The innermost circumstellar environment of massive young stellar objects revealed by infrared interferometry

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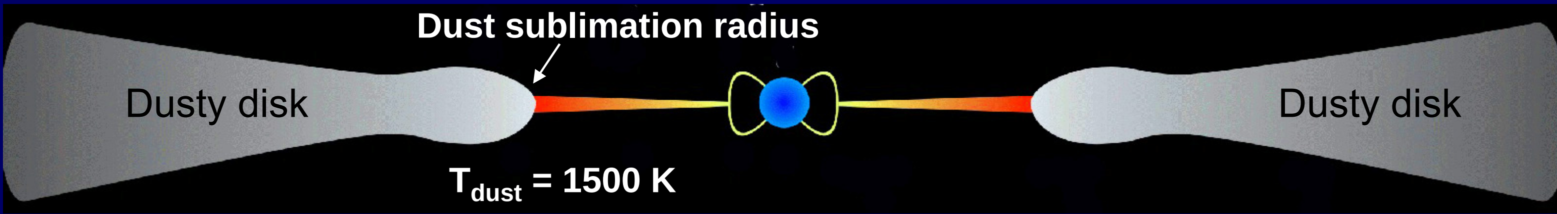
Artists view: www.owlnet.rice.edu/~seli/

The inner circumstellar regions of young stellar objects



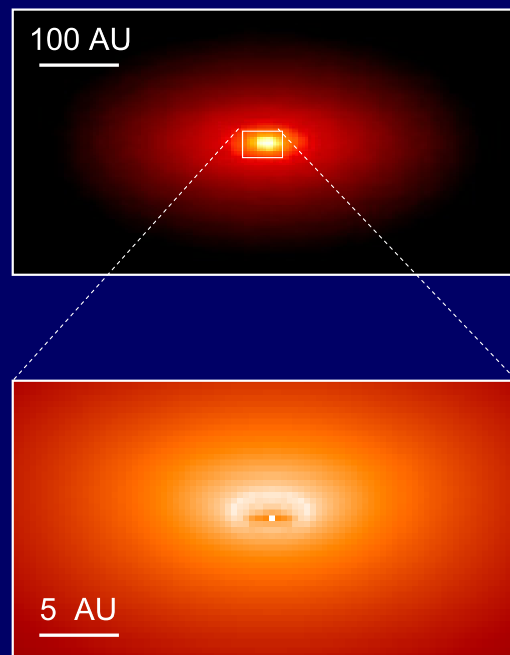
solar-mass star: $R_{sub} \sim 0.1$ AU, 18 $M_{\odot}$ star: $R_{sub} \sim 10$ AU ~ 270 $R_{\star}$

Spatial resolution at D = 500 pc:

- **HST, Adaptive Optics, Speckle**:

  mirror Ø ≤ 8 m

  NIR resolution ~ 0.05 arcsec = **25 AU**

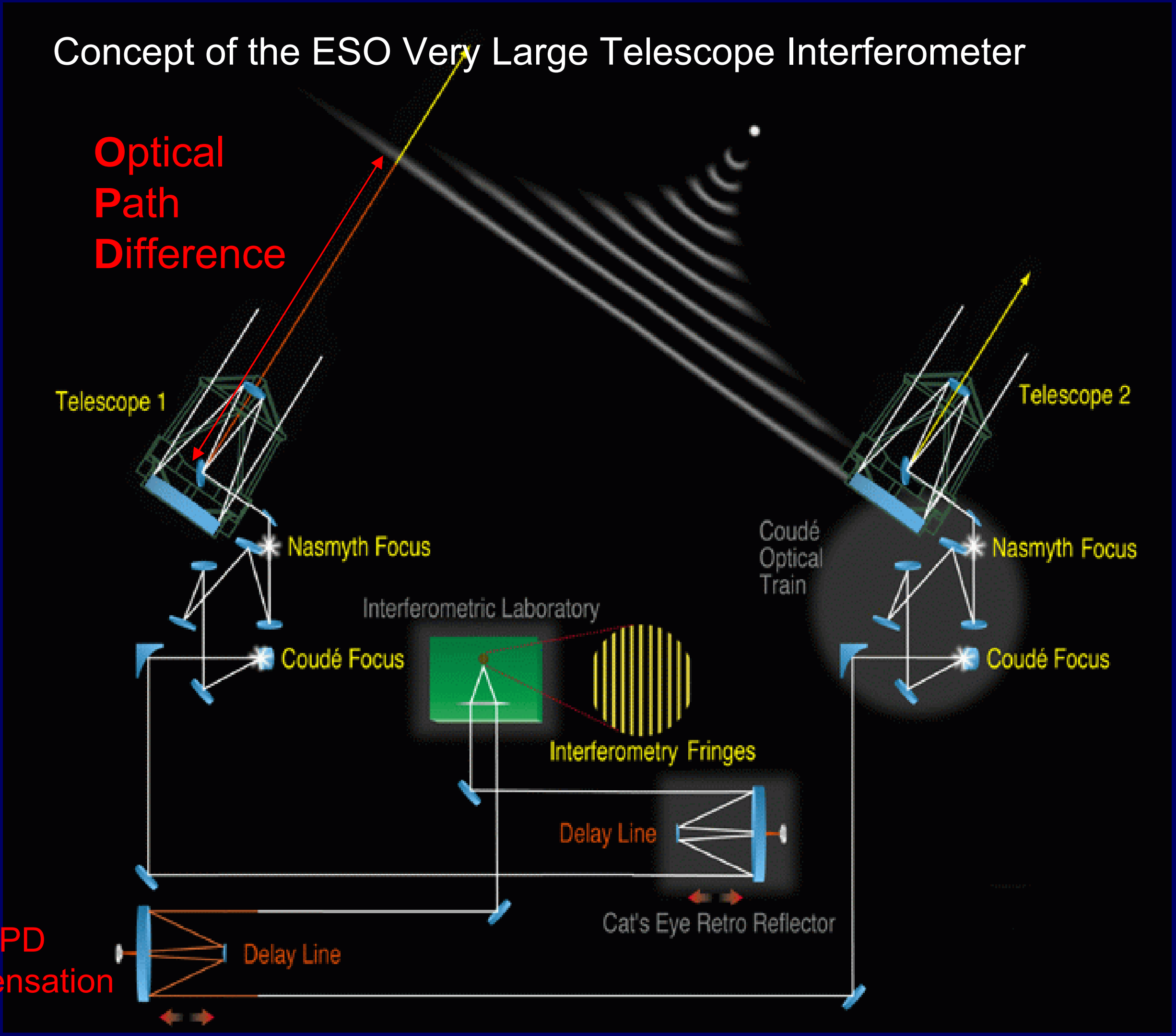


- **Long-Baseline Interferometry:**

  B ≤ 200 m

  NIR resolution ~ 2 mas = **1 AU**

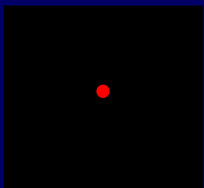
Long Baseline Interferometry

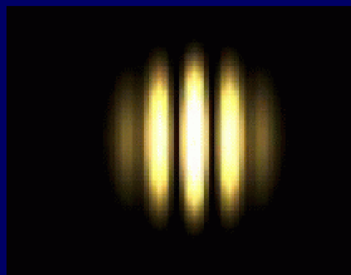


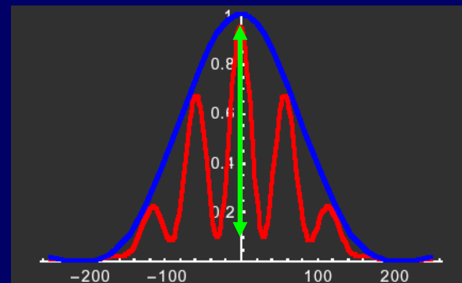
Visibility := contrast of the fringe system

- point source: Ø << λ/B — 100% contrast — Visibility = 1 — unresolved

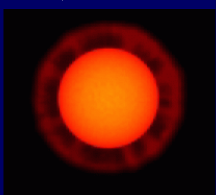
- "small" source Ø < λ/B — high contrast — high Visibility — marg. resolved

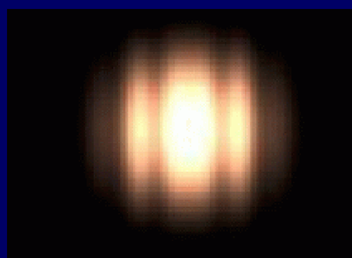


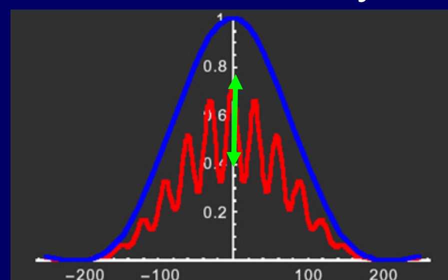




- "large" source Ø ~ λ/B — low contrast — low Visibility — resolved

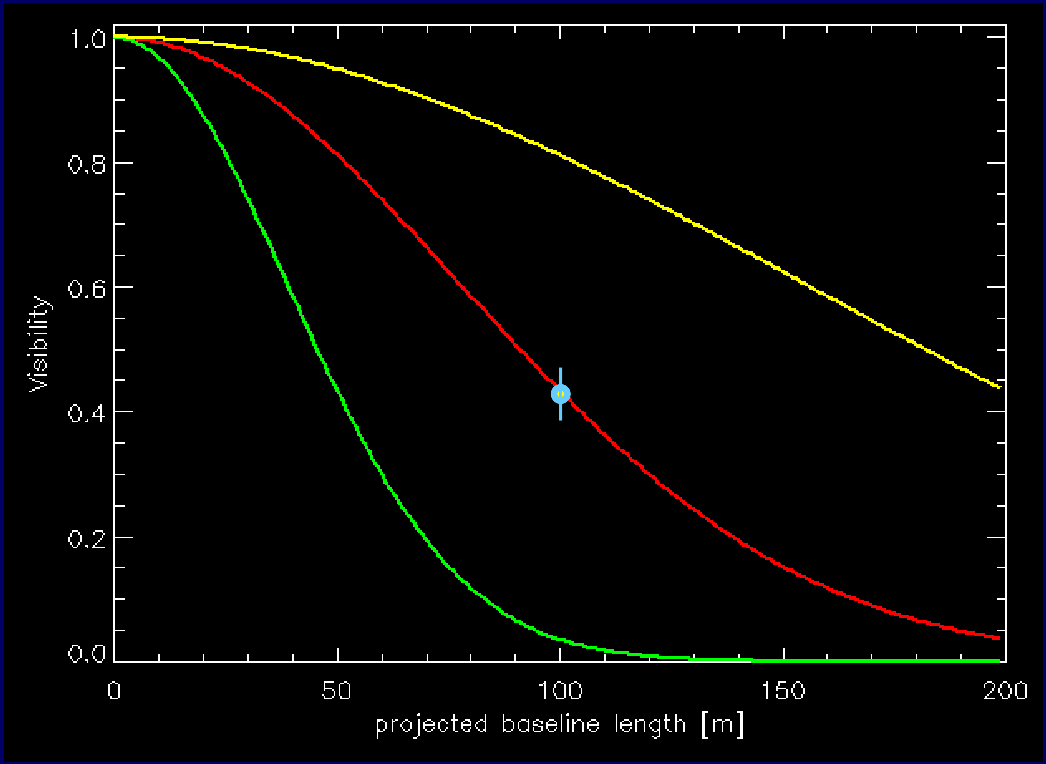






- extended source: Ø >> λ/B — 0% contrast — Visibility = 0 — over-resolved

Visibility as function of object size and baseline length

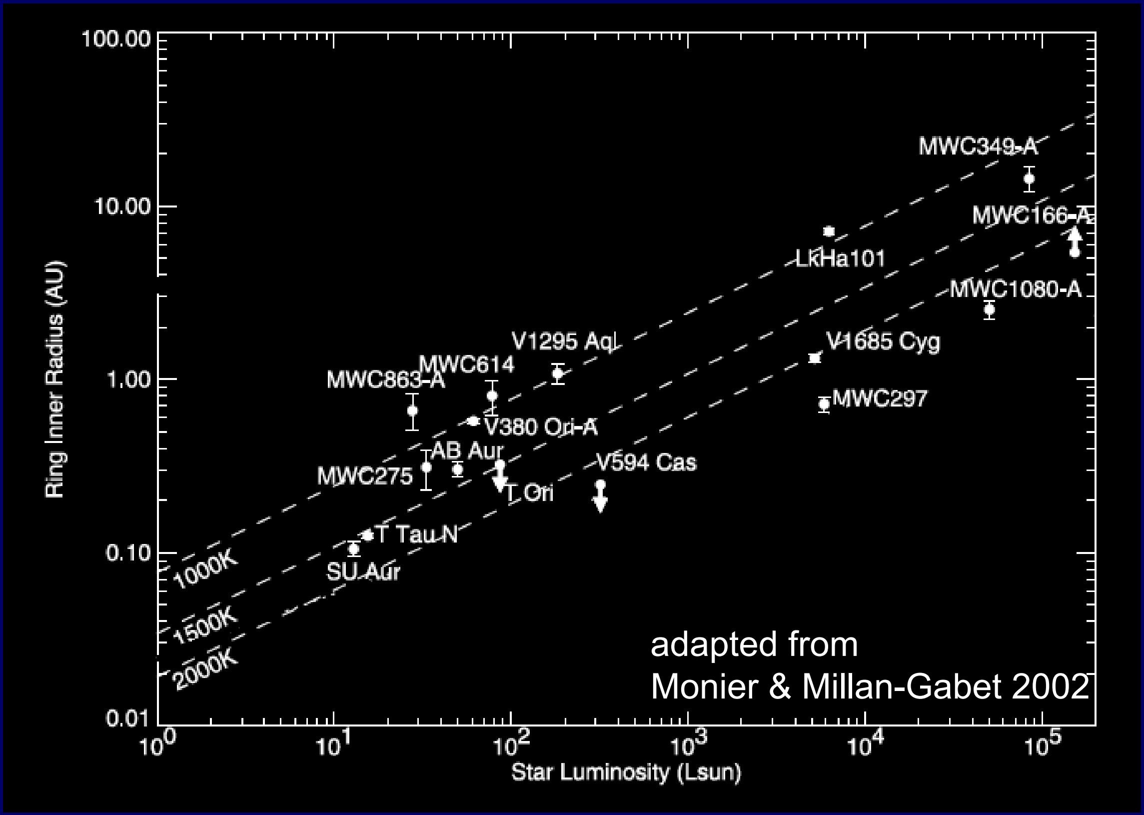


Gauss models

FWHM =
5, 10, 20 mas

V = 0.42 @ B = 100 m → Gauss Ø = 10 mas

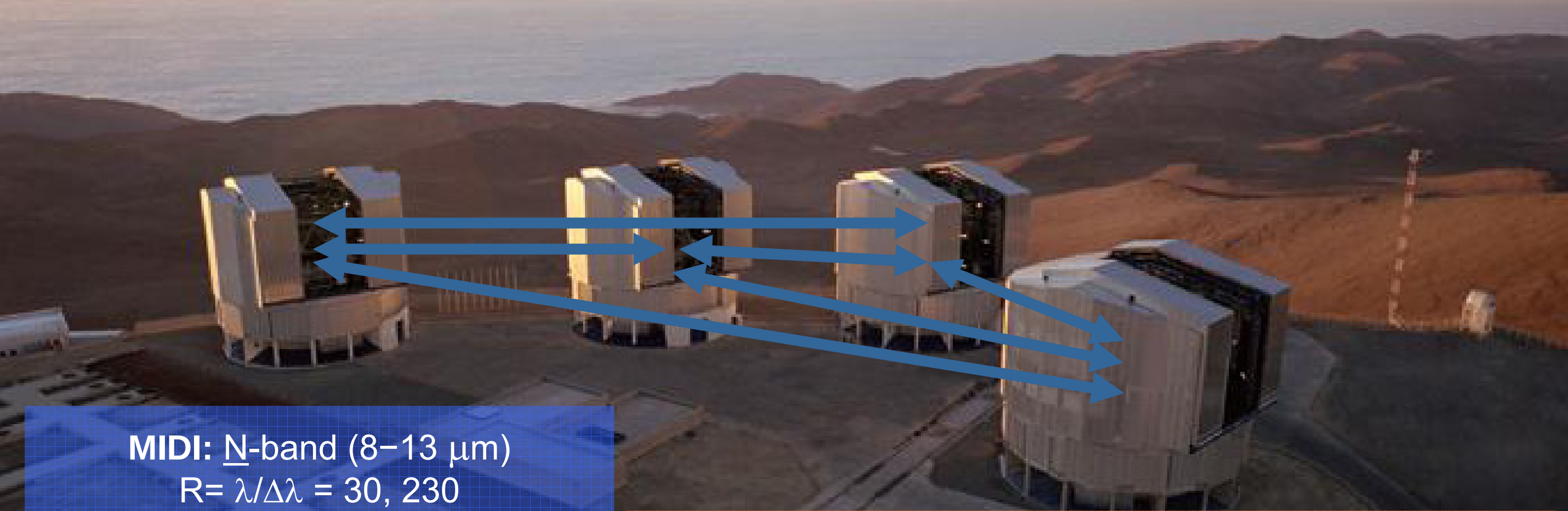
1.) Interferometric NIR size estimates



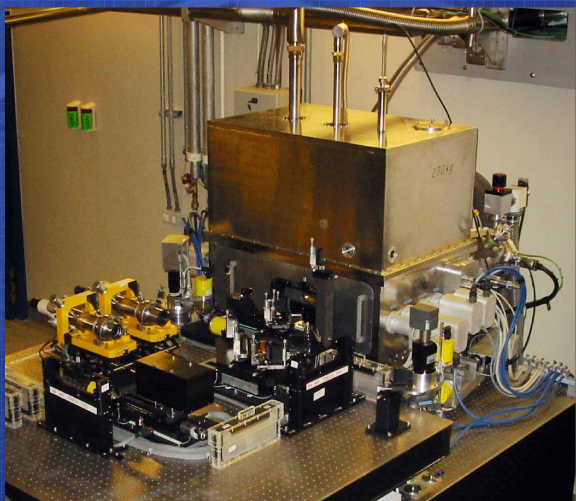
Sublimation radius $R_{subl} \propto L^{1/2}$

Near-infrared emission comes (mainly) from hot dust near the inner edge of the dusty disk at the dust sublimation radius

Near- + mid-infrared spectro - interferometry with MIDI + AMBER at the ESO VLTI



MIDI: N-band (8−13 μm)
R= $\lambda/\Delta\lambda$ = 30, 230

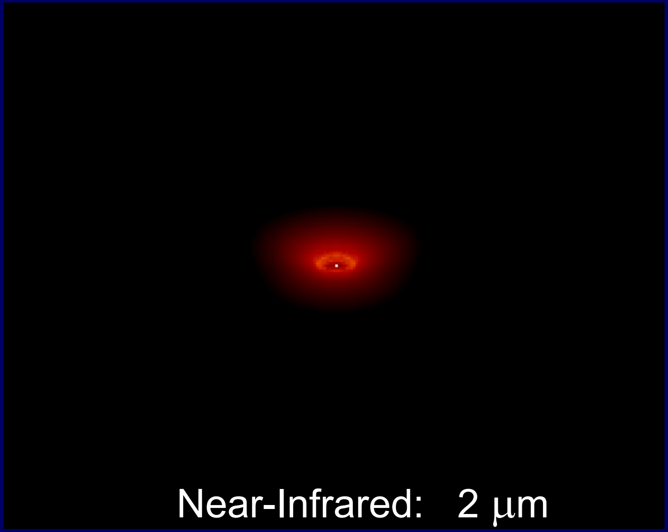


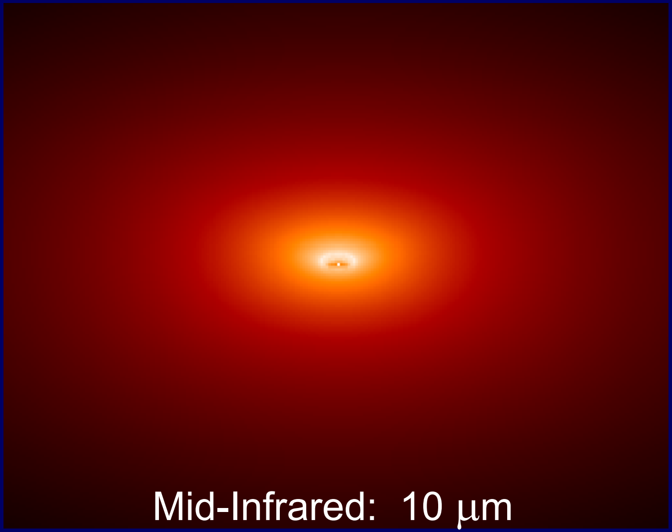
AMBER: J, H, K-band (1−2.5 μm)
R = 30, 1500, 12000

Near- and mid-infrared emission probe different regions:

- NIR: usually dominated by
  hot (1500 - 1000 K) dust
  at inner disk edge
  + scattered stellar light

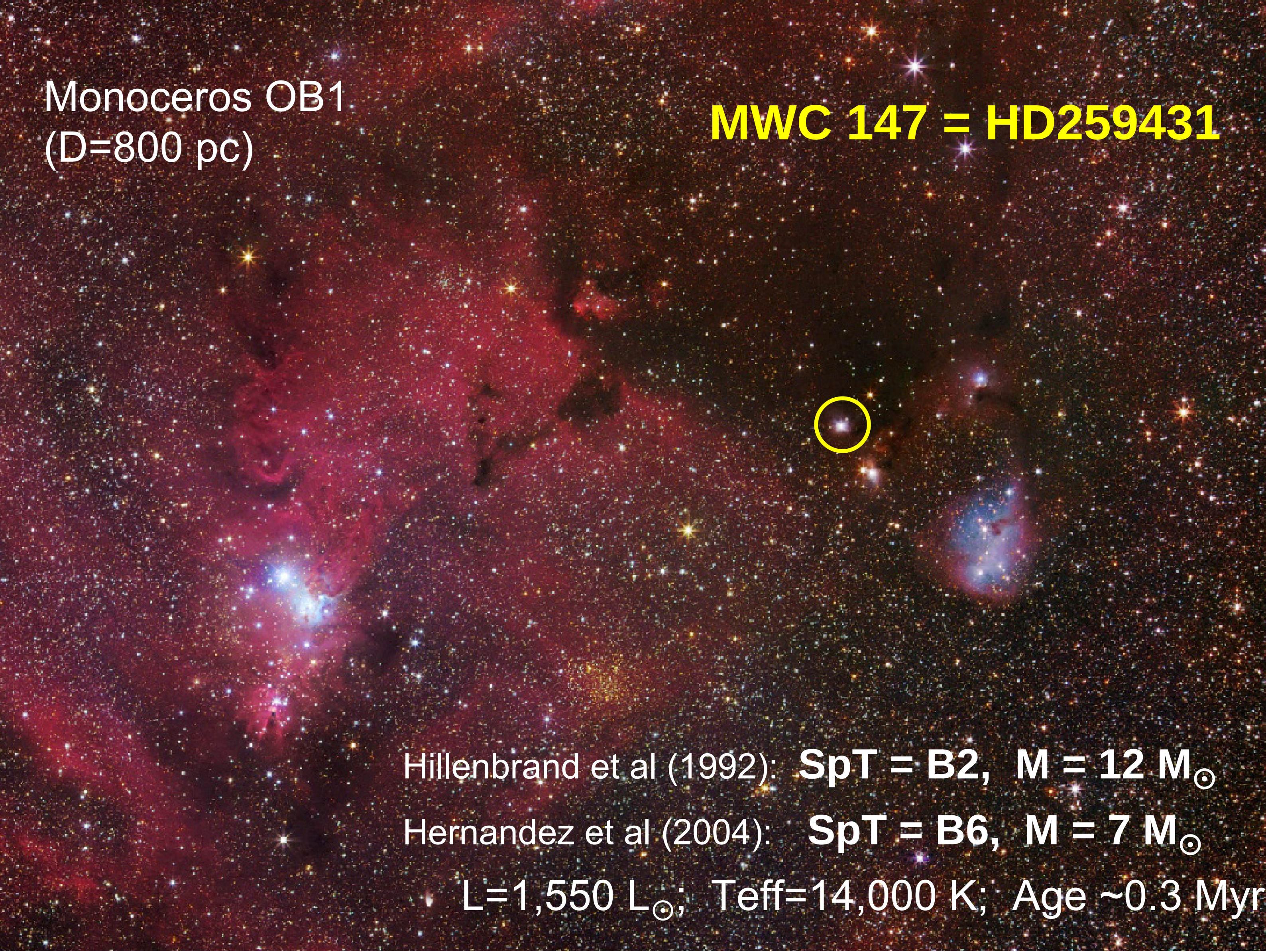
- MIR:
  hot & warm dust
  (1500 - 300 K)





<u>Combination of near- & mid-infrared spectro-interferometry</u> can probe the detailed <u>physical conditions</u> in the disk,

e.g. radial temperature profile, dust chemistry/grain size distribution, …



Monoceros OB1
(D=800 pc)
MWC 147 = HD259431
Hillenbrand et al (1992): **SpT = B2, M = 12 $M_\odot$**
Hernandez et al (2004): **SpT = B6, M = 7 $M_\odot$**
L=1,550 $L_\odot$; Teff=14,000 K; Age ~0.3 Myr

MWC 147

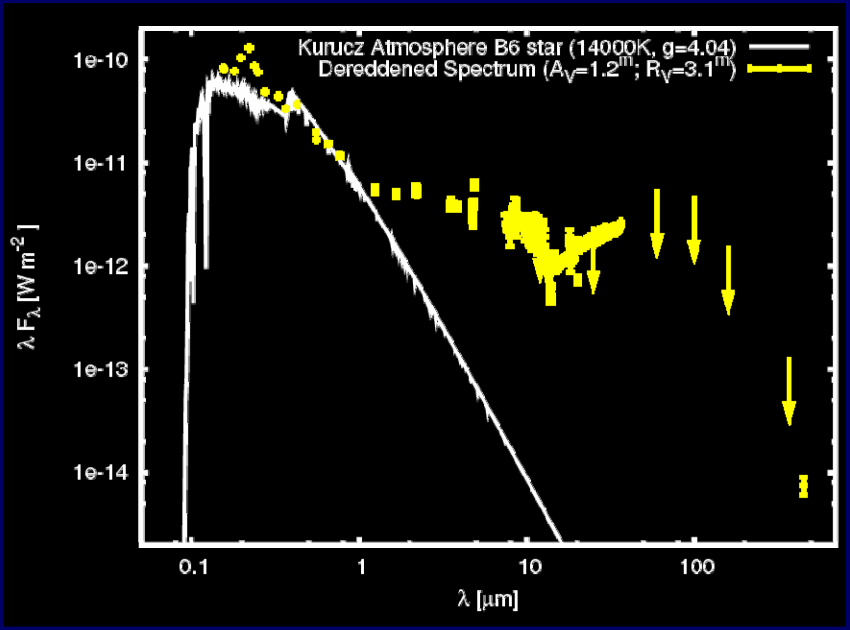
- reflection nebulosity
- extended mid-infrared emission (6 arcsec)
- strong infrared excess

SED modeling:

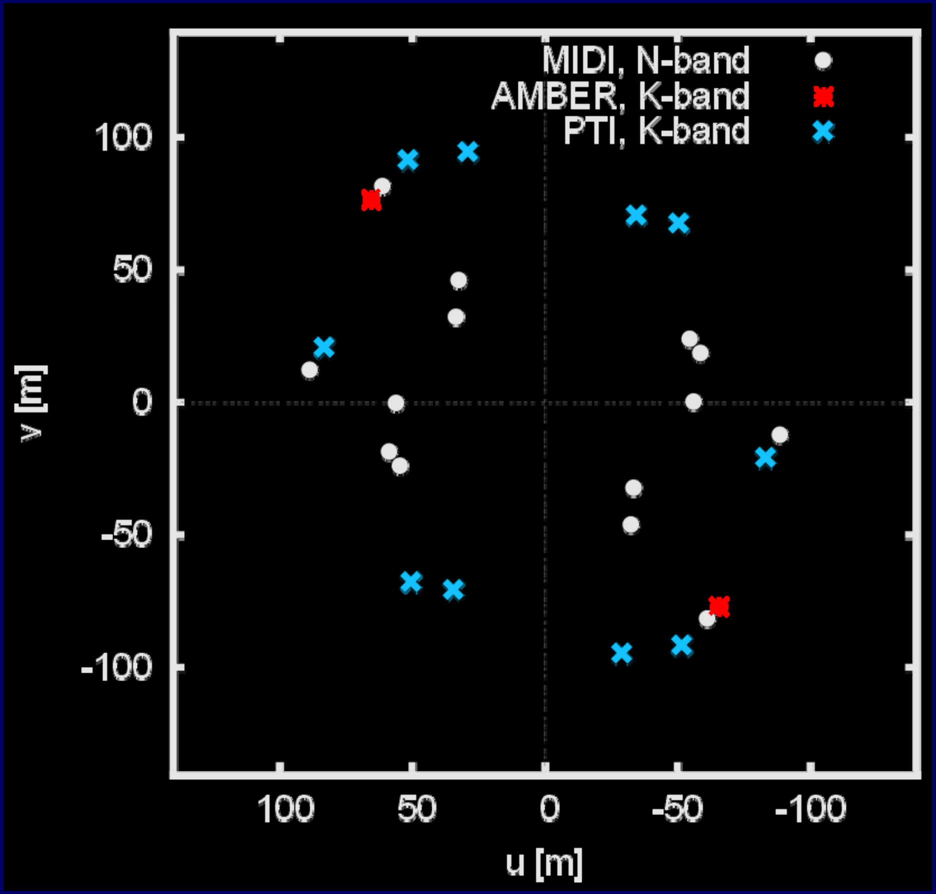
estimated accretion rate

$\dot{M}_{acc} = 1.0\times10^{-5}\ M_{\odot}/yr$

(Hillenbrand et al. 1992)



Interferometric observations of MWC 147



VLTI / MIDI: 7 observations

8 − 13 μm, R = 30

Vis = 0.5 ... 0.9

VLTI / AMBER: 1 observation

2.0 − 2.4 μm, R = 35

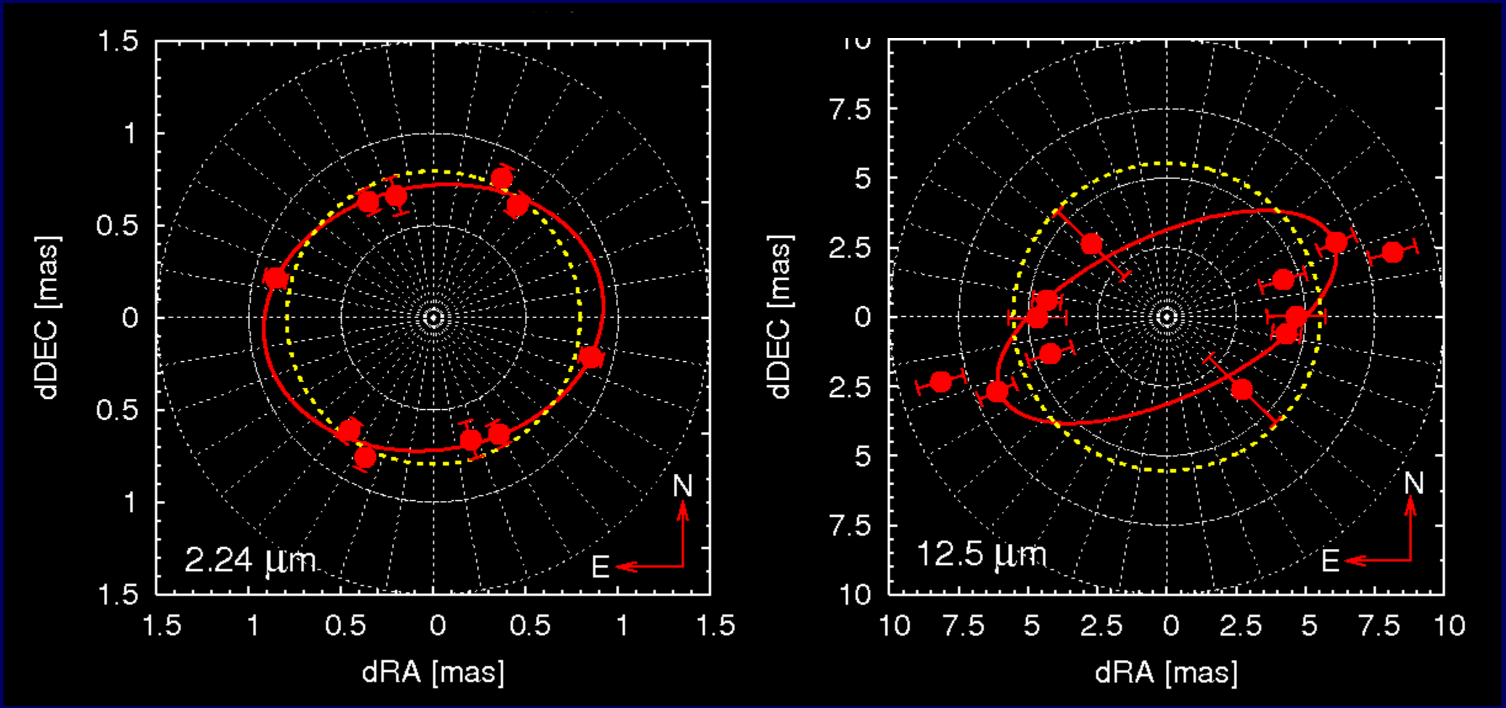
Vis = 0.75

PTI (archive): 5 observations

broadband K

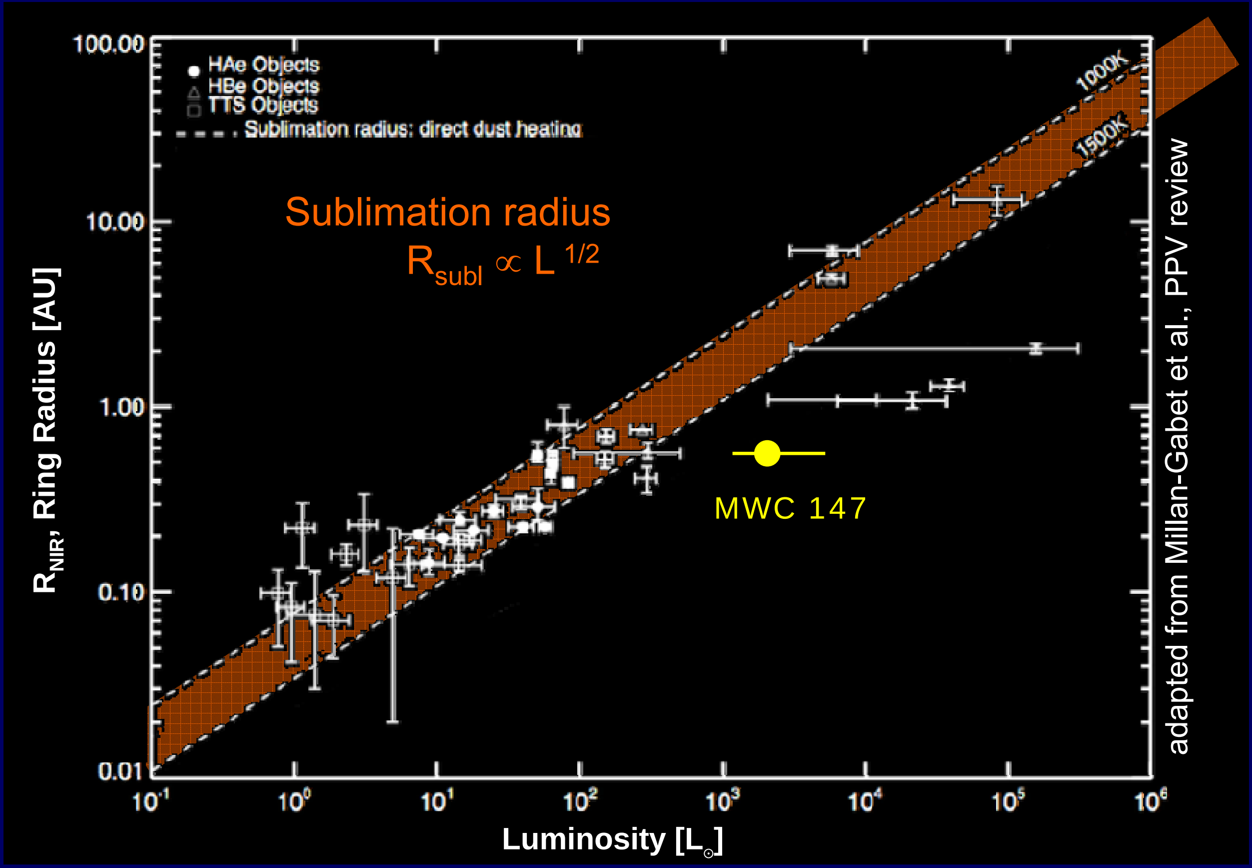
Vis = 0.8

Characteristic size at different position angles



source seems to be elongated

→ flattened structure (disk)



Characteristic near-infrared size (ring model radius) of MWC 147:

0.7 AU

Expected dust sublimation radius:

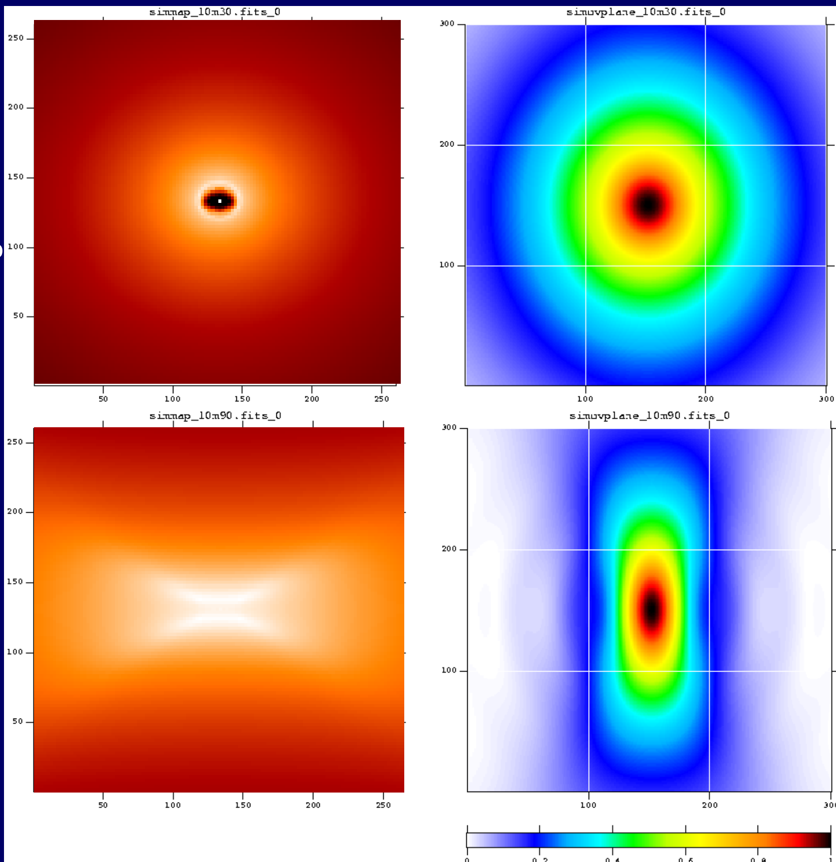
2.5 AU

2.) Interferometric observations at different wavelengths and baselines → *Parametric imaging*

Model images → Model visbilities → Comparison of predicted and observed visibilities (+ SED)

i = 30°

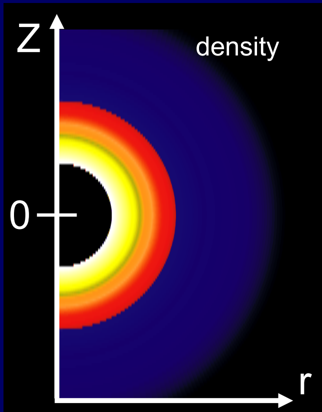
i = 90°



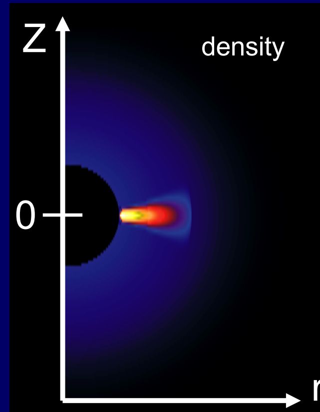
↓

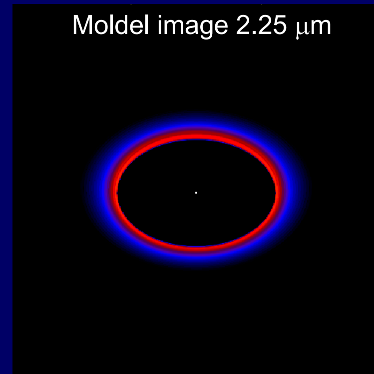
Constraints on model parameters

1: Spherical shell model



2: Disk model

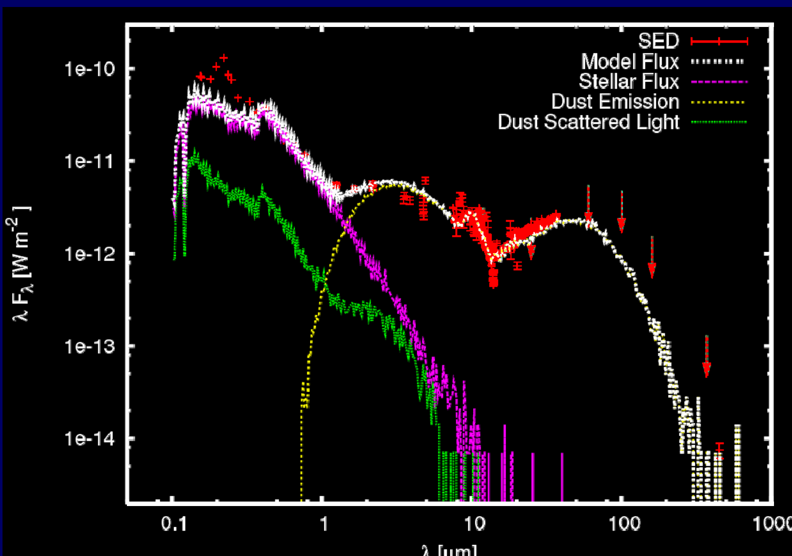


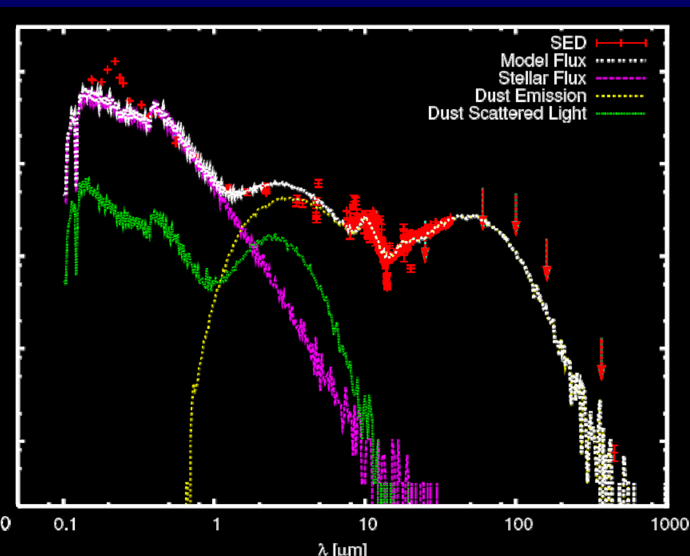


Spherical Shell

Flared Keplerian Disk

Inclination: 45º





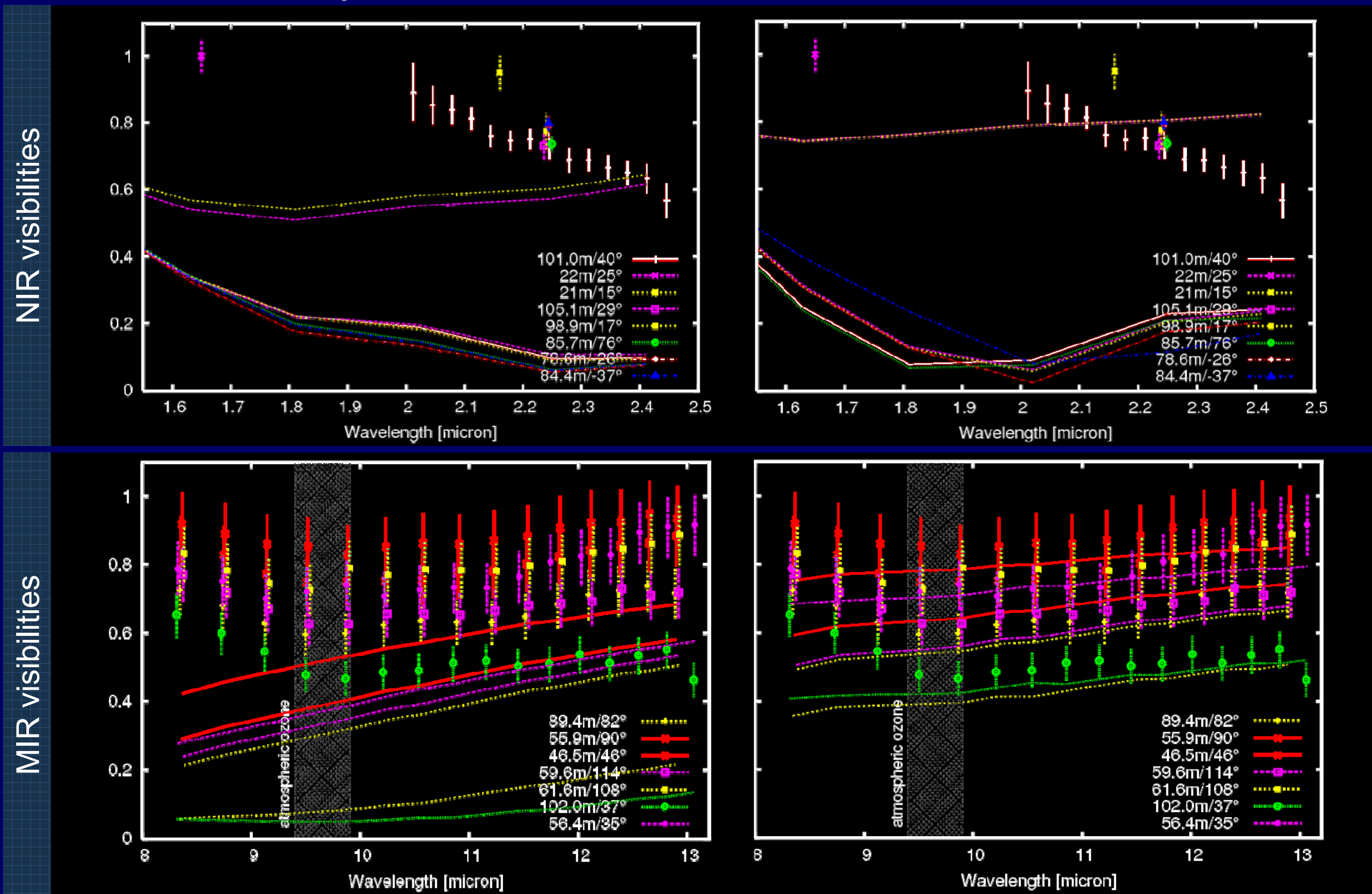
SED fits are highly ambiguous!

1: Spherical shell model

$\chi_r^2 = 80$

2: Disk model

$\chi_r^2 = 42$



1: Spherical shell model

$\chi_r^2 = 80$

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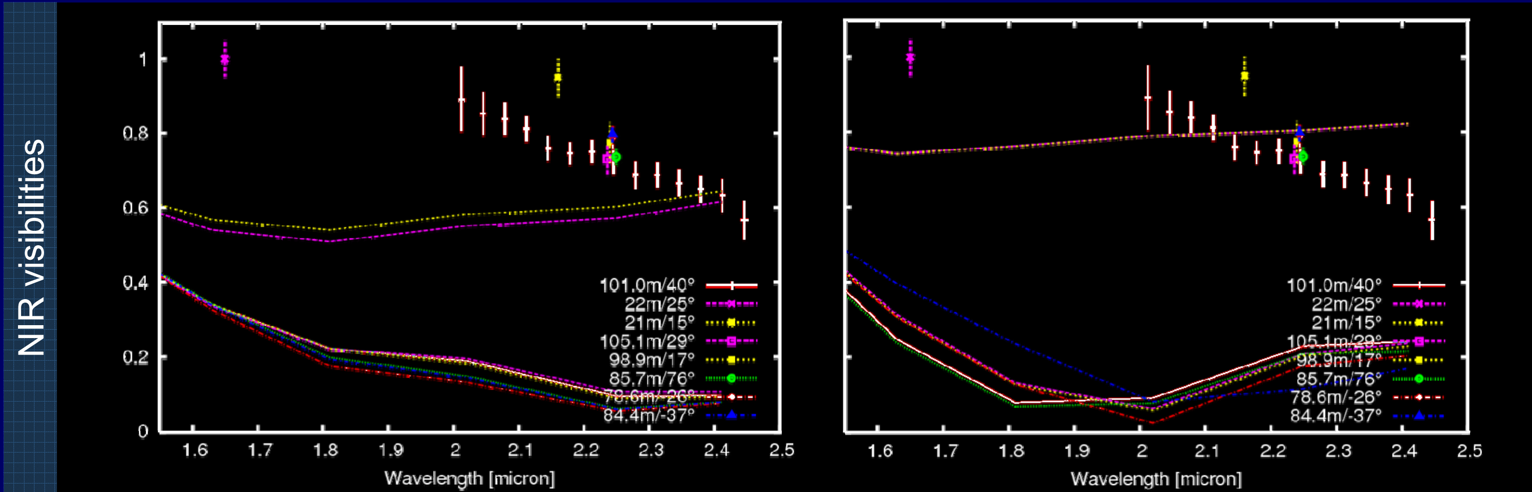
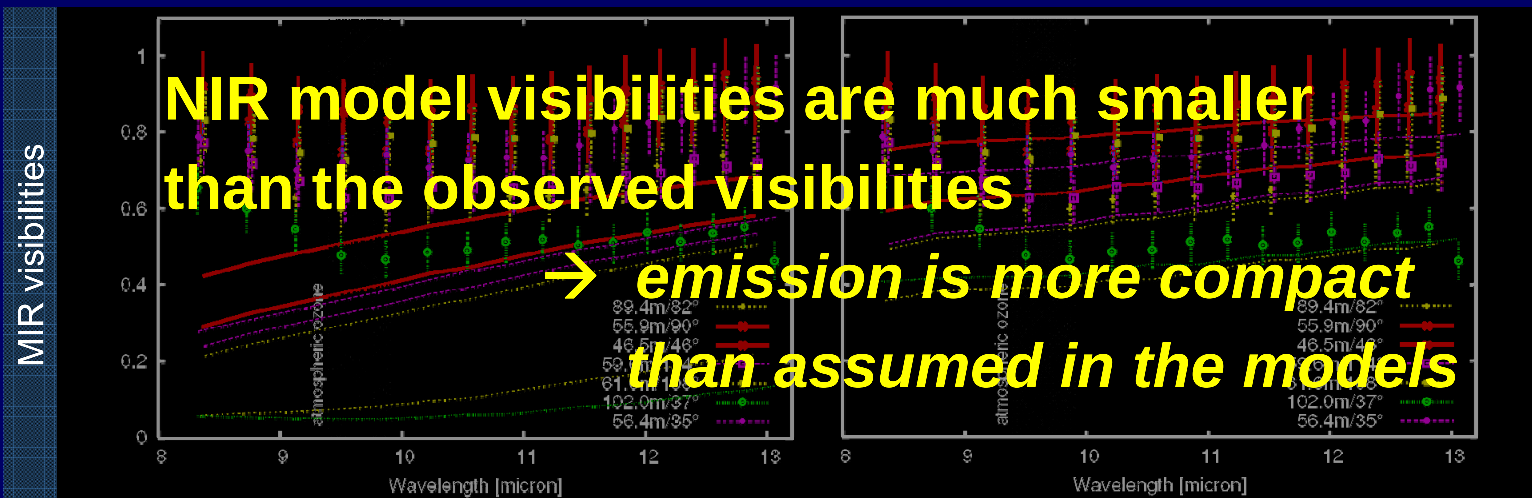
$\chi_r^2 = 42$

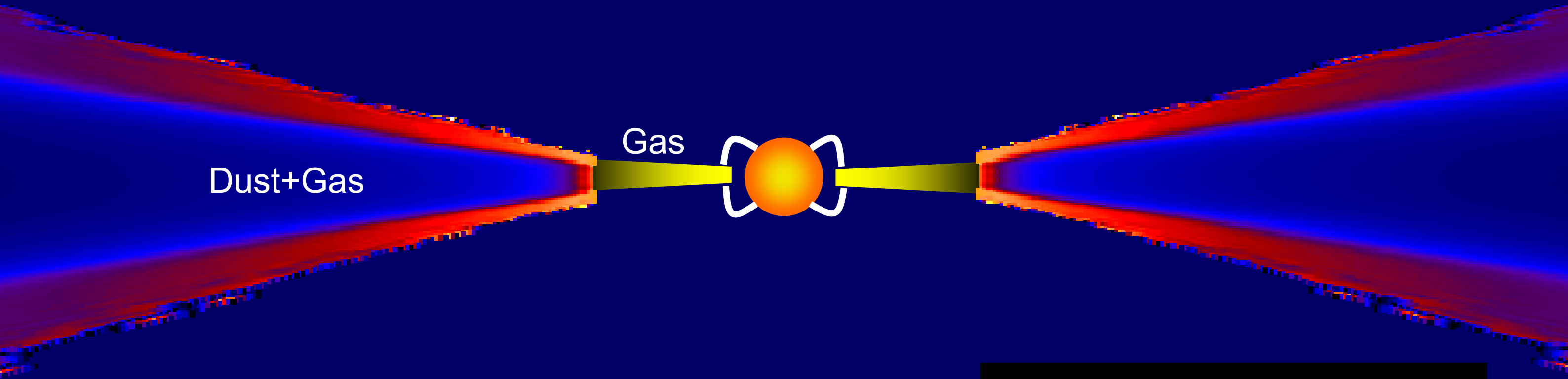




NIR model visibilities are much smaller than the observed visibilities

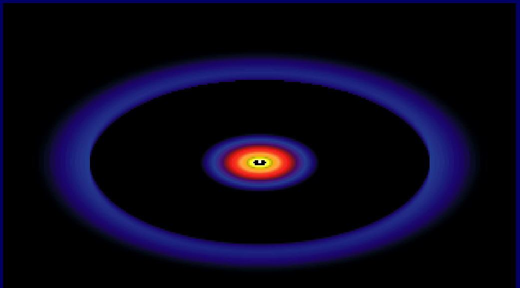
→ *emission is more compact than assumed in the models*

Solution: # Emission from gas in the inner disk



Muzerolle et al. 2004:

Emission from gas in the inner accretion disk can dominate near-infrared emission for accretion rates ≥ 10^{-6} $M_\odot$ / yr


K-band model image

→ We model the gas in the inner accretion disk to be

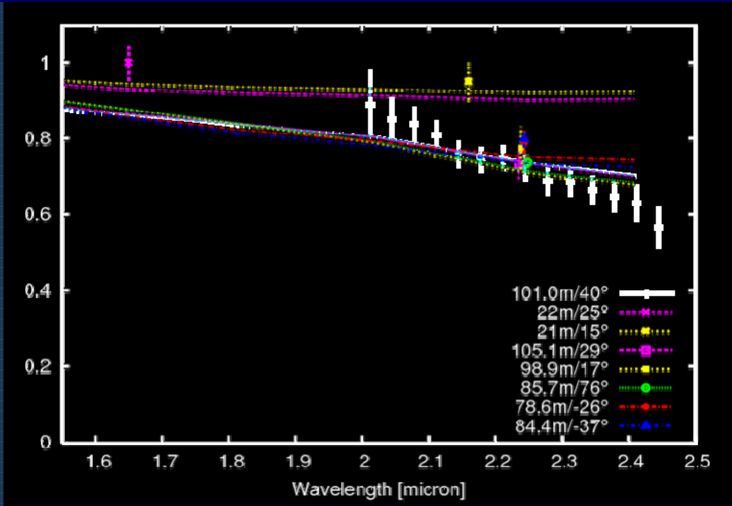
- geometrically thin
- extend from R_{corot} (~ 3 $R_\star$) to R_{subl} (~2.5 AU)
- follow the temperature-profile from Pringle (1981)

$$T^4_{\rm gas}(r) = \left(\frac{3GM_\star \dot{M}}{8\pi\sigma r^3}\right)\left(1-\sqrt{R_\star/r}\right)^{1/2}.$$

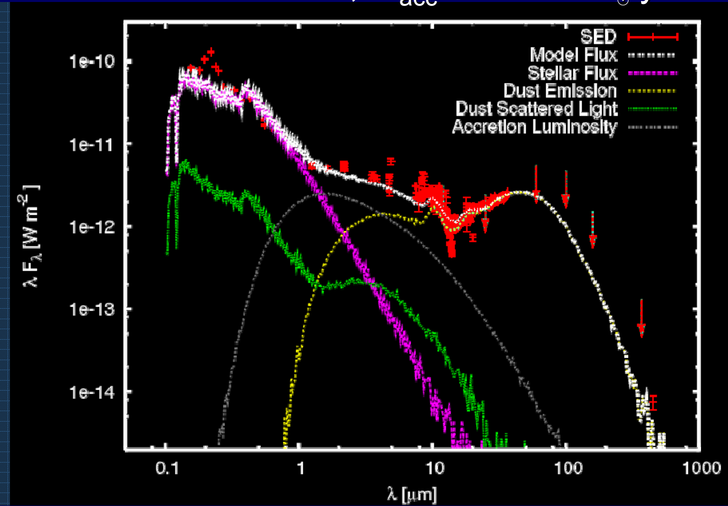
3: Flared dusty disk + inner gas disk: $\chi_r^2 = 1.28$

Inclination: 60°, $\dot{M}_{acc} = 9\times10^{-6}\ M_\odot/yr$

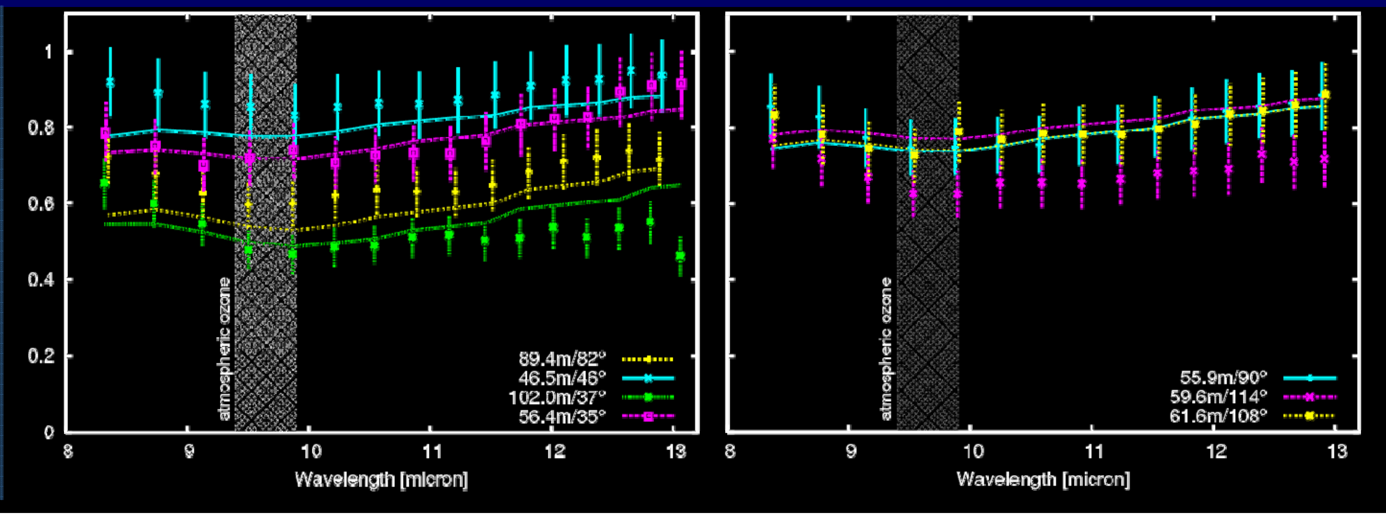
NIR visibilities



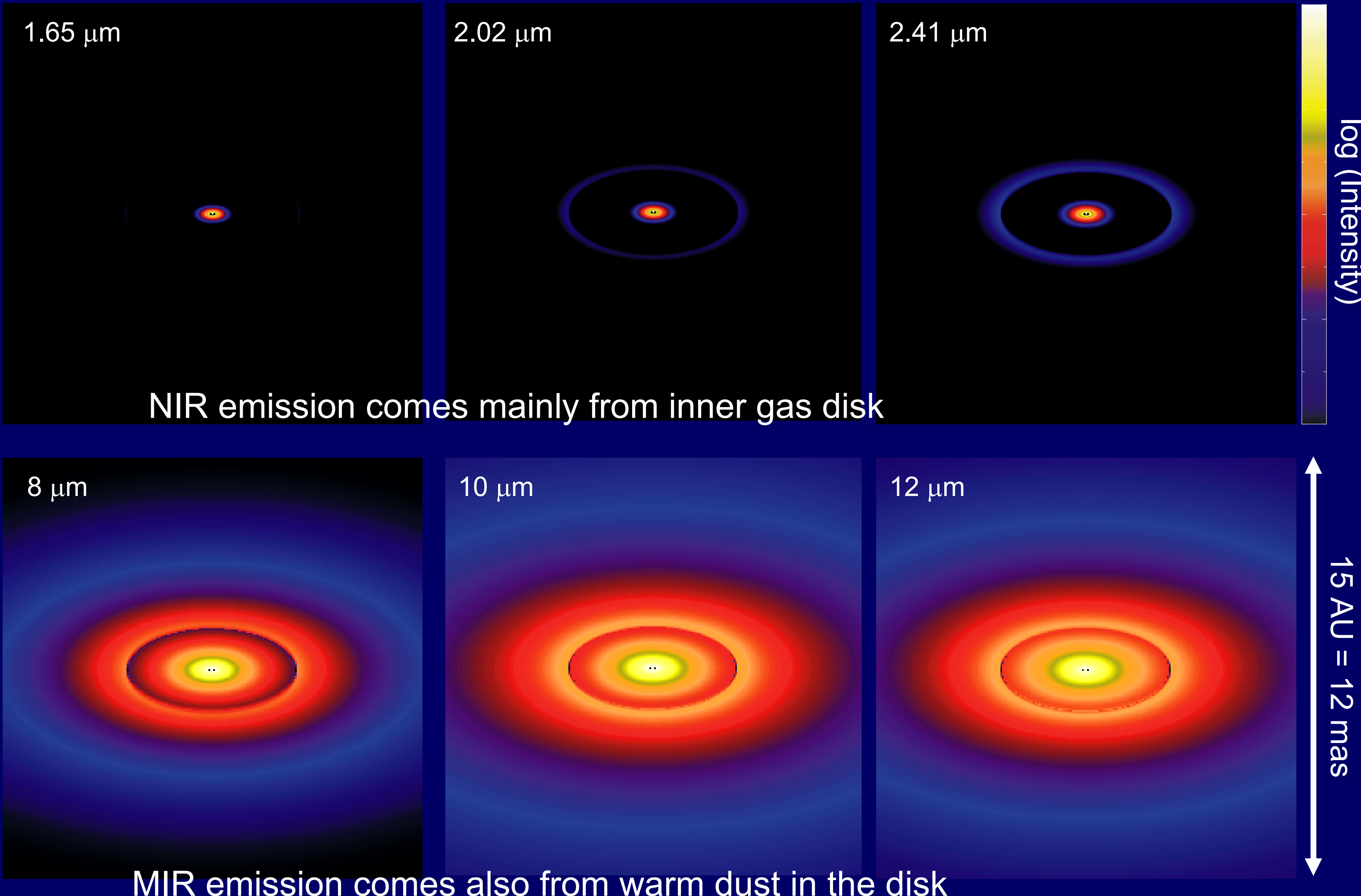
SED

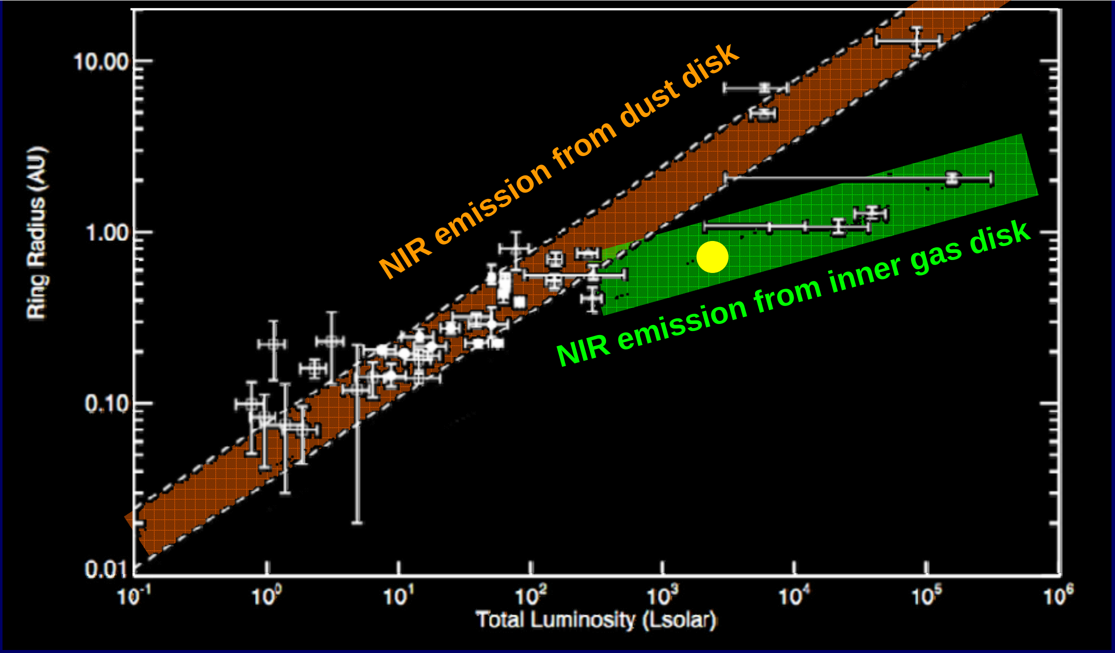


MIR visibilities



Best-fit radiative transfer model images

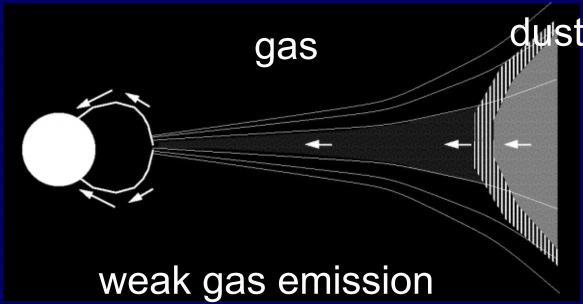


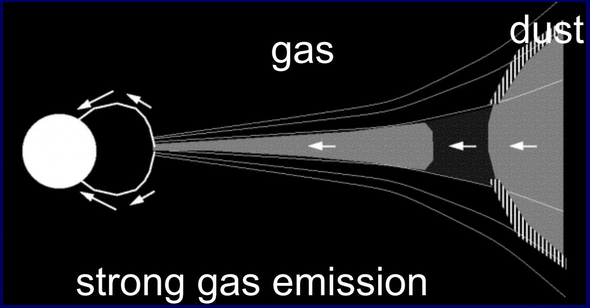


adapted from Millan-Gabet et al., PPV

NIR emission of massive young stars often dominated by gas emission

(see also Monnier et al. 2005, Eisner et al. 2005, Vinkovic & Jurkic 2007)





Muzerolle et al. 2004

Summary

- The combination of

 spectro-interferometric observations over a wide wavelength range
+
 radiation transfer modeling

 can provide unique constraints on the geometry/physics of the inner circumstellar environment of young stellar objects

- MWC 147:

 - resolved at near- and mid-infrared wavelengths
 - brightness distribution is asymmetric → flattened structure (disk)
 - size of NIR emission is smaller than expected dust sublimation radius
 - model of a **dust disk** + emission from an **inner gas disk** can simultaneously reproduce SED, near- and mid-infrared visibilities

 (Kraus, Preibisch, Ohnaka, submitted to ApJ)

- NIR contribution of inner gas disk seems to increase with stellar mass

The (near) future: Interferometric imaging

combine 3 (or more) telescopes (closure phase)

→ reconstruction of images with mas resolution

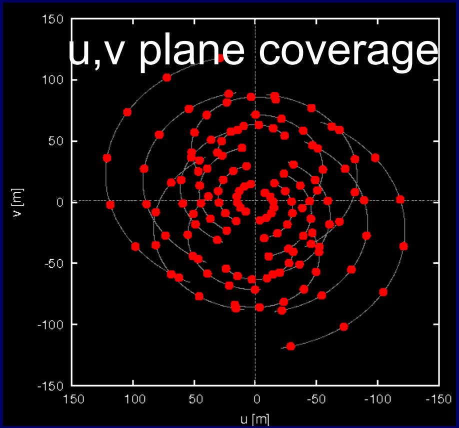
Example:

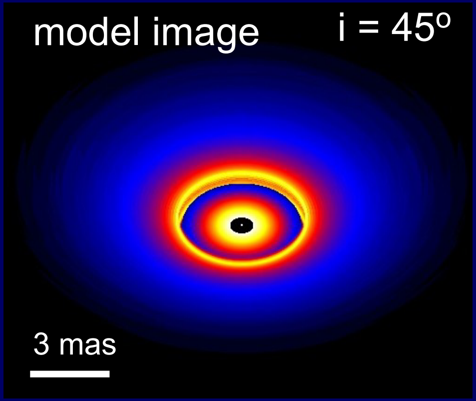
image reconstruction with

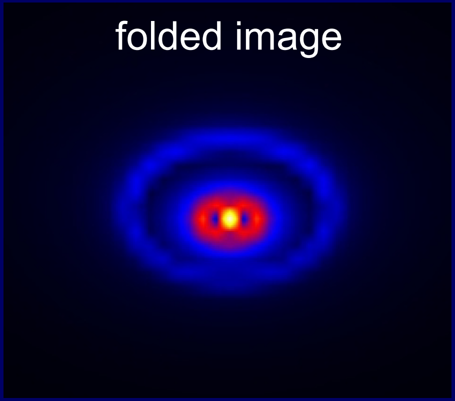
simulated VLTI / AMBER data:

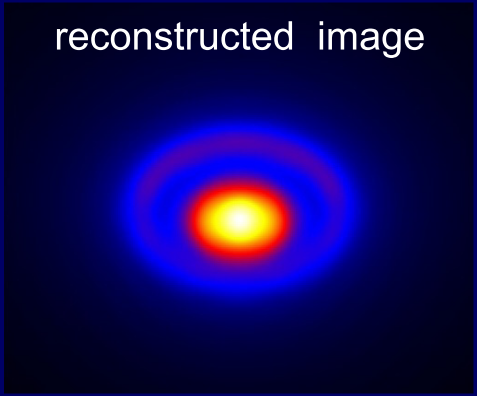
4 nights with 3 ATs

K-band, S/N = 50









simulation by K.-H. Hofmann and S. Kraus, MPIfR Bonn