Master in Space Sciences - Academic year 2021-2022

SPAT0063 Introduction to exoplanetology

Lecture 6: Direct exoplanet detection methods (1/2)
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Olivier Absil

FNRS Senior Research Associate — STAR Institute
olivier.absil@uliege.be

Outline

I. Direct detection: why and how?

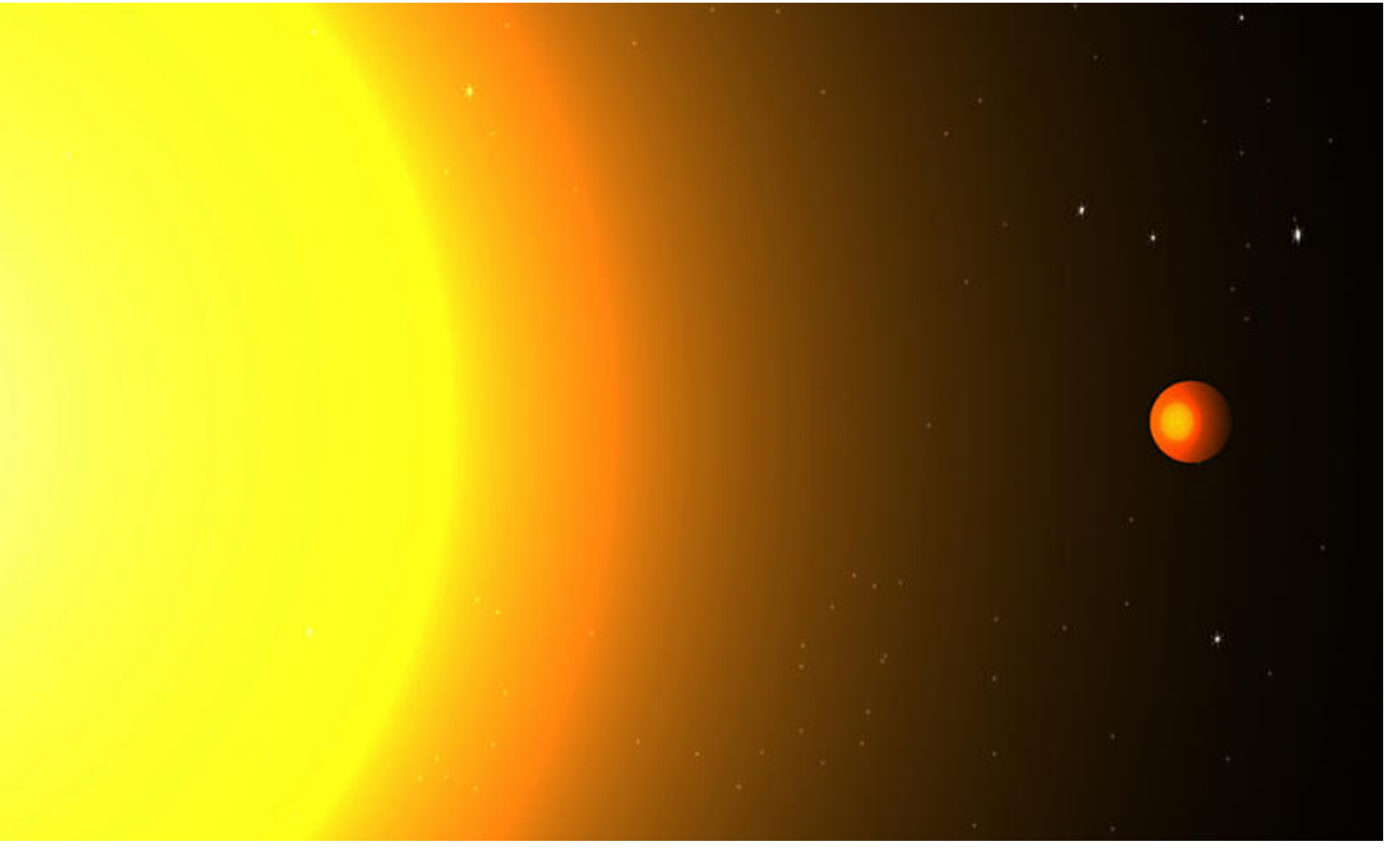
II. High contrast imaging

    I. Coronagraphy

    II. Observing strategies

    III. Image processing

III. Main results from high-contrast imaging

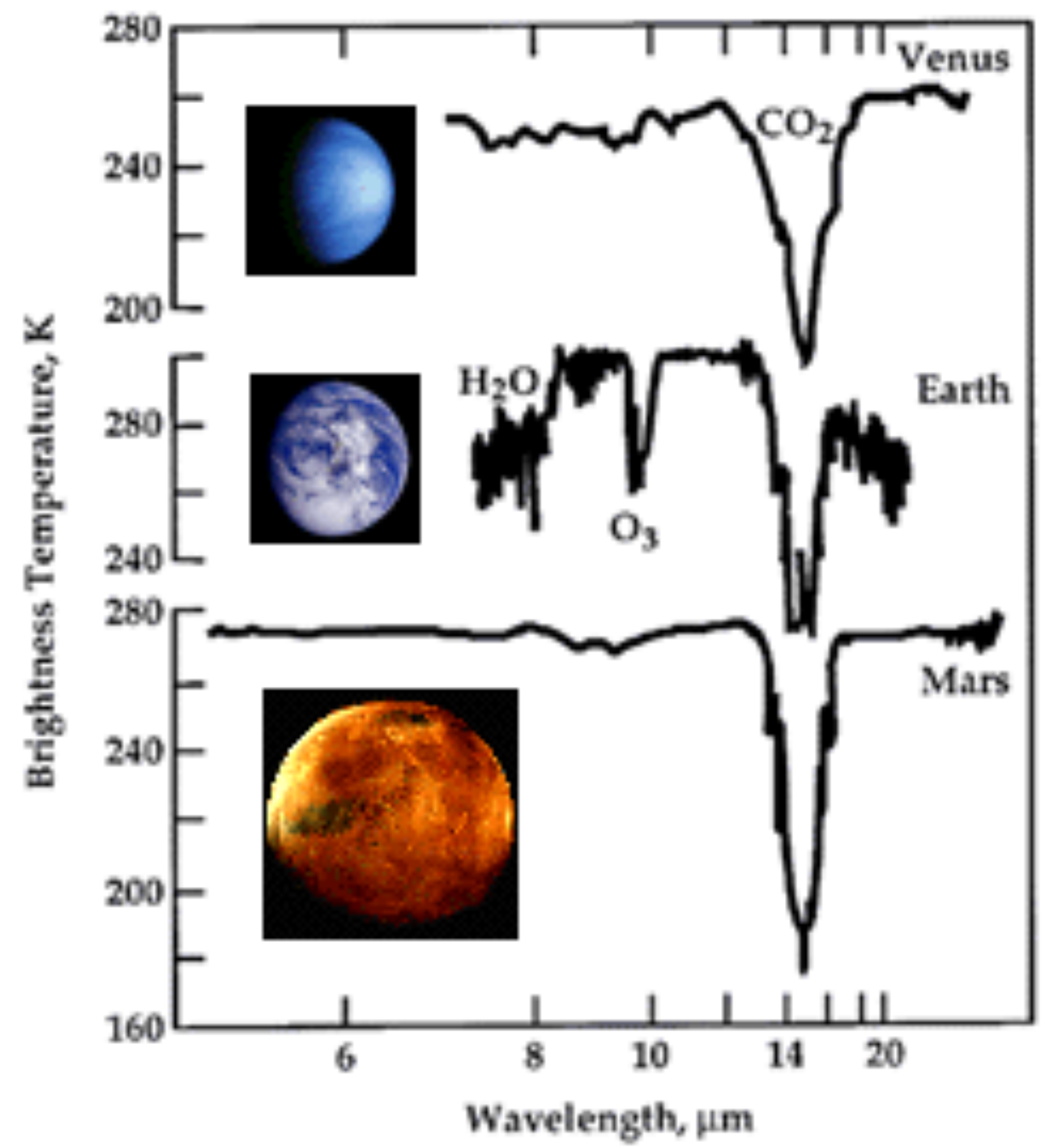


I. Direct detection

Why and how?

Why direct detection?

- Characterization of planetary atmospheres
    - Needs spectroscopy on actual planetary photons → isolate planet from star



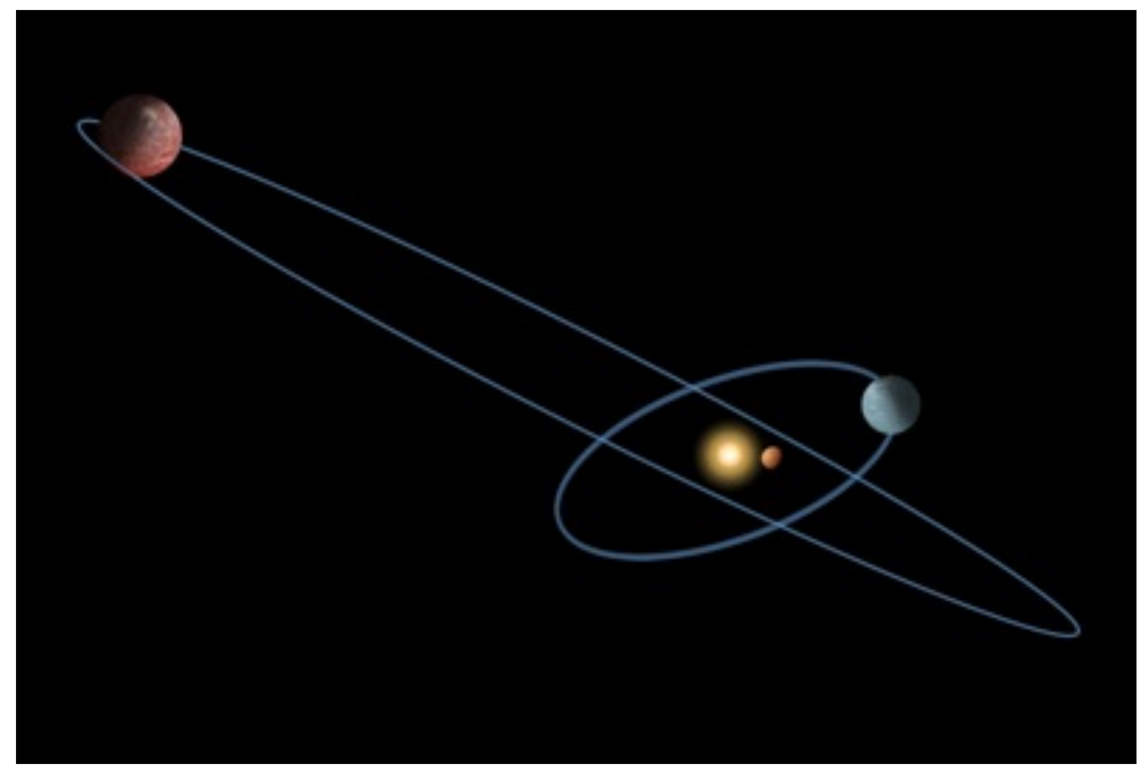
Why direct detection?

- Access non-transiting planets
  - Opens up a wide range of separations (beyond a few 0.1 au)
  - Complementary with transit spectroscopy

Transits mostly here

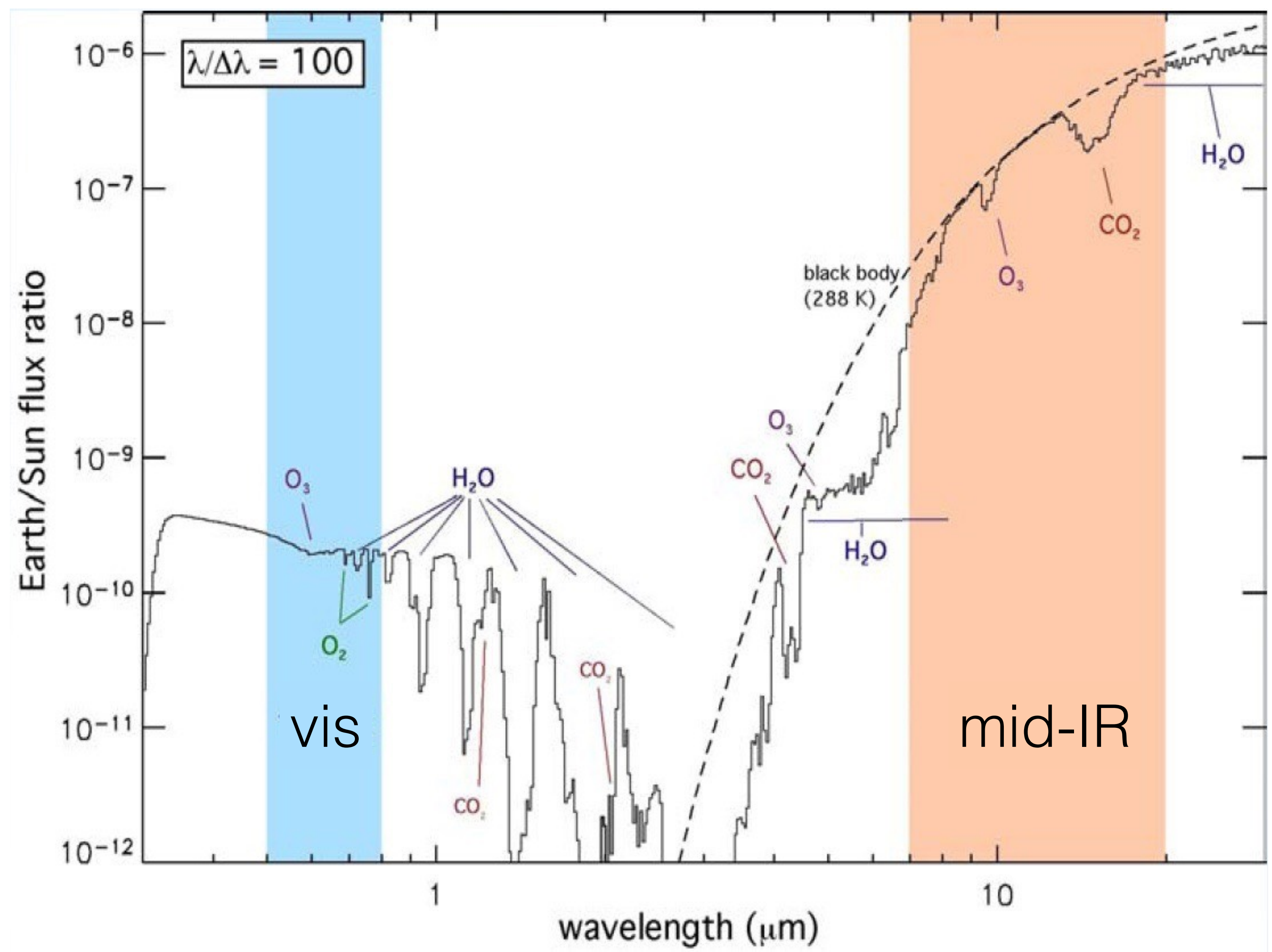
Why direct detection?

- Study architecture of planetary system based on visual orbit
  - Dynamics of planetary systems, interactions with dust disks, etc.
  - Full orbital solution when combined with RV or astrometry → direct, model-independent access to planet mass



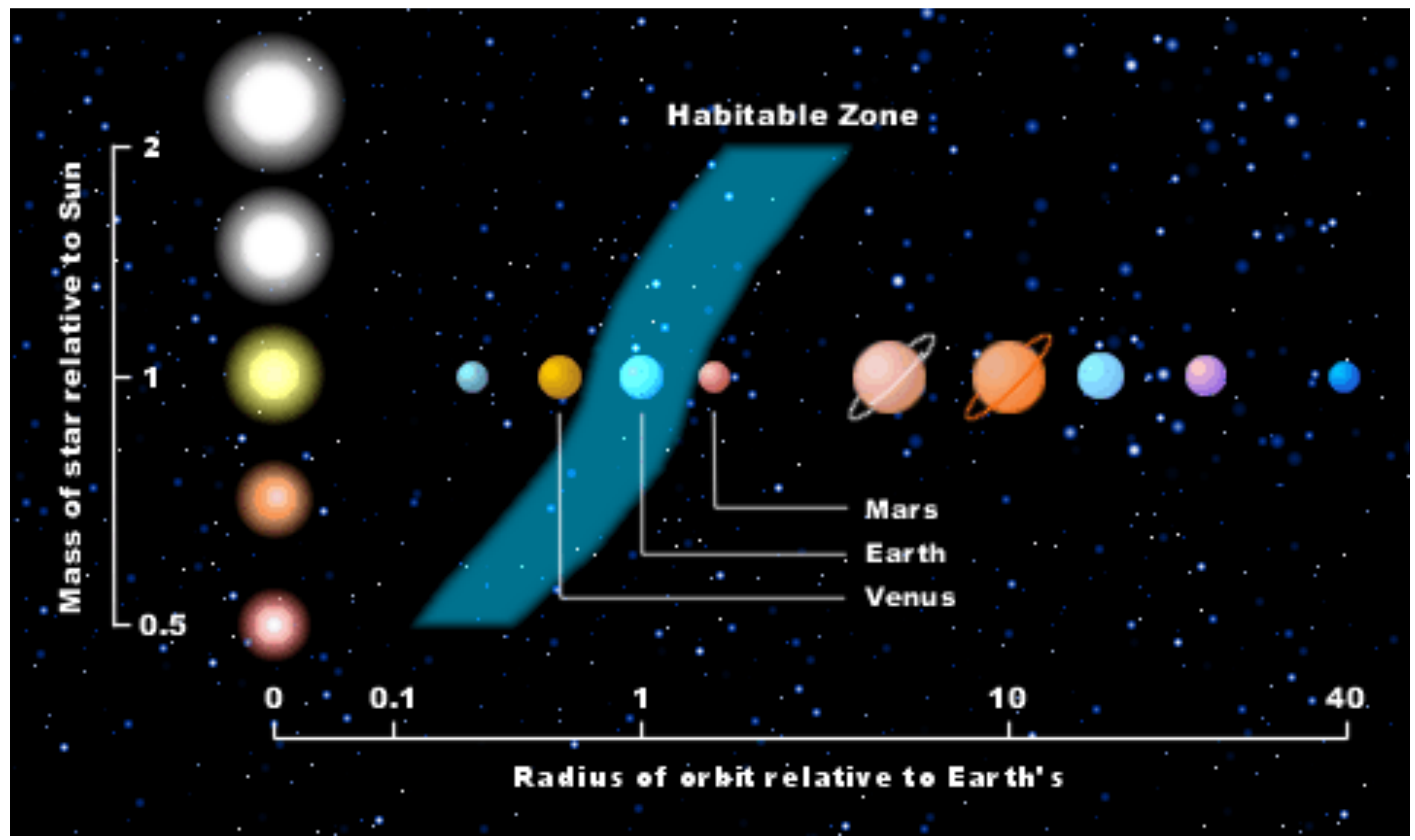
Challenge #1: contrast

- Visible: reflected light
- Infrared: thermal emission (blackbody)



Challenge #2: separation

- 1 au @ 10 pc
  = 0.1 arcsec
- Theoretically within reach of 10-m class telescope

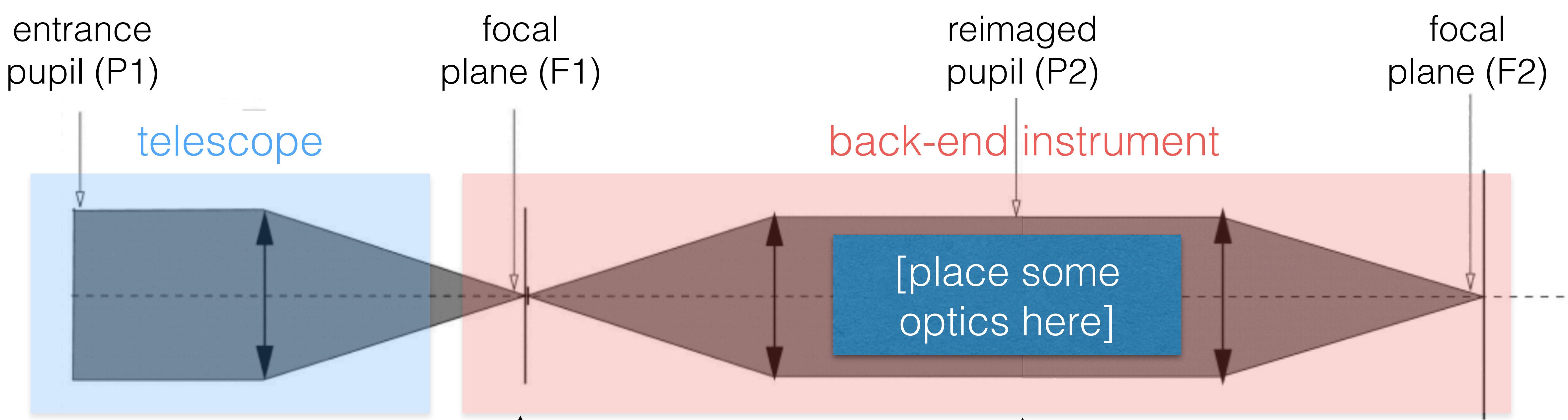


Challenge summary

A firefly close to a lighthouse … 1000 miles away!

(note: the star never turns off)

Reminder: Fourier optics

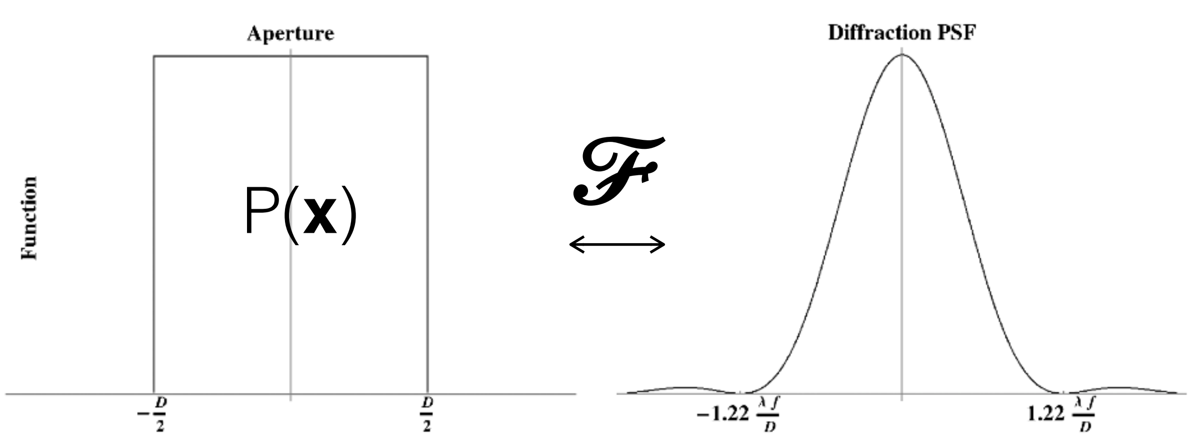


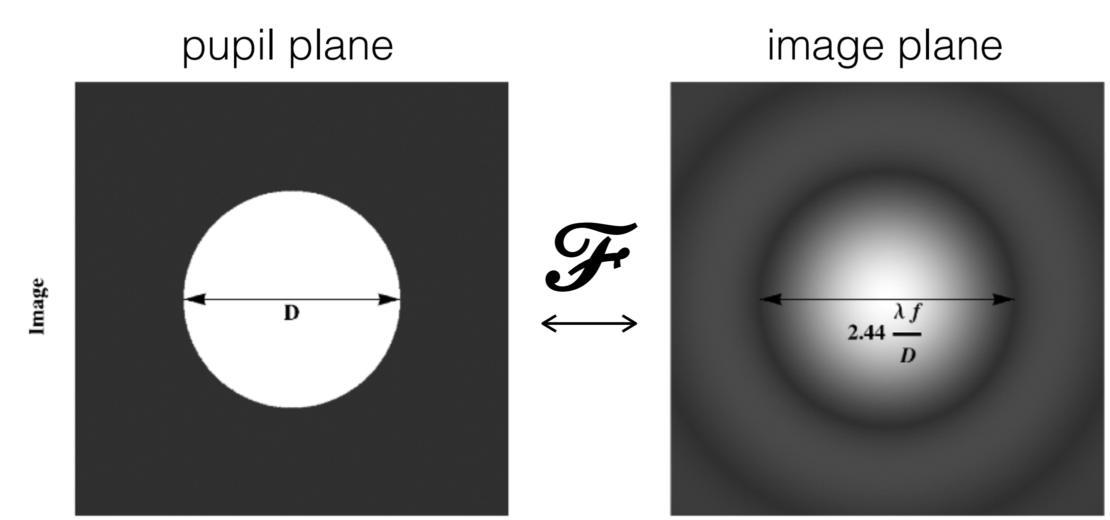
$\Psi_1(\mathbf{x}) = P(\mathbf{x}) \exp(i\phi(\mathbf{x}))$

$I_2(\boldsymbol{\xi}) = |A_2(\boldsymbol{\xi})|^2$

intensity = square modulus
of complex amplitude

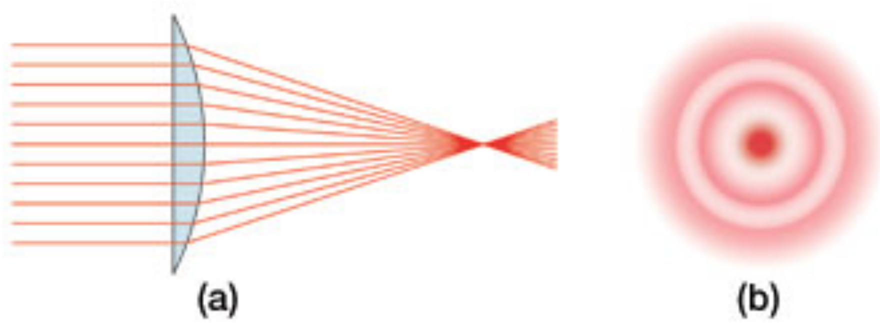
$A_1(\boldsymbol{\xi}) = \mathcal{F}(\Psi_1(\mathbf{x}))$ $\Psi_2(\mathbf{x}) = \mathcal{F}^{-1}(A_1(\boldsymbol{\xi}))$



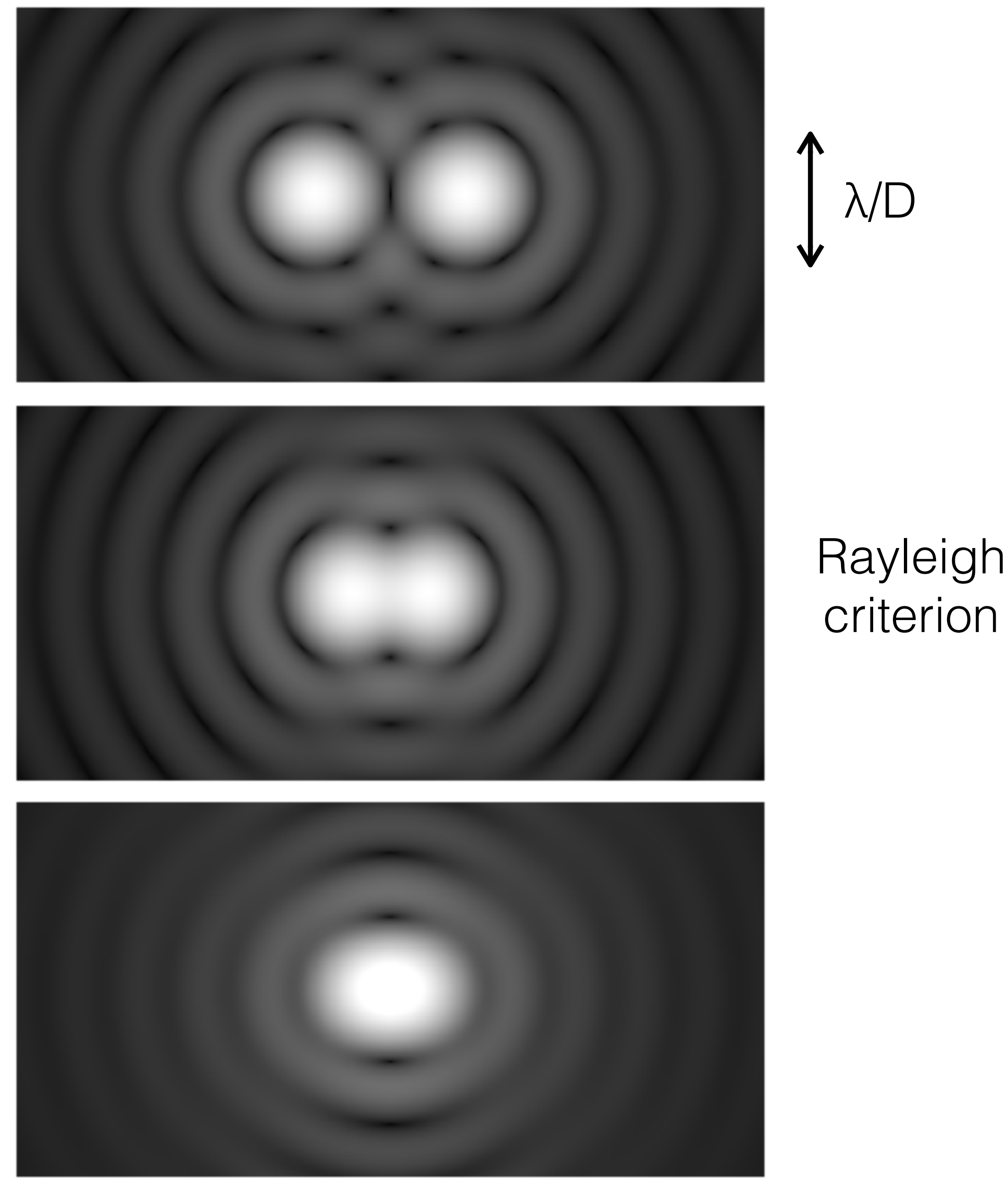


Technique #1: imaging

- Diffraction in circular aperture → Airy pattern



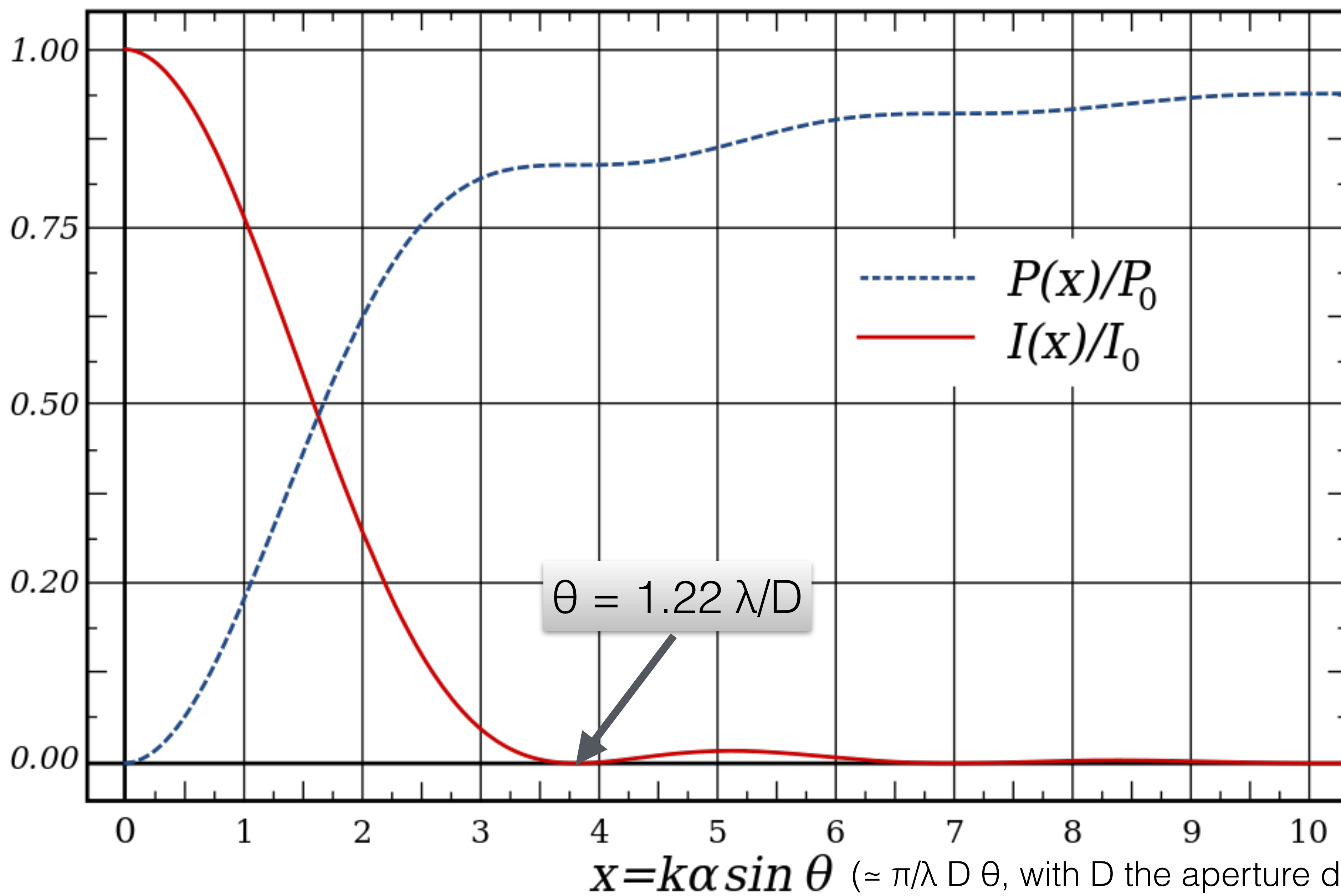
- Angular resolution = size of Airy disk: θ = 1.22 λ/D
  - λ = 2 μm, D = 10 m
    → θ = 0.05" (50 mas)
    = 1 au at 20 pc
  - Extended pattern → planets hidden in stellar glare!



The Airy pattern

$$I(\theta) = I_0 \left(\frac{2J_1(ka\sin\theta)}{ka\sin\theta} \right)^2 = I_0 \left(\frac{2J_1(x)}{x} \right)^2$$

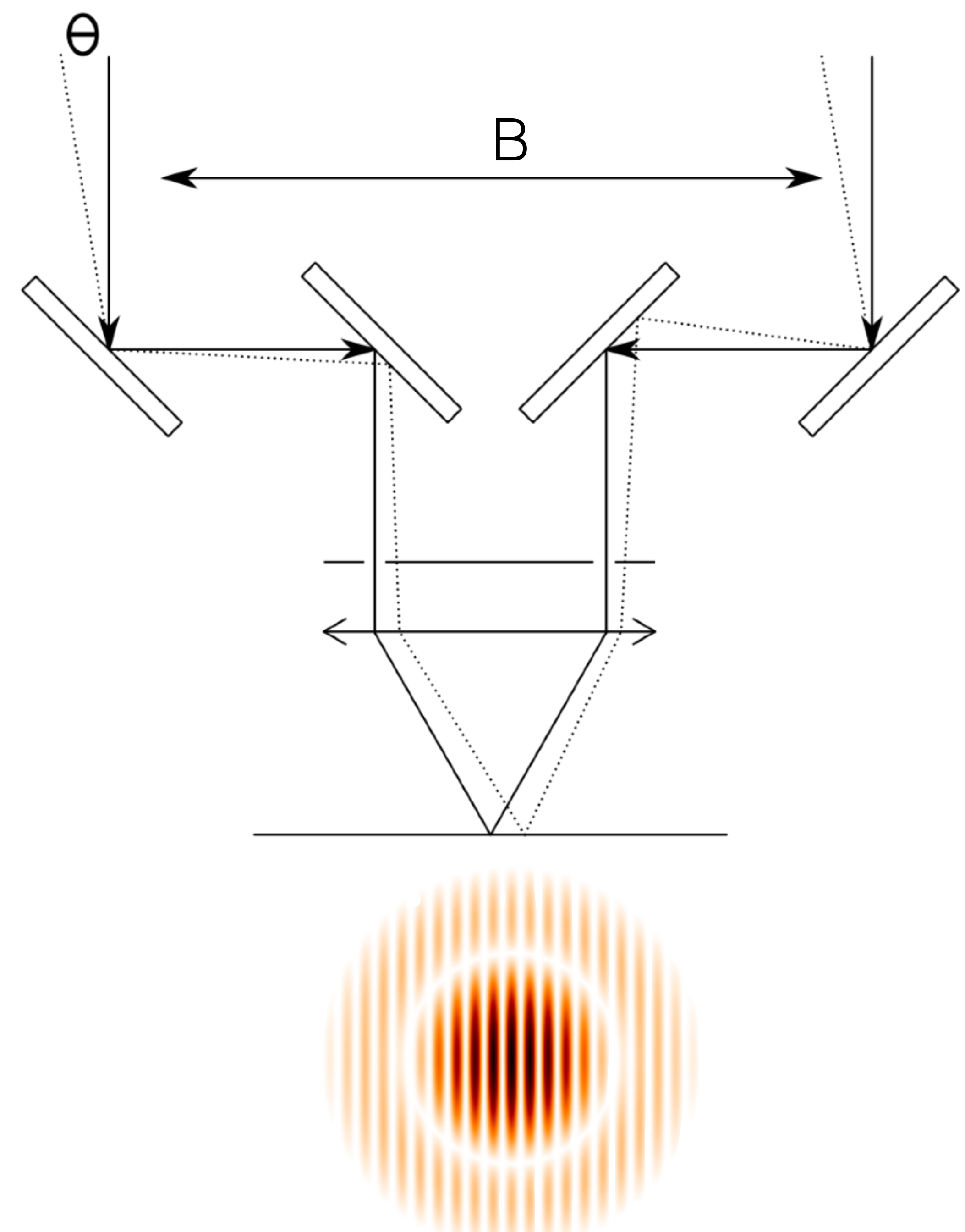
$k = 2\pi/\lambda$
a : aperture radius



(≃ π/λ D θ, with D the aperture diameter)

Technique #2: interferometry

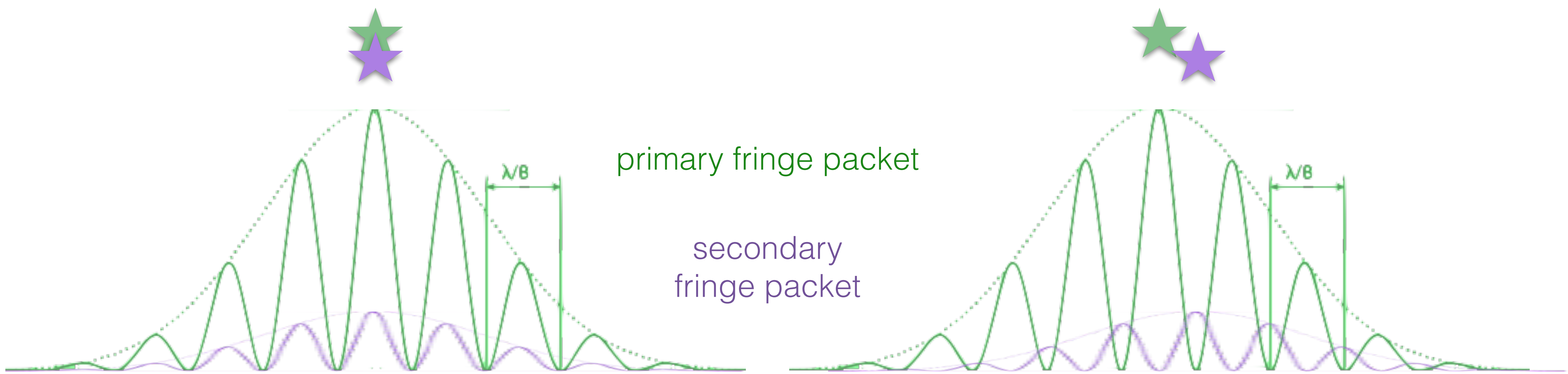
- Two separated telescopes → interference fringes
- Angular resolution set by baseline (B): $\theta = 0.5\ \lambda/B$
    - $\lambda = 2\ \mu m$, $B = 100\ m$ → $\theta = 2$ mas



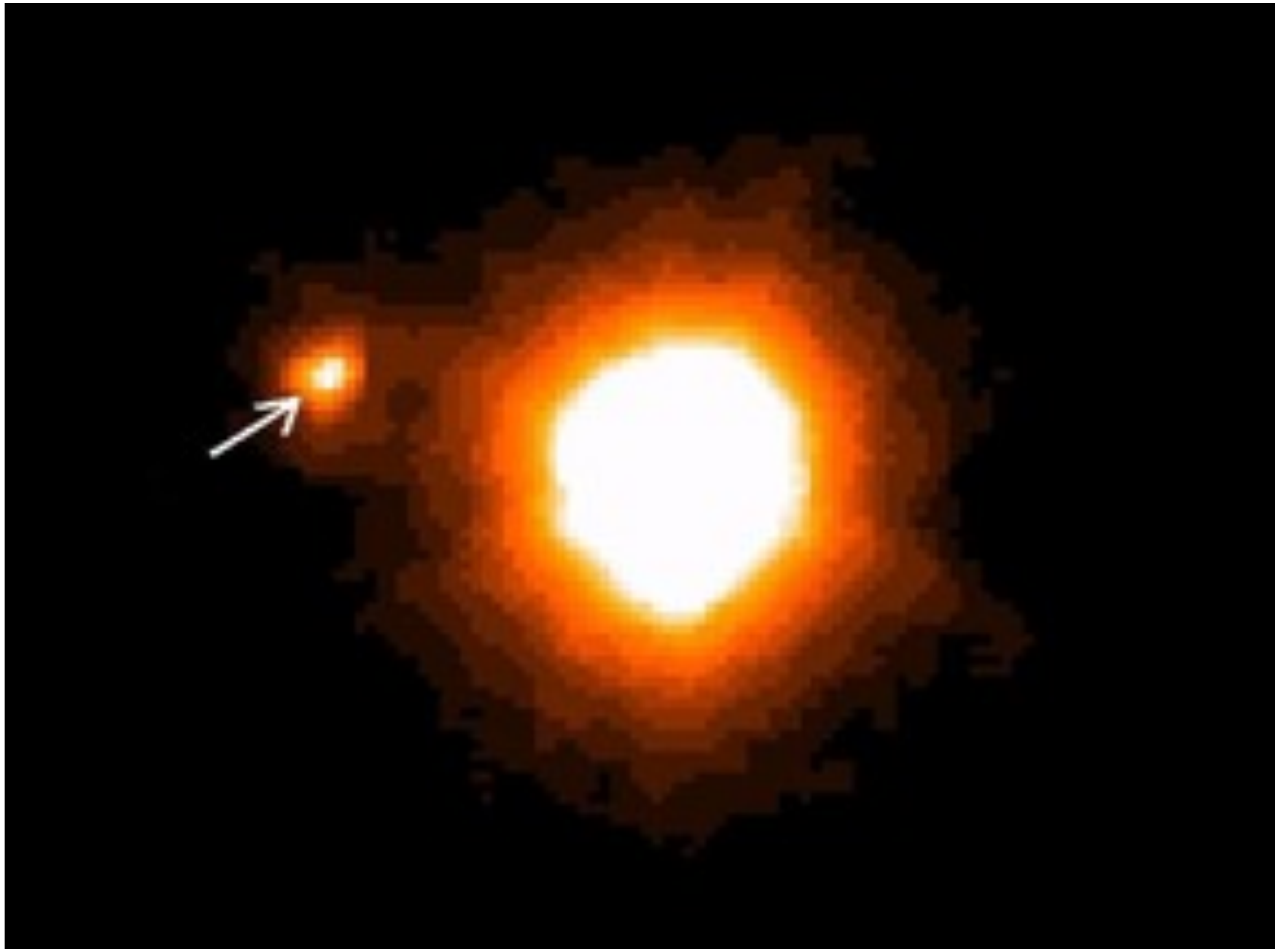
The fringe pattern

Resolved binary when crests of 1st packet fall on troughs of 2nd packet

unresolved binary | resolved binary

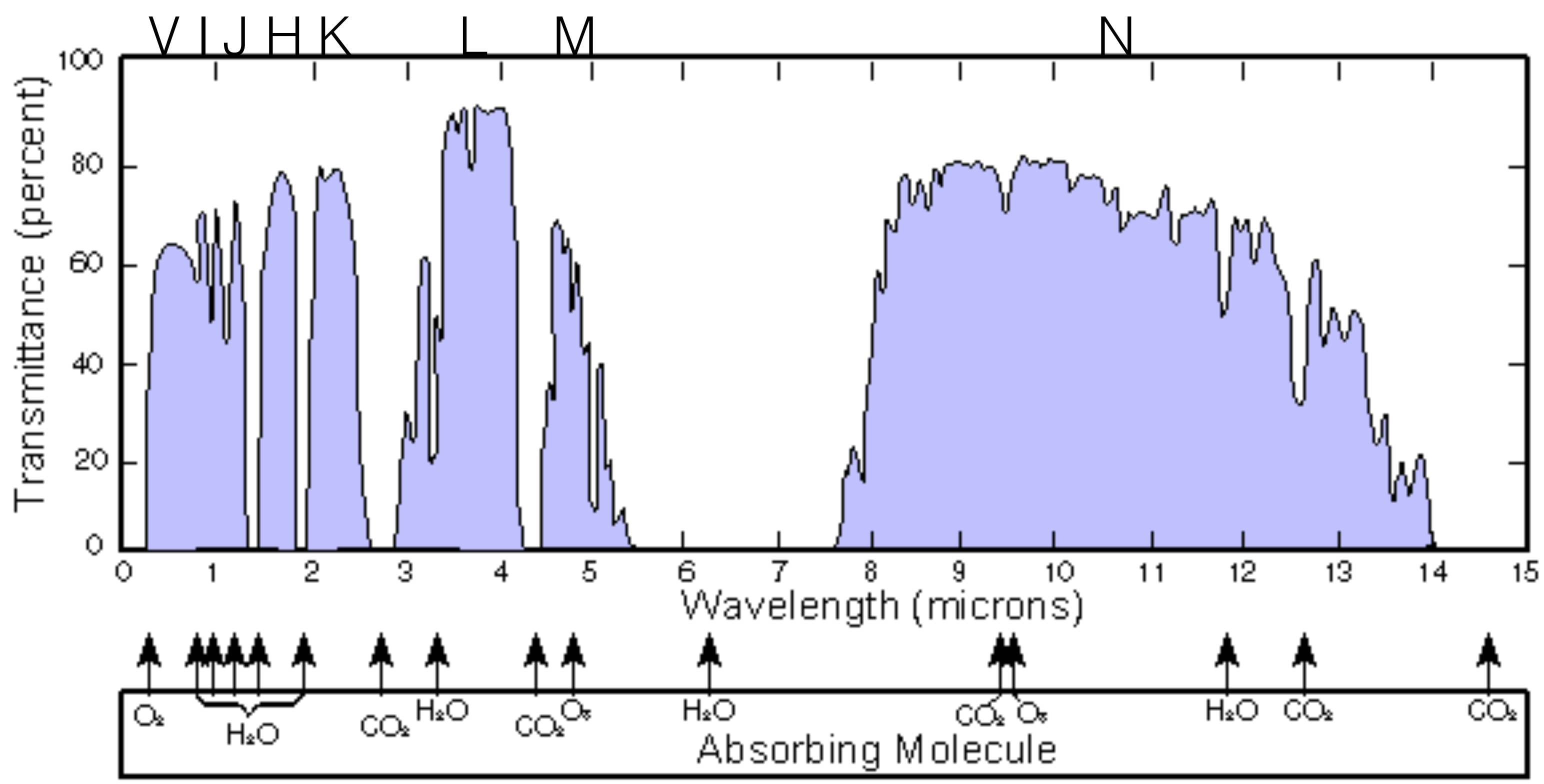


—> the binary is resolved when the two objects are separated by $\lambda/2B$



II. High contrast imaging

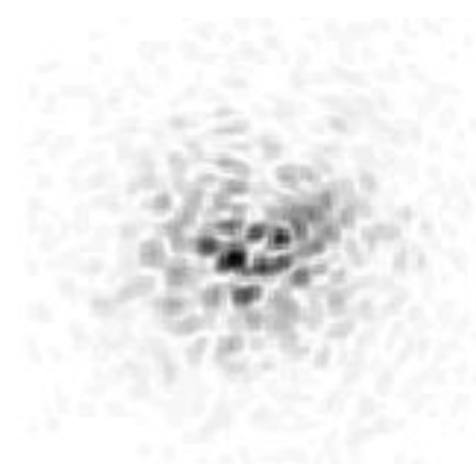
Atmospheric windows



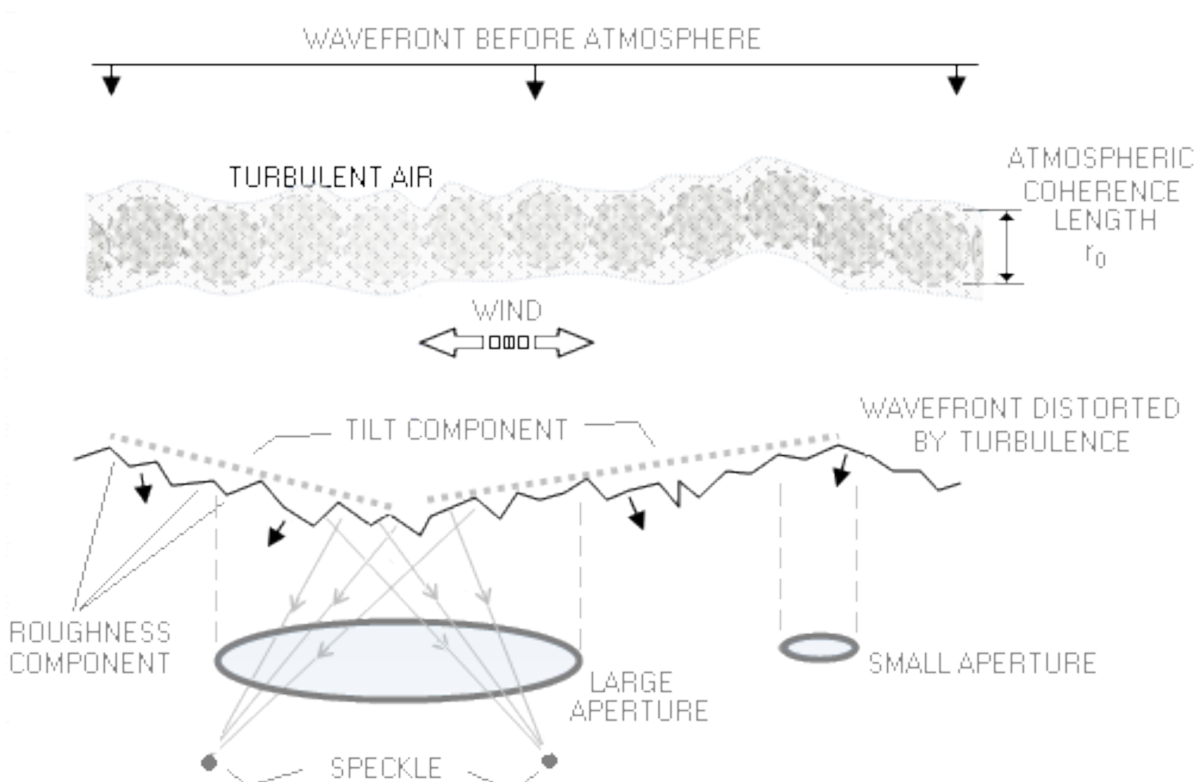
Imaging through the Earth atmosphere

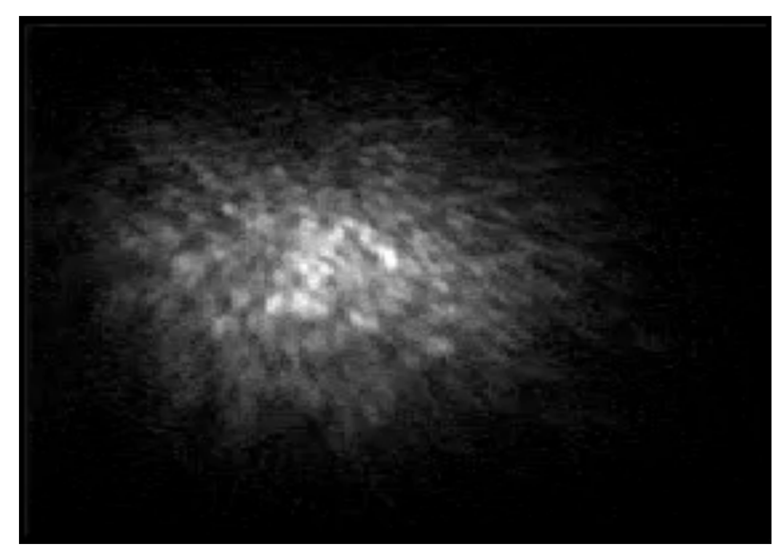
- Temperature variations act as tiny lenses
- Distorted wavefront
  - Short exposure: speckles
  - Long exposure: wide PSF

Short exposure



Long exposure

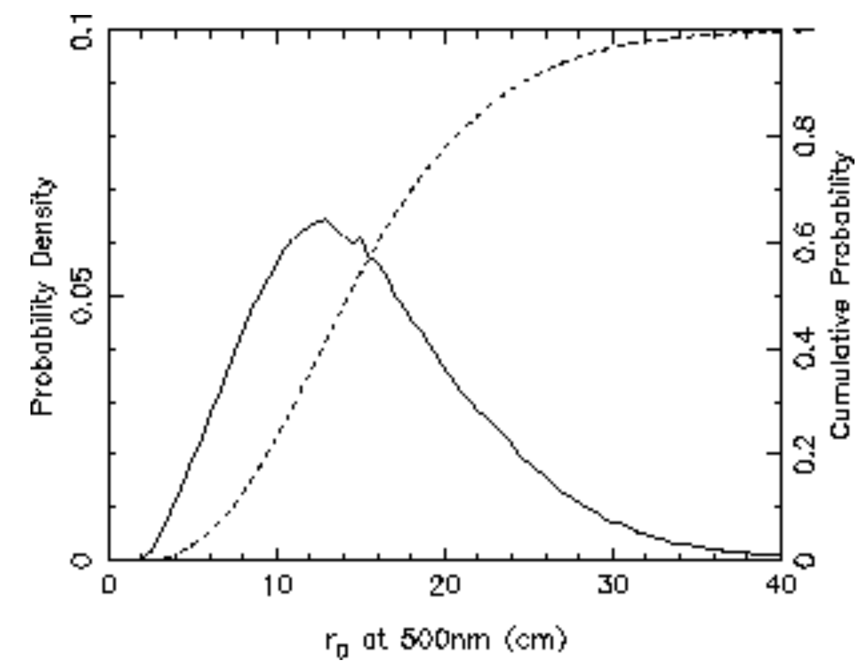




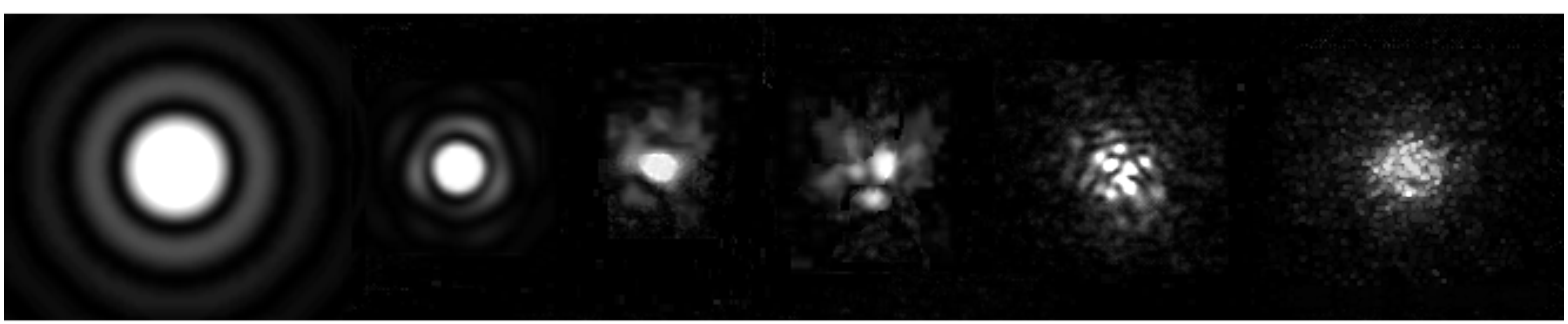
Loss of angular resolution

- Fried parameter r_0: diameter of circular area over which the wavefront is « sufficiently flat » (variance of the aberration = 1 rad^2)
  - r_0 ~ 10 cm at good astronomy site
    —> same resolution as 10 cm telescope!

La Palma



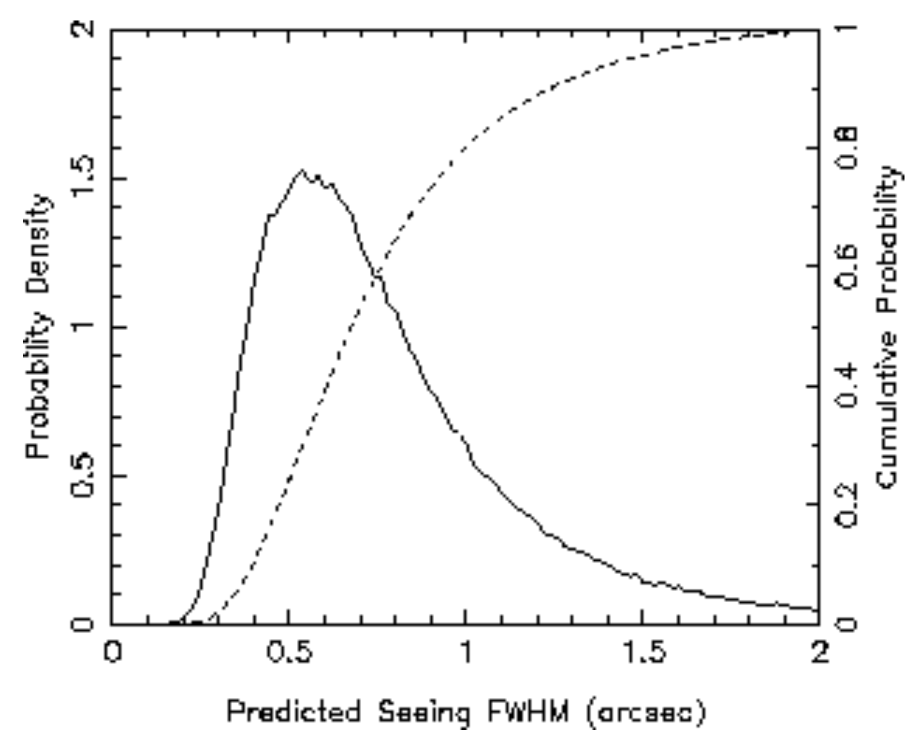
D = 5 cm 10 cm 60 cm 1.2 m



$(D/r_0) \rightarrow$ 0.5 1 1.75 3 6 12

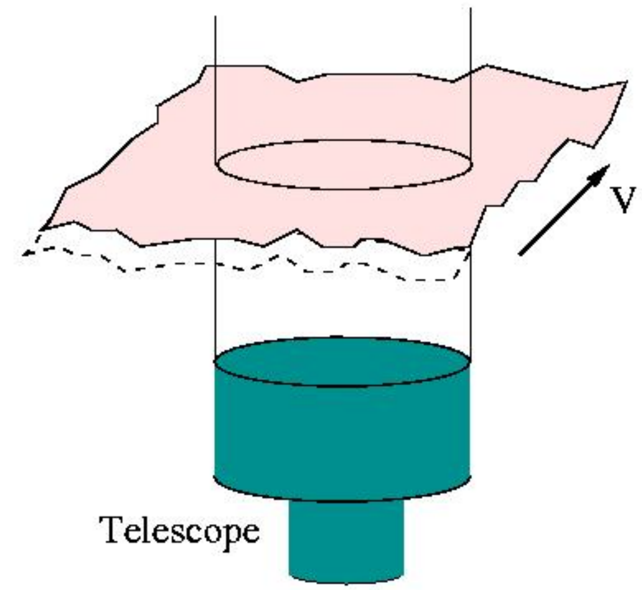
Atmospheric turbulence

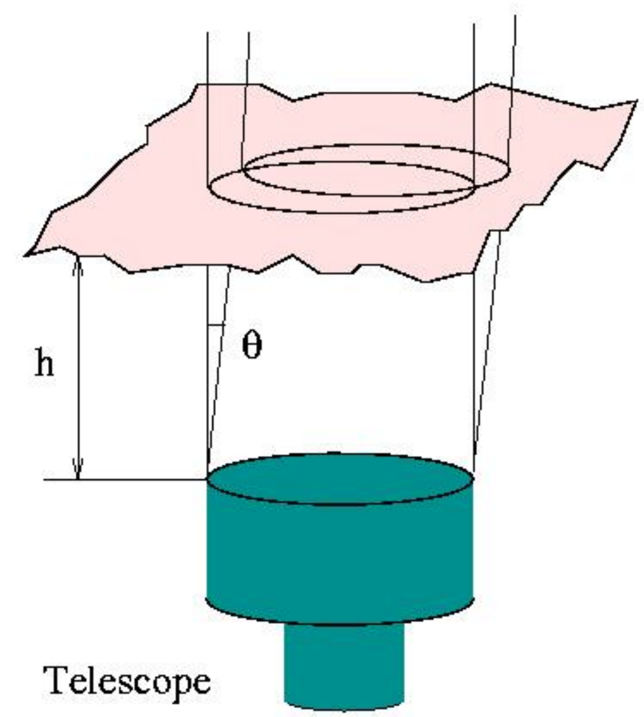
- Wavelength dependence: $r_0 \propto \lambda^{6/5}$
  - 10 cm @ 500 nm
  - 50 cm @ 2 μm
  - 4 m @ 10 μm
- Seeing = FWHM of long exposure image
  - Equal to $0.98 \lambda / r_0$
  - 1" seeing for r_0 = 10 cm @ 500 nm
  - Varies slowly with wavelength ($\lambda^{-1/5}$)



Atmospheric turbulence

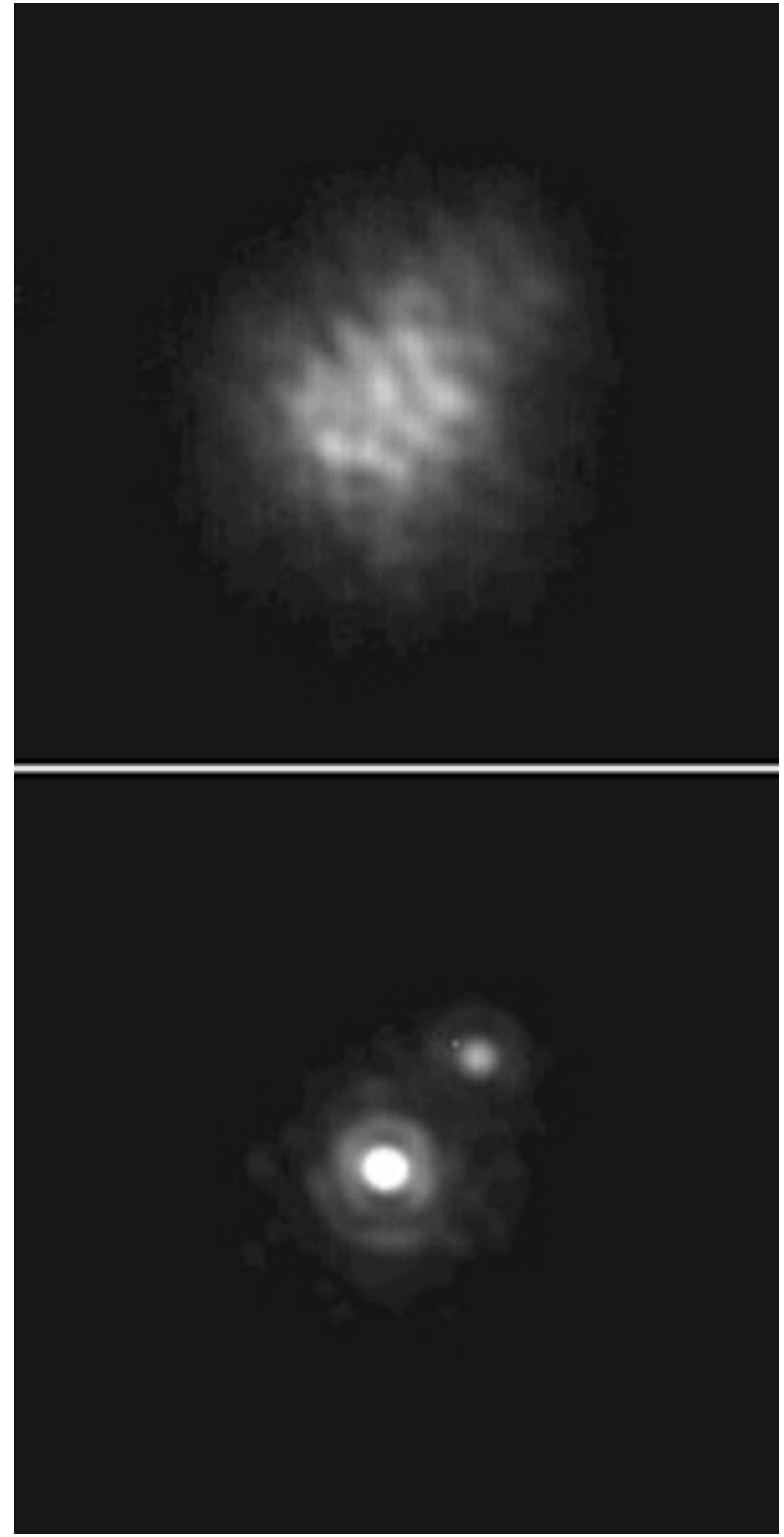
- Coherence time: $t_0 = 0.31\, r_0 / \langle v_{wind} \rangle$
  - Valid under Taylor's « frozen turbulence » hypothesis
  - $t_0 \simeq 3$ msec for $r_0 = 10$ cm and $\langle v_{wind} \rangle = 10$ m/s
- Isoplanatic angle: $\theta_0 = 0.31\, r_0 / \langle h \rangle$
  - $\theta_0 \simeq 1.3''$ for $r_0 = 10$ cm and $\langle h \rangle = 5$ km
  - Stars separated by θ_0 have different short-exposure PSFs



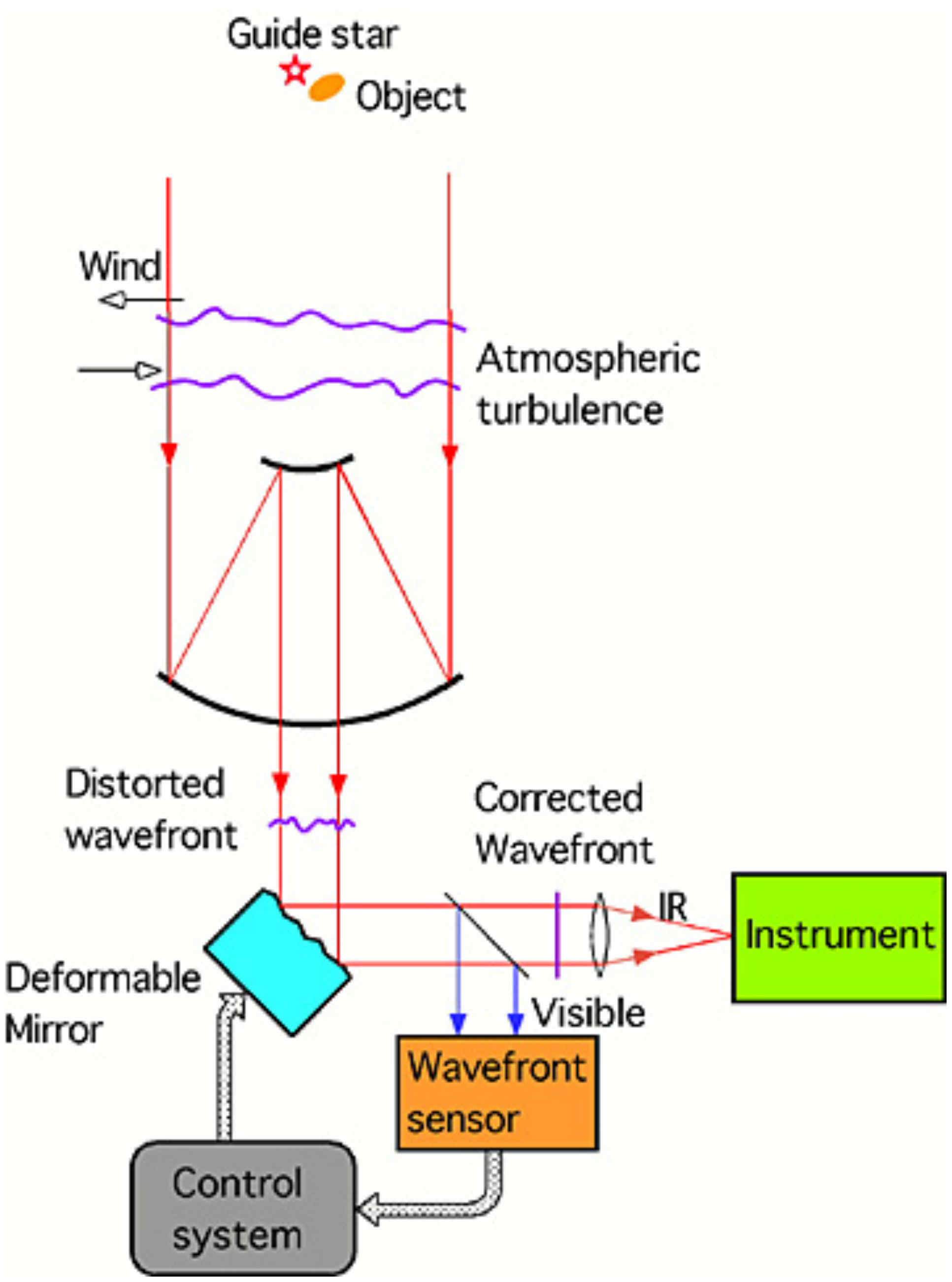


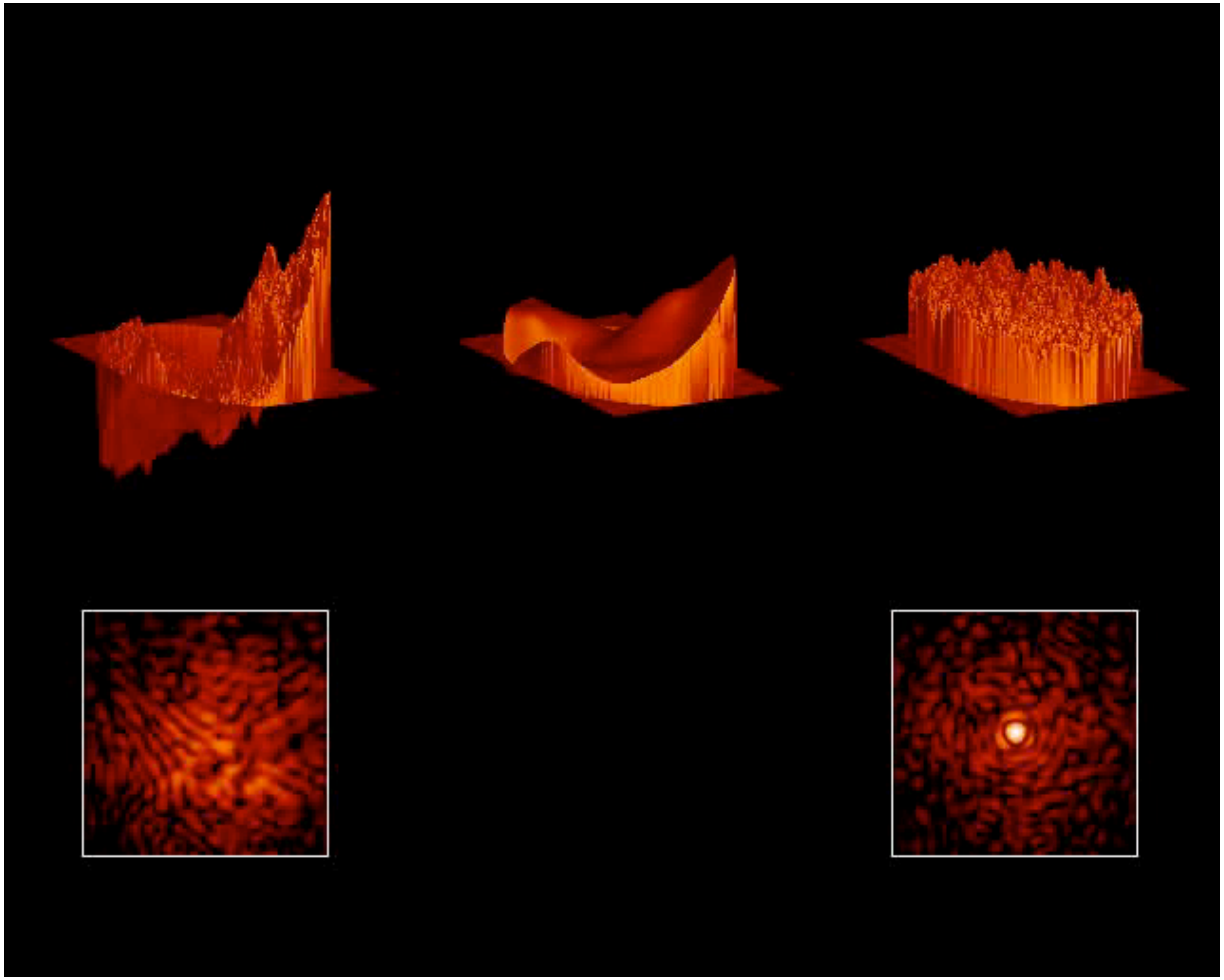
Correction needed!

Adaptive optics



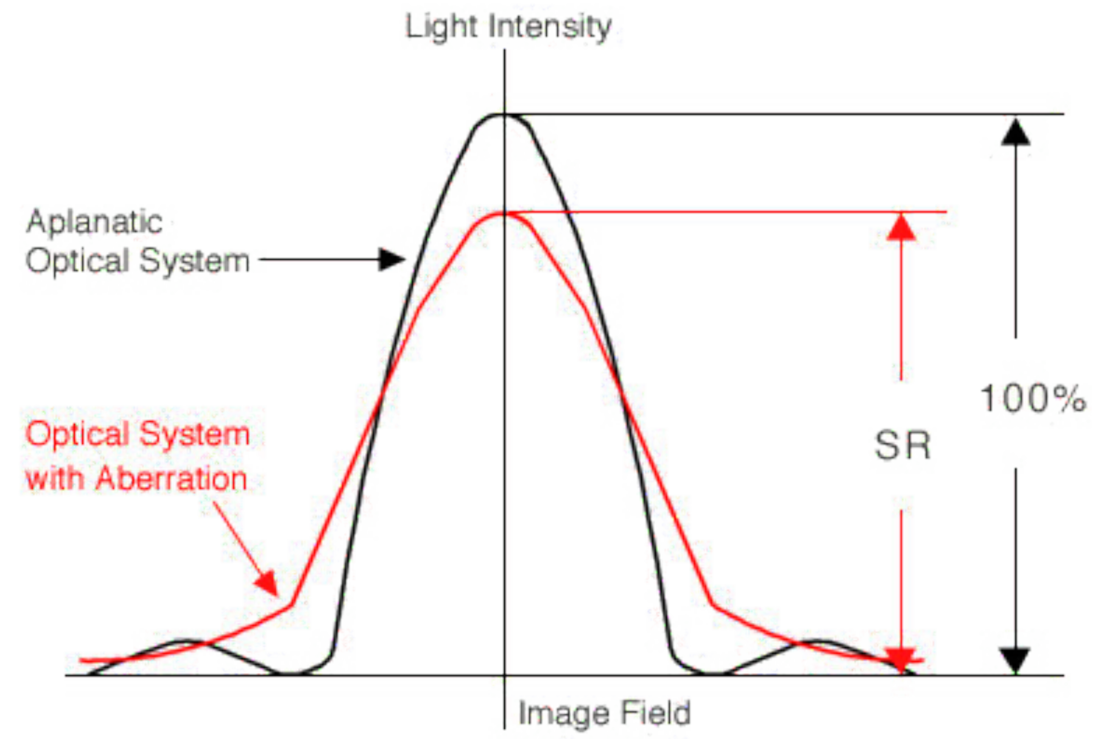
Adaptive optics





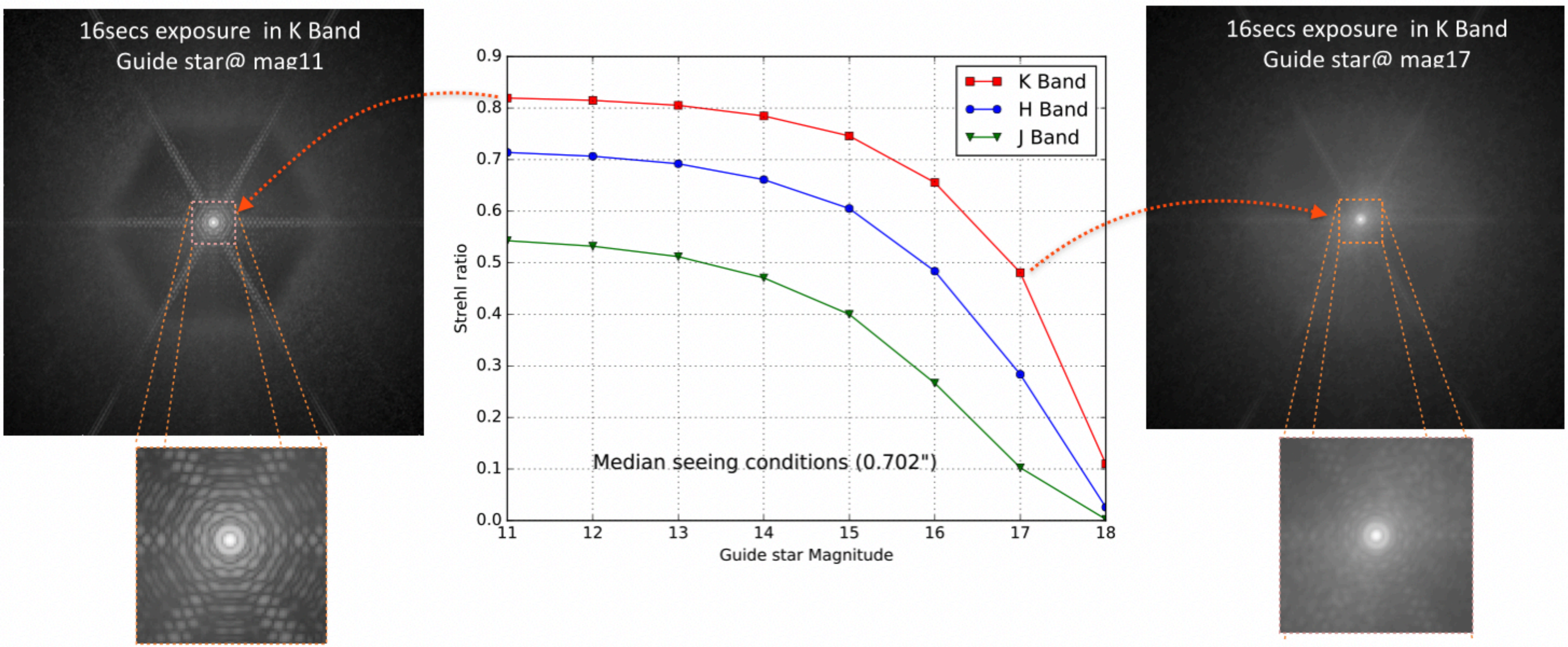
Strehl ratio

- $S = |\langle \exp(i\phi) \rangle|^2$
  $\simeq \exp(-\sigma_\phi{}^2)$
  - ϕ = wavefront phase
  - σ_ϕ = rms phase on pupil
- Quantifies image quality
  - $\simeq$ peak intensity ratio wrt perfect image
  - Perfect image → $S = 1$
  - $D = r_0$ → $S = 0.36$



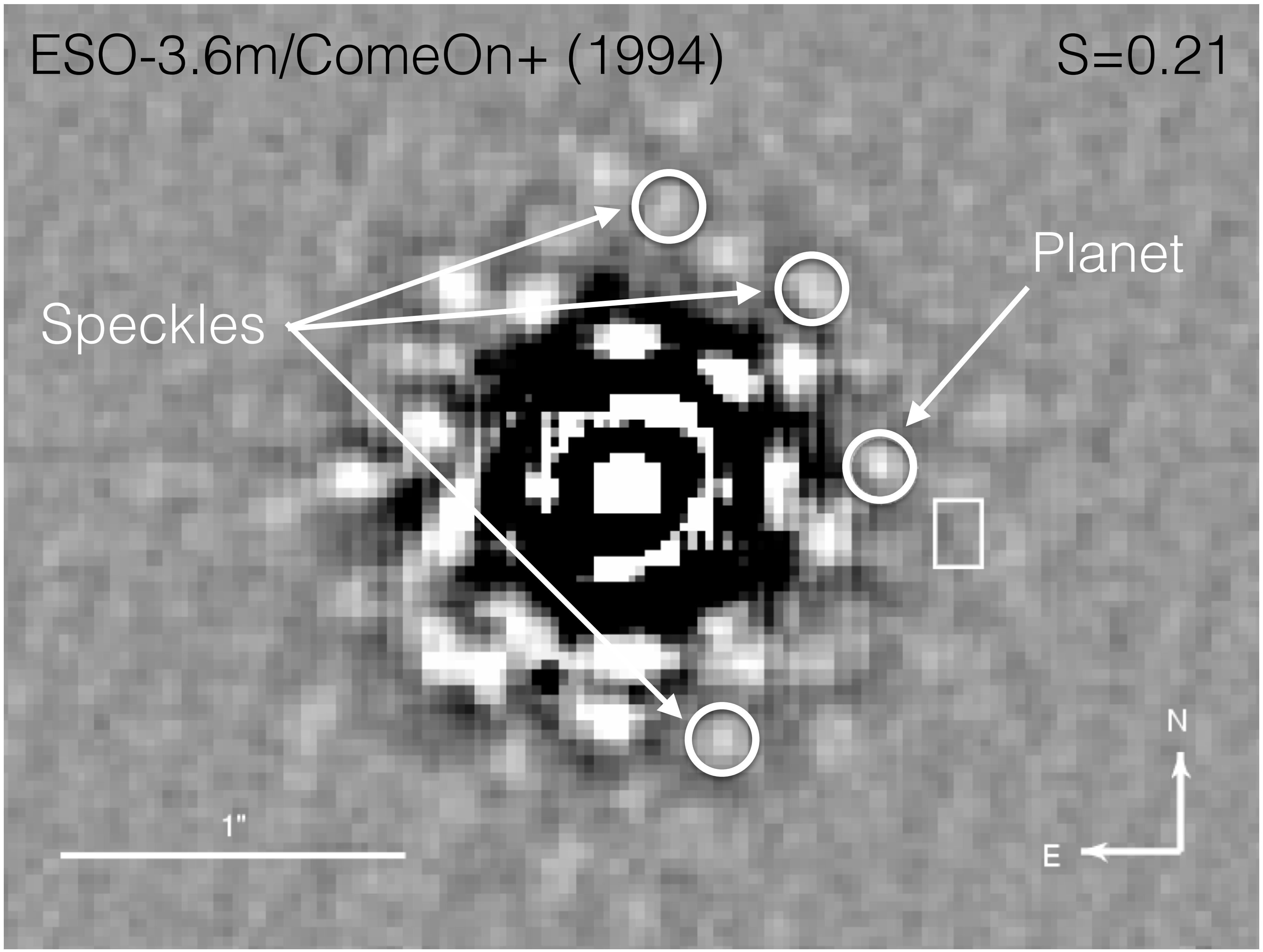
AO correction

Simulations for MICADO @ ELT



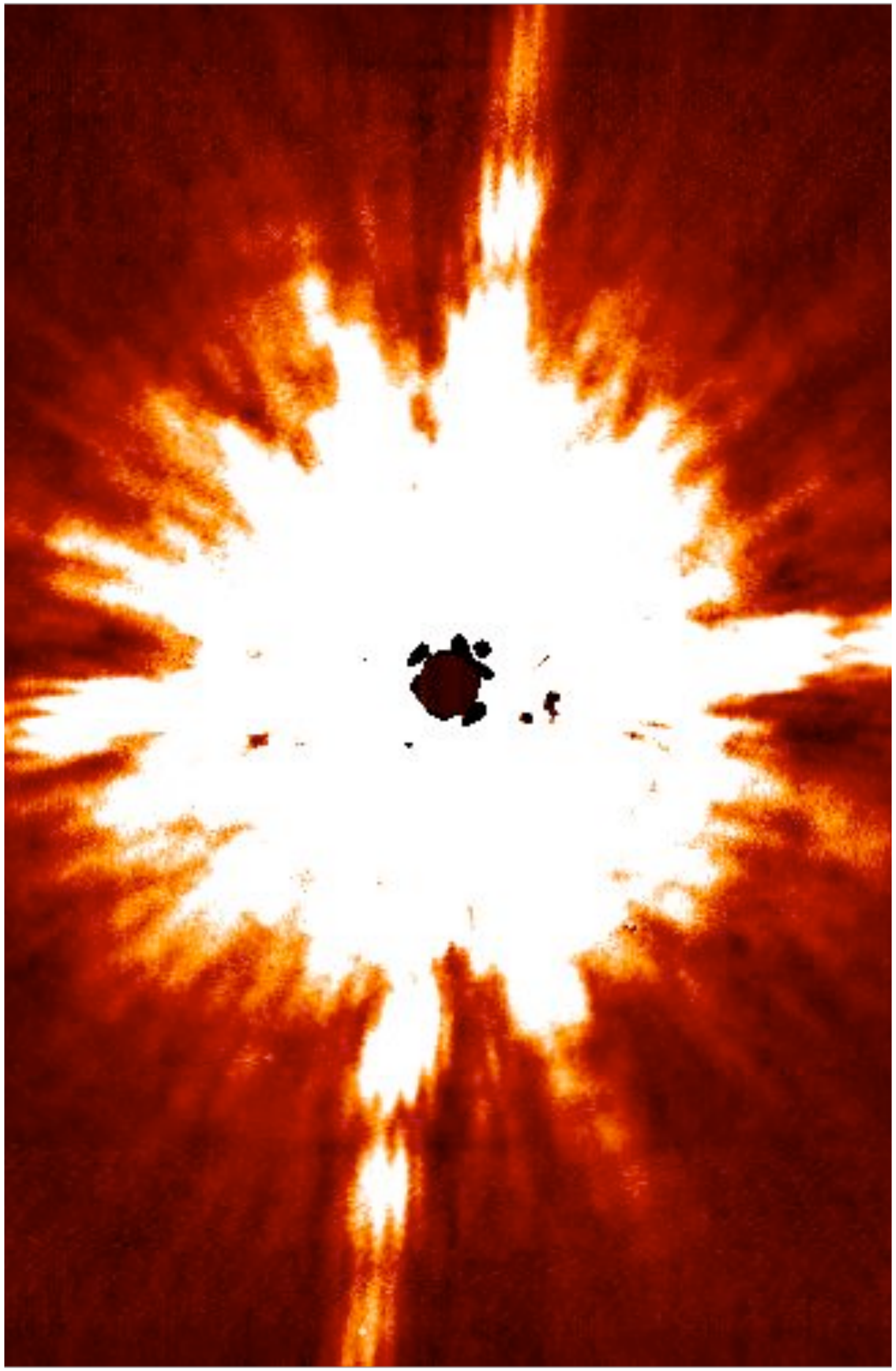
Correction performance drops for fainter stars and shorter wavelengths

Detection in speckle noise?

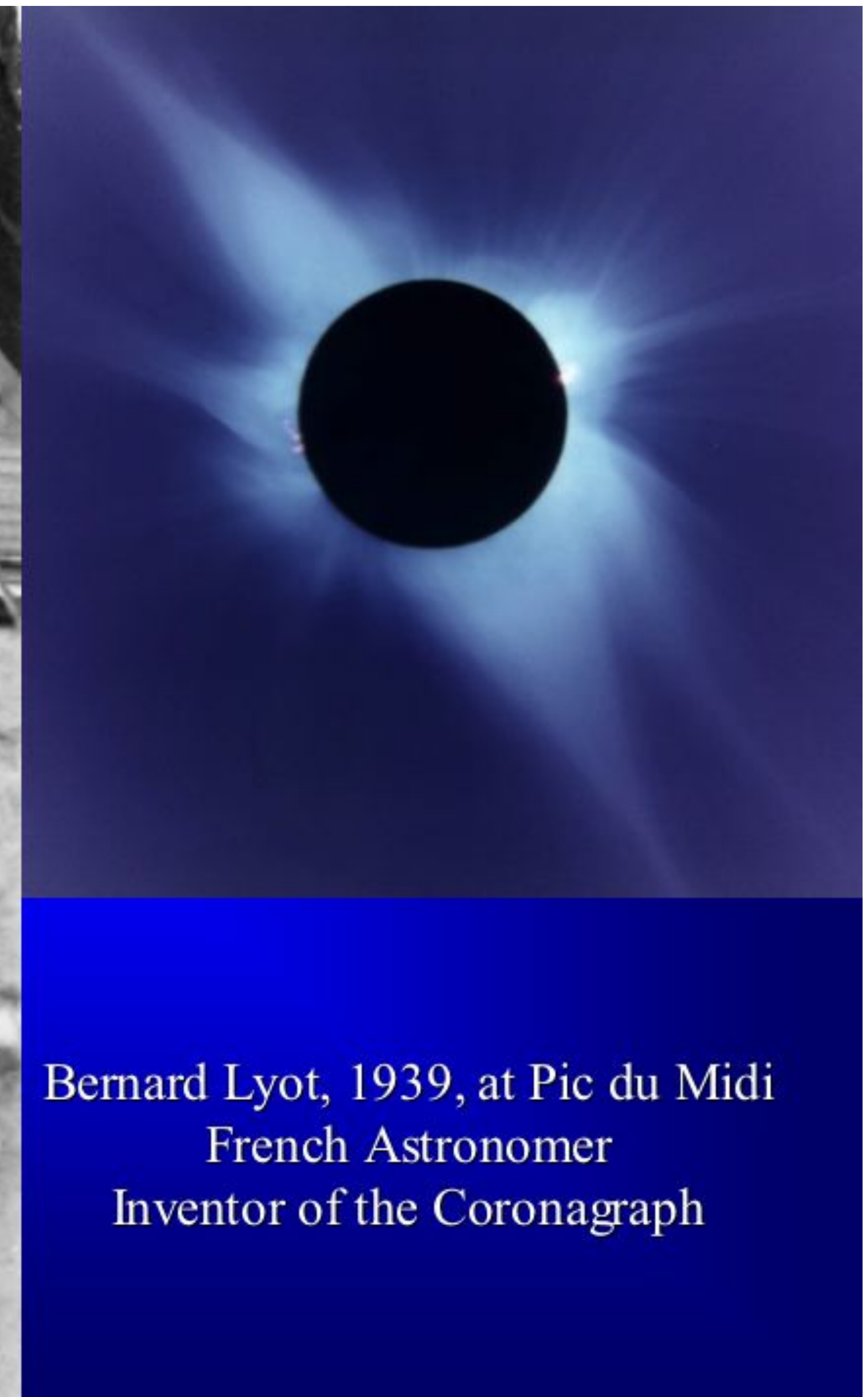


Getting rid of speckles

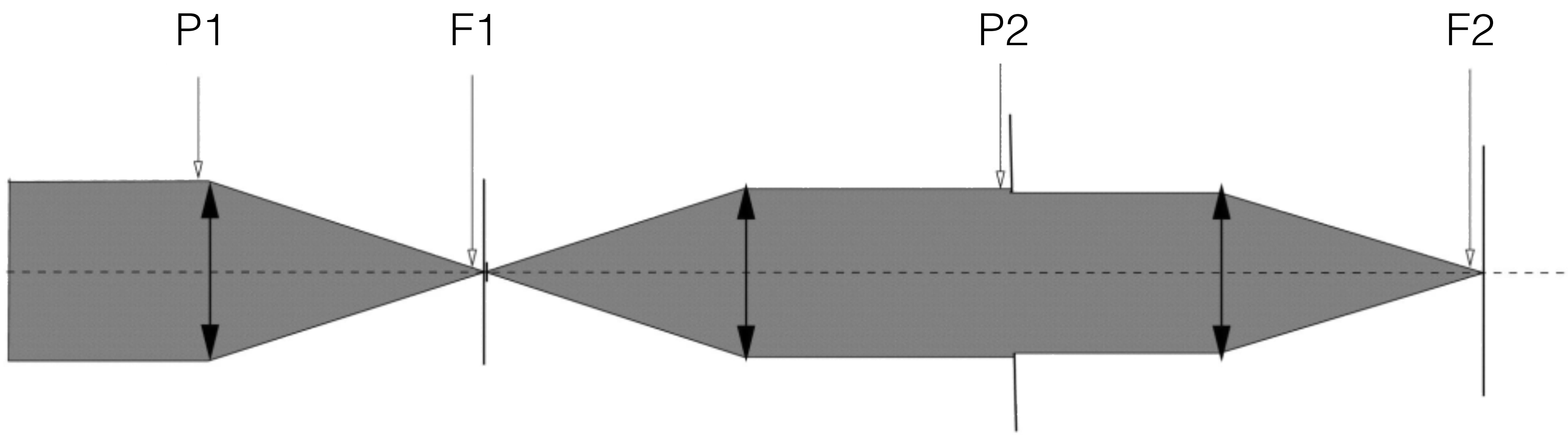
1. Coronagraphy

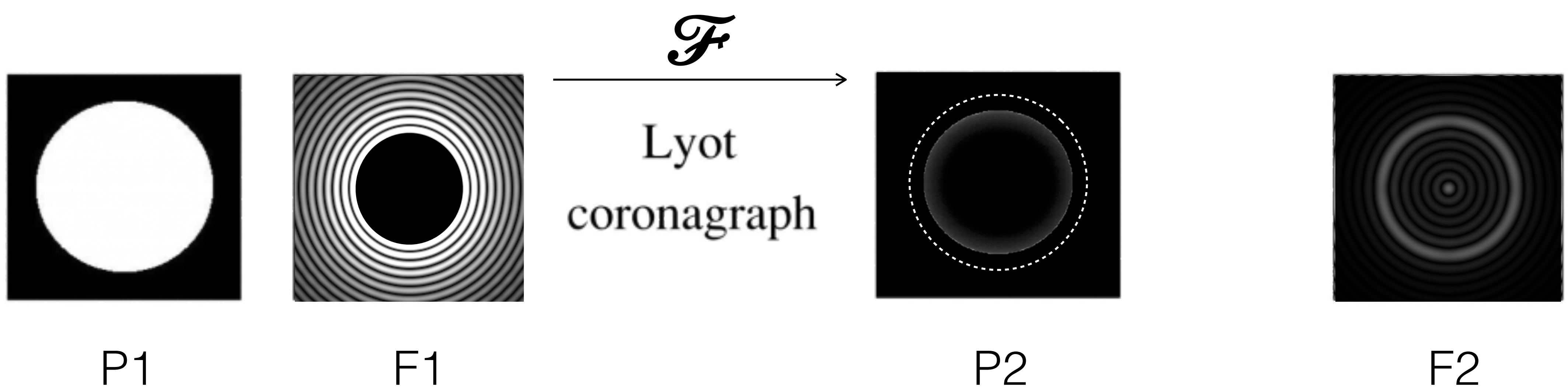


Coronagraphy



Lyot coronagraph





place occulting mask
with size a few λ/D

place undersized
pupil diaphragm

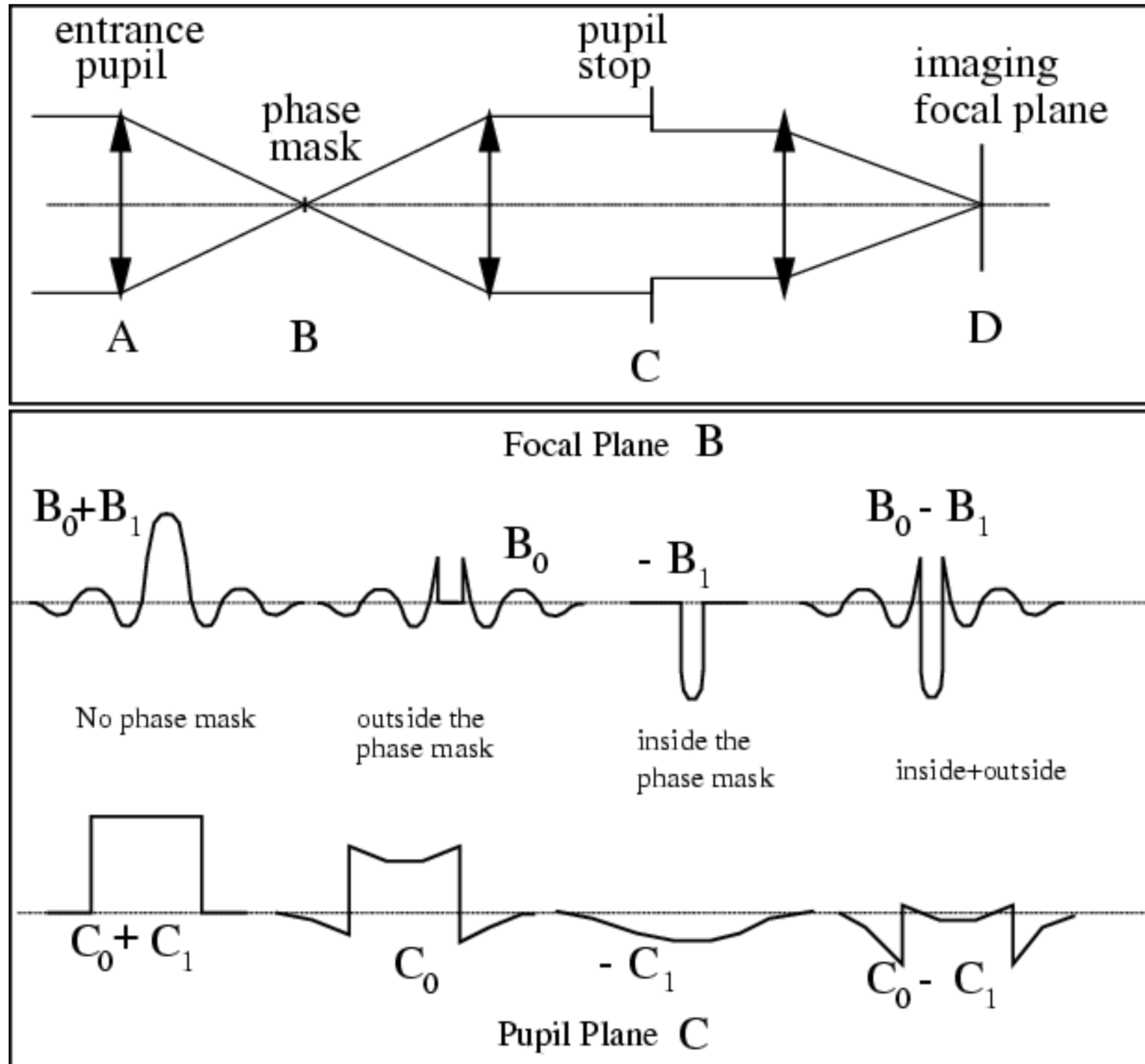
core removed,
wings attenuated

Lyot coronagraph: limitations

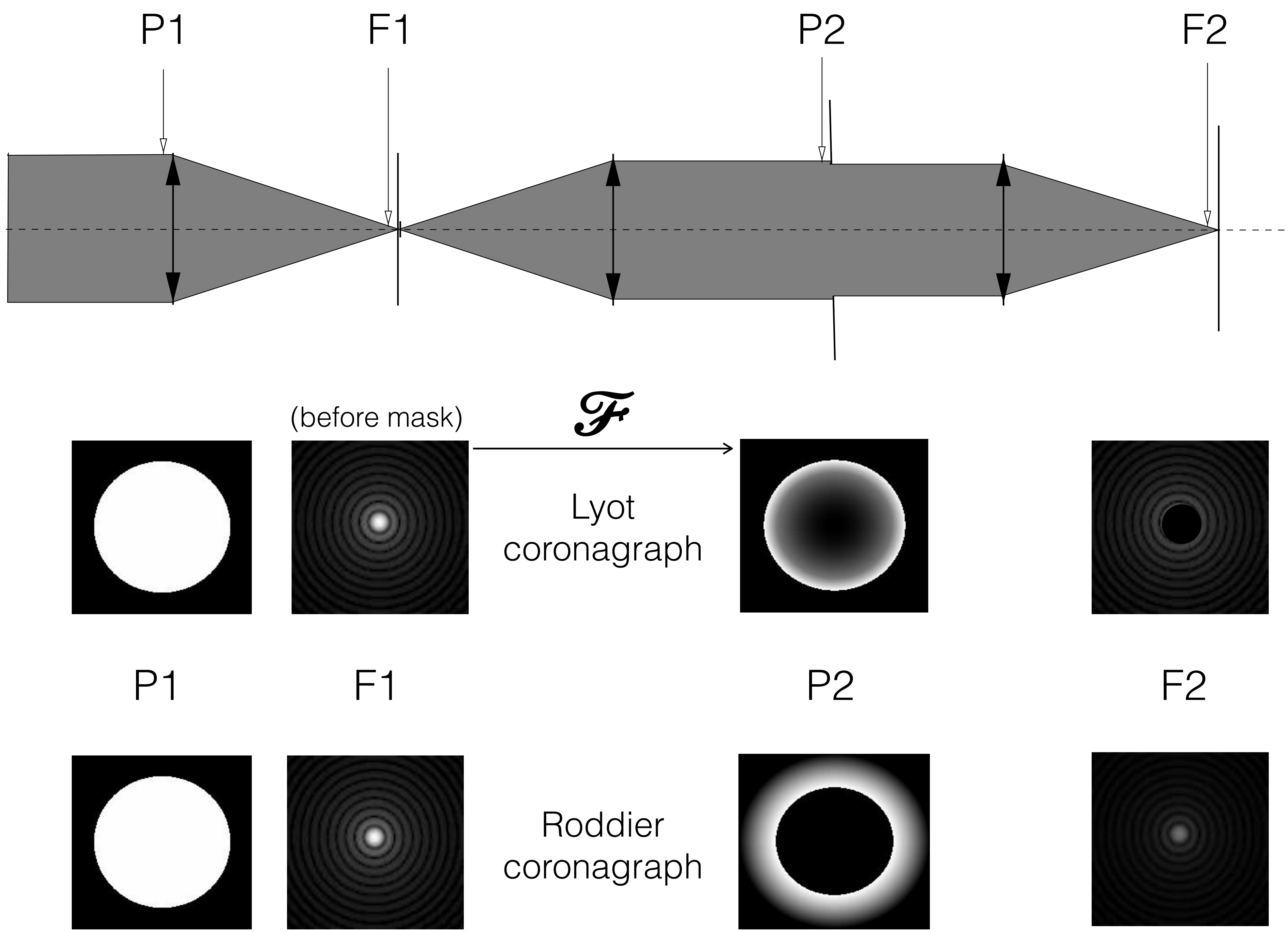
- Starlight cancellation only partial
  - improving cancellation requires smaller pupil diaphragm, i.e., lower throughput
- Chromatic behavior
  - fixed mask size while diffraction pattern scales as λ
- Limited inner working angle
  - planets closer than a few λ/D are also blocked

Phase mask coronagraph

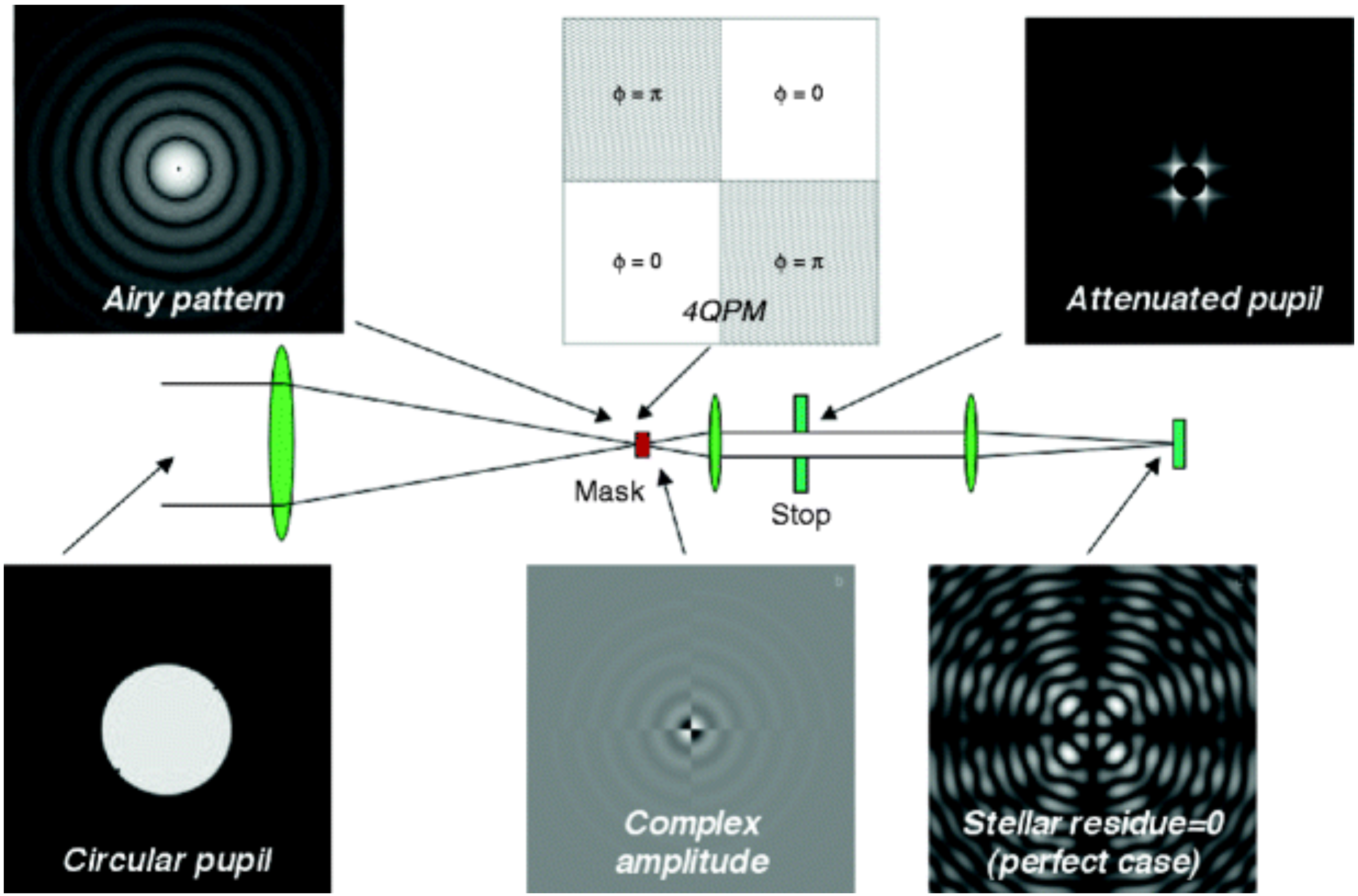
- Proposed by Roddier (1997)
- Goal: reach smaller inner working angle (IWA)
- Apply 180° phase shift to PSF center
- Ideal mask size = 43% of 1st Airy ring (0.53 λ/D)
- Very chromatic design



Lyot vs Roddier



Four Quadrant Phase Mask

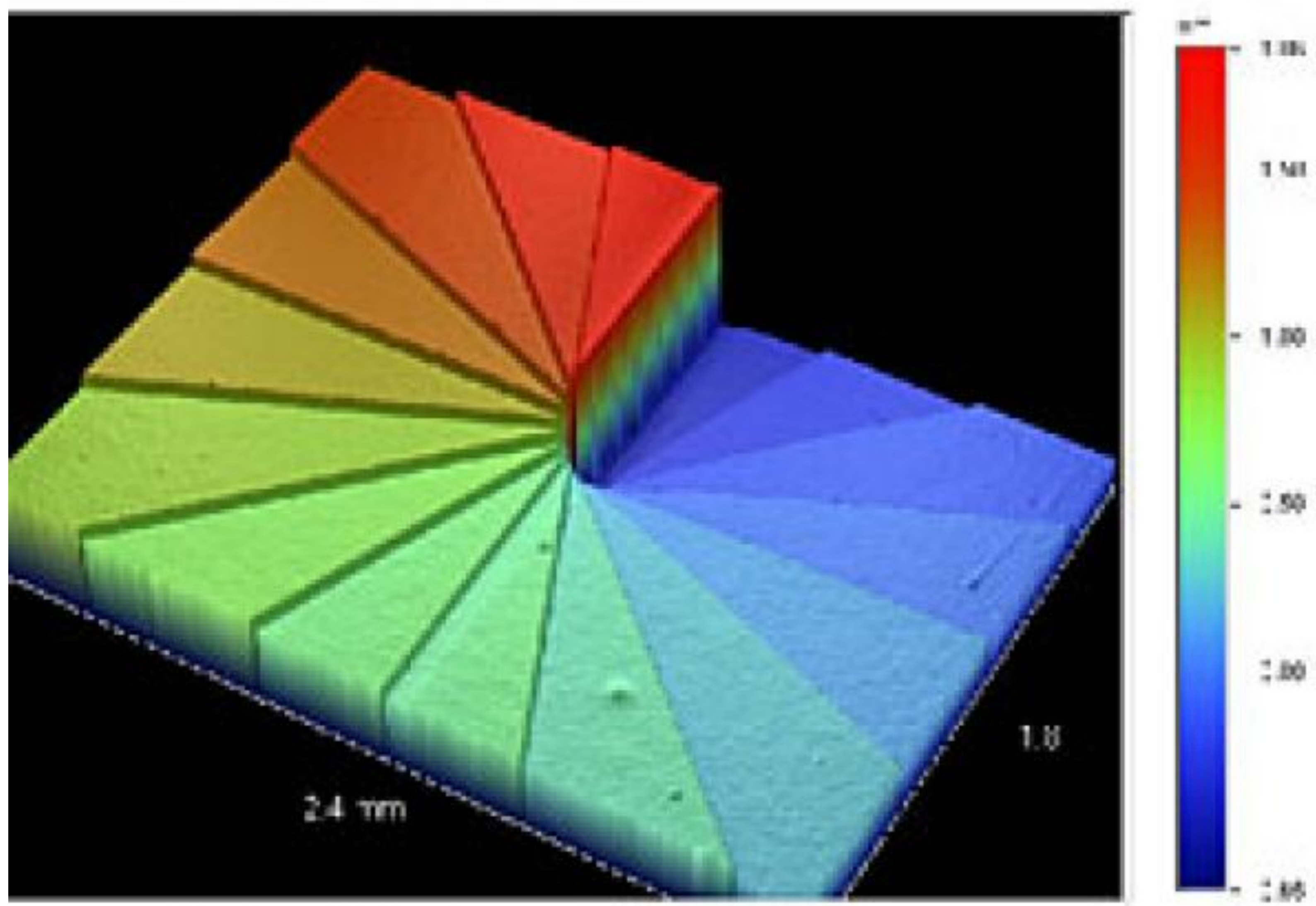


light completely rejected outside pupil by destructive interference

Design intrinsically achromatic … but phase shift generally only π at one wavelength. Another problem is that planets located on quadrant transitions are also cancelled.

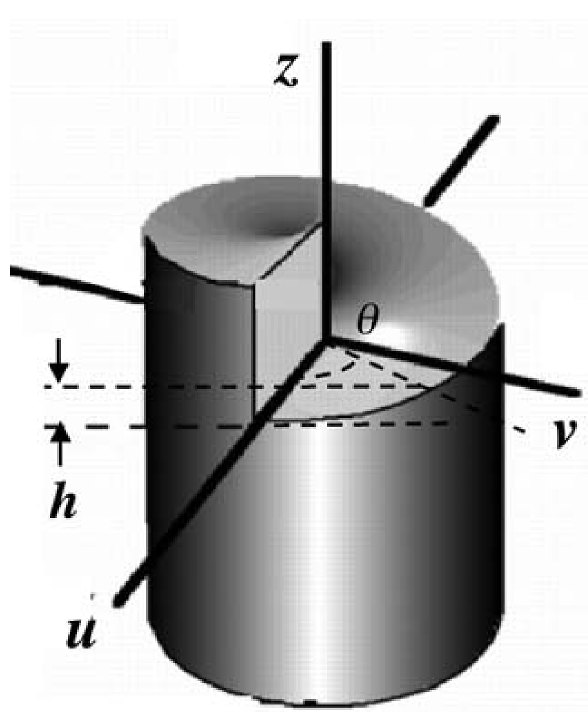
Beyond the FQPM

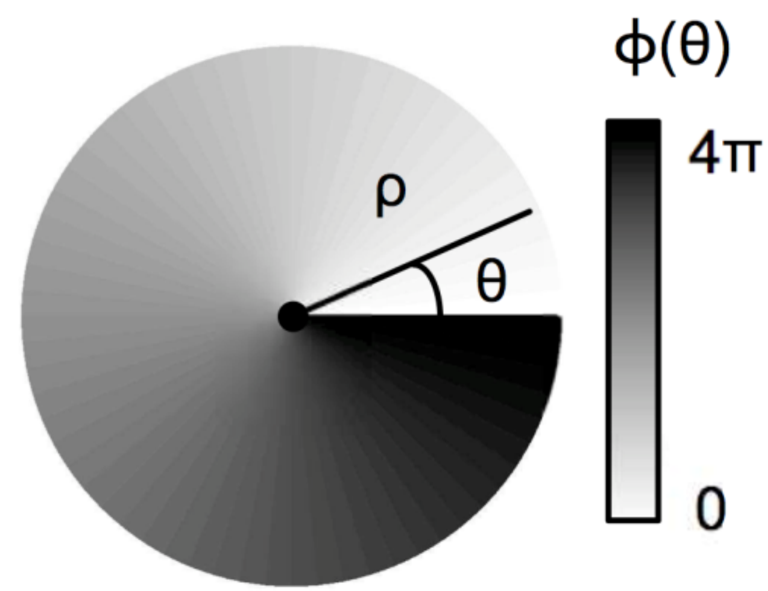
- Quadrants → octants → continuous phase ramp



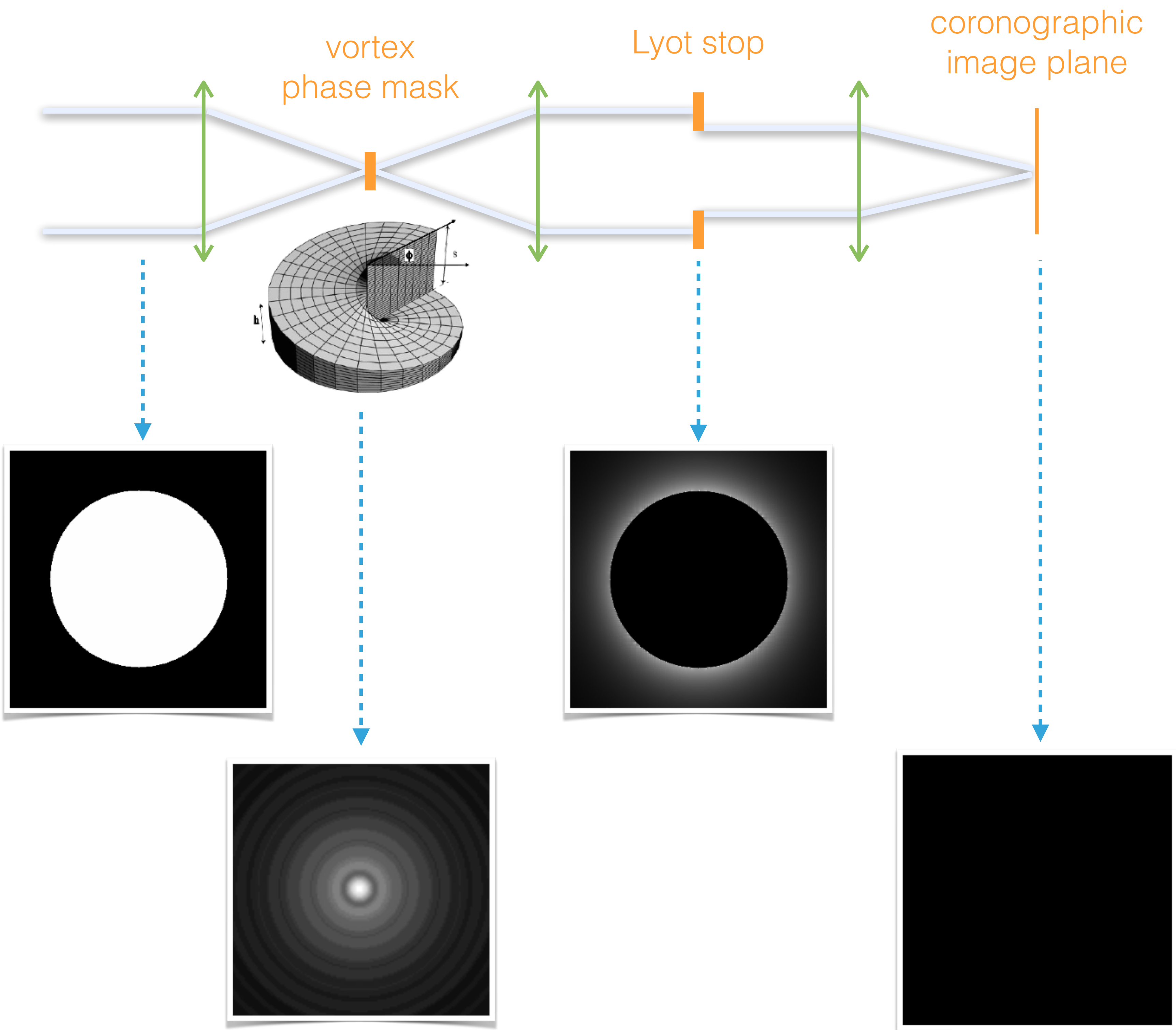
Vortex phase mask

- Continuous phase ramp from 0 to 4π
- Main problem: chromaticity of the phase ramp (only perfect for one given wavelength)

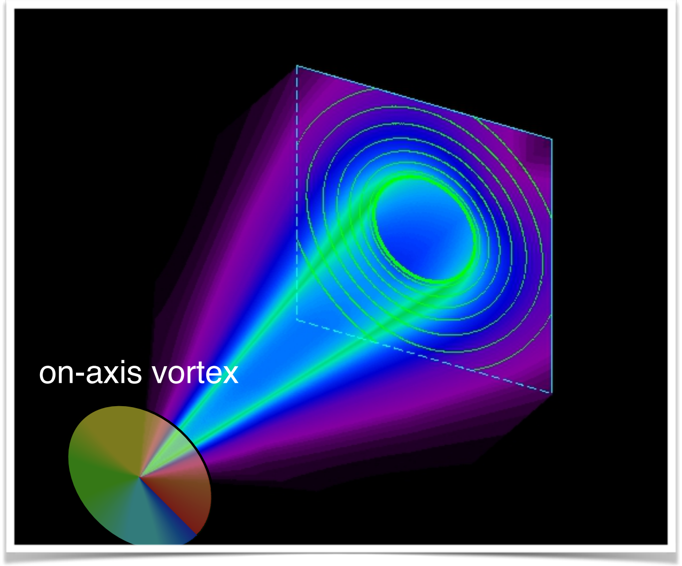


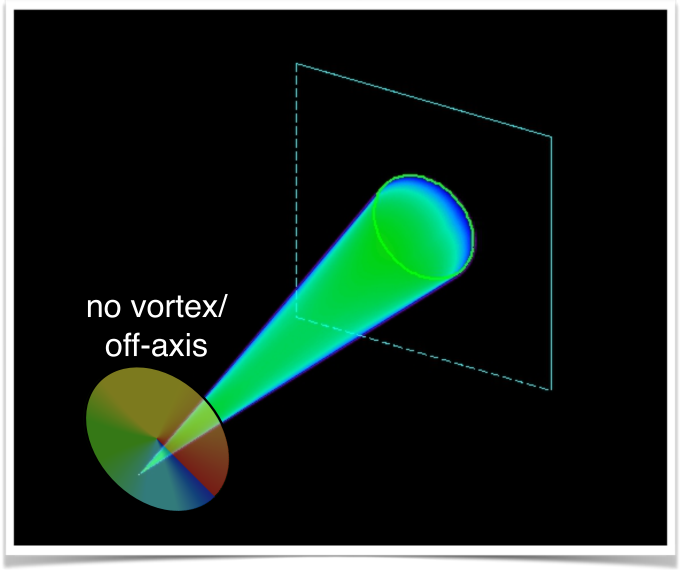


Vortex phase mask

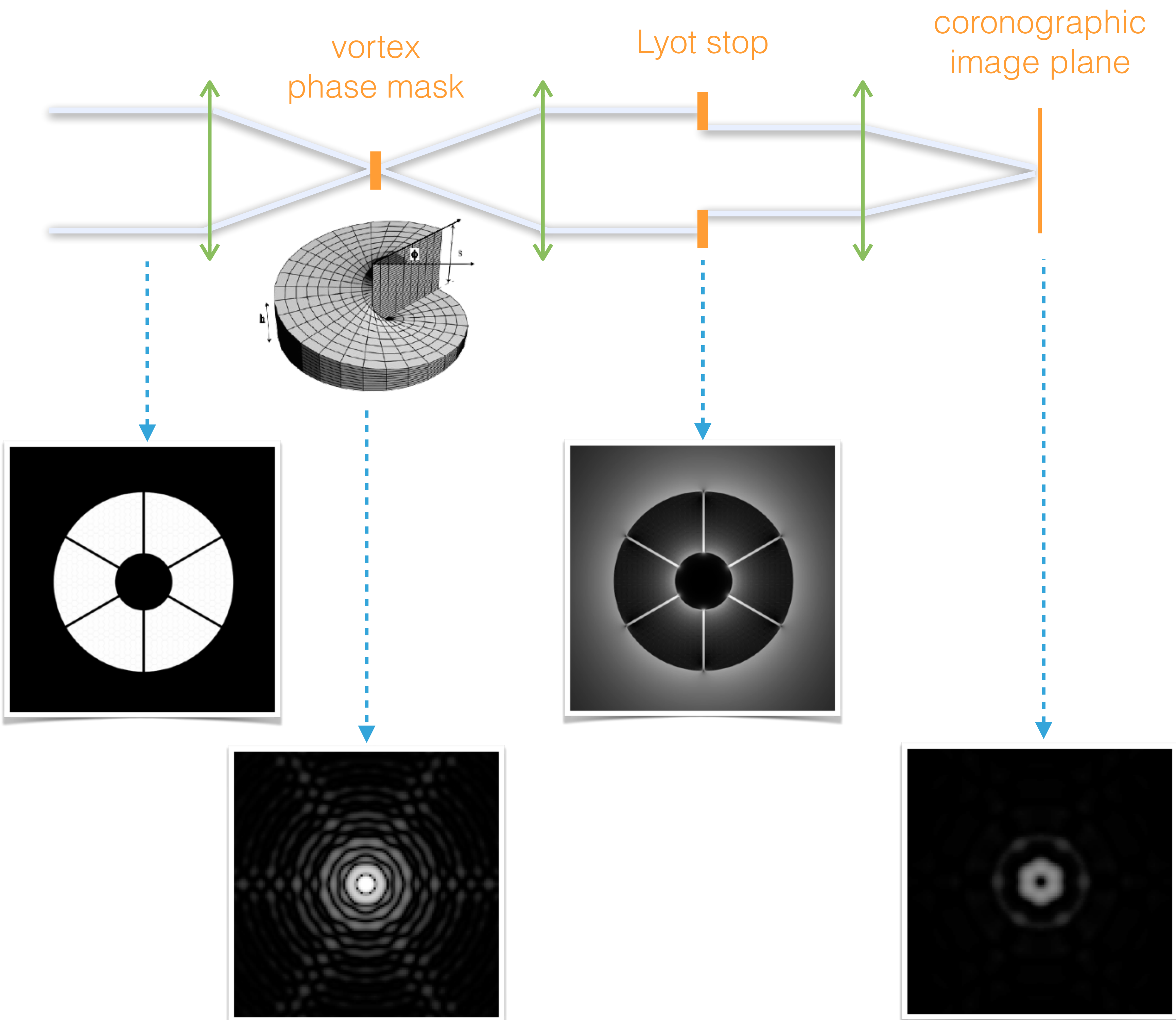


perfect on-axis cancellation
for a circular aperture





Vortex phase mask



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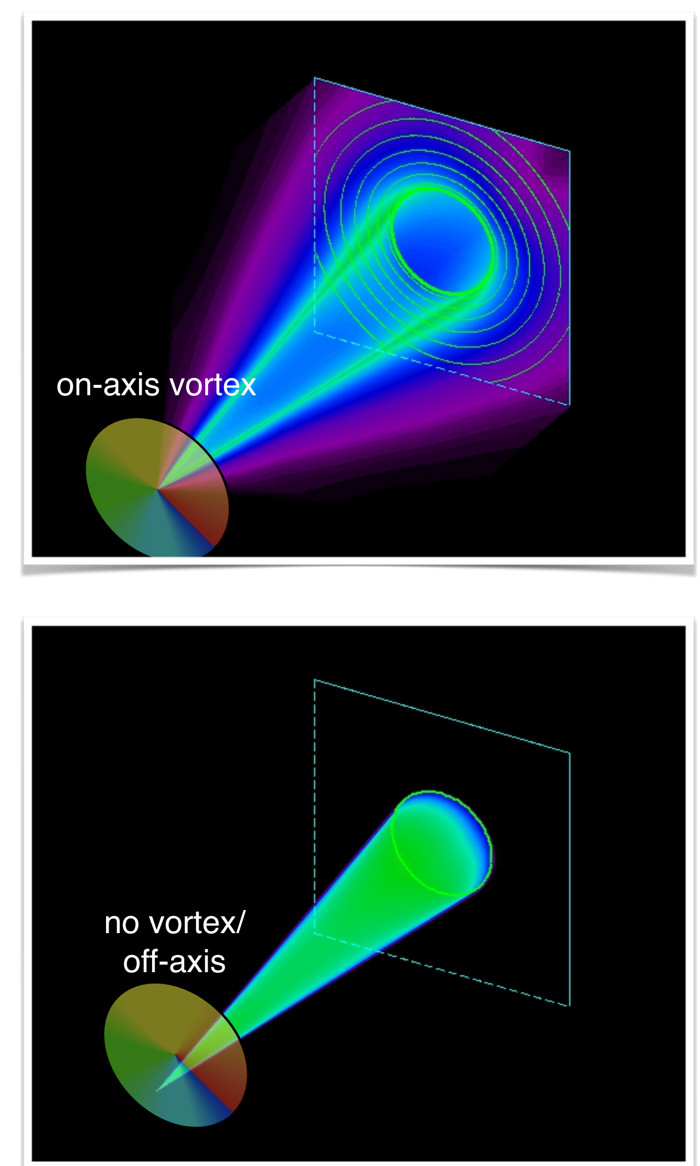
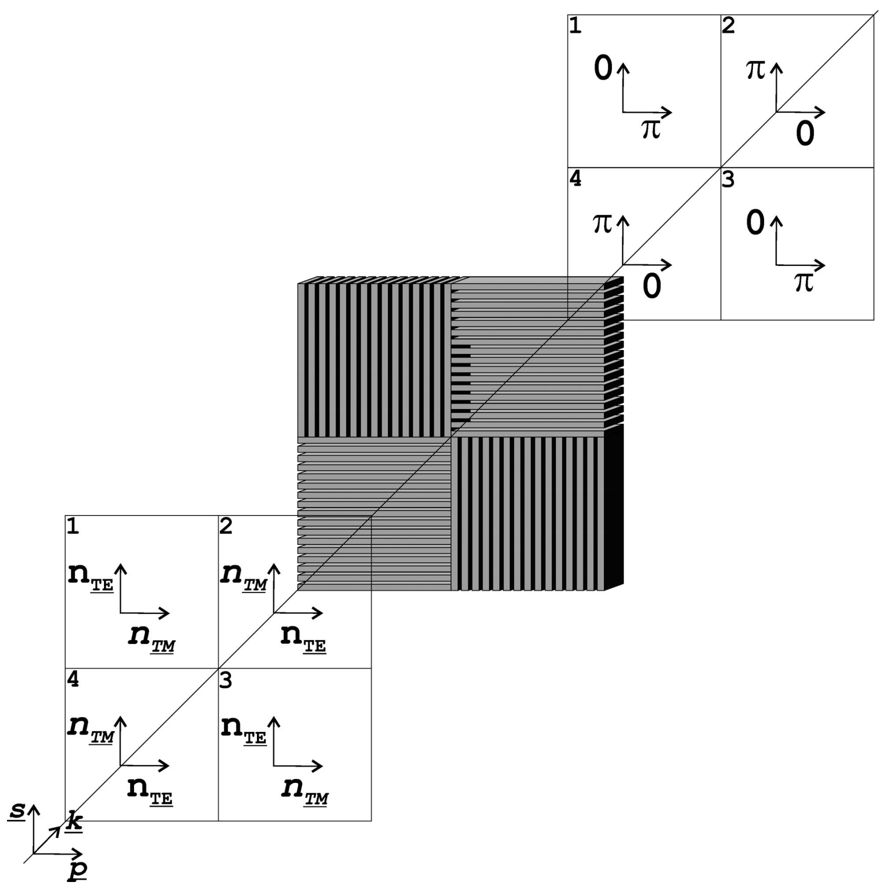
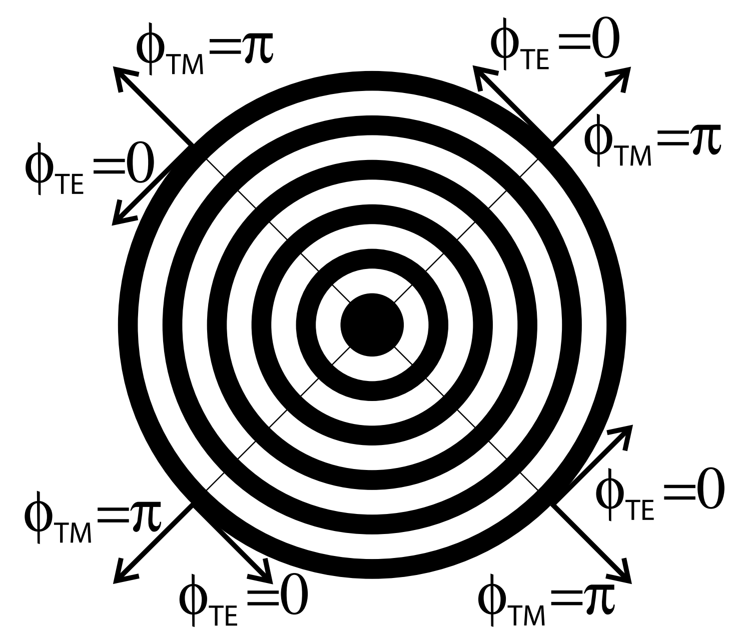


Achromatic phase mask?

- Sub-wavelength gratings → achromatic half wave plate





Annular Groove Phase Mask (AGPM)

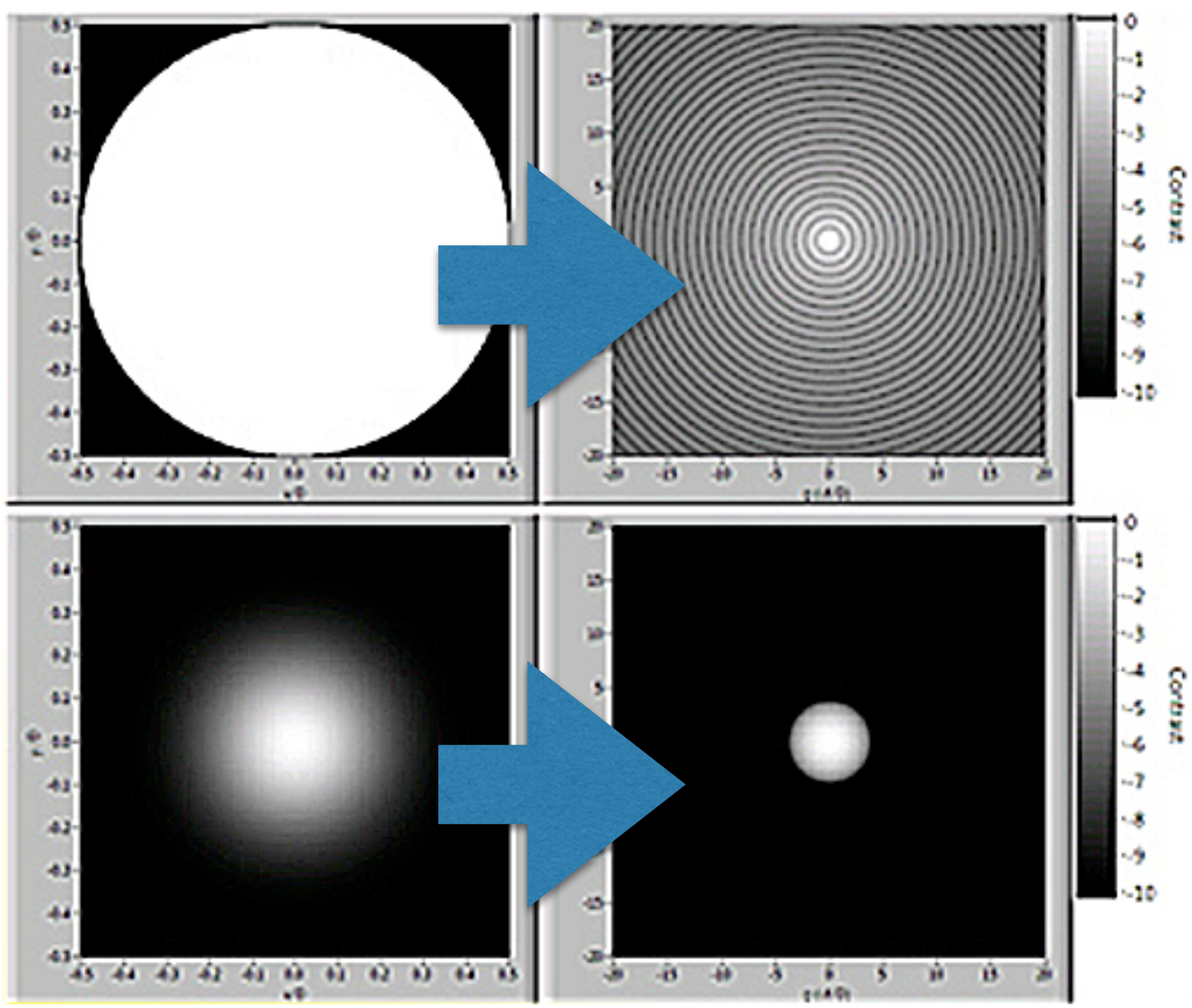
- Another solution is based on Liquid Crystal Polymers

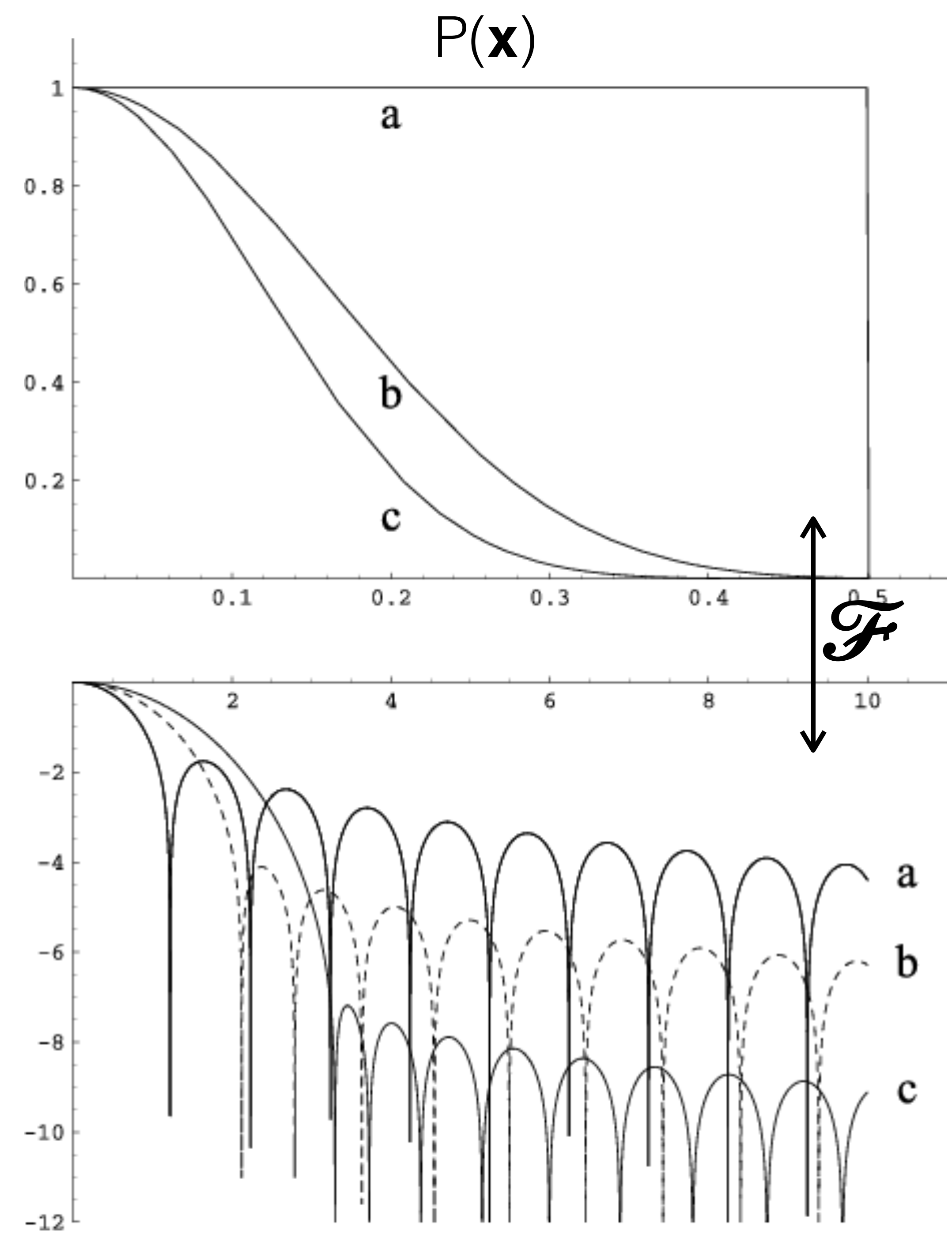
Apodization

- So far we've been relying on a mask in the focal plane, but we can also work in the pupil plane!
- Apodization
  - principle: modify amplitude or phase of wavefront in pupil
  - goal: redistribute the intensity in the focal plane to make it more compact or create a dark region

Amplitude apodization

- Goal: reduce PSF side lobes
- Degraded angular resolution

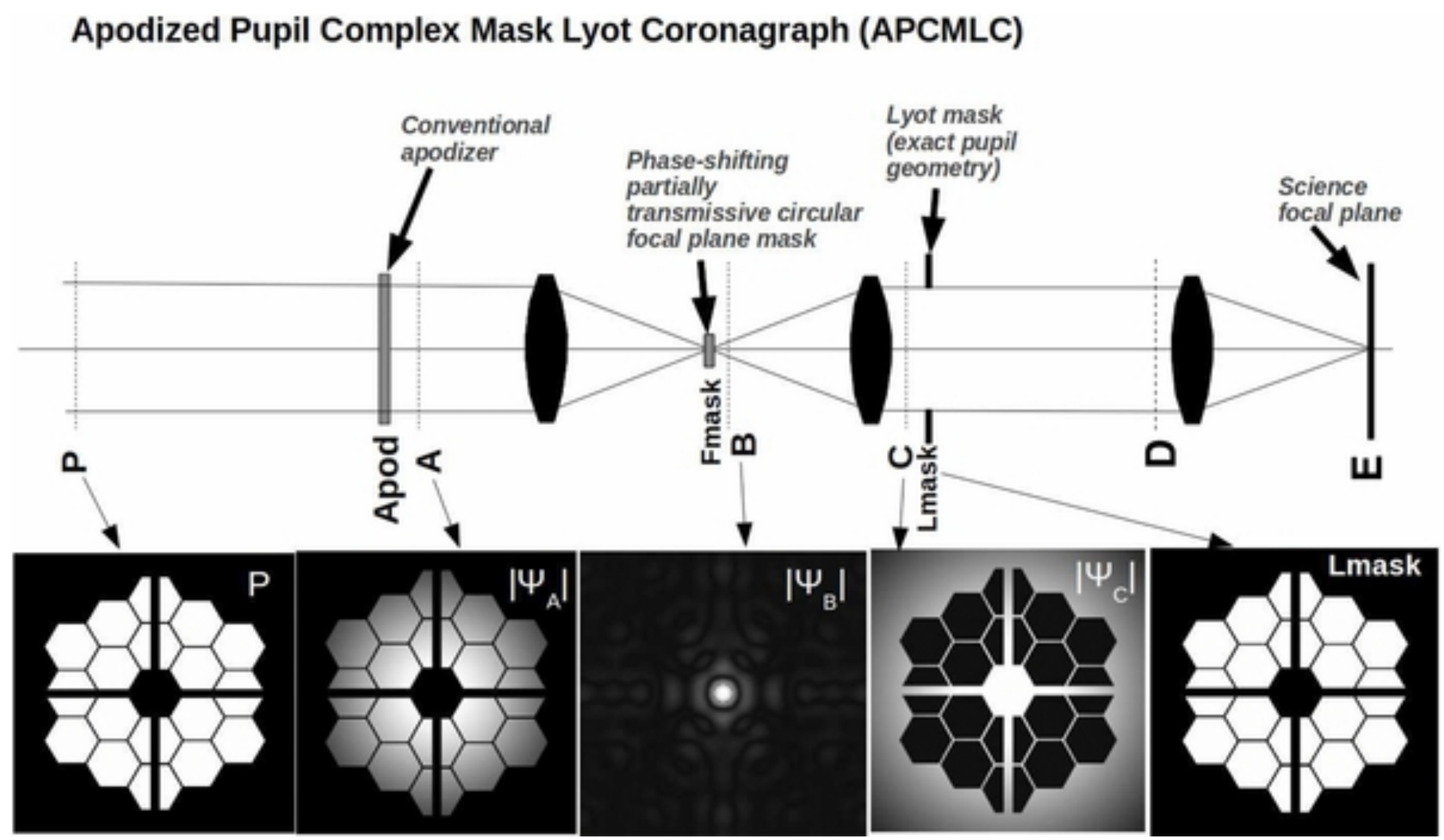




Apodized coronagraph

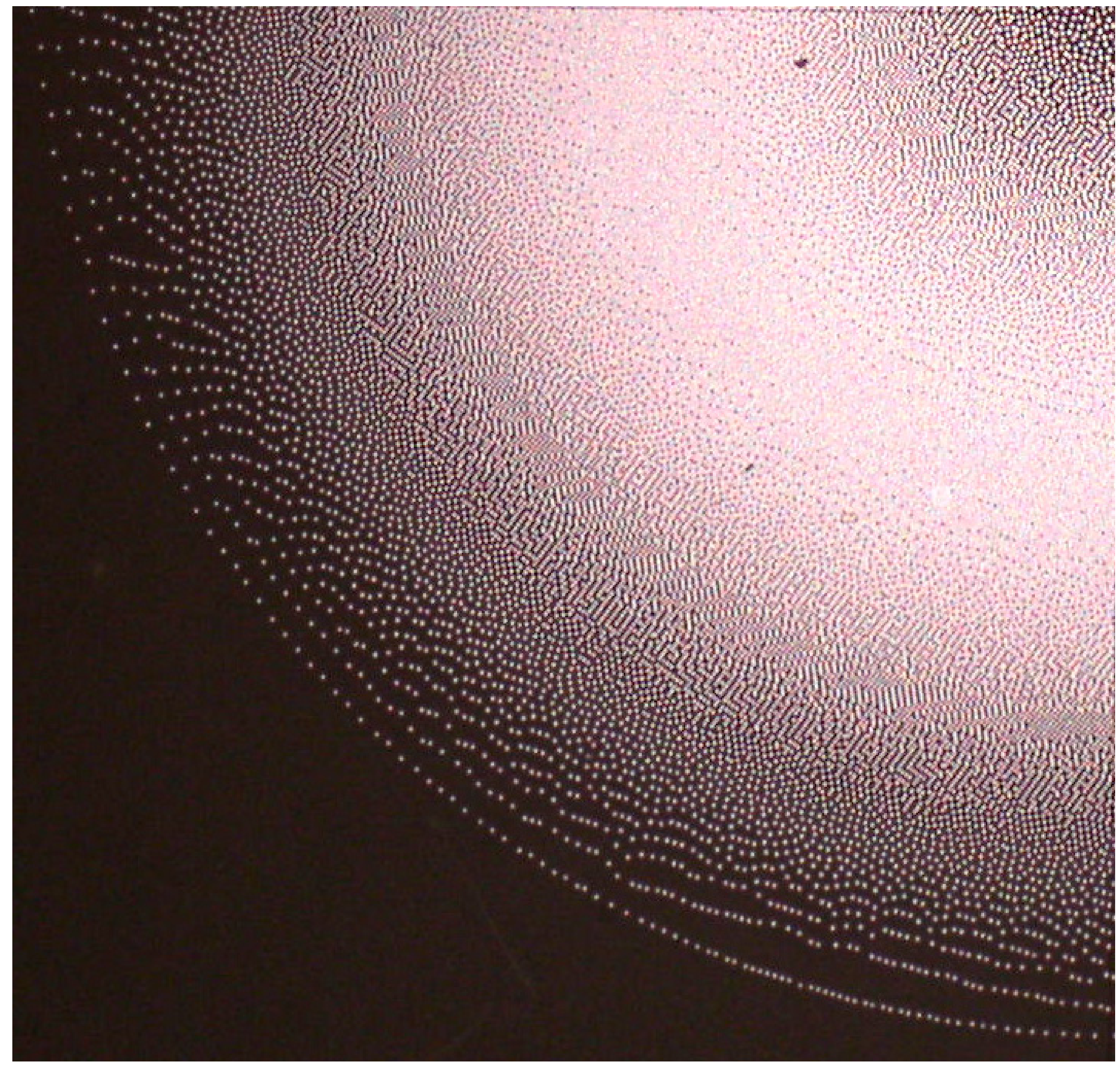
- Combination of apodization and focal plane amplitude or phase mask

- Apodization makes PSF more compact on the focal plane mask

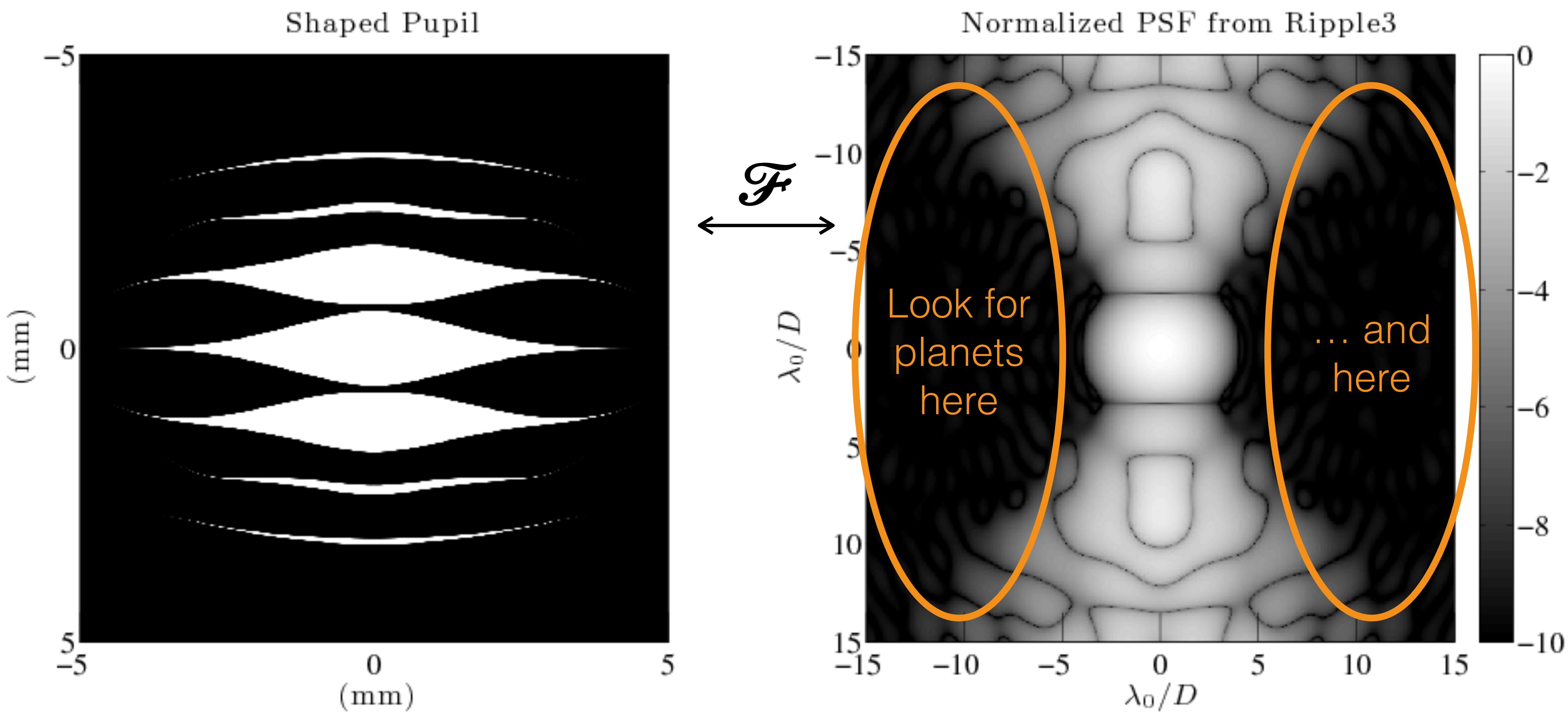


How it's done

- Microdot apodizer

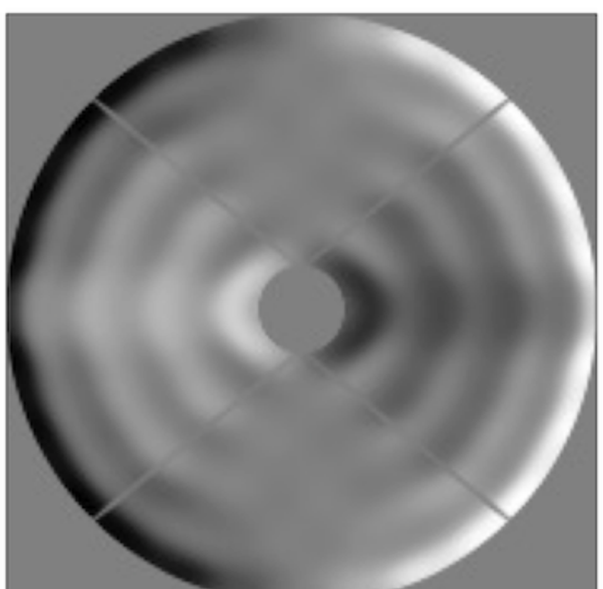


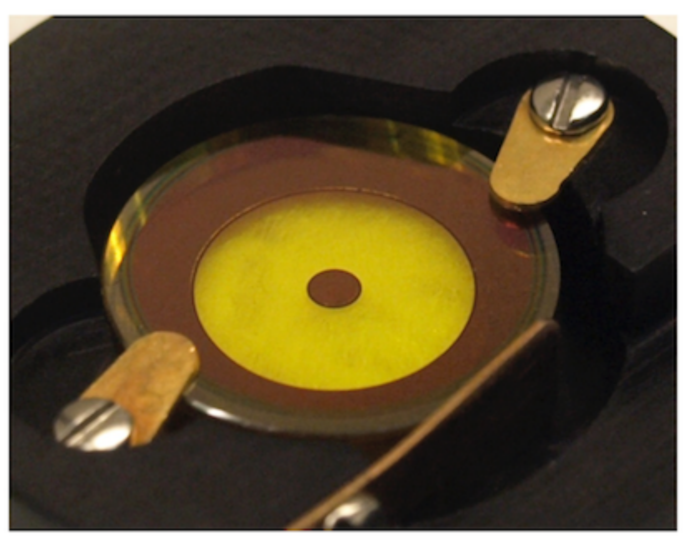
Shaped pupils



Phase apodization

- Act on wavefront phase instead of amplitude
- Can produce asymmetric PSF

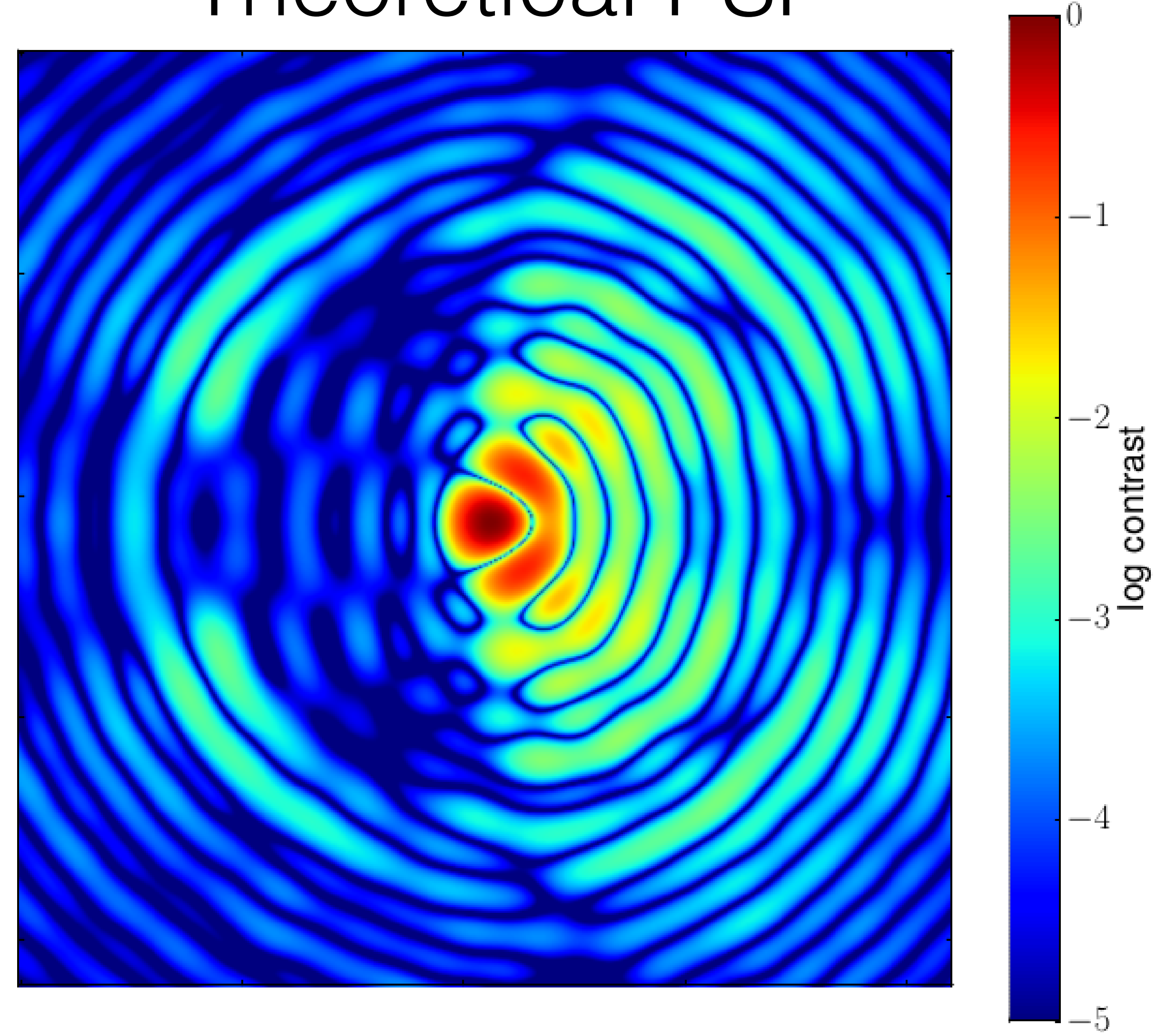




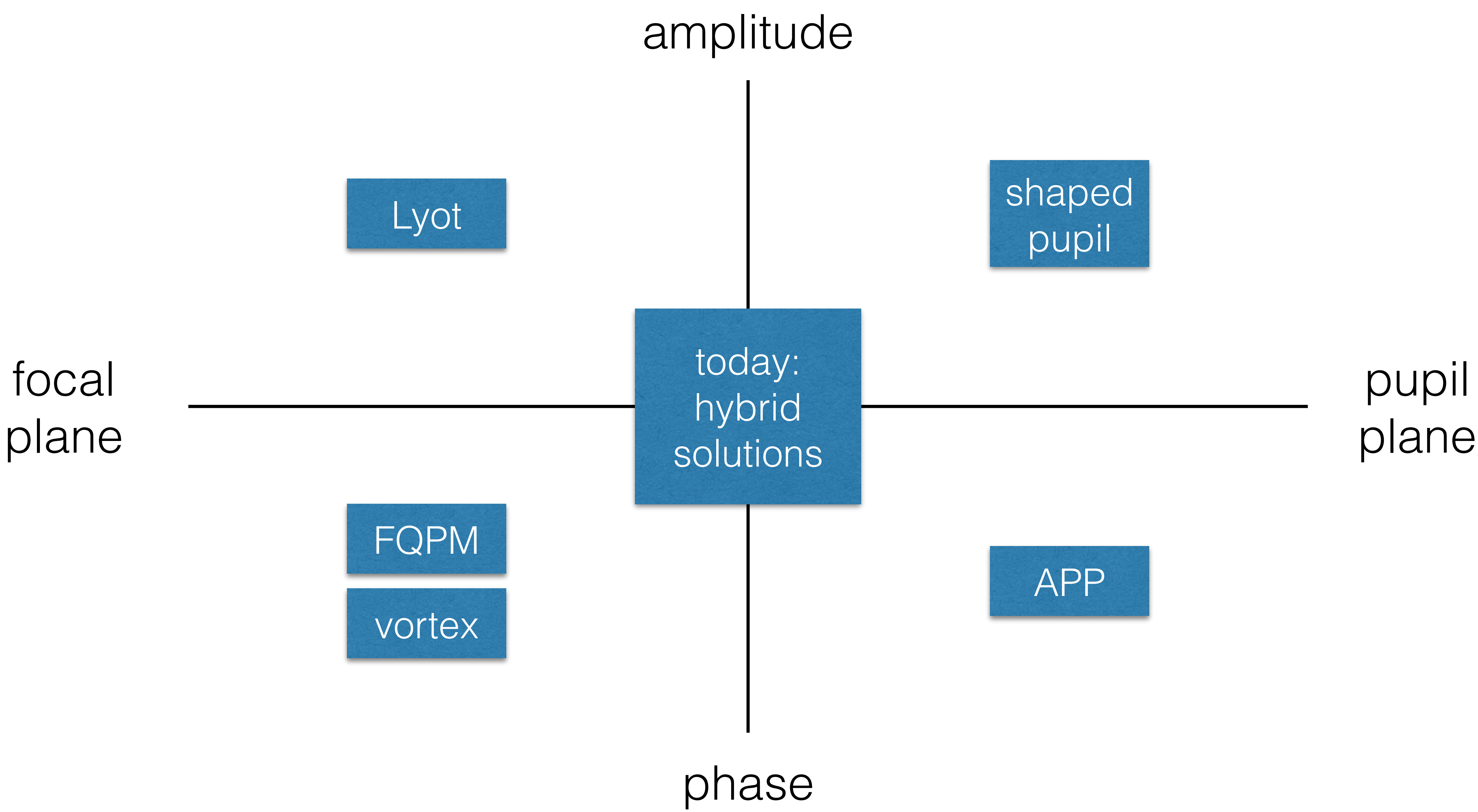
APP: Apodizing Phase Plate

$\mathcal{F}$

Theoretical PSF

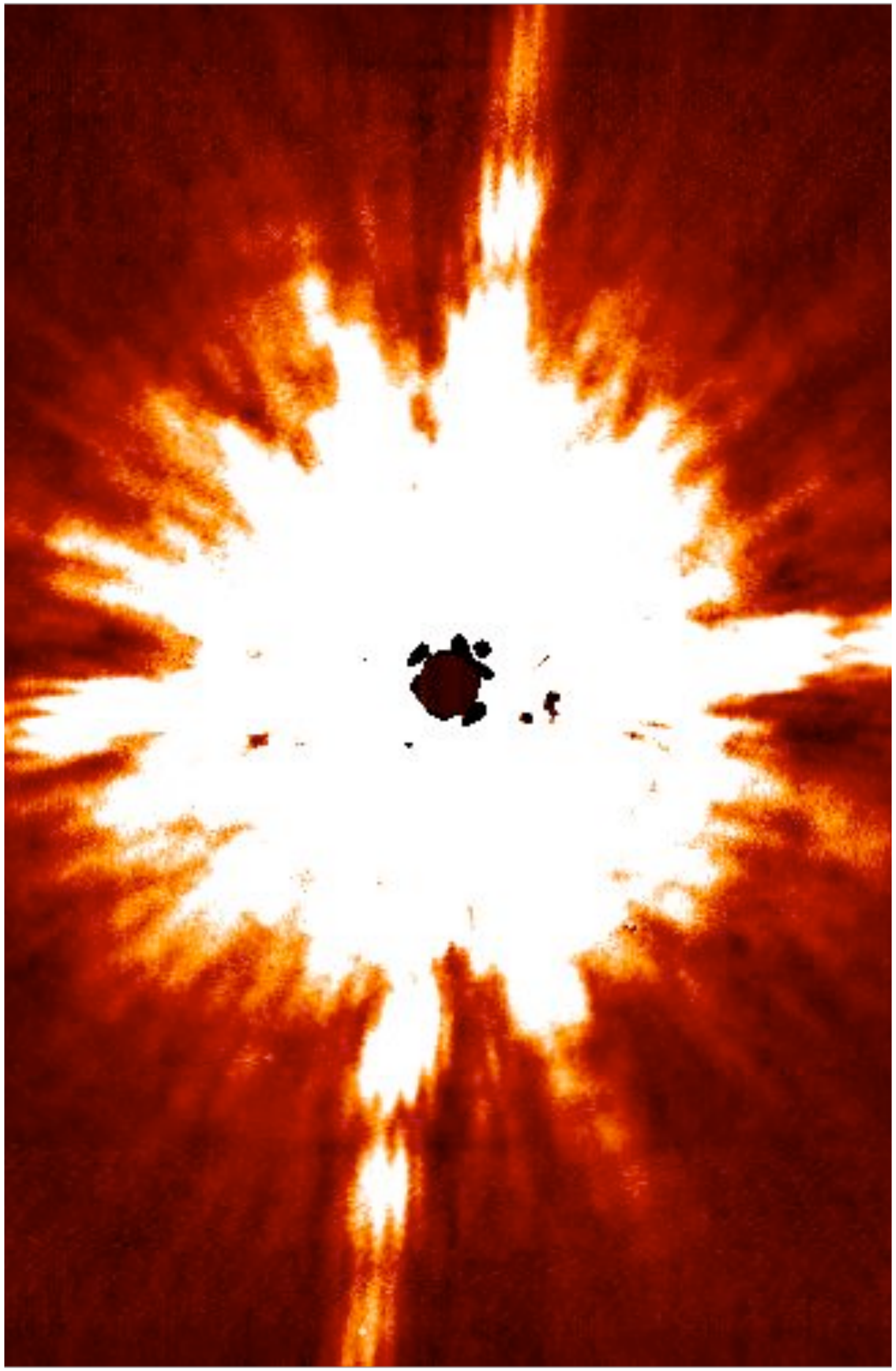


Coronagraph types



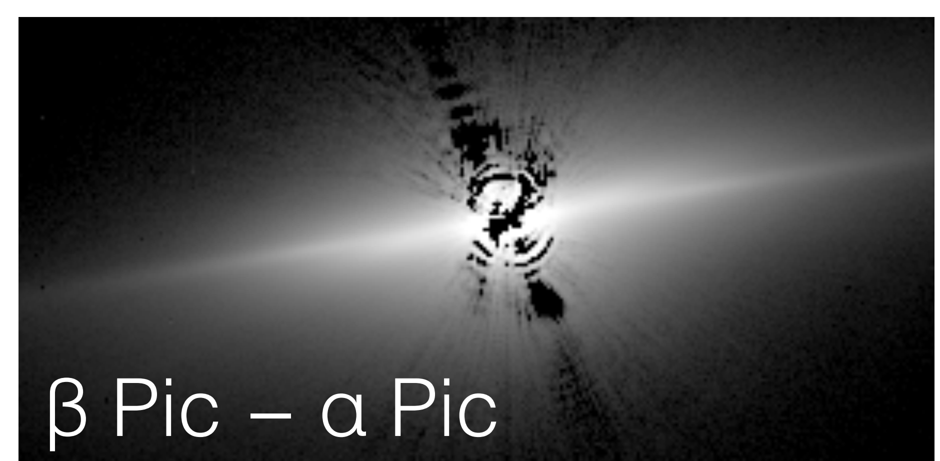
Getting rid of speckles

2. Observing strategies



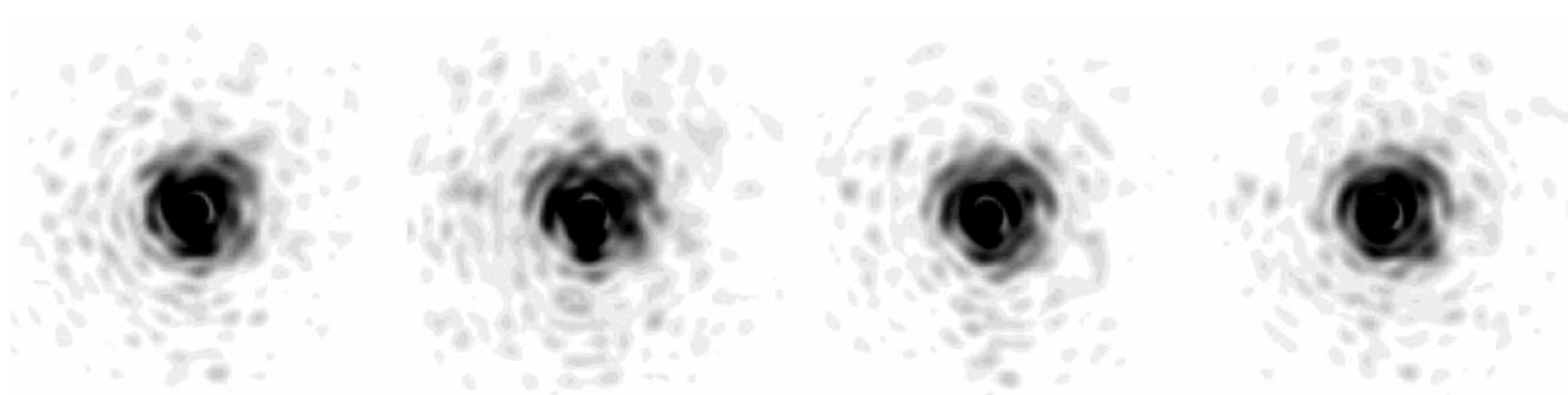
Solution: PSF subtraction

- Simplest concept: observe a reference star
    - —> ‘Reference-star Differential Imaging’ (RDI)
    - Reference must be similar to science target
- Procedure
    - Scale the reference PSF (flux)
    - Subtract it from science observation



Limitations of RDI

- No perfect reference star
  - Should be of same magnitude, color and position as science target
- Time spent on reference star is « lost » (no planetary photon)
- Atmospheric conditions change with time
- Telescope/instrument aberrations also change with time



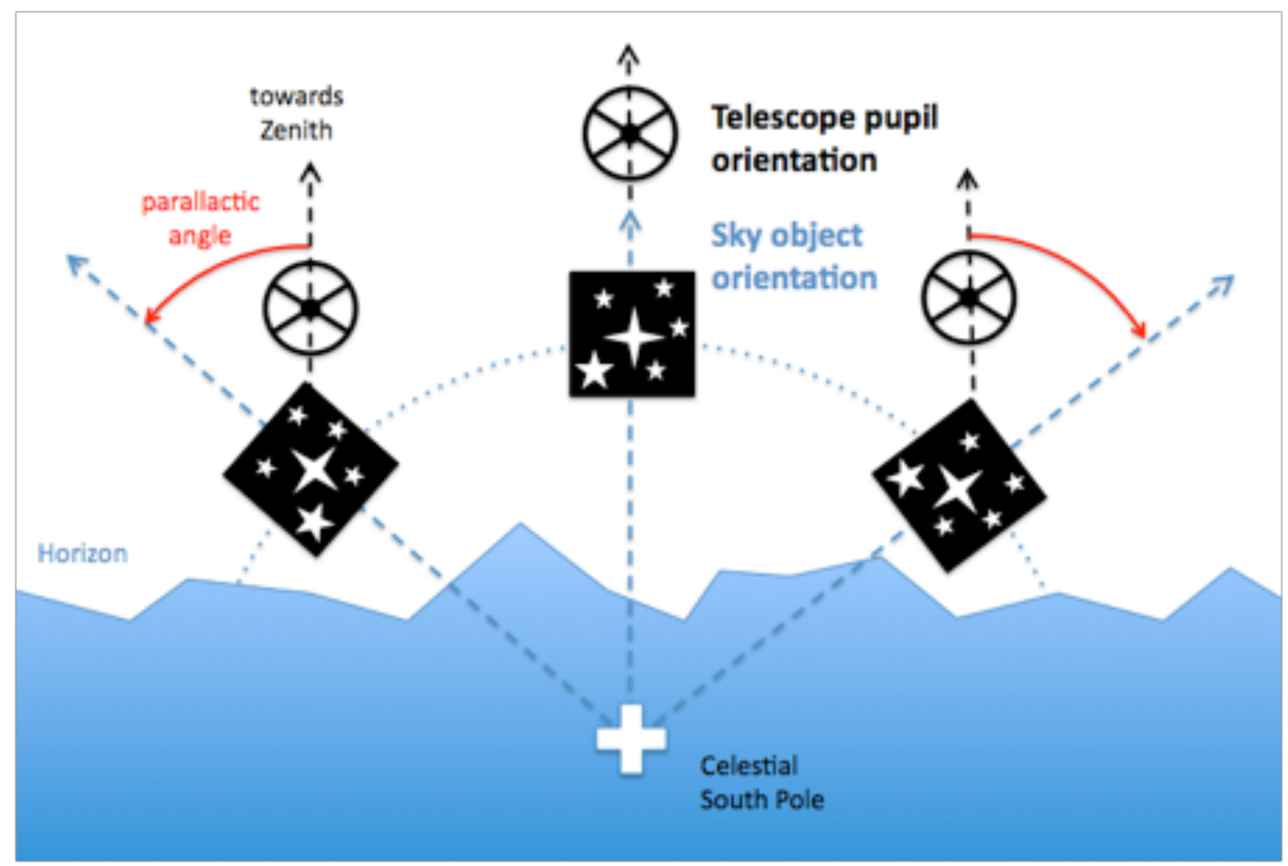
Three differential solutions

- Goal: keep observing the same target (no reference star)

- Method: tune an observing parameter to discriminate between stellar PSF and planet
  - Angular differential imaging (ADI)
  - Spectral differential imaging (SDI)
  - Polarimetric differential imaging (PDI)
  - [note: some additional techniques not explained here]

Angular differential imaging

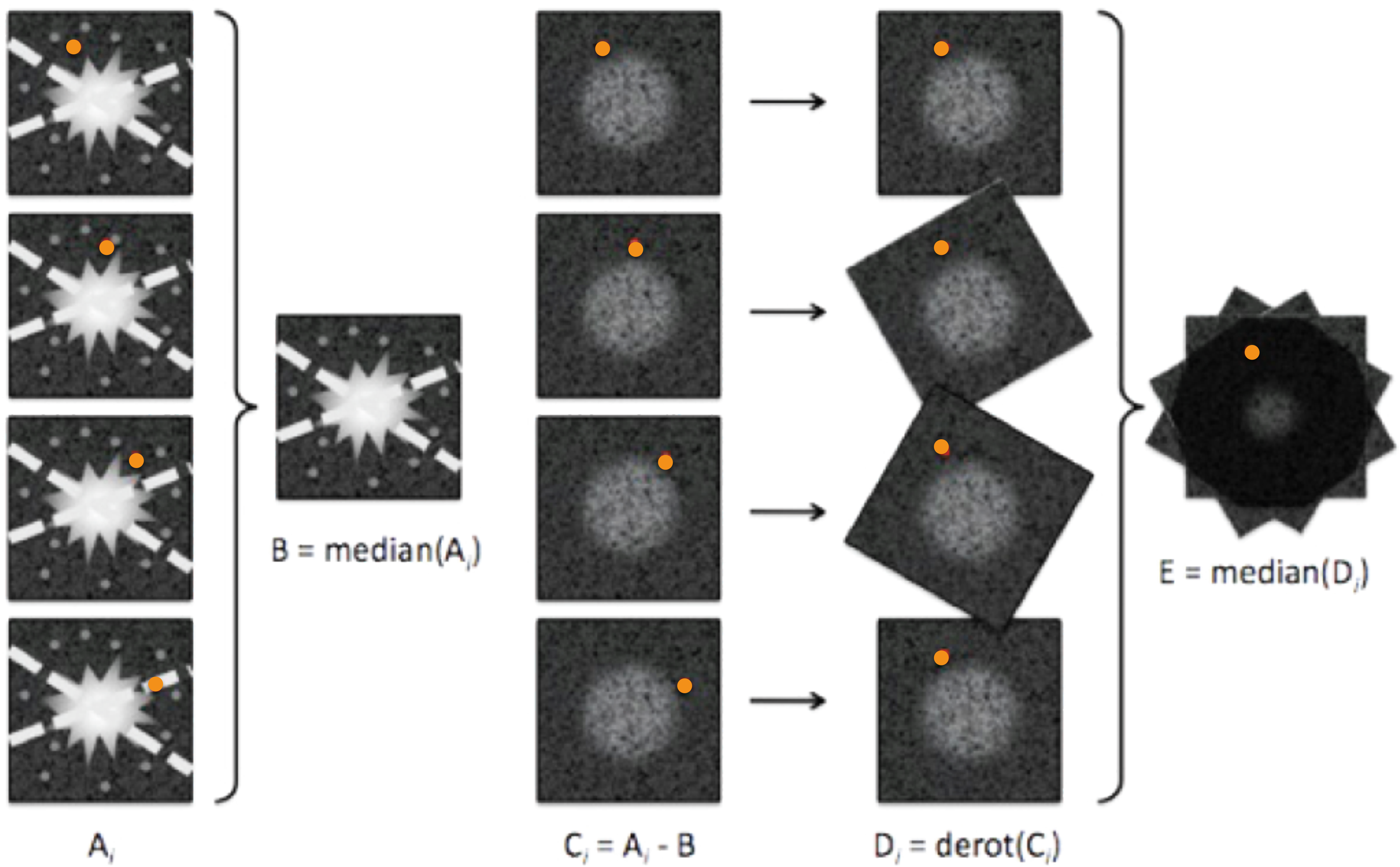
- Use field rotation while keeping telescope fixed
  - alt-az telescope, disabling field tracking mode
- Planet moves around on-axis star as a function of time (following the so-called parallactic* angle)
- Diffraction pattern & quasi-static speckles stay at fixed position



*parallactic angle = the angle between the great circle through a celestial object and the zenith, and the hour circle of the object

Marois et al. 2006

Classical ADI algorithm



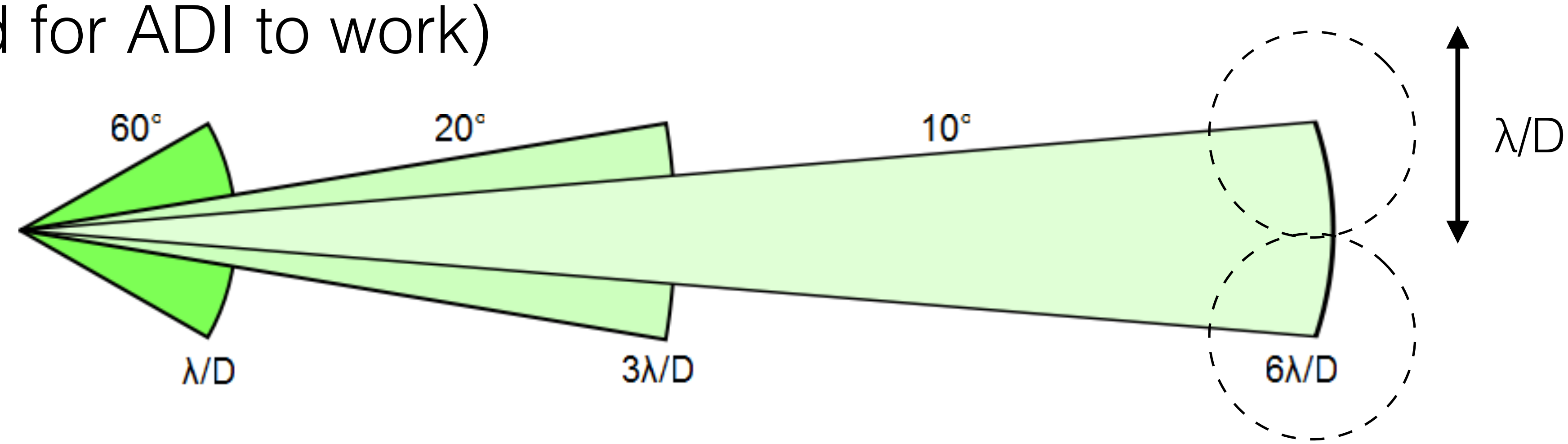
Pros and cons of ADI

+ Works with any type of planet (no specific feature)

+ Does not require specific hardware

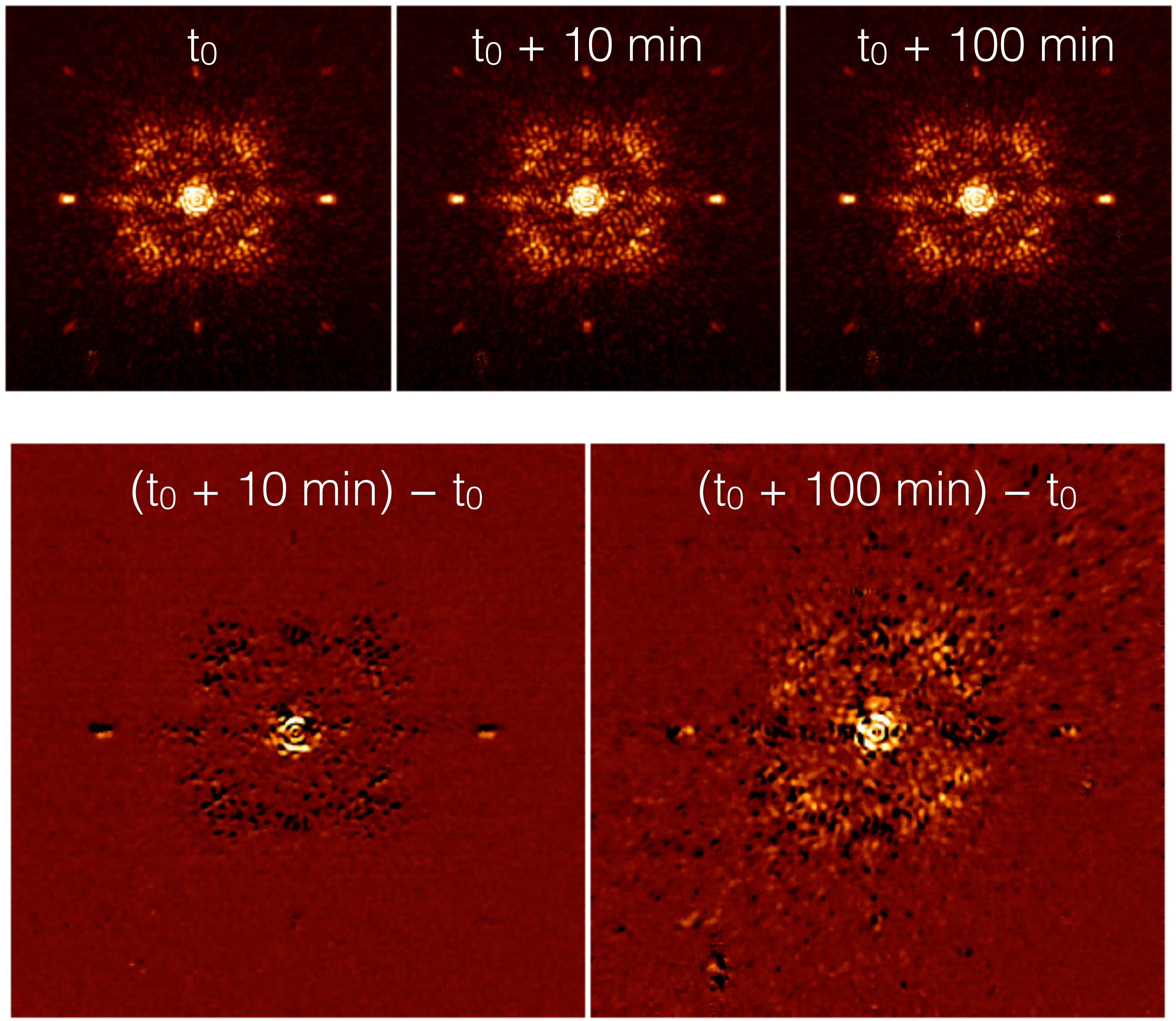
- Does not work well for stars far from zenith (small variation of the parallactic angle)

- Limited inner working angle (planet must move by more than 1 λ/D in the field for ADI to work)



- Speckle pattern evolves with time

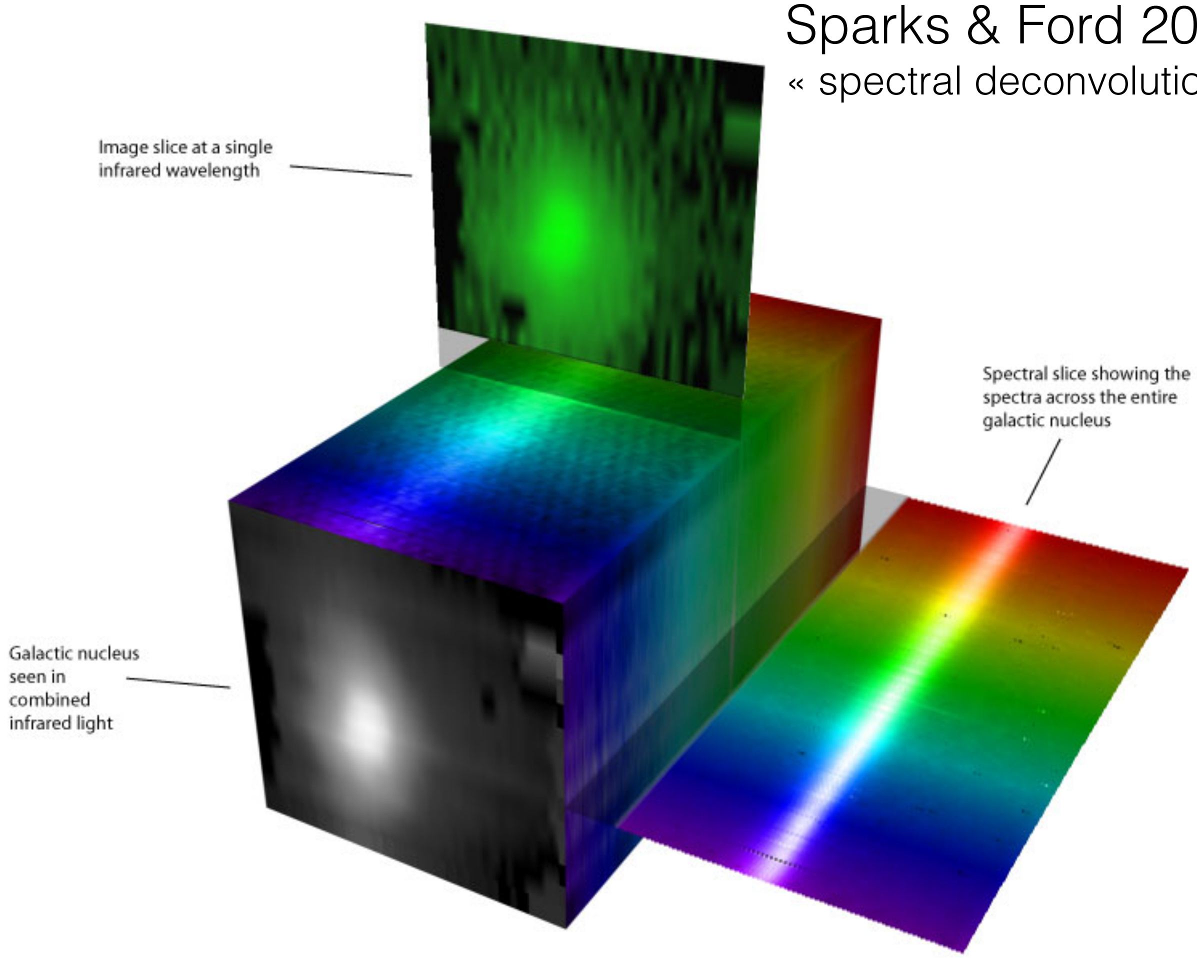
Speckle decorrelation

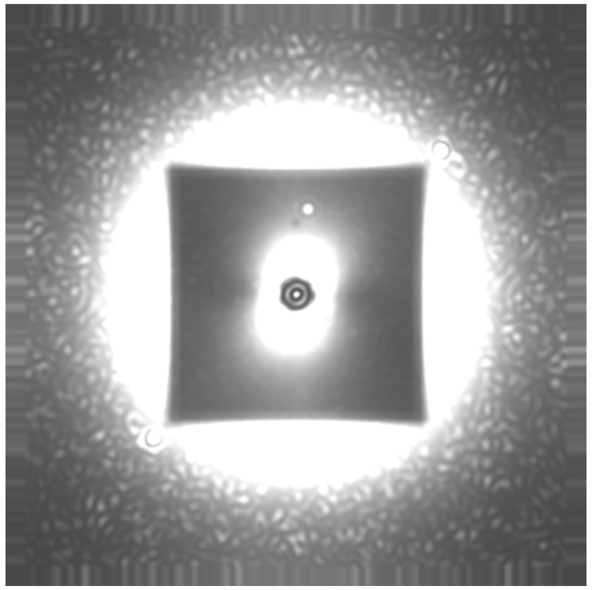


Spectral differential imaging

- Based on Integral Field Spectrograph (IFS) observations
  - provides field image as function of wavelength (« image cube »)
- Diffraction and speckle pattern scale as function of wavelength
  - speckle pattern moves away from star with increasing wavelength
- Exoplanet position is fixed
  - can be distinguished from speckles

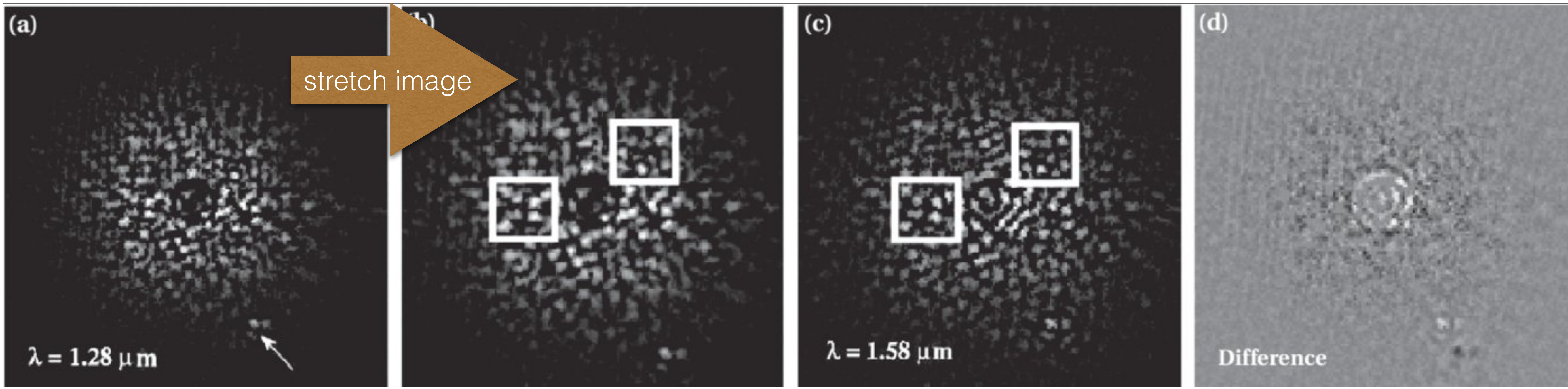
Sparks & Ford 2002
« spectral deconvolution »

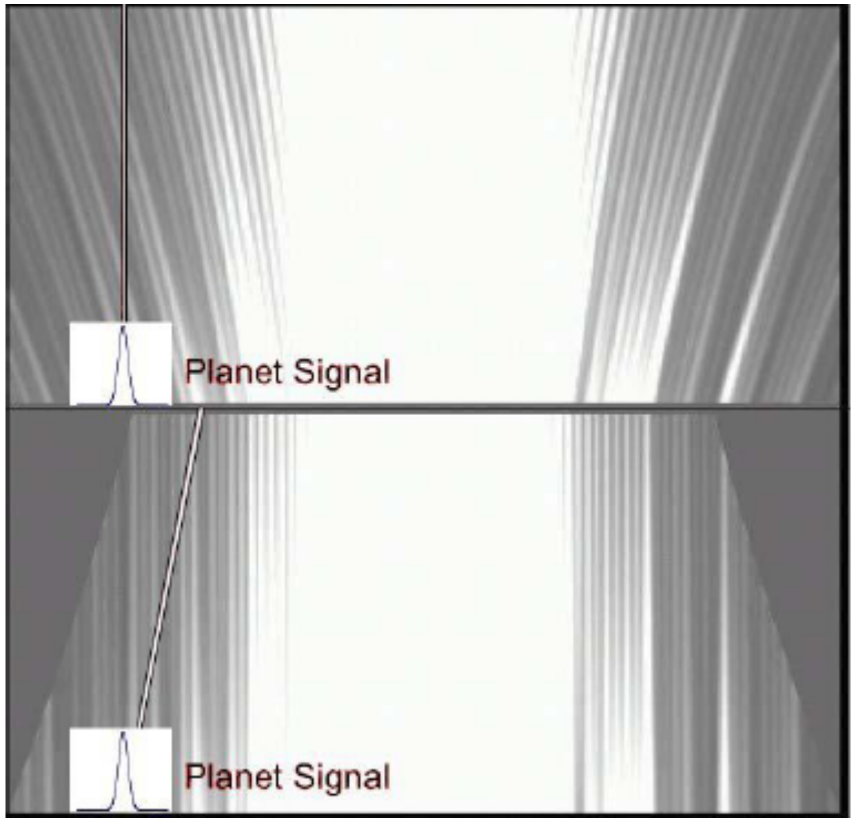




SDI in practice

Wide wavelength range → see speckles stretching vs λ





Observed (x,λ) slice

Rescaled (x,λ) slice

Pros and cons of SDI

\+ Works with any type of planet
(no specific feature needed in planet spectrum)

\+ No differential aberrations / simultaneous observations

\+ End product = spectrum of the planet!

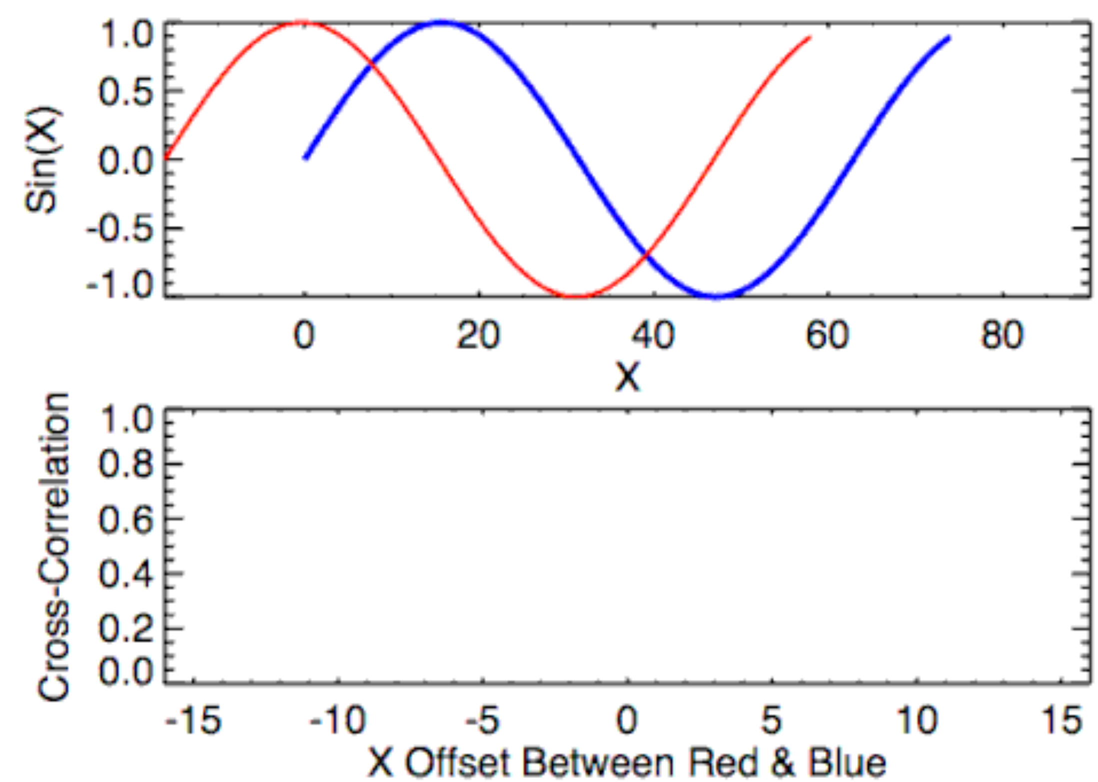
- Detect and characterize planet at the same time

– Speckle pattern not perfectly constant over wavelength

– Limited inner and outer working angles
(depend on wavelength range and spectral resolution)

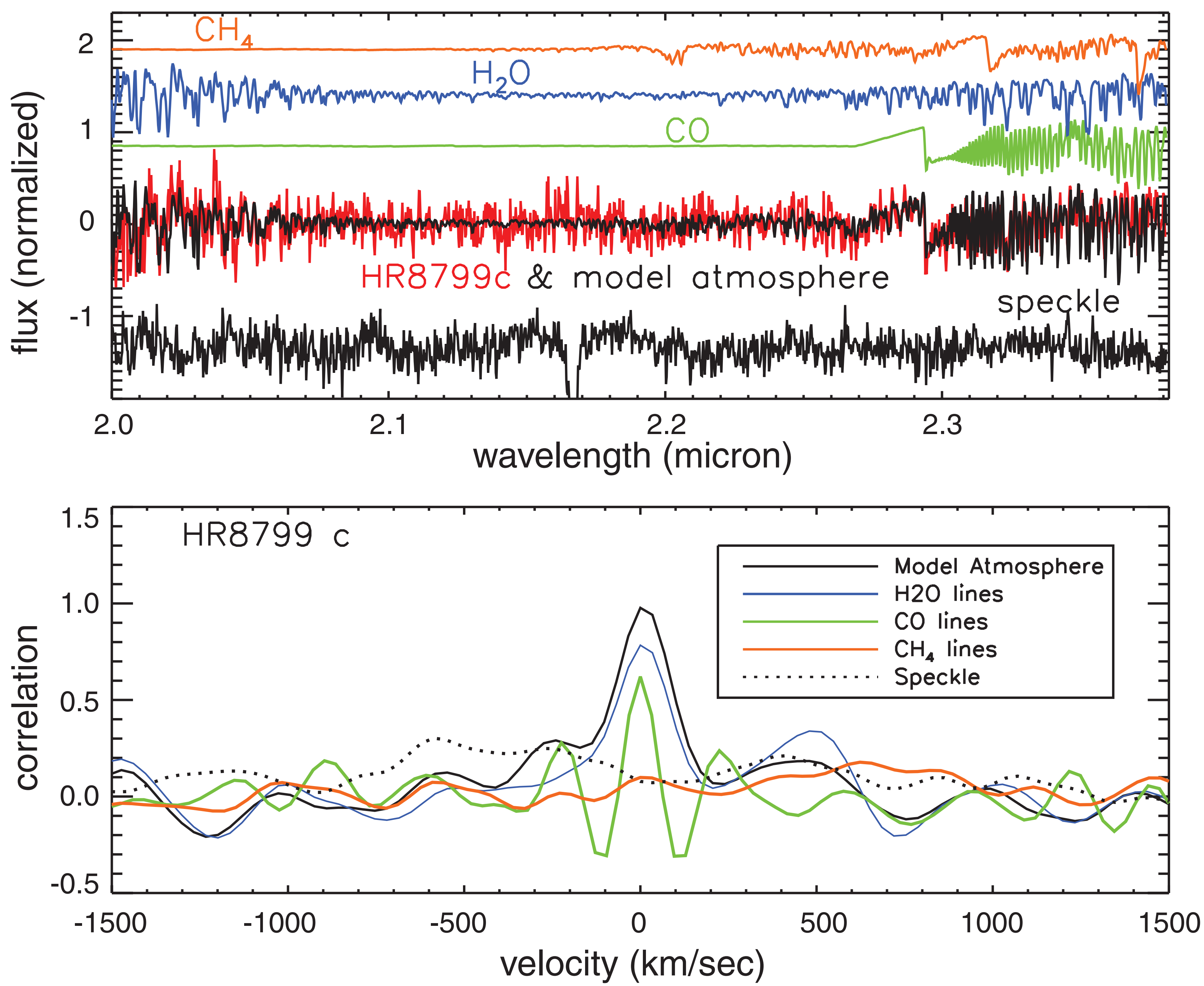
Cross-correlation: an alternative

- Developed first for non-imaging spectroscopy
- Principle: look for specific, planet-related features in spectral domain
  - use correlation between template and data to identify the presence of specific absorption lines or bands
- Only partly leverages the spatially-resolved nature of the SDI data set



Sparks & Ford 2002

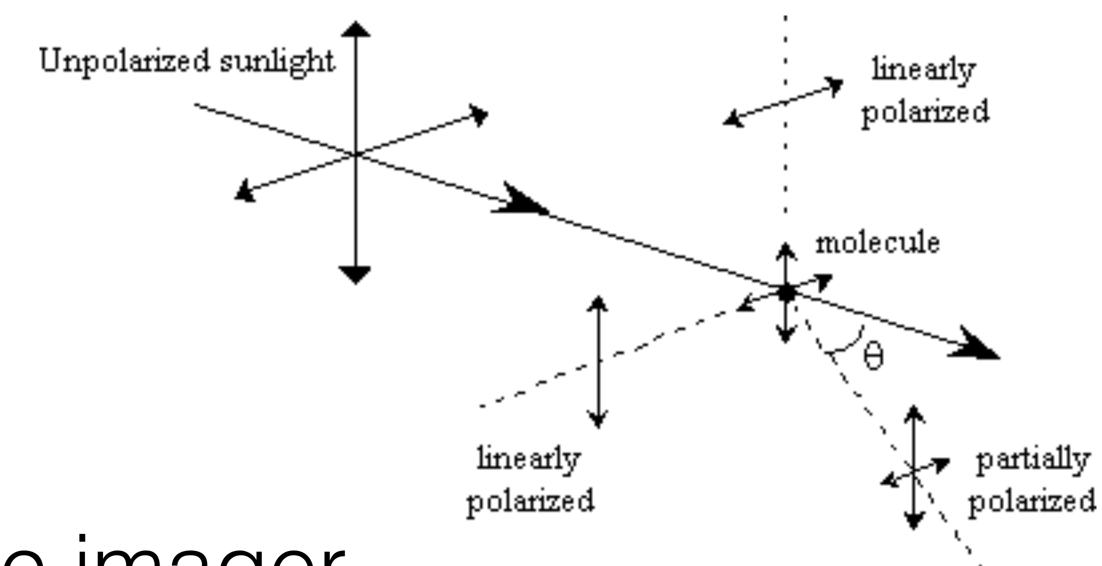
Cross-correlation: illustration

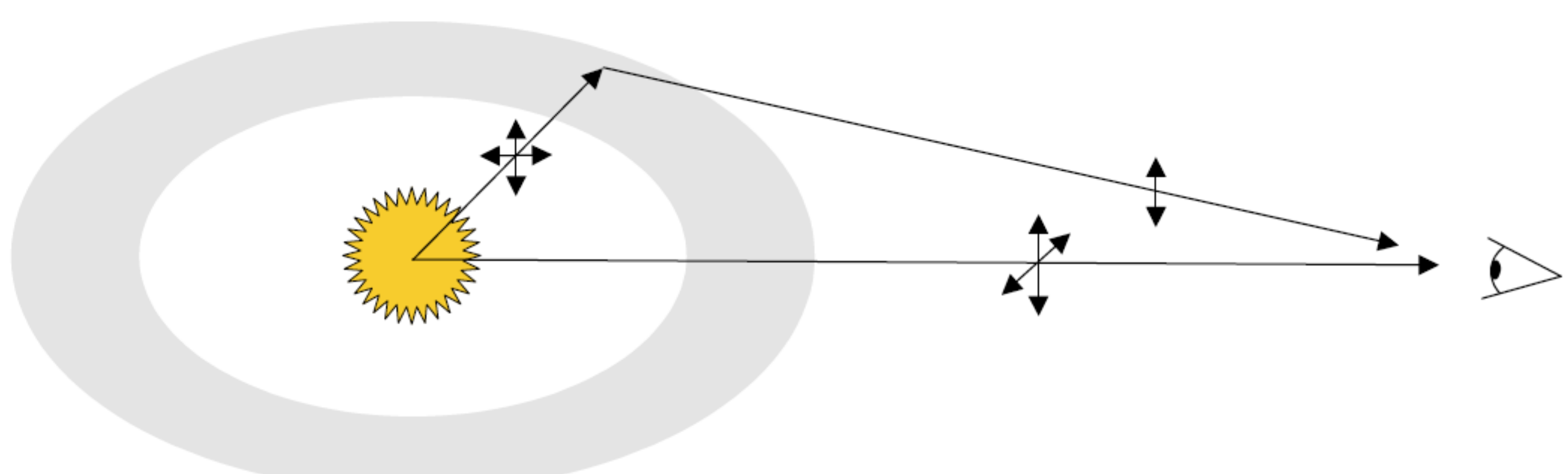


Konopacky et al. 2013

Polarimetric differential imaging

- Reflected light from planet is partially polarized
  - Typically 10% polarization
- Star produces unpolarized light
- Can be exploited by polarimetric imager





Kuhn et al. 2001

Pros and cons of PDI

+ Speckle subtraction can be very good
+ No limitation in inner or outer working angle
- Small fraction of planet light is polarized
  → low sensitivity
- Works only in reflected light (best in visible range)
- Requires specific, non-standard hardware