THE CARTOGRAPHY OF THE SUN AND THE STARS

INTERFEROMETRY TO DETERMINE STELLAR SHAPES (2/2)

OBSERVATIONS OF ACHERNAR WITH PIONIER

Pierre KERVELLA - pierre.kervella@obspm.fr

PIONIER OBSERVATIONS OF ACHERNAR

- Scientific objective
- Preparation of the observations
- (Execution of the observations)
- Analysis of the data

SCIENTIFIC OBJECTIVE

- VINCI observations do not constrain the inclination of the polar axis of Achernar + (u,v) coverage is limited
- PIONIER measures closure phases
- Thanks to Von Zeipel effect, the bright polar cap will affect the closure phase
- Measurement of ***sin(i)*** to derive the true equatorial velocity

EUROPEAN SOUTHERN OBSERVATORY

Organisation Européenne pour des Recherches Astronomiques dans l'Hémisphère Austral
Europäische Organisation für astronomische Forschung in der südlichen Hemisphäre

OBSERVING PROGRAMMES OFFICE • Karl-Schwarzschild-Straße 2 • D-85748 Garching bei München • e-mail: opo@eso.org • Tel.: +49-89-32 00 64 73

APPLICATION FOR OBSERVING TIME — PERIOD: **87A**

Important Notice:

By submitting this proposal, the PI takes full responsibility for the content of the proposal, in particular with regard to the names of CoIs and the agreement to act according to the ESO policy and regulations, should observing time be granted

1. Title — Category: **D–1**

Achernar's polar cap: a view to the internal rotation profile of a fast rotating Be star

2. Abstract / Total Time Requested

Total Amount of Time: 2.1 nights VM, 0 hours SM

Achernar is one of the brightest and nearest fast rotating stars. Back in 2002, we uncovered the spectacular elliptical profile of its photosphere using VLTI/VINCI, but with 2 telescopes, we could not map the photospheric light distribution. Now with 4 telescopes, PIONIER will give us an image of the star's surface. What do we expect? Models predict that the rotational distorsion of Achernar creates a dark equatorial belt and a bright and hot polar cap. The brightness and position of the pole are two fundamental parameters sorely needed to constrain our models. The position of the pole will give us the inclination of the rotation axis on the line of sight, and its brightness will give us the local effective temperature. We suspect that the internal rotation of Achernar is non-uniform, with a superfast core rotation and relatively slower external layers. These data will enable us to test this hypothesis. The single NACO observation is intended to localize Achernar's companion.

3.

Run	Period	Instrument	Time	Month	Moon	Seeing	Sky	Mode	Type
A	87	SpecialVLTI	2n	sep	n	n	THN	v	
B	87	NACO	0.1n	sep	n	n	THN	v	

4. Number of nights/hours — Telescope(s) — Amount of time

a) already awarded to this project:

b) still required to complete this project:

5. Special remarks:

For operational reasons we would like to request, when applicable, to regroup accepted proposals using PIONIER in continuous run. The PIONIER and NACO runs should be scheduled together (see Box 8B).

6. Principal Investigator: P. Kervella, pierre.kervella@obspm.fr, F, Observatoire de Paris,Site de Meudon - LESIA - Bat. TE (5)

6a. Co-investigators:

J.-B.	Le Bouquin	Laboratoire d'astrophysique de Grenoble,Observatoire de Grenoble,F
A.	Domiciano de Souza	Laboratoire Universitaire d'Astrophysique de Nice,F
J.-P.	Berger	ESO Office Santiago,ESO
B.	Lazareff	Laboratoire d'astrophysique de Grenoble,Observatoire de Grenoble,F

Following CoIs moved to the end of the document ...

7. Is this proposal linked to a PhD thesis preparation? State role of PhD student in this project

8. Description of the proposed programme

A – Scientific Rationale:

• **Introduction:** As the brightest ($m_V = 0.46$) and nearest (44 pc) Be star in the sky, Achernar (α Eri) has been the focus of a lot of interest over the last decade. Its very fast rotation velocity $v \sin i$ is estimated between 220 to 270 km.s^{-1} and its effective temperature between 15 000 and 20 000 K (Vinicius et al. 2006). Achernar is also a binary star, and is surrounded by a tenuous intermittent circumstellar disk and a permanent polar wind. The formation of the equatorial disk is probably caused by the periastron passage of the companion.

• **Flattening beyond the Roche model:** Achernar was chosen as the subject of the first VLTI observations (back in 2001), that revealed its distorted photosphere (Domiciano et al. 2003, **Fig. 1, left**). The measured flattening ratio $R_{equator}/R_{pole} = 1.56 \pm 0.05$ is too large to be explained using solid-body rotation (Roche model). This ratio was subsequently revised by to 1.41 ± 0.04 by Kervella & Domiciano de Souza (2006) due to the presence of a polar jet-like envelope (Kervella et al. 2009). Although slightly smaller, this flattening cannot be explained either in the Roche approximation, especially when taking the von Zeipel effect into account (i.e. the emerging flux is proportional to the effective gravity, resulting in a dark equator and a bright polar cap). To go beyond the Roche model, different alternative models were proposed (e.g. by Carciofi et al. 2008, Jackson et al. 2004), but they depend strongly on the adopted internal rotation profile, that is essentially arbitrarily chosen (shellular, cylindrical,...). The core of Achernar is suspected to rotate at a much higher angular velocity than the upper layers. Unfortunately, as demonstrated by Jackson et al. (2004, **Fig. 2**), the choice of the right model is degenerate: changing the stellar mass and/or inclination angle on the line of sight allows to reproduce the observed photospheric profile and projected rotational velocity for different internal rotation laws.

• **Achernar's pole as a window to its interior:** The extreme rotational velocity of Achernar flattens its disk into an ellipsoid, whose small axis is its rotation axis. This distorsion results in the amazing effect that the pole is actually closer to the center of the star than the equator, by at least 30%. Between the equator and the pole, we therefore directly observe the internal structure of the star over a significant range of radii. The requested PIONIER observations are intended to image the surface of Achernar, localize precisely the polar cap, and measure its relative brightness compared to the full disk of the star. This will give us two fundamental parameters of the star: 1) the inclination of its polar axis on the line of sight and 2) the effective temperature of the pole. The inclination i will allow us to retrieve unambiguously its equatorial rotation velocity (from the projected $v \sin i$ measured spectroscopically). The effective temperature will be derived from the brightness ratio of the polar cap to the full star disk. Practically, we plan to extract these parameters using a procedure similar to that employed by Monnier et al. (2008) for Altair (**Fig. 1, right**), i.e. an image reconstruction starting from a grid of *a priori* simple morphological models of the star (comprising e.g. the elliptical profile, limb darkening and equatorial darkening). We will combine the PIONIER observations (in the H band) with the existing visibility measurements obtained with VINCI (in the K band) to enhance the image reconstruction procedure.

• **Subtraction of Achernar's companion:** In 2006, we discovered a close-in faint companion to Achernar, from high resolution thermal infrared imaging with the VLT/VISIR instrument (Kervella & Domiciano de Souza 2007). Using NACO imaging and spectroscopy, we established that Achernar B is an A1V-A3V star (Kervella et al. 2008, **Fig. 3**), that is 30 times fainter than A at infrared and visible wavelengths. Its orbit brings it very close to Achernar A, and it will possibly be present in the interferometric field of view of PIONIER in 2011 (although its orbit is not yet determined). In order to remove its (faint) contribution to the interferometric signal of Achernar A, we need to obtain the relative astrometric position and flux of Achernar B, simultaneously with the PIONIER observations. This is the reason why we request one NACO observation of the pair.

References: **Berger** et al. 2010, SPIE Conf. Proc., 7734, 99; **Carciofi** et al. 2008, ApJ, 676, L41; **Domiciano de Souza** et al. 2003, A&A, 407, L47; **Jackson** et al. 2004, ApJ, 606, 1196; **Kervella** & Domiciano 2006, A&A, 453, 1059; **Kervella** & Domiciano 2007, A&A, 474, L49; **Kervella** et al. 2008, A&A, 484, L13; **Kervella** et al. 2009, A&A, 493, L53; **Vinicius** et al. 2006, A&A, 446, 643.

B – Immediate Objective:

We will take full advantage of **PIONIER**'s capability to combine the light from four telescopes simultaneously. The measurements we propose are essentially based on closure phases. From archival observations, we already have a large sample of accurate VLTI/VINCI visibility measurements, and this degree of resolution is sufficient considering the rather high temperature contrast expected between the pole ($\approx$ 20 000 K) and the average effective temperature of the star ($\approx$ 15 000 K). We will naturally combine the PIONIER data with the existing VINCI data set to better constrain our visibility/phase model.

The proposed **NACO cube** observations will give us a high accuracy relative astrometry of A–B. The cube mode is more accurate than the standard imaging mode, thanks to the thousands of frames available. The relative position of the two stars will be measured to $\sigma \approx 100\,\mu as$. In addition, we will obtain relative photometry in the NB filters of CONICA (H & K bands). Knowing the brightness and position of Achernar B, we will compute its fringe pattern and subtract it from the PIONIER measurements.

8. Description of the proposed programme and attachments

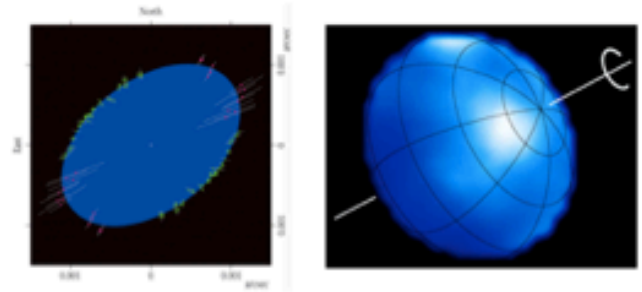


Fig. 1: Left: Interferometric profile of Achernar from VLTI/VINCI observations (Domiciano de Souza et al. 2003). **Right:** Reconstructed image of the surface of Altair from Monnier et al. (2008).

Fig. 2: Models of Achernar reproducing the observed interferometric profile with different masses (from Jackson et al. 2004). The pole properties derived from PIONIER observations will waive the degeneracy.

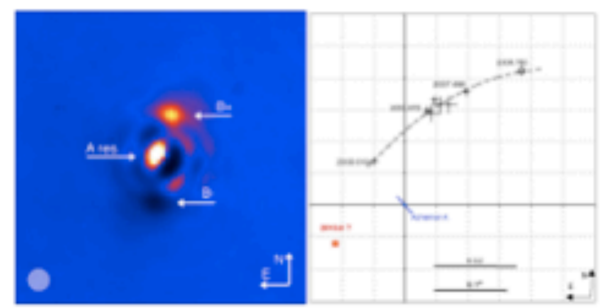
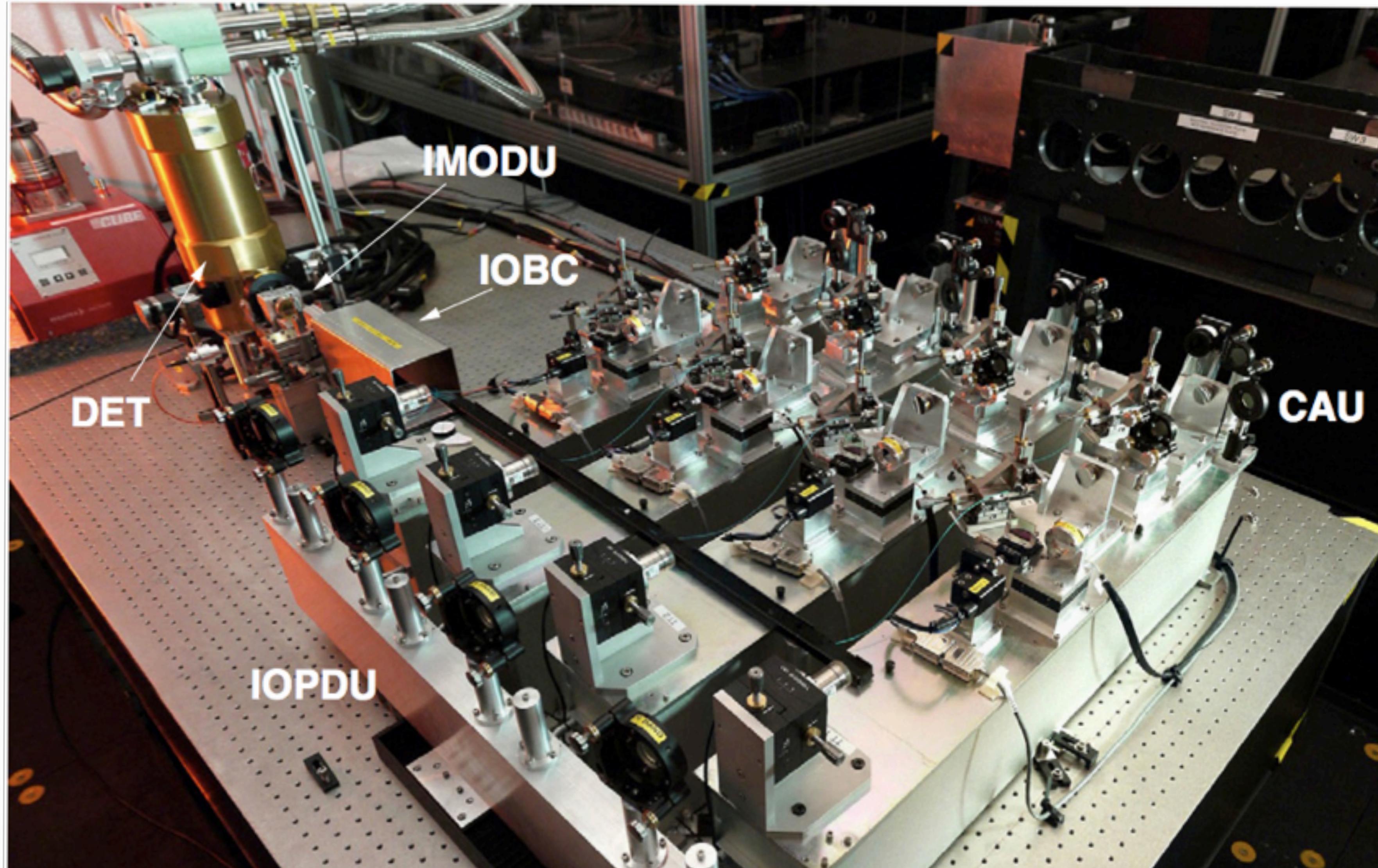


Fig. 3 (Left): PSF-subtracted NACO image obtained on 22 Dec. 2007 in the K band showing Achernar B (positive and symetric negative image). The field of view is $1 \times 1''$, and the white disk in the lower left part of the image gives approximately the FWHM of the star images. **(Right):** Position of Achernar B relatively to A for five epochs (black symbols). The open square indicates the VISIR observation (Kervella & Domiciano 2007), and the dots represent the NACO epochs. The dashed curve is a quadratic fit through the data points intended to guide the eye. The segment over Achernar A indicates its projected rotation axis and polar wind extension as measured by Kervella & Domiciano (2006).

PIONIER

- 4 telescope recombination
- Fringes in the pupil plane
- Temporal modulation of the OPD
- 6 baselines simultaneously
- 3 phase closures
- Broadband or low spectral resolution (7 channels)
- H band (1.6 μm)
- Simple, fast robust instrument
- 1 calibrated observations = 15-30 minutes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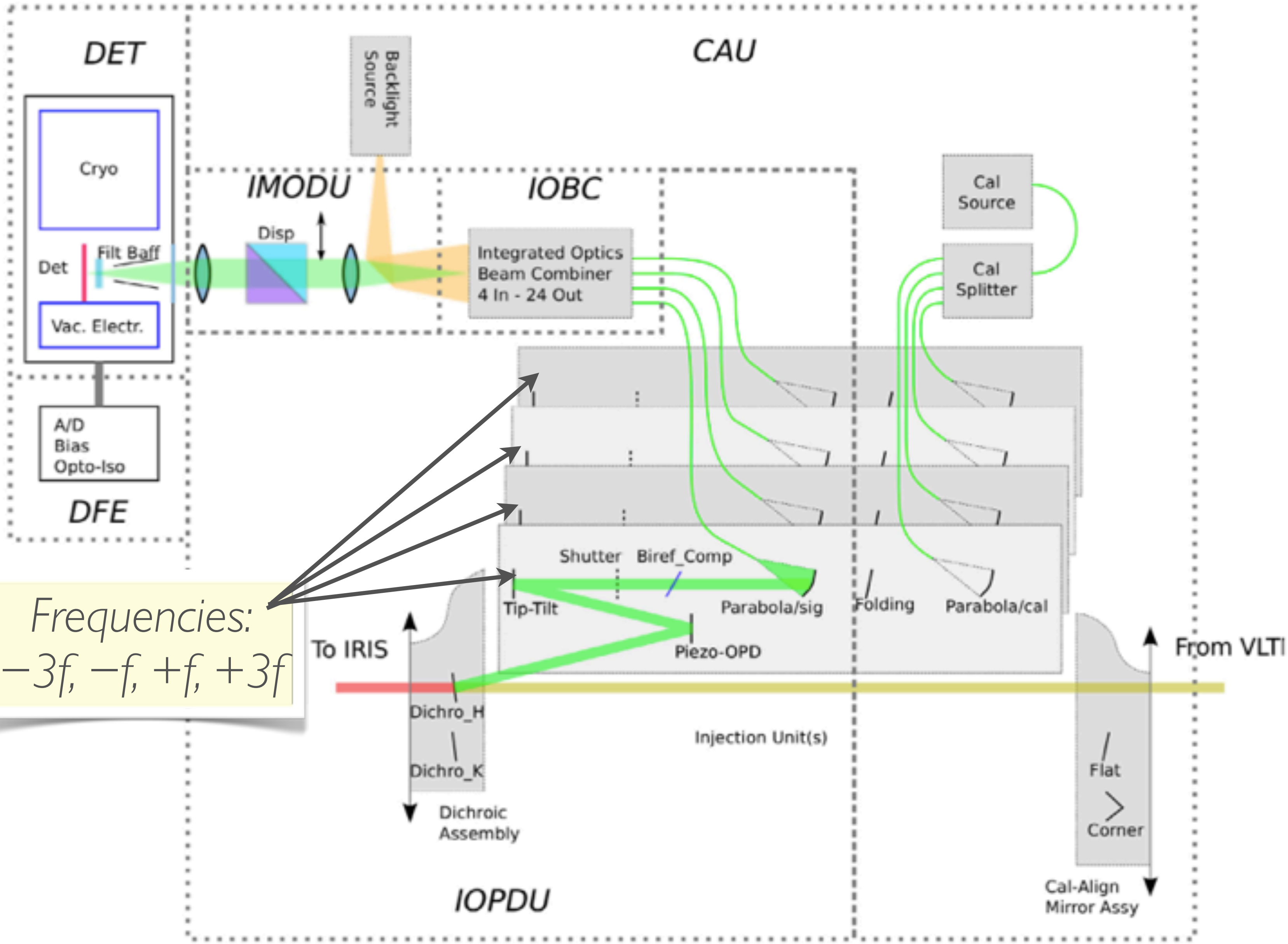
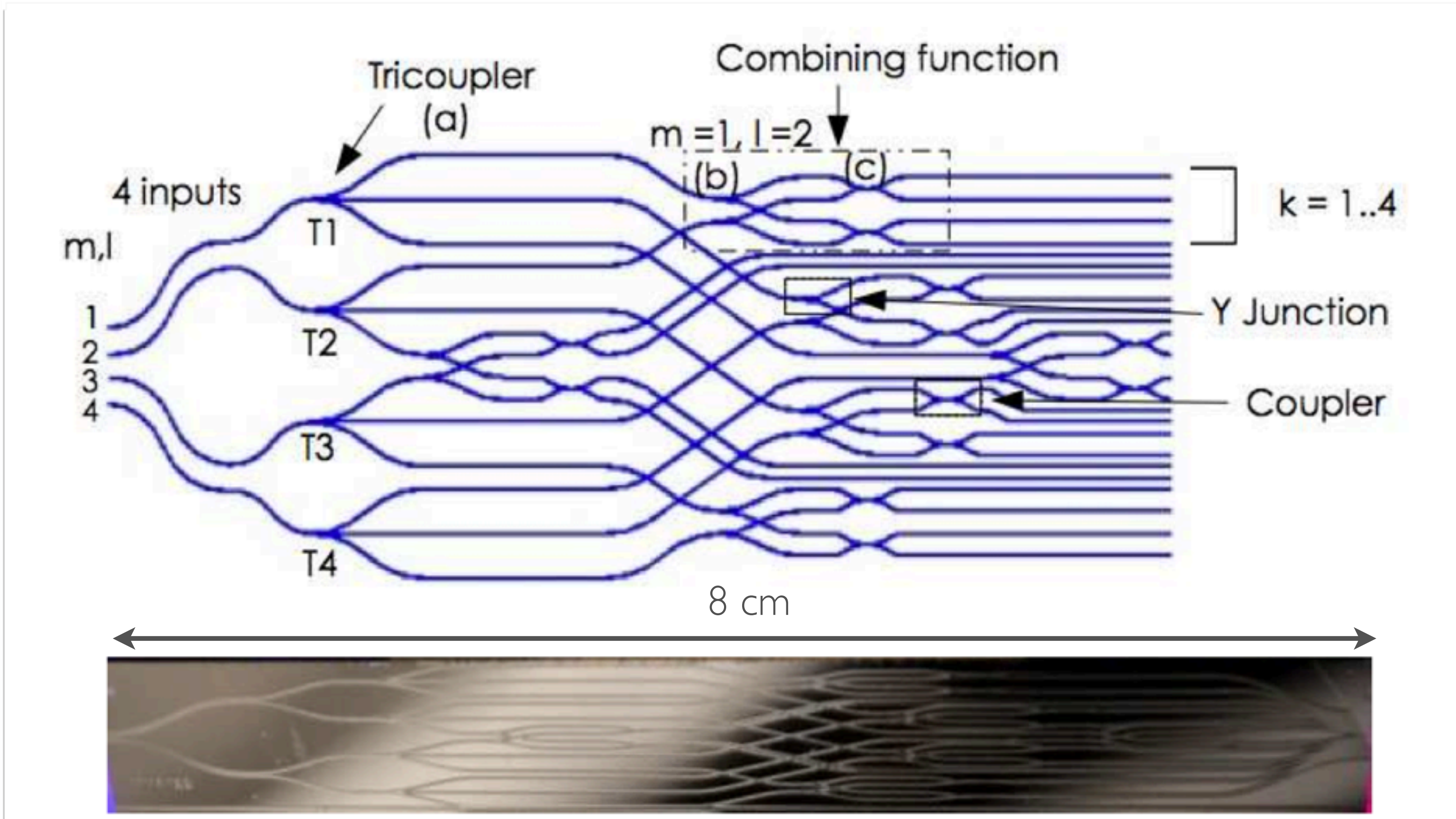
IOBC
DET
CAU
IOPDU



Frequencies:
$-3f, -f, +f, +3f$

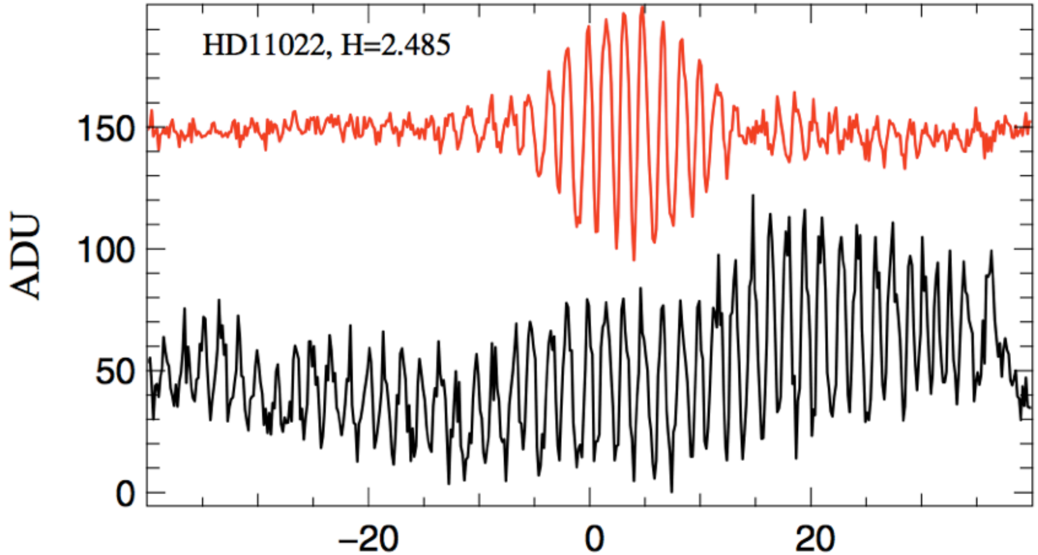
Le Bouquin et al. 2011, A&A 535, A67

INTEGRATED OPTICS 4T

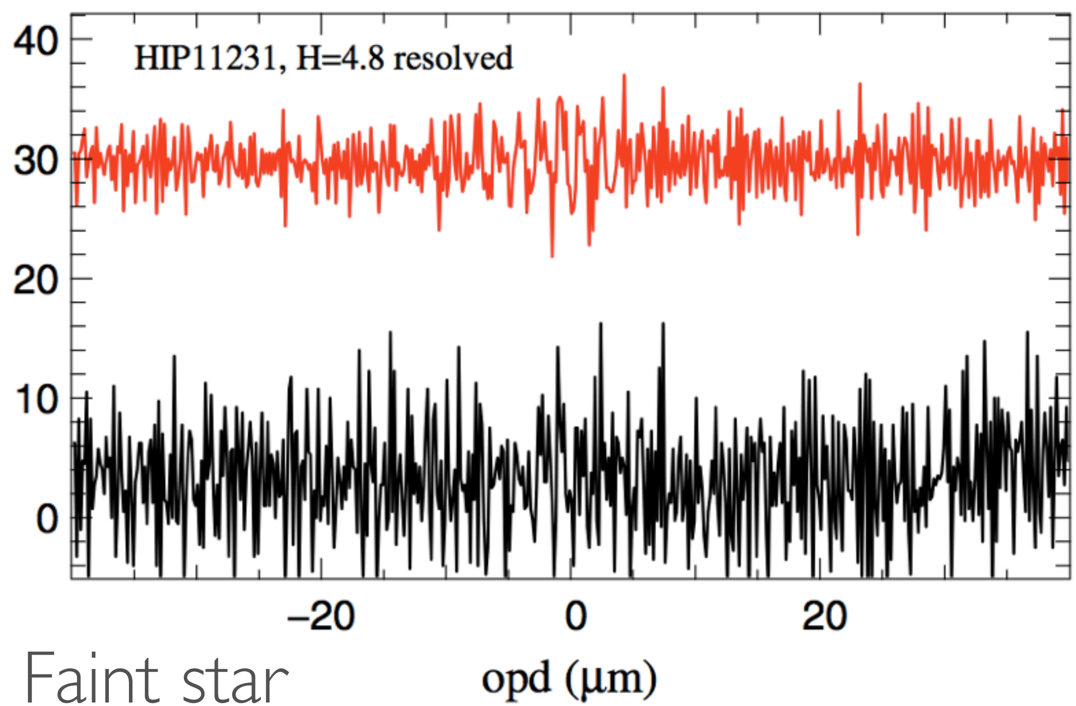


Benisty, M., Berger, J.-P., Jocou, L., et al. 2009, A&A, 498, 601

Le Bouquin et al. 2011, A&A 535, A67



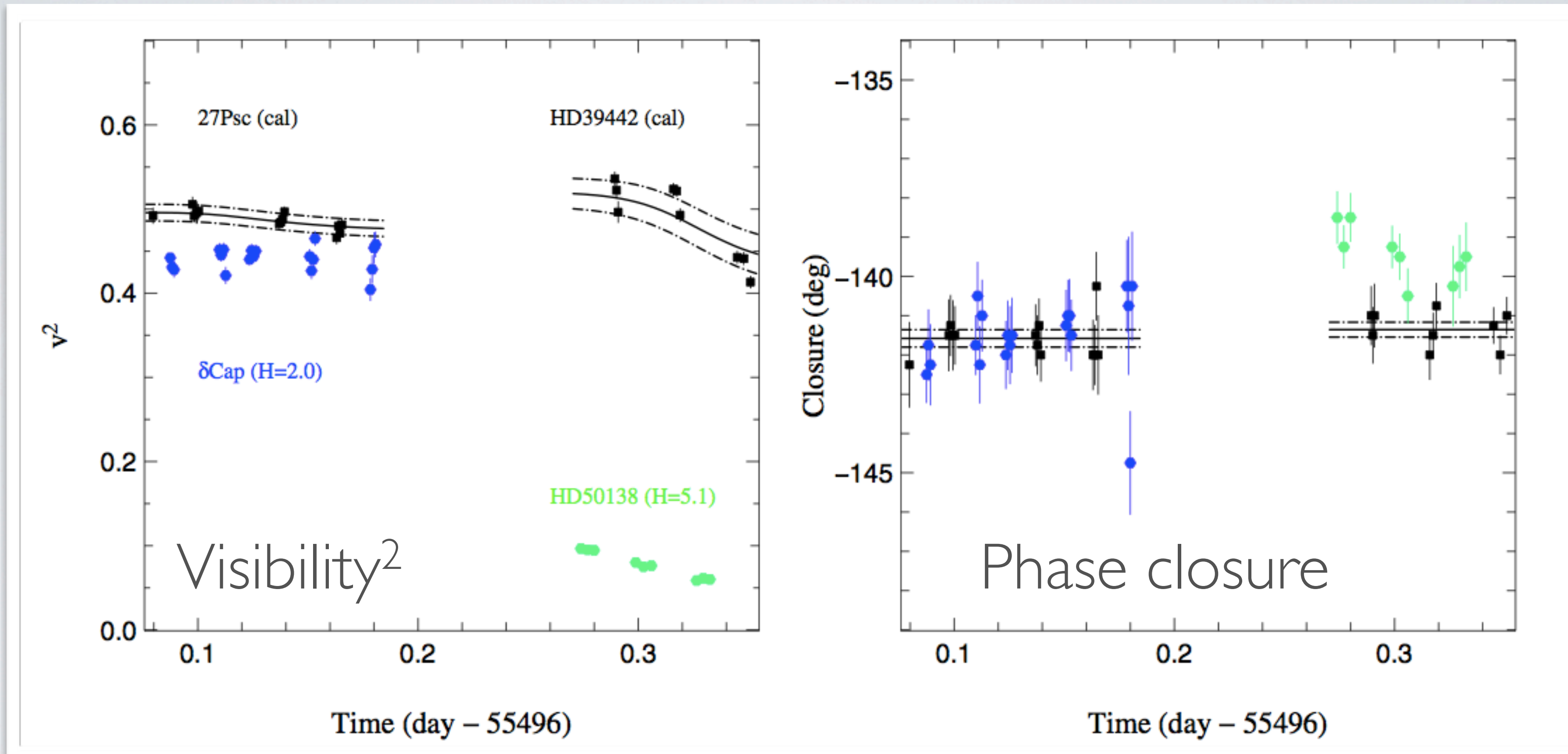
Bright star



Faint star

Le Bouquin et al. 2011, A&A 535, A67

CALIBRATION



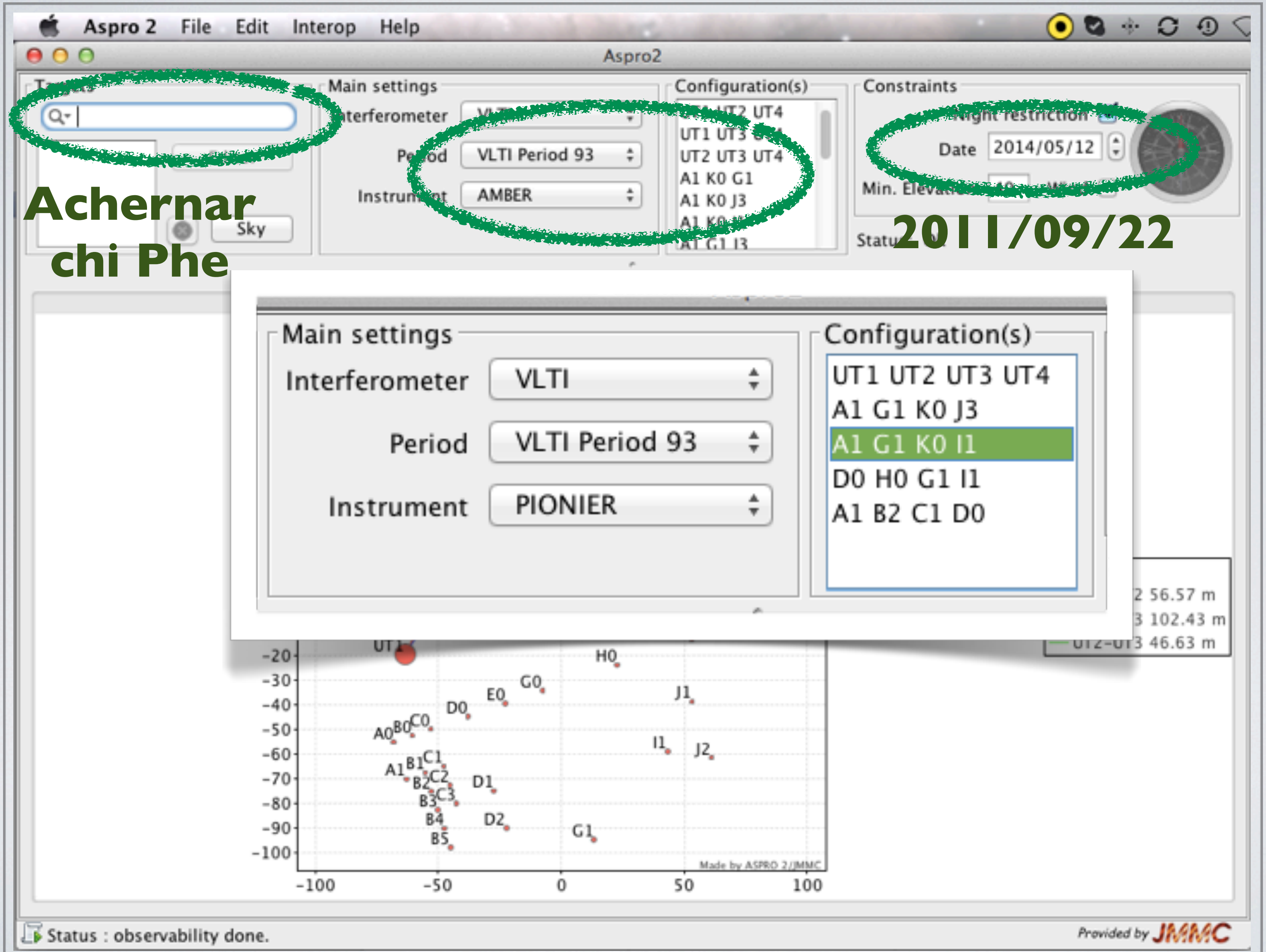
PREPARATION OF THE OBSERVATIONS

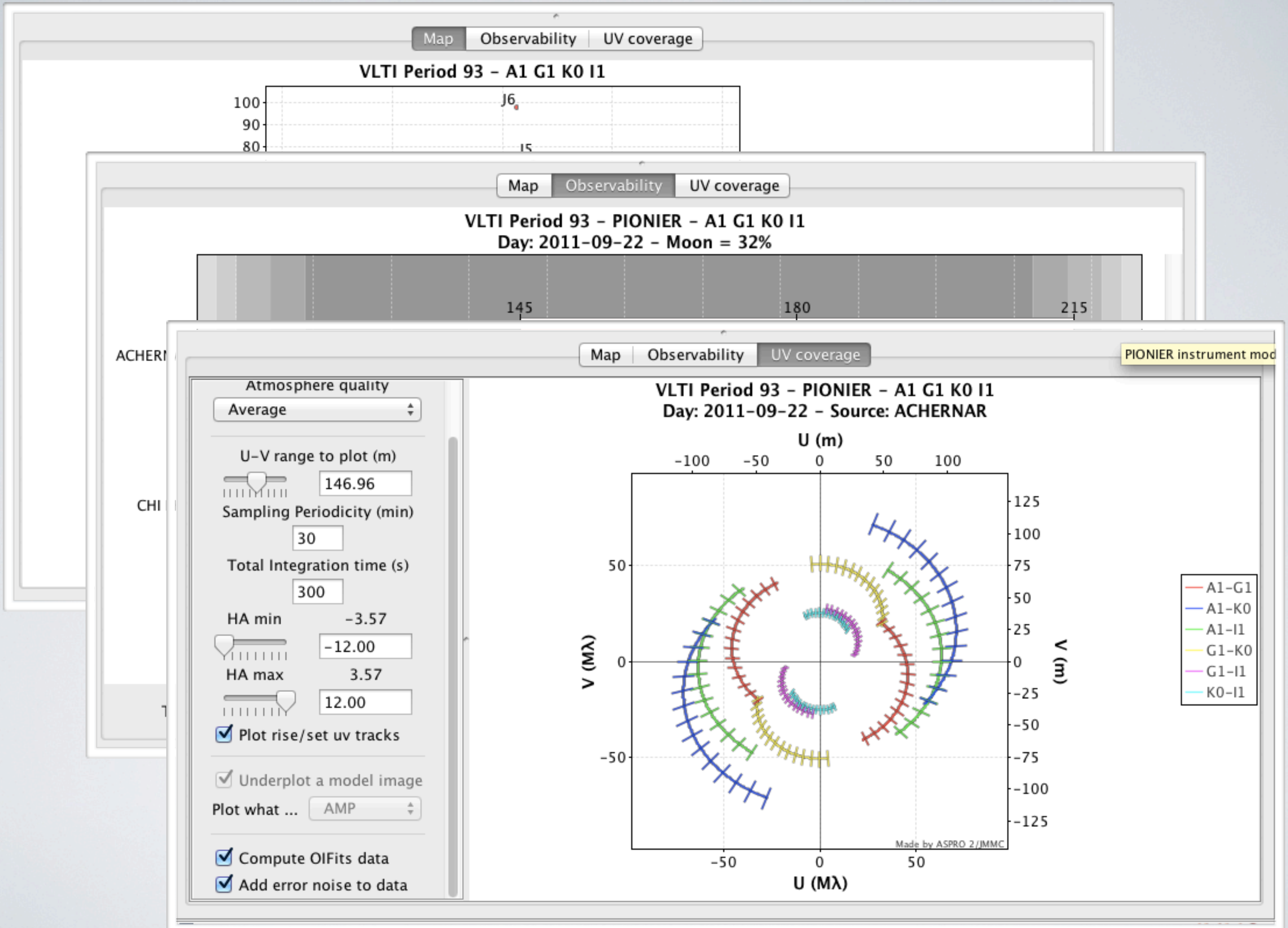
- User-friendly tools from the JMMC (*http://www.jmmc.fr*): **SearchCal** (selection of calibrators) and **ASPRO2** (observability, uv coverage)

- Interferometric observations have complex observability limits

- The selection of the calibrators is relatively simple, but some rules have to be followed (proximity on the sky, similar color, similar brightness) > we select χ *Phe* for the exercise

ASPRO2 (WWW.JMMC.FR)

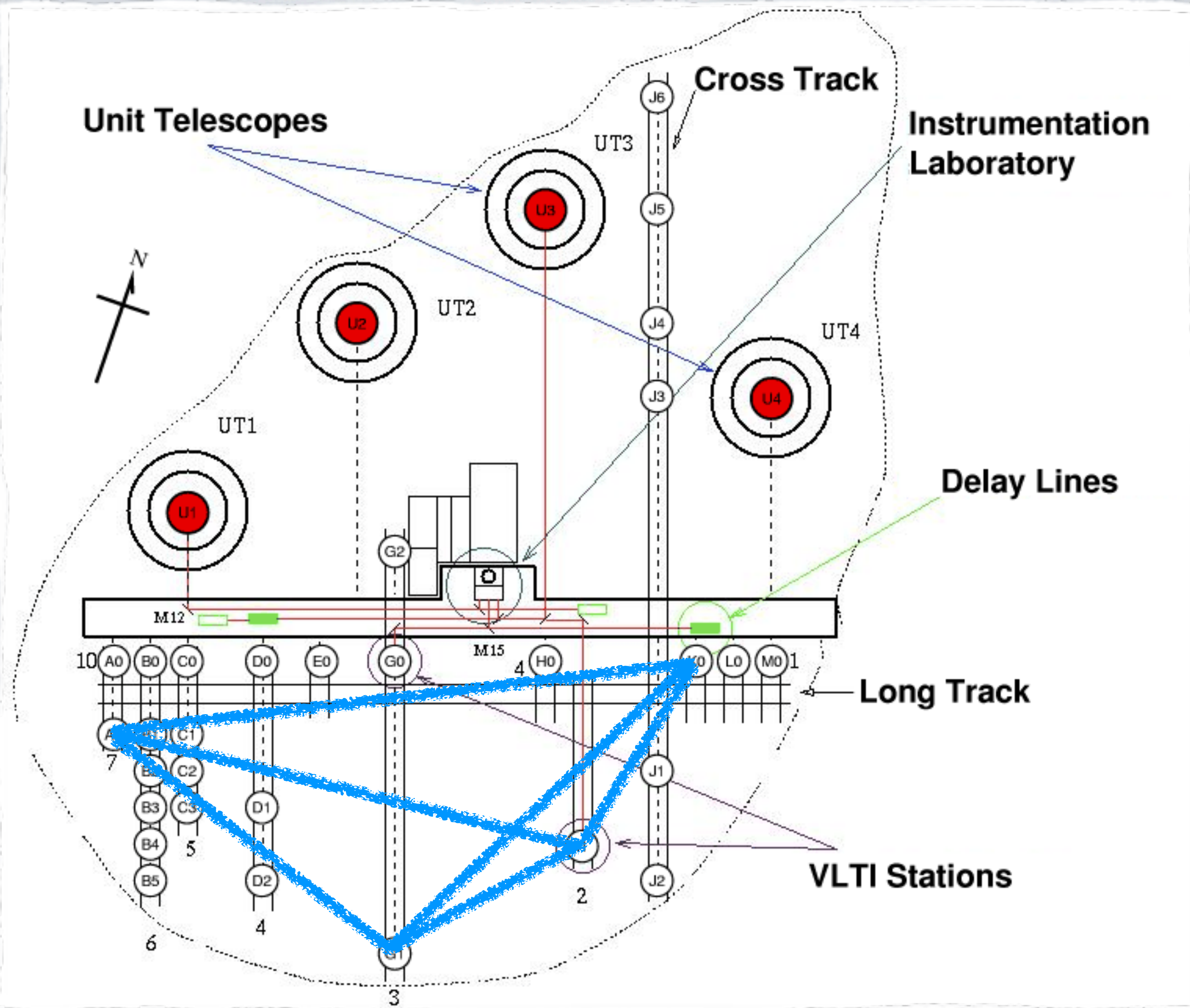




Map
Observability
UV coverage
VLTI Period 93 – A1 G1 K0 I1
VLTI Period 93 – PIONIER – A1 G1 K0 I1
Day: 2011-09-22 – Moon = 32%
PIONIER instrument mod
VLTI Period 93 – PIONIER – A1 G1 K0 I1
Day: 2011-09-22 – Source: ACHERNAR
Atmosphere quality
Average
U-V range to plot (m)
146.96
Sampling Periodicity (min)
30
Total Integration time (s)
300
HA min
-3.57
-12.00
HA max
3.57
12.00
Plot rise/set uv tracks
Underplot a model image
Plot what ...
AMP
Compute OIFits data
Add error noise to data
U (m)
V (Mλ)
V (m)
U (Mλ)
A1-G1
A1-K0
A1-I1
G1-K0
G1-I1
K0-I1
Made by ASPRO 2/JMMC

OBSERVATIONS AT PARANAL

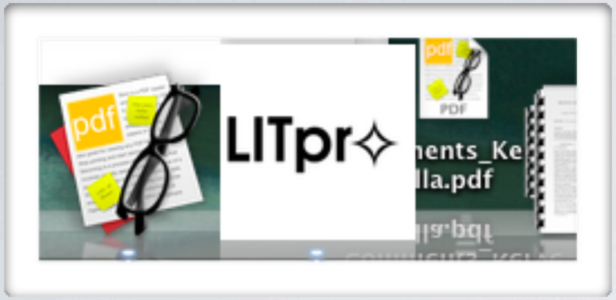
- Visitor mode (or delegated visitor mode)
- 2 nights (22 et 23 september 2011)
- Quadruplet of telescopes A1-G1-K0-I1 (maxi baseline ~130m)
- Observations of Achernar and 3 different calibrators
- 17 visibility measurements in dispersed mode (7 spectral channels)
- Dense coverage of the (u,v) plane


Cross Track
Unit Telescopes
Instrumentation Laboratory
UT3
UT2
UT4
UT1
N
U1
U2
U3
U4
J6
J5
J4
J3
J2
J1
Delay Lines
M12
M15
G2
A0
B0
C0
D0
E0
G0
H0
L0
M0
Long Track
VLTI Stations
C1
C2
B3
B4
B5
D1
D2
10
7
6
5
4
3
2
1

DATA ANALYSIS WITH LITPRO

MODEL FITTING WITH LITPRO

- The raw data processing and calibration of the PIONIER data are essentially automatic
- Processed data files in OIFITS format
- Rapid analysis of the data using **LITPro** (developed and distributed by the Jean-Marie Mariotti Center, http://www.jmmc.fr)


pdf
LITpro
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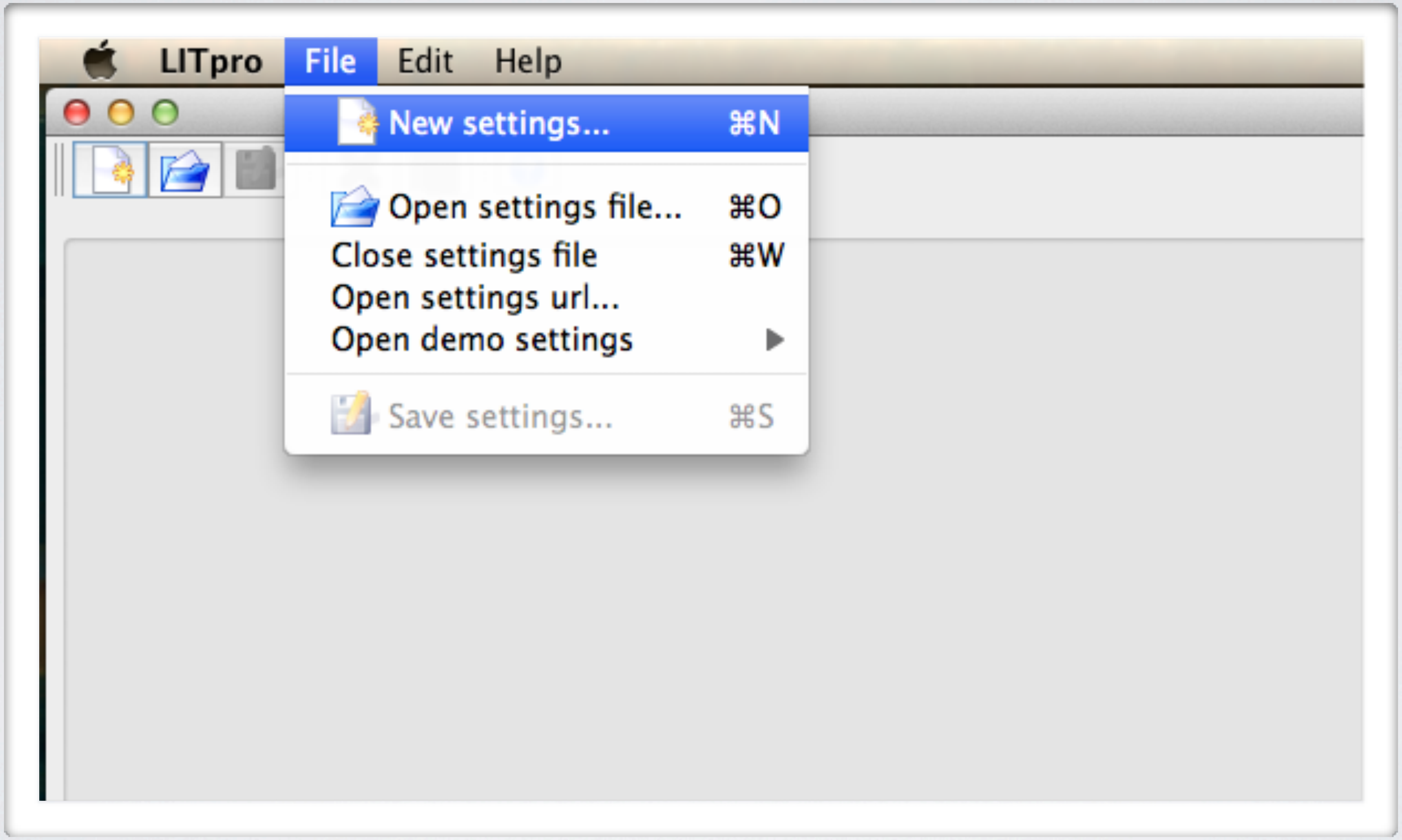
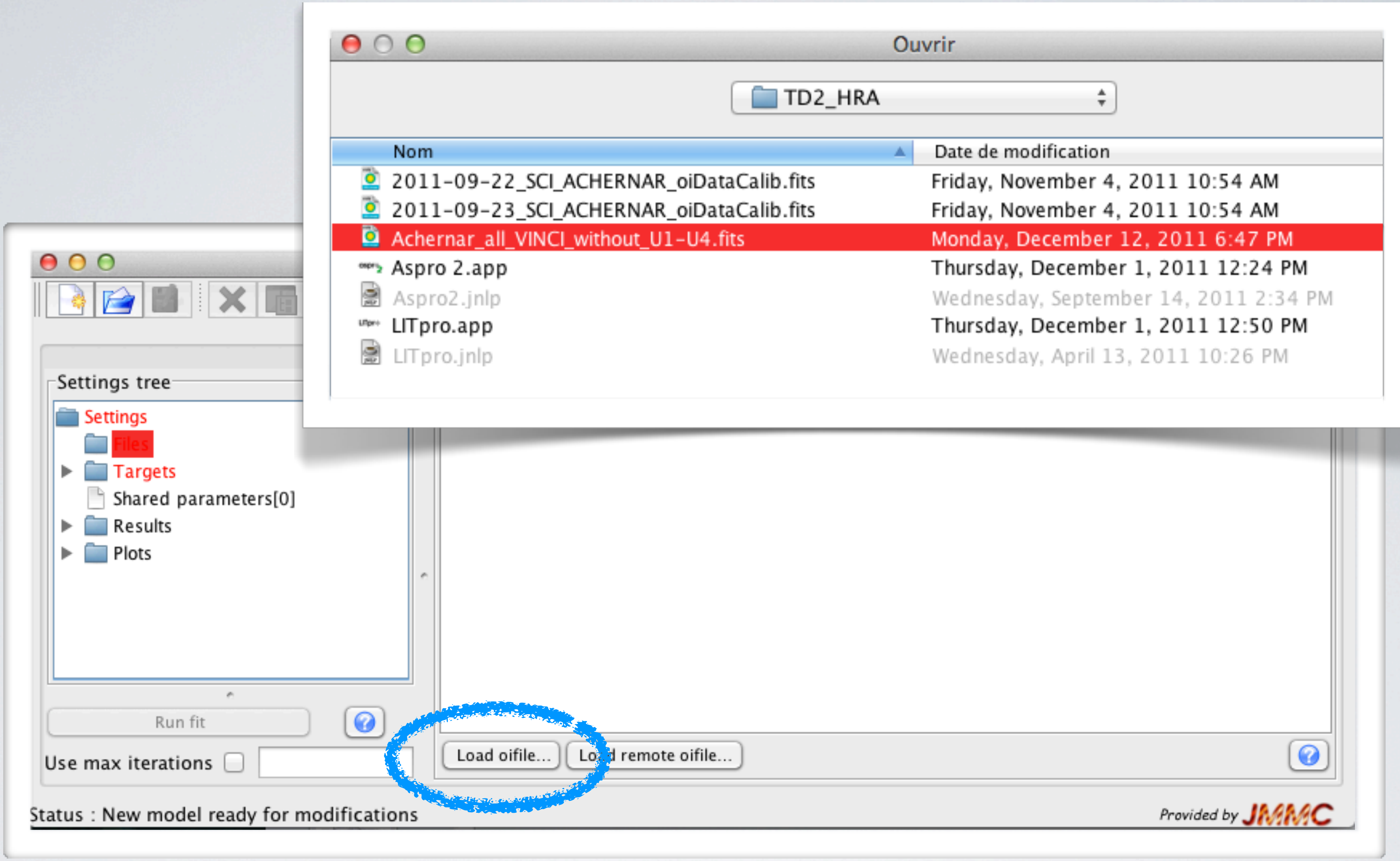
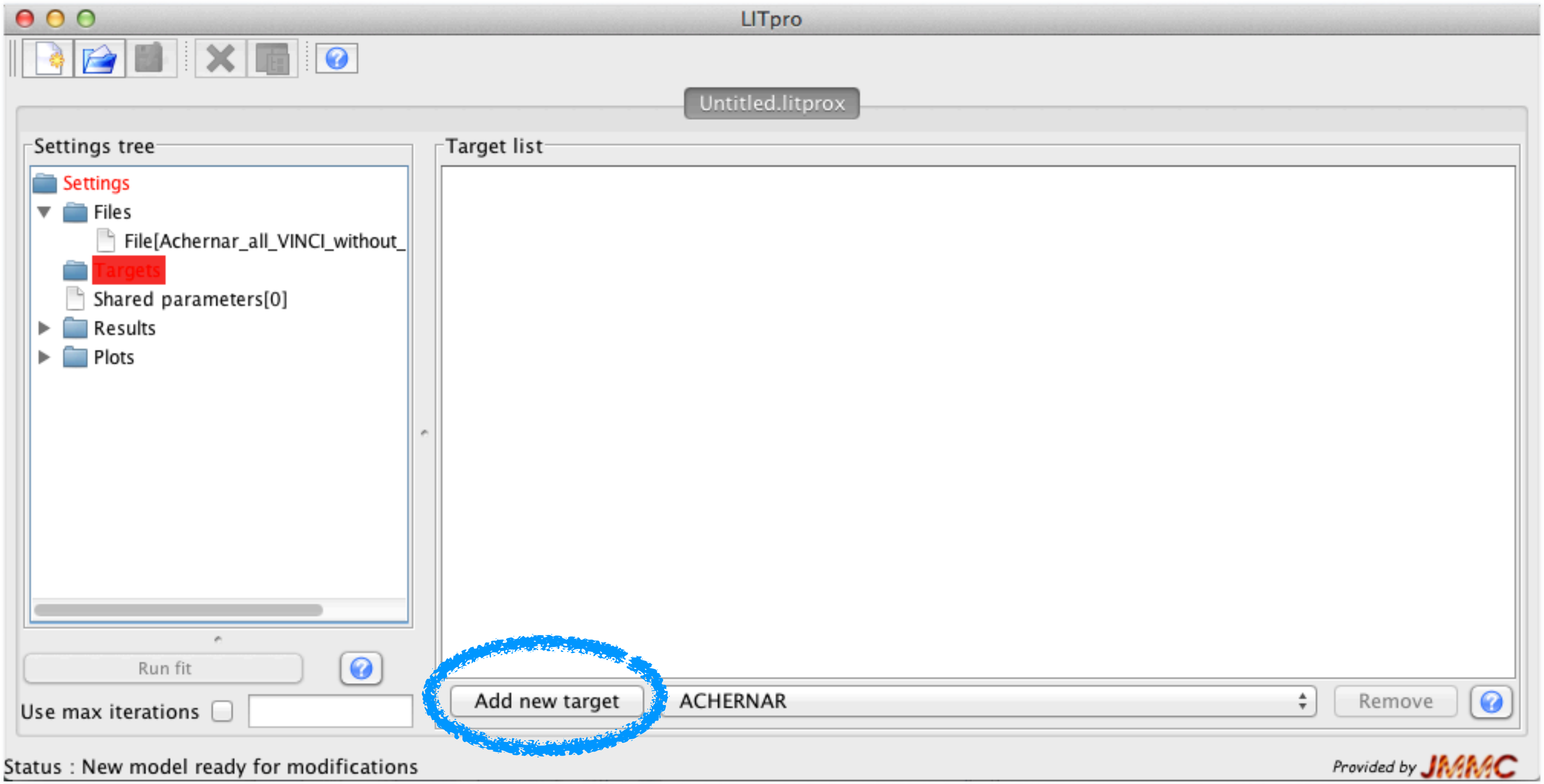
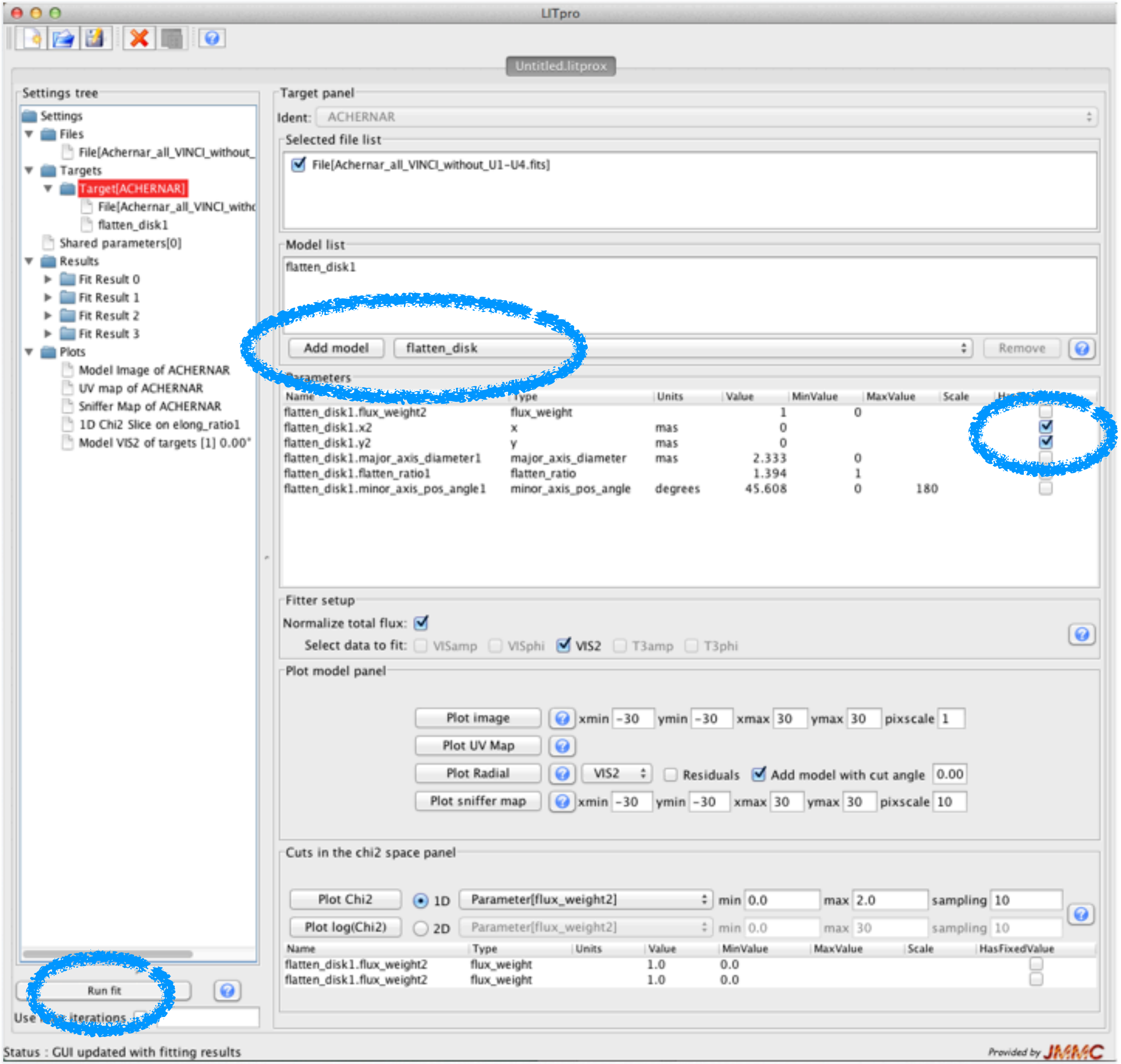
LITPRO


LITpro
File
Edit
Help
New settings... ⌘N
Open settings file... ⌘O
Close settings file ⌘W
Open settings url...
Open demo settings
Save settings... ⌘S


Ouvrir
TD2_HRA
Nom
Date de modification
2011-09-22_SCI_ACHERNAR_oiDataCalib.fits
Friday, November 4, 2011 10:54 AM
2011-09-23_SCI_ACHERNAR_oiDataCalib.fits
Friday, November 4, 2011 10:54 AM
Achernar_all_VINCI_without_U1-U4.fits
Monday, December 12, 2011 6:47 PM
Aspro 2.app
Thursday, December 1, 2011 12:24 PM
Aspro2.jnlp
Wednesday, September 14, 2011 2:34 PM
LITpro.app
Thursday, December 1, 2011 12:50 PM
LITpro.jnlp
Wednesday, April 13, 2011 10:26 PM
Settings tree
Settings
Files
Targets
Shared parameters[0]
Results
Plots
Run fit
Use max iterations
Load oifile...
Load remote oifile...
Status : New model ready for modifications
Provided by JMMC


LITpro
Untitled.litprox
Settings tree
Settings
Files
File[Achernar_all_VINCI_without_
Targets
Shared parameters[0]
Results
Plots
Target list
Run fit
Use max iterations
Add new target
ACHERNAR
Remove
Status : New model ready for modifications
Provided by JMMC


LITpro
Untitled.litprox
Settings tree
Settings
Files
File[Achernar_all_VINCI_without_
Targets
Target[ACHERNAR]
File[Achernar_all_VINCI_witho
flatten_disk1
Shared parameters[0]
Results
Fit Result 0
Fit Result 1
Fit Result 2
Fit Result 3
Plots
Model Image of ACHERNAR
UV map of ACHERNAR
Sniffer Map of ACHERNAR
1D Chi2 Slice on elong_ratio1
Model VIS2 of targets [1] 0.00°
Run fit
Target panel
Ident: ACHERNAR
Selected file list
File[Achernar_all_VINCI_without_U1-U4.fits]
Model list
flatten_disk1
Add model
flatten_disk
Remove
Name
Type
Units
Value
MinValue
MaxValue
Scale
flatten_disk1.flux_weight2 flux_weight 1 0
flatten_disk1.x2 x mas 0
flatten_disk1.y2 y mas 0
flatten_disk1.major_axis_diameter1 major_axis_diameter mas 2.333 0
flatten_disk1.flatten_ratio1 flatten_ratio 1.394 1
flatten_disk1.minor_axis_pos_angle1 minor_axis_pos_angle degrees 45.608 0 180
Fitter setup
Normalize total flux:
Select data to fit: VISamp VISphi VIS2 T3amp T3phi
Plot model panel
Plot image xmin -30 ymin -30 xmax 30 ymax 30 pixscale 1
Plot UV Map
Plot Radial VIS2 Residuals Add model with cut angle 0.00
Plot sniffer map xmin -30 ymin -30 xmax 30 ymax 30 pixscale 10
Cuts in the chi2 space panel
Plot Chi2 1D Parameter[flux_weight2] min 0.0 max 2.0 sampling 10
Plot log(Chi2) 2D Parameter[flux_weight2] min 0.0 max 30 sampling 10
Name Type Units Value MinValue MaxValue Scale HasFixedValue
flatten_disk1.flux_weight2 flux_weight 1.0 0.0
flatten_disk1.flux_weight2 flux_weight 1.0 0.0
Status : GUI updated with fitting results
Provided by JMMC

Result panel:

Personal notebook:

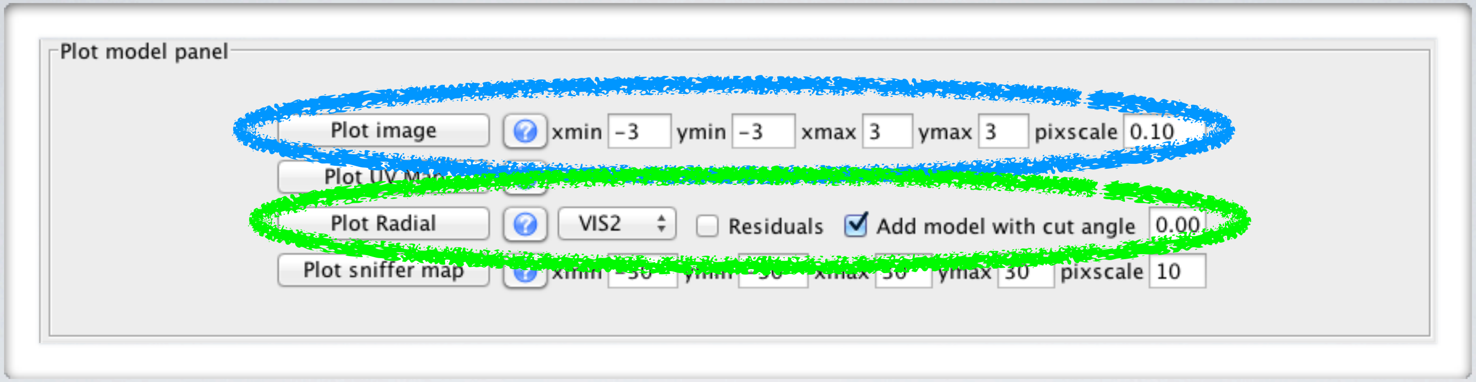
```
Chi2          Initial=  21895.6 -  Final=  313.27 -  Sigma=  14.83
reduced Chi2  Initial=  199.05 -  Final=  2.85 -  Sigma=  0.13
 minor_axis_pos_angle1=45.6082  flux_weight2=1  major_axis_diameter1=2.33277  flatten_ratio1=1.39392


Fit Result 4 occured on 2011-12-15T16:56:58+01:00
Chi2          Initial=  313.27 -  Final=  313.27 -  Sigma=  14.83
reduced Chi2  Initial=  2.85 -  Final=  2.85 -  Sigma=  0.13
 minor_axis_pos_angle1=45.6082  flux_weight2=1  major_axis_diameter1=2.33277  flatten_ratio1=1.39392
```

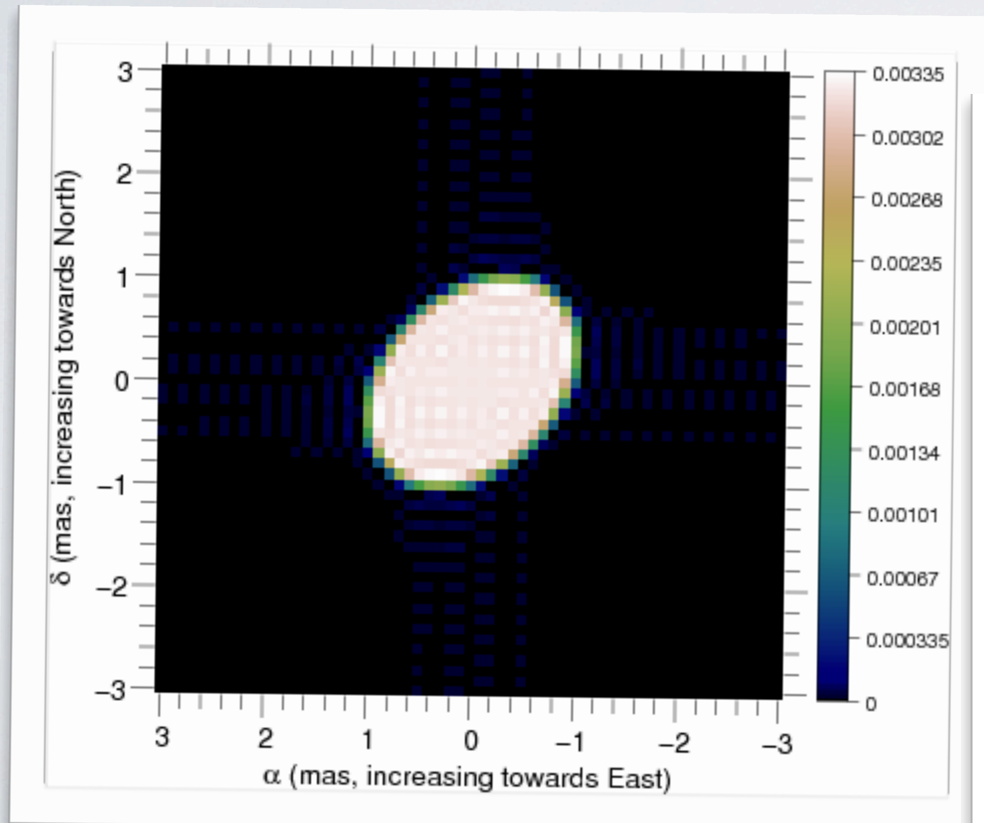
Iterations

Number of iterations: 2 (Max Number of iterations 200)

Parameters

name	value	standard deviation(+/-)	prev_val	vmin	vmax	scale	fixed	units
flatten_ratio1	1.39392	0.0264556	1.39392	1		AUTO	0	
flux_weight2	1	0.0936586	1	0		AUTO	0	
major_axis_diameter1	2.33277	0.0344444	2.33277	0		AUTO	0	mas
minor_axis_pos_angle1	45.6082	1.105	45.6082	0	180	AUTO	0	degrees
x2	0					AUTO	1	mas
y2	0					AUTO	1	mas


Plot model panel
Plot image
xmin -3 ymin -3 xmax 3 ymax 3 pixscale 0.10
Plot Radial
VIS2
Residuals
Add model with cut angle 0.00
Plot sniffer map
pixscale 10


δ (mas, increasing towards North)
α (mas, increasing towards East)
3
2
1
0
−1
−2
−3
0.00335
0.00302
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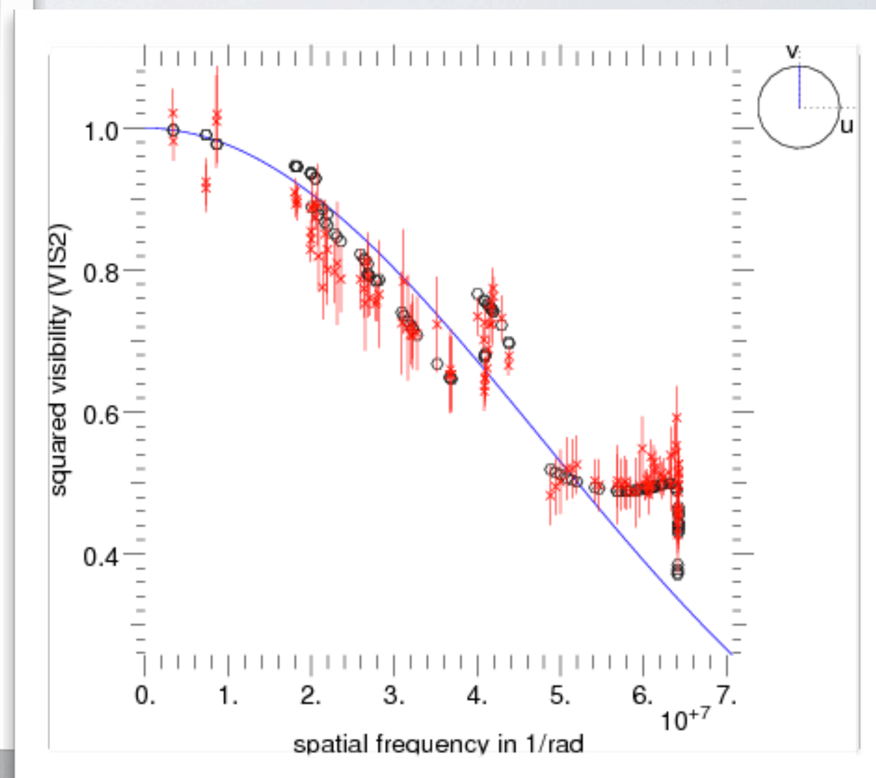
0.00235
0.00201
0.00168
0.00134
0.00101
0.00067
0.000335
0


squared visibility (VIS2)
spatial frequency in 1/rad
1.0
0.8
0.6
0.4
0. 1. 2. 3. 4. 5. 6. 7.
10+7
v
u

INTERPRETATION

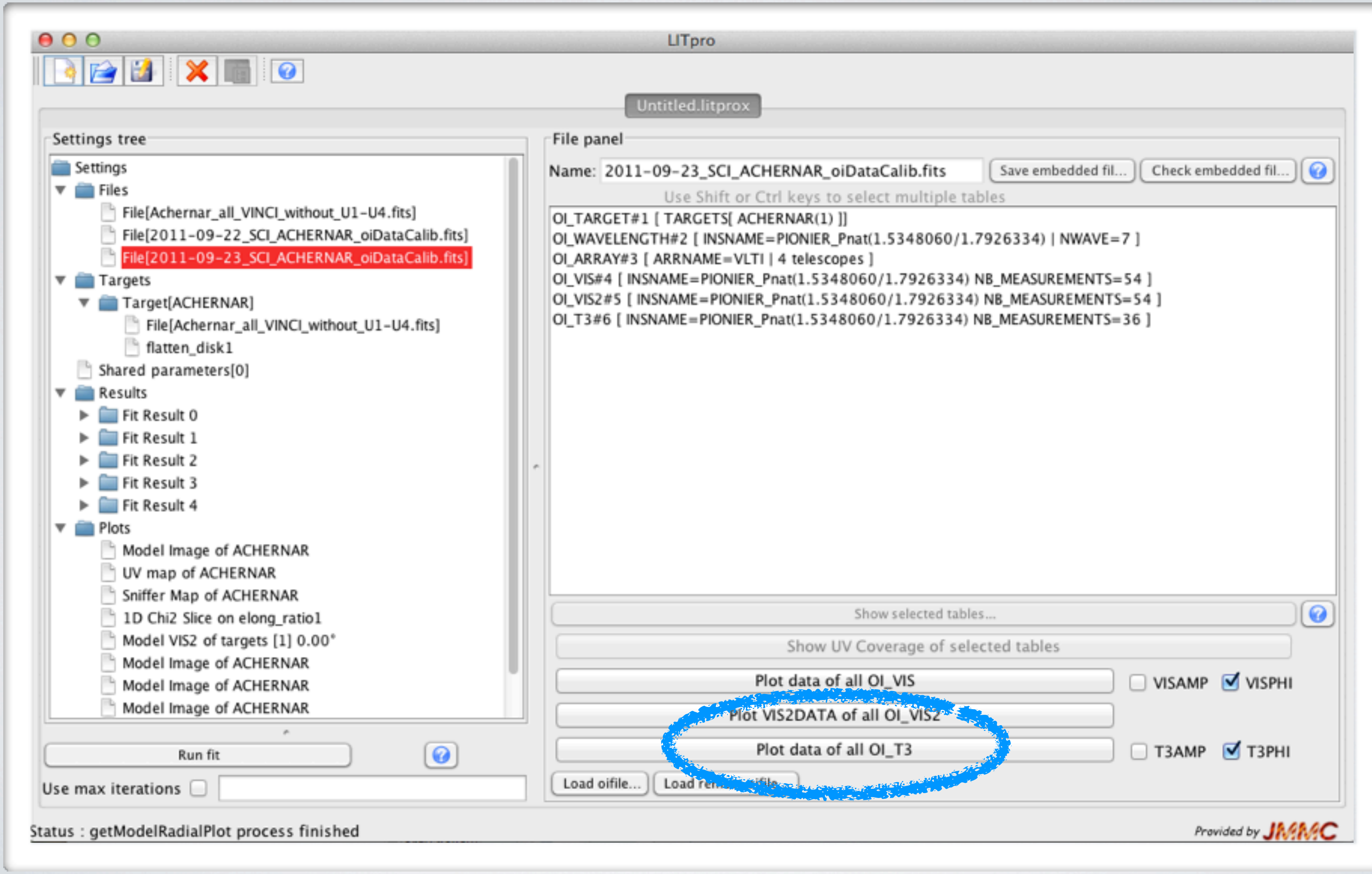
- The derived flattening ratio of Achernar is R_{eq} / R_{pol} = 1,394 +/- 0,026

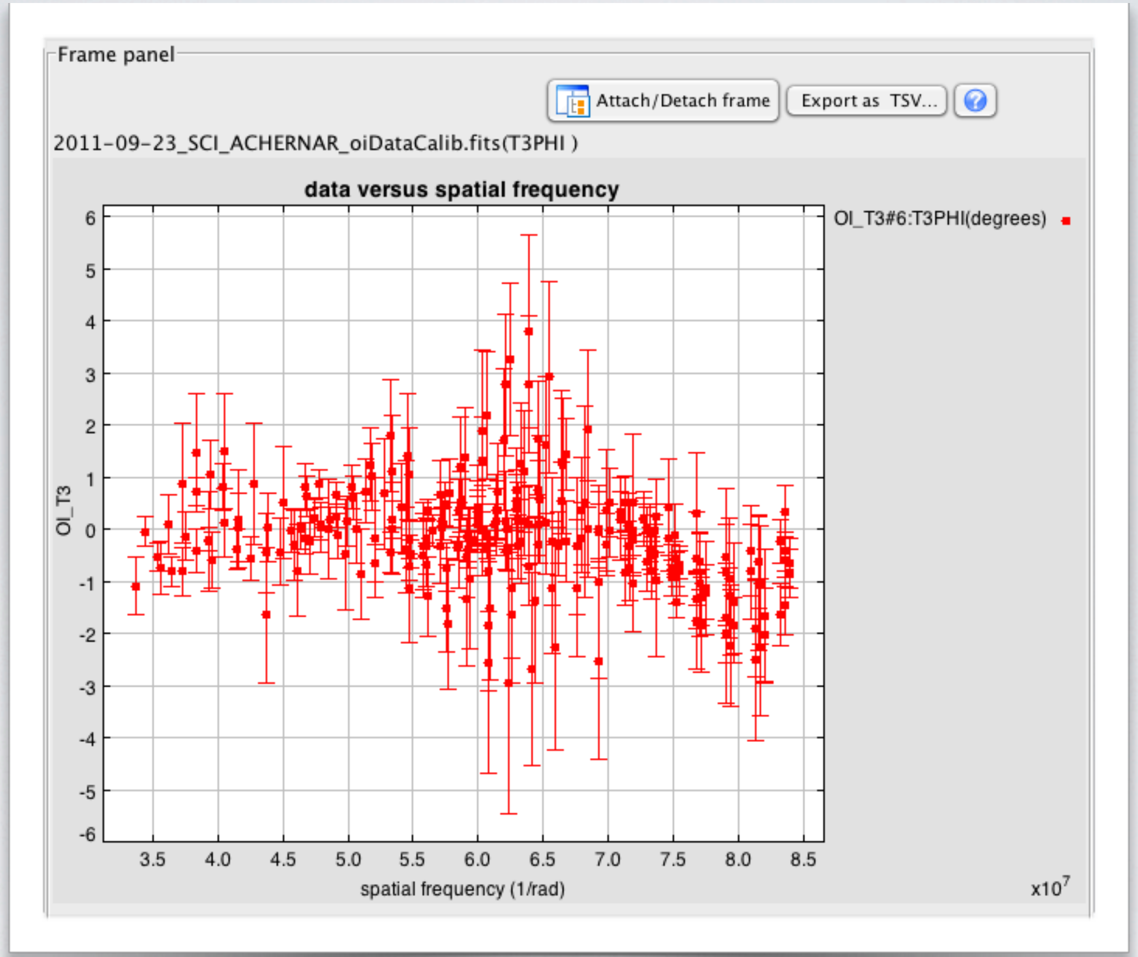
- The star is less flat than in our 2T VINCI fit

- Predicted value from the Huygens approximation: 1,367

Masse	6	Msol		
Rayon moyen	10	Rsol		
vitesse eq.	280	km/s		
Msol	2,00E+30	kg		
Rsol	7,50E+08	m		
G	6,67E-11	SI		
Période	1,68E+05	s	1,95	jours
omega	3,73E-05	rad/s		
Densité	6,79E+00	kg/m3		
Aplatissement	**1,367**			

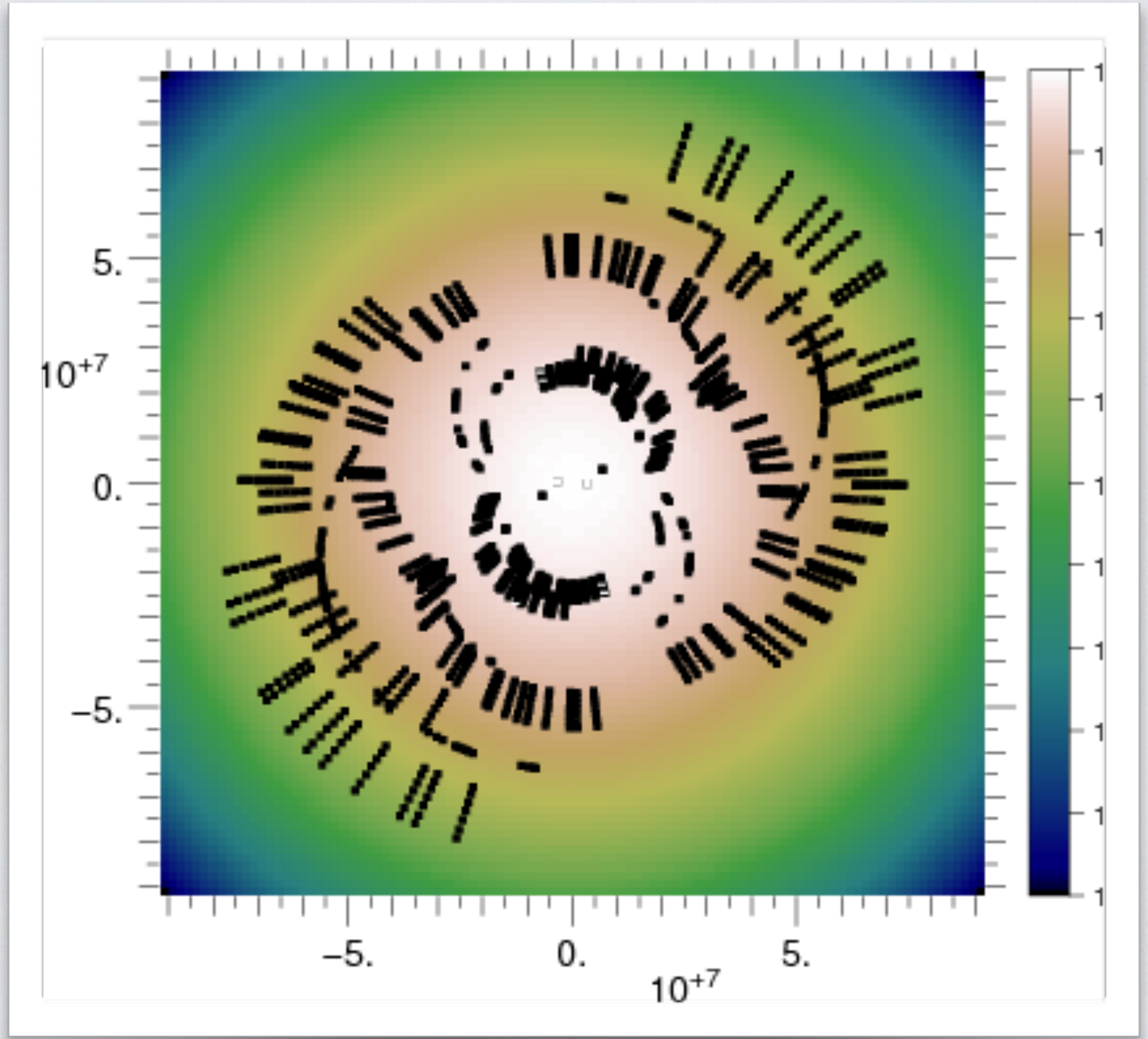
PIONIER DATA

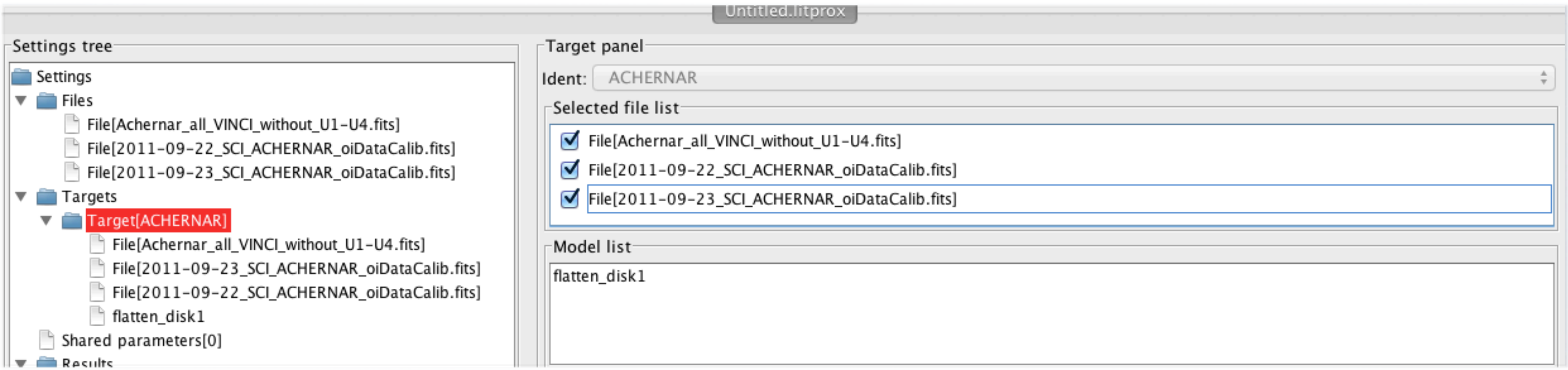




Very small phase closure signal

(U,V) COVERAGE





Adjustment of the complete data set

Result panel:

Personal notebook:

```
Chi2            Initial=  313.27 -  Final=  313.27 -  Sigma=  14.83
reduced Chi2    Initial=  2.85 -  Final=  2.85 -  Sigma=  0.13
 minor_axis_pos_angle1=45.6082  flux_weight2=1  major_axis_diameter1=2.33277  flatten_ratio1=1.39392


Fit Result 5 occured on 2011-12-15T18:30:29+01:00
Chi2            Initial=  23684.4 -  Final=  2667.95 -  Sigma=  42.61
reduced Chi2    Initial=  26.08 -  Final=  2.94 -  Sigma=  0.05
 minor_axis_pos_angle1=36.0857  flux_weight2=1  major_axis_diameter1=1.91397  flatten_ratio1=1.23879
```

Iterations

Number of iterations: 6 (Max Number of iterations 200)

Parameters

name	value	standard deviation(+/-)	prev_val	vmin	vmax	scale	fixed	units
flatten_ratio1	1.23879	0.00346[illegible]58	1.39392	1		AUTO	0	
flux_weight2	1	0.0331133	1	0		AUTO	0	
major_axis_diameter1	1.91397	0.00326059	2.33277	0		AUTO	0	mas
minor_axis_pos_angle1	36.0857	0.481381	45.6082	0	180	AUTO	0	degrees
x2	0					AUTO	1	mas
y2	0					AUTO	1	mas

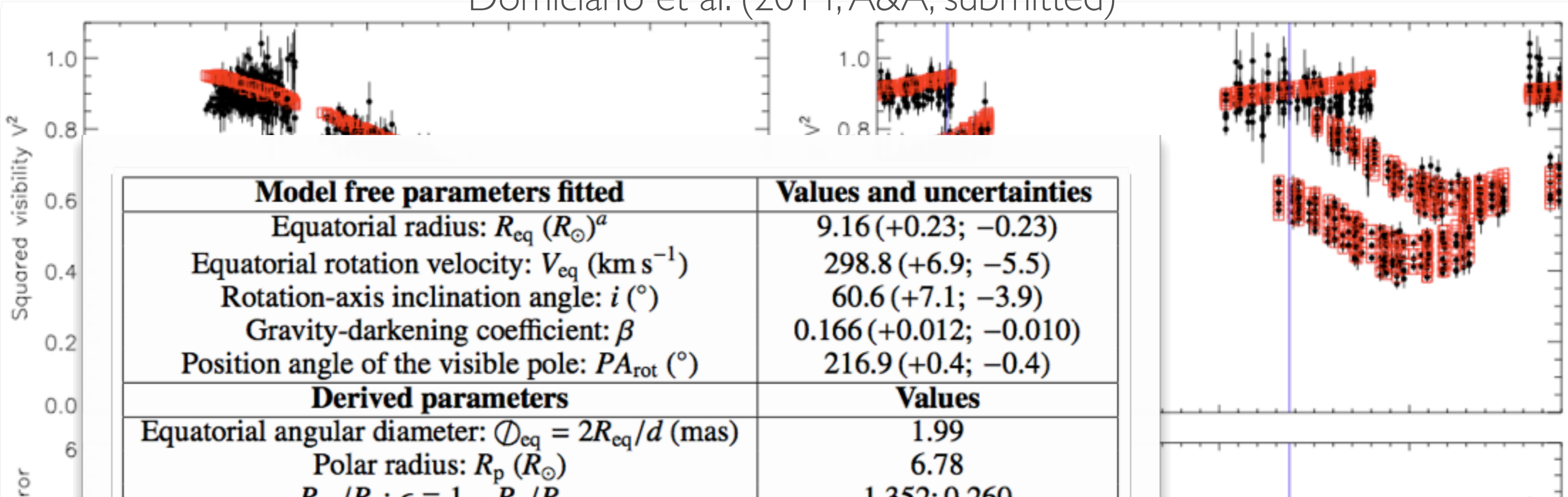
Chi2

Chi2: initial= 2.368E4 - final= 2.668E3 - sigma= 4.261E1

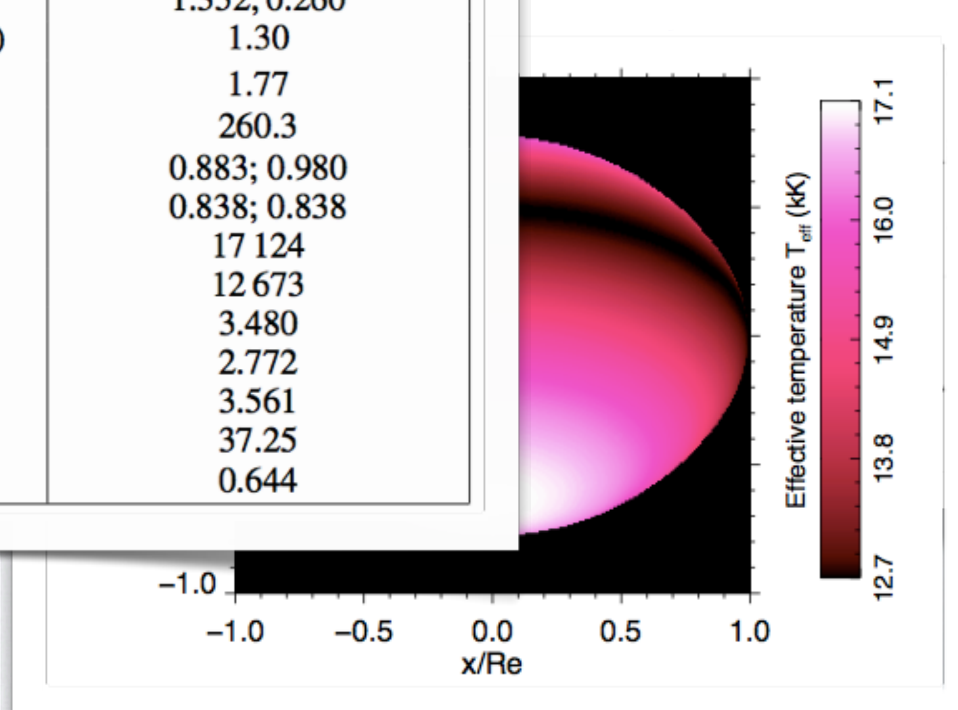
reduced Chi2: initial= 2.608E1 - final= 2.938E0 - sigma= 4.693E-2

Flattening = 1,239 +/- 0,003 : *conclusion ?*

Domiciano et al. (2014, A&A, submitted)

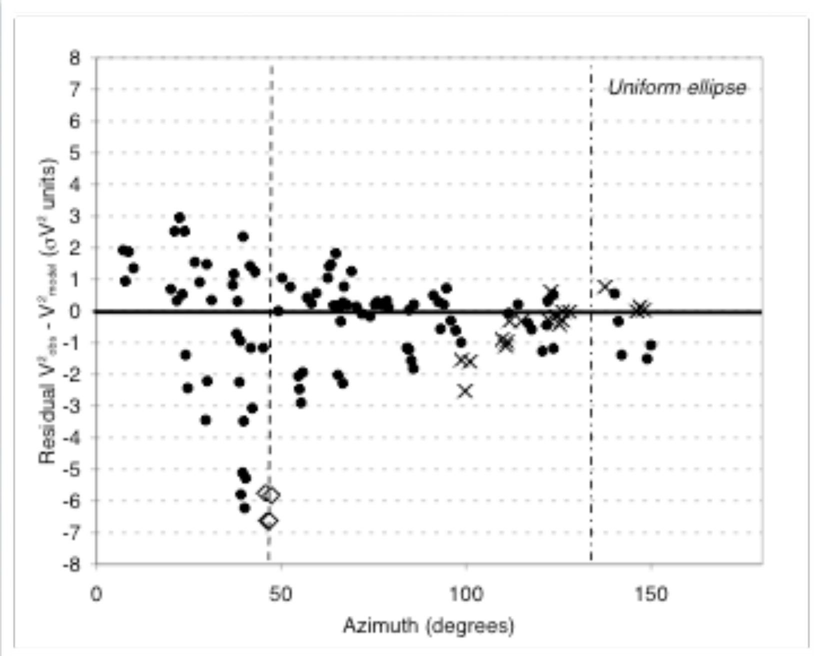


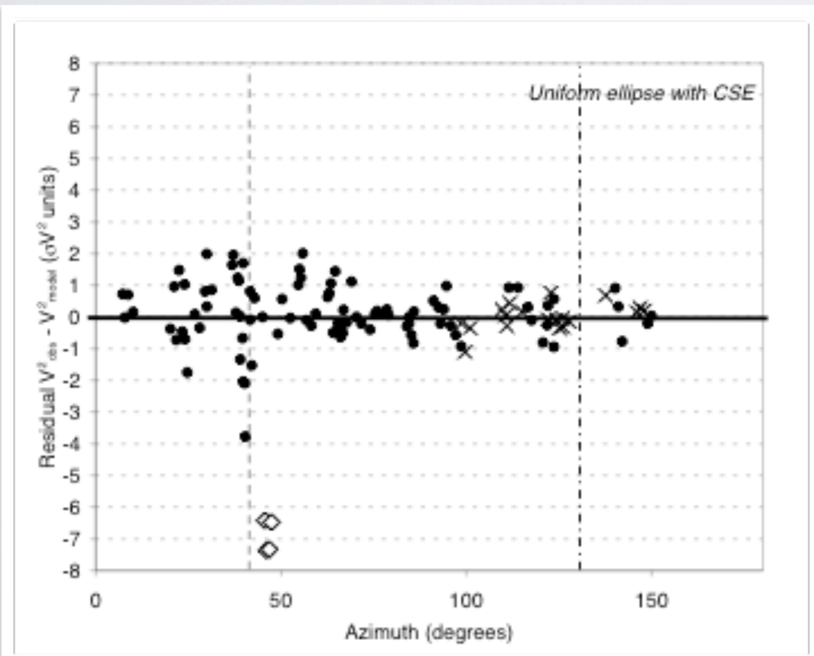
Model free parameters fitted	Values and uncertainties
Equatorial radius: R_{eq} ($R_\odot$)[a]	9.16 (+0.23; −0.23)
Equatorial rotation velocity: V_{eq} (km s^{-1})	298.8 (+6.9; −5.5)
Rotation-axis inclination angle: i (°)	60.6 (+7.1; −3.9)
Gravity-darkening coefficient: β	0.166 (+0.012; −0.010)
Position angle of the visible pole: PA_{rot} (°)	216.9 (+0.4; −0.4)
Derived parameters	**Values**
Equatorial angular diameter: $⊘_{eq} = 2R_{eq}/d$ (mas)	1.99
Polar radius: R_p ($R_\odot$)	6.78
R_{eq}/R_p; $\epsilon \equiv 1 - R_p/R_{eq}$	1.352; 0.260
Apparent flattening (major to minor axis ratio)	1.30
Mean angular diameter: $\overline{⊘}$ (mas)	1.77
$V_{eq} \sin i$ (km s^{-1})	260.3
Critical rotation rate[b]: V_{eq}/V_c; Ω/Ω_c	0.883; 0.980
Keplerian rotation rate[c]: V_{eq}/V_k; Ω/Ω_k	0.838; 0.838
Polar temperature: T_p (K)	17 124
Equatorial temperature: T_{eq} (K)	12 673
Luminosity: $\log L/L_\odot$	3.480
Equatorial gravity: $\log g_{eq}$	2.772
Polar gravity: $\log g_p$	3.561
Rotation period: P_{rot} (h)	37.25
Rotation frequency: ν_{rot} (d^{-1})	0.644

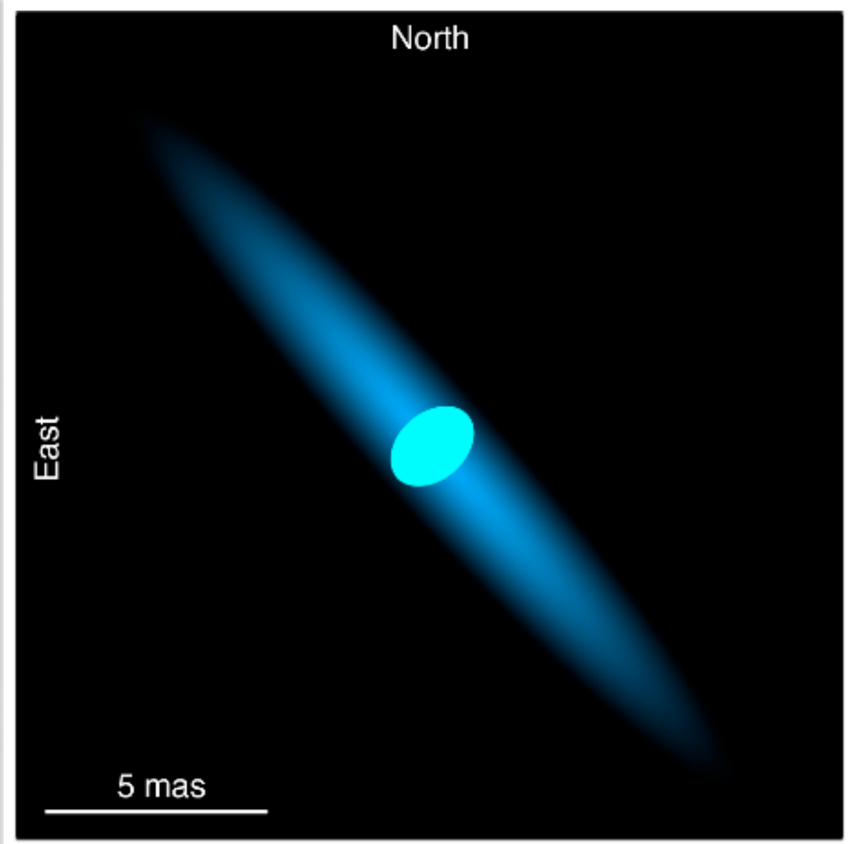


Flattening = 1,35 +/- 0,03

NEW QUESTIONS...



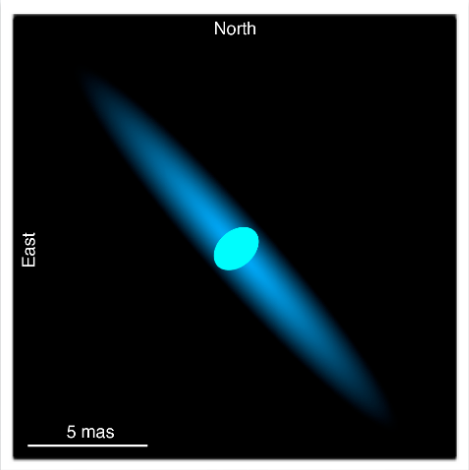


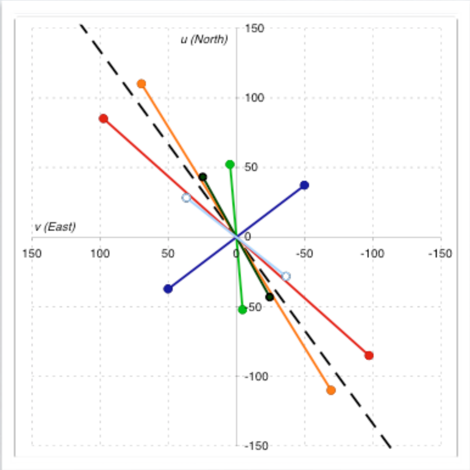


Polar envelope contributing ~5% of the total flux in K

Kervella & Domiciano 2006, A&A, 453, 1059

ACHERNAR WITH MIDI





Thermal infrared signature of the wind of Achernar

HWHM = 6 R*

Flux = 13% of the star (10 μm)