Direct Imaging of Exoplanets: Achieving the High Contrast Needed

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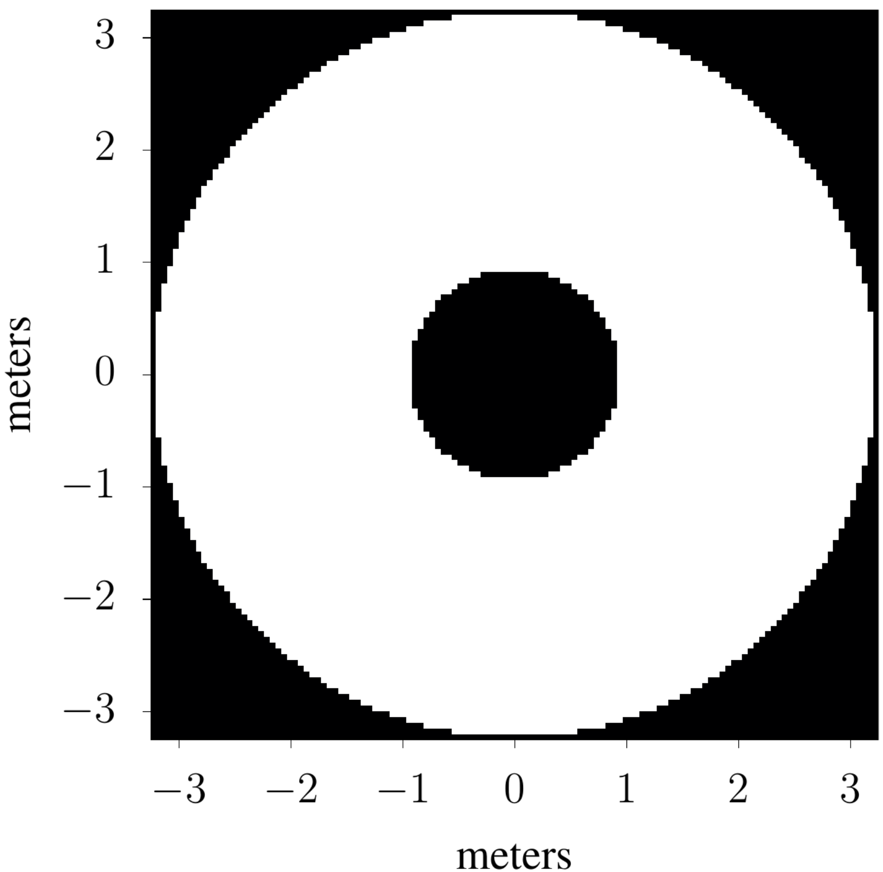
2018 Sagan Exoplanet Summer Workshop

Achieving the High Contrast Needed

What sets the limit of an attempt to image an exoplanet?

Imaging Basics



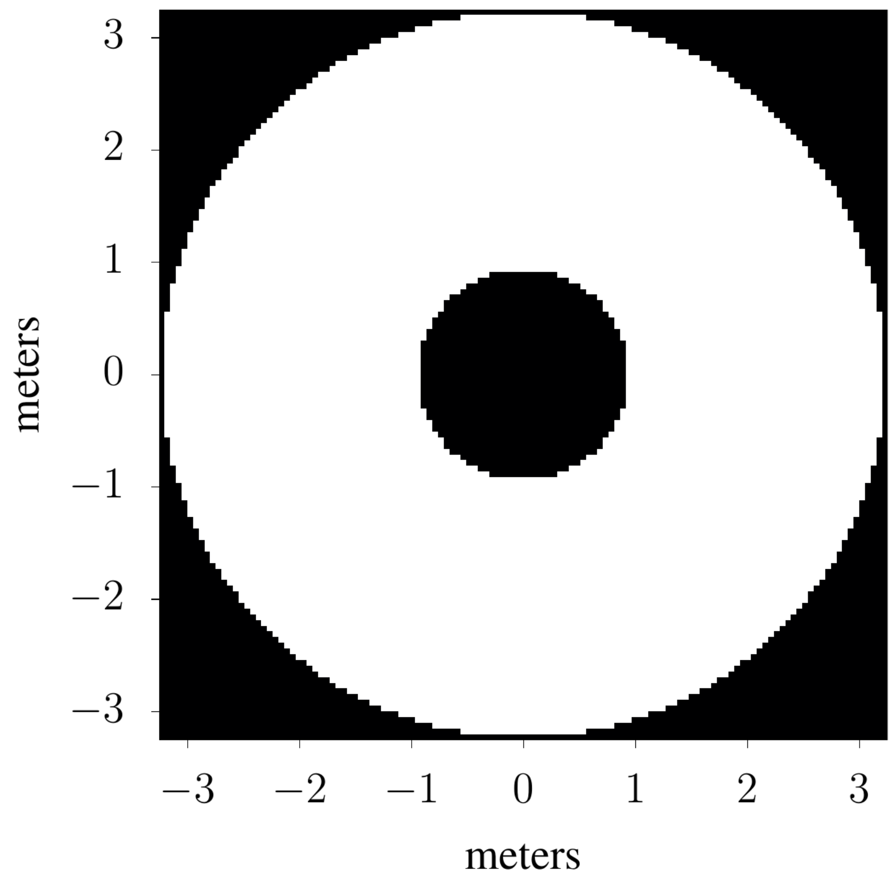
Pretend that this is the primary mirror of a 6.5 m telescope

- Same size as JWST and Magellan

Assume that it is perfectly smooth

Assume that there are no aberrations

Imaging Basics



Pretend that this is the primary mirror of a 6.5 m telescope
- Same size as JWST and Magellan

Assume that it is perfectly smooth

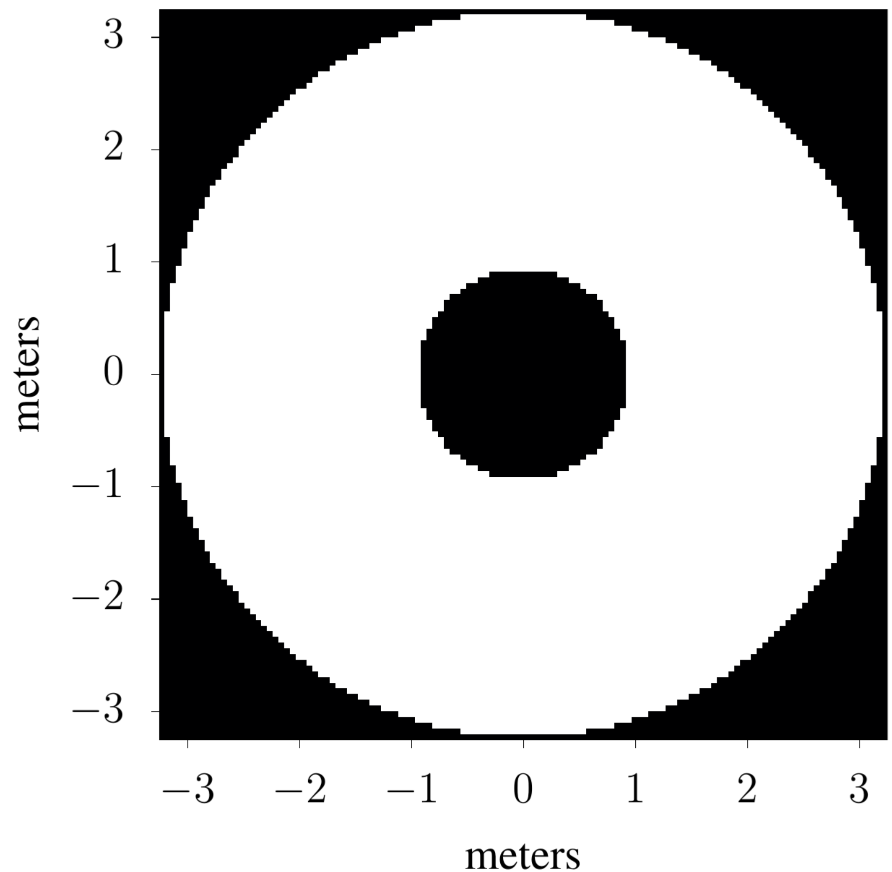
Assume that there are no aberrations

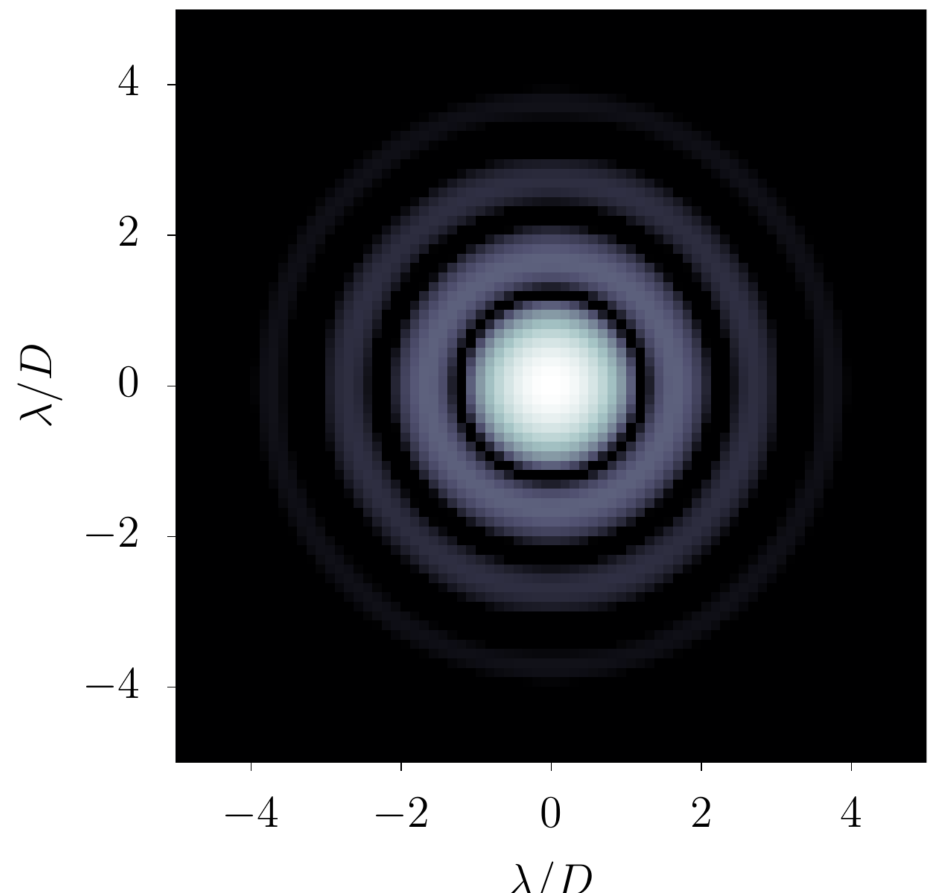
Then the image formed by this telescope is:

$$\mathrm{PSF}(\vec{\alpha}) = \left|\mathcal{F}[\mathcal{A}(\vec{u})]\right|^2$$

In words: the modulus squared of the Fourier transform of the aperture function

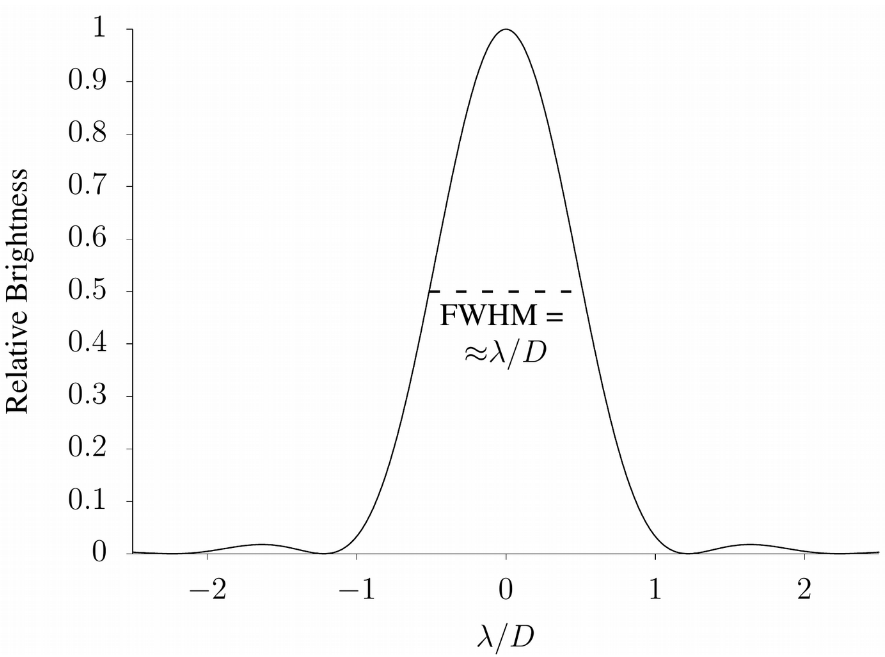
Imaging Basics

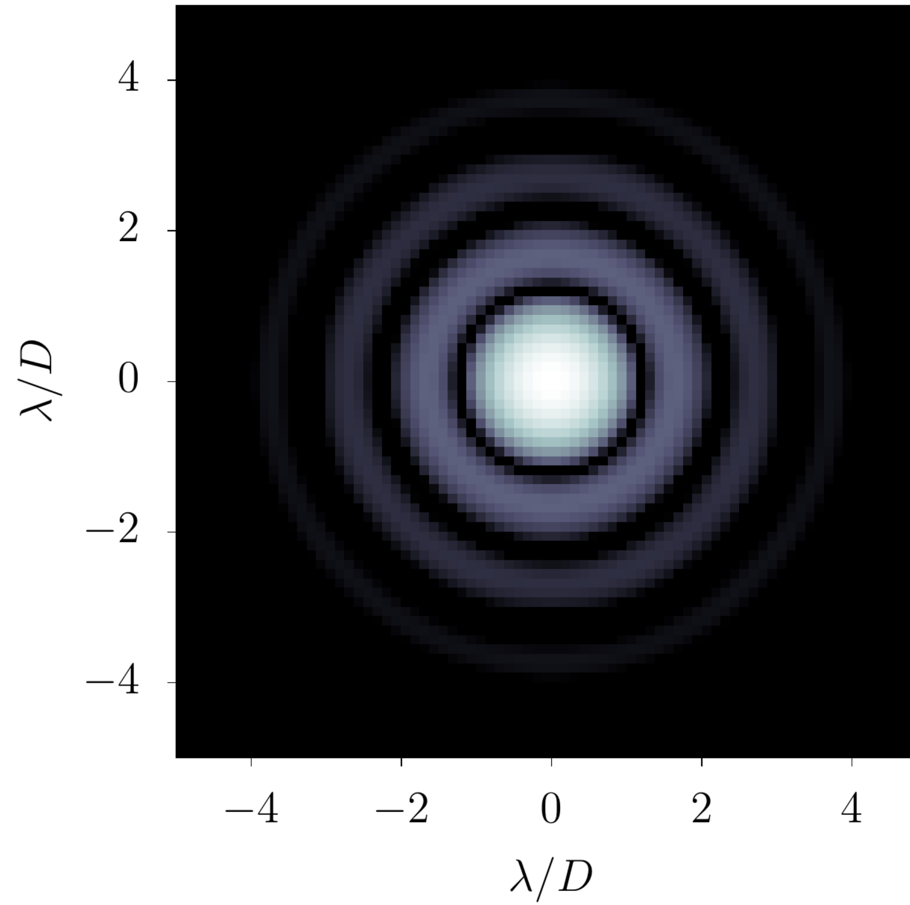




This is the Airy Pattern

Imaging Basics





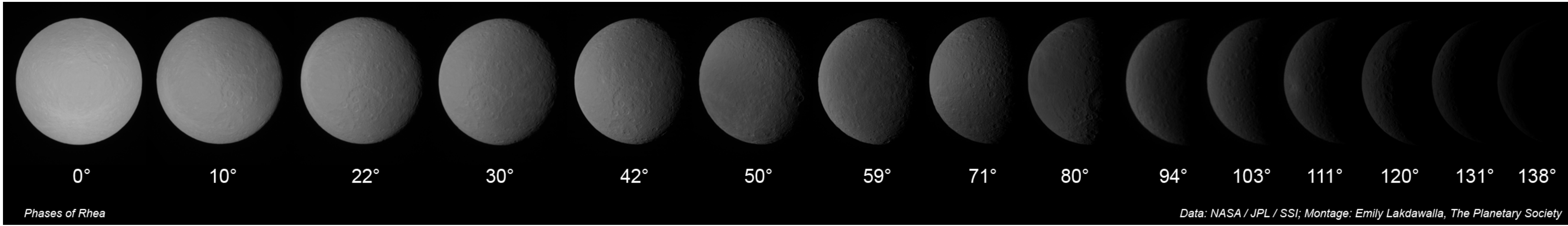
The diffraction limit (Sparrow Criterion)

Reflected Light Contrast

$$\frac{F_p}{F_*} = 1.818 \times 10^{-9} \left(\frac{R_p}{1R_\oplus} \times \frac{1\ \mathrm{AU}}{a} \right)^2 A_g \Phi(\alpha)$$

- R_p = planet radius
- a = planet separation
- A_g = geometric albedo (function of wavelength)
- α = phase angle
- Φ = phase function

Montage of Rhea, by Emily Lakdawalla/Planetary Society



Reflected Light Contrast

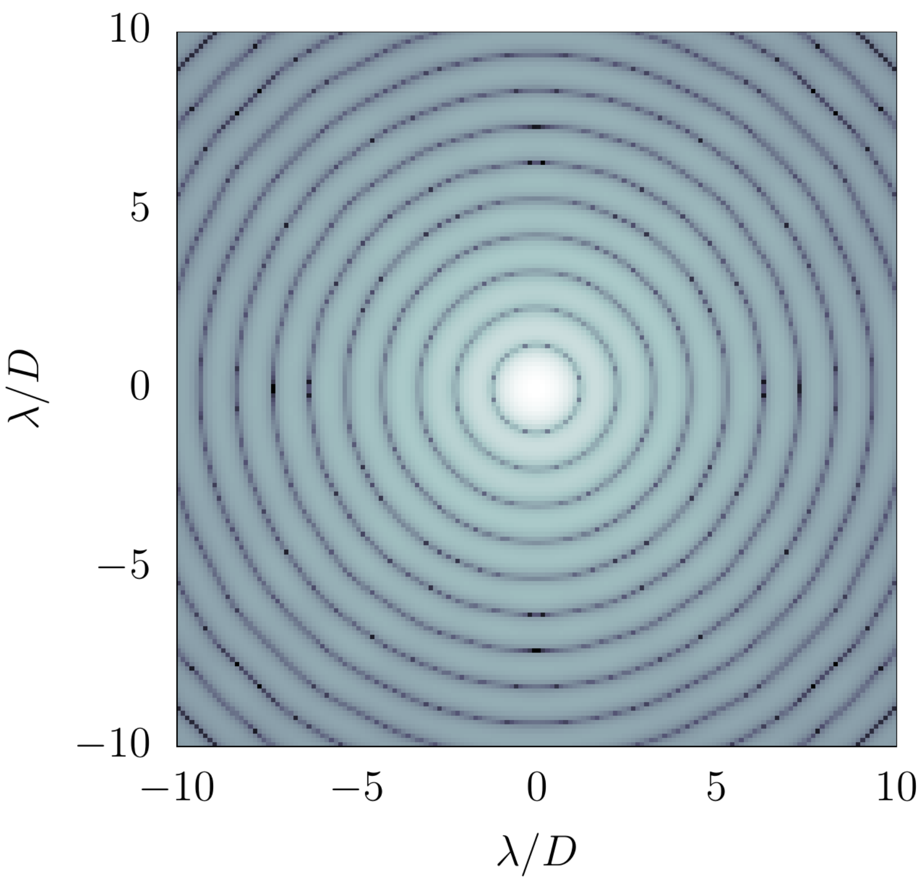
$$\frac{F_p}{F_*} = 1.818 \times 10^{-9} \left(\frac{R_p}{1 R_\oplus} \times \frac{1\ \mathrm{AU}}{a} \right)^2 A_g \Phi(\alpha)$$

- R_p = 1 Earth radius
- A = 1 AU
- A_g = 0.25 (V band)
- α = 90 degrees
- Φ = 0.32

Earthrise, Apollo 8

Earth contrast is 1.5×10^{-10}

Imaging An Earth-Hosting Star



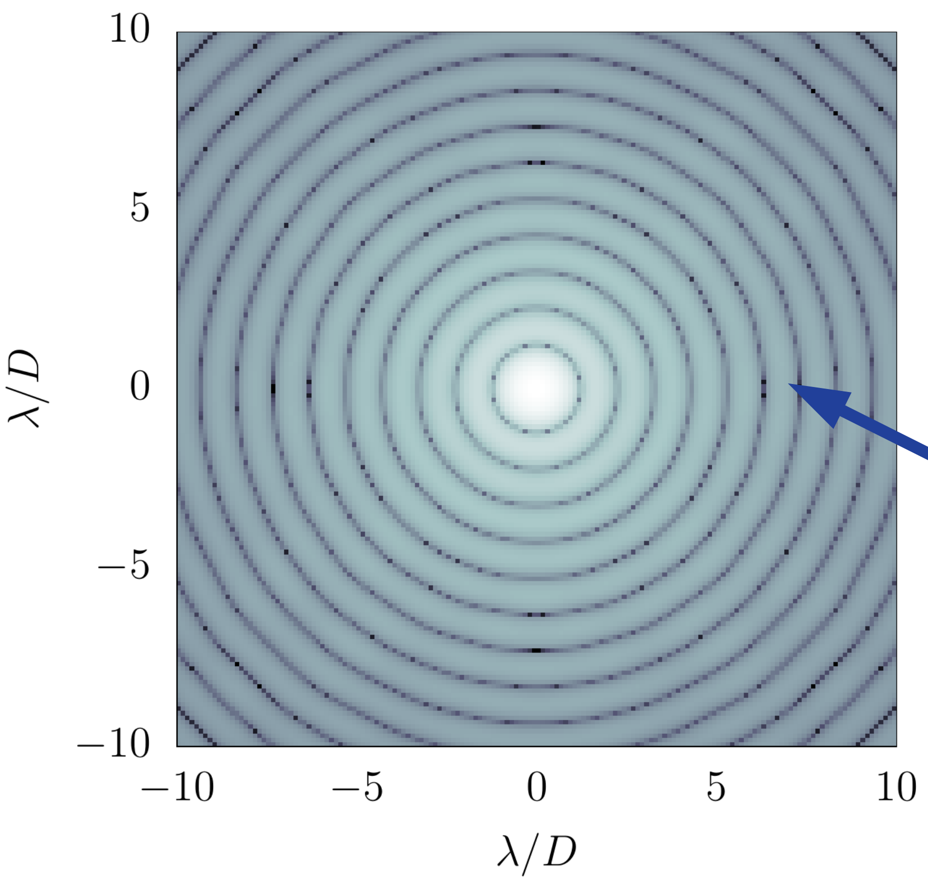
At 10 pc:

G2V star ~ 5th mag

1 AU = 0.1 arcseconds

=> 6.3 λ/D on a 6.5 m telescope

Imaging An Earth-Hosting Star



At 10 pc:

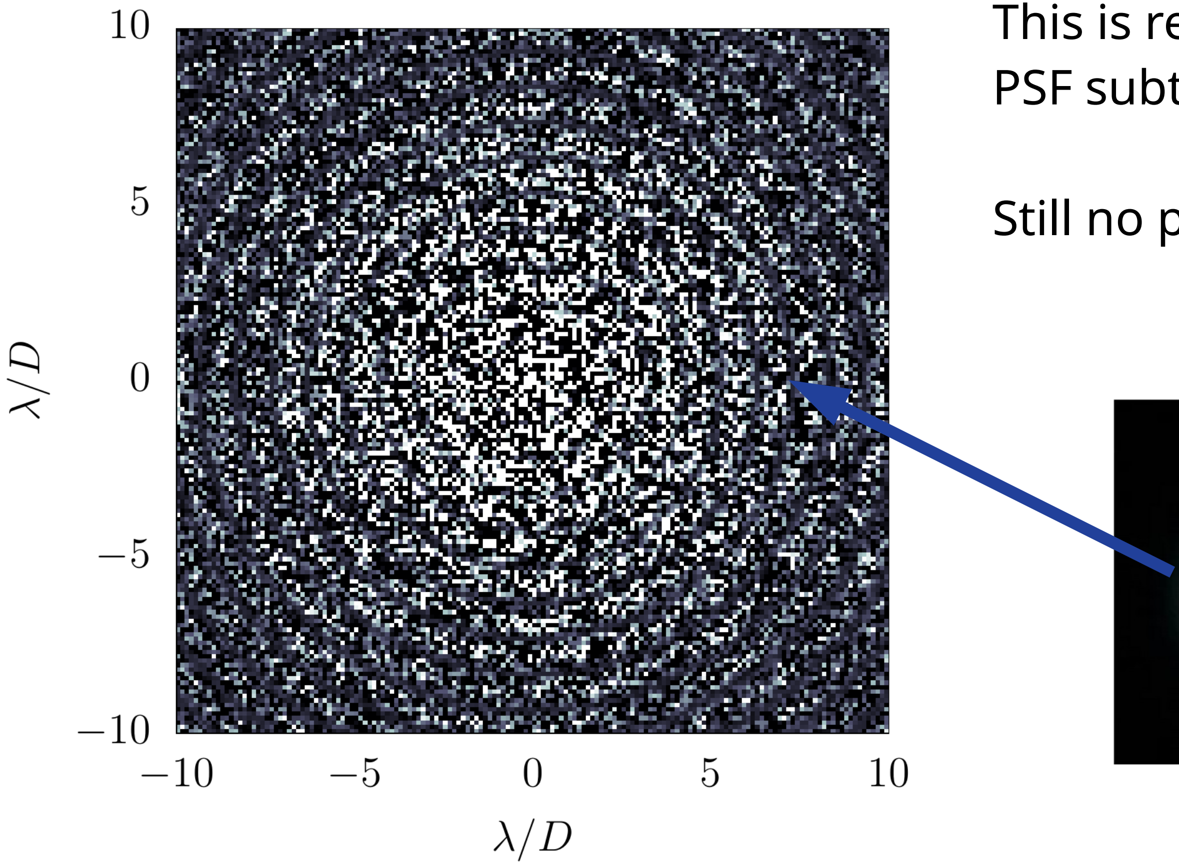
G2V star ~ 5th mag

1 AU = 0.1 arcseconds

=> 6.3 λ/D on a 6.5 m telescope

Image at left contains such an Earth, and shows a 1 hr exposure with photon noise.

Imaging An Earth-Hosting Star

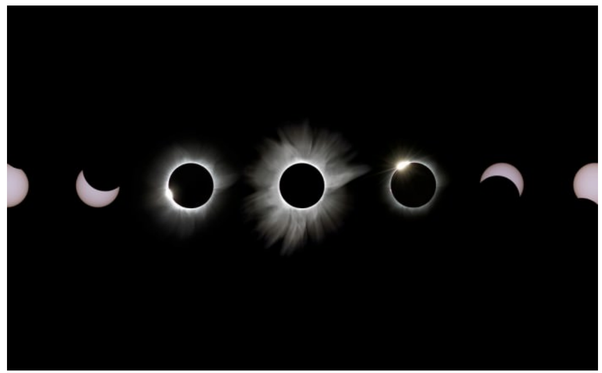


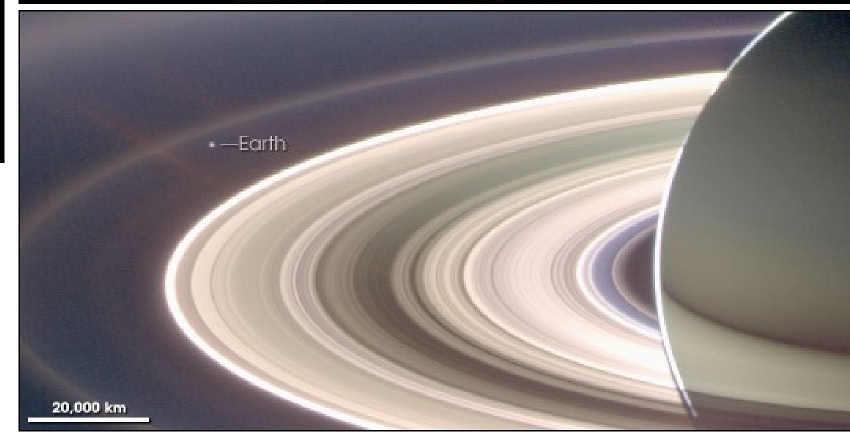
This is residual photon noise after perfect PSF subtraction.

Still no planet . . .

The Coronagraph

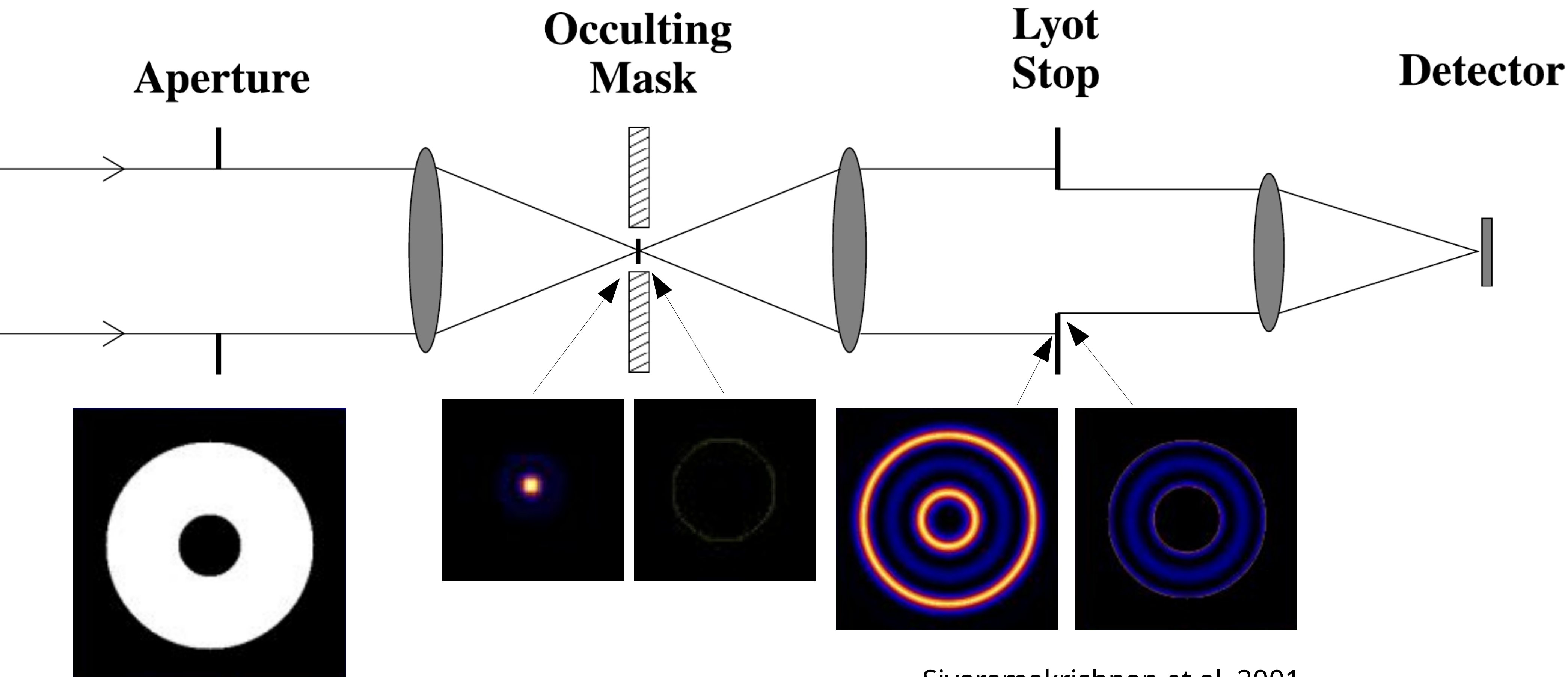
We need a way to block the star's light, without blocking the planet…





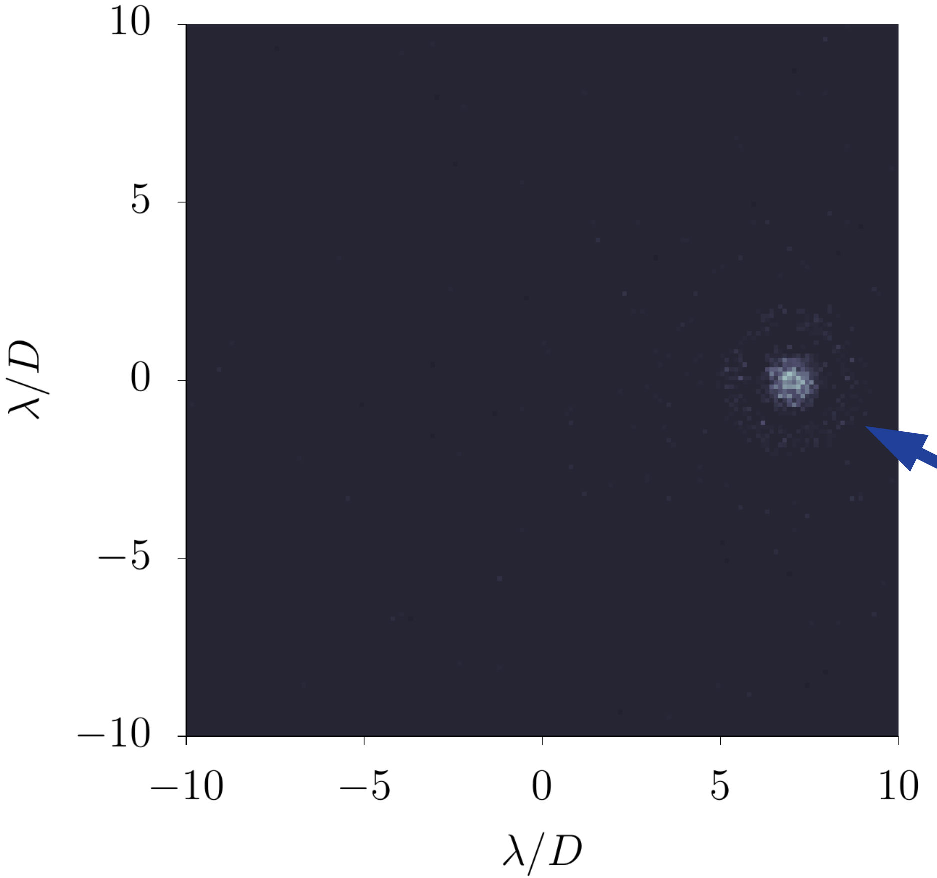
Note: none of these techniques work for our purposes. Not even Olivier Guyon's thumb.

The Basic Lyot Coronagraph

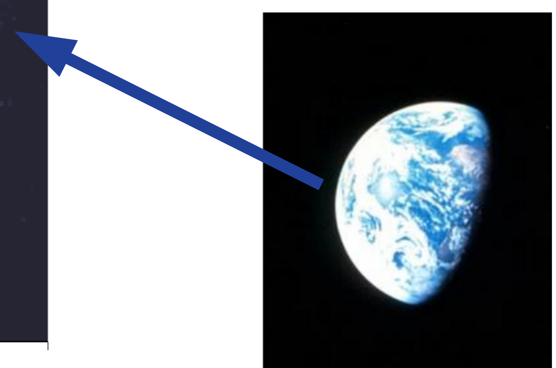


Sivaramakrishnan et al, 2001
http://lyot.org/background/coronagraphy.html

With a Coronagraph

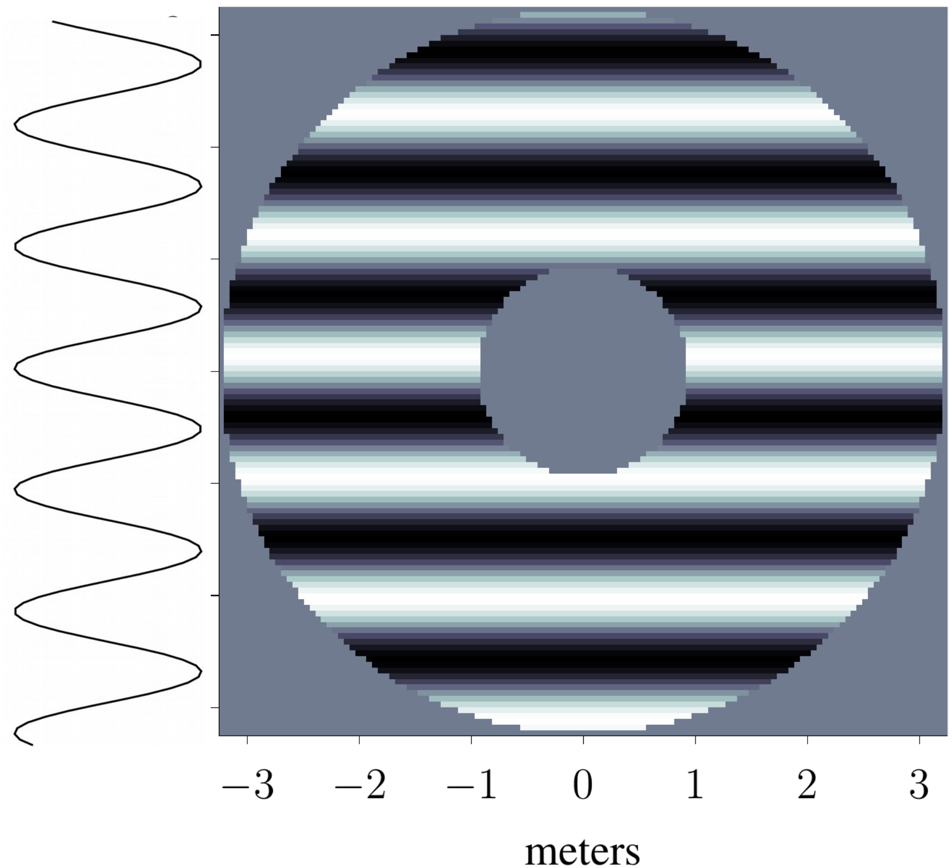


With an ideal coronagraph, on our ideal 6.5 m telescope, we could image an Earth in V band in just 1 hour.



Narrator: there are no ideal coronagraphs, and there are no ideal telescopes.

Real Optics

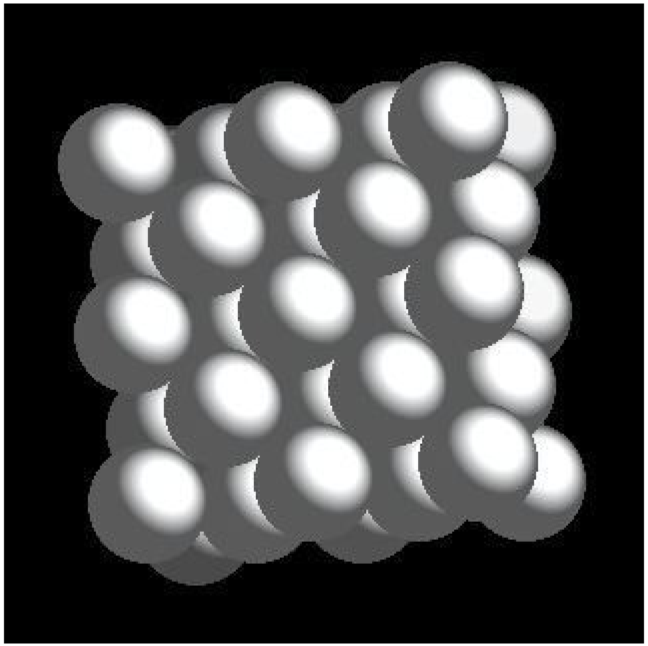


A Fourier aberration:

$$\Phi(\vec{u}) \propto \cos(2\pi f u_y)$$

Let's assume that this cosine wave on the surface of the primary mirror has an amplitude of 1.0 picometers . . .

An Aside About Picometers

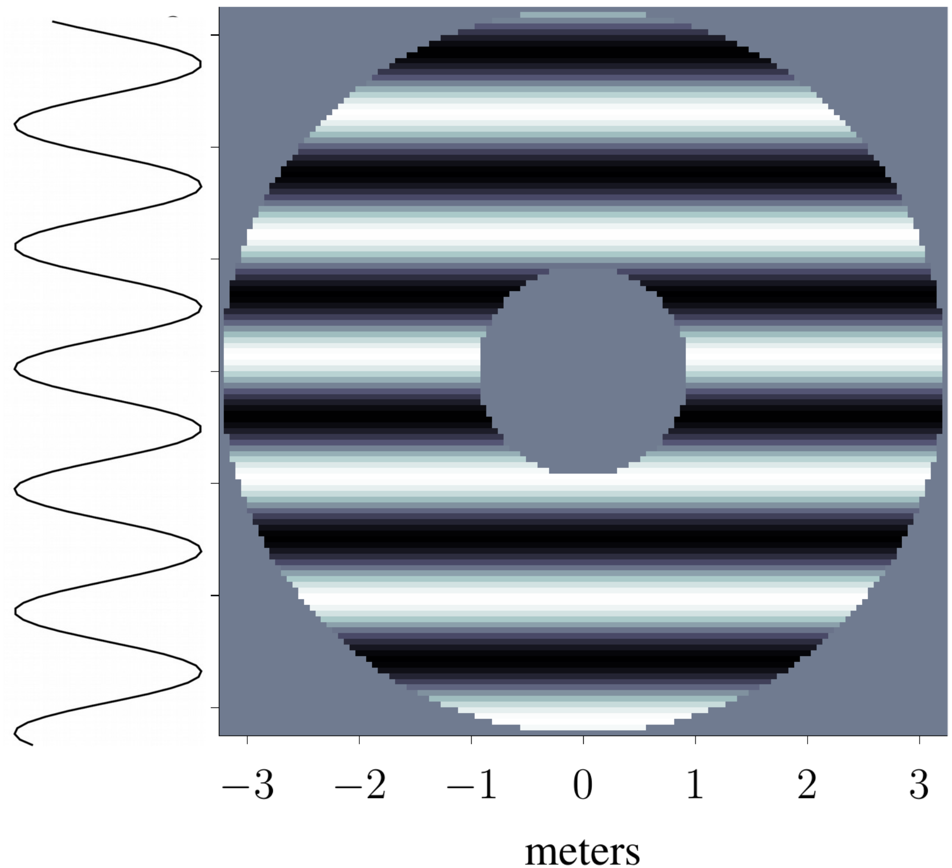


From: https://www.webelements.com/silver/crystal_structure.html

The Silver atoms in the coating of our optics are 320 picometers in diameter!

That’s 0.3 nanometers.

Real Optics



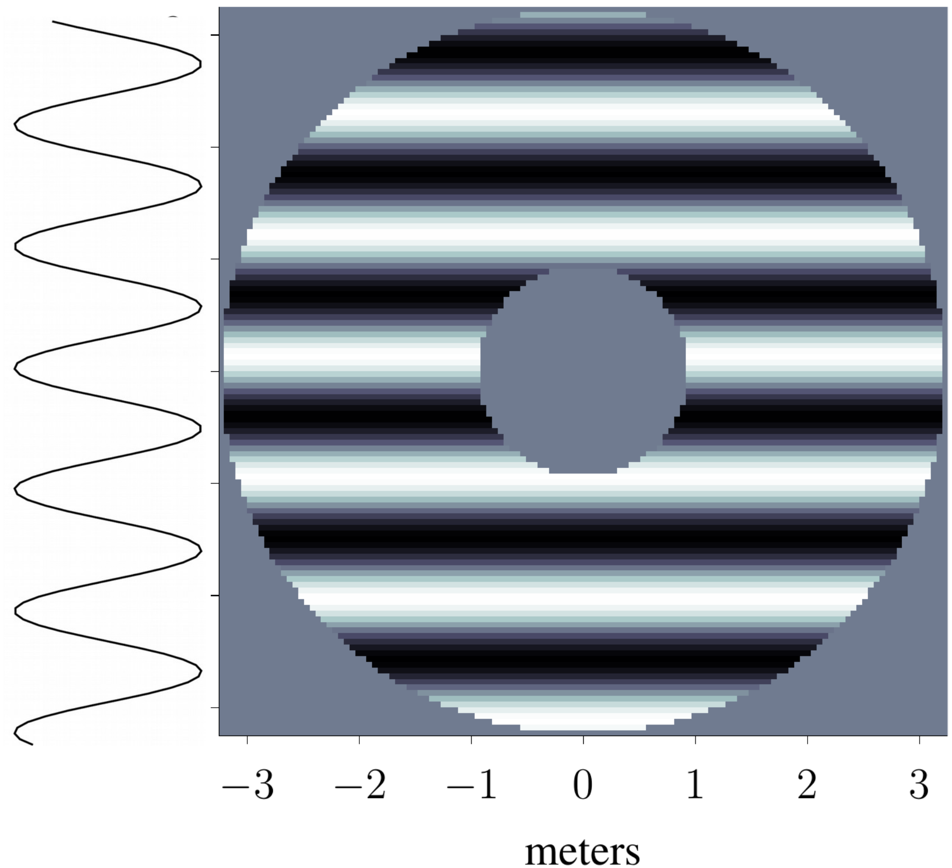
A Fourier aberration:

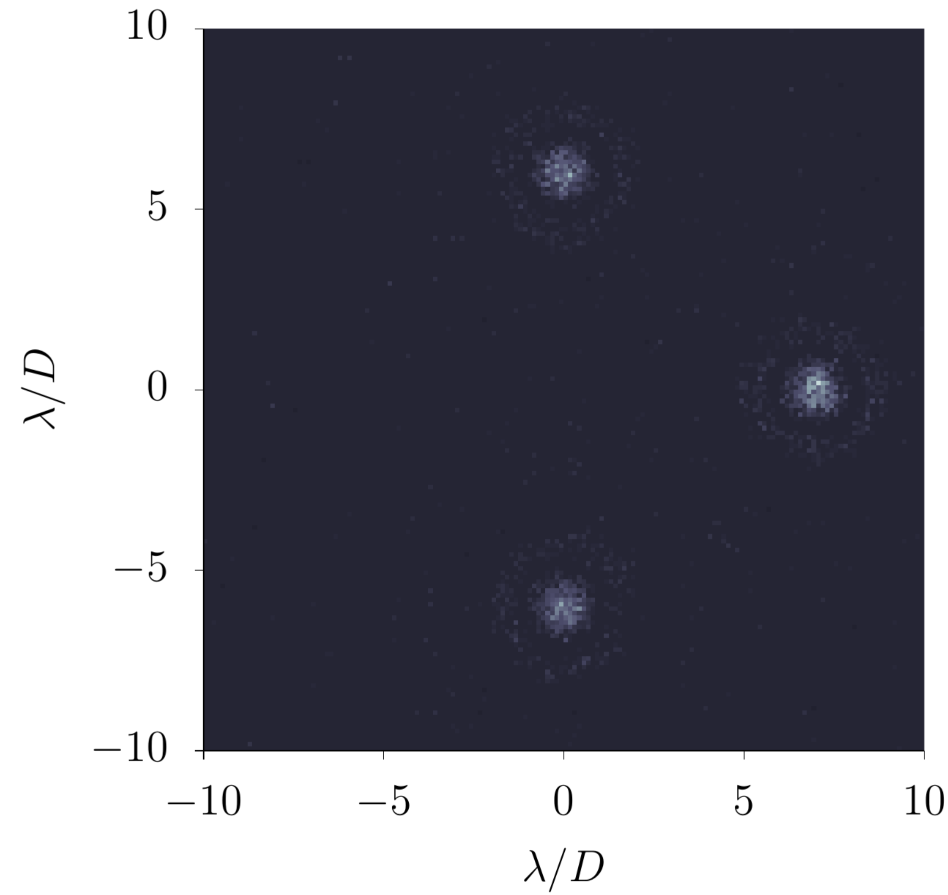
$$\Phi(\vec{u}) \propto \cos(2\pi f u_y)$$

Cosine amplitude = 1.0 picometers
(or 1/320 Silver atoms)

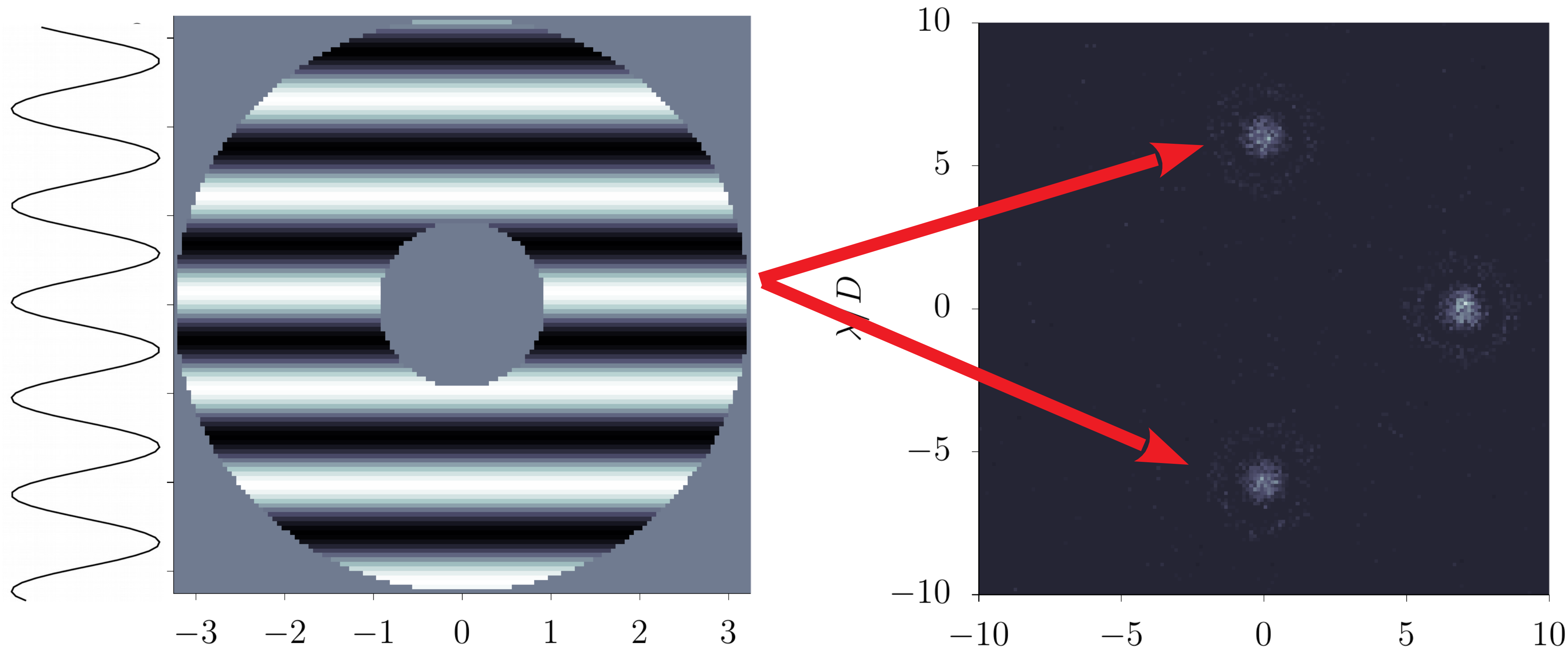
$$\mathrm{I}(\vec{\alpha}) = \left| \mathcal{F}[\mathcal{A}(\vec{u})e^{i\Phi(\vec{u})}] \right|^2$$

Real Optics





Real Optics



$$I(\vec{\alpha}) = \left| \mathcal{F}[\mathcal{A}(\vec{u}) e^{i\Phi(\vec{u})}] \right|^2$$

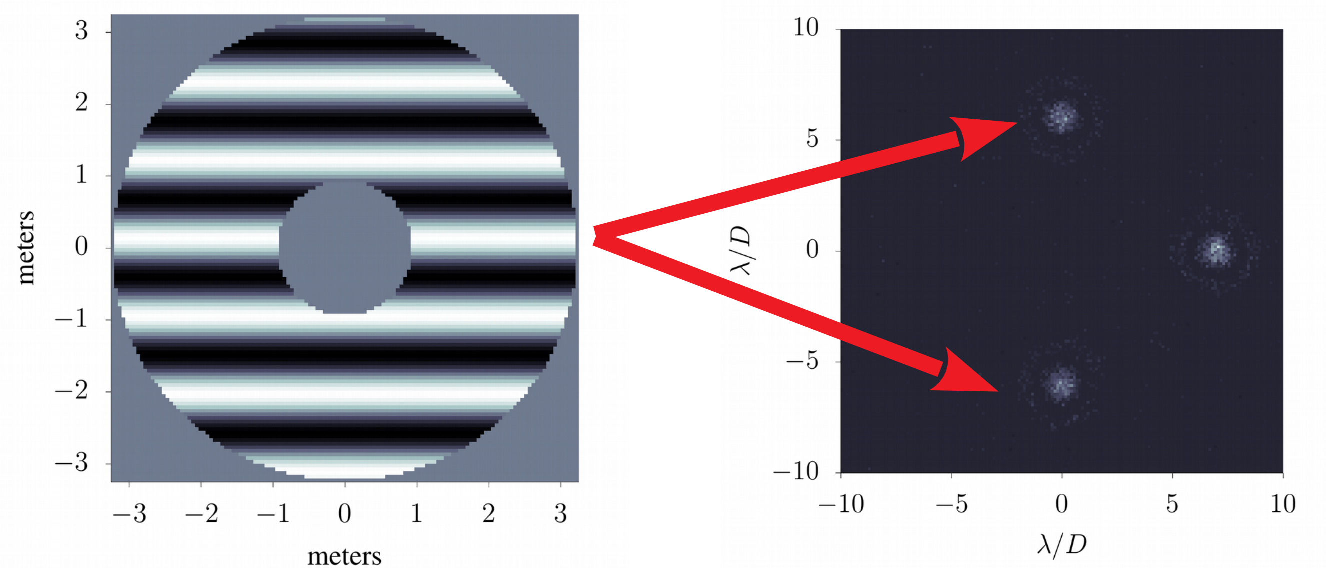
Speckles – The Big Problem

A Fourier aberration in a pupil . . .

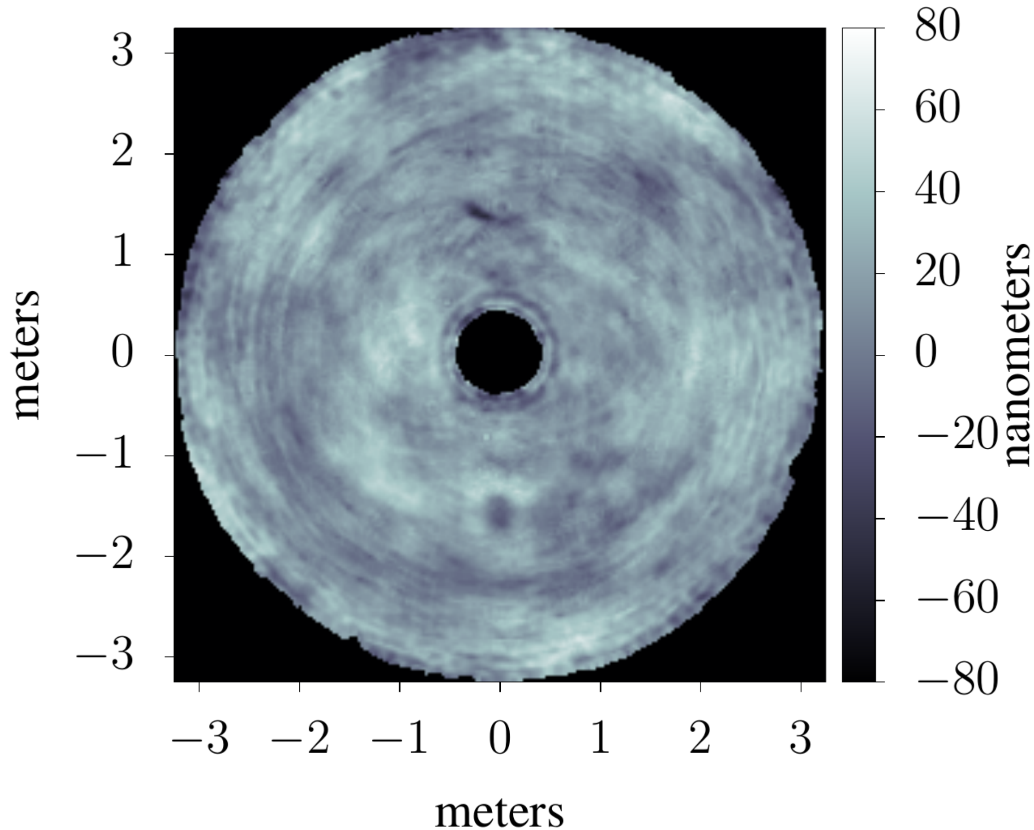
produces a pair of symmetric speckles . . .

a speckle is a copy of the image of the star (the PSF) . . .

AND THEY LOOK JUST LIKE AN IMAGE OF A PLANET!



A Real Mirror



This is the Magellan Clay 6.5 m primary mirror after polishing at U. Arizona.

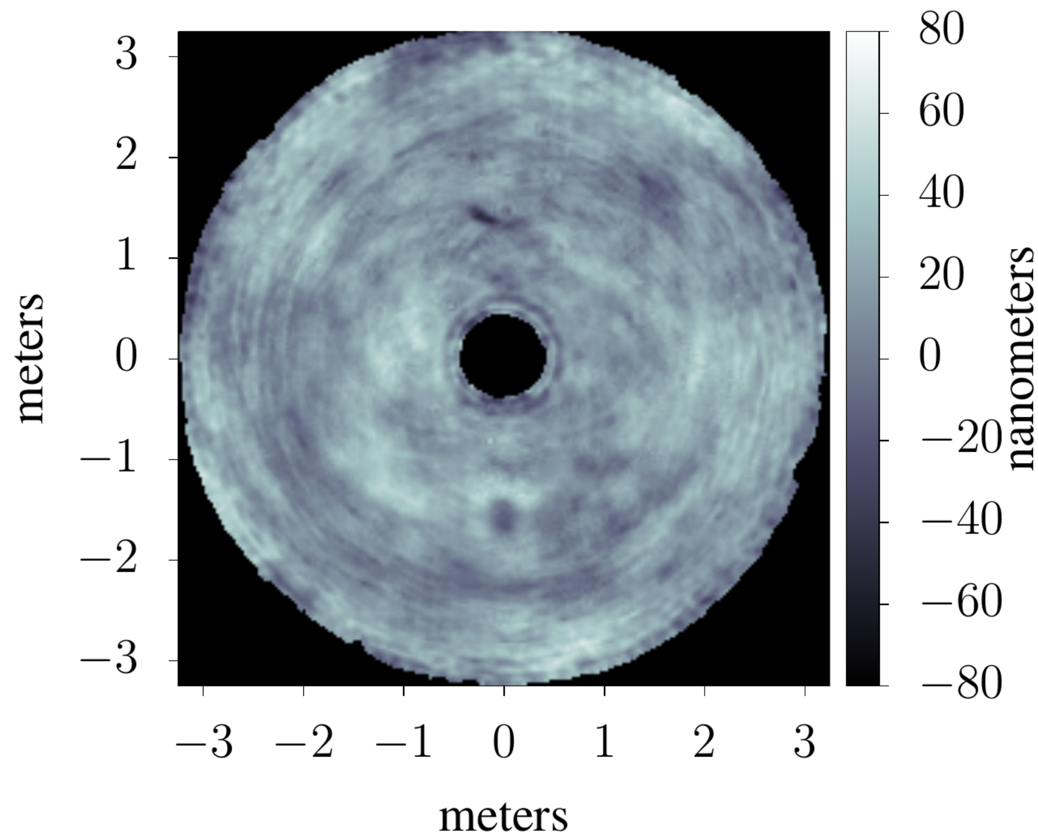
Note the scale.

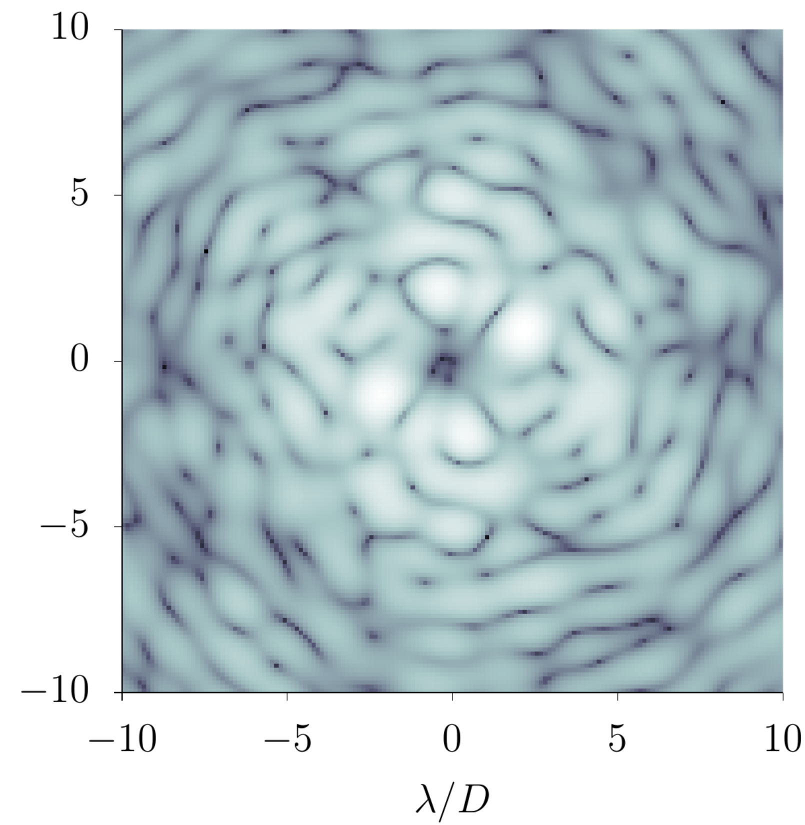
rms = 12.52 nm

$$\Phi(\vec{u}) = \sum_i h_i e^{i2\pi \vec{f}_i \cdot \vec{u}}$$

In words: any aberration can be written as the superposition of Fourier modes (sines and cosines) of various spatial frequencies.

A Real Mirror





The result: the post-coronagraph focal plane is covered with speckles, completely swamping the planet.

Video Source

See the complete video at:

https://exoplanets.nasa.gov/exep/coronagraphvideo/

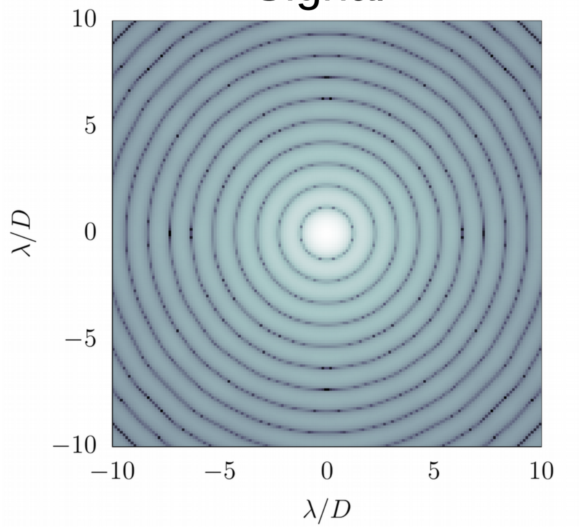
Residual Speckles

The limit of the planet:star flux ratio that we can detect & characterize is set by the variance of intensity in the focal plane:

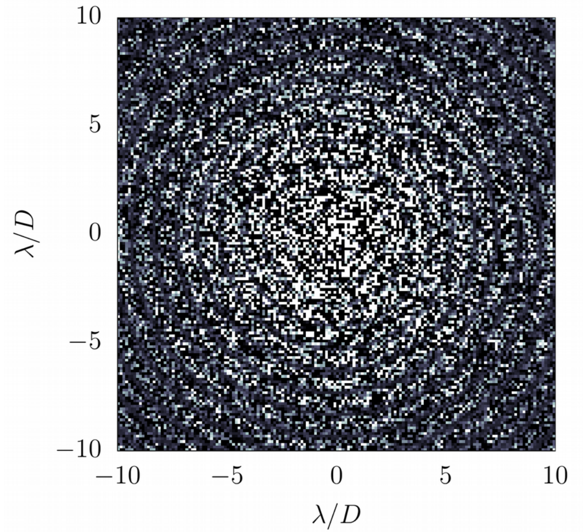
Pure photon noise:

$$\sigma_{tot}^2 = F_* \Delta t I$$

Signal



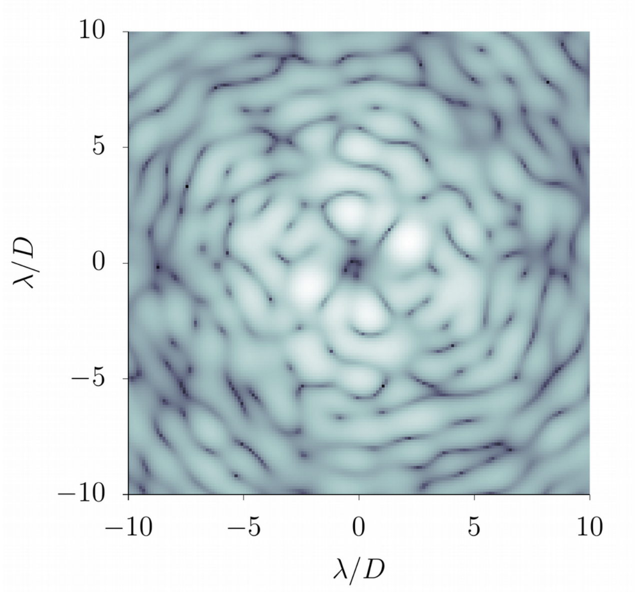
Noise



Residual Speckles

The limit of the planet:star flux ratio that we can detect & characterize is set by the variance of intensity in the focal plane:

$$\sigma_{tot}^2 = F_* \Delta t \left\{ I_c + I_{as} + I_{qs} + F_* \left[\tau_{as} \left(I_{as}^2 + 2[I_c I_{as} + I_{as} I_{qs}] \right) + \tau_{qs} \left(I_{qs}^2 + 2 I_c I_{qs} \right) \right] \right\}$$



Residual Speckle Variance

$$\sigma_{tot}^2 = F_* \Delta t \left\{ I_c + I_{as} + I_{qs} + F_* \left[\tau_{as} \left(I_{as}^2 + 2[I_c I_{as} + I_{as} I_{qs}] \right) + \tau_{qs} \left(I_{qs}^2 + 2 I_c I_{qs} \right) \right] \right\}$$

$$\begin{aligned}
F_* &= \text{photons/sec from the star} \\
\Delta t &= \text{total integration time} \\
I_c &= \text{intensity residual from the coronagraph \& static aberrations} \\
I_{as} &= \text{intensity residual from atmospheric speckles} \\
\tau_{as} &= \text{lifetime of atmospheric speckles} \\
I_{qs} &= \text{intensity residual from quasi-static speckles} \\
\tau_{qs} &= \text{lifetime of quasi-static speckles}
\end{aligned}$$

cf. Soummer et al., “Speckle Noise and Dynamic Range in Coronagraphic Images”, ApJ 669:642 (2007)

Residual Speckle Variance

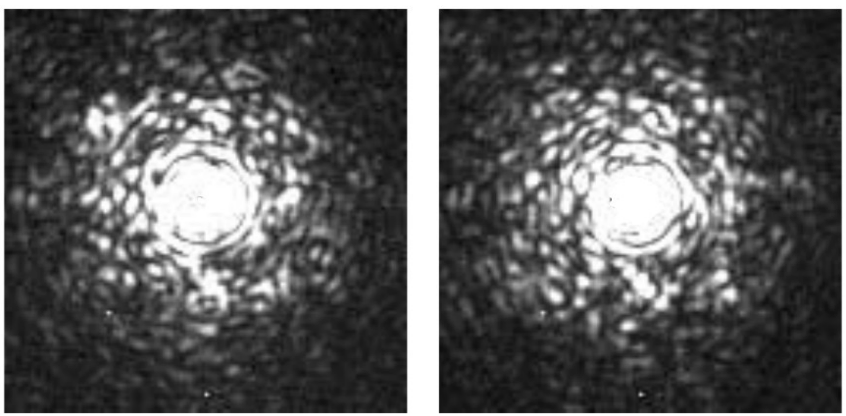
$$\sigma_{tot}^2 = F_* \Delta t \left\{ I_c + I_{as} + I_{qs} + F_* \left[\tau_{as} \left(I_{as}^2 + 2[I_c I_{as} + I_{as} I_{qs}] \right) + \tau_{qs} \left(I_{qs}^2 + 2 I_c I_{qs} \right) \right] \right\}$$

Photon Noise (Poisson statistics)

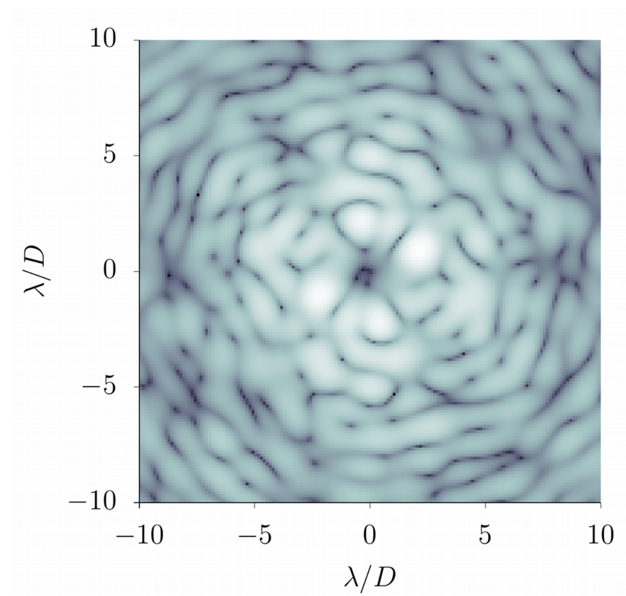
Residual Speckle Variance

$$\sigma_{tot}^2 = F_* \Delta t \left\{ I_c + I_{as} + I_{qs} + F_* \left[\tau_{as} \left(I_{as}^2 + 2[I_c I_{as} + I_{as} I_{qs}] \right) + \tau_{qs} \left(I_{qs}^2 + 2 I_c I_{qs} \right) \right] \right\}$$

Speckle Noise



Soummer et al., 2007



Residual Speckle Variance

$$\sigma_{tot}^2 = F_* \Delta t \left\{ I_c + I_{as} + I_{qs} + F_* \left[\tau_{as} \left(I_{as}^2 + 2[I_c I_{as} + I_{as} I_{qs}] \right) + \tau_{qs} \left(I_{qs}^2 + 2 I_c I_{qs} \right) \right] \right\}$$

Speckle Noise

nasty

Consider two classes of speckles:

– residual atmospheric speckles (short lived)

– quasi-static, or instrumental, speckles (long lived)

Residual Speckle Variance

$$\sigma_{tot}^2 = F_* \Delta t \left\{ I_c + I_{as} + I_{qs} + F_* \left[\tau_{as} \left(I_{as}^2 + 2[I_c I_{as} + I_{as} I_{qs}] \right) + \tau_{qs} \left(I_{qs}^2 + 2 I_c I_{qs} \right) \right] \right\}$$

Speckle lifetimes >> “lifetime” of photon noise

Residual Speckles

Key Results:

– Speckles are an inevitable result of imaging with real optics

– Speckle noise will limit any coronagraphic direct imaging observation

– Speckle noise is fundamentally different from photon noise

– It is spatially and temporally correlated
  Bad: Averages away slowly
  Good: Can be post-processed away!

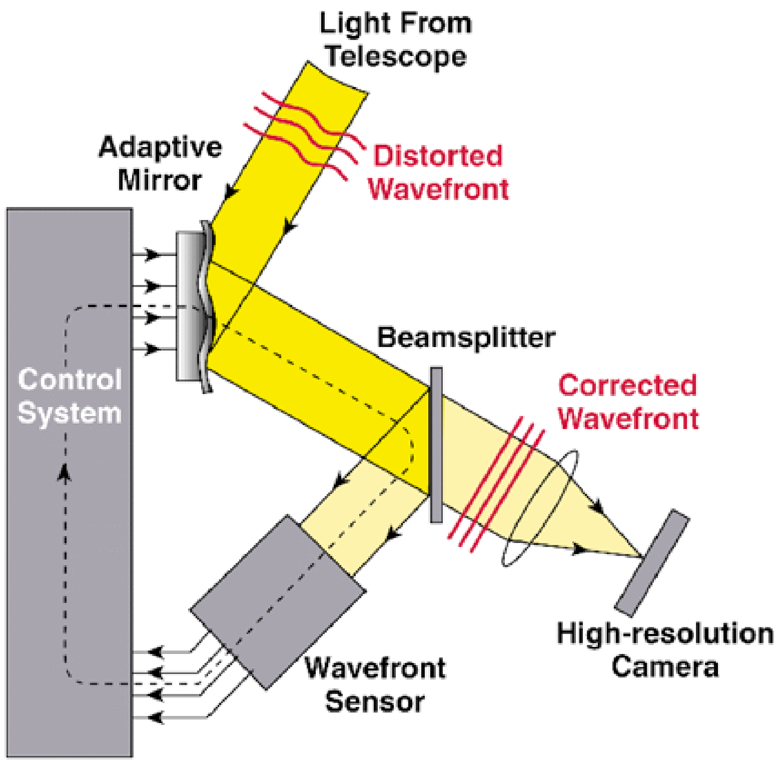
What We Need To Achieve High Contrast

- On the ground, and in space:
  - Large Telescopes
  - A way to block starlight
    - Coronagraphs
    - In space: also Starshades
  - Very good optics
  - A way to deal with imperfections
    - In our optics
    - On the ground: the atmosphere

Dealing With Imperfections

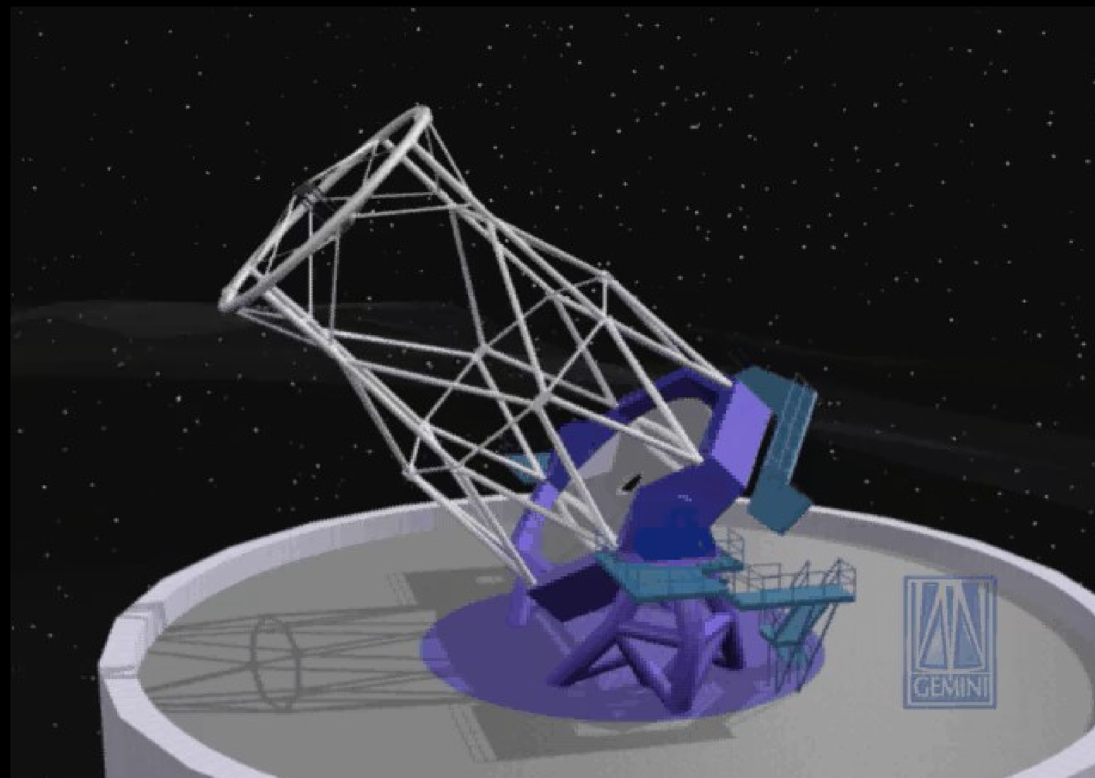
- All optics are imperfect.
- The atmosphere exists.
- This all changes with time
  - Spacecraft aren't static (thermal changes, vibrations, etc.)
  - Wind blows the atmosphere around
- Solution: real-time wavefront control

Wavefront Control (a.k.a. Adaptive Optics)



- Wavefront Sensor
  - Measure the aberrations
- Control System
  - Calculates wavefront
  - Sends commands
- Wavefront Corrector

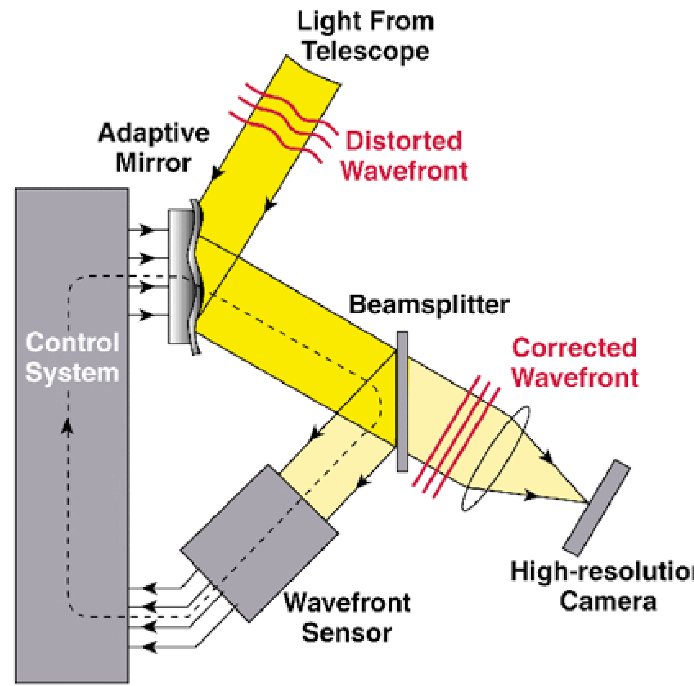
  (Deformable mirror)
  - Removes the aberration


GEMINI

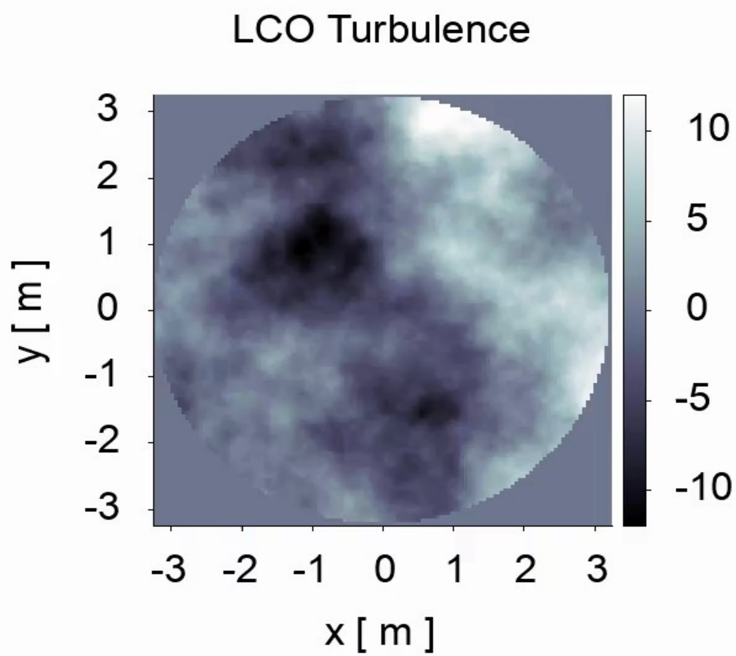
Closed-Loop Control and Servo-Lag

- The WFS is after the DM
  - Senses the residual wavefront (how much is not corrected)
- The WFS measures the wavefront at some time t.
- The control system take some time τ to calculate and communicate
- Result: the correction applied by the DM is time τ late.
- But now the aberrations have changed

→ This is called "servo-lag".



Atmospheric Turbulence



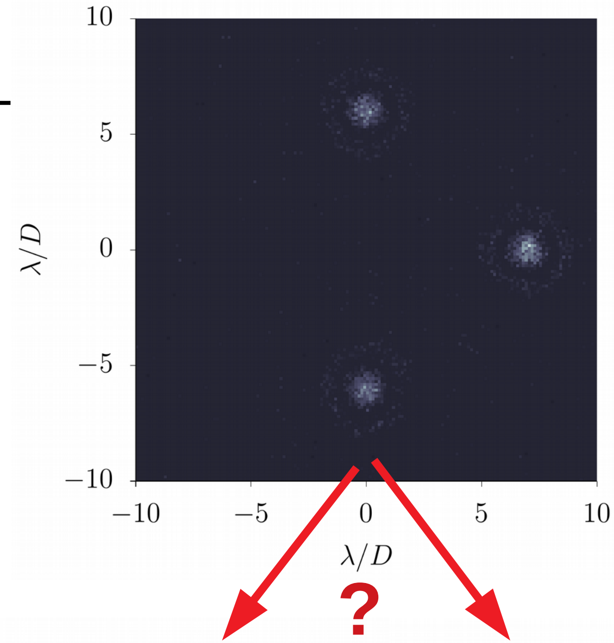
- Simulation of typical atmospheric turbulence at Las Campanas Observatory
- 7 Layer model
- High layer winds up to 30 m/s
- 0.62” seeing

- Requirement on AO system:

  1kHz or faster

Post-Coronagraph WFS&C

$$\mathrm{I}(\vec{\alpha}) = \left|\mathcal{F}[\mathcal{A}(\vec{u})e^{i\Phi(\vec{u})}]\right|^2$$

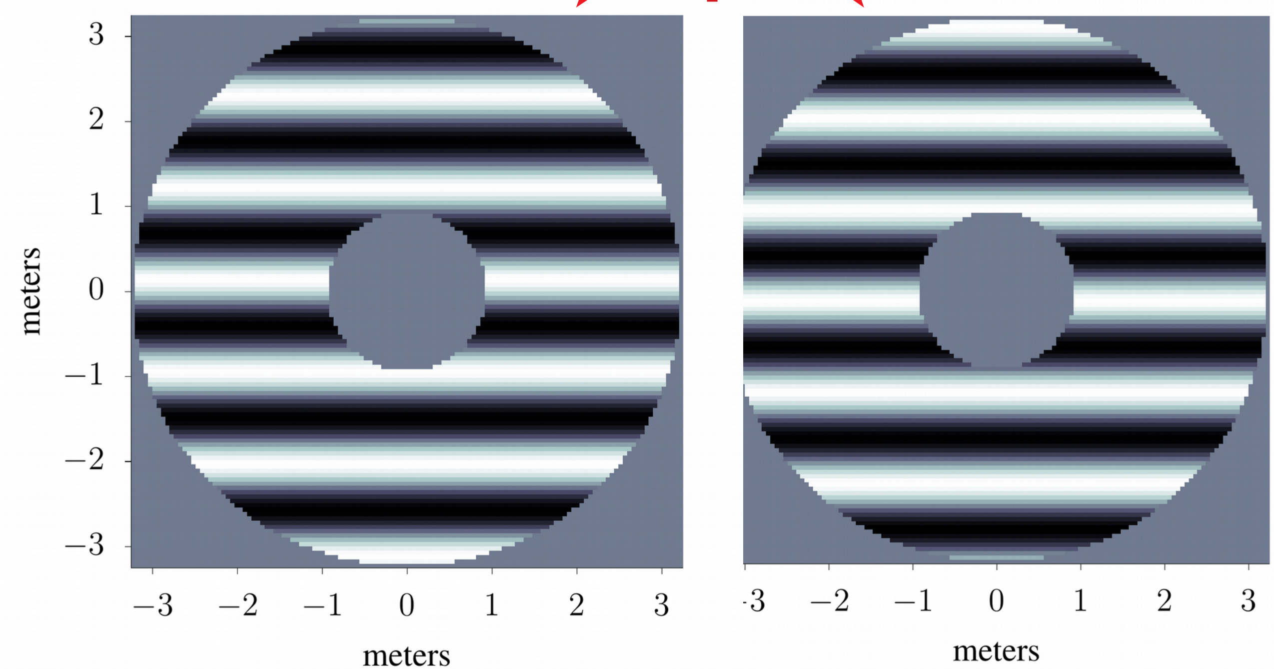


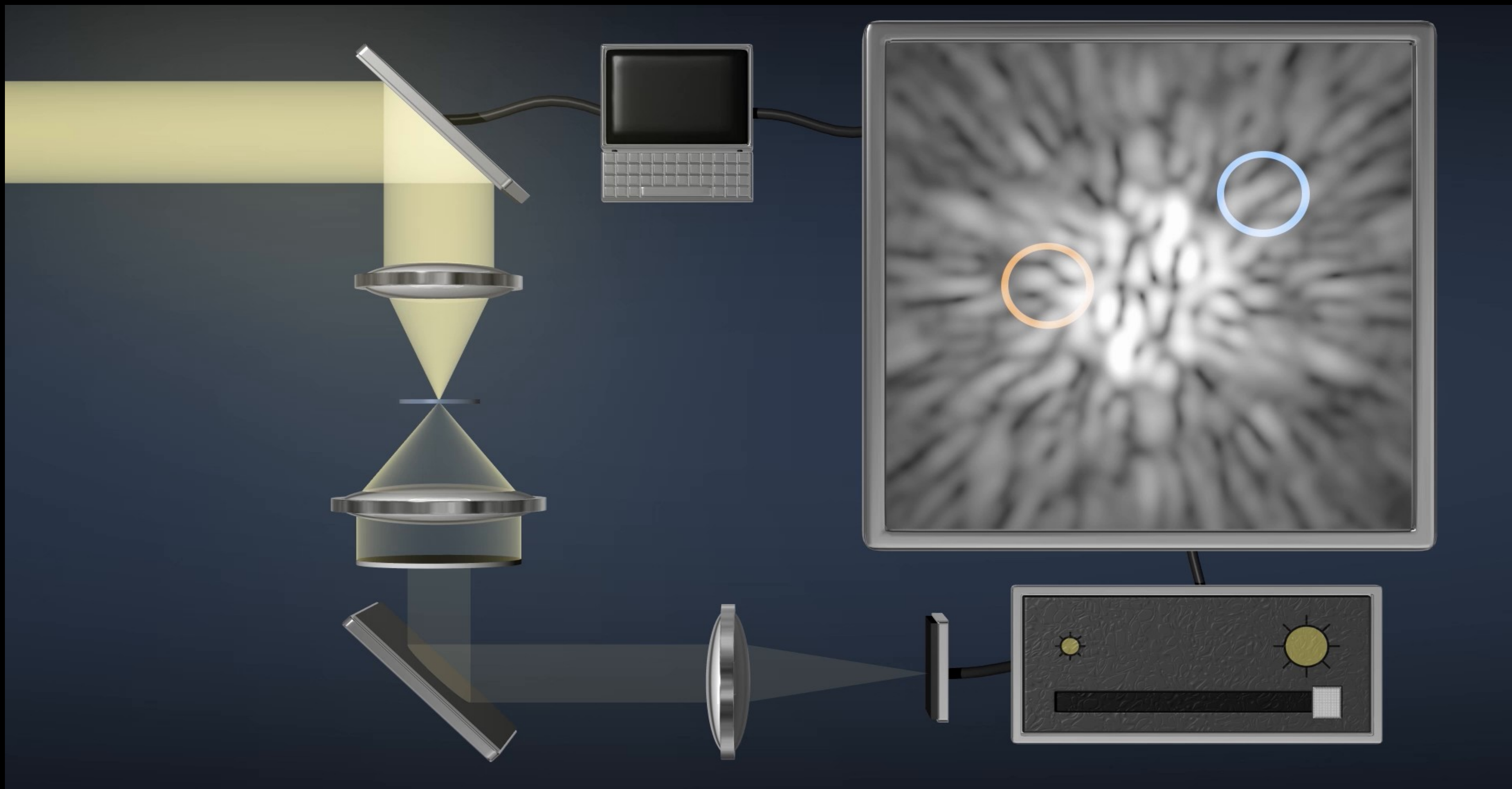
Consequence: in the focal plane, we can't tell which Fourier aberration (of the two shown) is causing the speckles.

Solution: Probe and Iterate

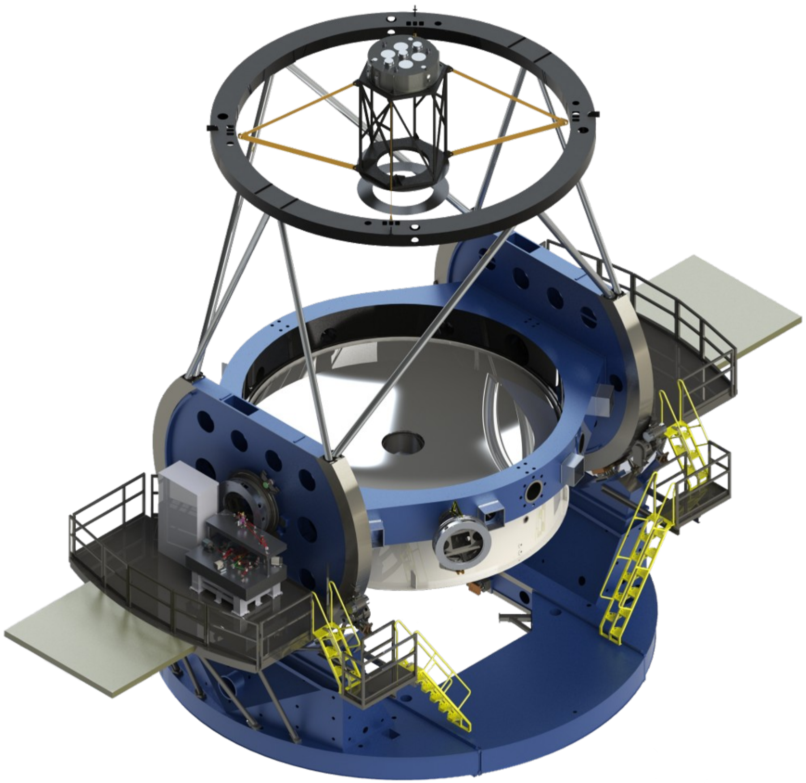
Speckle Nulling (Borde' 2006)

Pairwise Probing & EFC (Give'on 2009)





A Ground-Based Example

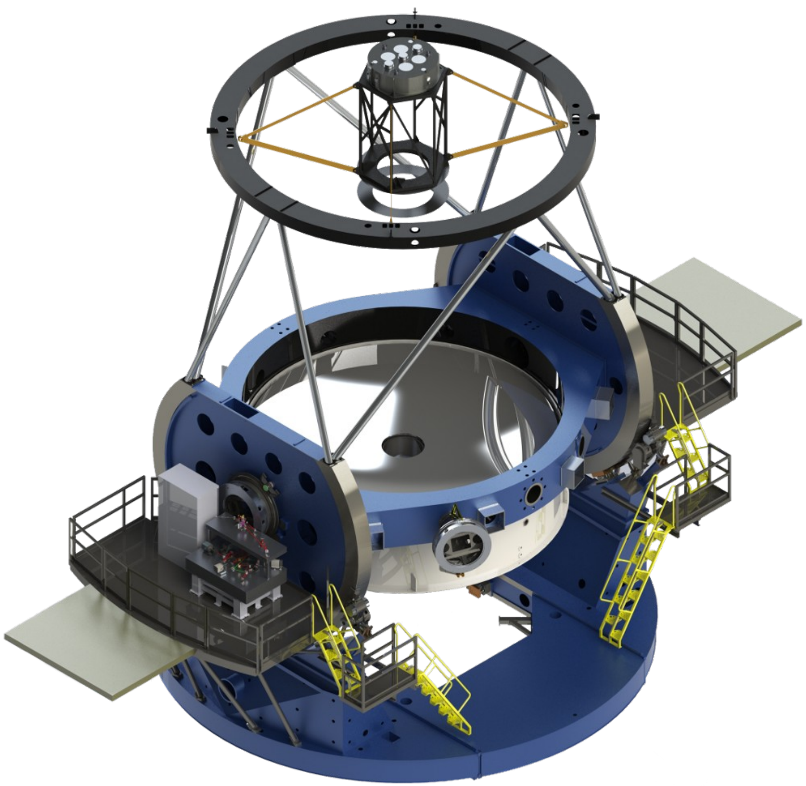


This is MagAO-X

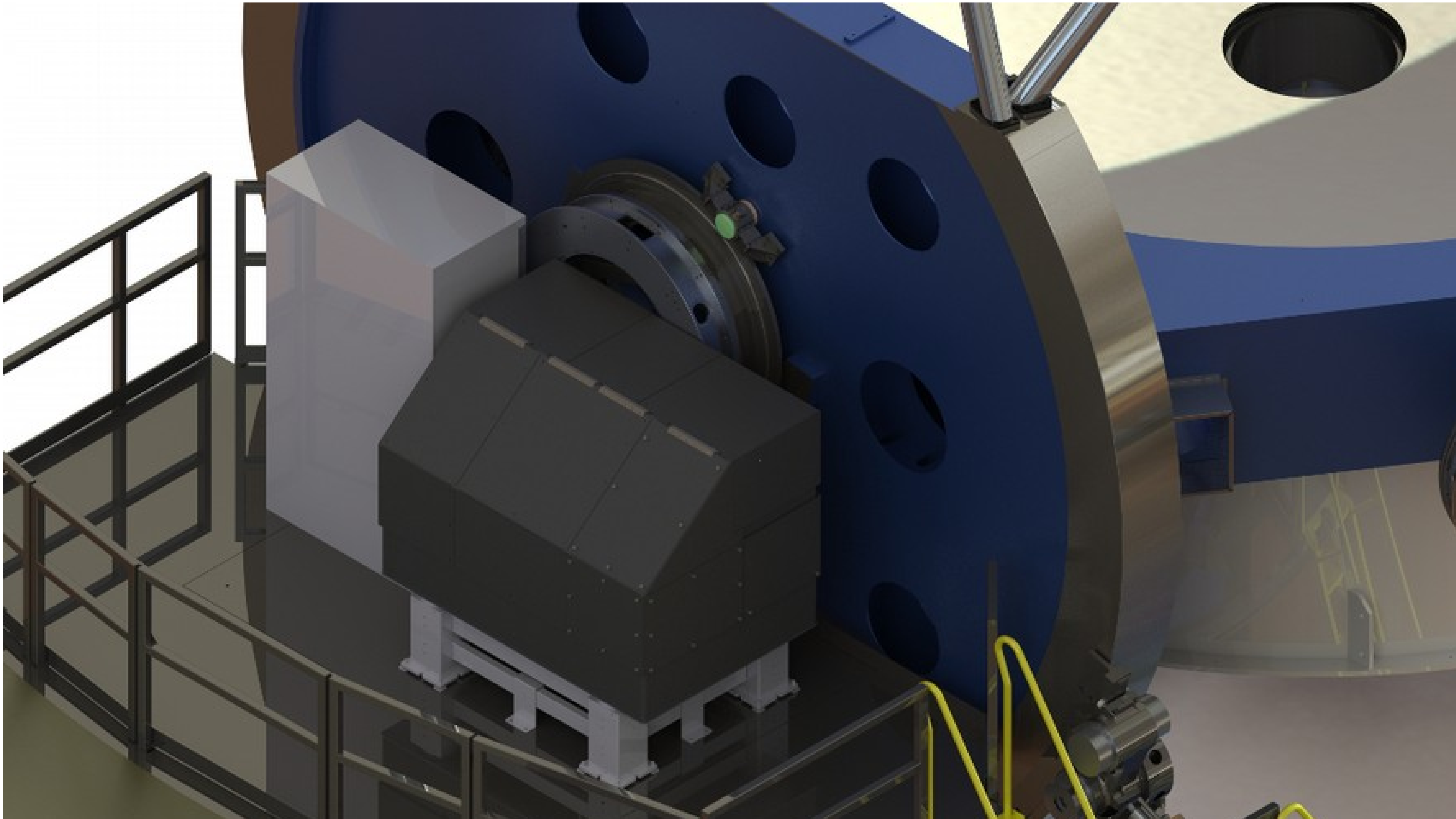
A new “Extreme” AO system for Magellan Clay

2000 Actuators, 3.6 kHz control loop

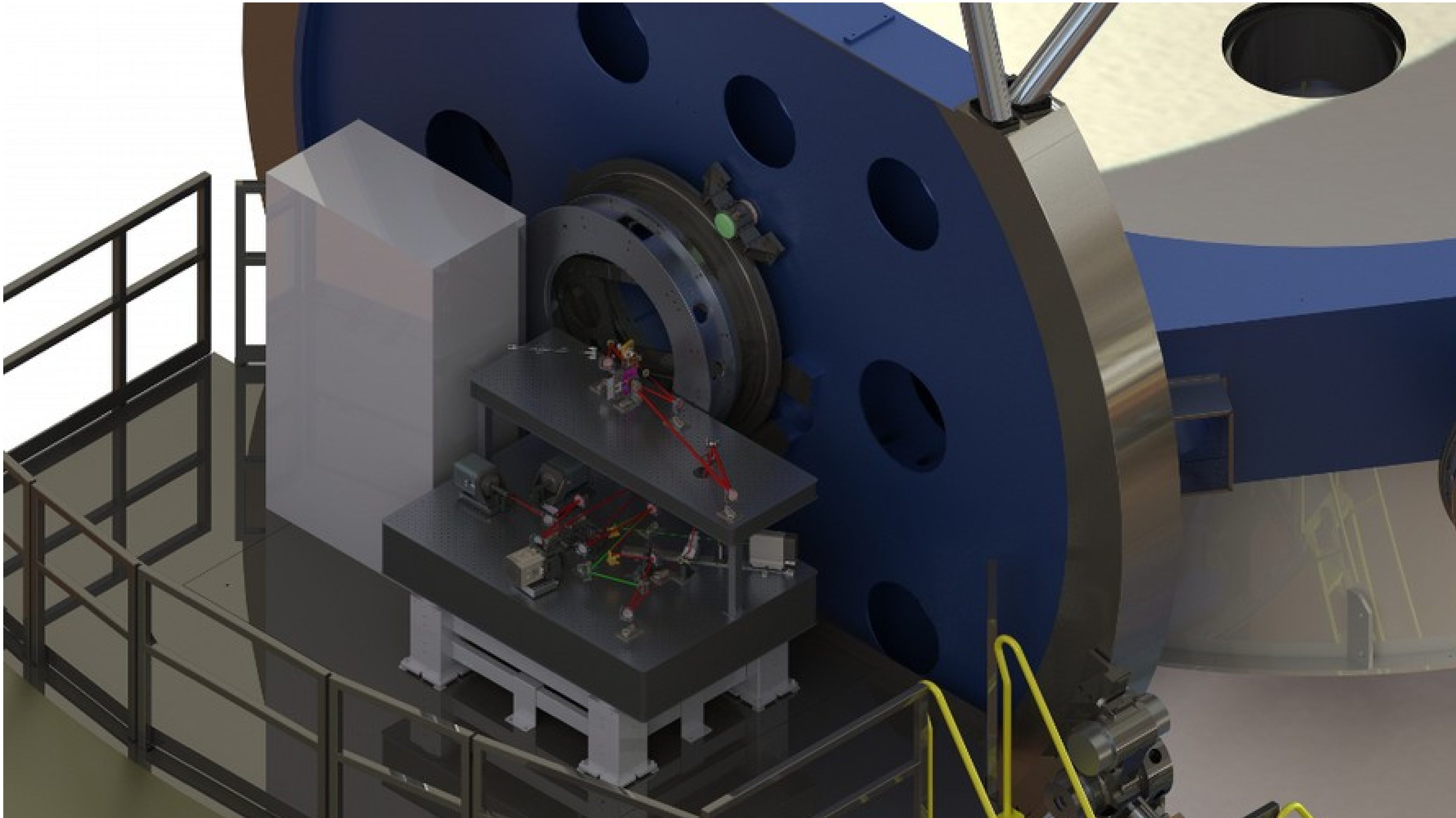
A Ground-Based Example



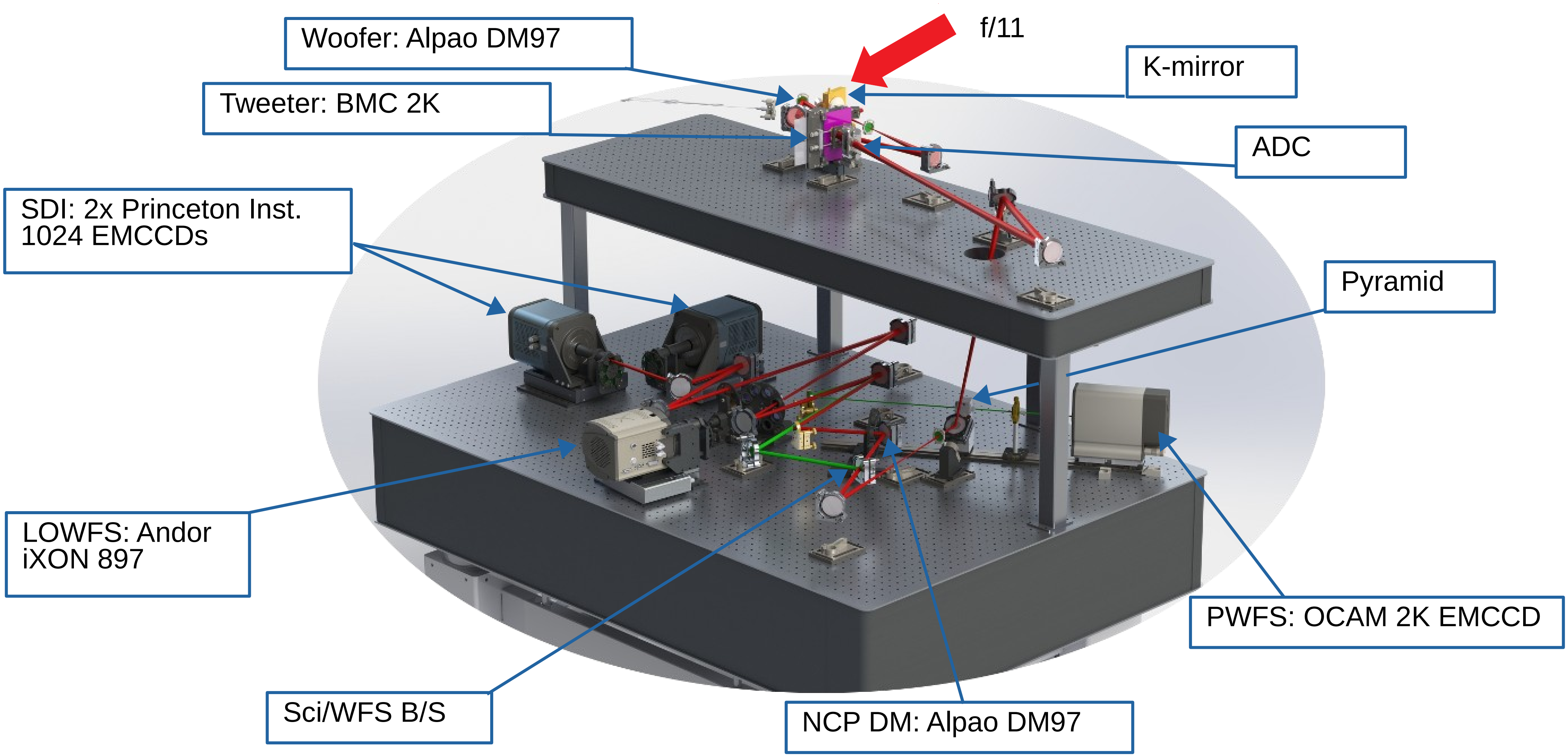
MagAO-X



MagAO-X

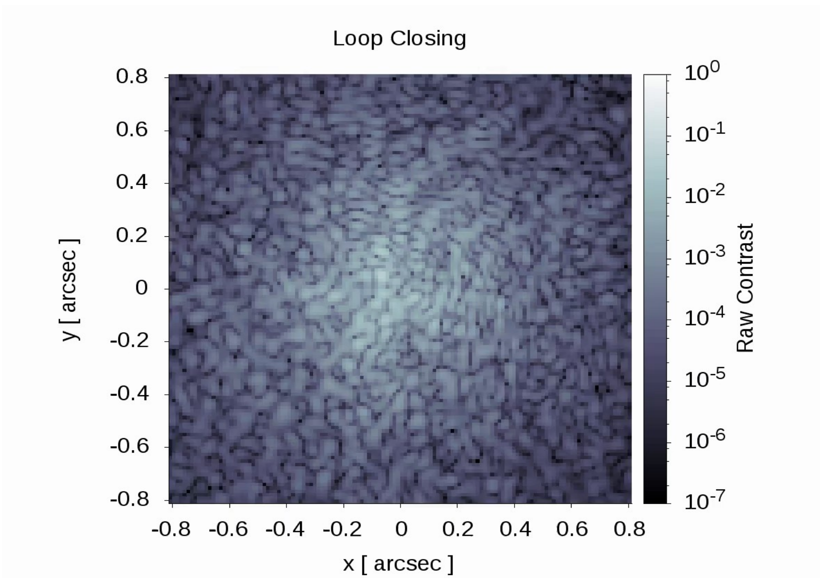


MagAO-X


Woofer: Alpao DM97
Tweeter: BMC 2K
f/11
K-mirror
ADC
SDI: 2x Princeton Inst. 1024 EMCCDs
Pyramid
LOWFS: Andor iXON 897
PWFS: OCAM 2K EMCCD
Sci/WFS B/S
NCP DM: Alpao DM97

It's Real

Predictive Control



The aberrations are spatially and temporally correlated

So they are subject to prediction

Integrator: use only last measurement

Predictor: here using “Linear Prediction”

(buzzword if needed: Speech Recognition)

See Males & Guyon 2018

Where Does This Leave Us?

- Adaptive Optics fed coronagraphs are now routinely used on ground-based telescopes.
  - GPI, SPHERE, MagAO, LBTI, SCExAO
  - Soon to be joined by MagAO-X
- Space coronagraphs are maturing rapidly
  - WFIRST-CGI
- Even with sophisticated WFS&C, we will always have speckles.

Further Reading

- Fundamental Theory:
  - Jeremy Kasdin's 2014 Sagan Workshop Lecture: https://www.youtube.com/watch?v=OSDBvxIl0ic
- High Contrast AO Limits:
  - Guyon 2005 (http://adsabs.harvard.edu/abs/2005ApJ...629..592G)
- Coronagraph Theory:
  - Guyon 2006 (http://adsabs.harvard.edu/abs/2006ApJS..167...81G)
- FPWFS&C:
  - Groff+ 2016 (http://adsabs.harvard.edu/abs/2016JATIS...2a1009G)