Nulling Interferometry

Basic Approach

Motivation

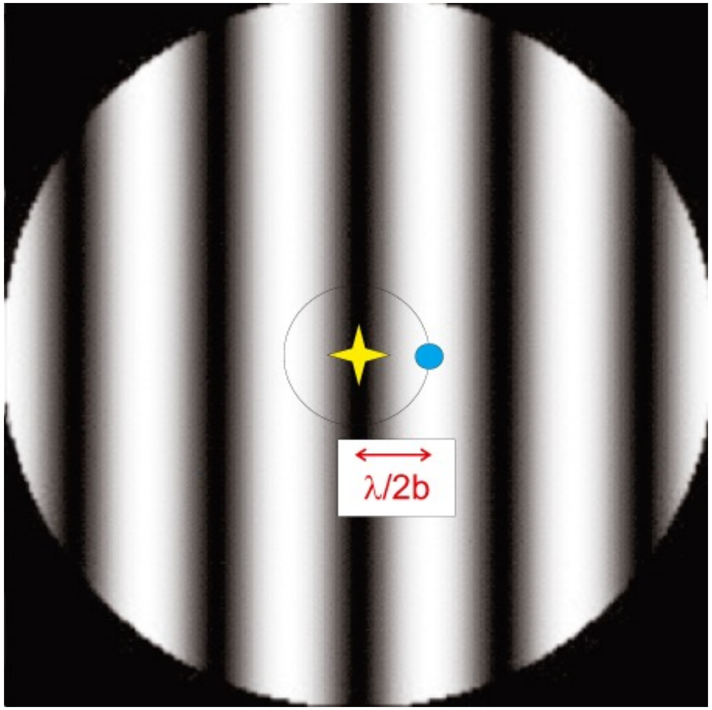
Implementation

An Exo-Earth Mission using Nulling

Nulling interferometry

Combining high-angular resolution and high-contrast imaging

- First proposed by Bracewell (1978) to directly detect “non-Solar” planets;
- Subtracting starlight by destructive interference;



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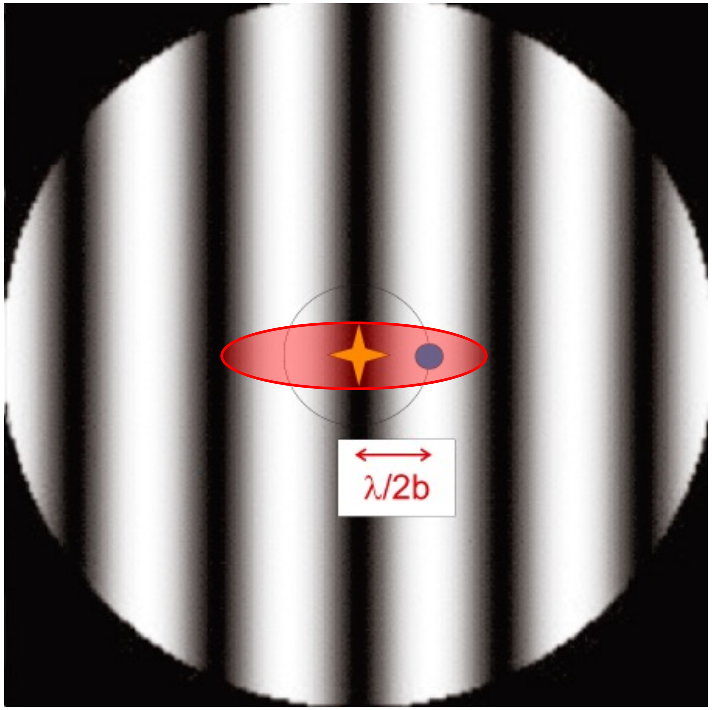

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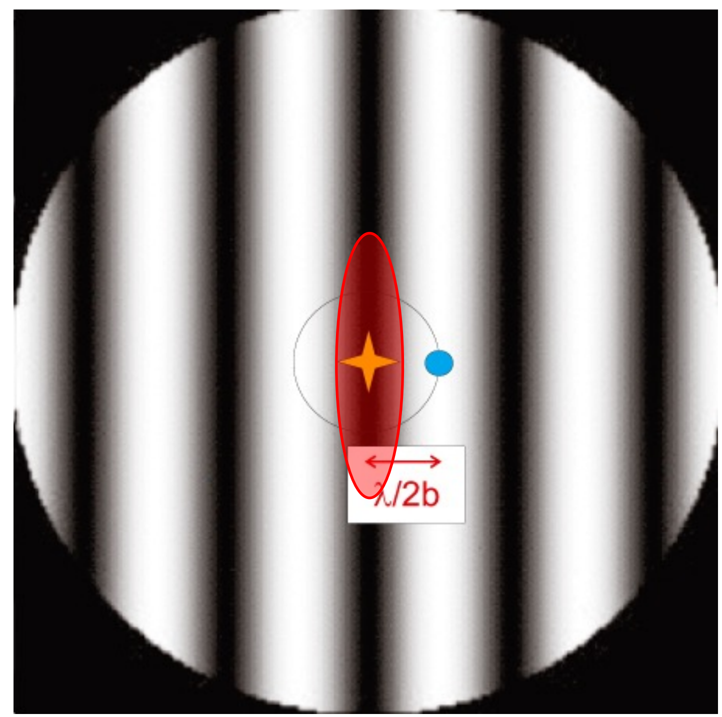
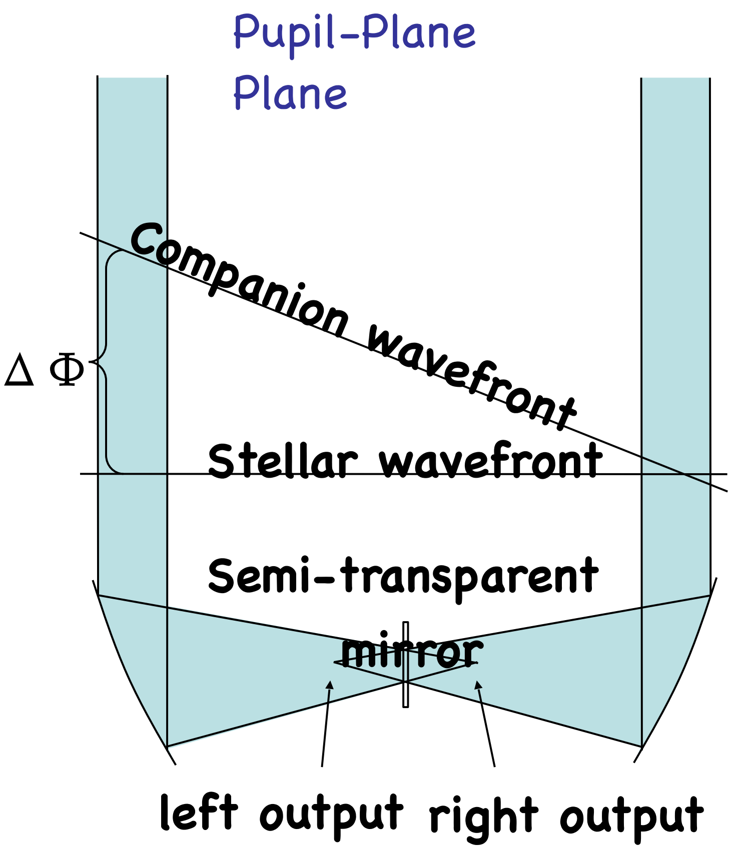


Astronomical Interferometry



Pupil-plane interferometry is used in long-baseline interferometry. Bracewell (1978) first suggested using this technique to null a stellar point source for detection of planets.

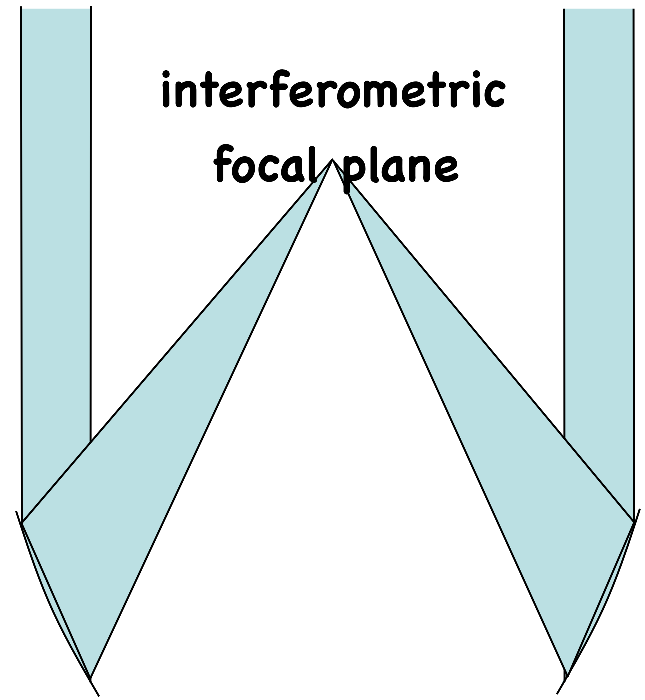
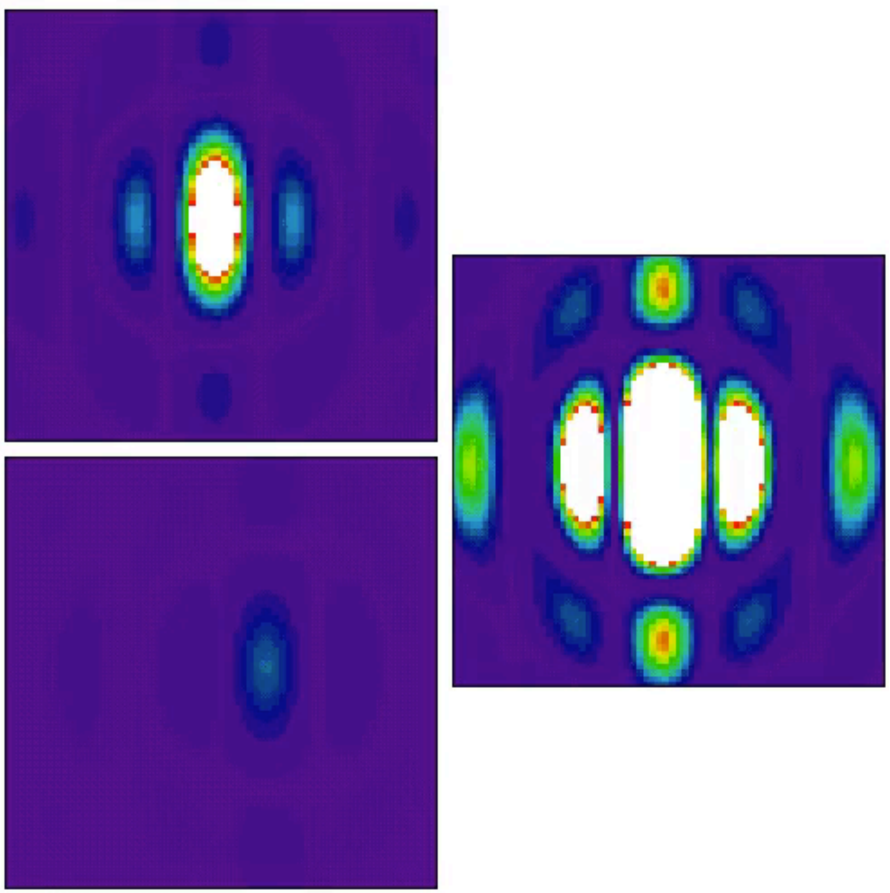


Image-plane interferometry was successfully used by Michelson in 1890 to measure the satellites of Jupiter. An imaging interferometer can be designed to create high resolution images over a wide field of view.

Resolving Faint Companions

Pupil-plane interferometry is well-suited for suppression of starlight.

Star Star+Companion

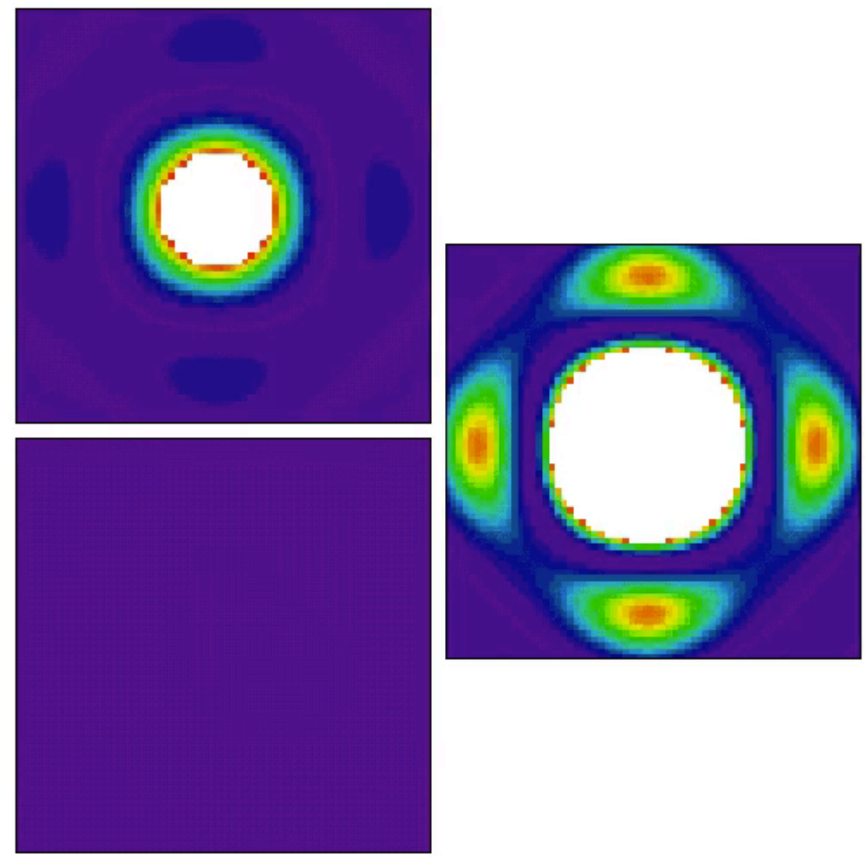


Companion

(1% of star brightness)

Image-plane interferometry is well -suited fo
high spatial resolution studies

Star Star+Companion



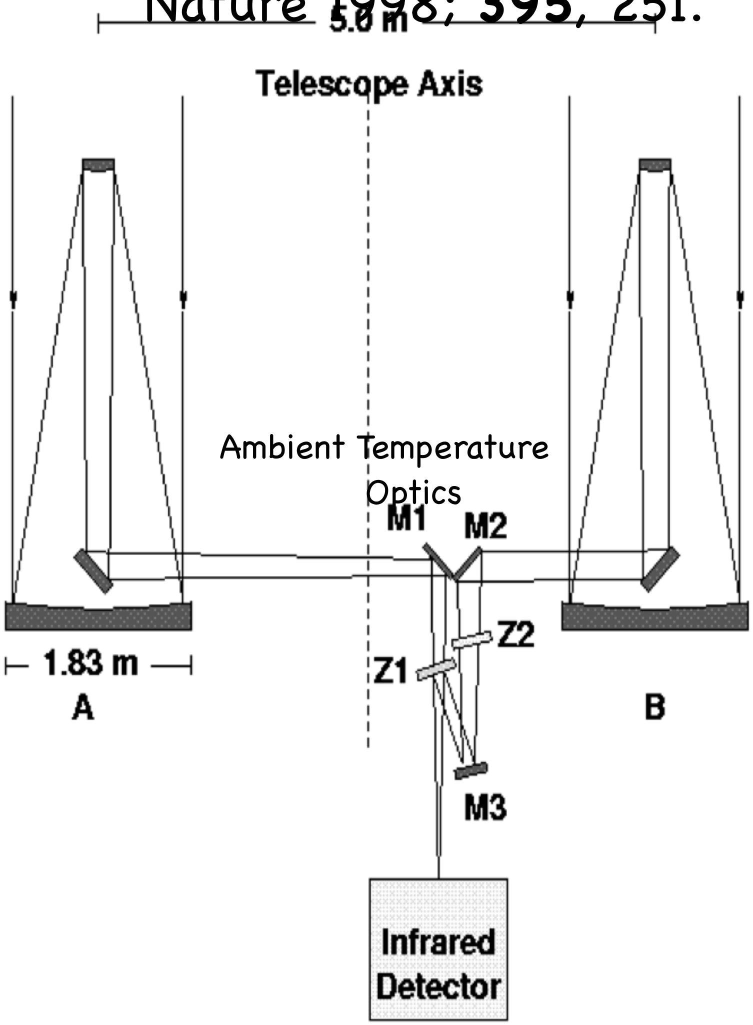
Companion

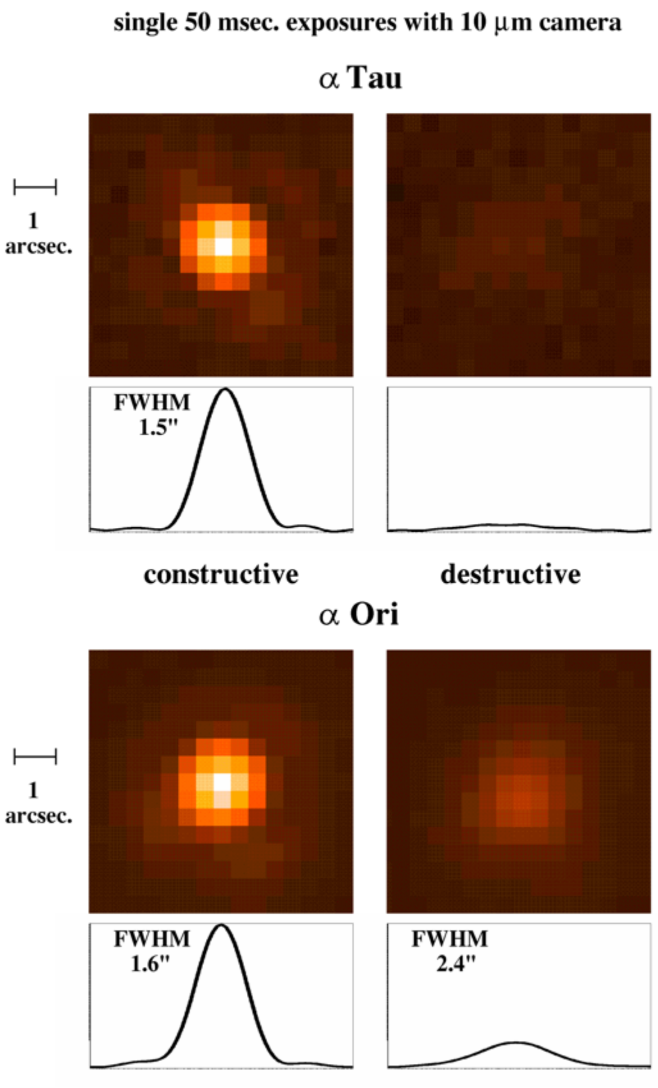
(1% of star brightness)

First Telescope Demonstration of Nulling

Nulling at the MMT

Nature 1998; **395**, 251.

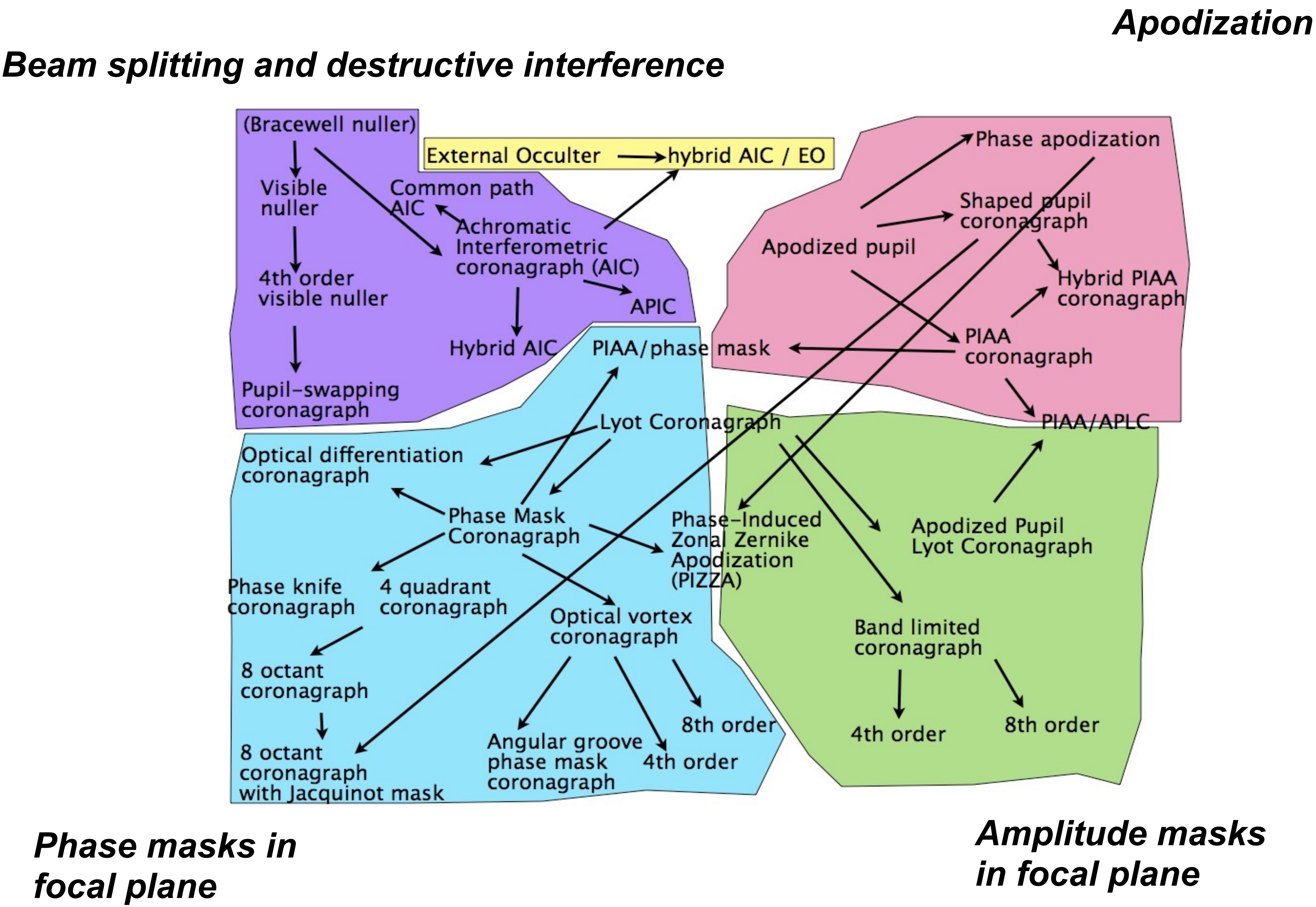




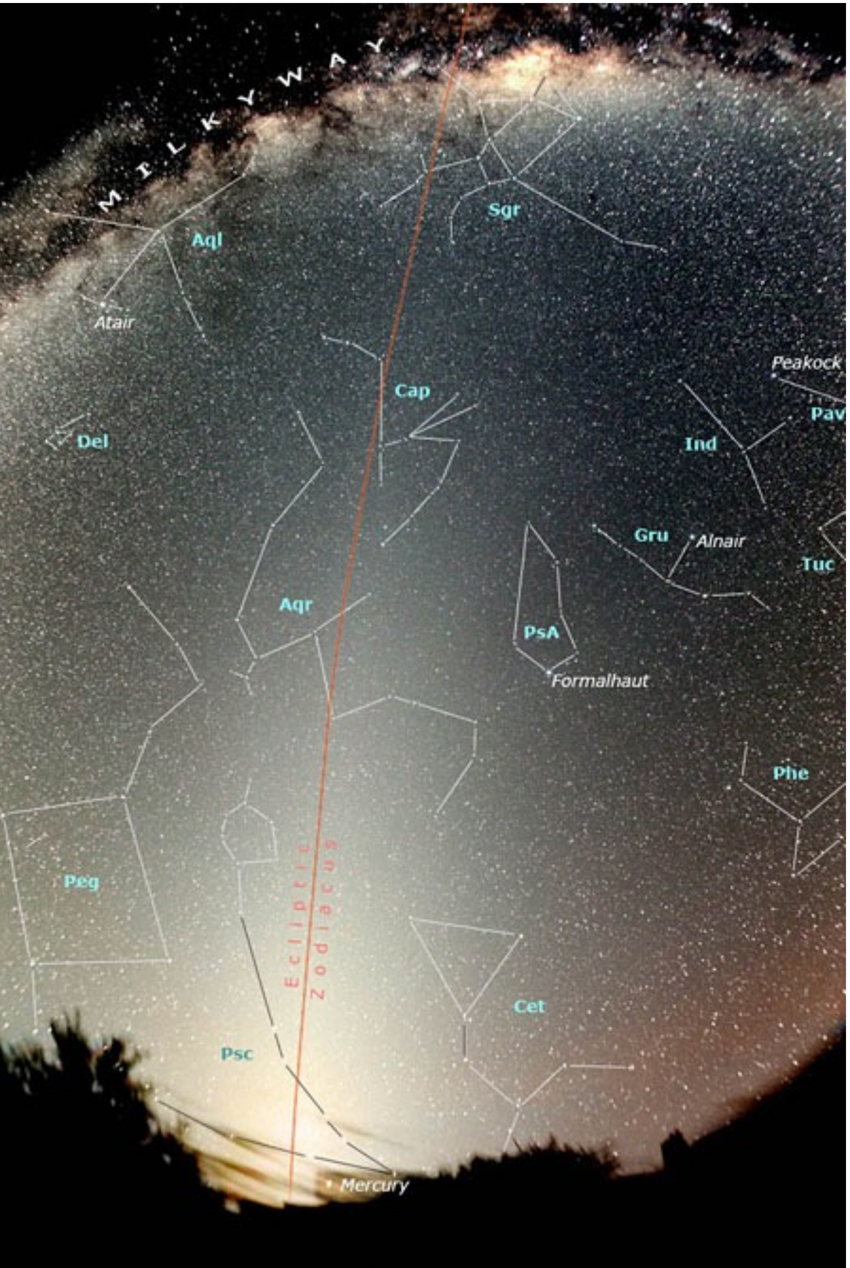
For unresolved star, destructive/ constructive peak ratio = 0.04

For α Ori, peak ratio = 0.18
Residual flux is a direct thermal image of the extended dust nebula

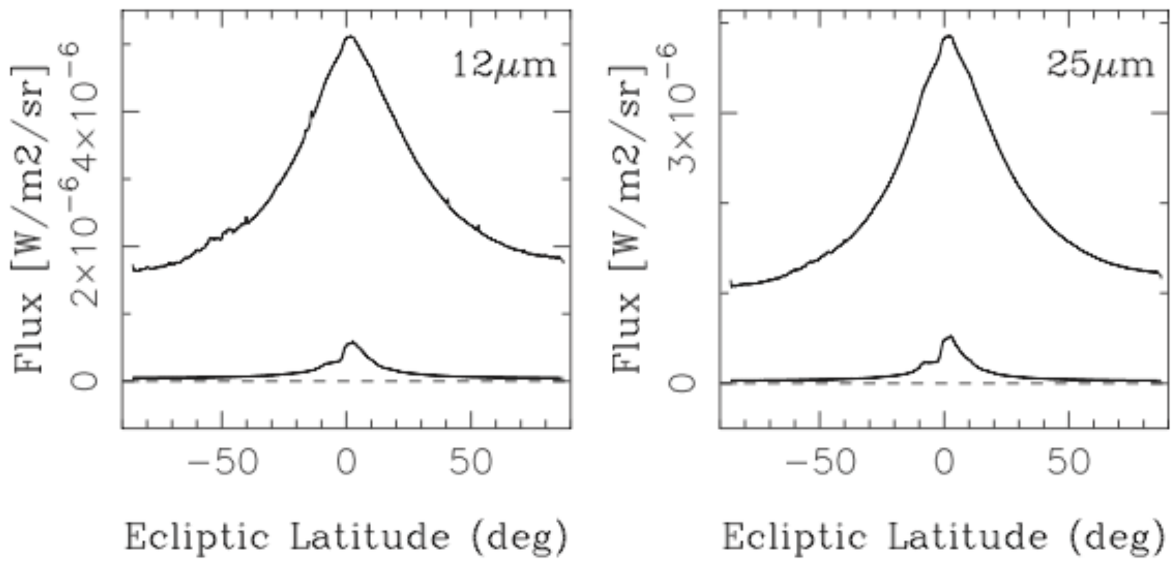
Internal Coronagraphs: main approaches



Zodiacal dust

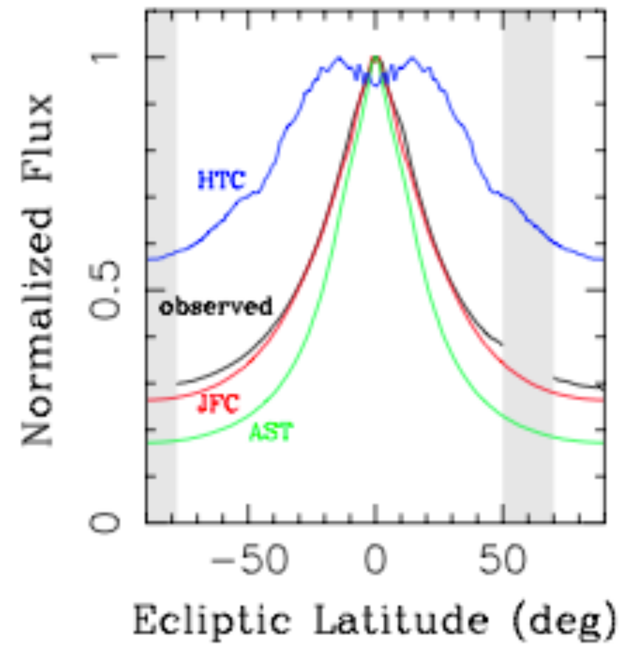


- Scattered light in ecliptic plane.
- Infrared emission first seen by IRAS.



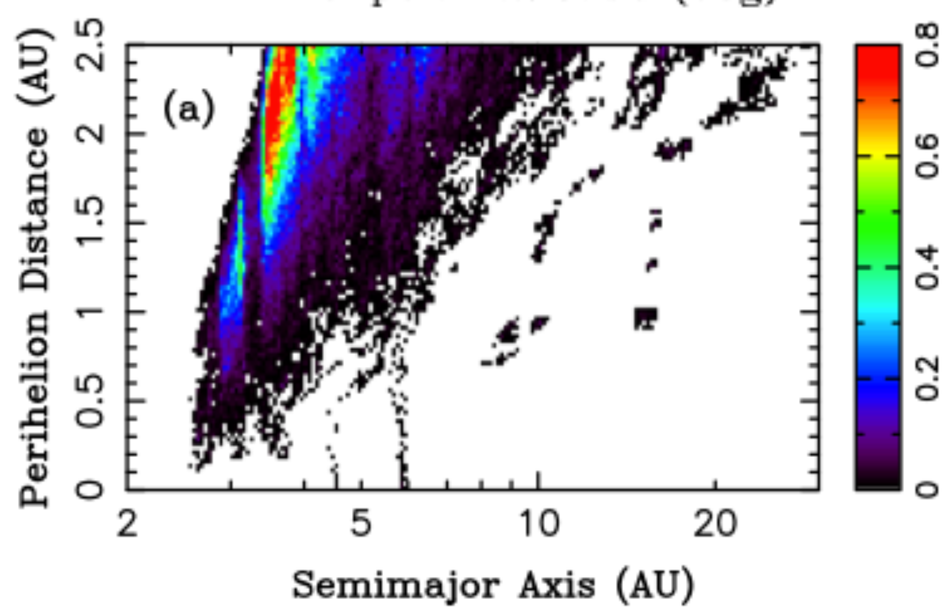
from Nesvorney et al. 2010

Origin of zodiacal dust



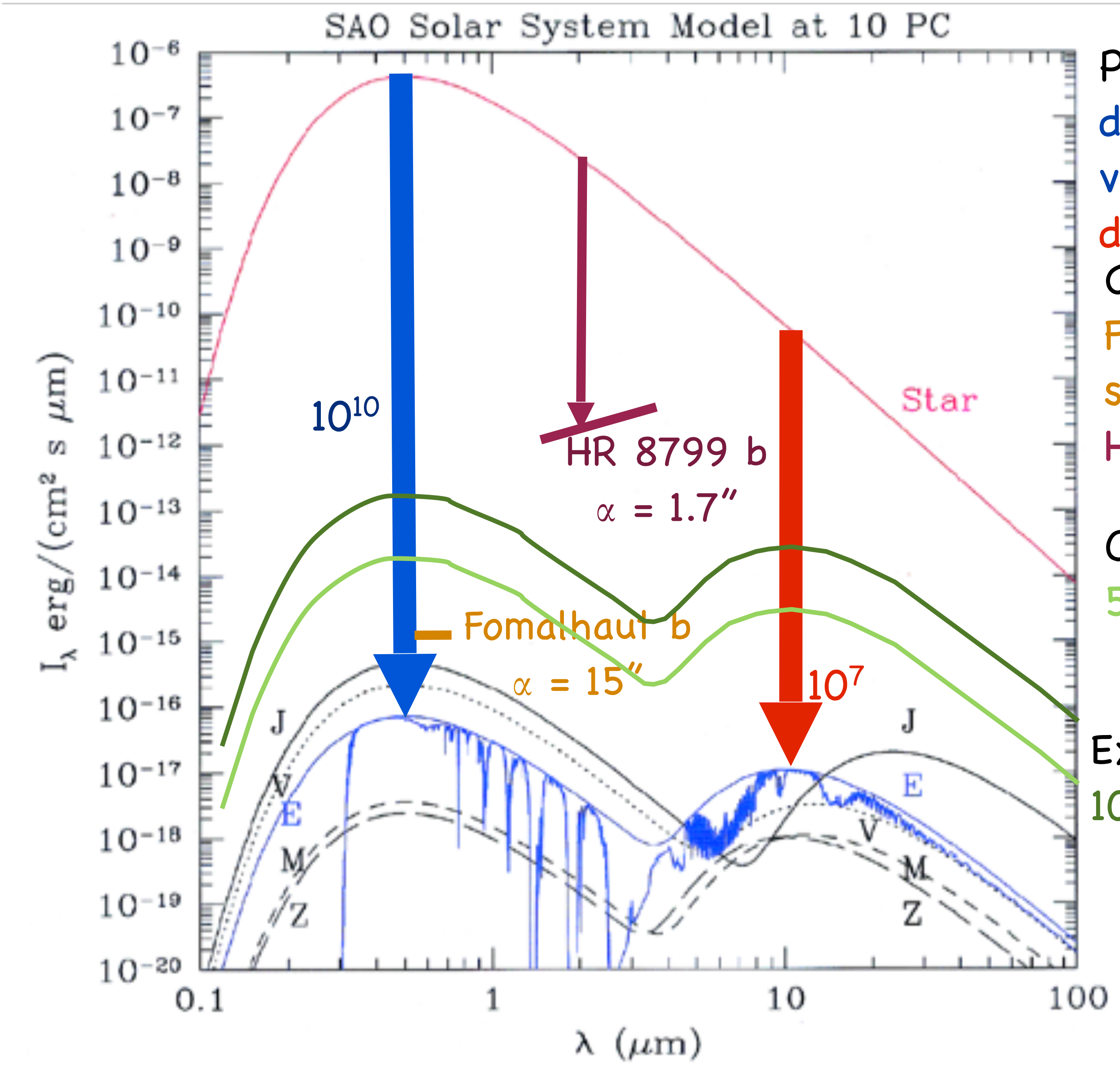
Asteroid belt thought to provide much of the dust seen at Earth (Dermott et al. 2002).

Recent Dynamical models (cf. Nesvorney et al. 2010) suggest Jupiter-family comets provide the majority of the dust for the zodiacal cloud.



from Nesvorney et al. 2010

The Contrast Problem



Planet Finding missions aim to:

detect Earths 10^{-10} fainter in visible.

detect Earth 10^{-7} in the IR.

Current state of the art:

Fomalhaut b: 10^{-9}, but 150x separation.

HR 8799b: 10^{-4} but 17x separation.

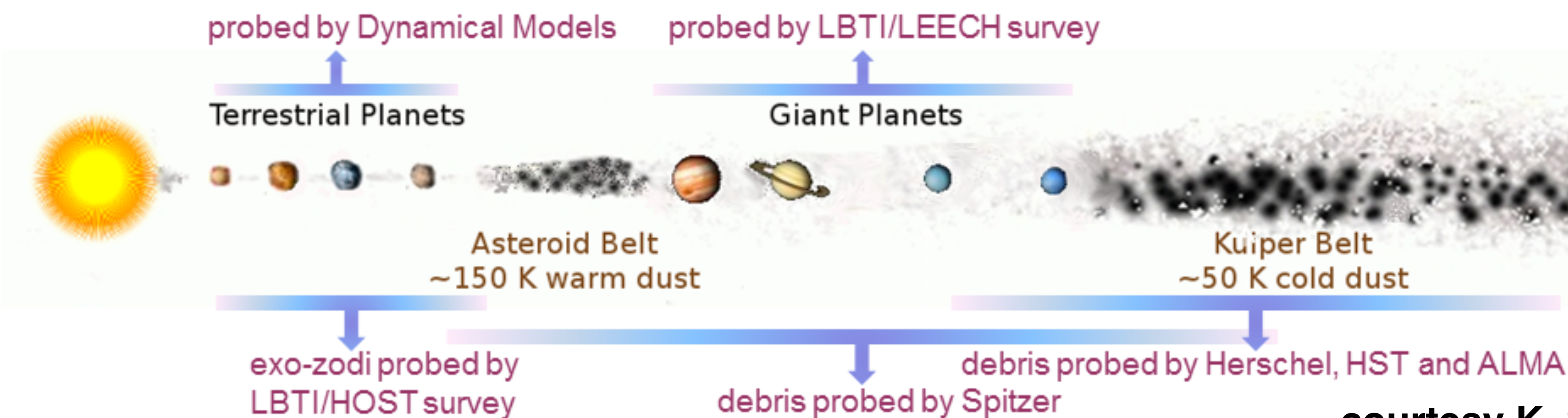
Our own Zodiacal dust:

5x 10^{-5} at 10 μm =1 zody.

Exozodiacal dust becomes a problem: 10 zody or above.

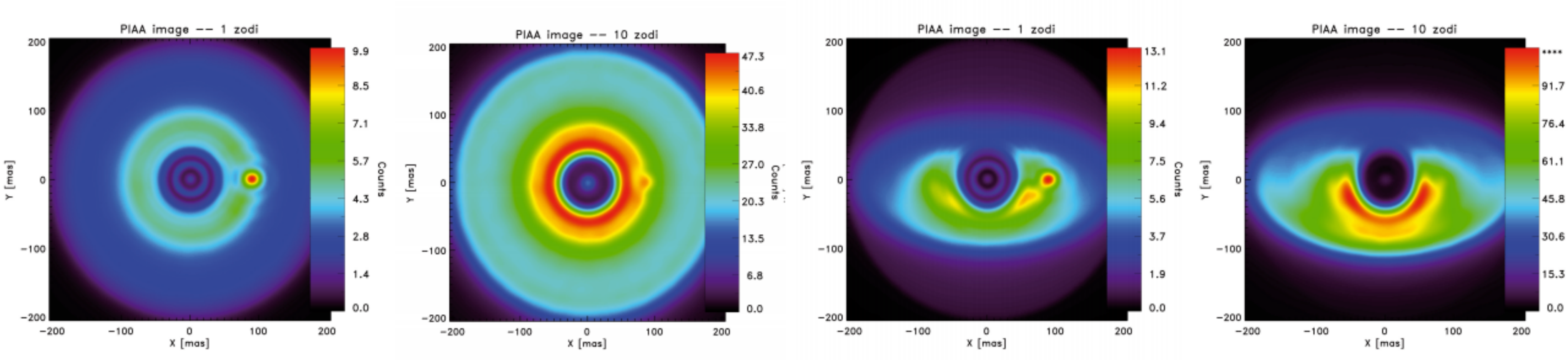
LBTI can show us what exists (planets or dust disks) at faint levels around nearby stars.

Zodiacal Dust in Context



courtesy K. Su

An Earth embedded in a zodiacal dust disk



from Defrere et al. 2012

Flux is problematic for any imaging mission.

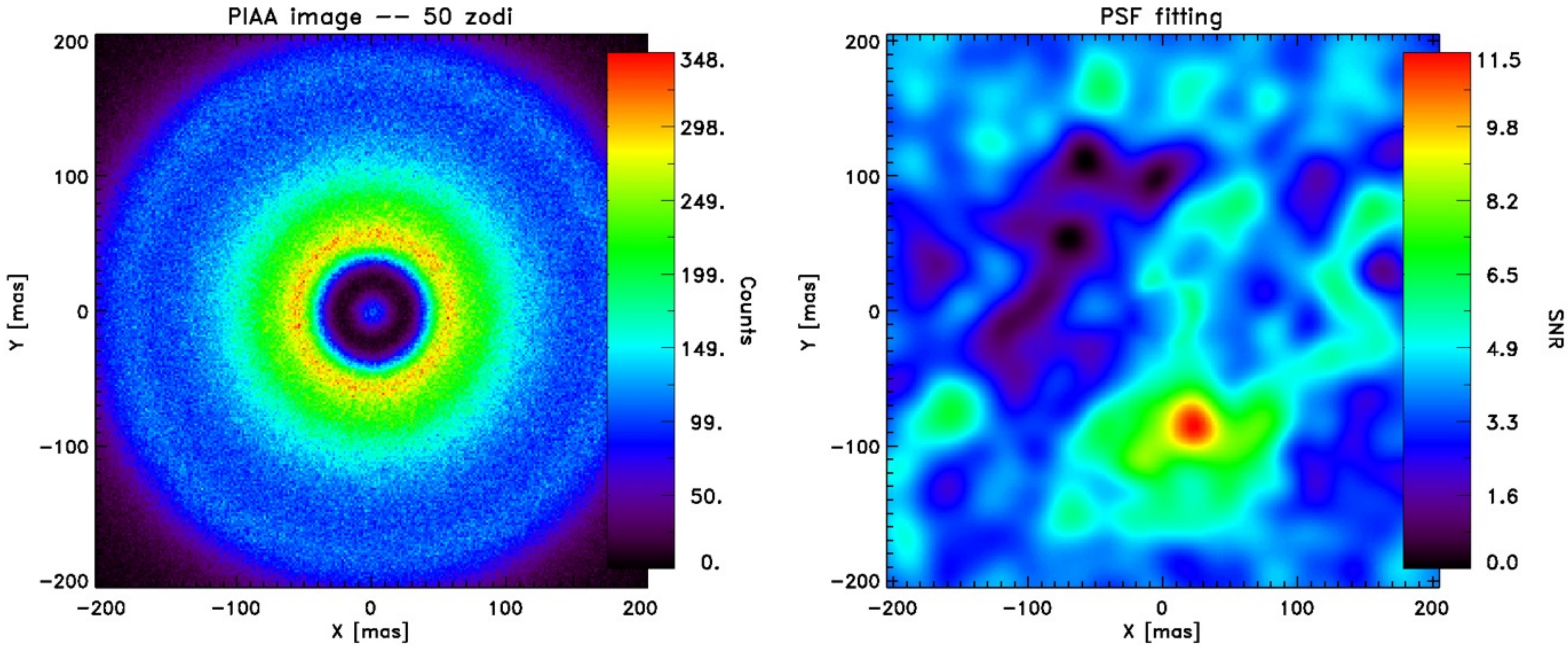
Clumpiness (resonances) complicates the detection.

The problem with exozodiacal dust

Source of noise and confusion for future exoEarth direct imaging instruments:

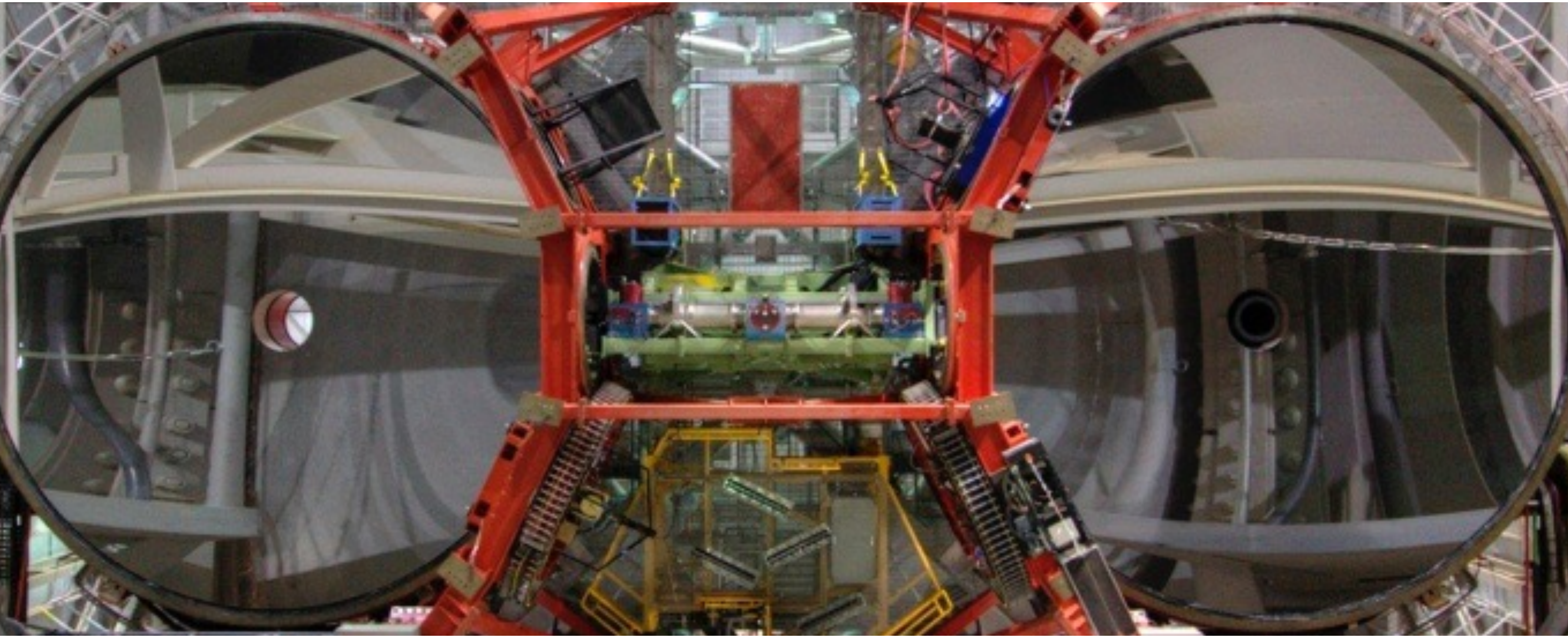
1. Solar zodiacal cloud ~300 times brighter than Earth (IR and Visible);

2. Asymmetric features can mimic the planetary signal.



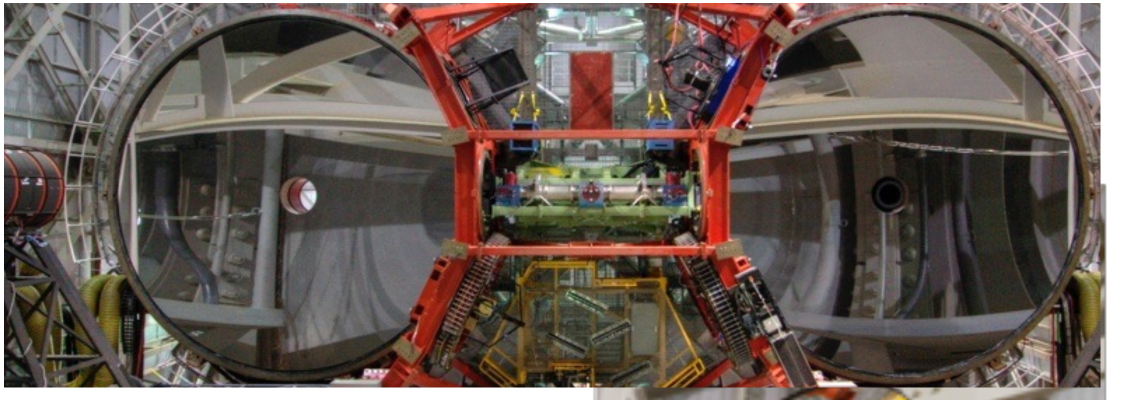
Sun-Earth system at 10 pc surrounded by a 50-zodi exozodiacal disk (according to self-consistent models of Stark et al. 2012)

The Large Binocular Telescope



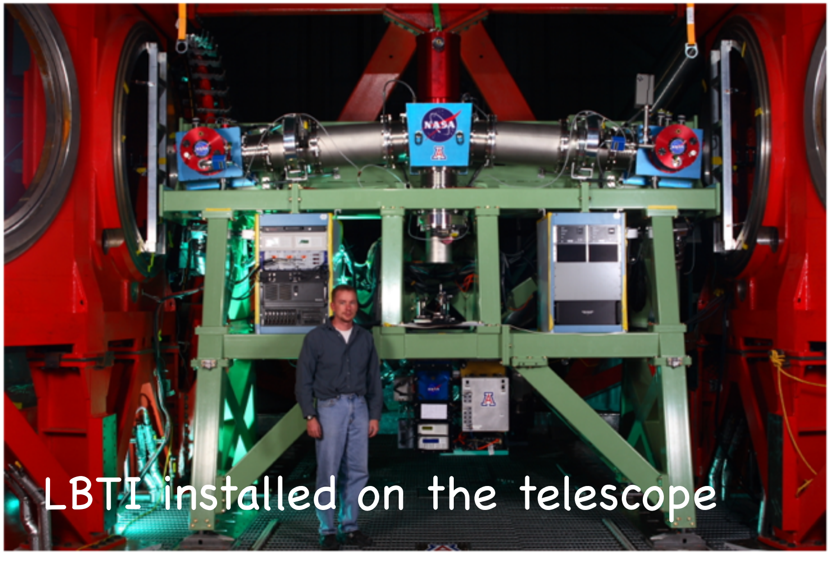
Sensitivity

LBTI has two 8.4 m mirrors mounted on a single structure.



High Contrast

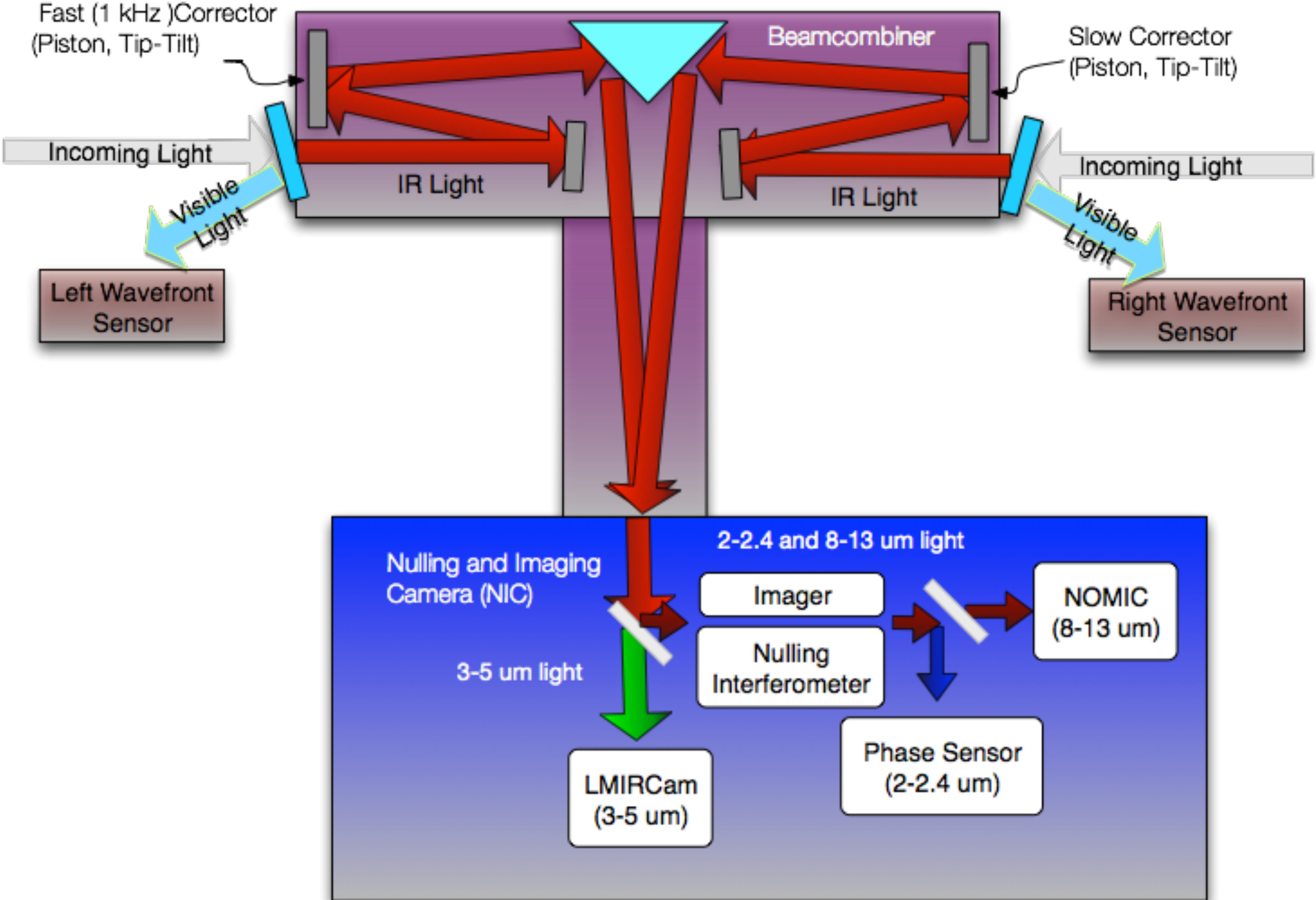
The AO system creates an image with a Strehl of >95% at 3.8 μm.



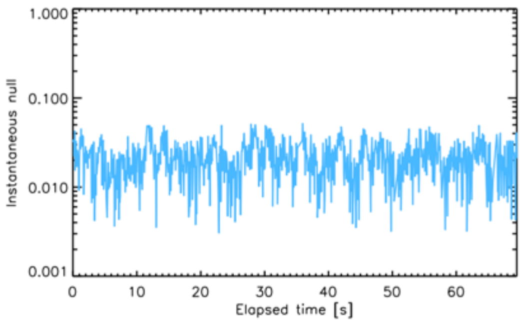
Resolution

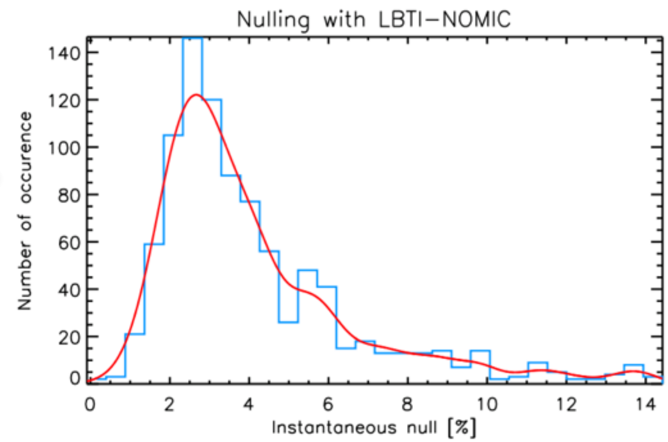
Beam combination provides the equivalent resolution of a 22.7 m telescope.

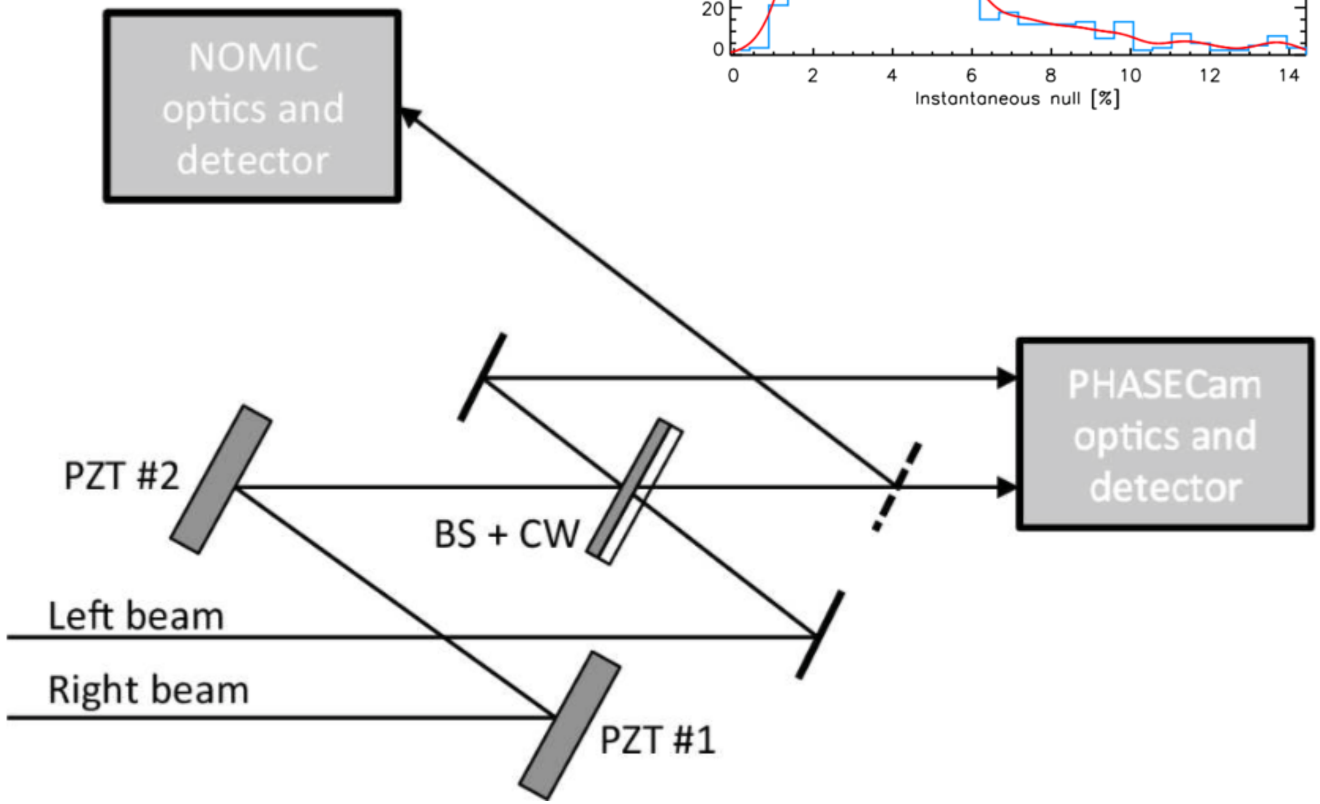
LBTI Layout

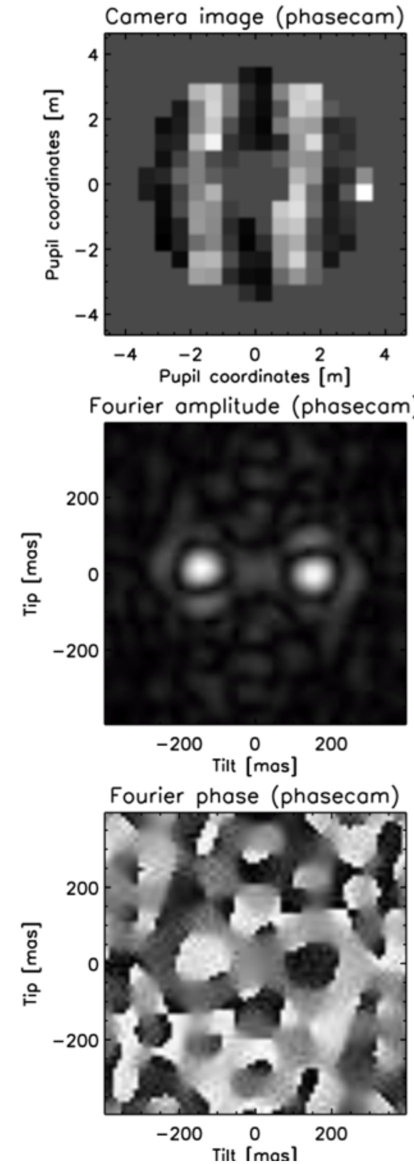

Fast (1 kHz)Corrector
(Piston, Tip-Tilt)
Beamcombiner
Slow Corrector
(Piston, Tip-Tilt)
Incoming Light
IR Light
Visible Light
IR Light
Incoming Light
Visible Light
Left Wavefront Sensor
Right Wavefront Sensor
Nulling and Imaging Camera (NIC)
2-2.4 and 8-13 um light
Imager
Nulling Interferometer
NOMIC (8-13 um)
3-5 um light
Phase Sensor (2-2.4 um)
LMIRCam (3-5 um)

Nulling Implementation









Chromaticity of Null

Fraction of light remaining in nulled out put is given by

$$N(\lambda) = \frac{1 + \cos(\Phi(\lambda))}{2}$$

where

$$\Phi(\lambda) = \frac{\lambda_0}{4\lambda} + \frac{1}{4}$$

Level of suppression is good over only a narrow bandwidth.

Three fixes: Rotate one beam 180 degrees (Shao and Colavita)
Send one beam through focus (Gay and Rabbia)
Balance dispersion in air by dispersion in glass
(Angel, Burge and Woolf)

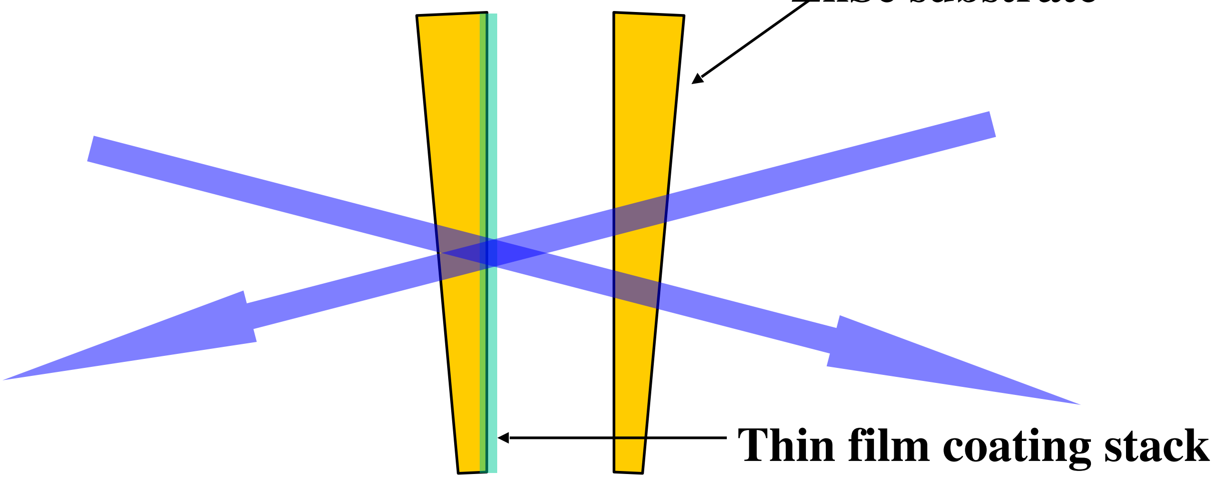
Dispersion Compensation allows out-of band light to be used to sense phase
(Angel and Woolf 1997)

Creating an Achromatic Null

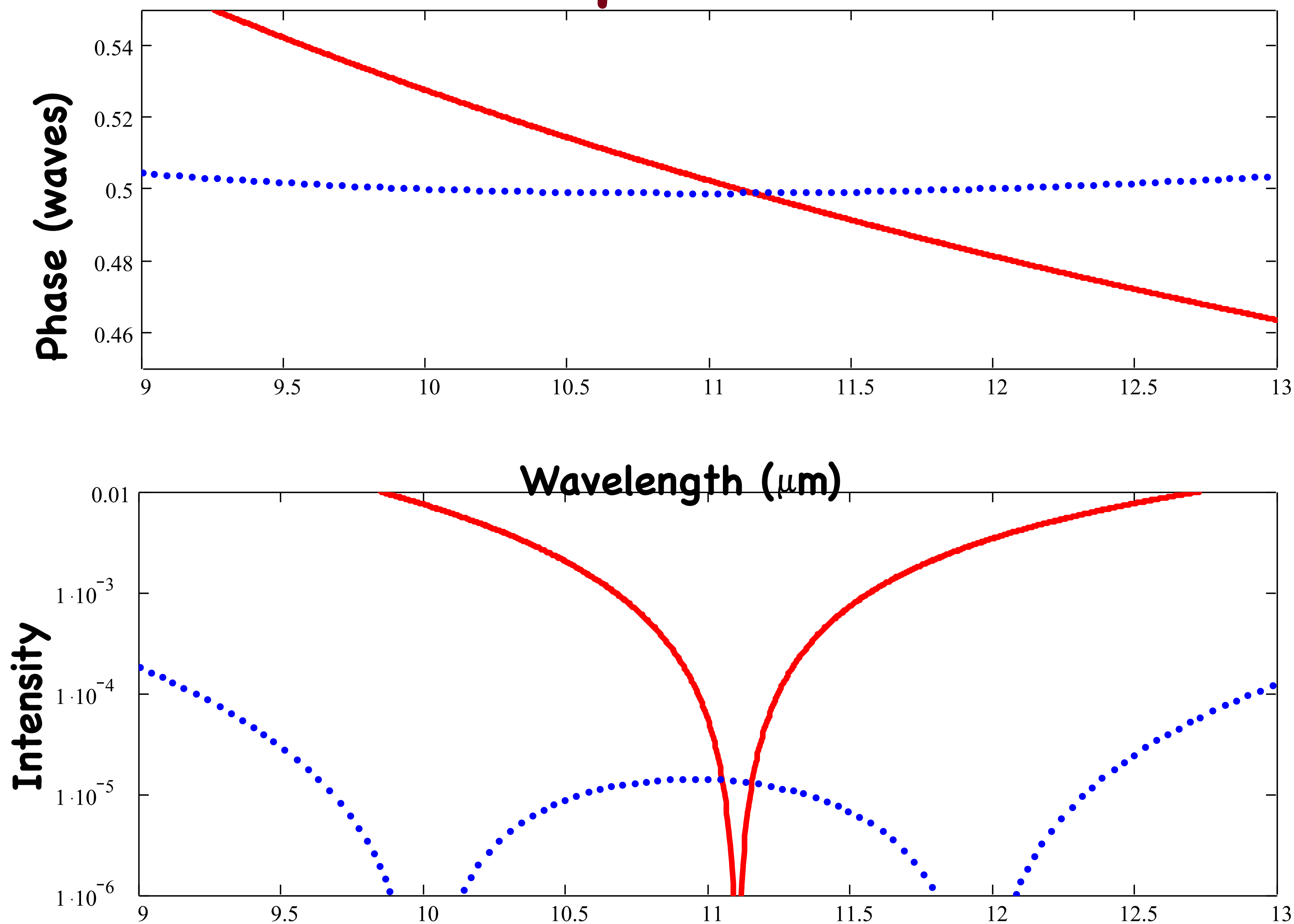
An null is created by introducing a 0.5 wave path difference between the two beams. This phase shift can be made achromatic by balancing a slight difference in path with an

Path difference: 51 μm

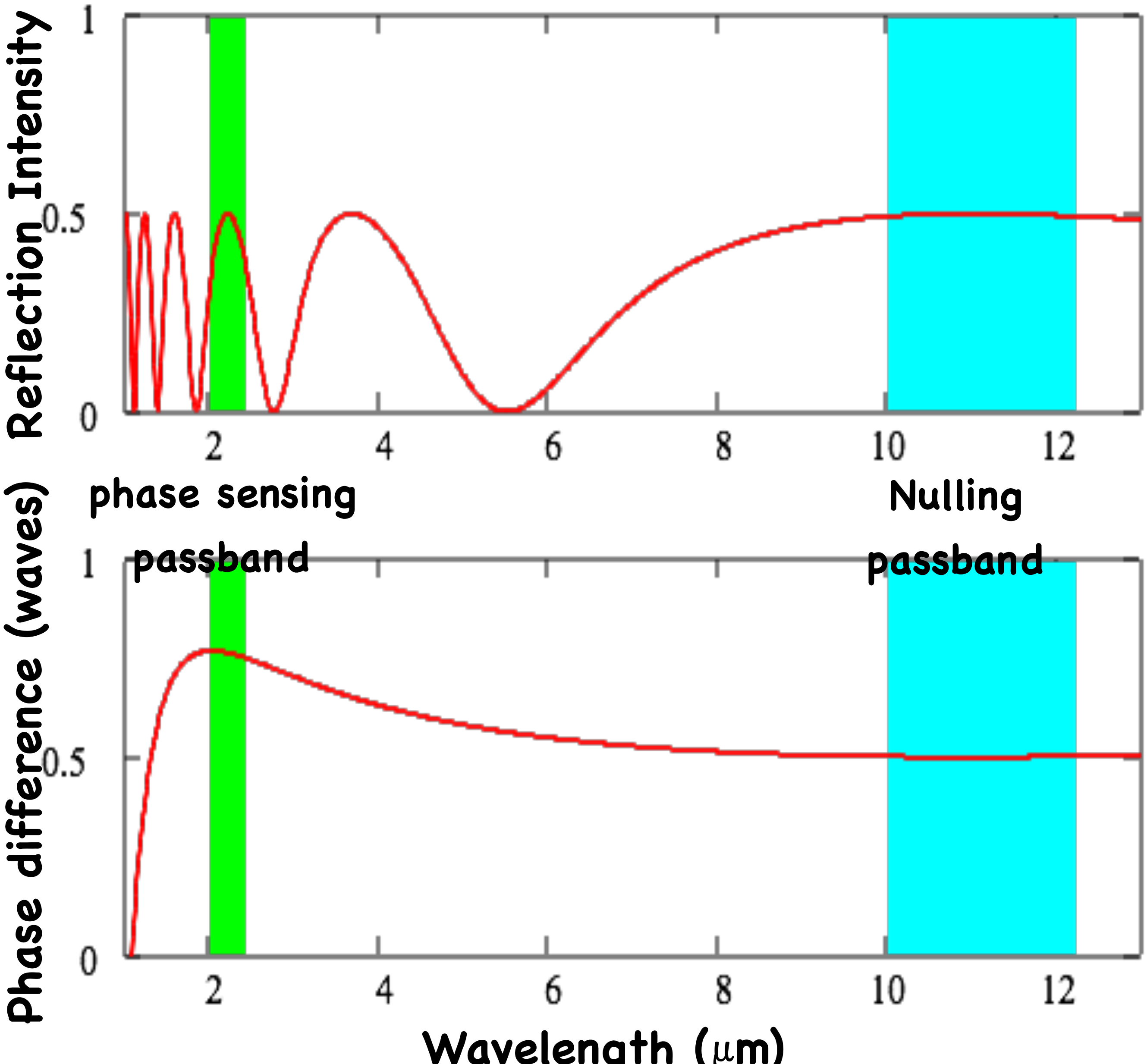
difference in substrate thickness: 21 μm



Phase Compensation of Null



Beam-Combiner Design



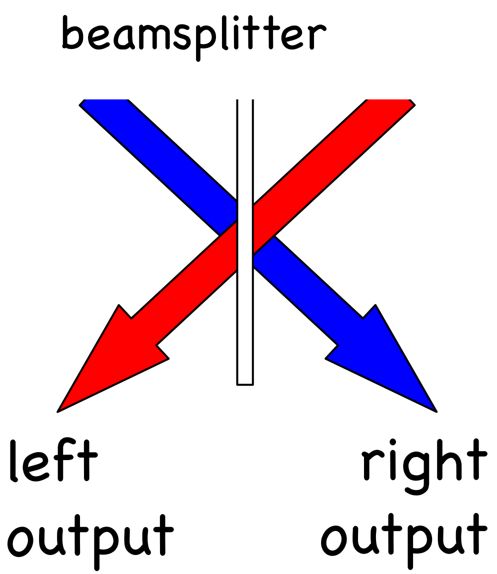
Thin film design creates 50% amplitude splitting in nulling and phase sensing bands.

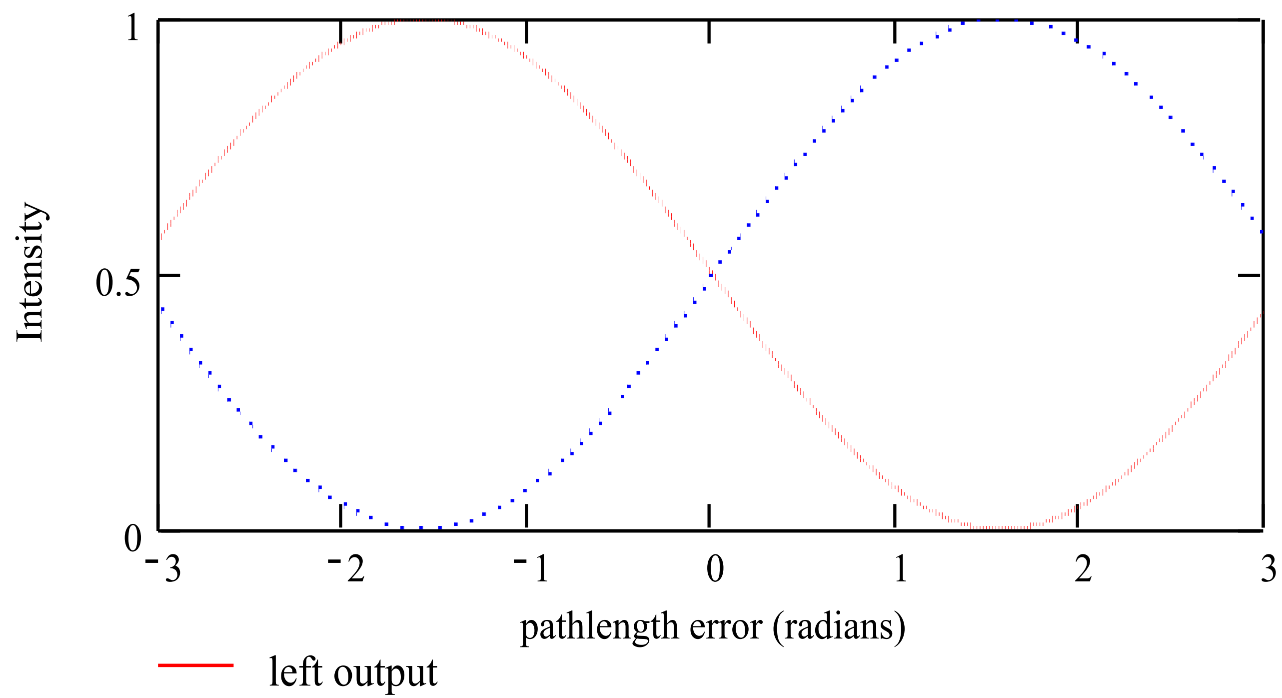
ΔI = 2 % between outputs for 2×10^{-5} null.

Differential thickness of glass creates 0.5 waves phase difference at 11 μm and 0.75 wave phase difference at 2 microns.

$\Delta\Phi$ = 0.5 degrees = 15 nm
for 2×10^{-5} null.

Phase Sensing Outputs





For a ¾ wave phase shift the outputs are approximately equal when the phase is correct.

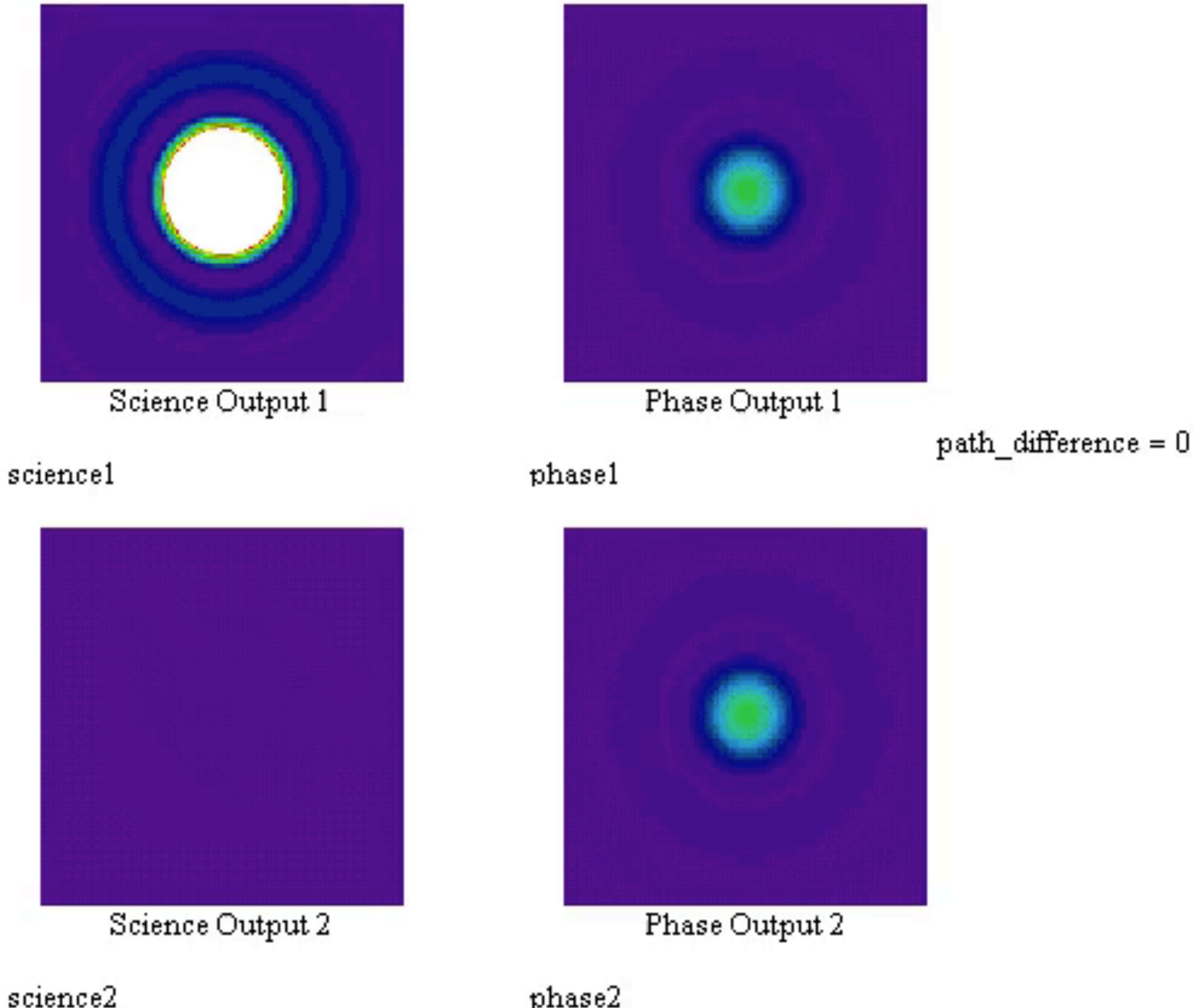
The difference of the outputs divided by the sum provides a sensitive error signal for pathlength variations, independent of variations in relative intensity.

Common-Path Phase Sensing and Correction

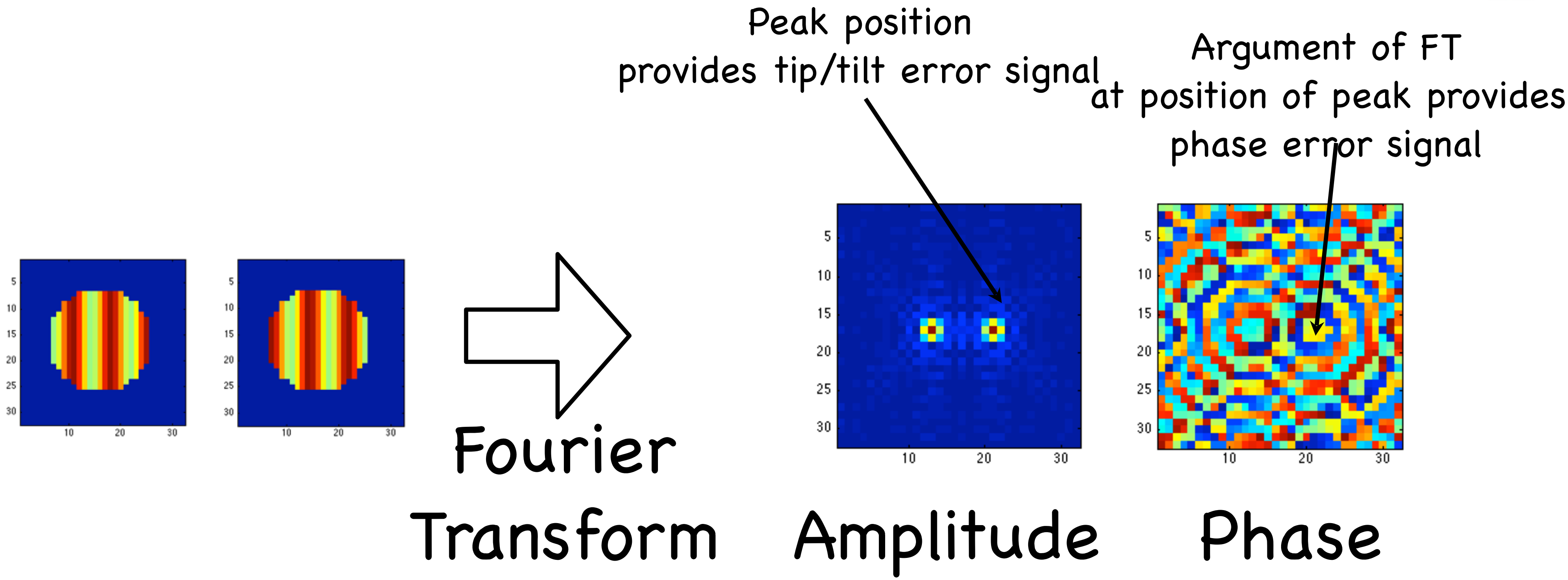
11 μm **2.2 μm**

Output 1

Output 2



Phasing Algorithm

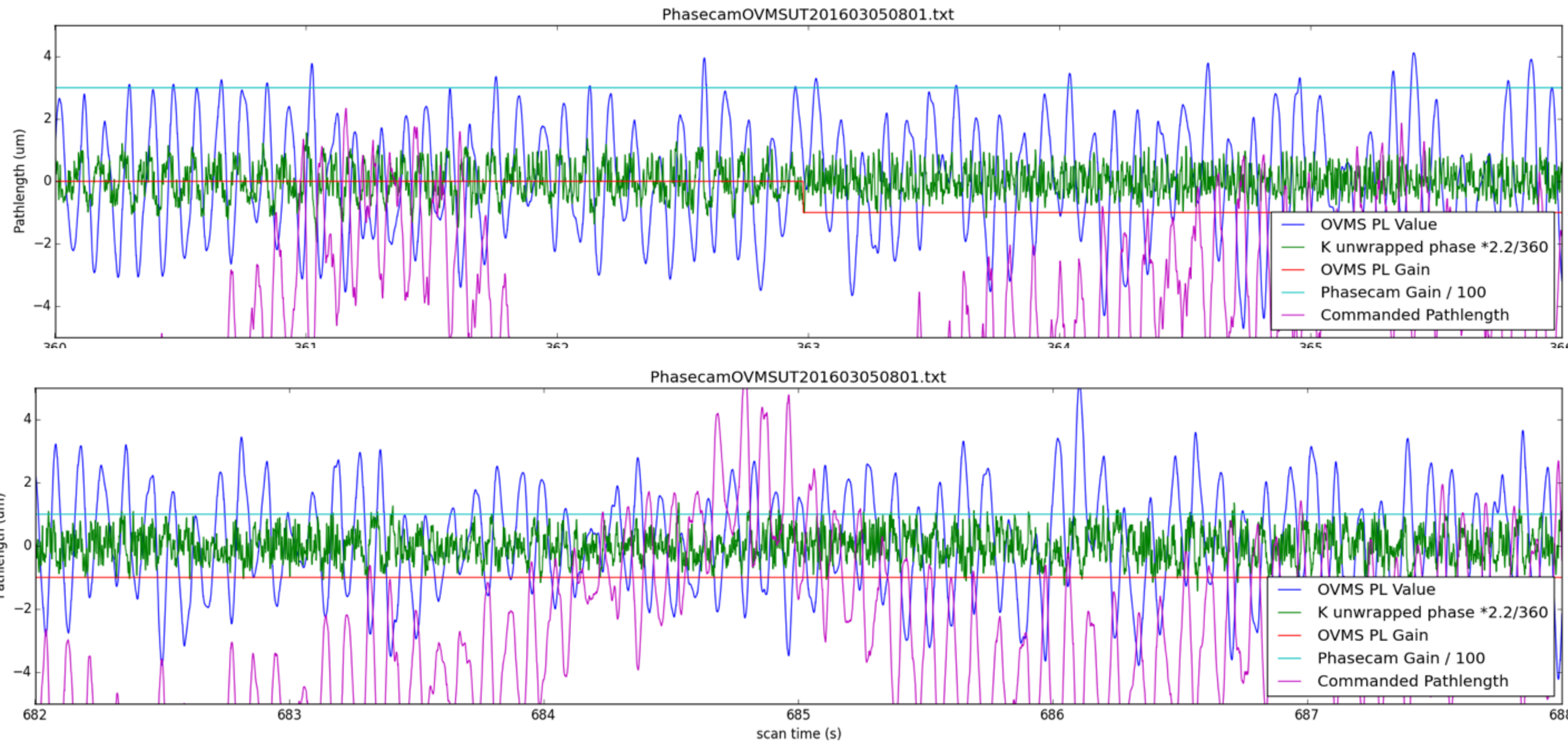


Create small pupil images

Introduce tilt difference.

Fourier Transform provide three observables: Φ, θ_{tip}, θ_{tilt}

Phase Tracking with LBTI



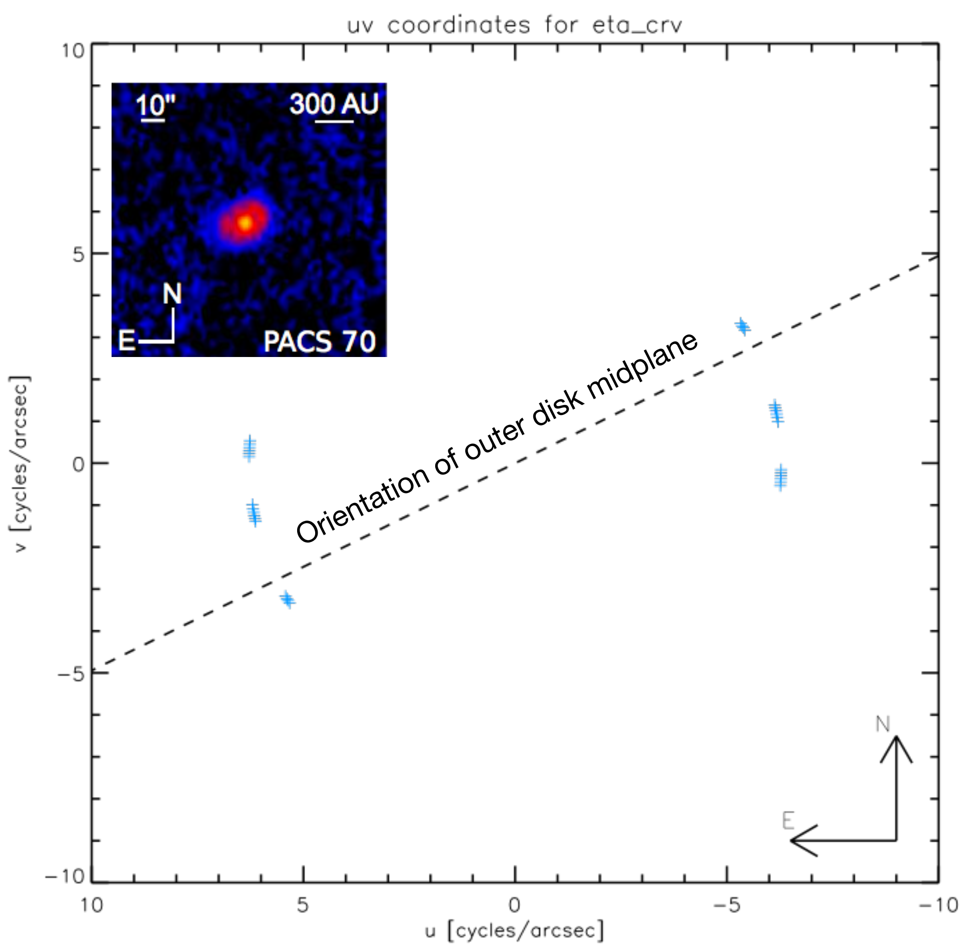
Feed-forward (FF) off vs. on

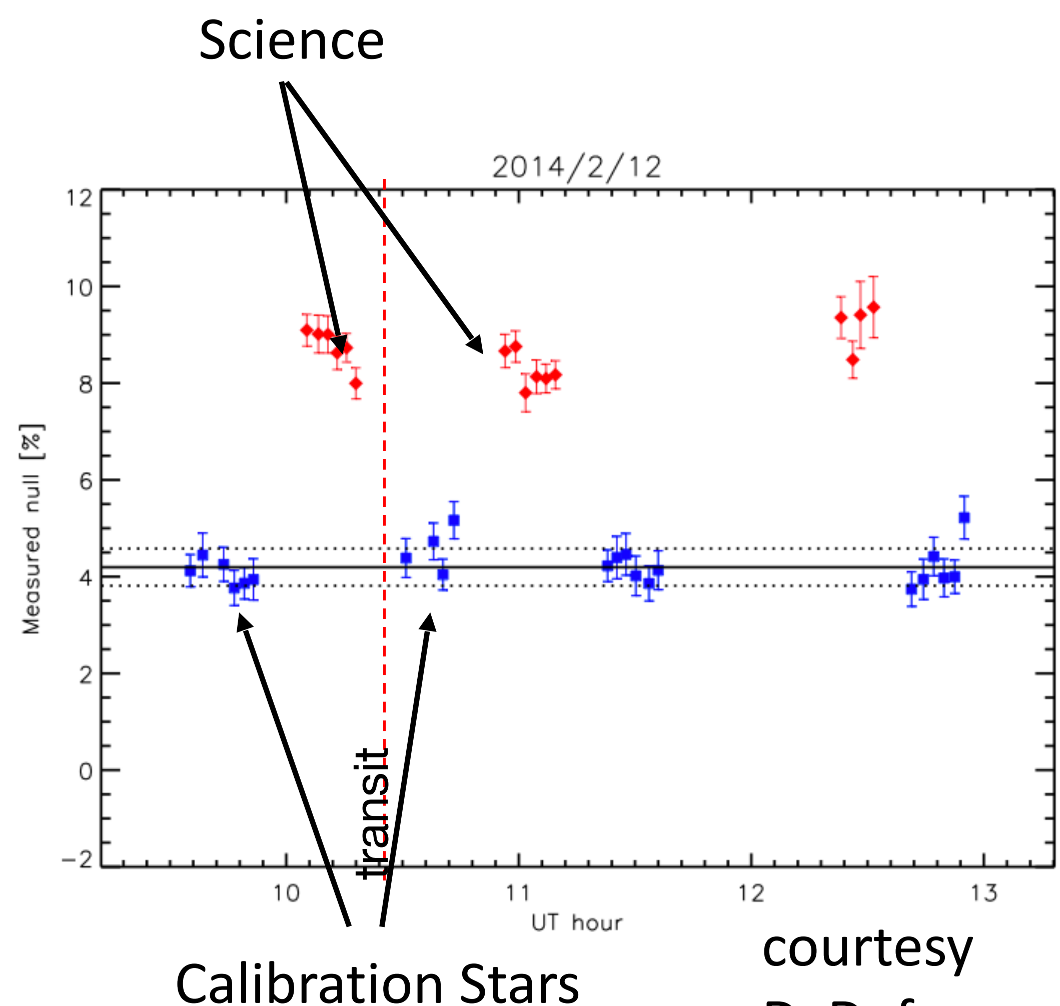
Phase corr. at low gain to show FF is working

- RMS was reduced from 95 deg. to 65 deg. when using OVMS+
- Still diagnosing low frequency transients that appeared other nights in FF signal.

Our first detection: η Crv

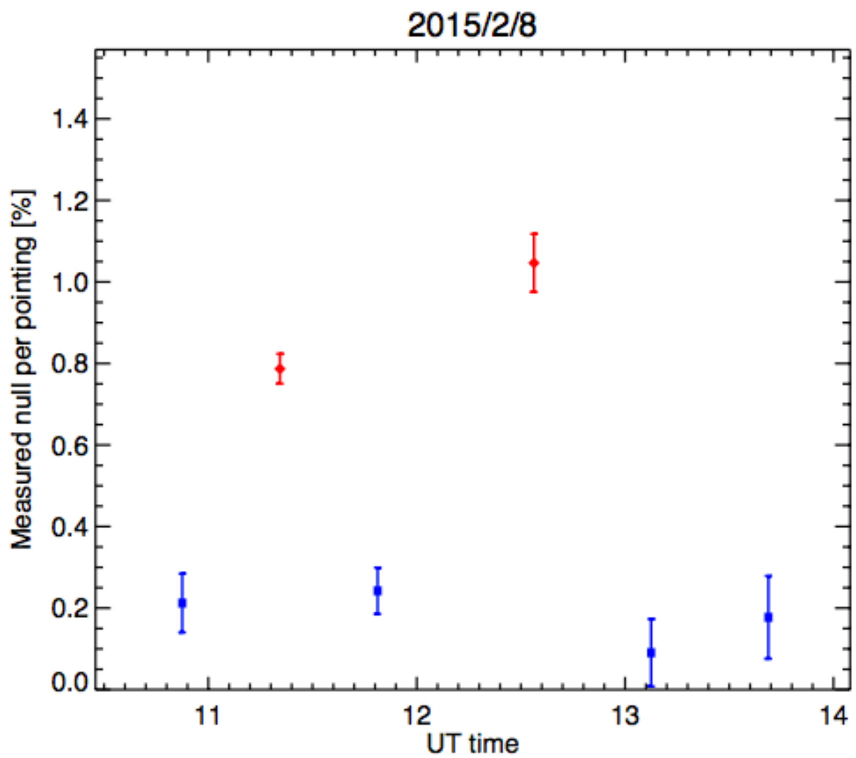
- 3 hours of nulling observations in February 2014 around transit;
- Outer disk seen by Herschel (i = 46.8°, PA = 116.3°, Duchene et al. 2014);
- Excess: 17% (IRS), 4% (KIN);

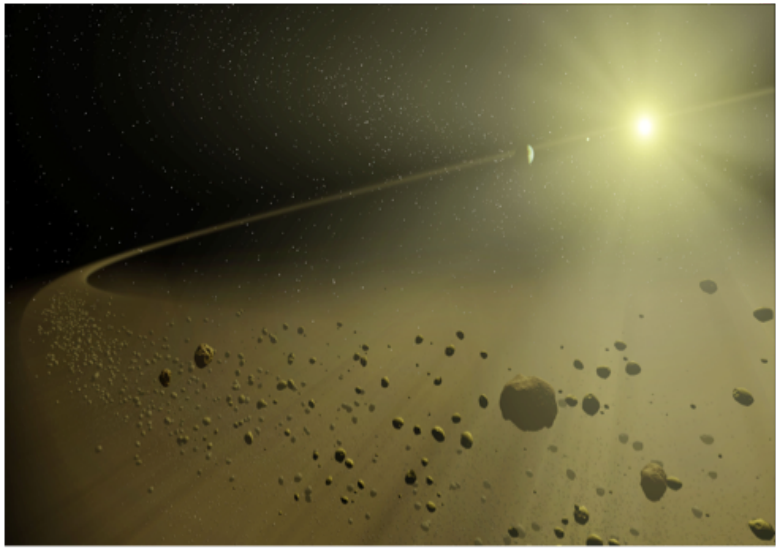




courtesy
D. Defrere

HOSTS Target 1: beta Leo





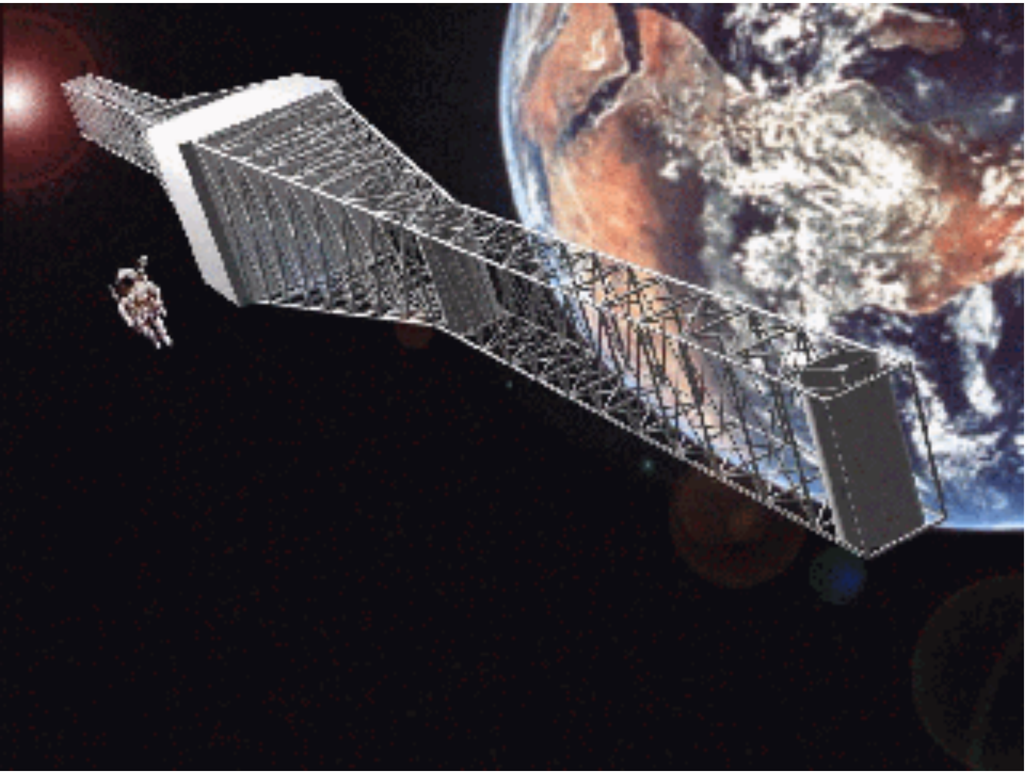
Commissioning tests on the star β Leo detected a disk at the level of 6000±500 ppm.

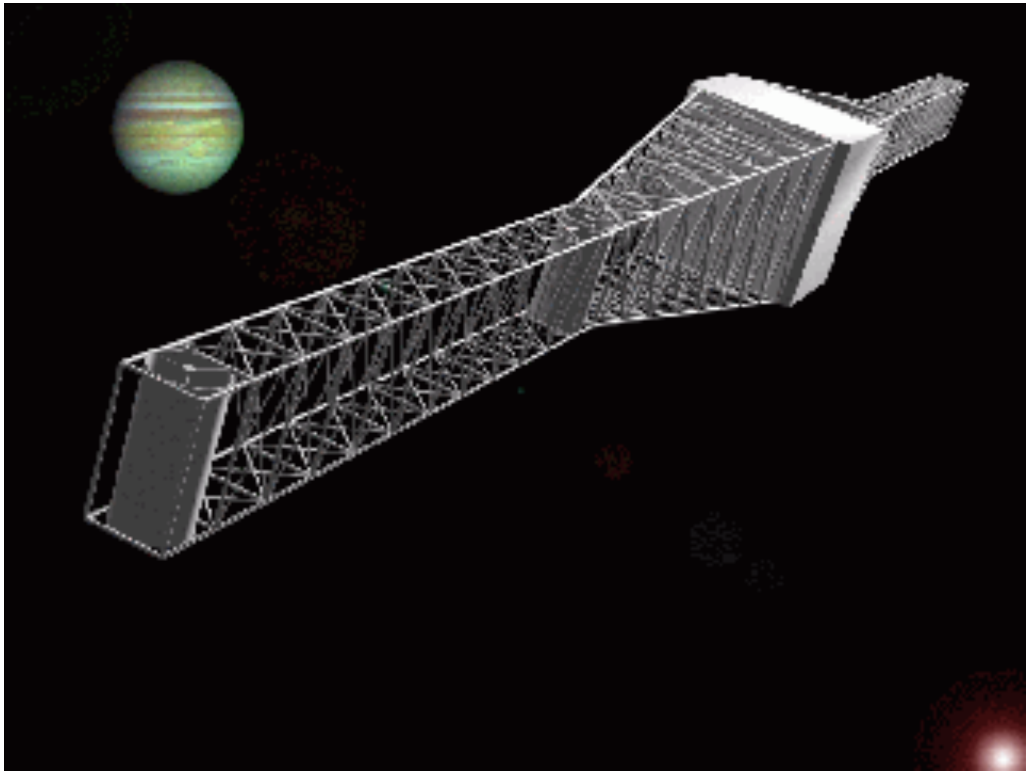
This corresponds to a disk that is **90 ± 8 zodi.**

Cold disk known from Herschel to be at R=40 AU.

11 μm emission detected by LBTI is likely at ~4 AU.

Nulling Interferometry: Space-based

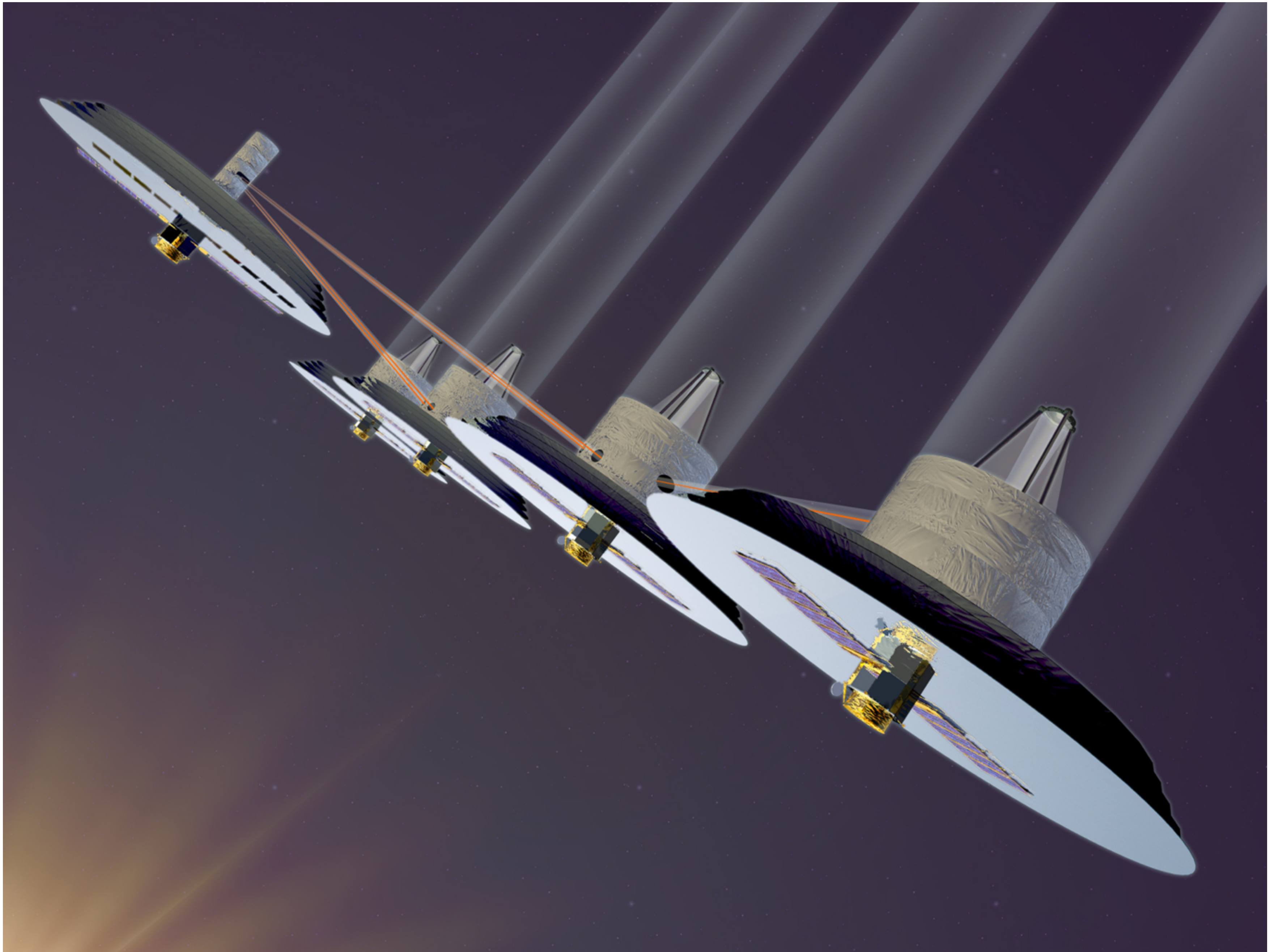




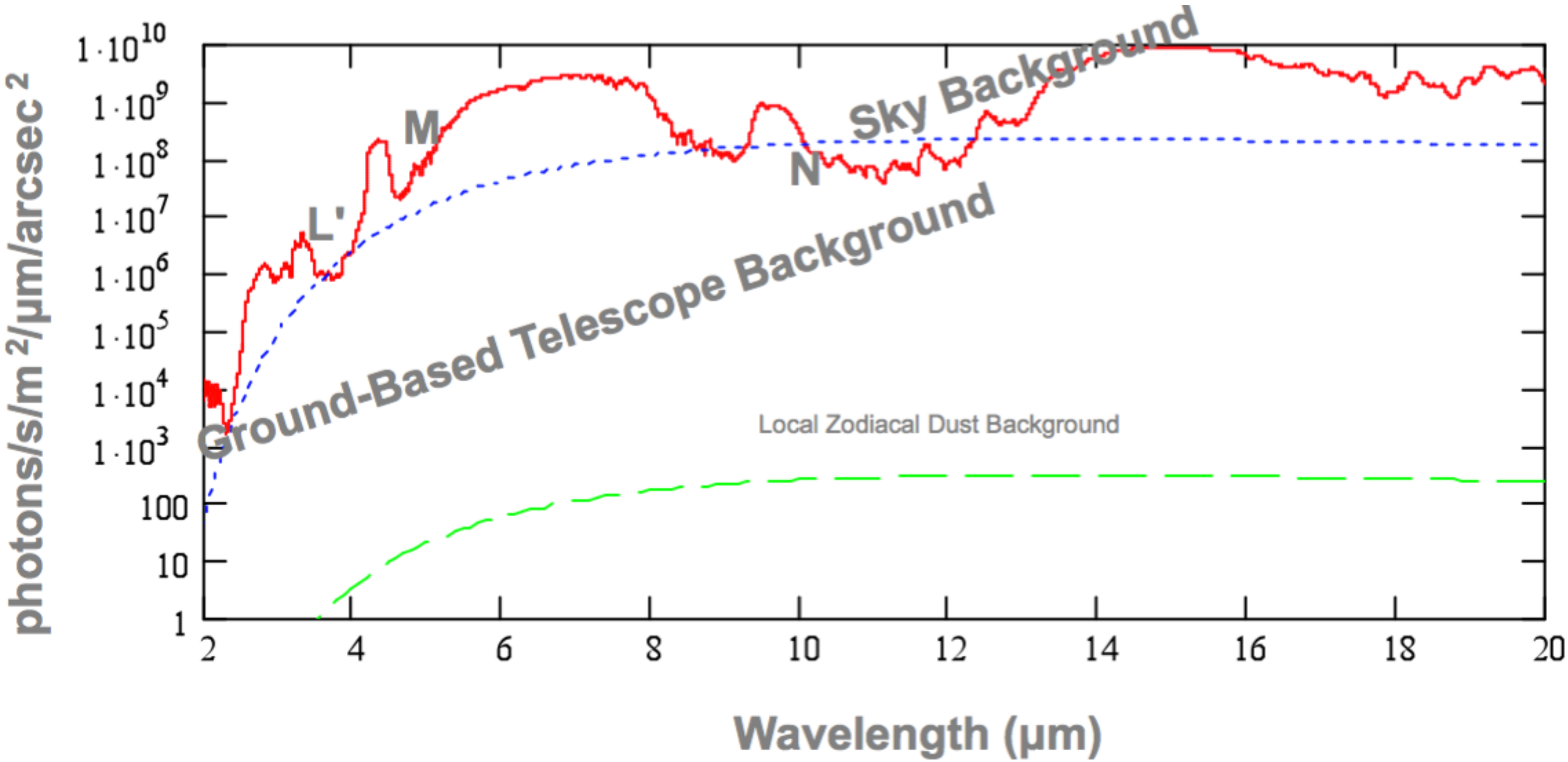
NASA studied using nulling interferometry in 1990's and 2000's. They developed a telescope design to search
for terrestrial planets, and probe them for life. The mission was called Terrestrial Planet Finder Interferometer.

Further studies have suggested a coronagraph or occulter will be more cost-effective and versatile.

Nulling Interferometry: Space-based



Why from space?



Space-based telescope gives $>10^6$ reduction in background light.
=> Collecting area can be $<10^{-3}$ of ground based system.

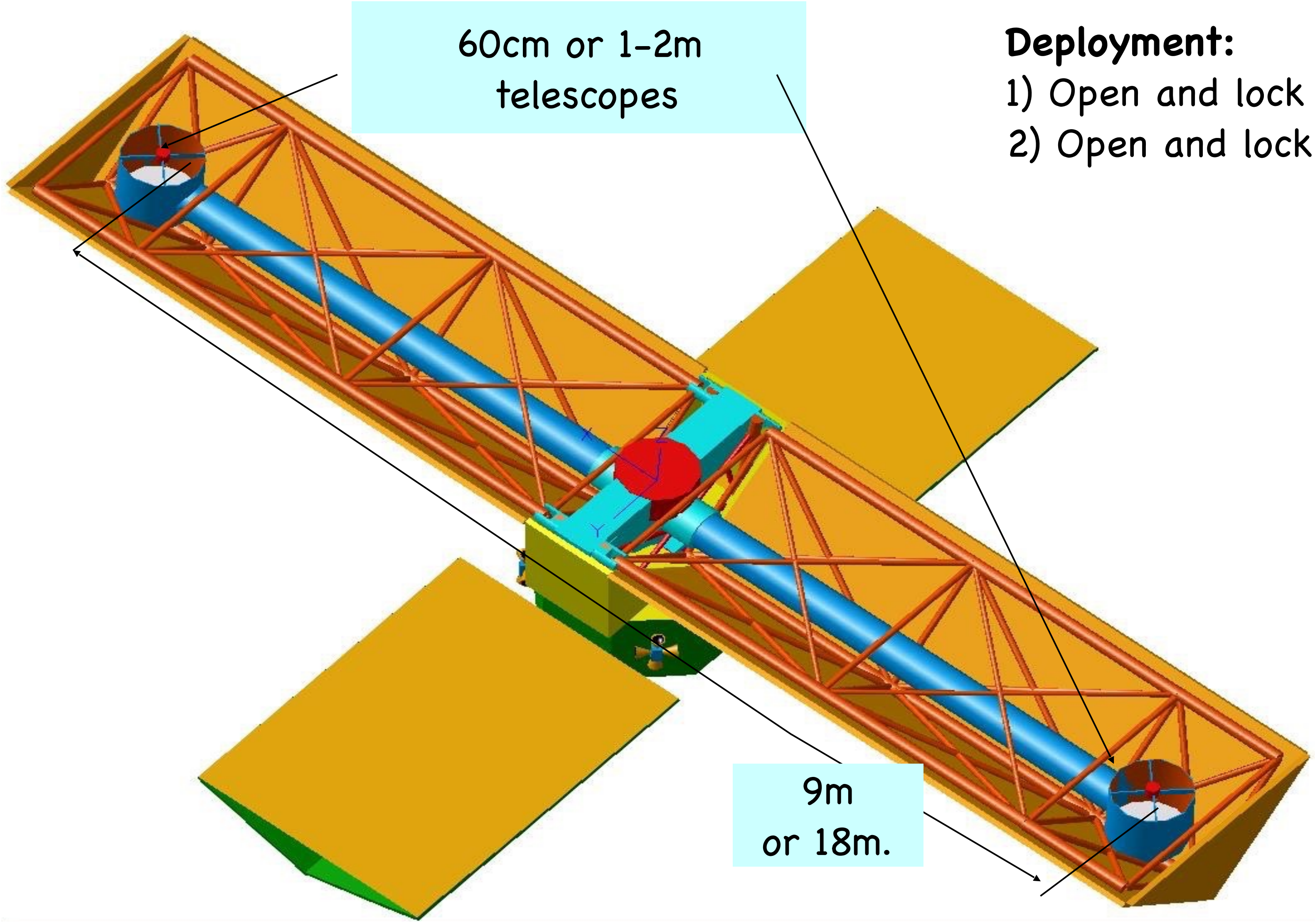
Why an interferometer?

Need resolution < 0.1 arcsec to spatially resolve a planetary system. (10 m at 10 μm)

Only need a couple of meters^2 collecting area for cooled space-based system to get detectable flux from planet (1 photon/s/micron, in the presence of 100 photons/s of background).

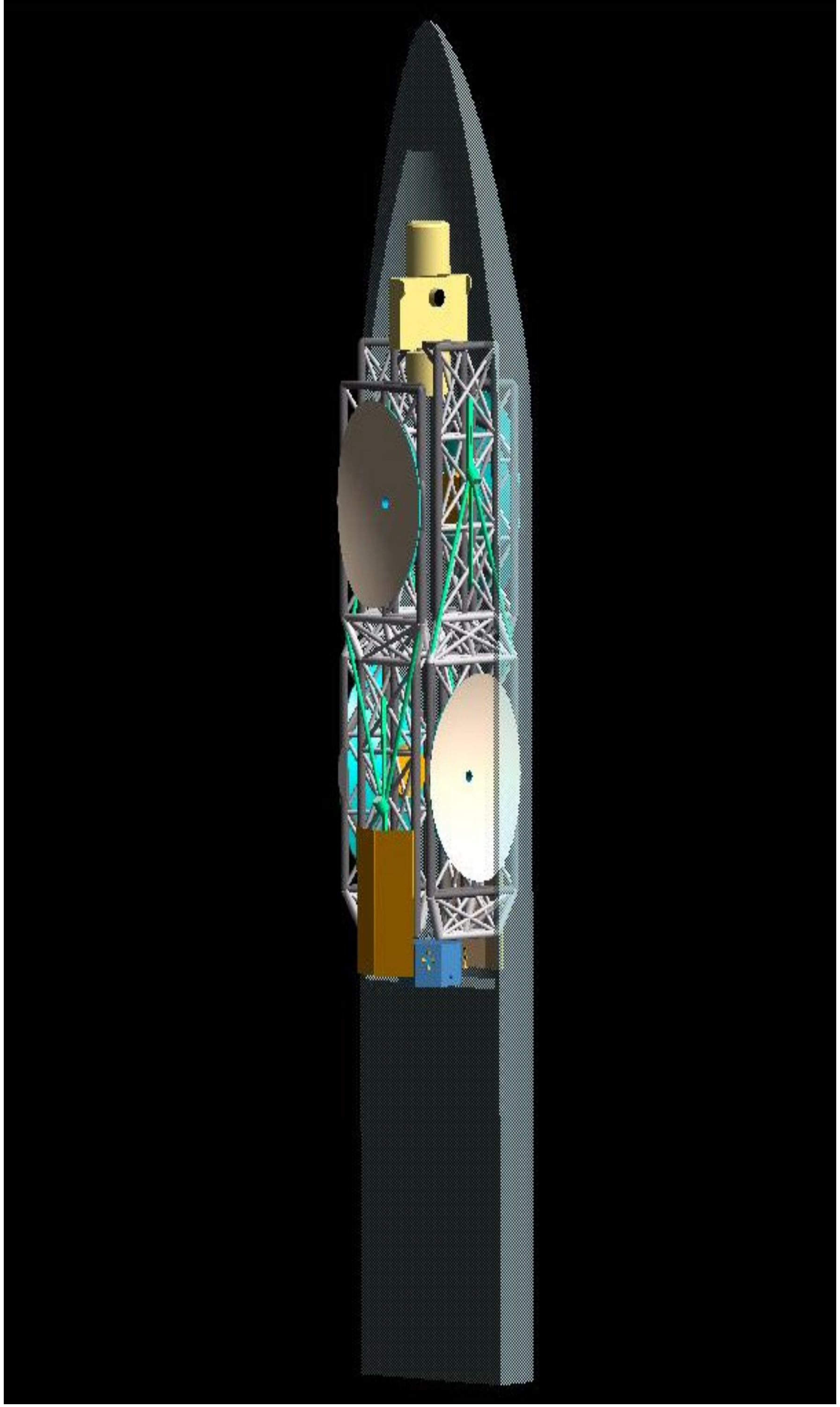
9m nuller
folded in
Delta II
rocket
shroud

Small Interferometer deployment



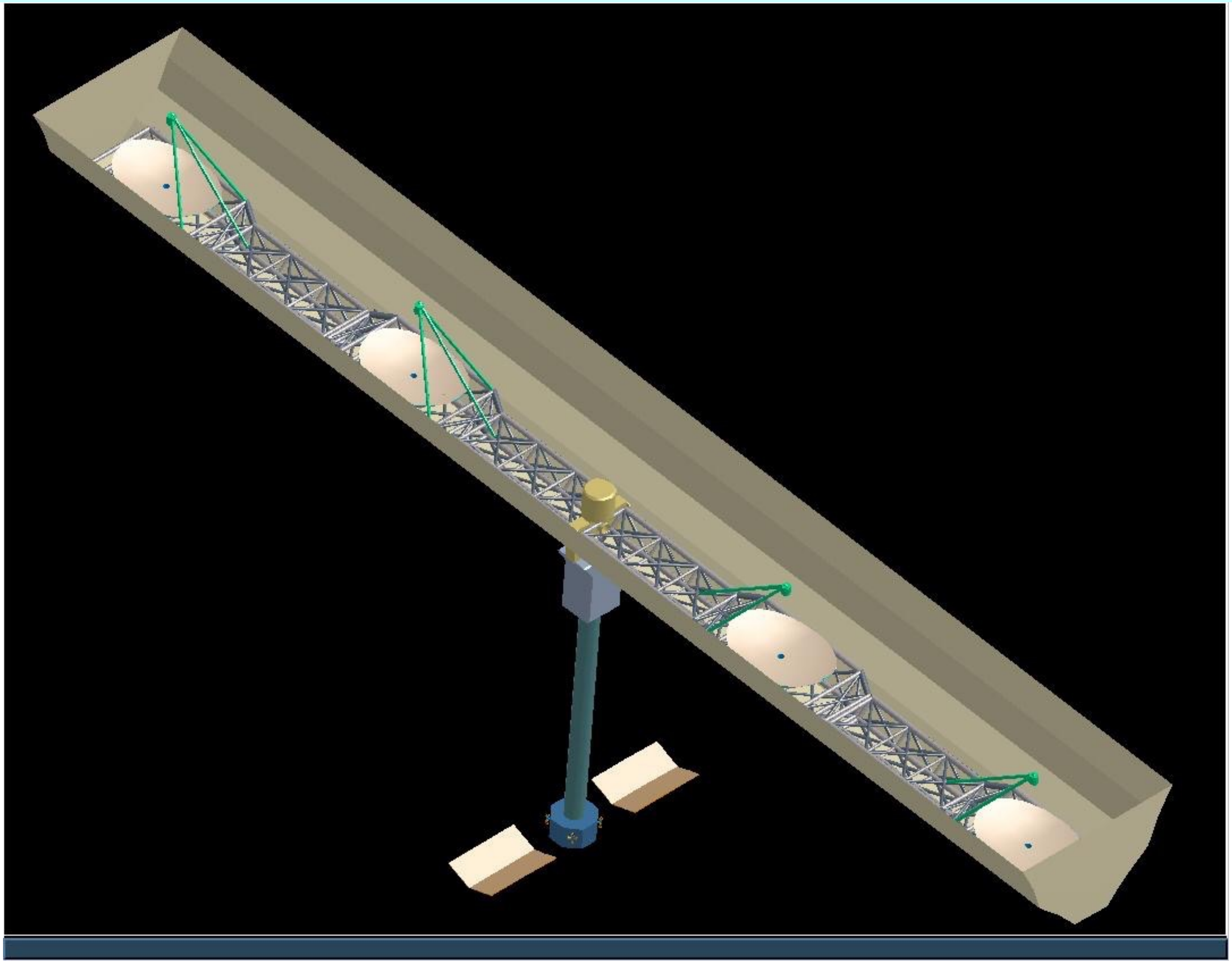
Deployment:

1) Open and lock solar panels.
2) Open and lock truss

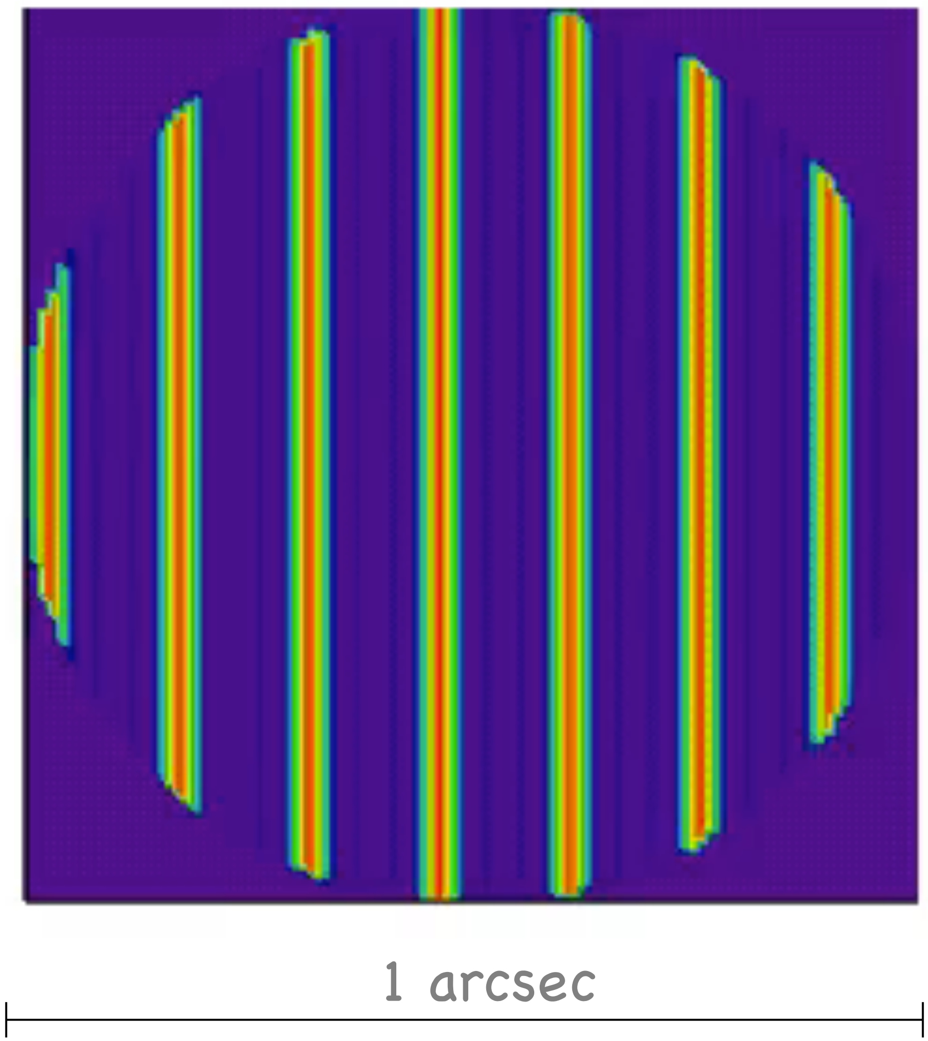


40m TPF folded in an Atlas V rocket shroud

TPF truss nuller ready for use



TPF Transmission Pattern

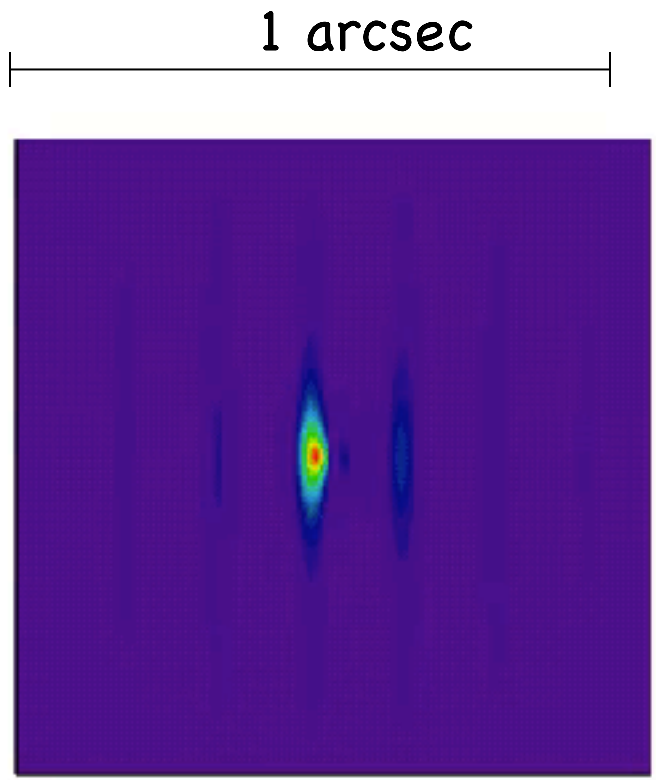


Interferometer rotates about its pointing center to rotate the beam pattern about the star.

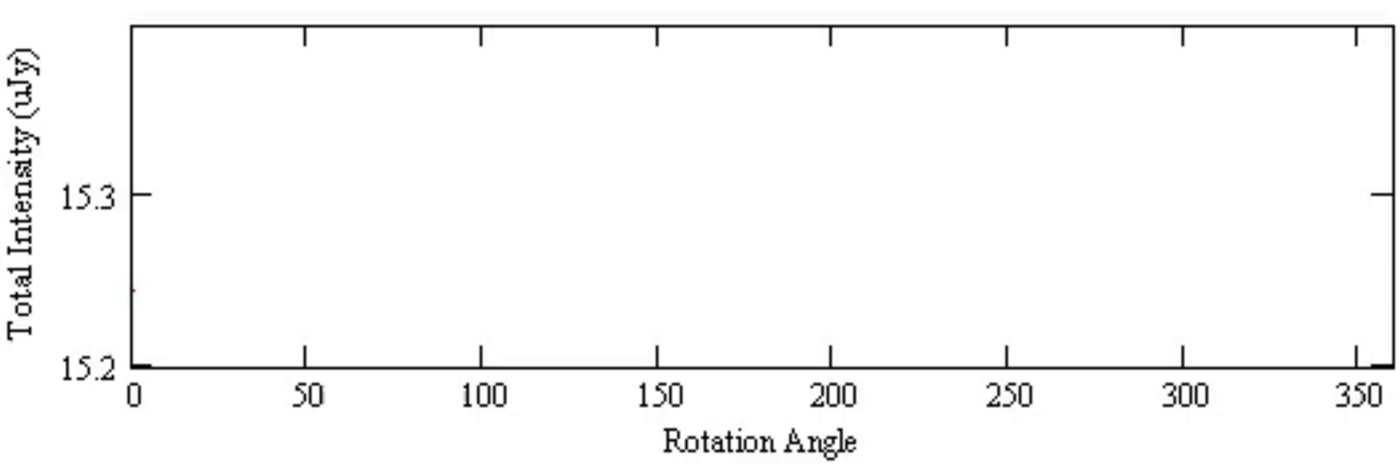
Planet Signals are modulated by rotation.

Detected Signal is the sum of all the light transmitted through the beam pattern.

Signal from an Earth-like Planet

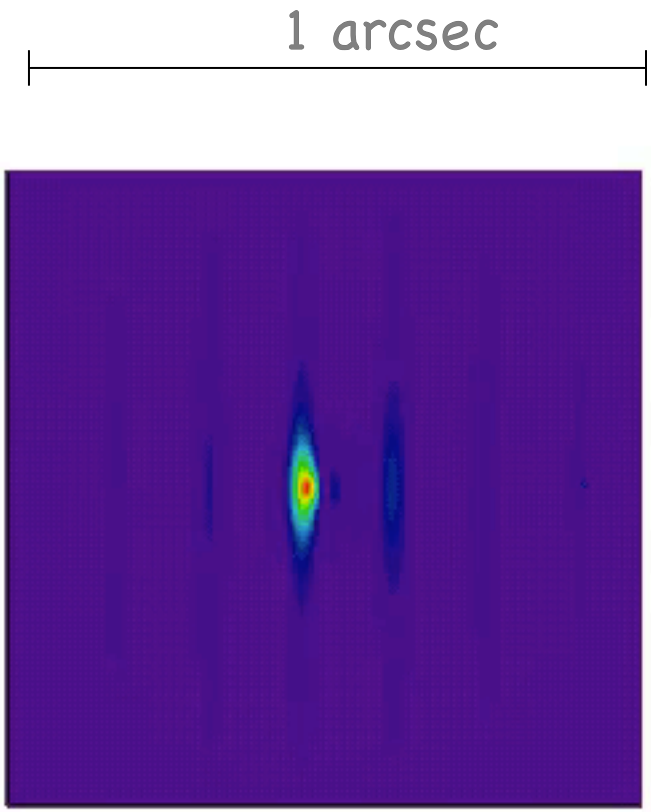


TPF

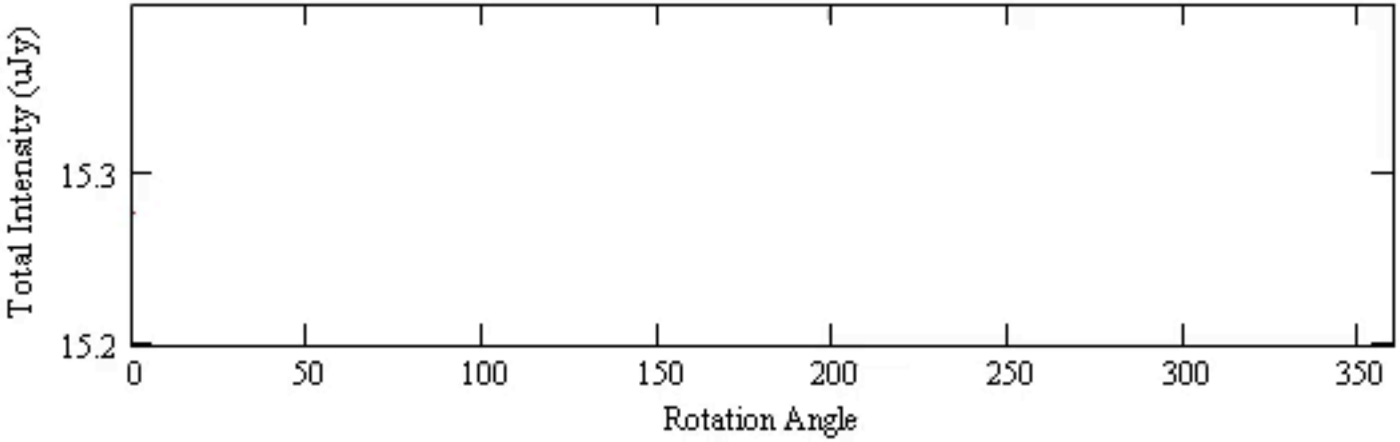


Detected signal in TPF beam-combiner.

Signal from a system of planets

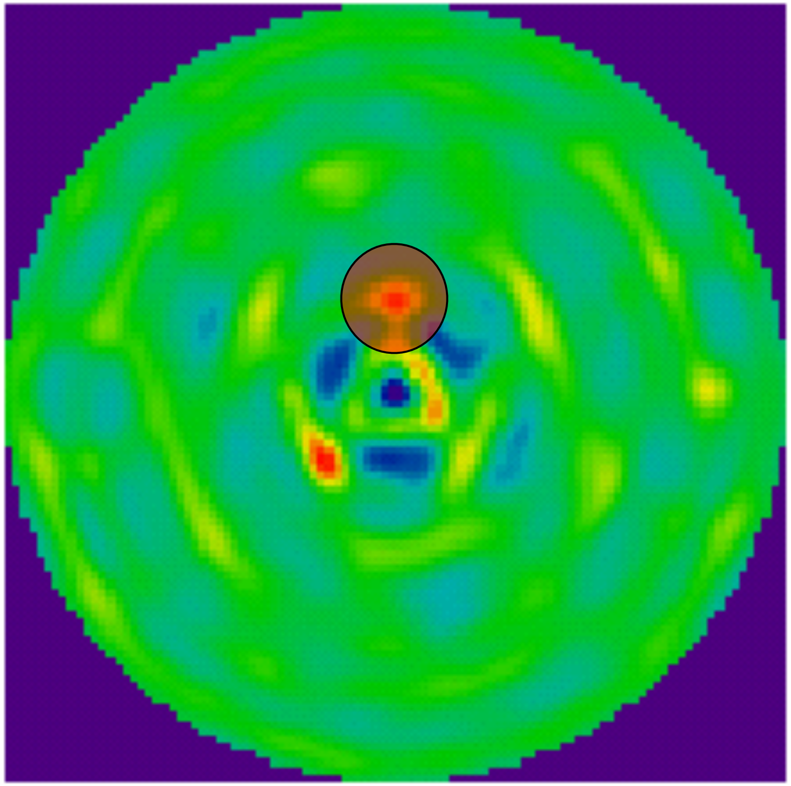


TPF



Signal of Earth,
Venus and Jupiter.

Reconstruction of the Image



Intensity of a given position is the sum of the signal as a function of rotation times the beam pattern transmission for that rotation

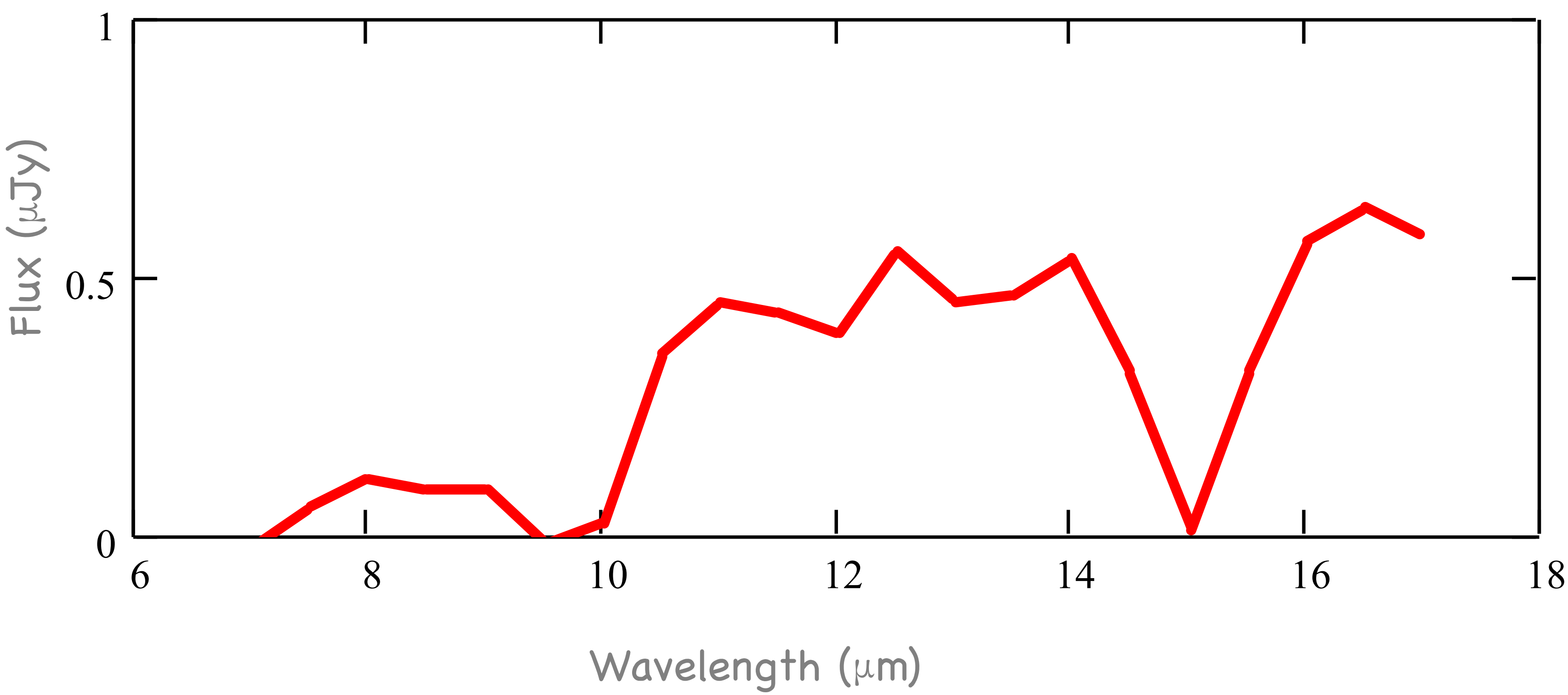
Raw image shows the prominent sources plus artifacts.

Algorithm similar to CLEAN can be used to form a higher fidelity image.

An image can be generated for each channel of the instrument spectrometer. This results in a spectrum for each point source

Extracting the Spectra

Each wavelength channel allows a similar image reconstruction, and a measurement of the flux in that channel. The spectrometer will have a resolution of R=20.



Which planet does it resemble (if any)?