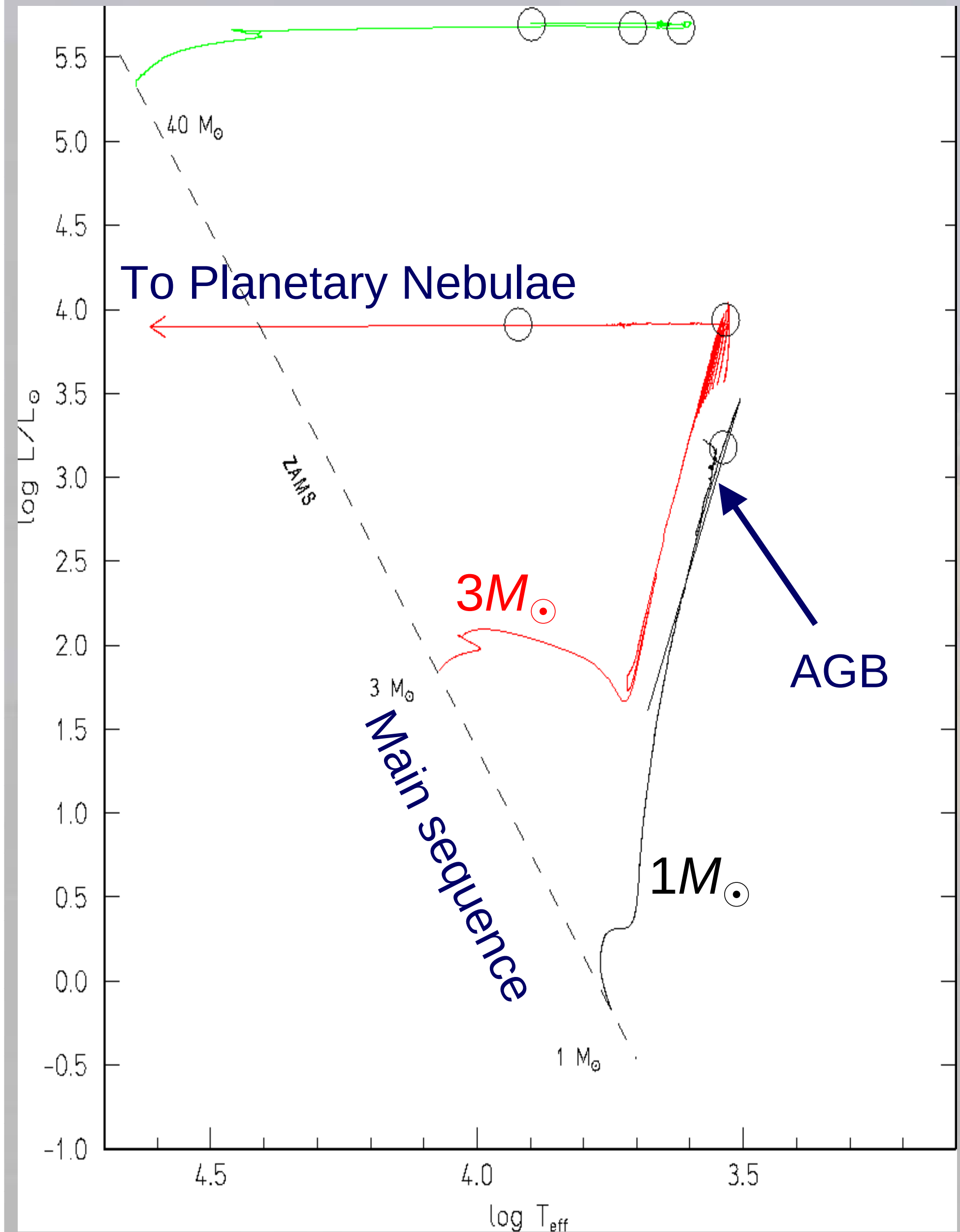
VLTI's view on the circumstellar environment of cool evolved stars:

EuroSummer School

Observation and data reduction with the Very Large Telescope Interferometer

Goutelas, France
June 4-16, 2006

K. Ohnaka
Max-Planck-Institut für Radioastronomie
6 June 2006

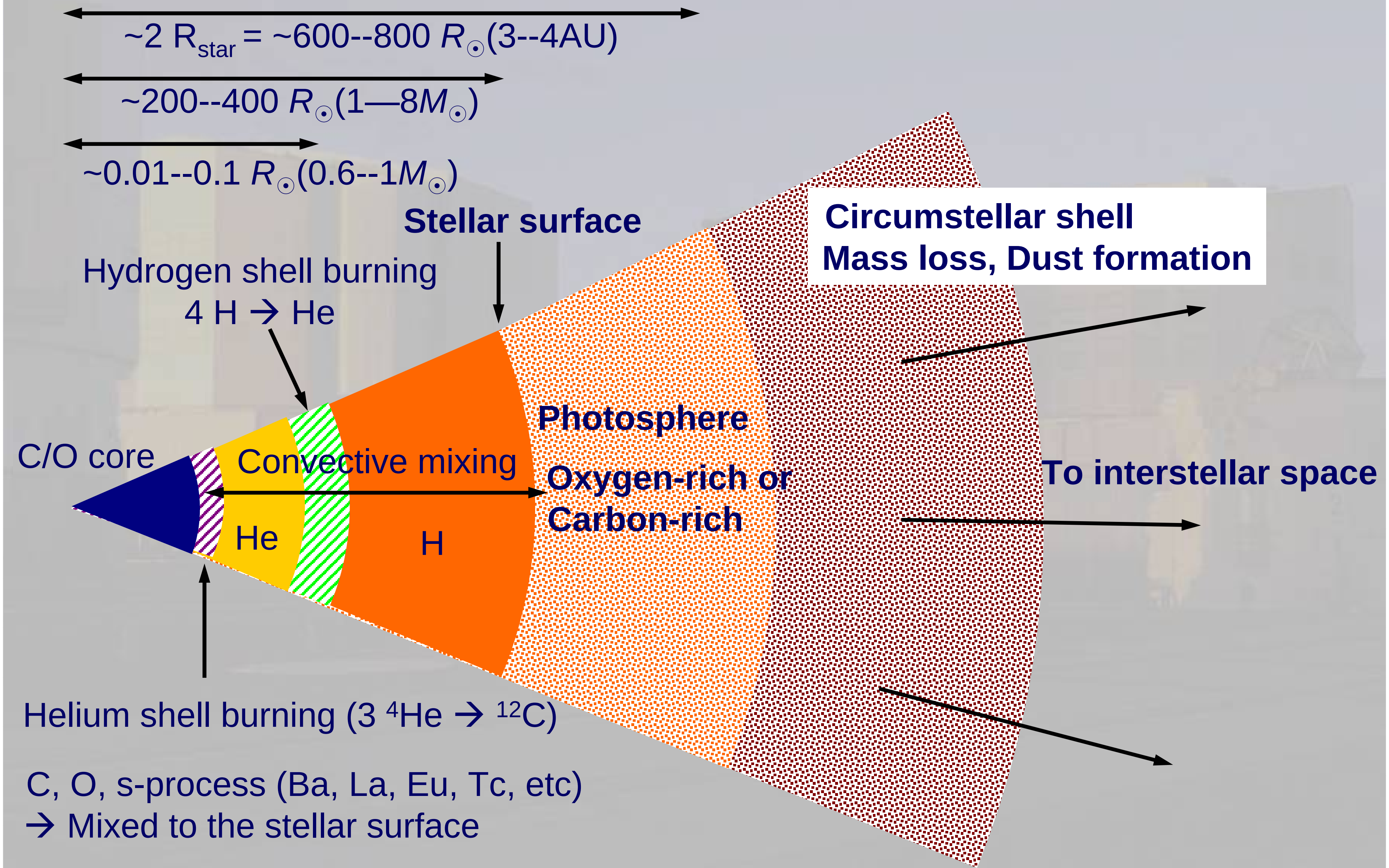


Asymptotic Giant Branch (AGB)

Late evolutionary stage of 1-8 $M_\odot$ stars

Teff ~ 3000K

L ~ 10^3--10^4 $L_\odot$


~2 R_{star} = ~600--800 $R_\odot$(3--4AU)
~200--400 $R_\odot$(1—8$M_\odot$)
~0.01--0.1 $R_\odot$(0.6--1$M_\odot$)
Stellar surface
Hydrogen shell burning
4 H → He
Circumstellar shell
Mass loss, Dust formation
C/O core
Convective mixing
He
H
Photosphere
Oxygen-rich or
Carbon-rich
To interstellar space
Helium shell burning (3 ^{4}He → ^{12}C)
C, O, s-process (Ba, La, Eu, Tc, etc)
→ Mixed to the stellar surface

Why AGB stars are important?

1. Majority of the stellar population

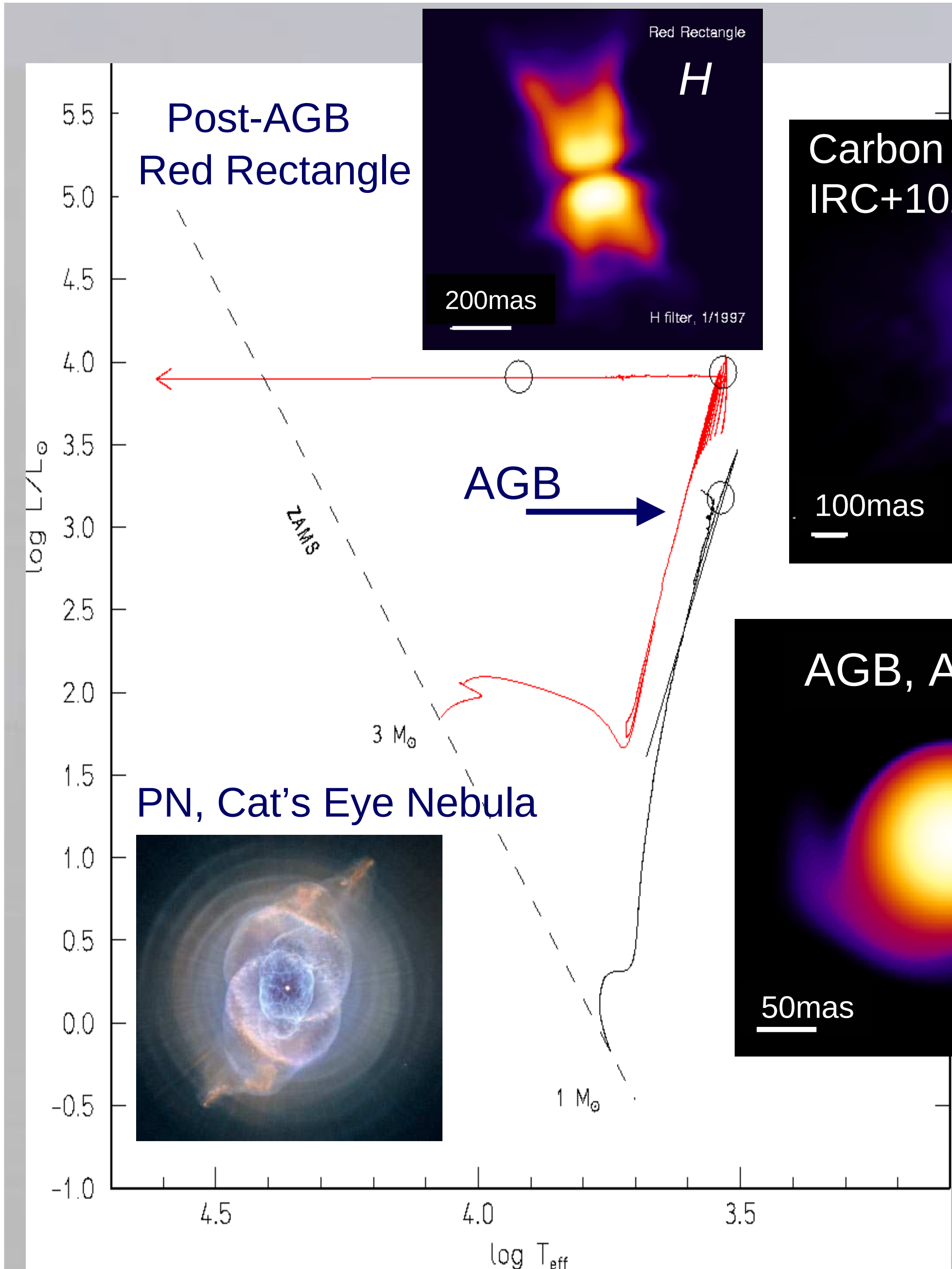
2. Nucleosynthesized material mixed to the stellar surface

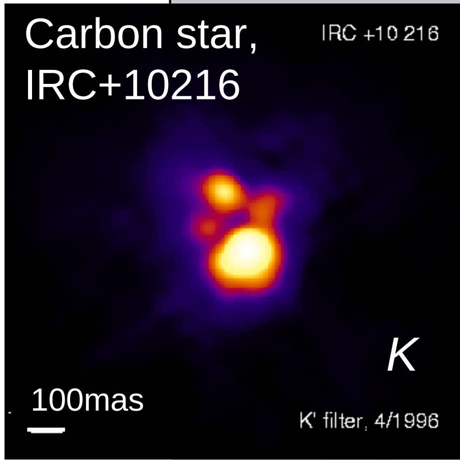
   → Change of chemical composition
   (e.g., oxygen-rich star to carbon-rich star)

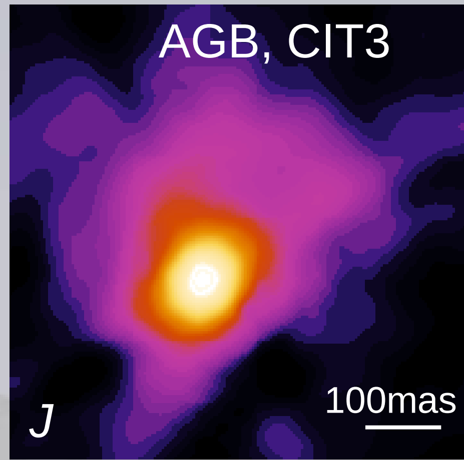
3. Enrichment of ISM via mass loss

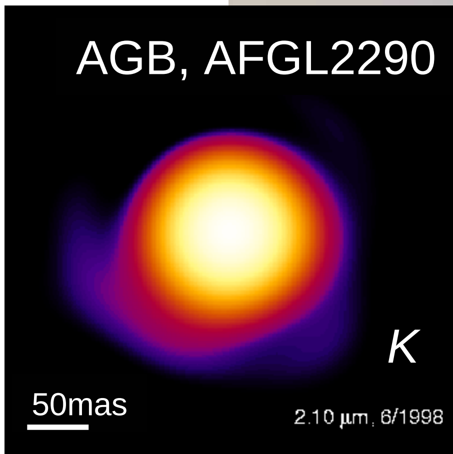
   Major "Dust Factory",
   together with supernovae

But mass loss phenomenon is not yet well understood









Mass loss

~10^{-8}—10^{-5} $M_\odot$/yr

Driving mechanism little understood

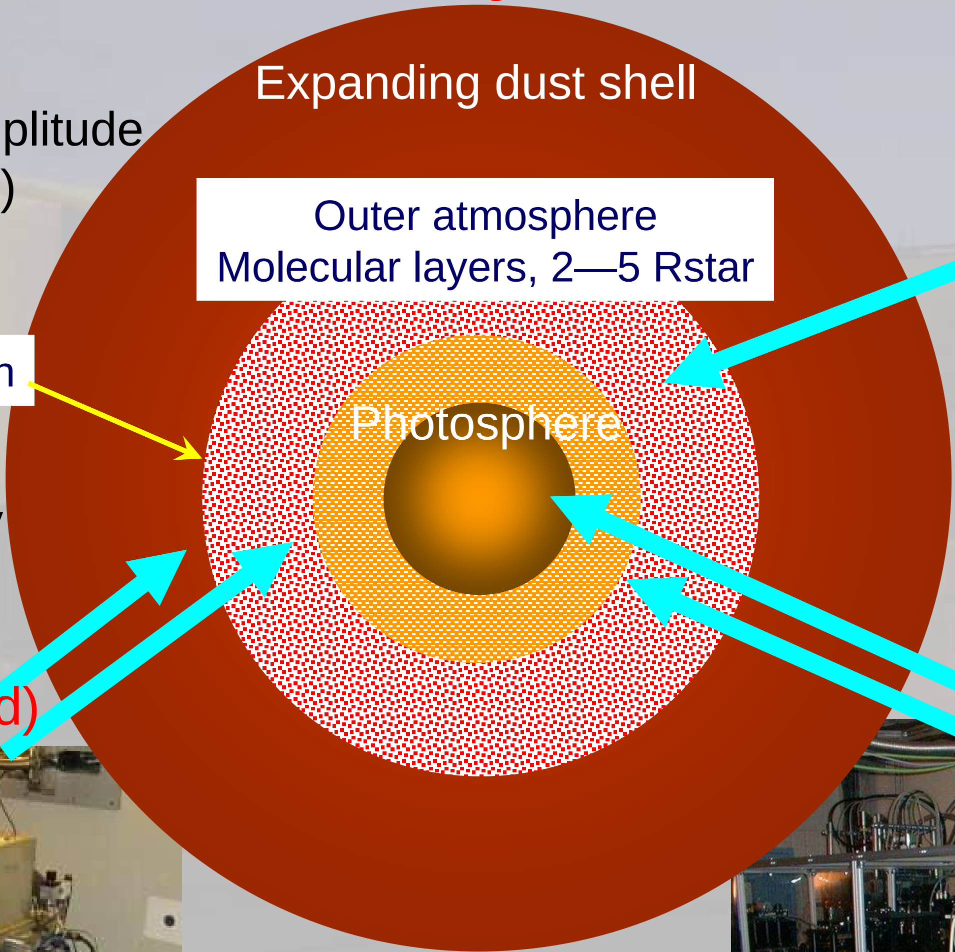
Morphology change from AGB to planetary nebulae

How and at what stage?

→ Good targets for IR interferometry

IR interferometry of Mira stars

Mira variables:
Large variability amplitude
~ 9 mag (in V)



ISO & high-resolution spectroscopy,
Spatially unresolved

Spectro-interferometry
Spatial + Spectral resolution

Mid-infrared (*N* band)

Near-infrared (JHK)

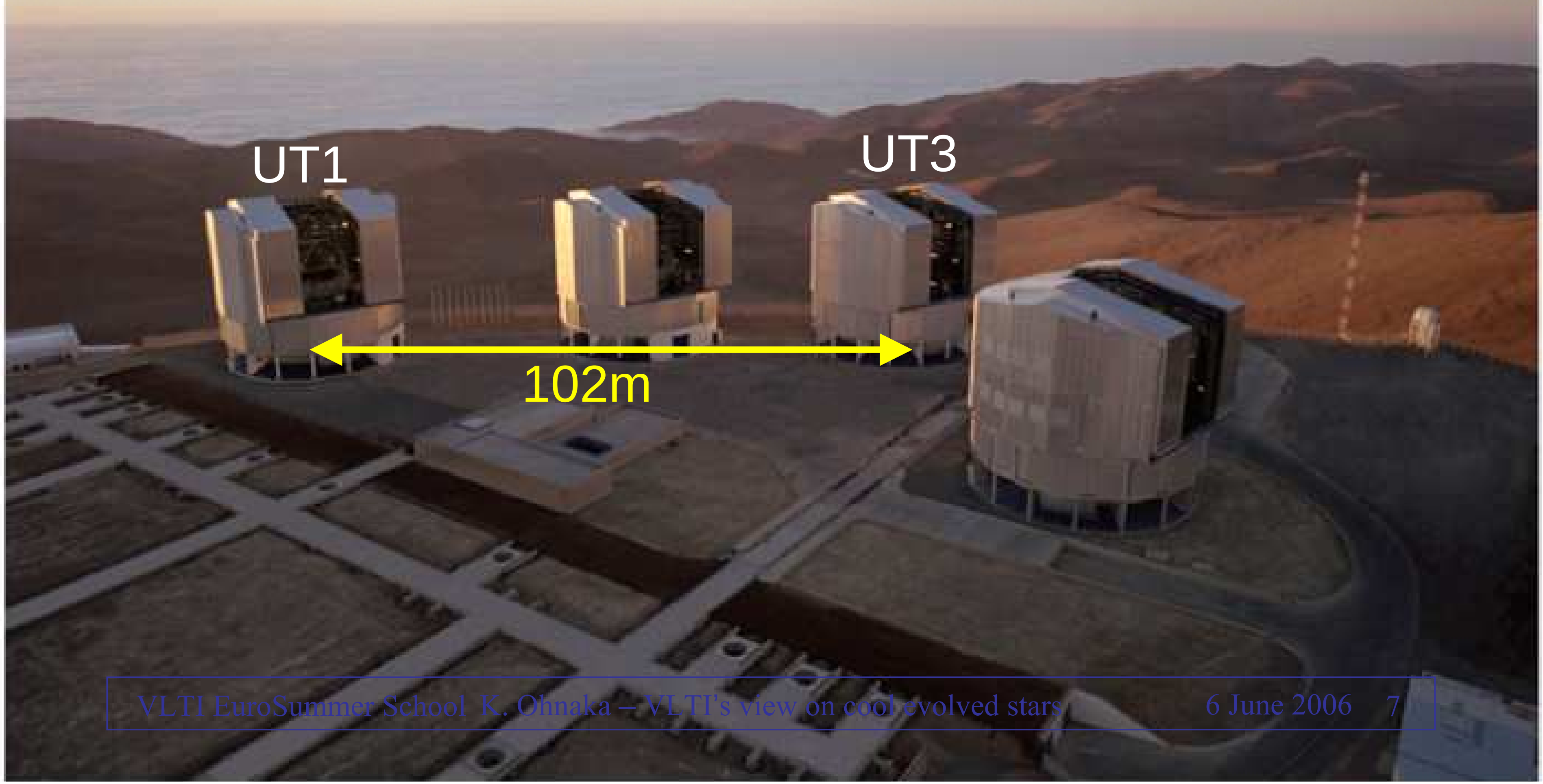
MIDI observation of the Mira variable RR Sco

2003 June

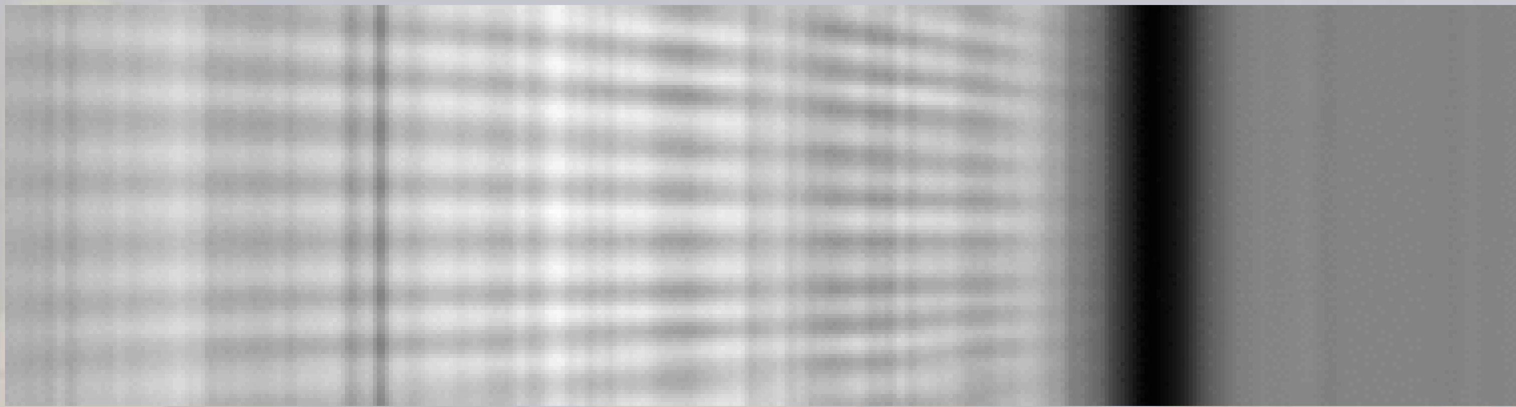
Unit Telescopes 1 & 3, Projected baseline = 74—100m

Angular resolution @ 10μm = ~20mas, Spectral resolution = 30

Measure the angular size and shape over the whole *N* band (8 – 13 μm)



MIDI observation of RR Sco
spectrally dispersed fringes extracted from raw data



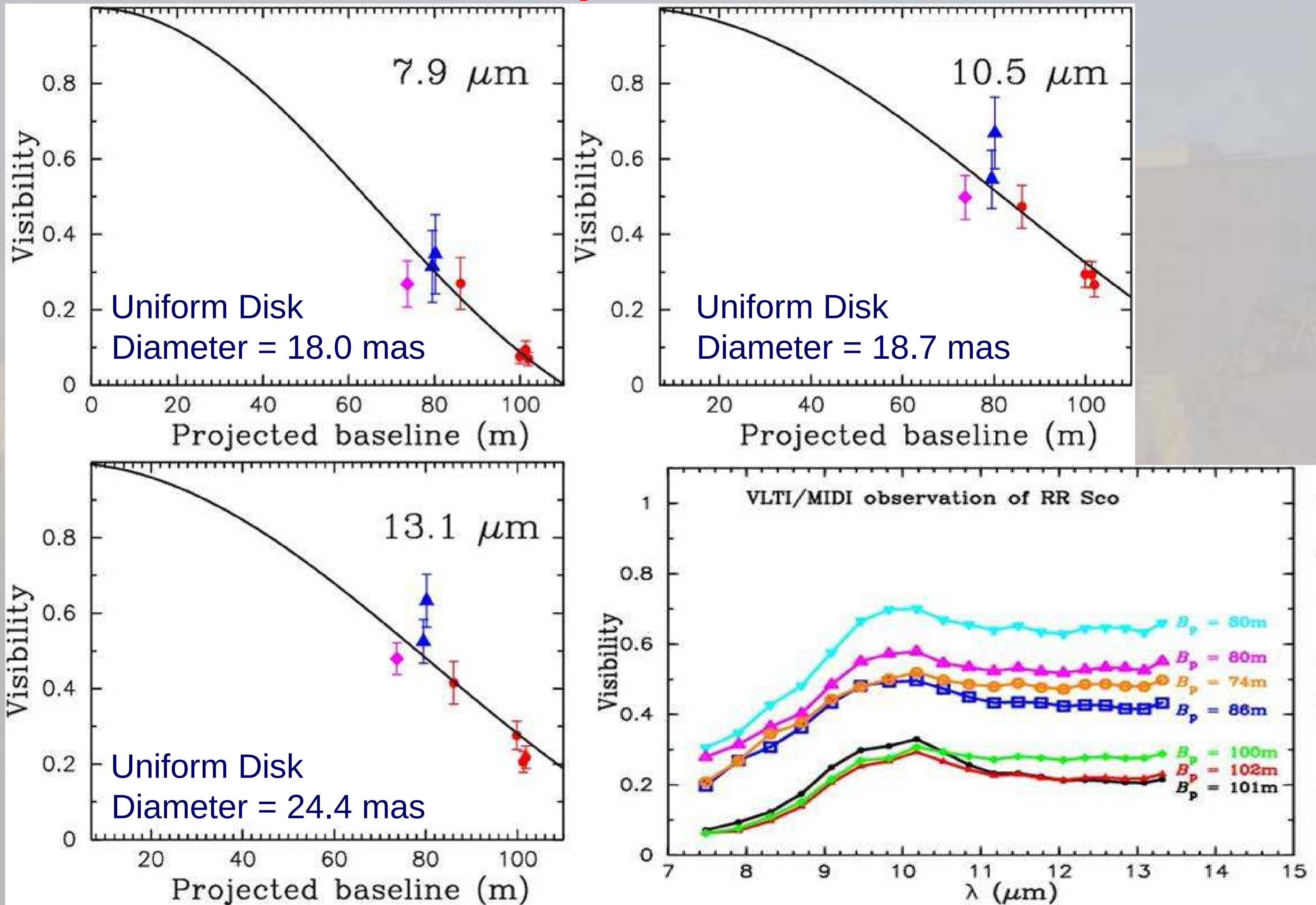
13.3 μm 8.0 μm

Fringe recording on a science target (30 min)
+ acquisition, photometric data

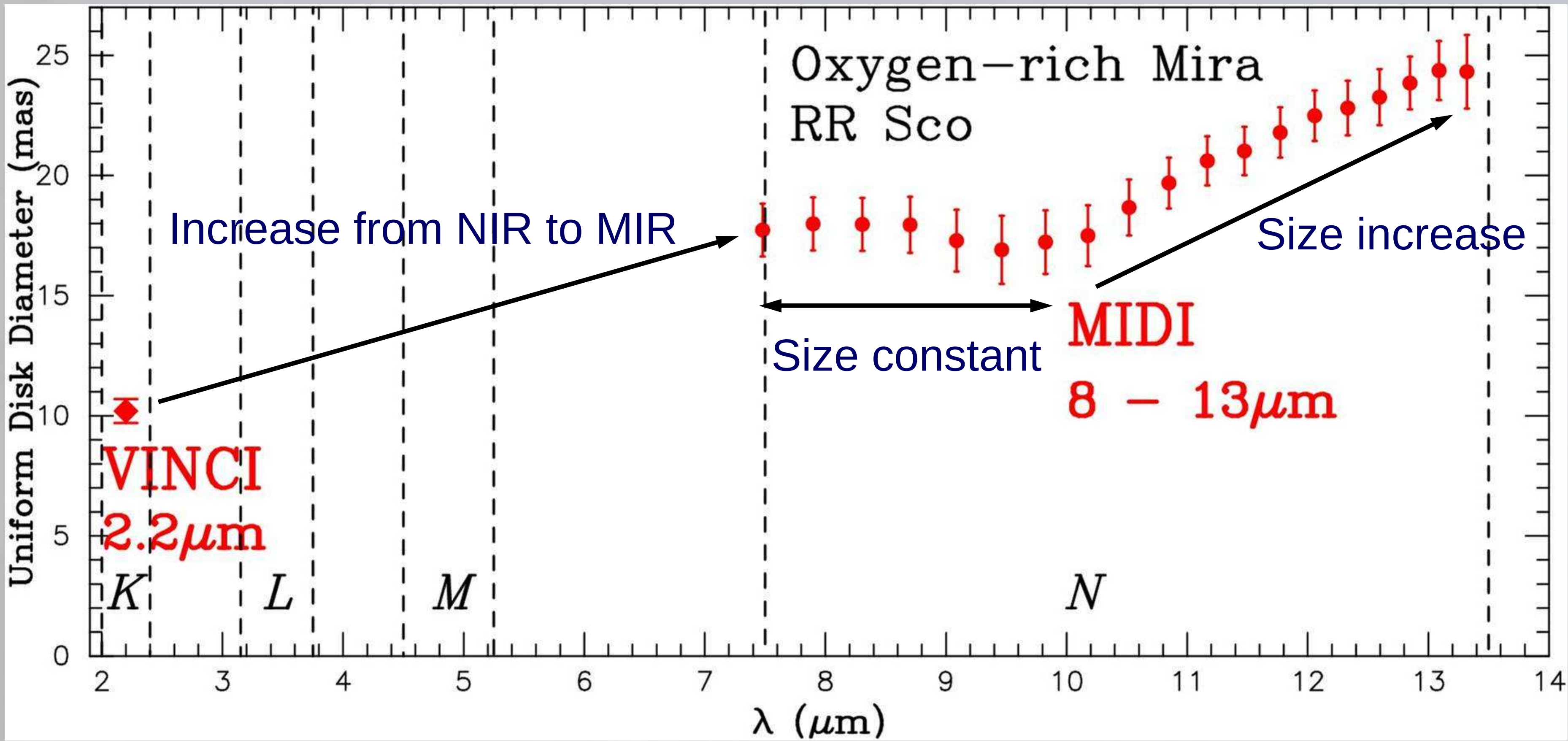
Fringe recording on a calibrator (30 min)
+ acquisition, photometric data

→ **Calibrated visibility**

Observed N-band visibility of RR Sco



Wavelength dependence of RR Sco's angular size

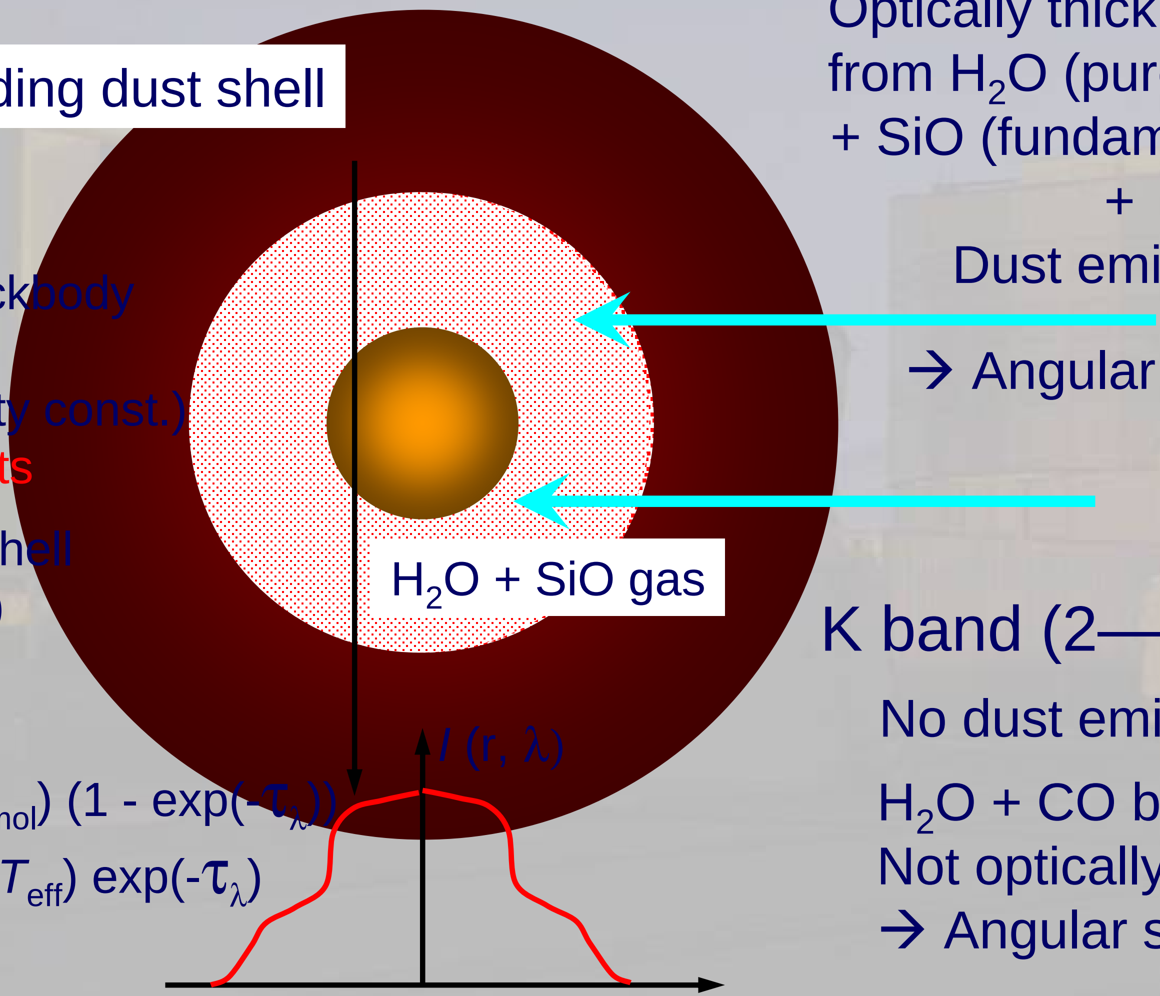


- UD diameter constant between 8 and 10 μm: ~18 mas,
  UD diameter increases λ > 10 μm: ~25 mas @ 13 μm
  UD diameter 10.2 +/- 0.5 mas @ 2.2 μm
- N-band UD diameter = twice as large as K-band UD diameter (VINCI, 3 weeks after MIDI observation)

Basic idea

(ad hoc) Modeling
Photosphere → blackbody
H_2O + SiO gas →
one-layer (T, density const.)
+ molecular line lists

Optically thin dust shell
(silicate+corundum)



$$I(r,\lambda) = B_\lambda(T_{mol})\,(1 - \exp(-\tau_\lambda)) + B_\lambda(T_{eff})\,\exp(-\tau_\lambda)$$

N band (8—13µm)

Optically thick emission
from H_2O (pure rotation)
+ SiO (fundamental) gas
+
Dust emission

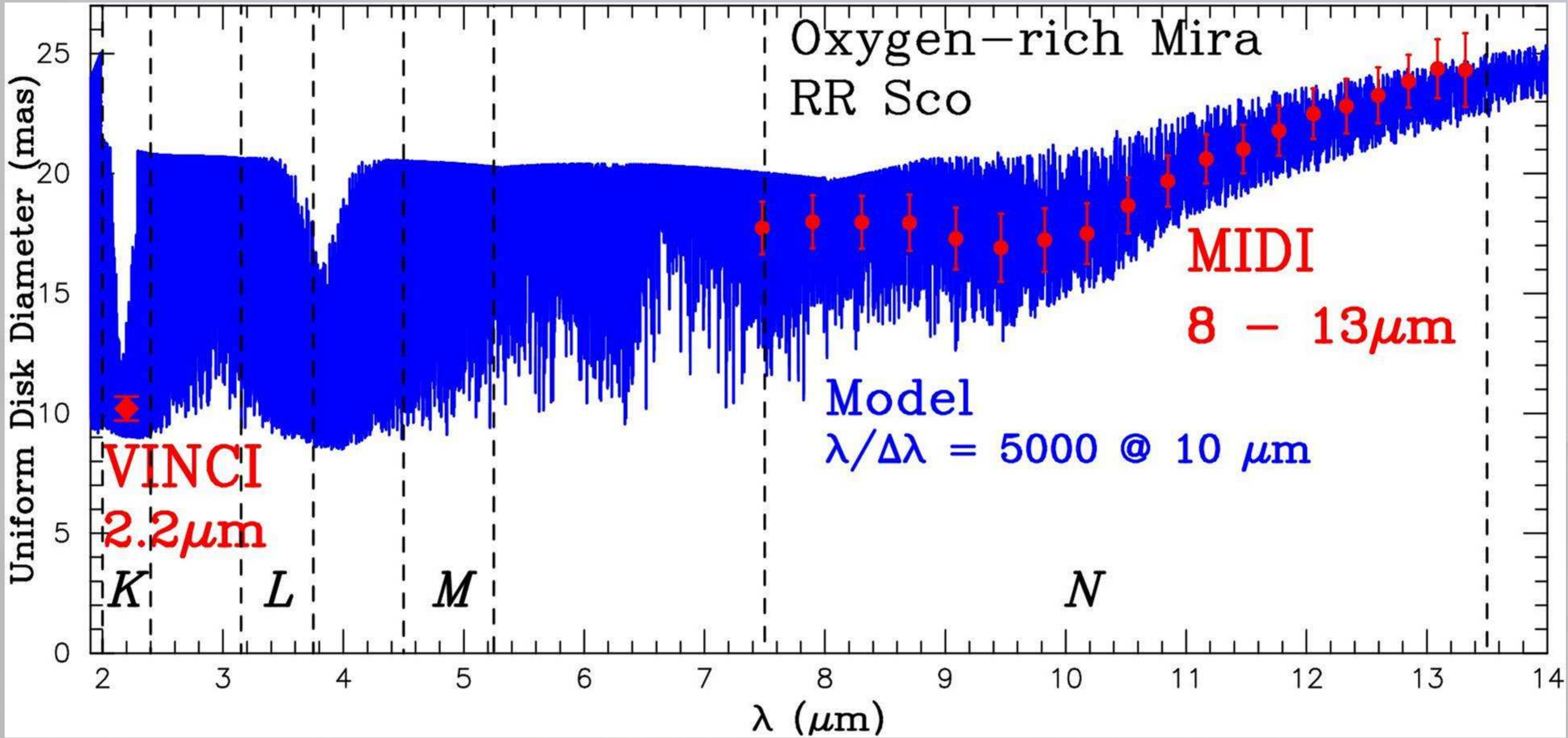
→ Angular size larger

K band (2—2.4µm)

No dust emission

H_2O + CO bands
Not optically thick
→ Angular size smaller

Comparison of model with MIDI / VINCI observations



- Warm molecular layer makes the star appear larger in MIR than in NIR
  ~1400K, 2.3 R_*, column densities = 10^{20}--10^{21} cm^{-2}
  (Large-amplitude pulsation may explain the formation of warm H_2O layers)
- Dust shell emission is responsible for the size increase beyond 10 μm
  Inner radius = 7--8 R_*, Tin = 700--800 K, silicate 20%, corundum 80%

MIDI observation of the silicate carbon star IRAS08002-3803 (Hen 38)

Silicate carbon star : Carbon-rich photosphere,
Silicate emission at 10 and 18 μm
(oxygen-rich circumstellar dust)

CO molecules locks up the least abundant of O or C

Photosphere of M giants (oxygen-rich): C/O < 1

CO, H_2O, TiO, OH, SiO, etc

Circumstellar dust around M giants

Silicate (SiO), Corundum (Al_2O_3), etc

Photosphere of carbon stars: C/O > 1

CO, C_2, CN, HCN, C_2H_2, CS, C_3

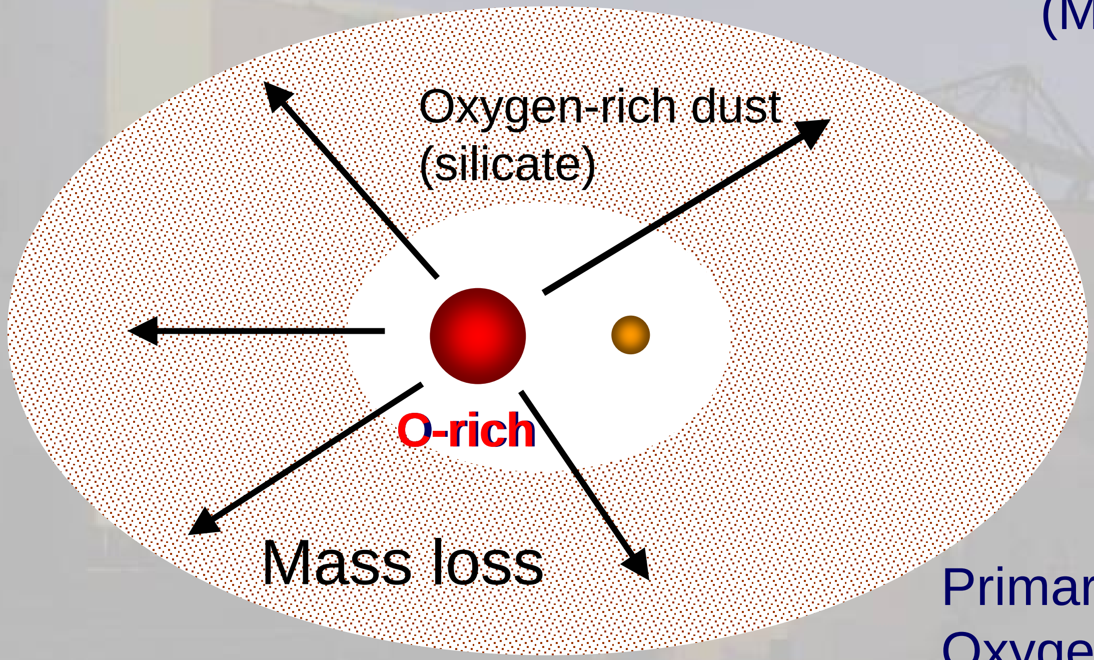
Circumstellar dust around carbon stars

C(amorphous carbon), SiC

How can silicate (O-bearing dust) exist around a carbon star?

Origin of silicate carbon stars:

AGB star + main sequence star (or white dwarf)



No theoretical or observational confirmation

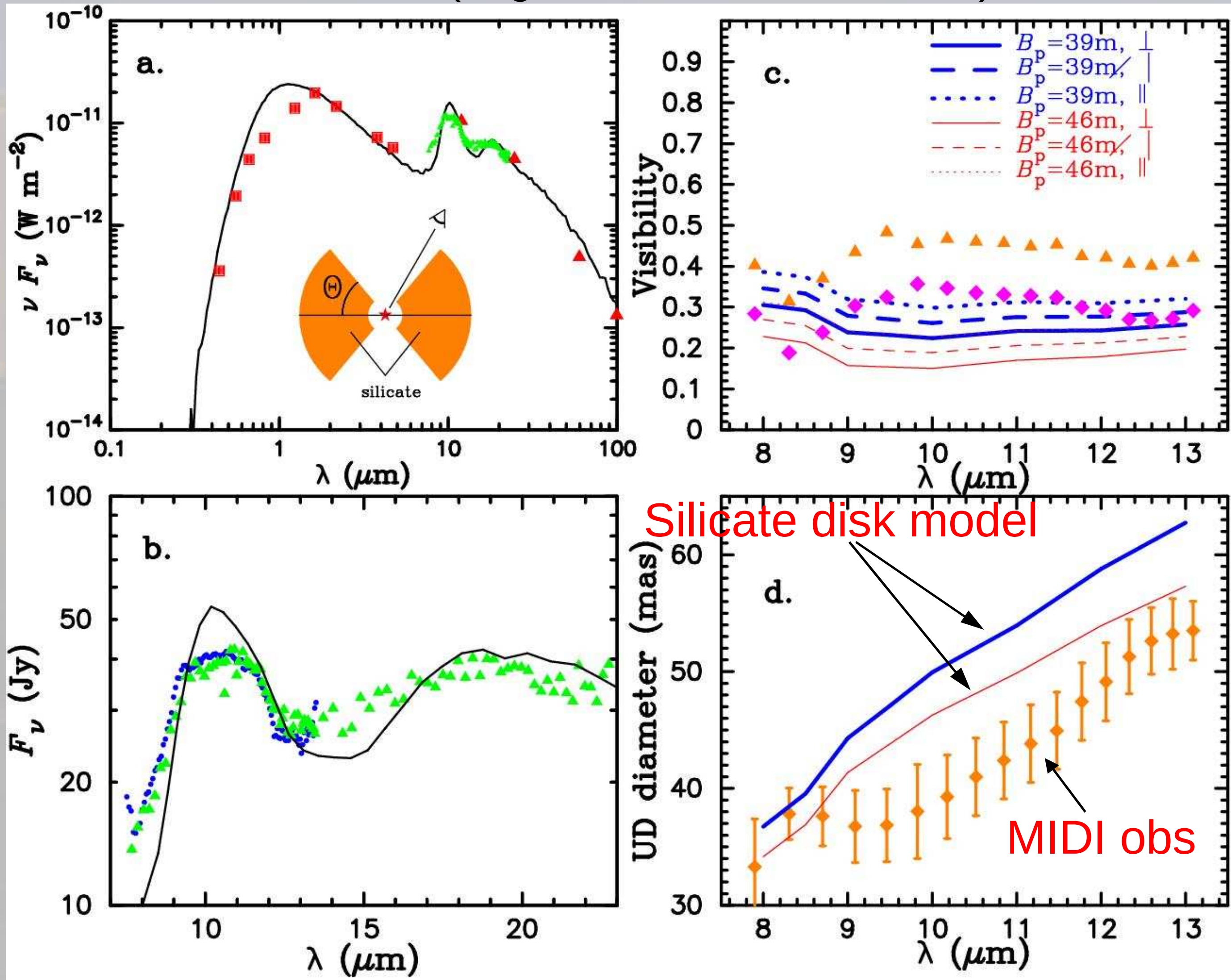
AGB, primary star: oxygen-rich, mass loss
→Circumbinary disk is formed
(Morris 1987; Lloyd-Evans 1990)

Primary star becomes a carbon star.
Oxygen-rich dust is stored in the disk
→ Silicate carbon star

High-resolution observation in the silicate emission feature is the most direct approach → VLTI/MIDI

Wavelength dependence of the angular size of Hen 38

2004 Feb. 09,10,11
UT2—UT3: projected baselines = 40 – 46 m (angular resolution ~15 mas)
P.A. = 30 – 55 deg



Dusty environment spatially resolved for the first time!

Shell or disk models (Monte Carlo code) fail to explain MIDI visibilities!

Possible scenario: disk with 2 grain species

2 grain components may have different angular sizes and different wavelength dependences
← different absorption/scattering properties

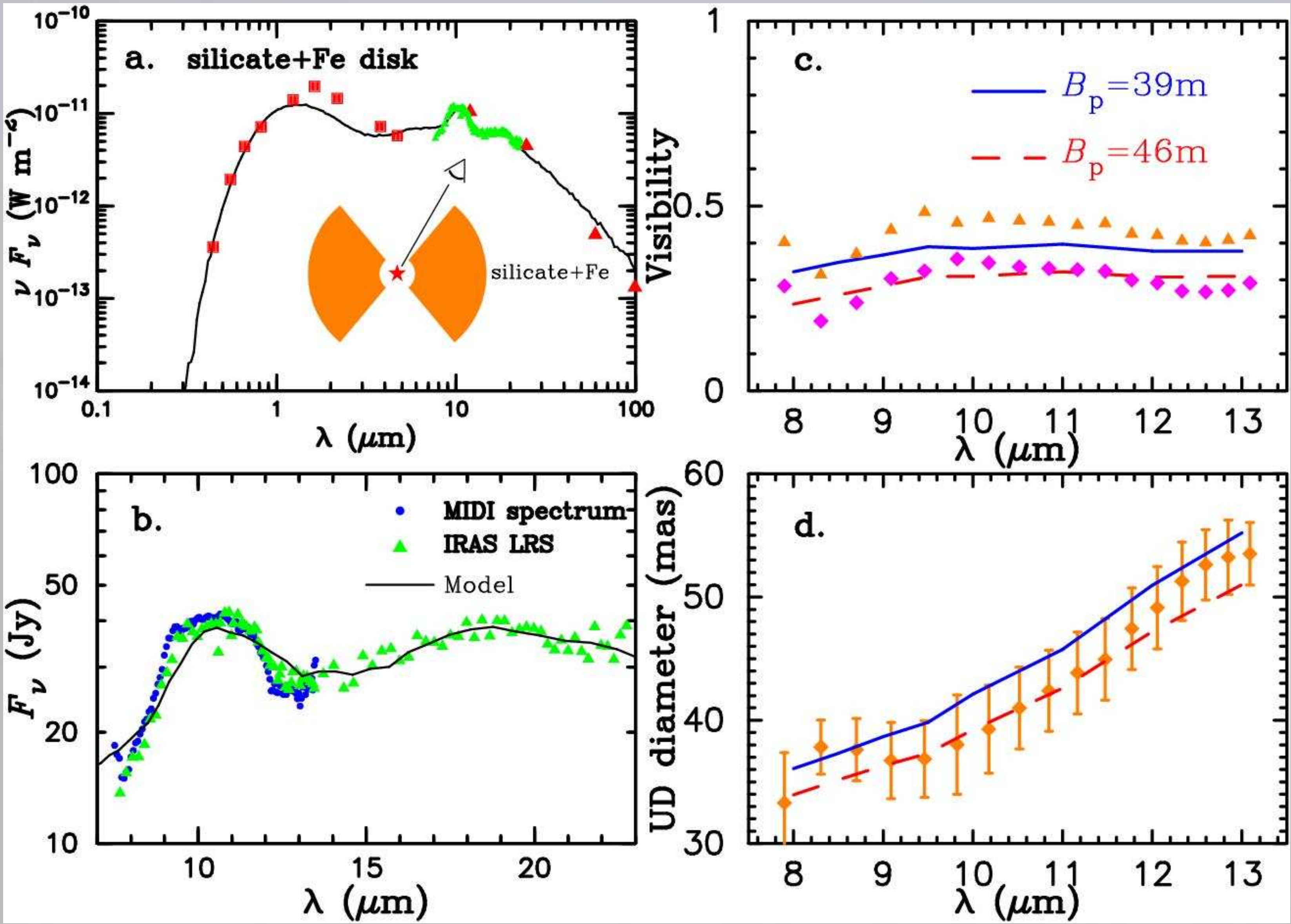
Total visibility (angular size)
= flux-weighted sum of 2 components (+ unresolved star)

(Amorphous) silicate + what grain species?

No conspicuous features in IRAS LRS / MIDI spectrum

→ Amorphous carbon grains
Large silicate grains
Metallic iron grains
→ All 3 species are OK
(ambiguities)

Two-grain-species model: silicate + metallic iron grains



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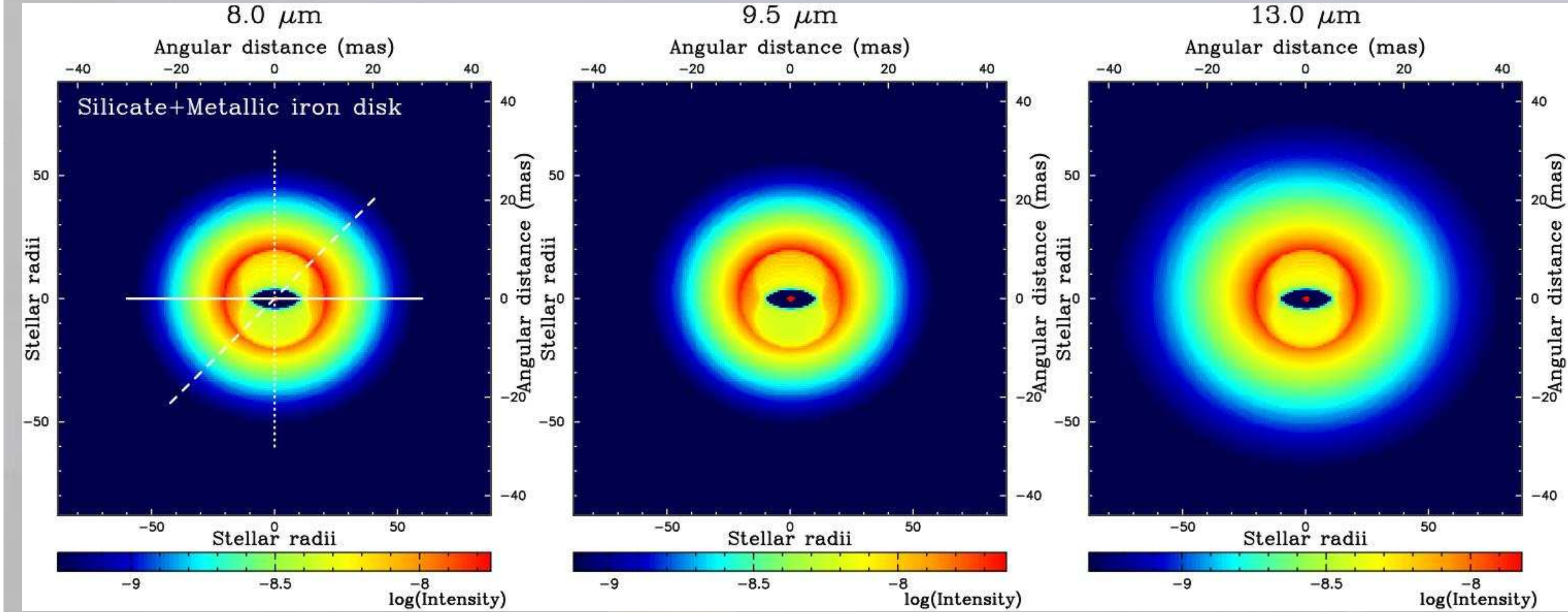

Disk half-opening angle = 50 (+/- 10) deg, Density power law: $r^{-1.6}$

Inclination angle = 30 (+/- 10) deg

Disk is optically thick : τ(V) = 20(+/- 5) (silicate), 3(+/- 1) (iron)

Disk inner radius: 15--20 R_*

→ Binary separation ~10--20R_*

Support for the circumbinary disk scenario

May be related to a close companion

Concluding remarks

Power of spectro-interferometry:

Warm molecular layers
Innermost region of the dust shell in Miras → **Expected picture**

Circumstellar dusty environment of a silicate carbon star

→ **Unexpected picture**

Combine with complementary data (SED, spectra, etc)