Theory and Early Results from the Large Binocular Telescope Interferometer

2014 Sagan Exoplanet Summer Workshop
Imaging planets and disks

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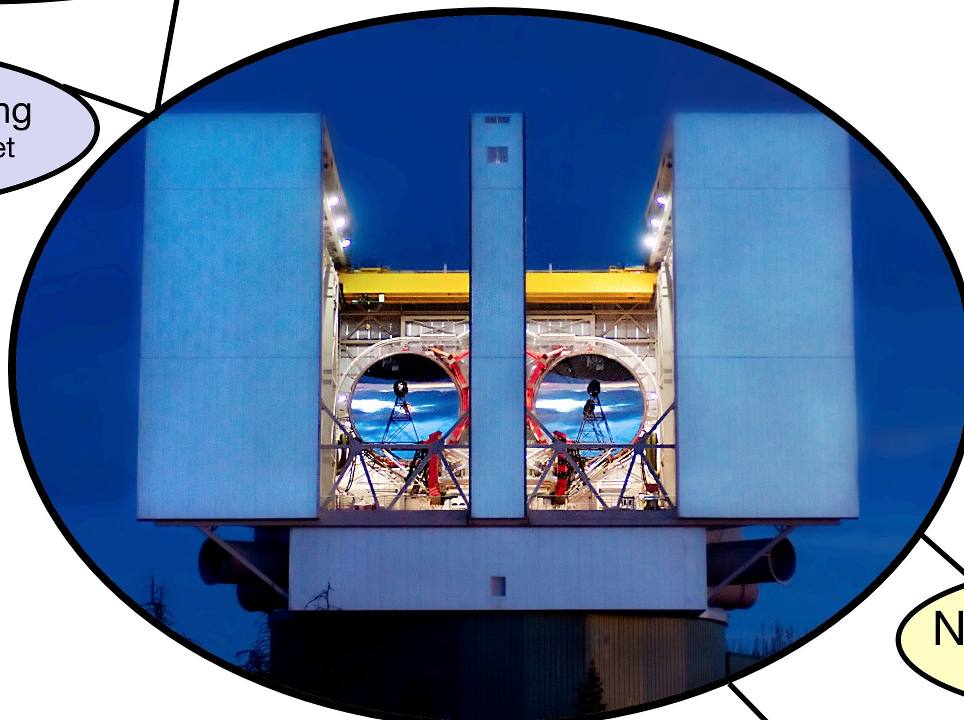
Acknowledgments:
P. Hinz, A. Skemer, R. Millan-Gabet, C. Haniff, and B. Mennesson.

Preamble

High-contrast AO imaging
Theory covered by J. Kasdin

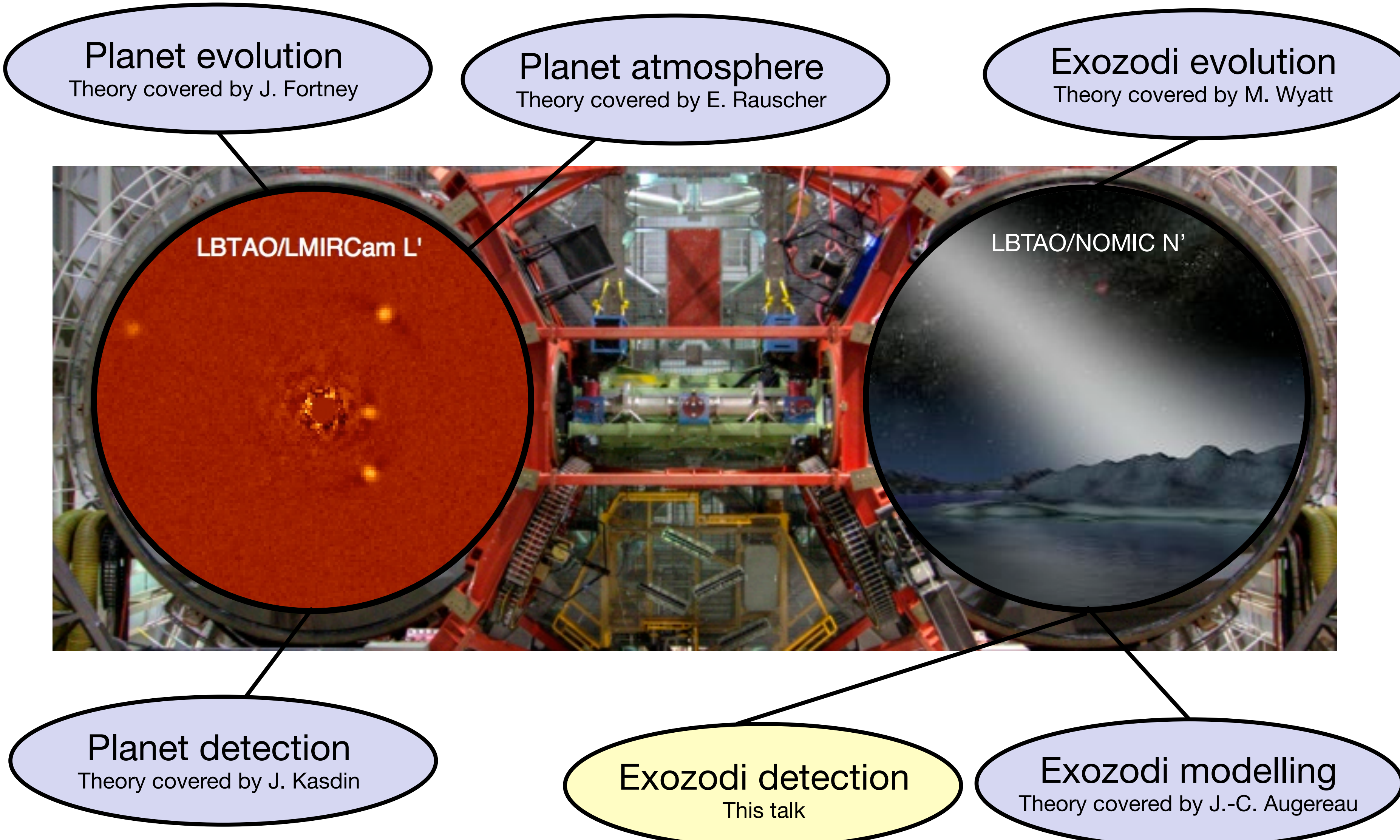
High-contrast AO imaging
Concept covered by D. Mawet

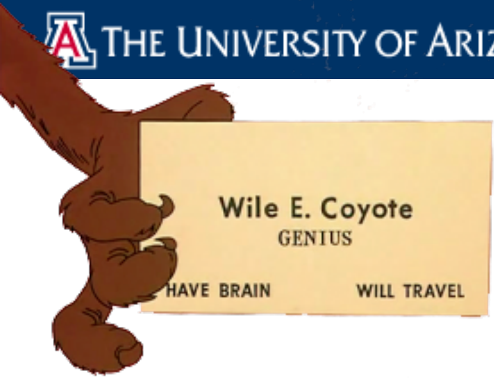


Nulling interferometry
This talk

NRM/Fizeau interferometry
Theory covered by J. Monnier

Preamble 2


Planet evolution
Theory covered by J. Fortney
Planet atmosphere
Theory covered by E. Rauscher
Exozodi evolution
Theory covered by M. Wyatt
LBTAO/LMIRCam L'
LBTAO/NOMIC N'
Planet detection
Theory covered by J. Kasdin
Exozodi detection
This talk
Exozodi modelling
Theory covered by J.-C. Augereau



Preamble 3

- Learning interferometry is like learning any new skill (e.g. walking):
  - You have to want to learn
  - You start by crawling, then you walk, then you run.
  - Having fancy shoes doesn't help at the start.
  - You don't have to know how shoes are made.
  - At some stage you need to know what direction to head off in.

- This is a school:
  - You should assume nothing.
  - Knowing what questions to ask is what is important.
  - Please ask, again and again if necessary – especially at the start.

- I am not here to sell interferometry, I'm here to help you understand it.

Outline

- What is nulling interferometry?
  - Theory -- how does it work?
  - History and scientific motivations -- what is it for?
- The Large Binocular Telescope Interferometer
  - Concept and instrument specificities
  - Main scientific goals
  - First results
- Summary and quiz

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What is light?

Interferometry: basic principles

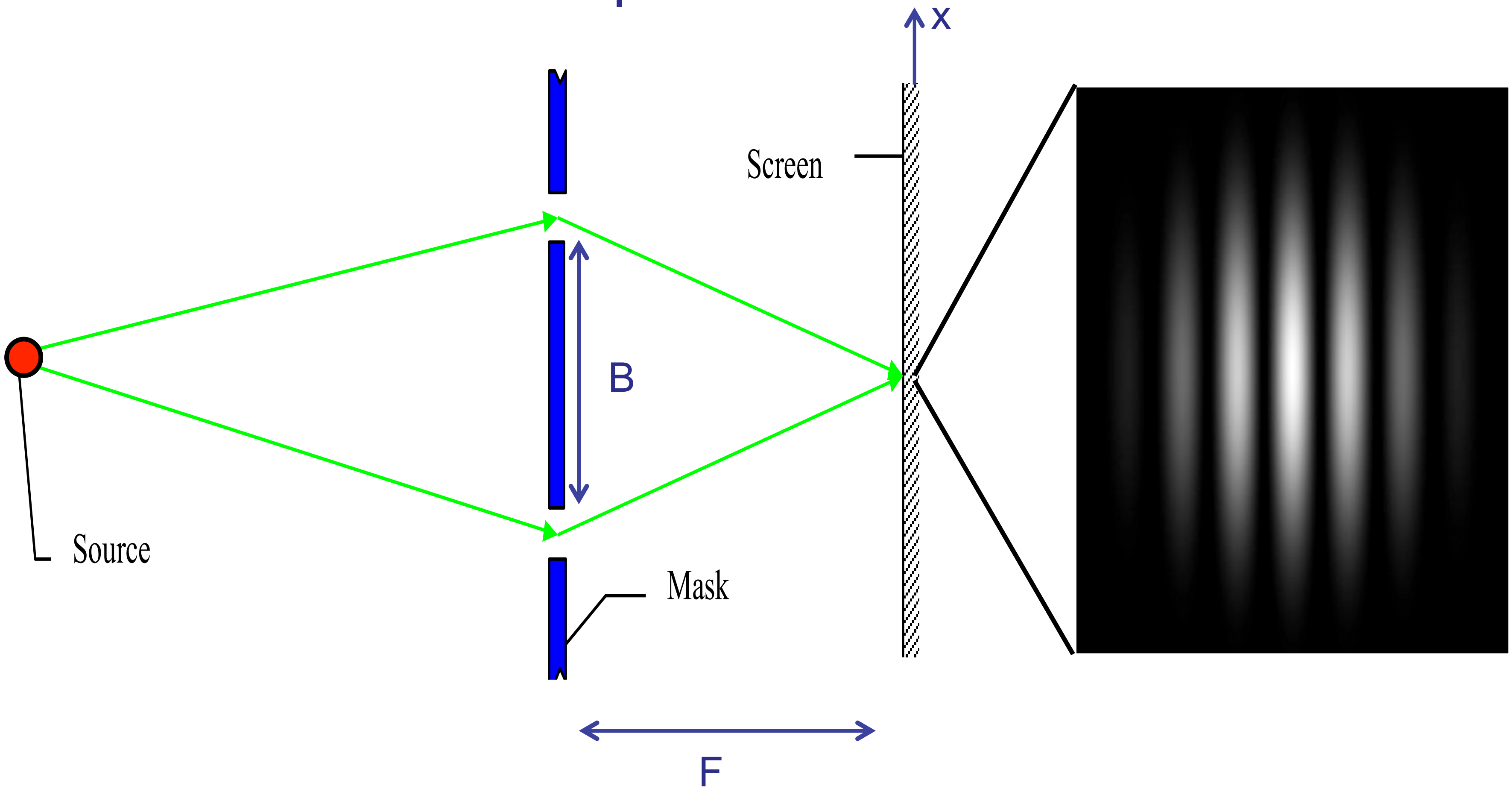
- What is light?

  - 1704: Newton. Corpuscular Theory of Light: light is a stream of small particles, because it:
    - travels in straight lines at great speeds
    - is reflected from mirrors in a predictable way

  - 1802: Young. Wave Theory of Light: light is a wave because it undergoes diffraction and interference (Young's double-slit experiment)

Interferometry: basic principles

- The double-slit experiment:



Interferometry: basic principles

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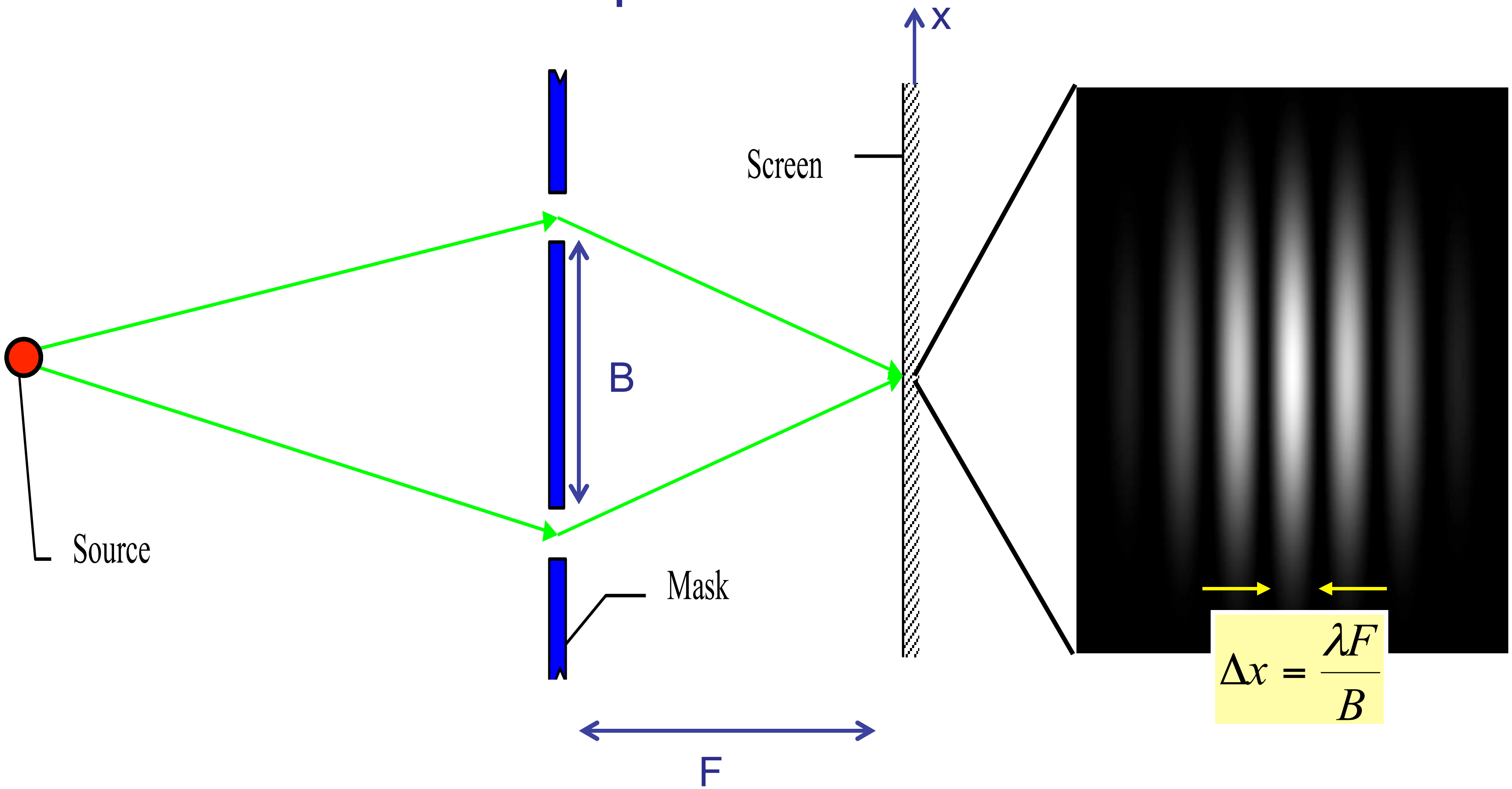


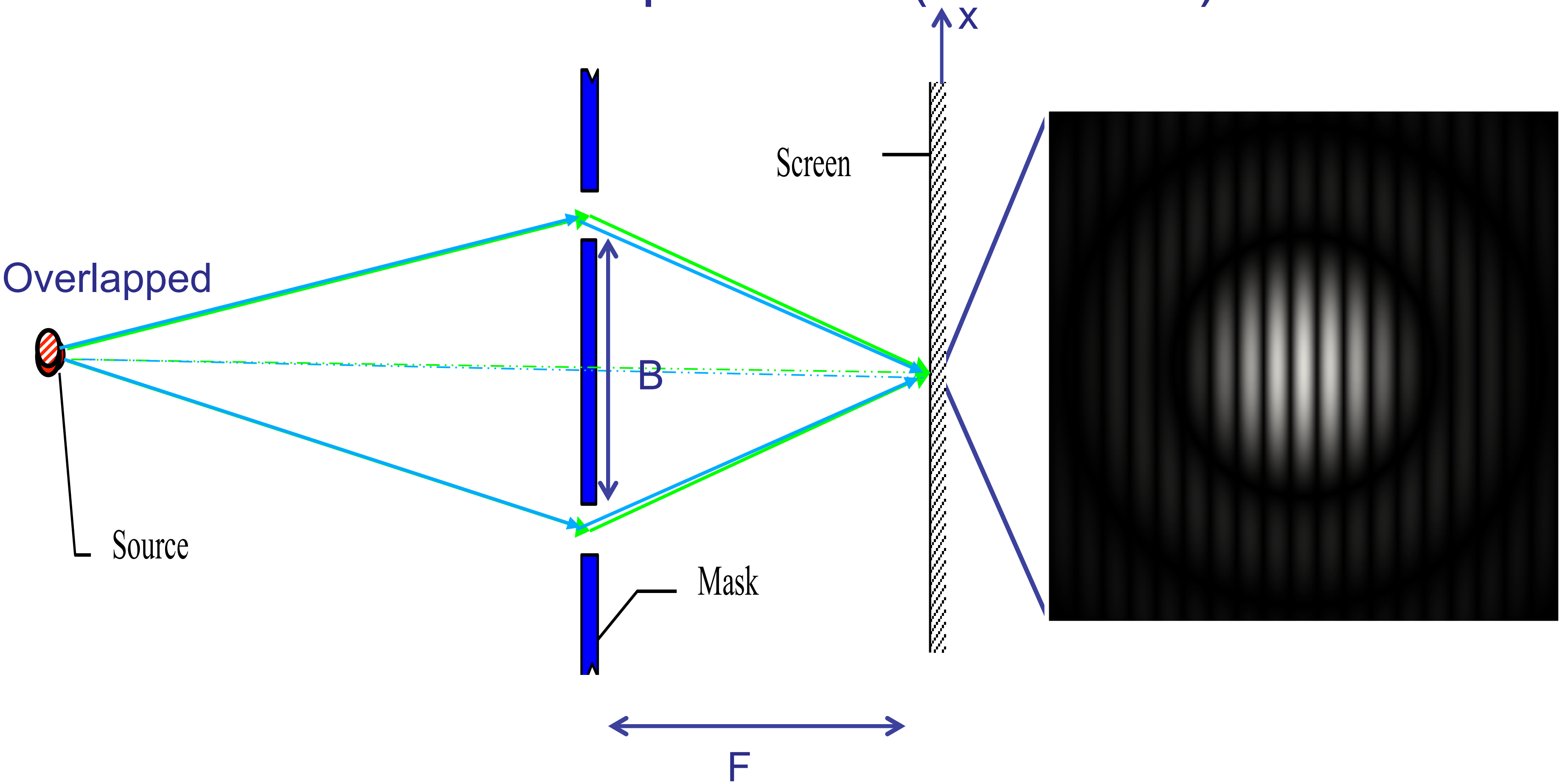
Interferometry: basic principles

- The double-slit experiment: analogy

Movie sequence from Veritasium (www.youtube.com/user/1veritasium)

Interferometry: basic principles

- The double-slit experiment (2 sources):



Interferometry: basic principles

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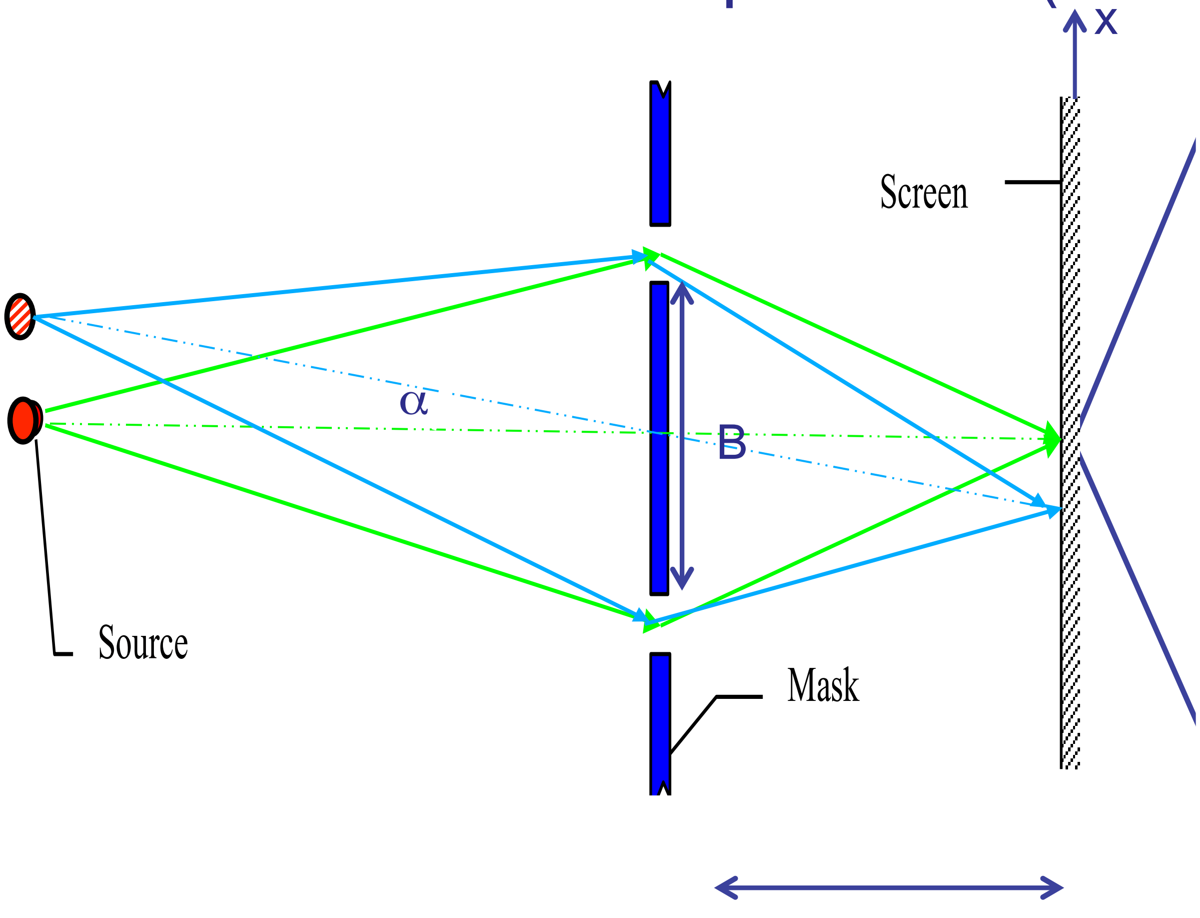
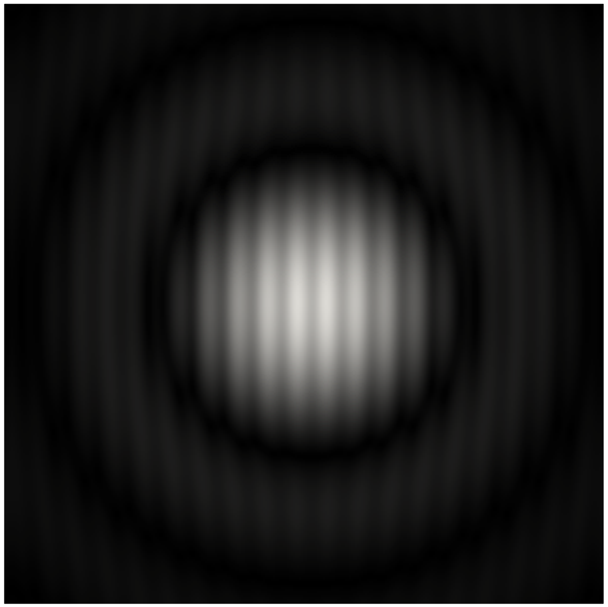


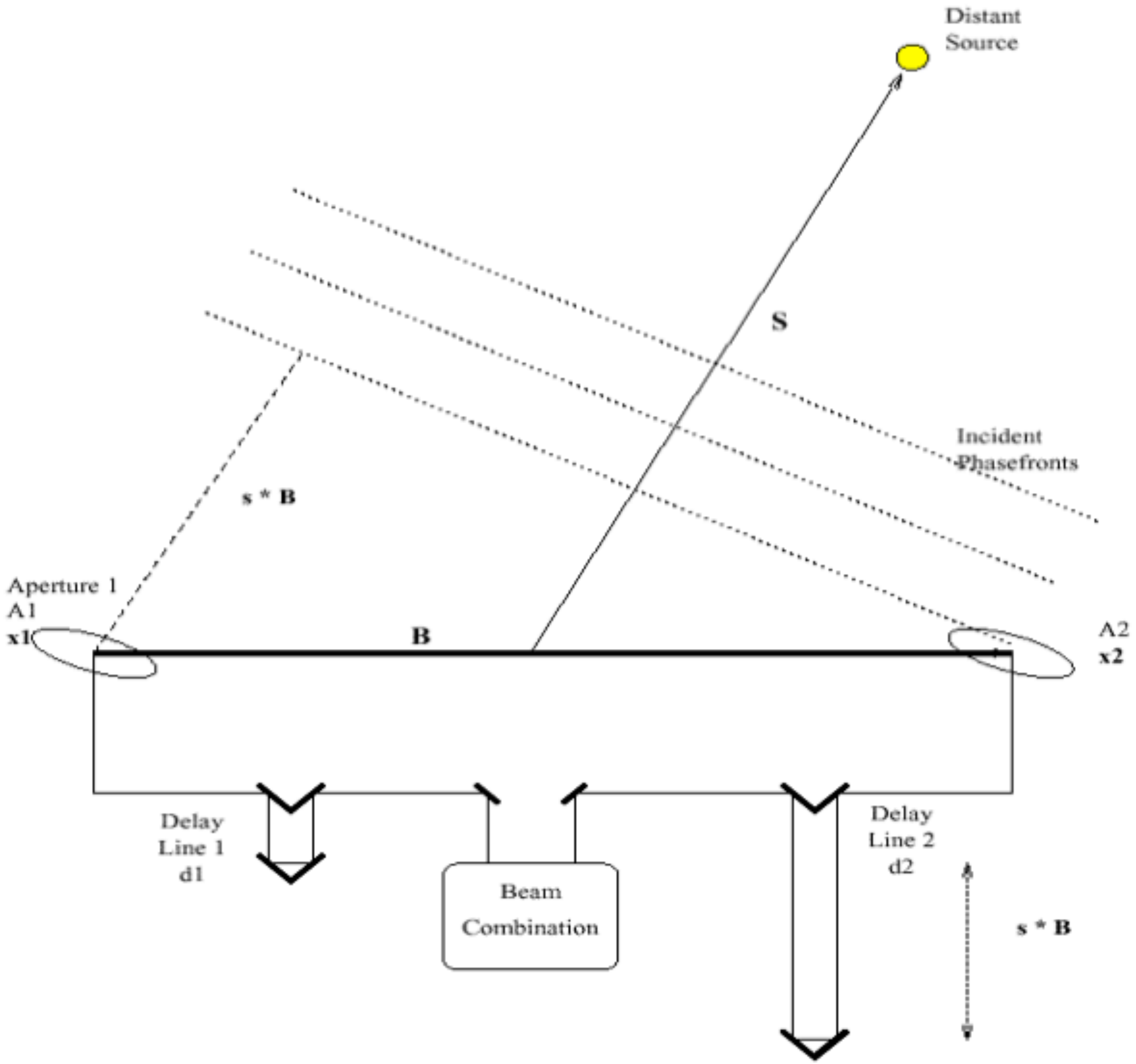


Lower fringe contrast!

The fringes completely disappear for $\alpha = \lambda/2B$:

A two-element interferometer

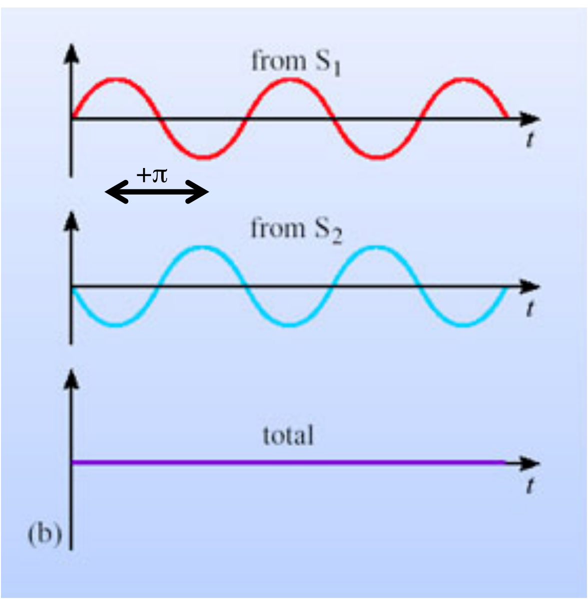
- Sampling of the radiation (from a distant point source).
- Transport to a common location.
- Compensation for the geometric delay.
- Combination of the beams.
- Detection of the resulting output.

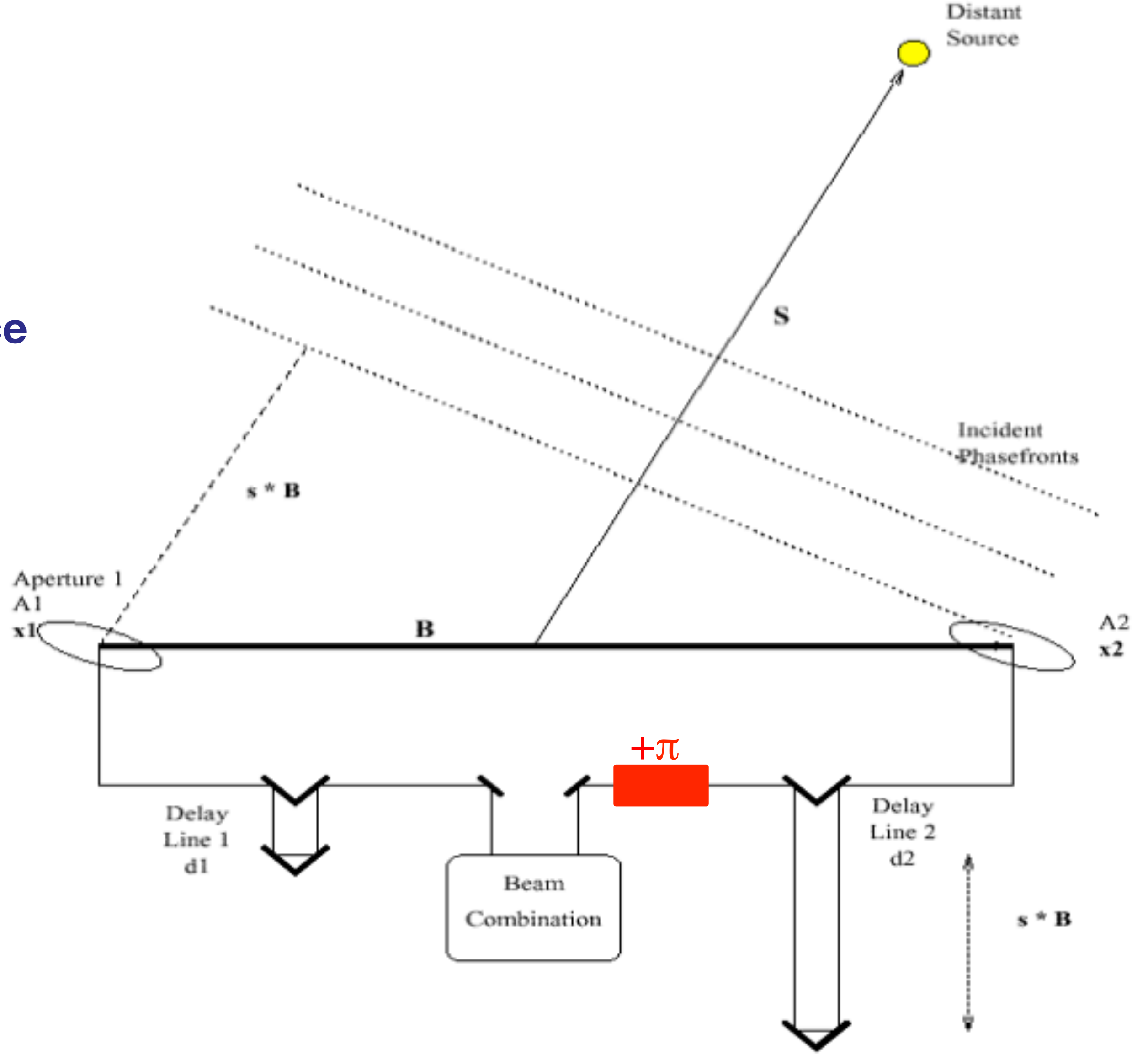


(C.A. Haniff – Michelson summer school 2006)

A two-element nulling interferometer

- Introduction of an extra phase delay of π in one arm to produce a **destructive interference**





Key ideas 1

- Light sometimes behaves like particles, sometimes like a wave (double slit experiment);
- Wave behavior at the basis of interferometric combination;
- Critical functions of an interferometer:
  - Sampling
  - Optical path matching
  - Combination
  - Detection
- Nulling interferometer:
  - Extra phase delay of π in one arm
  - Destructive interference of light

The output of a 2-element nulling interferometer

- At combination, the E fields from the two collectors can be described as:

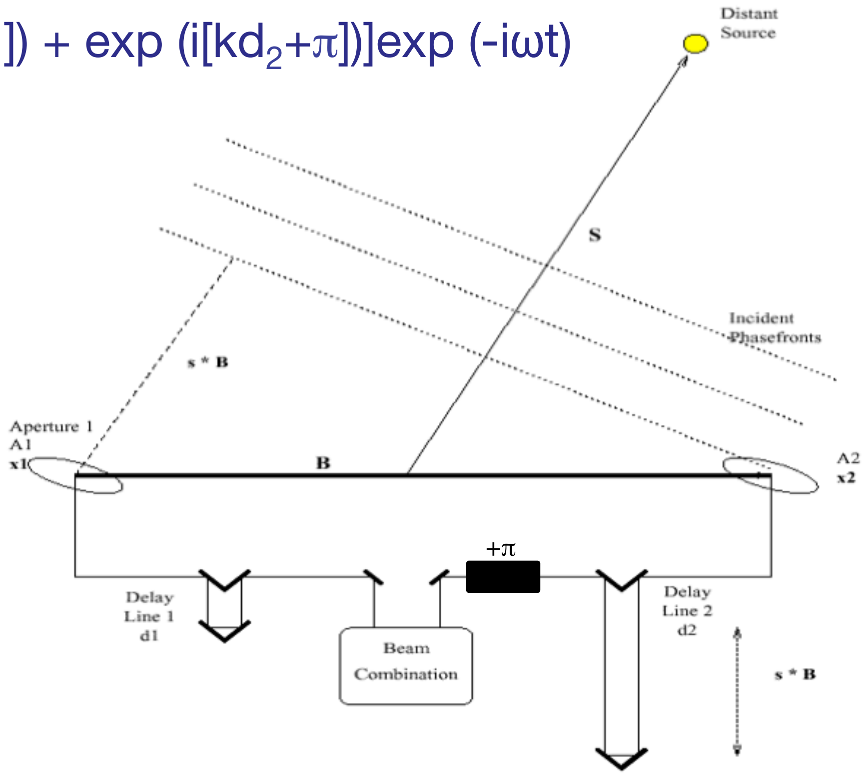
$$\psi_1 = A \exp(ik[\hat{s}.B + d_1]) \exp(-i\omega t) \quad \text{and} \quad \psi_2 = A \exp(i[kd_2+\pi]) \exp(-i\omega t).$$

- When these interfere, we obtain their sum:

$$\Psi = \psi_1 + \psi_2 = A\,[\exp(ik[\hat{s}.B + d_1]) + \exp(i[kd_2+\pi])]\exp(-i\omega t)$$

where

- B is the interferometric baseline
- $\hat{s}.B$ is the geometric delay with $\hat{s} = S/|S|$
- d_1 and d_2 are the two optical paths along the two arms
- k is the wavenumb er (= $2\pi/\lambda$)

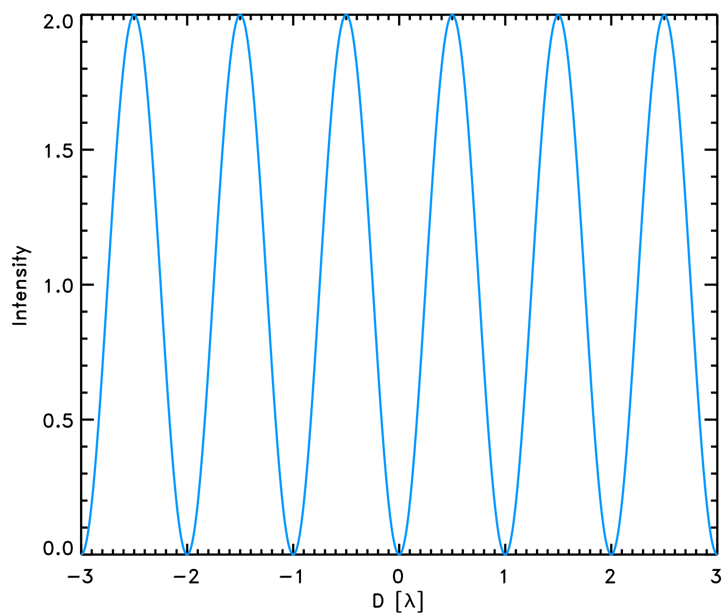


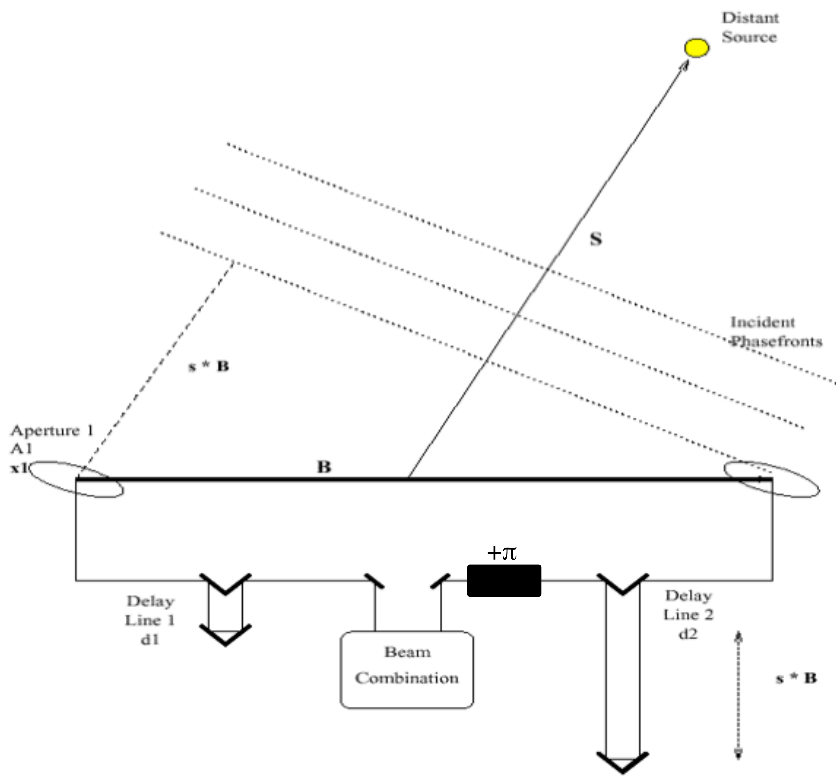
The output of a 2-element nulling interferometer

- Hence the time averaged intensity, <ψψ*>, will be given by:

$$\langle \psi\psi^* \rangle \propto A^2[\exp(ik[\hat{s}.B + d_1]) + \exp(i[kd_2+\pi])] \times [\exp(-ik[\hat{s}.B + d_1]) + \exp(i[kd_2+\pi])]$$
$$\propto 1+\cos(k[\hat{s}.B+d_1-d_2]-\pi)$$
$$\propto 1-\cos(k[\hat{s}.B+d_1-d_2])$$
$$\propto 1-\cos(kD)$$
$$\propto 2\sin^2(kD/2)$$

where $D=[\hat{s}.B+d_1-d_2]$ and assuming $A^2=0.5$.





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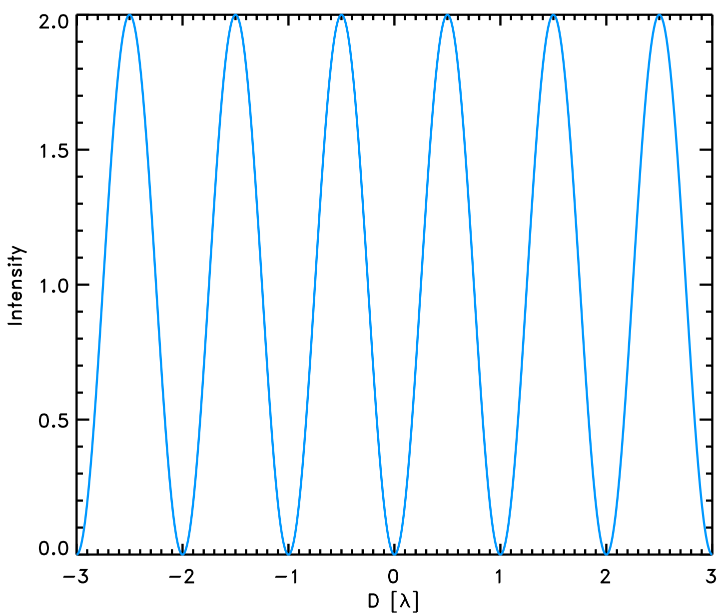


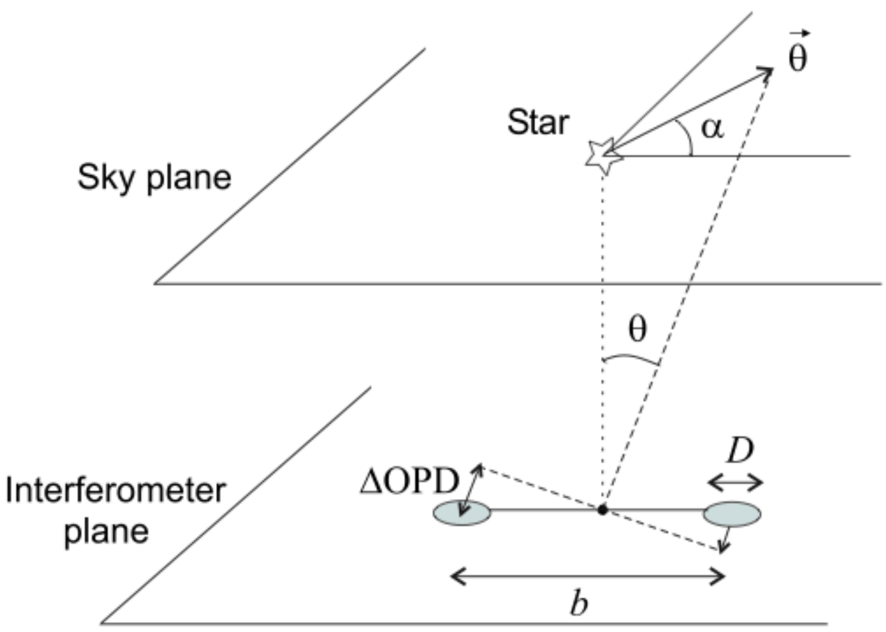
Adjacent fringe peaks separated by

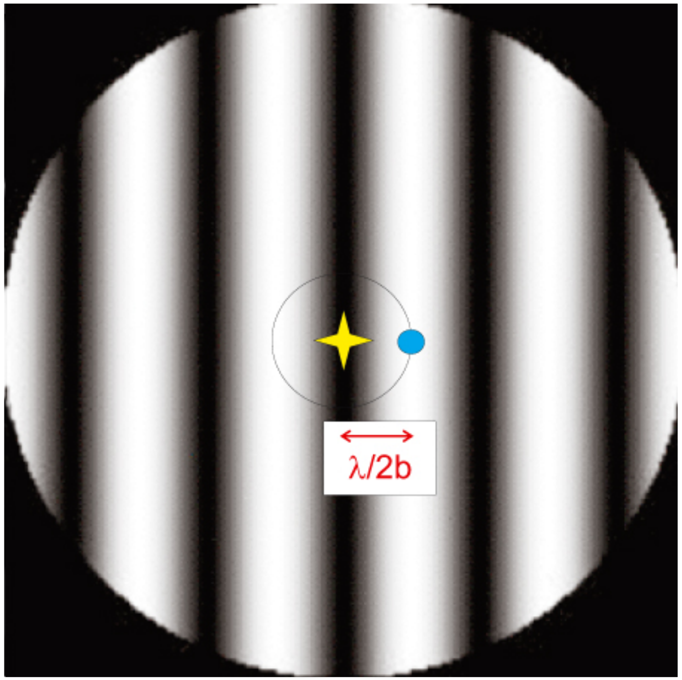
- $\Delta d_{1or2} = \lambda$ or
- $\Delta(\hat{s}.B) = \lambda$ or
- $\Delta(1/\lambda) = 1/D$

The output of a 2-element nulling interferometer

- For a slightly off-axis source, the additional phase due to its differential external path equals $\Delta(\hat{s}.B) = \pm\pi b\theta/\lambda\cos\alpha$
- Mapped on the sky, we can define the so-called transmission map:

$$TM = 2\sin^2(\pi b\theta/\lambda\cos\alpha)$$





Key ideas 2

- The output of the interferometer is a time averaged intensity.

- The intensity has a co-sinusoidal variation – these are the “fringes”.

- The fringe varies a function of (kD), which itself can depend on:
  - The wavenumber, $k = 2\pi/\lambda$.
  - The baseline, B.
  - The pointing direction, s.
  - The optical path difference between the two interferometer arms.

- If things are adjusted correctly, the interferometer output is fixed: there are no fringes. This is what most interferometers aim to achieve.

- The transmission map defines which region of the sky is transmitted and which region is not (“photon sieve” analogy).

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- What is nulling interferometry?
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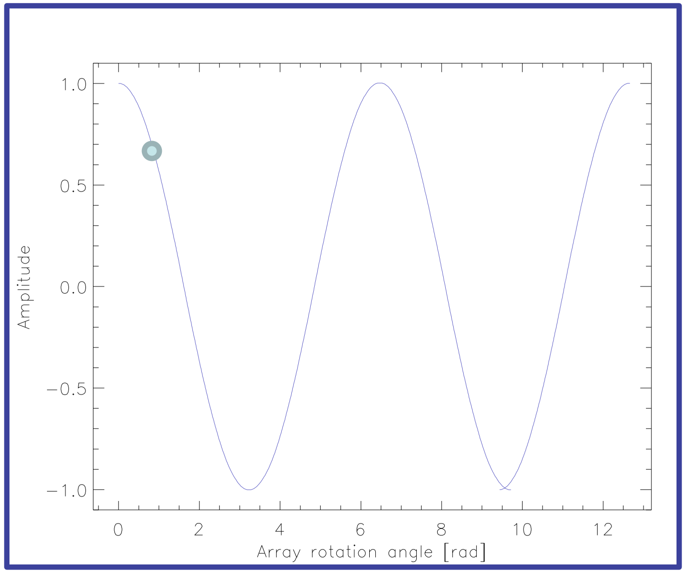
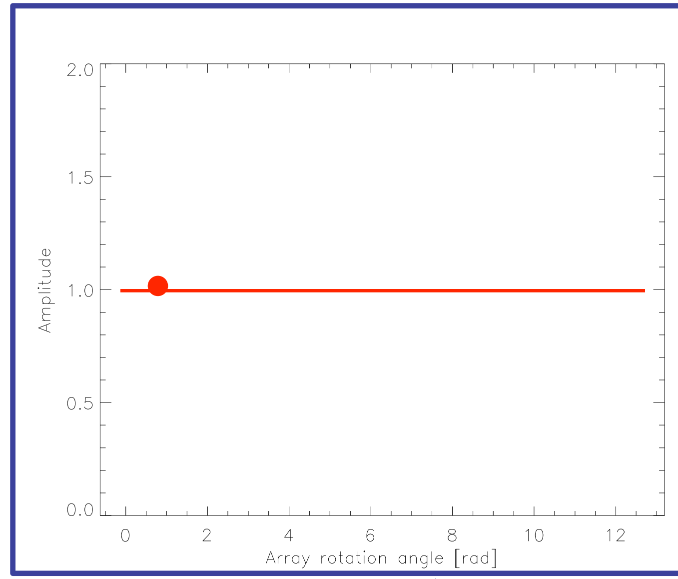
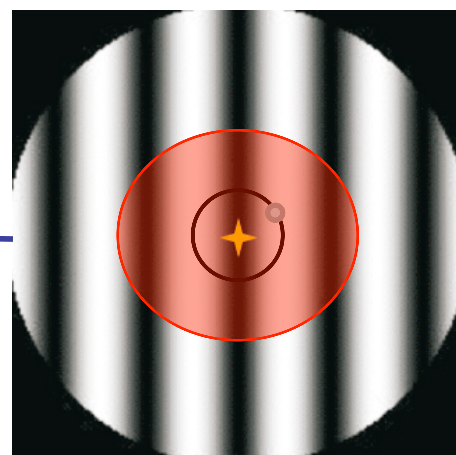
The first concept

- First proposed by Bracewell in 1978 to image non-solar planets with a rotating nuller (Nature, 274, 1978):





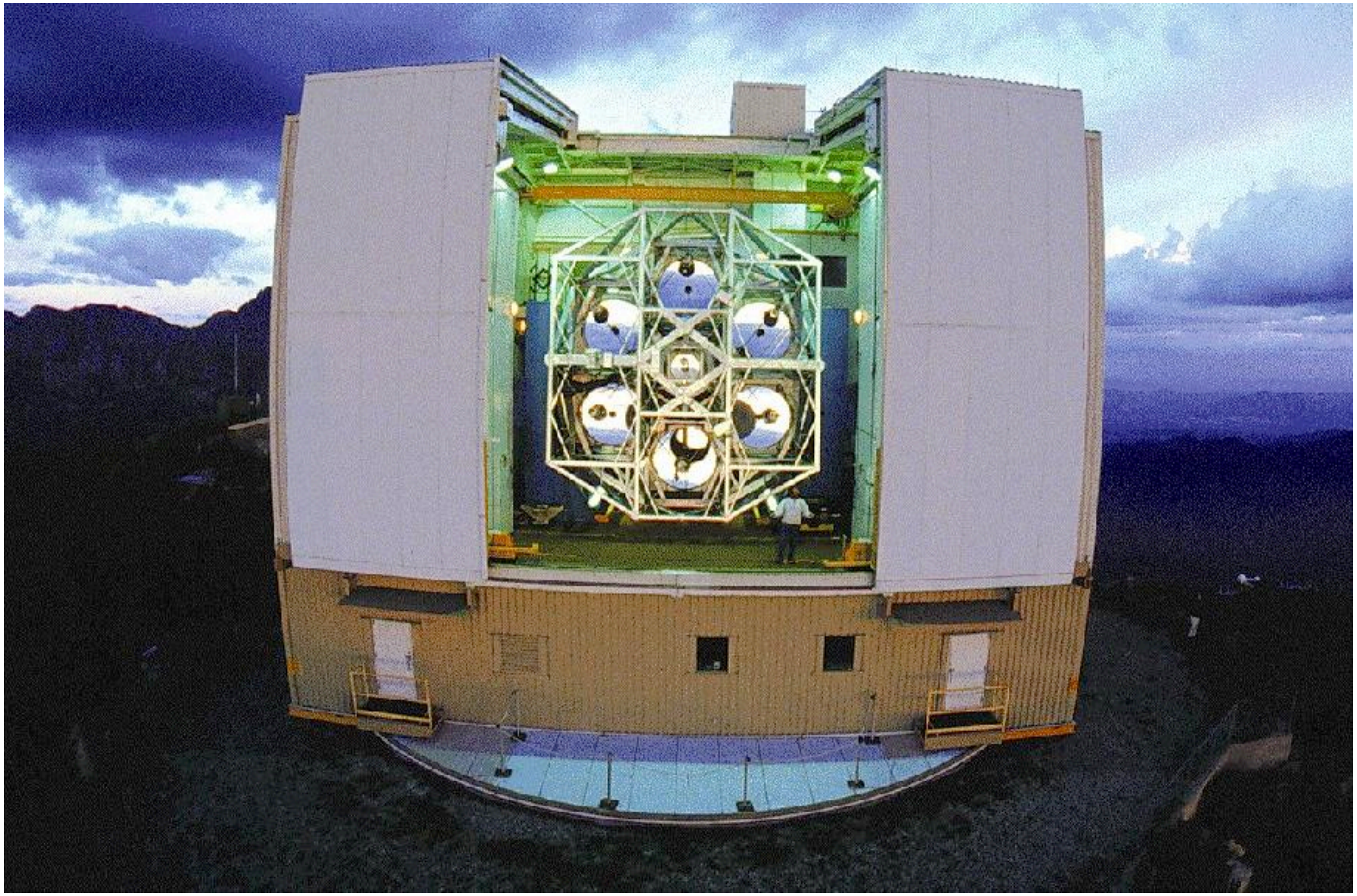


Planet signal

Symmetric sources
(e.g., star, disk)

The first telescope implementation

- First telescope implementation by Hinz et al. in 1998 on the Multiple Mirror Telescope in Arizona (Nature, 395, 1998):



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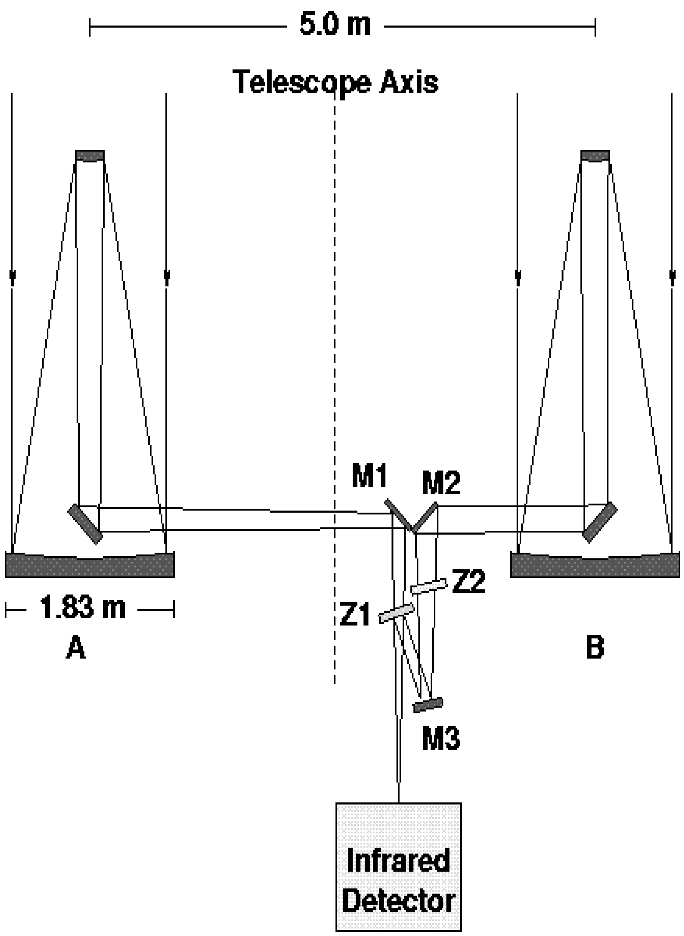
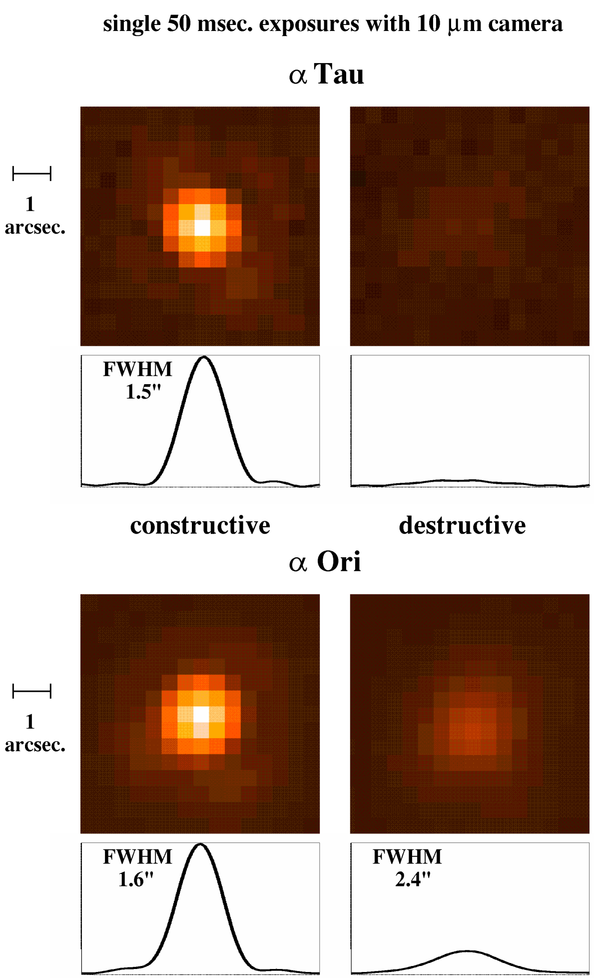


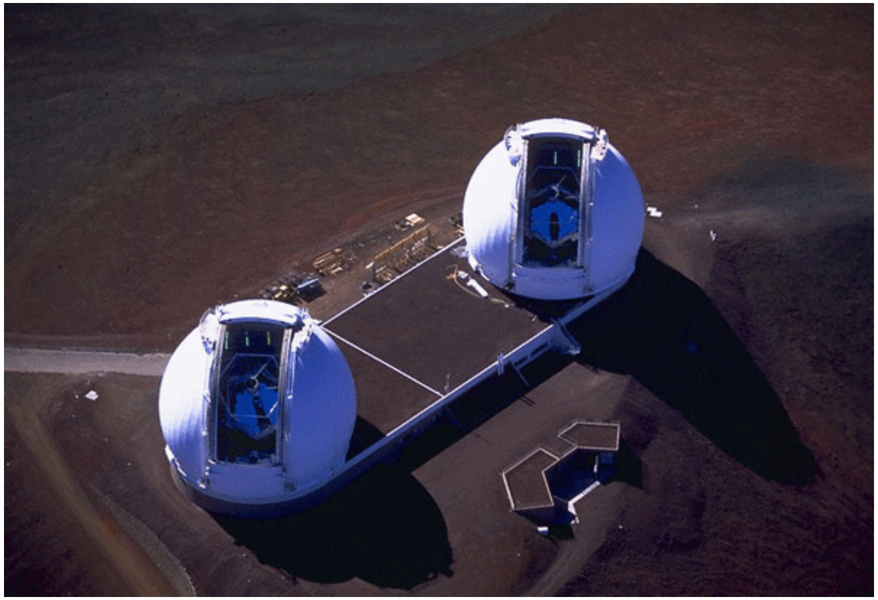


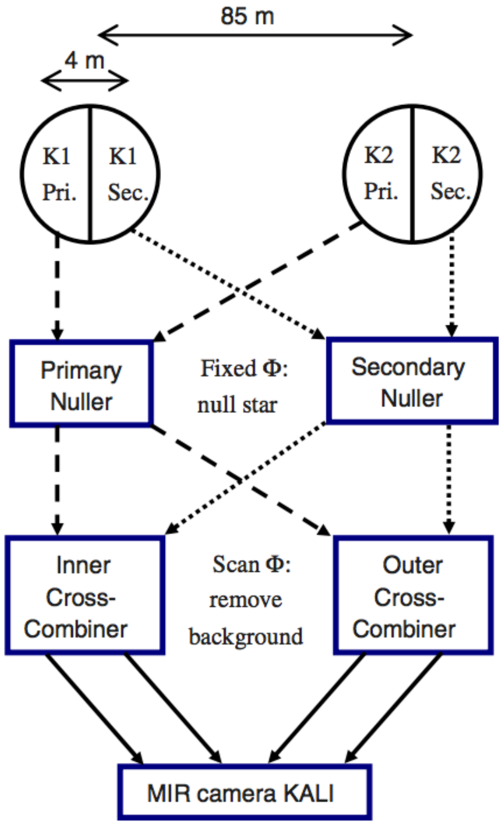
For unresolved star, destructive/ constructive peak ratio = 0.04

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

The Keck Interferometer Nuller (KIN)

- First telescope implementation of a four-beam interferometric nuller;
- Technology demonstrator for TPF-I;
- Main scientific goal: measure and put limits on emission from exozodiacal dust around nearby main-sequence stars;

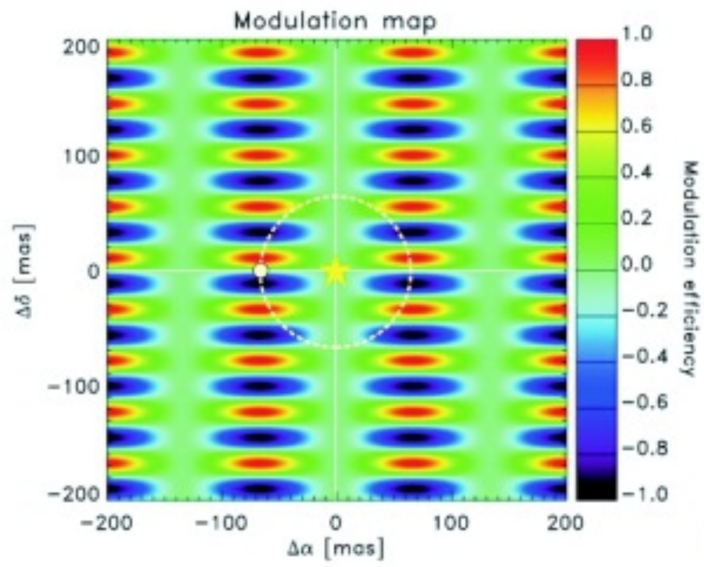


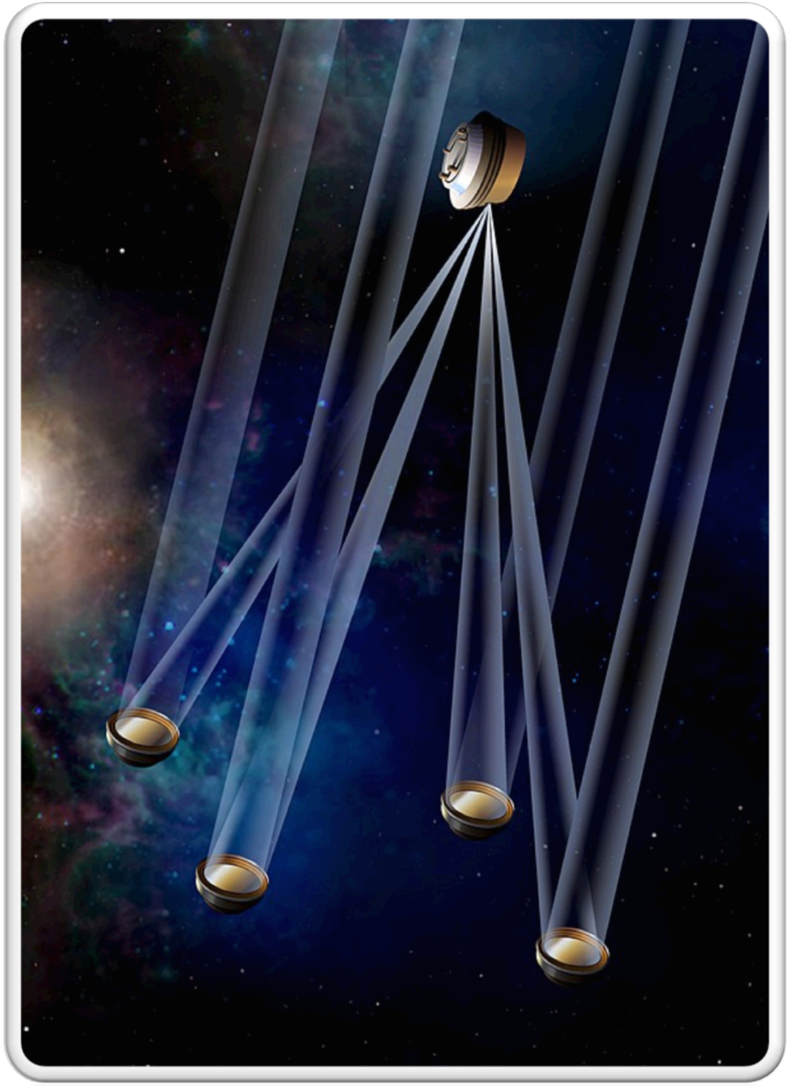


Long-term ambitious project

- The Darwin/TPF-I project:
  - Space-based 4-telescope mid-IR nulling interferometer;
  - Main goal: detect and characterize Earth-like planets.

- Transmission map:





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  - History and scientific motivations -- what is it for?
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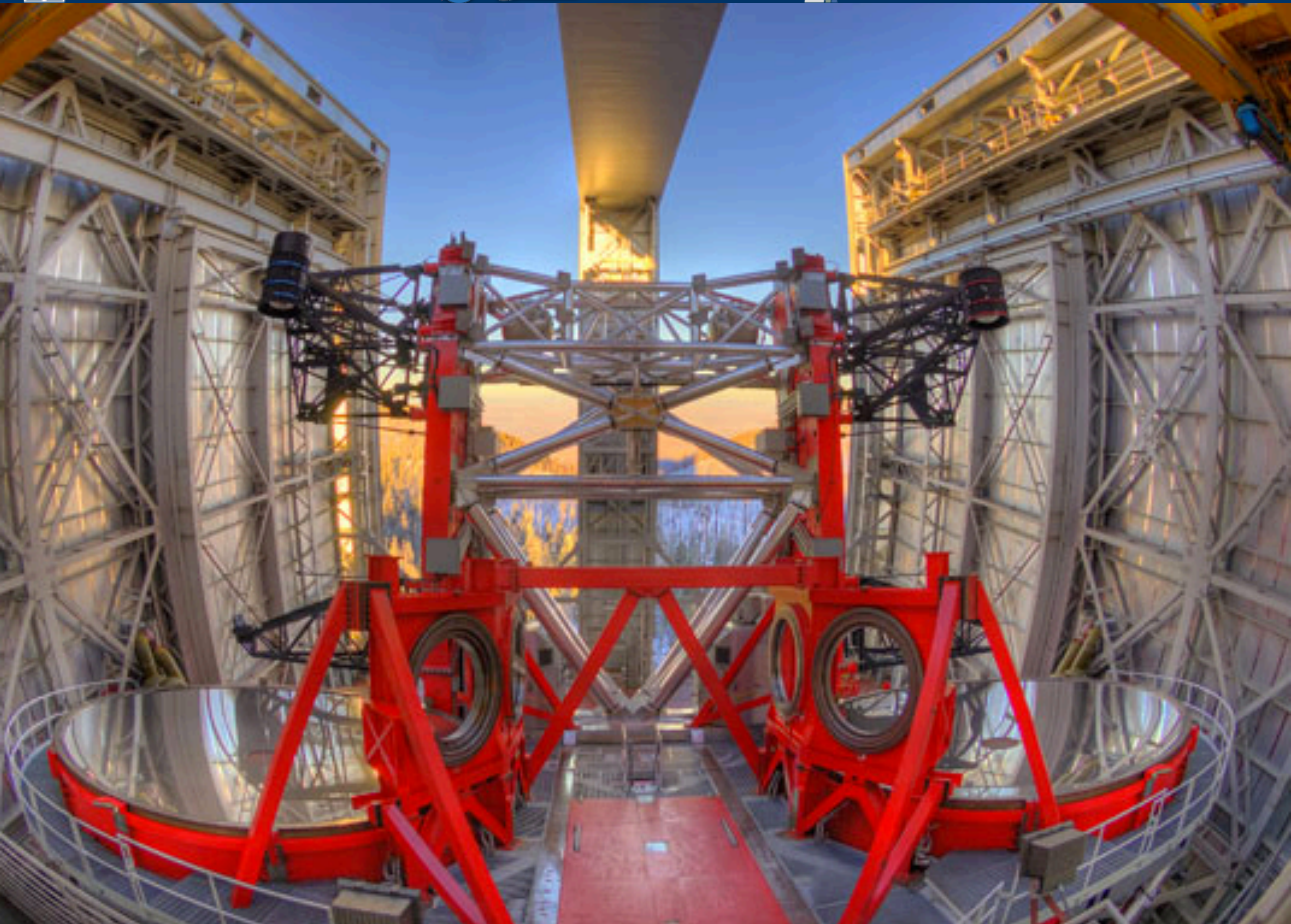
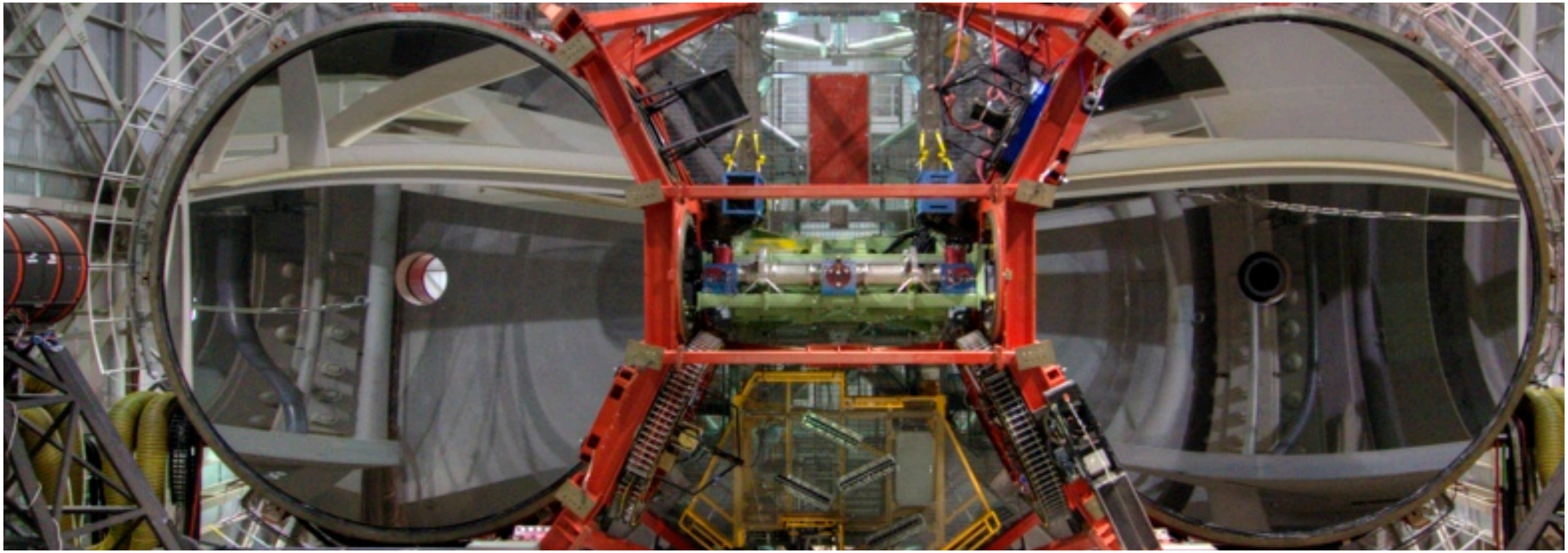
The LBT

Built and operated by partners in USA, Germany, and Italy



LBT key parameters

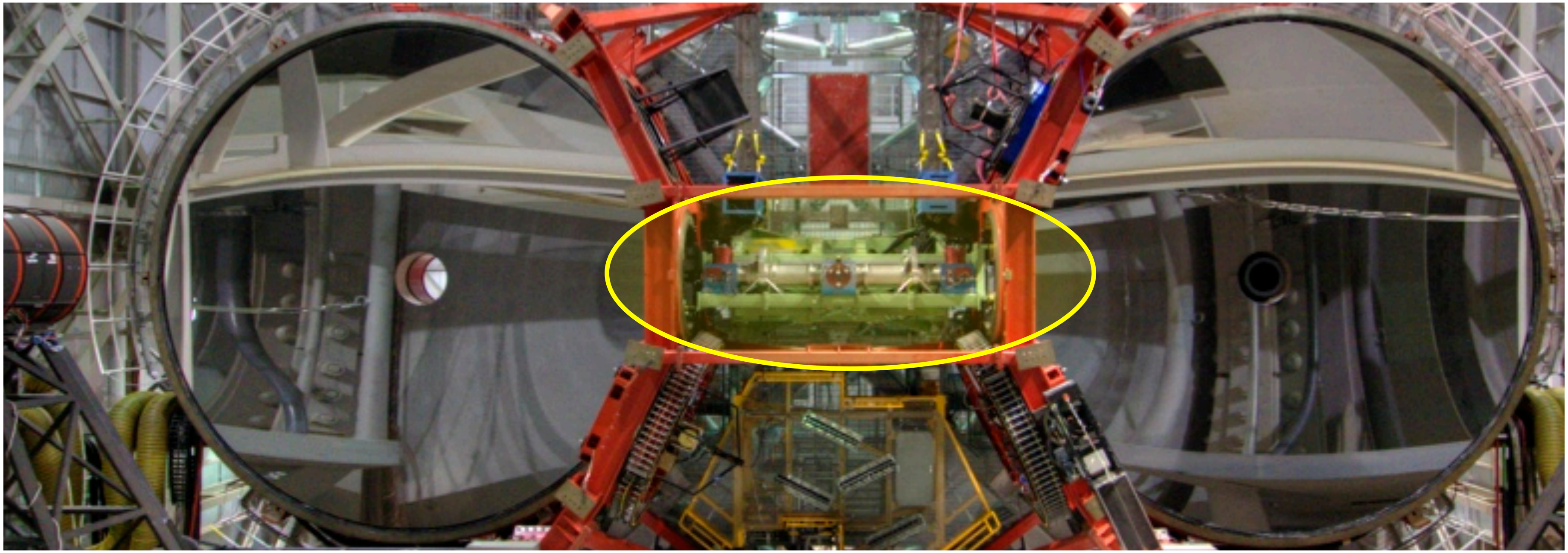


Resolution
Beam combination provides the equivalent resolution of a 22.7-m telescope.

High Contrast
The AO system creates an image with a Strehl of >90% at 3.8 μm.

Sensitivity
LBT has two 8.4-m mirrors mounted on a single structure (collecting area of a single 11.8-m aperture)

LBT key parameters



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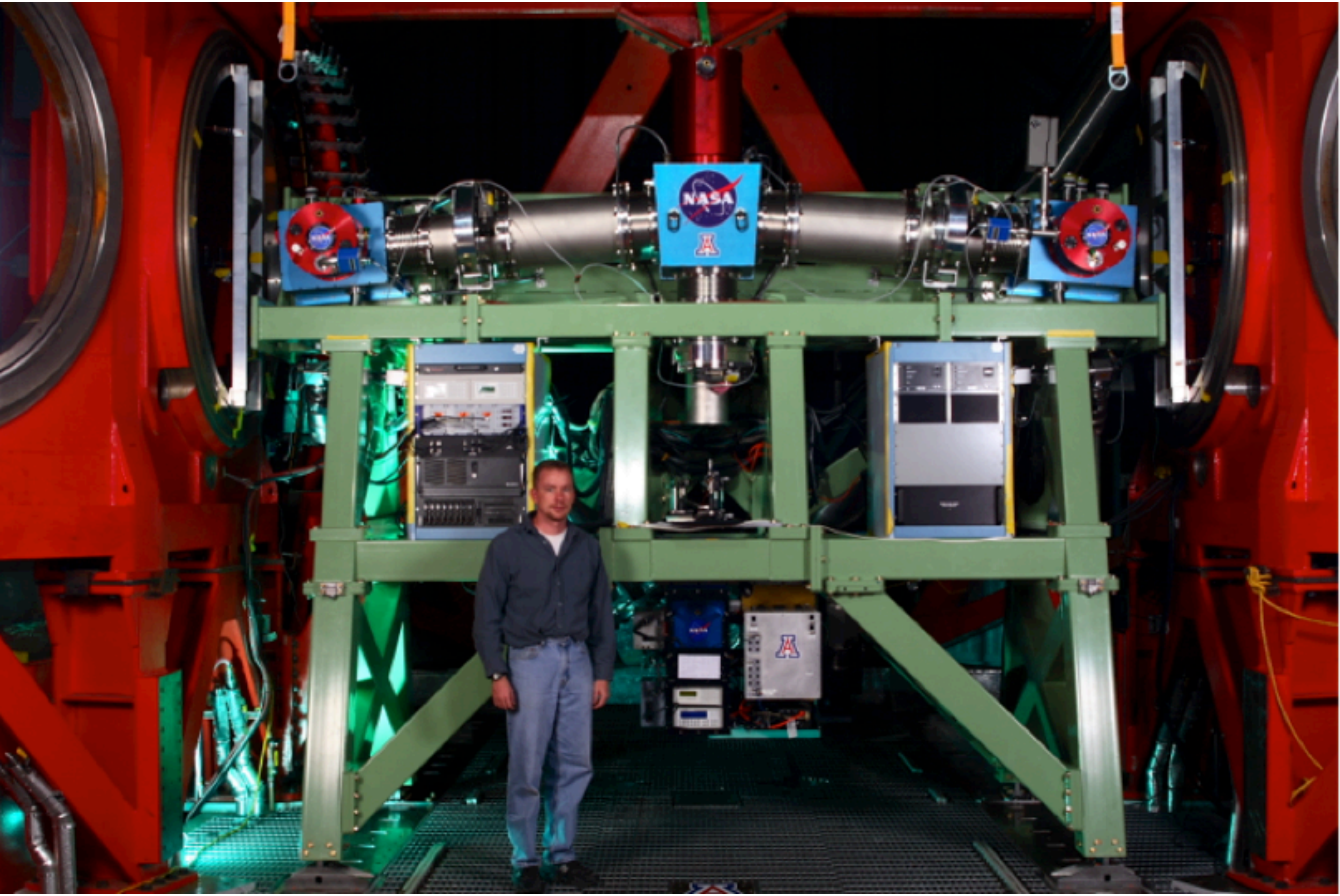
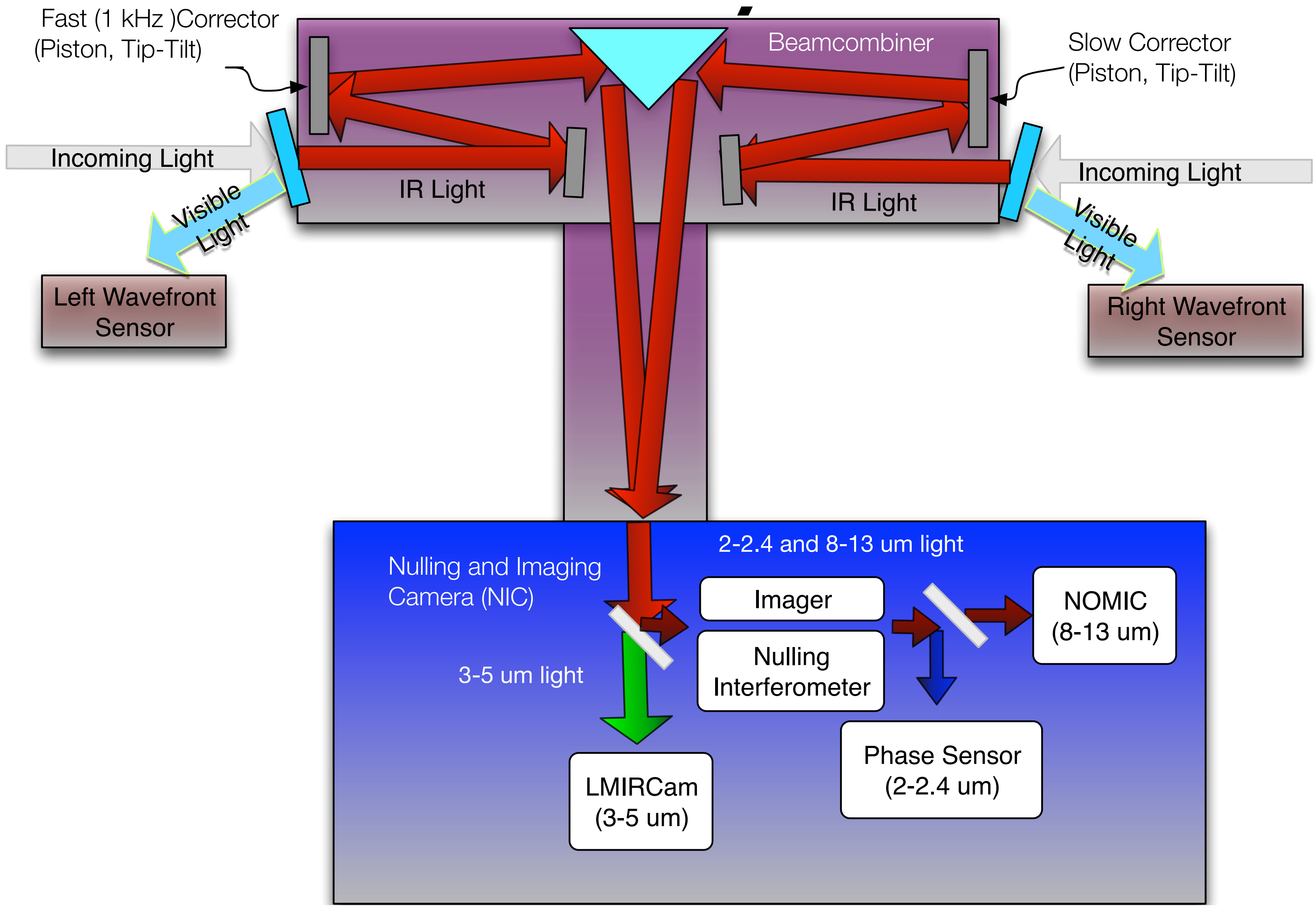


The LBTI


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

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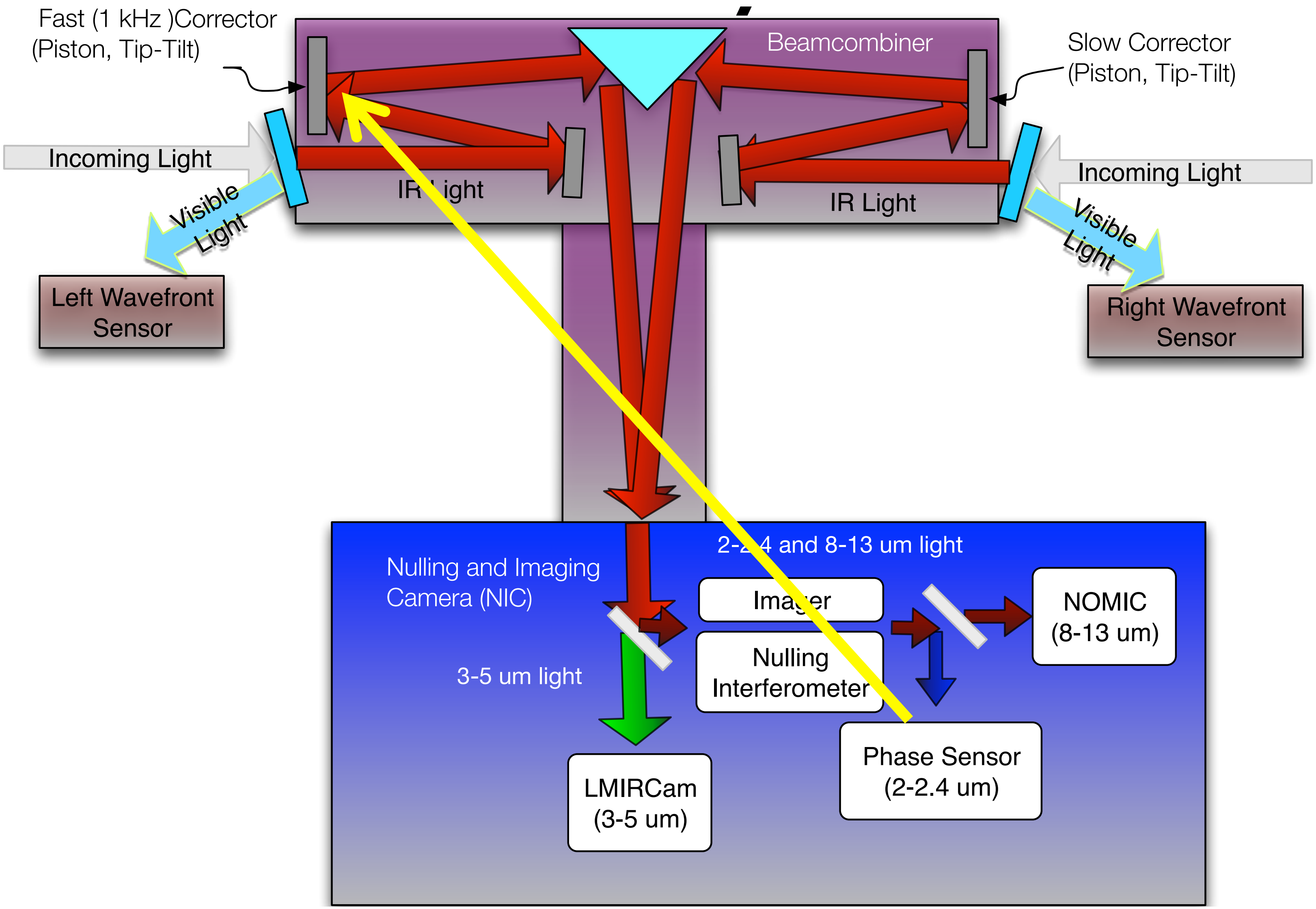
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Phase Sensor (2-2.4 um)
LMIRCam (3-5 um)

LBTI science Cameras

	LMIRcam	NOMIC
Wavelength Coverage (µm)	2.9-5.1(1.5-5.1 capable)	8-14 (8-25 capable)
Throughput	>30%	>20%
Pixel Size	0.011"	0.018"
FOV	20"	12"
Minimum Strehl	90% (3.8 µm)	98% (11 µm)
Spectral Resolution	350	100
5 sigma detection, 1 hour	19.0 (7 µJy) @ L'	13.3 (200 µJy) @ N
Spatial Resolution	40 mas @ L'	100 mas @ N'

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	LMIRcam	NOMIC
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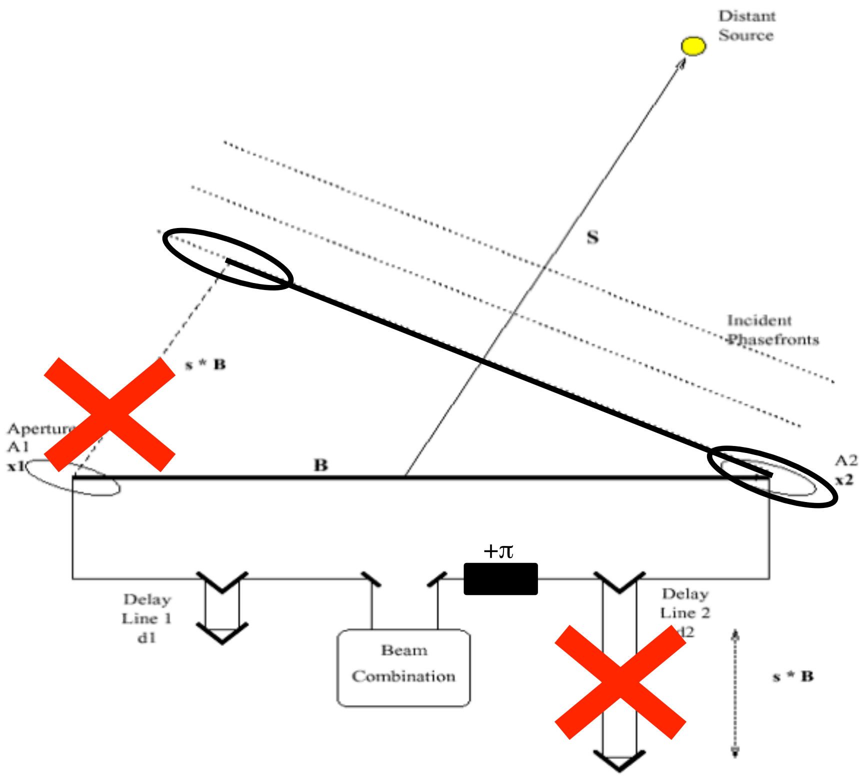
Pixel Size	0.011”	0.018”
FOV	20”	12”
Minimum Strehl	90% (3.8 μm)	98% (11 μm)
Spectral Resolution	350	100
5 sigma detection, 1 hour	**~2 M_J planet at 1 Gyr**	**~1 zodi debris disk**
Spatial Resolution	**0.4 AU at 10 pc**	**1 AU at 10 pc**

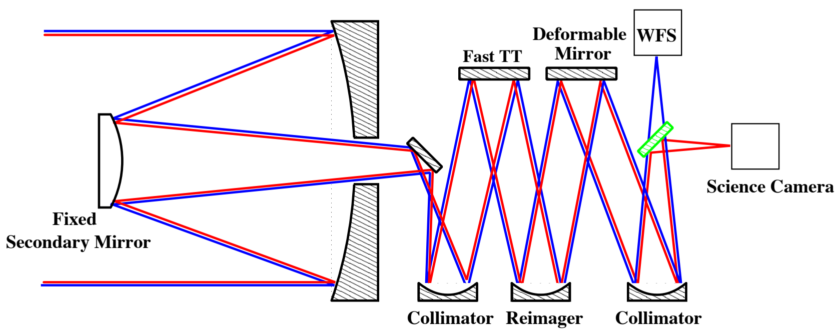
Instrumental specificities

1. Common mount interferometer
   ⇒ No geometric delay ($\hat{s}.B = 0$)
   ⇒ No long delay line

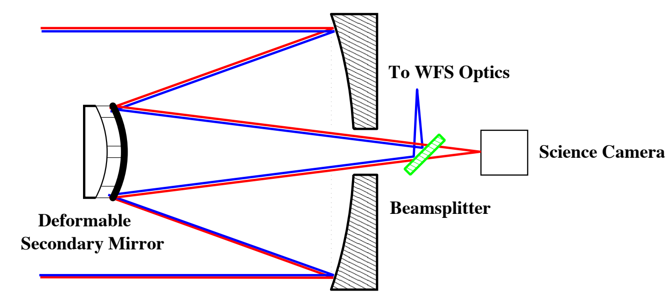


2. Deformable secondary mirrors
   => Low thermal background

<u>Typical AO system</u>



<u>LBT AO system</u>

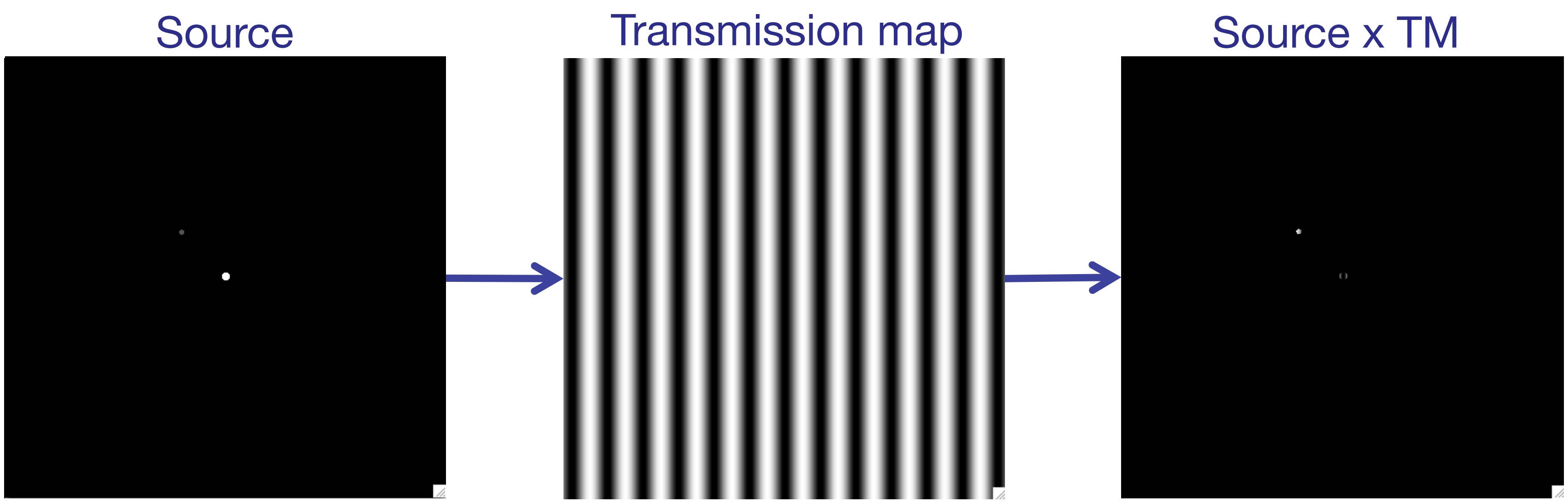


AO figures by Matt Kenworthy

Interferometric combination

- LBTI has been designed as a versatile instrument:
  - Single-aperture high-contrast imaging (beams can be separated or overlapped);
  - Coronagraphy;
  - Fizeau and NRM imaging;
  - Dispersed interferometry;
  - Nulling interferometry;

- Unlike most nulling interferometers, the LBTI nuller is a direct imager:



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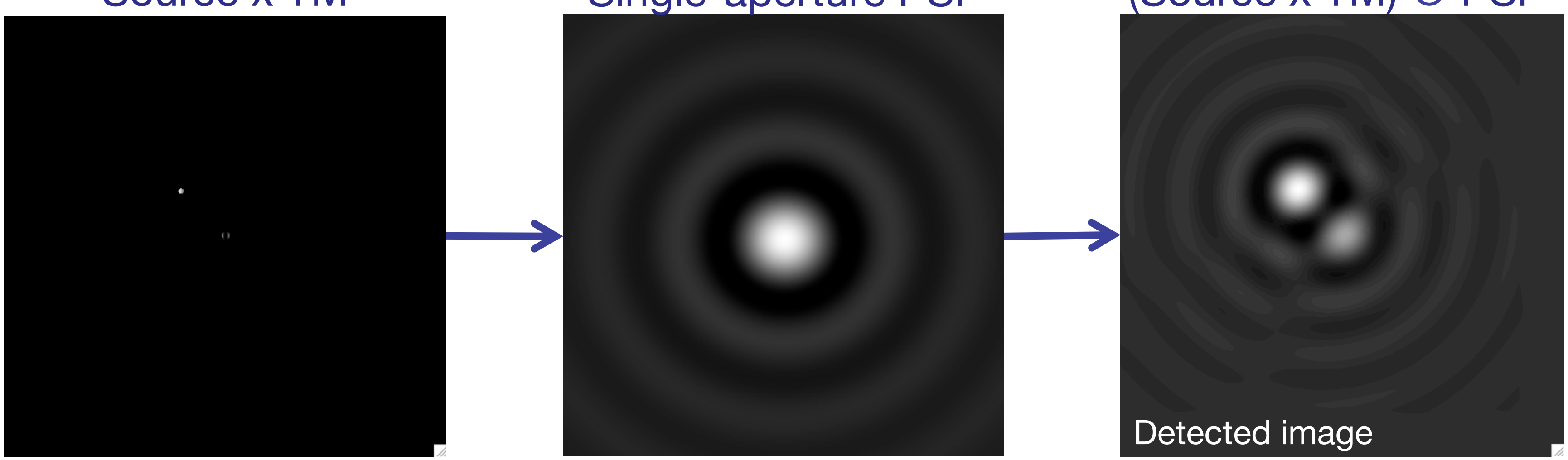
- Unlike most nulling interferometers, the LBTI nuller is a direct imager:

Source x TM | Single-aperture PSF | (Source x TM) ⊙ PSF



Key ideas 3

- LBT's instrumental specificities:
  - Two large 8.4-m telescopes;
  - Common mount;
  - Deformable secondary telescope.
- LBTI can be used for single-aperture high-contrast AO imaging, Fizeau interferometry, and nulling interferometry.
- Unlike most interferometric instruments, LBTI's nuller is a direct imager.

Outline

- What is nulling interferometry?
  - Theory -- how does it work?
  - Scientific motivations -- what is it for?
  - A brief review and history
- The Large Binocular Telescope Interferometer
  - Concept and instrument specificities
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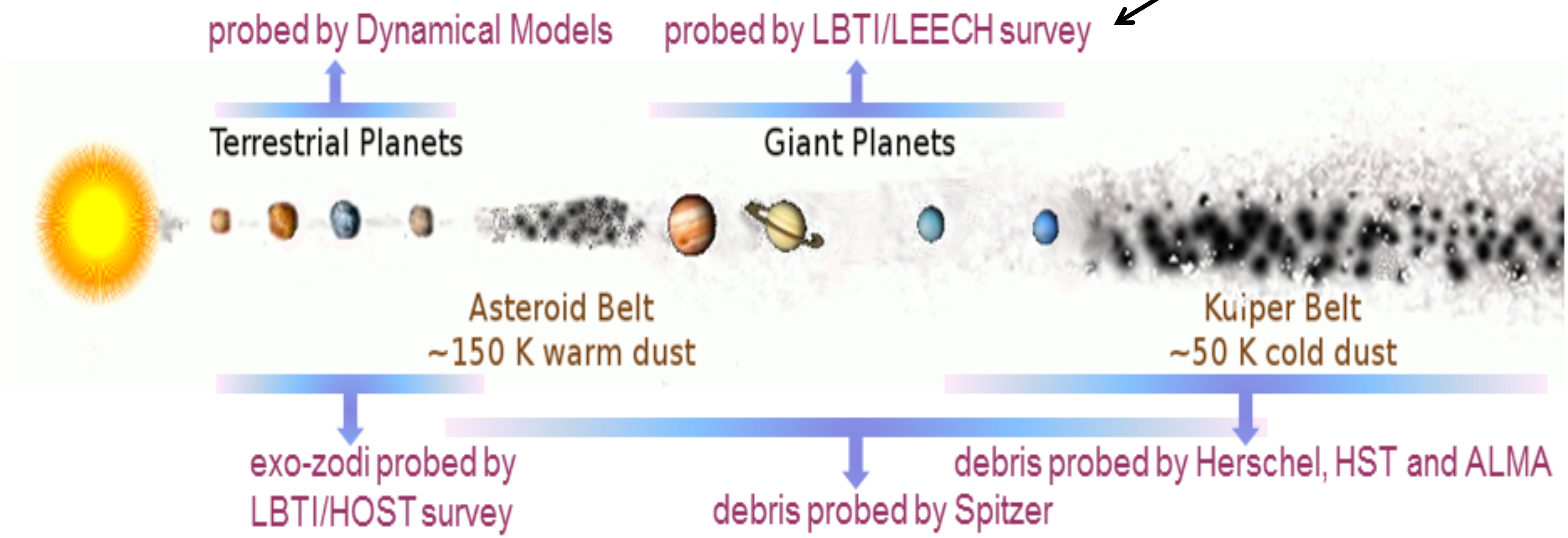
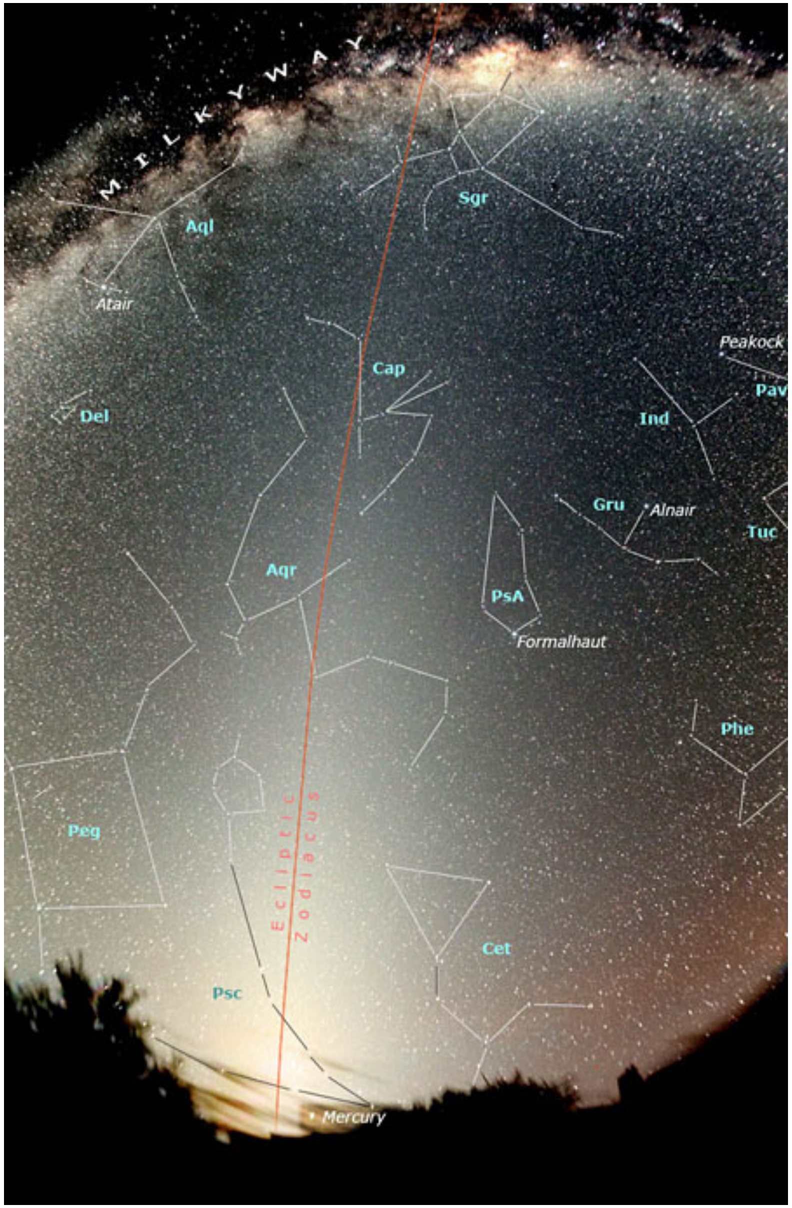
Zodiacal dust in context

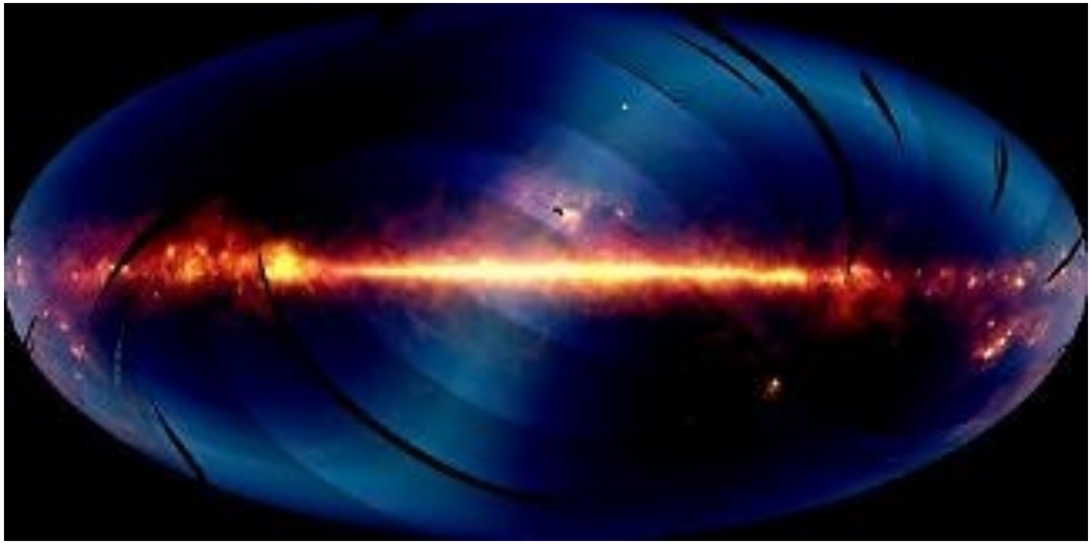
Mawet's talk

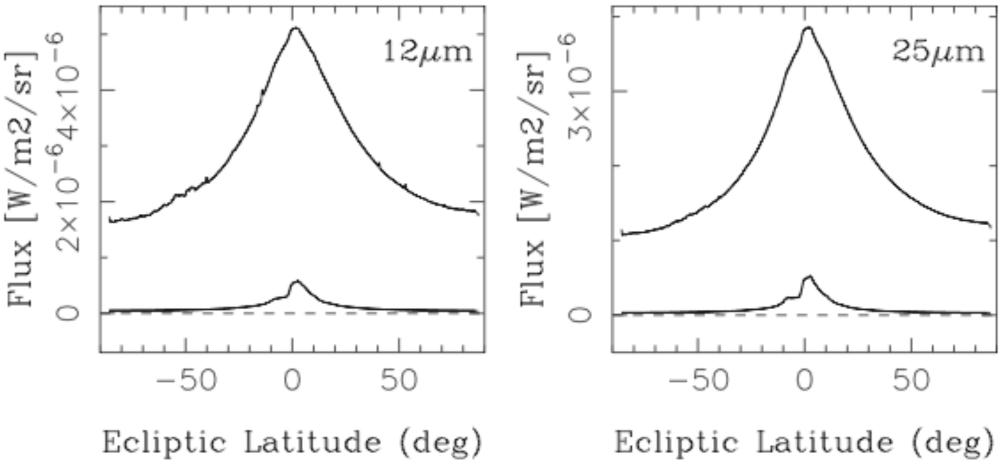


This talk

Zodiacal dust





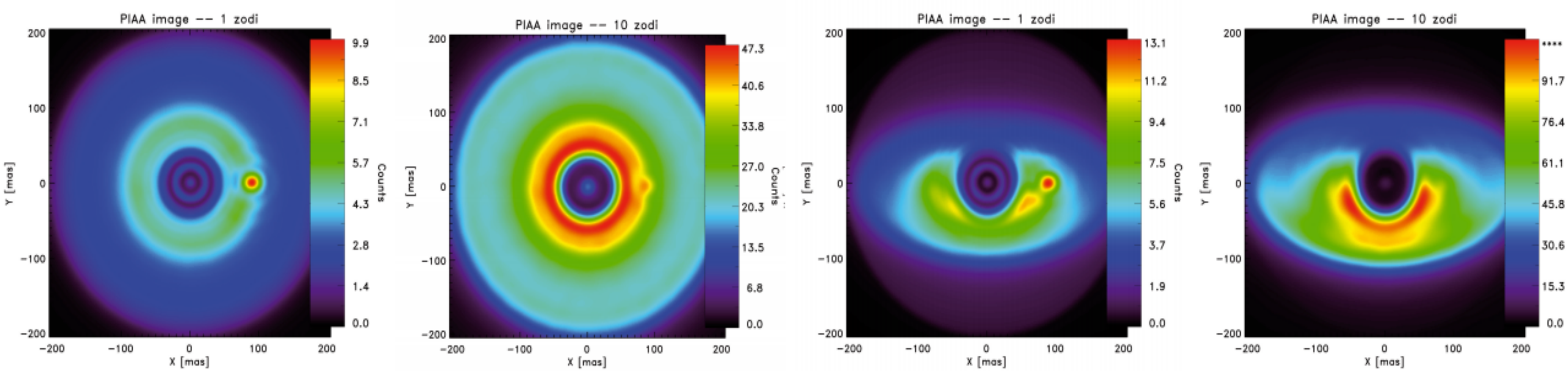


from Nesvorney et al. 2010


© Yuri Beletsky

Why is NASA interested in 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 1 and a 10-zodi exozodiacal disk (Defrère et al. 2012)

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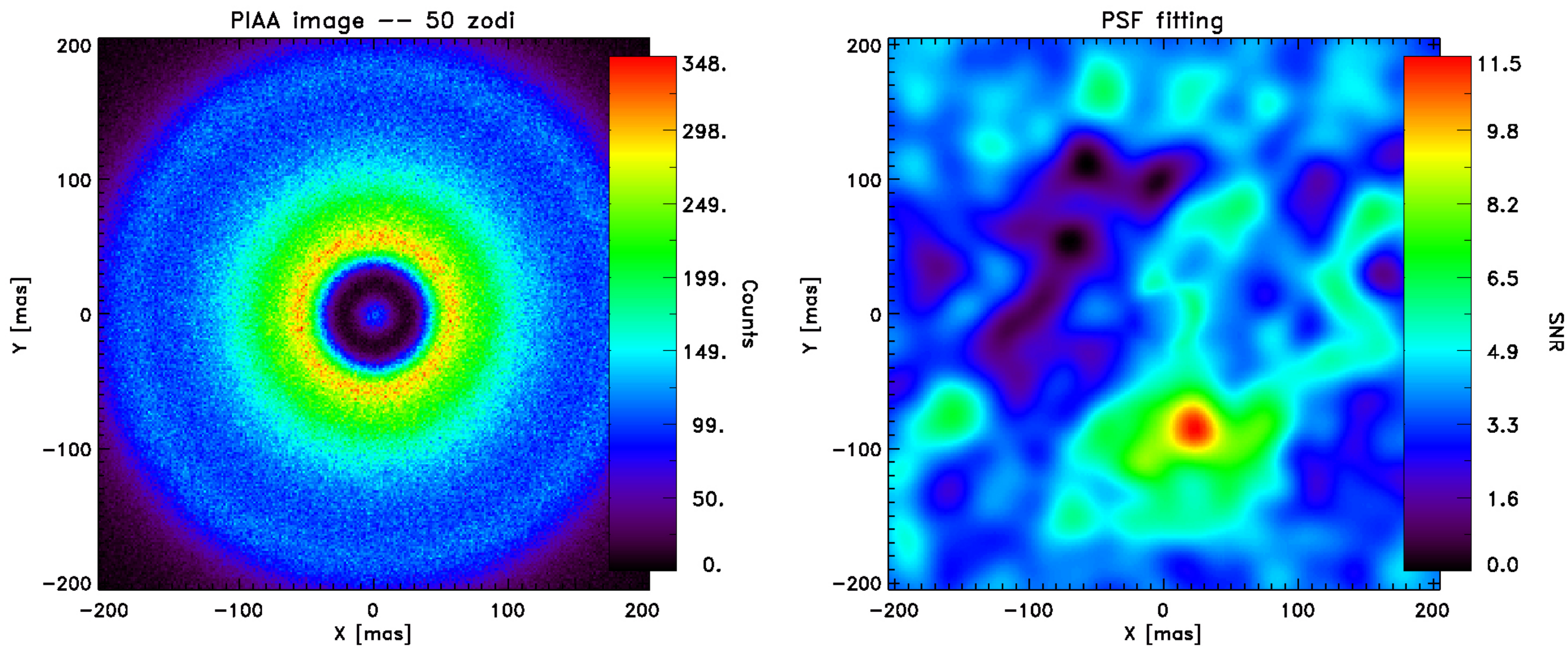

Now with a 50-zodi exozodiacal disk (Defrère et al. 2012)

Why is NASA interested in exozodiacal dust?

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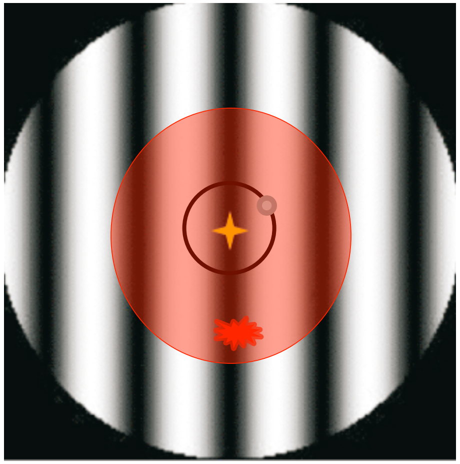
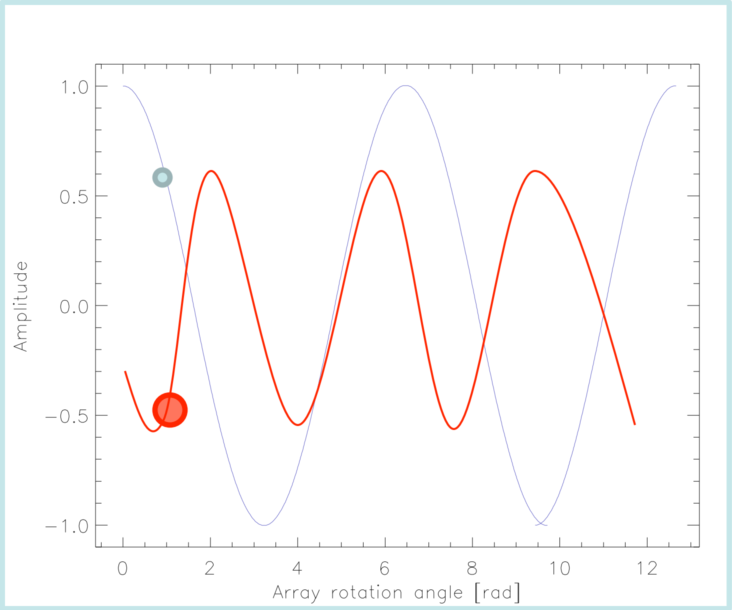


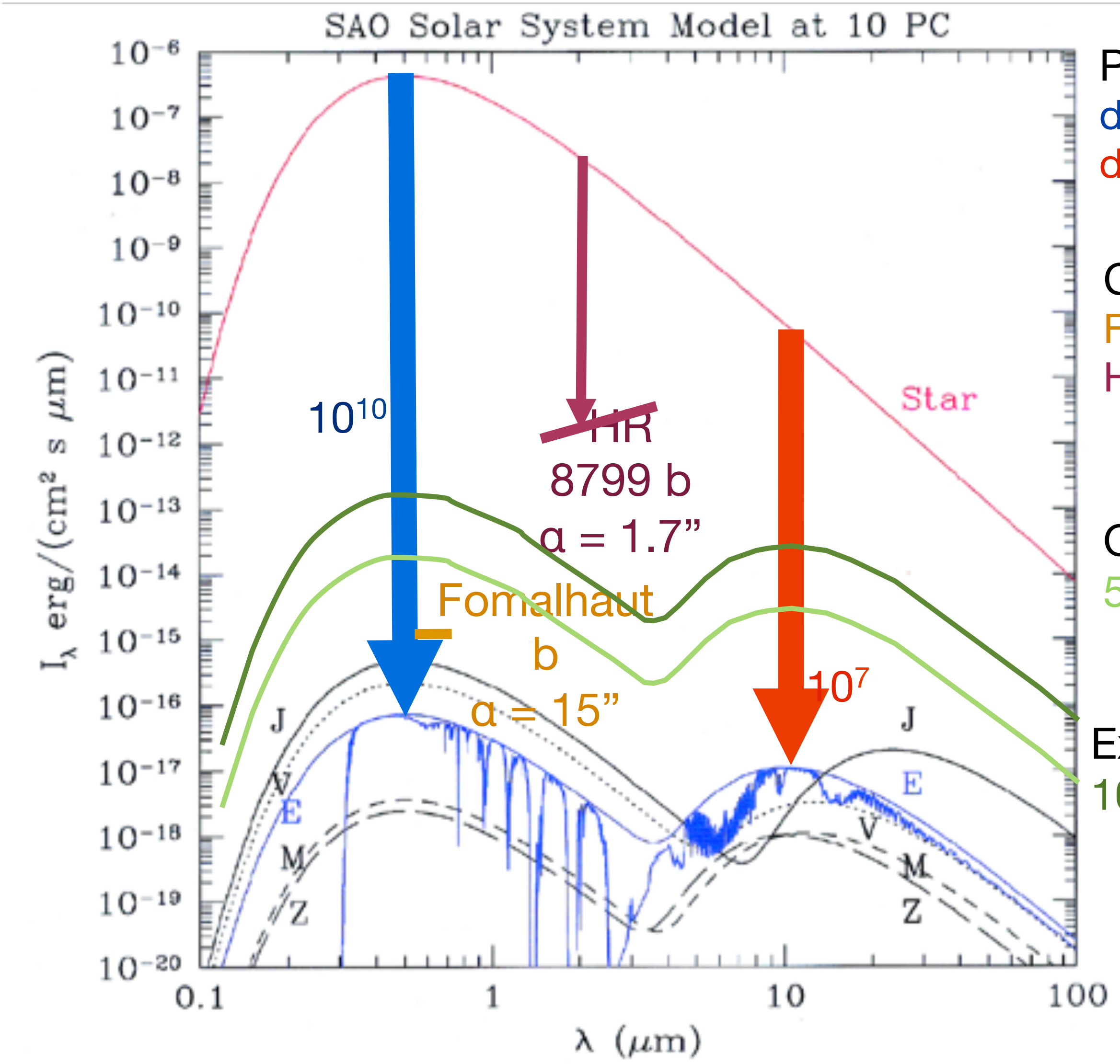


What do we know? …not much

- Single-dish photometry
  - ✓ Spitzer: ~1% of 152 main-sequence stars (Lawler et al., 2009)
  - ✓ WISE: ~1% of 350 main-sequence stars (Morales et al. 2012)
  - ✓ Sensitivity threshold ~1000 zodis

- Infrared interferometry
  - ✓ CHARA/FLUOR and VLTI/PIONIER: detection in the near-infrared (Absil et al. 2013, see also S. Ertel's poster).
  - ✓ VLTI/MIDI: HD 69830 and η Crv (Smith et al., 2009), HD 113766 and HD 172555 (Smith et al. 2012), β Pic (di Folco et al., in prep).
  - ✓ KIN : below 60 zodis with a 95% confidence level (Millan-Gabet et al. 2011, Mennesson et al. 2014).

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.

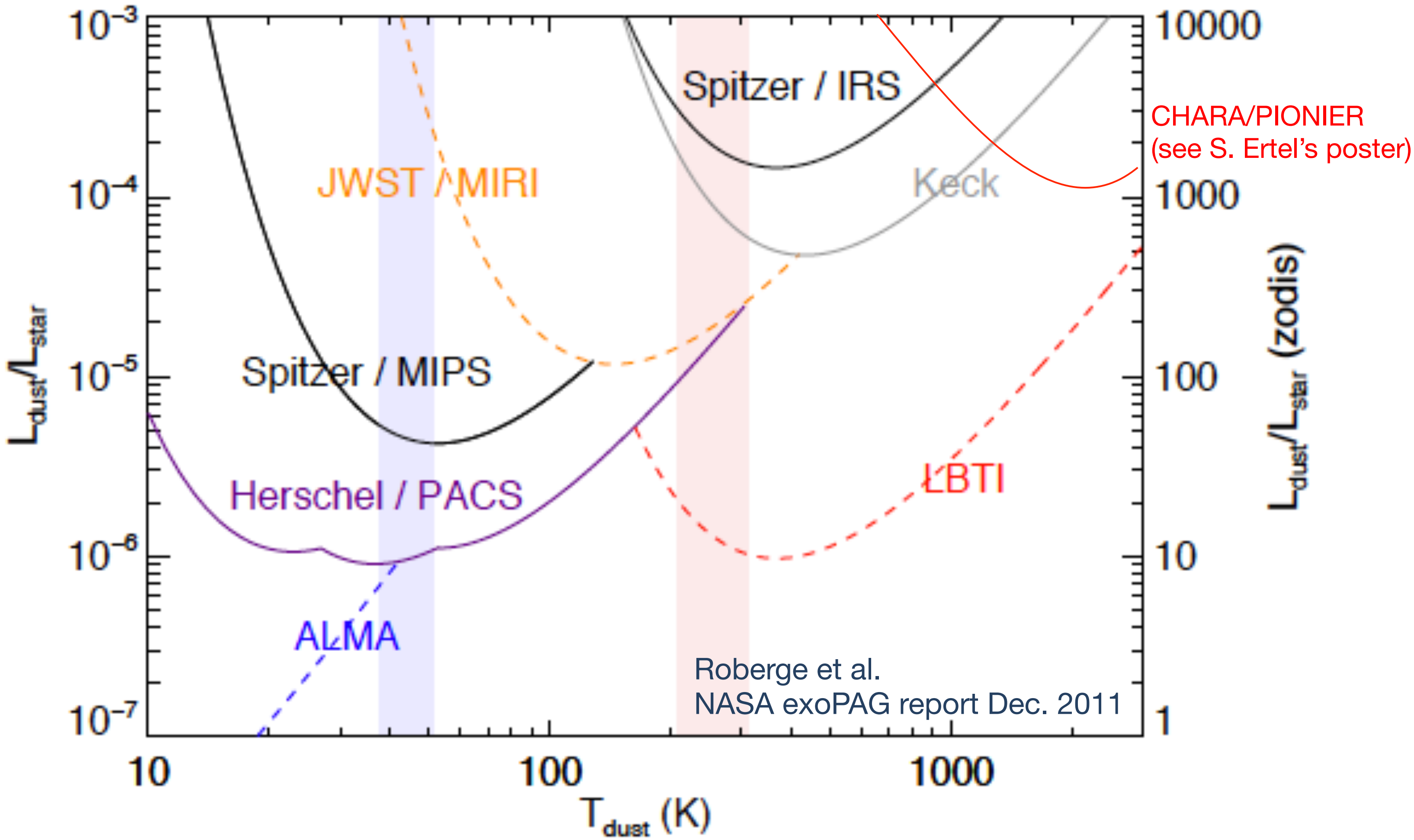
HOSTS:

Hunt for Observable Signatures of Terrestrial Planetary Systems

- NASA-supported 50 night survey to be carried out in the 2014-2017 time frame.
- Top level goal is to reduce risk for future NASA exoplanet imaging missions.
- Search actual candidate stars for exozodiacal emission.
- Understand trends and correlations for zodiacal dust:
  - Comparison to outer disk strength
  - Dependence on age and stellar mass.
  - Existence and influence of Jupiter-mass planets.
- Competitively selected Science Team

More information in R. Millan-Gabet's poster

LBTI exozodi program in context



Comparison of current facilities' sensitivity to exozodiacal dust. LBTI can detect dust in the habitable zone down to 10 zodis.

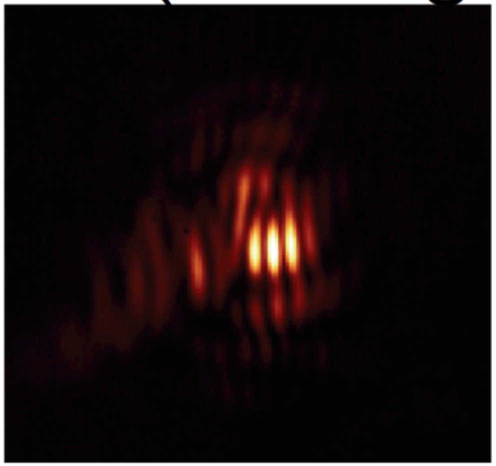
Key ideas 4

- Exozodiacal emission is a source of noise and confusion for future exoEarth direct imaging instruments.
- One of the main goals of the LBTI is to determine the prevalence of exozodiacal light

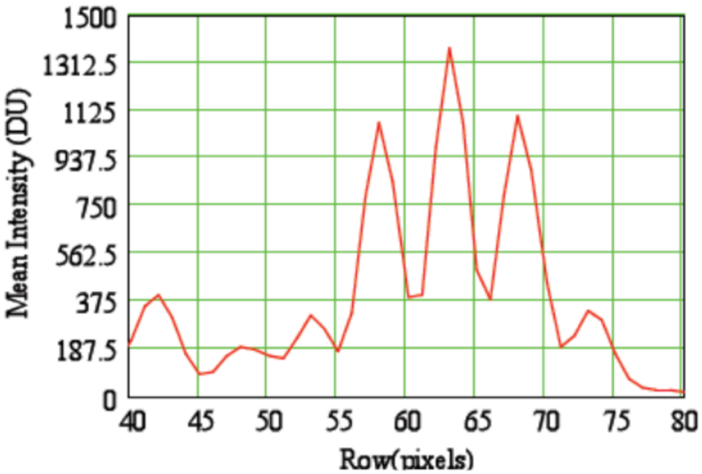
Outline

- What is nulling interferometry?
  - Theory -- how does it work?
  - Scientific motivations -- what is it for?
  - A brief review and history
- The Large Binocular Telescope Interferometer
  - Concept and instrument specificities
  - Main scientific goals
  - First results
- Summary and quiz

First Fringes! (First night on sky: Oct. 14, 2010)



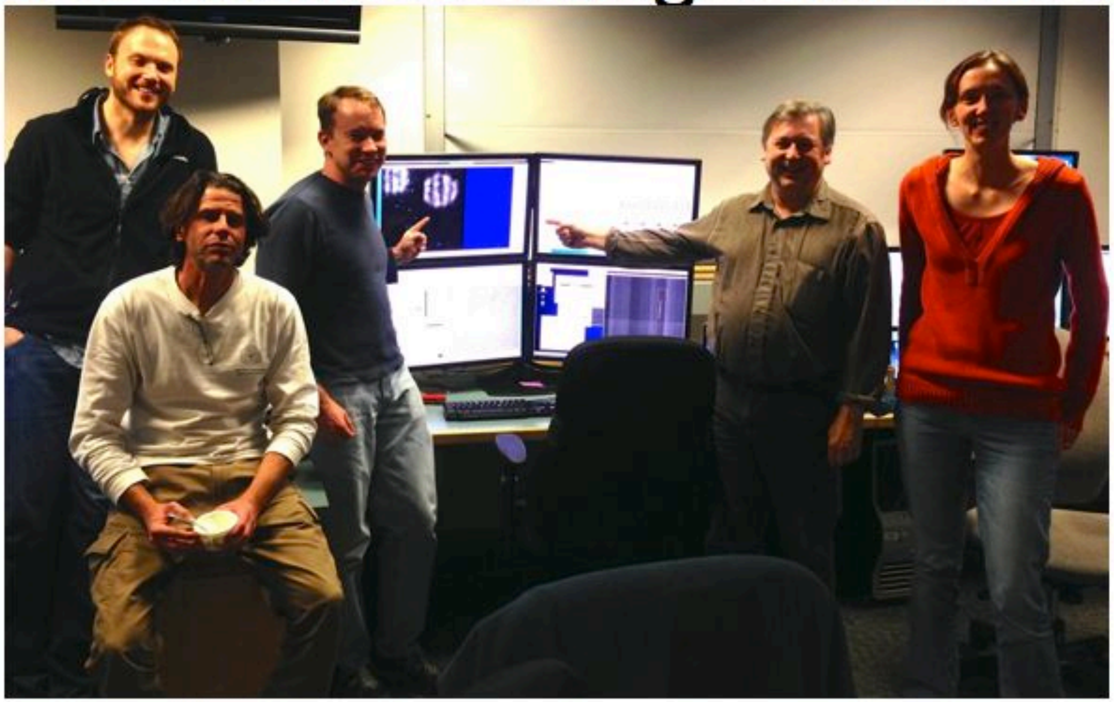
Beta Peg: Combined 10μm image from the LBTI imager. Image is "seeing limited" under poor weather conditions (seeing ~1.2 arc sec).



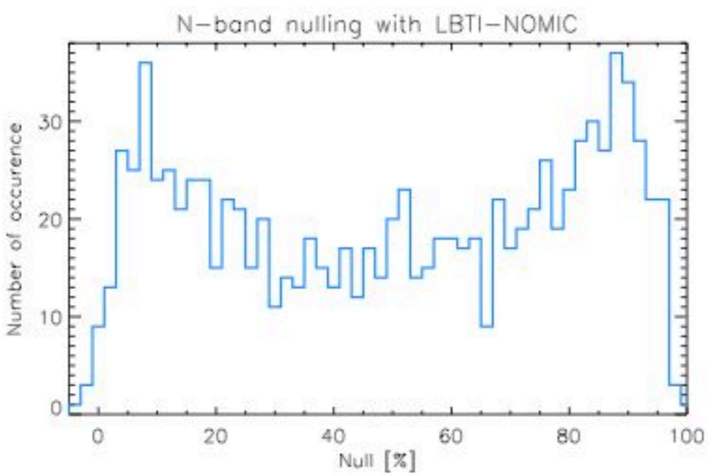
This image shows that:

- The two telescopes are co-pointed and tracking to 0.3"
- The pathlength difference between the two beam paths is less than ~10 μm and stable.

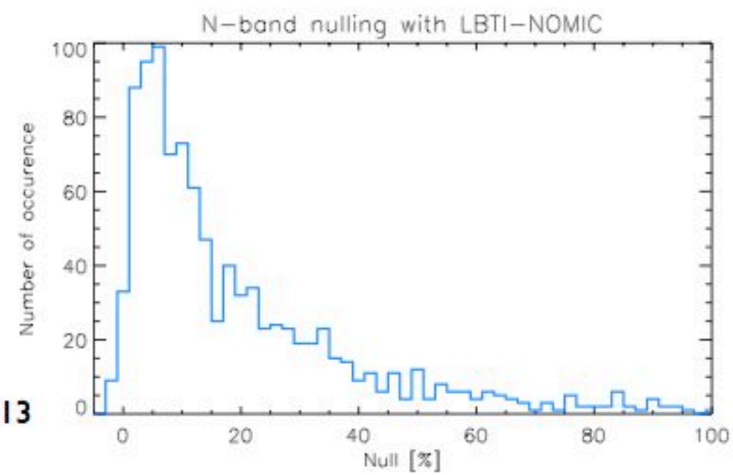
First Stabilized Fringes with LBTI



Open Phase Loop

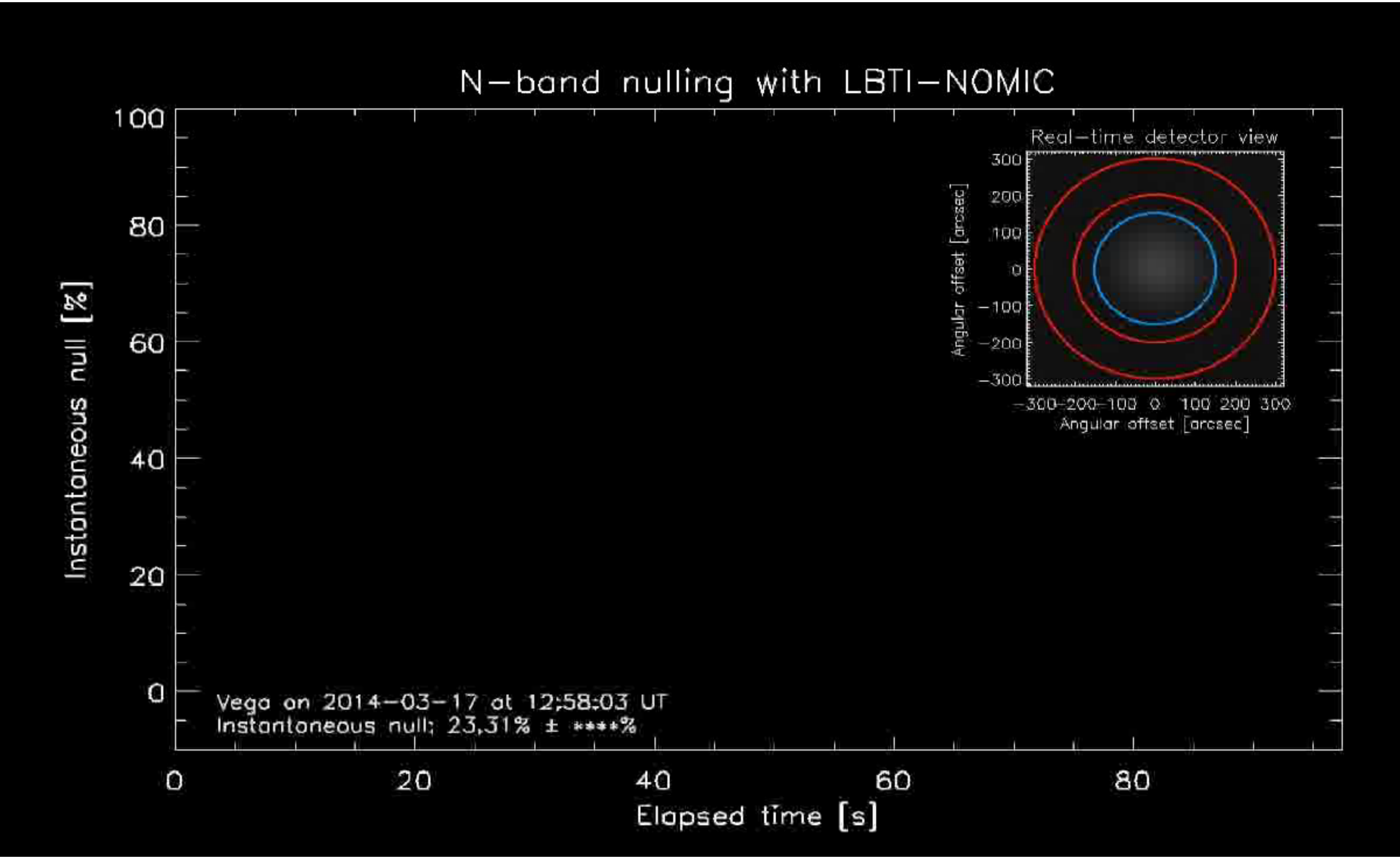


Closed Phase Loop



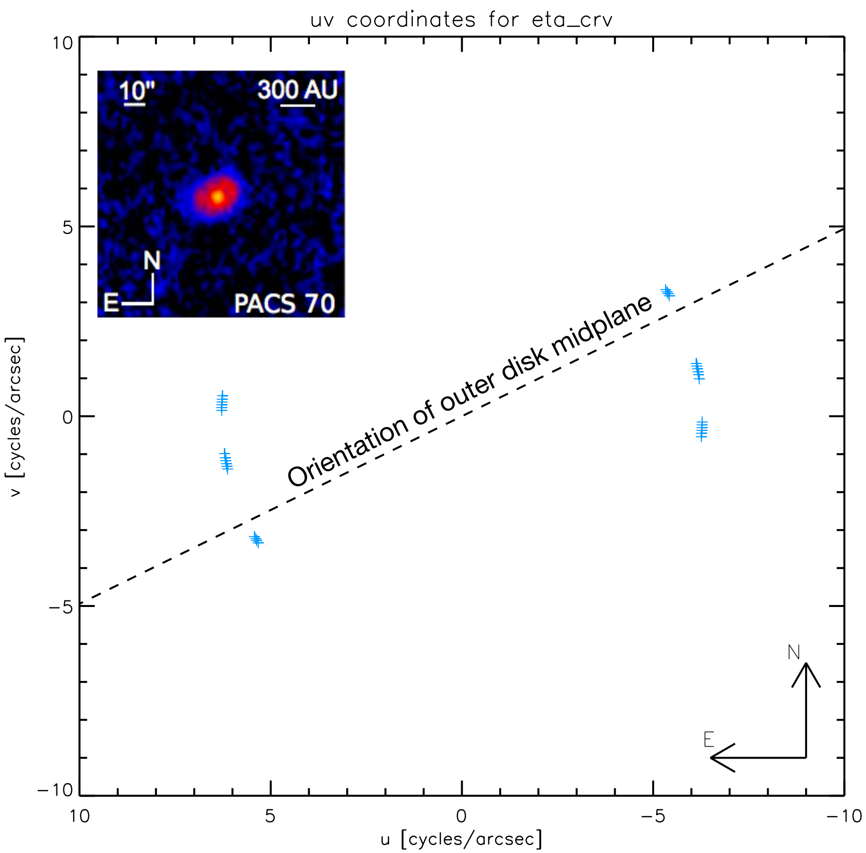
Dec. 30, 2013

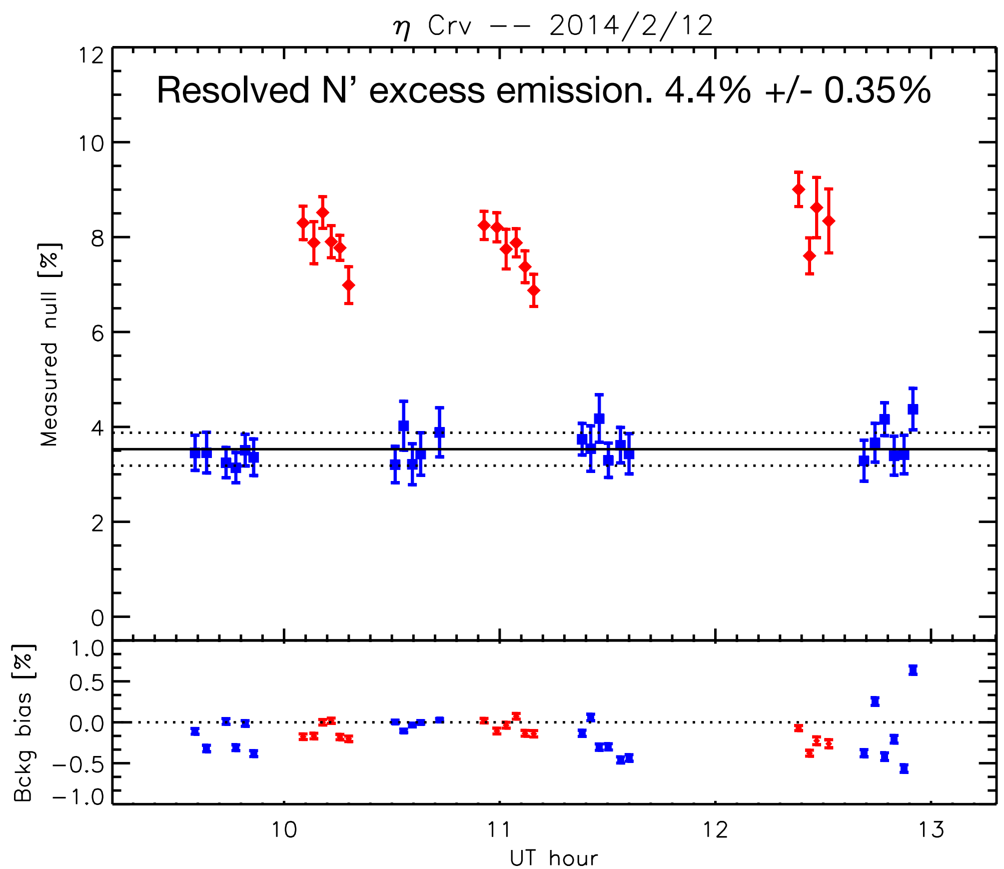
LBTI stabilized N-band null



The first detection: η Crv

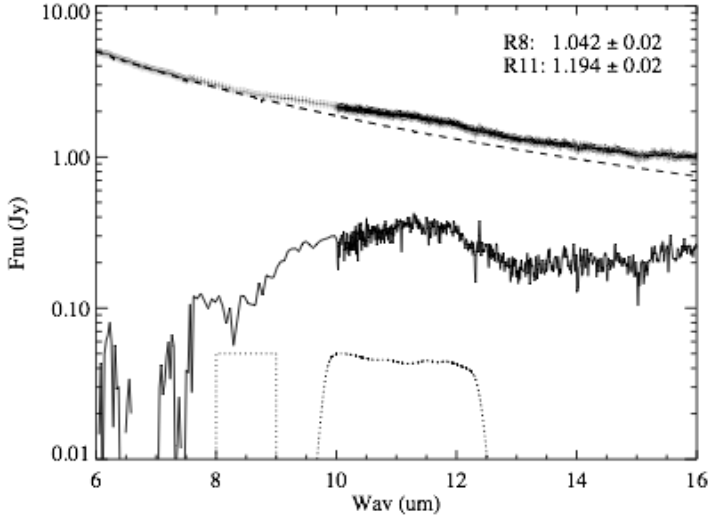
- 3 hours of nulling observations in February 2014 around transit;
- Outer disk seen by Herschel (i = 46.8°, PA = 116.3°, Duchene et al. 2014);
- Excess: 17% (IRS), 4% (KIN);





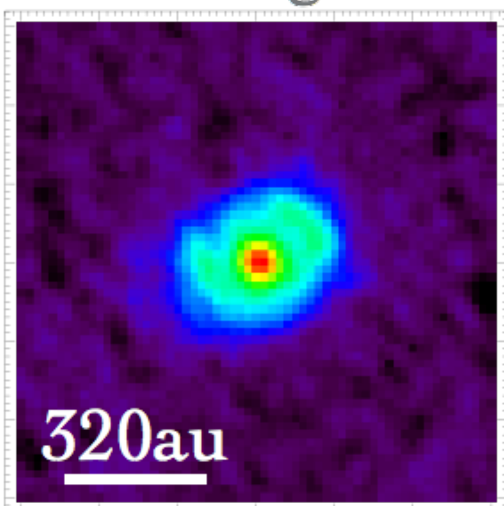
Courtesy G. Kennedy

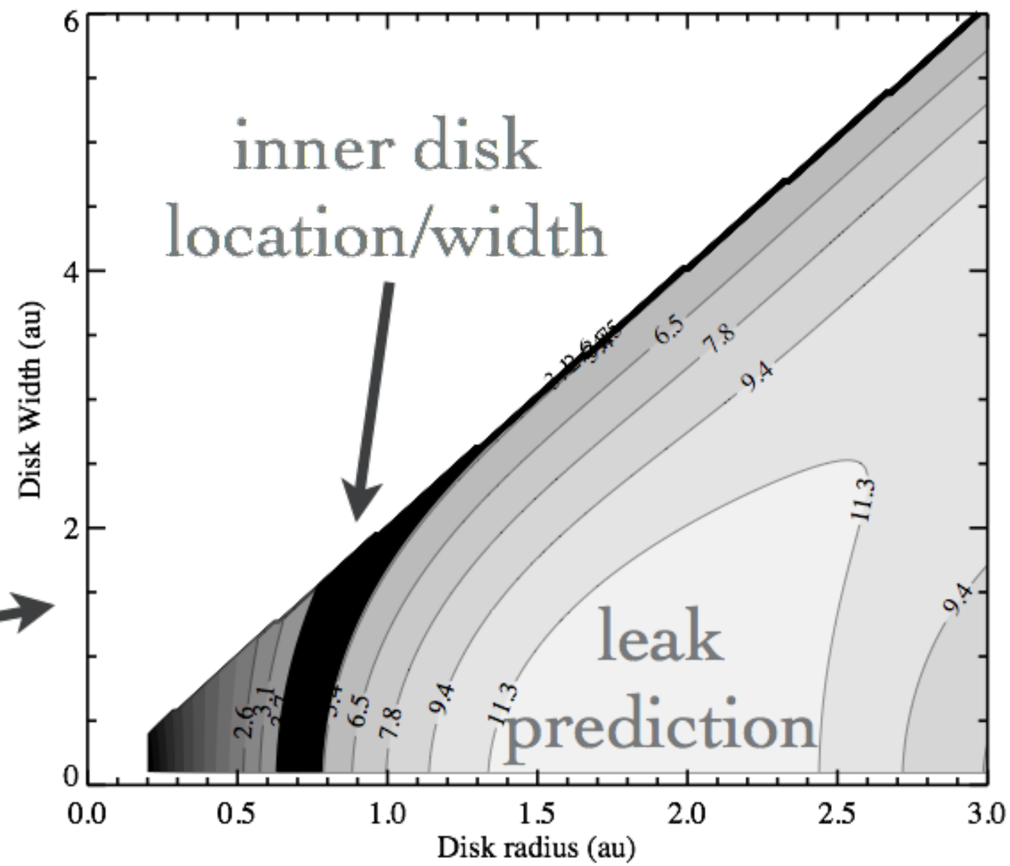
Disk/star flux ratio ~20%



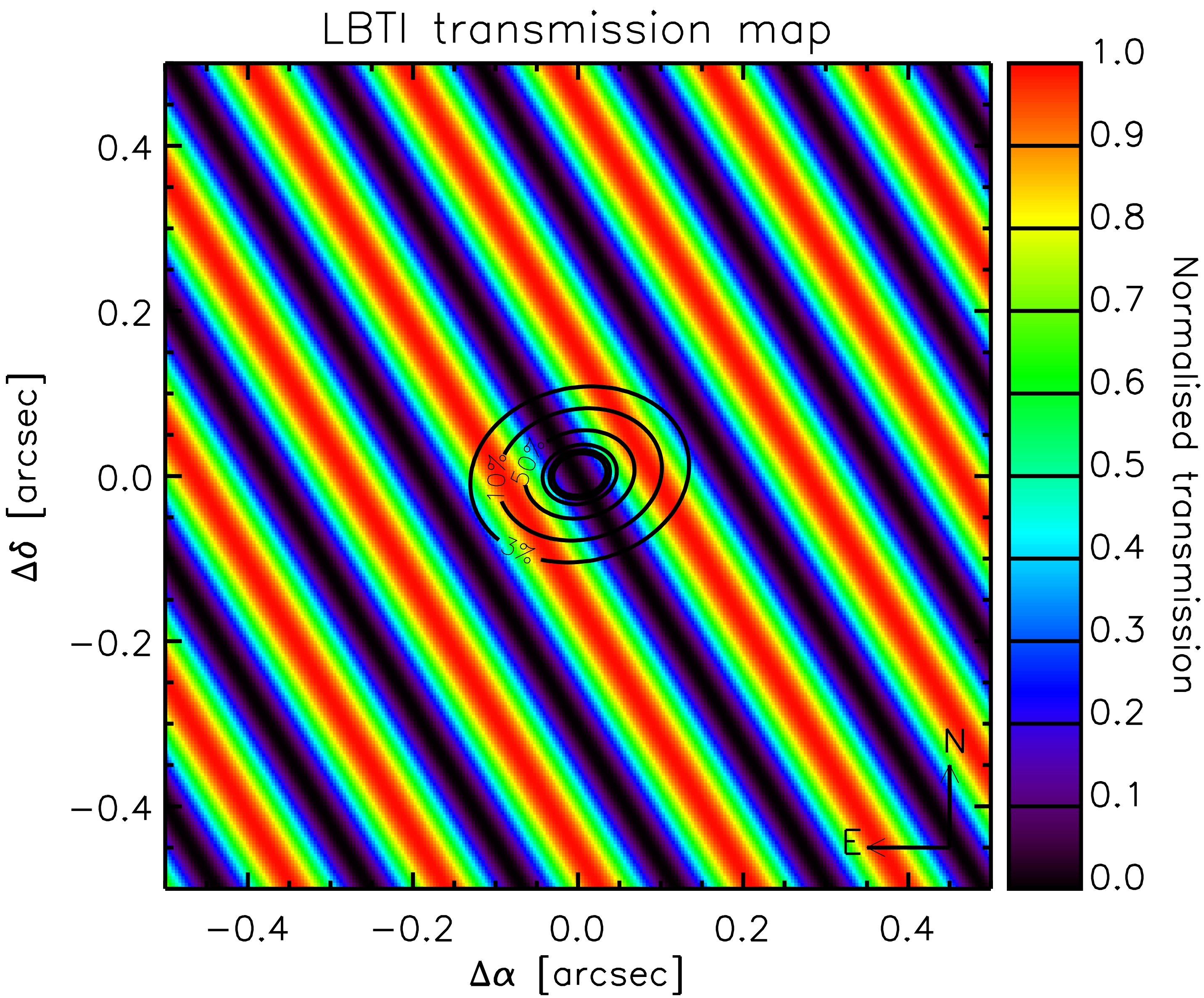
4.5% LBTI leak

Outer disk geometry





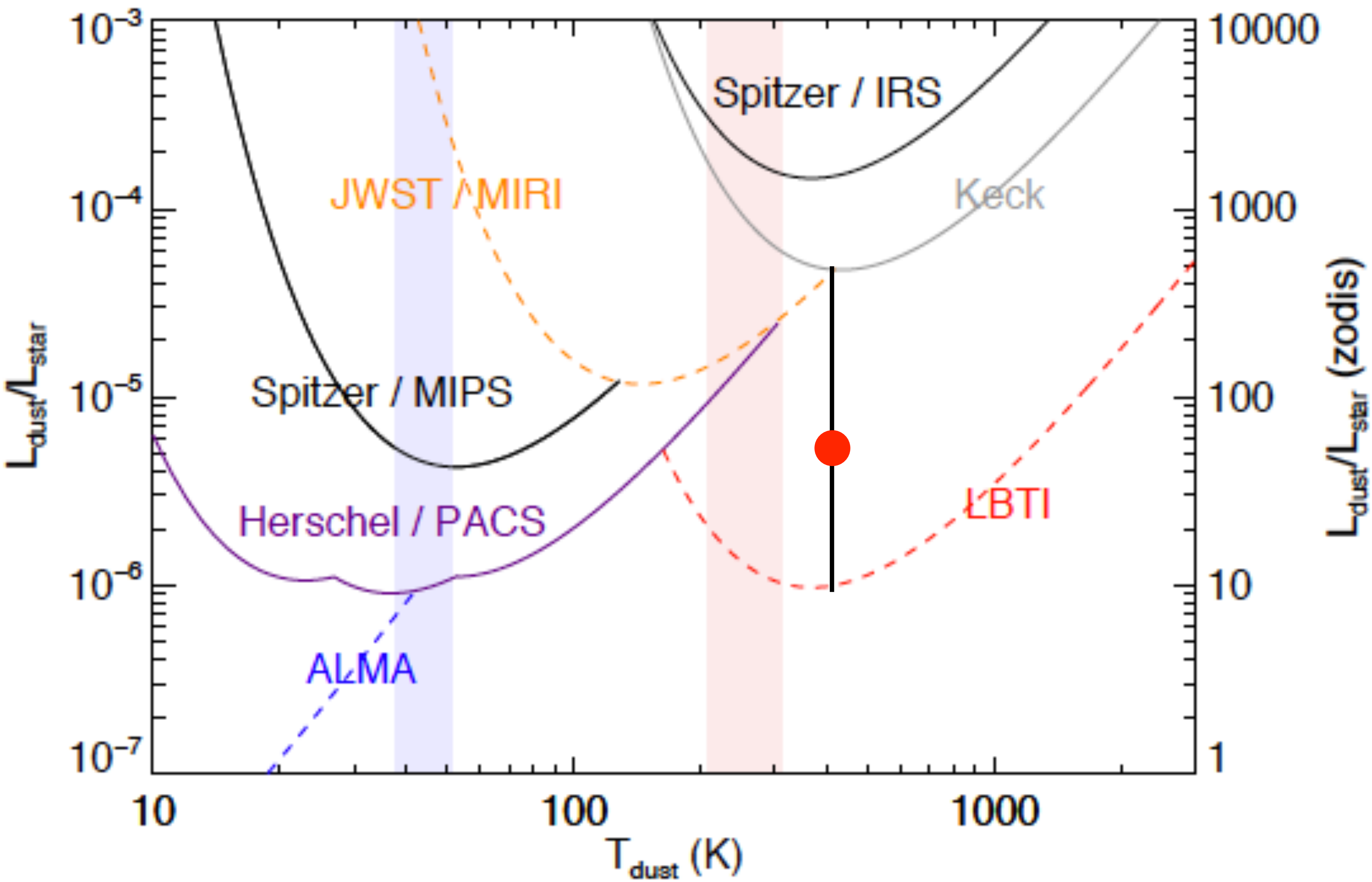
Exozodiacal resolved around η Crv



Nuller performance status

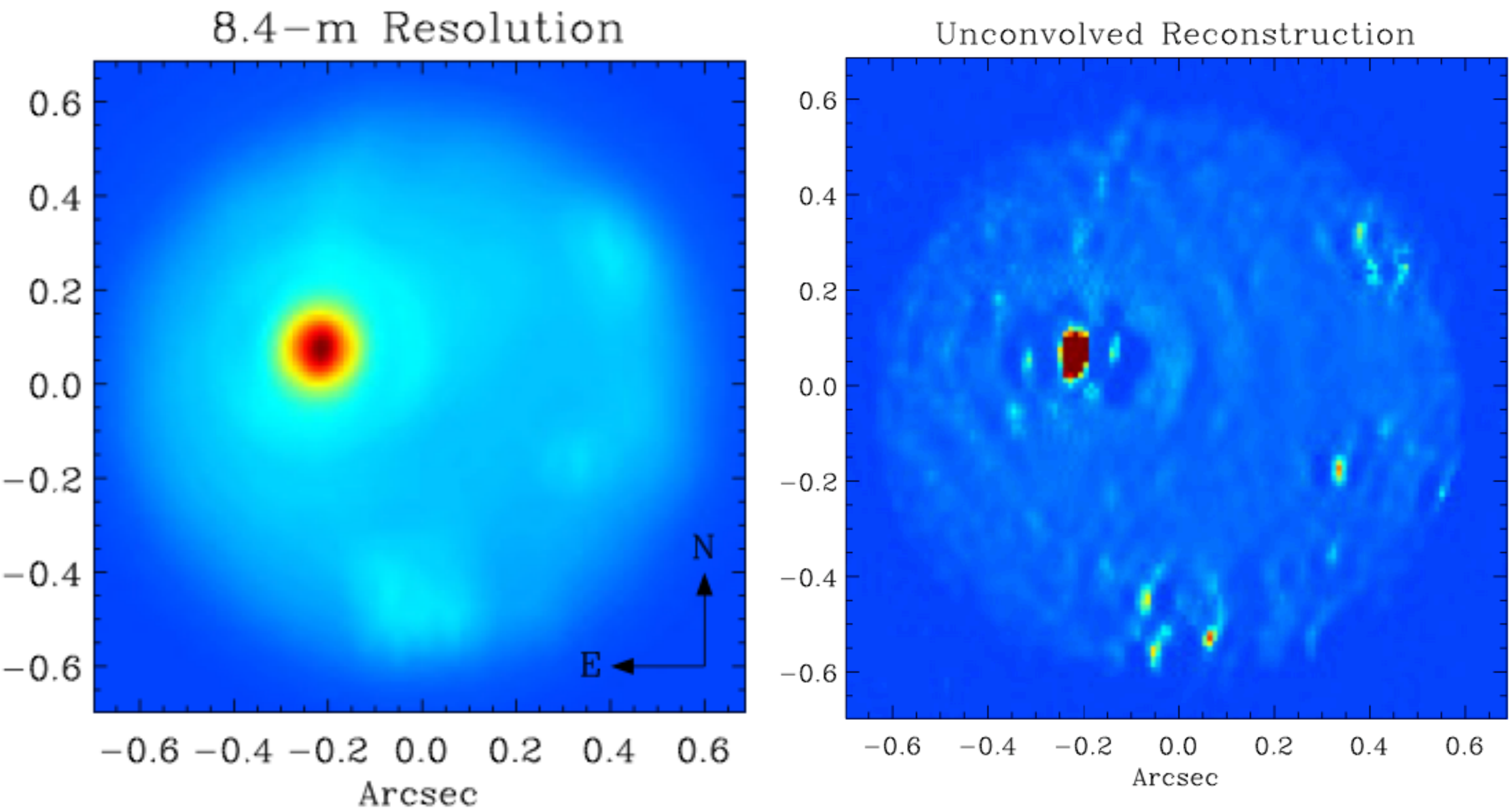
- Demonstrated null depth of ~1% with a stability in the 0.3-0.6% range per observing sequence;
- Data calibration accuracy of ~0.2%;
- Goal for HOSTS is 0.01% or 3 zodis

Nuller performance status



Other results from the LBTI

- Fizeau imaging of Io volcanism with LBTI/LMIRcam:



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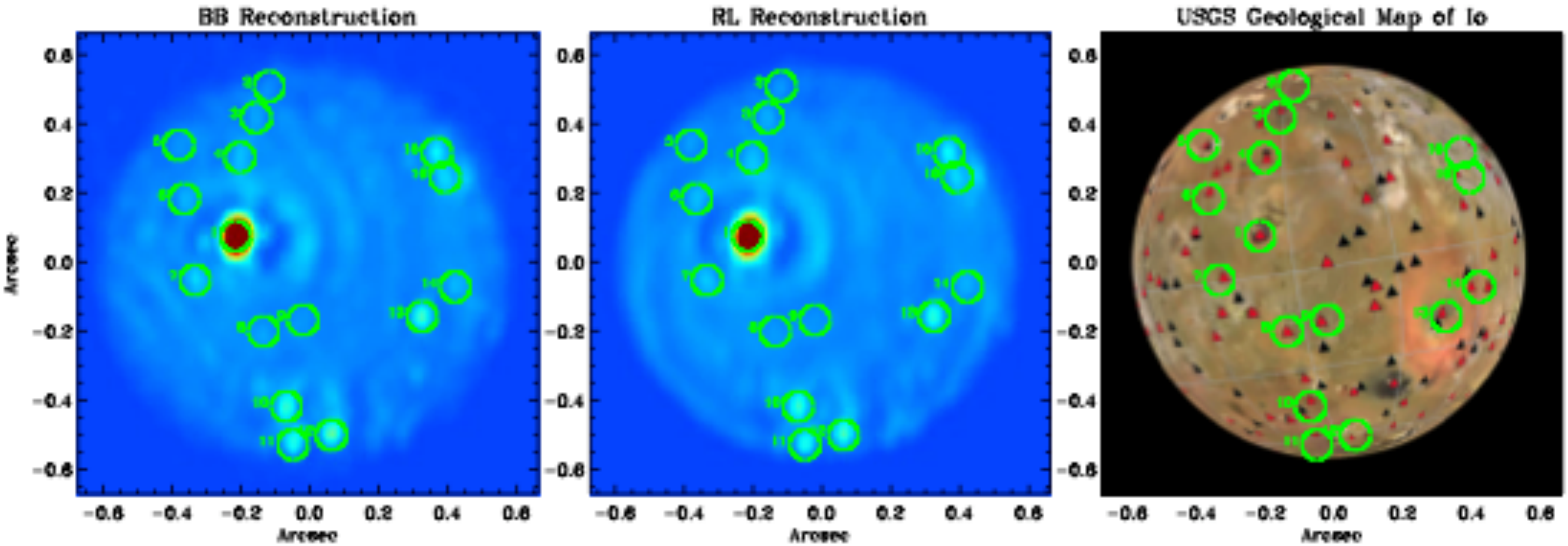
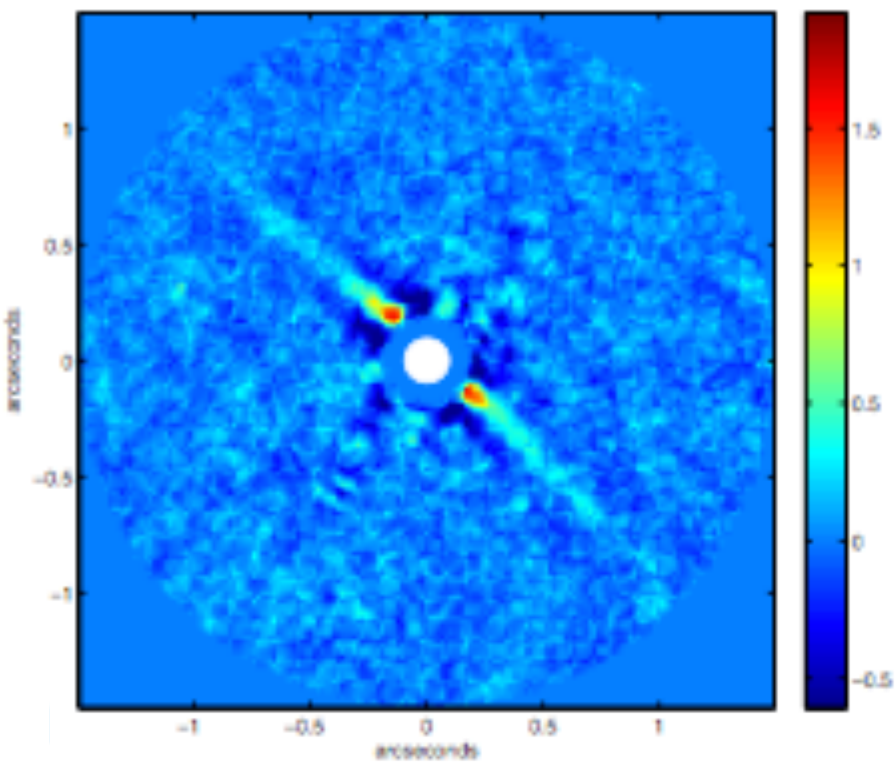
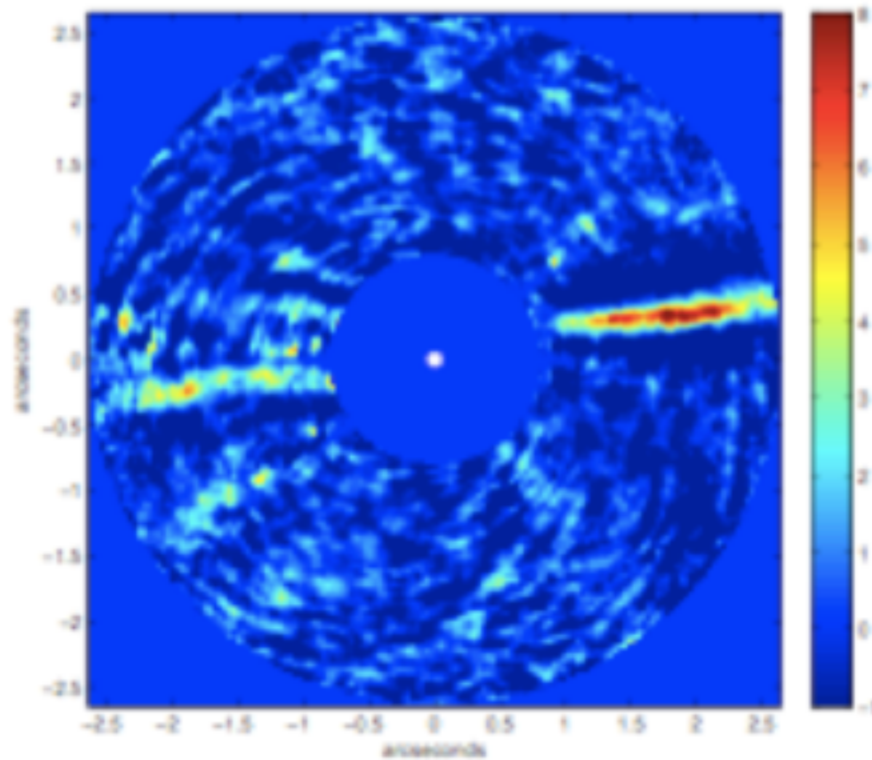


Identified 15 volcanoes, including Loki which is resolved

Other results from the LBTI

- Single-aperture observations of HD 15115 (Rodigas et al. 2012) and HD 32297 (Rodigas et al. 2014):





Outline

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  - History and scientific motivations -- what is it for?
- The Large Binocular Telescope Interferometer
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Summary

- The LBTI is a versatile instrument. It can be used for single-aperture high-contrast AO imaging, Fizeau interferometry, and nulling interferometry.

- Nulling interferometry:
  - High-angular resolution;
  - High-contrast imaging (destructive interference of starlight).

- Exozodiacal emission is a source of noise and confusion for future exoEarth direct imaging instruments.

- One of LBTI's goals is to determine the prevalence of exozodiacal light.

Quiz

- What's the image obtained by the LBTI nuller of the following sources (see next slides)?

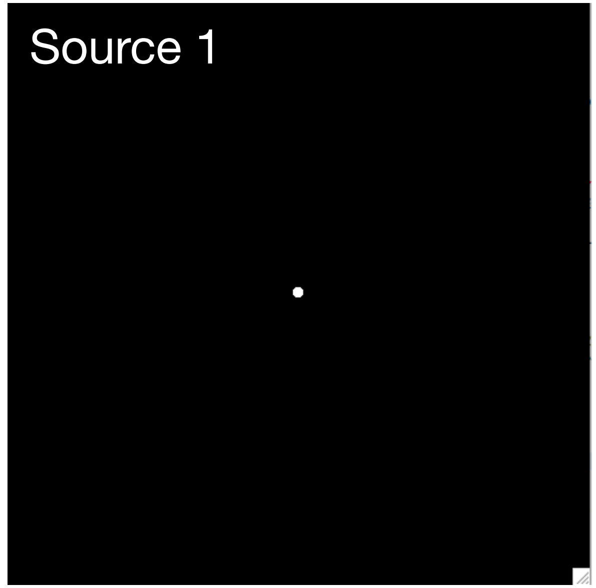


Image 1

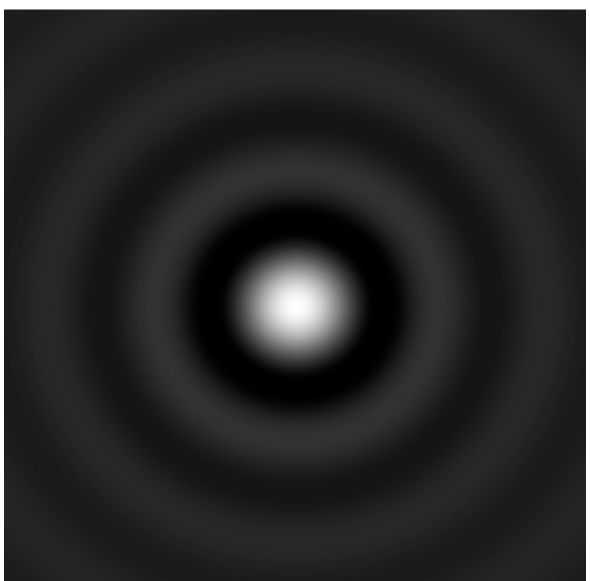


Image 2

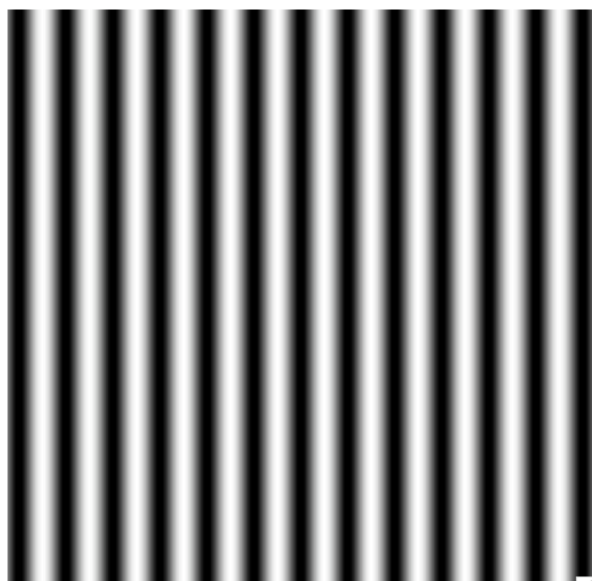
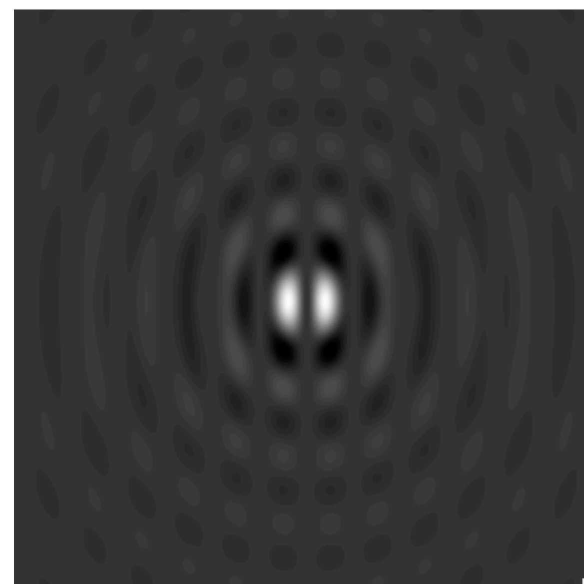


Image 3



Baseline orientation

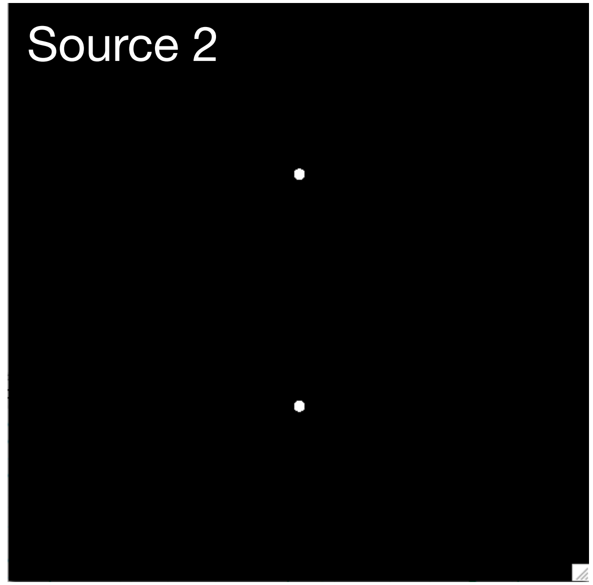


Image 1

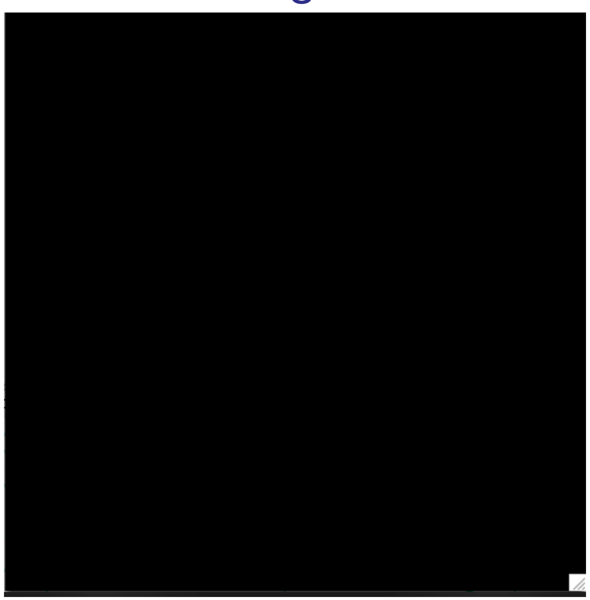


Image 2

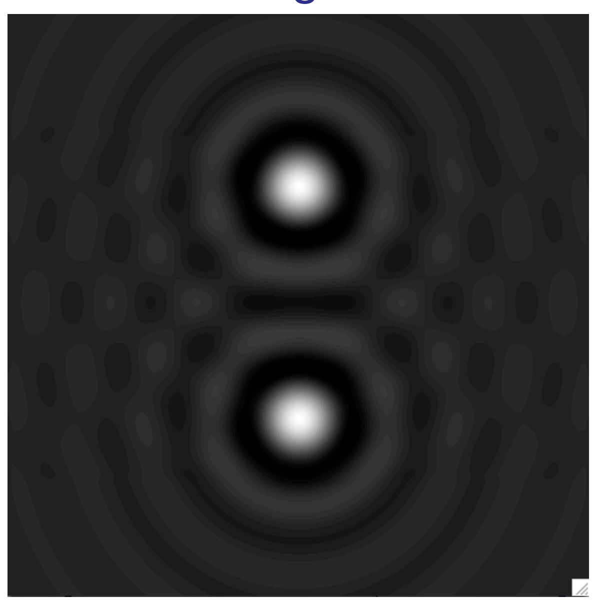
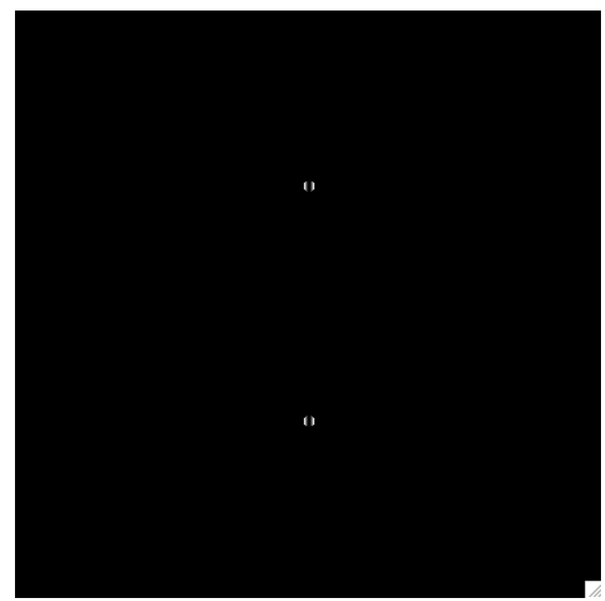


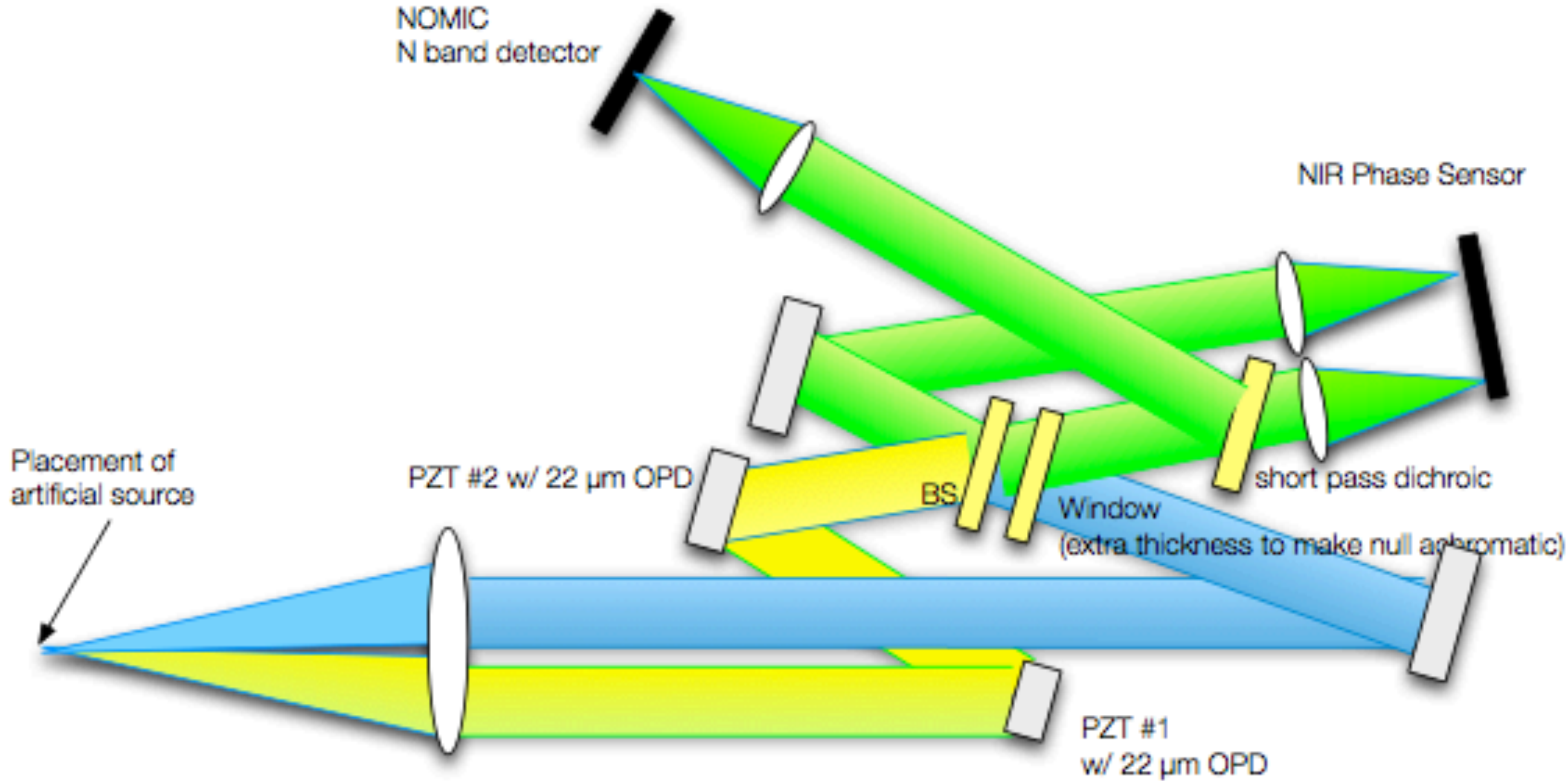
Image 3



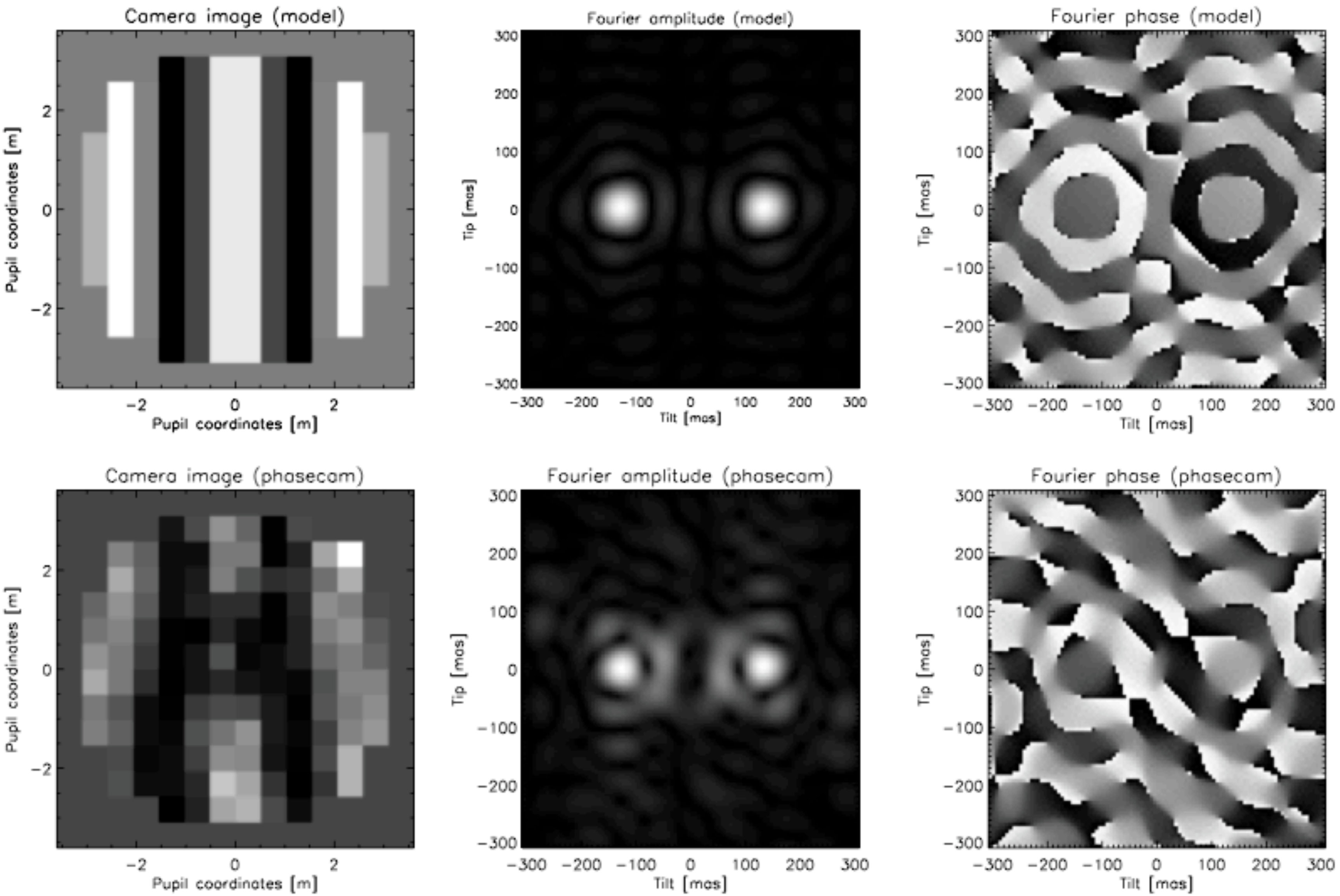

THAT'S ALL
FOLKS !

Backup slides

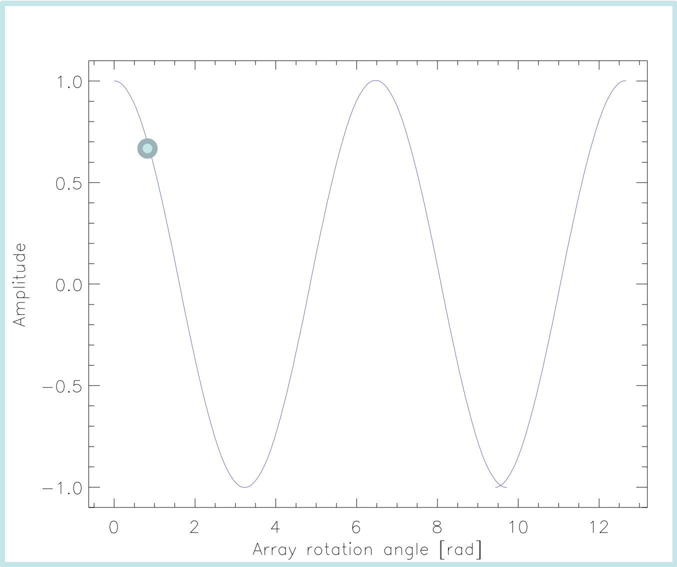
PHASEcam

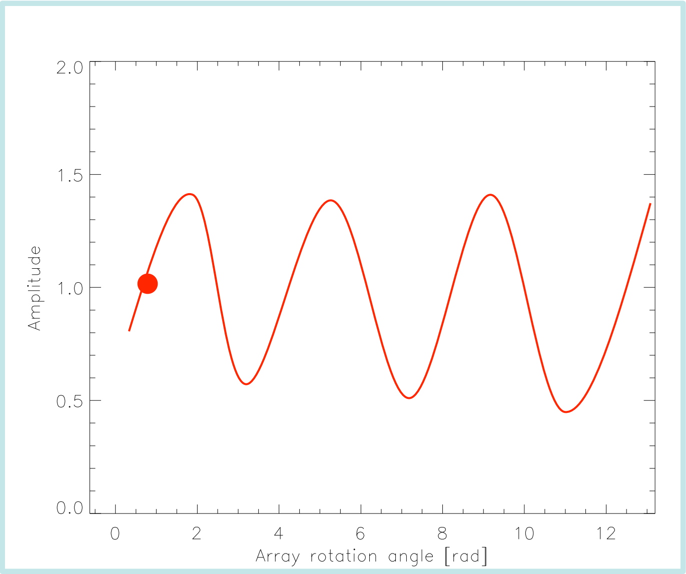

NOMIC
N band detector
NIR Phase Sensor
Placement of
artificial source
PZT #2 w/ 22 µm OPD
BS
short pass dichroic
Window
(extra thickness to make null achromatic)
PZT #1
w/ 22 µm OPD

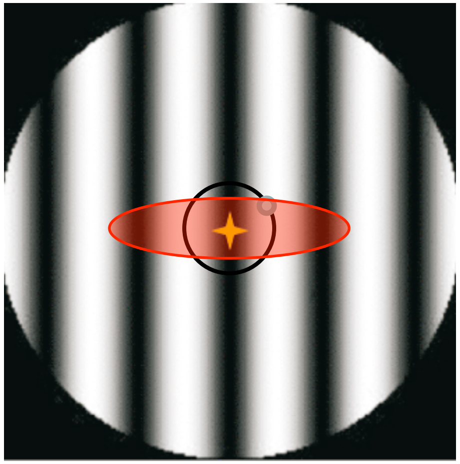
Tip/tilt and phase sensing approach



Rotating nulling interferometer







Planet signal

Symmetric sources