Near and mid-infrared visibilities to study cool (super-)giant stars

Ringberg Workshop

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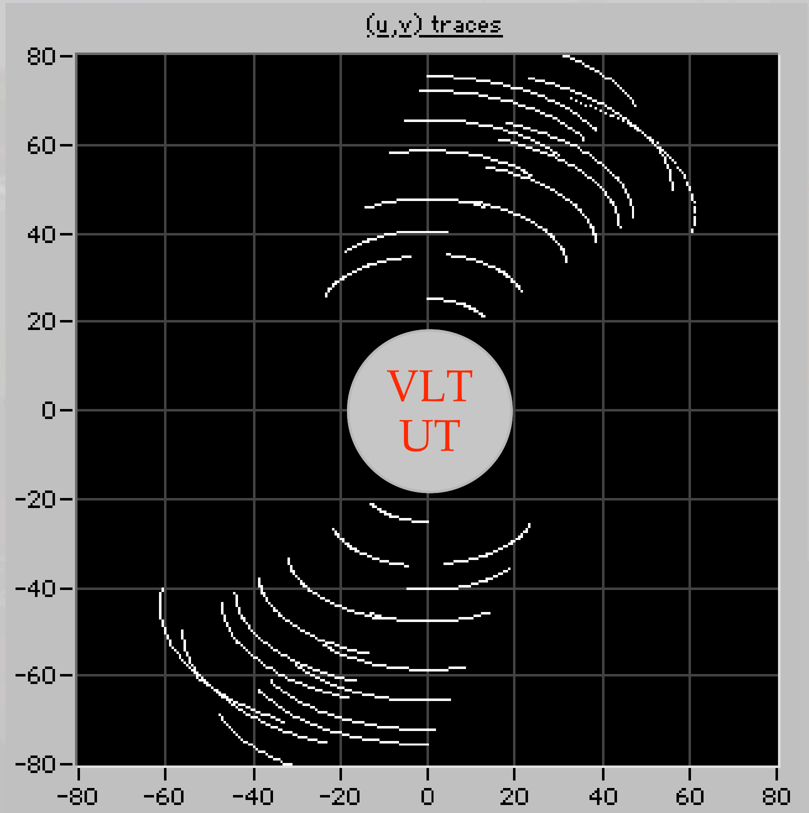
Mont Hopkins

Arizona

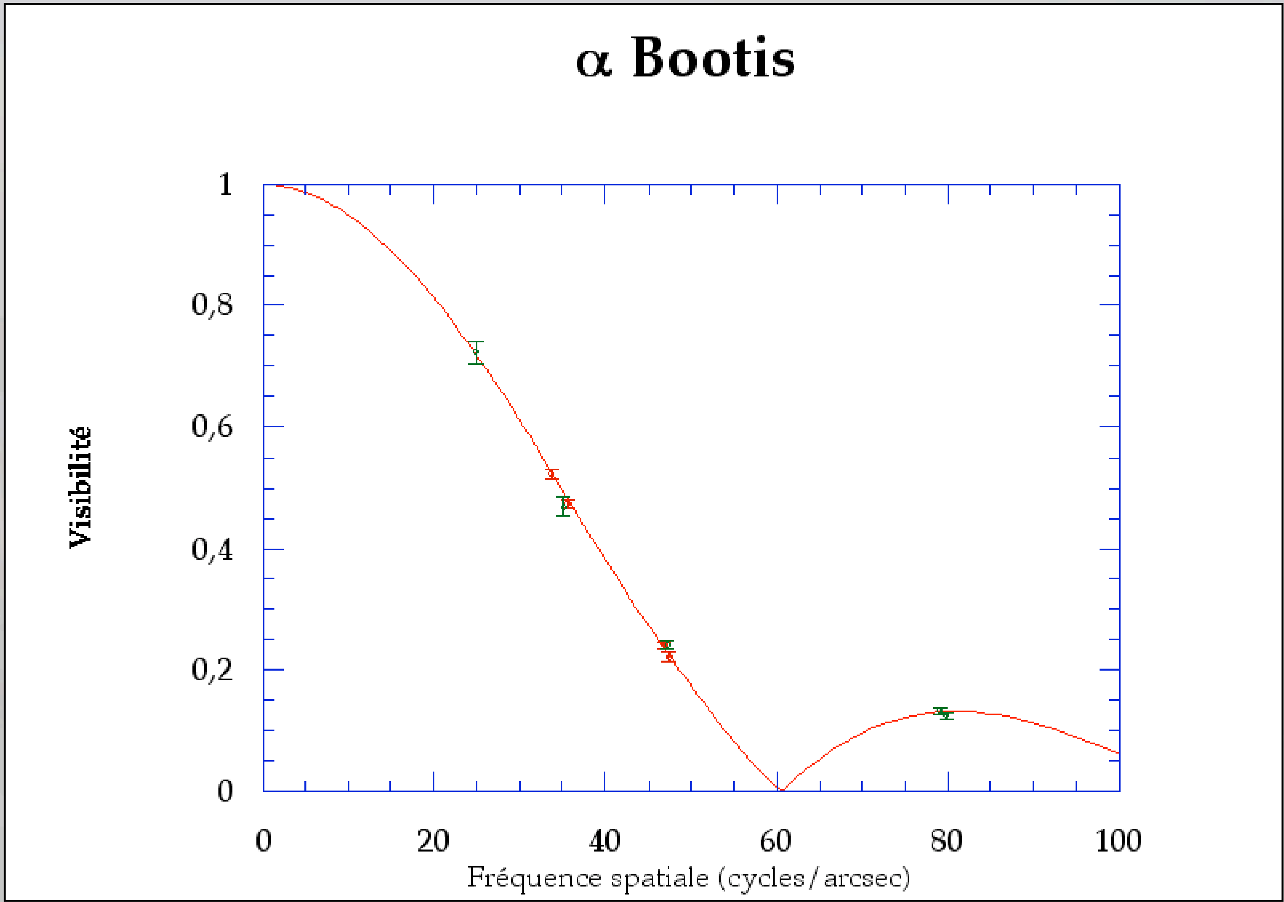
IOTA

Infrared and Optical Telescope Array



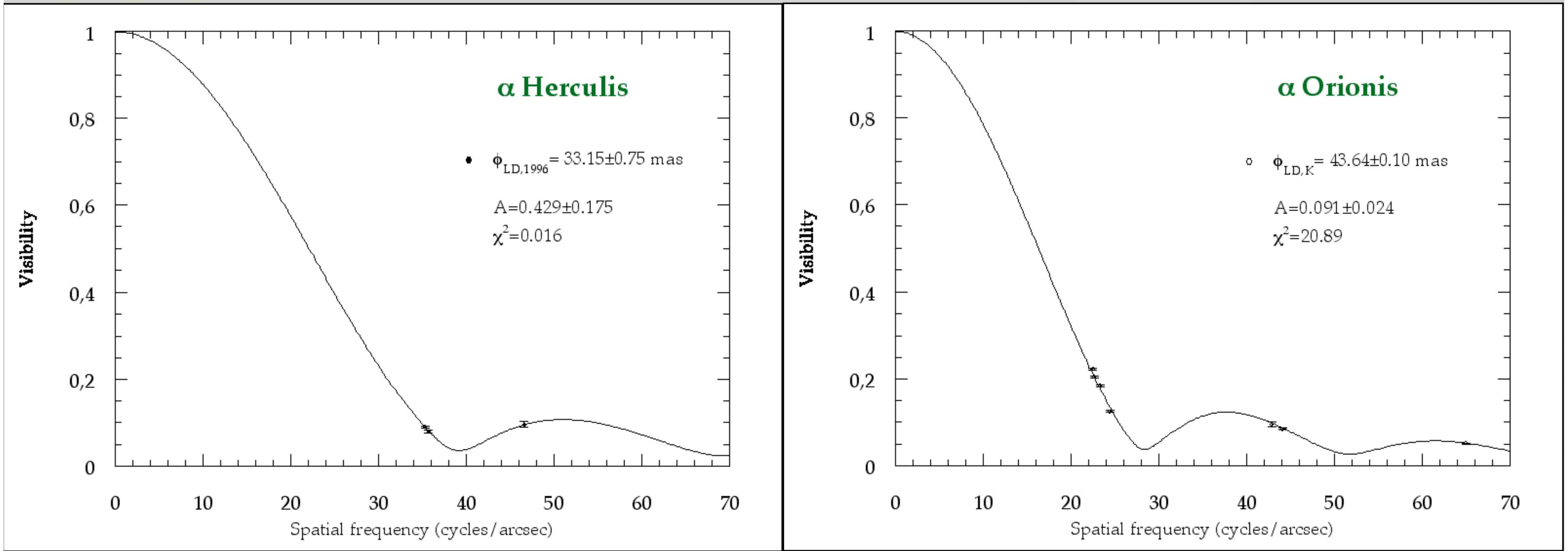
- 3 relocatable 45cm siderostats
- Minimum baseline: 5m
- Maximum baseline: 38m
- FLUOR:
  - 2–2.4 μm (K band)
  - 3.4 – 4μm (L band) (TISIS)

Giants



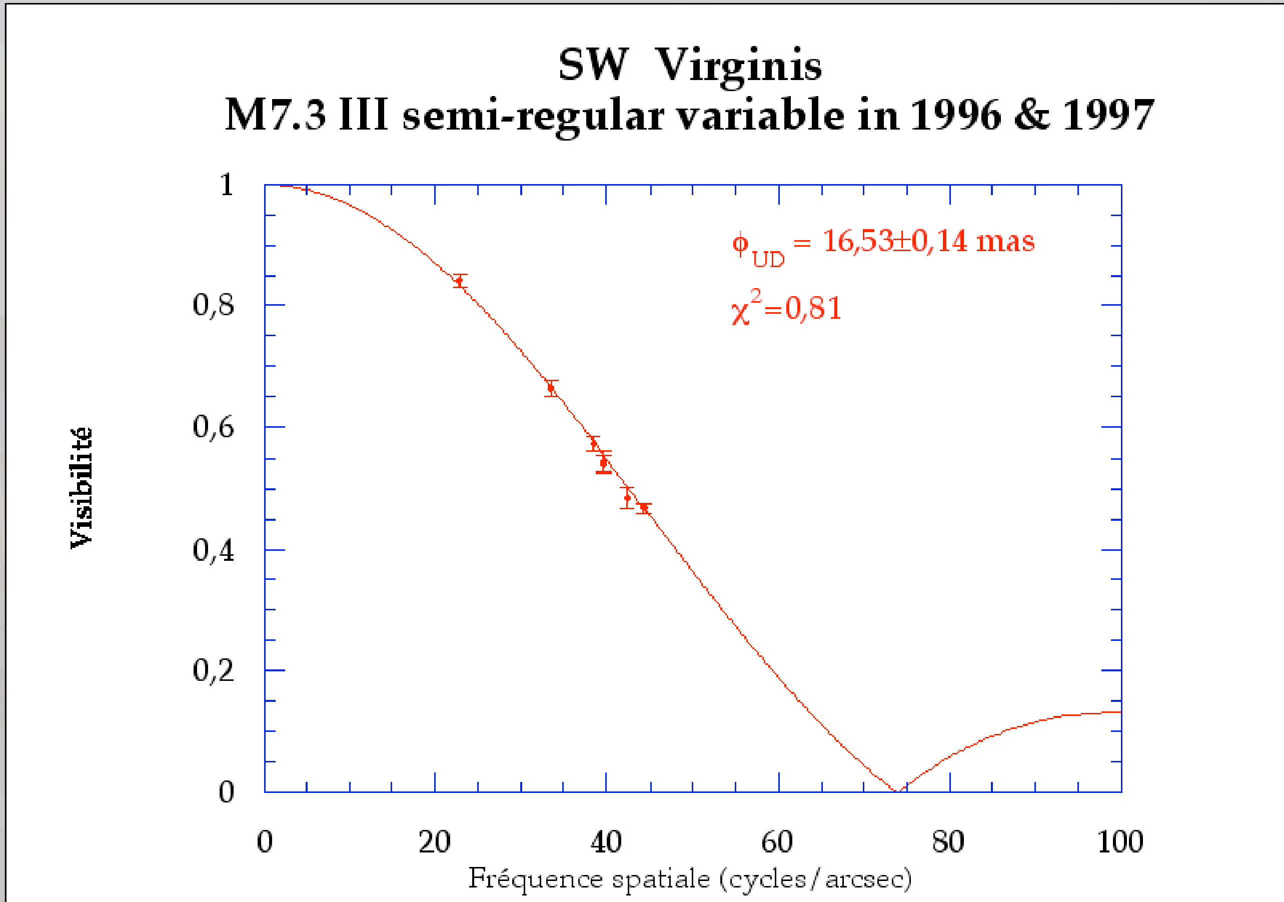
(Perrin et al. 1998)

Supergiants

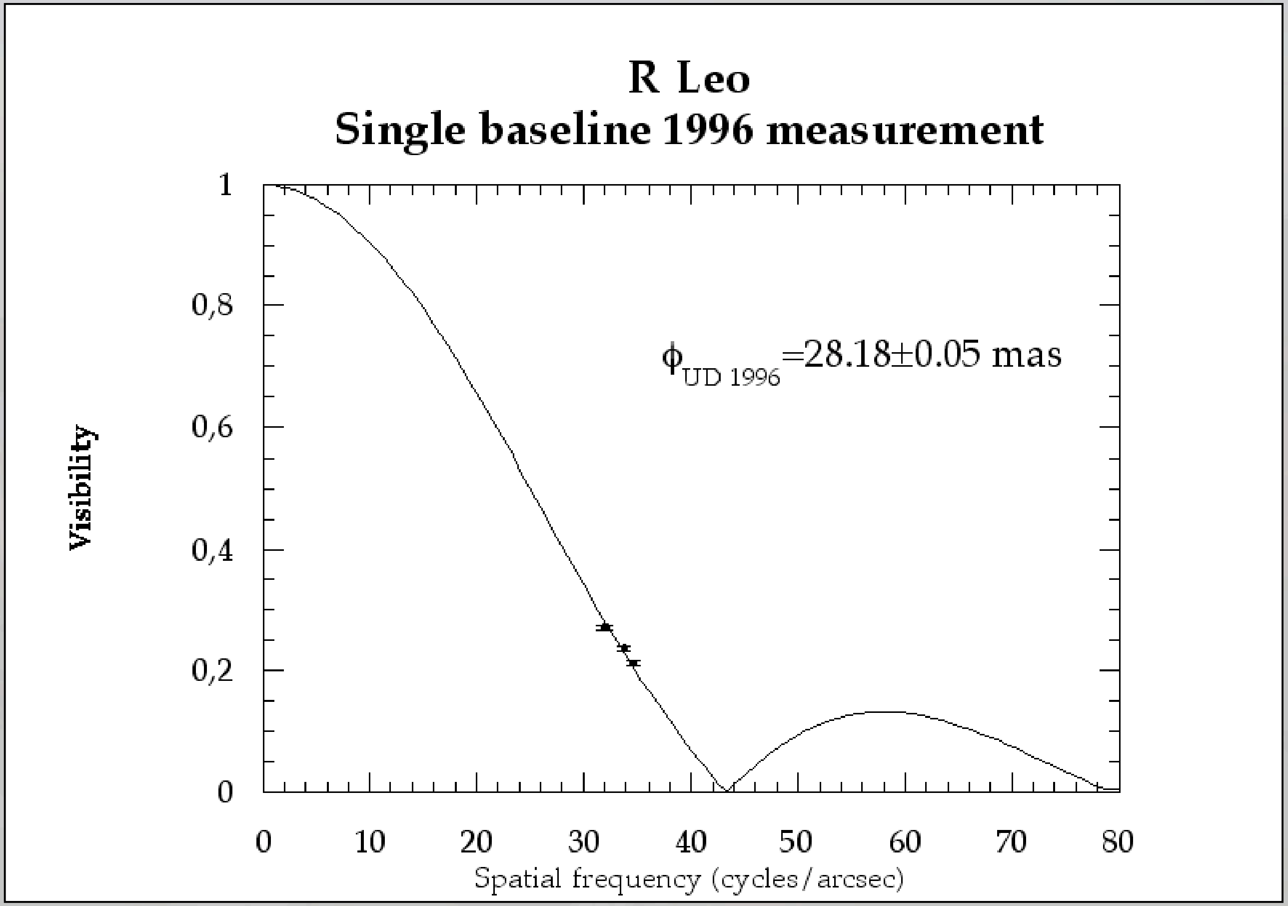


(Perrin et al. 2003, submitted)

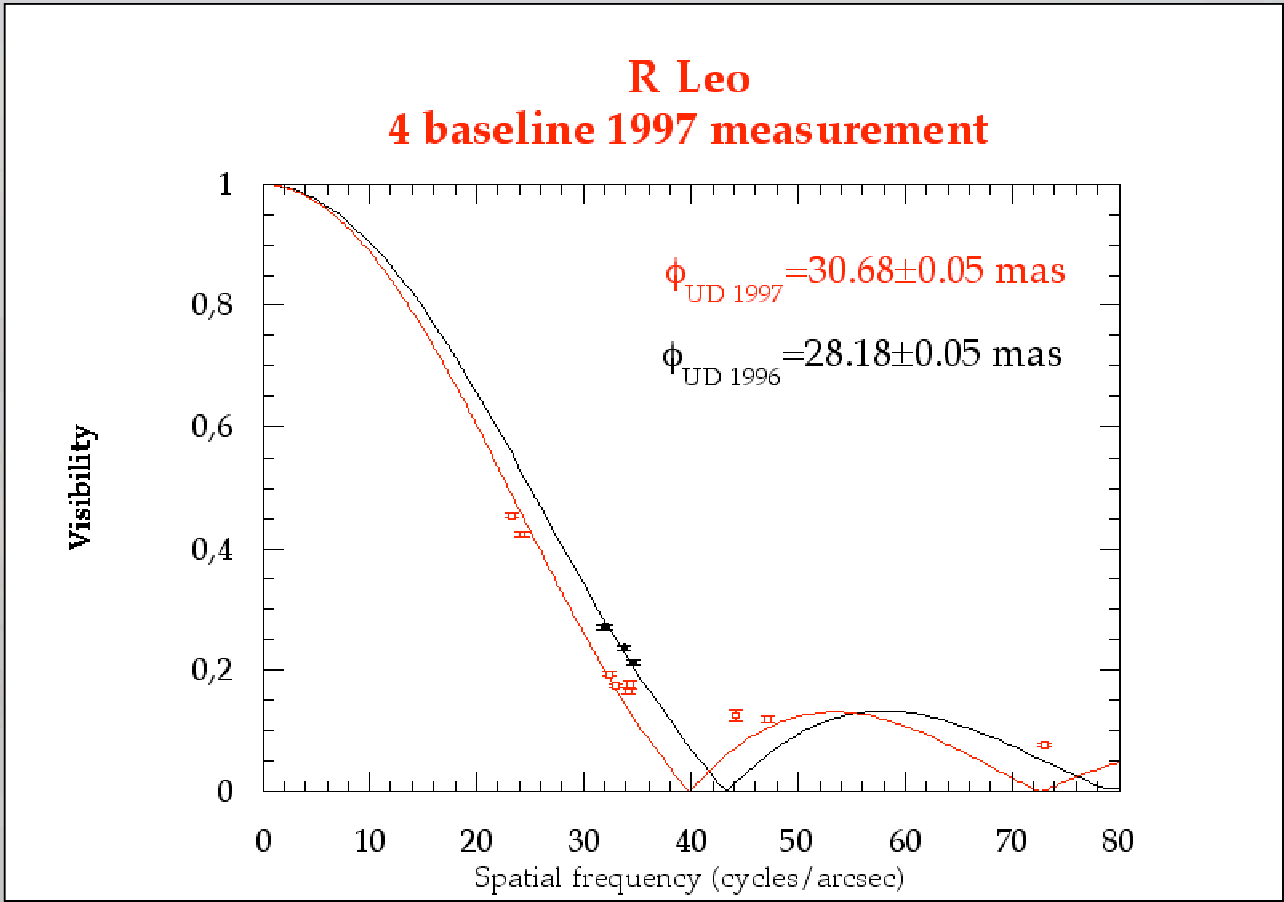
Semi-regular variables



Mira stars


R Leo
Single baseline 1996 measurement
Visibility
1
0,8
0,6
0,4
0,2
0
$\phi_{UD\ 1996}$=28.18±0.05 mas
0
10
20
30
40
50
60
70
80
Spatial frequency (cycles/arcsec)

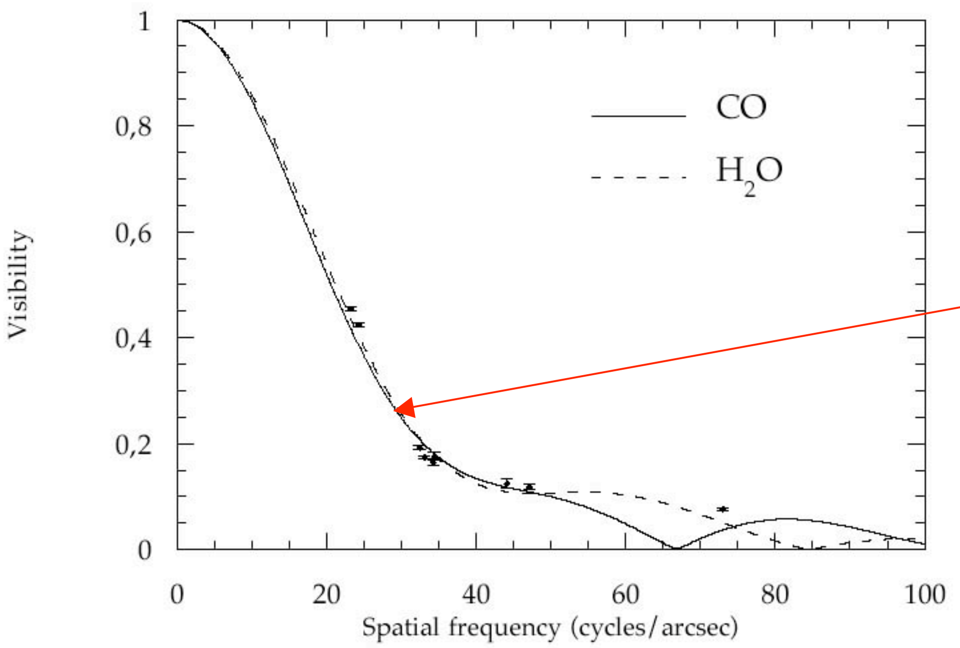
Mira stars



R Leo
4 baseline 1997 measurement
ϕUD 1997=30.68±0.05 mas
ϕUD 1996=28.18±0.05 mas
Visibility
1
0,8
0,6
0,4
0,2
0
0
10
20
30
40
50
60
70
80
Spatial frequency (cycles/arcsec)

Mira stars

R Leo K band measurements with FLUOR in 1997 (Perrin et al. 1999)



Possible explanations:

- spots
- limb-brightening
- «scattering» by envelope

Scholz &Takeda (1987) models in molecular bands only

If this hypothesis is correct then:

Ø$_{photosphere}$ ~ 24 mas
T_{eff} ~ 3000 K
Pulsation mode = fundamental

Spatial characterization of the close environment is necessary : molecular or dust effect or both?

Available High Angular Resolution data

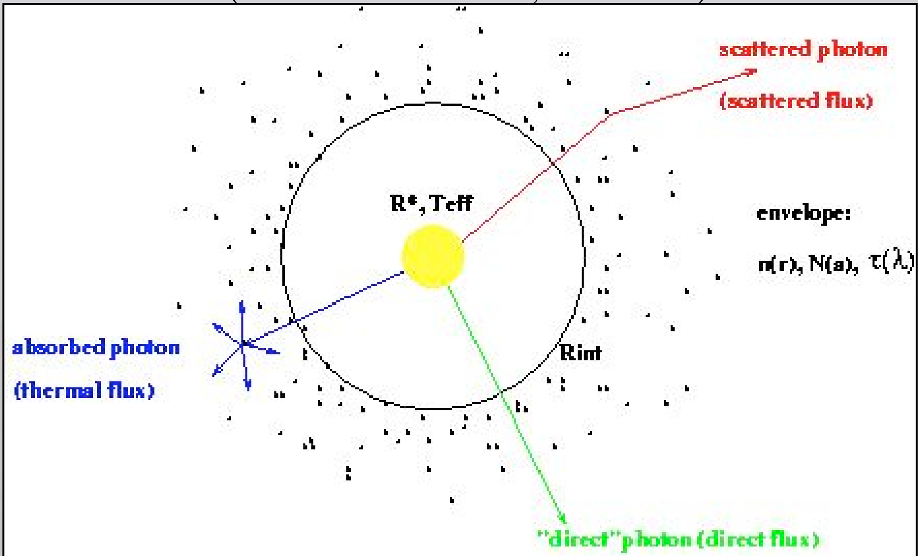
- **<u>Below ~ 1μm:</u>**
  - Very strong molecular bands (TiO) which obscure the photosphere
  - Visibility curves are gaussian and the equivalent diameters are quite big
  - Not a good probe of the photosphere which is confused by the thick atmosphere

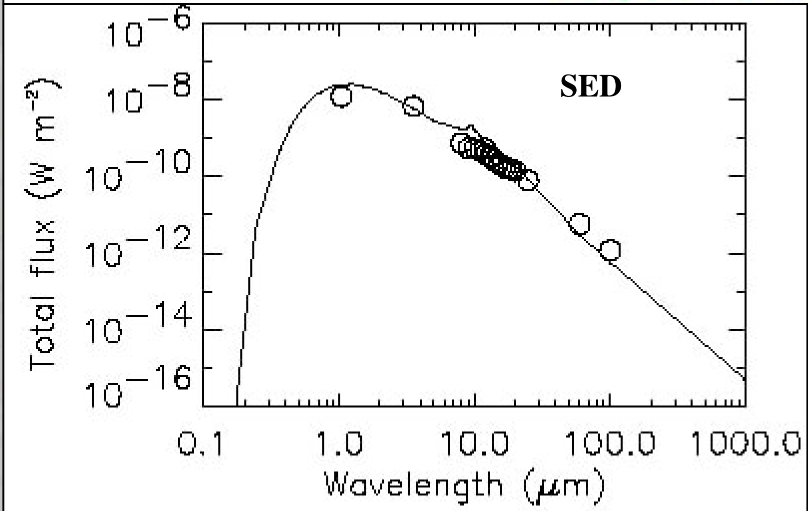
- **<u>Above ~ 10μm:</u>**
  - Detection of dust but far from stellar photosphere (~ 300 K)
  - *A priori* poor sensitivity to molecular bands

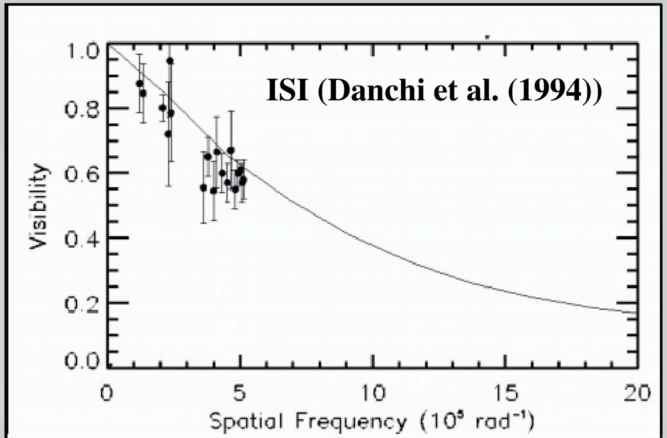
- **<u>« Choices »:</u>**
  - K band : continuum + CO and H_2O bands
  - L band : continuum, sensitive to close circumstellar environment ~ 1000 K

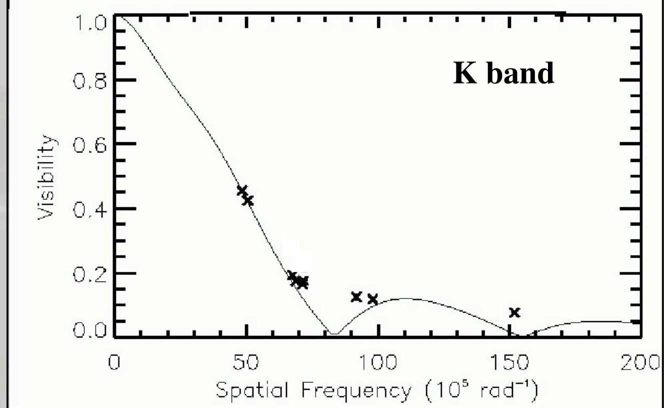
Wide band K & L: the dust hypothesis

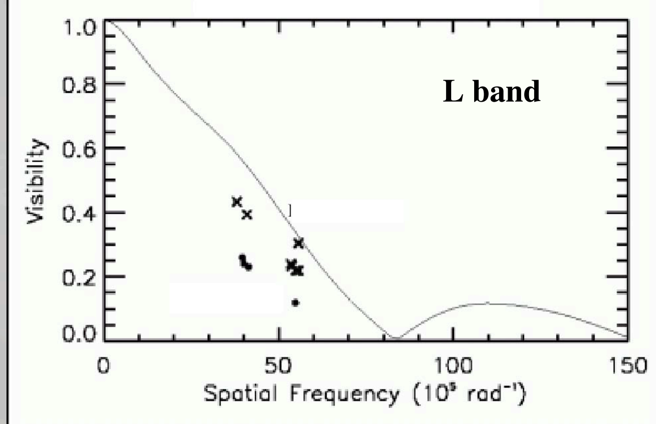
(Schuller et al. 2003, submitted)





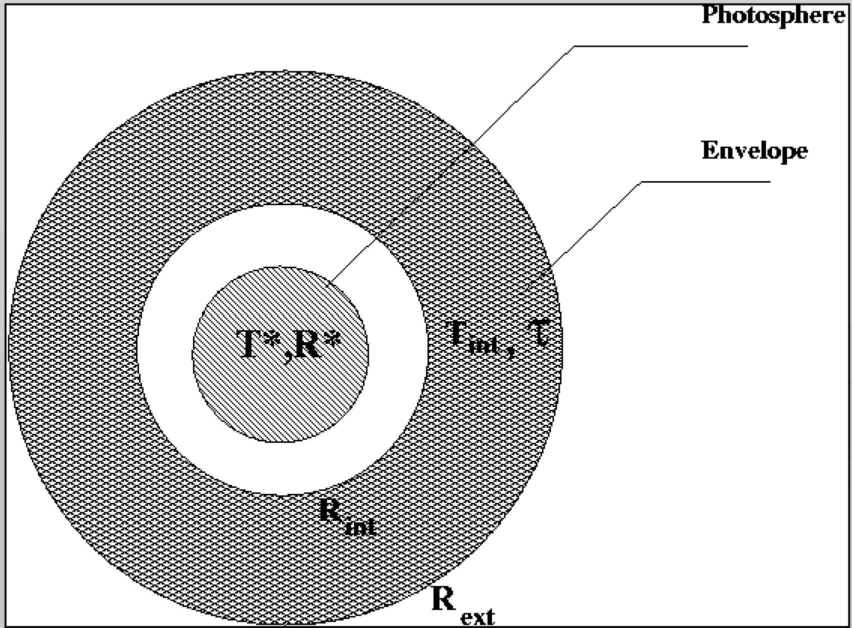


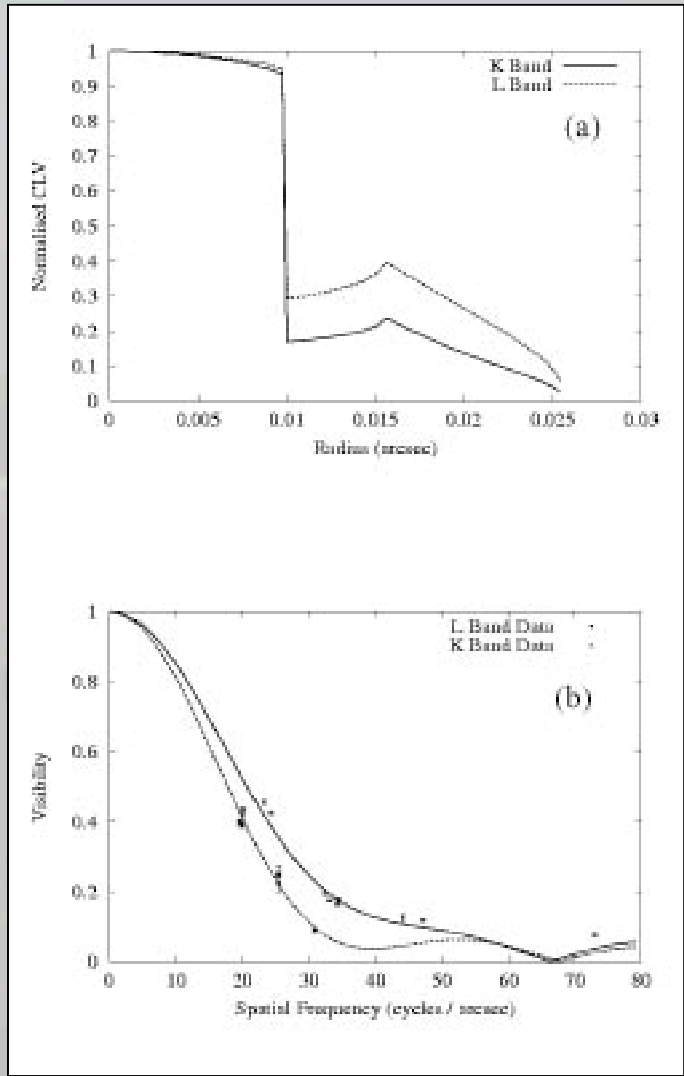




Wide band K & L: the close layer hypothesis

(Mennesson et al. 2002)



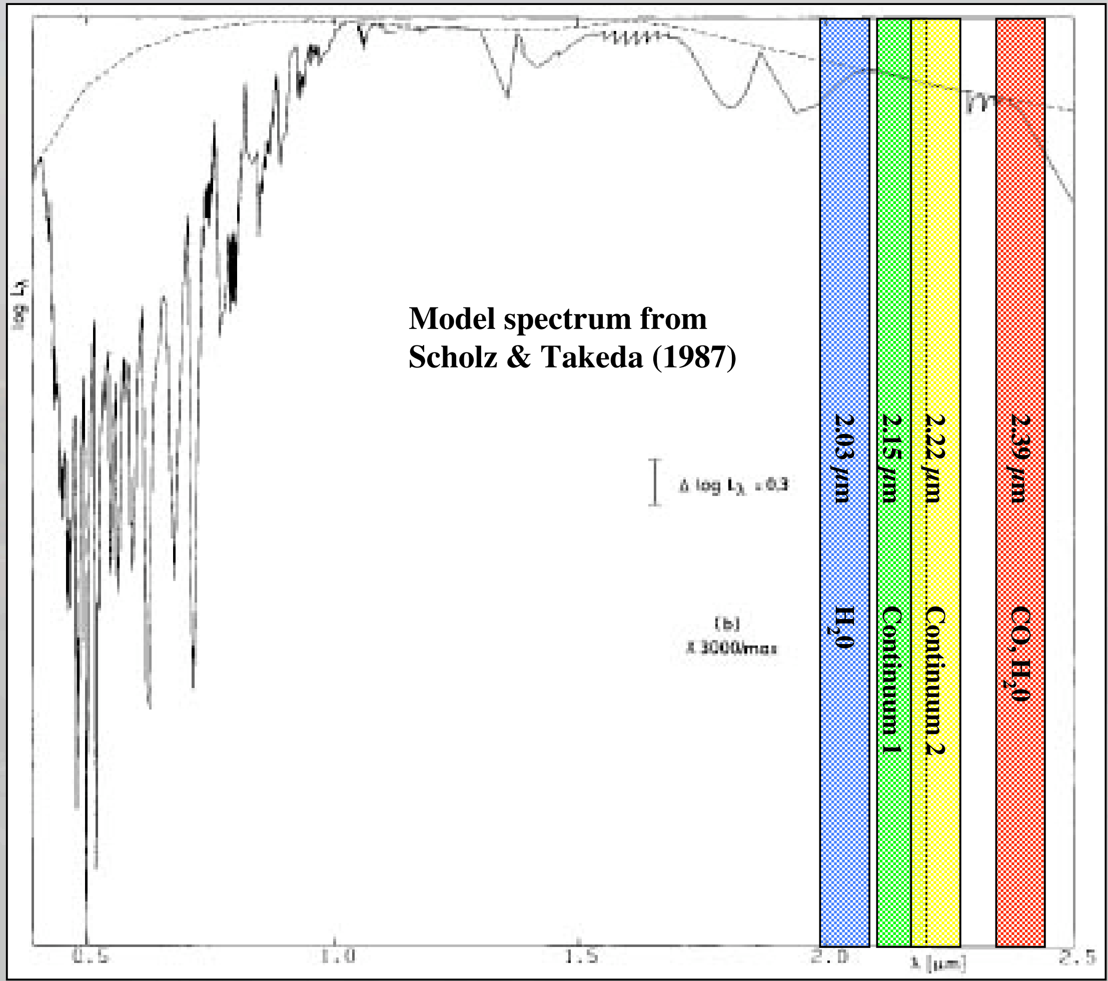


<u>Main model parameters:</u>

$R_* = 10$ mas	$R_{in} = 15$ mas
$T_* = 2700$ K	$R_{out} = 27$ mas
$\tau = 0.5$	$T_{in} = 1730$ K

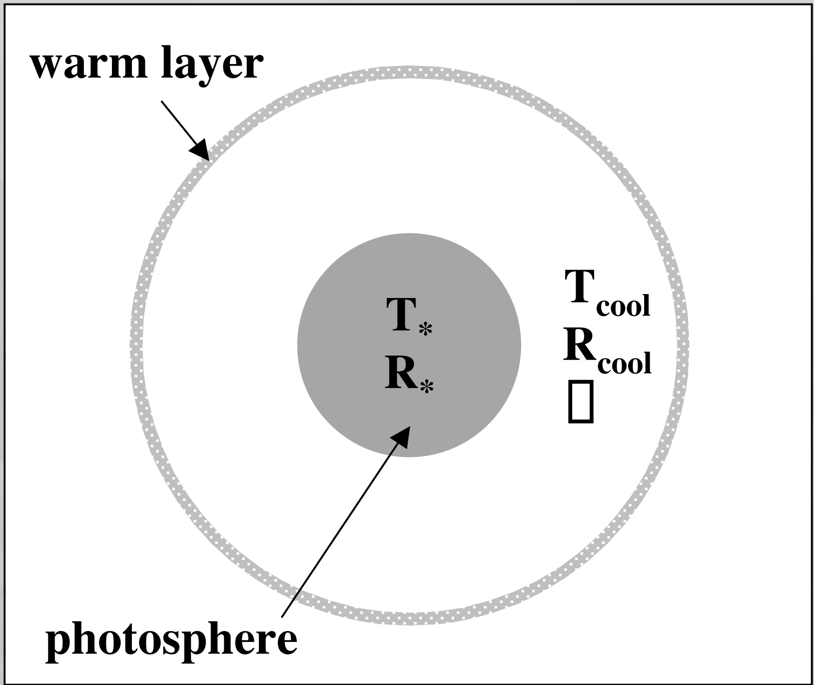
(manual optimization of parameters)

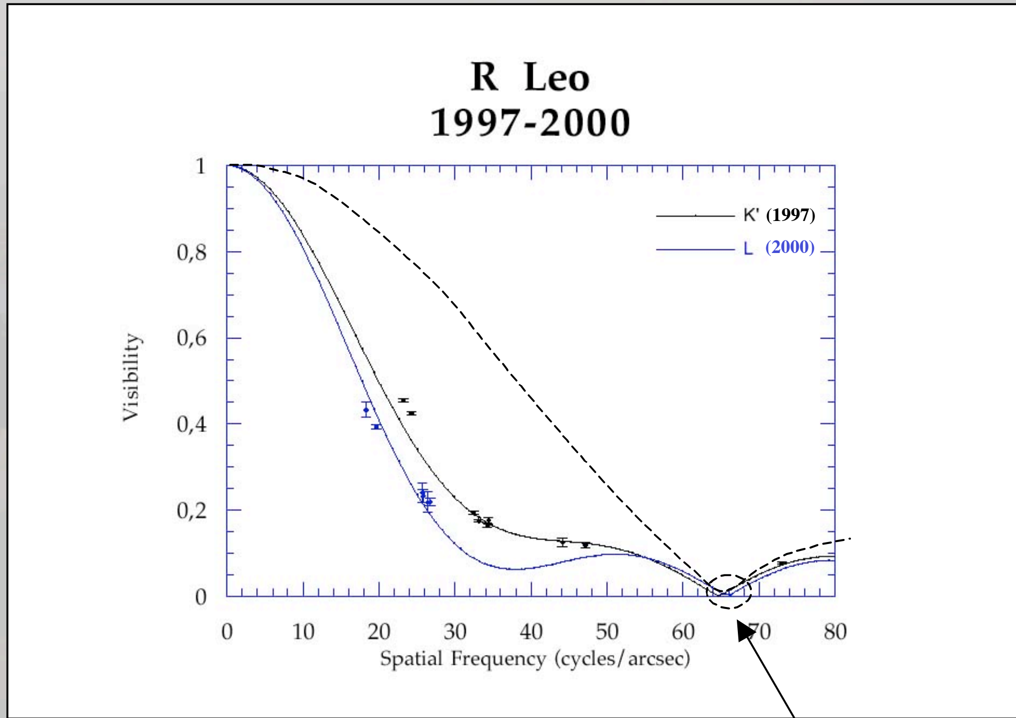
Narrow band observations in K



Simple model: photosphere + single layer

(also described in Scholz 2001)





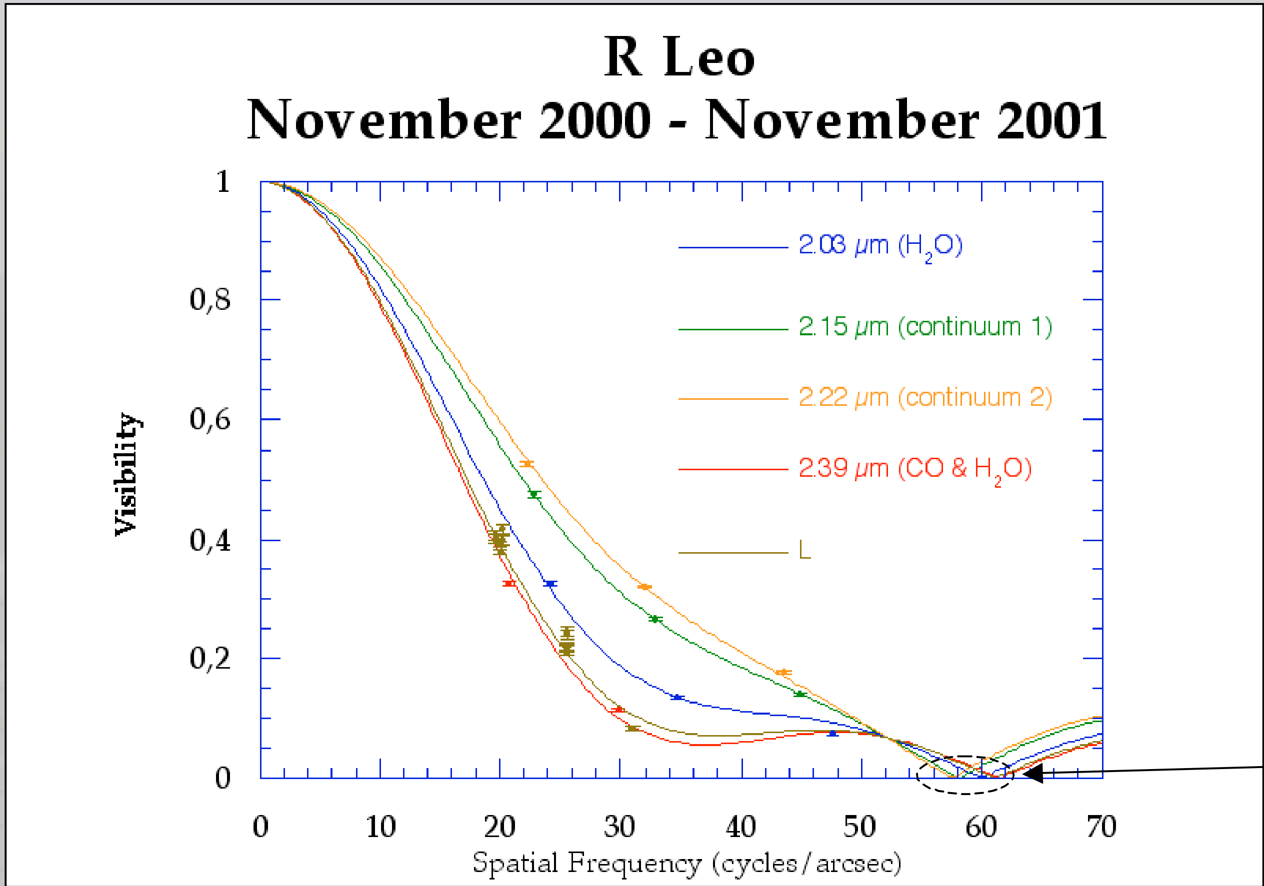
Diameter of the photosphere

R_* = 10 mas
T_* = 2700 K
□ = 0.30
(manual parameter optimization)

R_{cool} = 23 mas
T_{cool} = 1700 K

Phase K: 0.28
Phase L: 0.81

Fitting the narrow and L band data of R Leo with the model



$□_{2.03\mu m}$ = 1.19±0.01

$□_{2.15\mu m}$ = 0.51±0.01

$□_{2.22\mu m}$ = 0.33±0.01

$□_{2.39\mu m}$ = 1.37±0.01

$□_{L}$ = 0.63±0.01

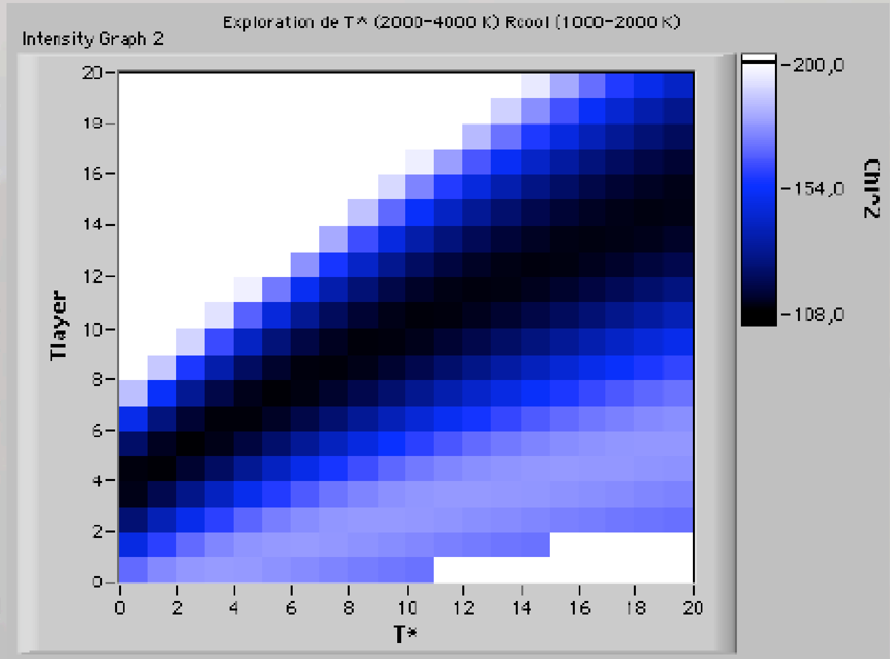
apparent diameter decreases with □
= limb-darkening effect

R_* = 10.94±0.09 mas **R_{layer} = 25.00±0.17mas** **Phase K: 0.79** **Type: M0-M1**

T_* = 3856±119 K **T_{layer} = 1598±24 K** **Phase L: 0.64**

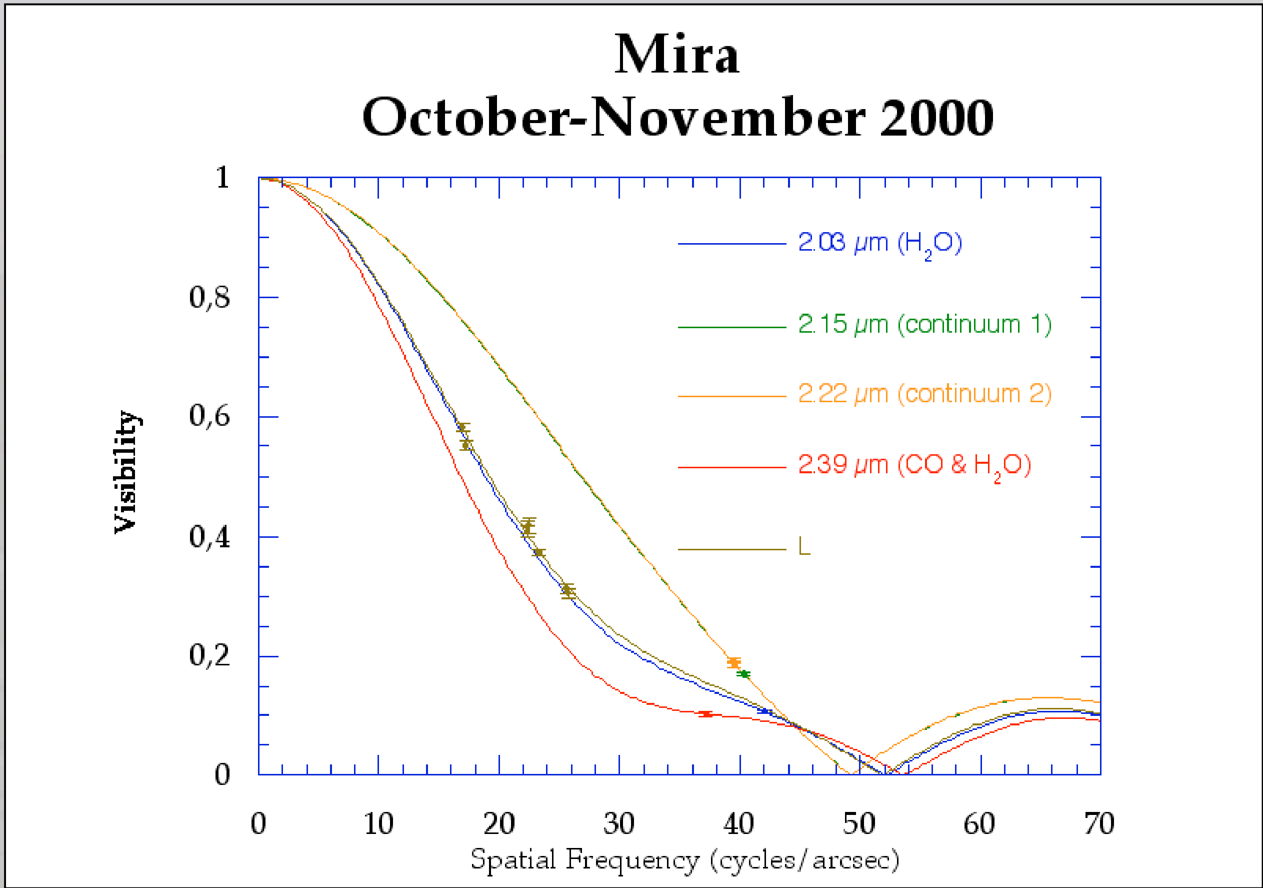
Method to find the optimum parameters

1. Explore (R_*,R_{layer}) space and pick-up optimum
2. T_* and T_{layer} are linked at optimum: $T_*=f(T_{layer})$



1. Constrain T_* and T_{layer} with K (and L) magnitudes
2. Fit best optical depths in each band

Fitting the narrow and L band 2000 data of Mira



$□_{2.03\mu m}$ = 0.14±0.02

$□_{2.15\mu m}$ = 0.01±0.01

$□_{2.22\mu m}$ = 0.01±0.01

$□_{2.39\mu m}$ = 0.21±0.01

$□_{L}$ = 0.08±0.01

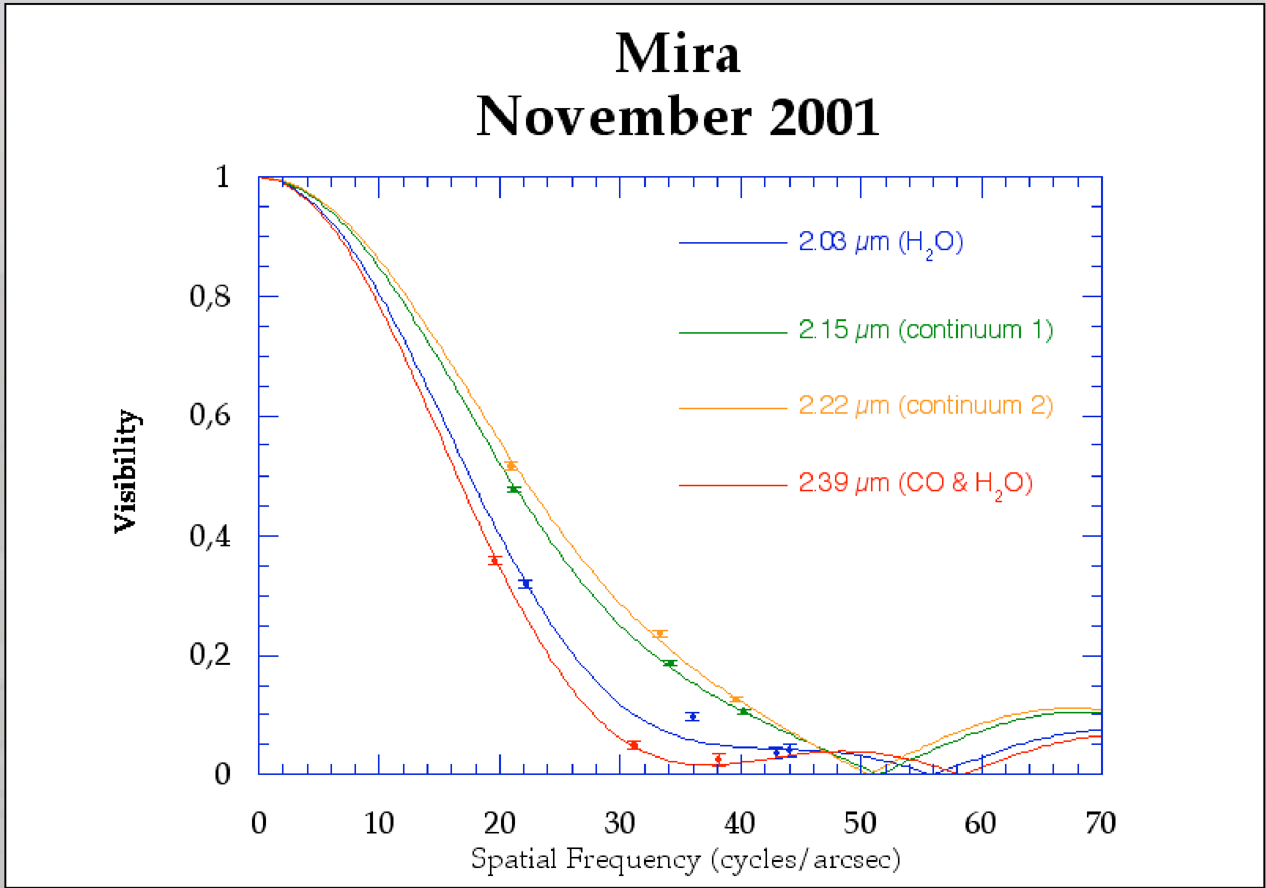
R_* = 12.34±0.02 mas
T_* = 3263±105 K

R_{layer} = 26.84±0.06 mas
T_{layer} =2106±53 K

Phase K: 0.01
Phase L: 0.10

Type: M6

Fitting the narrow band 2001 data of Mira



$\square_{2.03\mu m}$ **= 0.63±0.21**

$\square_{2.15\mu m}$ **= 0.19±0.05**

$\square_{2.22\mu m}$ **= 0.12±0.04**

$\square_{2.39\mu m}$ **= 0.76±0.50**

R_* = 12.71±0.15 mas **R_{layer} = 24.95±0.10 mas** **Phase: 0.19** **Type: M3-M4**

T_* = 3600±67 K **T_{layer} = 1961±17 K**

Comparison of Mira data at phases 0 and 0.2

Phase 0 (October 2000)

$R_* = 12.34 \pm 0.02$ mas $R_{layer} = 26.84 \pm 0.06$ mas

Phase 0.2 (November 2001)

$R_* = 12.71 \pm 0.15$ mas $R_{layer} = 24.95 \pm 0.10$ mas

R_* ↗ 0.37 mas (3%)

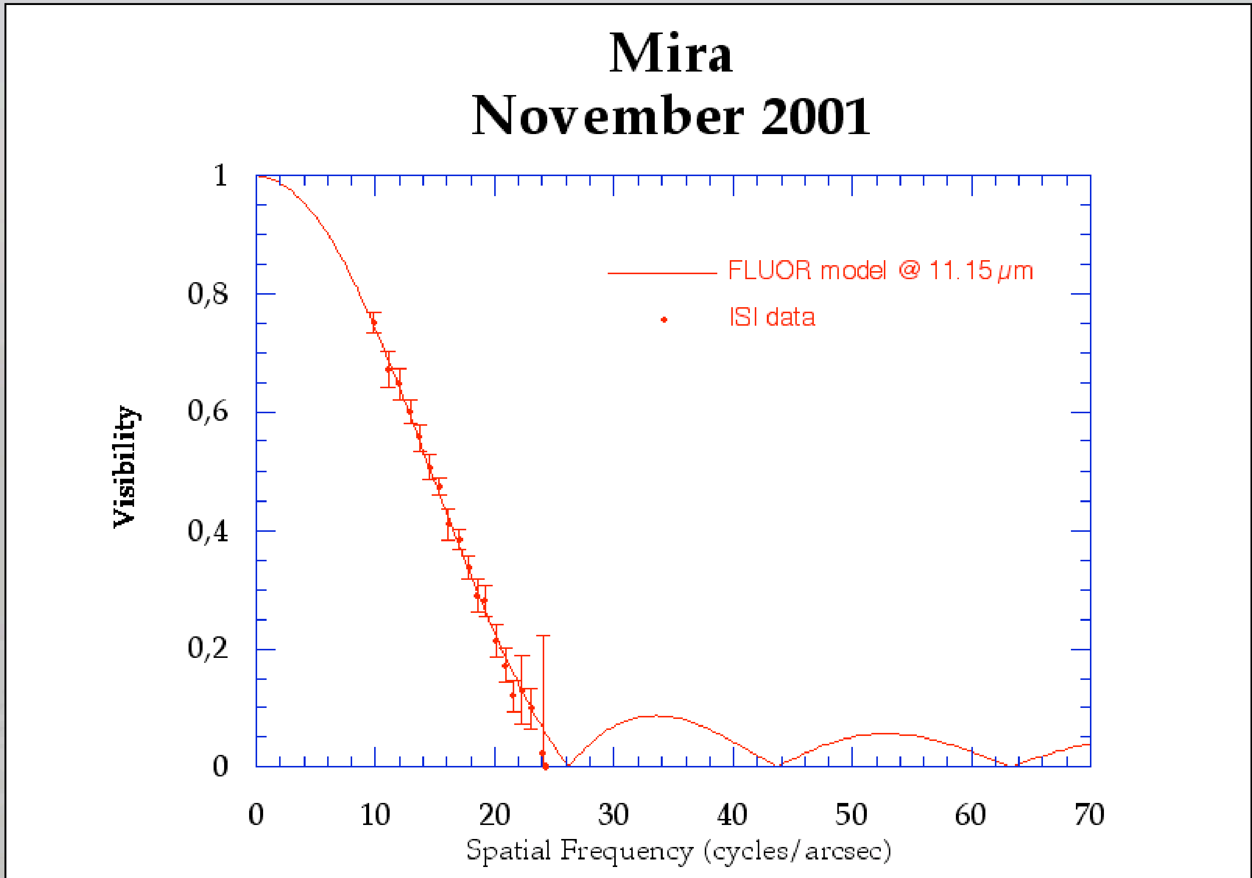
R_{layer} ↘ 1.89 mas (7.3%)

although the apparent diameter change (UD) is + 20%

Phase 0		Phase 0.2
$\square_{2.03\mu m} = 0.14 \pm 0.02$	⇒	$\square_{2.03\mu m} = 0.63 \pm 0.21$
$\square_{2.15\mu m} = 0.01 \pm 0.01$		$\square_{2.15\mu m} = 0.19 \pm 0.05$
$\square_{2.22\mu m} = 0.01 \pm 0.01$		$\square_{2.22\mu m} = 0.12 \pm 0.04$
$\square_{2.39\mu m} = 0.21 \pm 0.01$		$\square_{2.39\mu m} = 0.76 \pm 0.50$

The apparent diameter change could be due to a pure optical depth effect

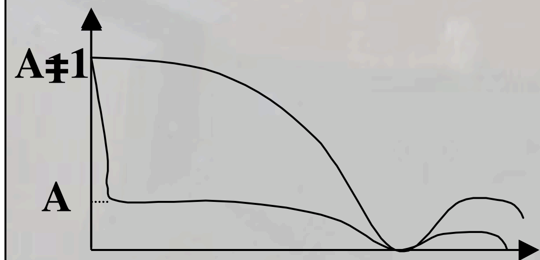
Comparison to ISI 11.15 μm data



A=7.10^{-2}

$$V(x) = \frac{2AJ_1(2\pi r x)}{(2\pi r x)}$$

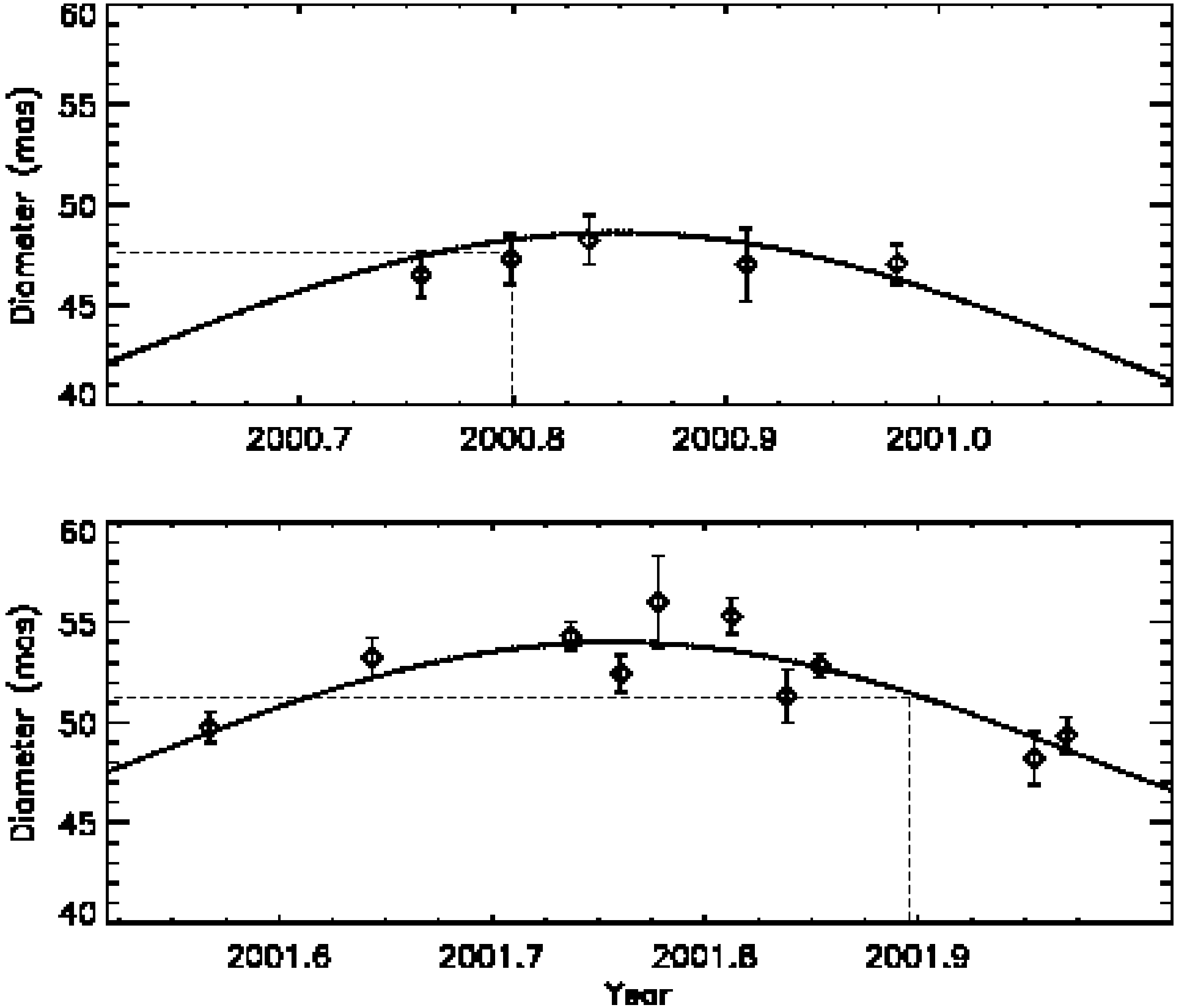
A=1



The disk seen by ISI @ 11.15 µm may be the molecular layer above the photosphere

□= 1.06±0.14

(Weiner et al. 2003)

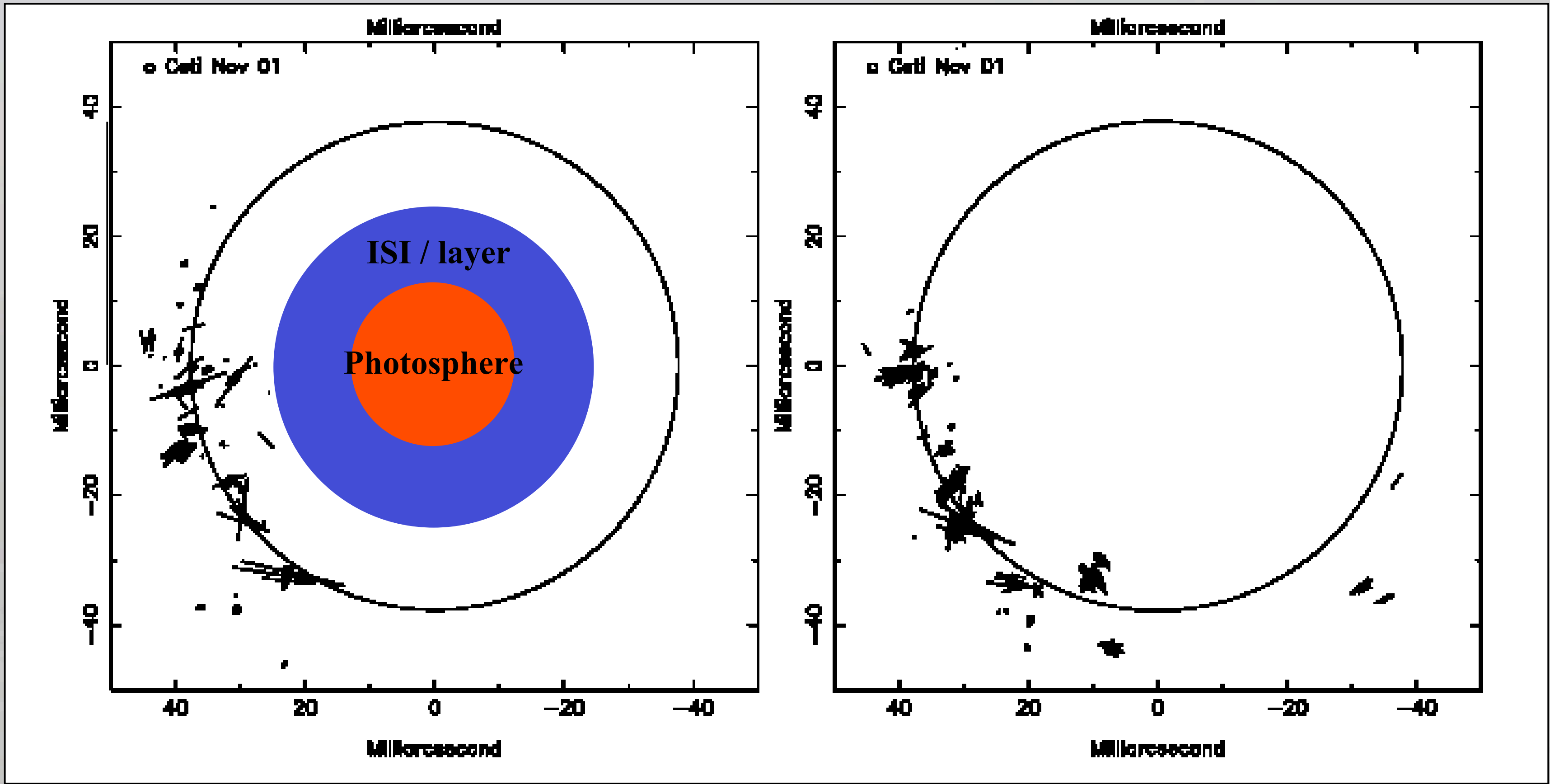


	2000.8		*2001.9*
FLUOR (R_{layer})	**27 mas**	↘	**25 mas**
ISI (R_*)	**24 mas**	↗	**25,5 mas**

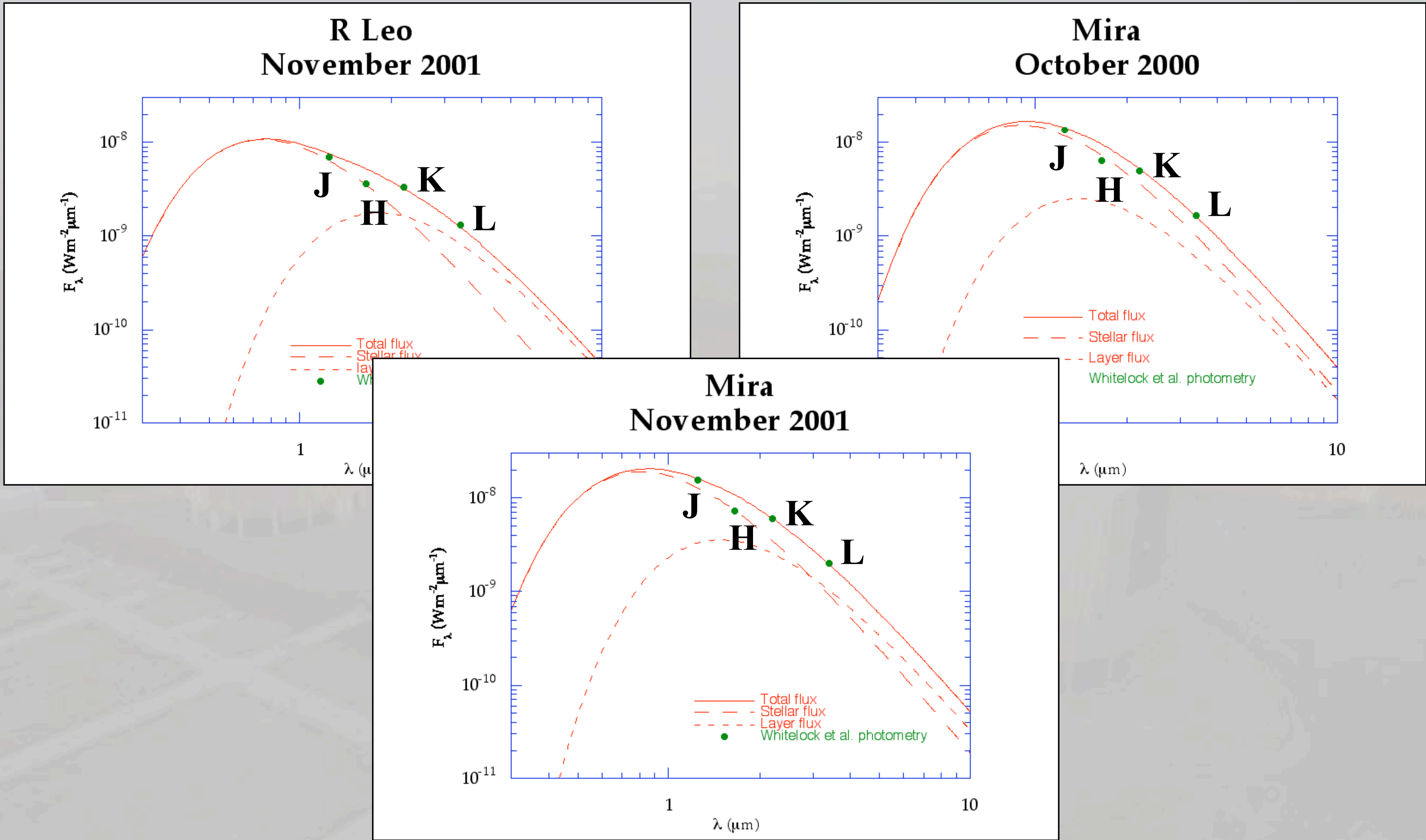
Optical depth effect ?

Connection to closest masers (SiO)

(Cotton et al. 2003, submitted)

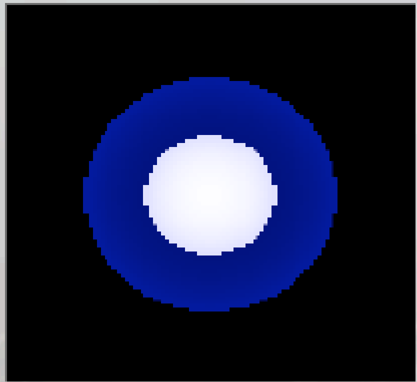


Consistency check with JHKL magnitudes

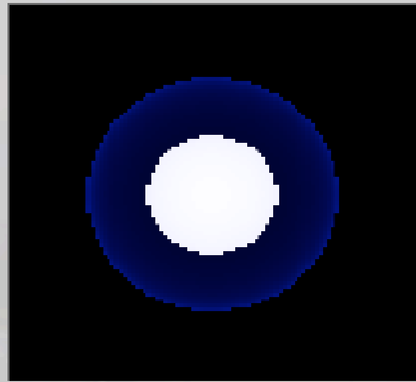


Brightness distributions for Mira 11/2001

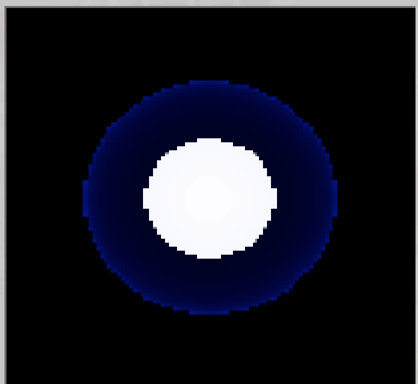
2.03 µm (H_2O)



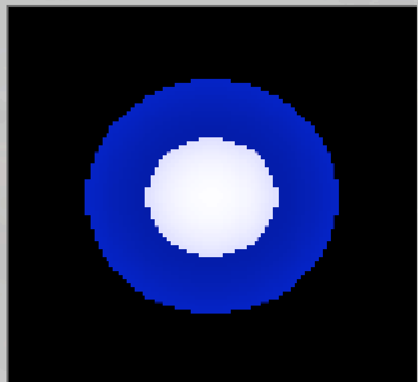
2.15 µm



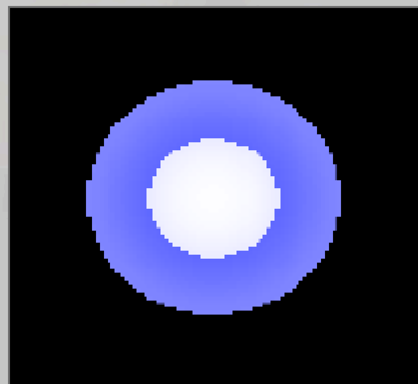
2.22 µm



2.39 µm (CO & H_2O)



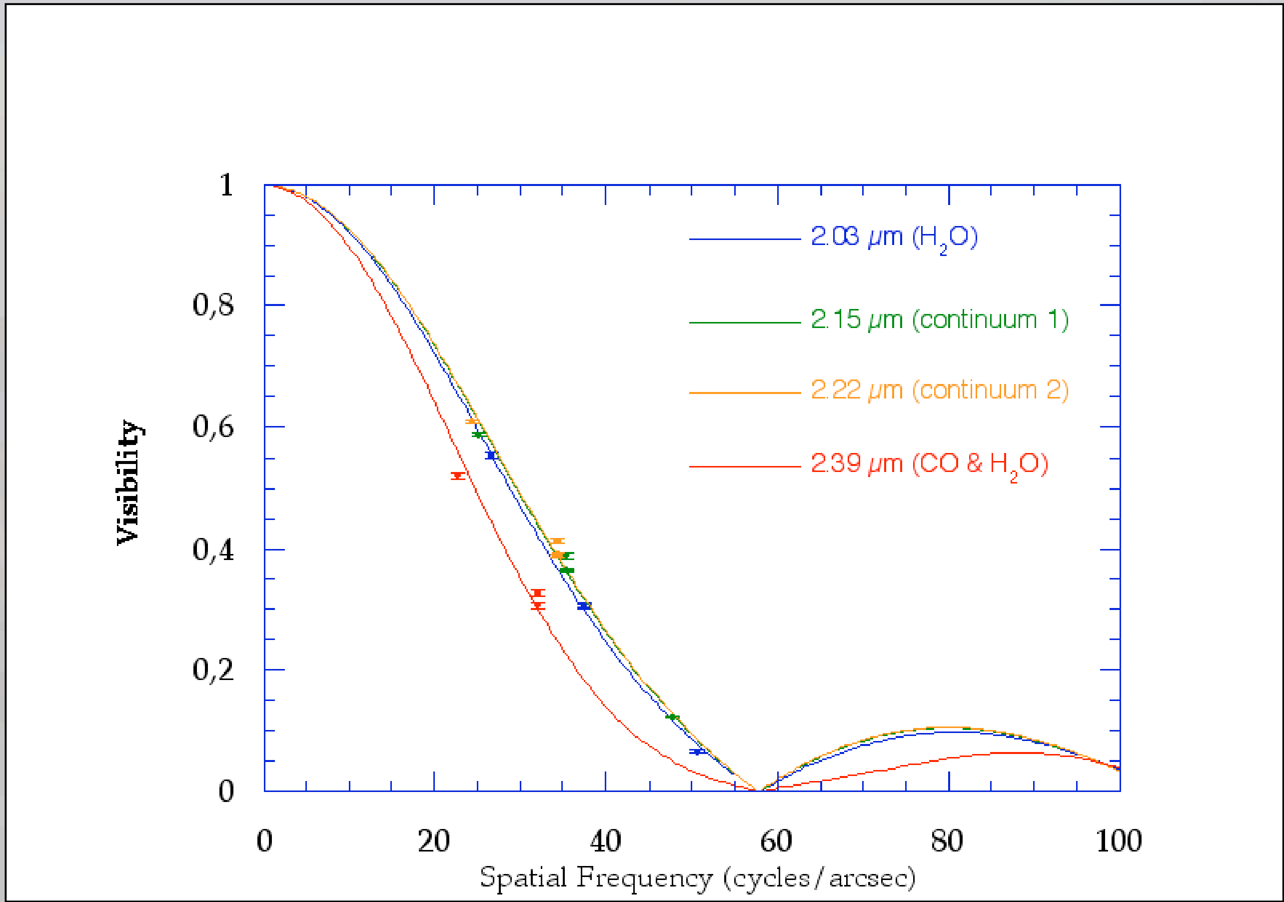
11.15 µm



First conclusions

- The layer model provides a likely explanation to both K and L data (and ISO data)
- The narrow band data show that H_2O is present in this layer
- The narrow band data can be interpreted as a variation of this layer
- Apparent diameter variations can be interpreted as pulsation and/or variations
- Open questions:
  - Is CO contributing to the of the cool layer ?
  - What are the relative importances of CO and H_2O ?
  - What about other contributors to opacity like OH^-?
  - ...

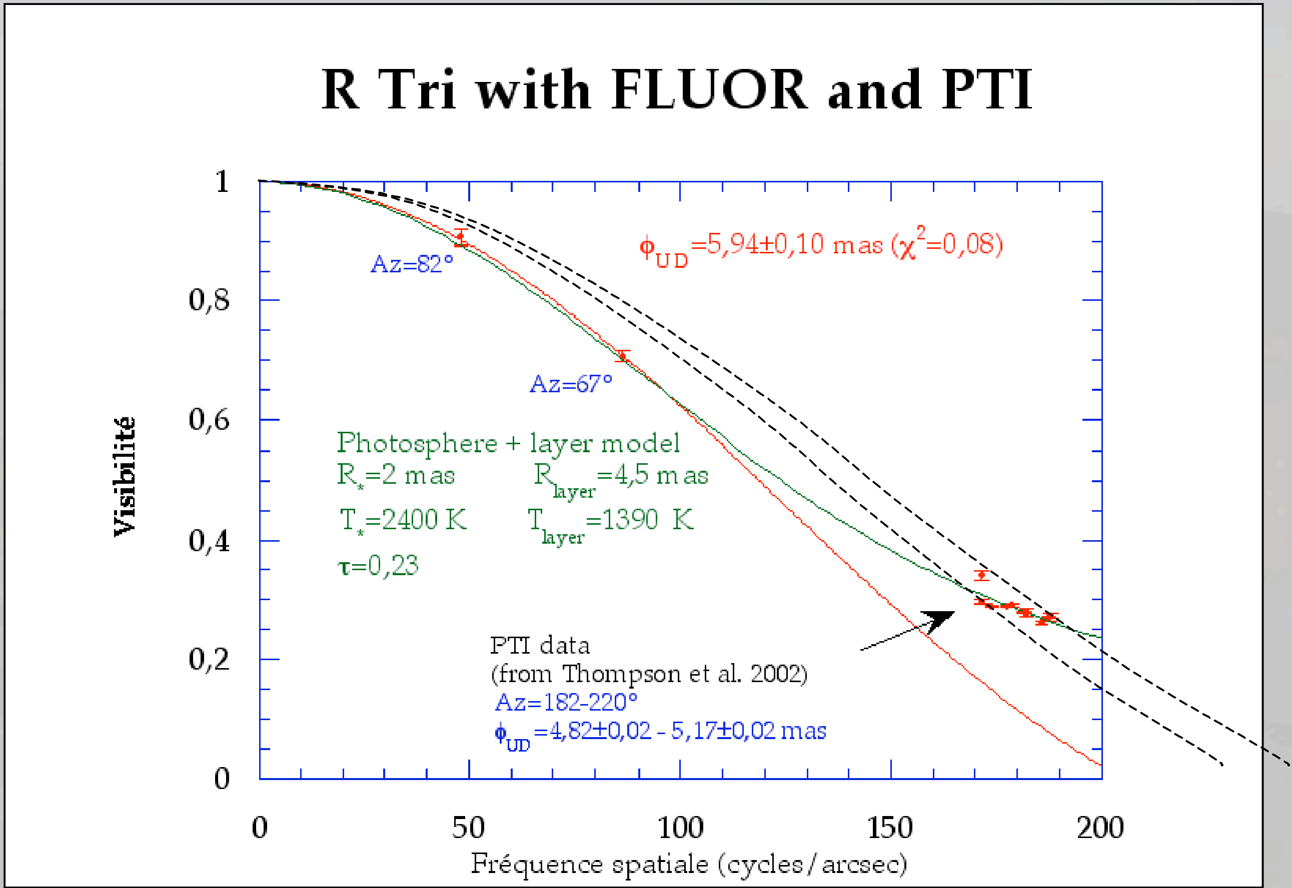
Narrow band data on an S star: □ Cyg



Second conclusions

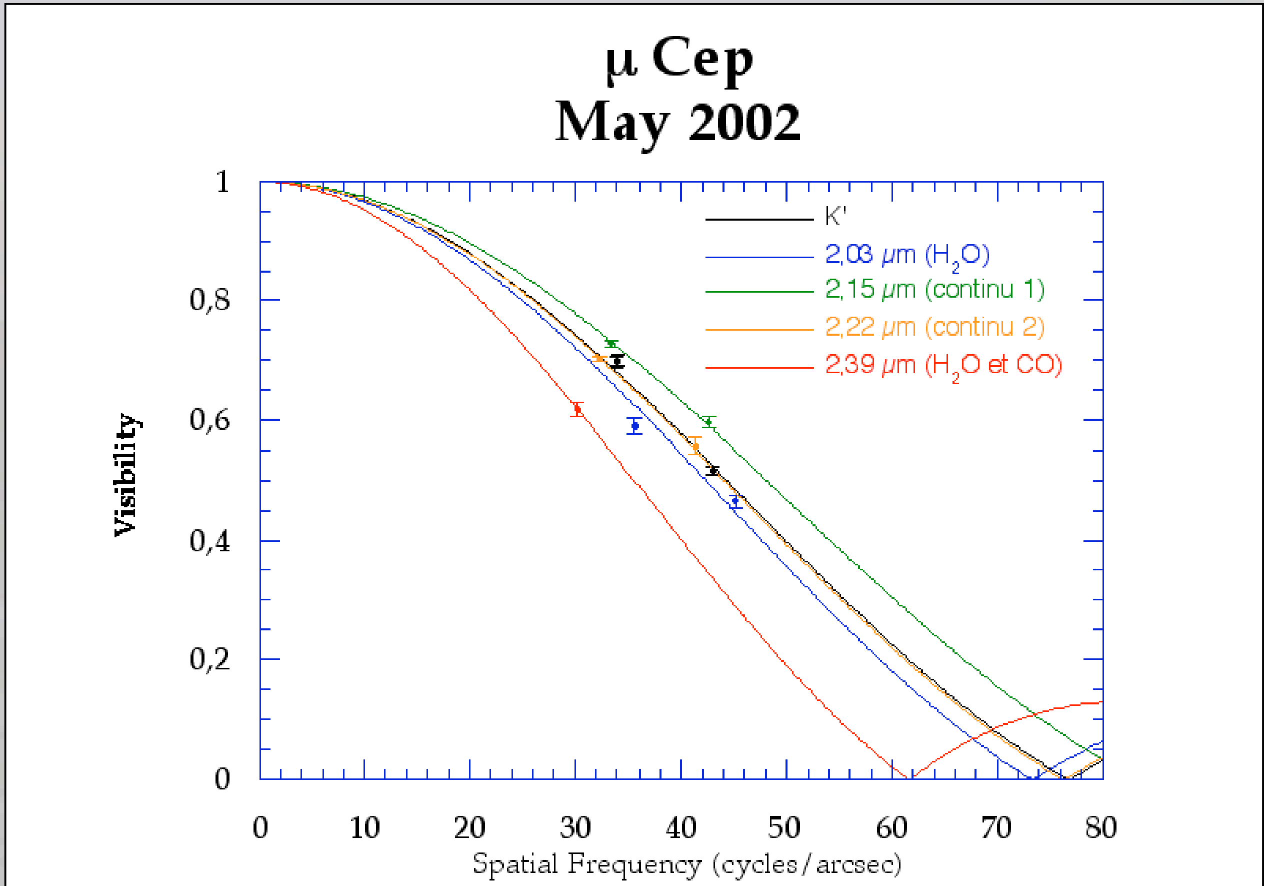
- CO is likely to be also a major contributor to optical depth
- Mira stars visibility curves are very far from classical LD disk visibility curves
- Classical visibility curves lead to overestimating Mira stars diameters by 30-40% in the K band
- Mira stars visibility curves need to be interpreted in terms of photosphere + cool layer model. Simpler models interpretations are misleading (V plateau after the « first lobe »)
- At least Mira and R Leo are fundamental pulsators

R Tri



R Tri with FLUOR and PTI
1
0,8
0,6
0,4
0,2
0
0
50
100
150
200
Visibilité
Fréquence spatiale (cycles/arcsec)
Az=82°
Az=67°
ϕUD=5,94±0,10 mas (χ2=0,08)
Photosphere + layer model
R*=2 mas
Rlayer=4,5 mas
T*=2400 K
Tlayer=1390 K
τ=0,23
PTI data
(from Thompson et al. 2002)
Az=182-220°
ϕUD=4,82±0,02 - 5,17±0,02 mas

Applicability to Supergiants



□$_{2.03\mu m}$ = 0.68±0.10

□$_{2.15\mu m}$ = 0.03±0.03

□$_{2.22\mu m}$ = 0.15±0.03

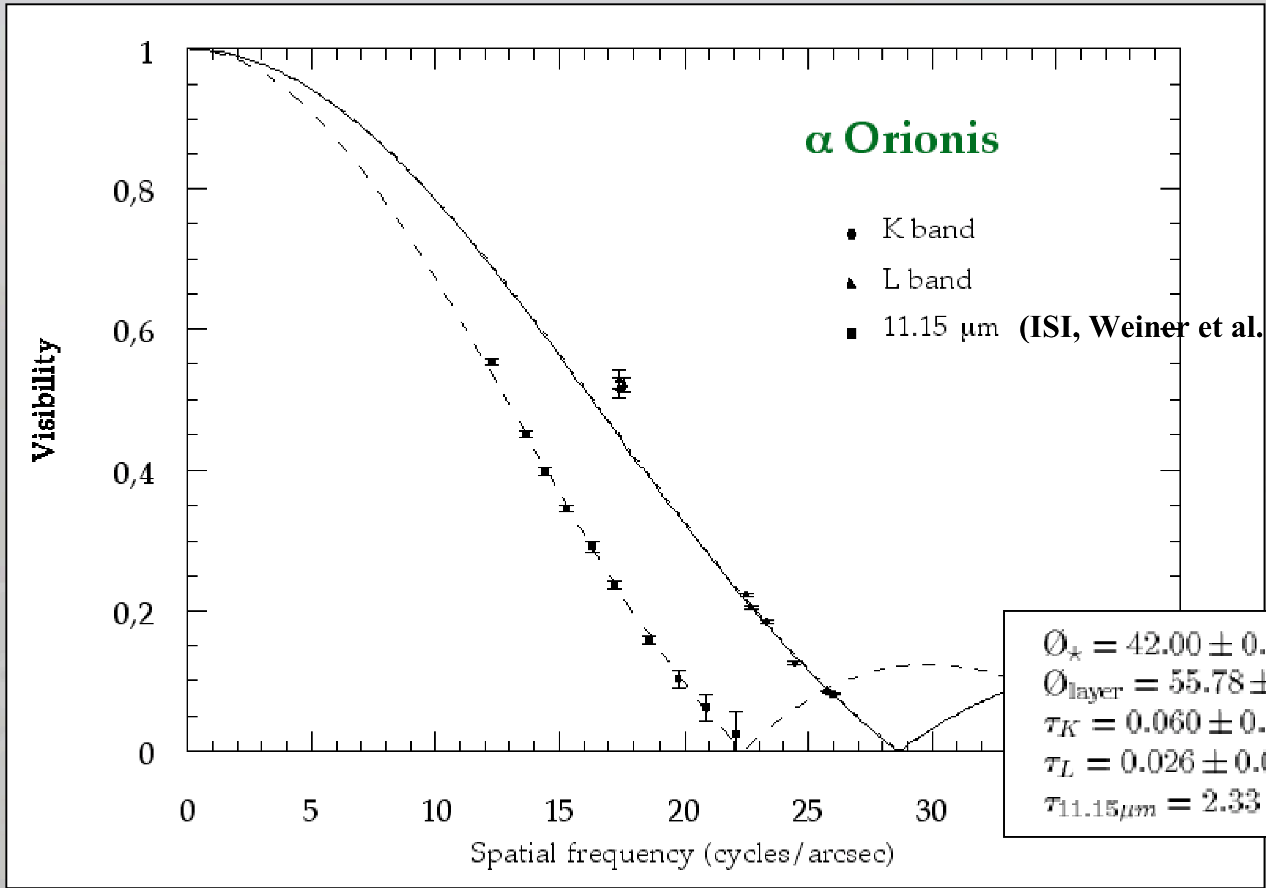
□$_{2.39\mu m}$ = 4.78±3.91

R_* = 7.17±0.13 mas **R_{layer} = 9.17±0.13mas**

T_* = 4106±150 K **T_{layer} = 2158±53 K**

Hypothesis : MOLsphere of Tsuji (2000) **$T_{MOLsphere}$ = 1500 ± 500 K**

Applicability to Supergiants



$\O_\star = 42.00 \pm 0.06\,\mathrm{mas}$, $T_\star = 3690 \pm 50\,\mathrm{K}$

$\O_{\mathrm{layer}} = 55.78 \pm 0.04\,\mathrm{mas}$, $T_{\mathrm{layer}} = 2055 \pm 25\,\mathrm{K}$

$\tau_K = 0.060 \pm 0.003$

$\tau_L = 0.026 \pm 0.002$

$\tau_{11.15\mu m} = 2.33 \pm 0.23$

(Perrin et al. 2003, submitted)

Conclusions

- Demonstration of the potential of combining high precision interferometry and spectroscopy (AMBER, MIDI)
- A good sampling of the visibility curve is very important
- The simple model will be very useful to derive basic parameters as inputs/first guess for more sophisticated models
- MIDI and AMBER both need to be used for these objects.
- Mine of future results with VLTI and MIDI in particular thanks to spectroscopic capabilities : model, photospheric pulsation, shocks, nature of molecular layers and physical properties …