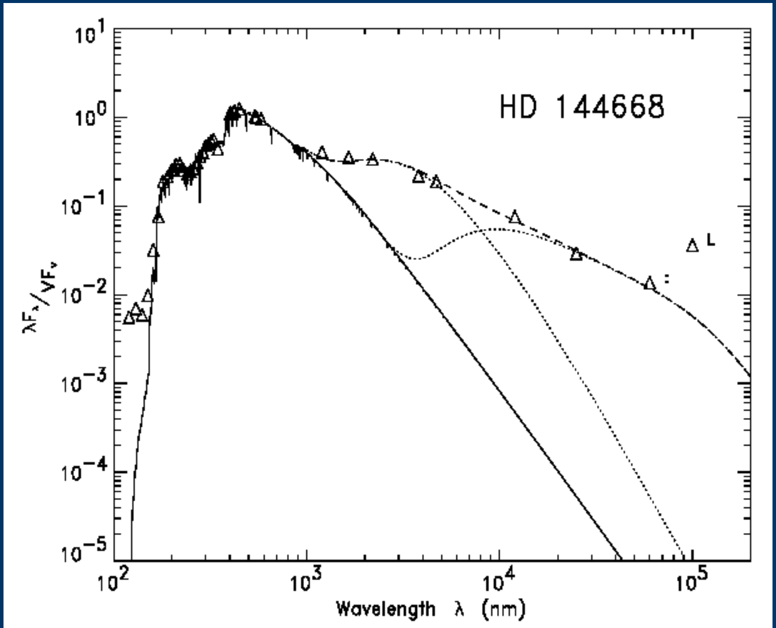
MIDI Observations of the Herbig Ae Star HR 5999

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

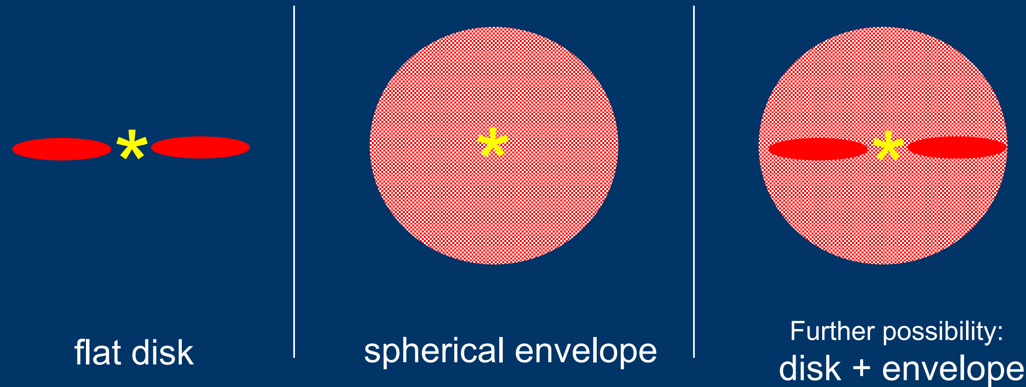
$M \sim 2 - 10\ M_{sun,}$ age ~ 0.1 – 5 Myr



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**

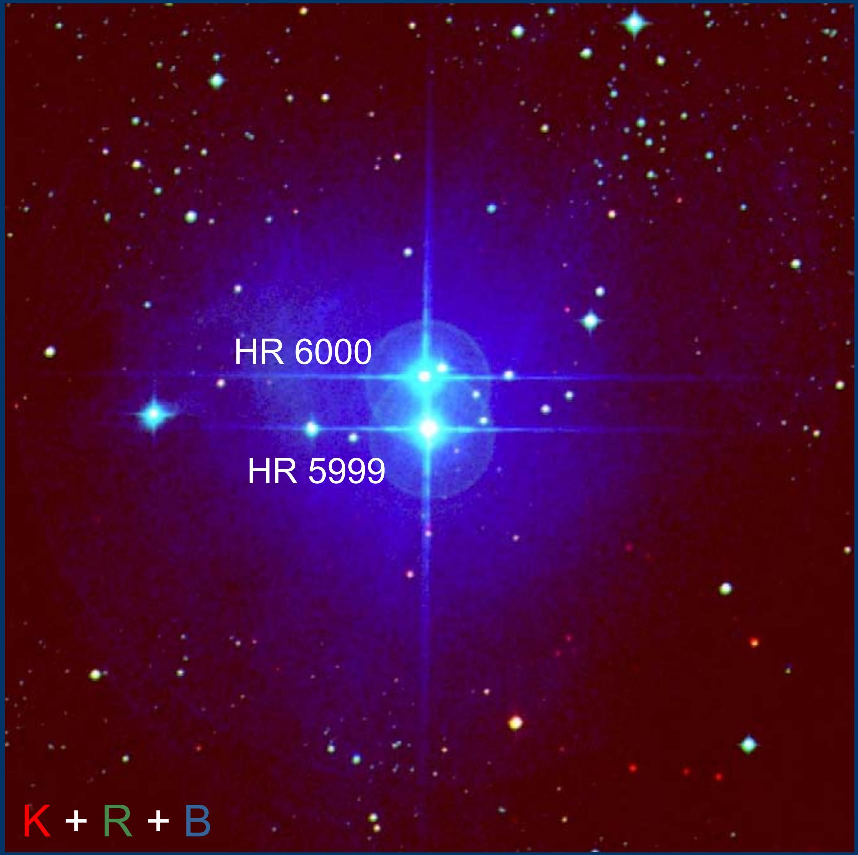
→ ***information on source sizes***

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_{bol} = 100 L_o , A_V = 0.5 mag

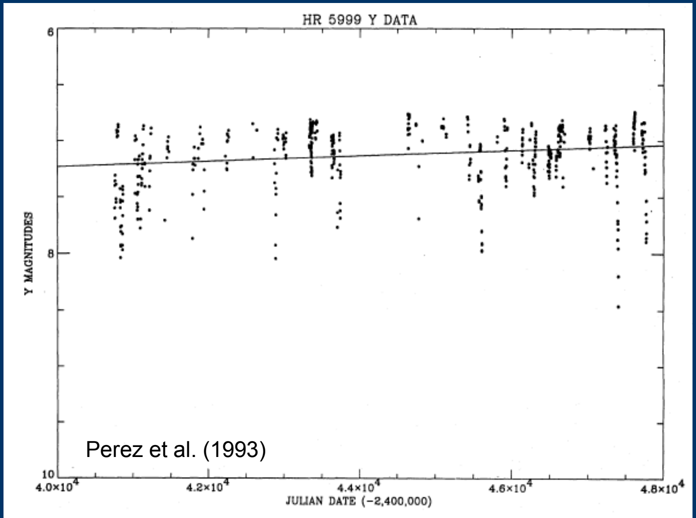
M = 3.9 M_o , age = 0.5 Myr

v sin i = 180 km/sec

Infrared excess:
circumstellar mass ~ 0.01 M_o

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

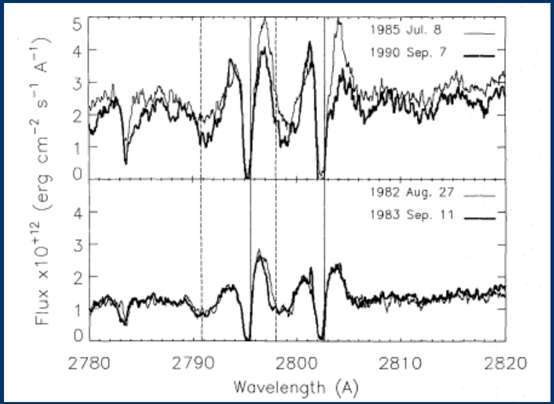
Evidence for circumstellar disk:



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
- $v_{accretion}$ ~ 300 km/sec
- dM/dt ~ 7 x 10^{-7} M_o/yr

HR 5999 has a visual companion (Rossiter 3930)

separation = 1.5 arcsec
ΔV = 4.6 mag, ΔK = 3.6 mag

Dynamic disk clearing
by binary interaction:

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

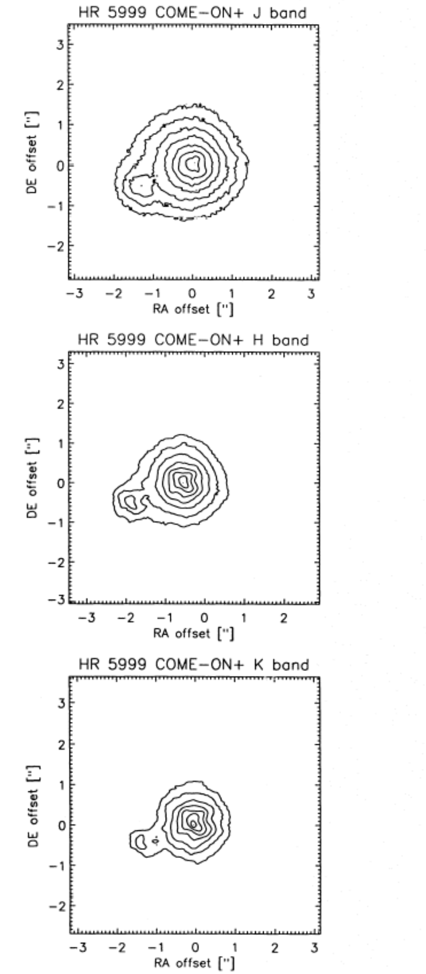
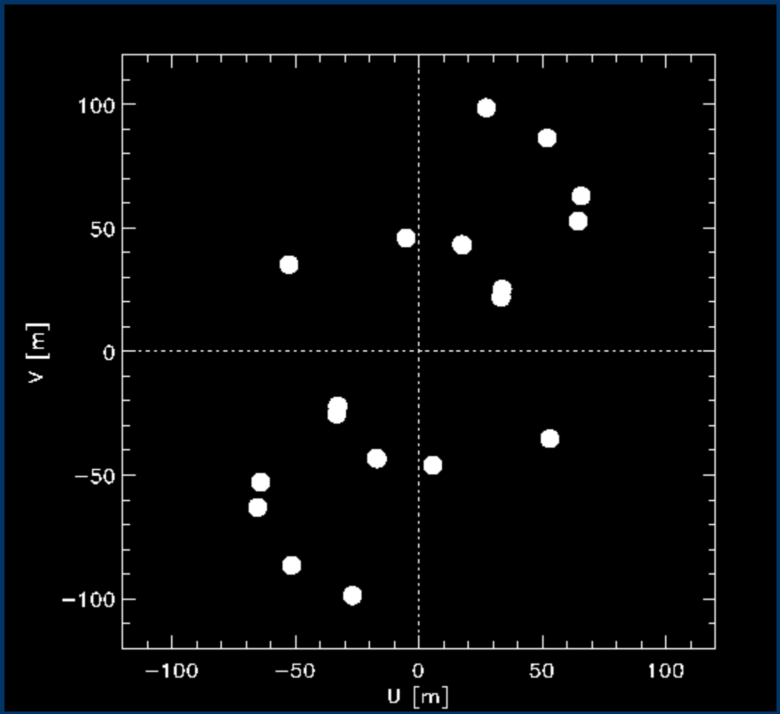


Fig. 2. Contour plots of the COME-ON+ JHK images. Levels increase from 1% to 64% of the peak intensity by the factor of two

Stecklum et al. (1995, A&A 296, 463)

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

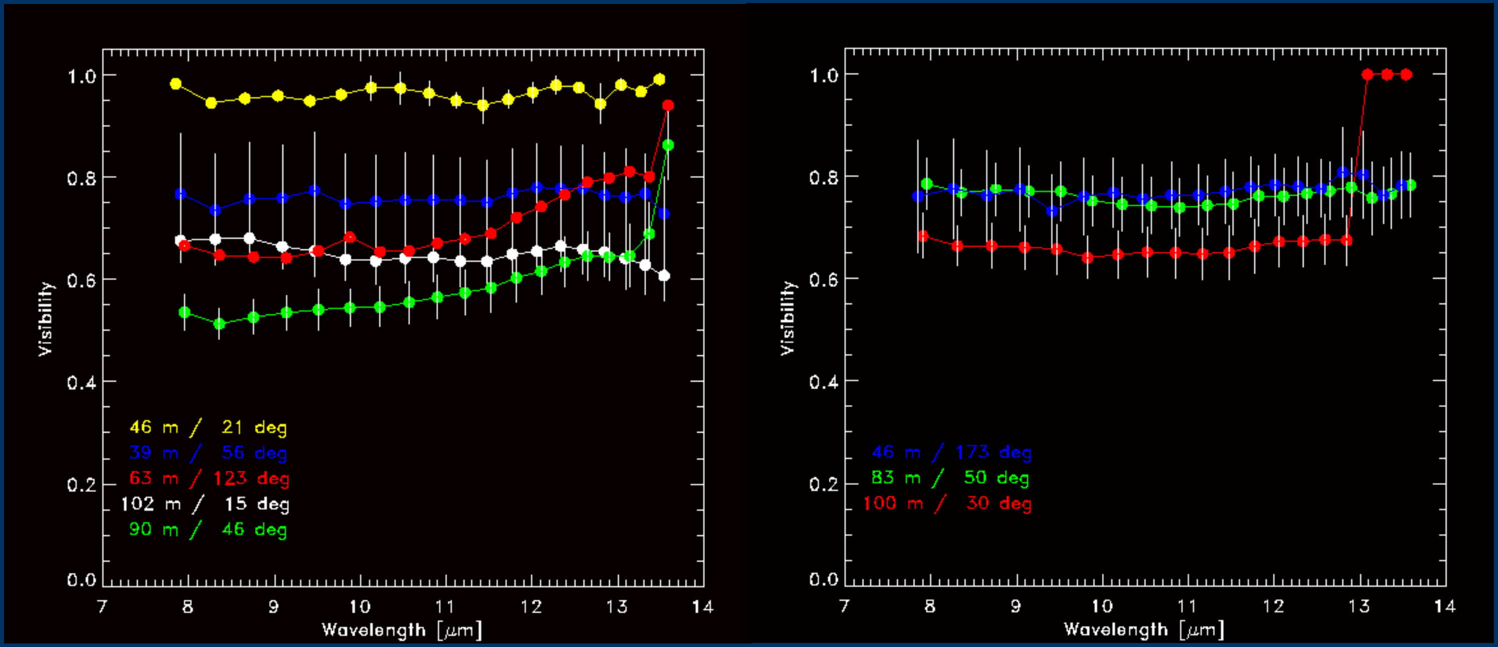
resolution @ 10 μm:

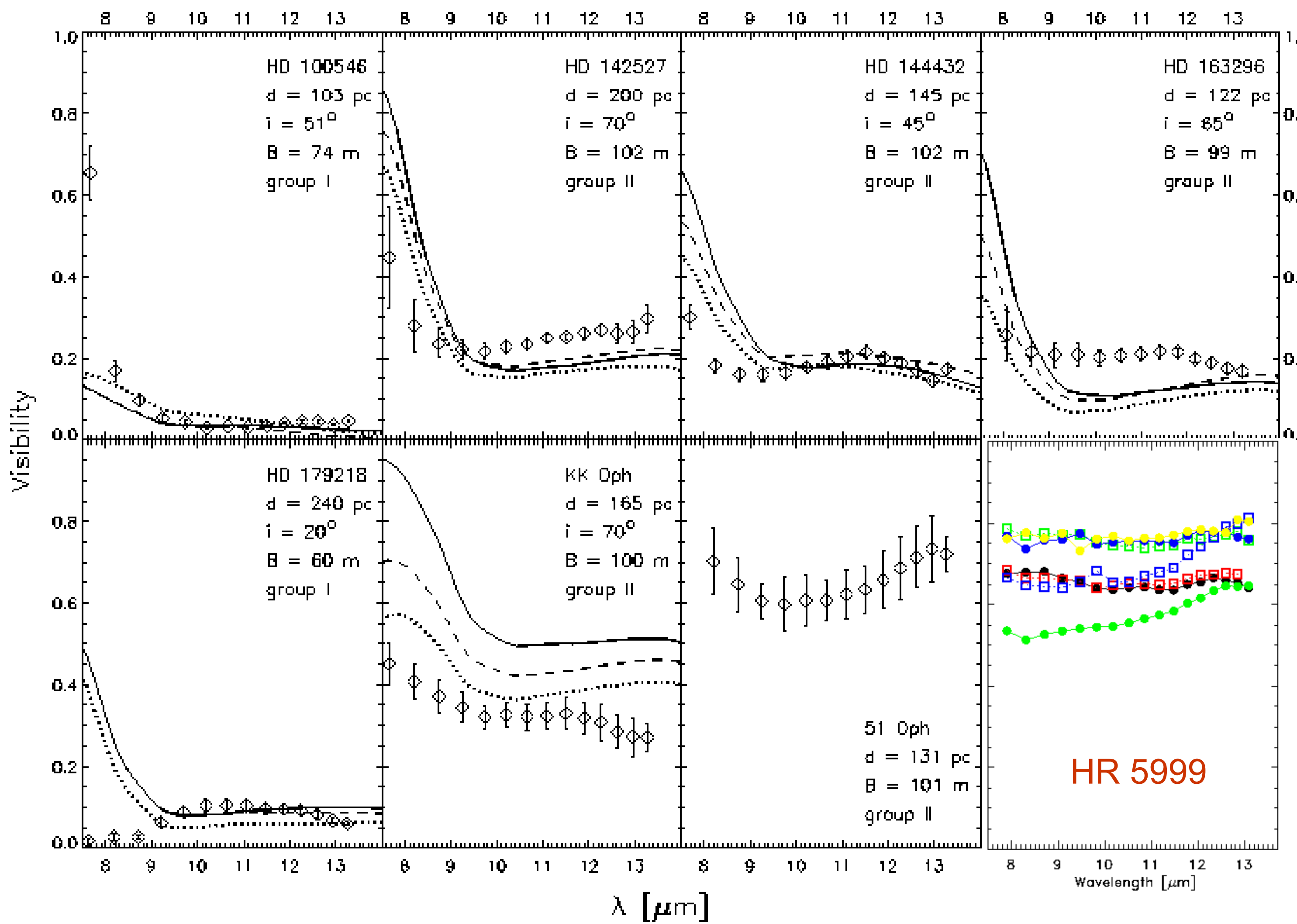
10 AU ... 4 AU

Position angles:

15^o .... 173^o

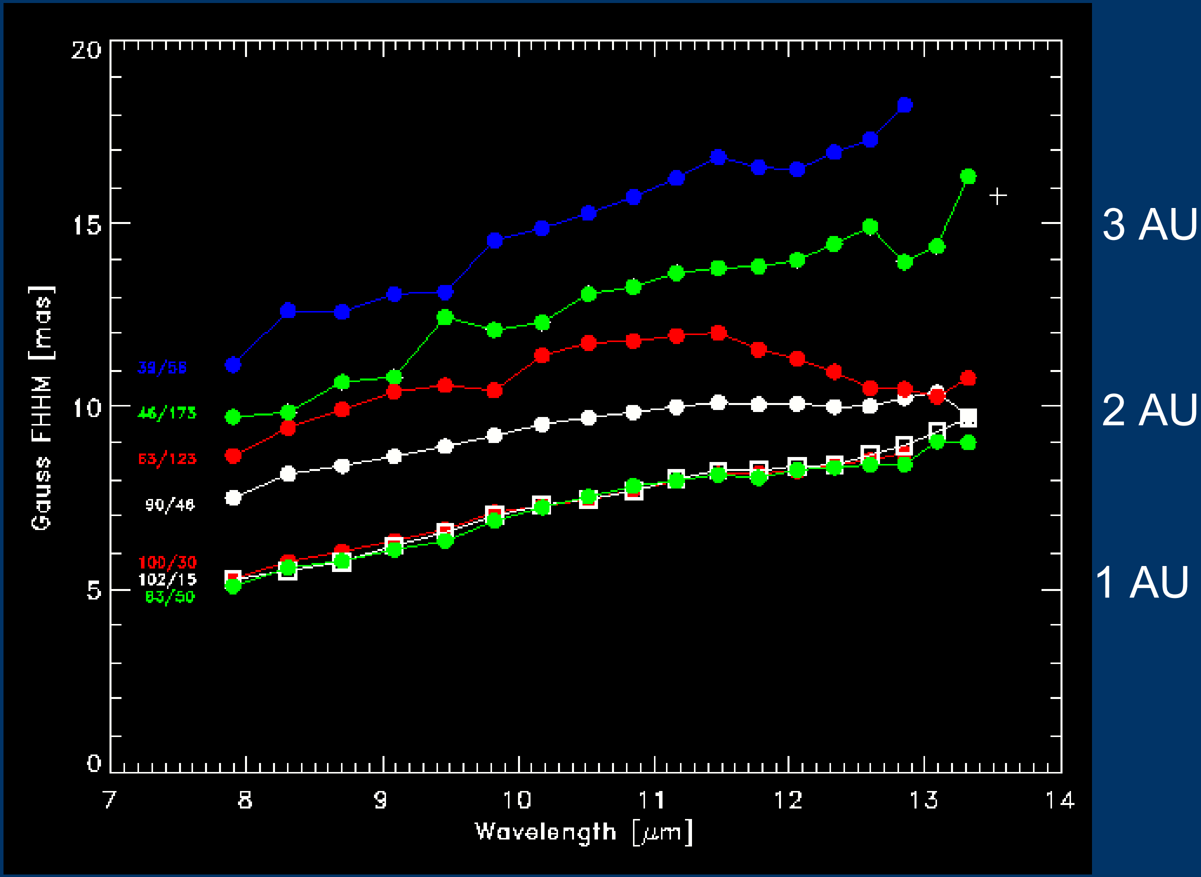
MIDI visibilities of HR 5999:





HD 100546
d = 103 pc
i = 51°
B = 74 m
group I
HD 142527
d = 200 pc
i = 70°
B = 102 m
group II
HD 144432
d = 145 pc
i = 45°
B = 102 m
group II
HD 163296
d = 122 pc
i = 65°
B = 99 m
group II
HD 179218
d = 240 pc
i = 20°
B = 60 m
group I
KK Oph
d = 165 pc
i = 70°
B = 100 m
group II
51 Oph
d = 131 pc
B = 101 m
group II
HR 5999
Visibility
λ [μm]
Wavelength [μm]

Characteristic size: Gauss fits



- size increases with wavelength → extended dust emission
- very compact structure (~1 – 3 AU)

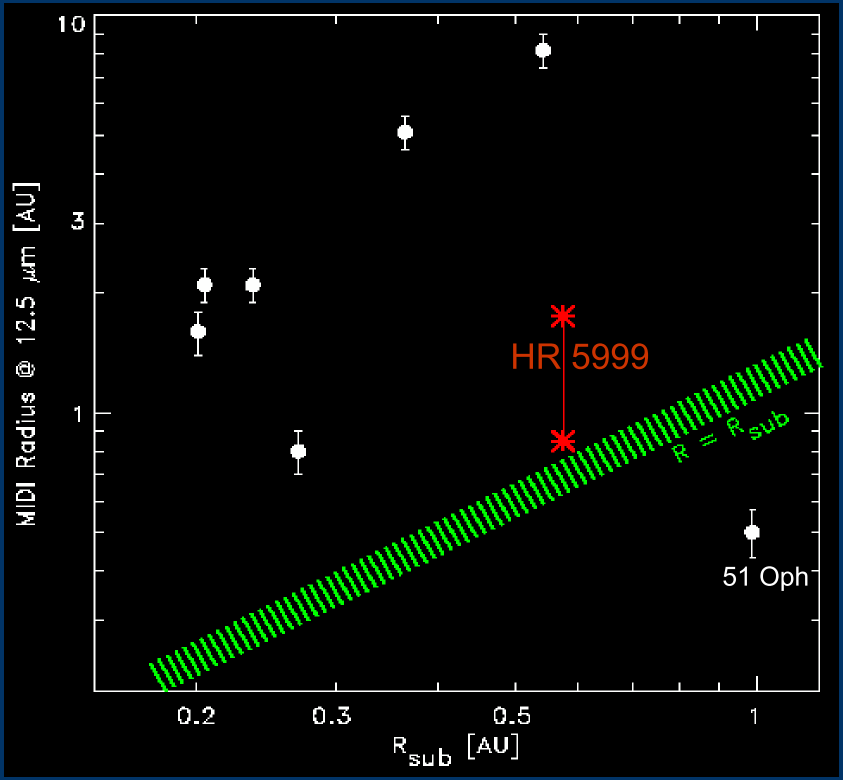
Expected dust sublimation radius for HR 5999:

L_{bol} = 100 L_o , T_{eff} = 8000 K, T_{sub} = 1500 K

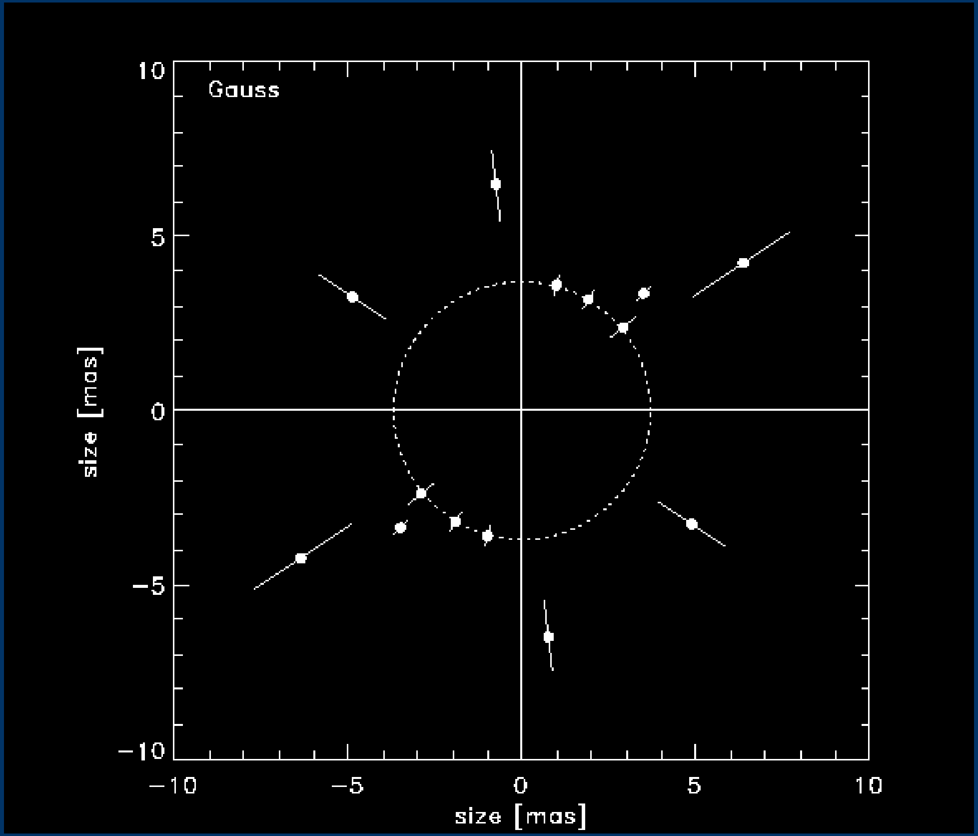
→ R_{sub} ~ 0.5 – 1 AU   Gauss fit radii: ~ 0.8 – 1.7 AU

Observed sizes and theoretical sublimation radii for Herbig stars

- Objects from Leinert et al. (2004)

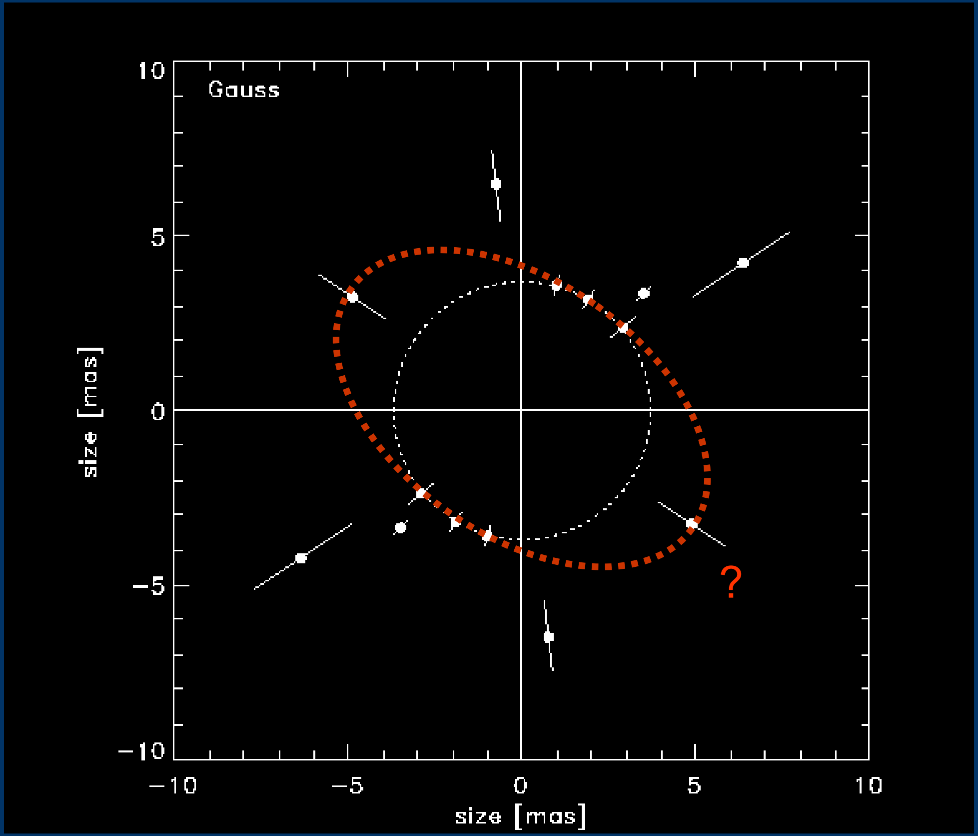


Gauss fit size as a function of position angle:



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

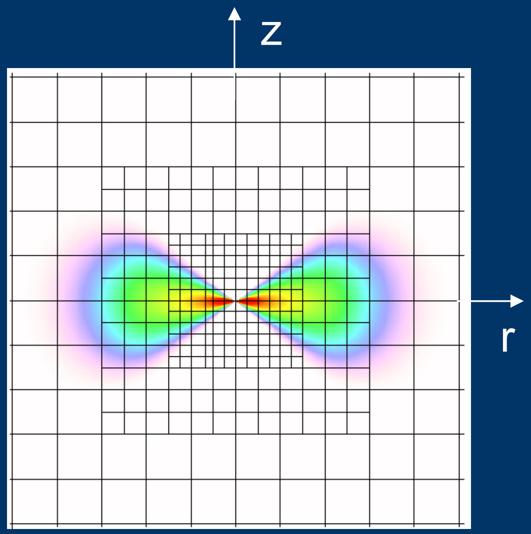
Radiative transfer simulations

Code from Sonnhalter, Preibisch, Yorke (1995):

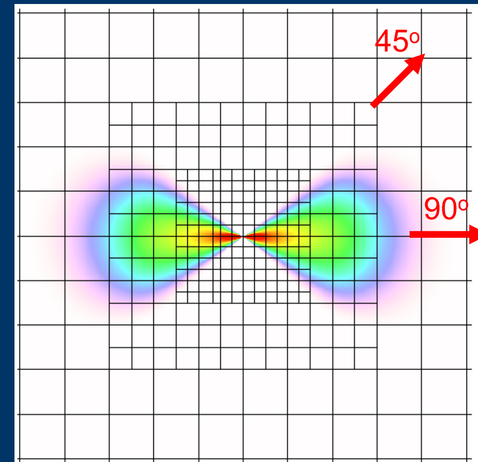
- 2D, frequency dependent, nested grids
- INPUT: density distribution + radiation source
- dust model: Silicate + Carbon grains

  ice mantles for T < 150 K
- self consistent, iterative determination of radiation field and dust temperatures

  (→ dust sublimation radius)
- RAY TRACING: → images + spectra

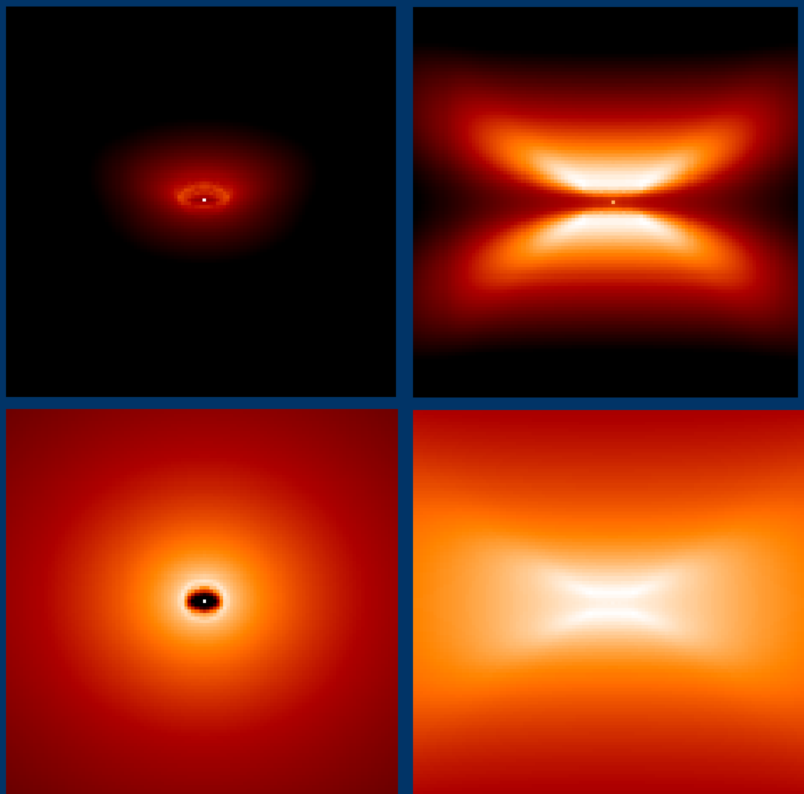


Density distribution
+ computational grid



Simulated images:

log (intensity)



J-band
(1 μm)

N-band
(10 μm)

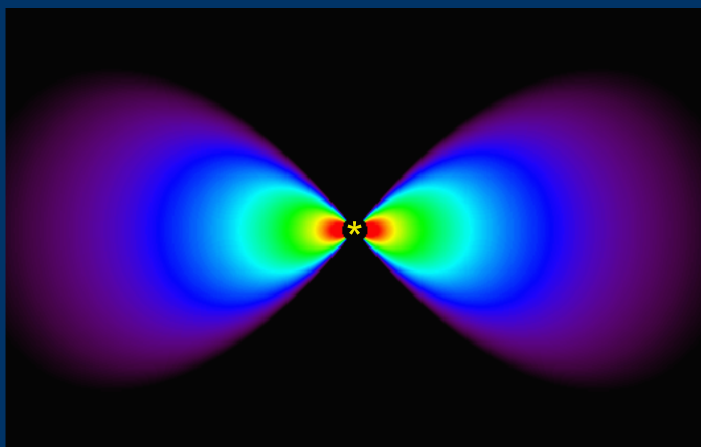
i = 45 degr   i = 90 degr

1) Keplerian disk models

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

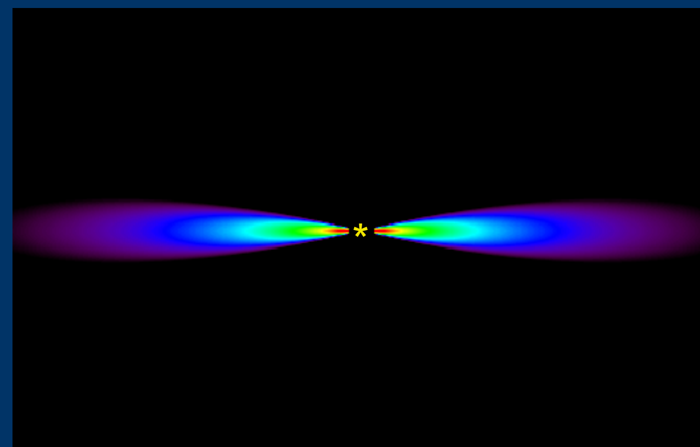
log (density)

$z_s/r_s = 0.4$



← 50 AU →

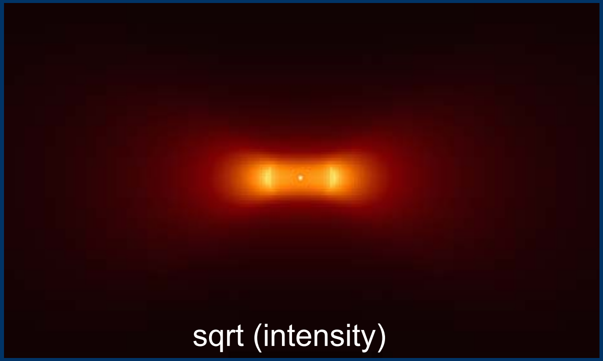
$z_s/r_s = 0.1$

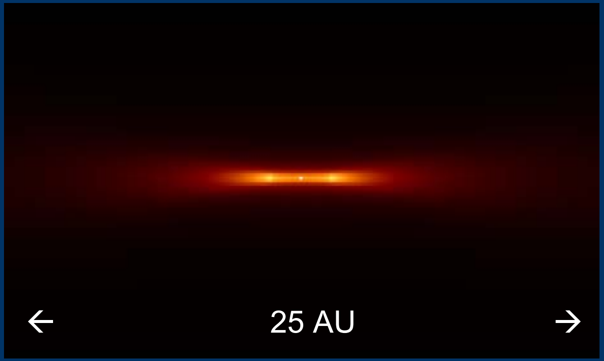


Keplerian disk models

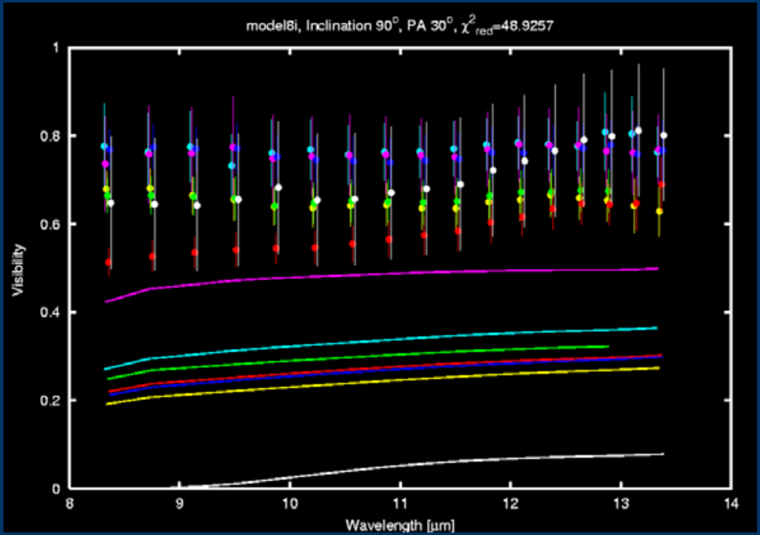
simulated images

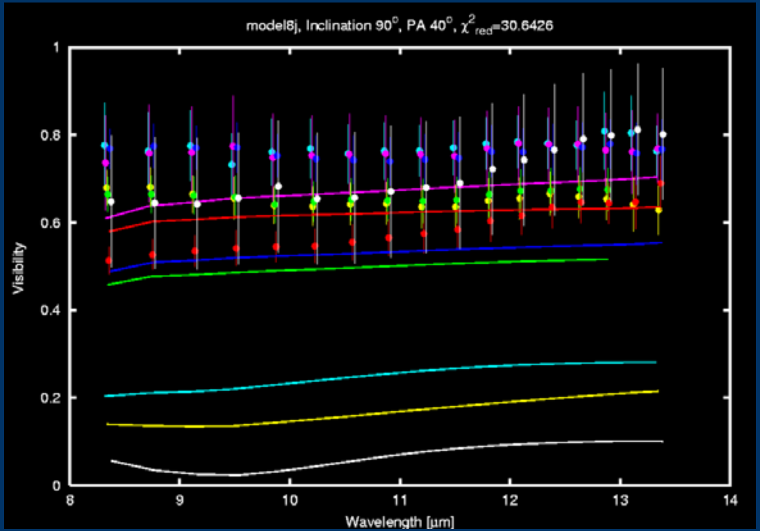
i = 90°





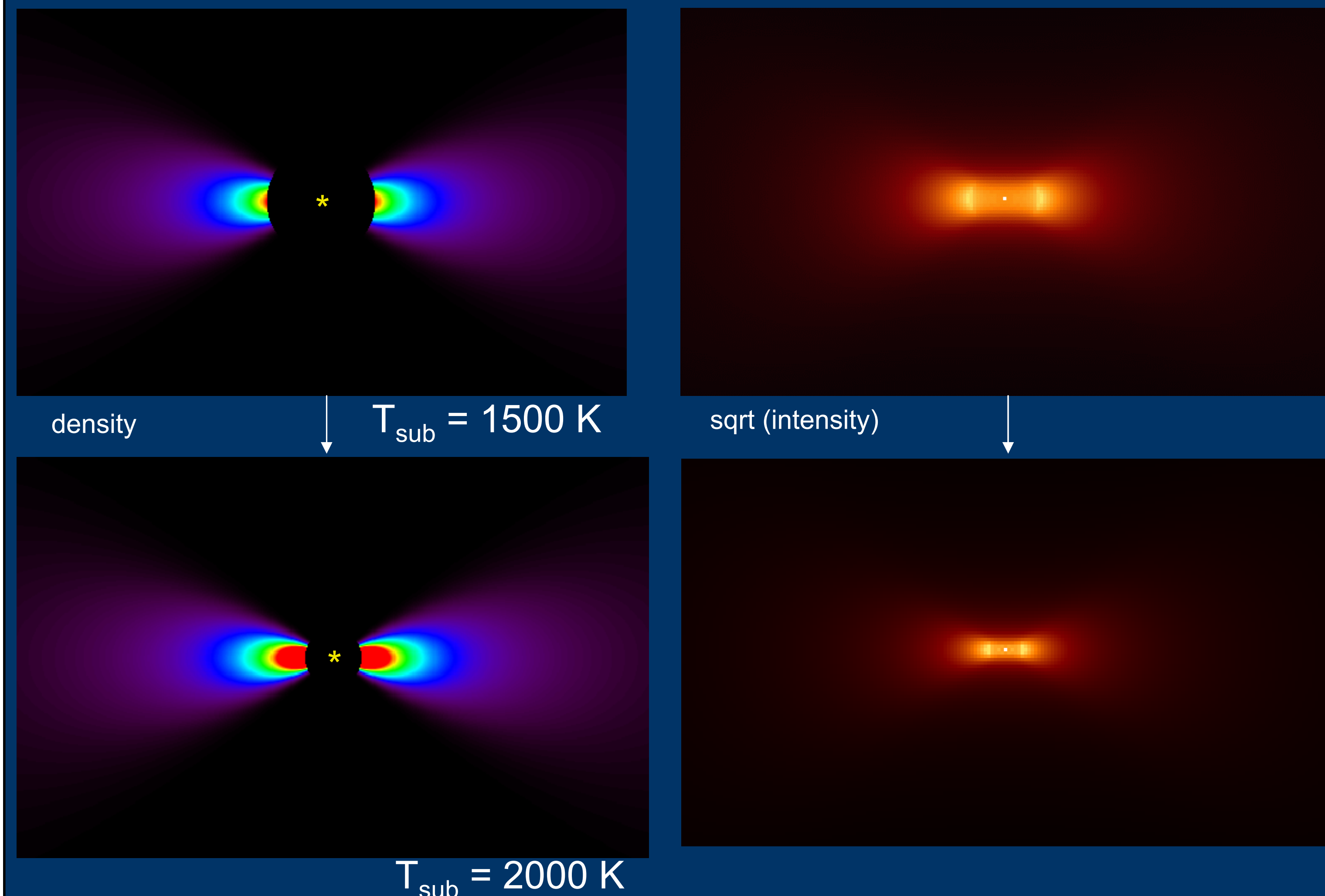
Model predictions compared to observed visibilities:



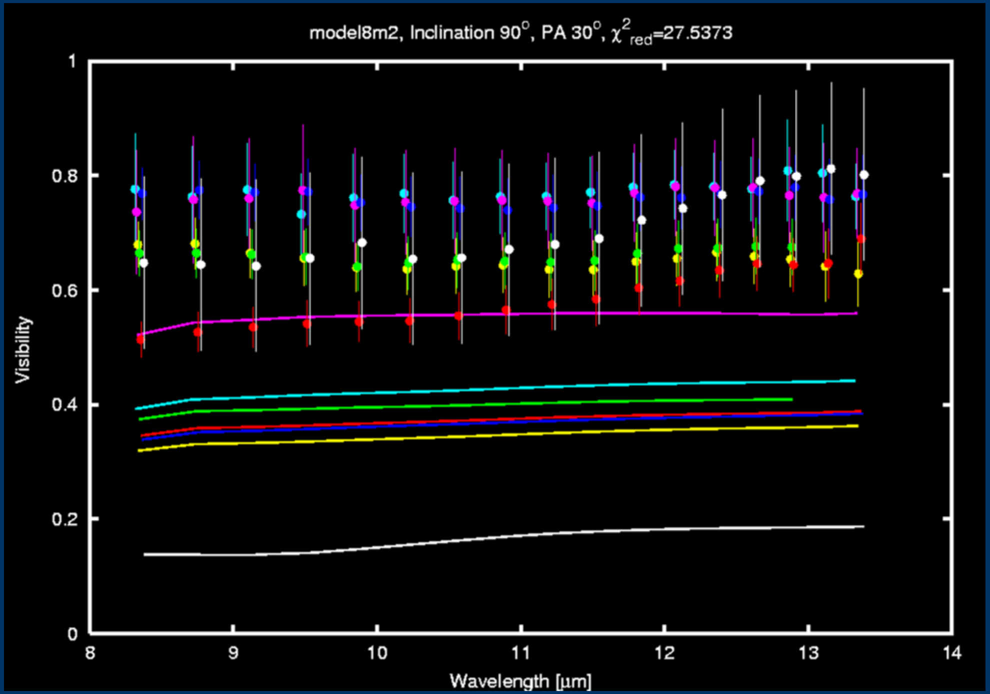


Simulated structure is several times too large

2) Higher sublimation temperature

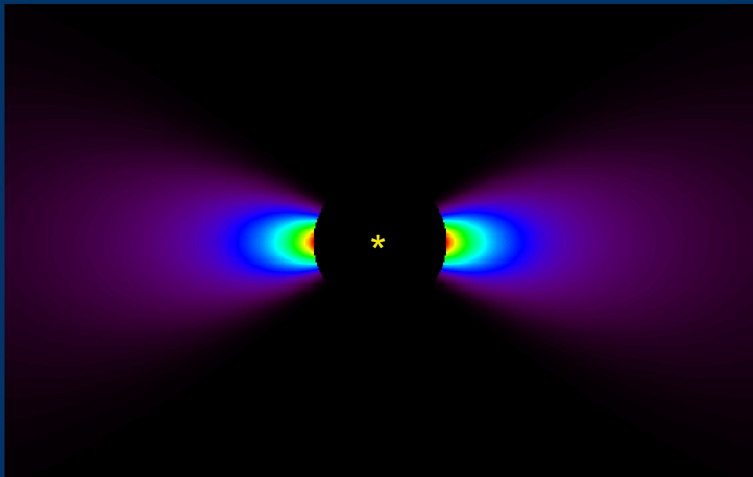


2) Higher sublimation temperature

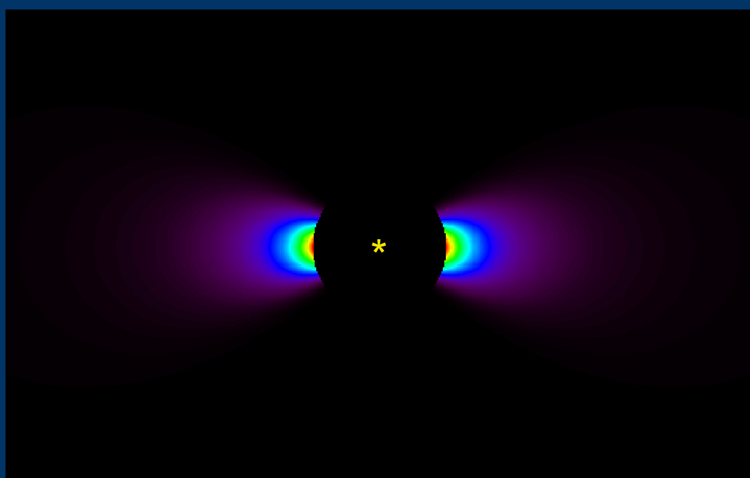


→ model structure is still significantly too large

3) Steeper radial density distribution

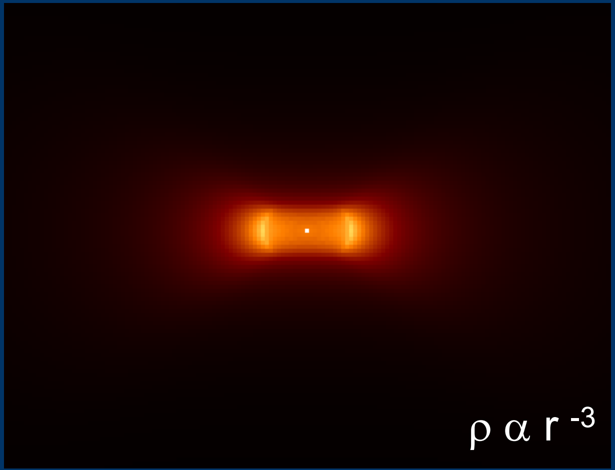


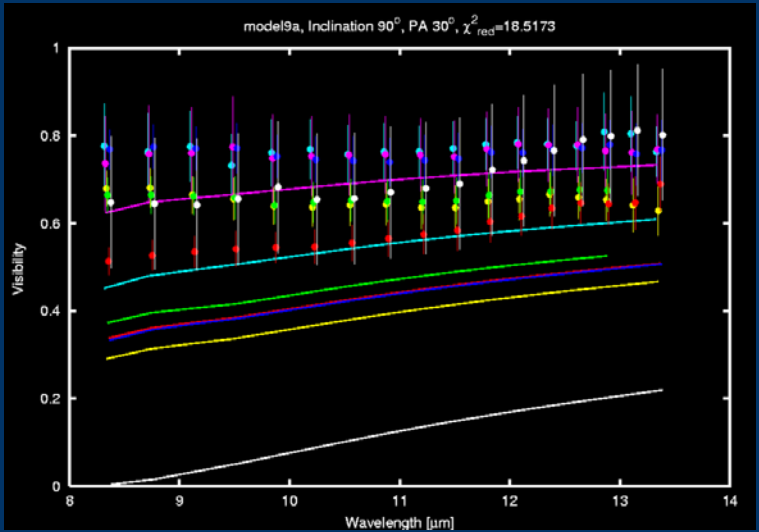
density

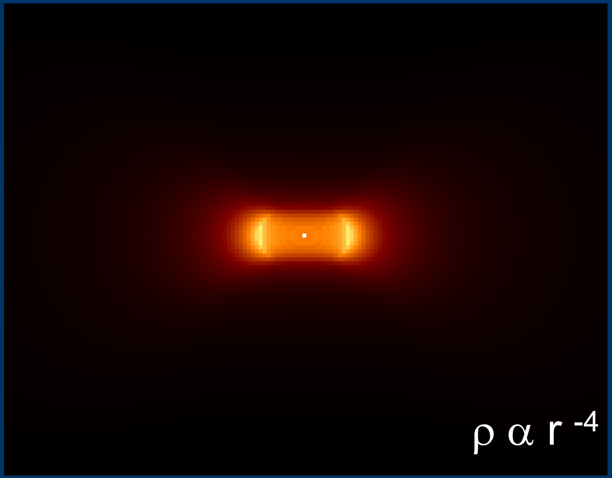


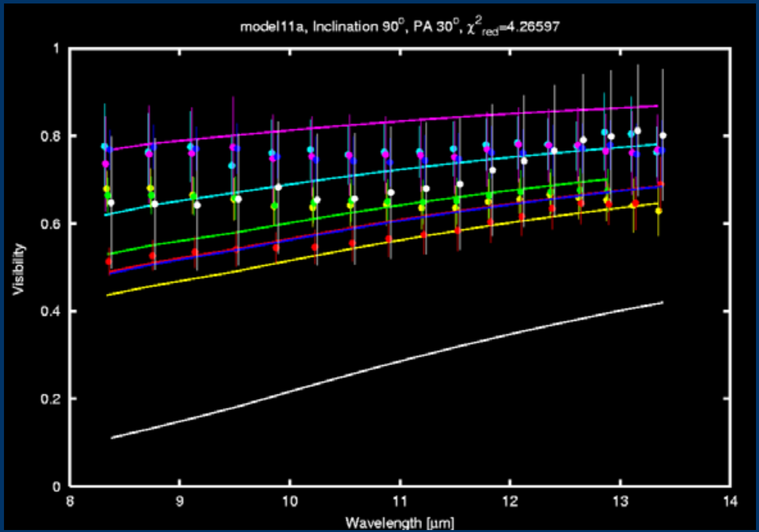
$$\varrho_{\rm disk} = \varrho_s \left(\frac{r_s}{r}\right)^{\not{2}\ 3} e^{-\pi/4 \left(z/z_s \left(r_s/r\right)^{9/8}\right)^2}$$

3) Steeper radial density distribution

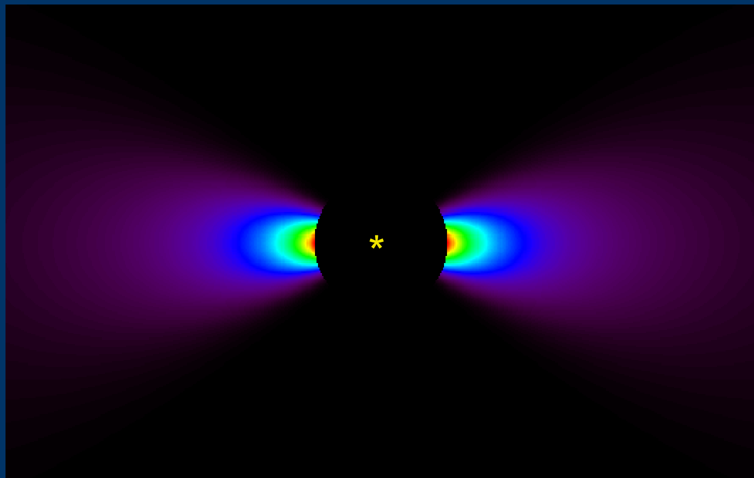








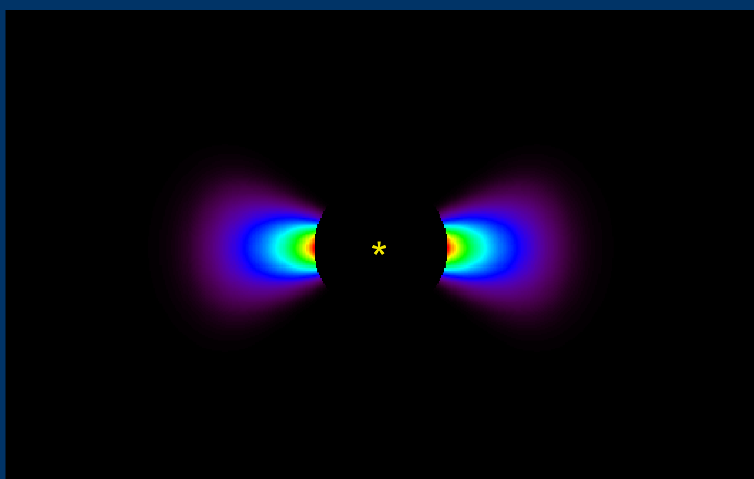
4) Truncated disk models



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

Kepler disk

density



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

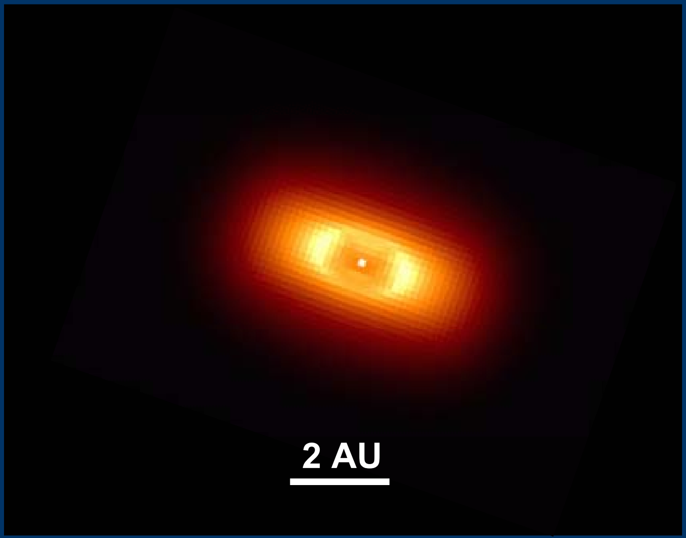
Kepler disk truncated at r_f = 2.2 AU

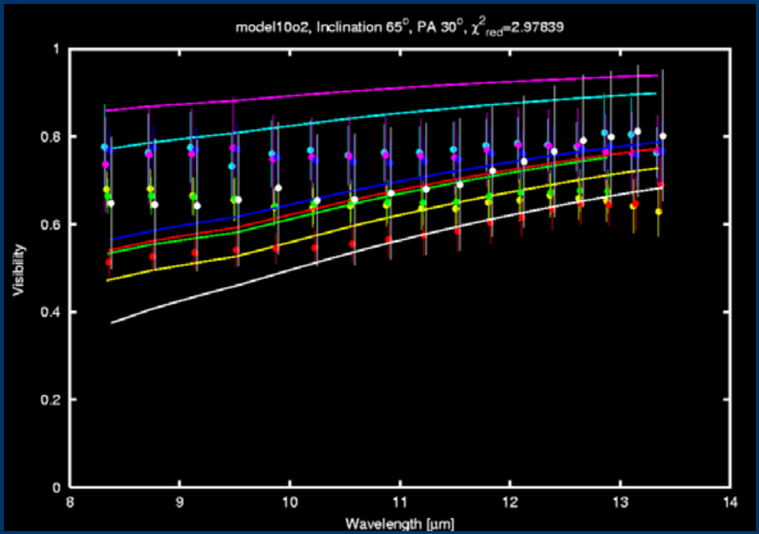
Fitting strategy

Model parameters:

- **thickness of the disk**: z_s/r_s = [0.1 ... 0.5]
- **truncation radius**: r_f = [1 ... 20] AU
- **inclination angle**: i = [45 ... 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: $r_f \sim 2.6$ AU
- inclination angle: $i \sim 65^o$
- position angle: PA $\sim 30^o$

Conclusions:

- MIDI resolved the emission from circumstellar material around HR5999

- Spatial extent of the warm dust is very compact (<~ 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 ~ 65^{o}