A Summary of Results from Nulling Interferometry:
2001-2005

W. Liu, P. Hinz, W. Hoffmann, and the MMT Adaptive Optics Group
Steward Observatory, University of Arizona

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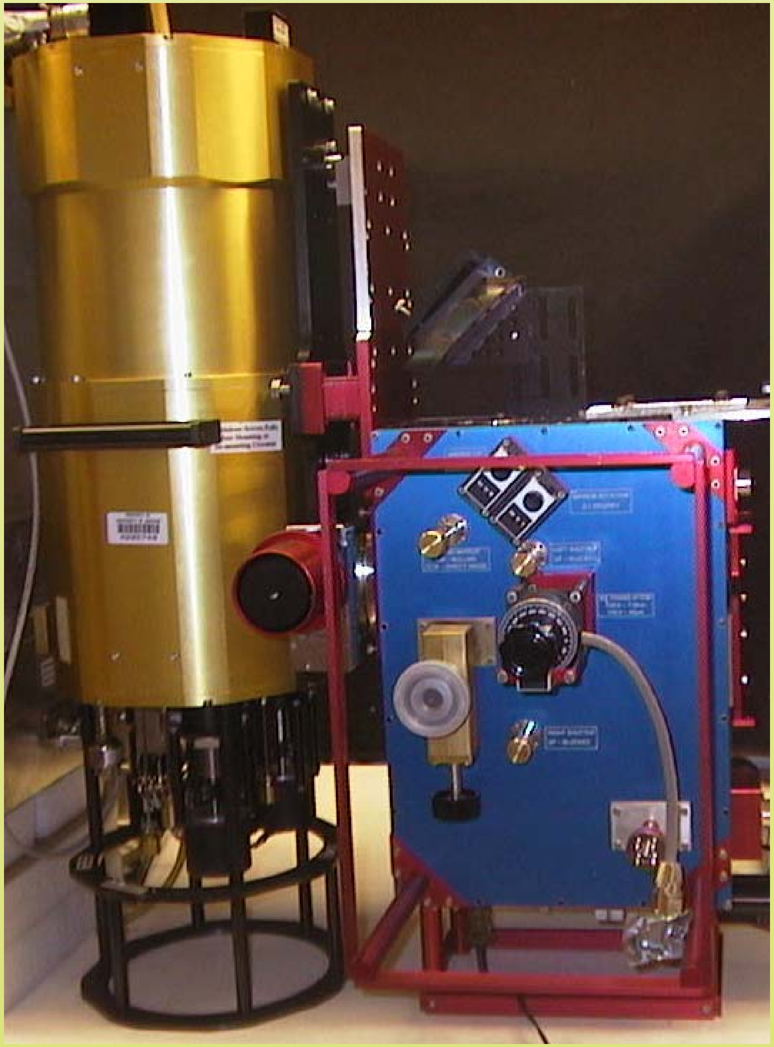
Nulling Interferometry



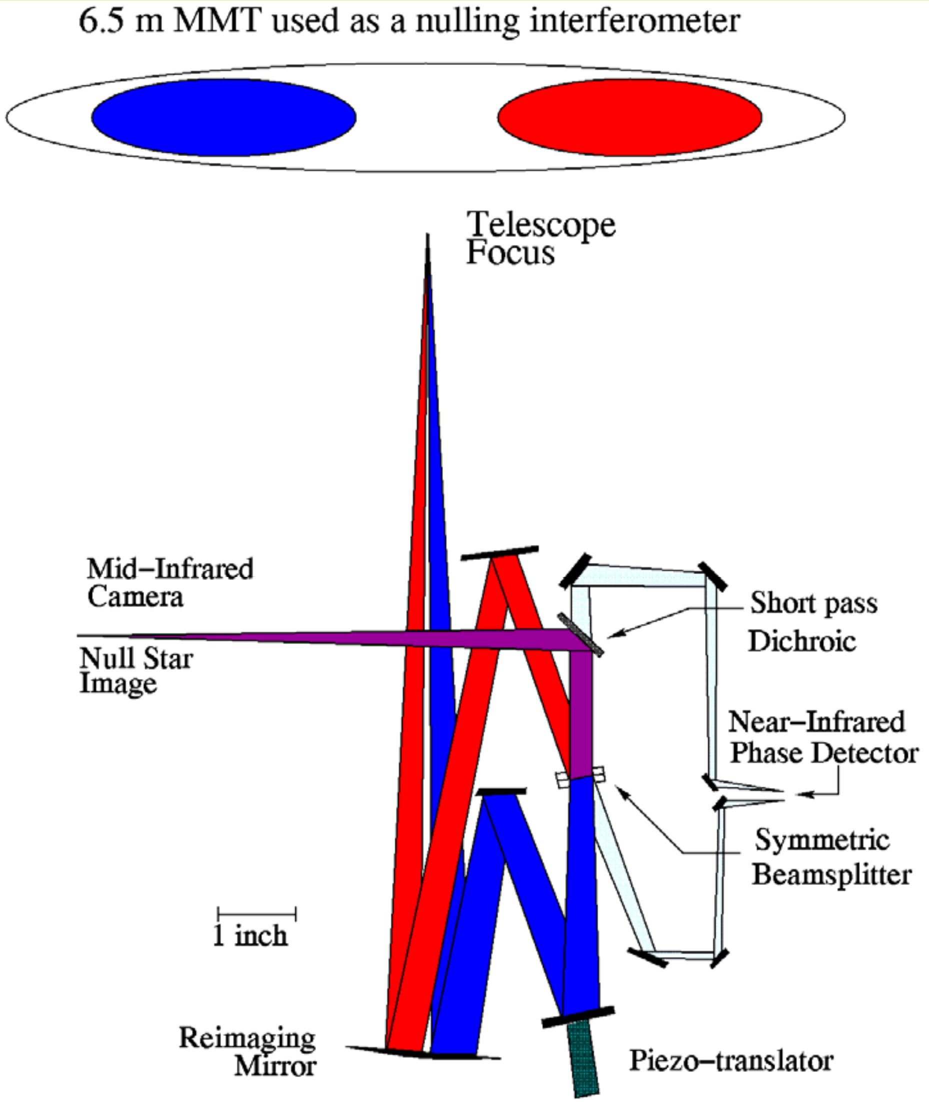
The Bracwell Infrared Nulling Cryostat (BLINC) mated with the Mid-Infrared Array Camera (MIRAC) in the lab

* Basic principle: To suppress the image of the star by destructive interference in order to make the relatively faint circumstellar disk visible, and to separate stellar flux from circumstellar flux.

* On a single aperture (6.5 m) telescope, two subapertures (2.5 m diameter) are used. The images of the pupils are overlapped and the path length between the two beams are adjusted until they are out of phase.

* The result: An interference pattern with the destructive interference fringe placed on the central point source.
Any emission from half a fringe length away (≈0.12”) can be detected.

BLINC Optical Design Overview



Optical layout of the BracewelL Infrared Nulling Cryostat (BLINC)

Nulling Projects: 2001 to present

2001-2004: A survey of Herbig Ae stars for resolved circumstellar disks

- Using MMT and Magellan I (Baade) 6.5 m telescopes
- 13 targets in the north and south at 10-12 μm
- Non-AO implementation
- Detected resolved disks around 2 stars (HD 100546 and AB Aur), with evidence for disks around an additional 3 objects
- Follow-up observations with AO (one additional disk resolved: HD 179218)

2003-present (ongoing): A survey of intermediate-mass main-sequence stars for habitable zone material (exozodiacal dust)

- Target list includes nearby A-type stars
- 10 μm - thermal emission corresponding to habitable zone
- Limits on exozodiacal dust around Vega

Nulling Observations, Data, & Calibration:

* Wavelengths: 10.3 μm, 11.7 μm, 12.5 μm (thermal continuum, silicate emission)

* For non-AO, the atmospheric variation modulates the null on the timescale of the integration: Fast frames are taken to freeze the seeing (sets of 500, 0.5 s)

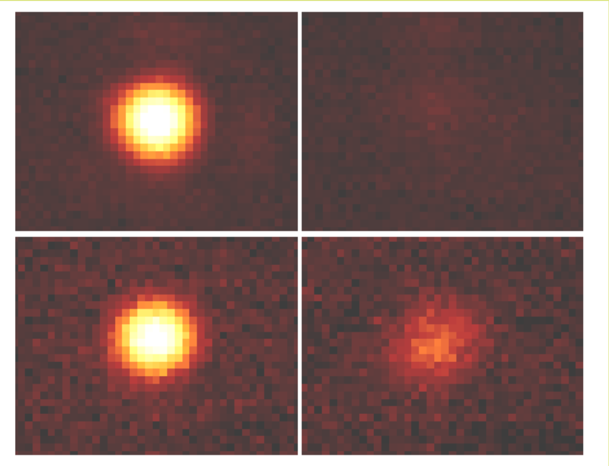
* Each set of images is examined for the frame with the best null and best contructively interfered image. The *'instrumental null'* is calculated:

$$\textit{Instrumental null} \text{ (expressed as a \%)} = \text{Flux}_{\text{NULL}} / \text{Flux}_{\text{FULL}}$$

* Observations of calibrator stars are interlaced with science observations

* The *'source null'* is derived by subtracting the calibrator null from the instrumental null on the science object:

$$\textit{Source null*} = \text{Instrumental null of HD 100546} - \text{Calibrator null}$$



<------ Calibrator, ε Mus (null = 10%)

<------ HD100546 (Instr. Null = 41%; source null = 31%)

* A non-zero source null is indicative of resolved emission

Herbig Ae Survey - Results:

* 13 Herbig Ae objects were observed over 4 years

* Selection criteria:
    * Initial list from Thé et al. (1994)
    * B8 or later
    * d < 250 pc
    * 12 μm IRAS flux > 10 Jy

51 Oph	HD 163296
AB Aur	HD 179218
DK Cha	HR 5999
HD 98922	KK Oph
HD 100546	R CrA
HD 104237	V892 Tau
HD 150193	

* We find that 3 disks are conclusively resolved (HD 100546, AB Aur, and HD 179218 are conclusively resolved
* Some evidence of resolved emission around an additional 3 stars (V892 Tau, R CrA, DK Cha)

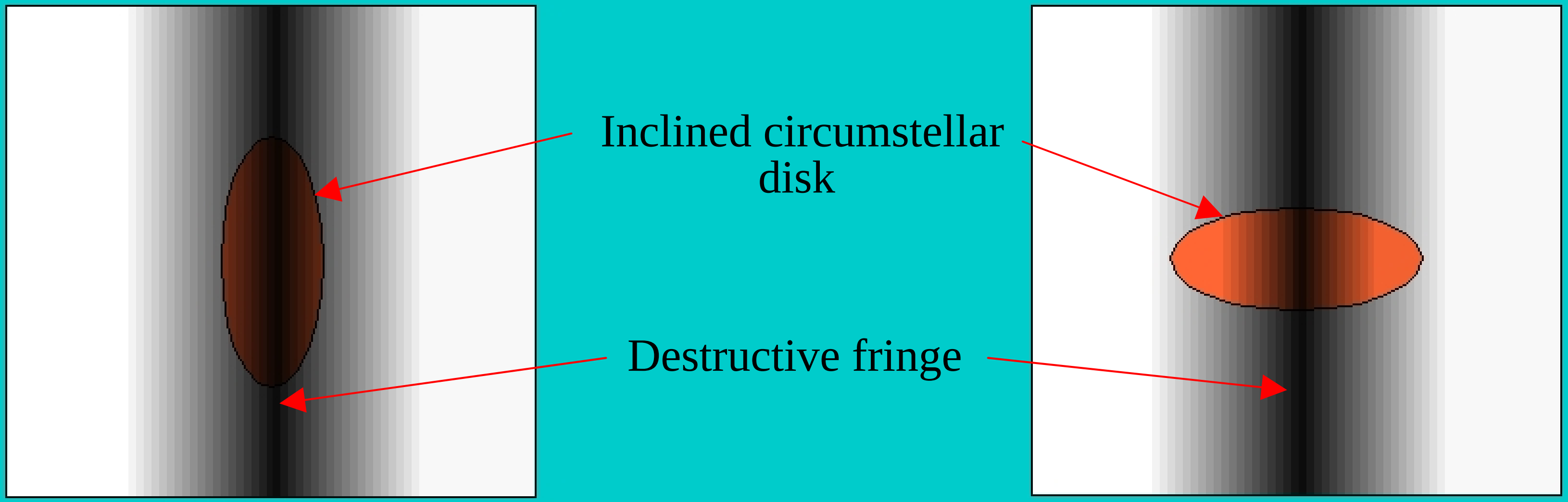
* Our ability to resolve these disks seems to be correlated to the Meeus et al. (2001) group classification - all three conclusively resolved objects are “Group I” characterized by large mid-infrared excess. Possible explanation: disk flaring

* Disk geometries were derived for two of the resolved objects, HD 100546 and AB Aur...

Resolved Disks - Determining Dust Distribution:

* The geometry of the resolved disk can be inferred by rotating the baseline of the interferometer

* In the presence of an inclined disk or other elongated structure, a deeper null is achieved when the destructive fringe is parallel to the major axis:

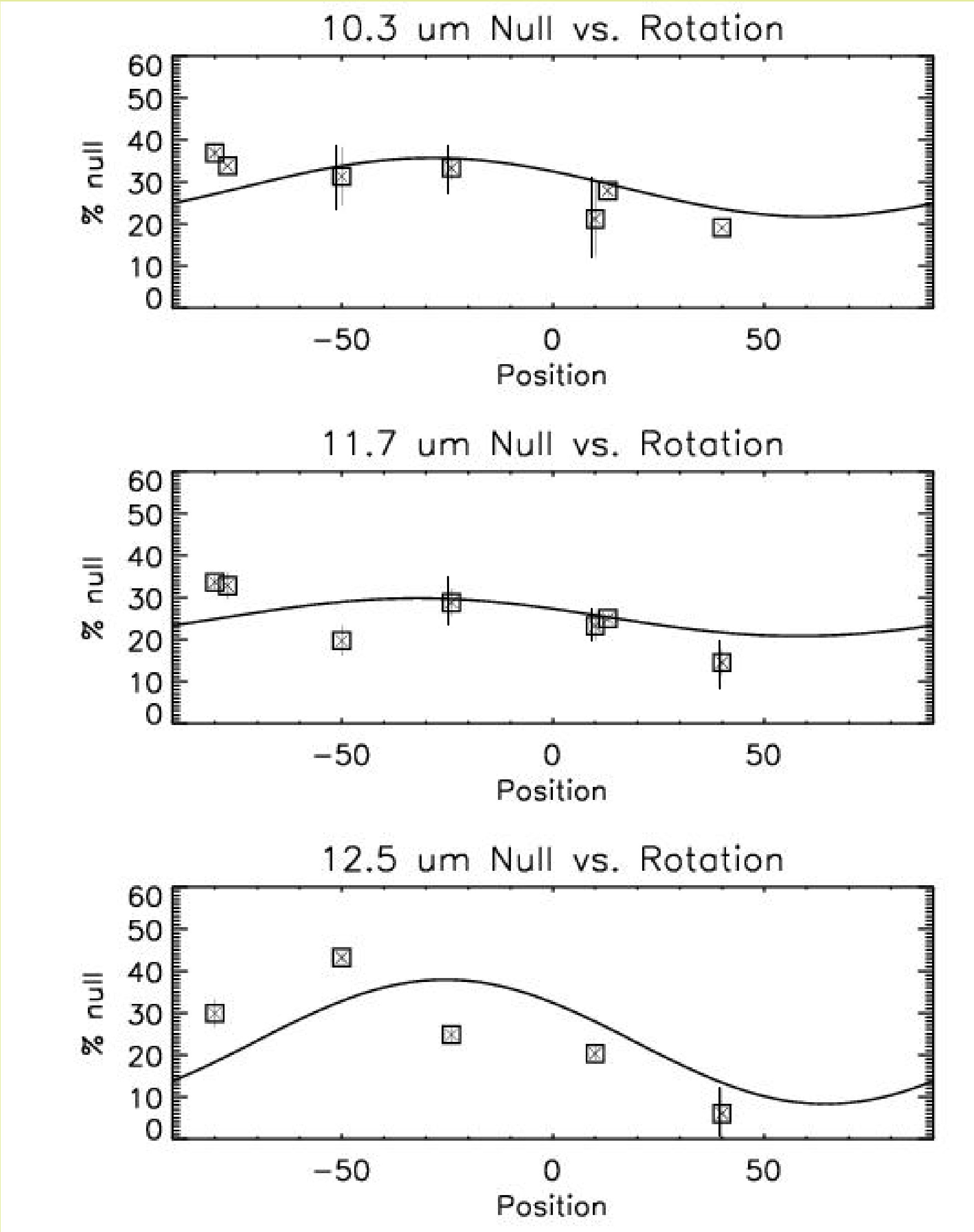


* The variation in null vs. rotation of the interferometer will have the form:

$A + B \sin(PA + \theta)$

Where: 'A' is the the vertical offset (physically related to the size of the disk)
'B' is the amplitude (physically related to the inclination of the disk)
'PA' is the position angle of the major axis of the disk
'θ' is the rotation of the interferometer baseline

Resolved Disk - HD 100546:

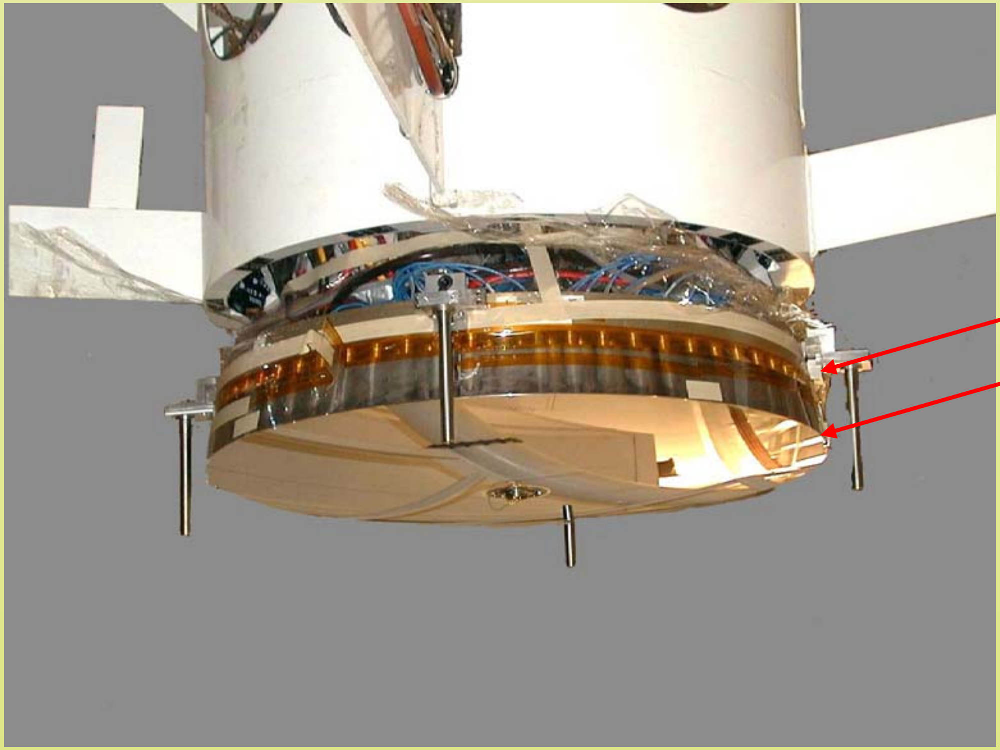


* The source null shows variation in all wavelengths (factor of 2 at 10.3 and 11.7 microns, factor of 4 at 12.5)

* The fits to the data suggest a disk that is 25-35 AU in diameter with an inclination between 40-60^{o}

* The relatively large size of the warm disk suggests that the inner disk is not a continuous optically thick flared disk, but may contain a gap or clearing

Resolved Disk - AB Aur - AO observations:



MMT Adaptive Optics system:

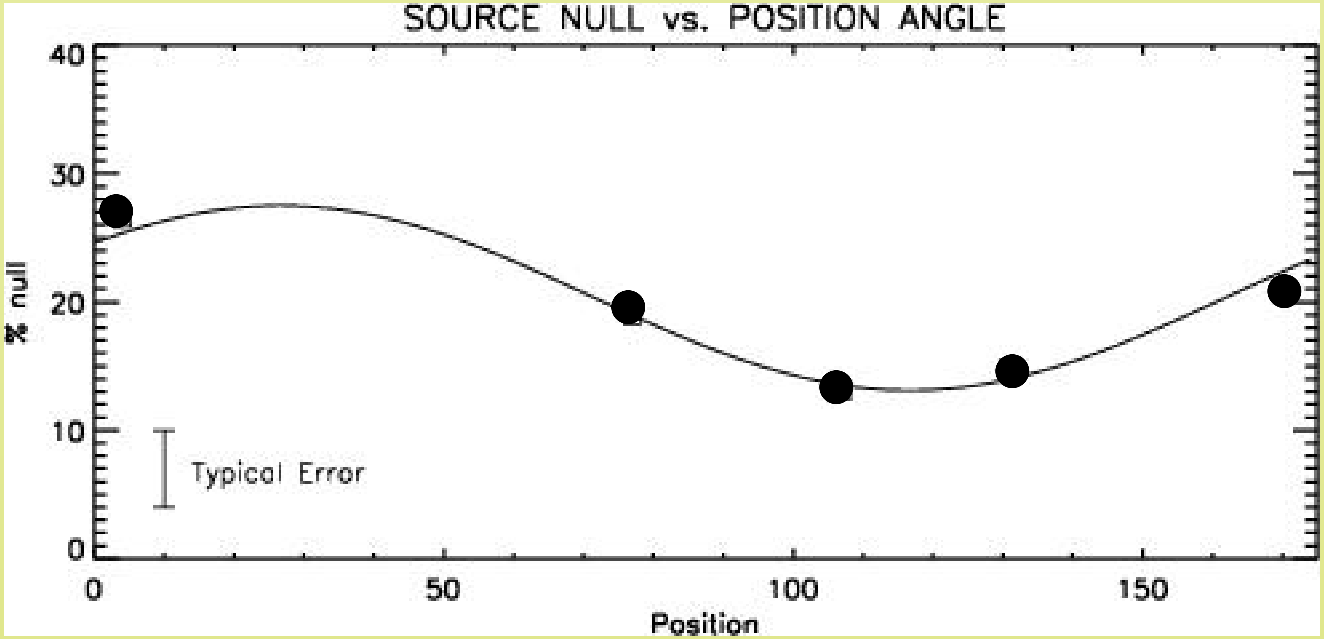
- The deformable secondary:
  - Diameter: 64 cm
  - 336 actuators
  - Shell thickness = 2mm

- Advantage:
  - Optimized for the thermal infrared - fewer warm surfaces than a conventional AO system

Nulling with AO: Adaptive optics provides 3 main benefits to nulling:

1) Stabilization of wavefront - precisely tune the path length of the arms for maximum suppression of stellar flux
2) Random atmospheric variation in null removed - fewer data frames
3) Stability in null - calibration is more robust, frames can be integrated on faint sources

Resolved Disk - AB Aur (continued):



- AB Aur was observed at 5 different rotations (over a full range of 170^{o}) of the baseline w/ AO

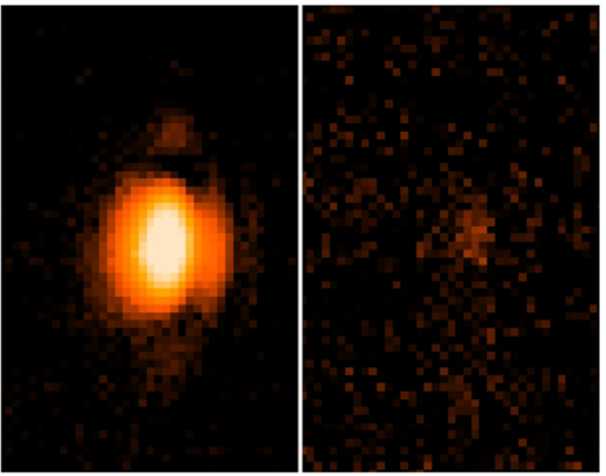
- A fit to the null vs. rotation relation yields disk parameters:
  - Diameter: 24-30 AU
  - Inclination: 45-65^{o}
  - PA = 15-45^{o}

- Differences between MIR and other wavelengths (NIR and mm) suggest a complex structure - not a disk alone

Main-Sequence Observations - Results:

- A search for warm, habitable zone planetary material around main-sequence stars at 10 μm
- Selection criteria:
  - Intrinsically luminous stars (A-type)
  - Nearby stars (d < 40 pc)
  - MIR excess detected by Sptizer (24 μm)

Results - Observations of Vega:



- We find no resolved emission at 10.6 μm outside of 0.8 AU at a level above 2.1% of the photospheric flux. This corresponds to a dust density of 650 zodis (1 zodi = density of solar system zodiacal dust)

- This is clear compared to the outer system (> 100 AU), which has dust observed by Sptizer and attributed to dust produced by collisions and populating the outer system by radiation pressure blowout (Su et al. 2005).

- Possible scenario: collisional processes producing dust occurred 10^4 to a few x 10^5 years ago.

Summary:

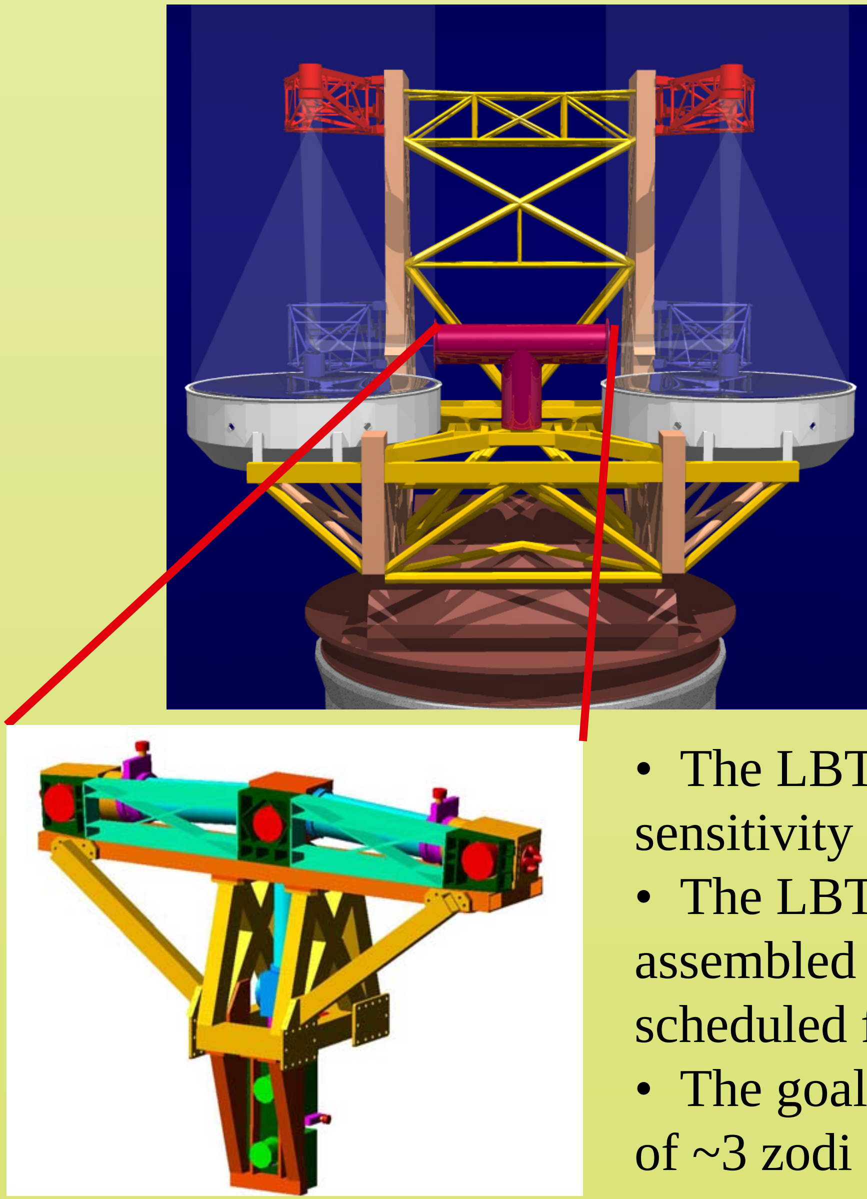
- We have completed a survey of 13 Herbig Ae stars in both hemispheres, conclusively identifying resolved emission surrounding 3

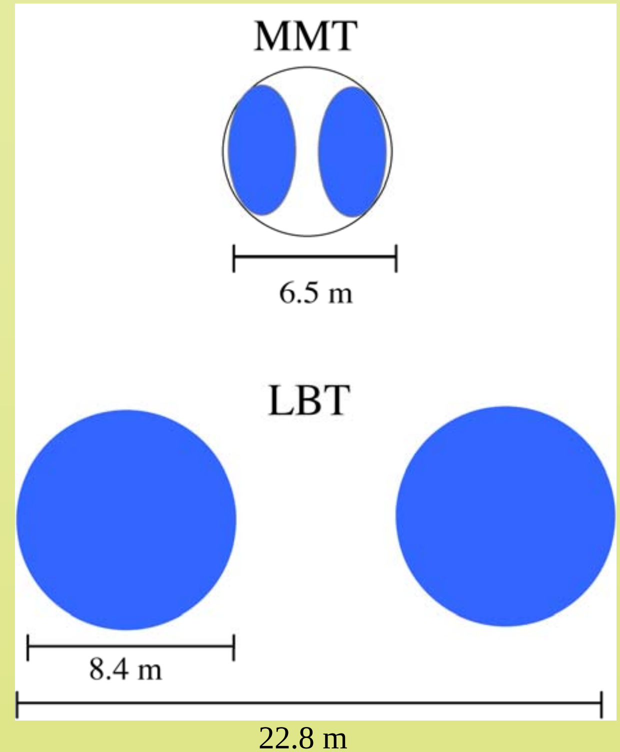
- We have derived physical characteristics for the disks around HD 100546 and AB Aur

- Our observations of intermediate-mass main-sequence stars is ongoing

- The Vega system shows a relative lack of material in the inner system (< 10 AU) compared to longer wavelengths observed by Spitzer

Future Directions: Nulling on the LBT:

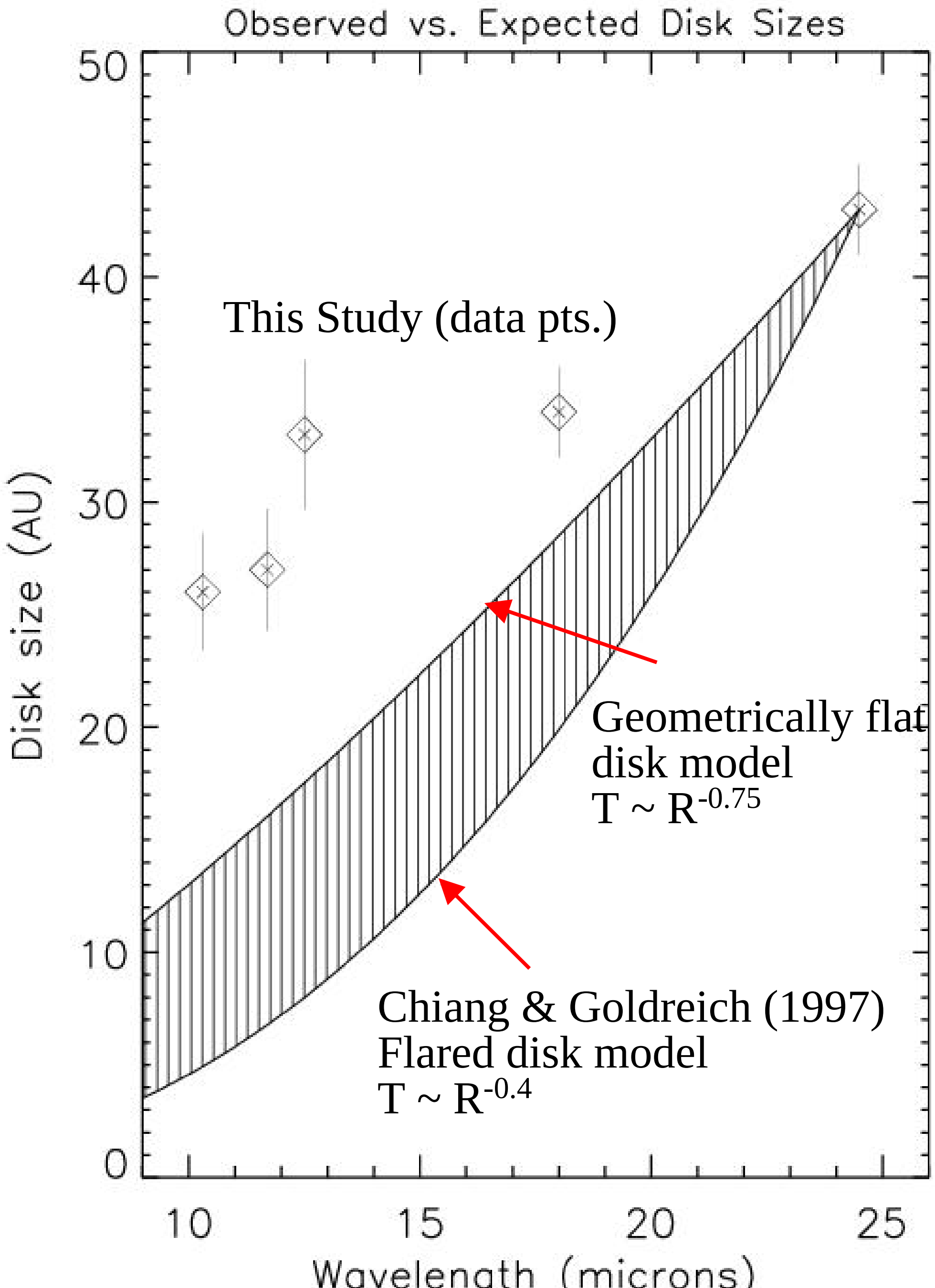




- The LBT nulling interferometer will have both better sensitivity and resolution for exo-system searches
- The LBT Interferometer (LBTI) is currently being assembled at Steward Obs. with delivery to the LBT scheduled for sometime in 2007
- The goal for LBTI is to be sensitive to dust densities of ~3 zodi around nearby main-sequence stars.

begin “question” slides

Implications for the HD 100546 system:



* If we assume that the mid-IR emission is thermal in nature, we can compare our disk sizes to those expected from current models of circumstellar disks...

* The shaded region indicates the range of disk sizes expected from current models

* The sizes derived in this study are 2 - 3 times larger than the expected values

* Q: Why is this the case?
  A: A large inner gap in the disk...

HD 100546 Disk Structure

Typical Protoplanetary disk model

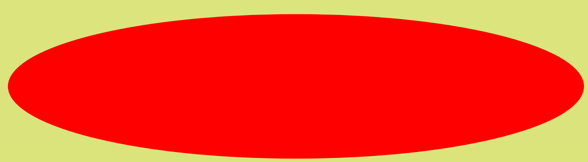
*A protoplanetary disk model has a temperature gradient due to stellar heating and accretion

* The short wavelength emission is dominated by a very small inner region of the disk, subject to most heating

10 μm emission

* The size at 20 μm is expected to be spatially about 4 times as larger than the 10 μm emission

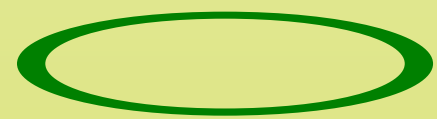
20 μm emission



HD 100546 model

*A gap in the disk would cause a lack of emission from hot inner dust.

* We expect less 10 μm emission due to the gap, but this emission will be spatially further out in the disk, making it more similar in size to the 20 μm emission and therefore resolvable



* The size at 20 μm for a disk with an inner gap is similar to that at 10 μm