Theory and Early Results from the Large Binocular Telescope Interferometer

2014 Sagan Exoplanet Summer Workshop
Imaging planets and disks

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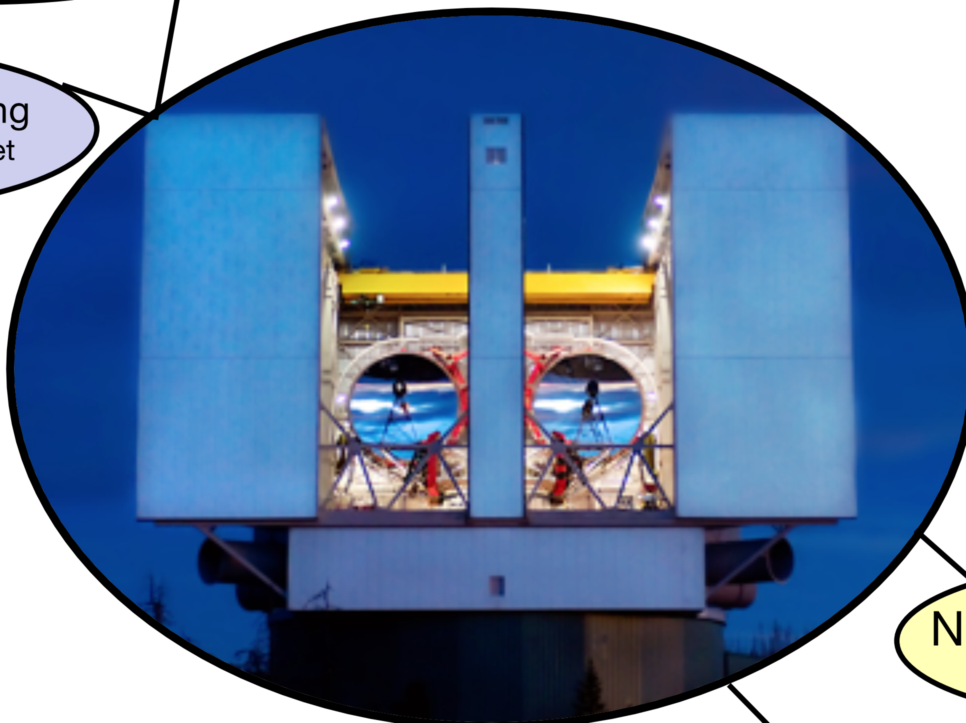
University of Arizona

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

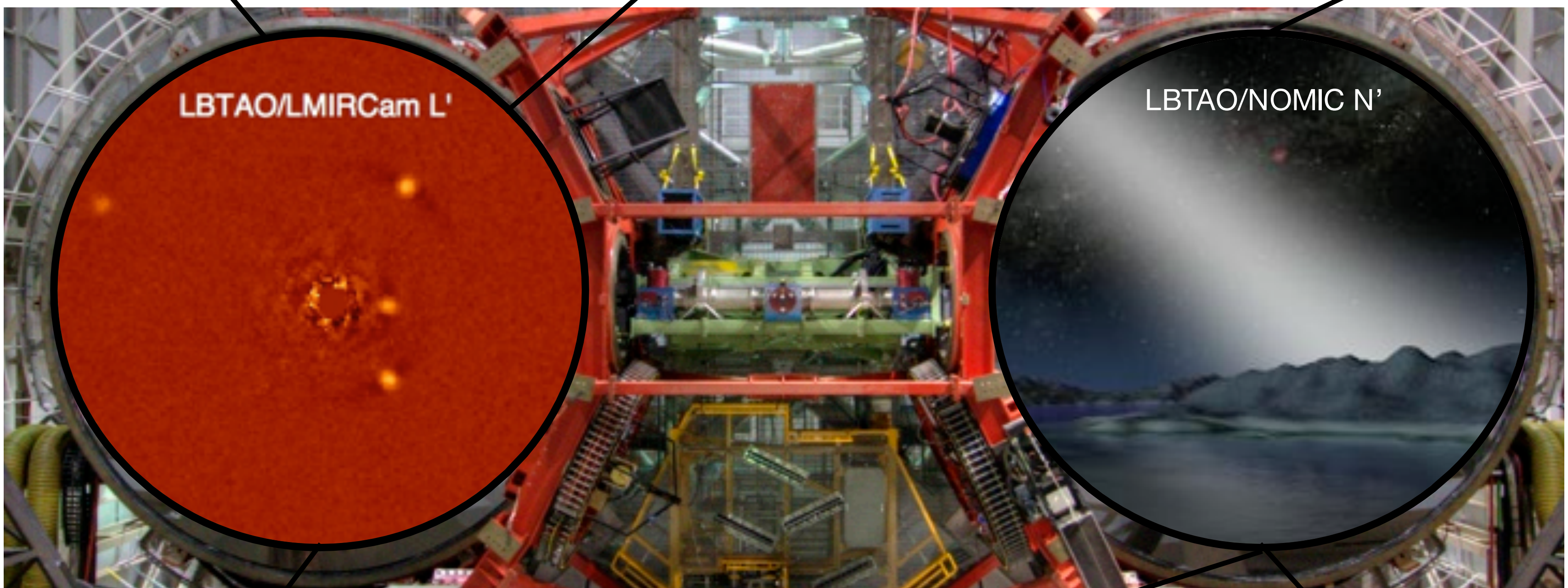
NRM/Fizeau interferometry
Theory covered by J. Monnier

Preamble 2

Planet evolution
Theory covered by J. Fortney

Planet atmosphere
Theory covered by E. Rauscher

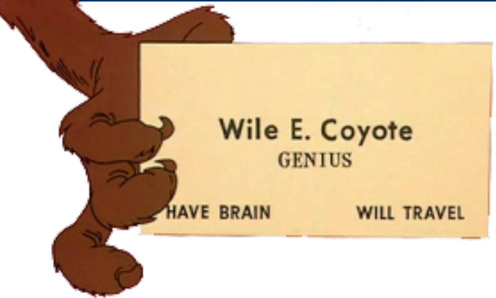
Exozodi evolution
Theory covered by M. Wyatt



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

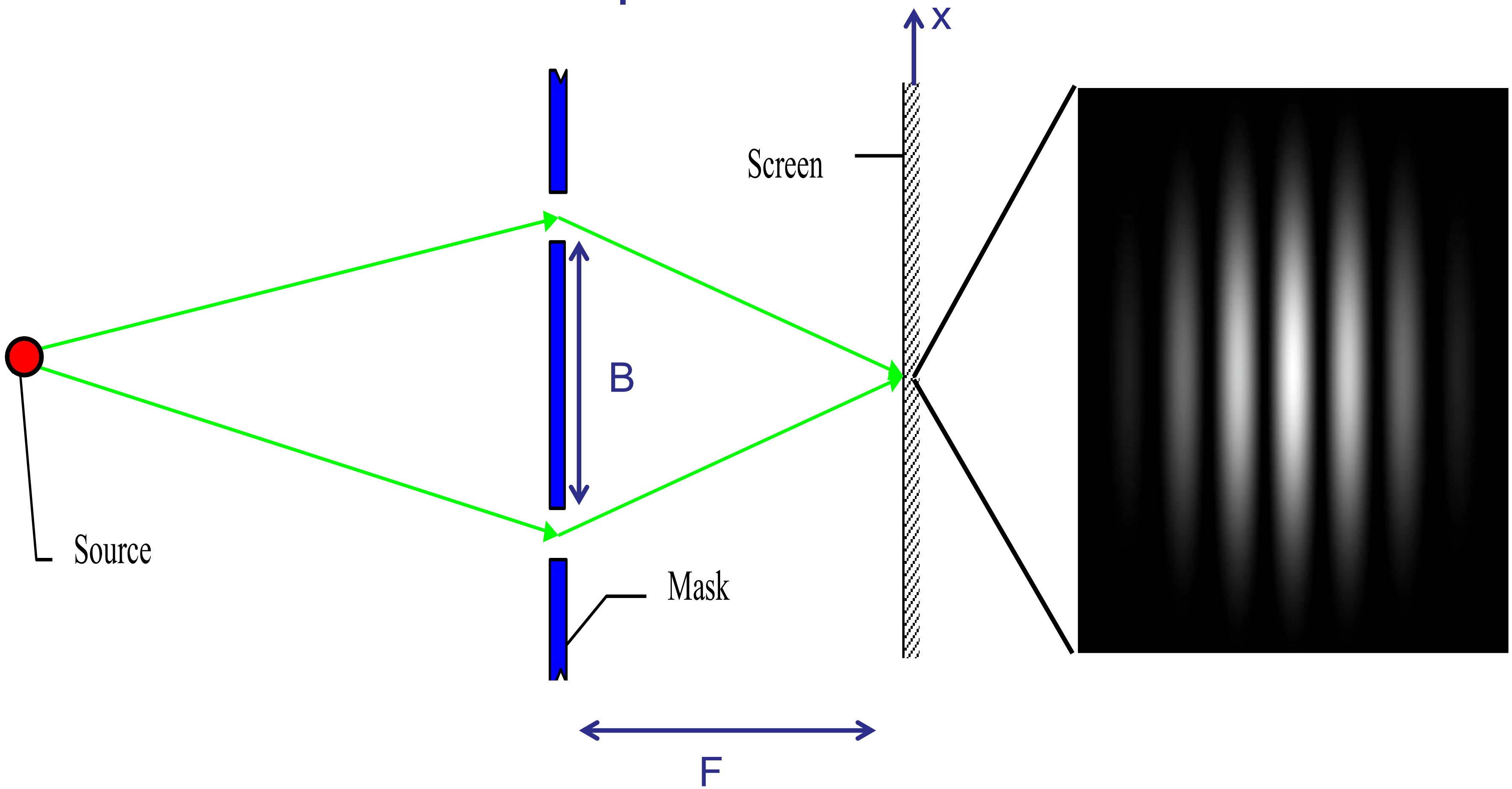
- What is light?

  - 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)

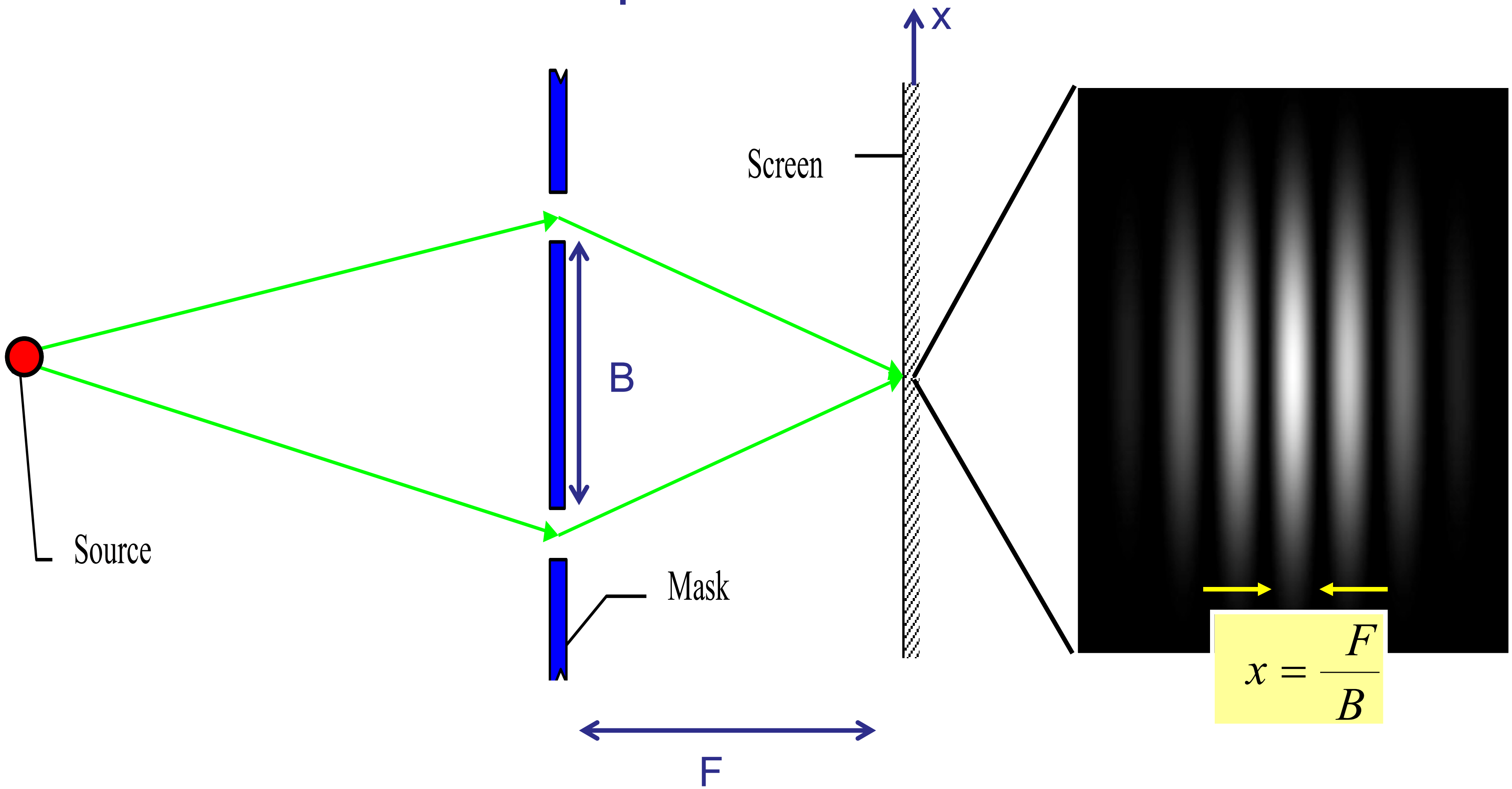
Interferometry: basic principles

- The double-slit experiment:



Interferometry: basic principles

- The double-slit experiment:



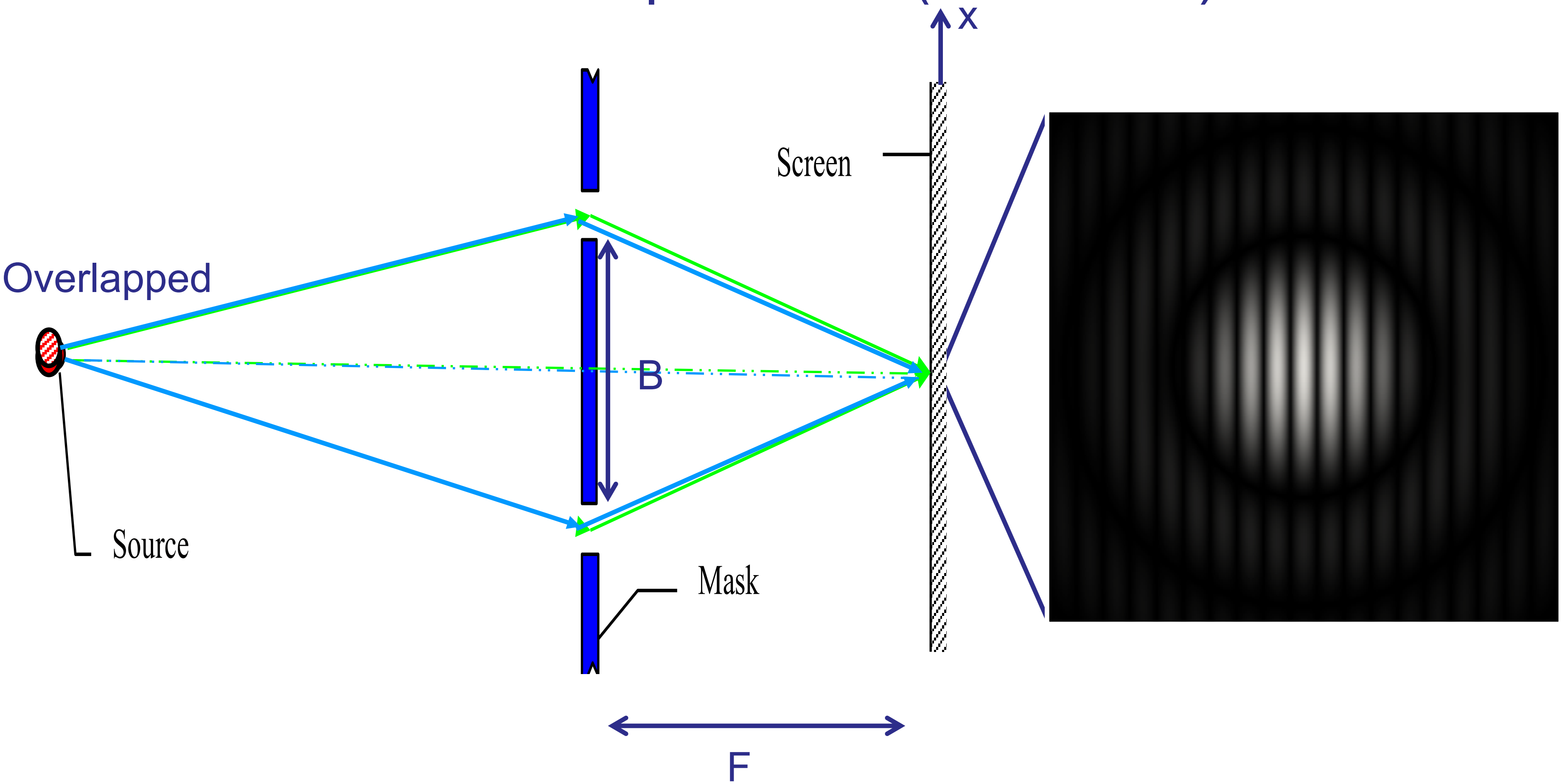
Interferometry: basic principles

- 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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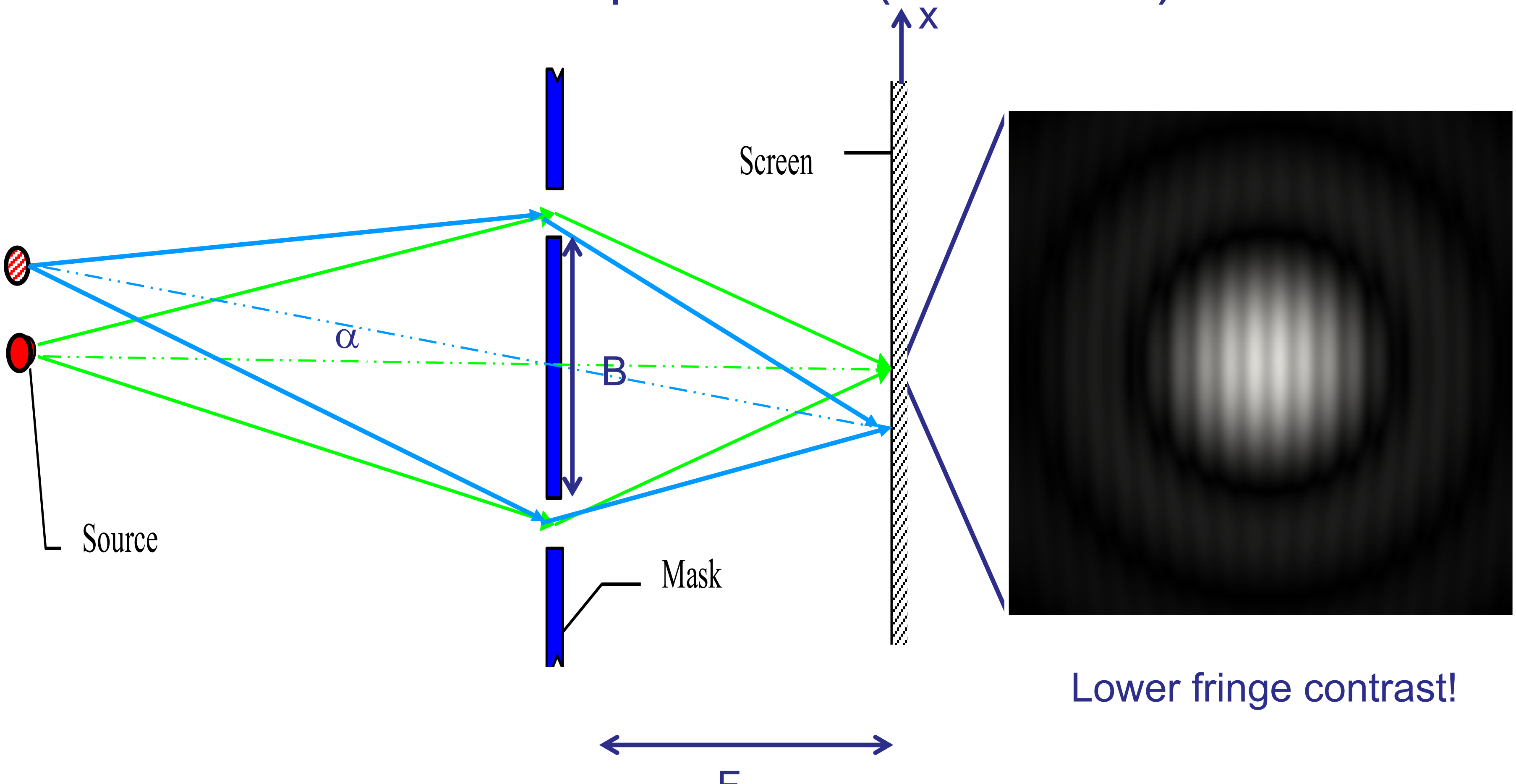
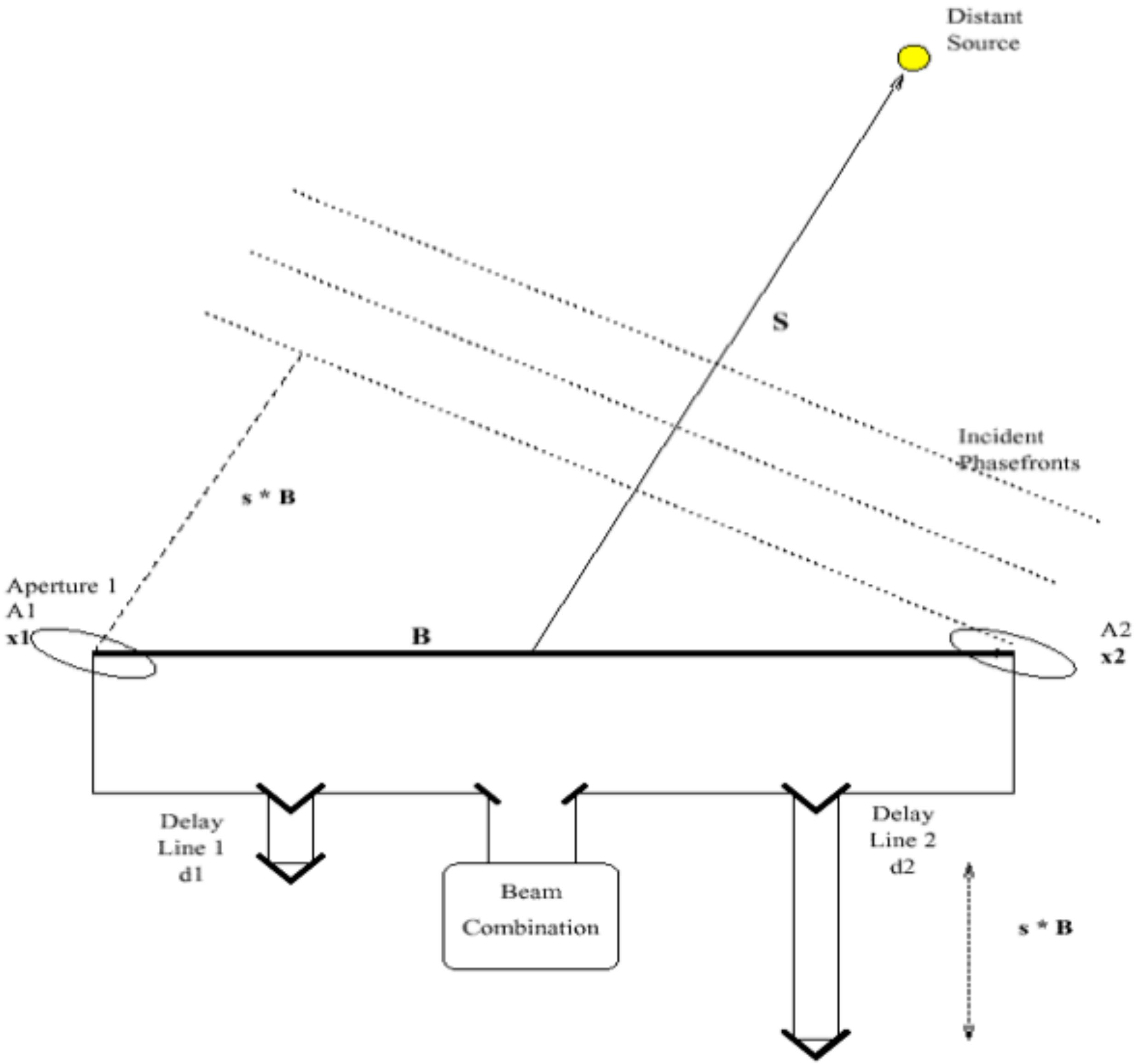


Lower fringe contrast!

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

A two-element interferometer

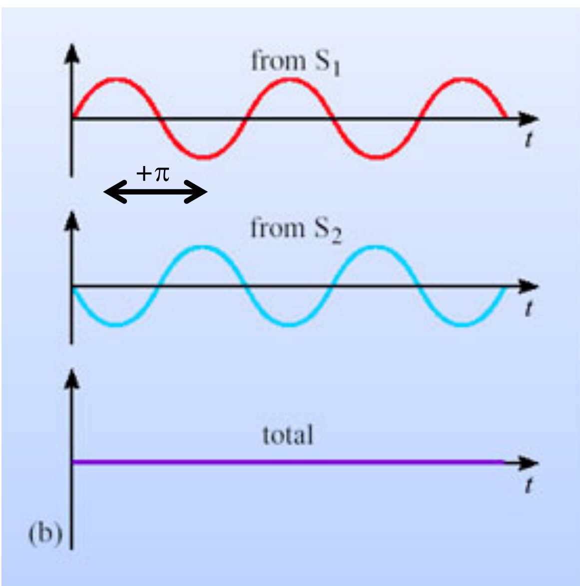
- Sampling of the radiation (from a distant point source).
- Transport to a common location.
- Compensation for the geometric delay.
- Combination of the beams.
- Detection of the resulting output.

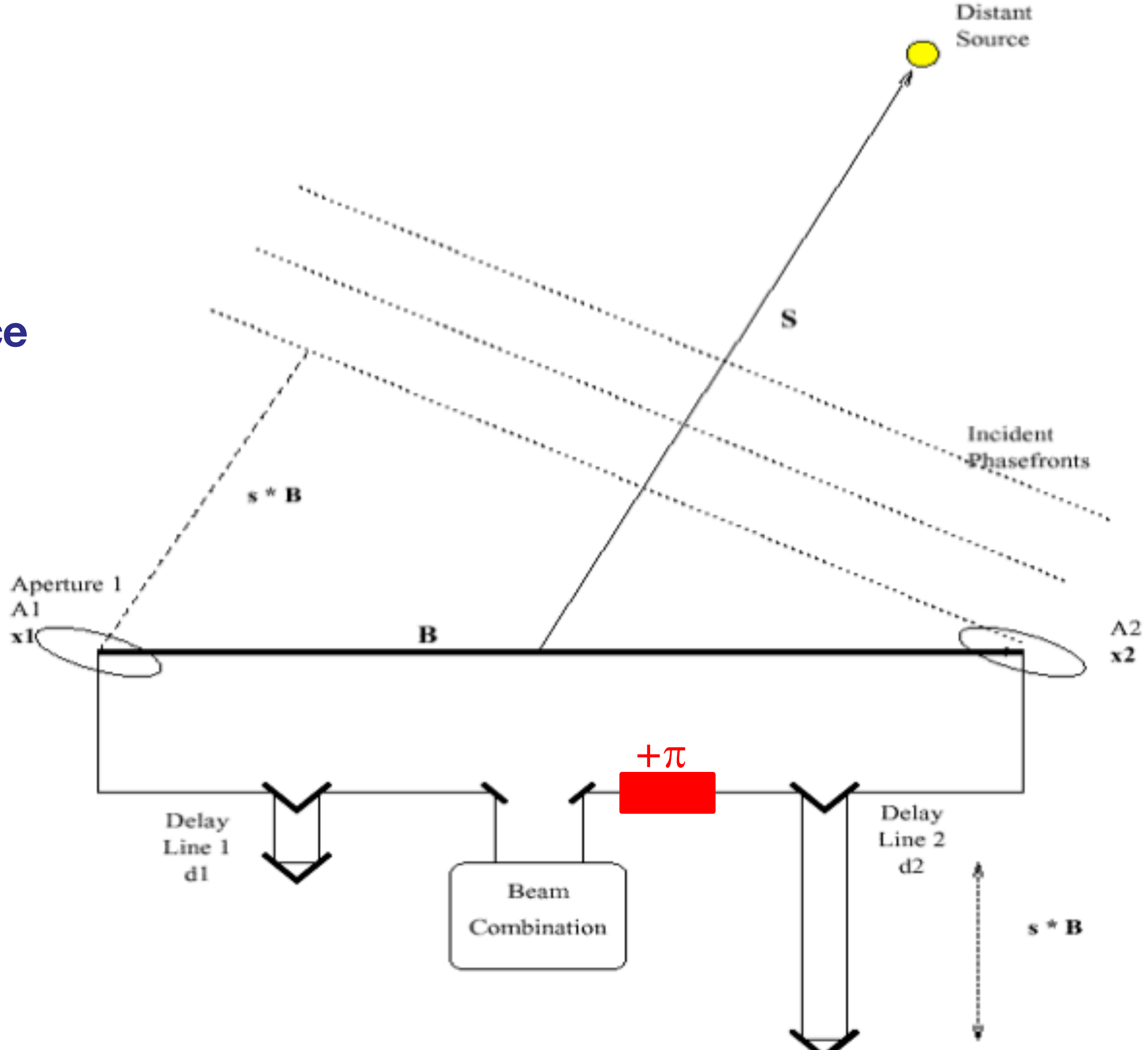


(C.A. Haniff – Michelson summer school 2006)

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:

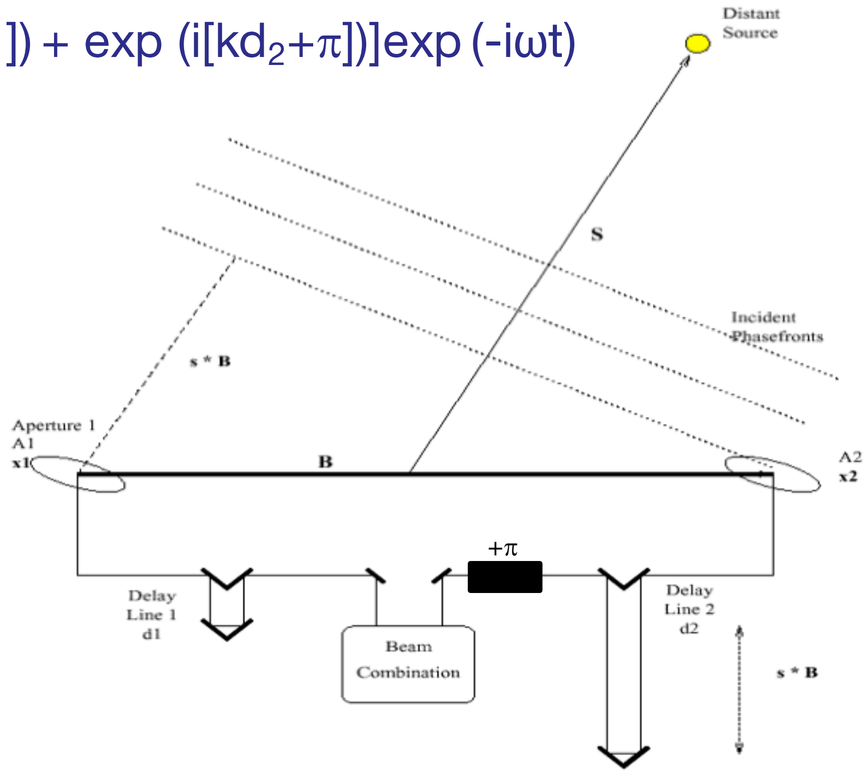
$$\psi_1 = A \exp(ik[\hat{s}.B + d_1]) \exp(-i\omega t) \quad \text{and} \quad \psi_2 = A \exp(i[kd_2+\pi]) \exp(-i\omega t).$$

- 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 wavenumber ($= 2\pi/\lambda$)

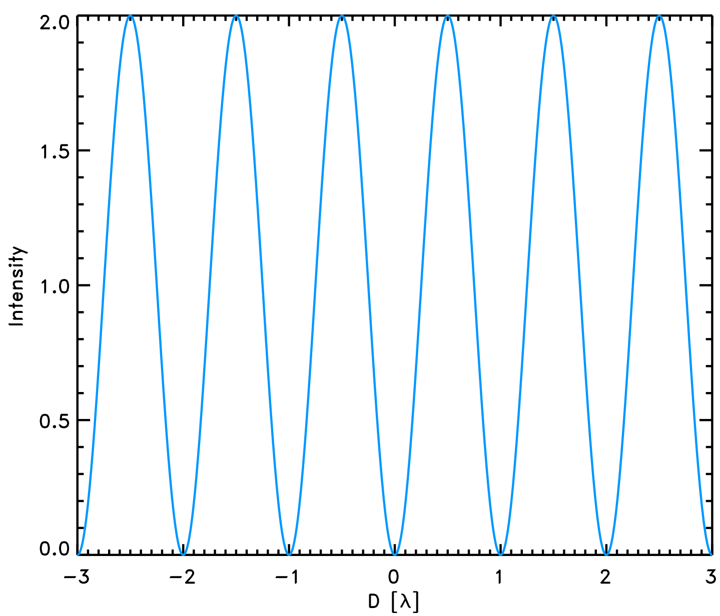


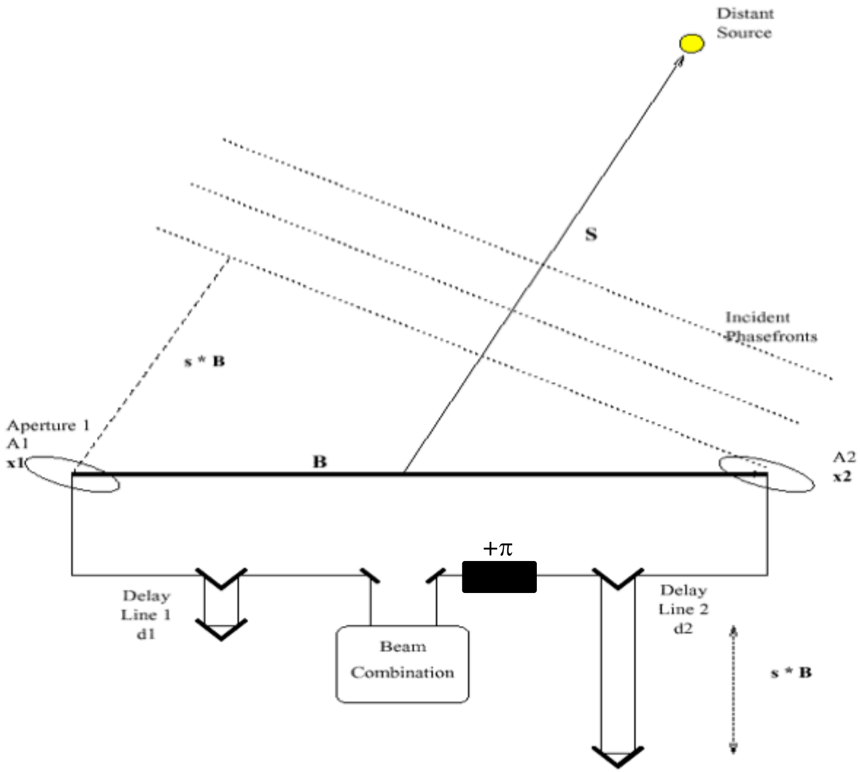
The output of a 2-element nulling interferometer

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

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

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





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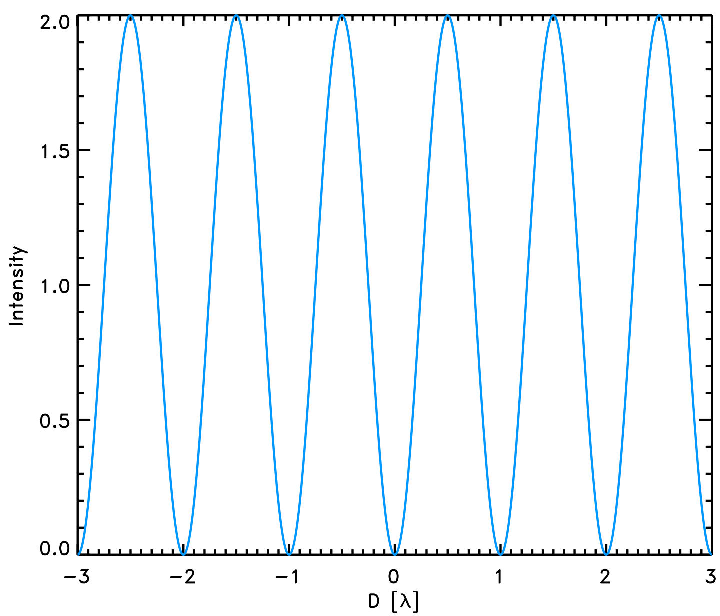
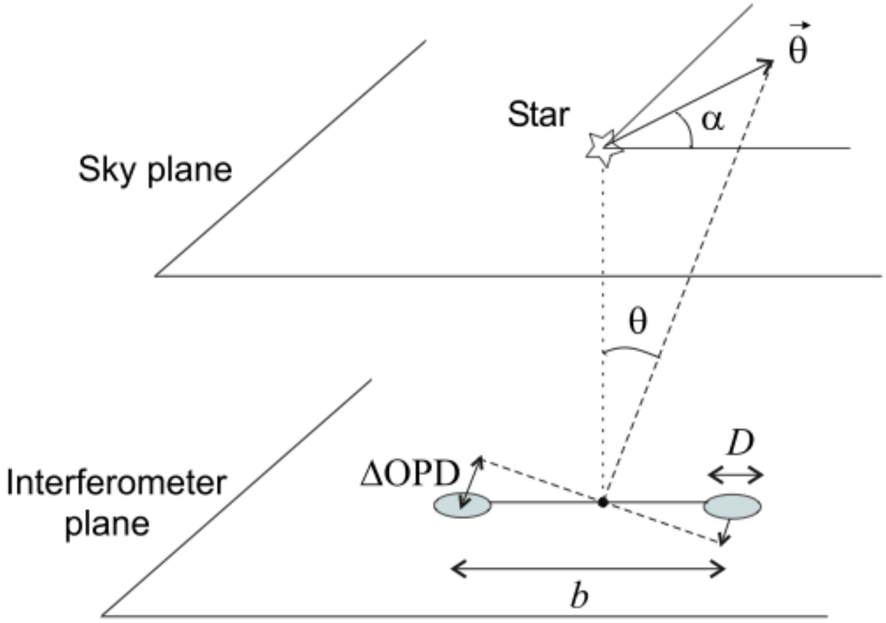


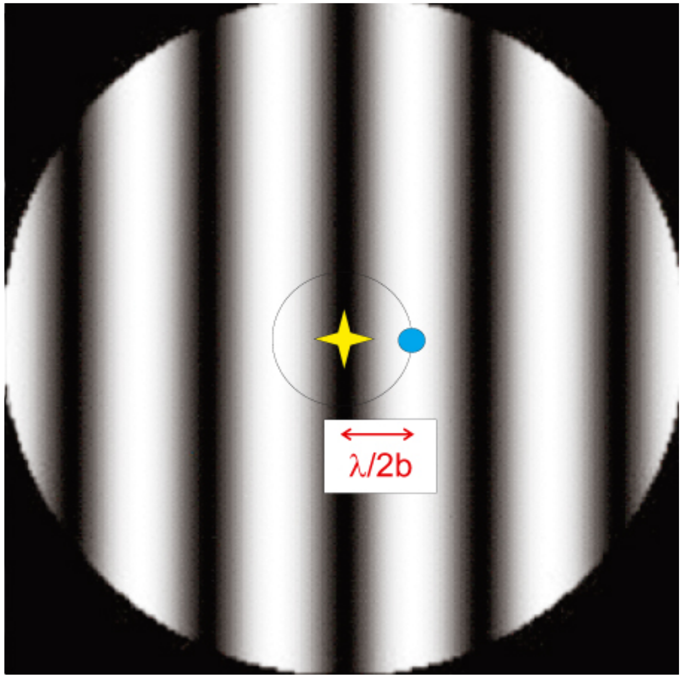
Adjacent fringe peaks separated by
- $\Delta d_{1or2} = \lambda$ or
- $\Delta(\hat{s}.B) = \lambda$ or
- $\Delta(1/\lambda) = 1/D$

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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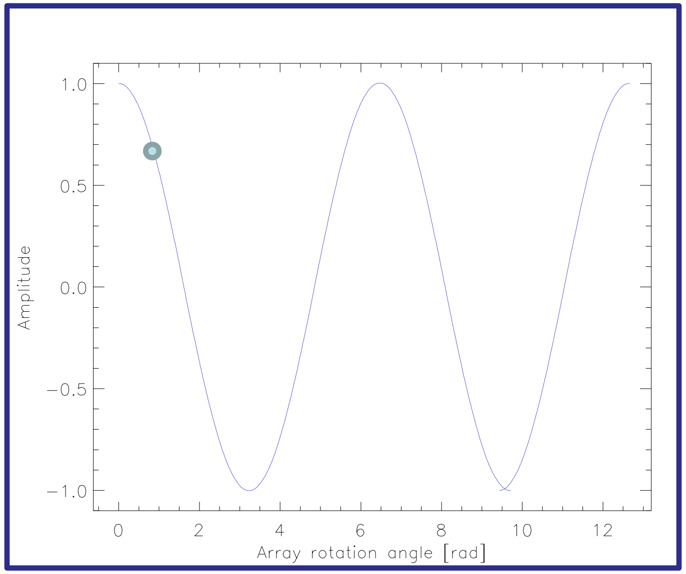
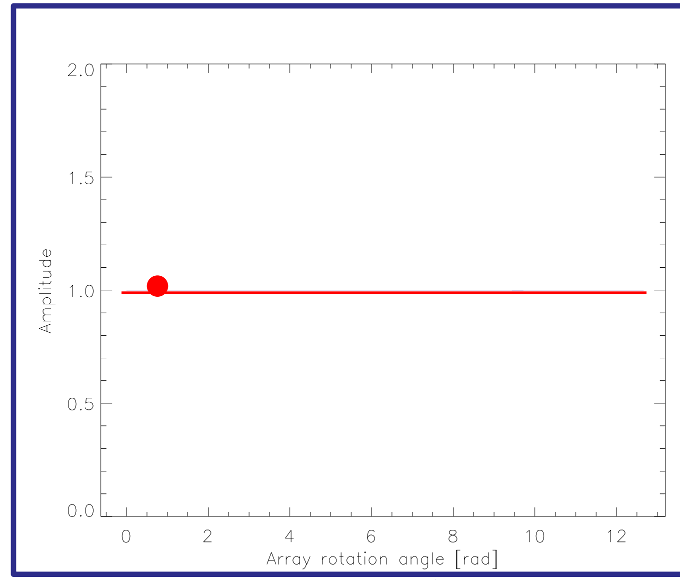
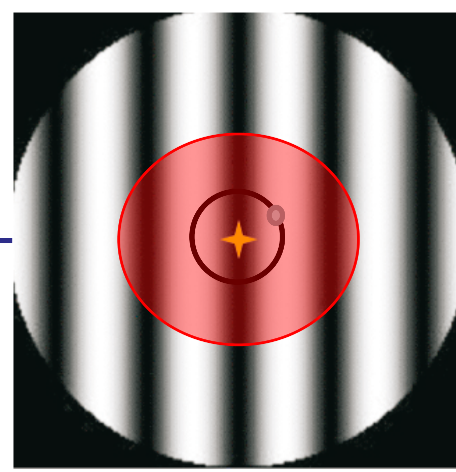
The first concept

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





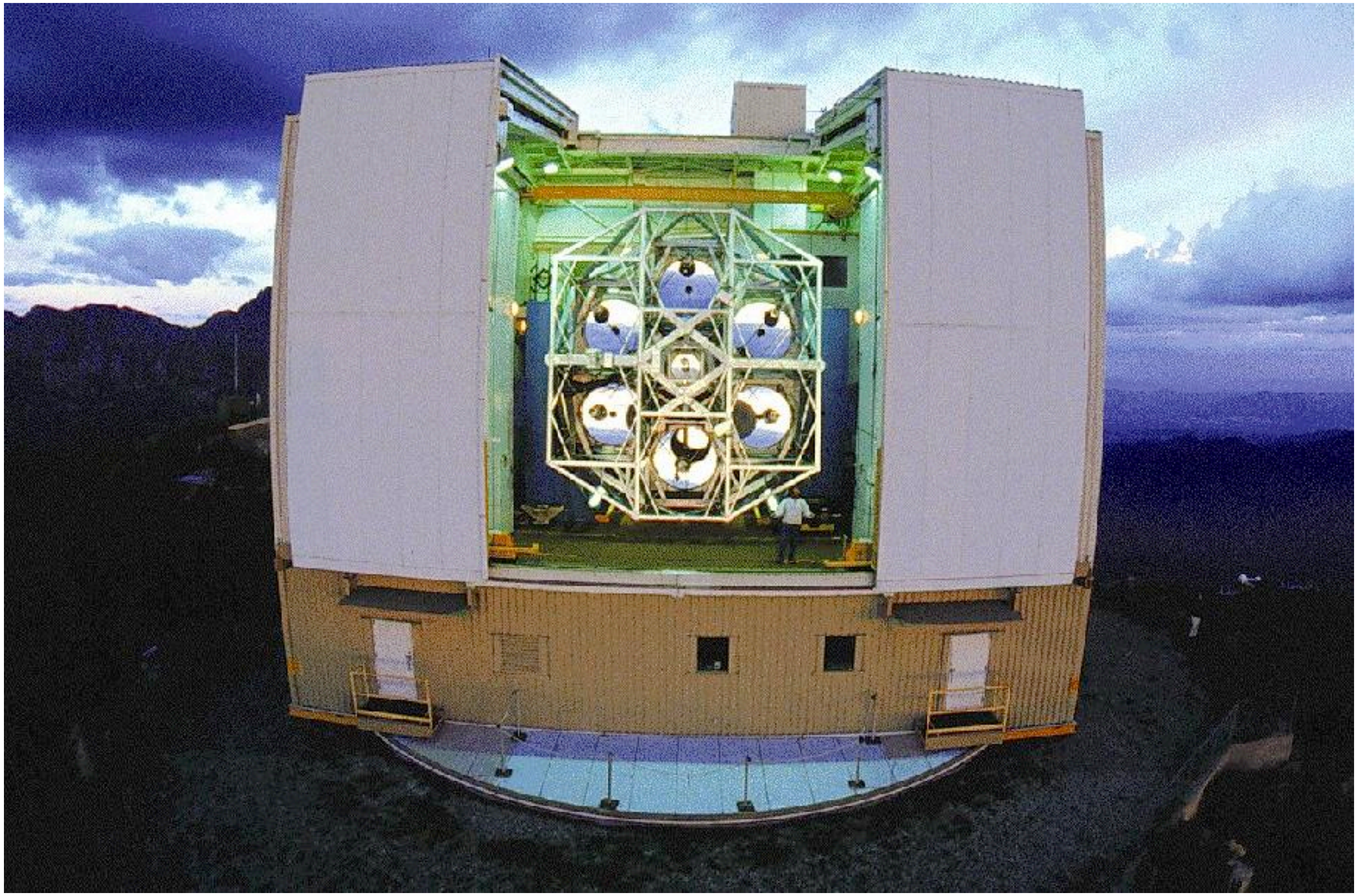


Planet signal

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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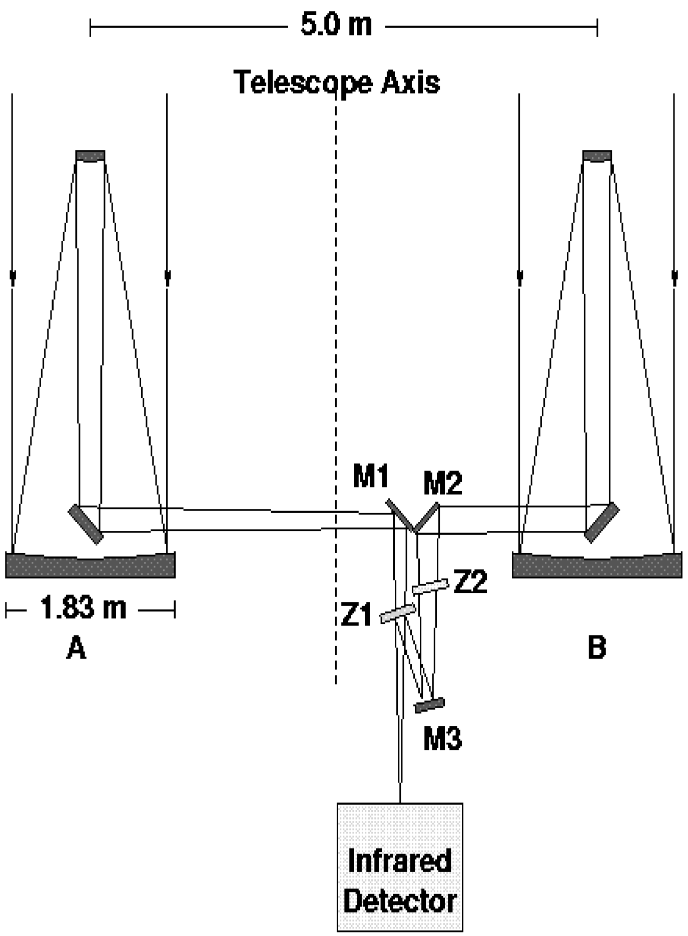
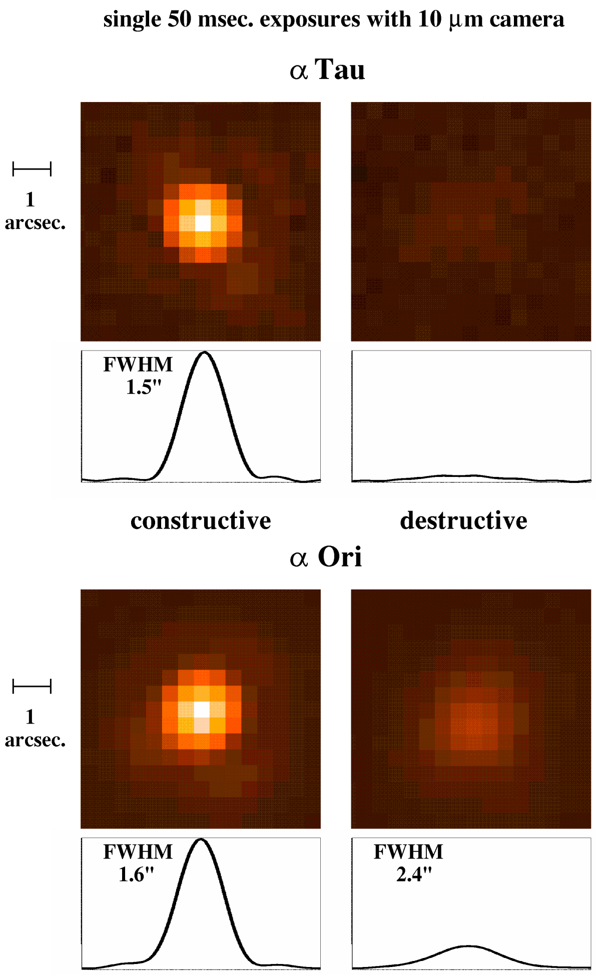


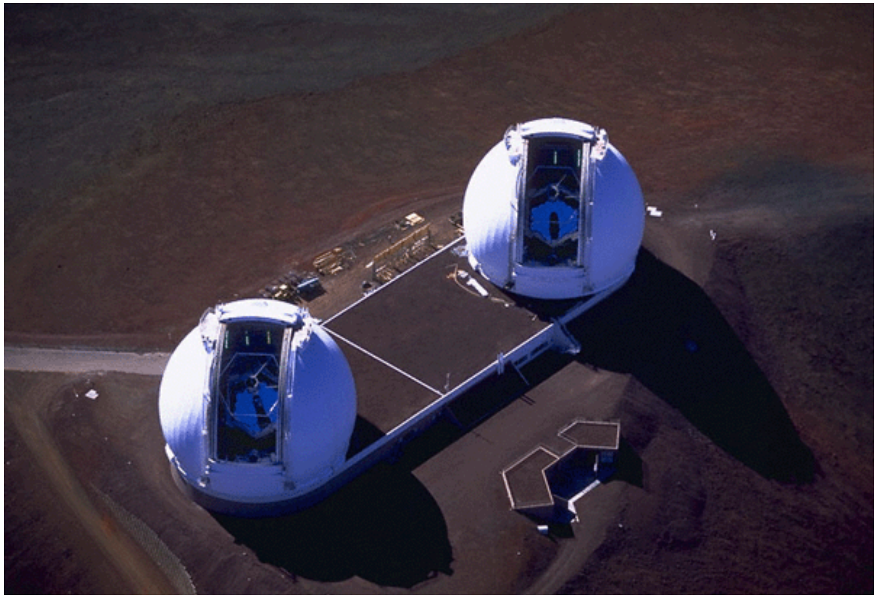


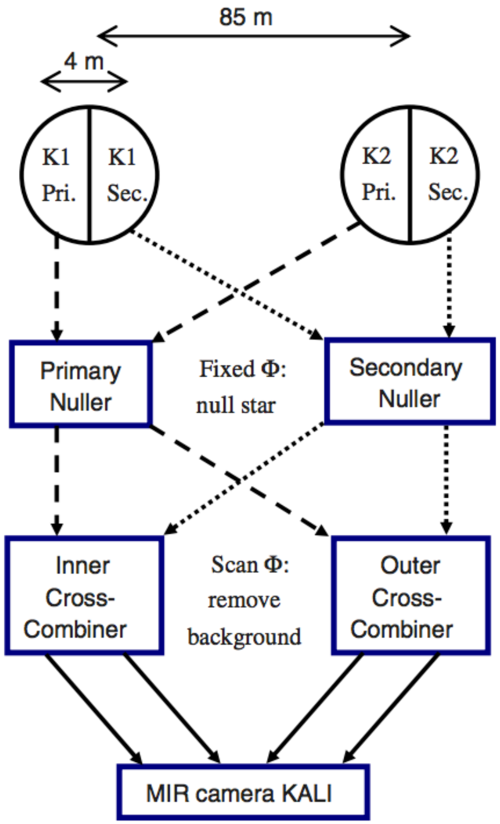
For unresolved star, destructive/ constructive peak ratio = 0.04

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;

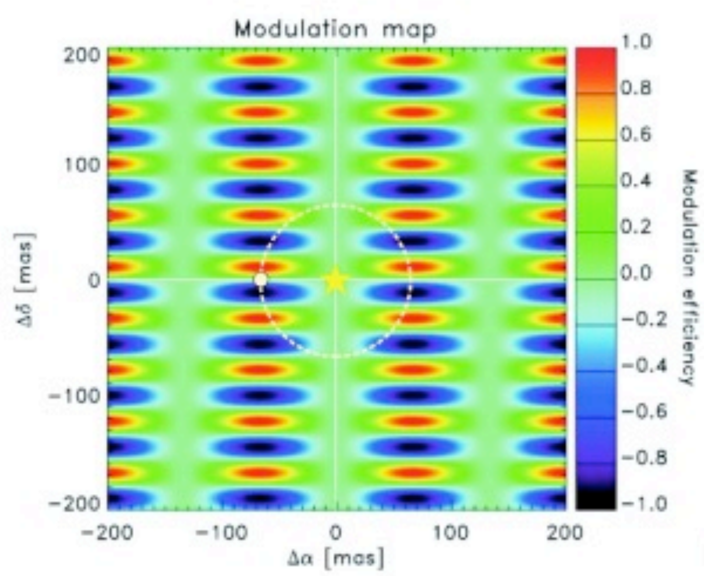


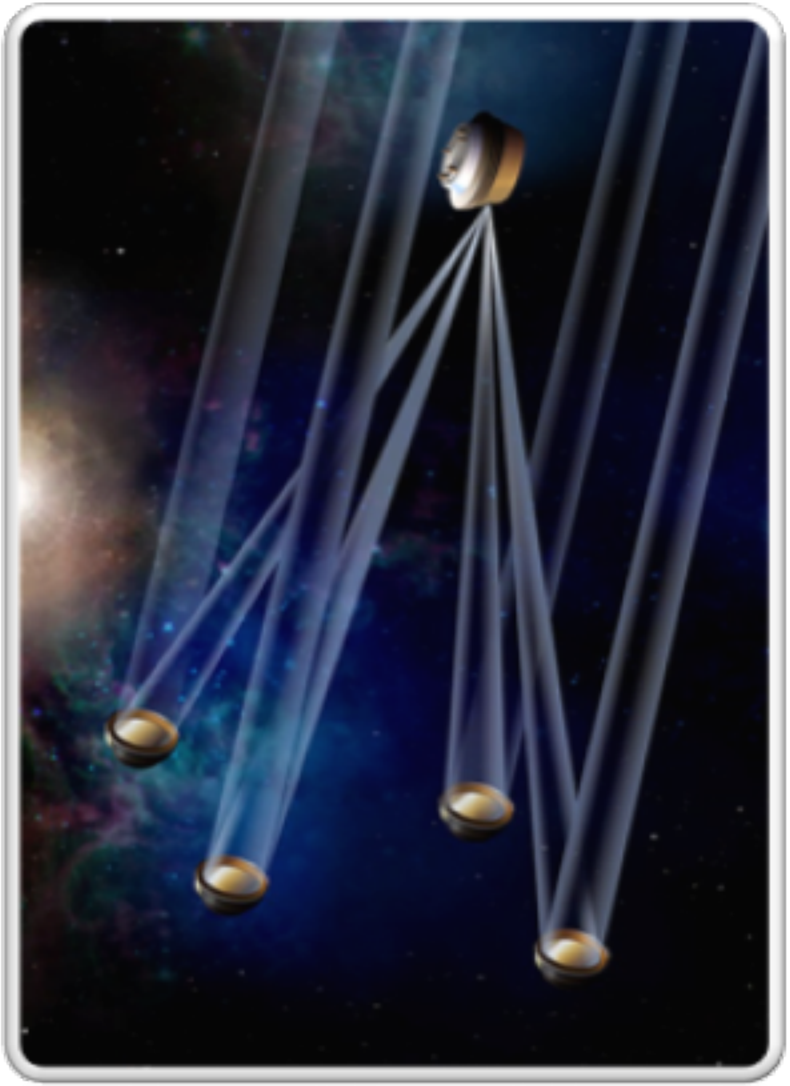


Long-term ambitious project

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

- Transmission map:





Outline

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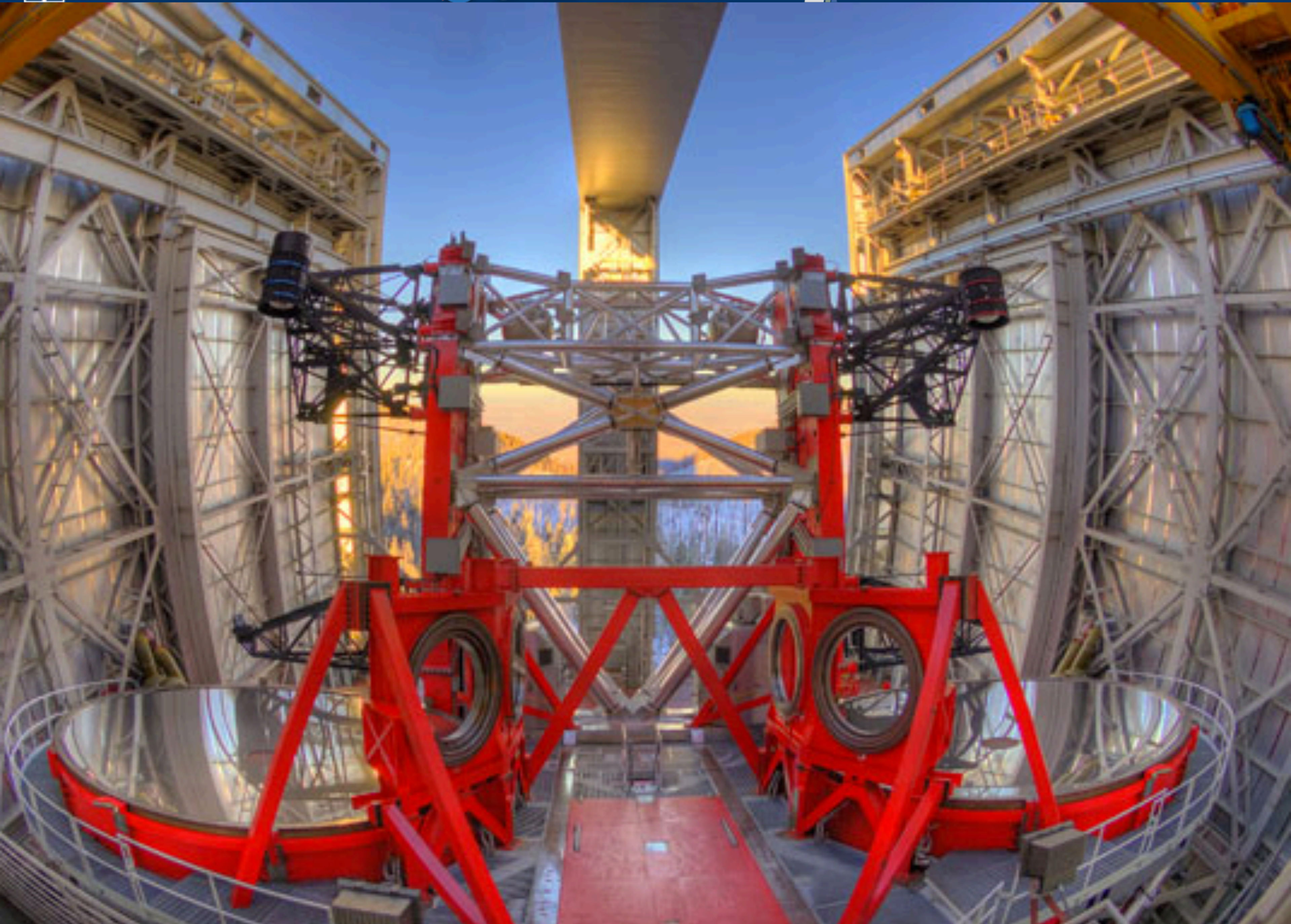
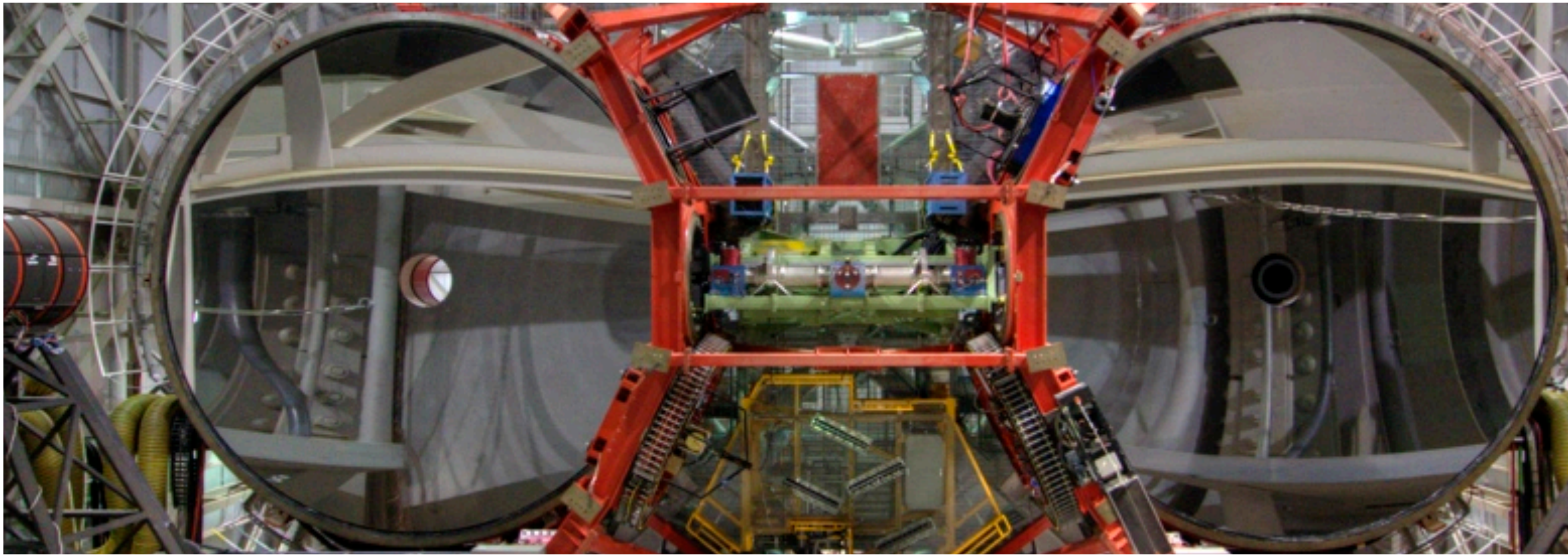
The LBT

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



LBT key parameters

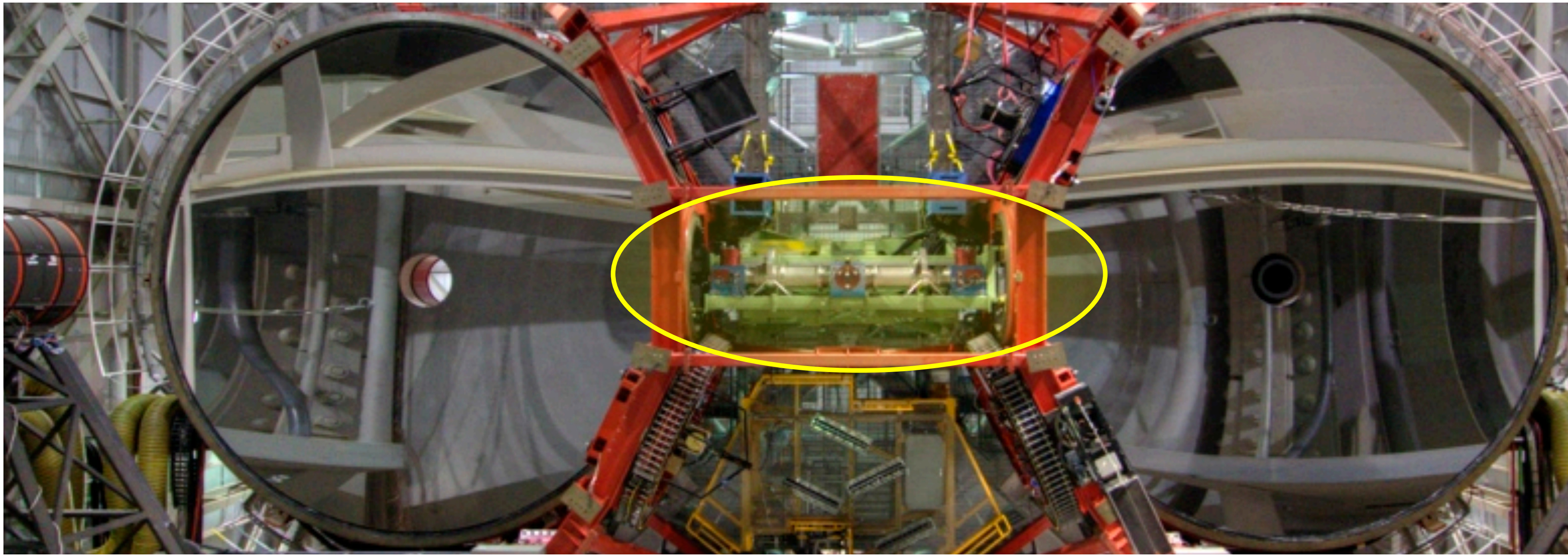


Resolution
Beam combination provides the equivalent resolution of a 22.7-m telescope.

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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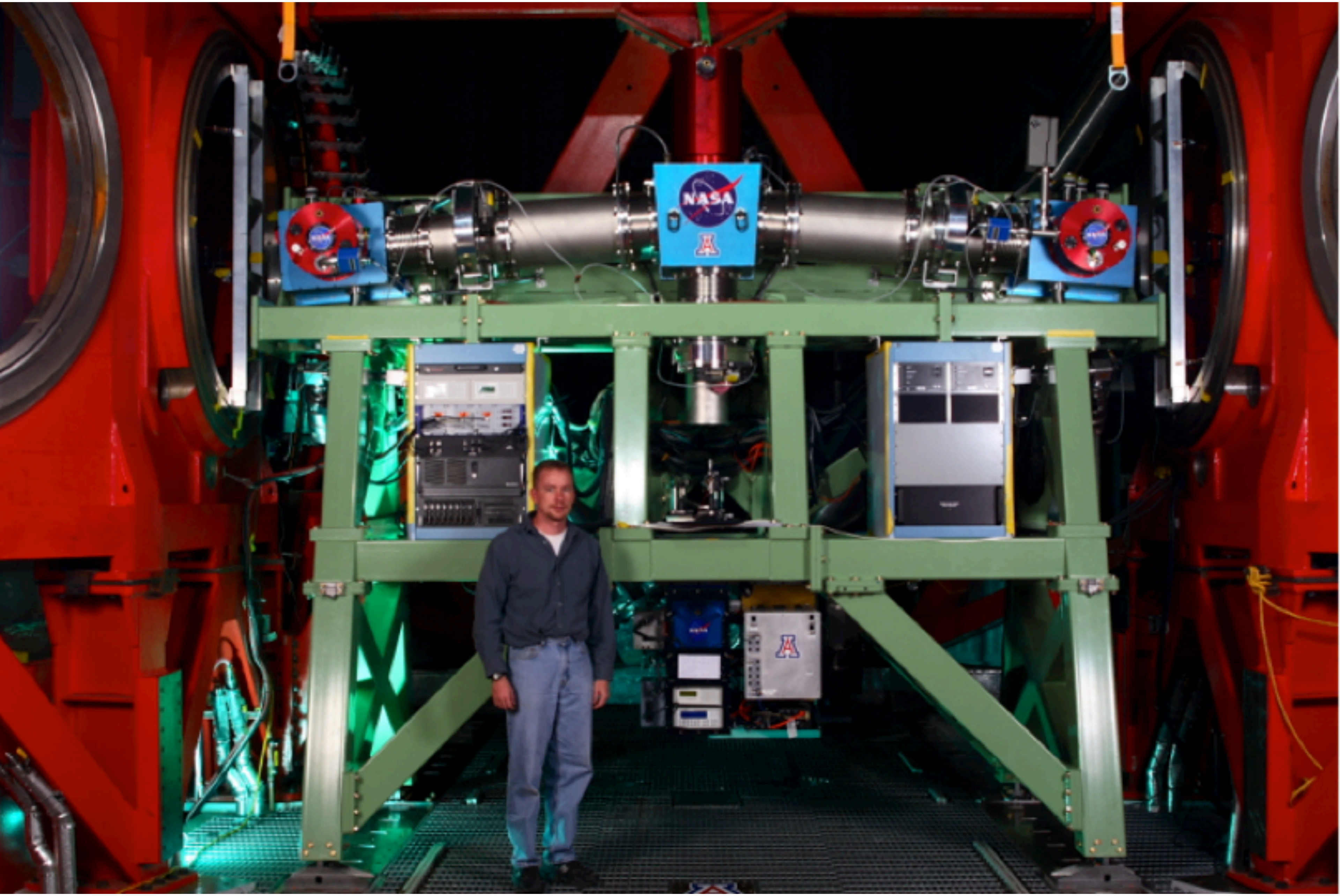
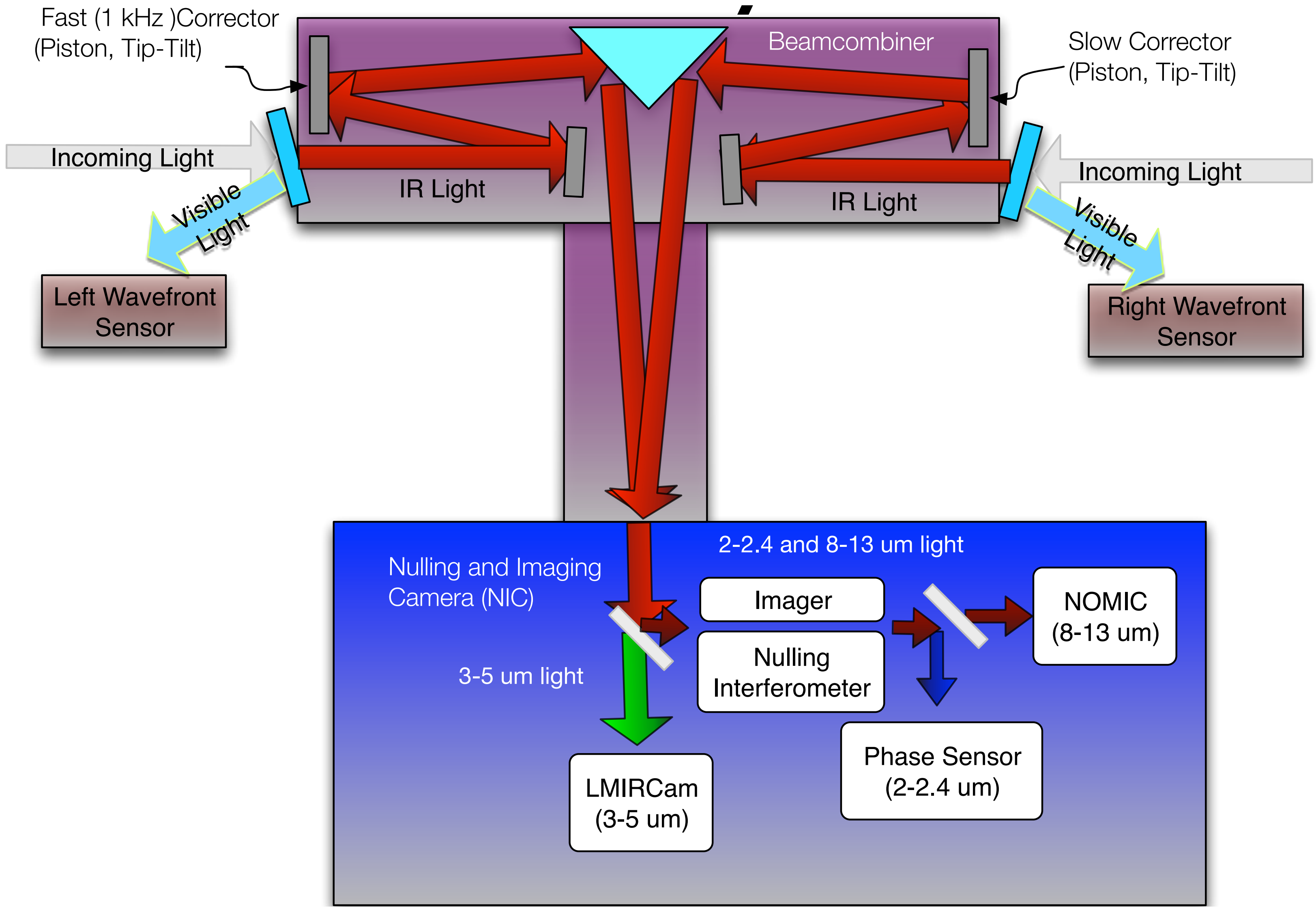

NASA

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
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)

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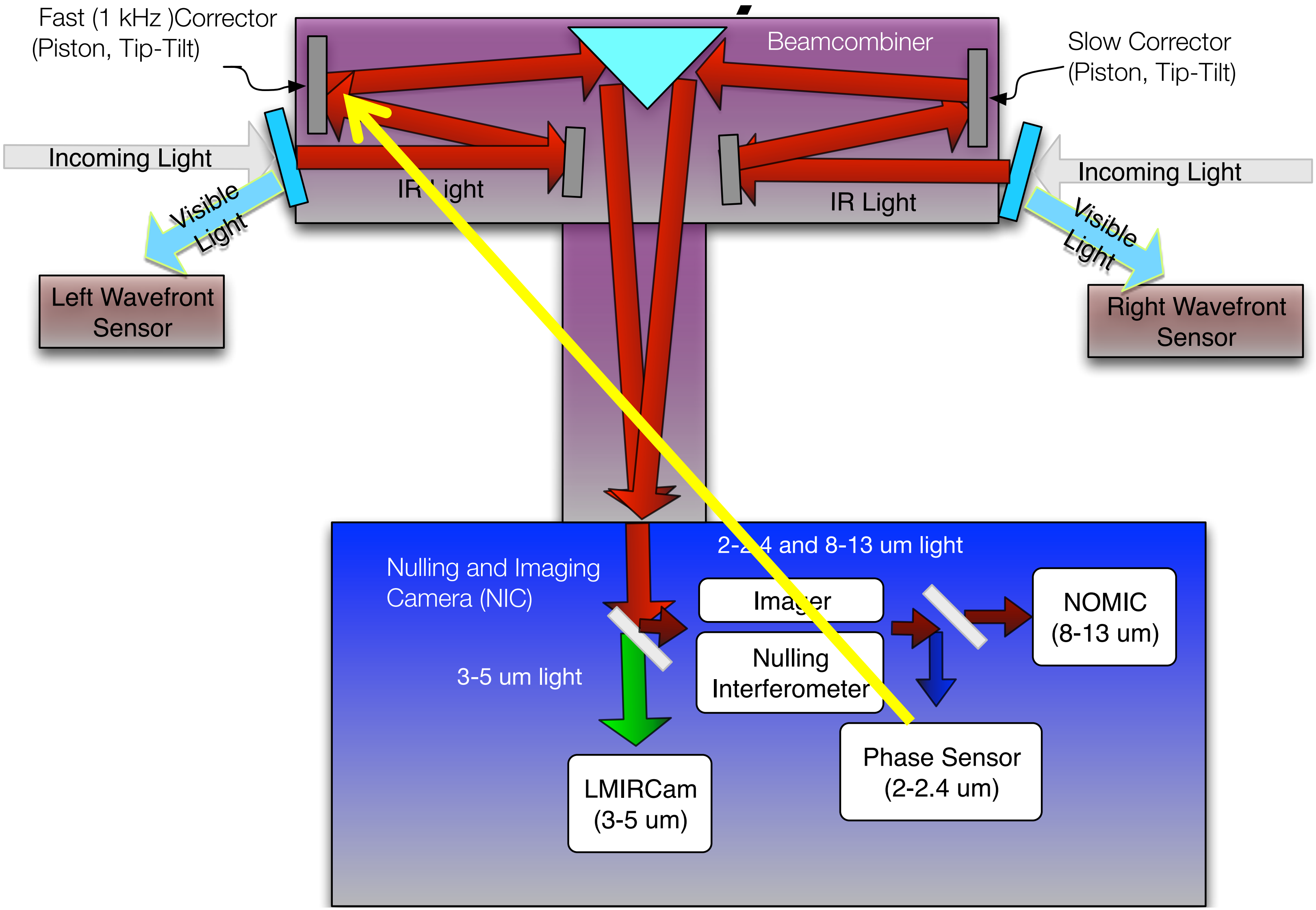
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LBTI science Cameras

	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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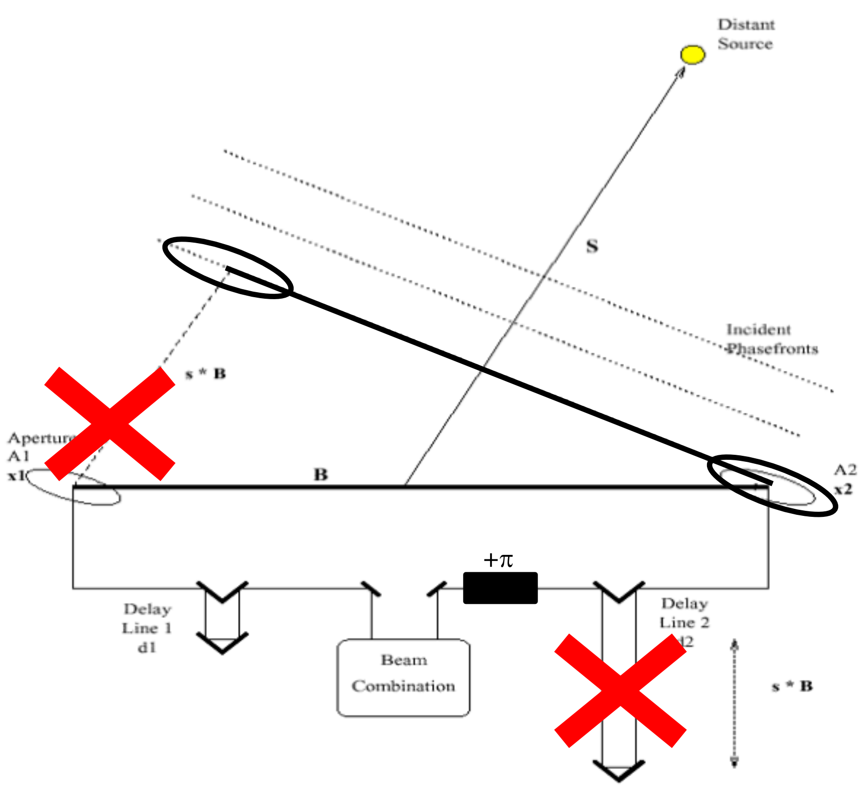
Spectral Resolution	350	100
5 sigma detection, 1 hour	**~2 M_J planet at 1 Gyr**	**~1 zodi debris disk**
Spatial Resolution	**0.4 AU at 10 pc**	**1 AU at 10 pc**

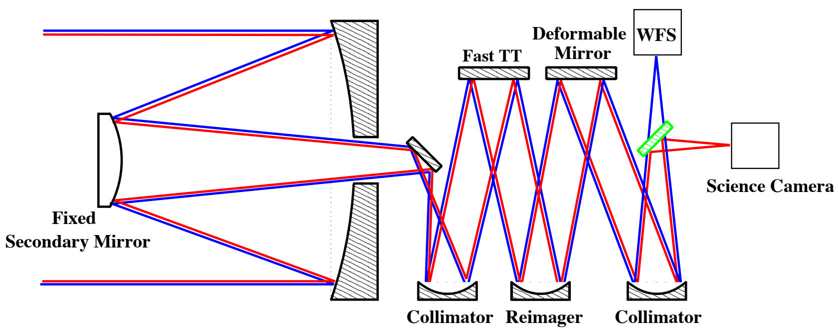
Instrumental specificities

1. Common mount interferometer
   ⇒ No geometric delay (ŝ.B = 0)
   ⇒ No long delay line

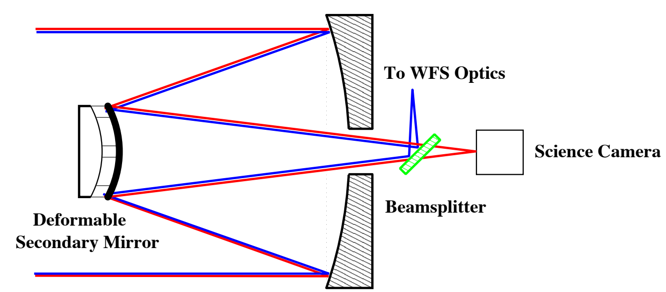


2. Deformable secondary mirrors
   => Low thermal background

Typical AO system



LBT AO system

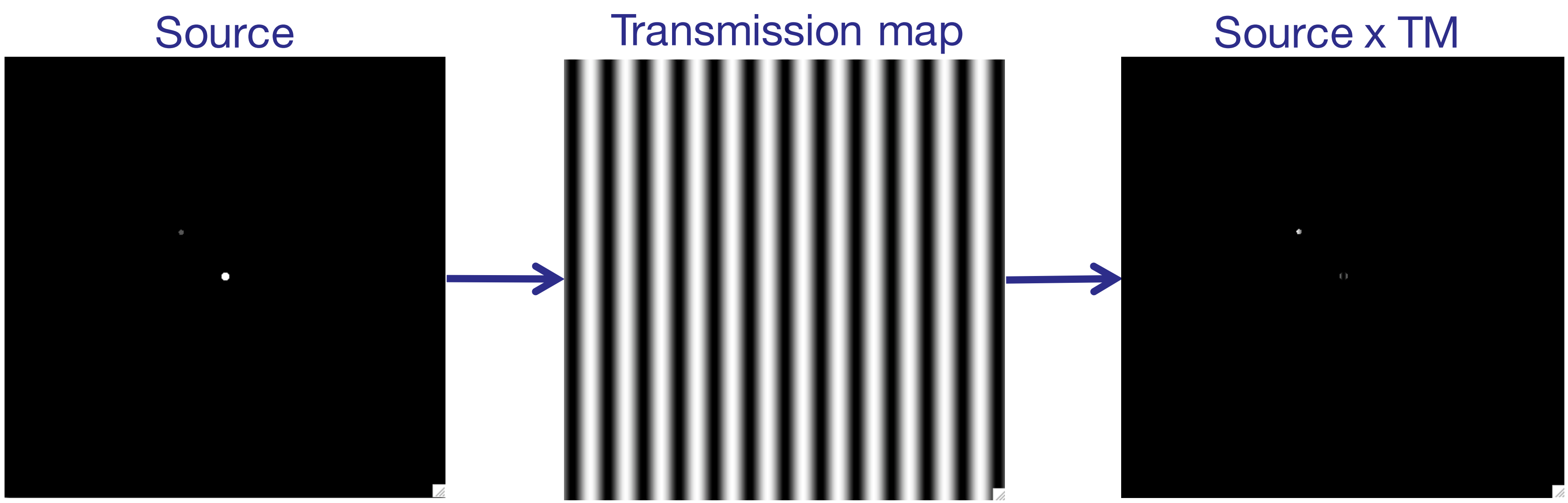


AO figures by Matt Kenworthy

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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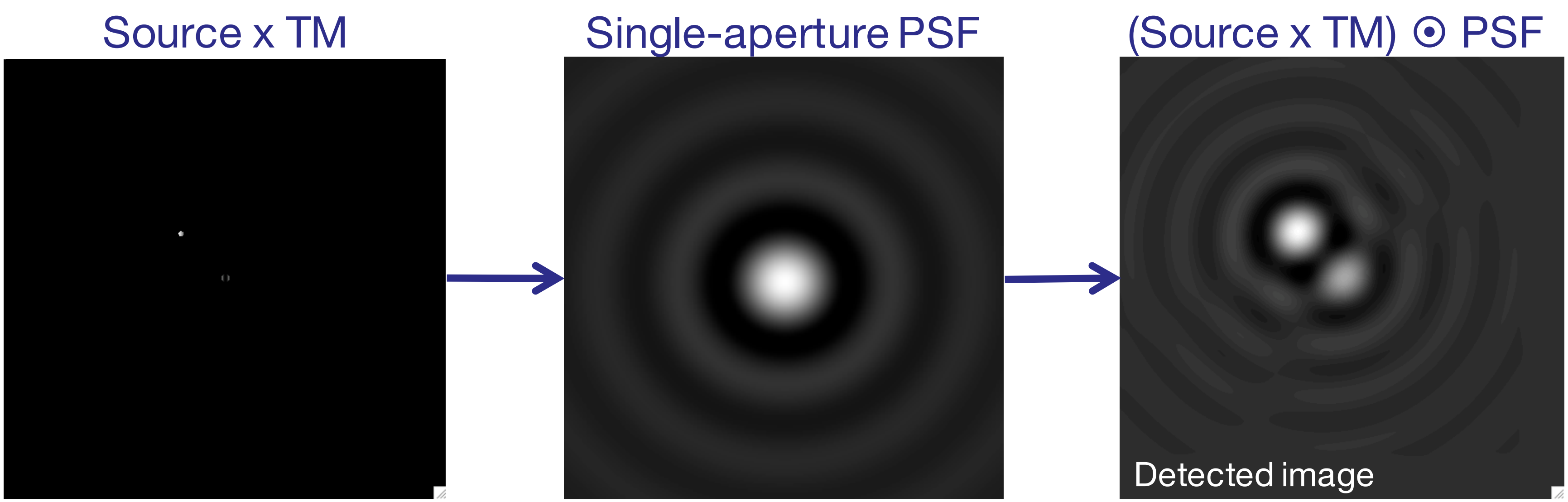

Key ideas 3

- LBT's instrumental specificities:
  - Two large 8.4-m telescopes;
  - Common mount;
  - Deformable secondary mirrors.
- 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
  - Main scientific goals
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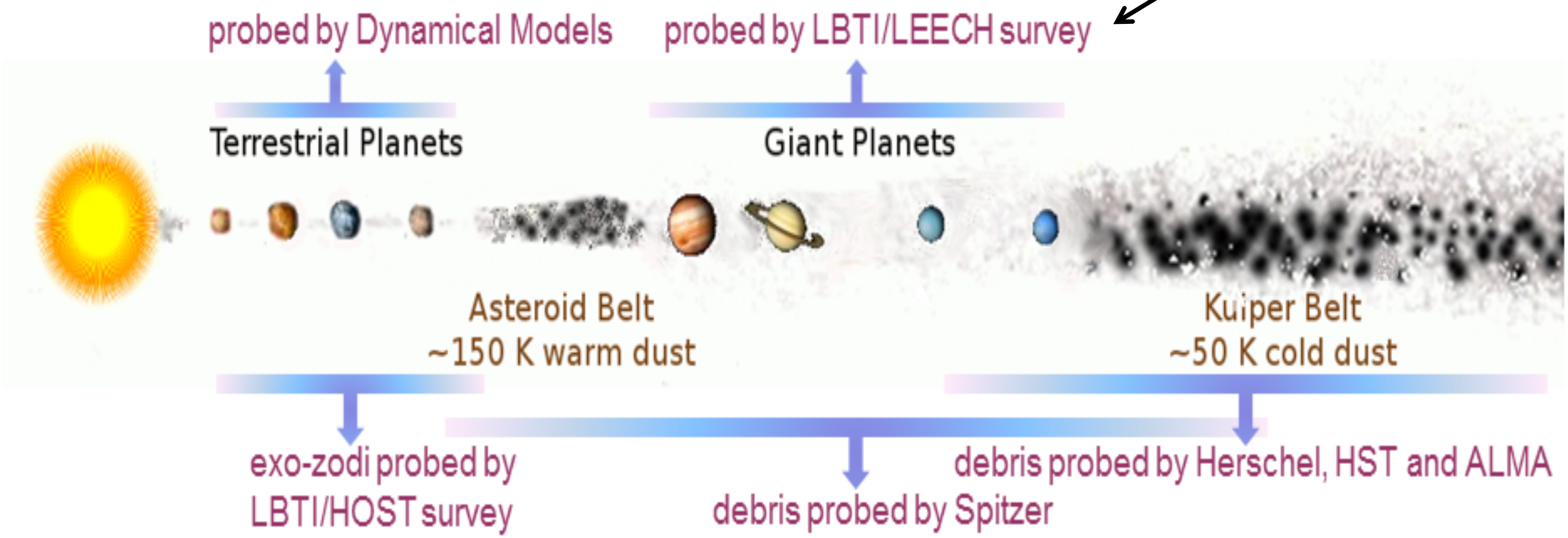
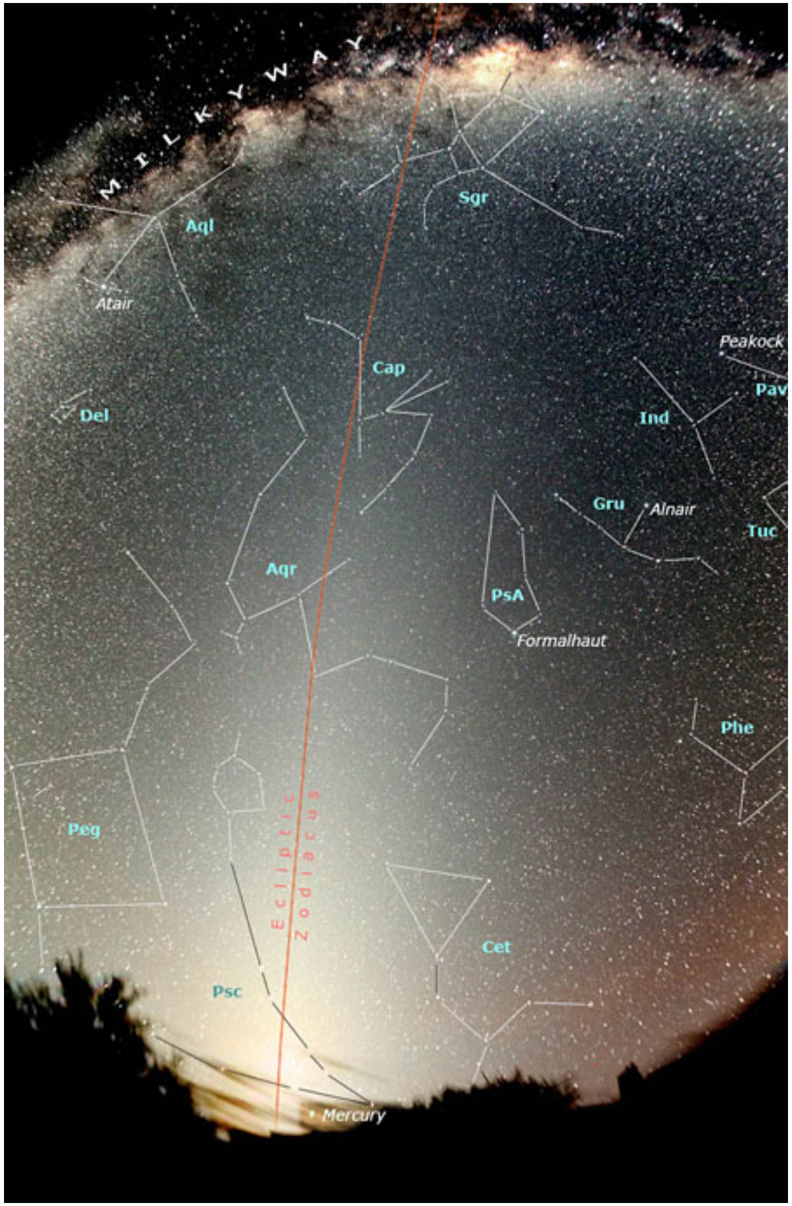
Zodiacal dust in context

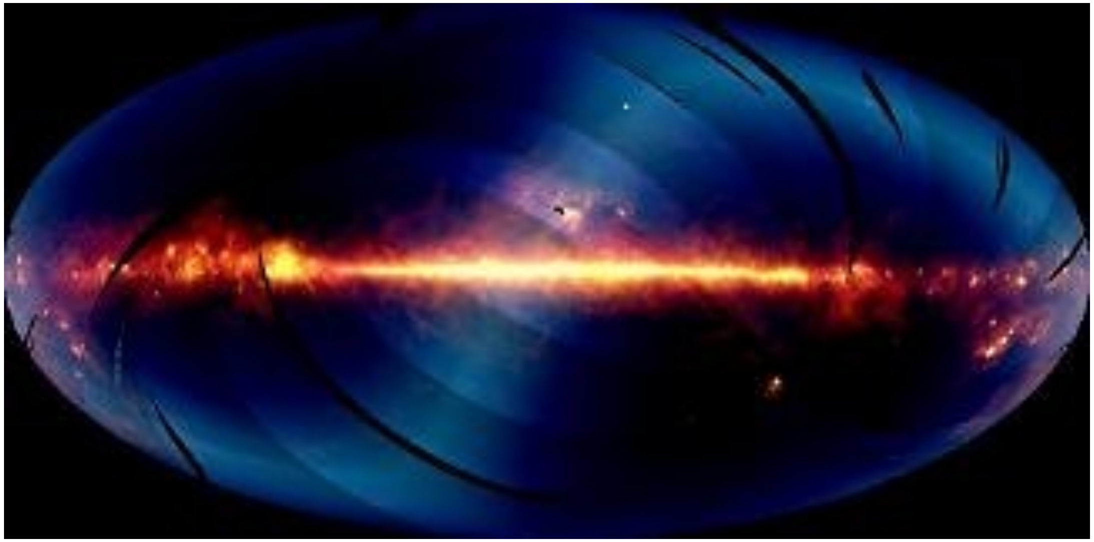
Mawet's talk

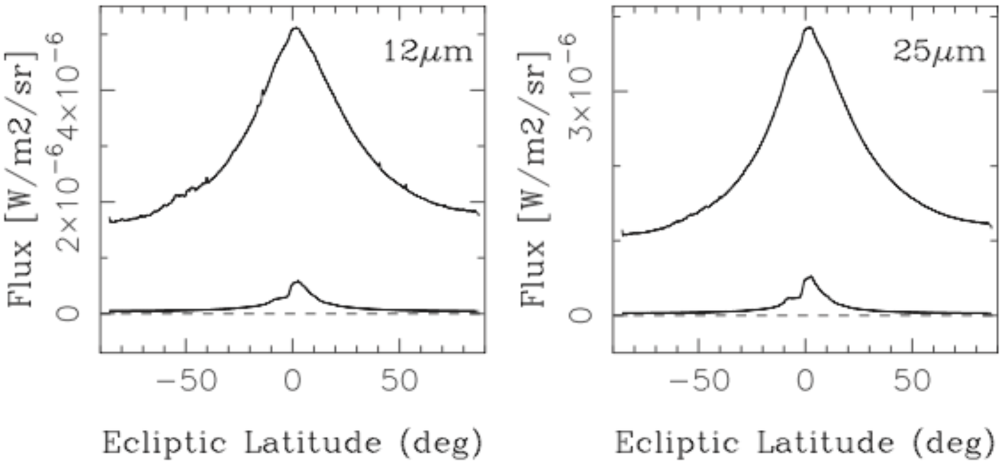


This talk

Zodiacal dust







from Nesvorney et al. 2010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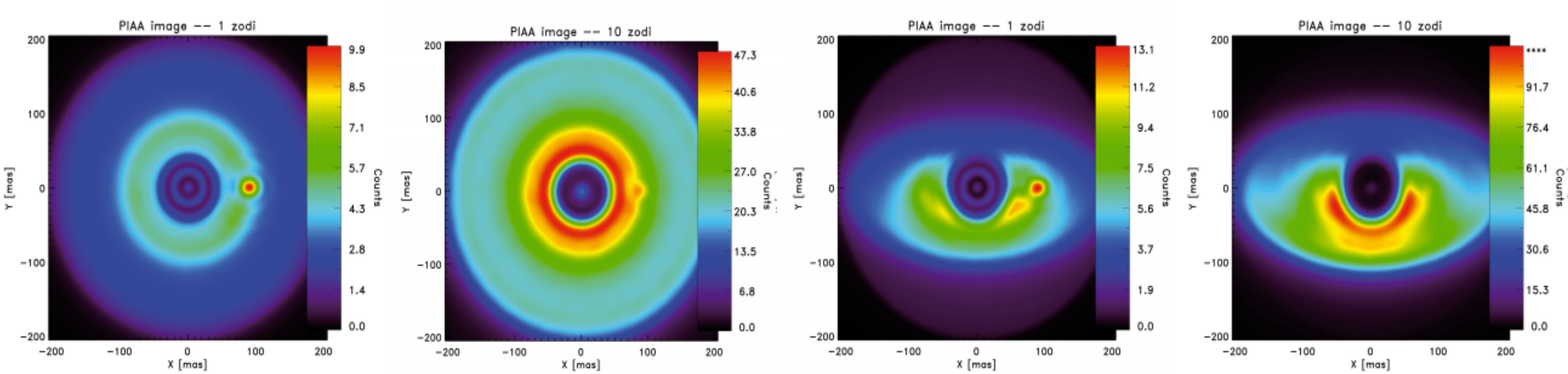
Why is NASA interested in exozodiacal dust?

- 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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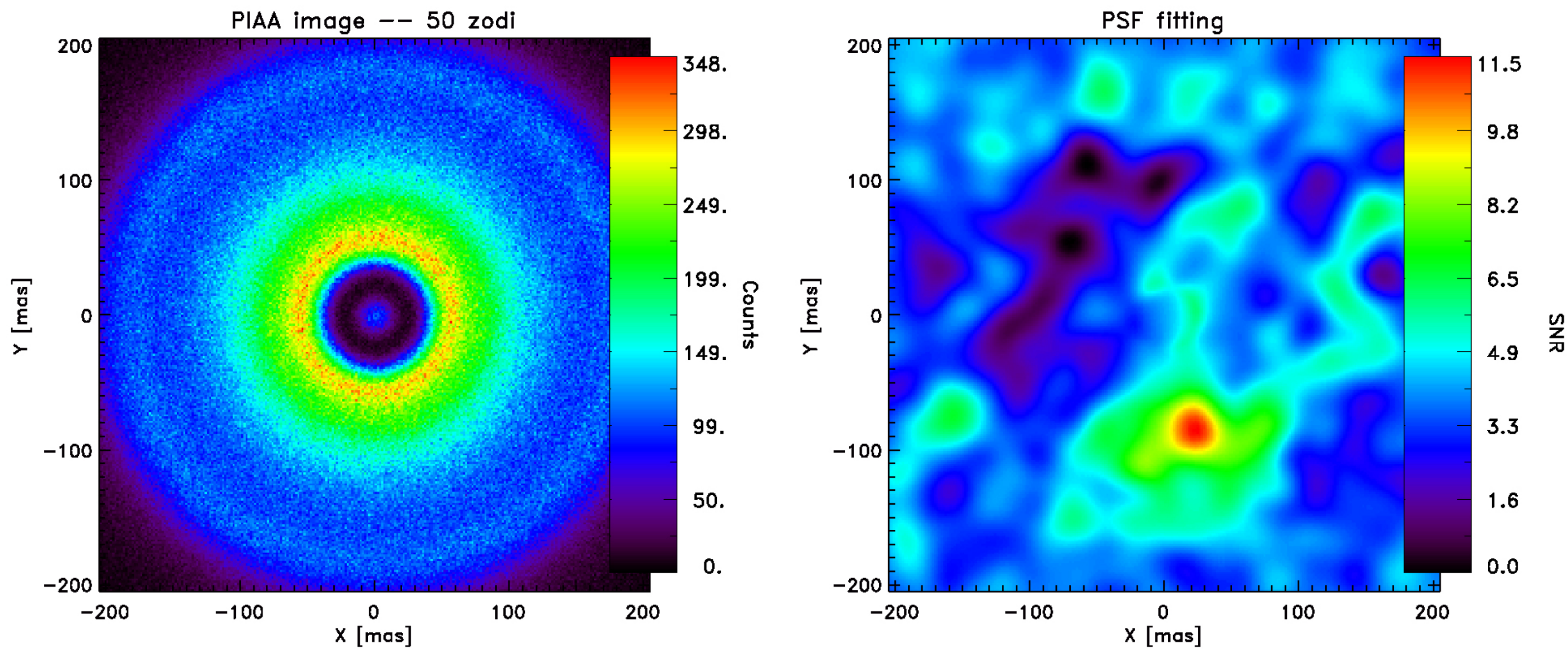

Now with a 50-zodi exozodiacal disk (Defrère et al. 2012)

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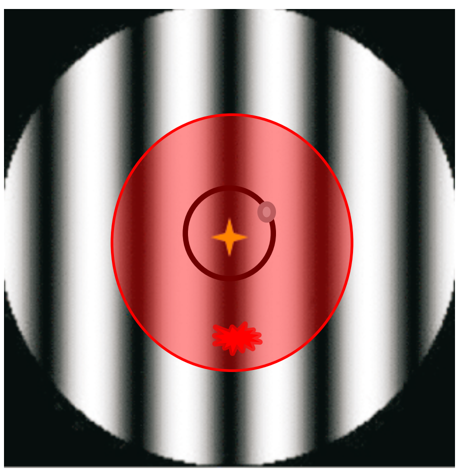
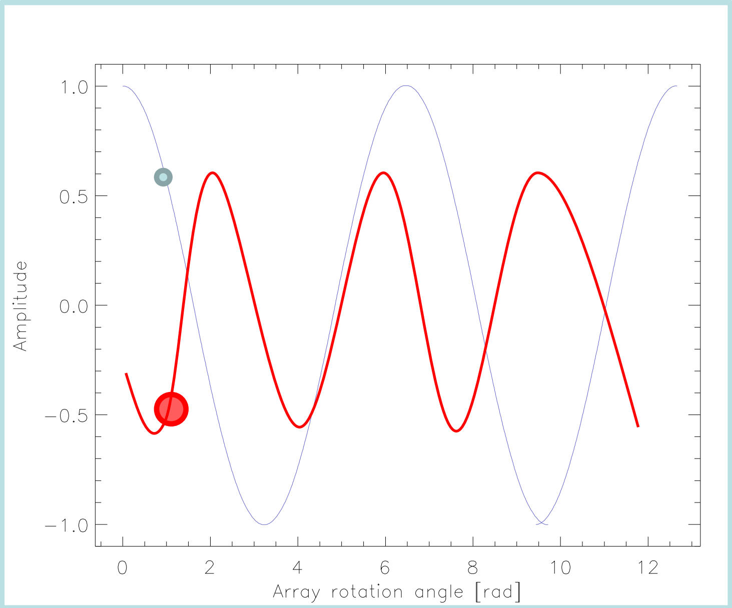


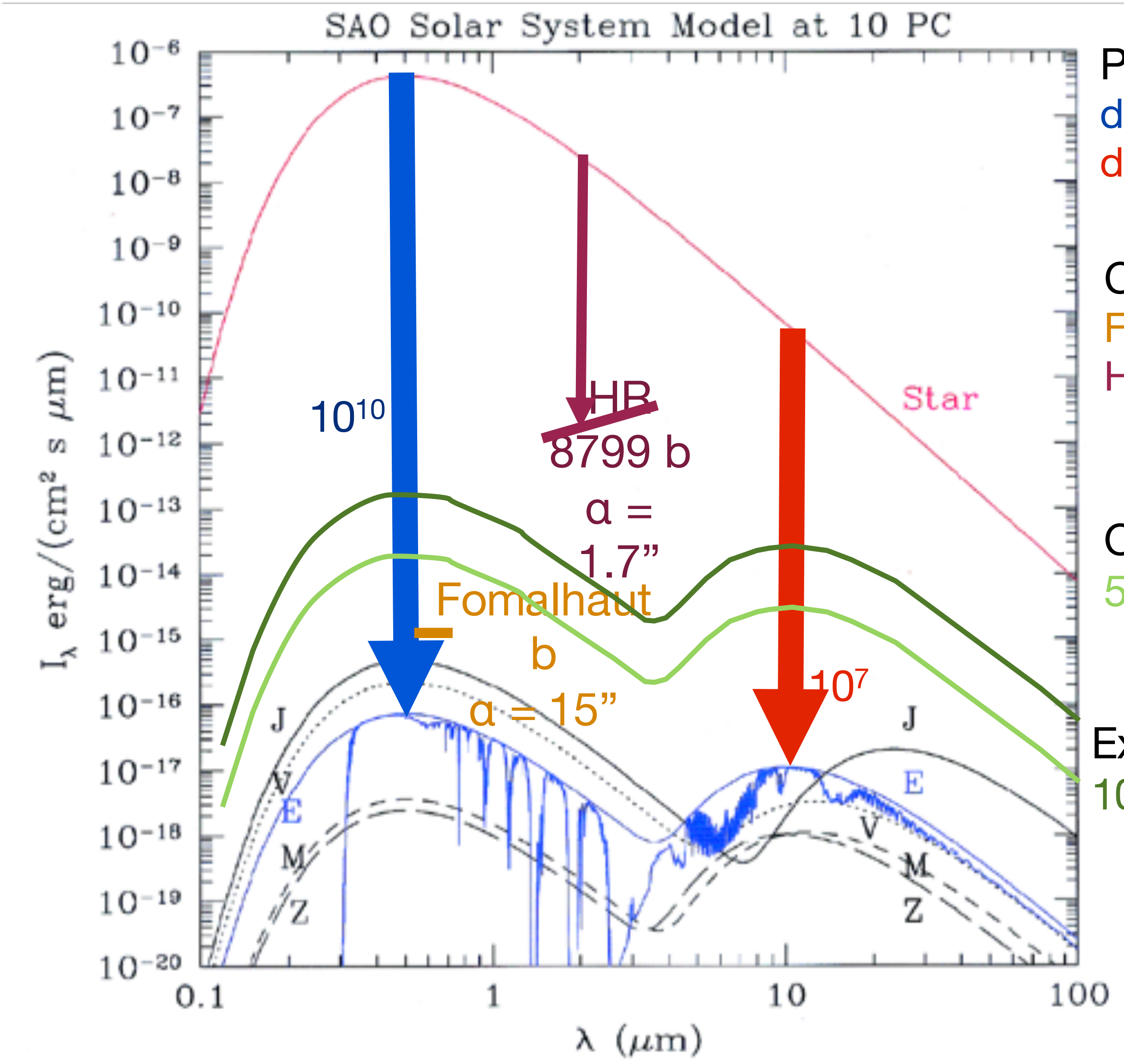


What do we know? …not much

- 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.

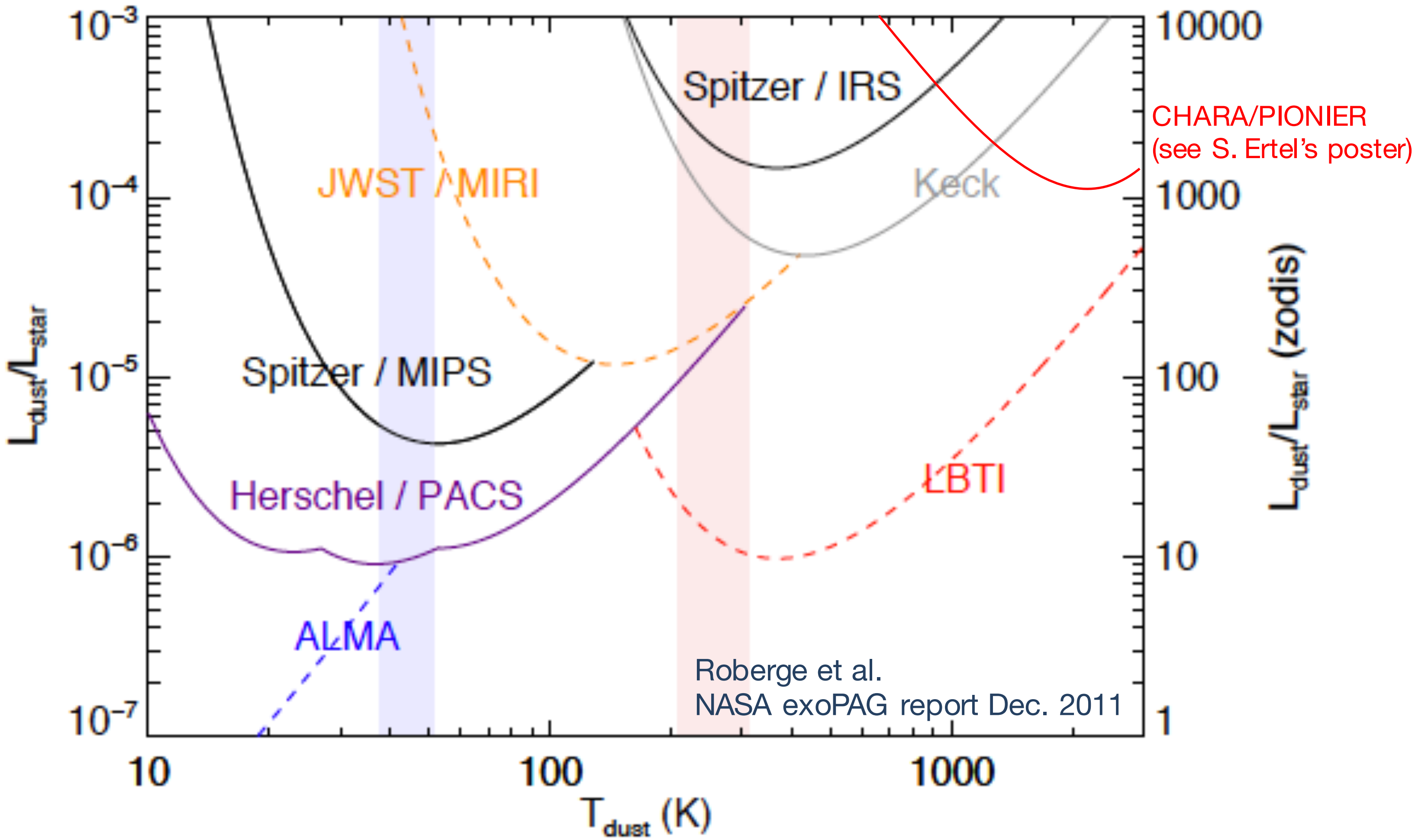
HOSTS:

Hunt for Observable Signatures of Terrestrial Planetary Systems

- NASA-supported 50 night survey to be carried out in the 2015-2017 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

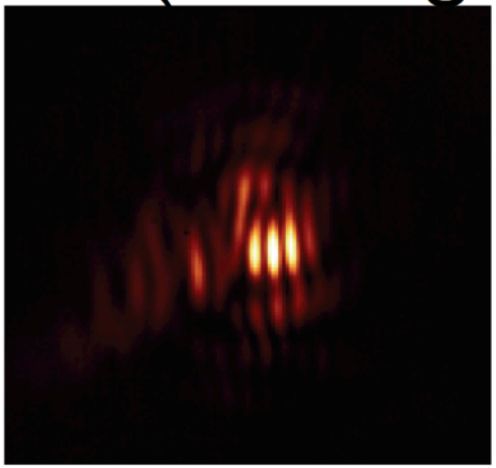
- Exozodiacal emission is a source of noise and confusion for future exoEarth direct imaging instruments.

- One of the main goals of the LBTI is to determine the prevalence of exozodiacal light

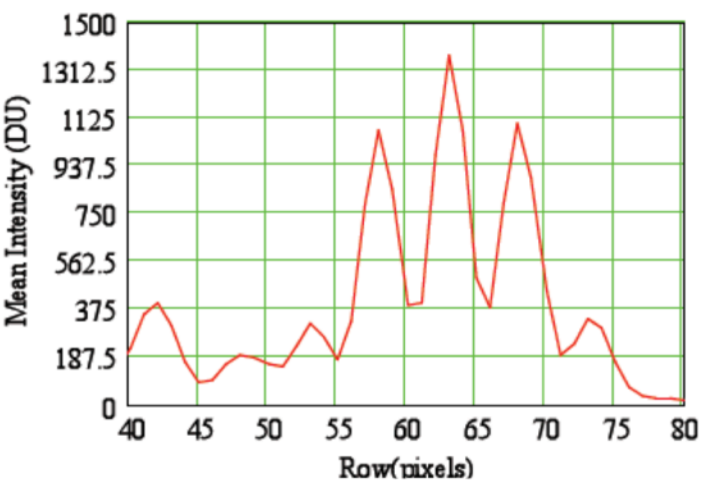
Outline

- 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)

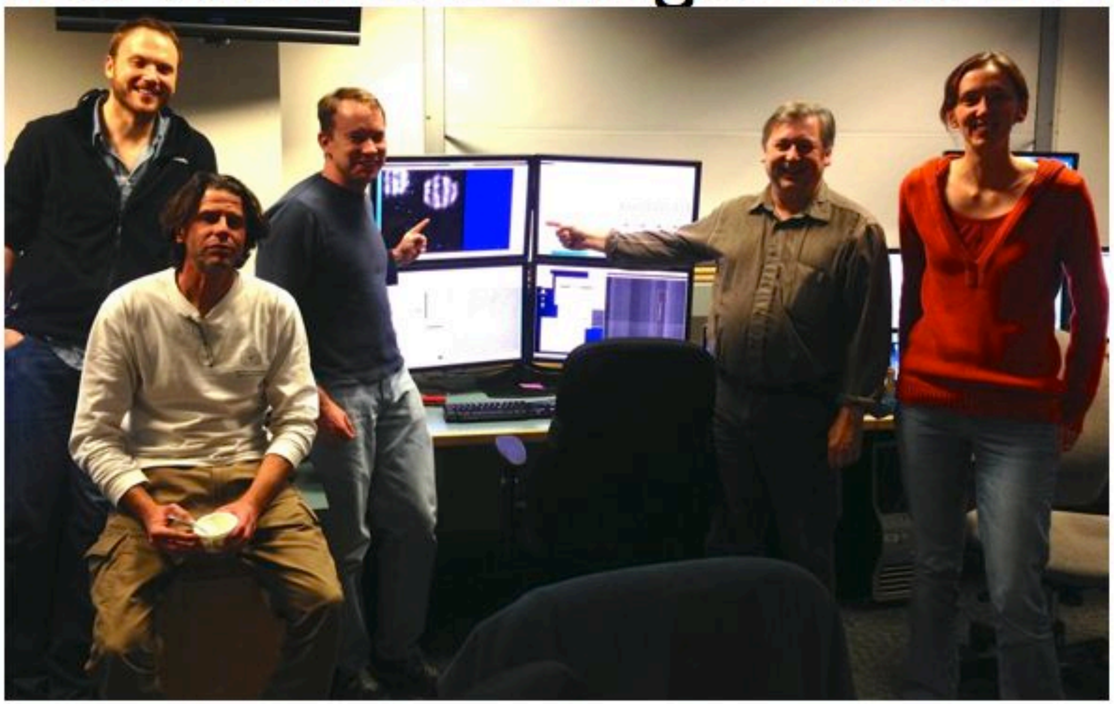


Beta Peg: Combined 10μm image from the LBTI imager. Image is "seeing limited" under poor weather conditions (seeing ~1.2 arc sec).

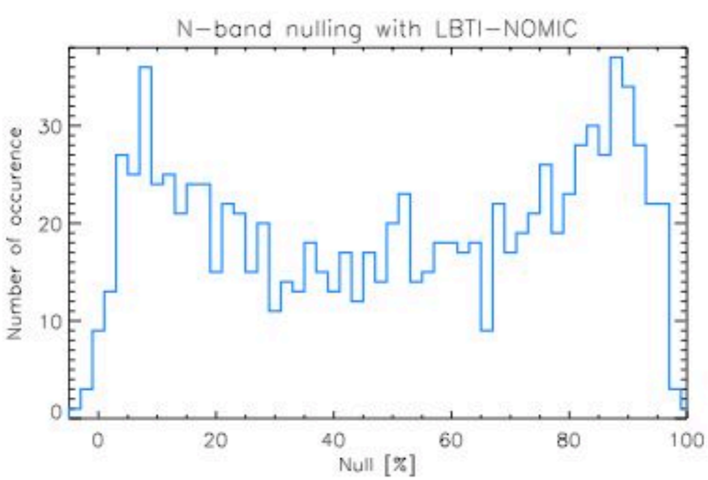


This image shows that:
- The two telescopes are co-pointed and tracking to 0.3"
- The pathlength difference between the two beam paths is less than ~10 μm and stable.

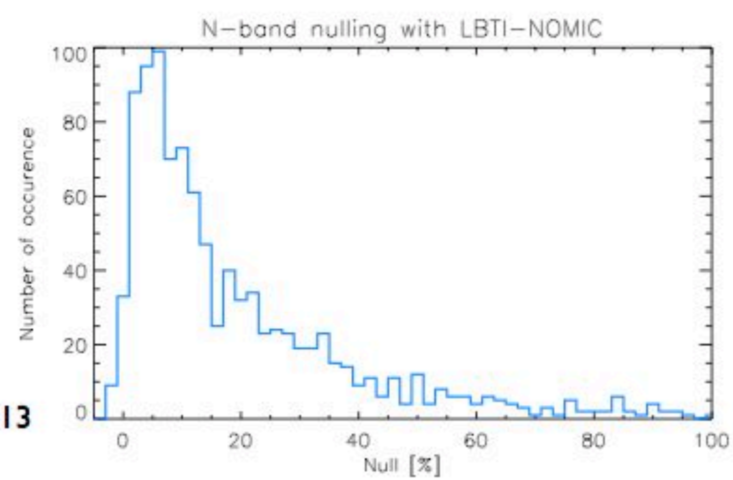
First Stabilized Fringes with LBTI



Open Phase Loop

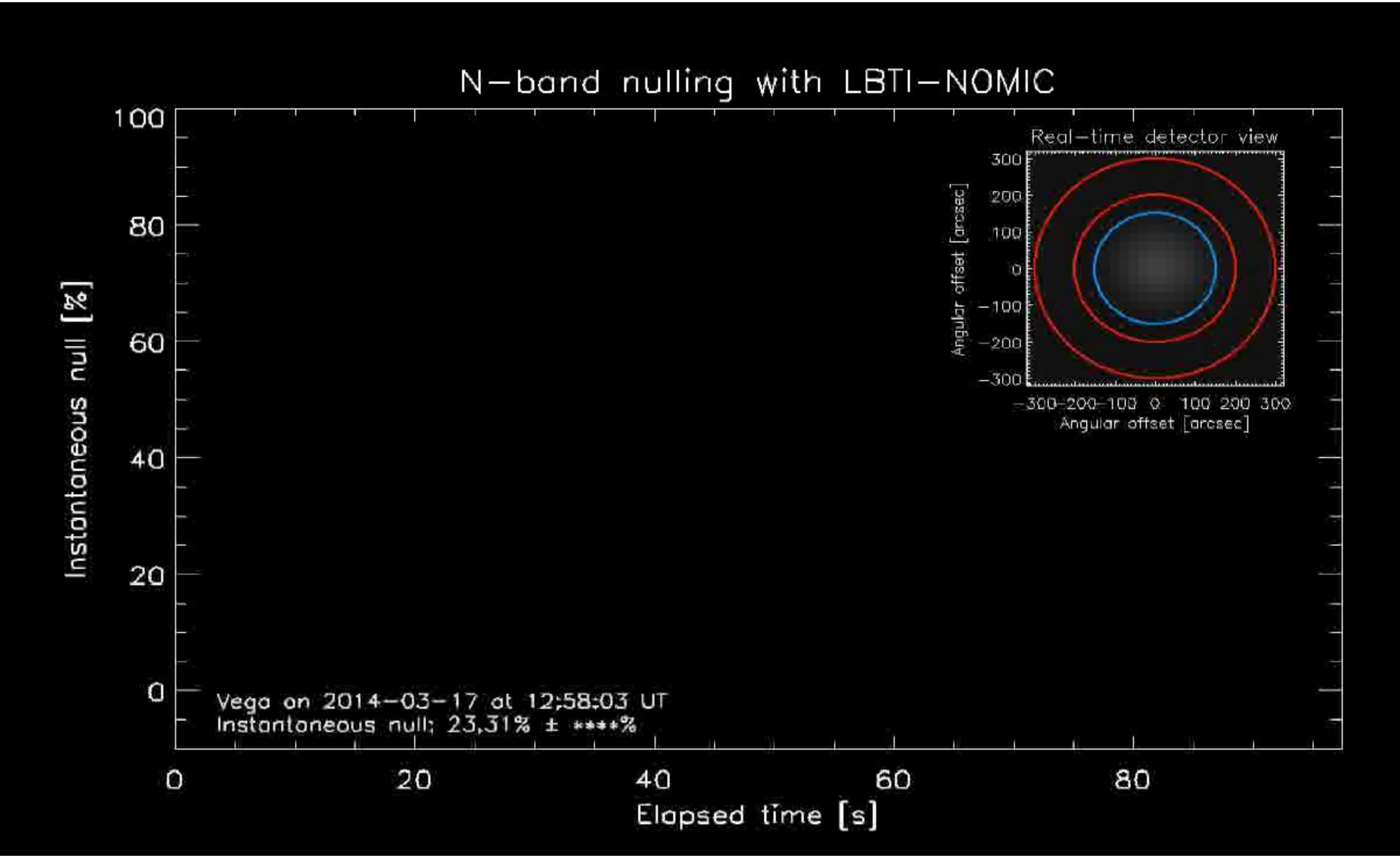


Closed Phase Loop



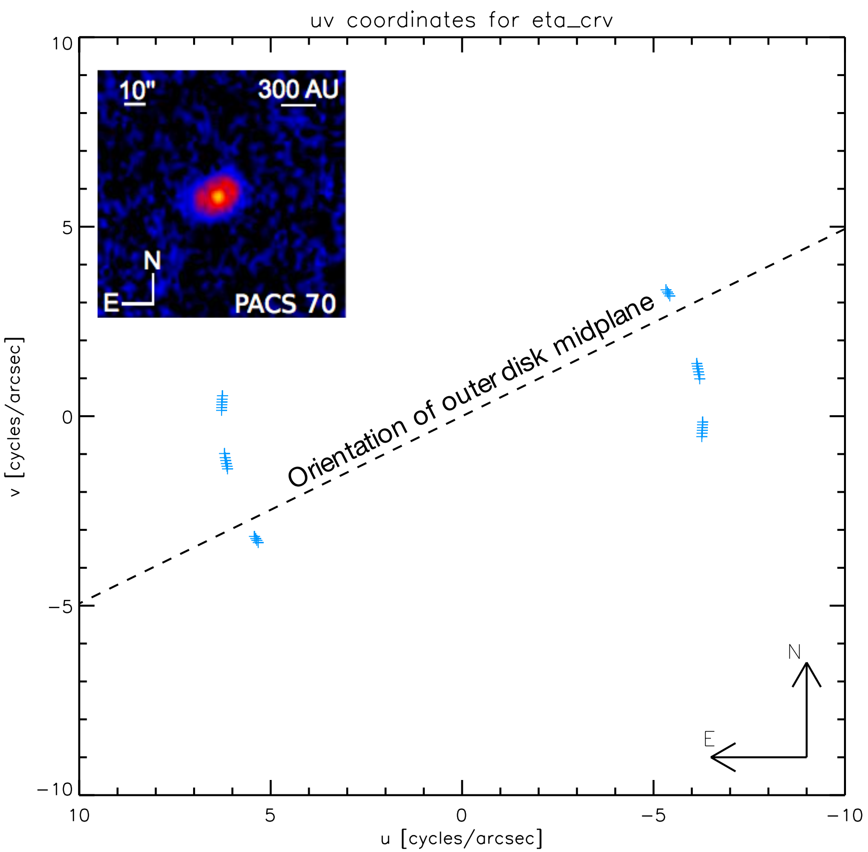
Dec. 30, 2013

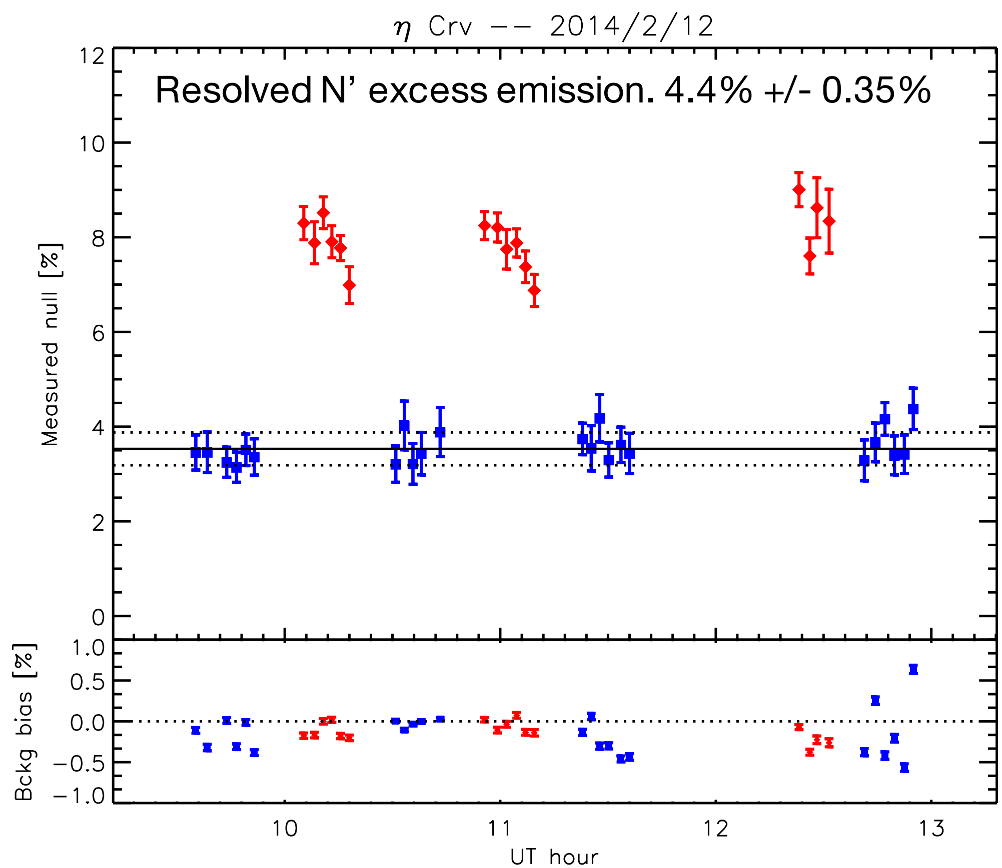
LBTI stabilized N-band null



The first detection: η Crv

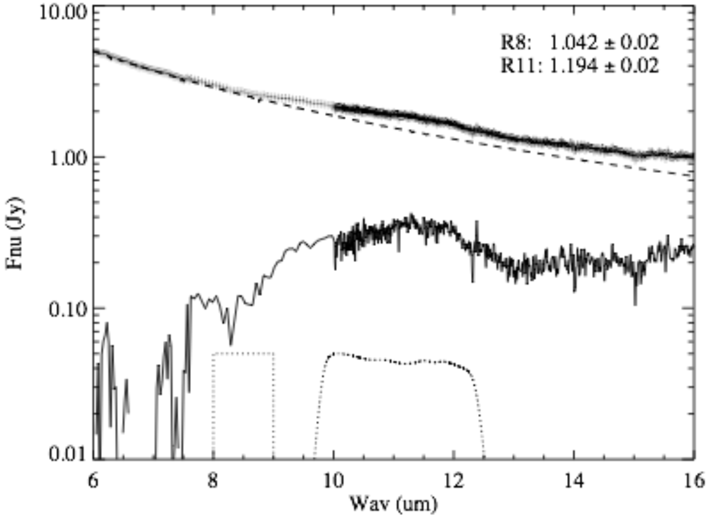
- 3 hours of nulling observations in February 2014 around transit;
- Outer disk seen by Herschel (i = 46.8°, PA = 116.3°, Duchene et al. 2014);
- Excess: 17% (IRS), 4% (KIN);





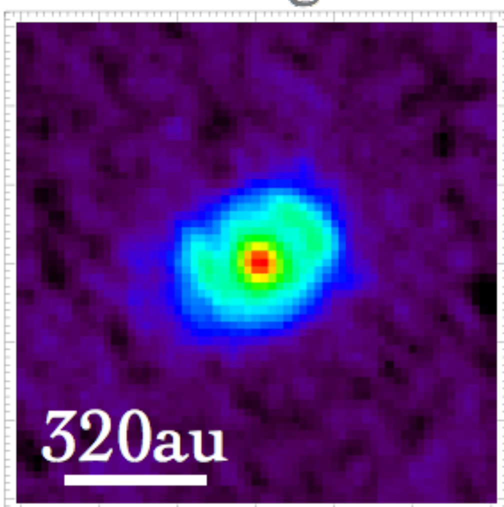
Courtesy G. Kennedy

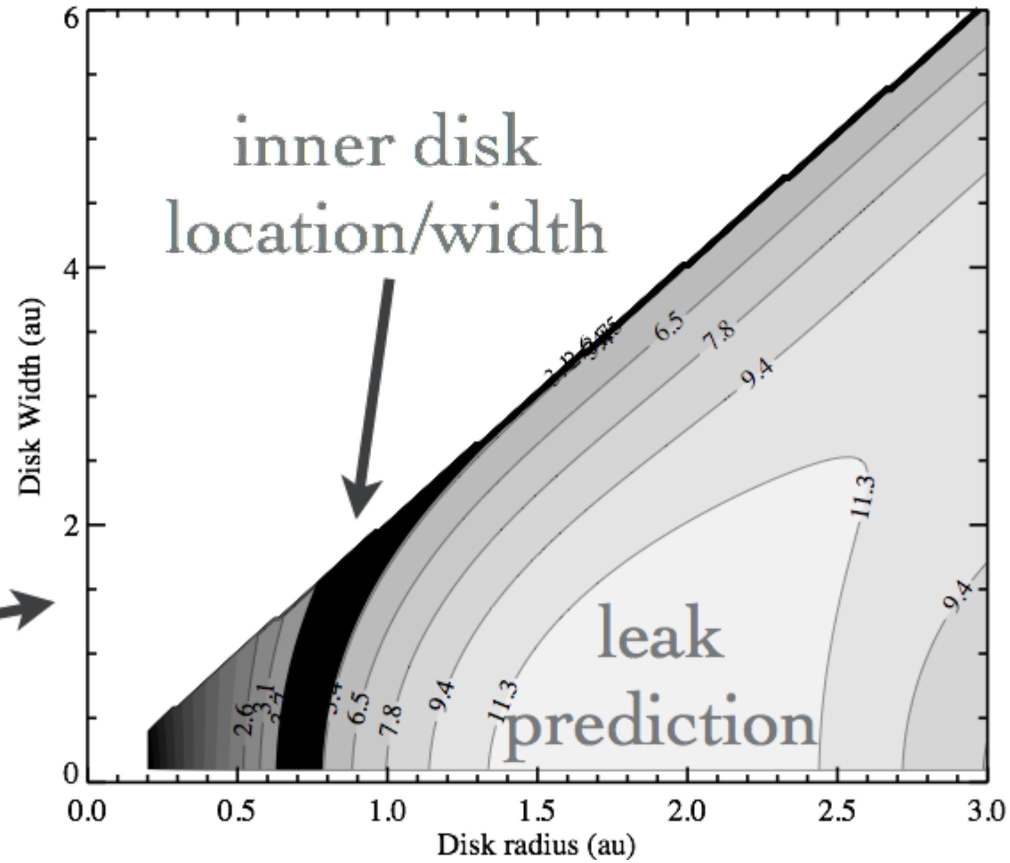
Disk/star flux ratio ~20%



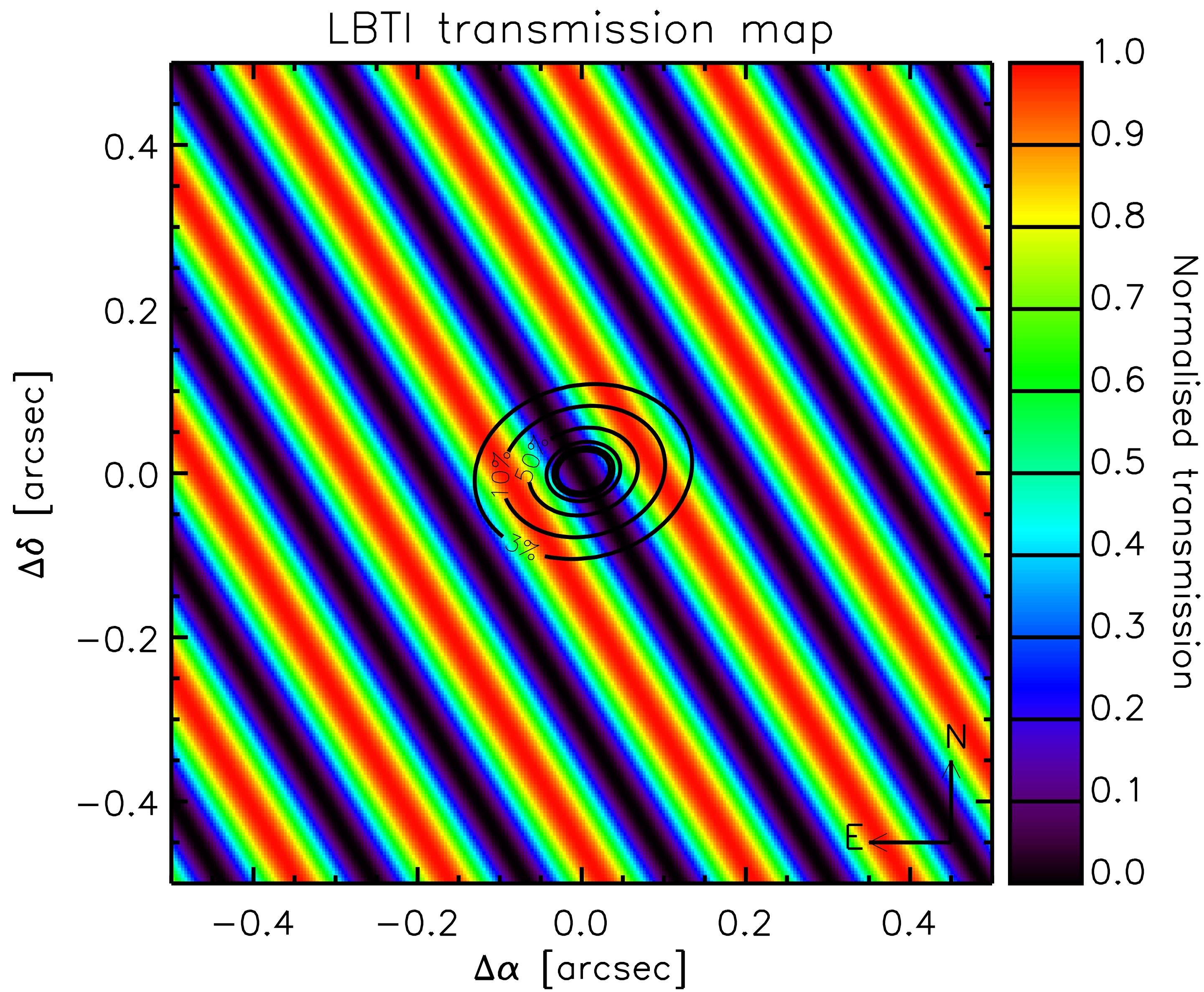
4.5% LBTI leak

Outer disk geometry





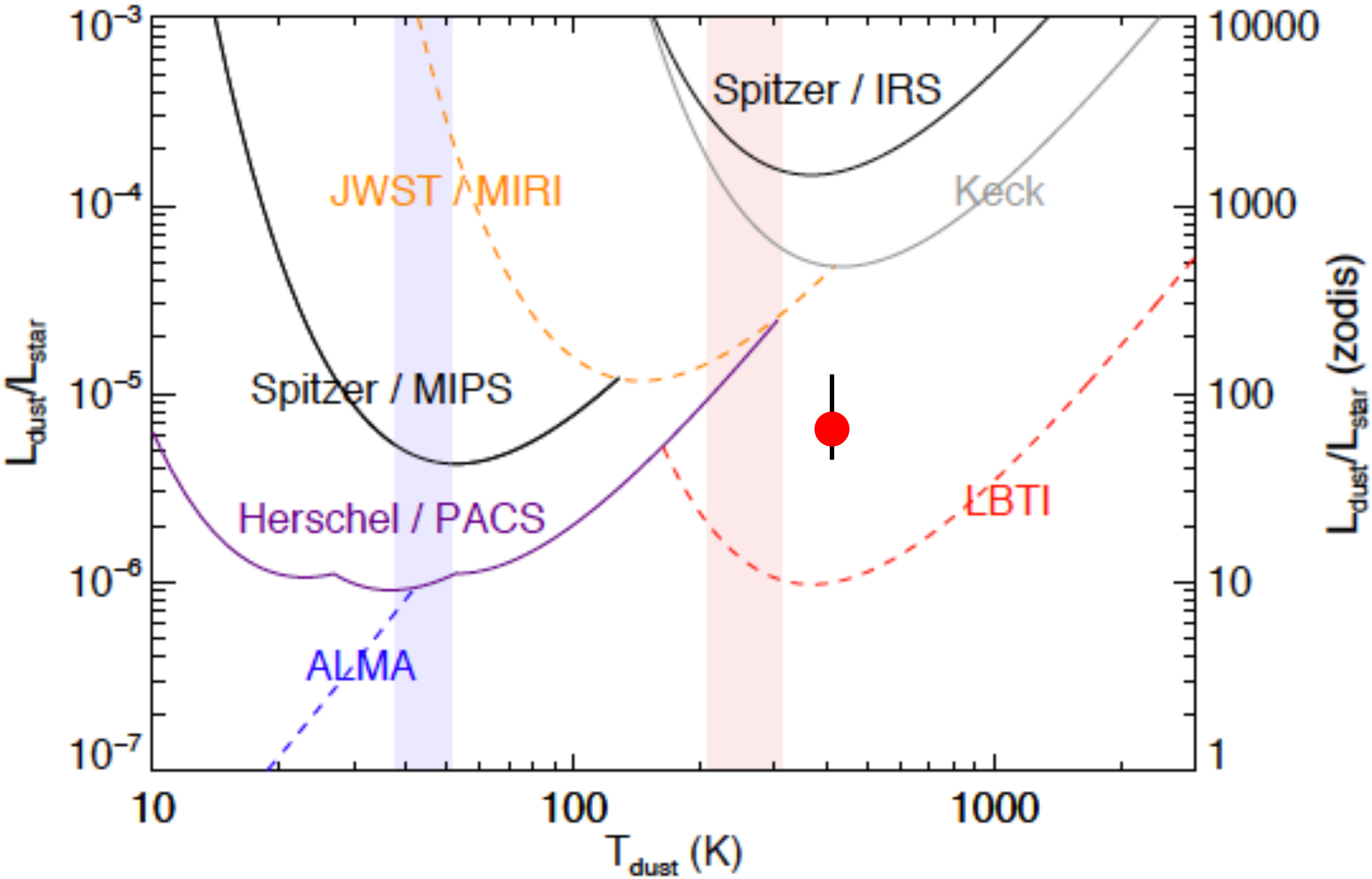
Exozodiacal resolved around η Crv



Nuller performance status

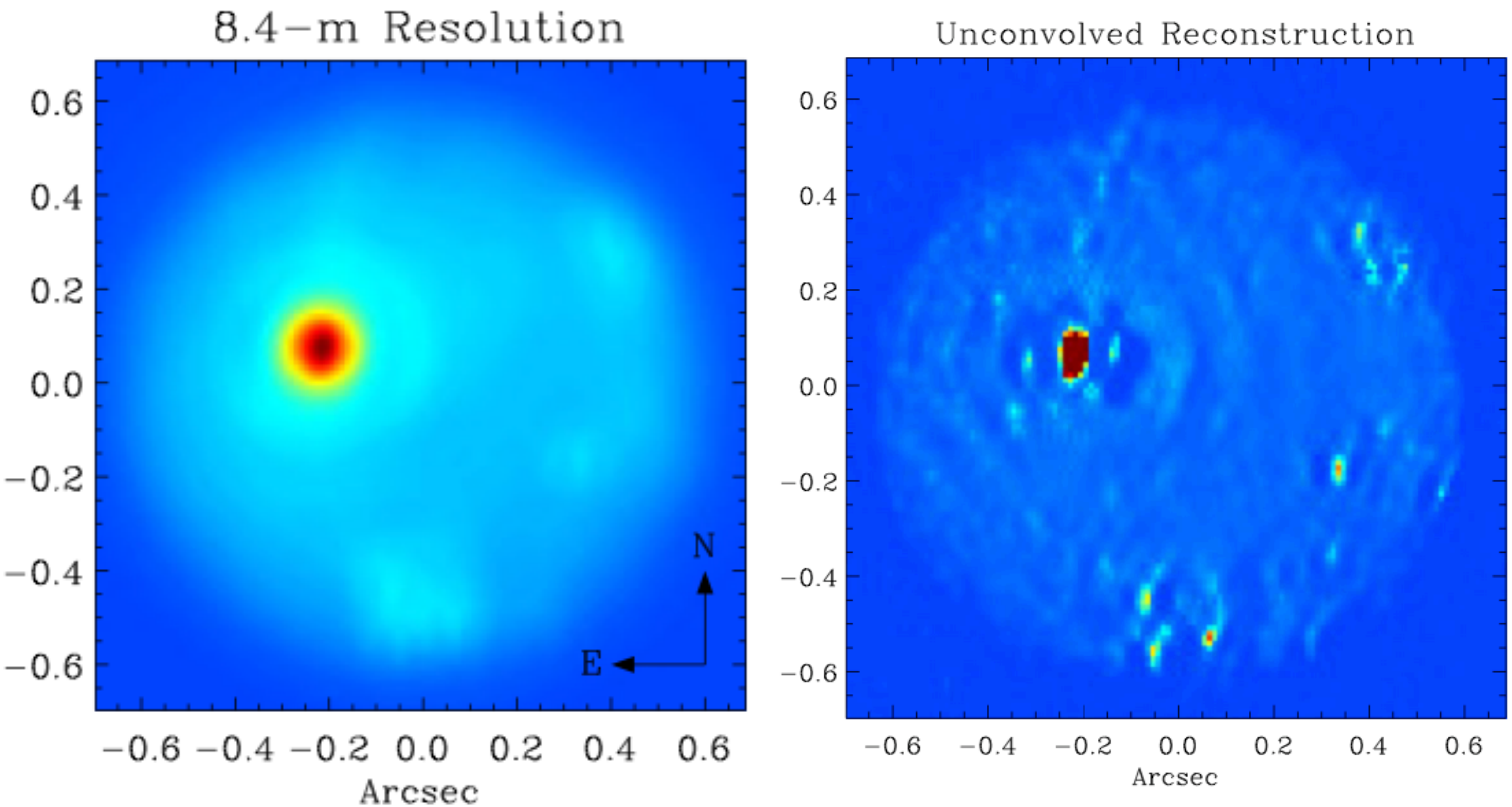
- Demonstrated null depth of ~1% with a stability in the 0.3-0.6% range per observing sequence;
- Data calibration accuracy of ~0.2%;
- Goal for HOSTS is 0.01% or 3 zodis

Nuller performance status



Other results from the LBTI

- Fizeau imaging of Io volcanism with LBTI/LMIRcam:



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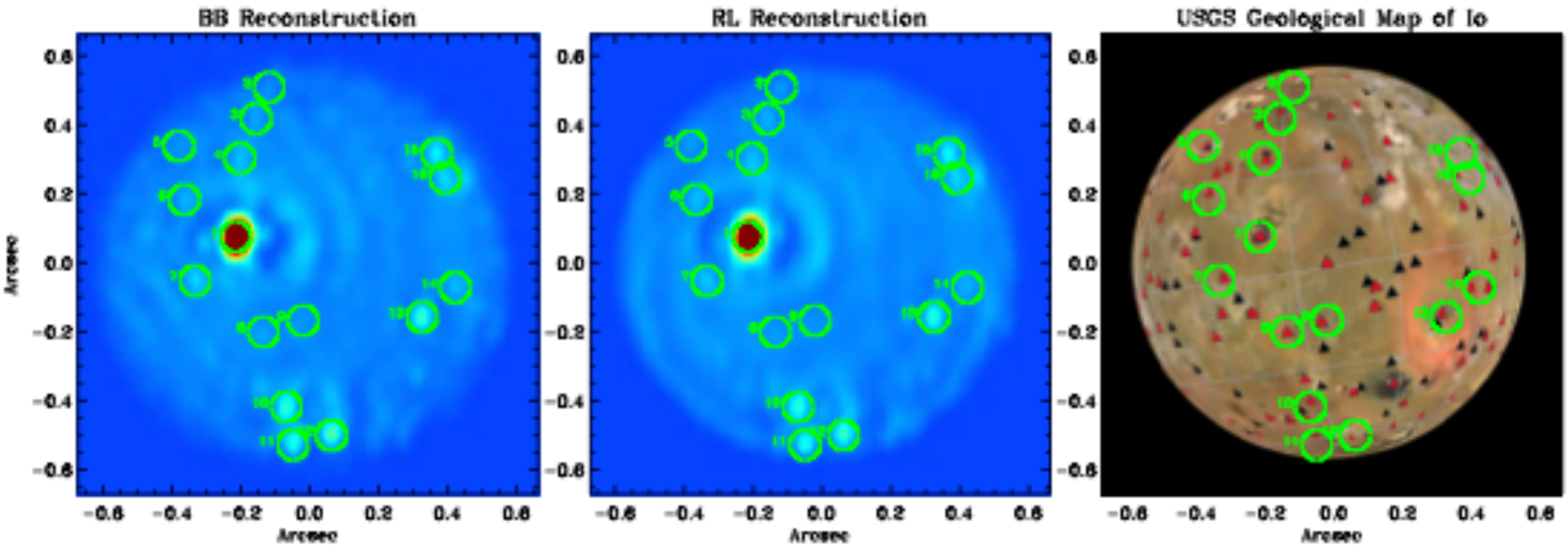
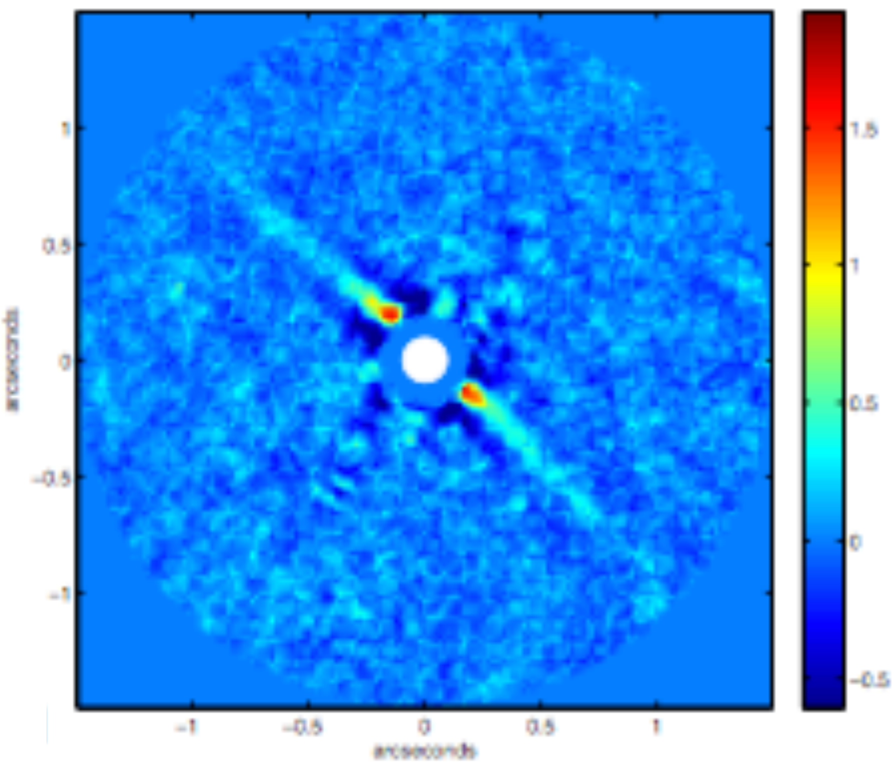
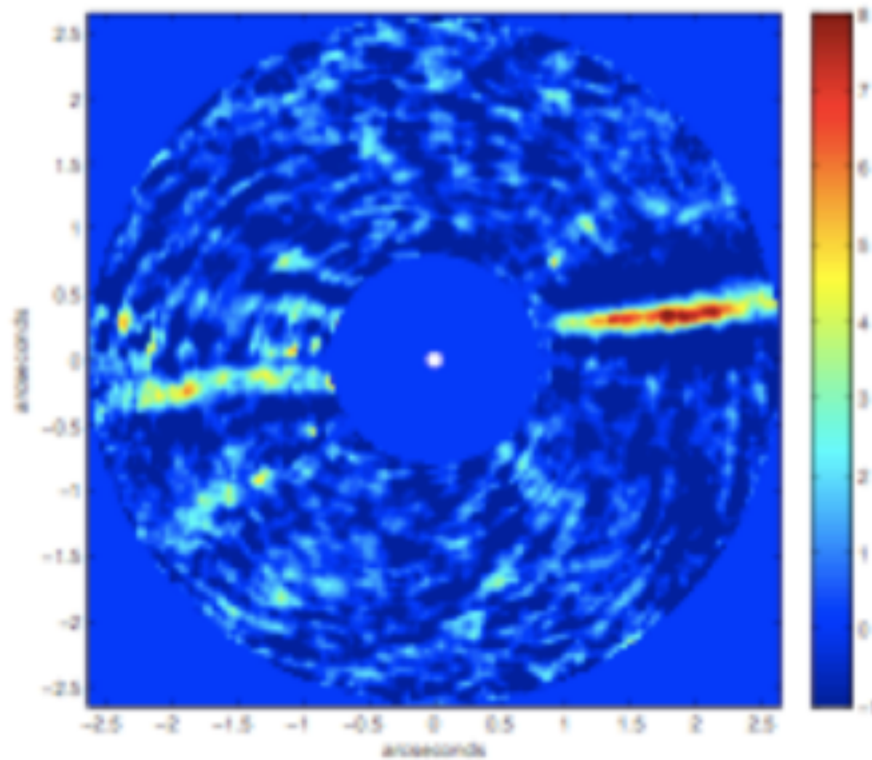


Identified 15 volcanoes, including Loki which is resolved

Other results from the LBTI

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





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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)?

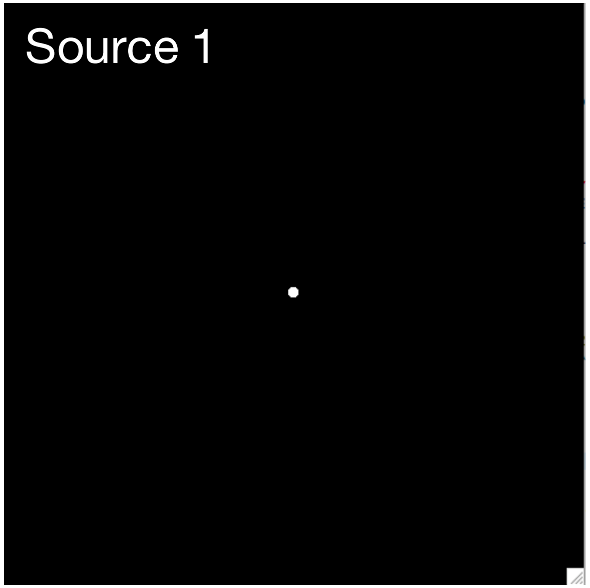


Image 1

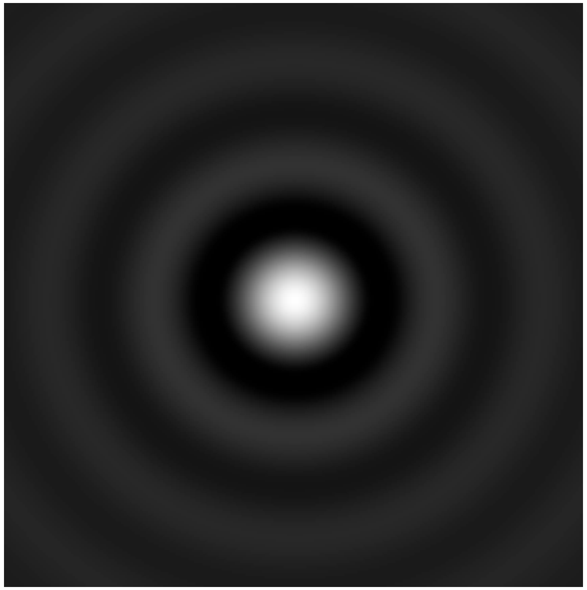


Image 2

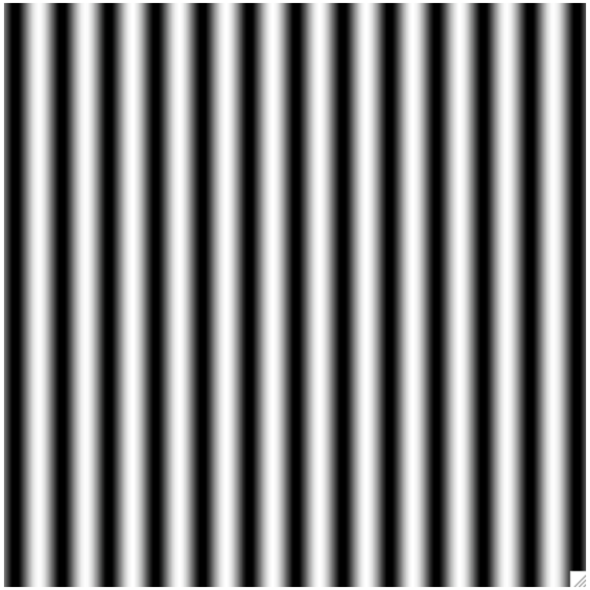
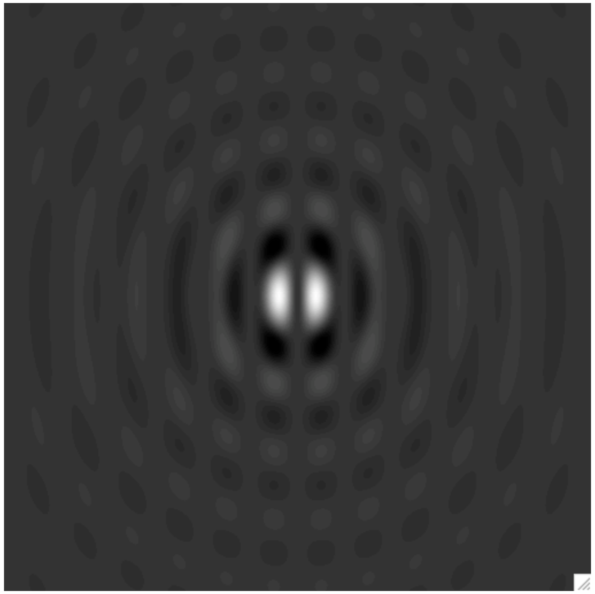
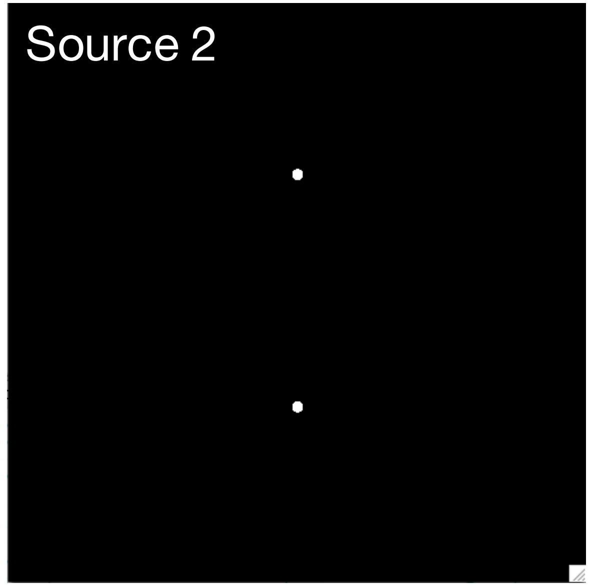


Image 3



Baseline orientation



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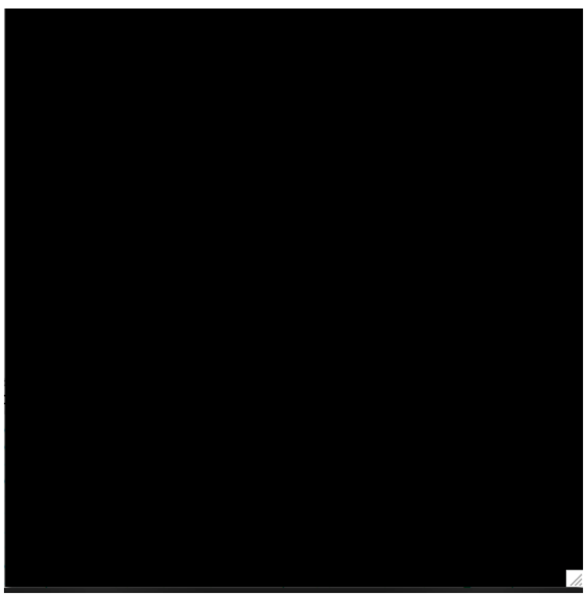


Image 2

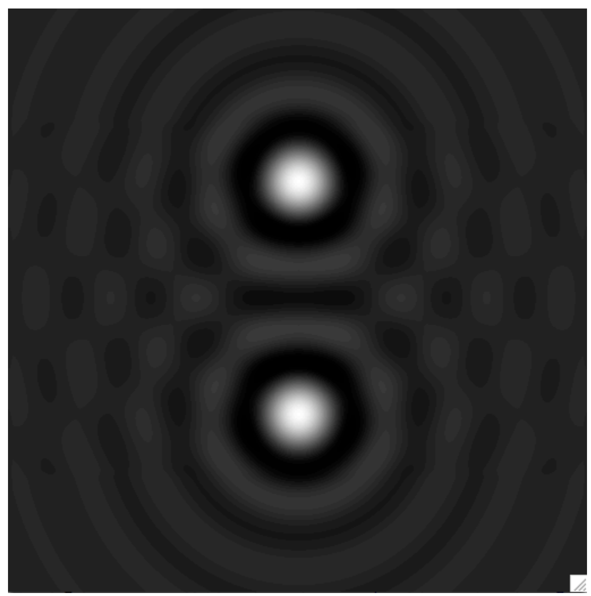
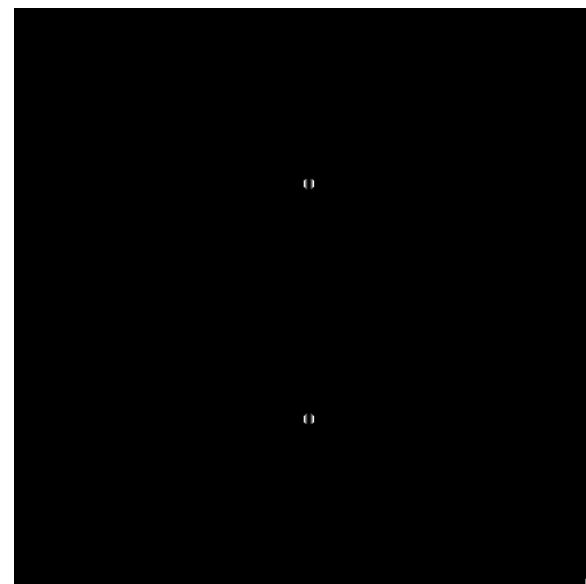


Image 3




THAT'S ALL
FOLKS !