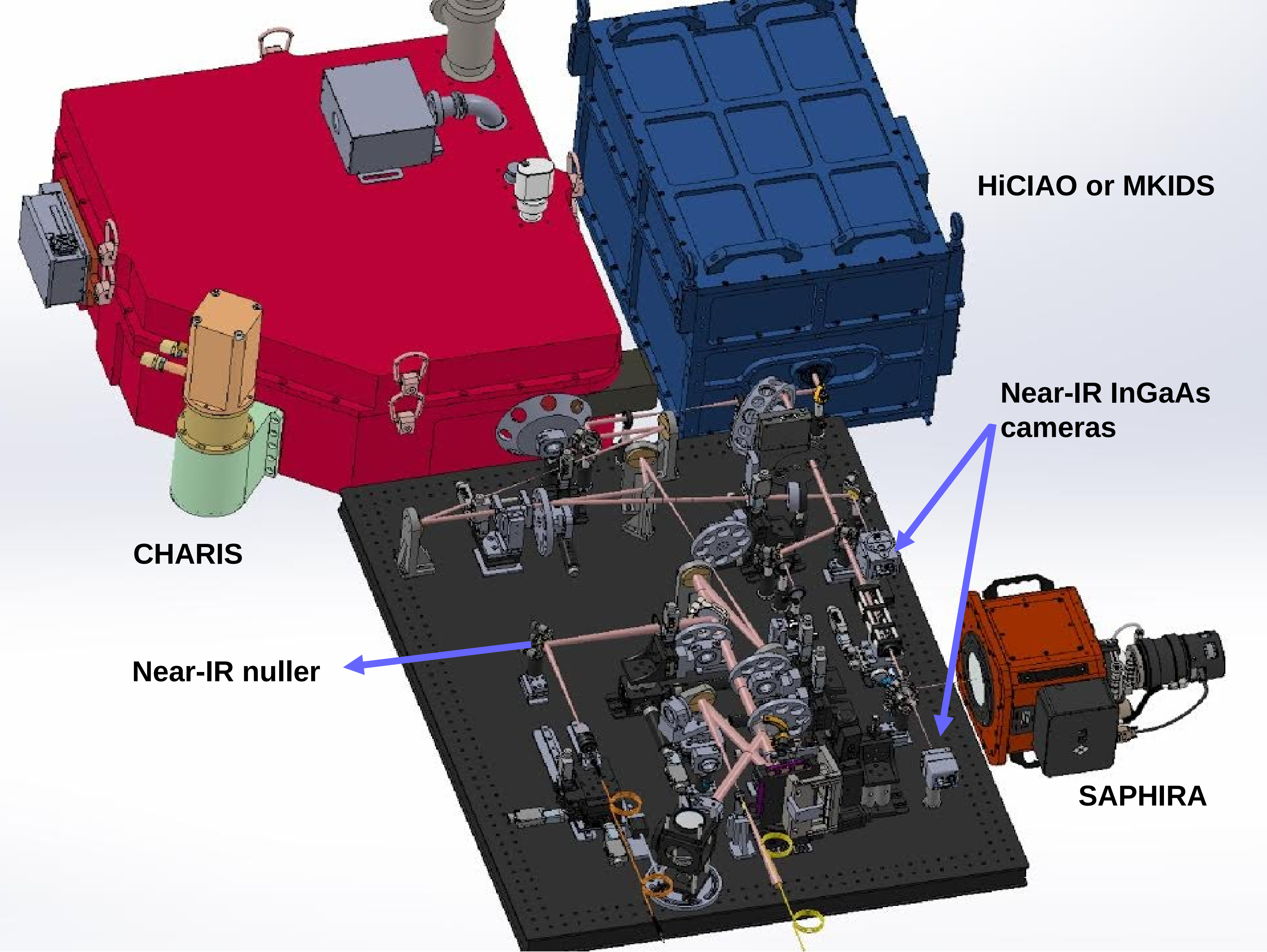
Subaru Coronagraphic Extreme Adaptive Optics



SCExAO

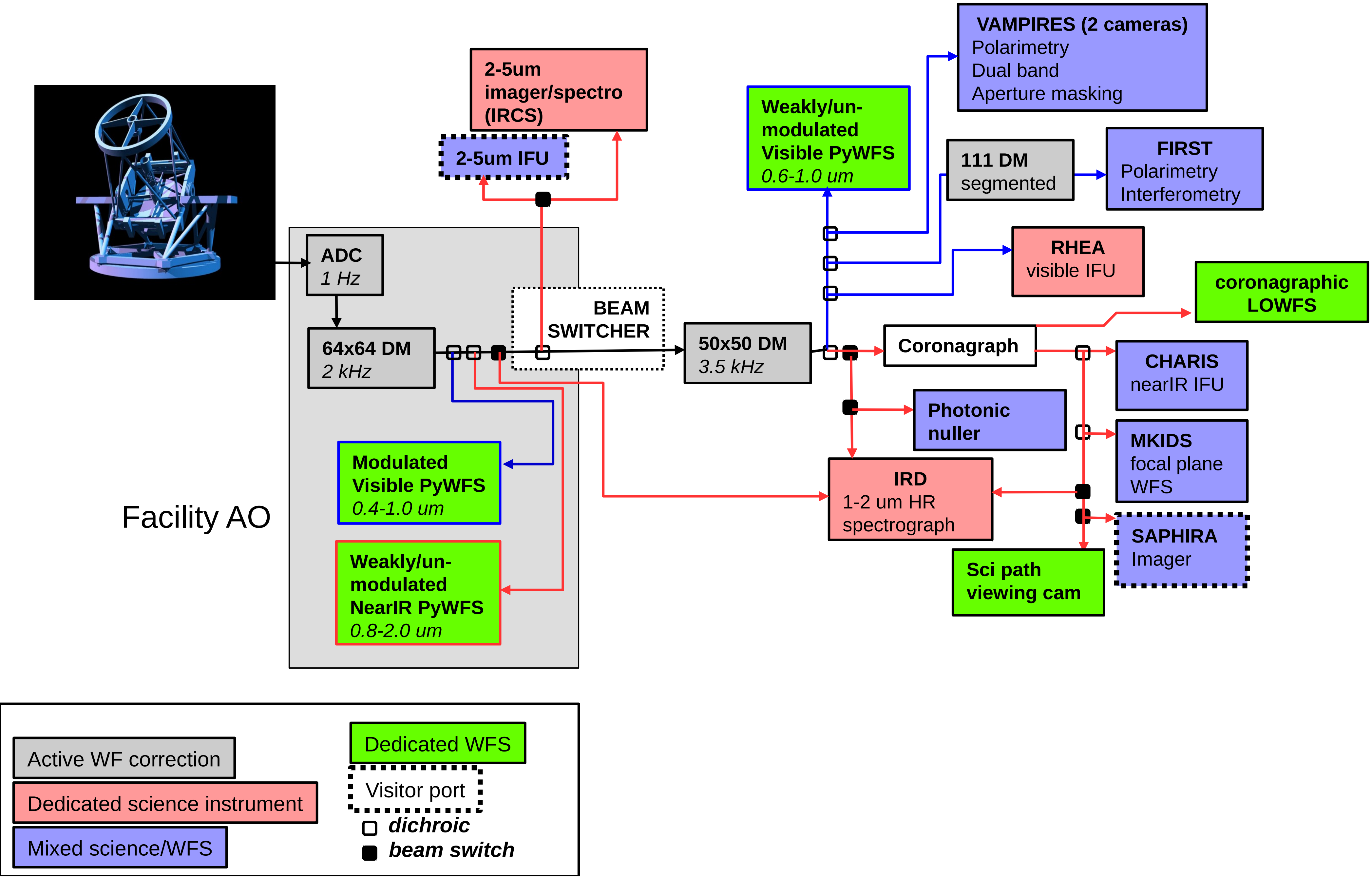
Subaru Coronagraphic Extreme Adaptive Optics




HiCIAO or MKIDS
Near-IR InGaAs
cameras
CHARIS
Near-IR nuller
SAPHIRA

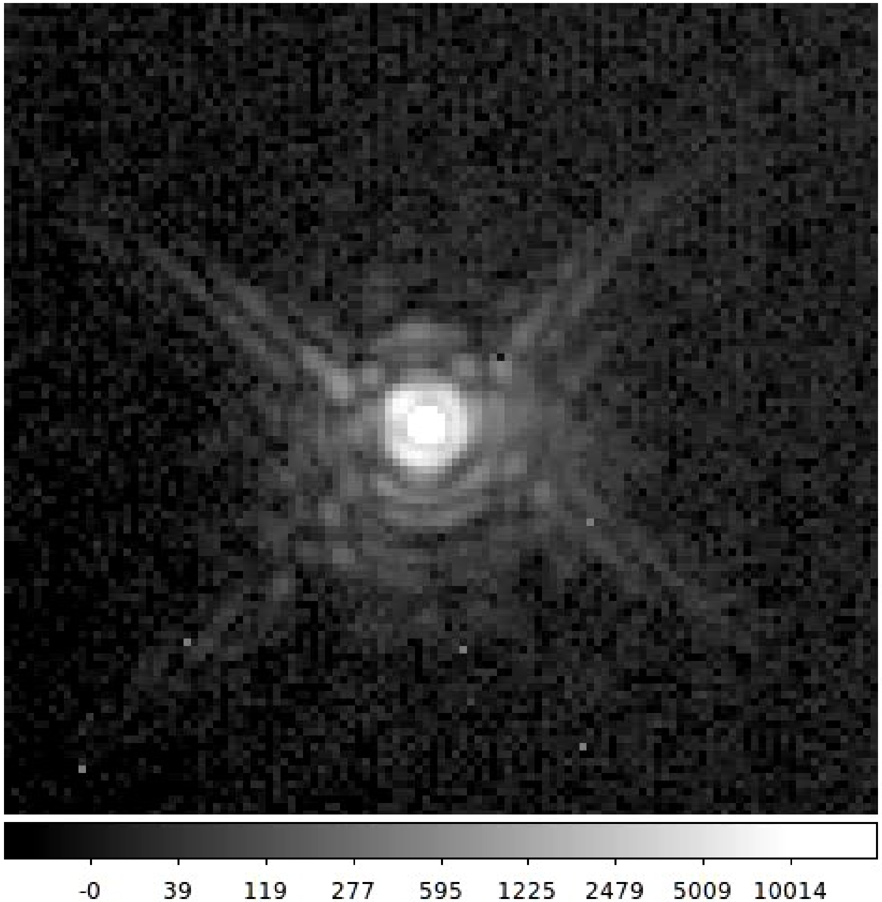
Subaru Coronagraphic Extreme Adaptive Optics

SCExAO Light path

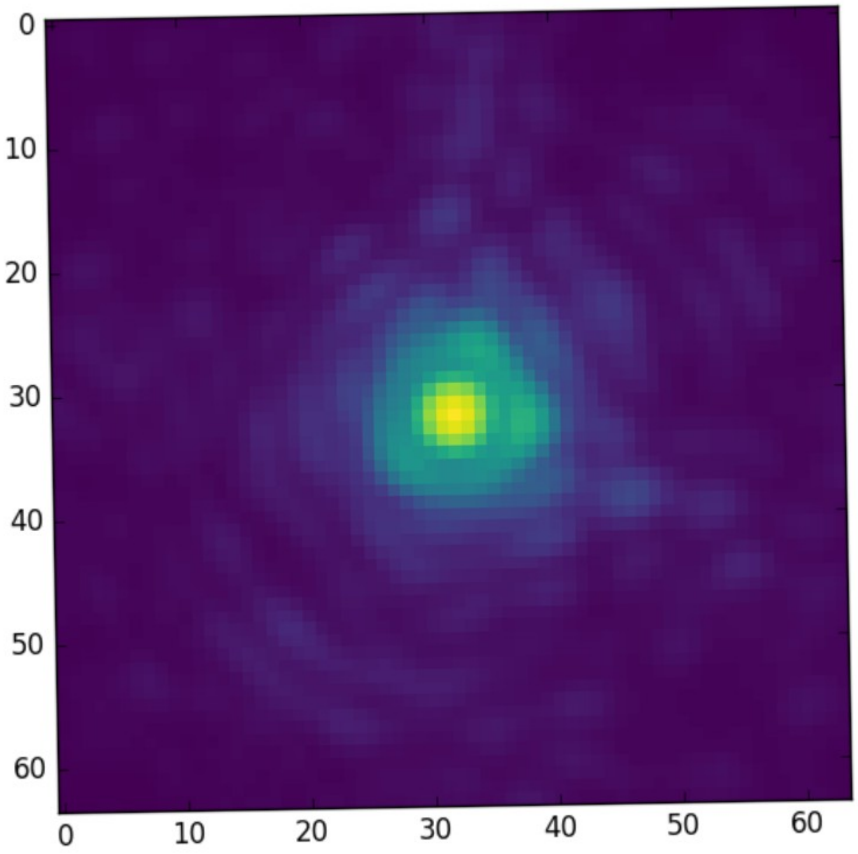


Current PSF stability @ SCExAO

Stable PSF for coronagraphy
SCExAO provides sensing and correction at 500 Hz - 3.5 kHz
14,400 pixel WFS → 2000 actuators



1630nm (SCExAO internal camera)
3 Hz sampling

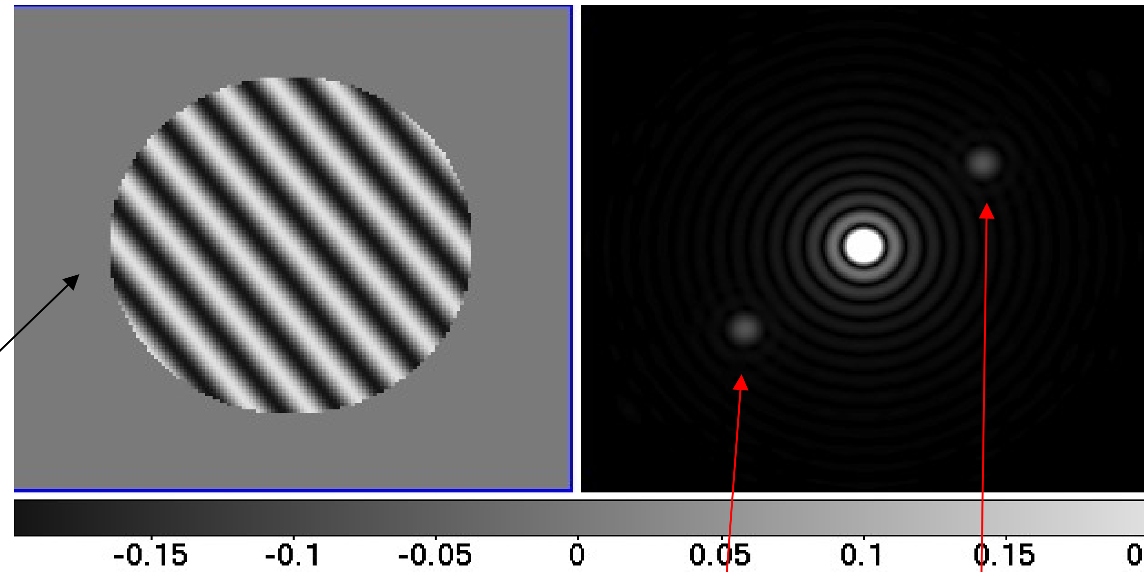


750nm (VAMPIRES)

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

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

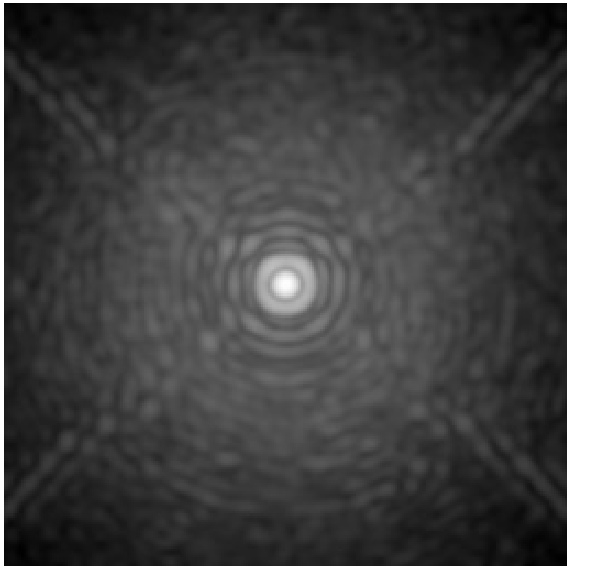
$$I(\vec{\alpha}) = PSF(\vec{\alpha}) + \left(\frac{\pi h}{\lambda}\right)^2 \left[PSF(\vec{\alpha}+\vec{f}\lambda) + PSF(\vec{\alpha}-\vec{f}\lambda)\right]$$

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

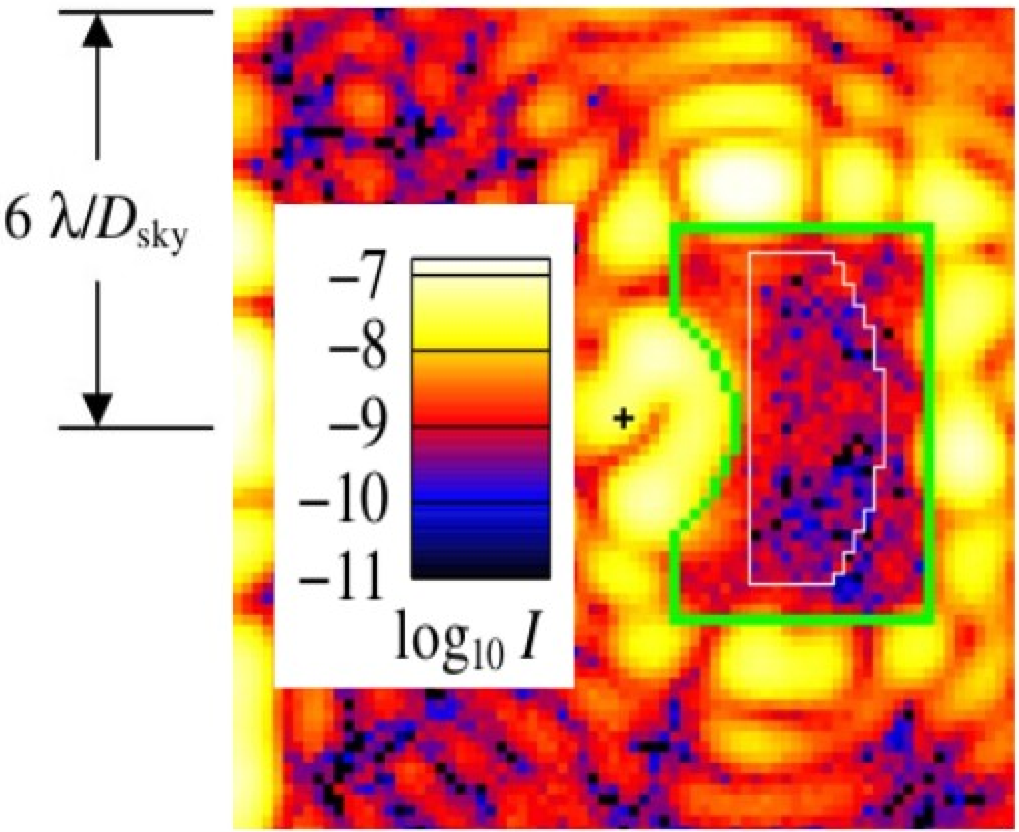
CORRECTION: Put "anti speckles" on top of "speckles" to have destructive interference between the two (Electric Field Conjugation, Give'on et al 2007)

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"

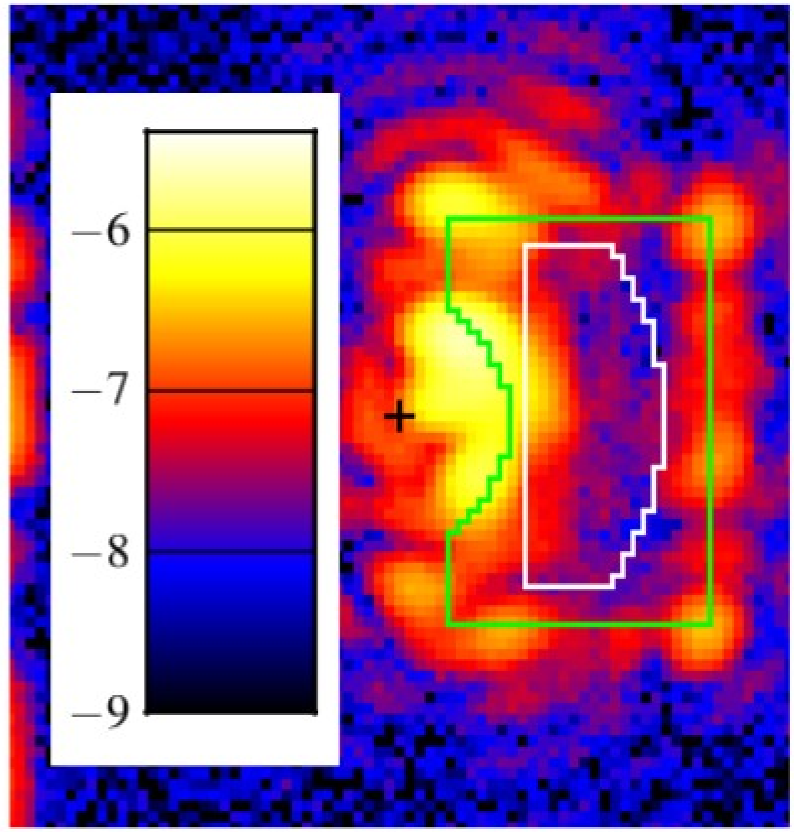
High contrast images obtained in NASA labs
Example: PIAA coronagraph lab results

Monochromatic light (800nm, vacuum)



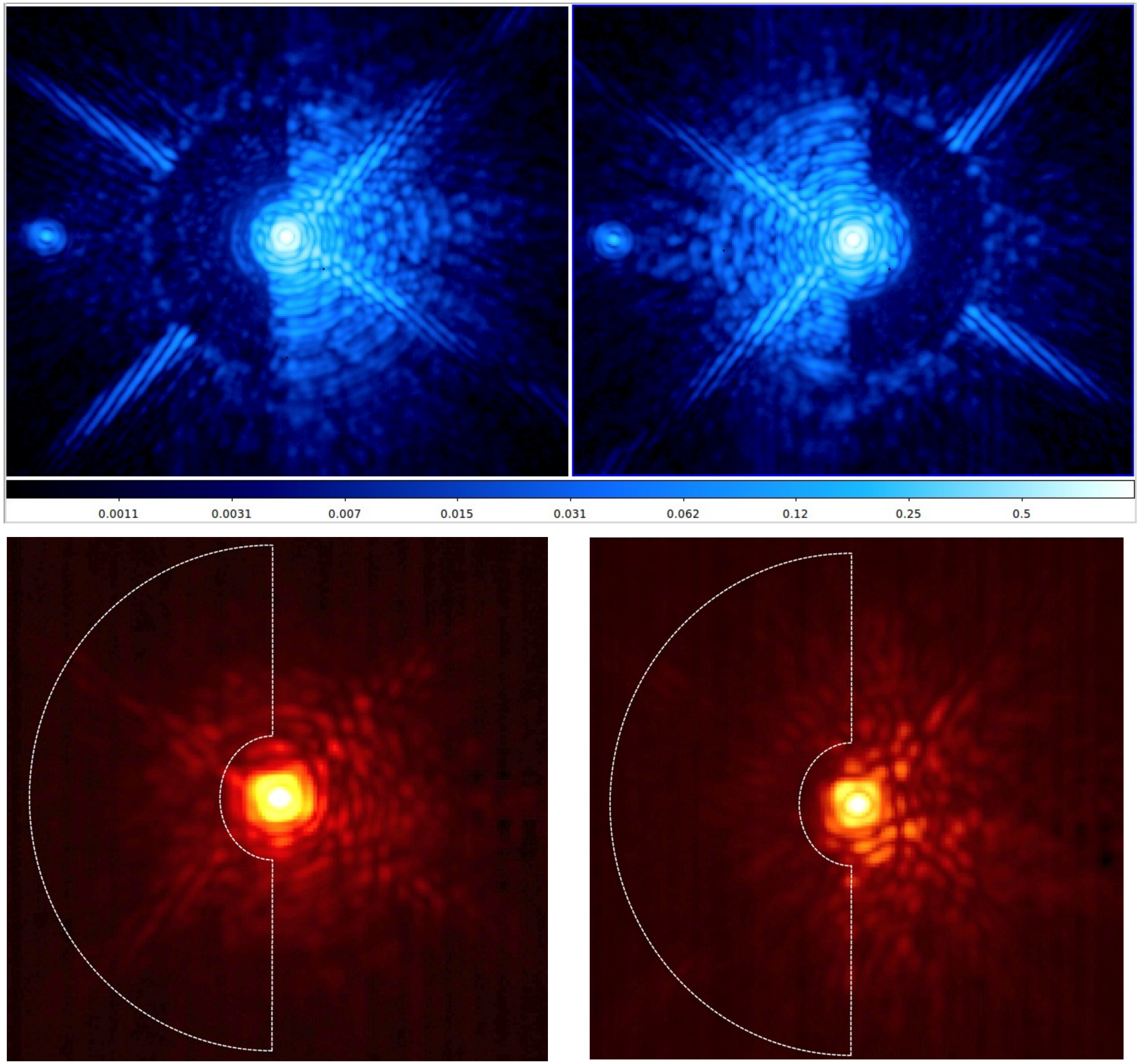
3 runs, contrast values averaged from 2 to 4 λ/D between 5.10^{-10} to 9.10^{-10} (figure shows $7.3.10^{-10}$ result)

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)

Speckle Control



Speckle nulling, in the lab and on-sky (no XAO).

Experience limited by detector readout noise and speed.

KERNEL project: C-RED-ONE camera.

From:
- 114 e- RON
- 170 Hz frame rate

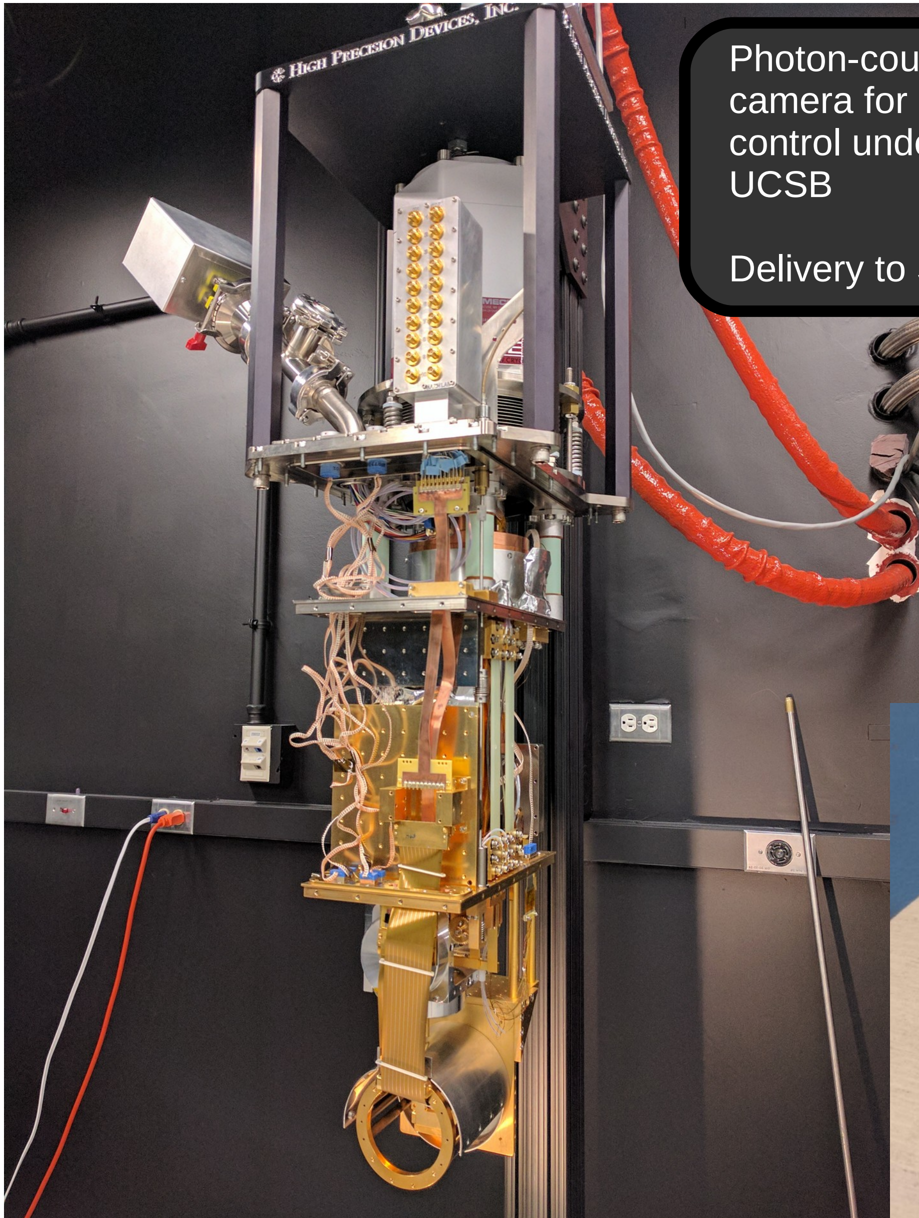
To:
- 0.8 e- RON
- 3500 Hz frame rate

Expect some updates

Observatoire de la CÔTE d'AZUR

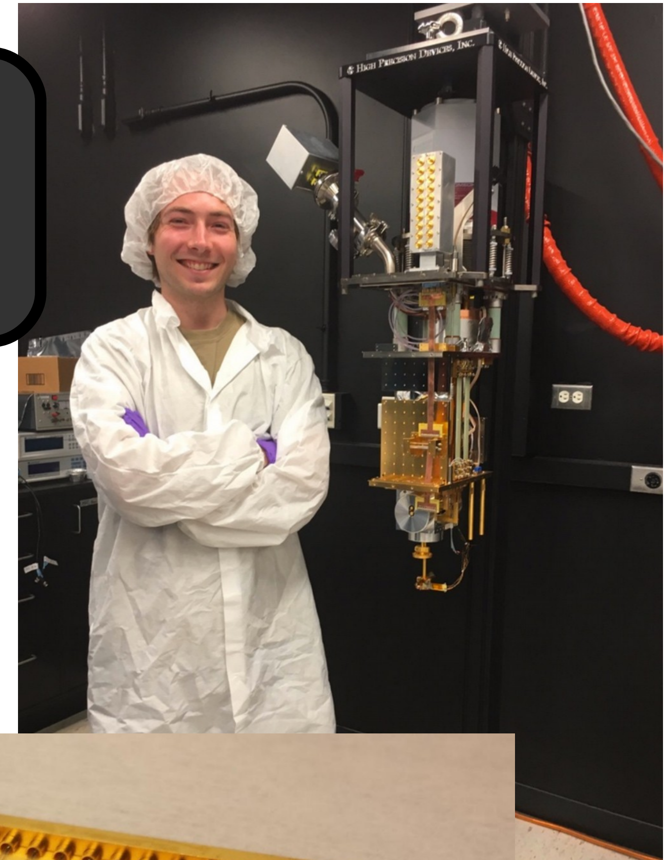
MKIDS camera

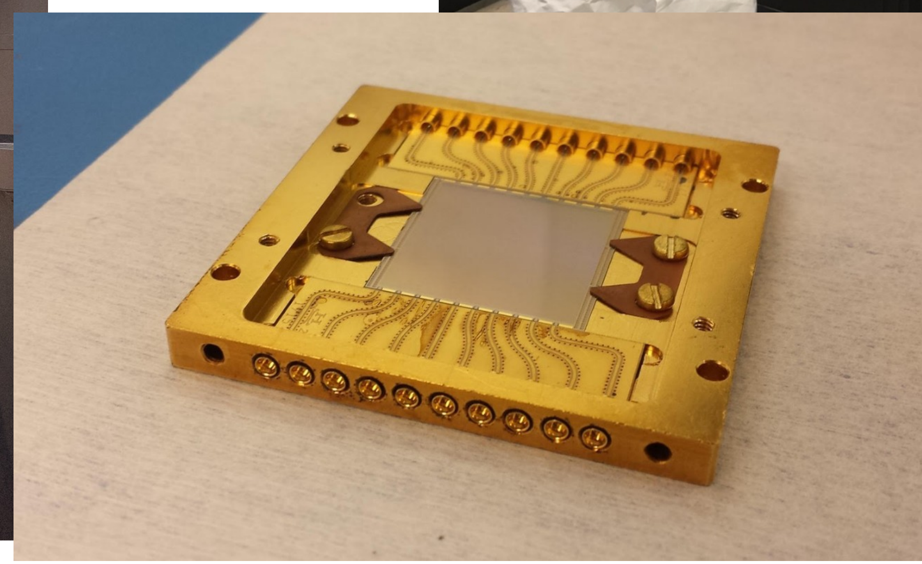
Photon-counting, wavelength resolving 140x140 pixel camera



Photon-counting near-IR MKIDs camera for kHz speed speckle control under construction at UCSB

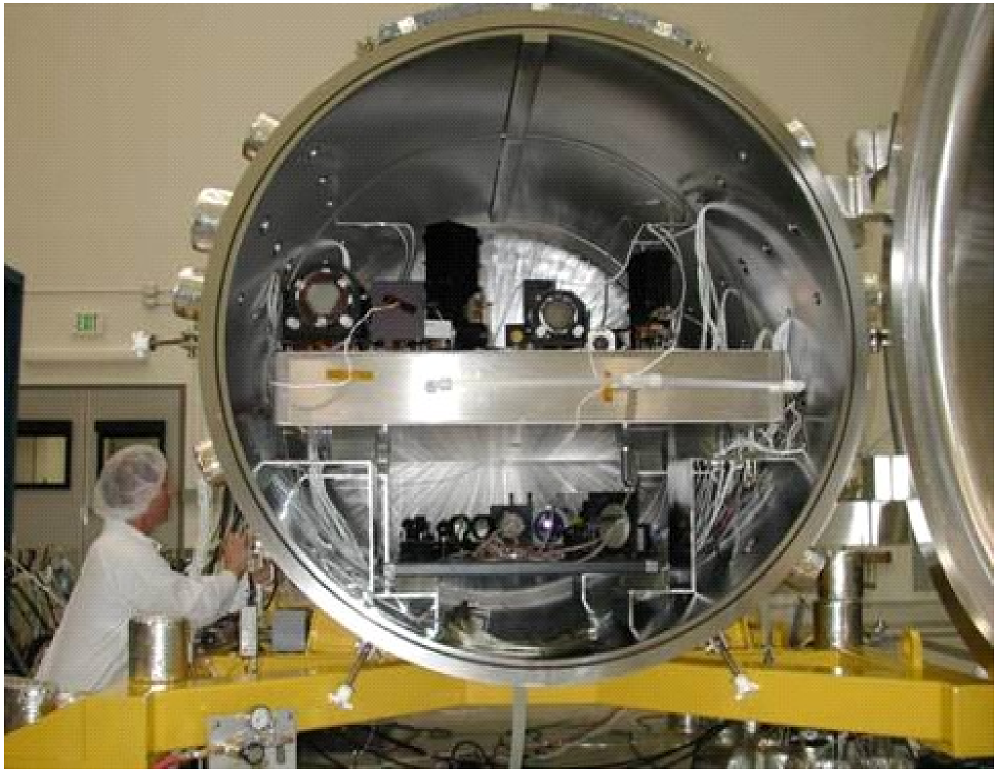
Delivery to SCExAO in late 2017



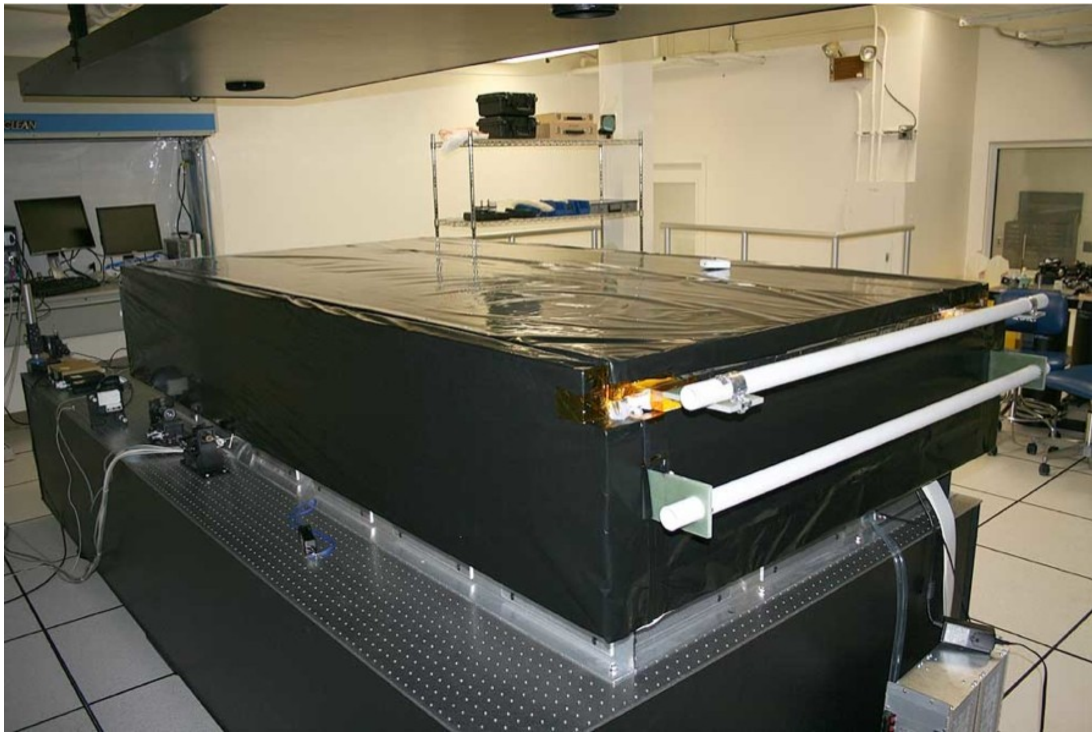


Coronagraphy testbeds for high contrast (< 1e-8) work need to achieve high stability

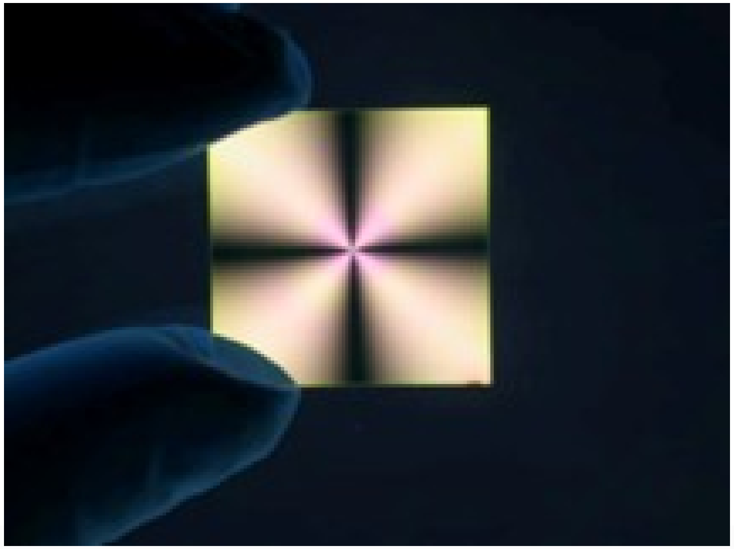
High Contrast Imaging Testbed (HCIT) is a vacuum facility at NASA JPL

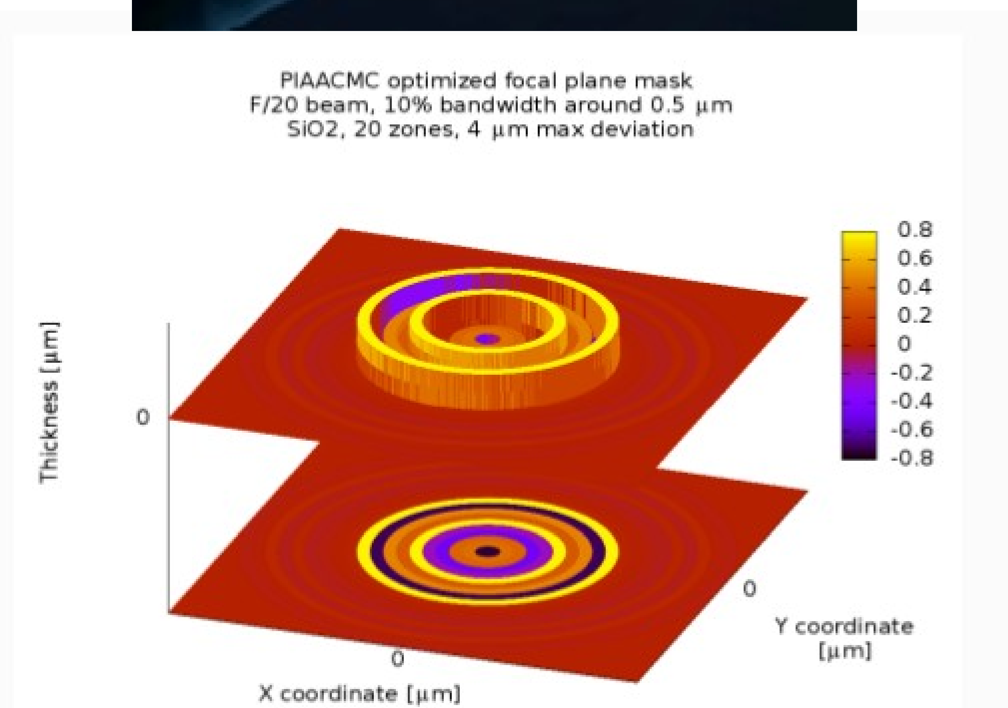


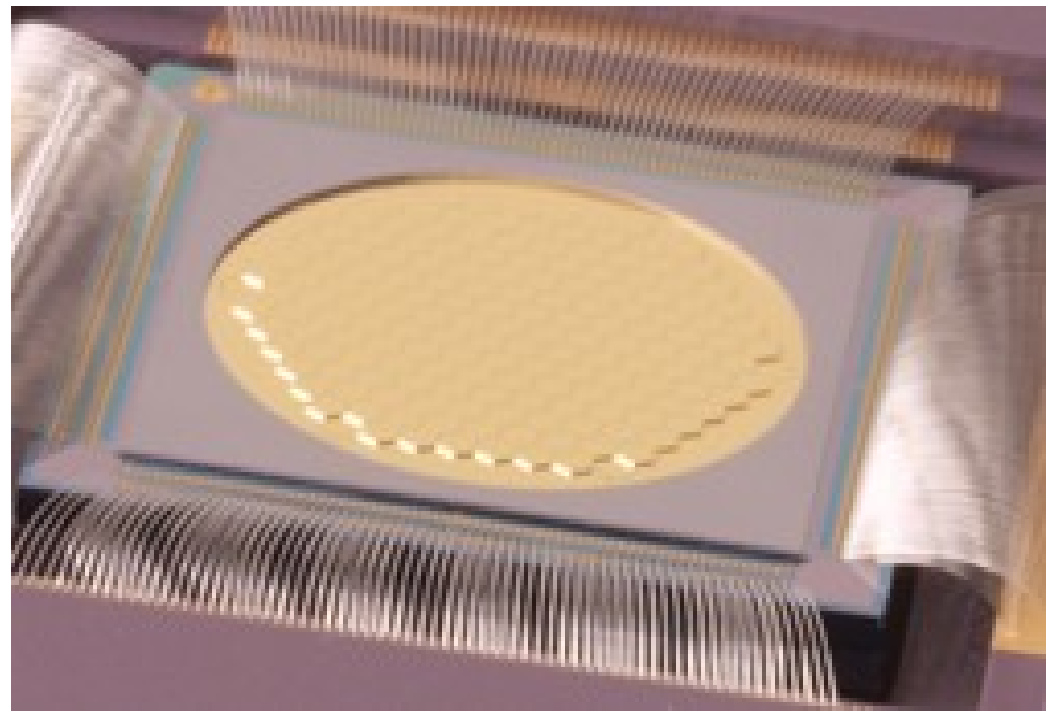
NASA Ames testing PIAA coronagraph / WFC architectures & MEMs DMs.



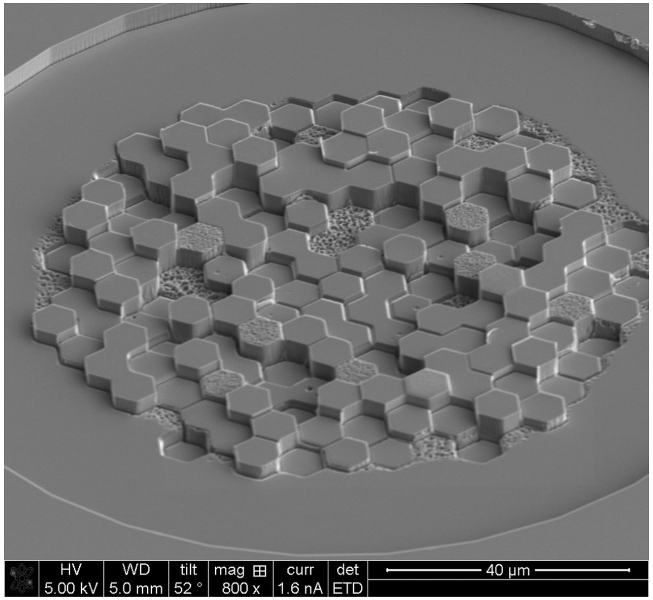
Technology: components



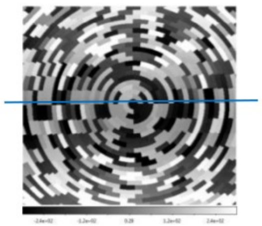


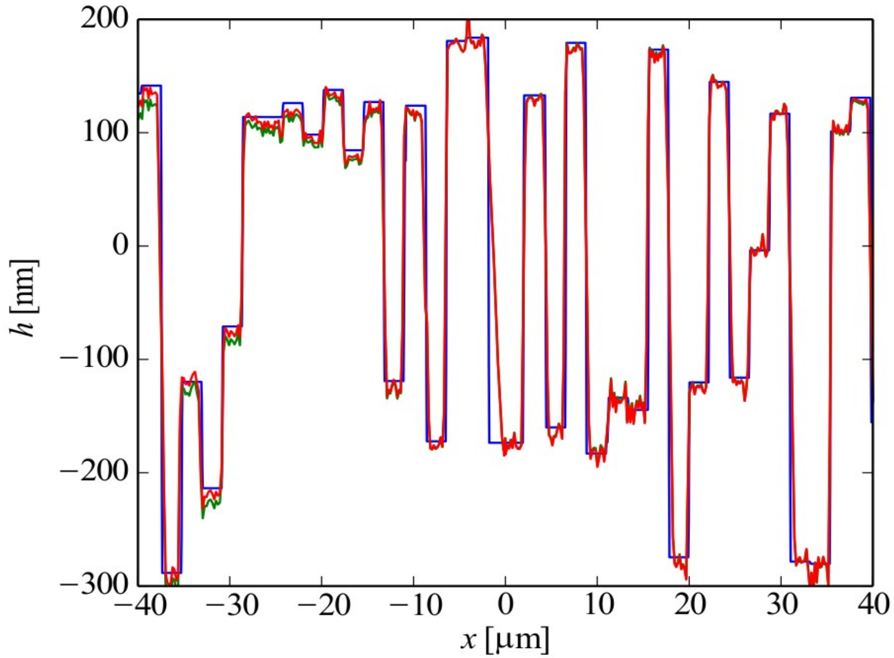


Multi-zone PIAACMC focal plane mask

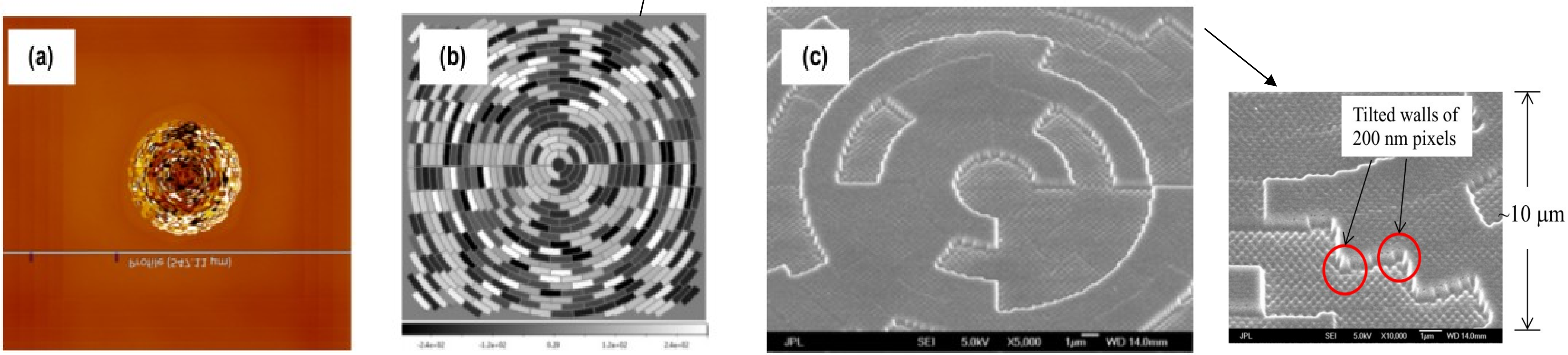


← SCExAO focal plane mask (2017)





Focal plane mask manufactured at JPL's MDL
Meets performance requirements
(WFIRST PIAACMC Milestone report)



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 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 = sqrt(a^3/M)
Example: Proxima Centauri...
1/600 Sun luminosity, 0.123 Sun Mass, d=1.3 pc

Habitable planets in reflected light: separation, contrast

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    Example: d=10pc, L = 1 → 0.1”

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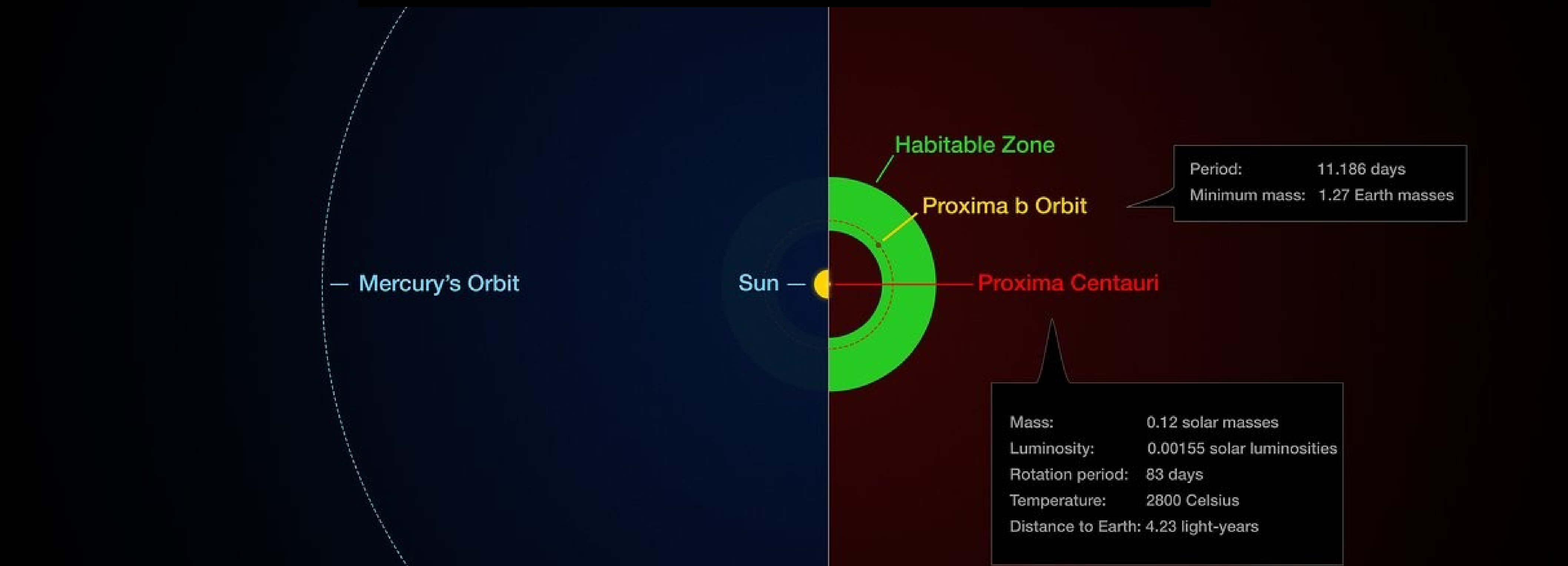
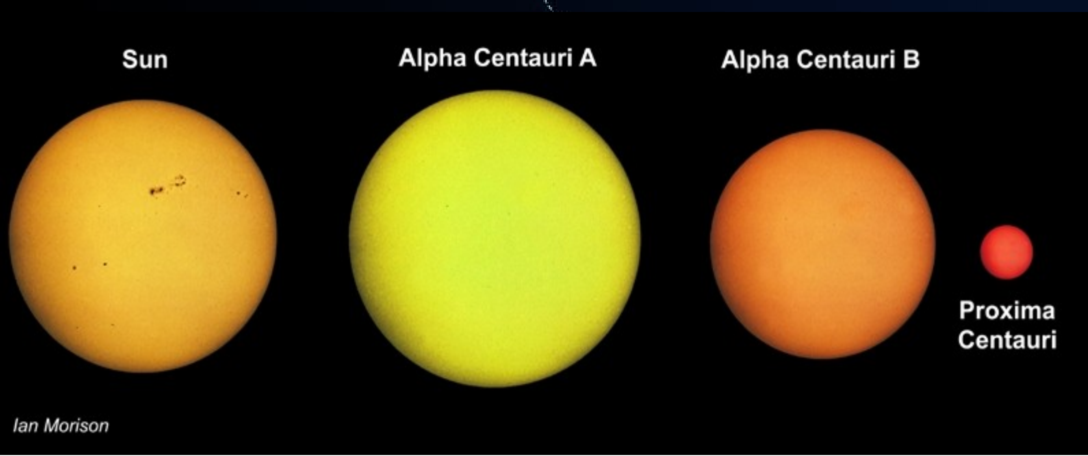
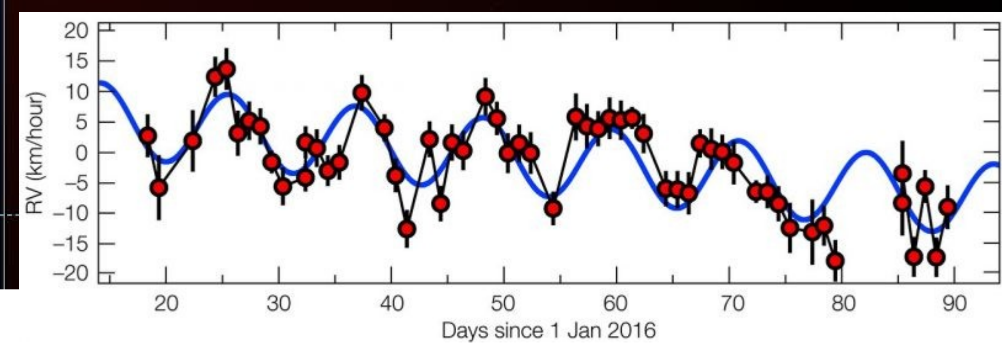
    Example: L=0.01 (M type star) → contrast = 2e-8

Orbital period P = 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

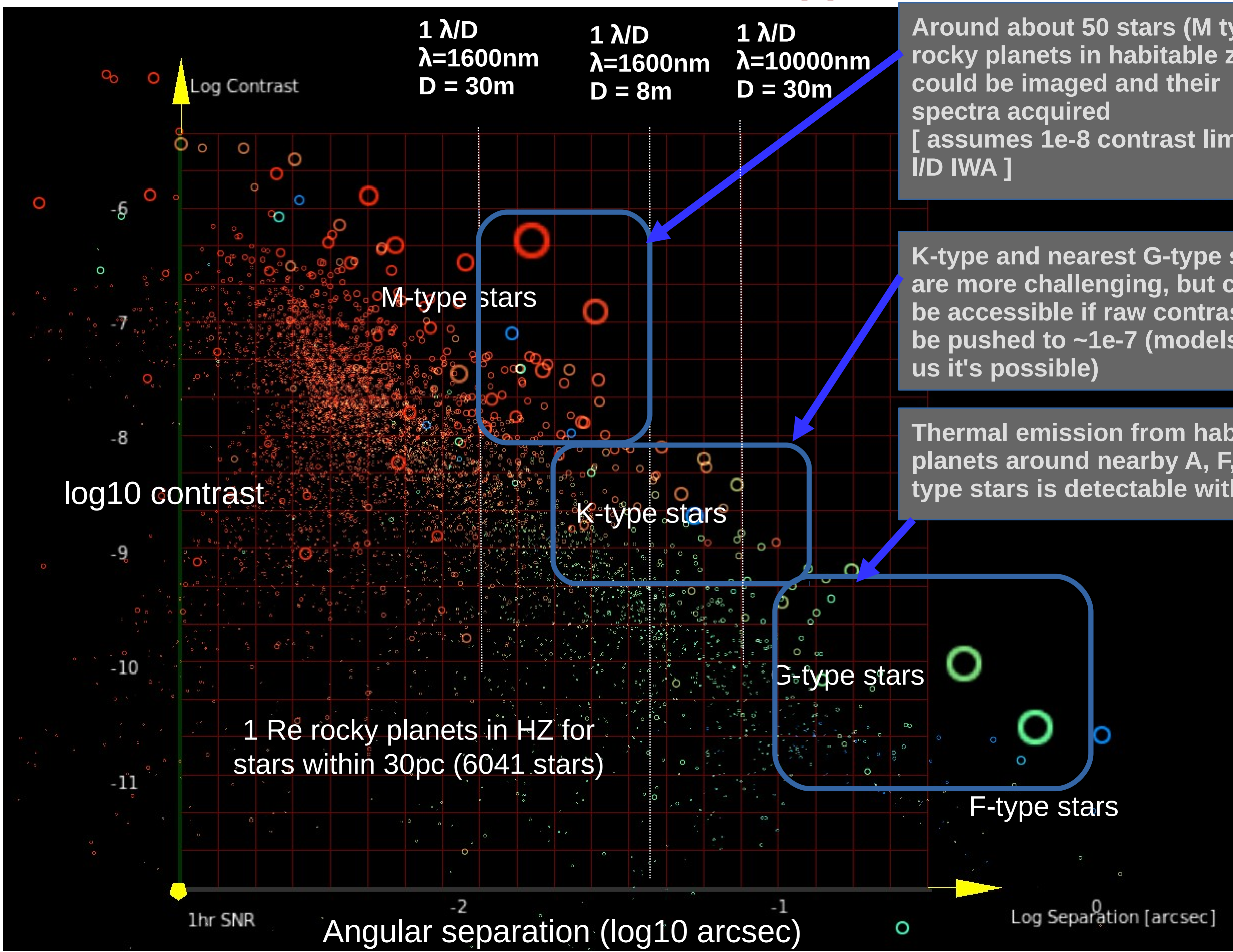
Proxima Centauri







Habitable Planets: Contrast and Angular separation
Ground-based observation opportunities

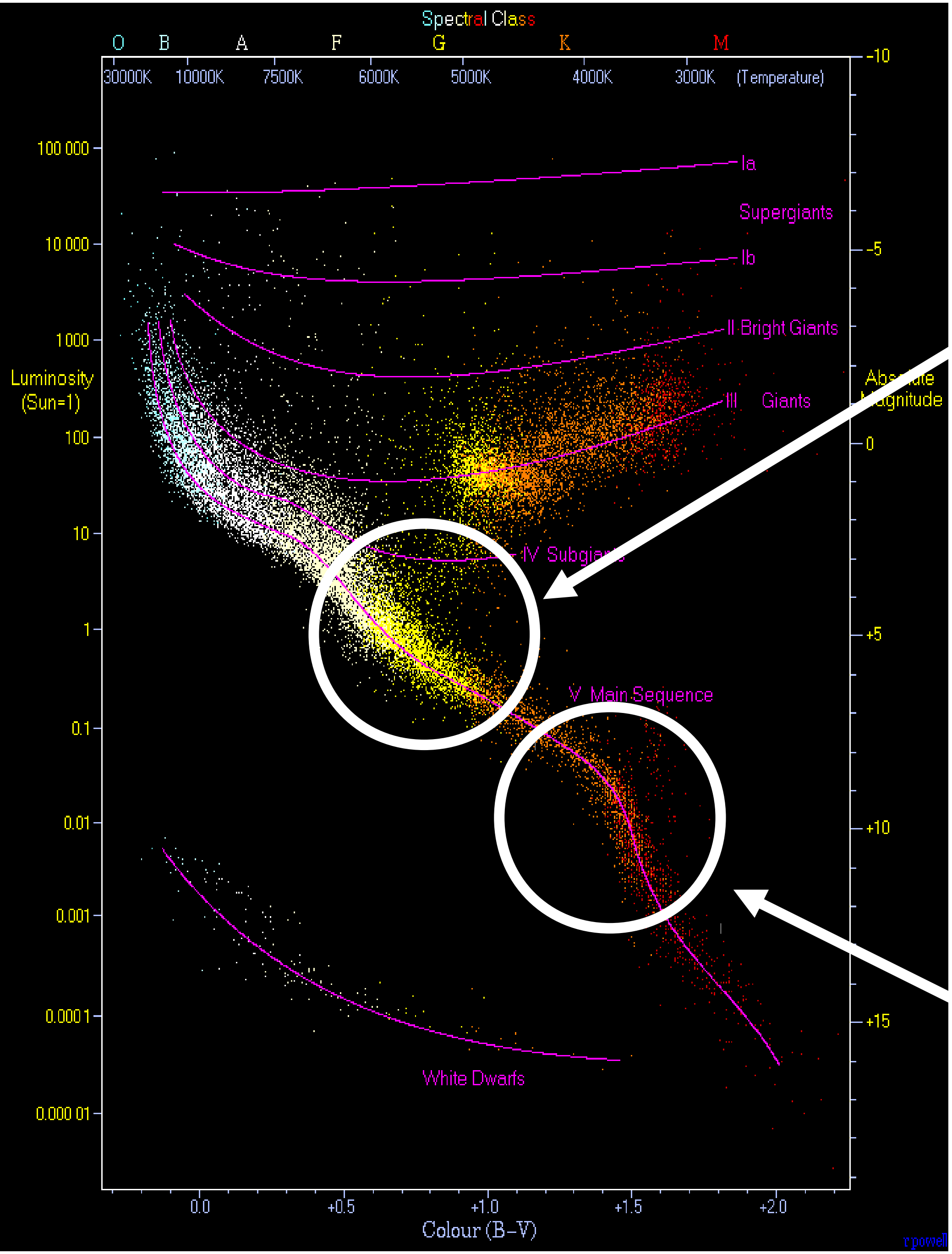


Around about 50 stars (M type), rocky planets in habitable zone could be imaged and their spectra acquired
[assumes 1e-8 contrast limit, 1 l/D IWA]

K-type and nearest G-type stars are more challenging, but could be accessible if raw contrast can be pushed to ~1e-7 (models tell us it's possible)

Thermal emission from habitable planets around nearby A, F, G type stars is detectable with ELTs

Imaging habitable planets from space and ground



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

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

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

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

Backup slides : Coronagraph design

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

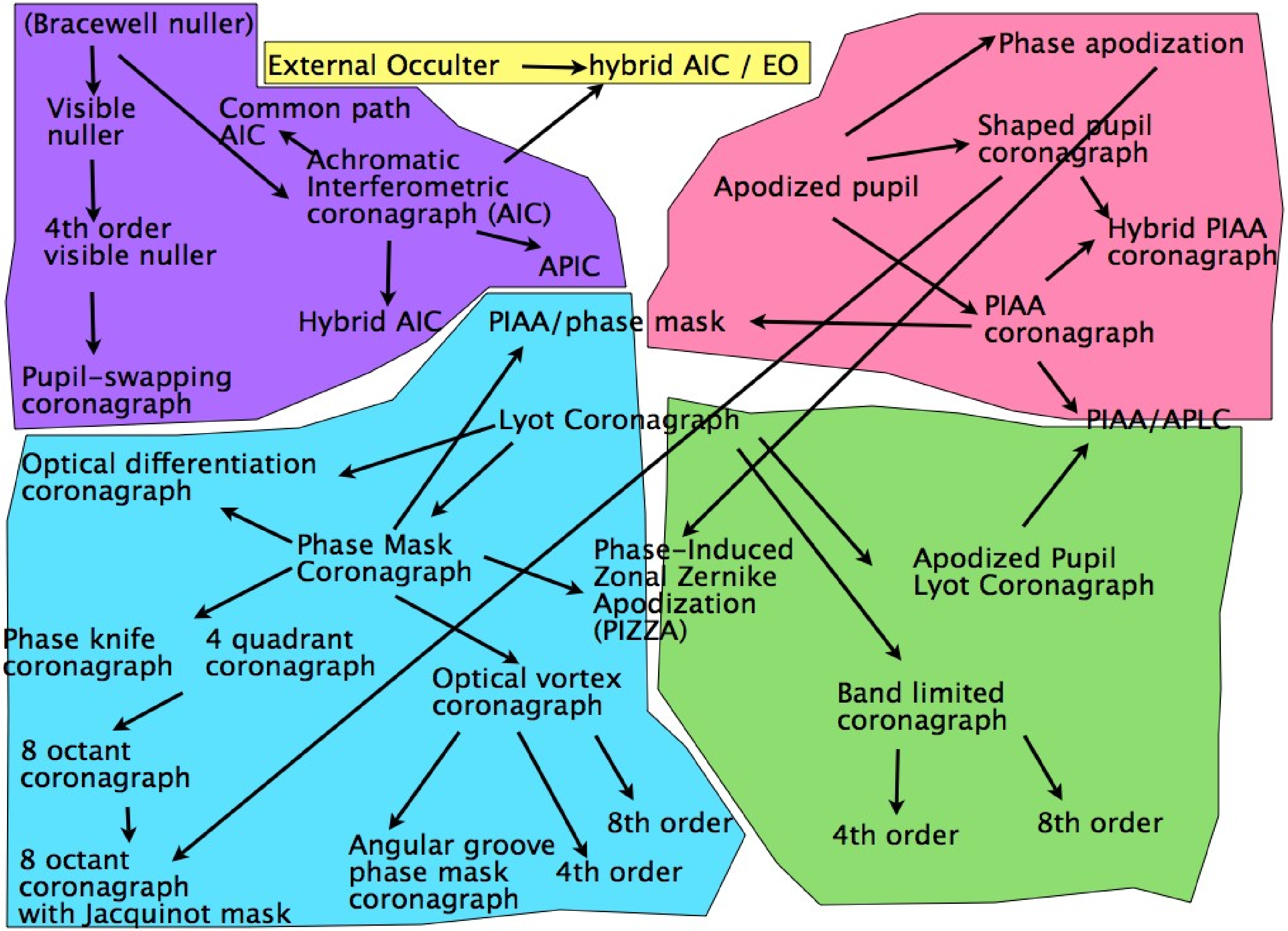
- Design masks and optical components inside the telescope to induce starlight destructive interference at the expected location of a planet in the image: ***internal coronagraph (this lecture)***

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

Internal Coronagraphs: main approaches

Apodization

Beam splitting and destructive interference



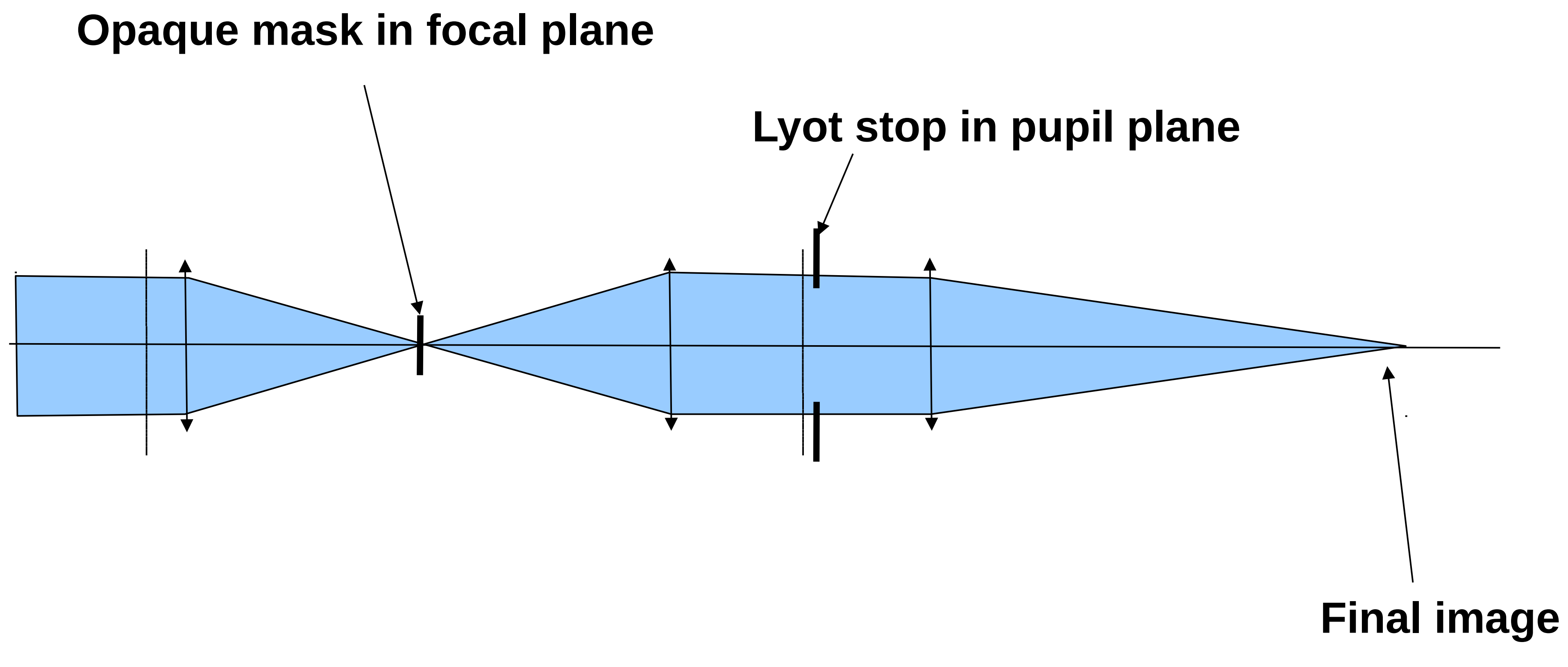
Phase masks in focal plane

Amplitude masks in focal plane

Lyot Coronagraph

Developped by Bernard Lyot in 1930 to observe the solar corona

It is the origin of many current high performance coronagraph designs

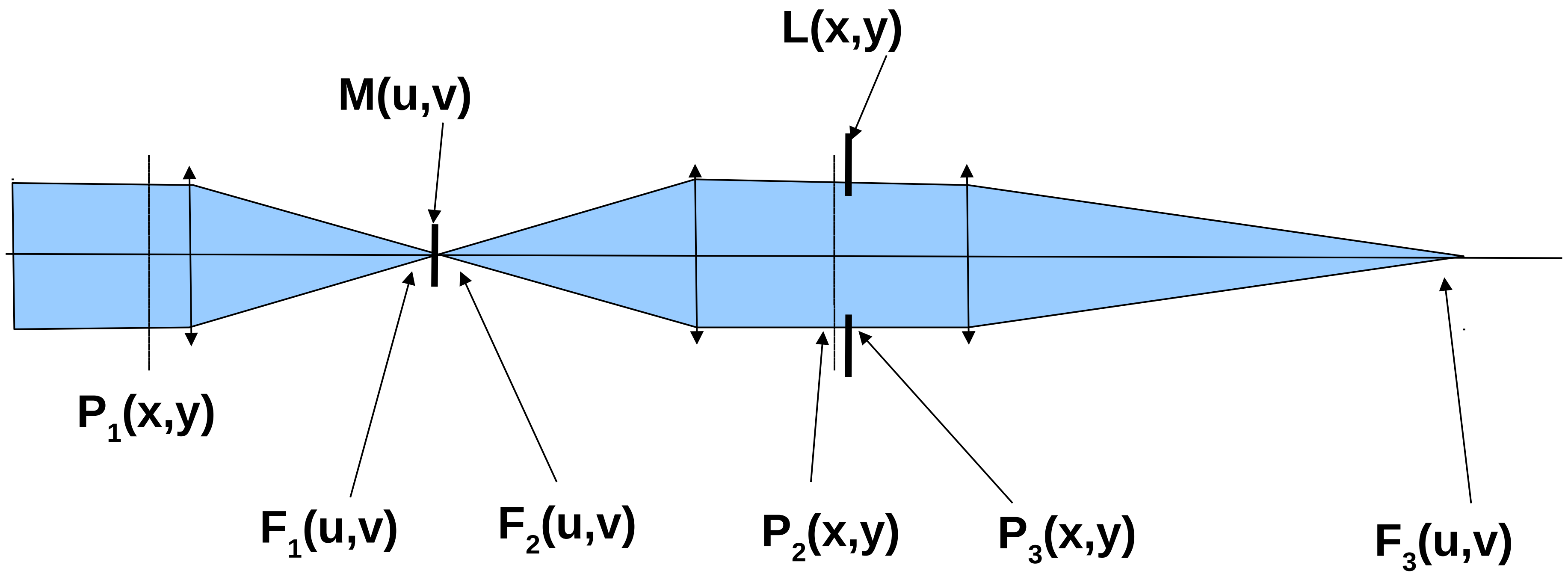


Lyot Coronagraph explained by Fourier transforms

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

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

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

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

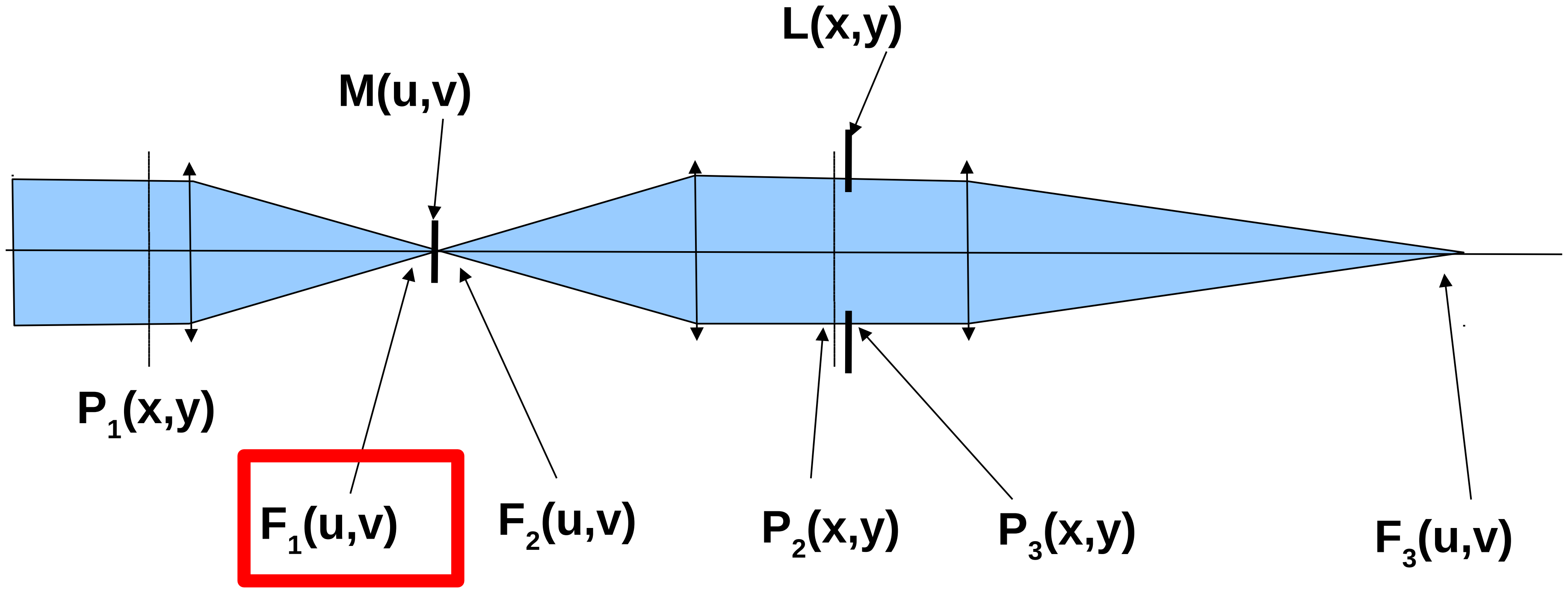
Coronagraphy problem: minimize $P_3(x,y)$ for on-axis point source

Lyot Coronagraph explained by Fourier transforms

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)

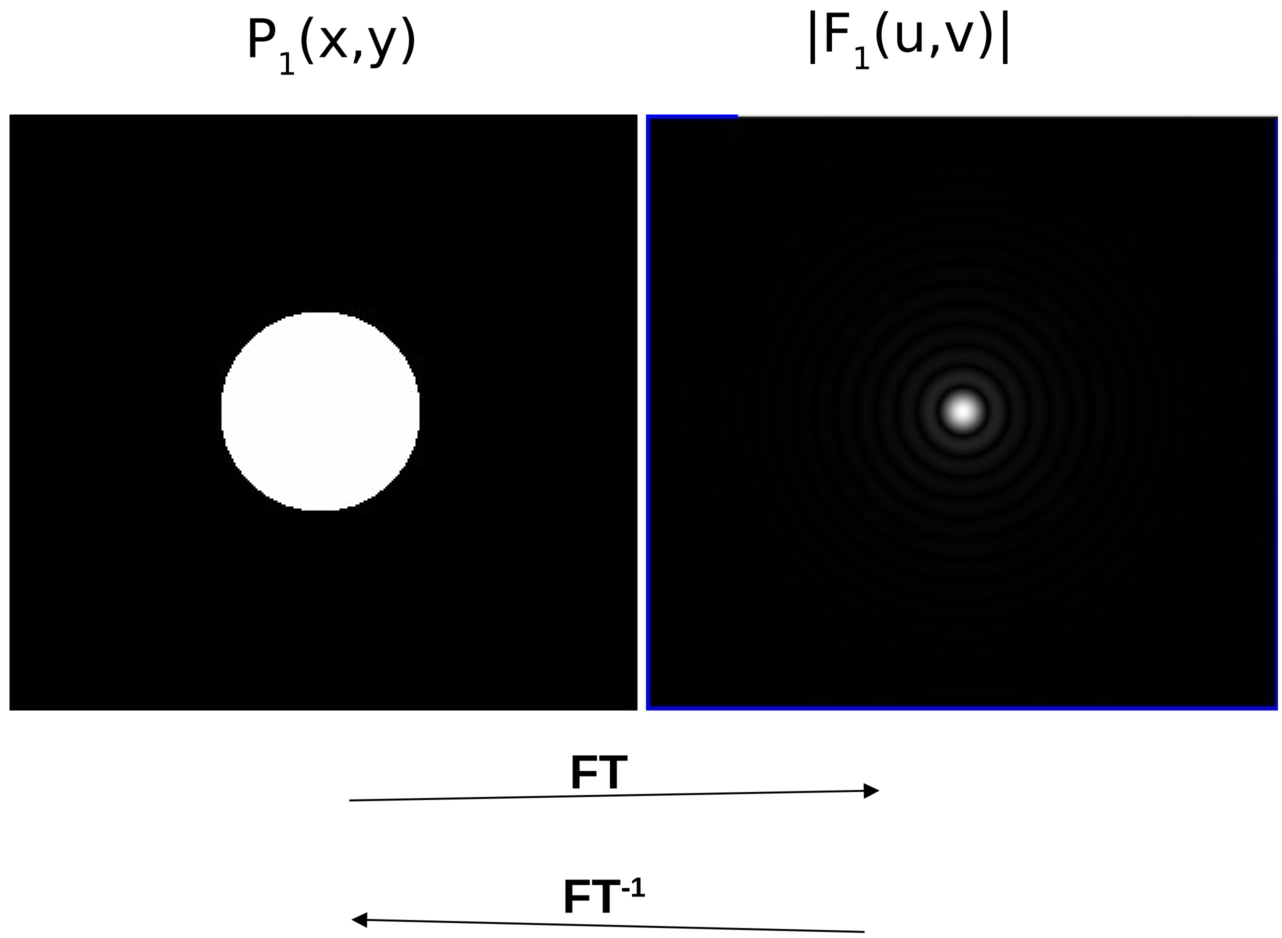


Focal plane image = FT of pupil complex amplitude

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

Pupil plane complex amplitude ↔ focal plane complex amplitude

→ Fourier transform
← Inverse Fourier transform

Coordinates in pupil plane: x,y
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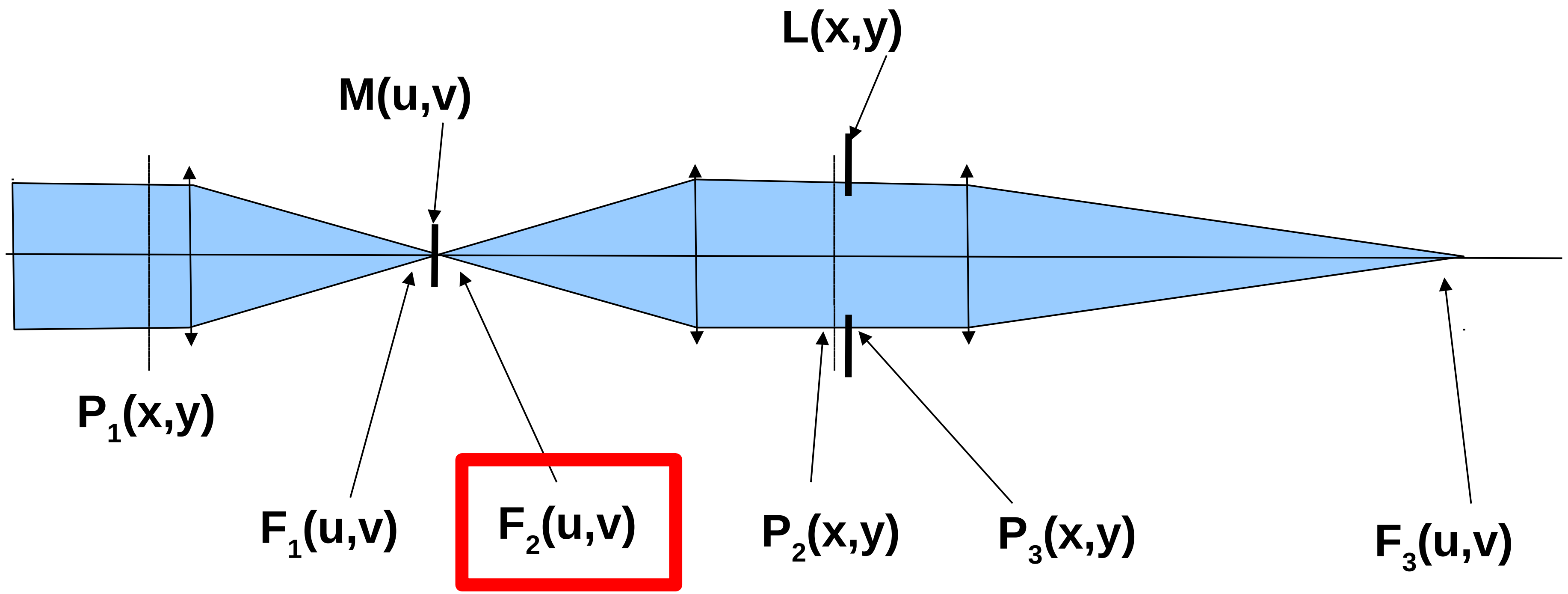
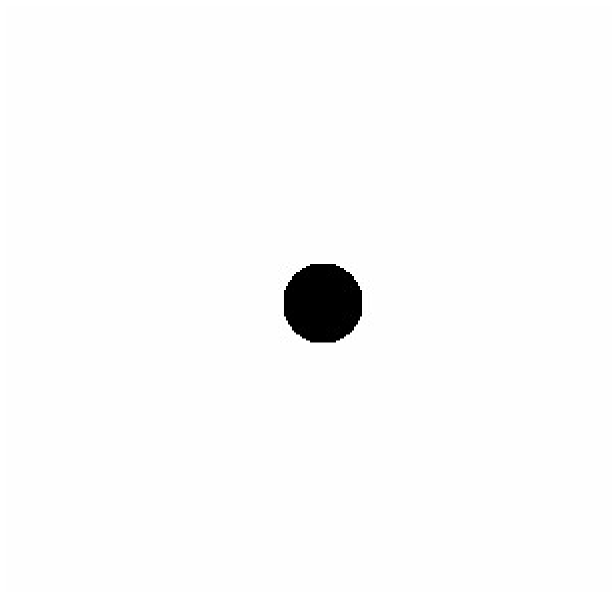


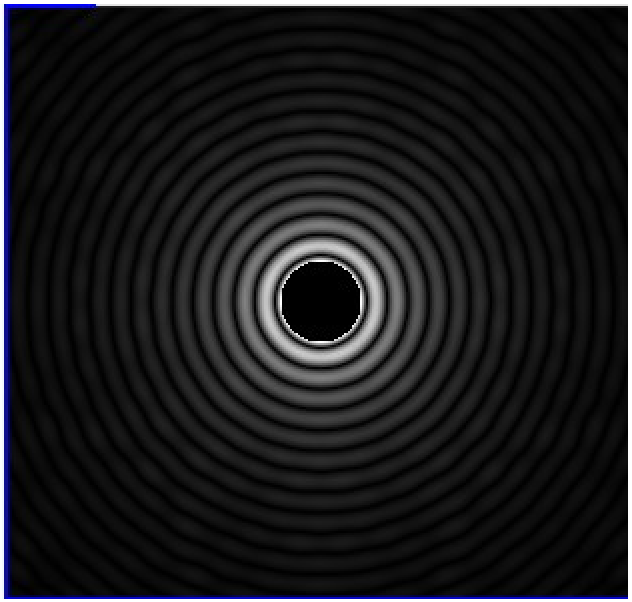
Inserting an opaque mask in the focal plane

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)



$|F_2(u,v)|$

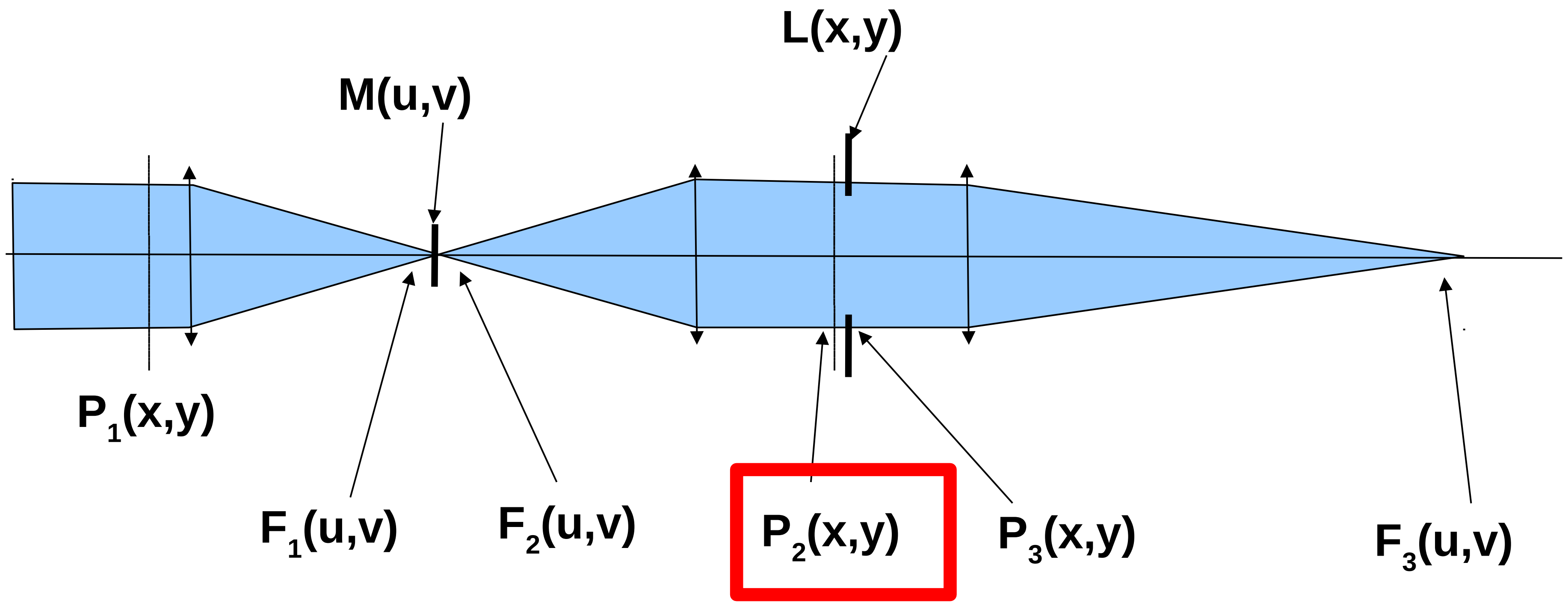


Lyot Coronagraph explained by Fourier transforms

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)



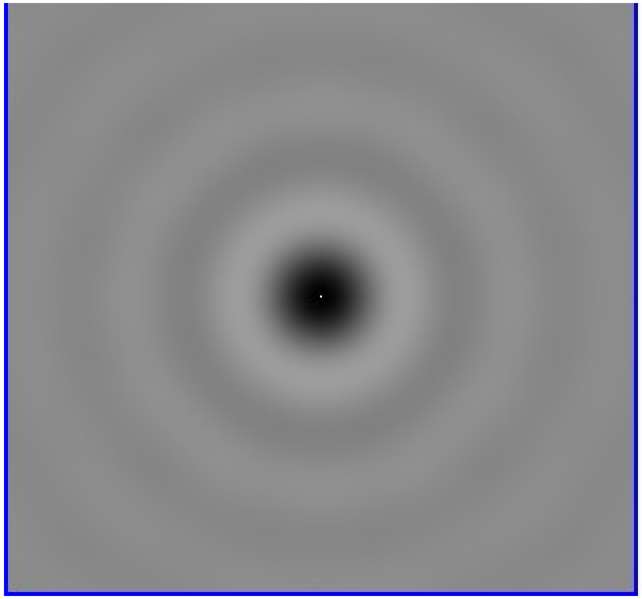
Lyot Coronagraph : light distribution in output pupil plane

Exit pupil plane:

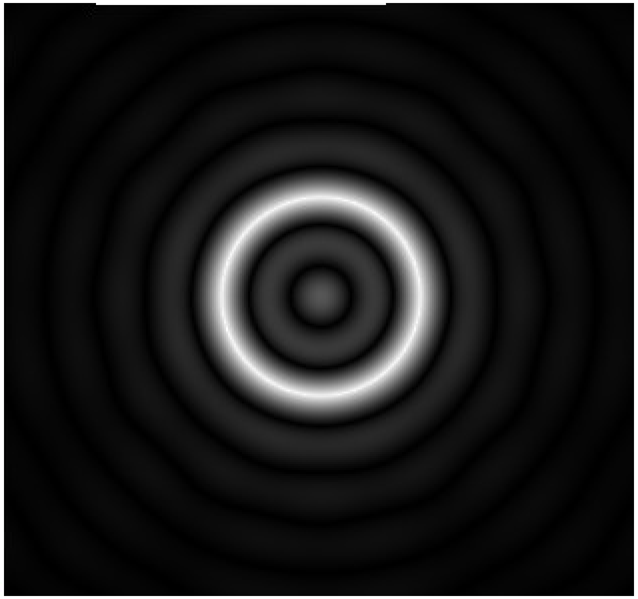
$P_2(x,y) = FT^{-1}(F_2(u,v))$

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

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



$|P_2(x,y)|$

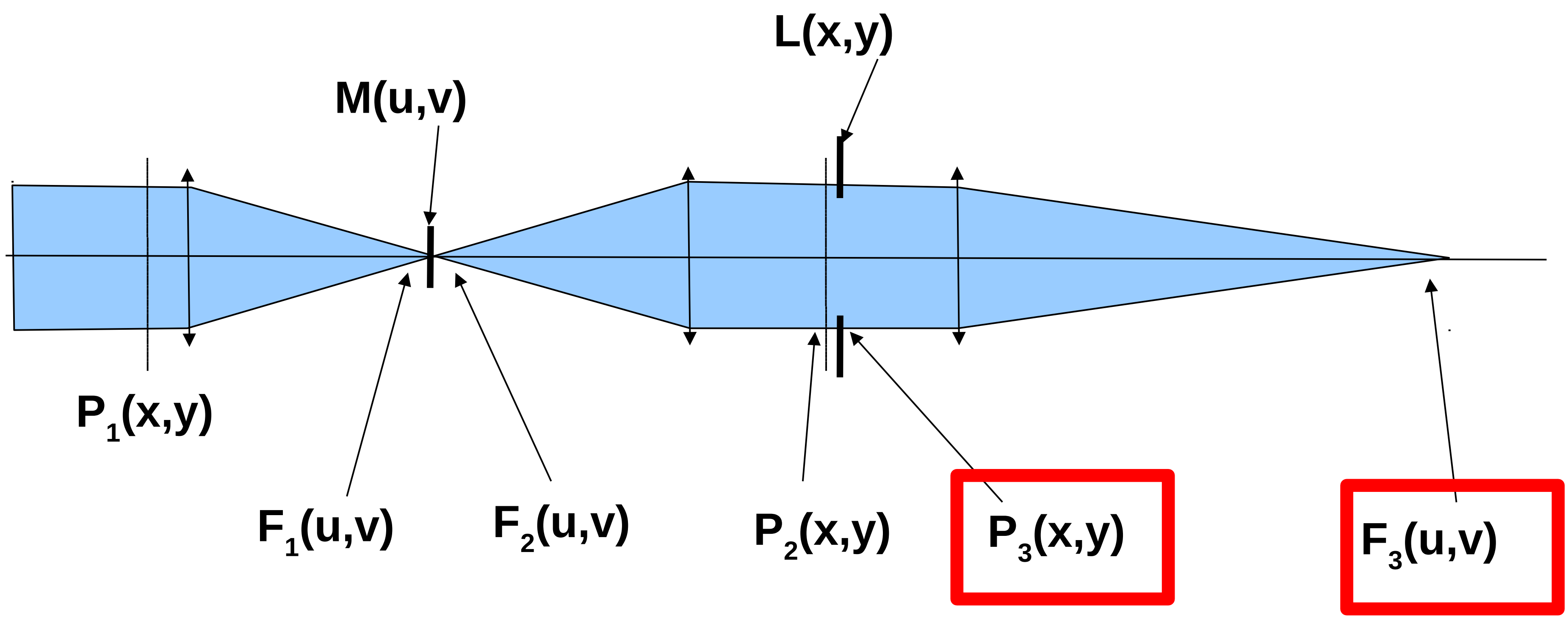


Lyot Coronagraph explained by Fourier transforms

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)



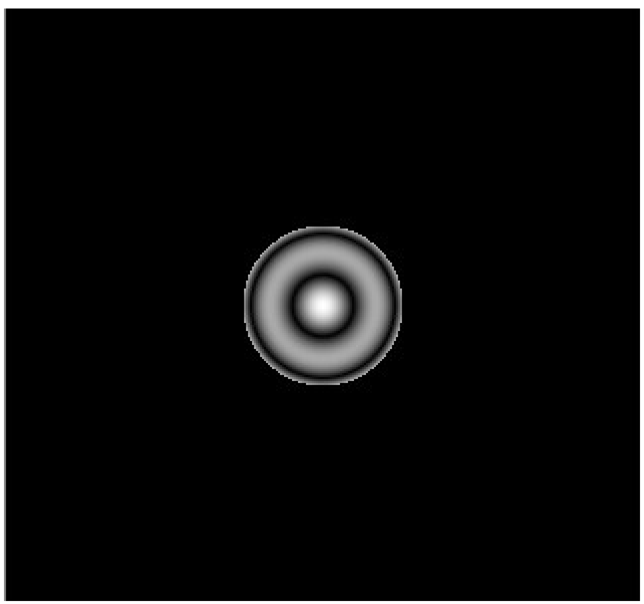
Lyot Coronagraph : Lyot stop (L)

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

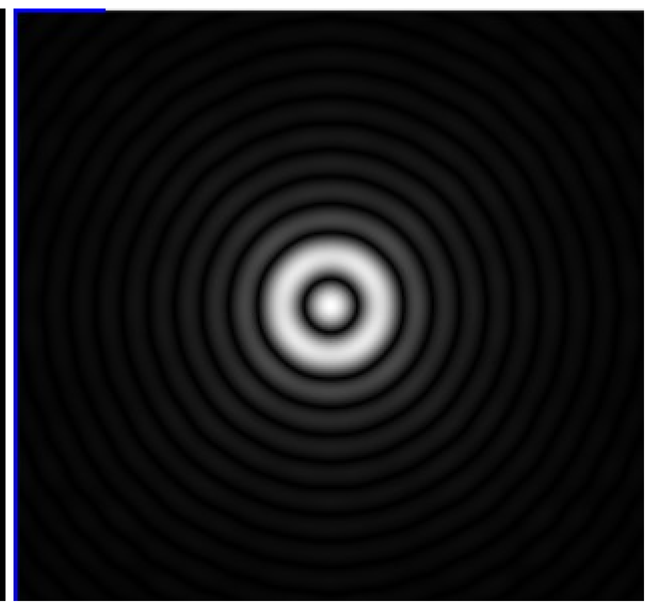
$\mathbf{P_3(x,y) = L(x,y) \times (P_1(x,y) * FT^{-1}(M(u,v)))}$

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

$|P_3(x,y)|$

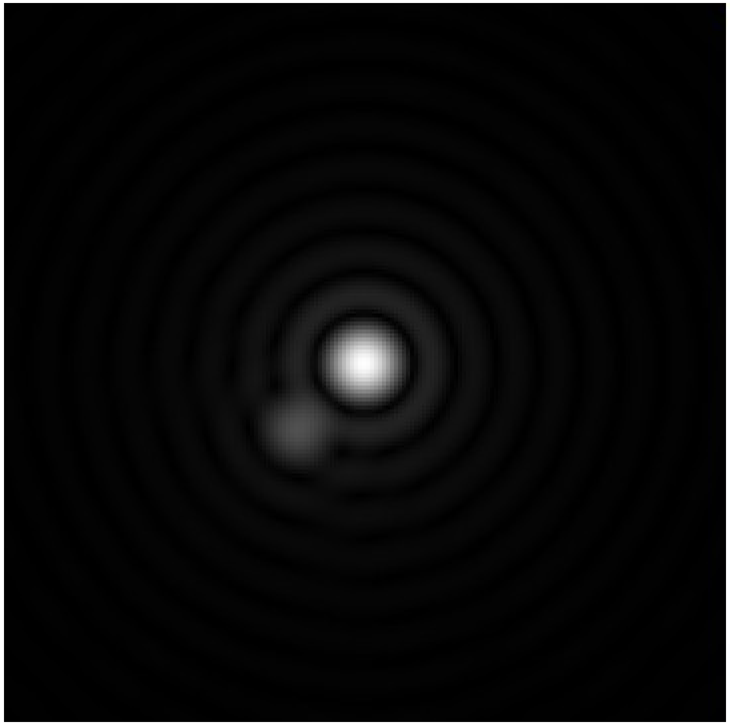


$|F_3(u,v)|$

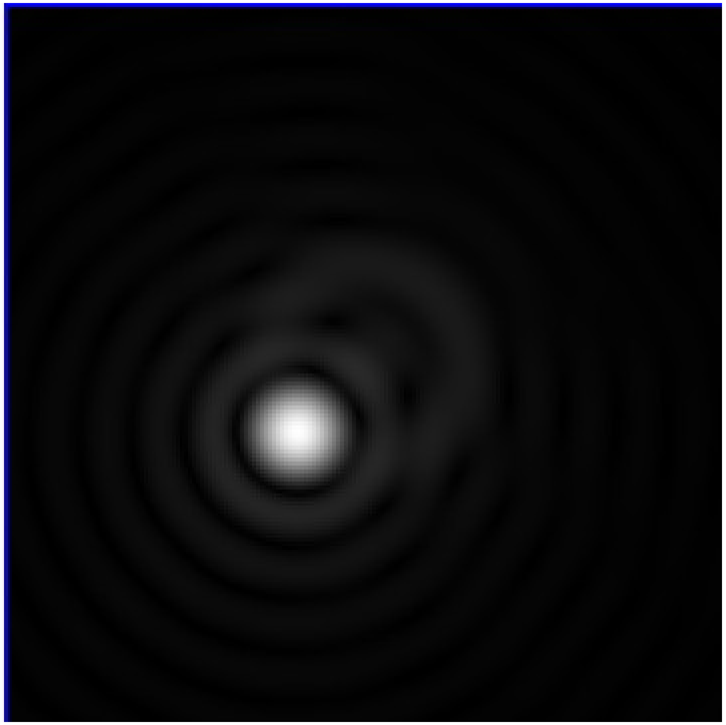


Numerical simulation of final image for 10:1 contrast

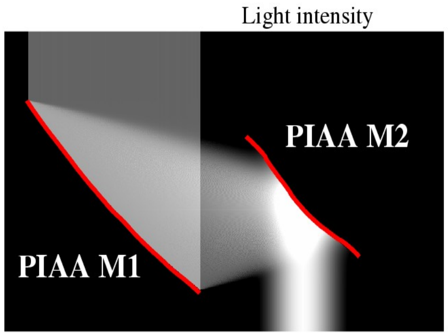
No coronagraph



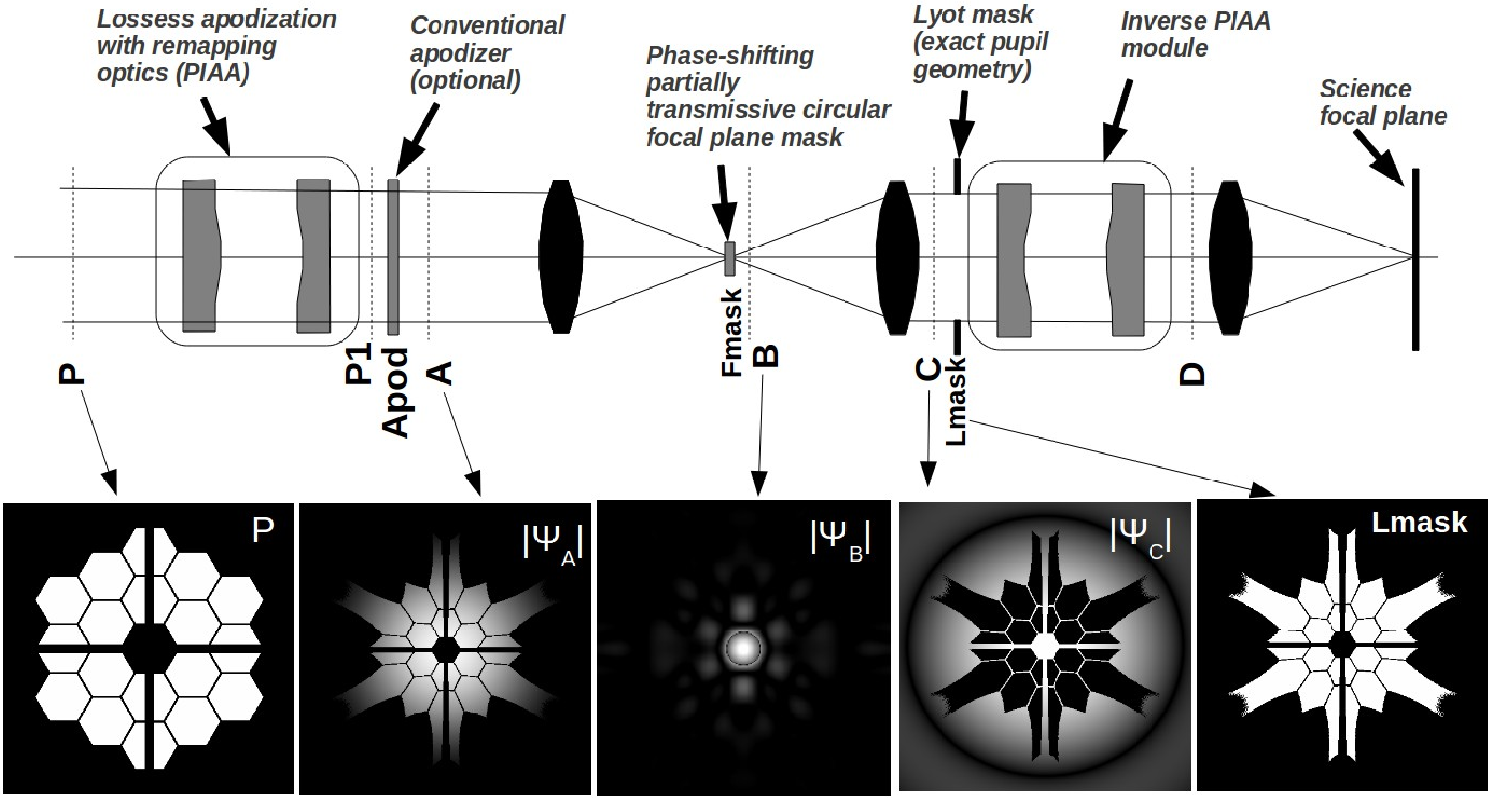
With Lyot Coronagraph



A more fancy coronagraph design



Phase Induced Amplitude Apodized Complex Mask Coronagraph (PIAACMC)



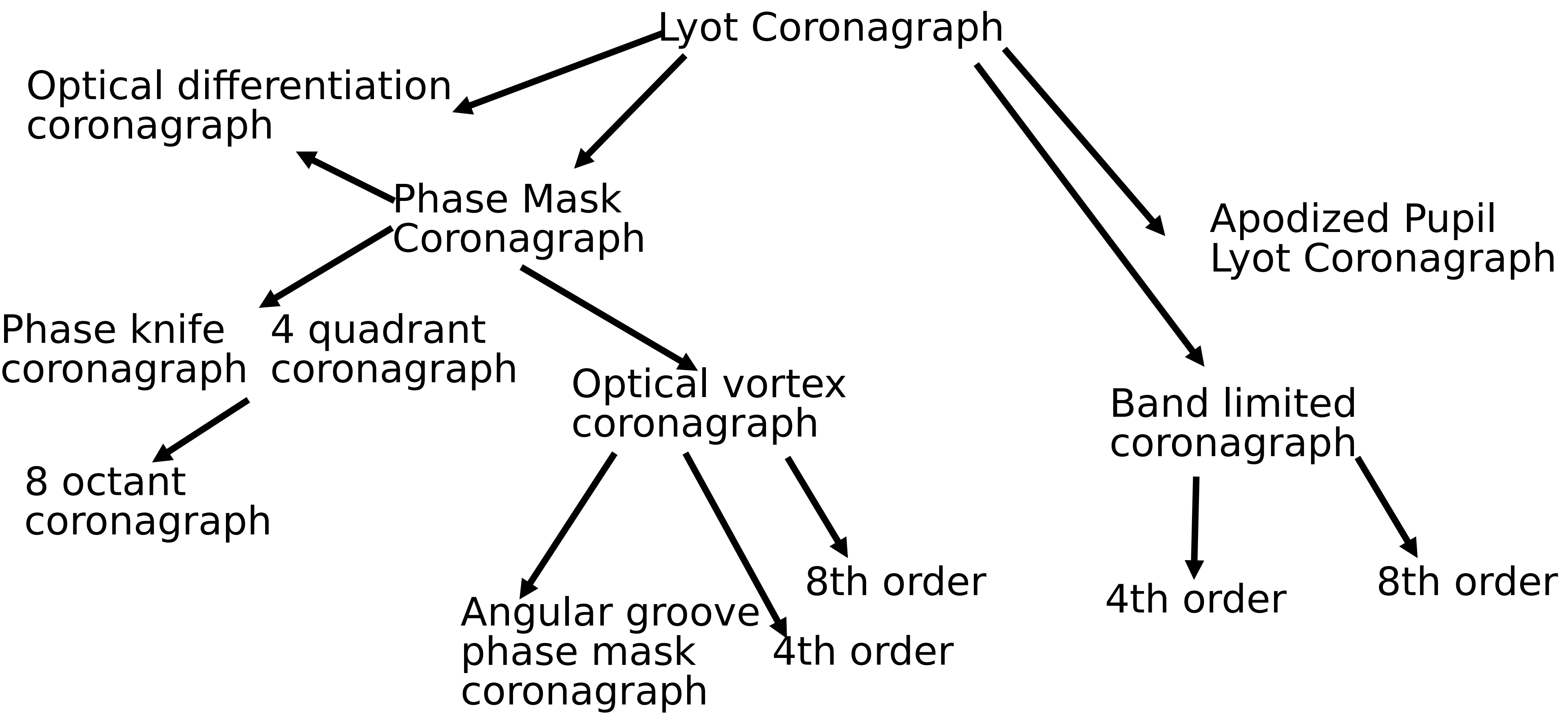
Lyot Coronagraph : optimizations

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

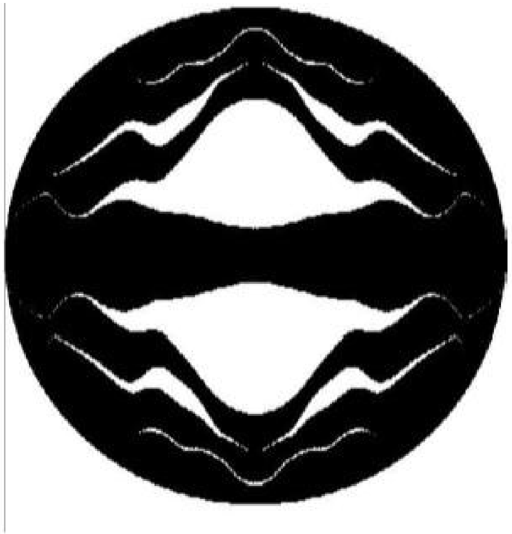
Phase Induced Zonal Zernike Apodization PIZZA
Martinache, 2003
Transform a pupil phase offset into an amplitude apodization thanks to a focal plane Zernike mask

Conventional Pupil Apodization (CPA)

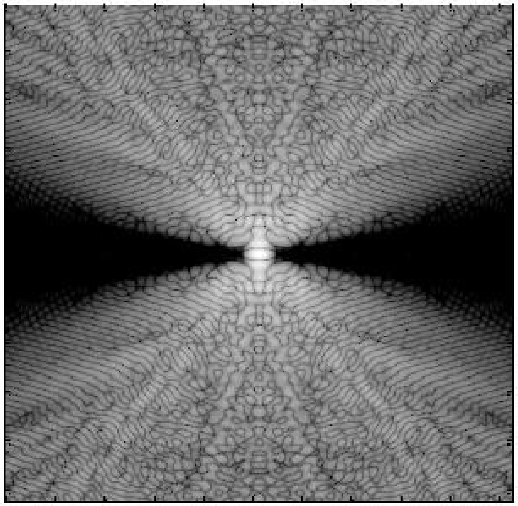
Many pupil apodizations have been proposed.

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



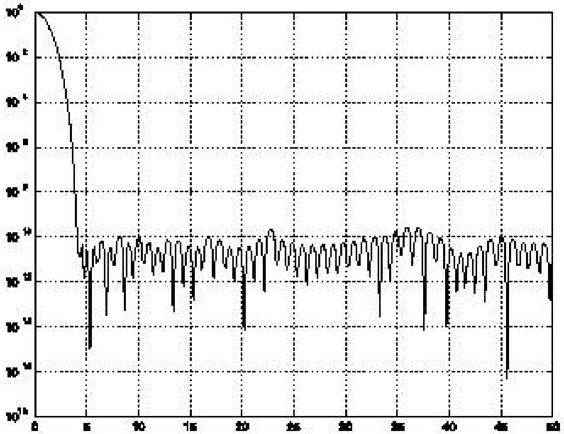


FIG. 9.—*Top*: Asymmetric multiopening mask designed to provide high-contrast, 10^{-10}, from $\lambda/D = 4$ to $\lambda/D = 100$ in two angular sectors centered on the x-axis. Ten integrations are required to cover all angles. Total throughput and pseudoarea are 24.4%. Airy throughput is 11.85%. *Bottom*: 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

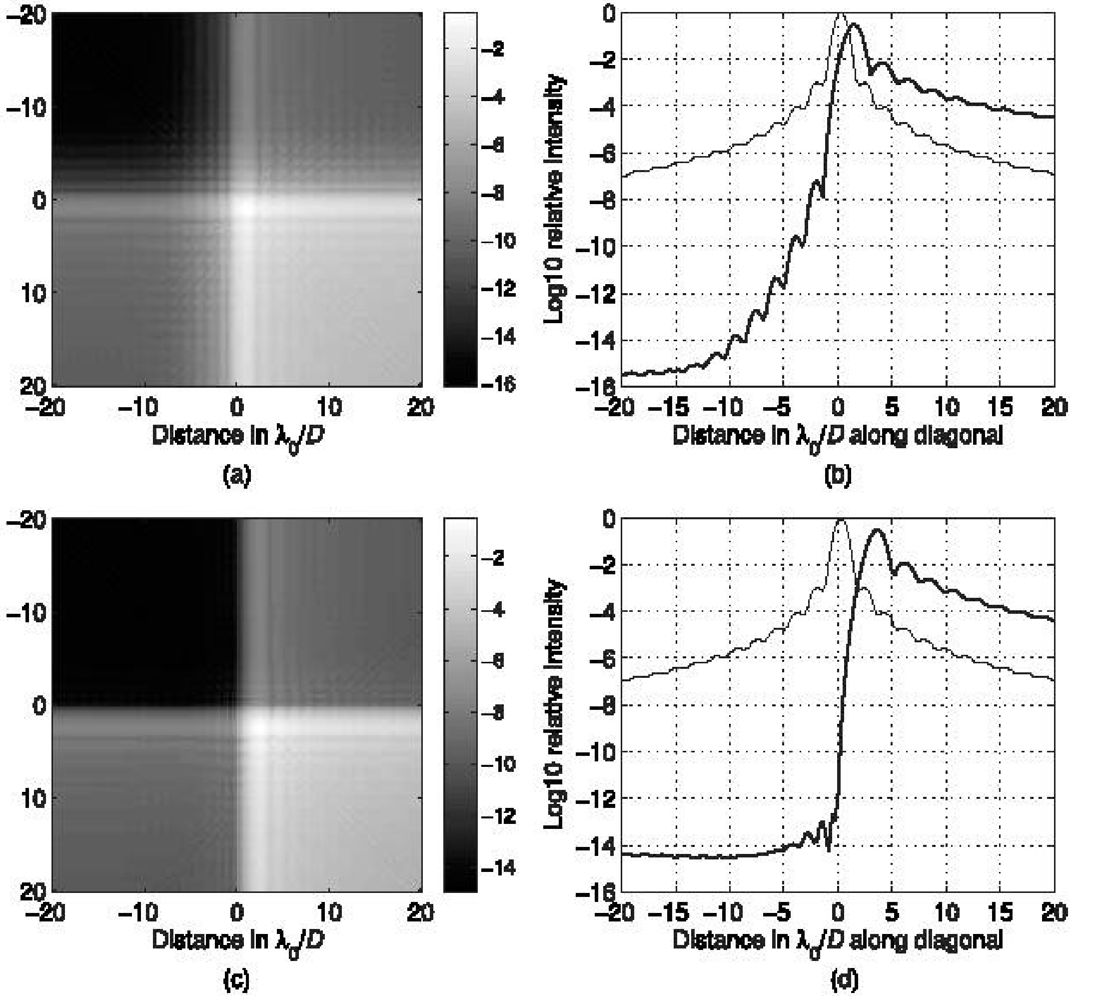
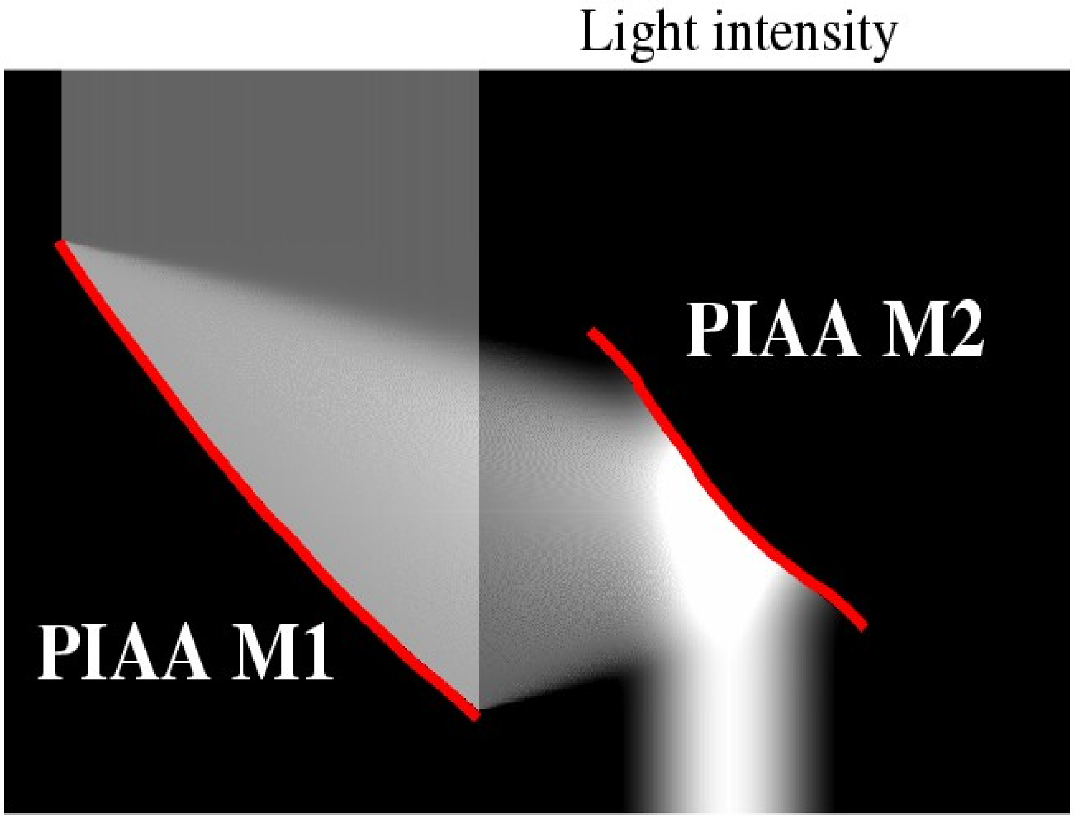
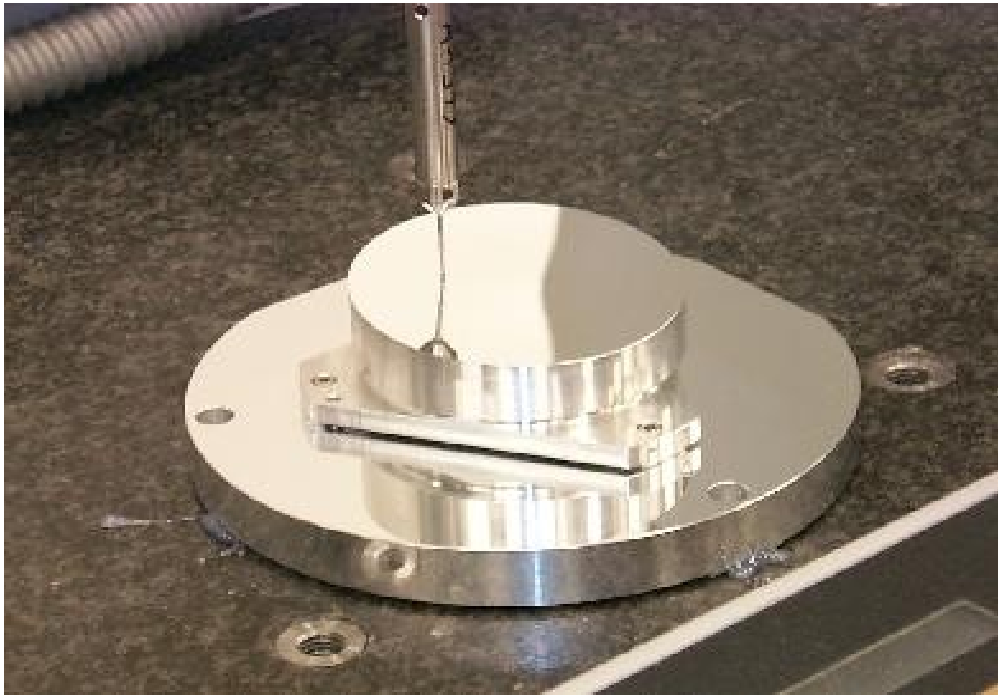


FIG. 9.—Broad-bandwidth light reduction effect on one quadrant of focal plane. The simulation is based on a rectangular spectrum distribution with total bandwidth of $0.6\lambda_0$. (*a*) $\log_{10}$ relative intensity image when phase $\phi(x, y) = a\tan[(0.5-\epsilon)2\pi x/D] + a\tan[(0.5-\epsilon)2\pi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

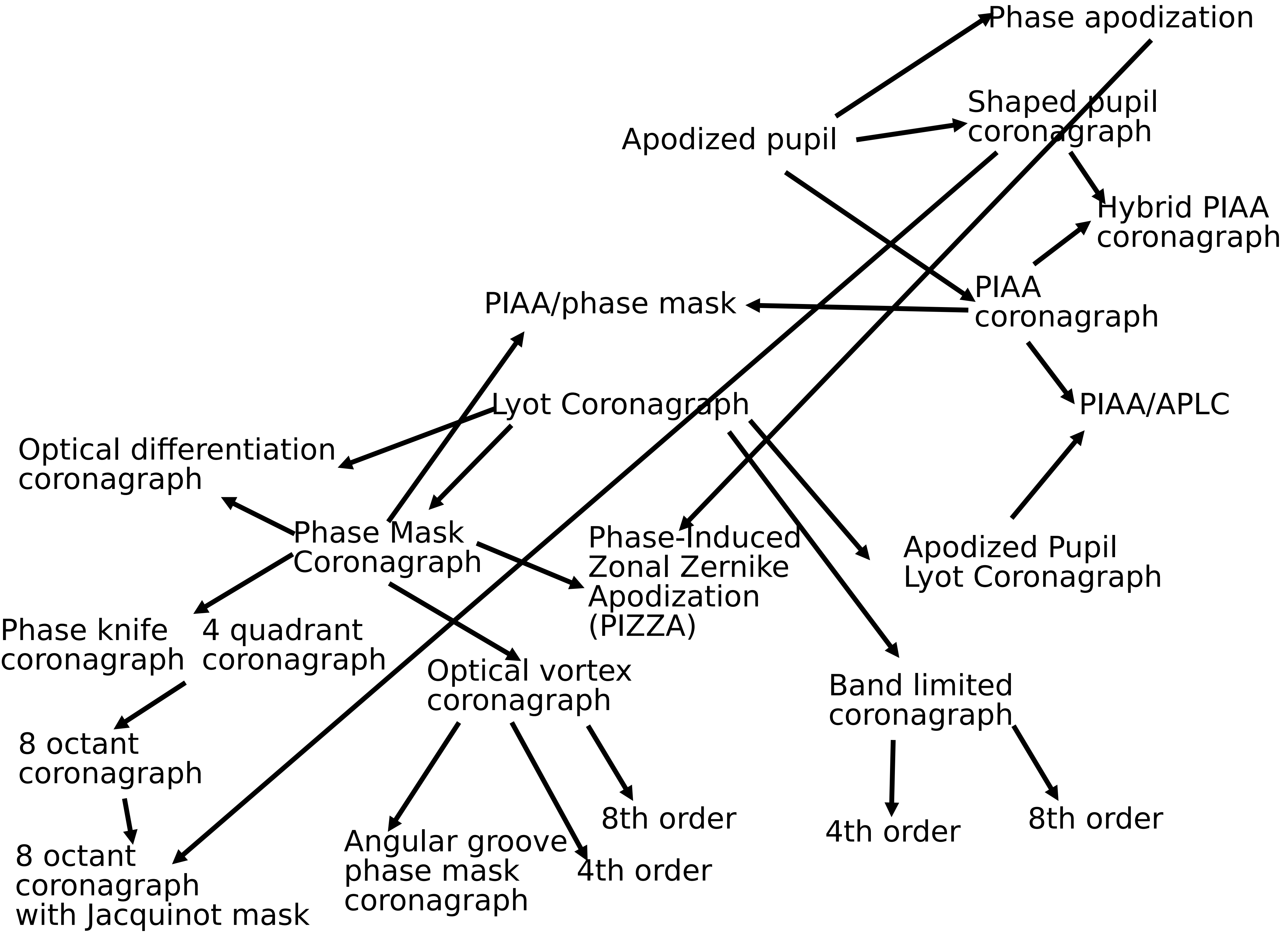
Phase-Induced Amplitude Apodization Coronagraph (PIAAC)

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
PIAA/APLC
Lyot Coronagraph
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

''Interferometric'' coronagraphs

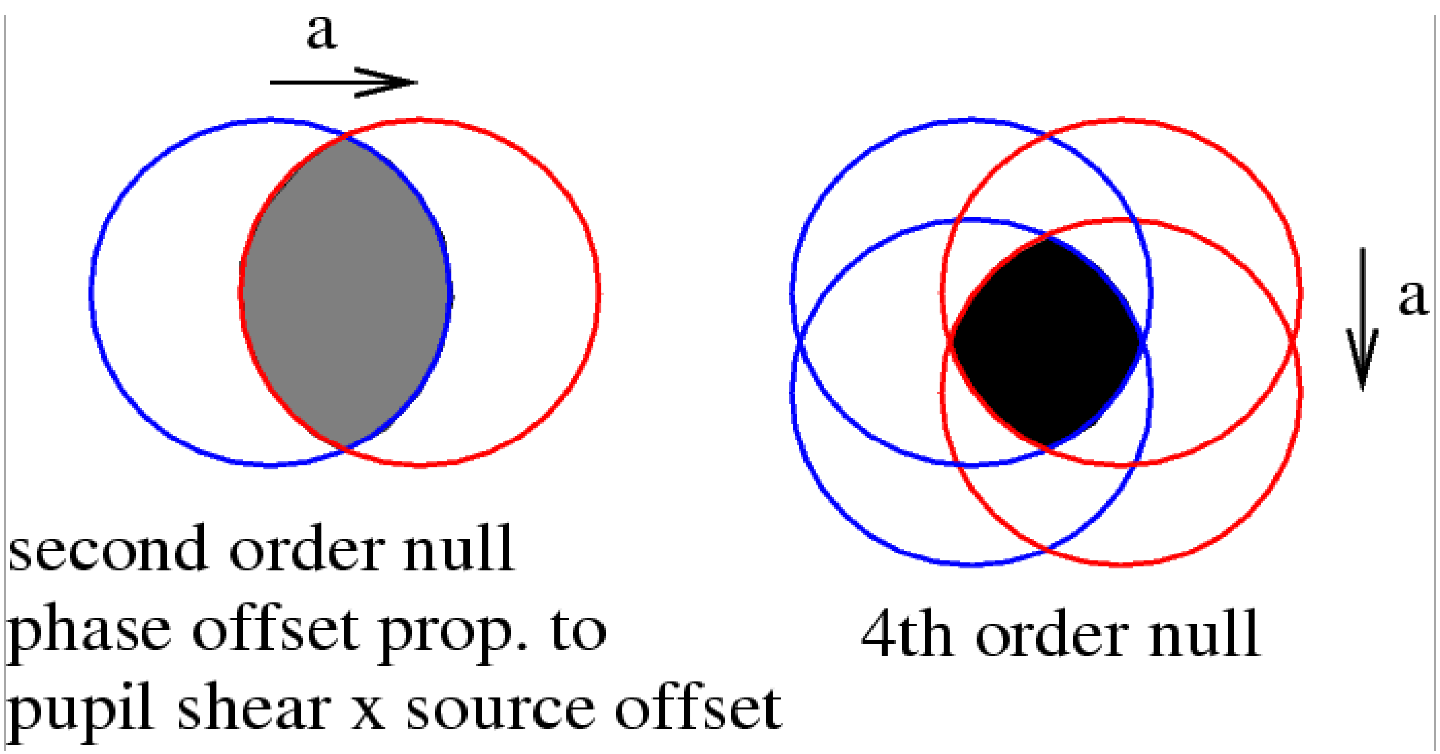
= Nulling interferometer on a single pupil telescope
- Creates multiple (at least 2) beams from a single telescope beam
- Combines them to produce a destructive interference on-axis and constructive interference off-axis

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

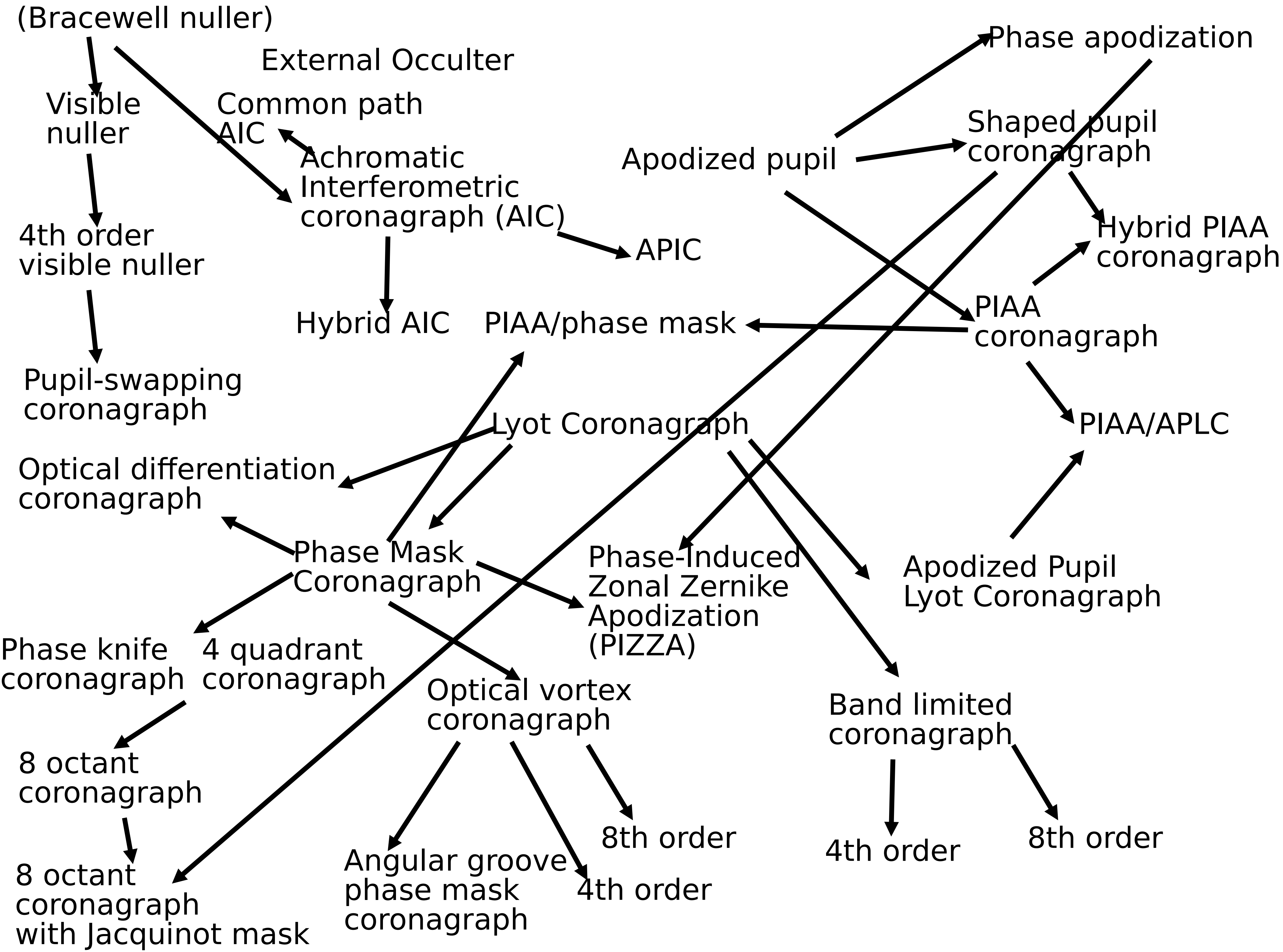
Visible Nuller Coron. (VNC)



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
4th order visible nuller
APIC
Hybrid PIAA coronagraph
Hybrid AIC
PIAA/phase mask
PIAA coronagraph
Pupil-swapping coronagraph
Lyot Coronagraph
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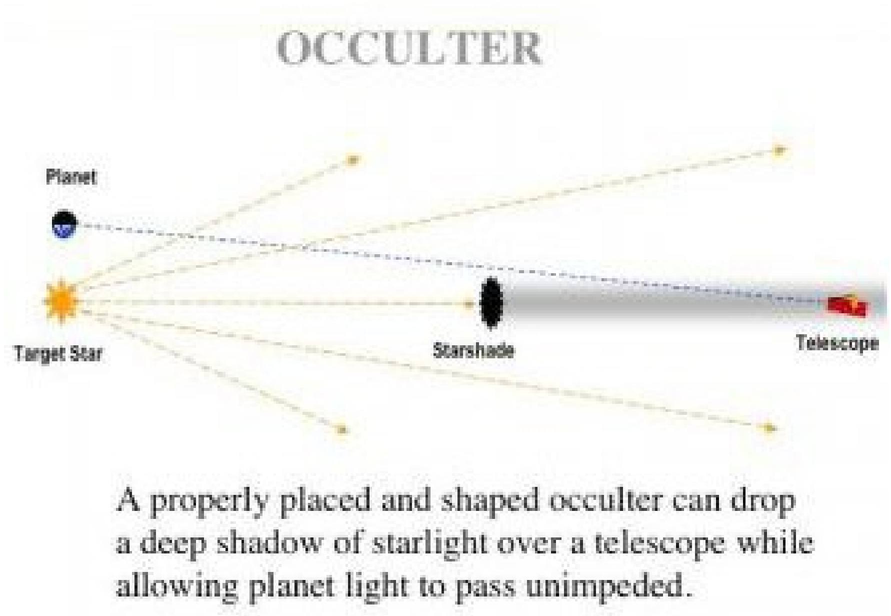
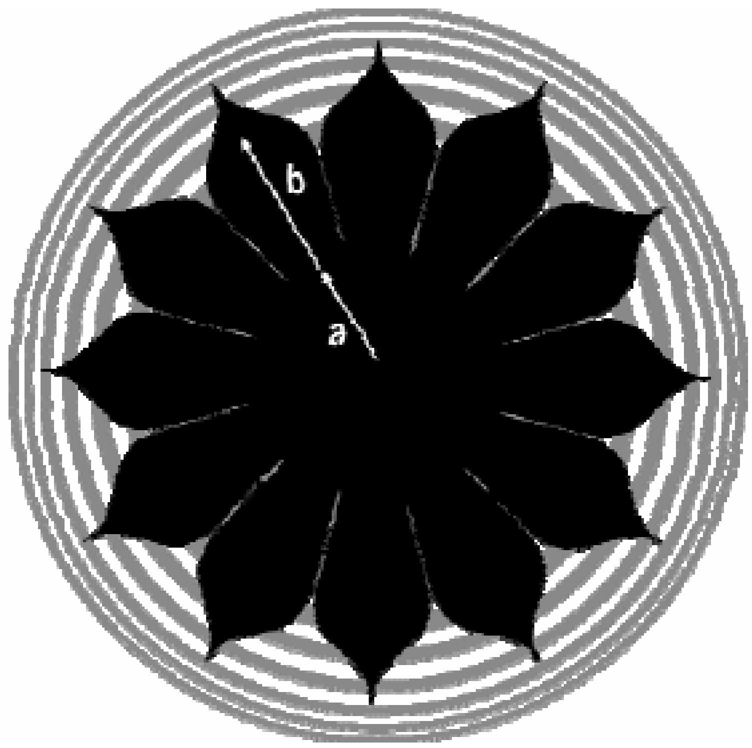
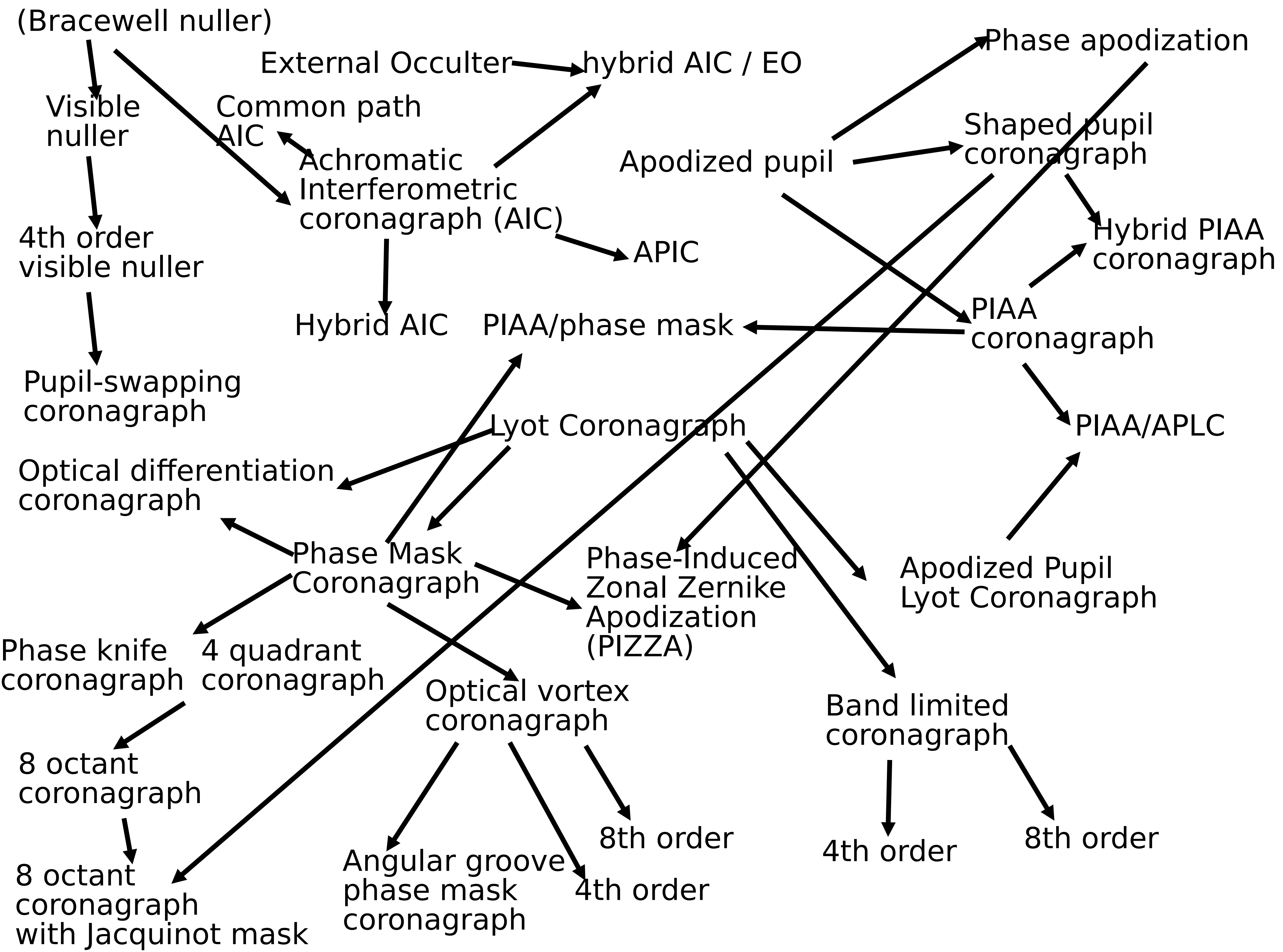
External Occulter







(Bracewell nuller)
External Occulter
hybrid AIC / EO
Phase apodization
Visible nuller
Common path AIC
Achromatic Interferometric coronagraph (AIC)
Apodized pupil
Shaped pupil coronagraph
4th order visible nuller
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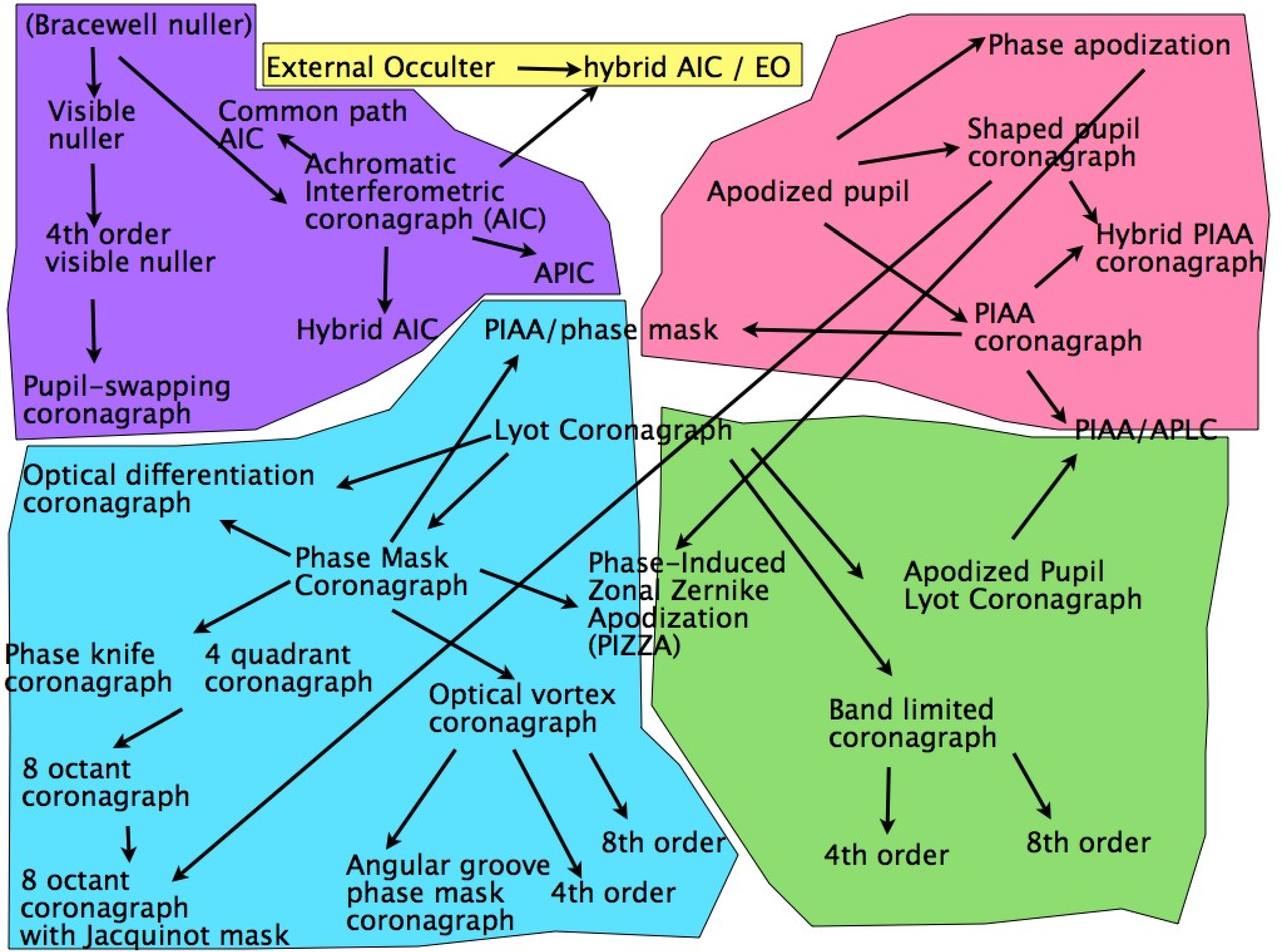

(Bracewell nuller)
Visible nuller
4th order visible nuller
Pupil-swapping coronagraph
Common path AIC
Achromatic Interferometric coronagraph (AIC)
APIC
Hybrid AIC
External Occulter
hybrid AIC / EO
Phase apodization
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