Observations of Achernar with VINCI

EuroSummer School

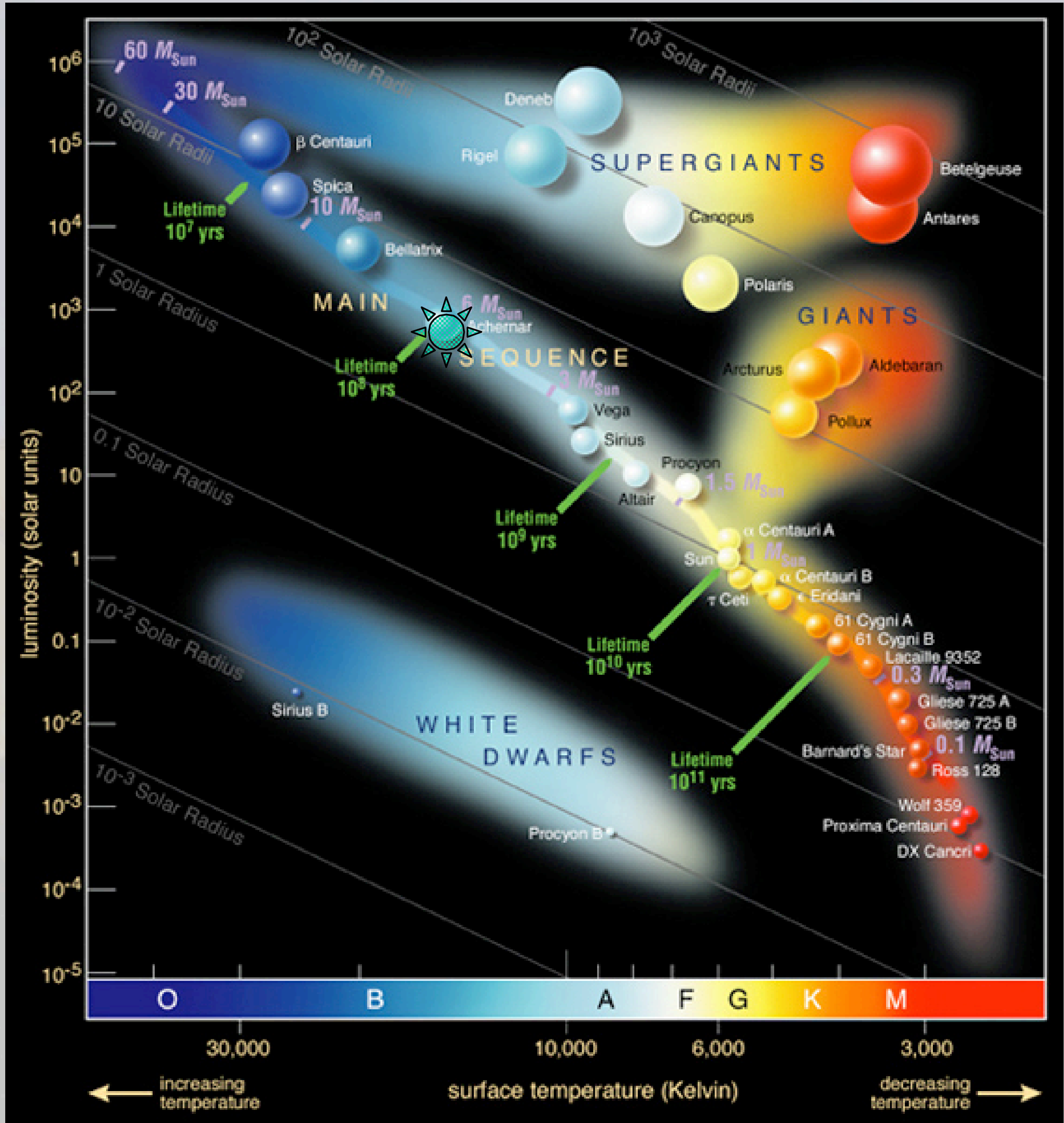
Observation and data reduction with the Very Large Telescope Interferometer

Goutelas, France
June 4-16, 2006

P. Kervella
Observatoire de Paris
5 June 2006

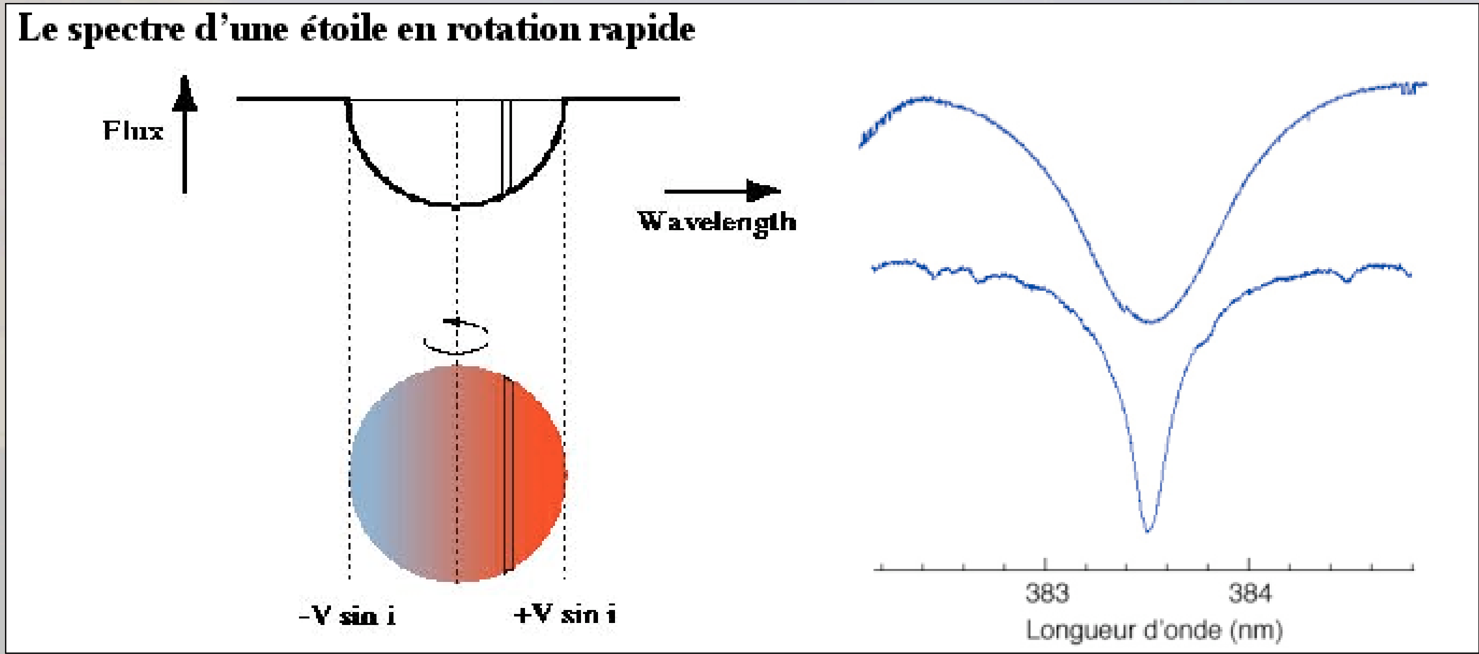
Why observe Achernar (α Eri) ?

- m_V=0.50
- Spectral type: **B3Vpe**
- Teff ~ 15000 K
- Luminosity ~ 3000 $L_\odot$
- Distance = 44 pc +/- 1 pc
- M ~ 6 $M_\odot$, R ~ 10 $R_\odot$
- Rotational velocity:
  $v_{eq}.\sin i$ = 225 km/s



Rotational velocity

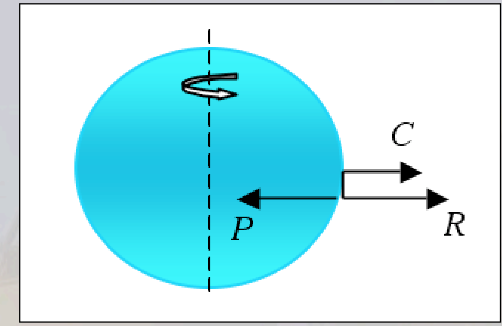
How do we know the rotational velocity of a star ?



Achernar: $v_{eq}.\sin i = 225$ km/s
Sun: $v_{eq} = 2$ km/s

This very fast rotation distorts the star... but by how much ?

Flattening... in a simplified way

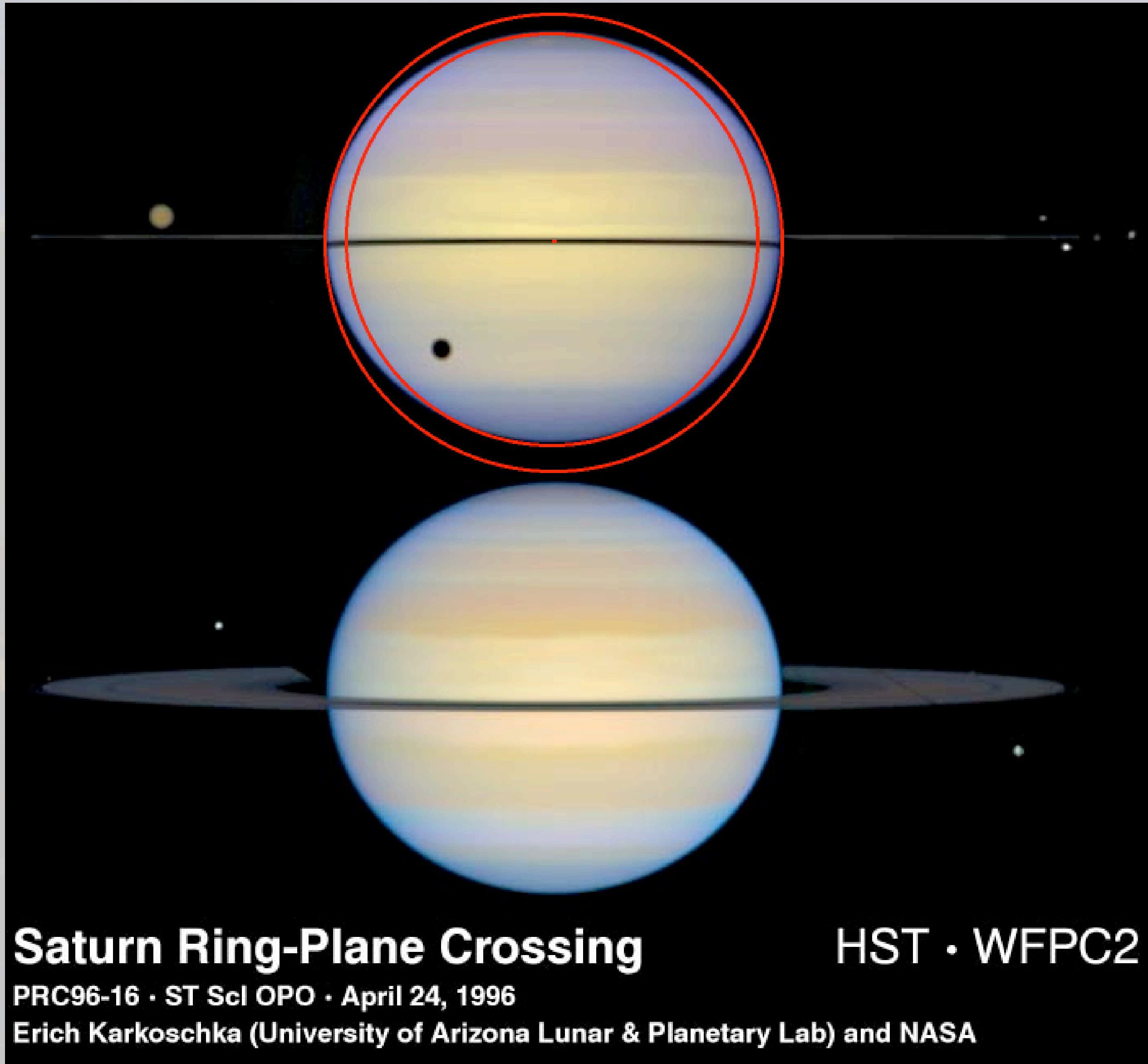


- A particle at the equator of the star is subject to its weight *P*, the pressure reaction *R* and the centrifugal force *C* created by rotation

- 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 then $R_{eq}/R_{pol}<1.5$


Saturn Ring-Plane Crossing
HST • WFPC2
PRC96-16 • ST ScI OPO • April 24, 1996
Erich Karkoschka (University of Arizona Lunar & Planetary Lab) and NASA

How can we « see » the effects of Achernar's rotation ?

We need to *resolve* the star...

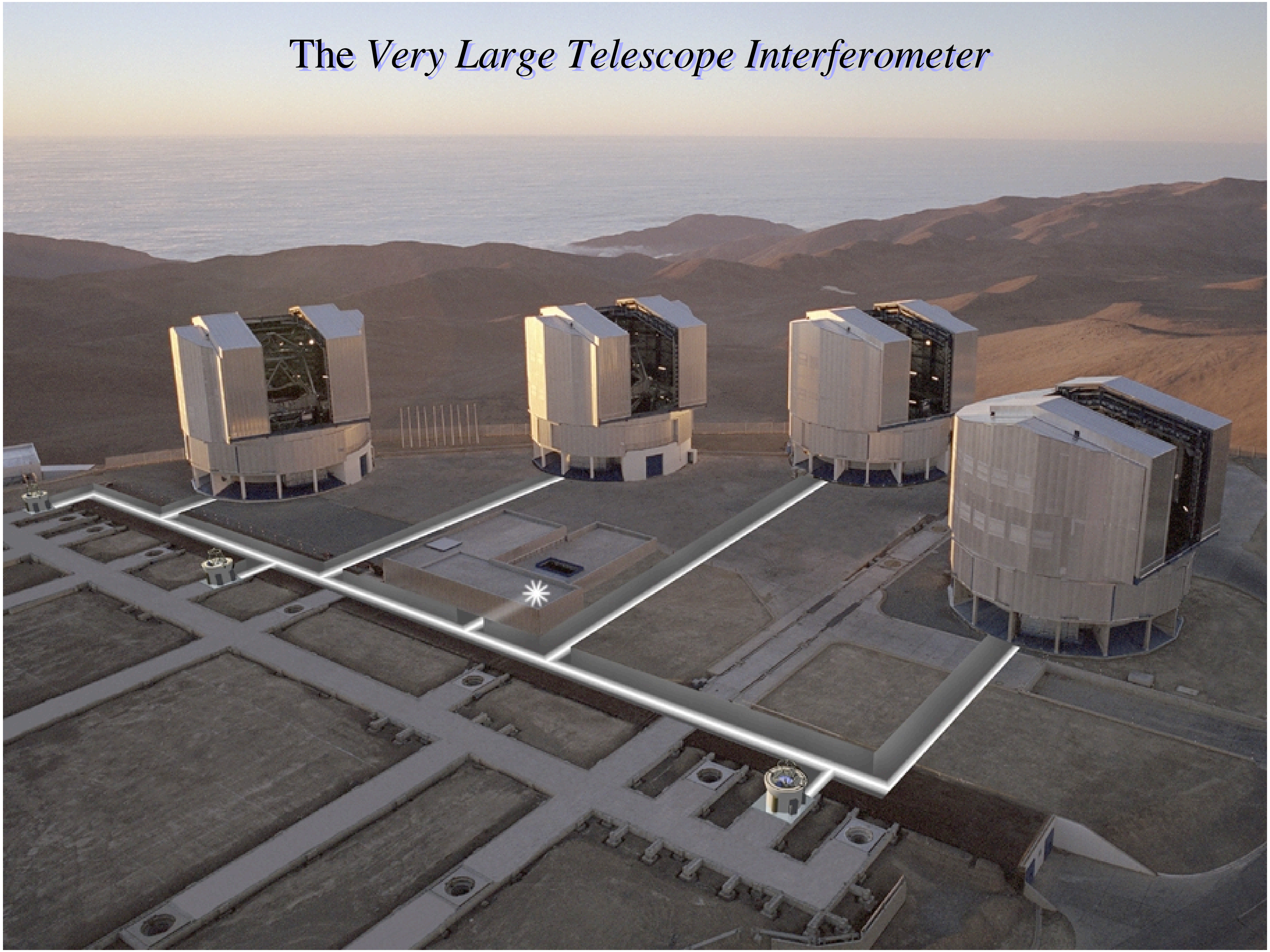
But it is *extremely* small angularly:

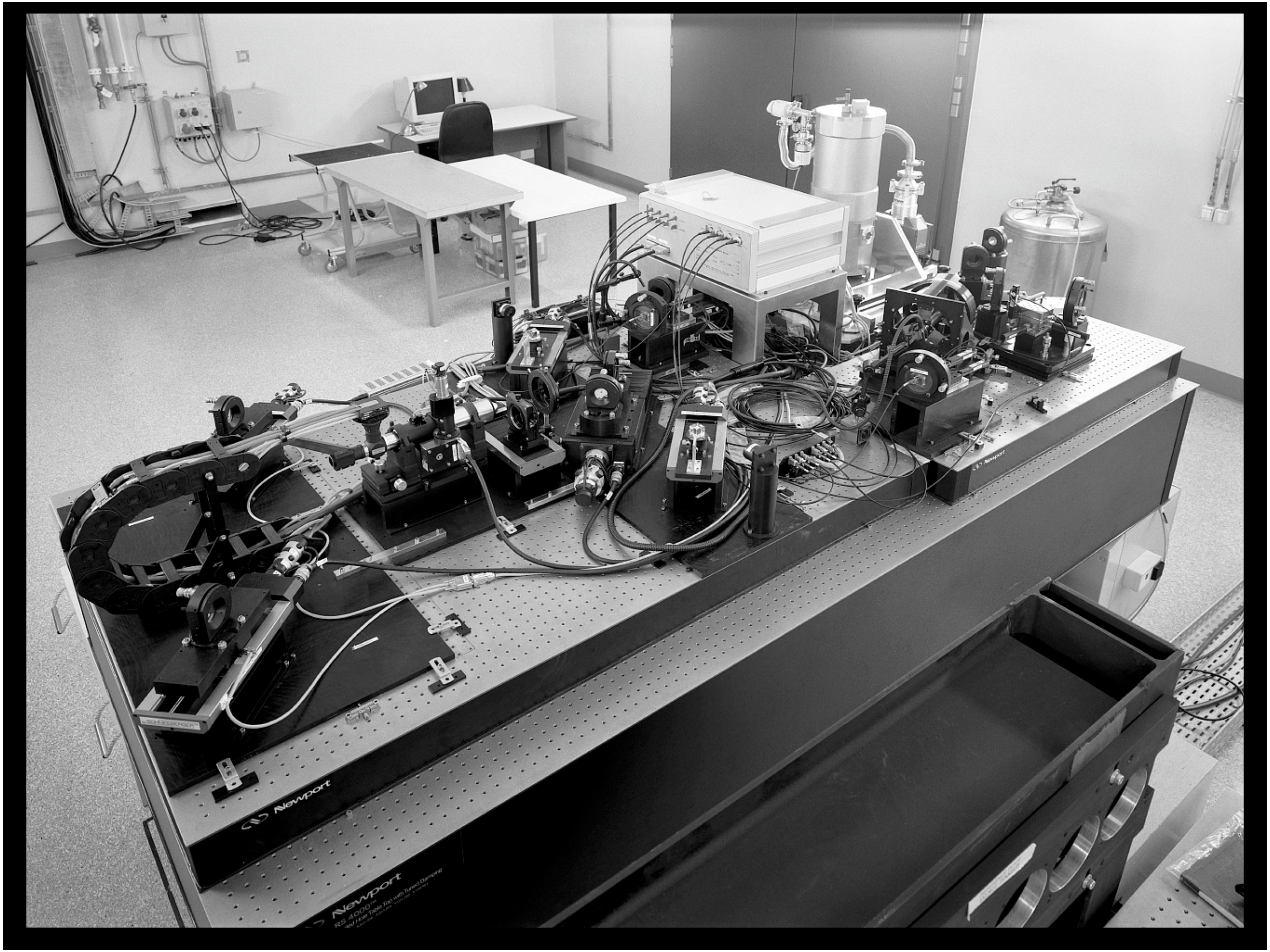
$D = 10\ D_{\odot}$ @ $d = 44$ pc gives $\theta = 2$ mas

Useful formula: θ [mas] = 9.305 $D[D_{\odot}]$ / d [pc]

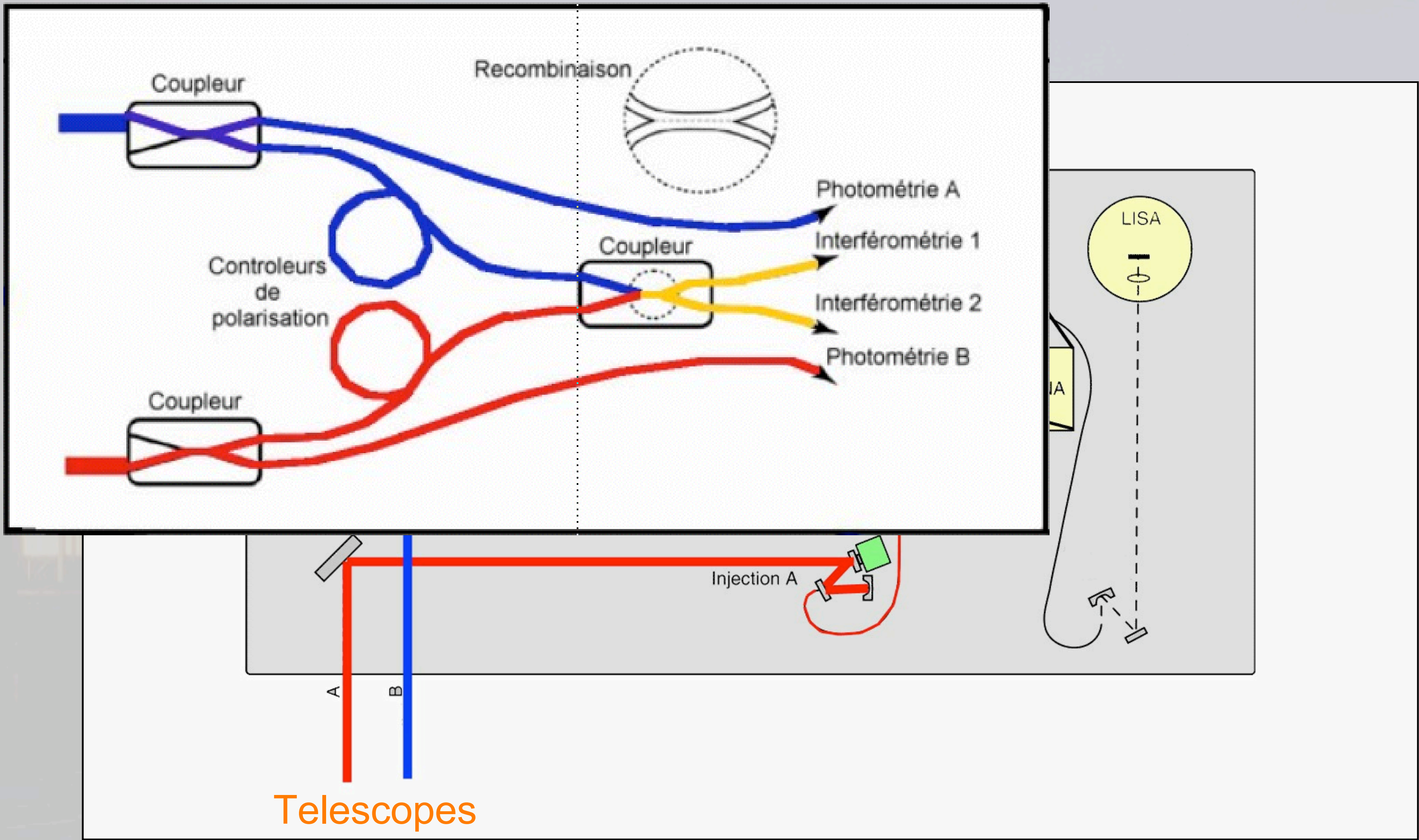
No single telescope has this resolving power (even ELTs...)

Long baseline interferometry !


The *Very Large Telescope Interferometer*


Newport
Newport
Newport
Newport

Principle of VINCI

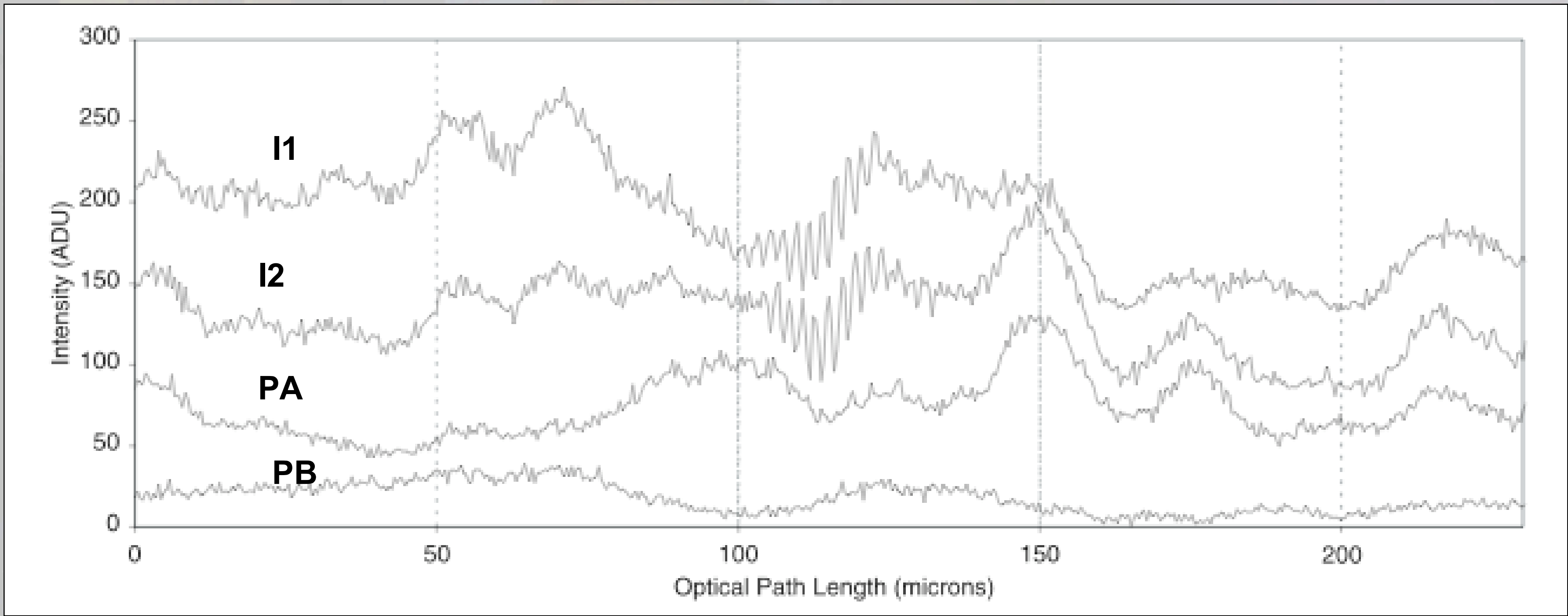


The total VLTI + VINCI photon efficiency is low... 1% !
(22 mirrors in each arm, injection, fibers, filter,...)

Data produced by VINCI (and FLUOR)

The raw data consist of 4 signals:

- two photometric signals PA and PB
- two interferometric signals I1 and I2

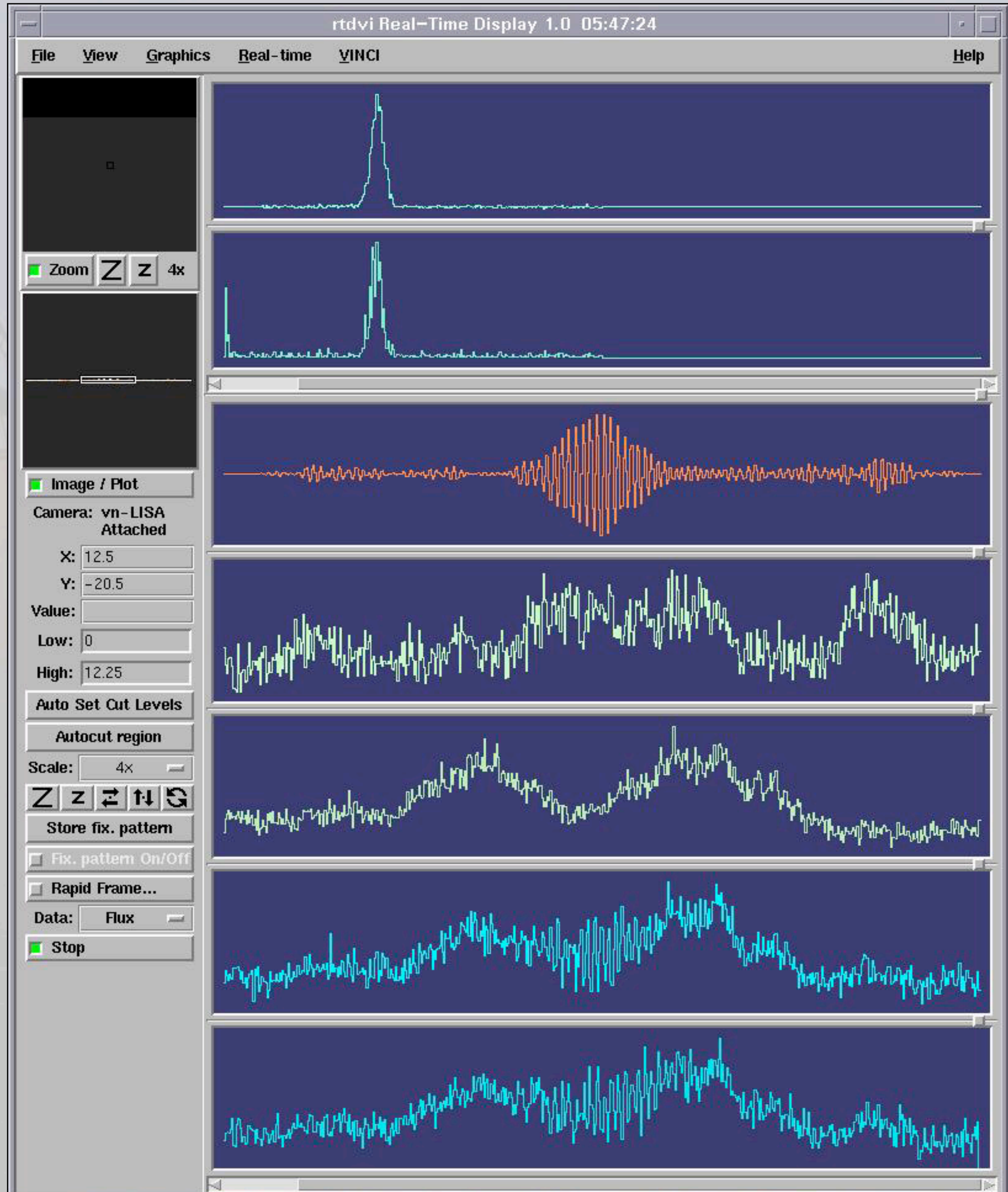


In real time...

~2 to 10 interférograms are produced per second

One observation is typically made of 500 interferograms, or ~5 minutes

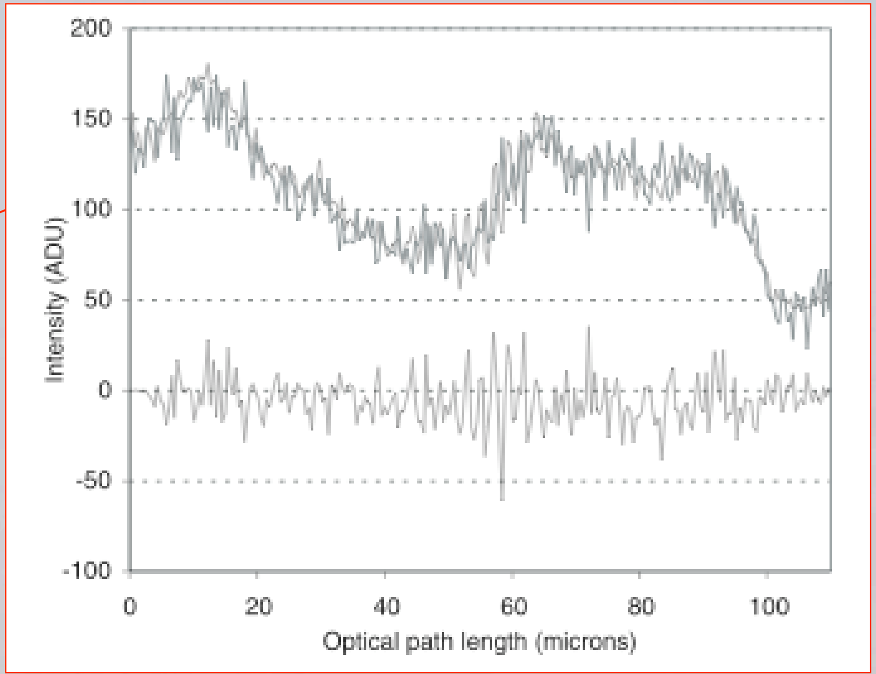
A calibrator is observed before an/or after the scientific target

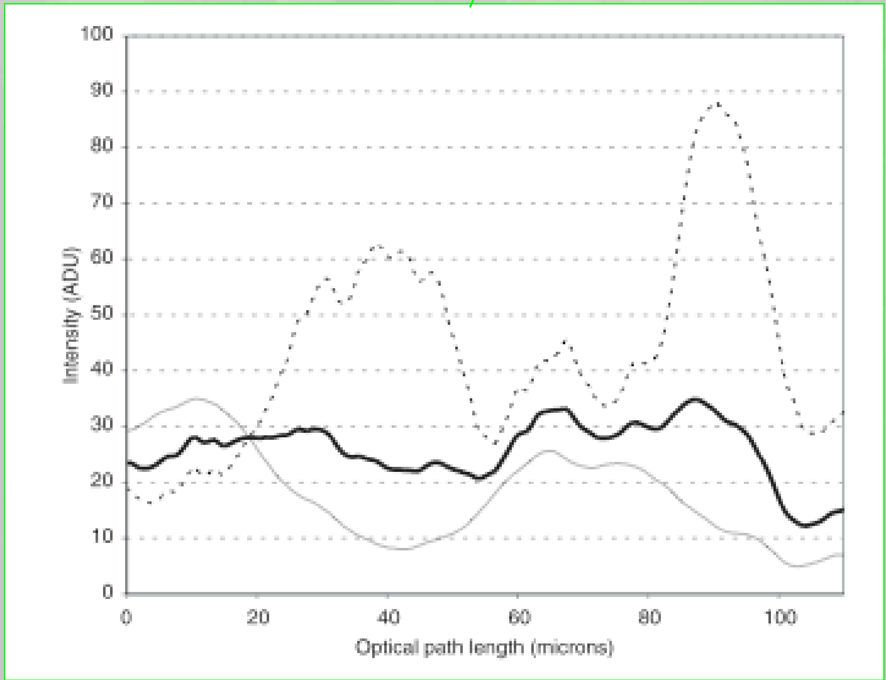


Data processing: Normalization

$$I_{1\,\mathrm{cal}} = \frac{1}{2\sqrt{\kappa_{1,\mathrm{A}}\ \kappa_{1,\mathrm{B}}}} \frac{I_1 - \kappa_{1,\mathrm{A}} P_\mathrm{A} - \kappa_{1,\mathrm{B}} P_\mathrm{B}}{[\sqrt{P_\mathrm{A}\ P_\mathrm{B}}]_{\mathrm{Wiener}}}$$

$$I_{2\,\mathrm{cal}} = \frac{1}{2\sqrt{\kappa_{2,\mathrm{A}}\ \kappa_{2,\mathrm{B}}}} \frac{I_2 - \kappa_{2,\mathrm{A}} P_\mathrm{A} - \kappa_{2,\mathrm{B}} P_\mathrm{B}}{[\sqrt{P_\mathrm{A}\ P_\mathrm{B}}]_{\mathrm{Wiener}}}.$$





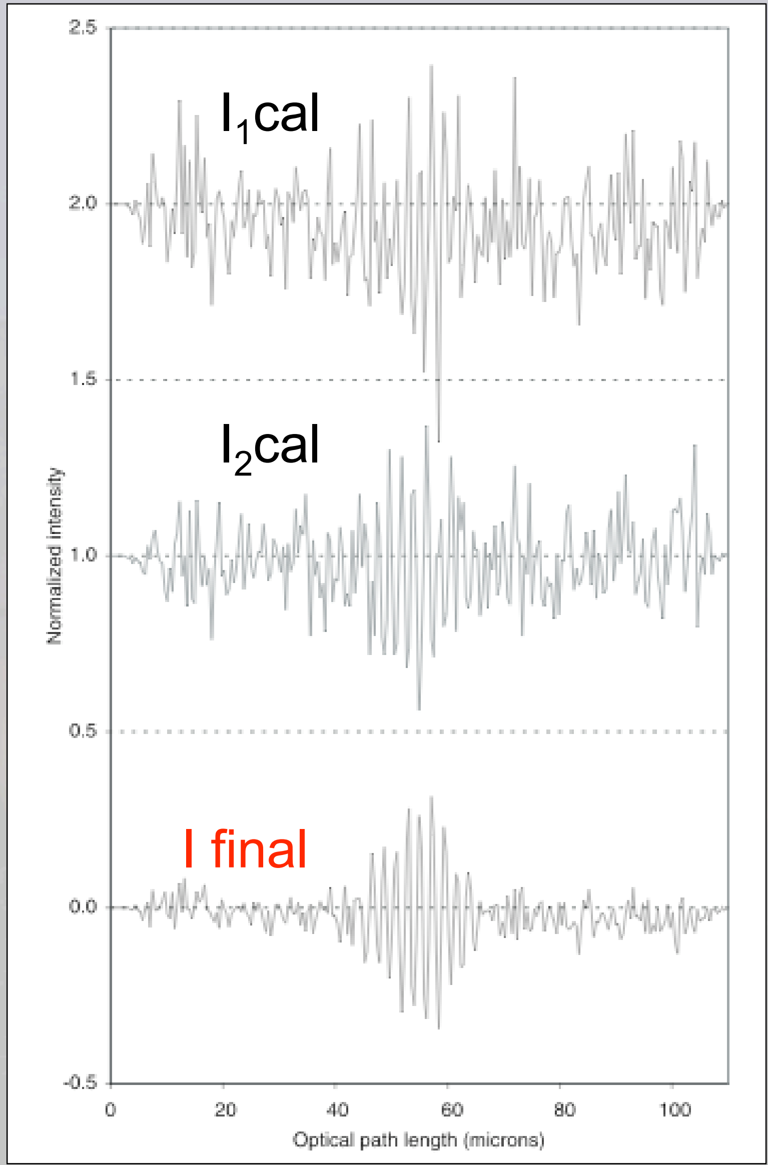
- This first operation allows to remove almost completely the atmospheric corruption of the data
- except the *piston effect*

See G. Perrin's course next week

Subtraction of the normalized outputs

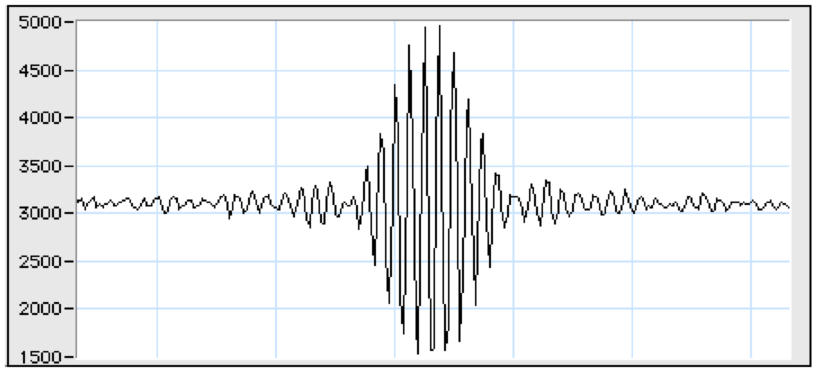
$$I = \frac{I_{1\,\mathrm{cal}} - I_{2\,\mathrm{cal}}}{2}.$$

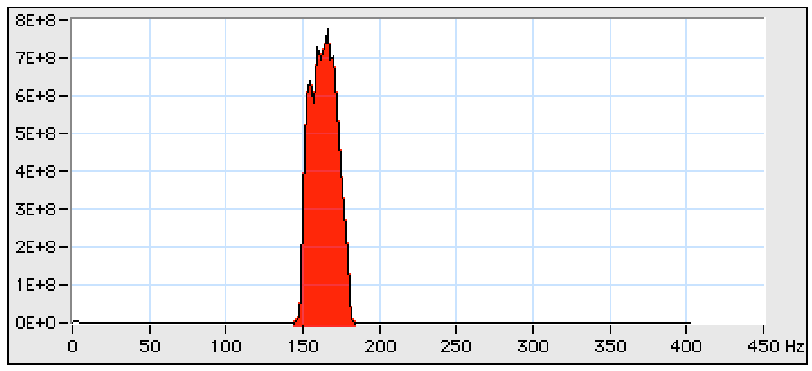
this allows to remove most of the correlated noise introduced by the normalization



Mesurement of the coherence factor

Estimator used for VINCI: based on the Fourier transform





⇨ Value of the **squared coherence factor μ^2**

Transfer Function: the Calibration of the visibility

The efficiency of the interferometer is not perfect, and it does not transmit 100% of the modulation of the fringes

We have to measure this loss to take it into account

$$T^2 = \frac{\mu^2_{\rm calib}}{V^2_{\rm calib}}$$

For this purpose, we observe a star with a known angular diameter: **the calibrator**

$$V^2_{\rm target} = \frac{\mu^2_{\rm target}}{T^2}$$

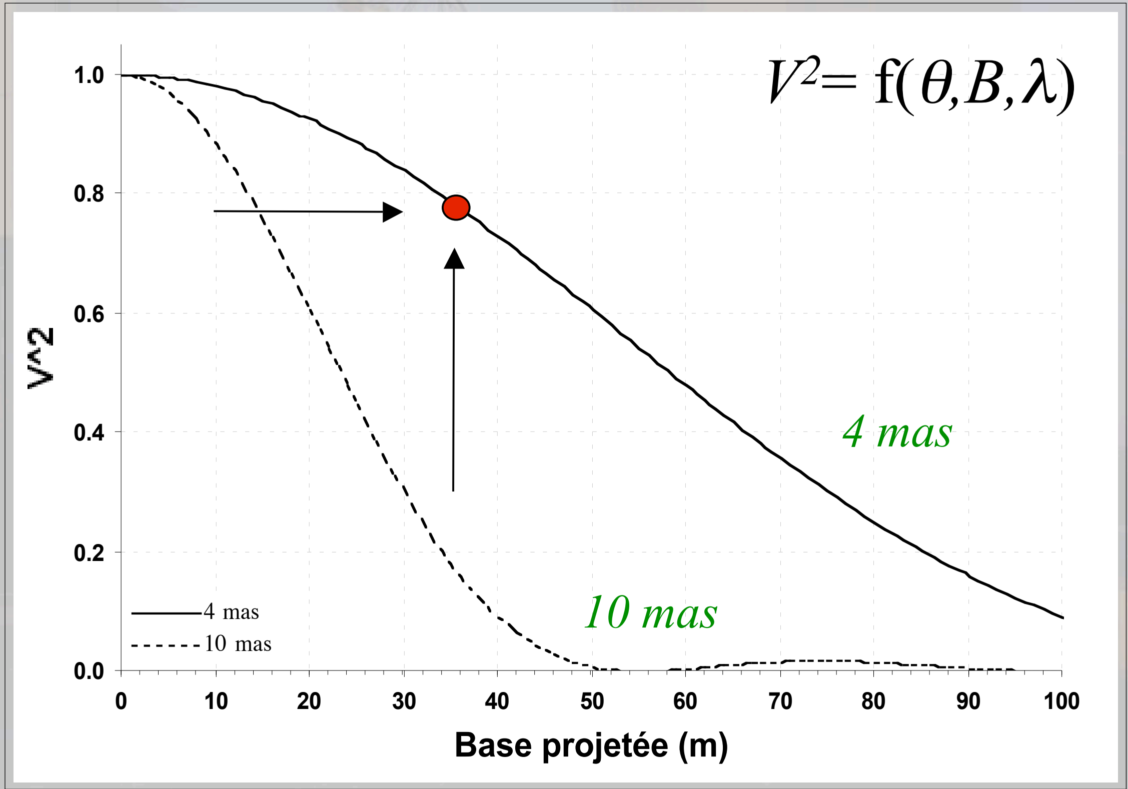
Knowing the expected $\mathbf{V^2}$ of the calibrator, we can estimate the transfer function $\mathbf{T^2}$, and correct the squared coherence factor $\boldsymbol{\mu^2}$ of the scientific target

How to predict the angular diameter of a calibrator ?

Answer Thursday ! (Lecture by A. Boden)

From visibility to angular diameter...

We need a model of the light distribution of the star



Observations

Achernar was observed with the VLTI in 2001-2002

Interspersed Achernar-calibrator observations

- in order to estimate the VLTI interferometric transfer function
- 4 different calibrators

Two small telescopes (0.35 m aperture), in the *K* band (2.2 μm)

Two almost orthogonal baselines

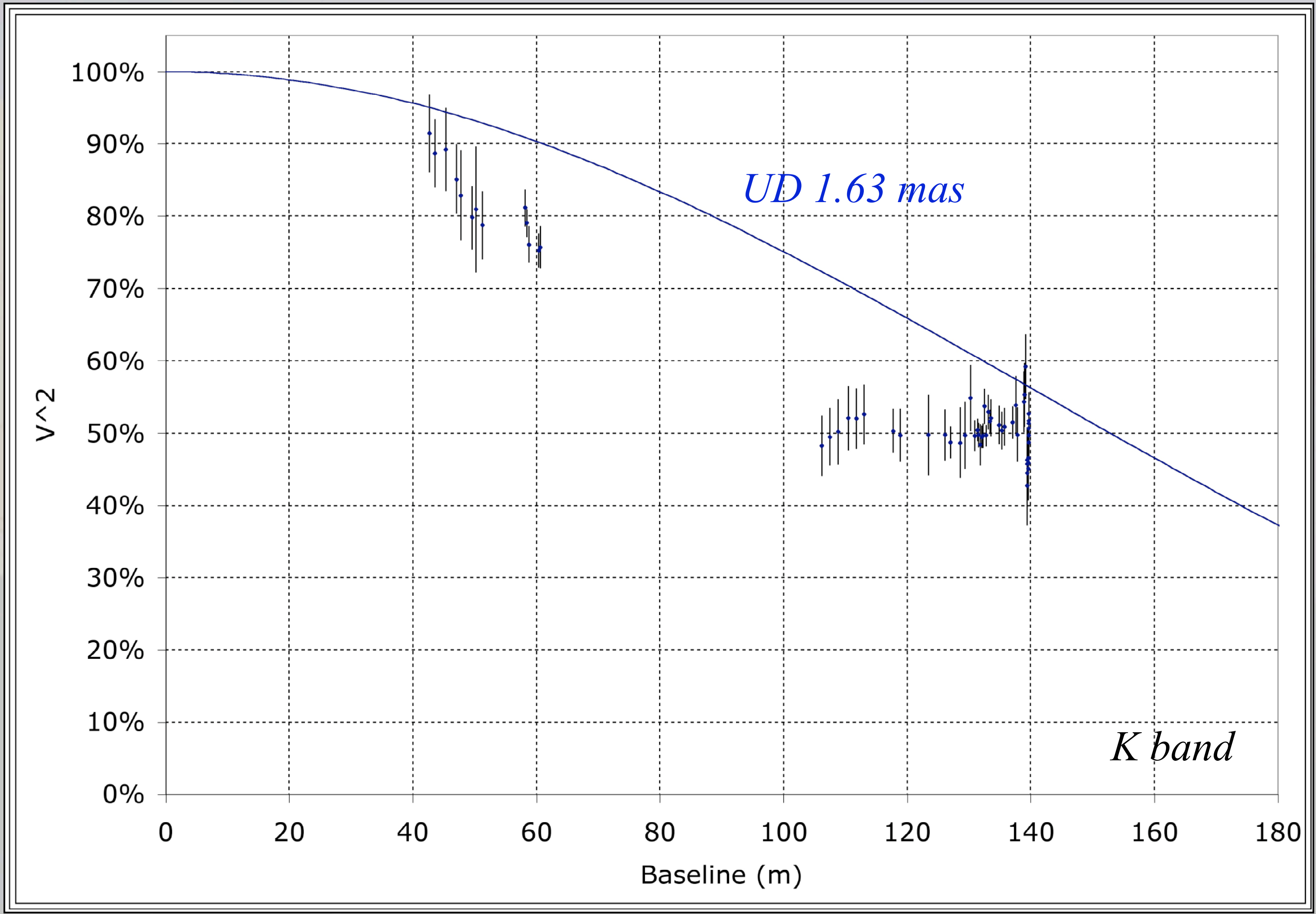
60 V^2 mesurements in the K band (over 16 nights)

14 V^2 mesurements in the H band (over 7 nights)

Supersynthesis

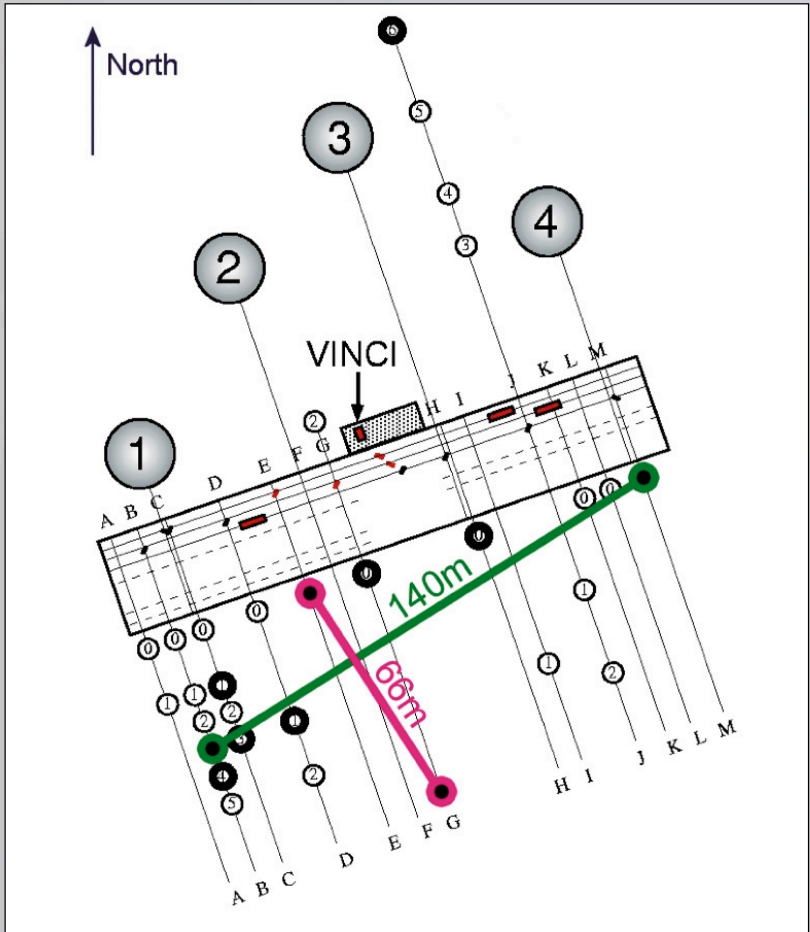
- Achernar = dec -60 deg ⇒ efficient supersynthesis
- observations at different hour angles
- variable projected baseline

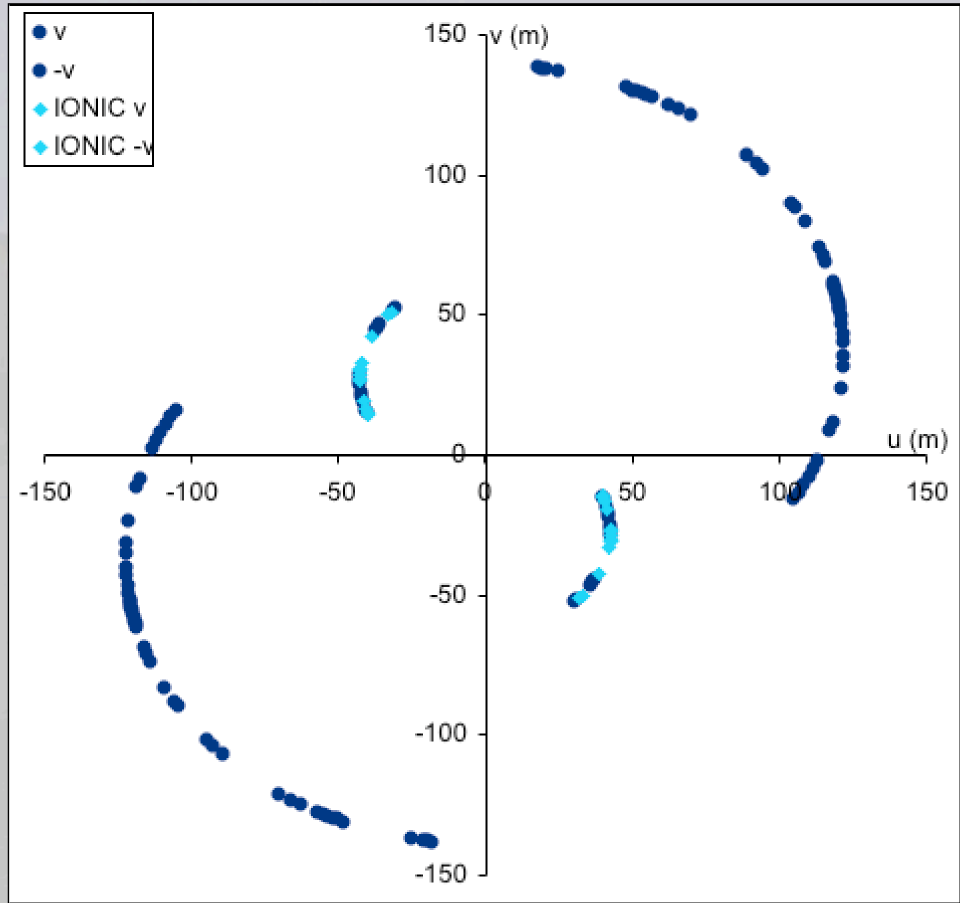
$V^2(B)$ of Achernar



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

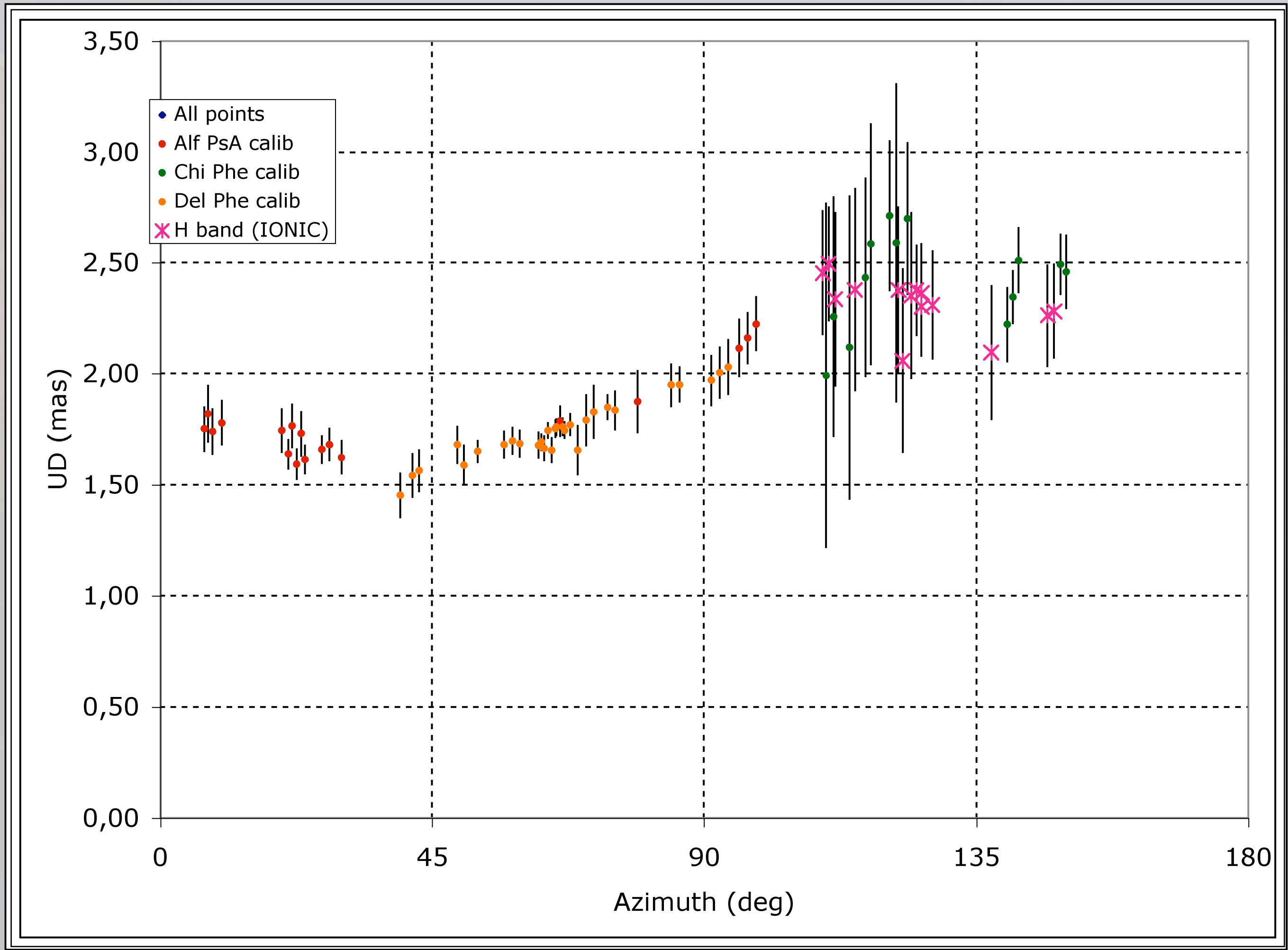
Supersynthesis





Almost complete azimuth coverage: nice coverage with only 2 baselines !

θ (Azimuth)



3,50
3,00
2,50
2,00
1,50
1,00
0,50
0,00
UD (mas)
All points
Alf PsA calib
Chi Phe calib
Del Phe calib
H band (IONIC)
0
45
90
135
180
Azimuth (deg)

Ellipse fit

Equator:

UD = 2.53 ± 0.06 mas

Pole:

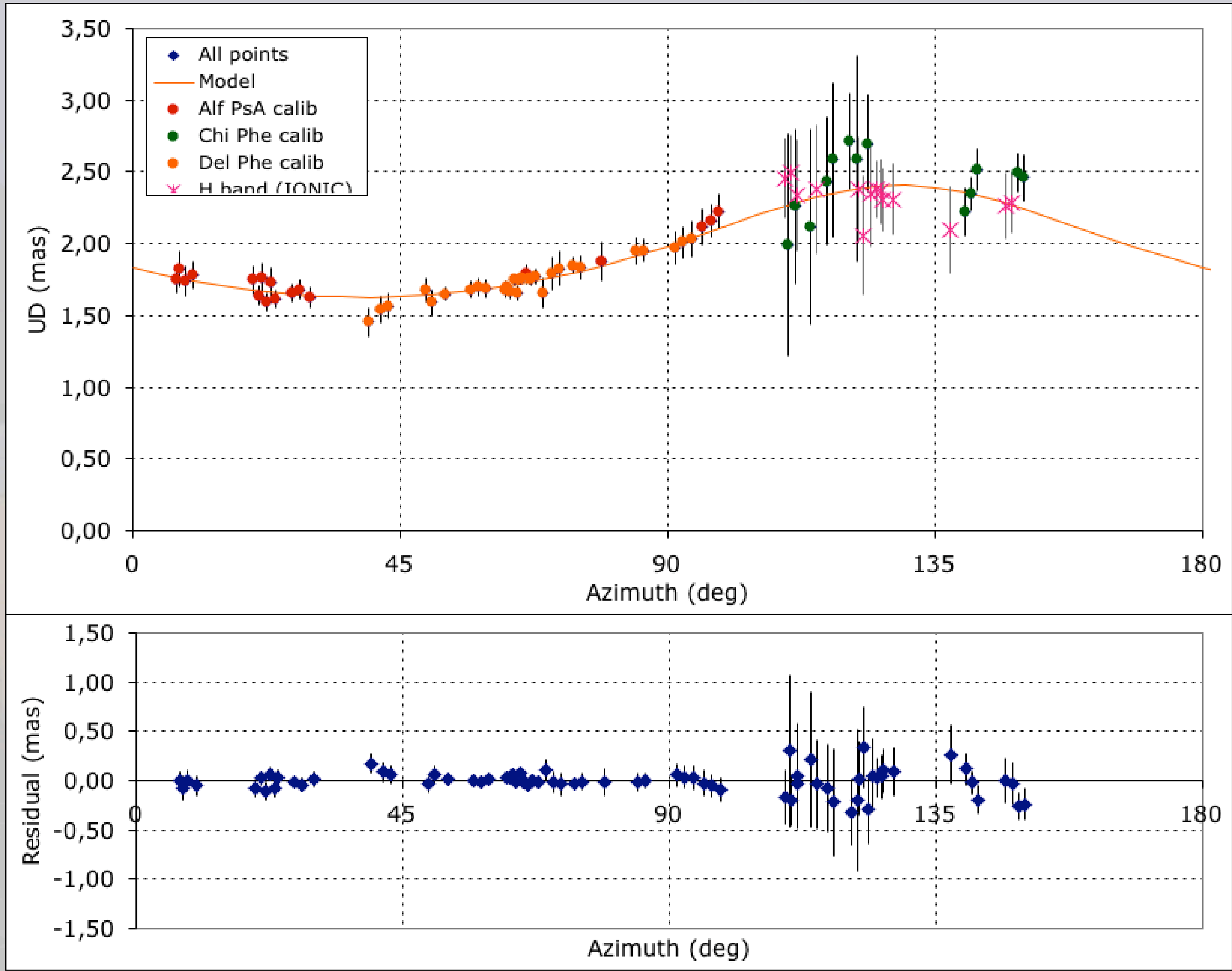
UD = 1.62 ± 0.01 mas

Polar axis Az.:

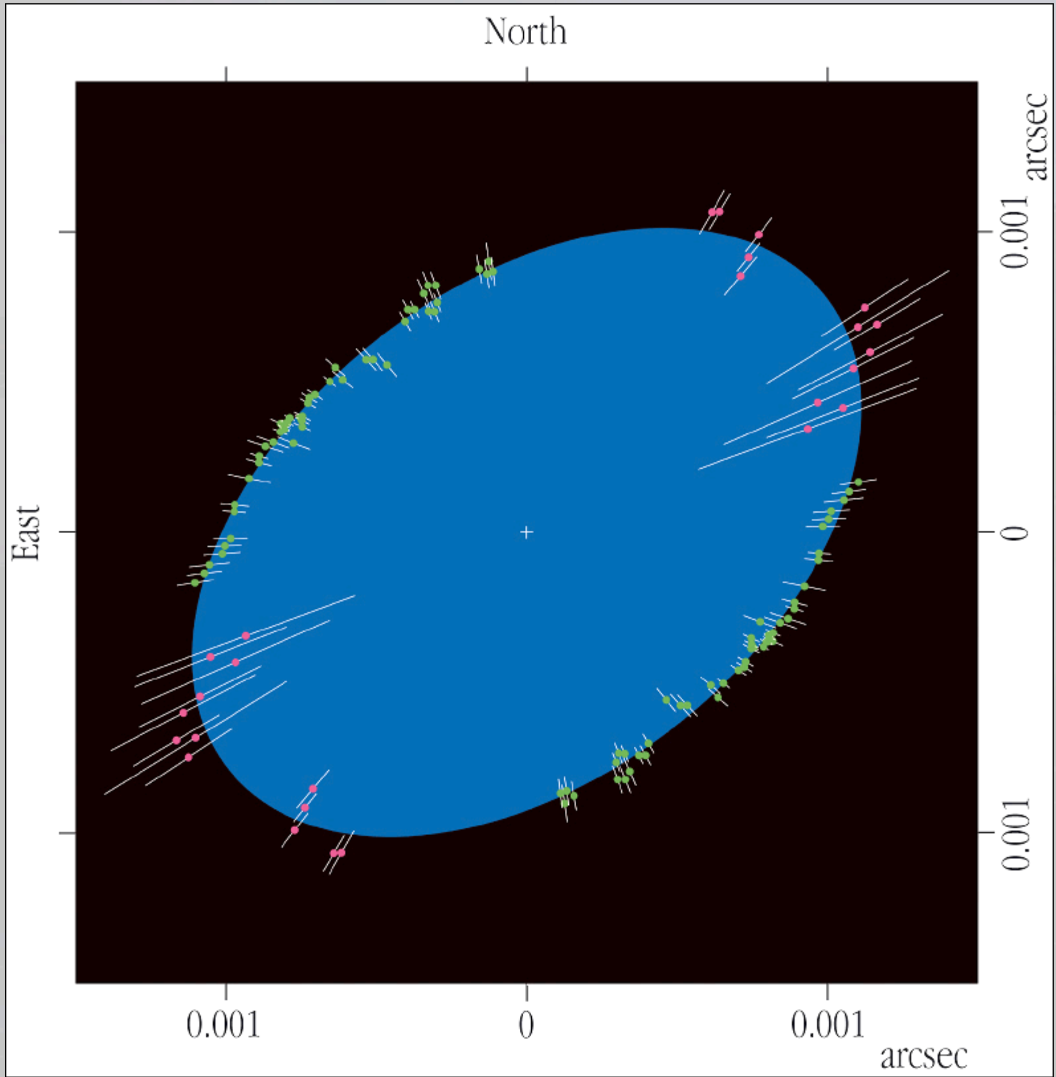
39 ± 1 deg

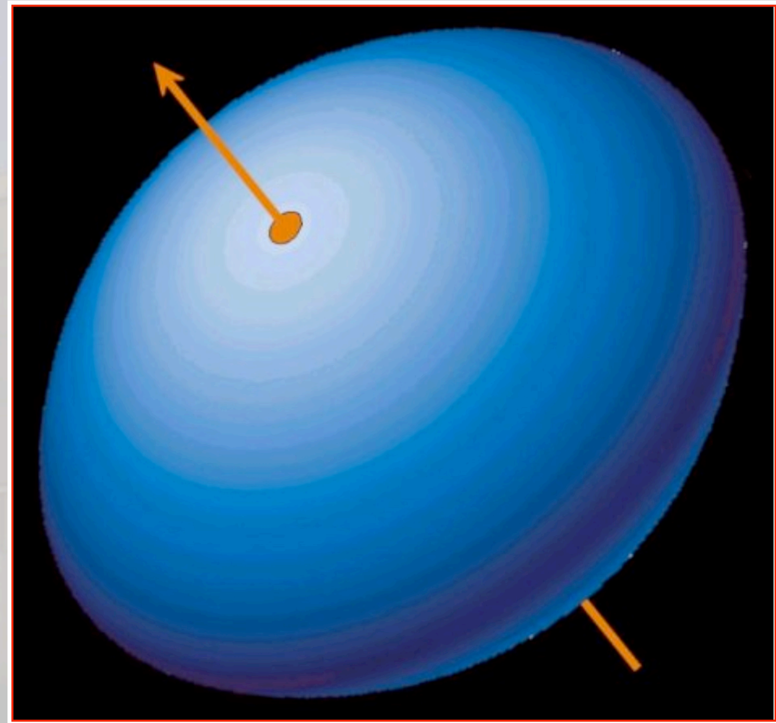
Ratio:

Eq/Pole = 1.56 ± 0.05



Modeling

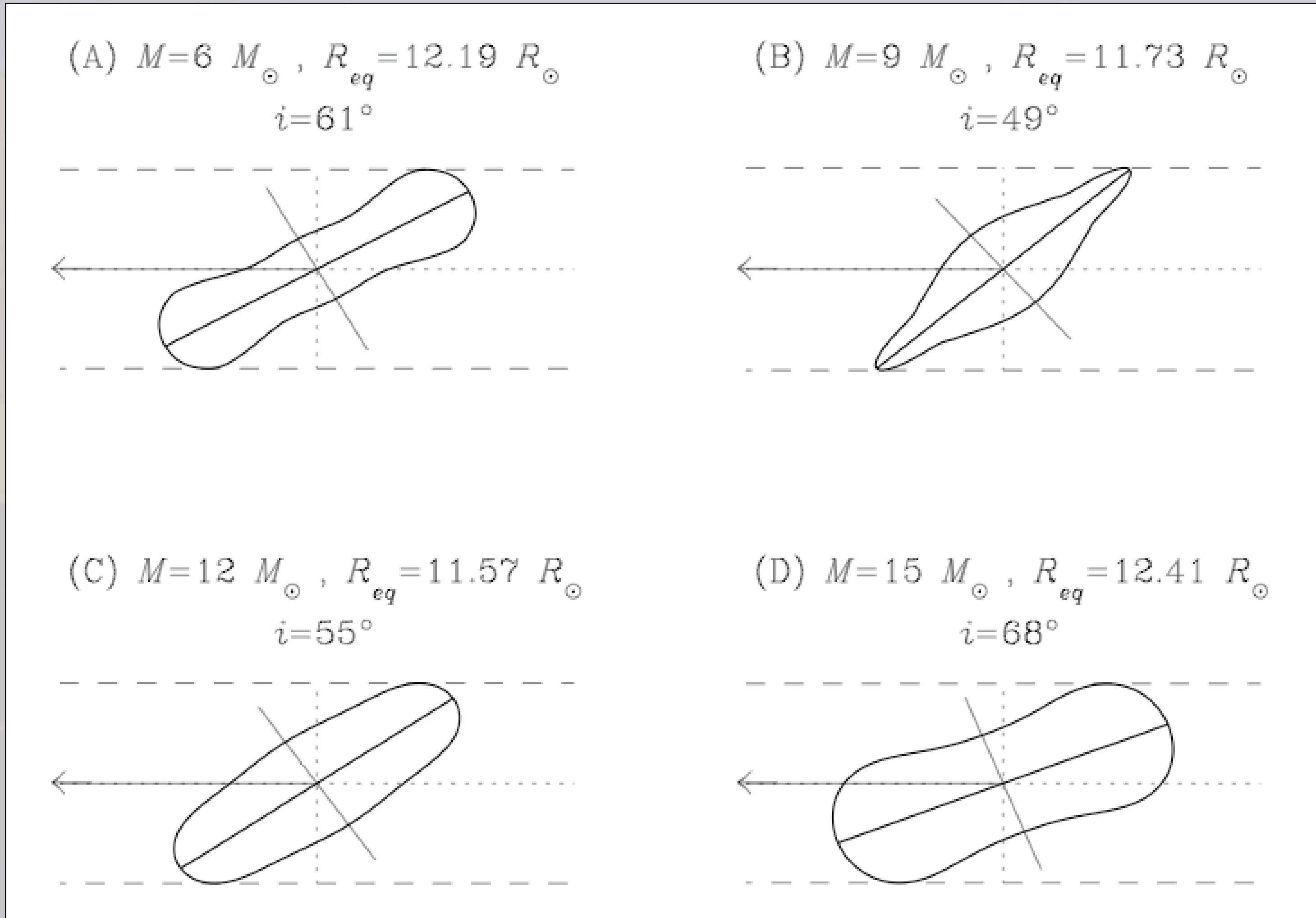




a/b ~ 1,56

- Roche model: not flat enough.... (including the Von Zeipel effect)
- Domiciano et al. (2003)

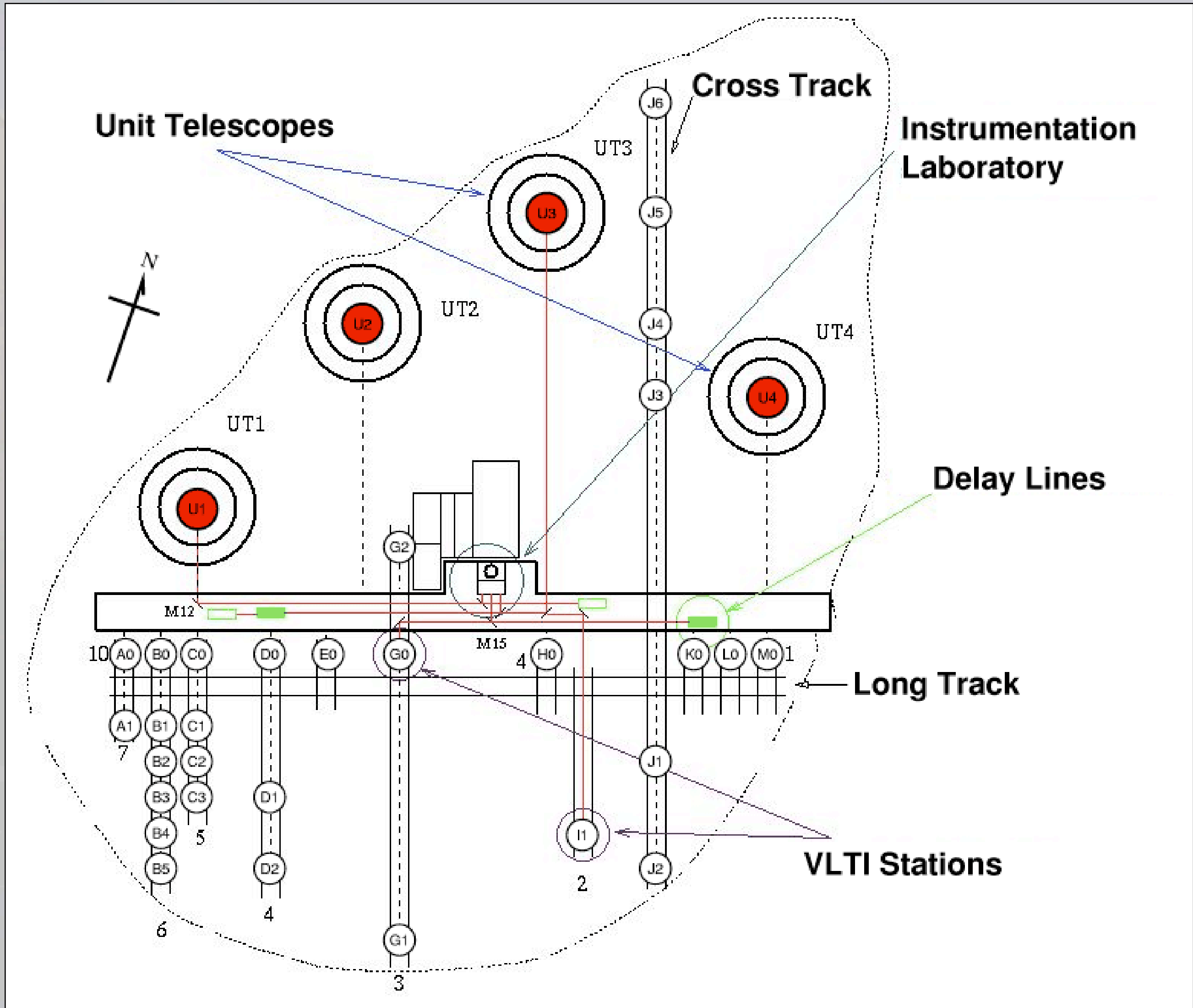
Differential rotation ?

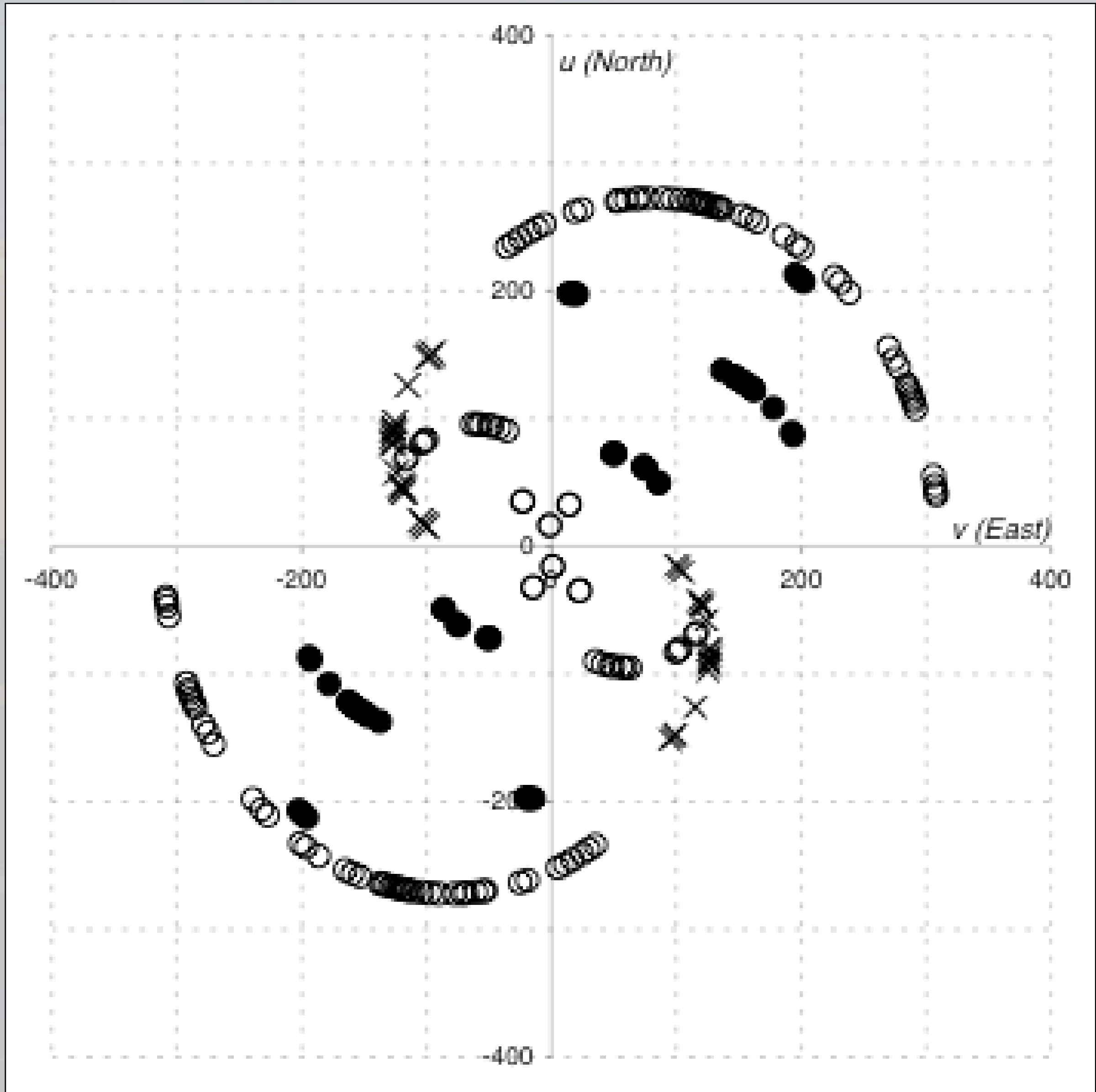


Jackson et al. (2004)

Many fast rotating stars...

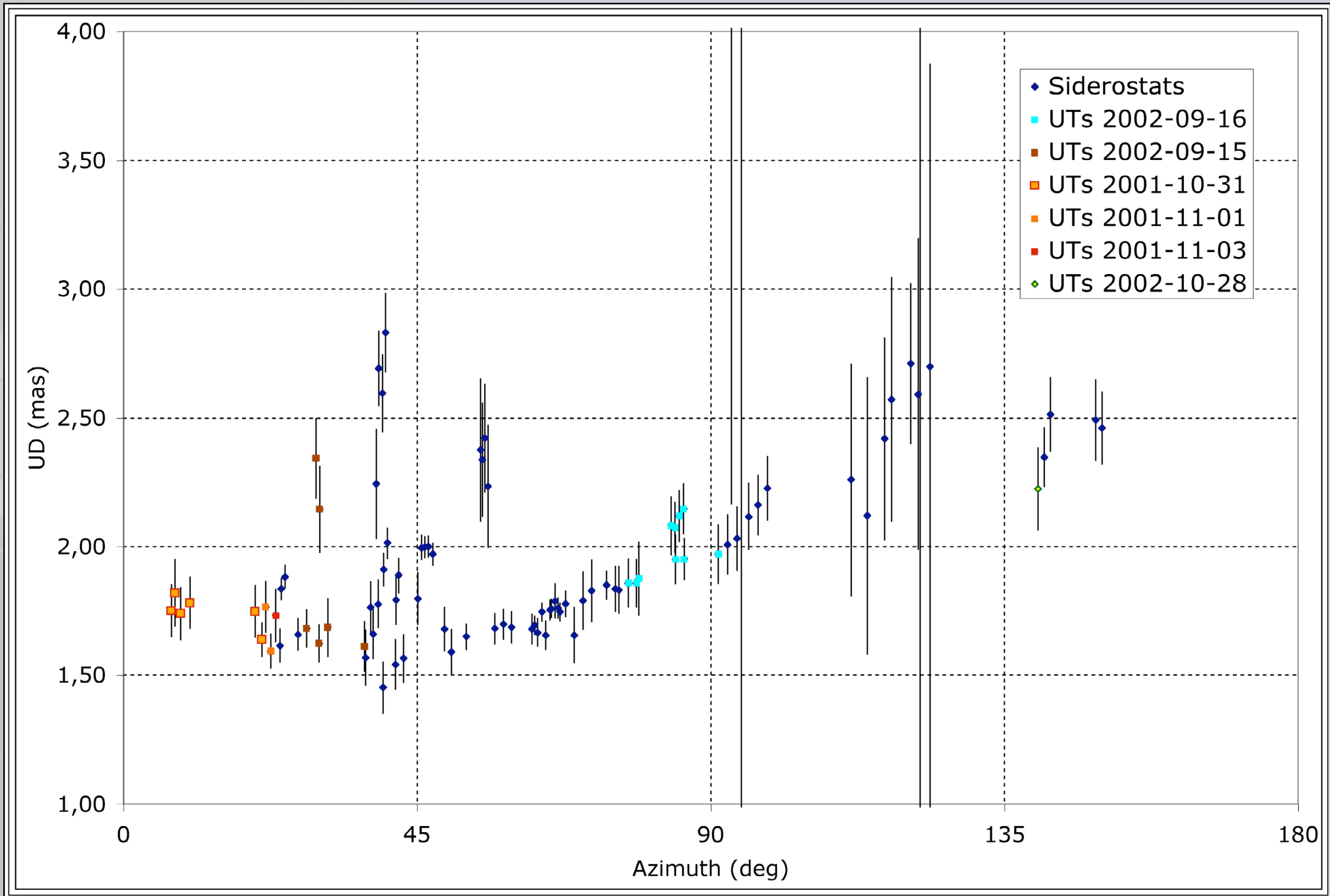
A « Bonus » data set...





400
u (North)
200
0
-400
-200
200
400
v (East)
-400

Troublesome data...

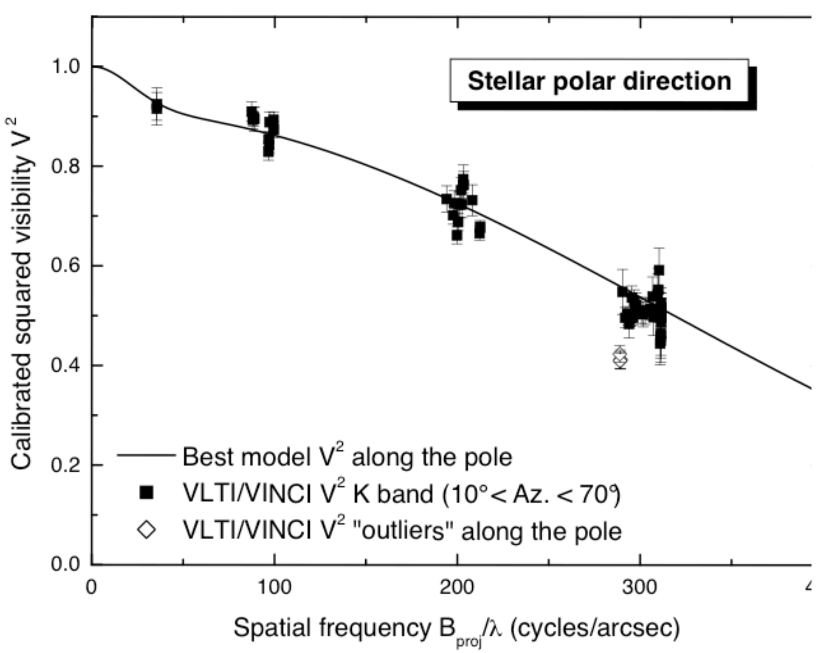


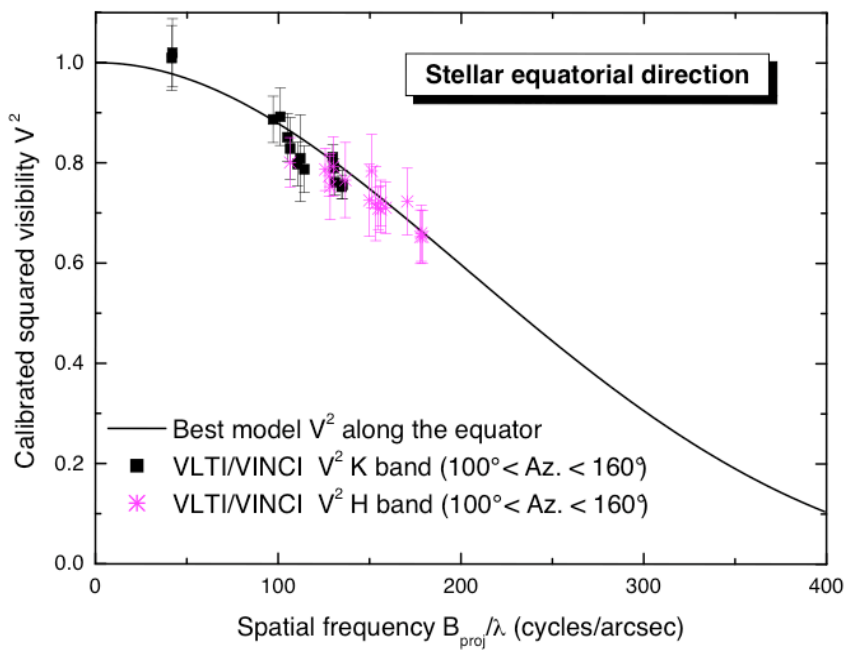
Something along the pole ?

The polar visibilities are not in line with the model...

There is apparently something extended in this direction (lower V^2)

Let's limit ourselves to the polar and equatorial directions +/- 30 degrees





This is strange... A disk is expected, but *along the equator*...

An « ad hoc » simple model

A uniform ellipse for the star +

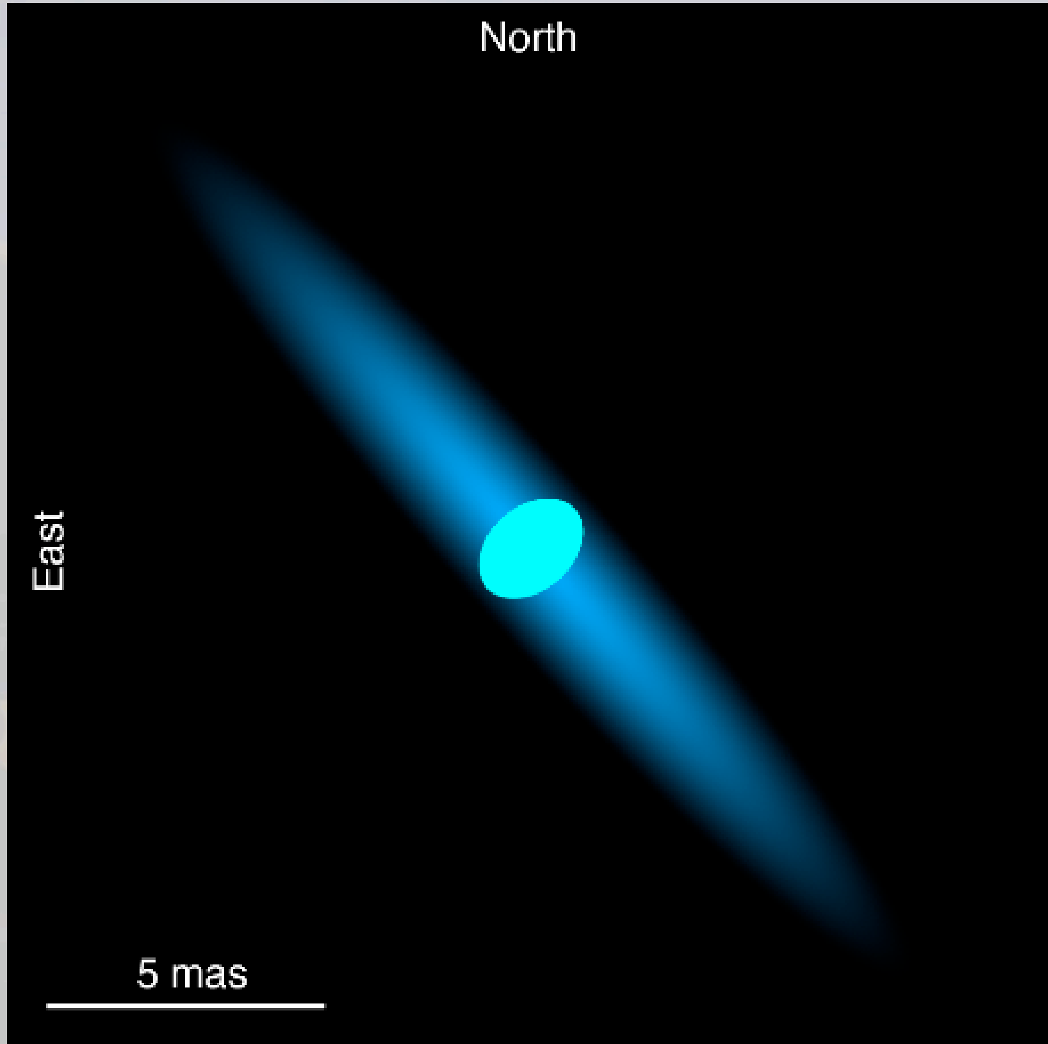
an elliptical Gaussian for the extended component (aligned with star)

$$V_{\rm star}(u, v, \theta_{\rm eq}, \theta_{\rm pol}, \alpha_1) = \frac{2\,J_1(x')}{x'}$$

$$\text{where } x' = \pi\,\sqrt{\theta_{\rm eq}^2\,u'^2 + \theta_{\rm pol}^2\,v'^2}.$$

$$V_{\rm env}(u, v, \rho_{\rm eq}, \rho_{\rm pol}, \alpha_1) = \exp\left[-\frac{\left(\pi\,\sqrt{\rho_{\rm eq}^2 u'^2 + \rho_{\rm pol}^2 v'^2}\right)^2}{4\,\ln 2}\right]$$

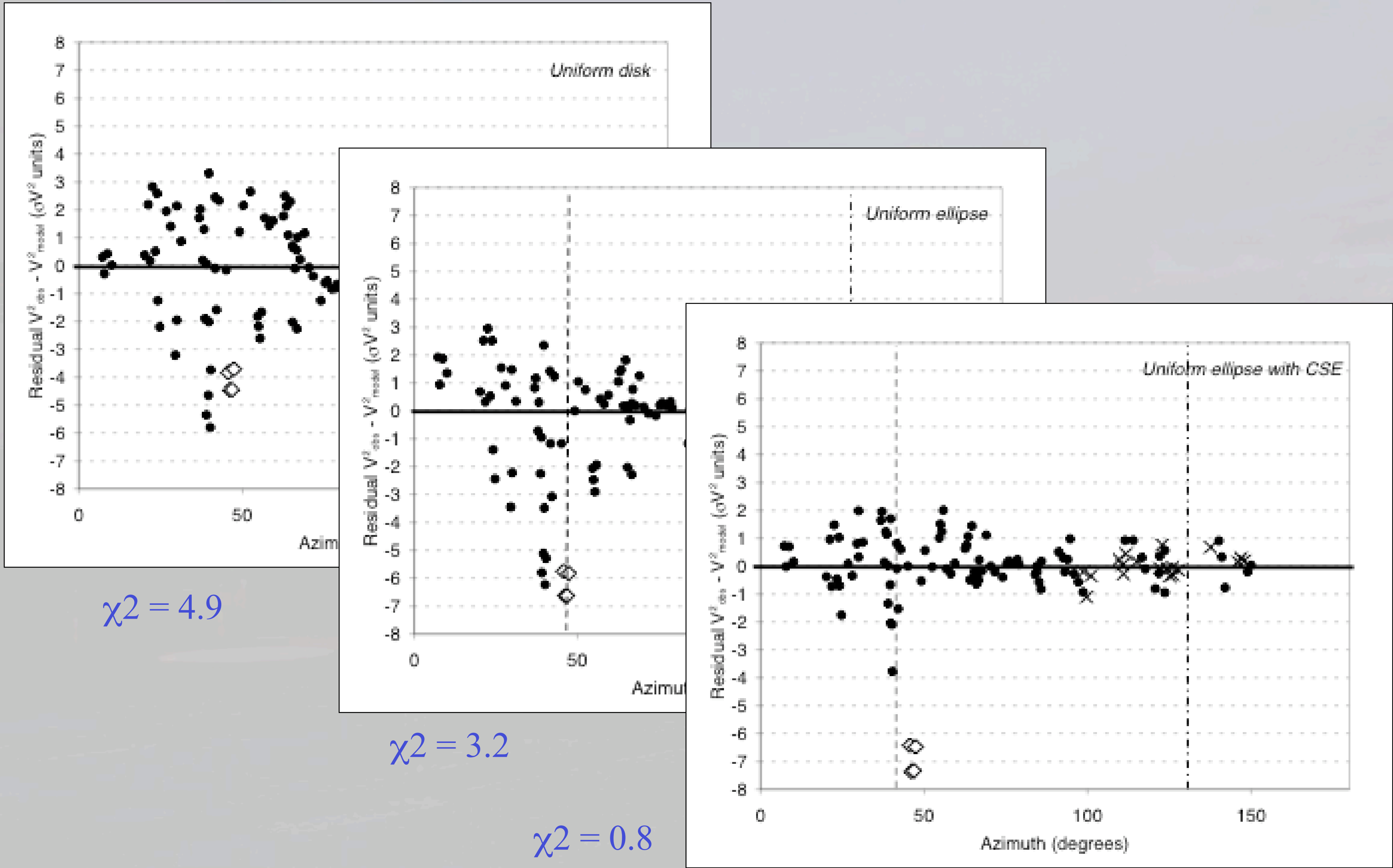
$$V_{\rm model}(u, v, \theta_{\rm eq}, \theta_{\rm pol}, \rho_{\rm eq}, \rho_{\rm pol}, \alpha_1, f) = \frac{V_{\rm star} + f\,V_{\rm env}}{1 + f}.$$



Contrast CSE-star ~ 5% in the K band

Most likely explanation: free-free radiation from the polar wind of the star

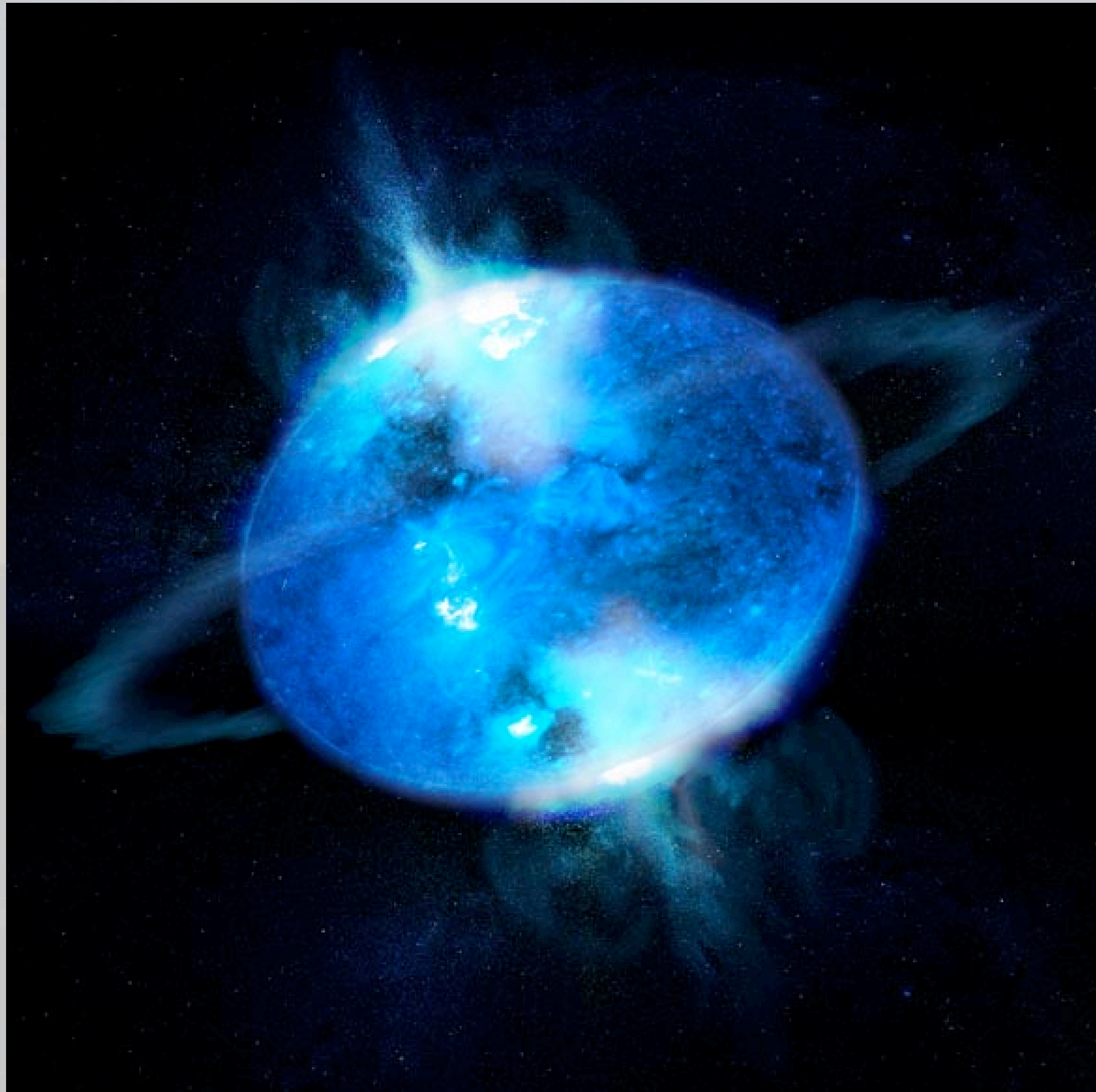
Different models... and residuals



$\chi2 = 4.9$

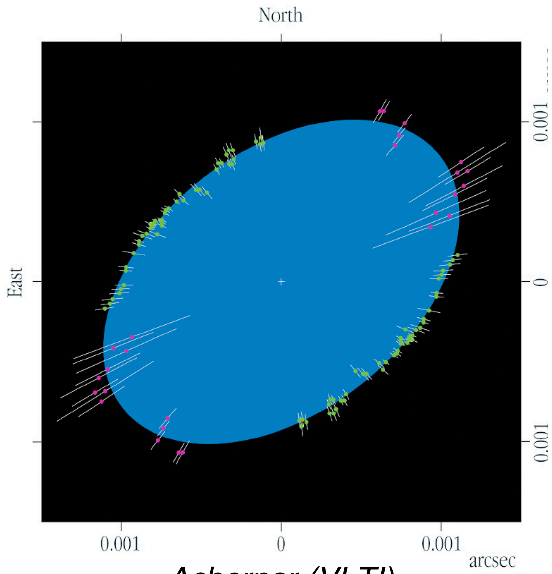
$\chi2 = 3.2$

$\chi2 = 0.8$

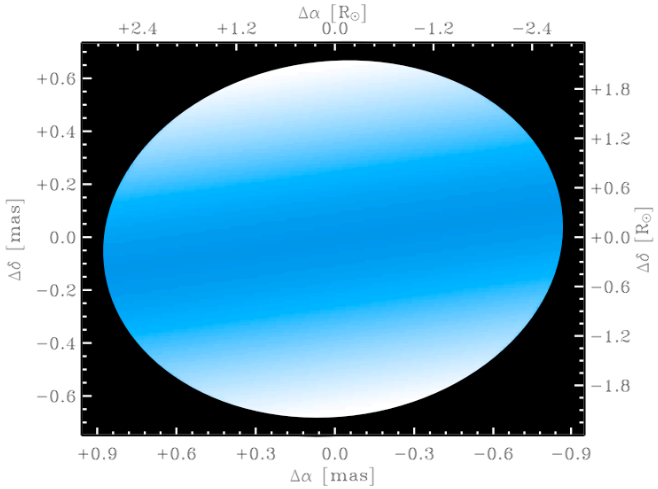


Artist's impression of Achernar

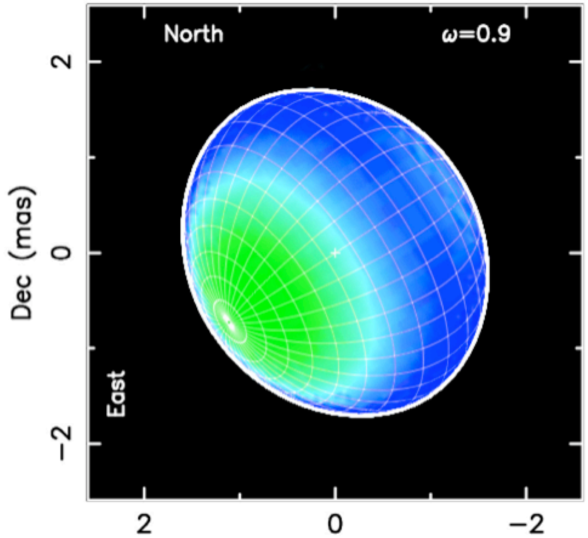
Fast rotating stars observed by interferometry



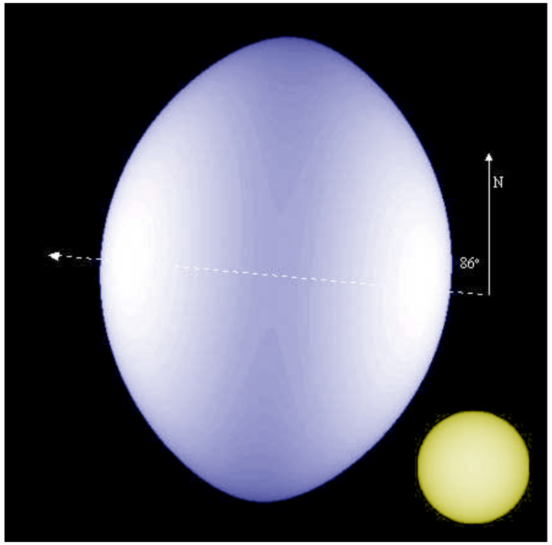
Achernar (VLTI)



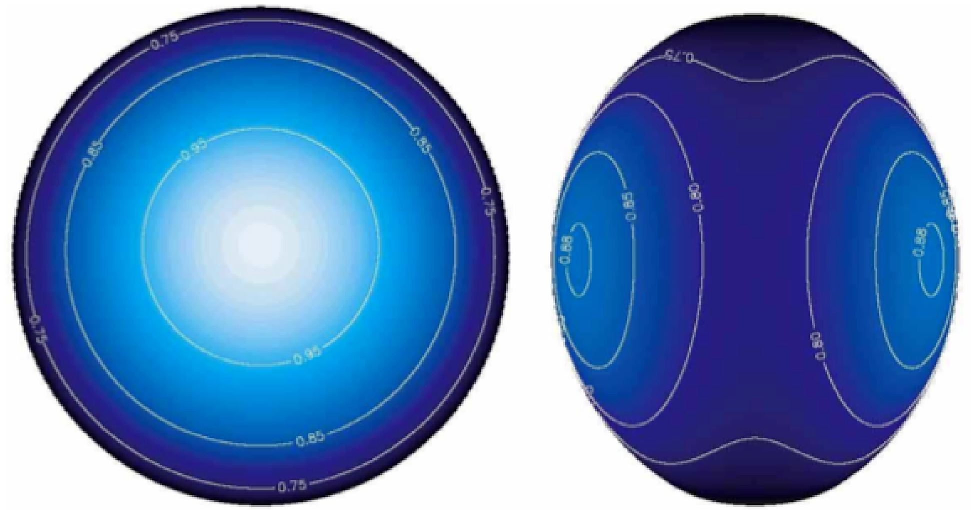
Alderamin (CHARA)



Altaïr (NPOI)



Regulus (CHARA)



Véga (CHARA)

Some references...

- Aufdenberg et al. 2006, *ApJ*, *in press*
- Domiciano de Souza et al. 2003, *A&A*, **407**, L47
- Jackson et al. 2004, *ApJ*, **606**, 1196; 2005, *ApJSS*, **156**, 245
- Kervella & Domiciano 2006, *A&A*, *in press*
- McAlister et al. 2005, *ApJ*, **628**, 439
- Peterson et al. 2006, *ApJ*, **636**, 1087
- Van Belle et al. 2001, *ApJ*, **559**, 1155