Stellar diameters, rotation and pulsation

2006 Michelson Summer Workshop

Frontiers of interferometry: stars, disks, and terrestrial planets

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Outline

- Measuring stellar diameters
- Why measuring stellar diameters ?
- Pulsations
- Rotation

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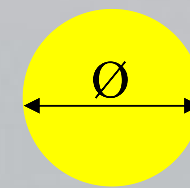
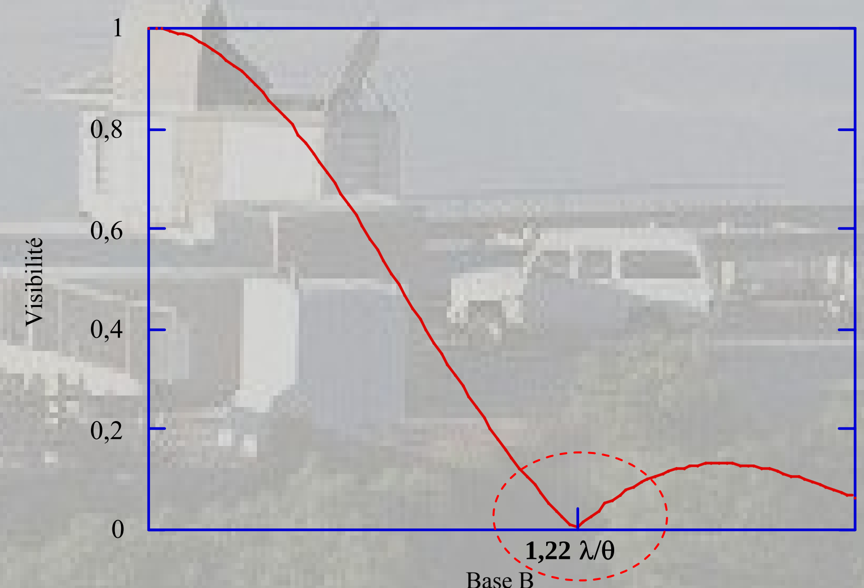
The uniform disk visibility function

Brightness distribution: $I(\vec{S}) = \Pi\left(\frac{S}{Ø}\right)$ with Ø the angular diameter and *S* the spatial coordinates

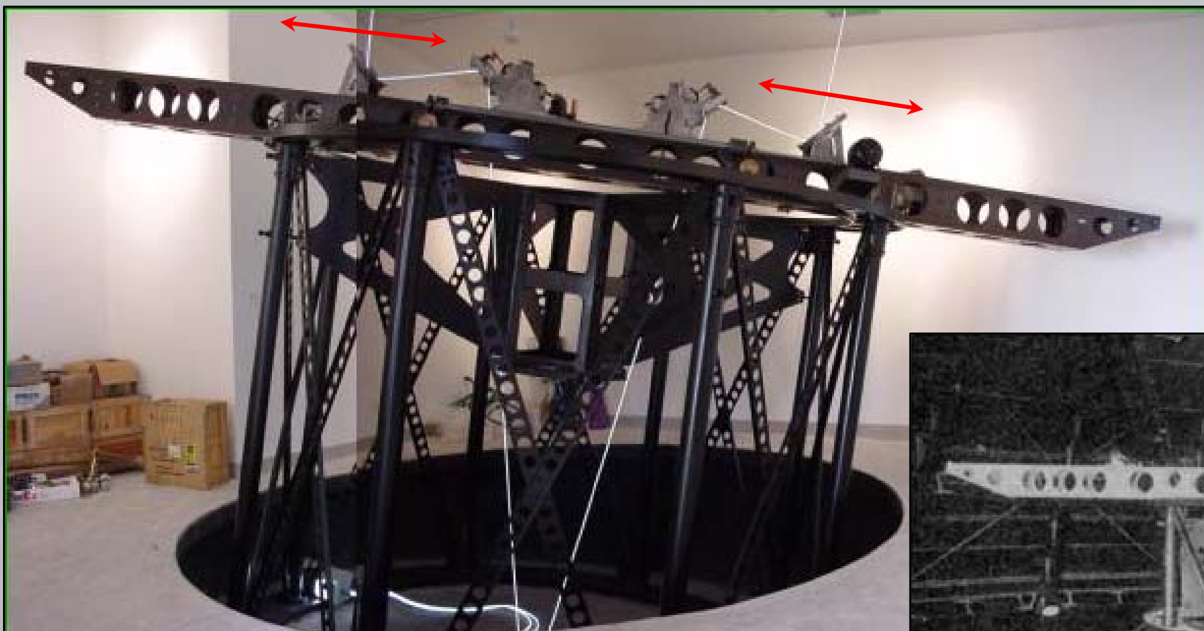


Visibility function: $V(\vec{B}) = \dfrac{2J_1\left(\dfrac{\pi Ø B}{\lambda}\right)}{\dfrac{\pi Ø B}{\lambda}}$

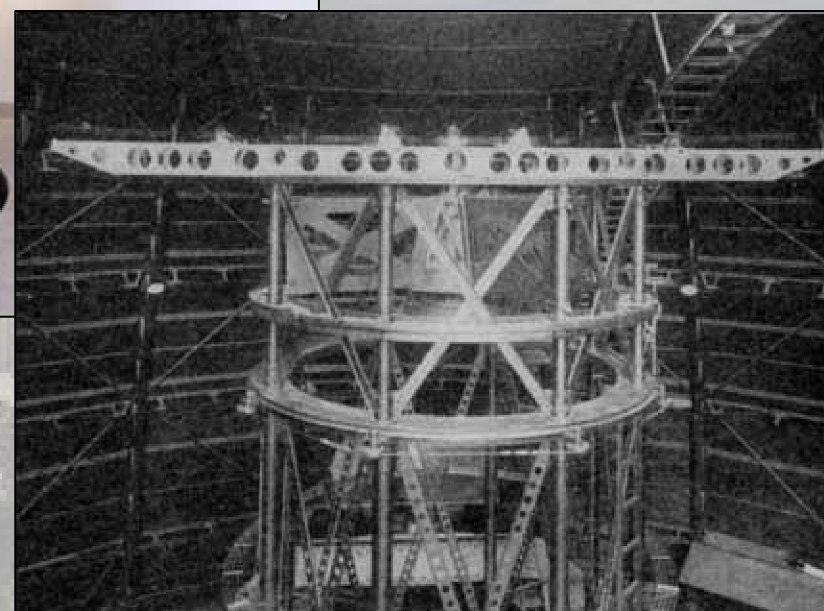
Modulus of the visibility function:



The Michelson interferometer at Mount Wilson (1921)



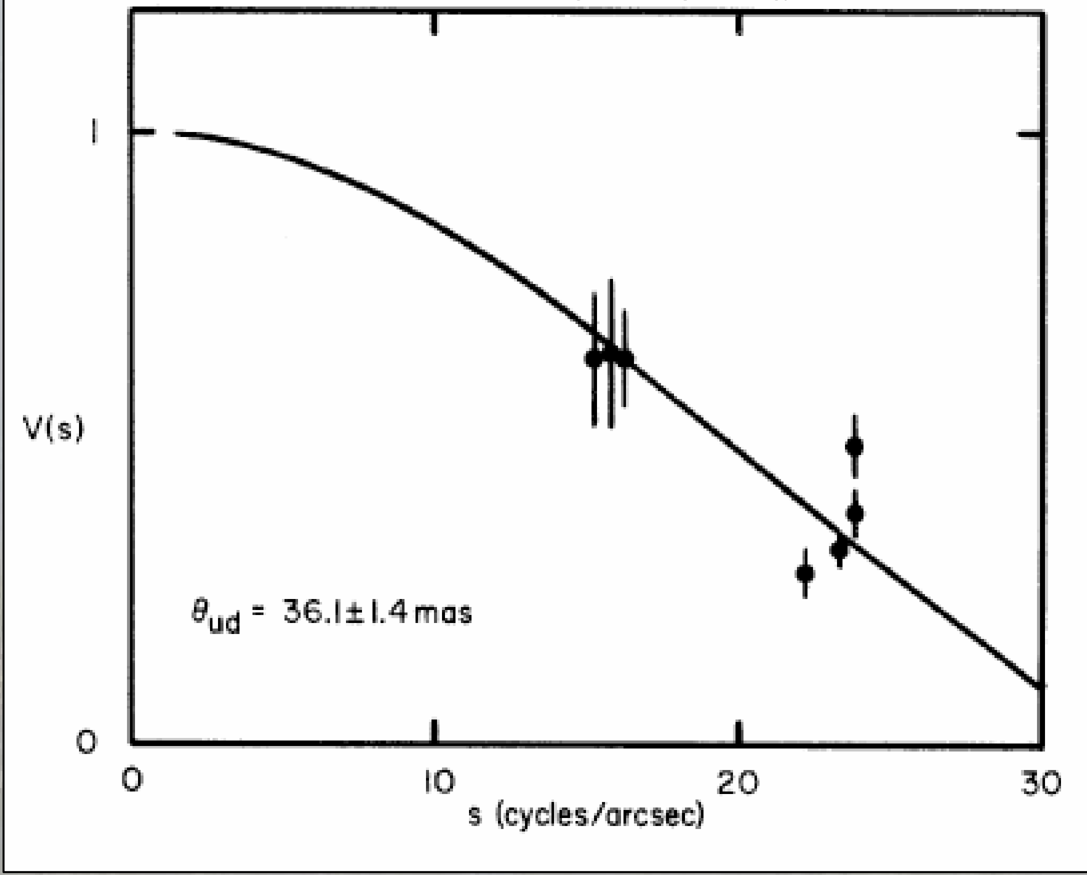
The baseline could easily be varied



Top of the 100'' telescope (telescope = beam combiner + delay line)

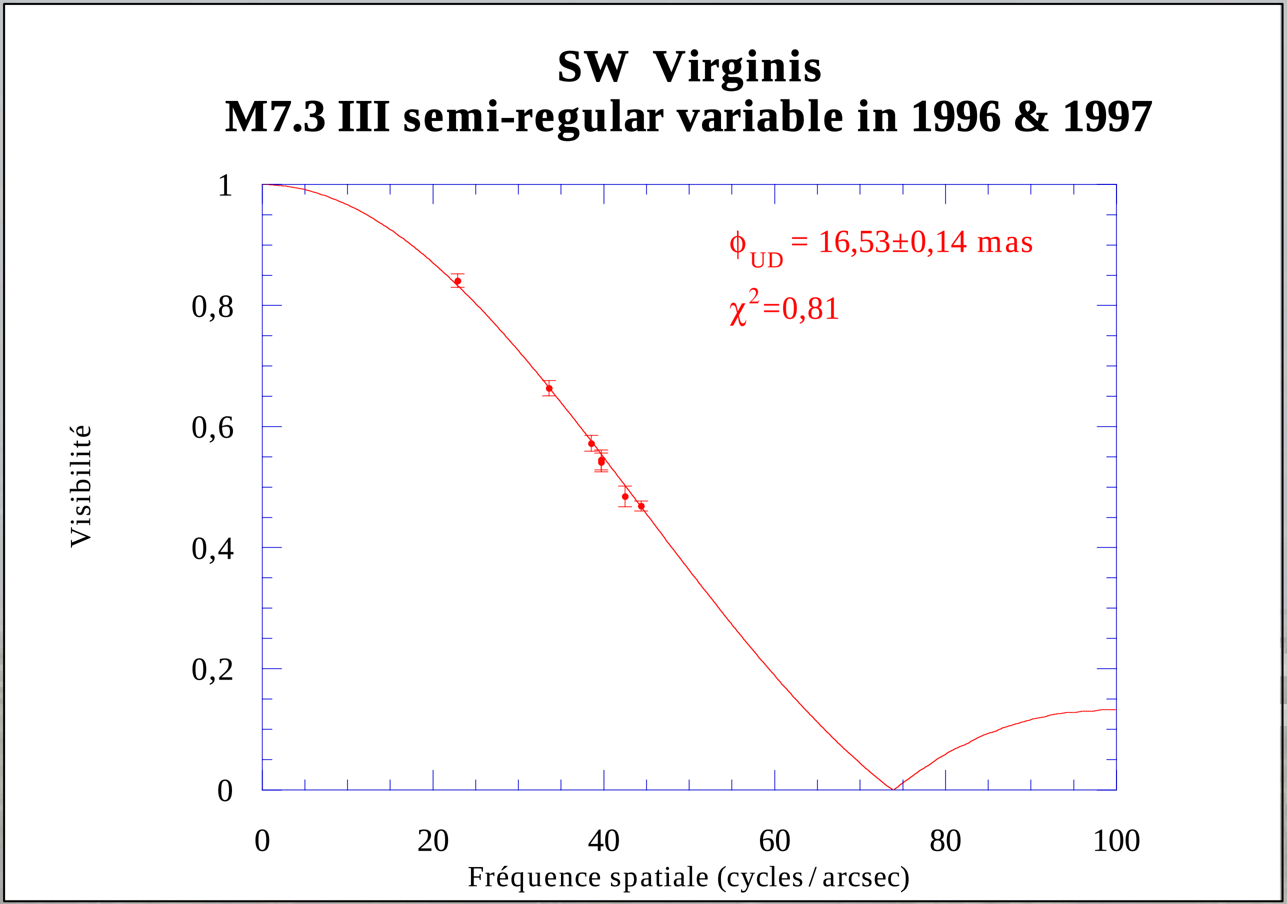
Examples of modern diameter measurements

Mira in the K band



Ridgway et al. (1992, IRMA)

Examples of modern diameter measurements



Perrin et al. (2003, IOTA)

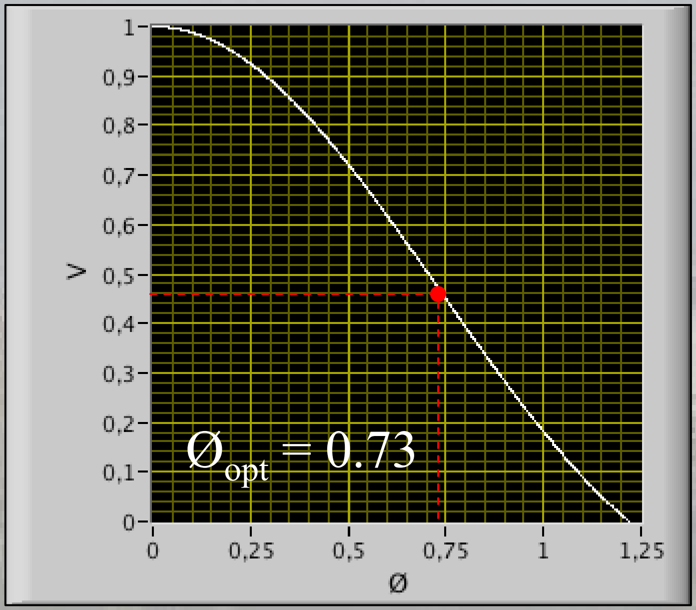
How to efficiently constrain stellar diameters

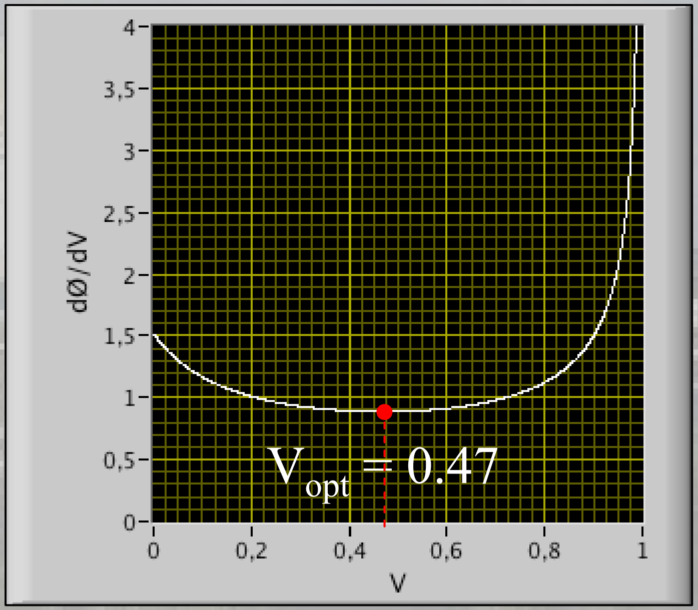
The diameter is best constrained when the derivative of the diameter wrt visibility is minimum:

$$\left.\frac{\partial Ø}{\partial V}\right|_{V_{opt}} ?$$

$$\leftarrow \quad \mathrm{Var}(Ø) = \mathrm{Var}(V) \times \left[\frac{\partial Ø}{\partial V}\right]^2$$

Let's use the product Øx*B/λ* (a *normalized* diameter) instead of Ø.





How to efficiently constrain stellar diameters

In practice, measurements close to the first null of the visibility function provide an excellent constraint

Why ?

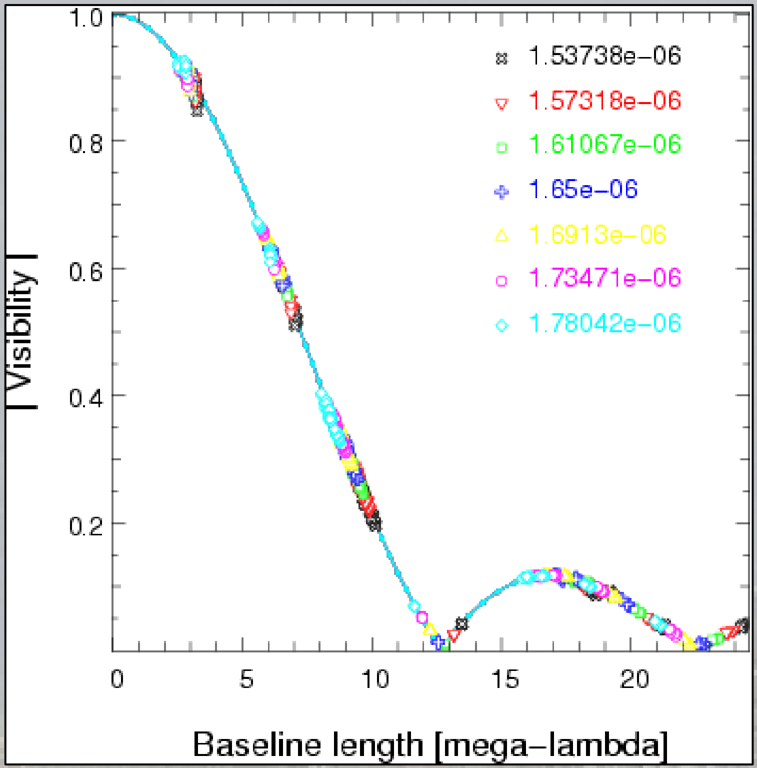
1. Multiplicative errors and biases (those produced by turbulence for example) are larger at higher visibilities

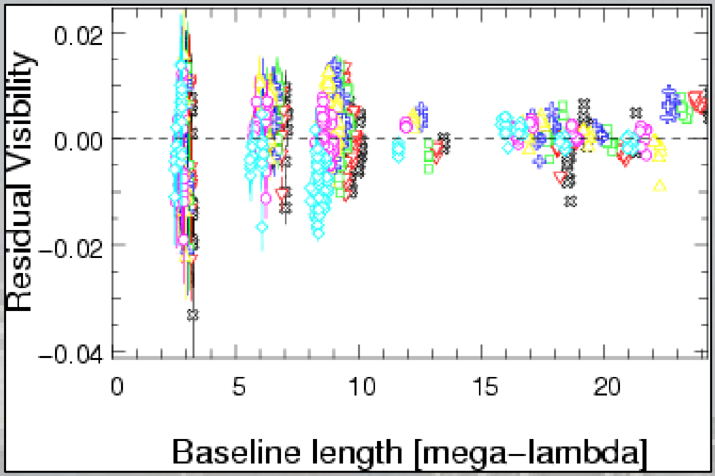
➲ Multiplicative errors and biases close to the first null therefore tend towards 0.

2. Multiple measurements around the first null are efficient to explore the star (e.g. limb-darkening, wait a little bit)

Diameter measurement and visibility noise

Arcturus data taken at IOTA with IONIC





Lacour et al. (≥ 2006, IOTA)

Accuracy of diameter measurements

Demonstrated accuracy ~ 0.5% in K

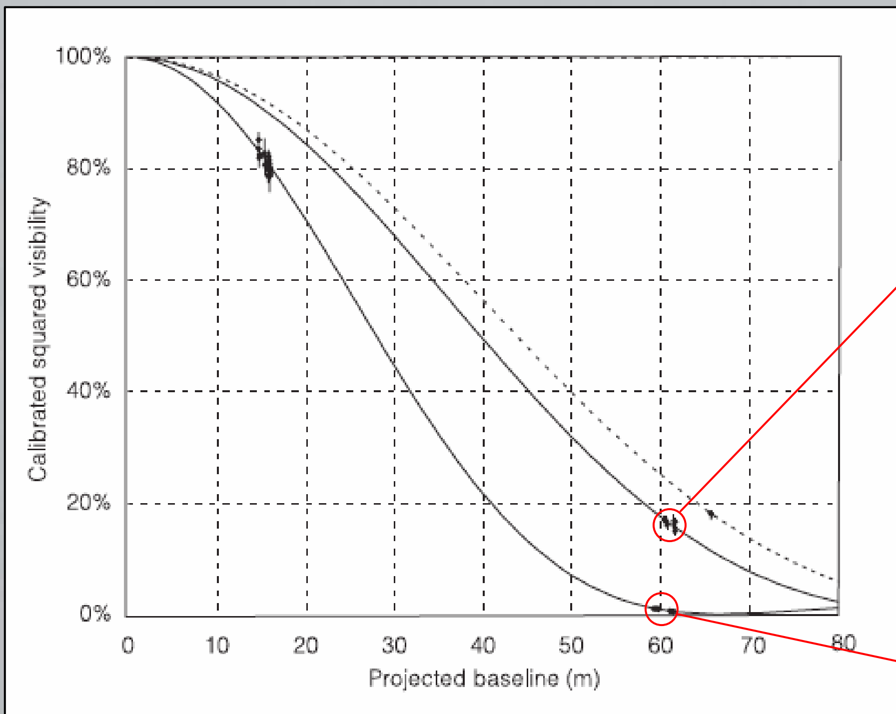
e.g. Kervella et al. (2003) with a 60 m baseline on α Cen A ($Ø_{LD}$=8.5 mas) and α Cen B ($Ø_{LD}$=6.0 mas) at VLTI

What sets the limit is probably the ability of the UD model or of other simple models to well describe the star.

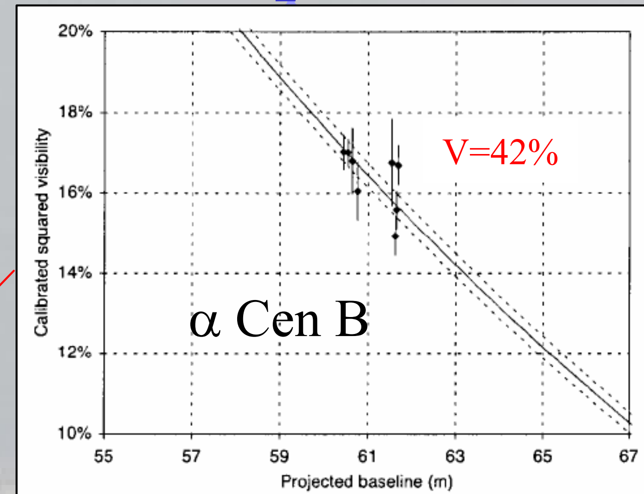
Extrapolated to a 330 m baseline and in the J band this means that CHARA should be able to measure all stellar diameters larger than 0.6 mas with an accuracy better than 0.5%

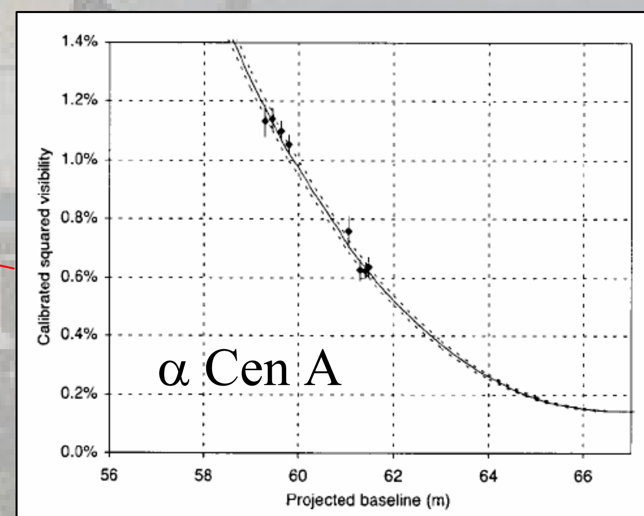
This is a few thousand stars !

Measurement of the α Cen components



Kervella et al. (2003, VLTI)





	α Cen A	α Cen B
θ_{UD} (mas)	8.314 ± 0.016	5.856 ± 0.027

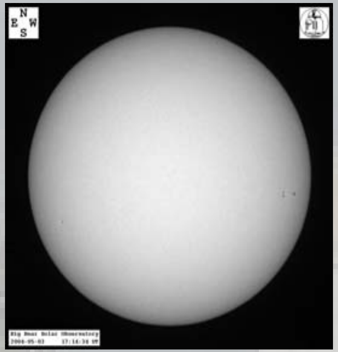
Limb darkening

A limit to the accuracy of the measurement

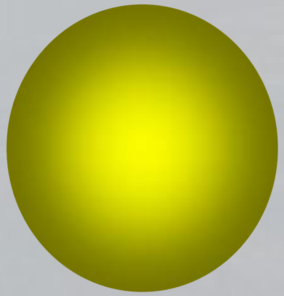
The uniform disk model provides the *apparent* size of an object

Limb darkening makes a star appear smaller than it is in reality.

Uniform disk



Limb darkening of the solar photosphere in the visible



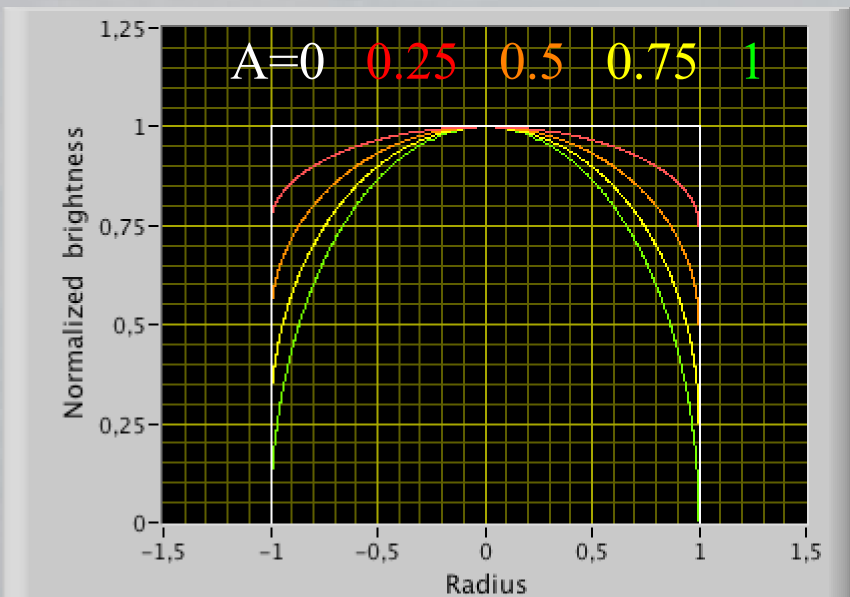
Limb darkened disk

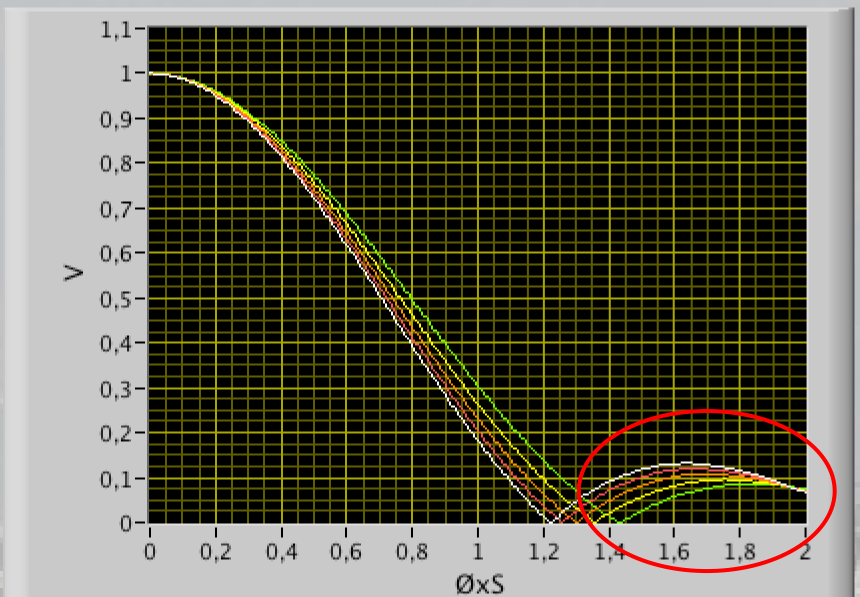
The apparent star diameter is smaller by a few percents

See J. Aufdenberg talk

Limb darkening needs to be modeled or directly measured

Limb-darkening, apparent diameter, visibility





Linear limb darkening

$$I(\mu) = 1 - A(1-\mu)$$

Apparent diameter ⇙

Outline

- Measuring stellar diameters
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- Rotation

What are diameters useful for ?

- Diameters are useful to constrain fundamental parameters: mass, radius, T_{eff}, …

- Comparison of (R,T_{eff}) with evolutionary models

- Differences between T_{eff} and T_c are illustrative of the complex atmospheric structure of a star (diverges above M0 III (Ridgway et al. 1980))

- Temperatures and diameters are useful to generate synthetic models of galaxies

- Temperatures and diameters are useful to generate models of parent stars of pulsating giants

- Prediction of diameters from models at ~ 1% precision

The fundamental parameters of α Cen B

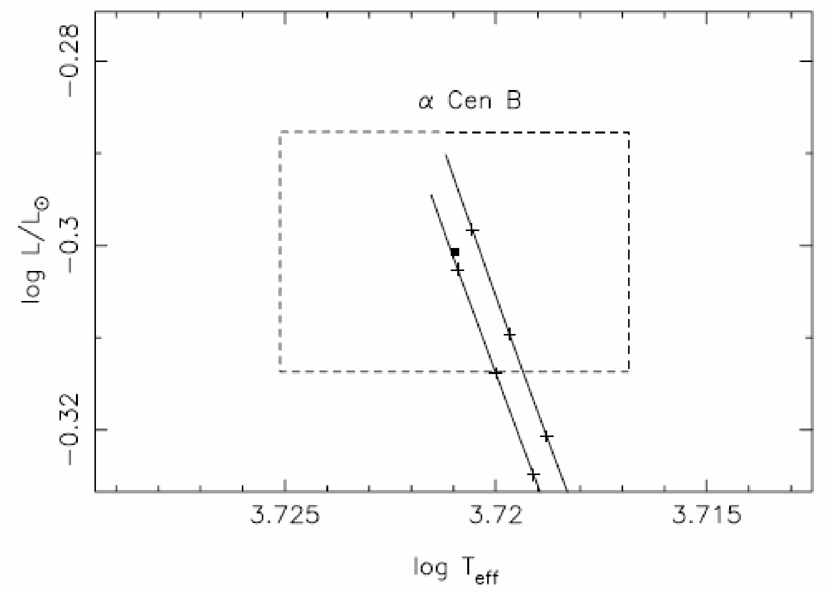
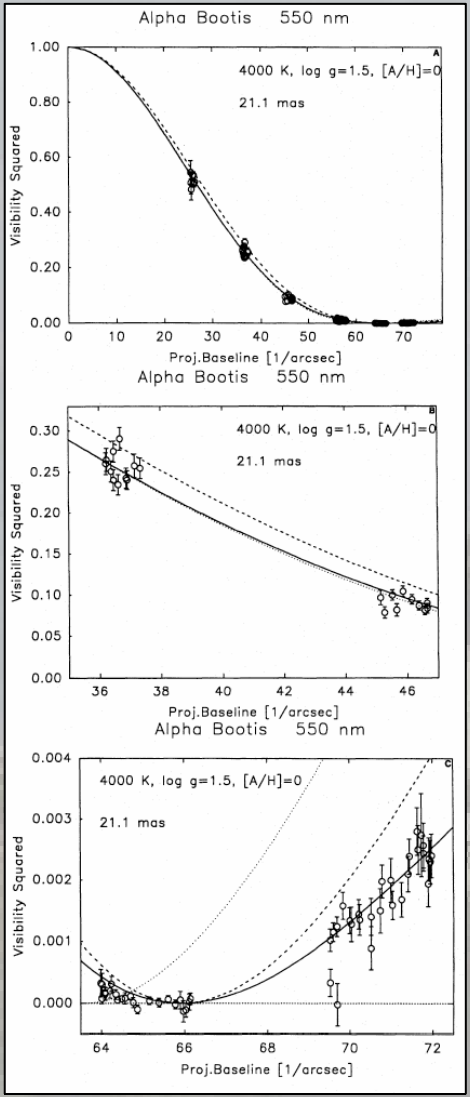


Fig. 10. HR diagram of α Cen B. The line on the right corresponds to a mixing length of $\lambda = 0.96$ and a mass of 0.909 $M_{\odot}$, the line on the left corresponds to the values published in Thévenin et al. 2002 ($\lambda = 0.98$, 0.907 $M_{\odot}$).

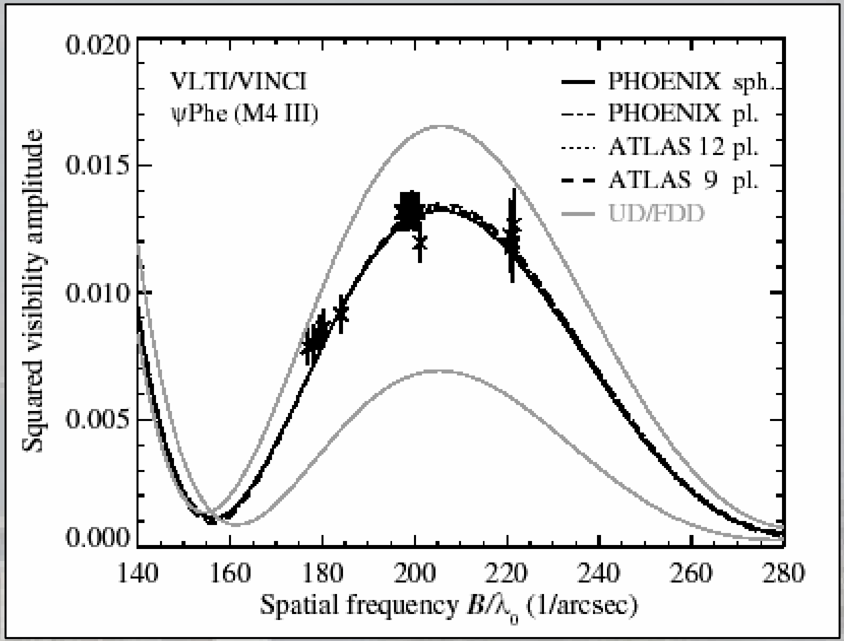
Kervella et al. (2003)

α Cen B diameter larger than the prediction ➲ reduce the mixing length ➲ increase the mass ➲ agreement with asteroseismic estimate

Measurement of Limb darkening



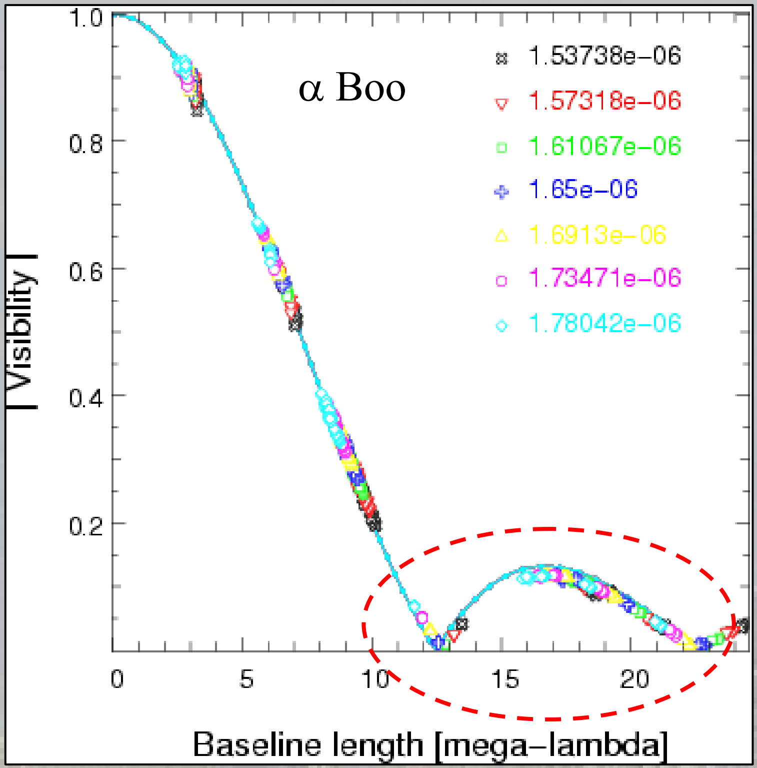
Quirrenbach et al. (1996, Mark III)



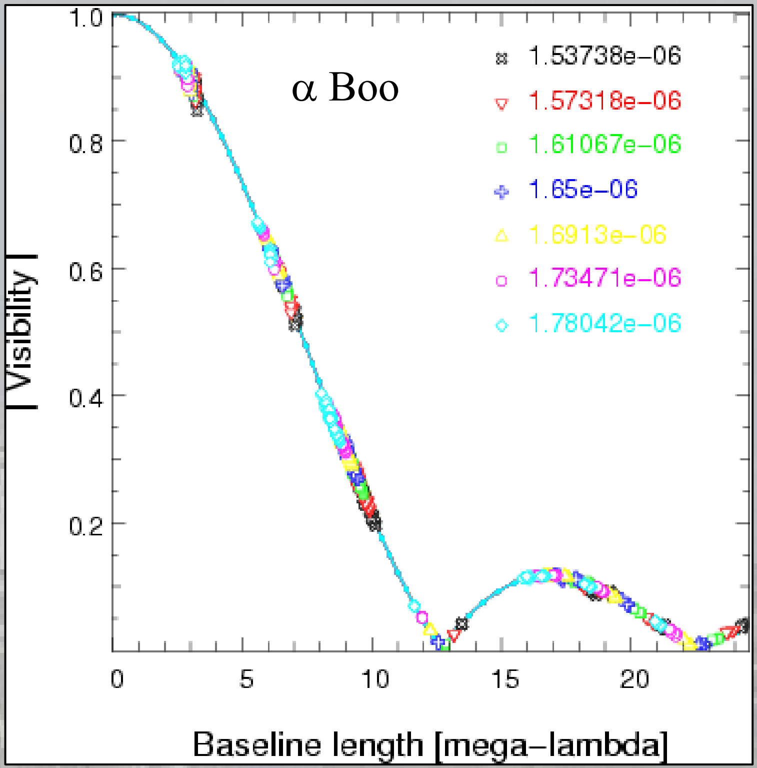
Wittkowski et al. (2004, VINCI)

Measurement of Limb darkening

Uniform disk model

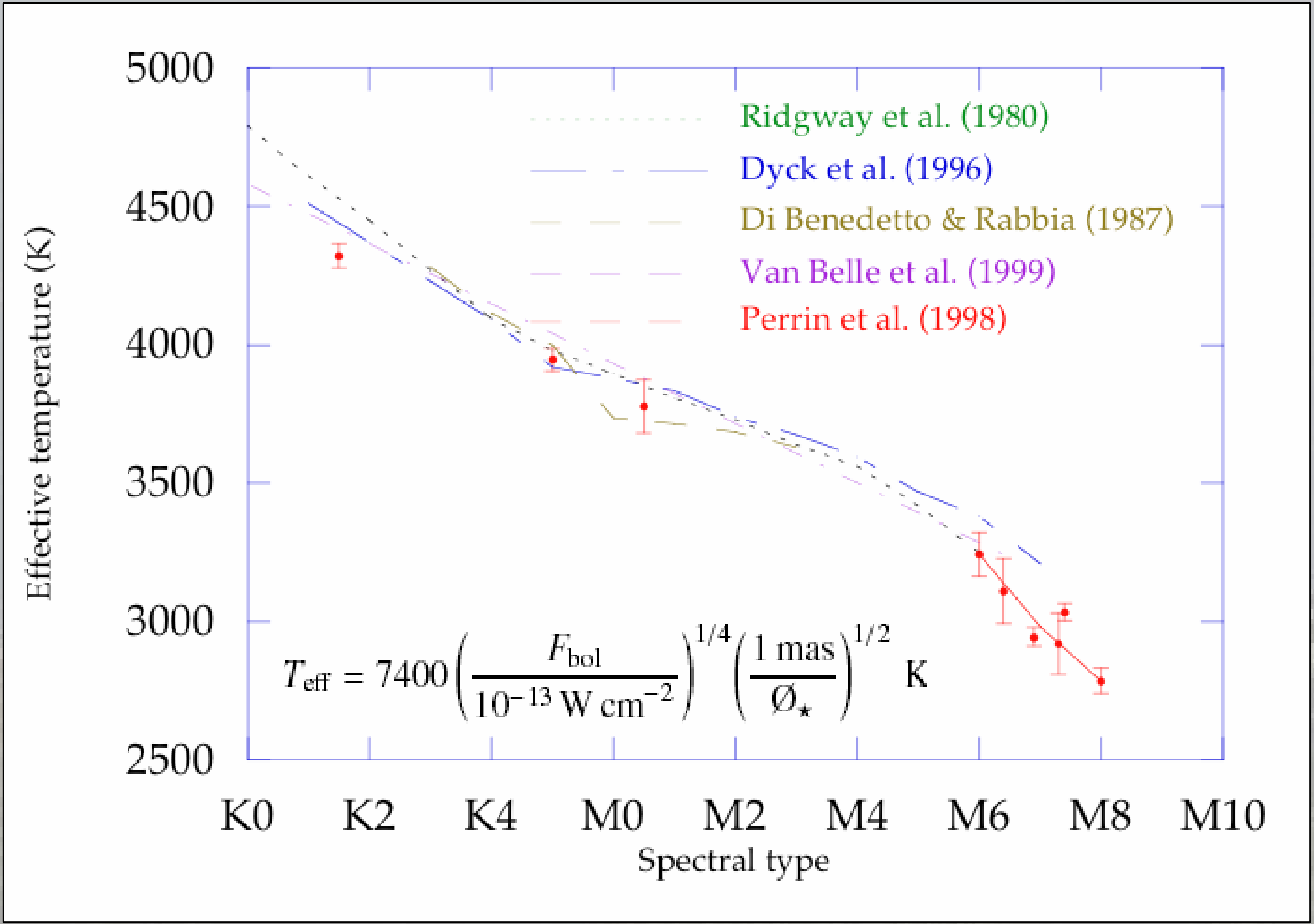


Lim-darkened disk model

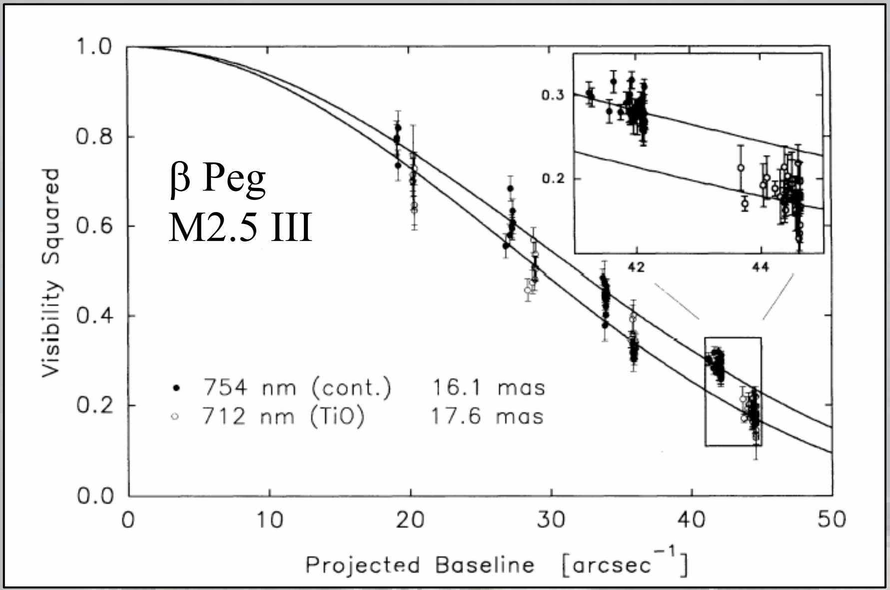


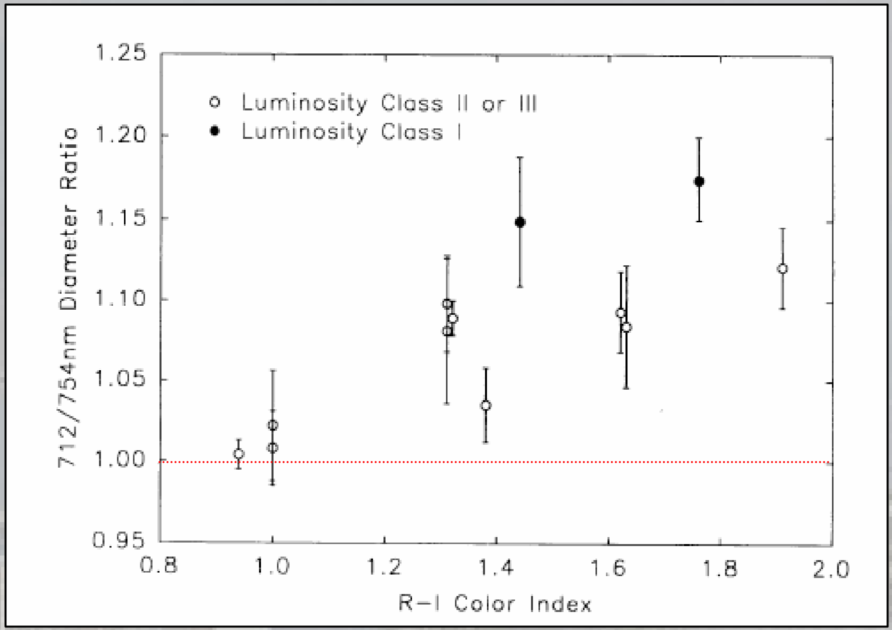
Lacour et al. (≥ 2006, IOTA)

The effective temperature scale of giants



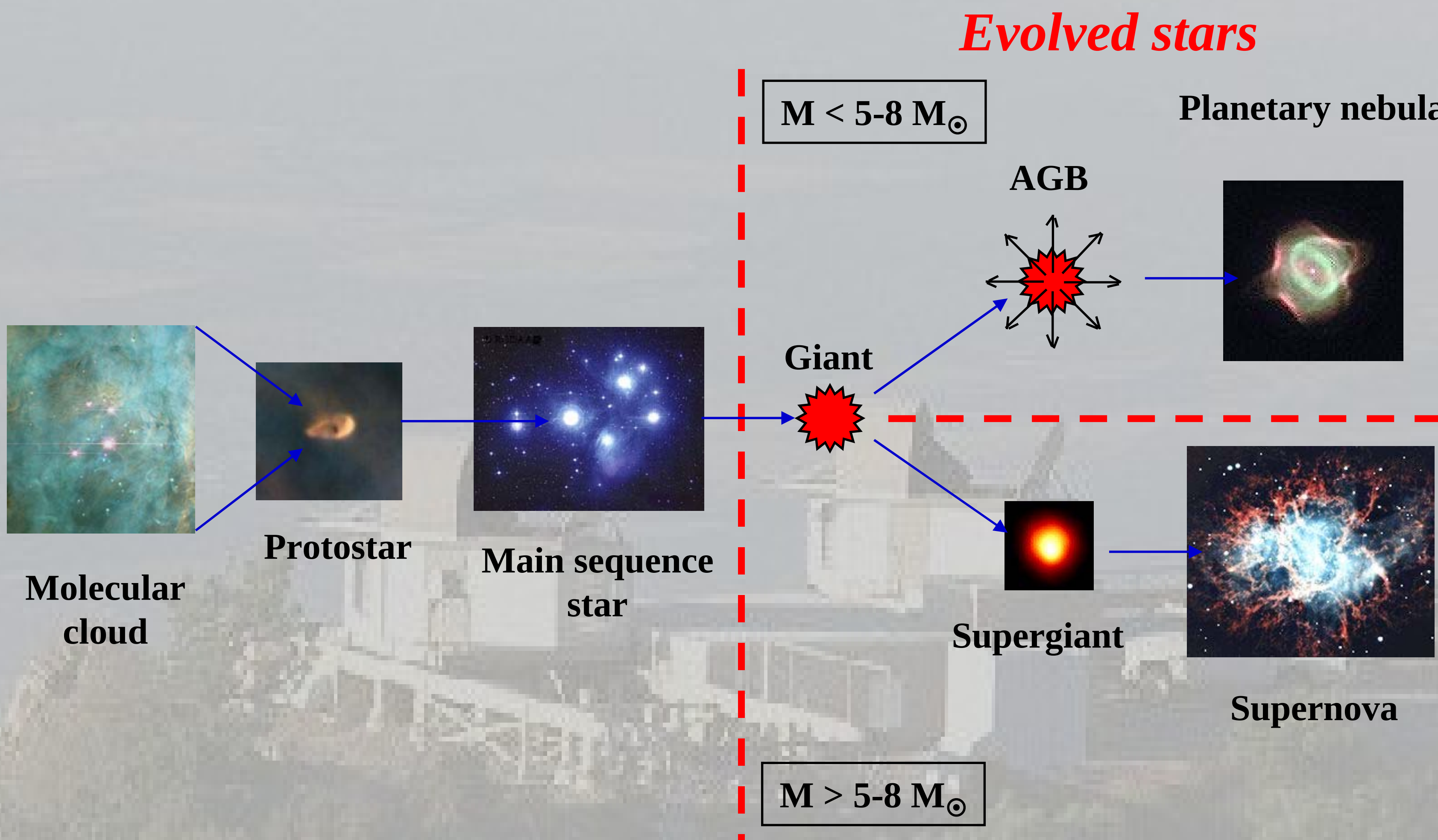
Diameters inside and outside TiO bands of late-type stars





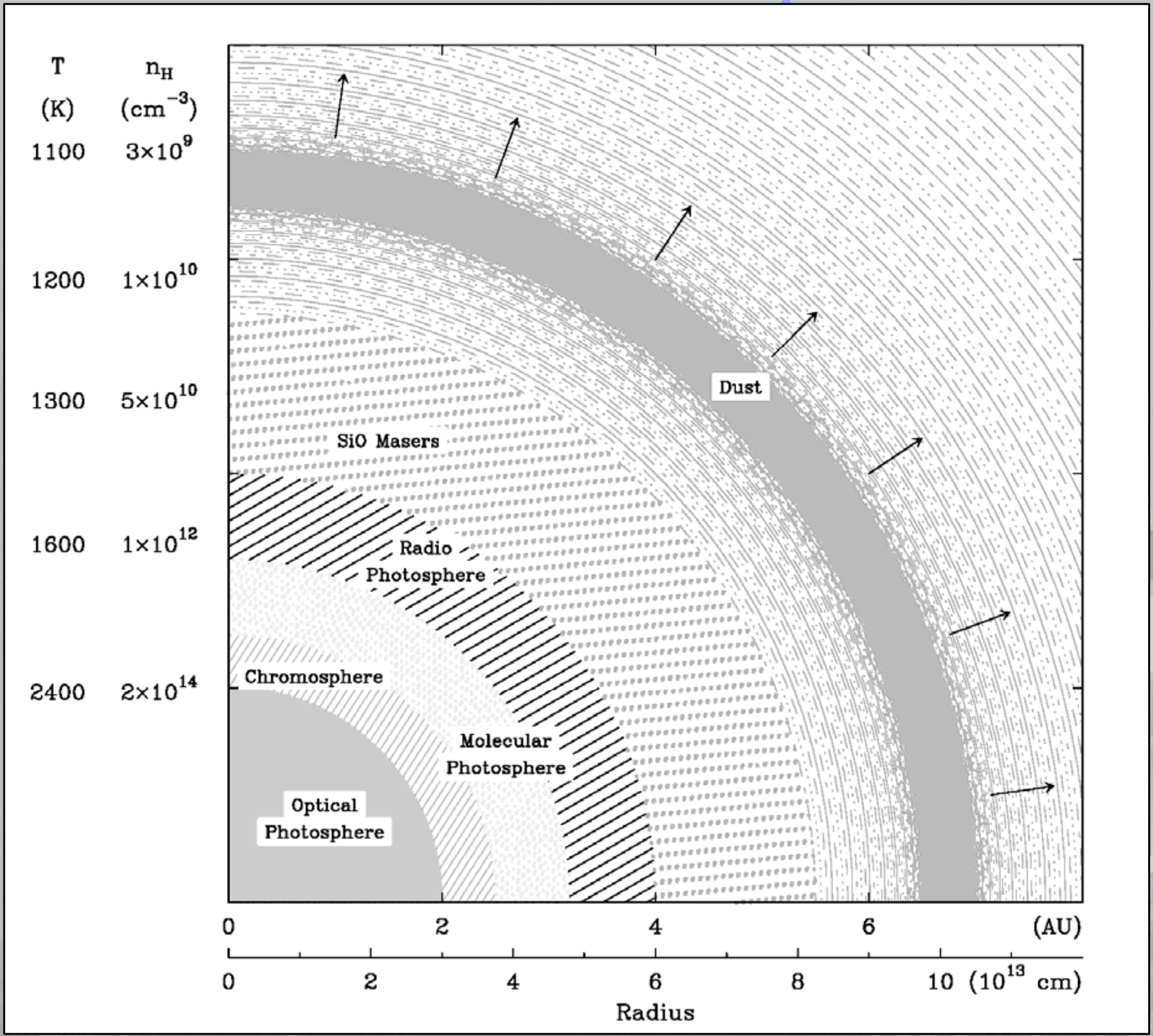
Quirrenbach et al. (1993, Mark III)

Life story



Evolved stars
M < 5-8 $M_\odot$
Planetary nebula
AGB
Giant
Molecular cloud
Protostar
Main sequence star
Supergiant
Supernova
M > 5-8 $M_\odot$

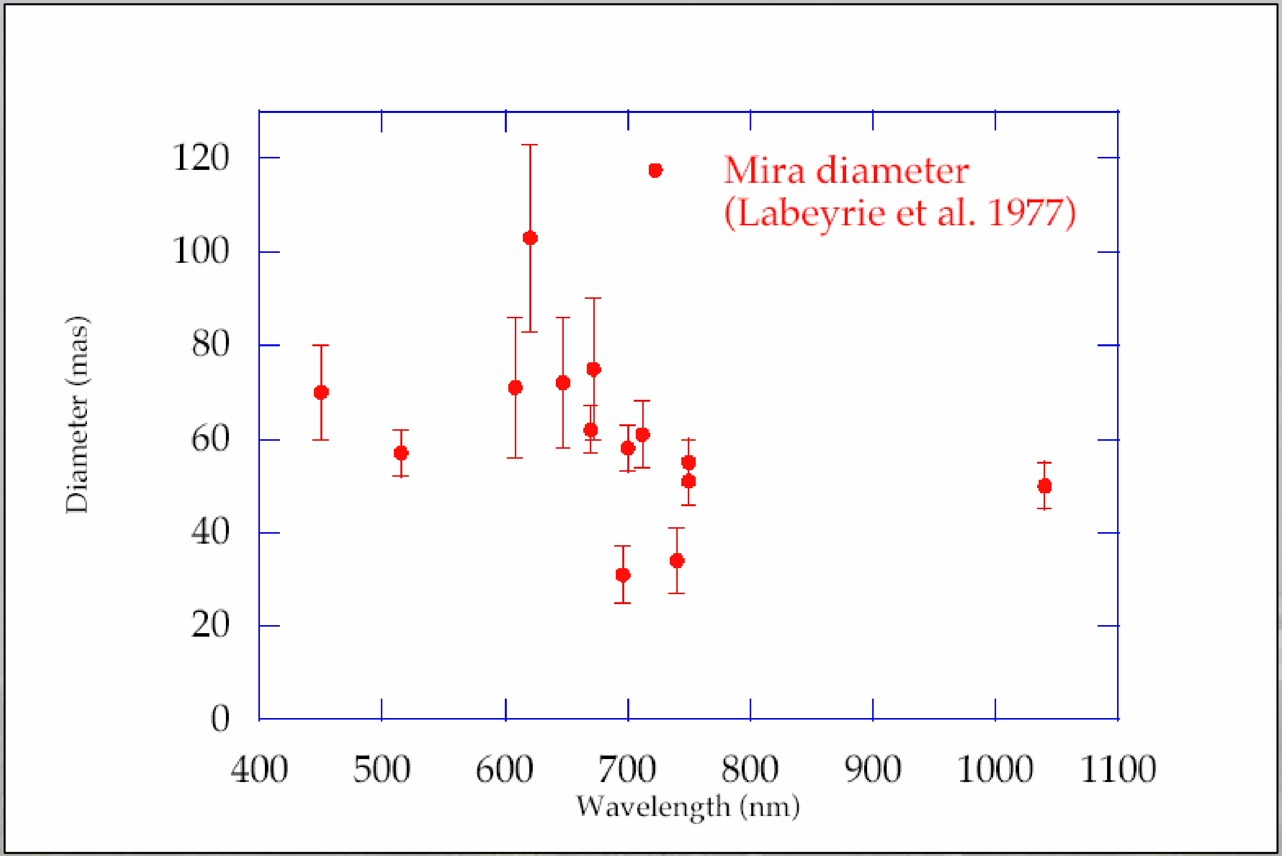
The atmosphere of Mira stars



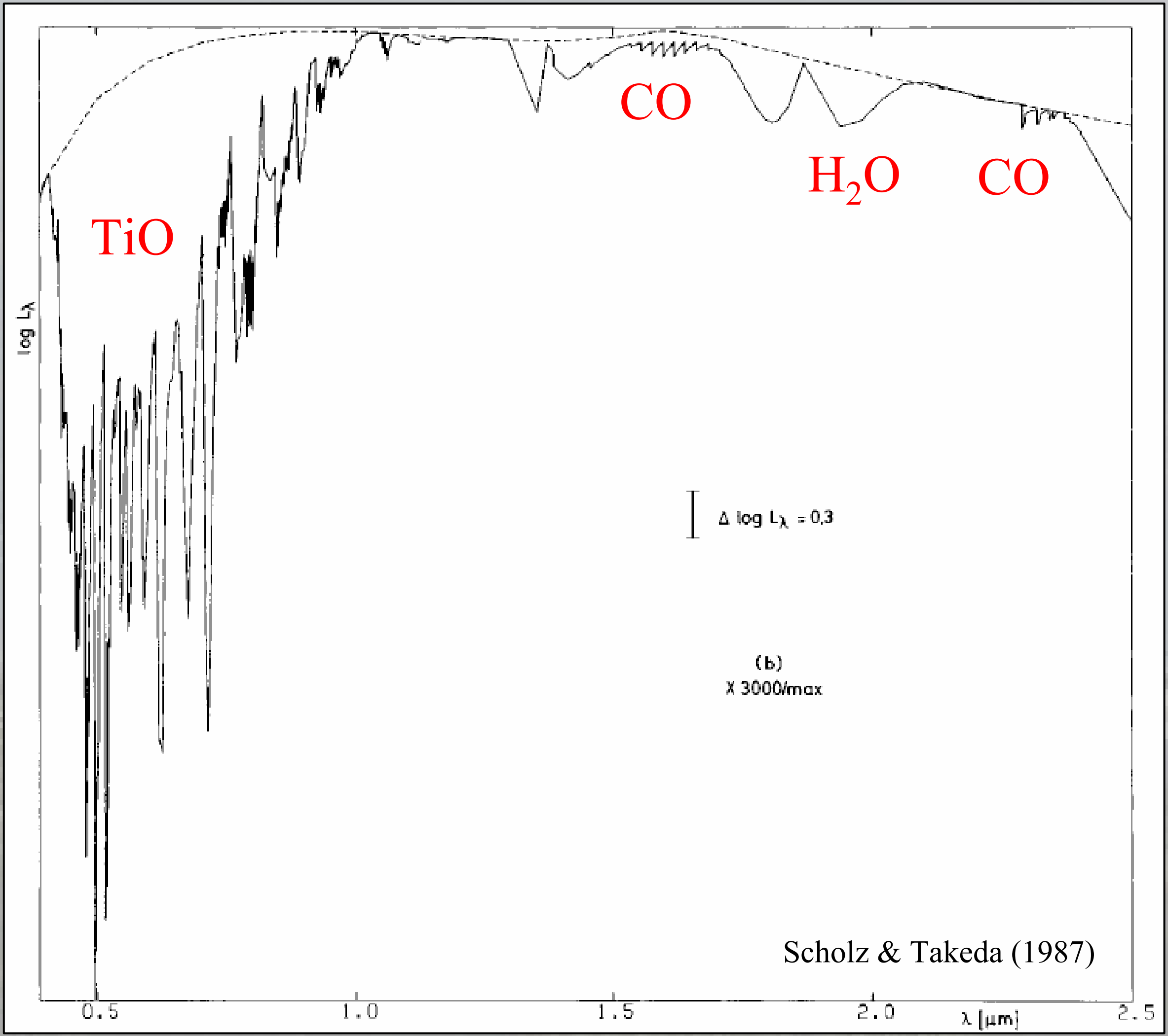
Reid & Menten (1997)

- Issue: to define and to measure a diameter

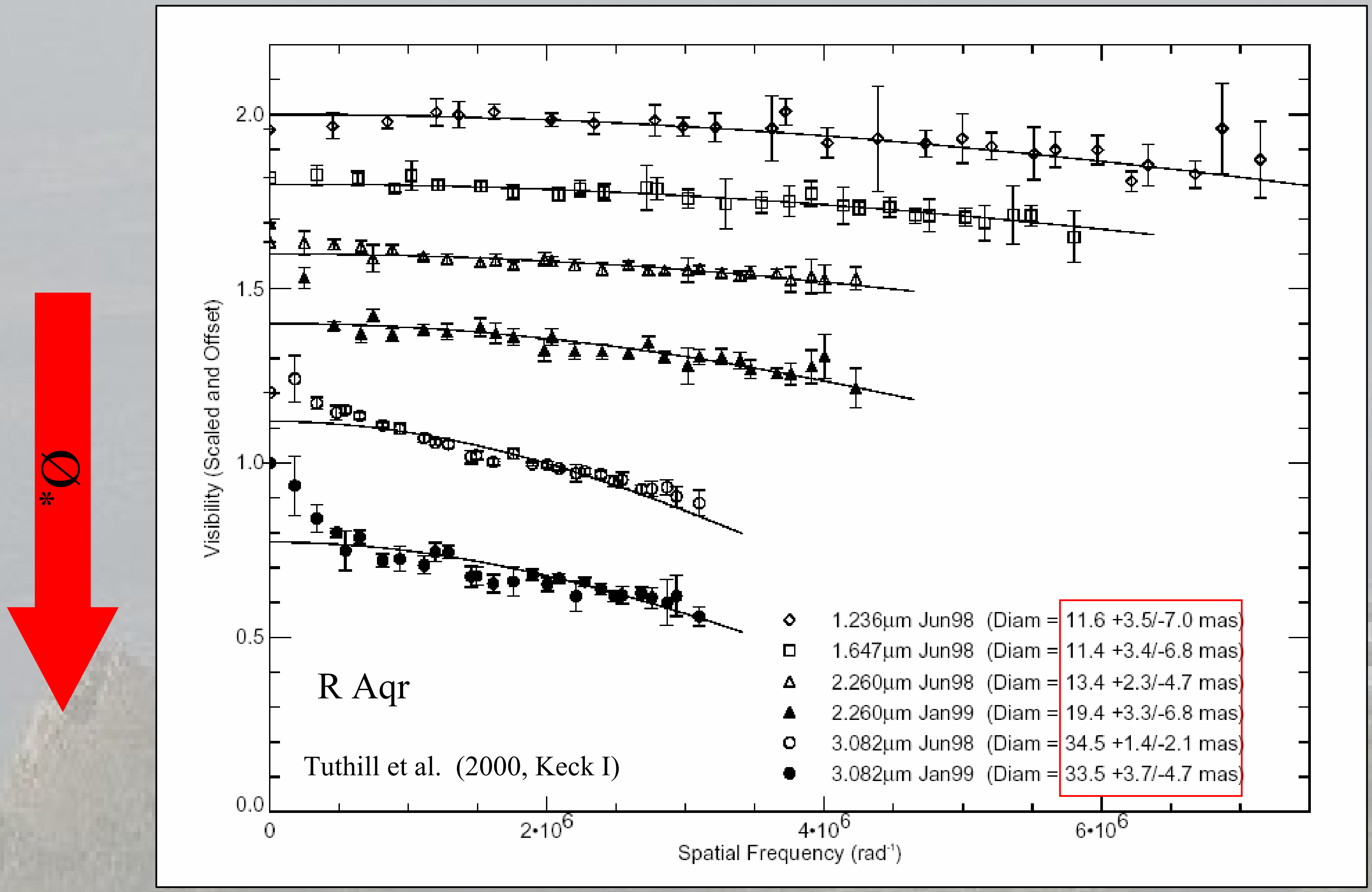
Measuring Mira star diameters



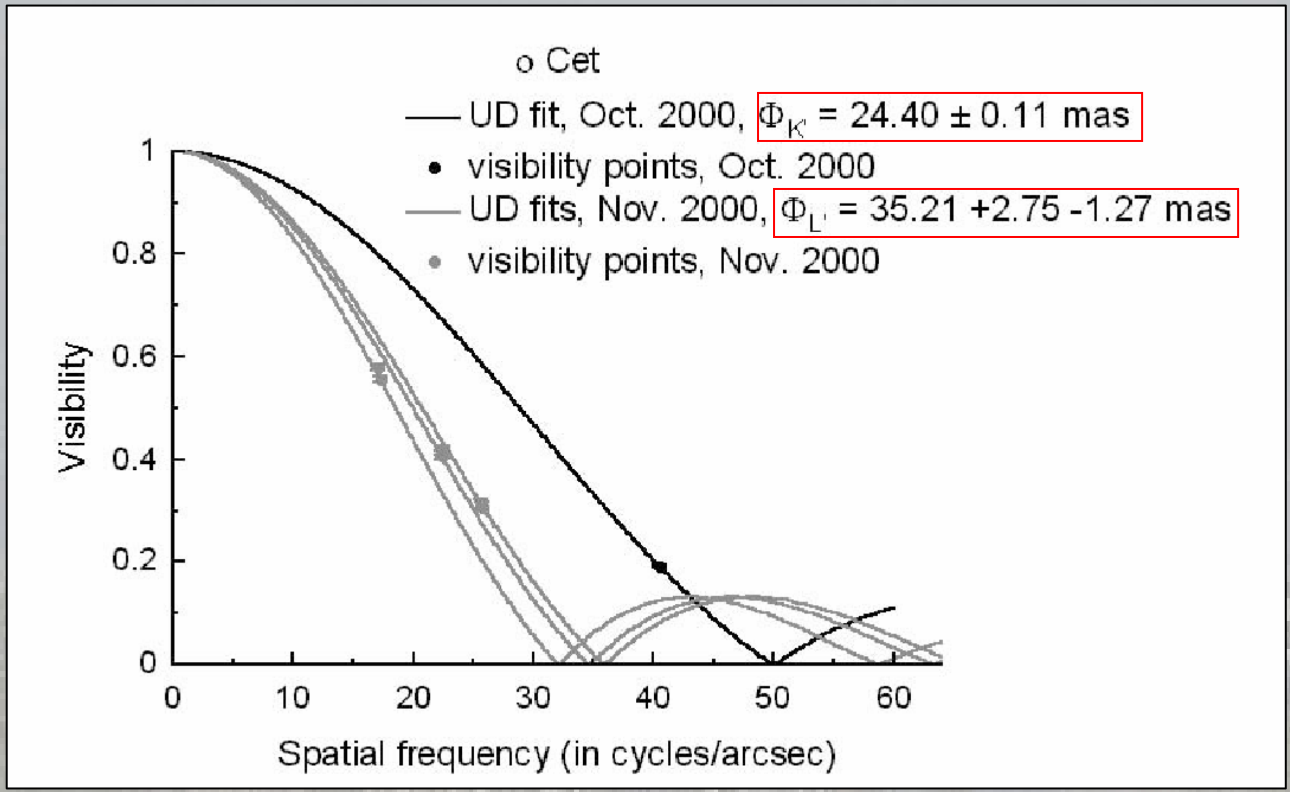
Measuring Mira star diameters



Measuring Mira star diameters

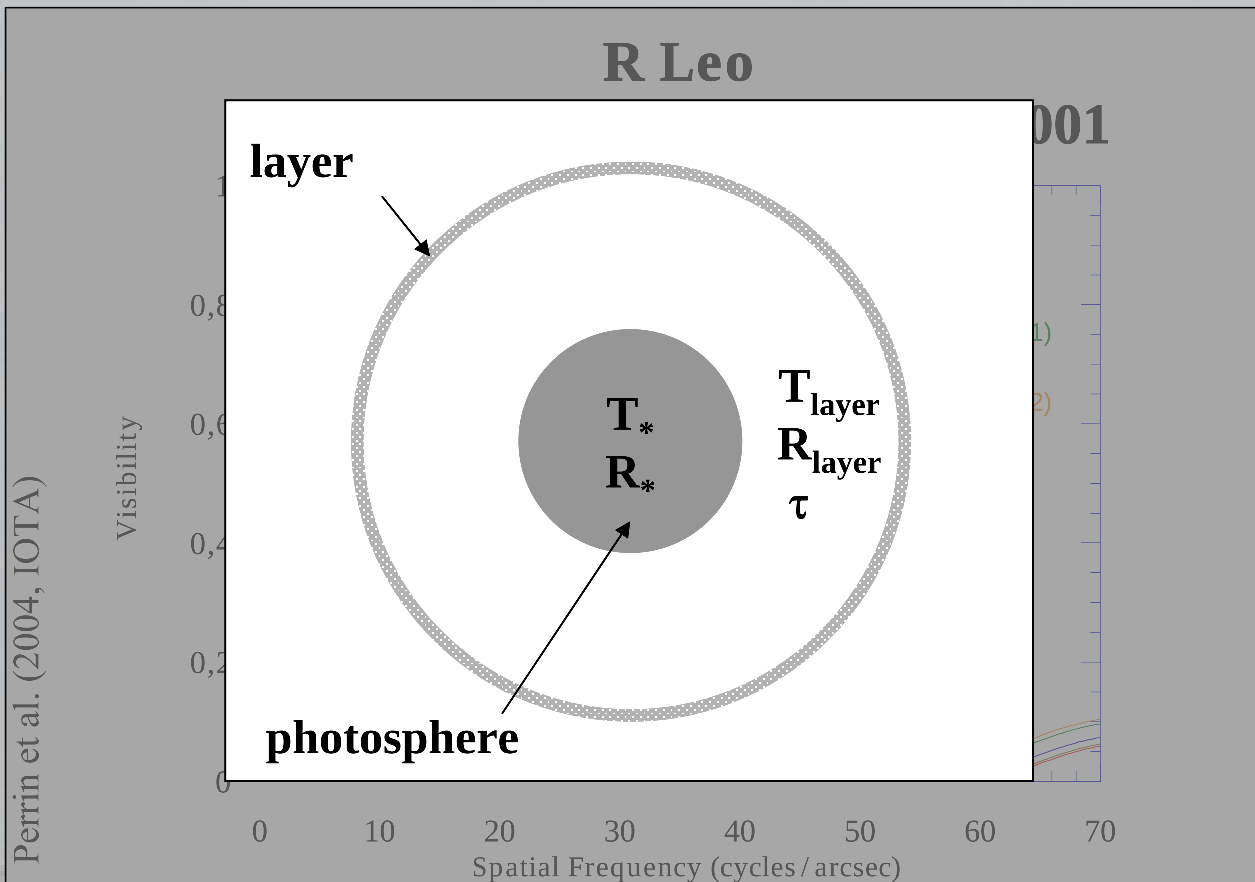


Measuring Mira star diameters



Mennesson et al. (2002, IOTA)

Multi-λ observations of R Leo



$\tau_{2.03\mu m}$ = 1.19±0.01

$\tau_{2.15\mu m}$ = 0.51±0.01

$\tau_{2.22\mu m}$ = 0.33±0.01

$\tau_{2.39\mu m}$ = 1.37±0.01

τ_{L} = 0.63±0.01

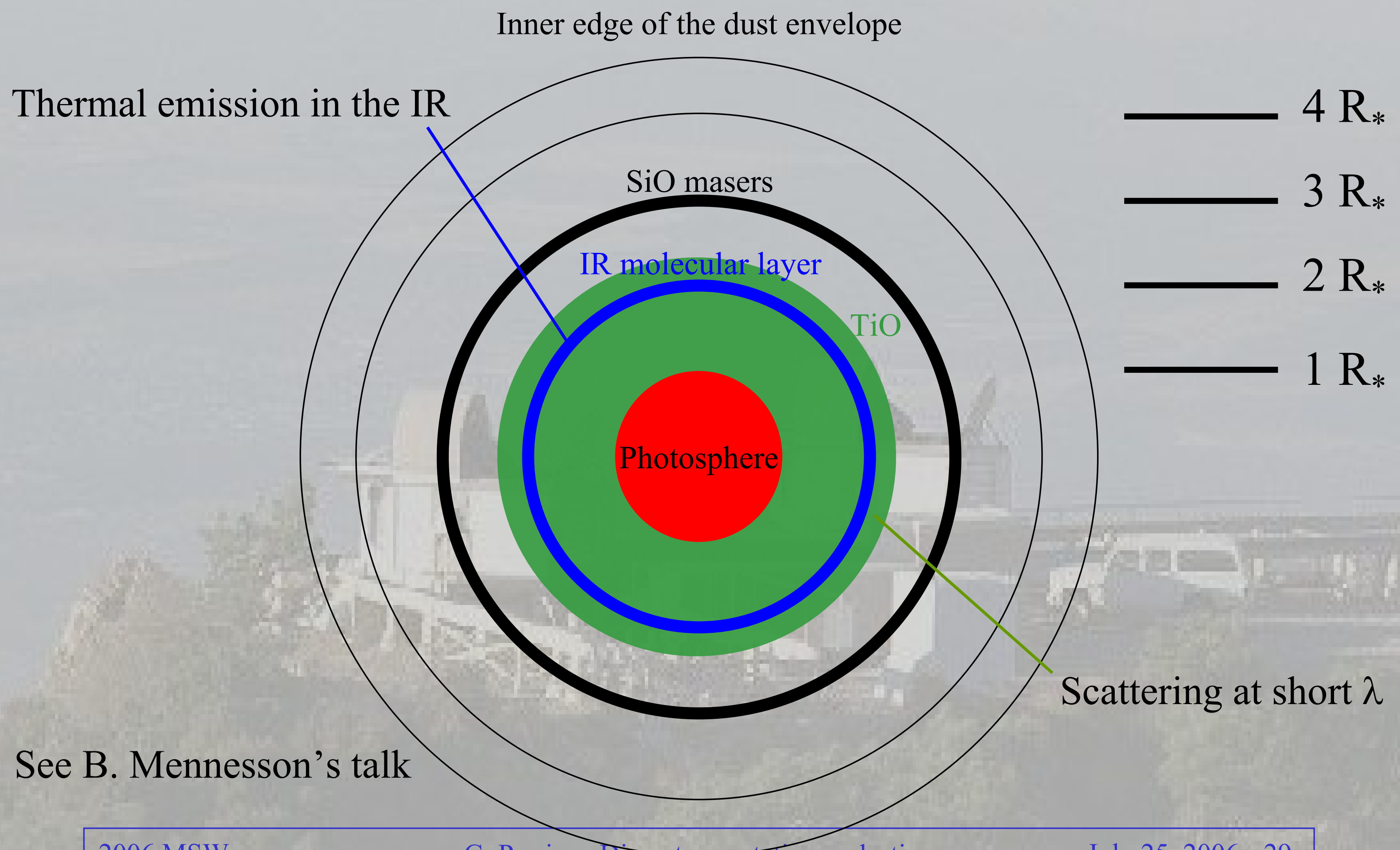
R_* = 10.94±0.85 mas
T_* = 3856±119 K

R_{layer} = 25.00±0.17mas
T_{layer} = 1598±24 K

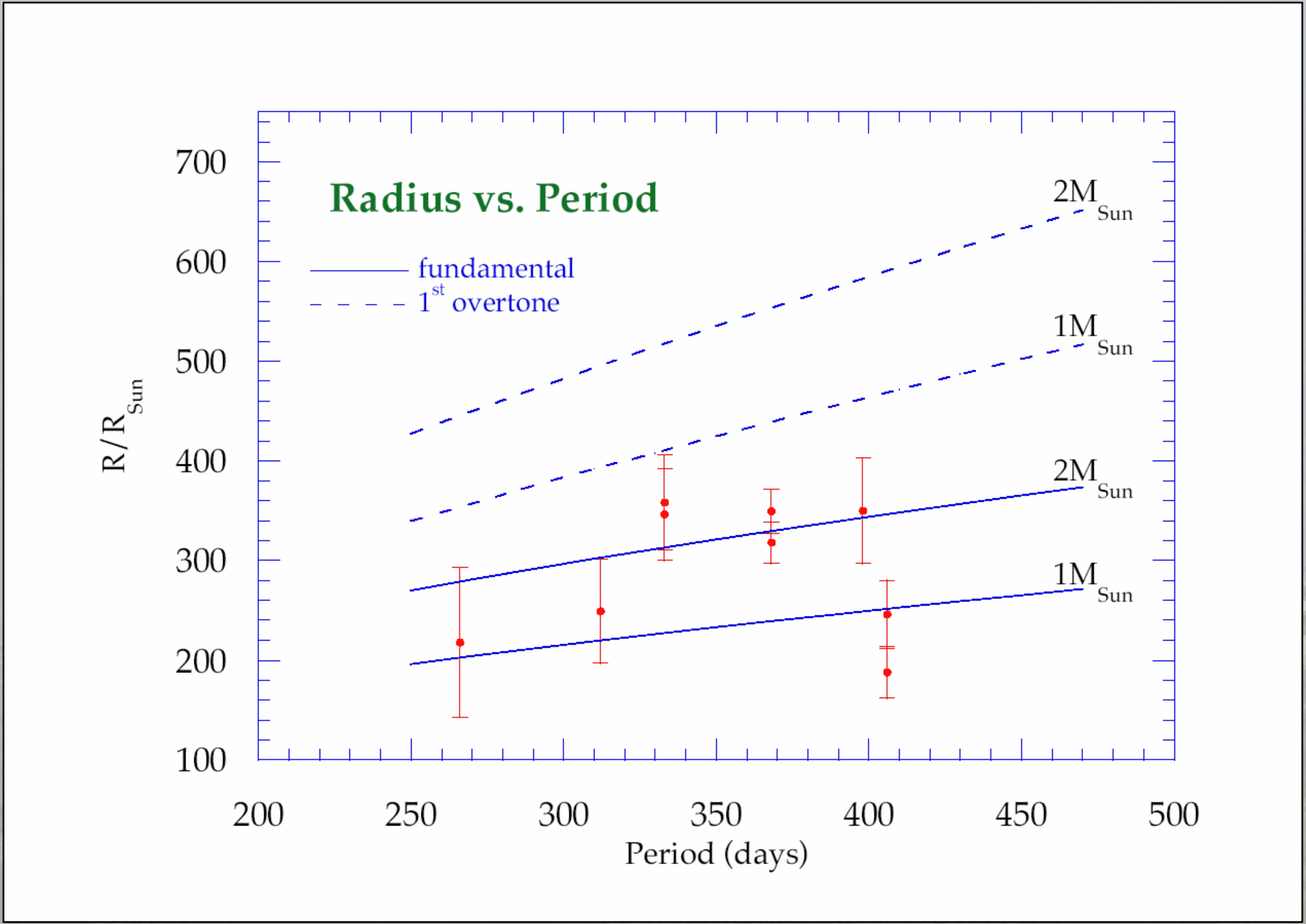
Phase K: 0.79
Phase L: 0.64

Type: M0-M1

A possible sketch for Mira stars



Radius and pulsation mode



Outline

- Measuring stellar diameters
- Why measuring stellar diameters ?
- **Pulsations**
- Rotation

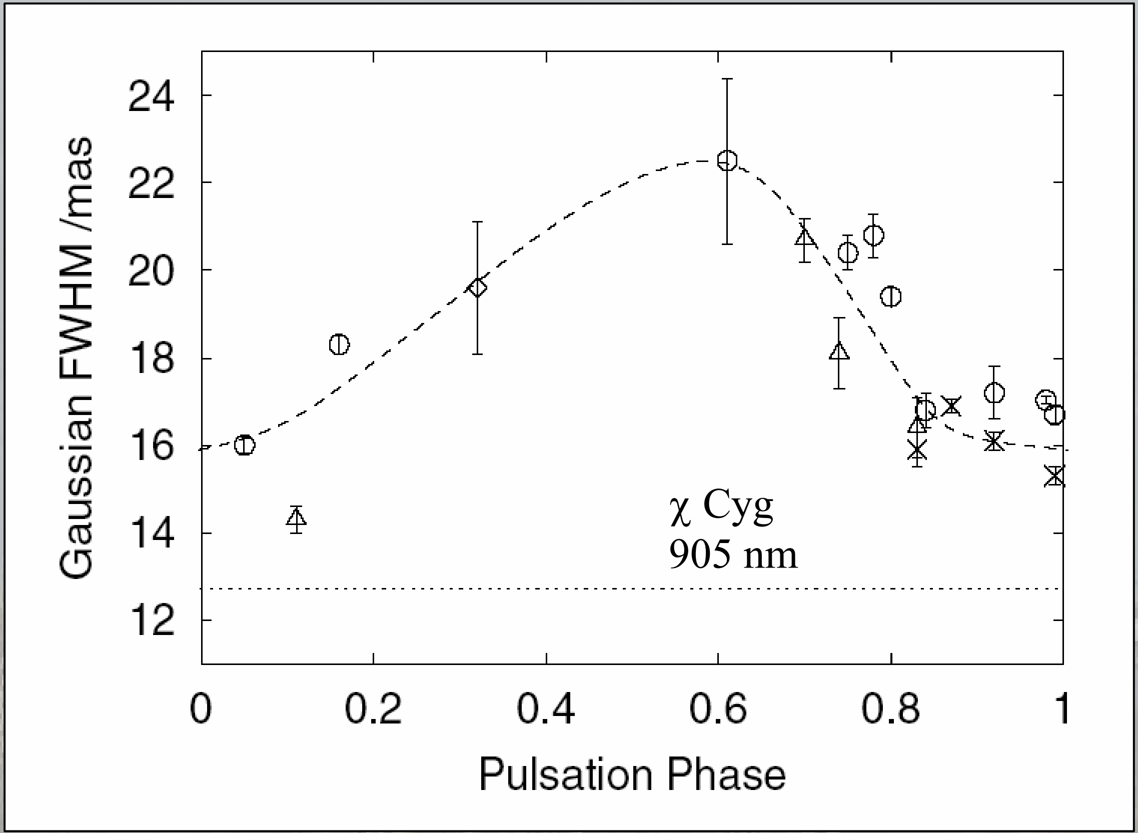
Meausuring the pulsation of stars

- A difficult task

- ***Either*** stars are well approximated by uniform or slightly darkened disks but have small amplitude pulsations

- ***Or*** stars have large amplitude pulsations but have complex structures that (may) evolve with time

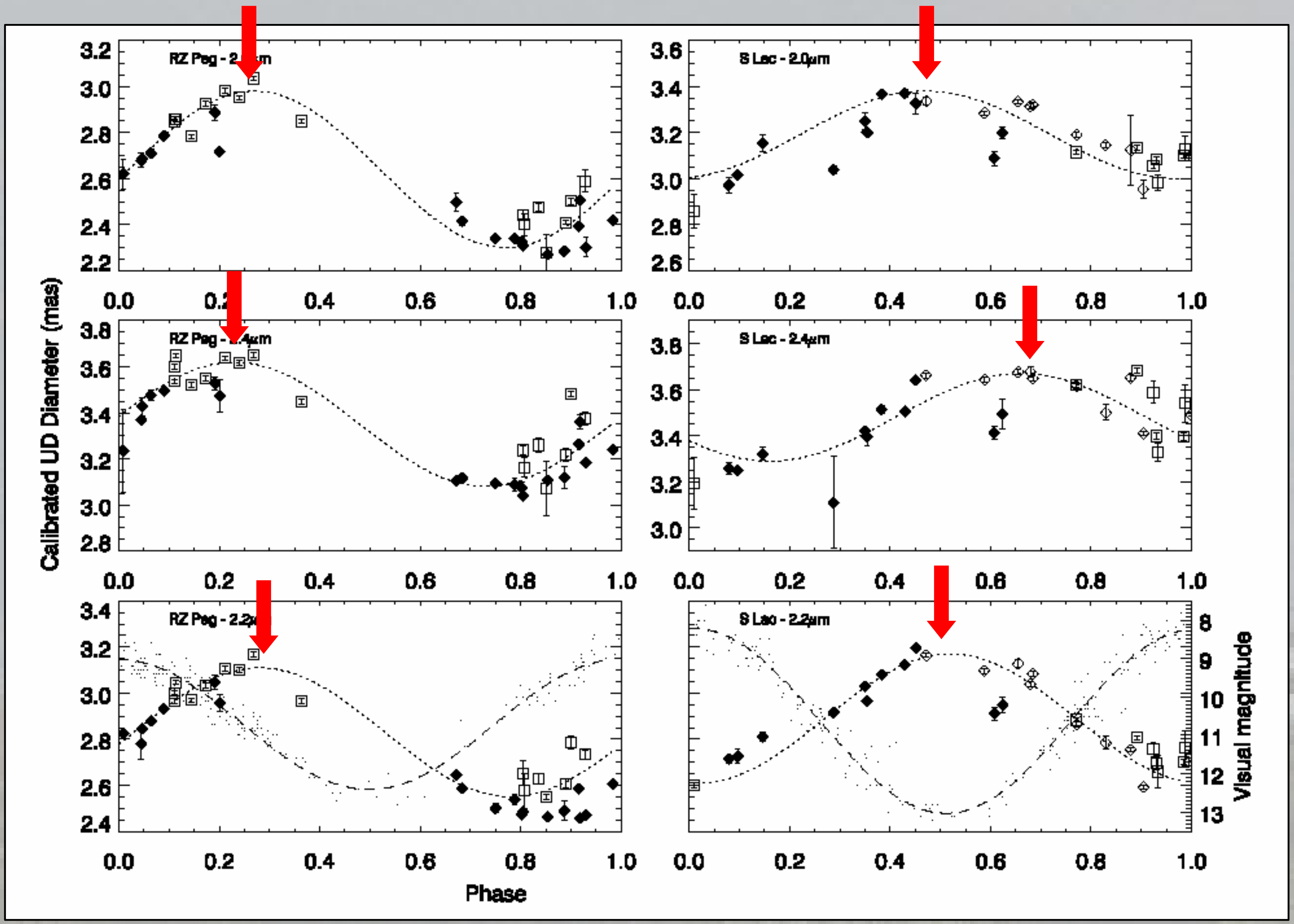
Diameter variations of Mira stars



Young et al. (2000, COAST)

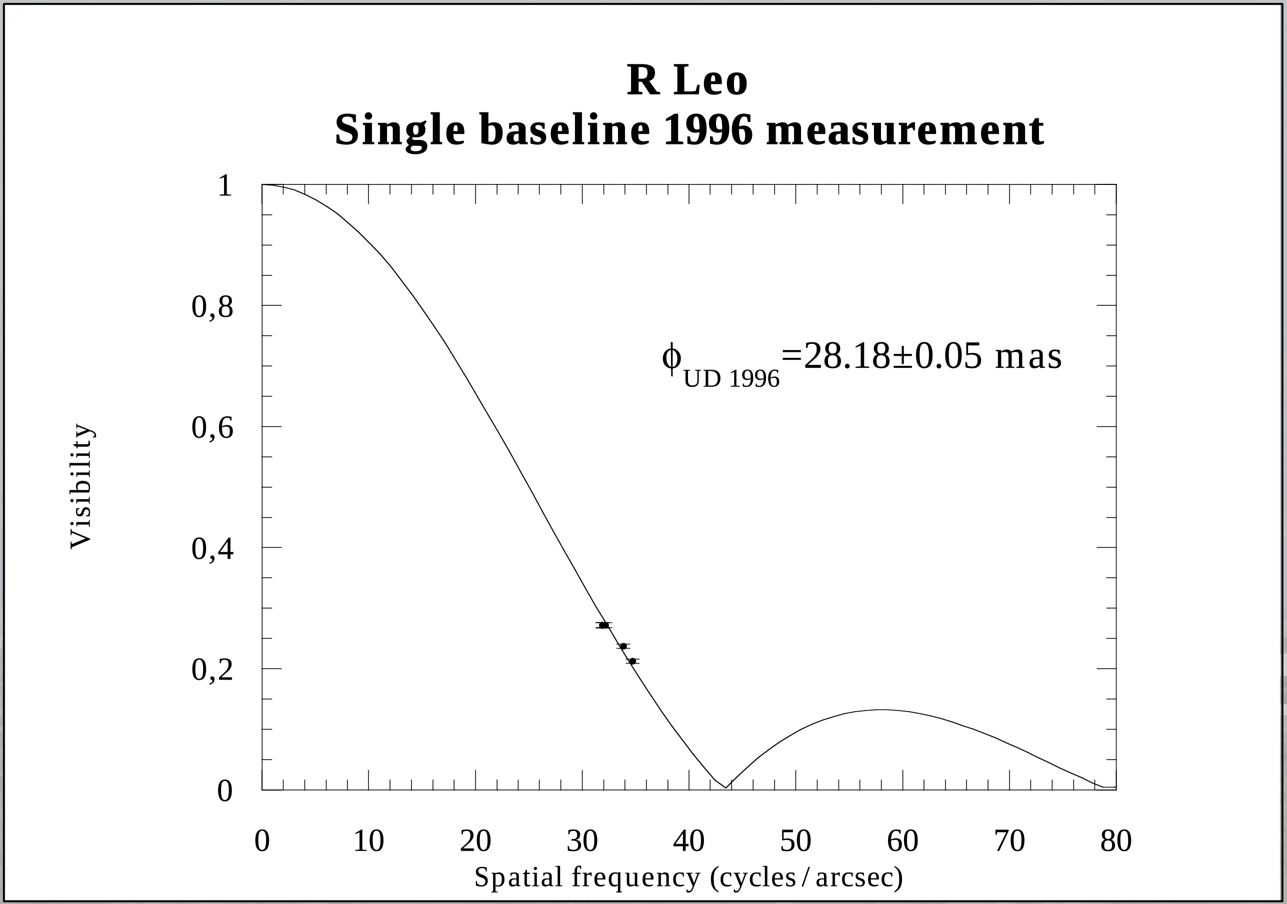
Almost no variations at 1290 nm

Diameter variations of Mira stars



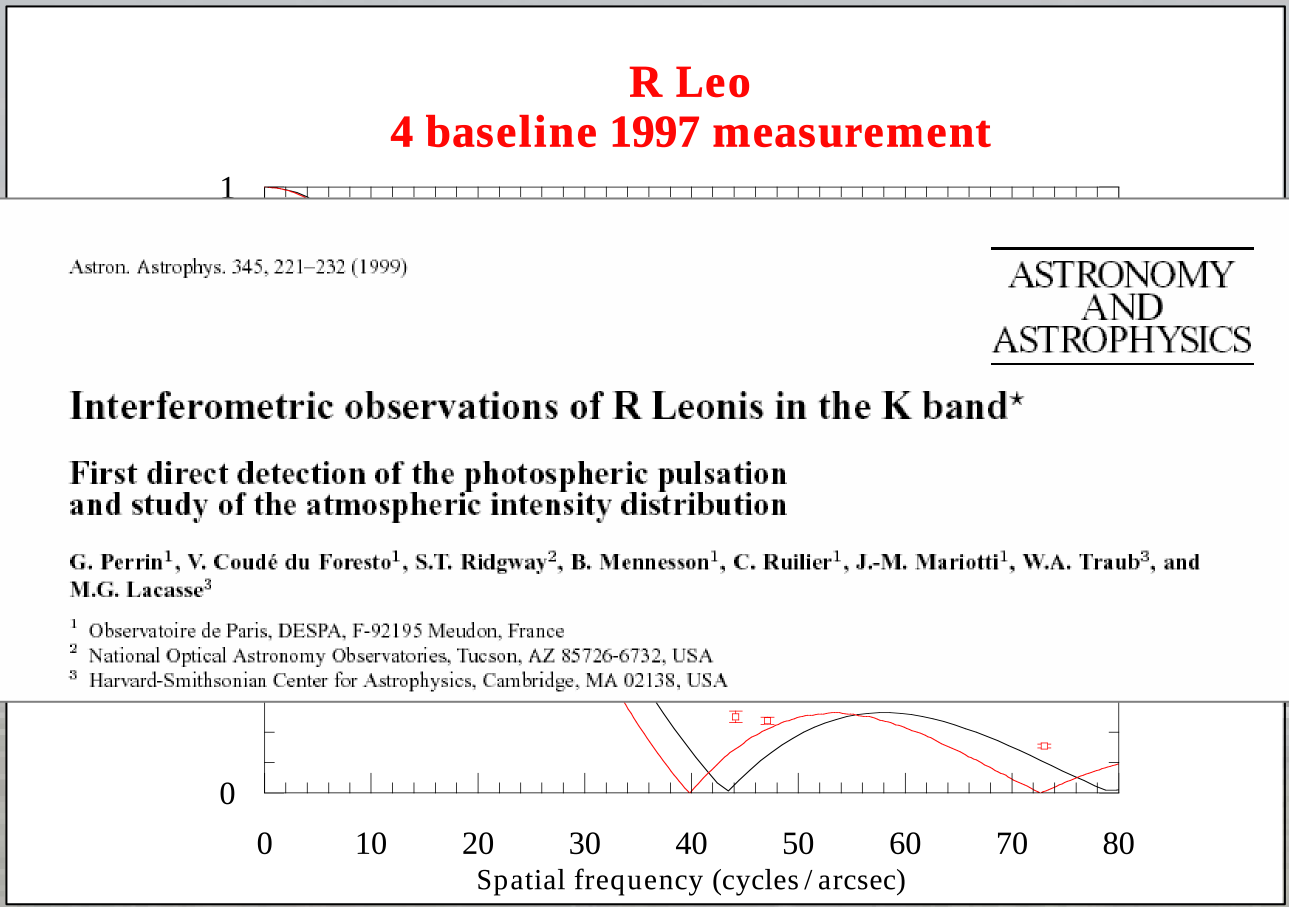
Thompson et al. (2002, PTI)

Diameter variations of Mira stars



Perrin et al. (1999, IOTA)

Diameter variations of Mira stars



Astron. Astrophys. 345, 221–232 (1999)

ASTRONOMY AND ASTROPHYSICS

Interferometric observations of R Leonis in the K band*

First direct detection of the photospheric pulsation and study of the atmospheric intensity distribution

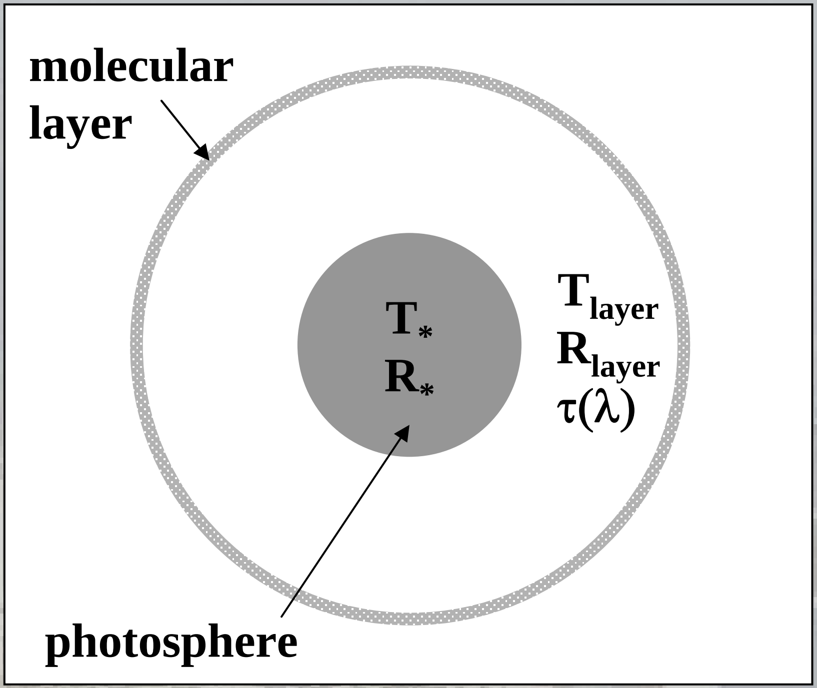
G. Perrin[1], V. Coudé du Foresto[1], S.T. Ridgway[2], B. Mennesson[1], C. Ruilier[1], J.-M. Mariotti[1], W.A. Traub[3], and M.G. Lacasse[3]

[1] Observatoire de Paris, DESPA, F-92195 Meudon, France
[2] National Optical Astronomy Observatories, Tucson, AZ 85726-6732, USA
[3] Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA

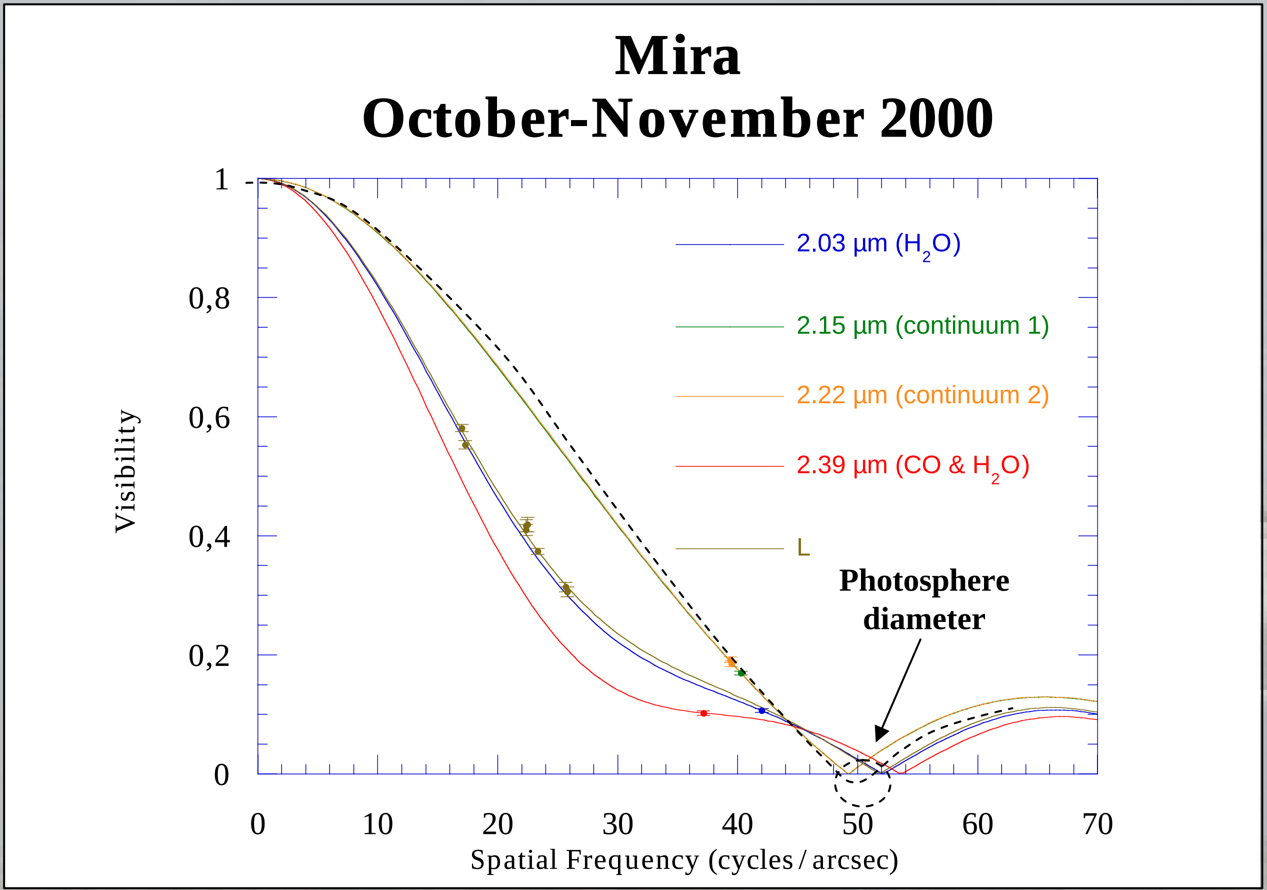
(Perrin et al. 1999)

Direct detection of pulsation ?

Simple ad-hoc model: photosphere + molecular layer



Apparent diameter variations of Mira



$\tau_{2.03\mu m} = 0.14 \pm 0.02$

$\tau_{2.15\mu m} = 0.01 \pm 0.01$

$\tau_{2.22\mu m} = 0.01 \pm 0.01$

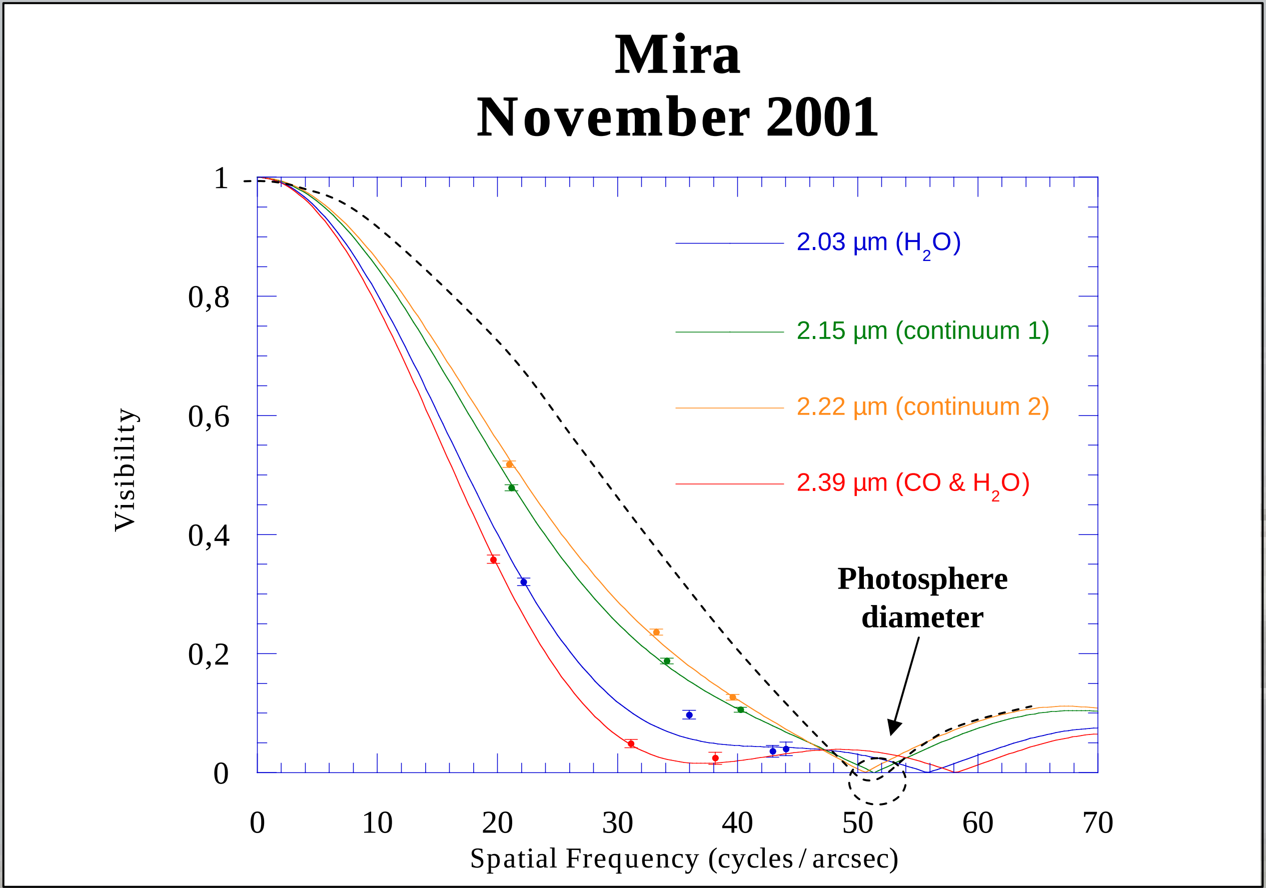
$\tau_{2.39\mu m} = 0.21 \pm 0.01$

$\tau_{L} = 0.08 \pm 0.01$

$R_* = 12.29 \pm 0.02$ mas **$R_{layer} = 26.84 \pm 0.06$ mas** **Phase K: 0.01** **Type: M6**

$T_* = 3263 \pm 105$ K **$T_{layer} = 2105 \pm 53$ K** **Phase L: 0.10**

Apparent diameter variations of Mira



$\tau_{2.03\mu m} = 0.63 \pm 0.21$

$\tau_{2.15\mu m} = 0.19 \pm 0.05$

$\tau_{2.22\mu m} = 0.12 \pm 0.04$

$\tau_{2.39\mu m} = 0.76 \pm 0.50$

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

$T_* = 3600 \pm 67$ K **$T_{layer} = 1961 \pm 17$ K**

Apparent diameter variations of Mira

Phase 0 (October 2000)

R_* = 12.29±0.02 mas R_{layer} = 26.84±0.06 mas

R_* □ 0.37 mas (3%)

Phase 0.2 (November 2001)

R_* = 12.71±0.15 mas R_{layer} = 24.95±0.10 mas

R_{layer} ⇗ 1.89 mas (7.3%)

Although the *apparent* diameter increased by 20%…

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

… the *apparent* diameter change may be a pure optical depth variation effect

The Cepheid stars and the distance scale

QuickTime™ et un
décompresseur TIFF (non compressé)
sont requis pour visionner cette image.

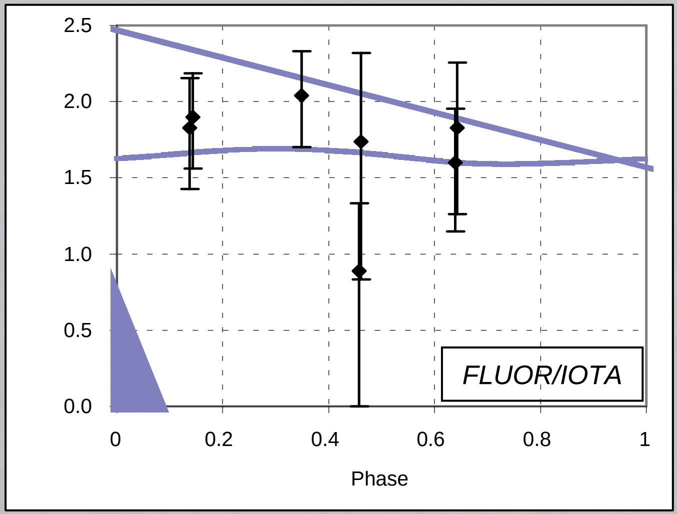
Henrietta S. Leavitt

QuickTime™ et un
décompresseur TIFF (non compressé)
sont requis pour visionner cette image.

$$L_{Earth} = \frac{1}{4\pi D^2{}_{Earth-Cepheid}} \times L_{\mathrm{Cepheid}}$$

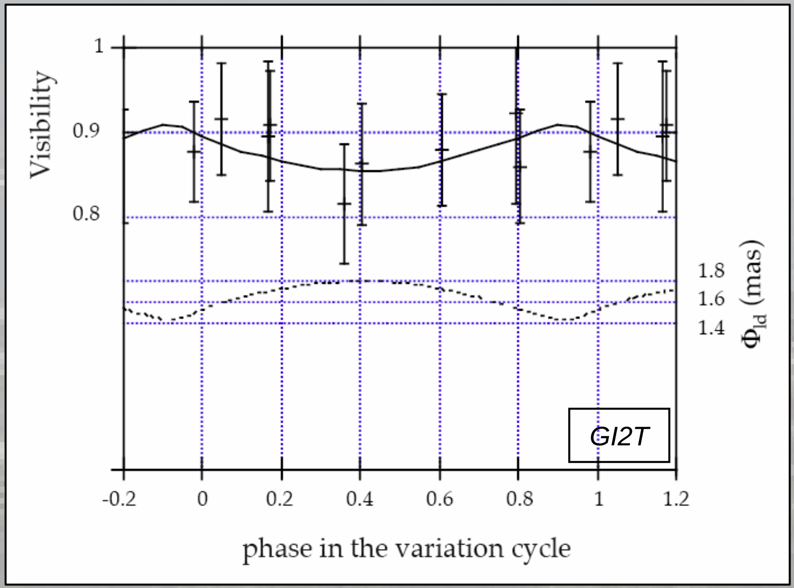
Interferometric measurements are useful to calibrate this law

Unsuccessful attempts



ζ Gem Kervella et al. (2001)

Baselines were just too short !



δ Cep Mourard et al. (1997)

Success !

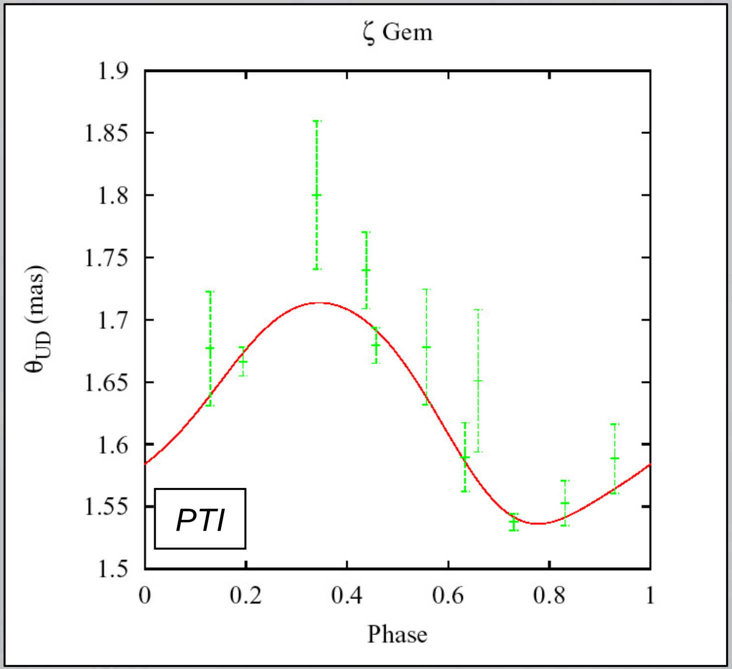
Measurement of pulsation by spectroscopy/Doppler effect:

$$\Delta R_{\text{Cepheid}}$$

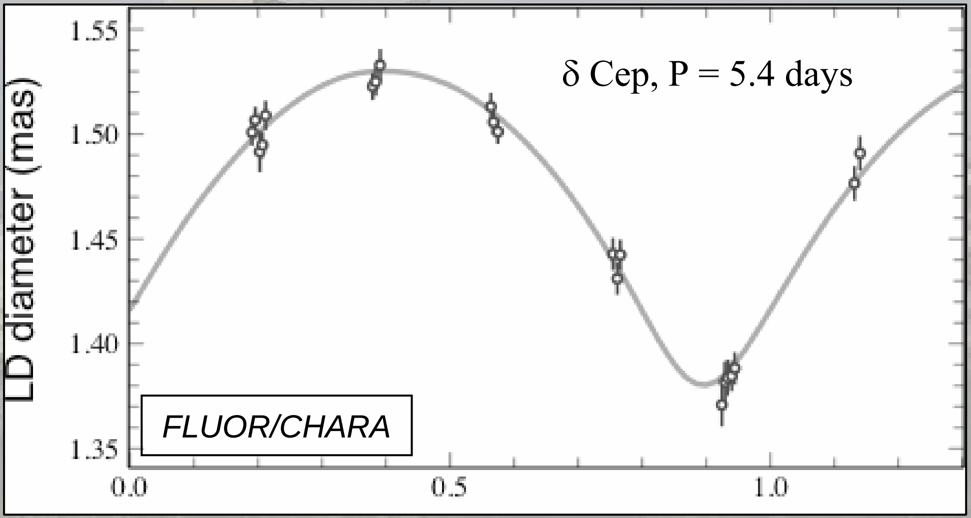
Measurement of the pulsation by interferometry :

$$\Delta R_{\text{Cepheid}} / D_{\text{Earth-Cepheid}}$$

$$\Rightarrow D_{\text{Earth-Cepheid}}$$

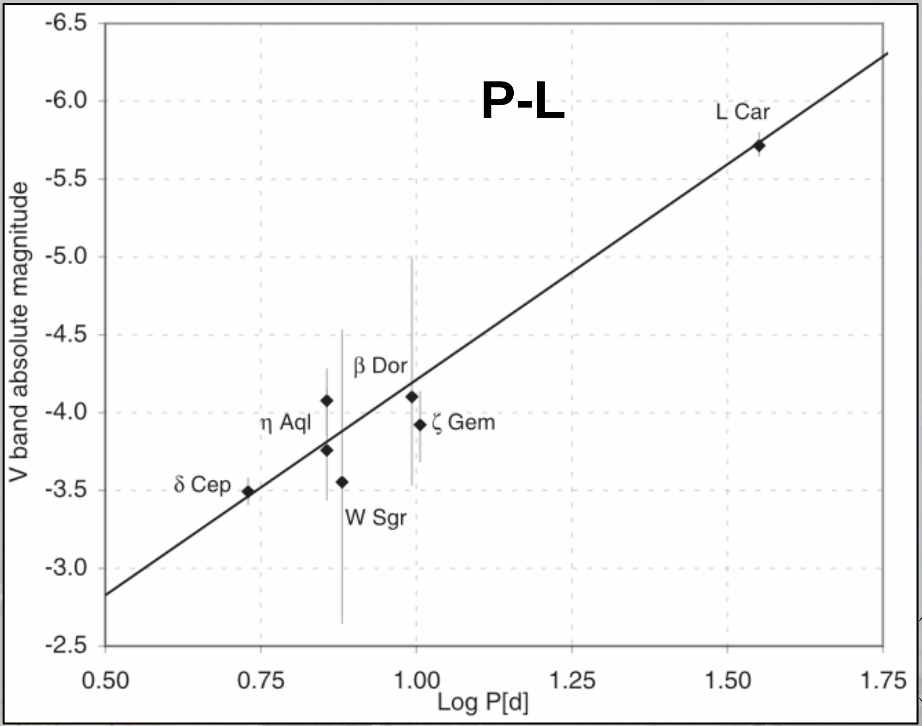


Lane et al. (2001)



Mérand et al. (2005)

The Cepheid law calibration



Kervella et al. (2004)

Cepheid measurements:

VINCI (7),PTI (2), NPOI (3), GI2T (1), IOTA/FLUOR (1), CHARA/FLUOR (1) …

Outline

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How to measure rotation ?

It should be easy:

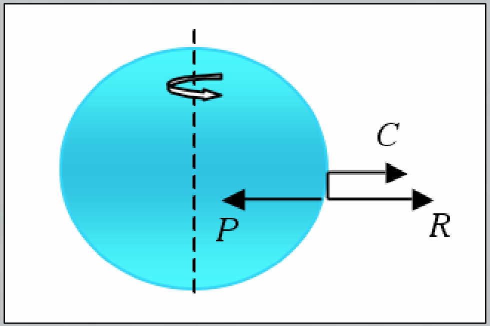
make an image of the star and watch the motion of spots with rotation

Maybe a little too difficult for now.

Another idea:

measure a quantity which is a consequence of rotation

Flattening ... in a simplified way



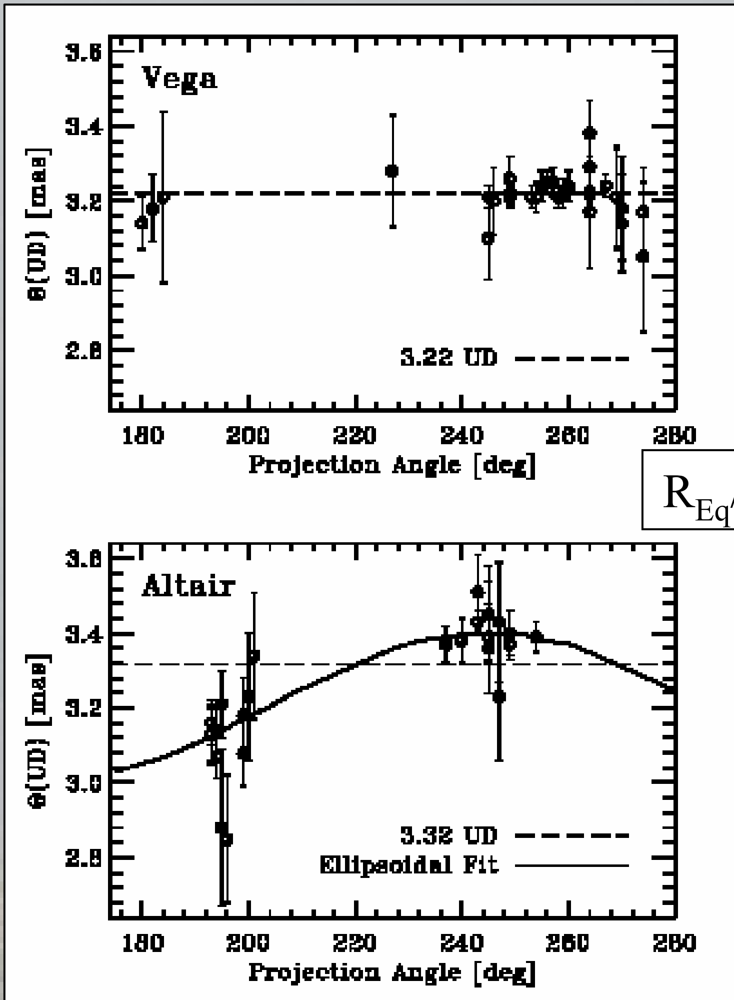
- A particle at the equator of the star is subject to its weight *P*, the pressure reaction *R* and the centrifugal force *C* created by rotation

- For a given central mass, the flattening is then simply given by (Huyghens approximation):

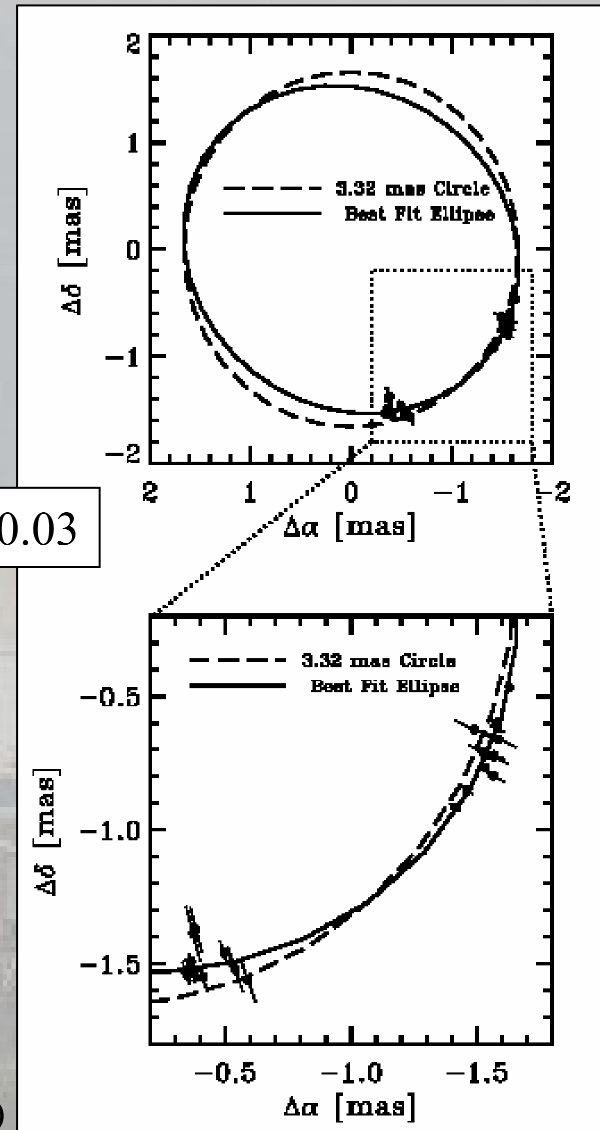
$$\frac{R_{eq}}{R_{pol}} = 1 + \frac{C}{2P}$$

For the matter to stay on the star, we have $C < P$, and therefore $R_{eq}/R_{pol} < 1.5$

Altair

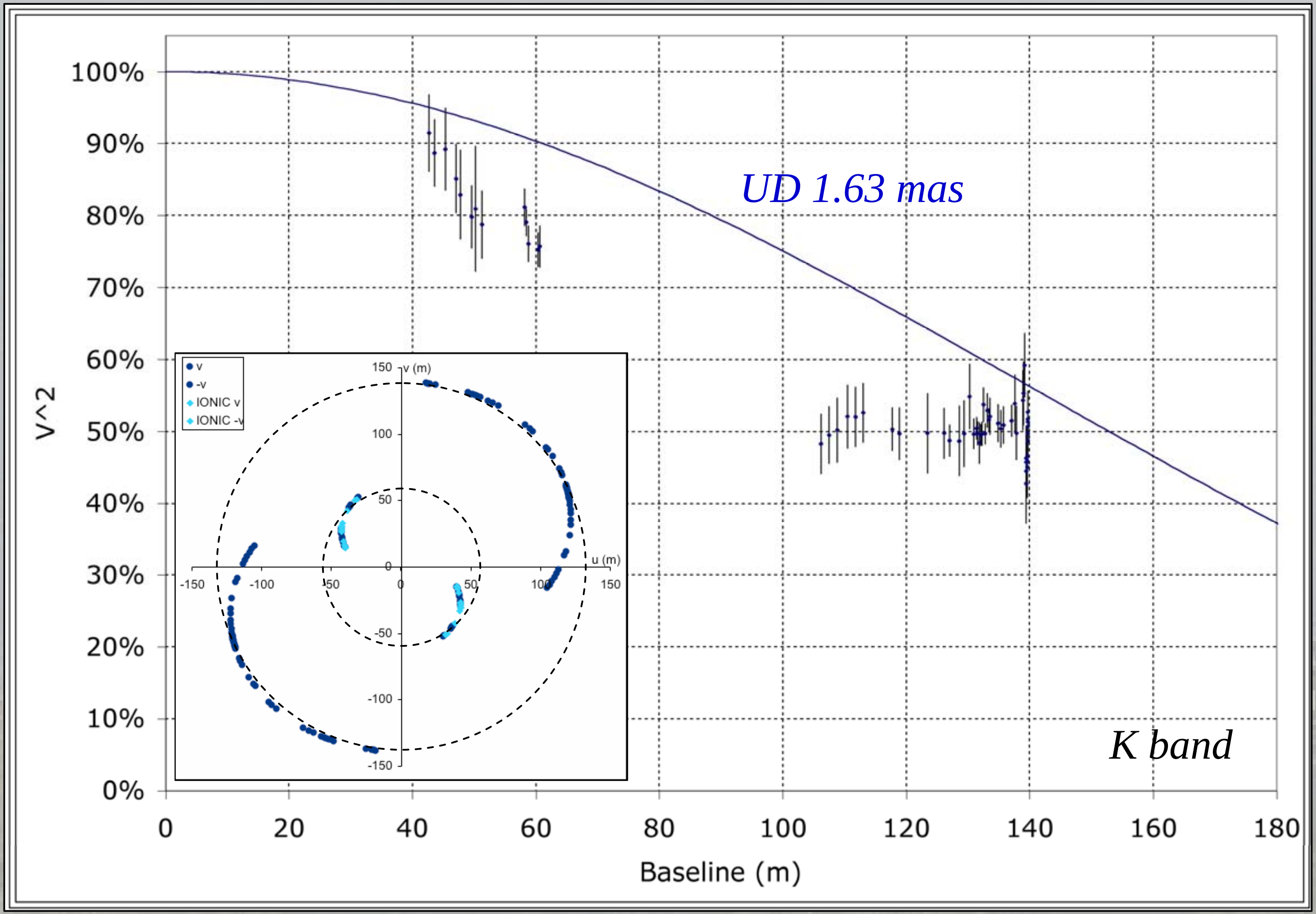


$R_{Eq}/R_{Pol} = 1.14 \pm 0.03$



Van Belle et al. (2001, PTI)

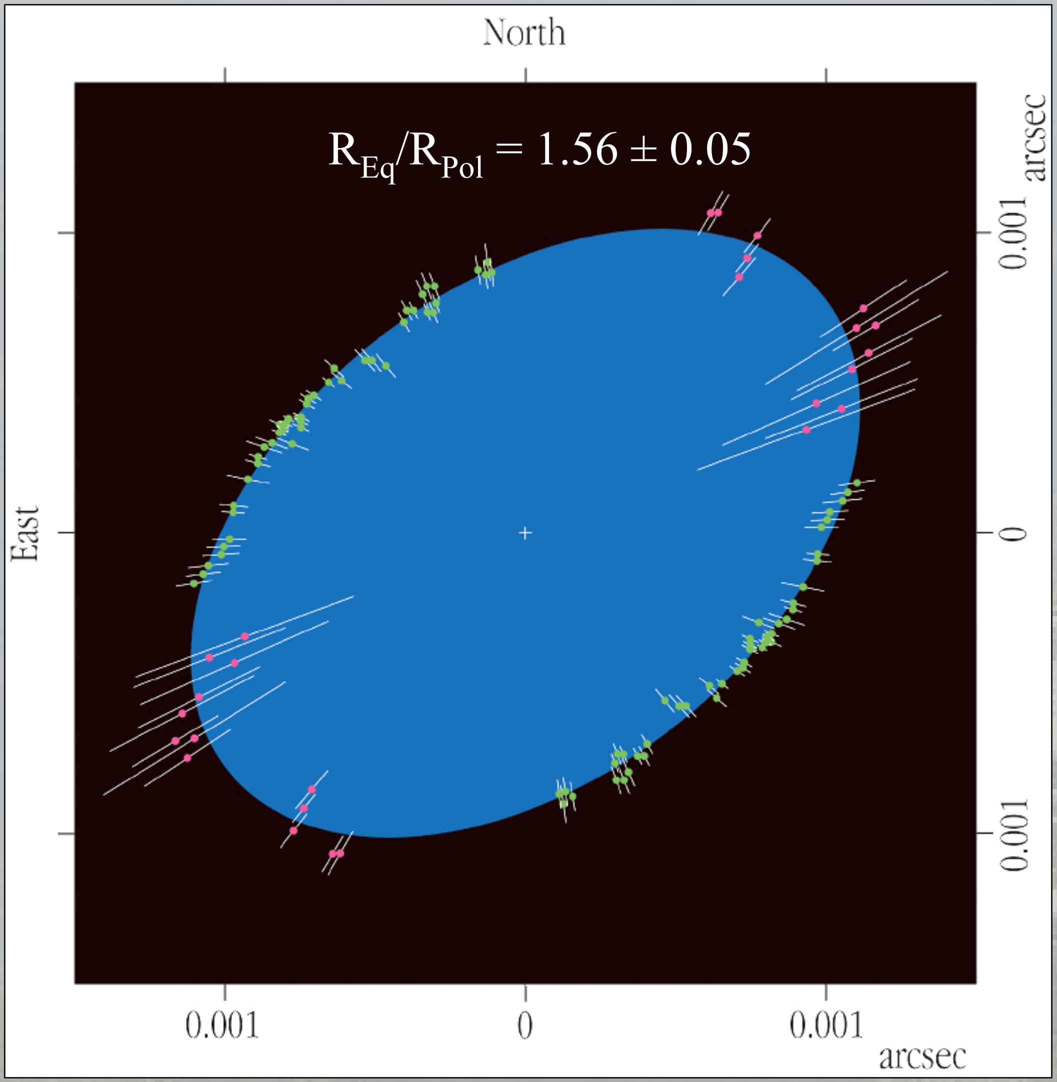
Achernar

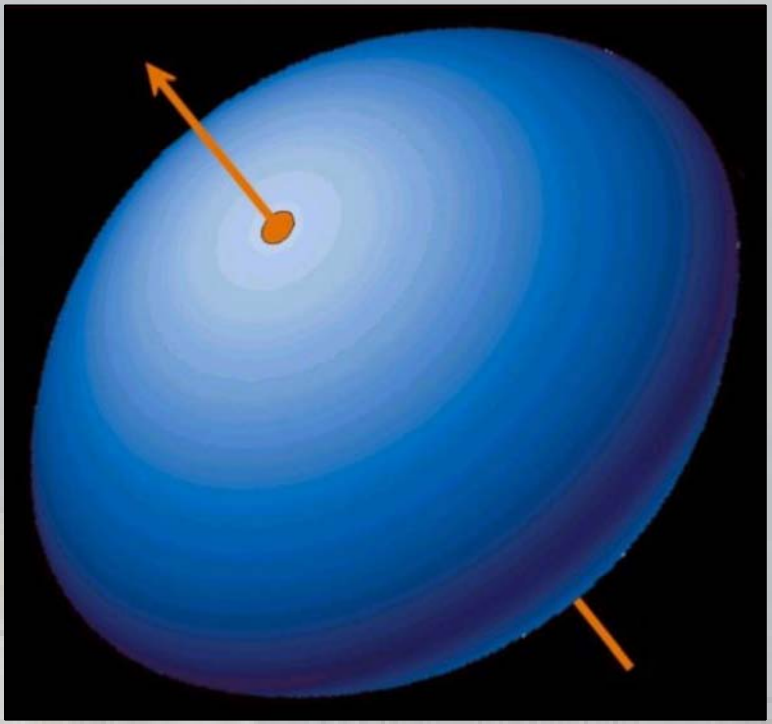


Domiciano et al. (2003, VLTI)

*Obviously, Achernar is **not** a uniform disk !*

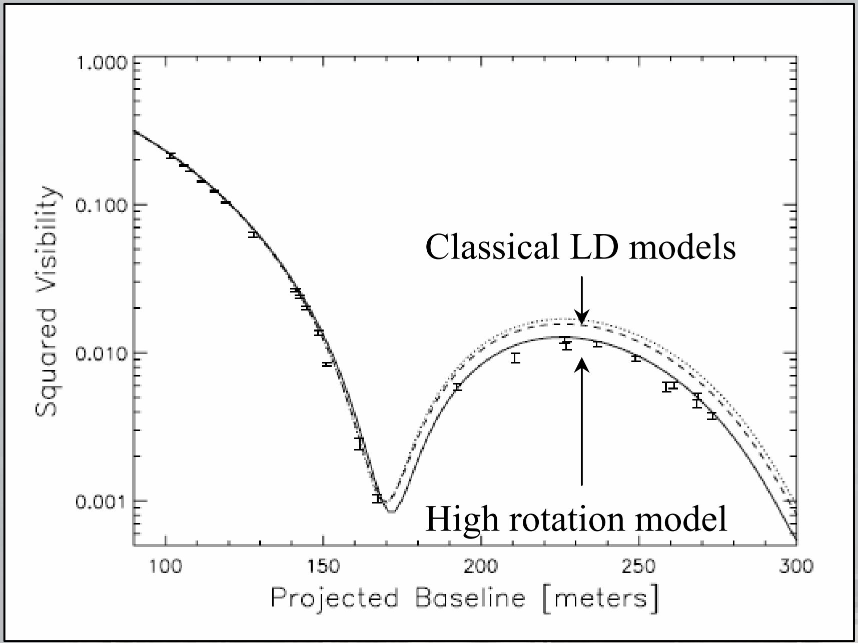
Modeling





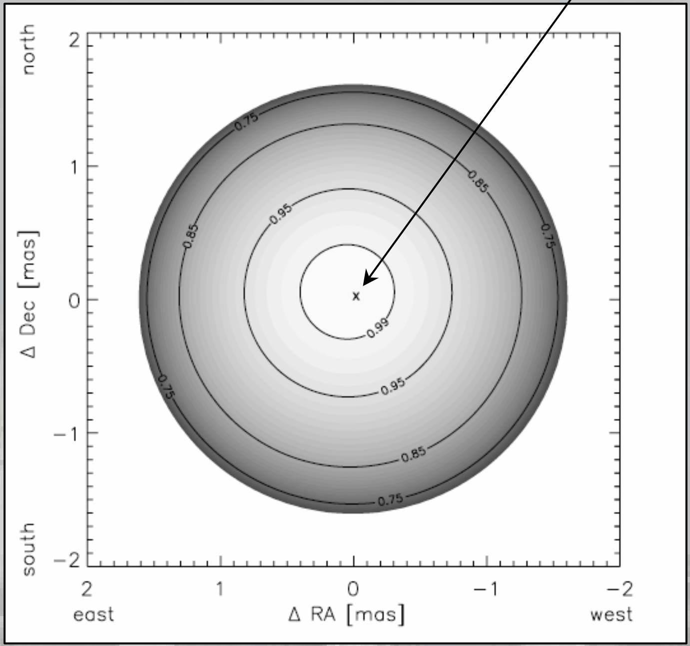
- The *Von Zeippel* effect needs to be taken into account to interpret visibilities (darkening at the equator)
- Models fail to explain Achernar
- Breakup speed is reached

The incredible case of Vega (K band)



Aufdenberg et al. (2006, CHARA)

Subsolar point

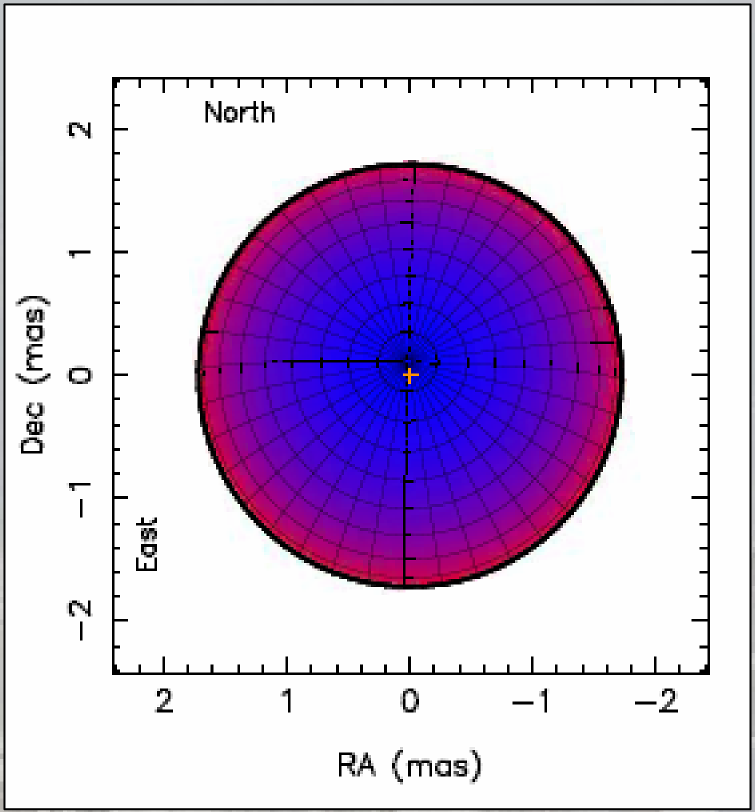


$$T_{eff}^{pole} = 10150\,K$$

$$T_{eff}^{equa} = 7900\,K$$

$$i = 4.7°$$

Closure phase imaging of Vega (500 nm)

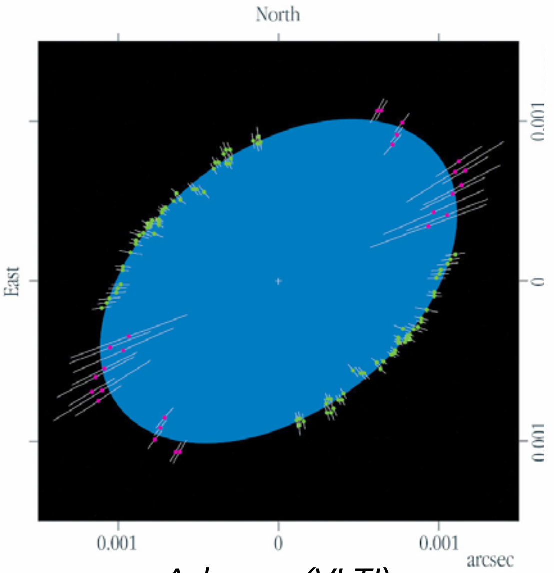


Peterson et al. (2006, NPOI)

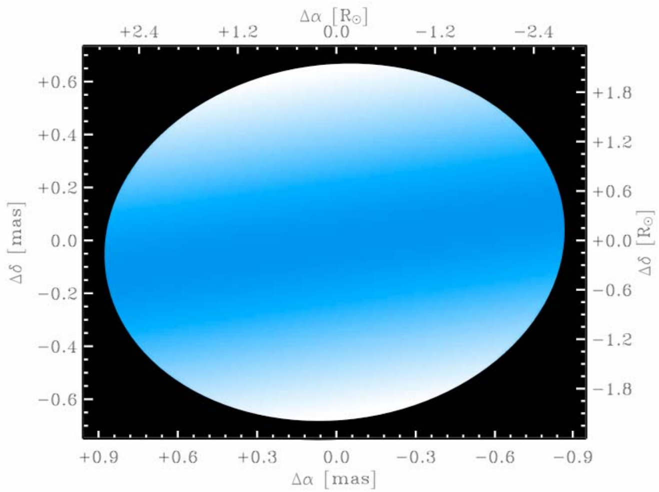
The asymmetry predicted by CHARA/FLUOR is detected with NPOI

i=4.6° 93% of the breakup speed !

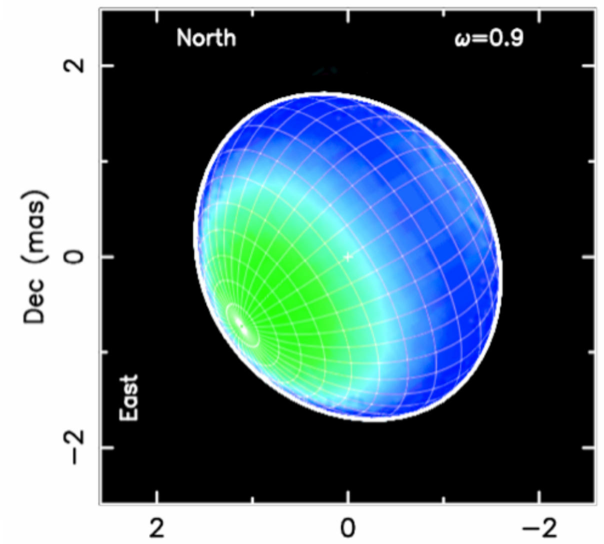
Fast rotating stars observed by interferometry



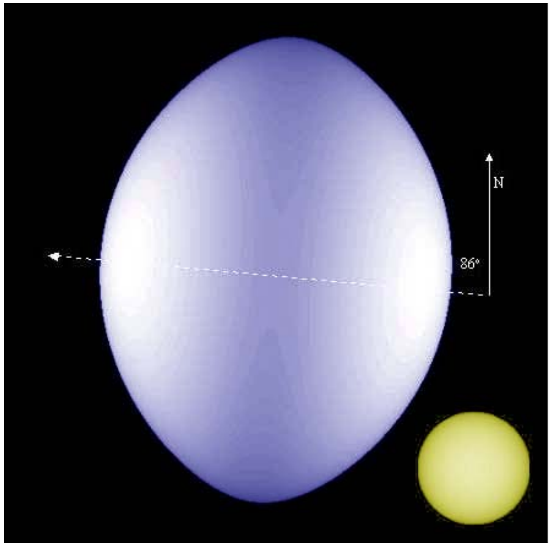
Achernar (VLTI)



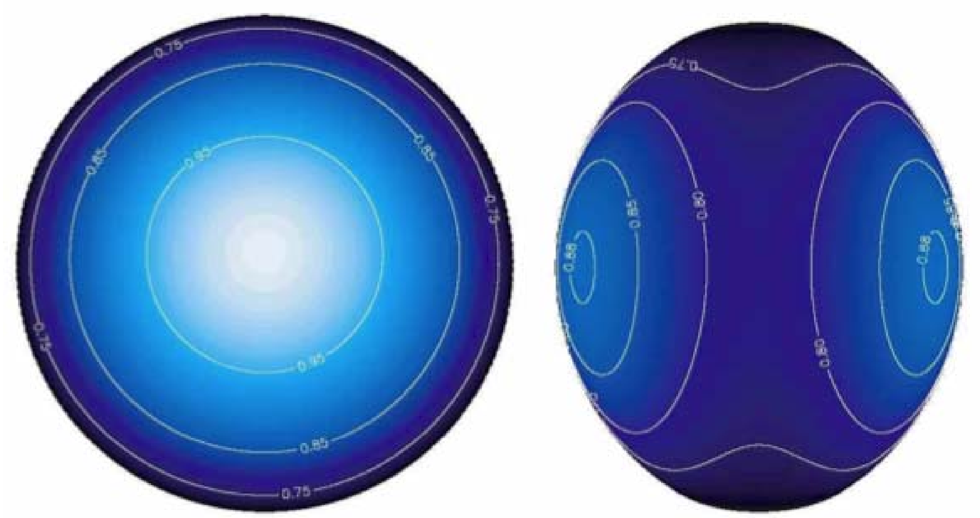
Alderamin (CHARA)



Altaïr (PTI, NPOI)



Regulus (CHARA)



Vega (CHARA, NPOI)

A brief conclusion

- Meausuring stellar diameters is a classical sport for interferometrists (the Australian intensity interferometer could have been mentioned here)
- Diameters can be measured with very high accuracies (~ 0.5%)
- Measuring diameters is useful for both stellar and extragalactic physics
- Measuring diameter spatial and temporal variations is useful for cosmology (distance scale) and also for fundamental physics (e.g. the Von Zeippel effect)
- Care should be taken when measuring diameters of non-ordinary stars

Thanks to P. Kervella for the stellar rotation slide fund