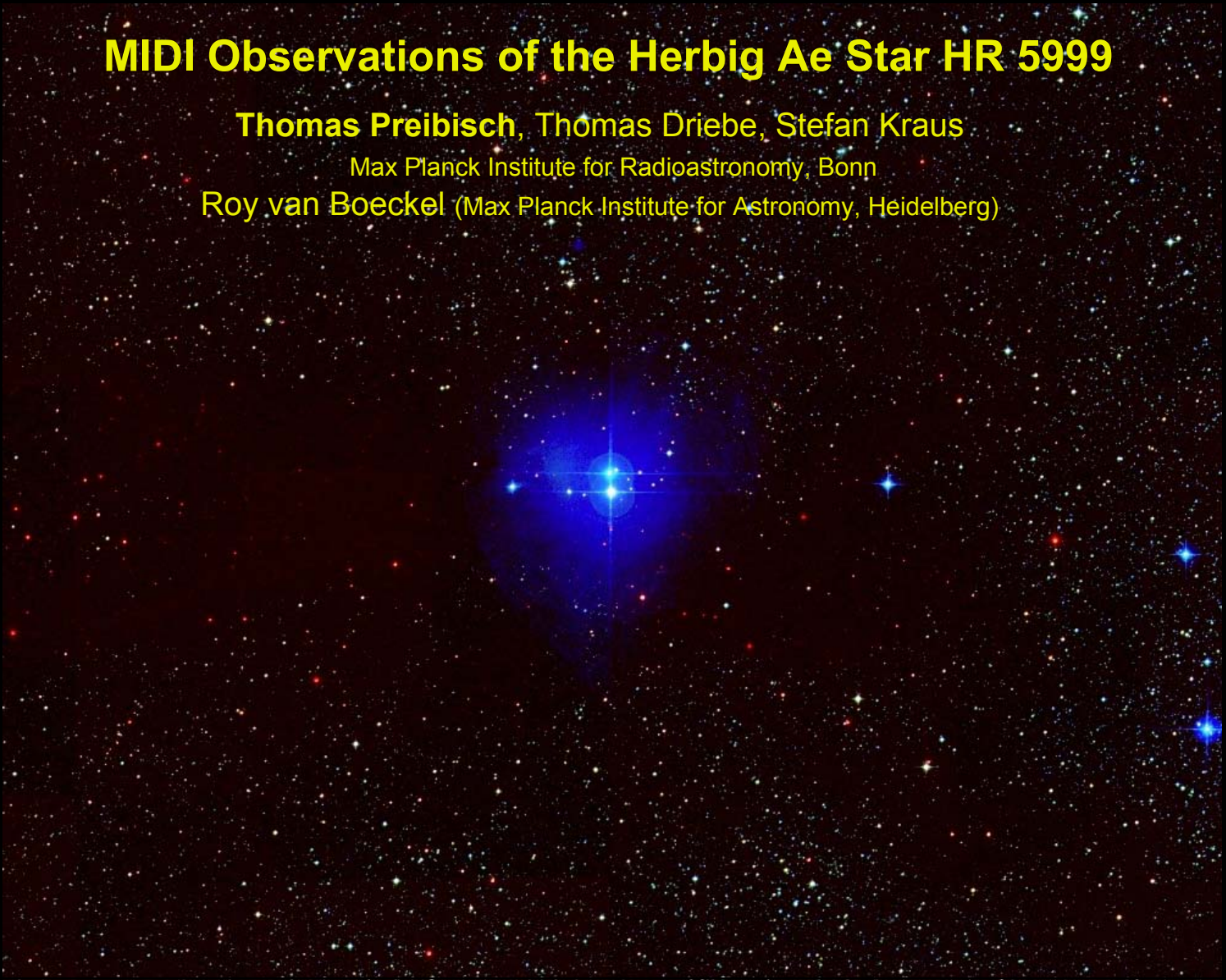


MIDI Observations of the Herbig Ae Star HR 5999

Thomas Preibisch, Thomas Driebe, Stefan Kraus

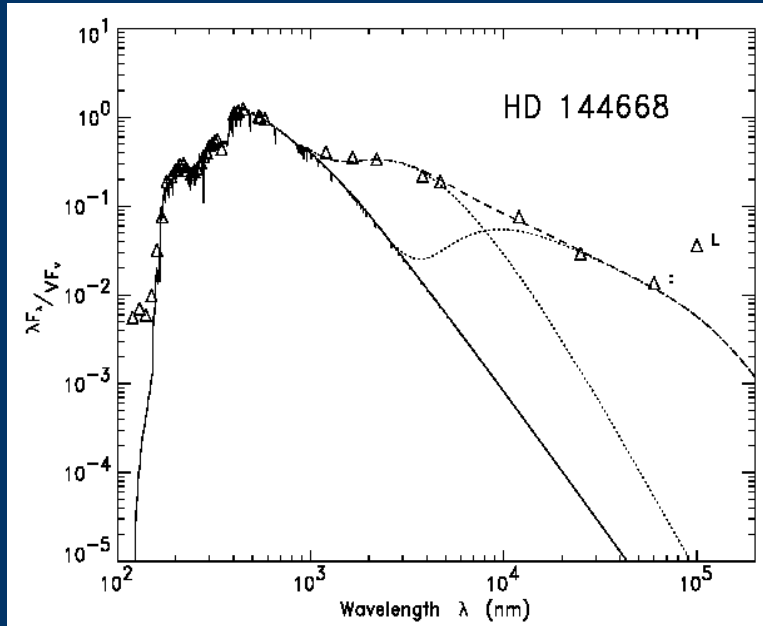
Max Planck Institute for Radioastronomy, Bonn

Roy van Boeckel (Max Planck Institute for Astronomy, Heidelberg)



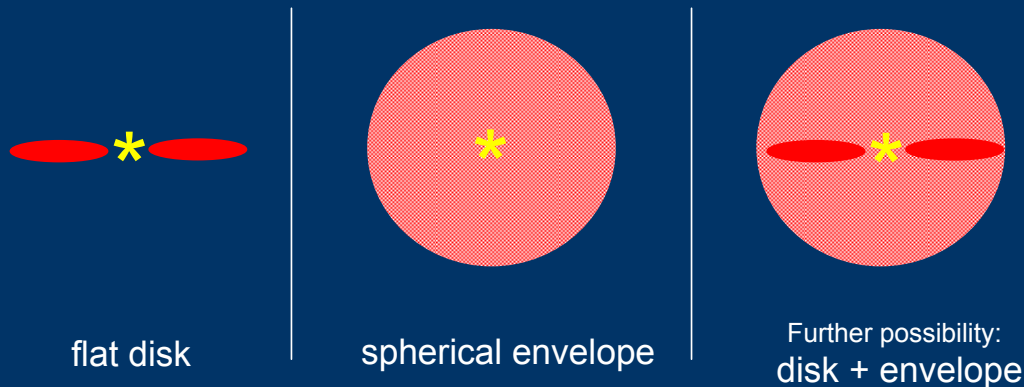
Herbig AeBe stars = Intermediate-mass young stellar objects

$M \sim 2 - 10 M_{\text{sun}}$, age $\sim 0.1 - 5$ Myr



Infrared excess in the spectral energy distribution
→ evidence for circumstellar material

The SEDs of many HAEBEs can be equally well fitted with flat disk and spherical envelope models



Which model is correct ?

Direct spatial information on scales < 100 AU is essential

Interferometric observations of HAEBEs:

Millan-Gabet et al. (1999) **IOTA**, Akeson et al. (2000) **PTI**, Monnier et al. (2005) **Keck**
Leinert et al. (2004), **MIDI**

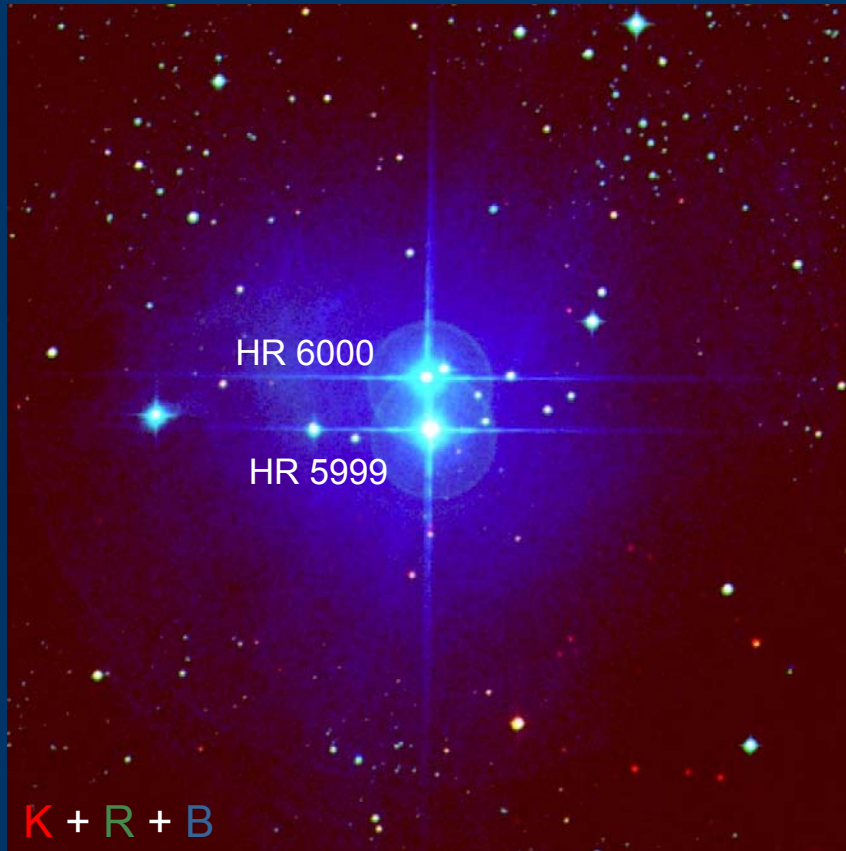
→ **information on source sizes**

BUT: mostly only one baseline, very few visibility points per object

→ **no information on the source geometry**

Studies with better UV coverage needed !

Properties of HR 5999 (alias HD 144668, V856 Sco):



12' x 12'

Hipparcos distance =
208 (+50, - 30) pc

Spectral Type: A 7 IV e

$L_{\text{bol}} = 100 L_{\odot}$, $A_V = 0.5$ mag

$M = 3.9 M_{\odot}$, age = 0.5 Myr

$v \sin i = 180$ km/sec

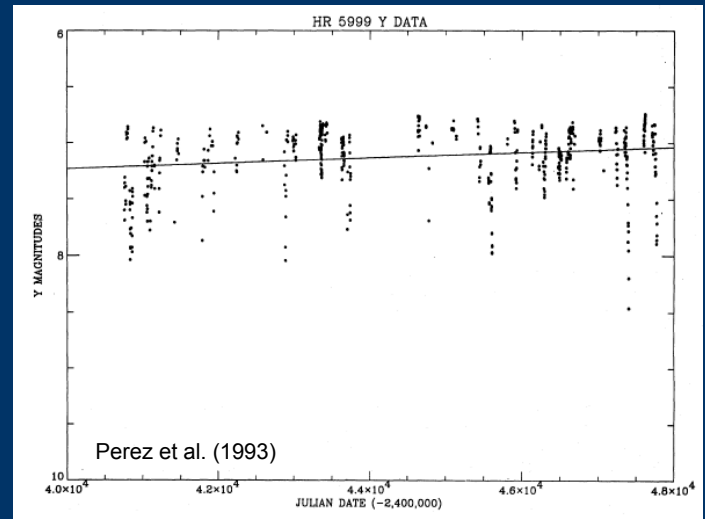
Infrared excess:
circumstellar mass $\sim 0.01 M_{\odot}$

HR 6000: SpT = A1.5
no emission lines
no infrared excess
→ not a Herbig star !

Evidence for circumstellar disk:

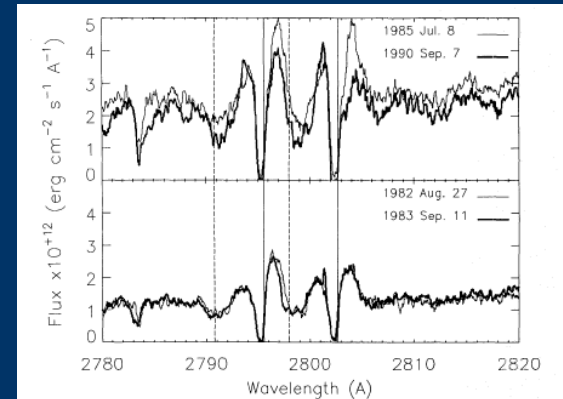
quasi-periodic + irregular
photometric + spectroscopic
variability

Obscuration by clumps
in the circumstellar disk (?)



Analysis of IUE spectra: Perez et al (1993; A&A 274,381):

- accretion disk, seen close to edge on
- $V_{\text{accretion}} \sim 300$ km/sec
- $dM/dt \sim 7 \times 10^{-7} M_{\odot}/\text{yr}$



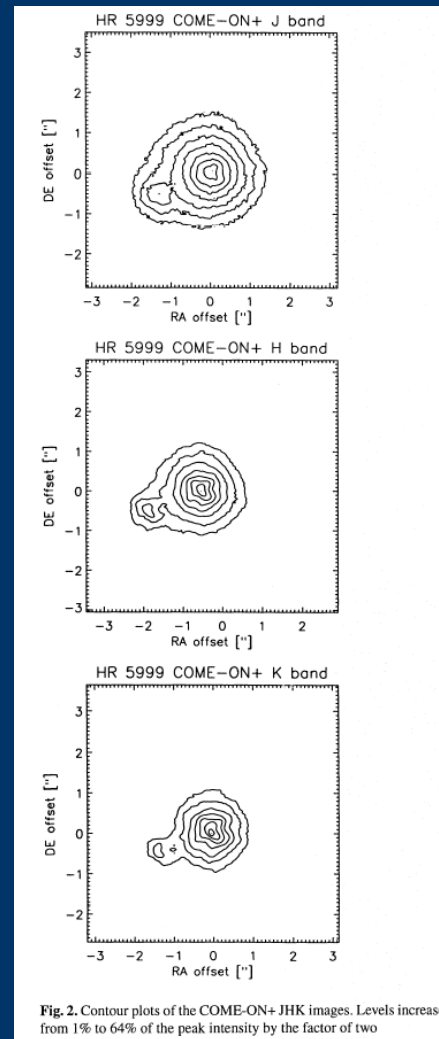
HR 5999 has a visual companion (Rossiter 3930)

separation = 1.5 arcsec

$\Delta V = 4.6$ mag, $\Delta K = 3.6$ mag

Dynamic disk clearing
by binary interaction:

Disk around HR 5999 should
be < 100 AU (500 mas)



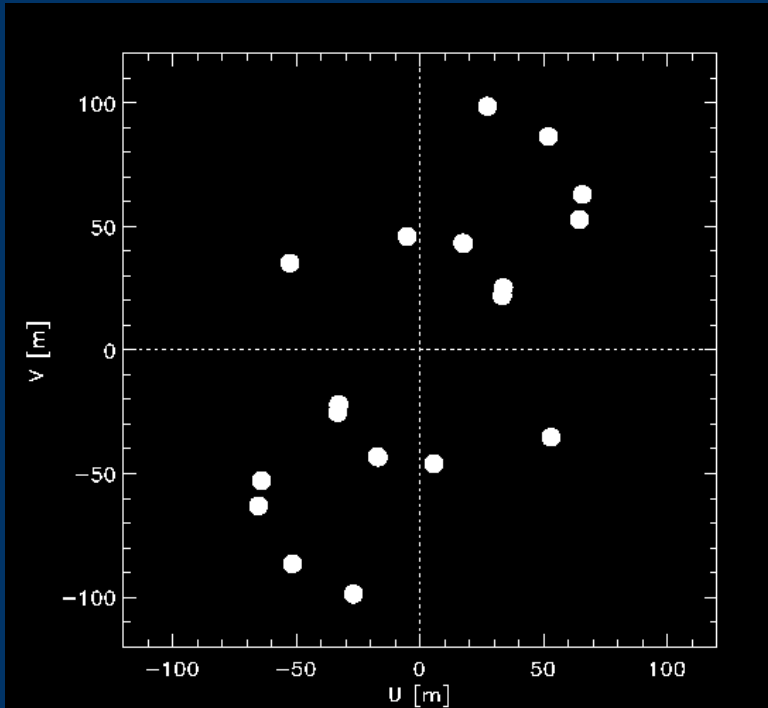
MIDI observations of HR 5999:

Programme 073.C-0248 (PI: Preibisch)

6 visibility points

Programme 073.C-0720 (PI: vanBoeckel)

4 visibility points



Projected baseline lengths:

39 m 102 m

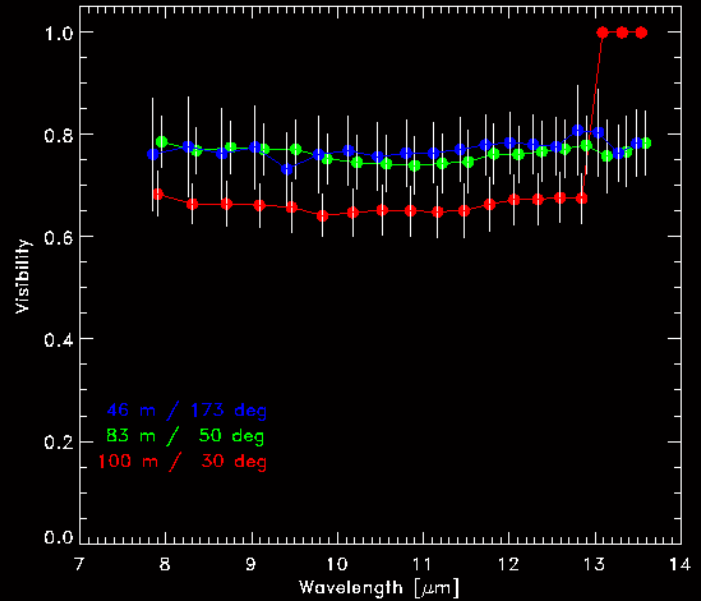
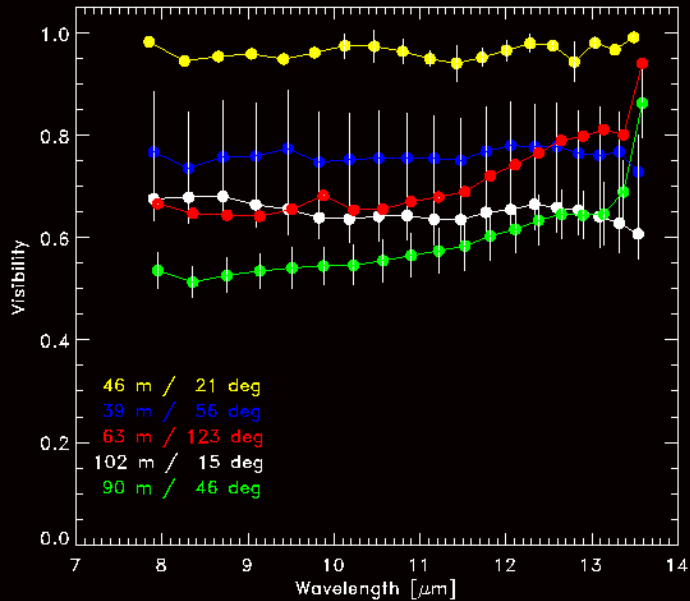
resolution @ 10 μm :

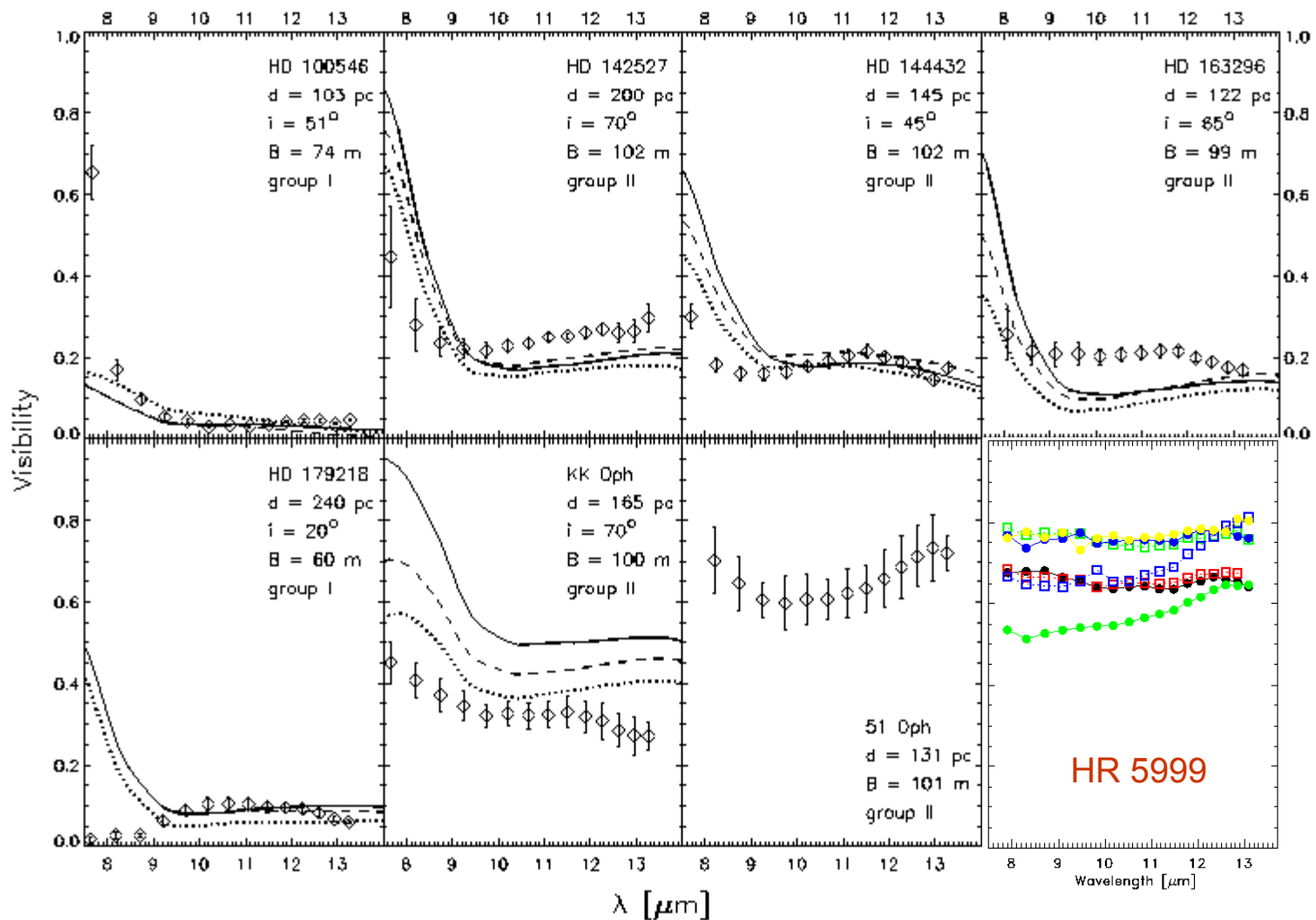
10 AU ... 4 AU

Position angles:

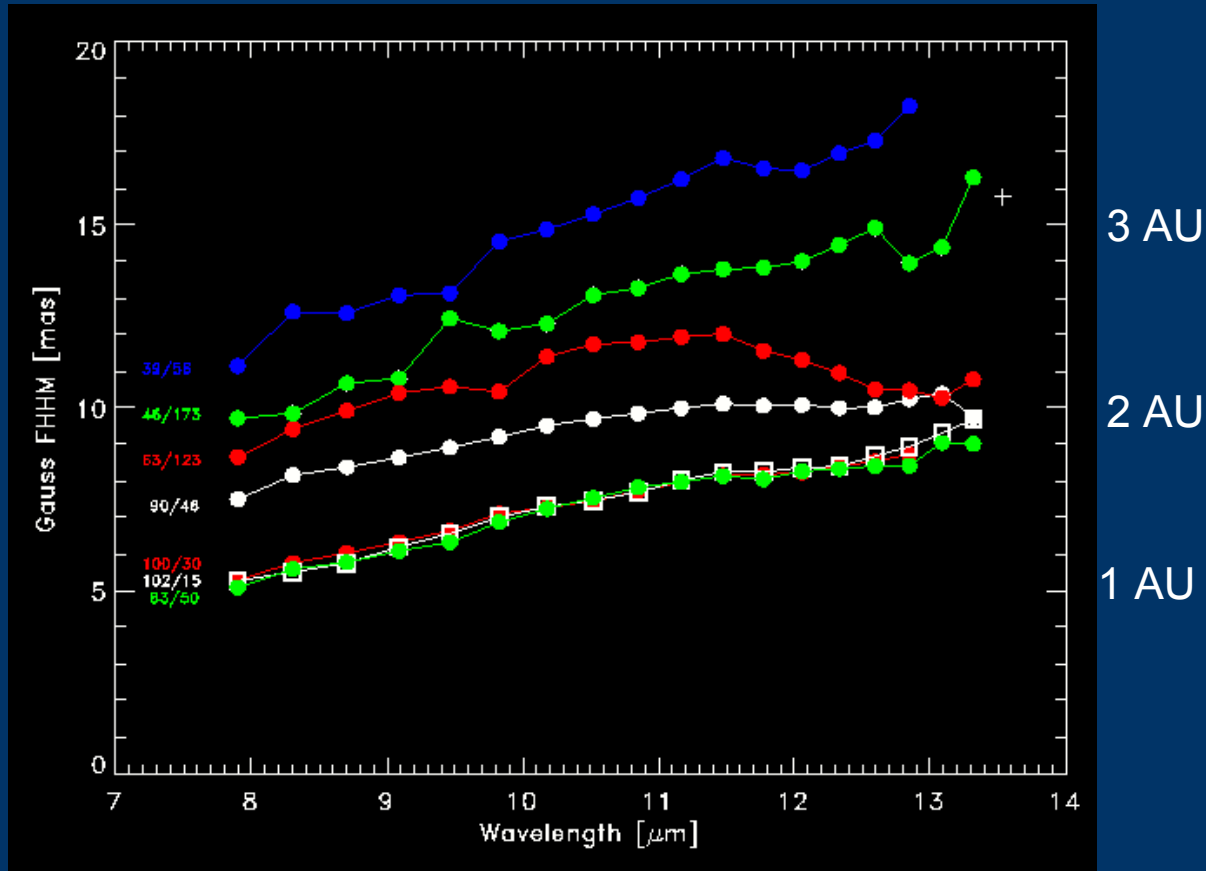
15° 173°

MIDI visibilities of HR 5999:





Characteristic size: Gauss fits



- size increases with wavelength \rightarrow extended dust emission
- very compact structure ($\sim 1 - 3$ AU)

Expected dust sublimation radius for HR 5999:

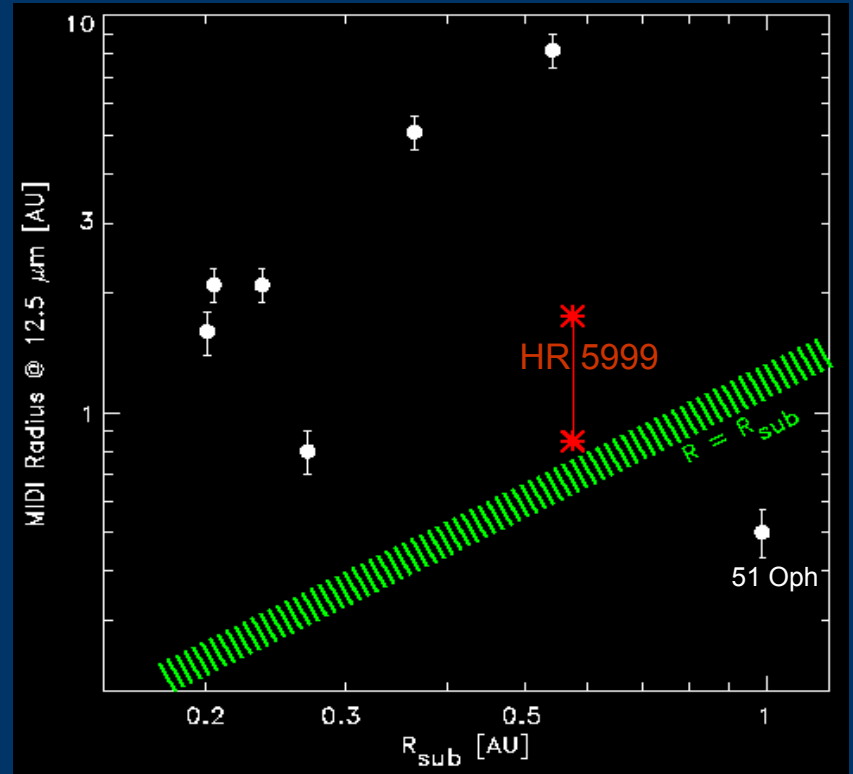
$$L_{\text{bol}} = 100 L_{\odot}, T_{\text{eff}} = 8000 \text{ K}, T_{\text{sub}} = 1500 \text{ K}$$

$$\rightarrow R_{\text{sub}} \sim 0.5 - 1 \text{ AU}$$

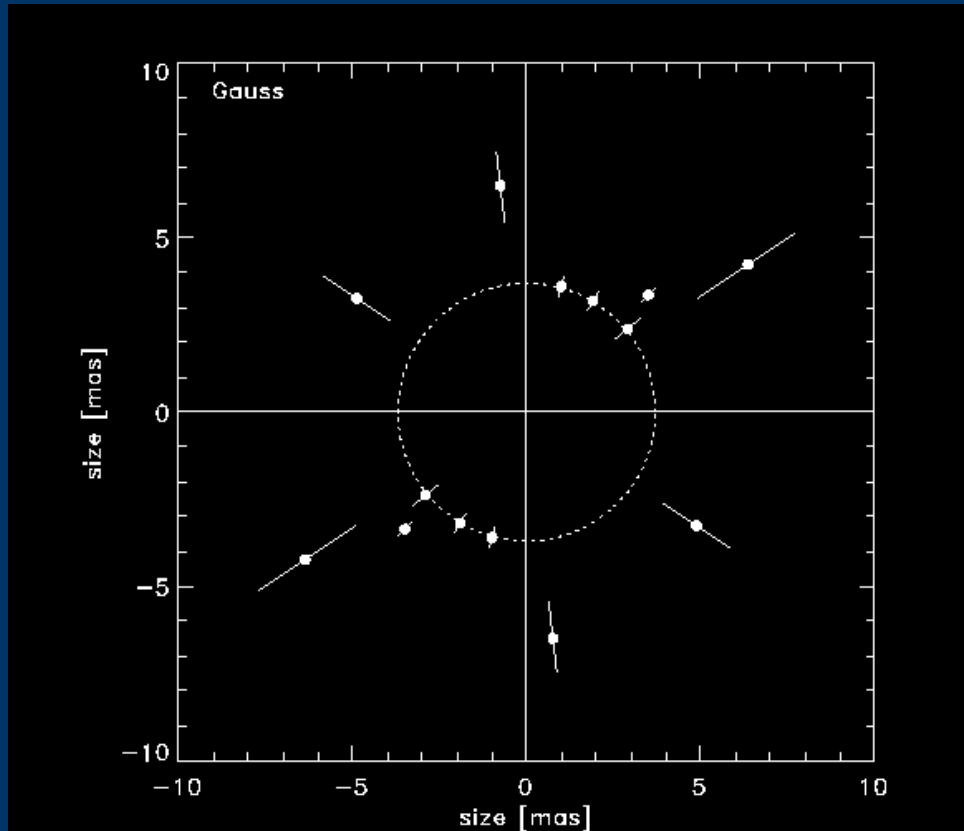
Gauss fit radii: $\sim 0.8 - 1.7 \text{ AU}$

Observed sizes and
theoretical sublimation radii
for Herbig stars

- Objects from Leinert et al. (2004)

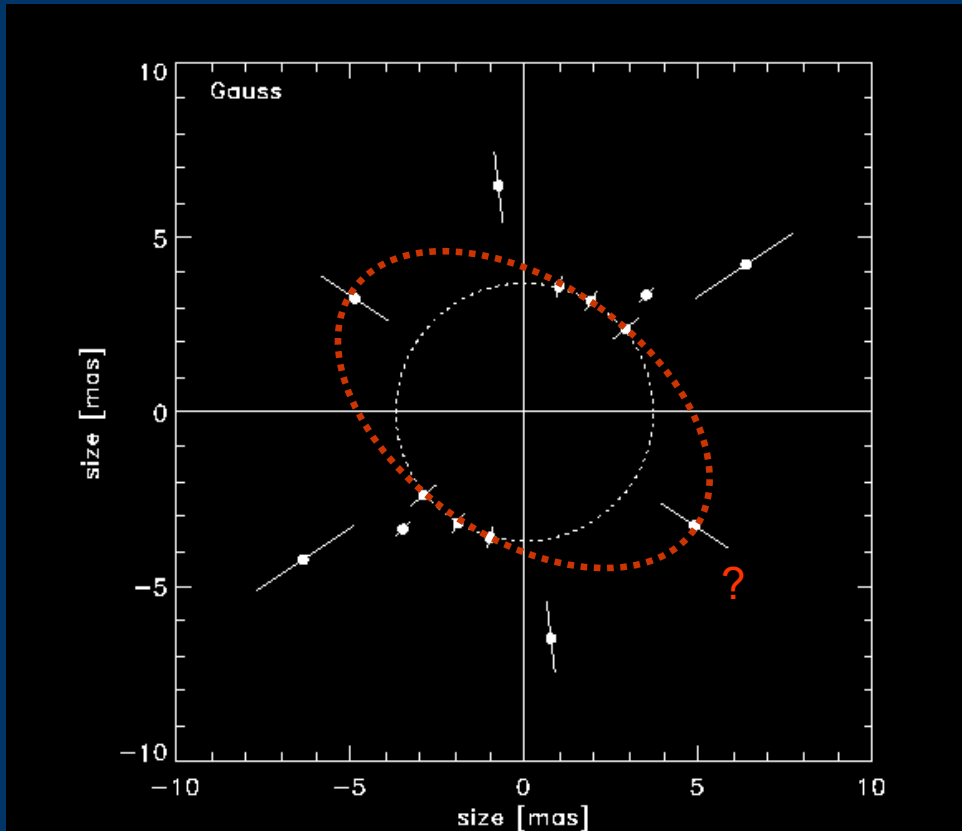


Gauss fit size as a function of position angle:



different sizes for different position angles → elongated structure

Gauss fit size as a function of position angle:

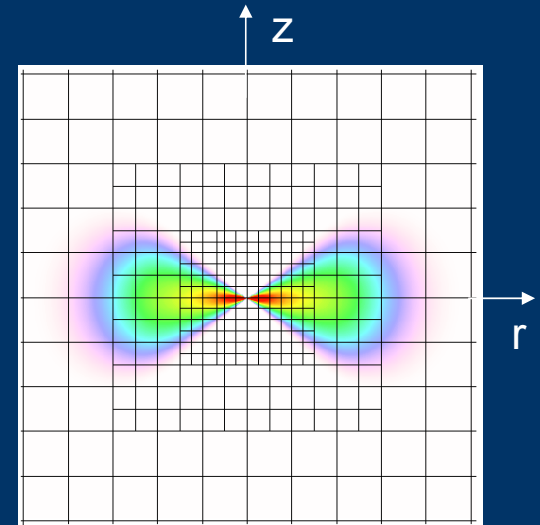


different sizes for different position angles → elongated structure

Radiative transfer simulations

Code from Sonnhalter, Preibisch, Yorke (1995):

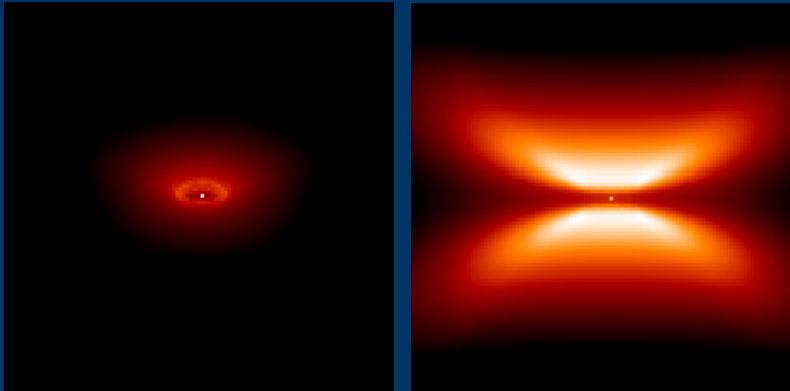
- 2D, frequency dependent, nested grids
- INPUT: density distribution + radiation source
- dust model: Silicate + Carbon grains
ice mantles for $T < 150$ K
- self consistent, iterative determination of radiation field and dust temperatures
(\rightarrow dust sublimation radius)
- RAY TRACING: \rightarrow images + spectra



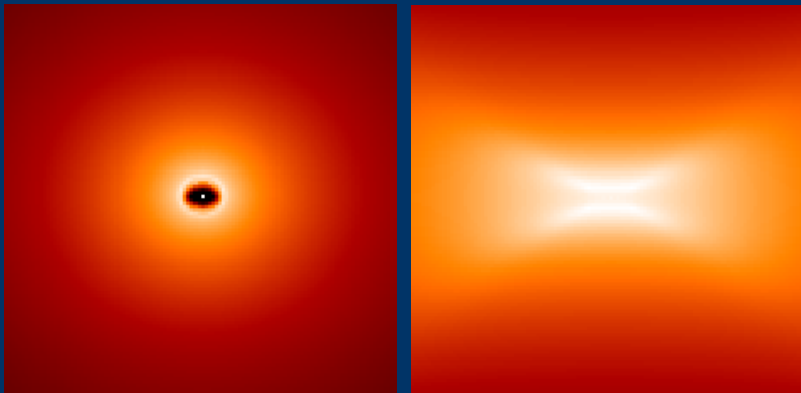
Density distribution
+ computational grid

Simulated images:

log (intensity)

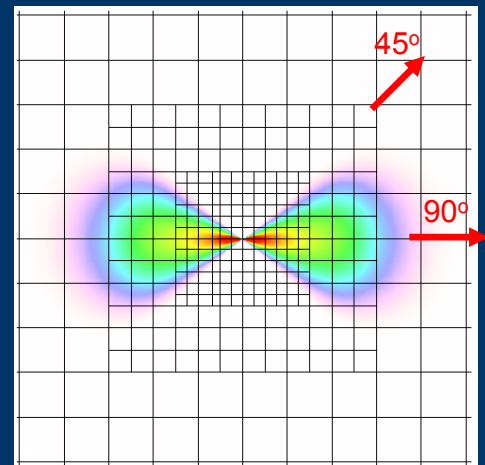


J-band
(1 μm)



$i = 45 \text{ degr}$

$i = 90 \text{ degr}$



N-band
(10 μm)

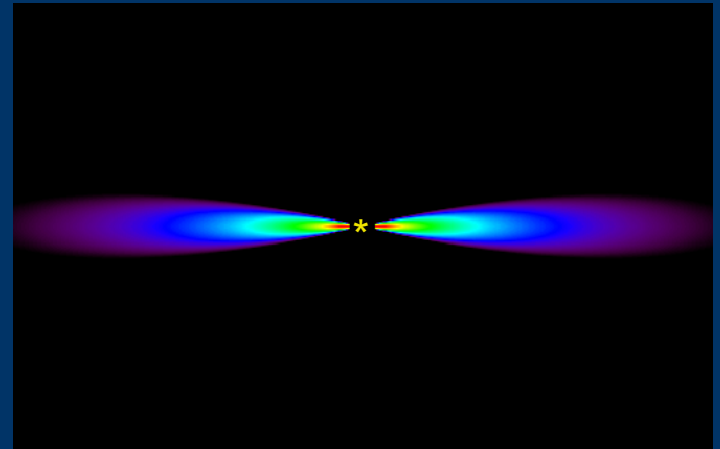
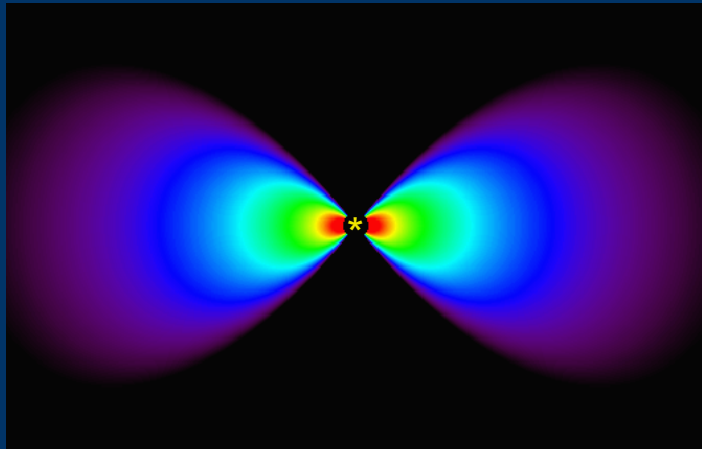
1) Keplerian disk models

$$\rho_{\text{disk}} = \rho_s \left(\frac{r_s}{r} \right)^{15/8} e^{-\pi/4 \left(z/z_s (r_s/r)^{9/8} \right)^2}$$

log (density)

$z_s/r_s = 0.4$

$z_s/r_s = 0.1$

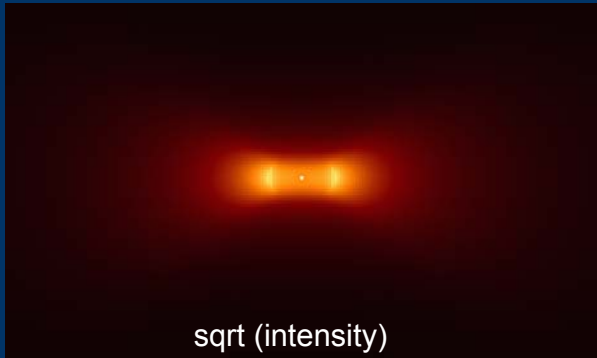


← 50 AU →

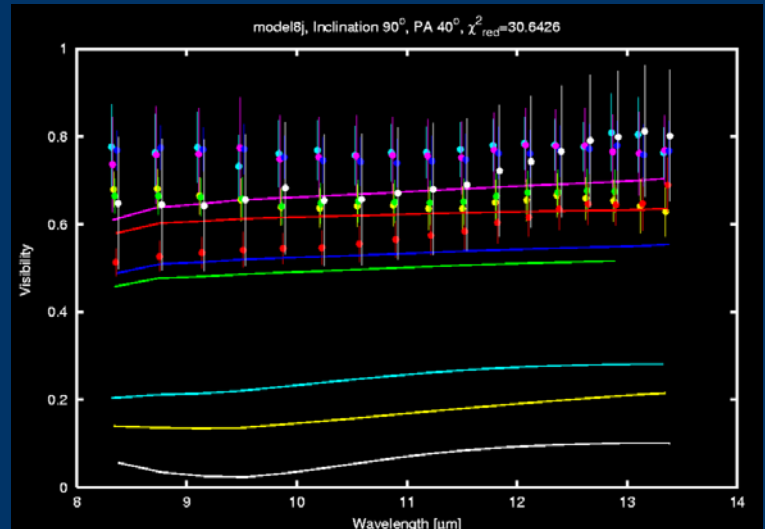
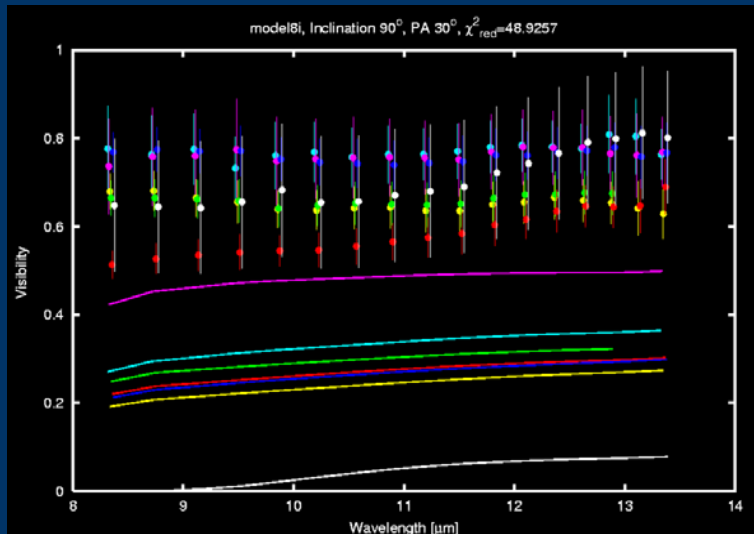
Keplerian disk models

simulated images

$i = 90^\circ$

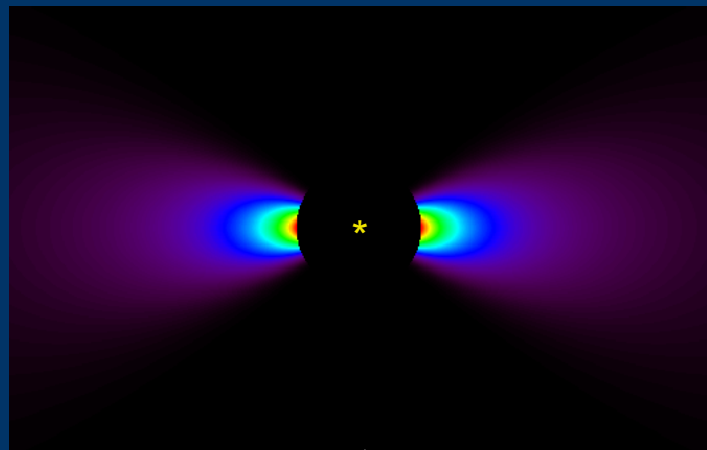


Model predictions compared to observed visibilities:



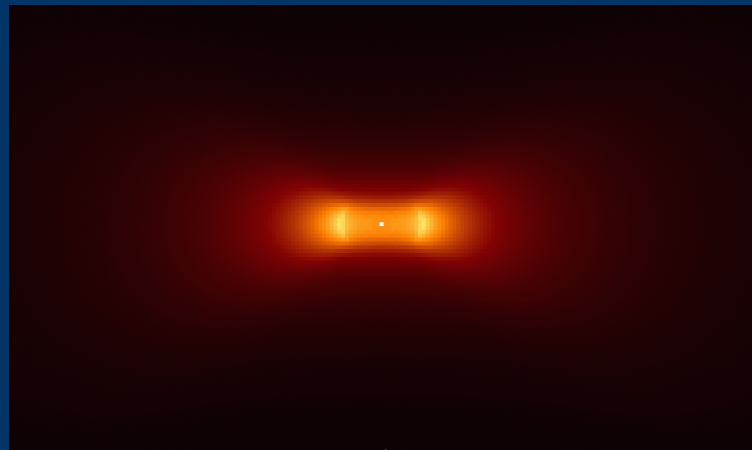
Simulated structure is several times too large

2) Higher sublimation temperature

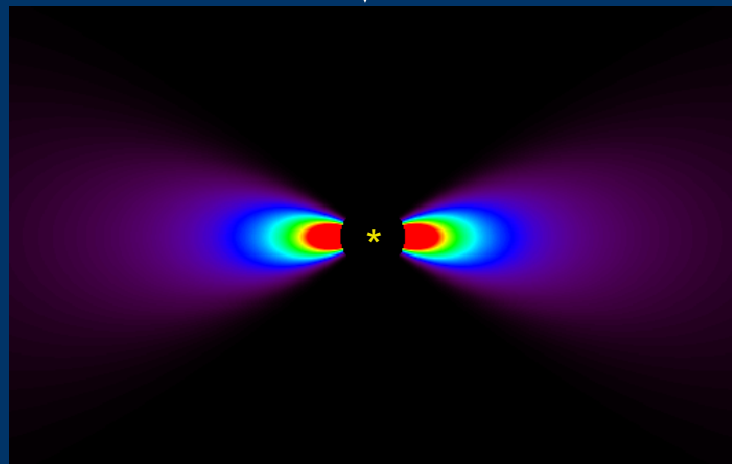


density

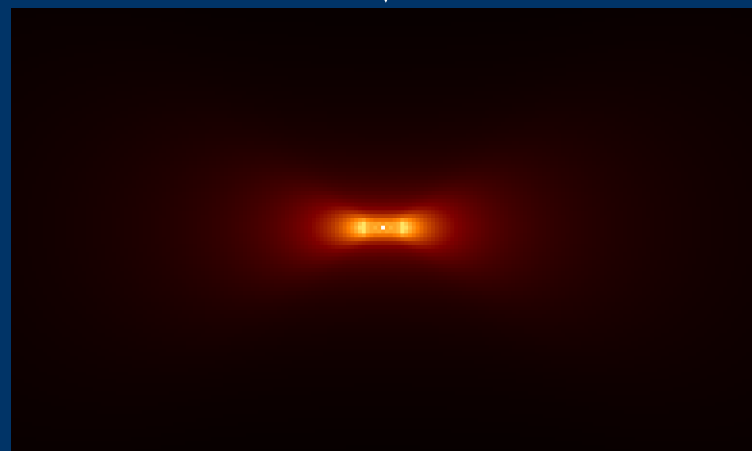
$T_{\text{sub}} = 1500 \text{ K}$



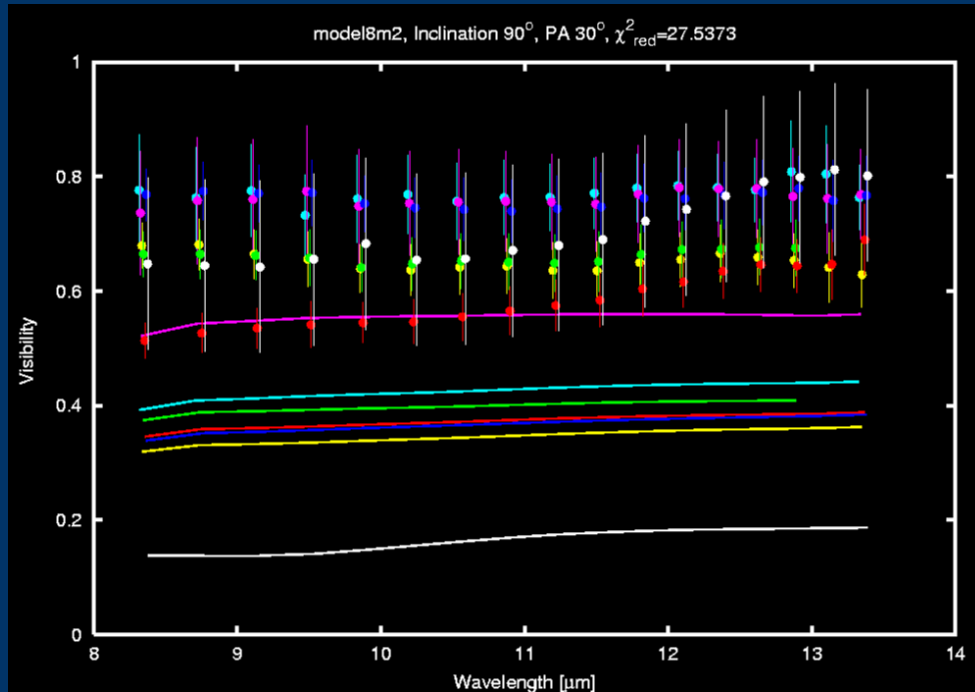
sqrt (intensity)



$T_{\text{sub}} = 2000 \text{ K}$

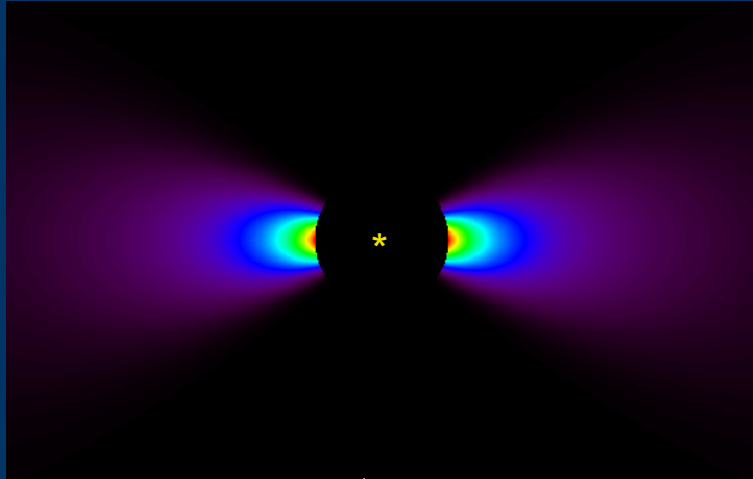


2) Higher sublimation temperature

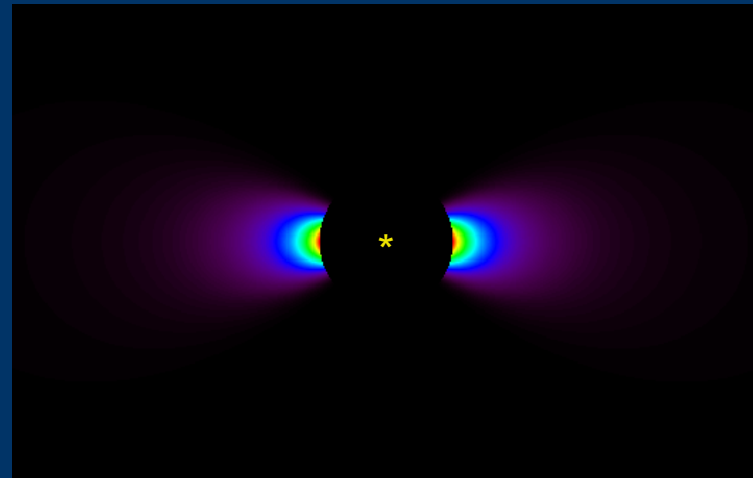


→ model structure is still significantly too large

3) Steeper radial density distribution

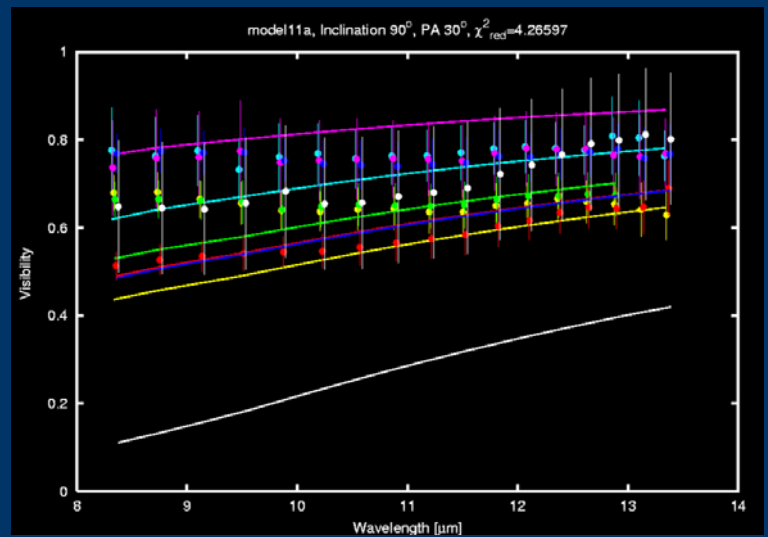
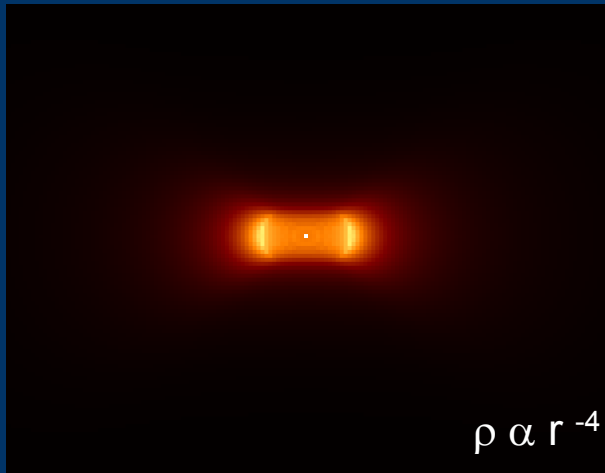
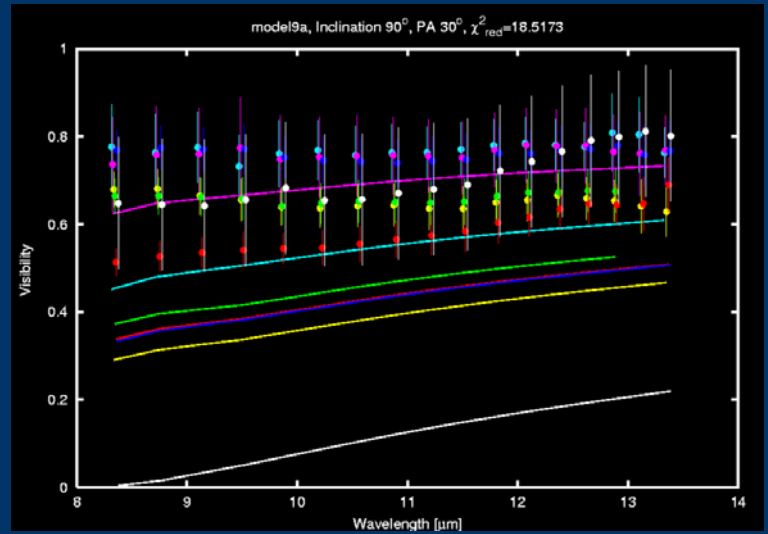
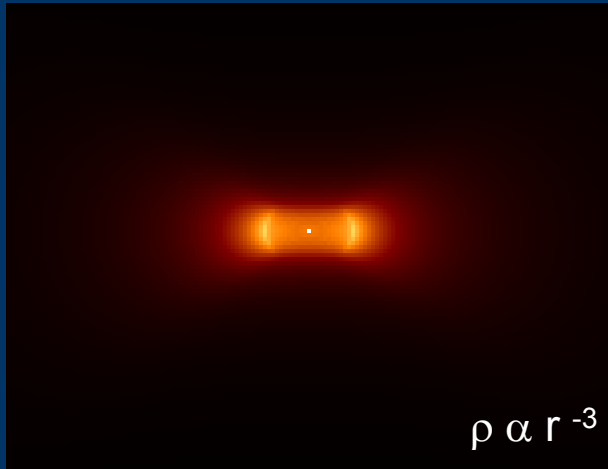


density

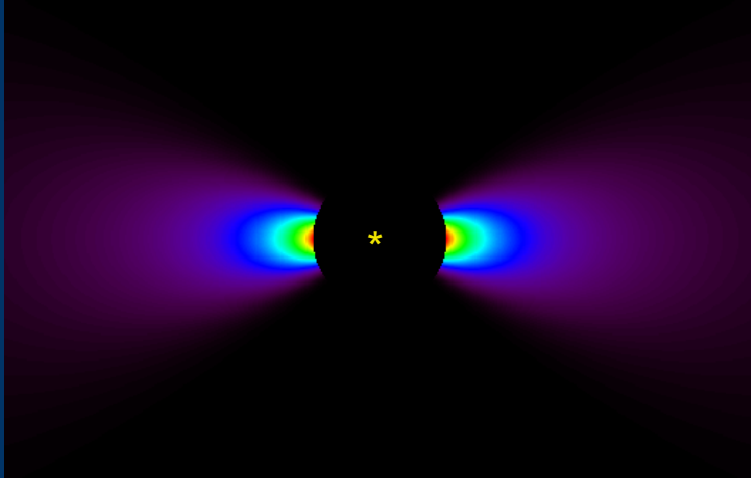


$$\rho_{\text{disk}} = \rho_s \left(\frac{r_s}{r} \right)^{3.3} e^{-\pi/4 \left(z/z_s \left(r_s/r \right)^{9/8} \right)^2}$$

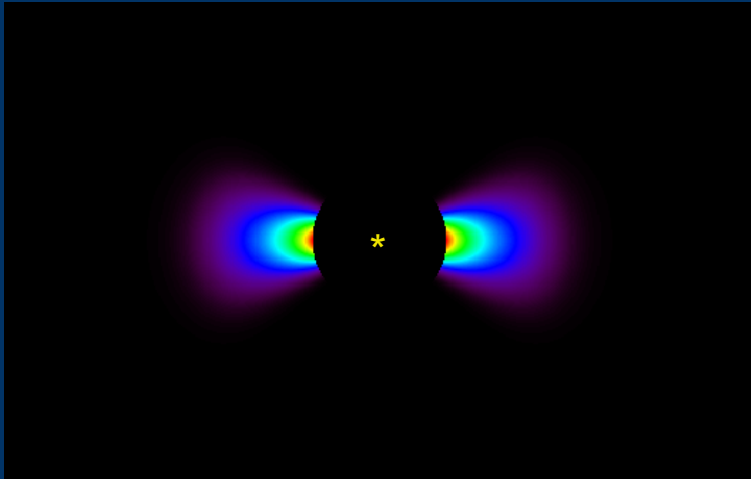
3) Steeper radial density distribution



4) Truncated disk models



density



$$\varrho_{\text{disk}} = \varrho_s \left(\frac{r_s}{r} \right)^{15/8} e^{-\pi/4 \left(z/z_s (r_s/r)^{9/8} \right)^2}$$

Kepler disk



$$\varrho(z, r) = \varrho_{\text{disk}} \left(1 + e^{(r - r_f)/\alpha} \right)^{-1}$$

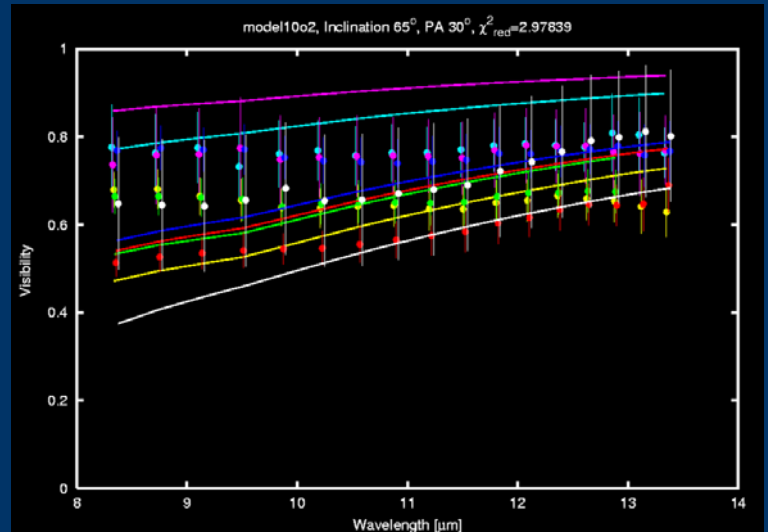
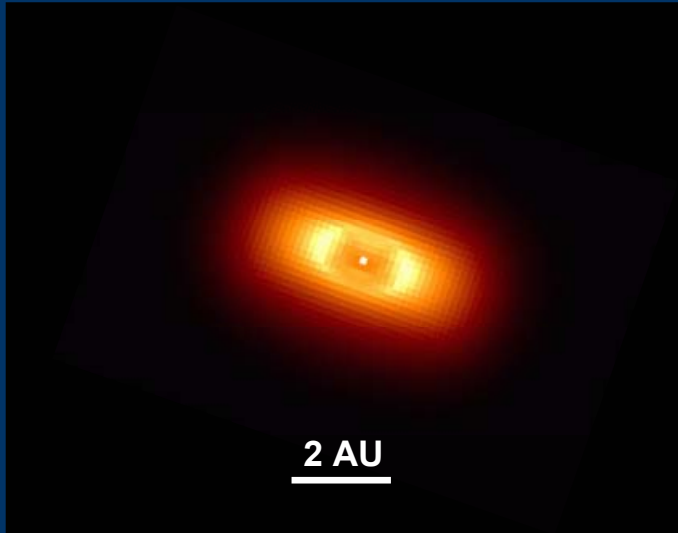
Kepler disk truncated at $r_f = 2.2$ AU

Fitting strategy

Model parameters:

- **thickness of the disk:** $z_s/r_s = [0.1 \dots 0.5]$
- **truncation radius:** $r_f = [1 \dots 20]$ AU
- **inclination angle:** $i = [45 \dots 90]$ deg
- **position angle of disk axis on the sky**
determined with chi-square fit

Preliminary best fit model:



- disk thickness: $z_s/r_s \sim 0.4$
- truncation radius: $r_f \sim 2.6 \text{ AU}$
- inclination angle: $i \sim 65^\circ$
- position angle: $\text{PA} \sim 30^\circ$

Conclusions:

- MIDI resolved the emission from circumstellar material around HR5999
- Spatial extent of the warm dust is very compact ($< \sim 2.5$ AU) considerably smaller than most Herbig AeBe stars, but similar to 51 Oph (Leinert et al. 2004)
- Structure is elongated
- (Preliminary) best fit to the data is found for a moderately thick truncated disk seen at inclination of $\sim 65^\circ$