IR Interferometry of Massive Evolved Stars

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The group

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+ IOTA collaborators

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+ J.Monnier, P.Tuthill and others for segment-tilting experiment on Keck-1

+ O.Chesneau, B.Lopez for VLTI observations.

Wolf Rayet Stars

Evolved, massive (can be >40 M_{sun}), luminous (10^5 - 10^6 L_{sun}) stars

Spectrum shows helium and broad wind emission lines: Carbon (for subtype WC) and Nitrogen (subtype WN)

Massive winds (10^{-5} to 10^{-4} M_{sun}) per year

Rough evolutionary scenario:

Massive O → Luminous Blue Variable (LBV)? → Late WN (hydrogen) → Early WN (no hydrogen) → WN+WC → WC → Supernova.

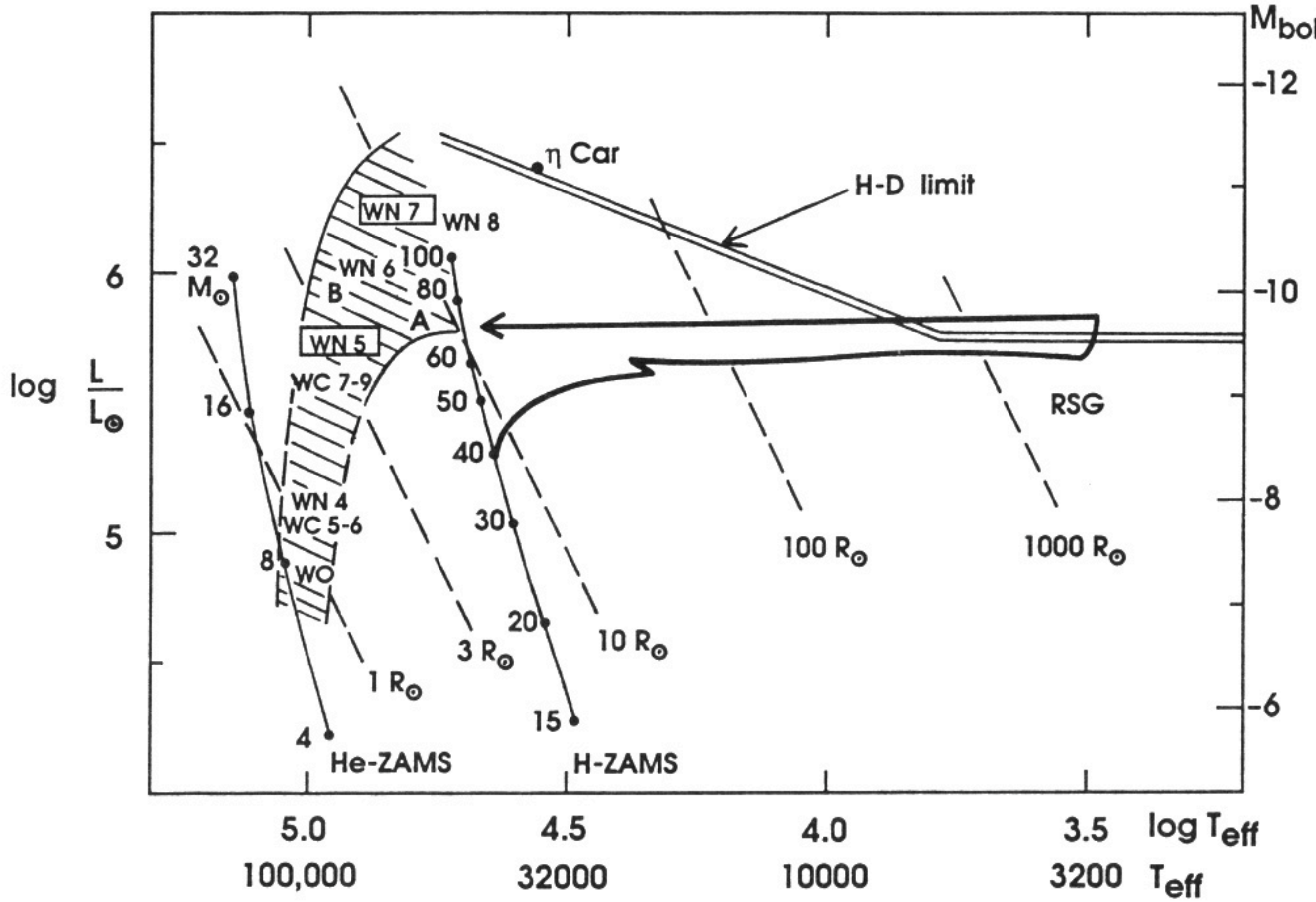
Program

High resolution IR interferometry of WRs in two stages of evolution where they produce dust.

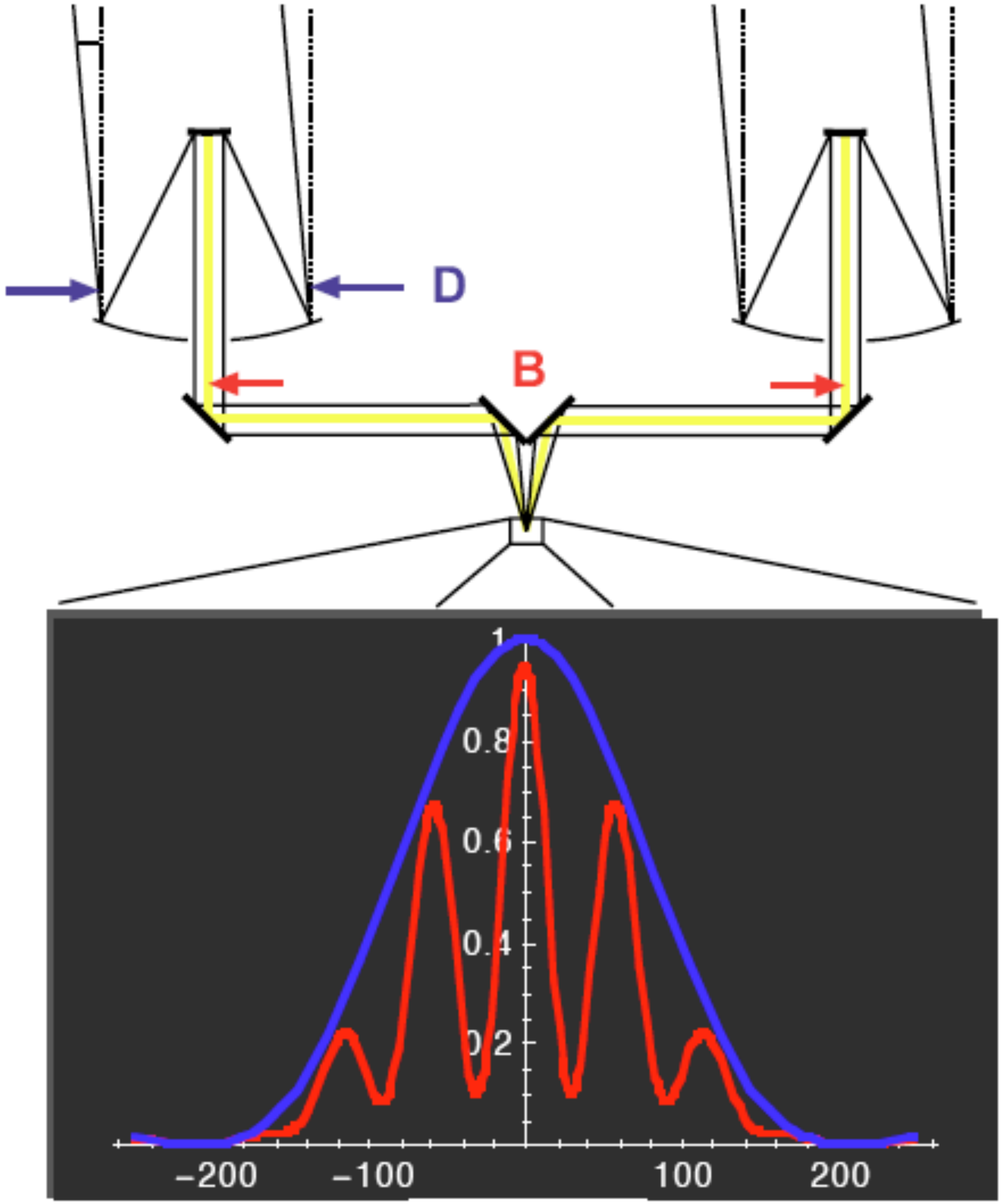
1) Late type WC stars. Periodic (e.g. WR 140, WR 137) and persistent (WR 106, WR 95) dust producers. Mounting evidence for colliding-wind binaries.
2) Post-LBV WN transition(?) stars and post-LBVs. WR 122: Central object obscured in a dust-cocoon. Nature unclear.

Goals: Get mid IR sizes of dust shells for post-LBV and persistent WCs and binary parameters for periodic WCs

WR evolution



Moffat '89



A.Glindemann
VLTI website

Interferometry

Generalized interferogram (fringe!):

$I = P_1 + P_2 + 2\sqrt{P_1}\sqrt{P_2}\, \mu\, \mathrm{Cos}(2\pi\sigma x + \phi)$

Measurables:

1) Visibility amplitude μ i.e. fringe contrast
2) Visibility phase ϕ i.e. fringe position

Visibility at any given baseline (u,v point) measures one Fourier component of the object brightness distribution.

Closure phase

- In the sum of the three phases the random fluctuation is eliminated:

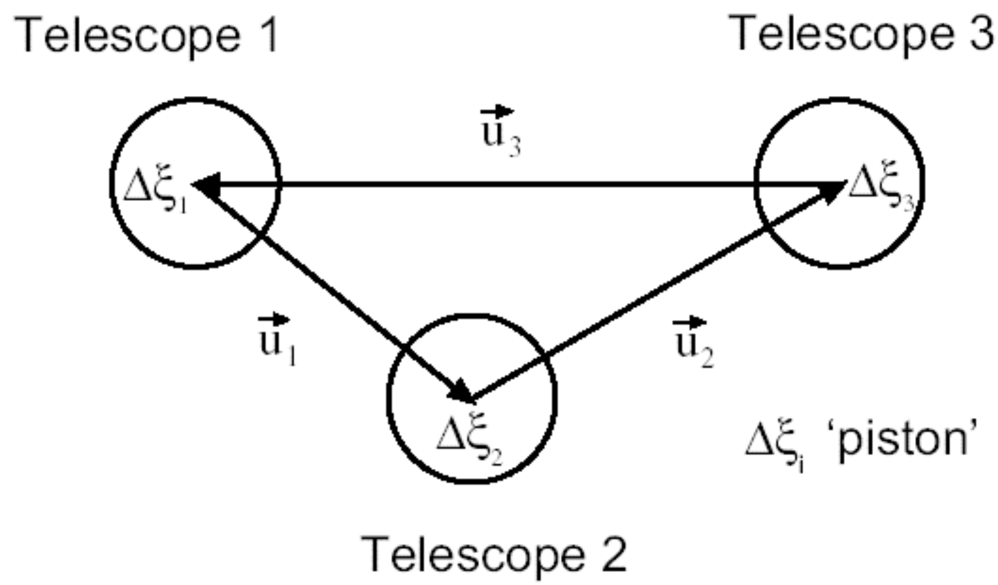
  $\psi_1 (u_1) = \phi_1 (u_1) + \Delta\xi_1 - \Delta\xi_2$

  $\psi_2 (u_2) = \phi_2 (u_2) + \Delta\xi_2 - \Delta\xi_3$

  $\psi_3 (u_3) = \phi_3 (u_3) + \Delta\xi_3 - \Delta\xi_1$

  $\psi_1 + \psi_2 + \psi_3 = \phi_1 + \phi_2 + \phi_3$

- Many baselines required to determine individual phases.
- The exposure time is limited, again by the individual fringe motion..



From A.Glindemann
VLTI website

Instruments used

Mid IR

- Very Large Telescope Interferometer (VLTI) (Mid IR, fringes dispersed 8-13 mu). 8m telescopes. We used one baseline. ~10 mas resolution. Sensitivity ~ 1 Jy.
- Keck Single Aperture 'Segment-Masking' (Mid IR, 10.7 mu). Resolution ~ 40 mas. Sensitivity of a few Jy.

Near IR

- Infrared-Optical Telescope Array (IOTA) (Near IR, H). Three 0.5 m telescopes. ~5 mas resolution. Sensitivity H mag 7
- Keck Interferometer (KeckI) (Near IR, K). Resolution ~ 5 mas.

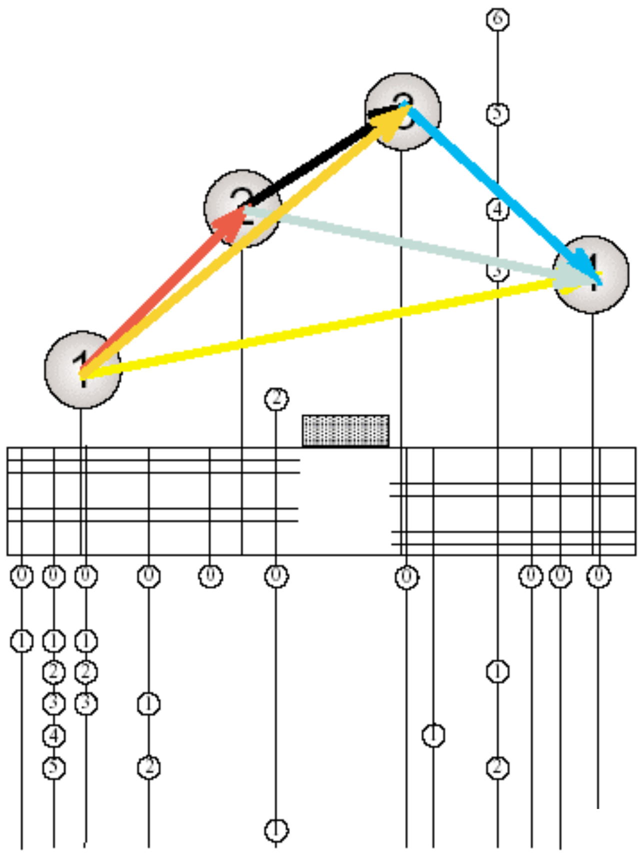
VLTI Study of WRs

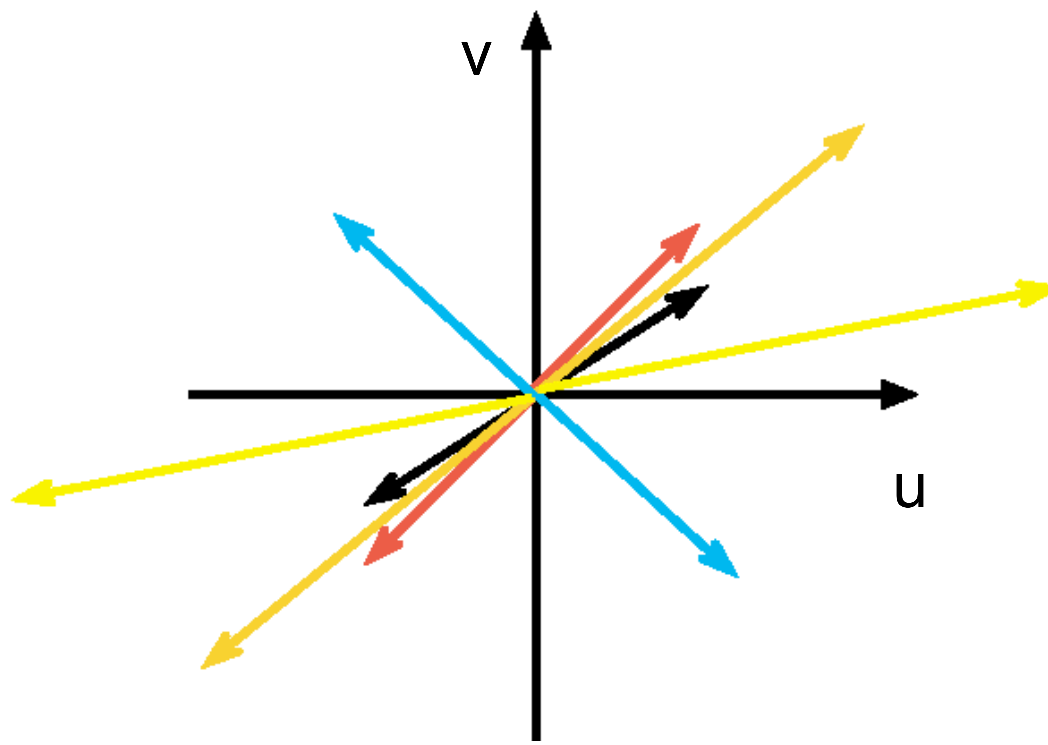
- VLTI (mid IR):

  WR 122 -> Suspected post LBV- early WN star.

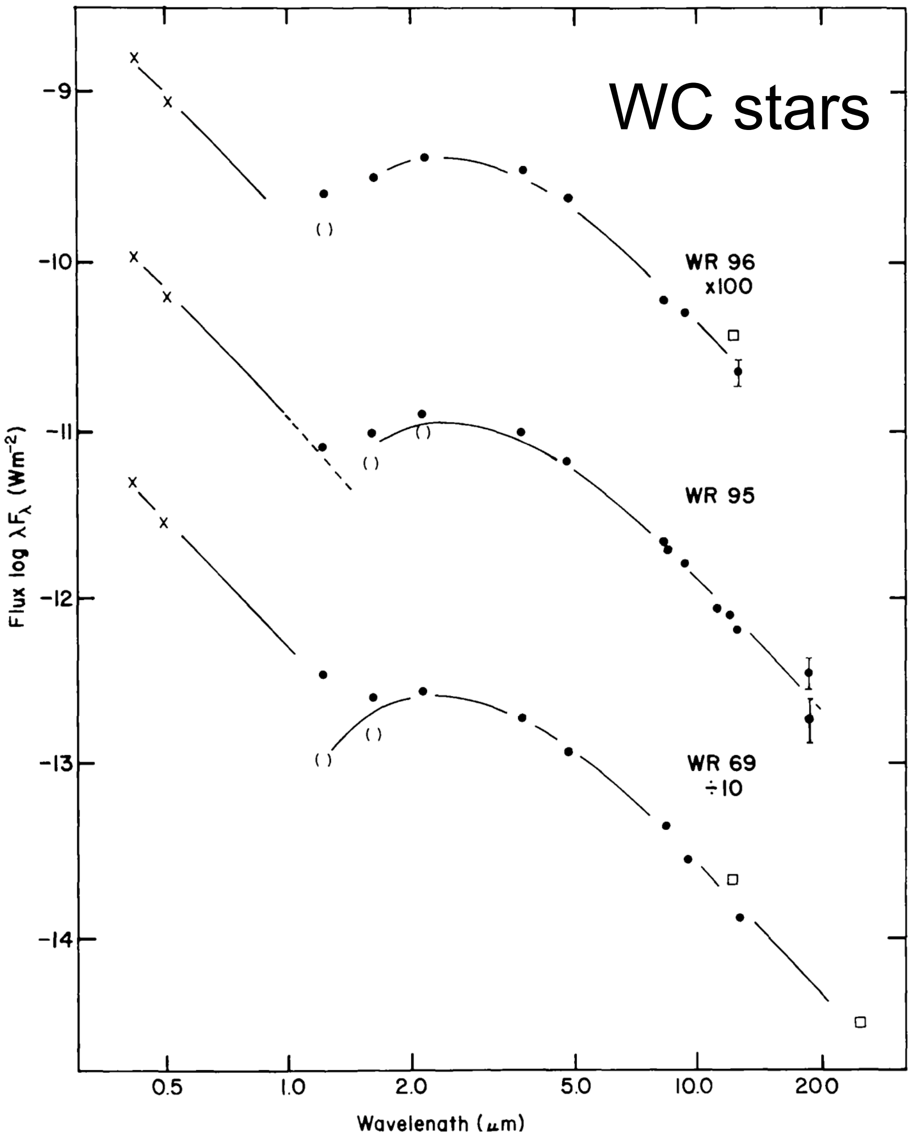
  WR 106, WR 95 -> Late type persistently dusty WCs. Aim: Resolve sizes of dust shells.

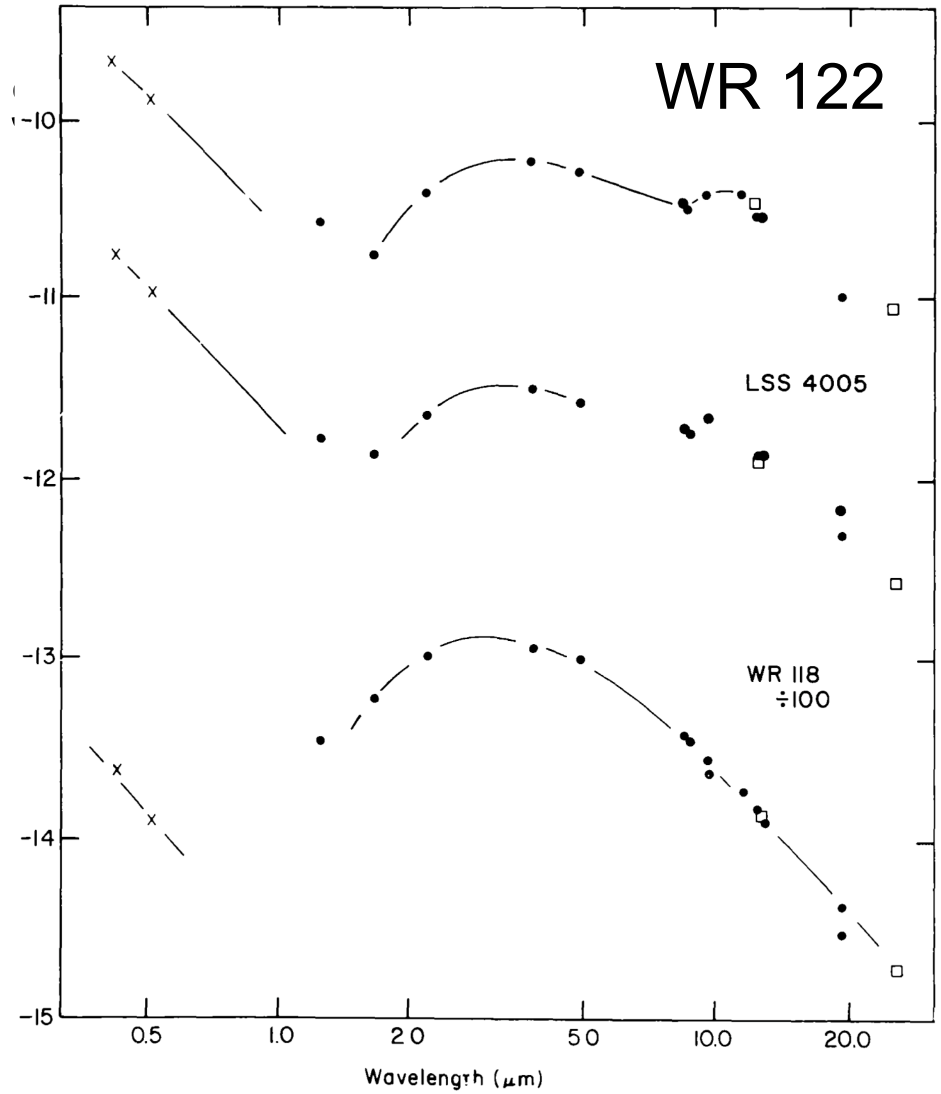
VLTI telescope configuration





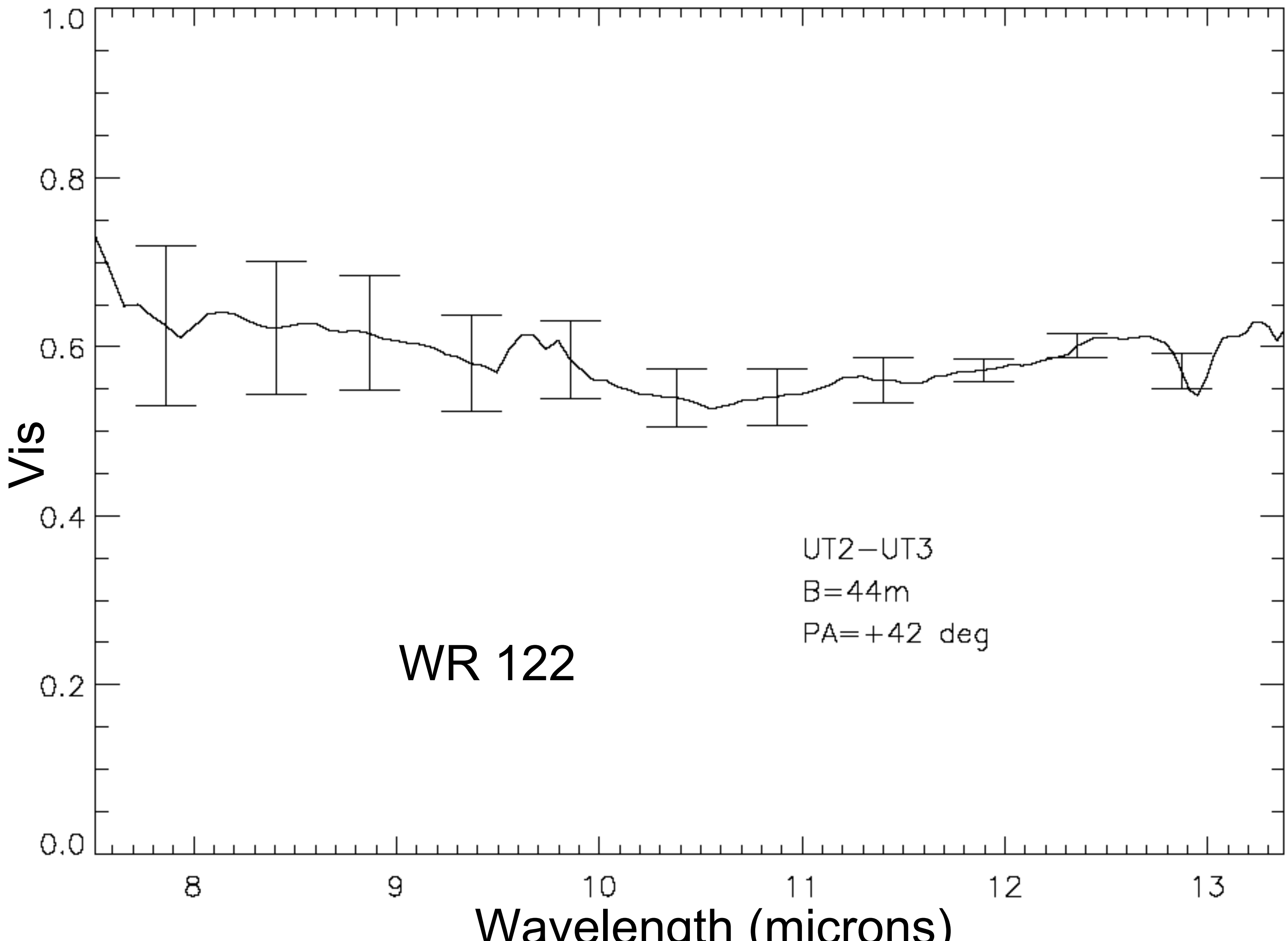
IR spectra



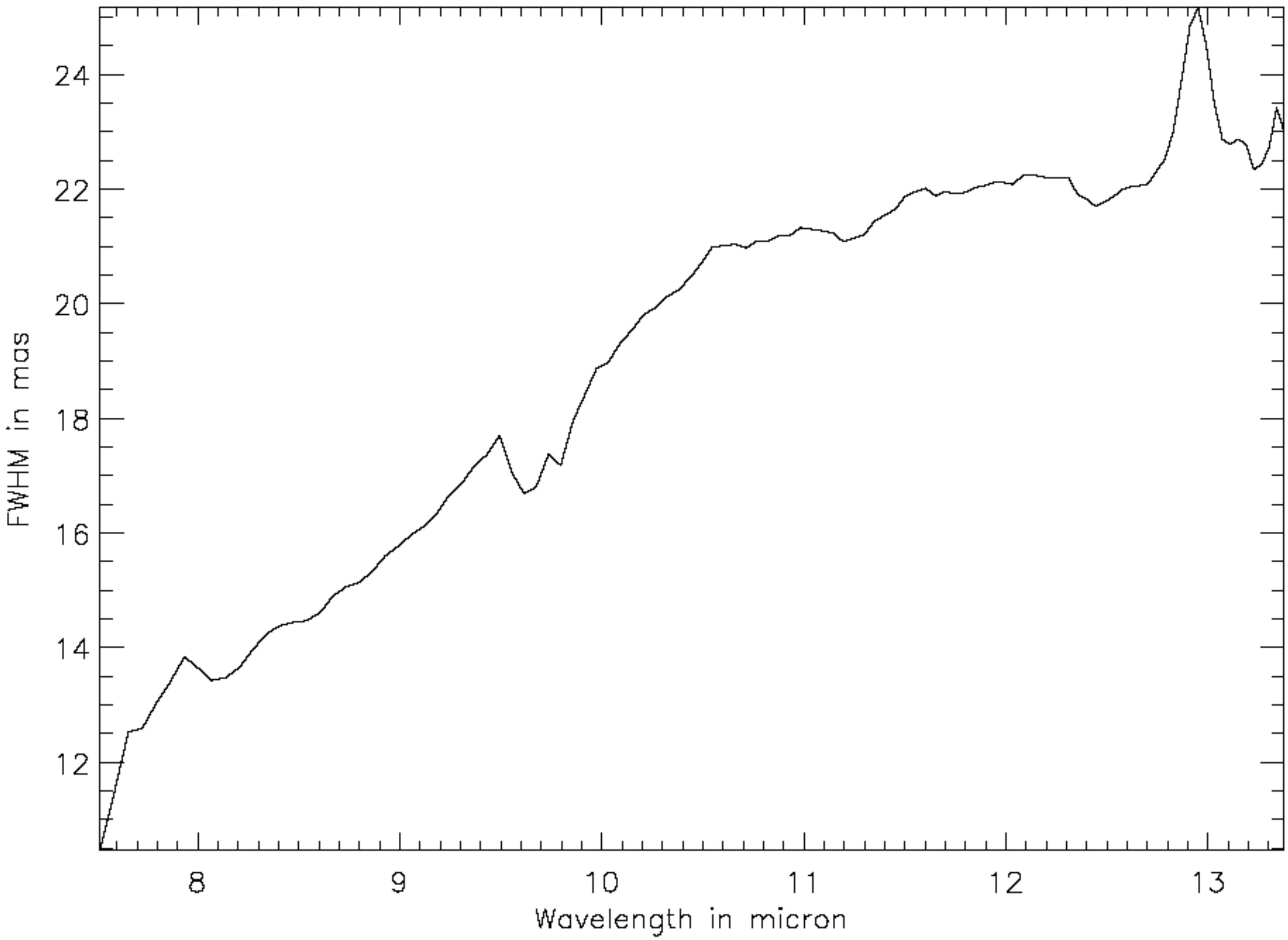


Williams et al. '87

VLTI: WR 122 visibilities



WR 122: Gaussian size



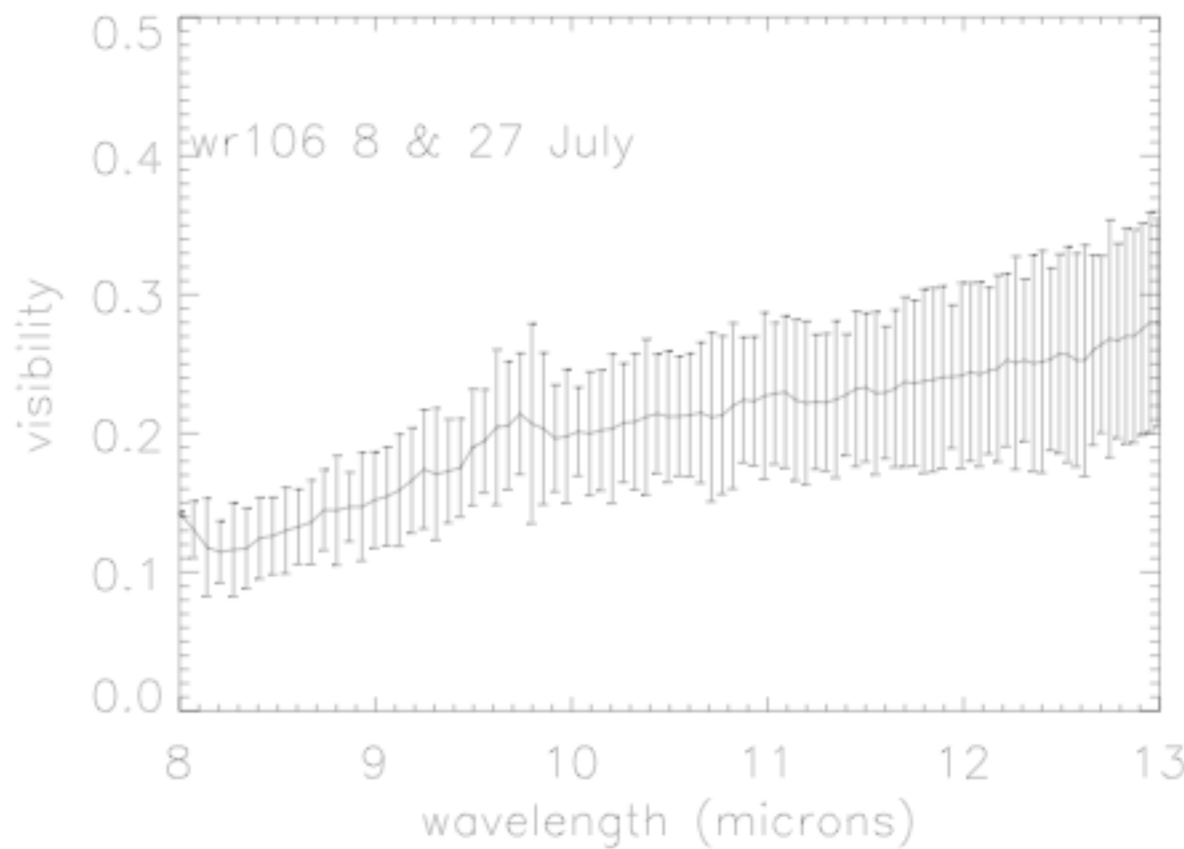
WR 122 Results

- Well resolved at 45 m baseline
- Size increases with wavelength. Hotter dust close to the star with cooler extended material
- No spectral features seen (silicates absent?)

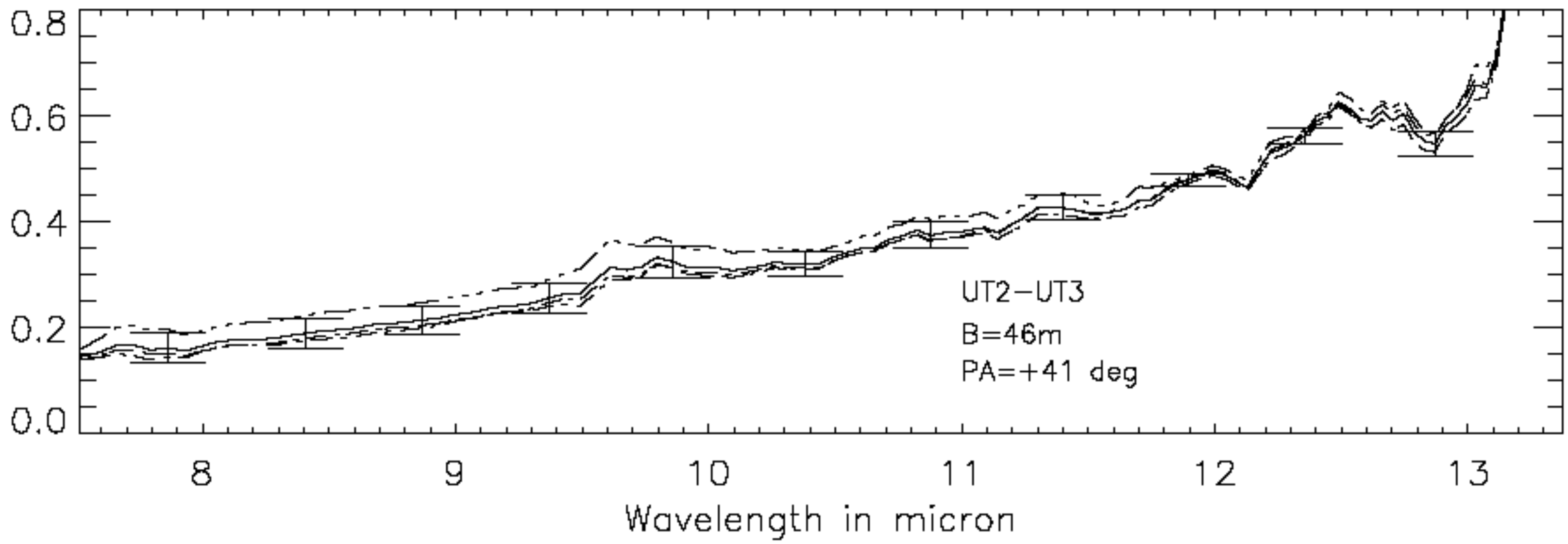
The WC stars

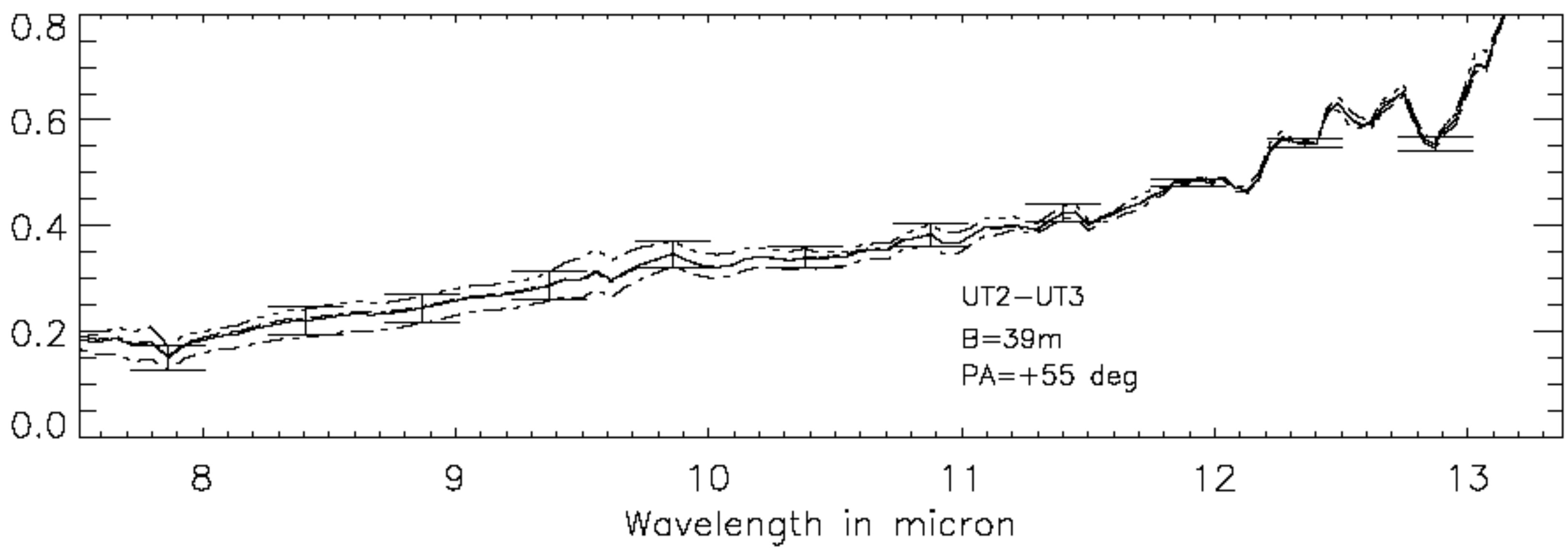
- WR 106, WR 95.
- Persistent dust
- Extensive long term IR spectroscopy (e.g. Williams et al. ‘87).
- SED based models try to estimate dust shell sizes and dust mass
- WR 104, WR 98a are similar stars now known to be binaries from aperture-masking

VLTI: WR 106 visibilities

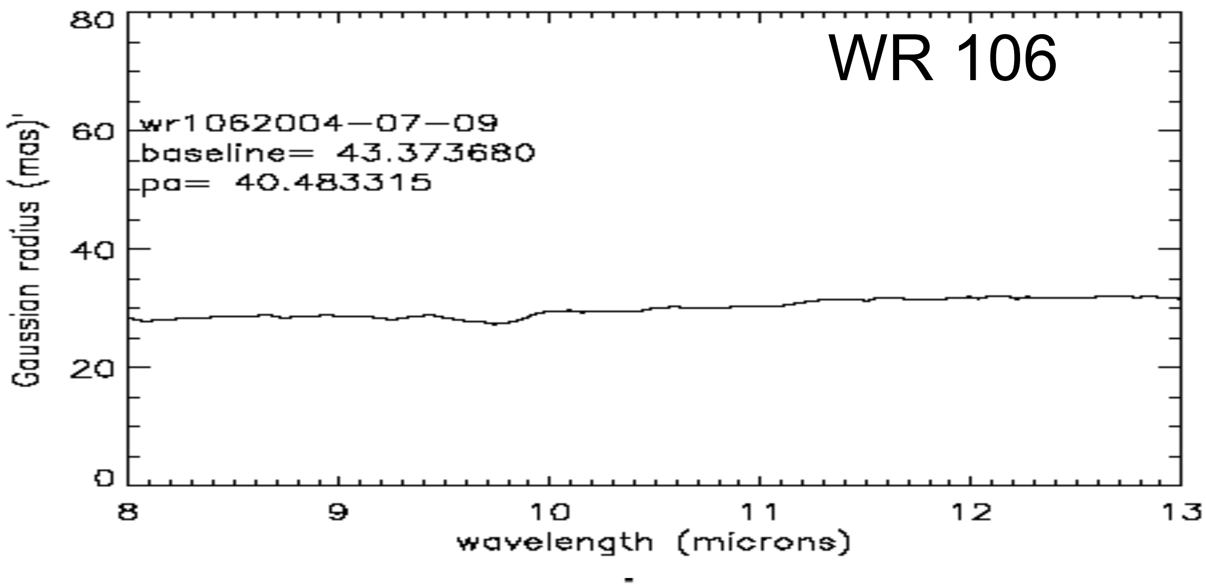


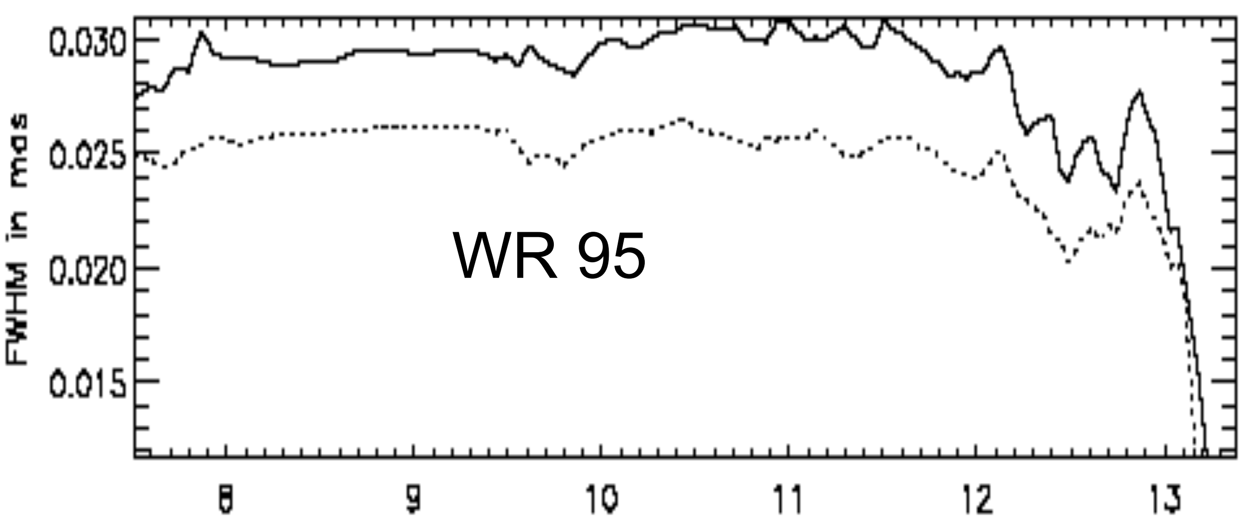
VLTI: WR 95 visibilities





WR 106, 95: Sizes





The WC stars: VLTI results

- Both WR 95 and WR 106 are well resolved
- Unlike WR 122, both show fairly constant size with wavelength. Maybe indicative of material in a disc or ring. Modeling will require further (u,v) sampling.
- No spectral features in visibility. Strengthens case for amorphous carbon dust in late type WCs.
- Sizes indicate current SED-base models could be over-estimating the extent of dust.

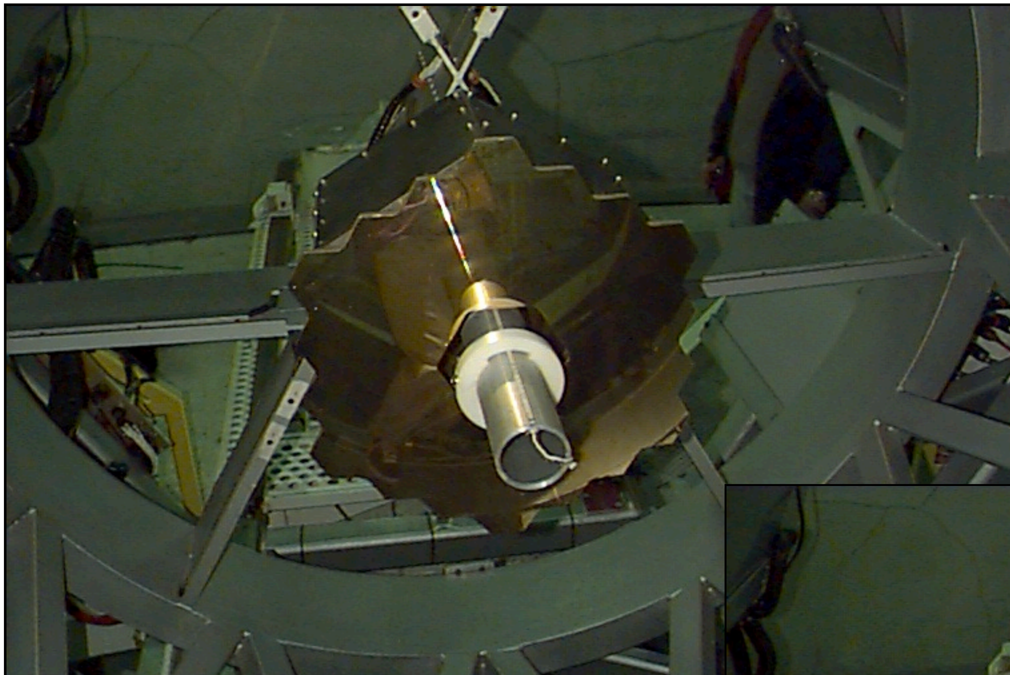
VLTI Results Summary

	Angular size (mas)	Distance (Kpc)	Linear size (AU)	Modeled radius of inner edge (thickness) Williams et al '87
WR 106	28 (flat)	2.3	~65	20 (x30)
WR 95	25-30	2.0	~50	28 (x3)
WR 122	12-22	1-3	22-66	none
WR 31b	<10 (unresolved)	6.1		none

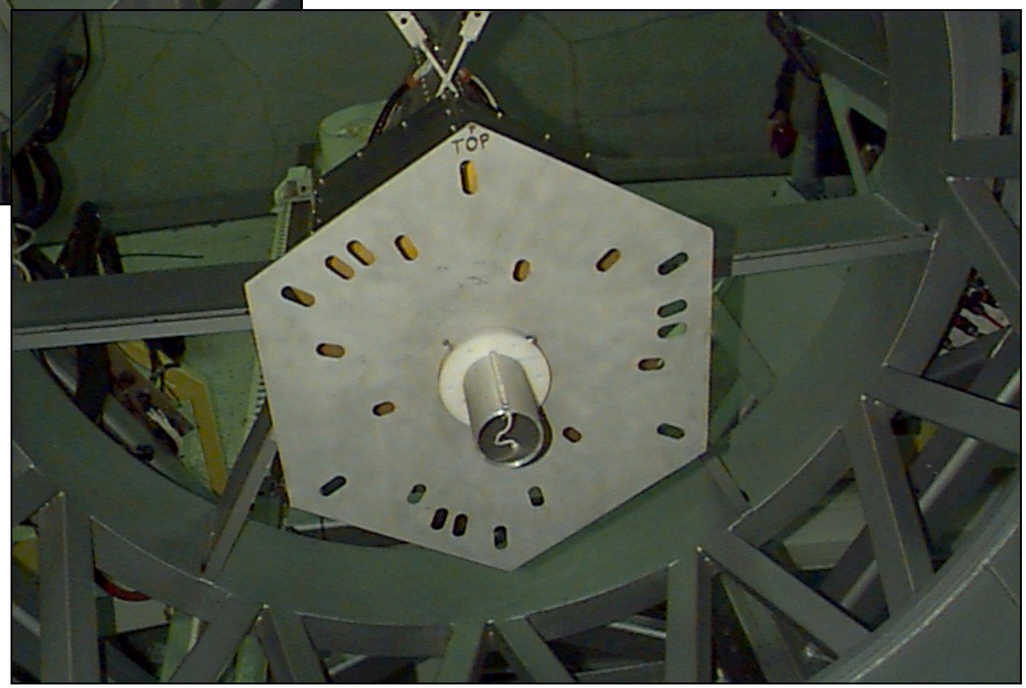
Keck Segment Tilting experiment
(Monnier, Tuthill)

- WR 122 (post-LBV) and WR 106 (WC)
- Achieves “aperture-masking” in the mid IR (10 microns), using the LWS camera on Keck1
- Tilt (and piston) sets of segments to form non-redundant sub-apertures
- Each sub-aperture forms a speckle pattern on the LWS chip
- Analyze the speckle power spectrum to get the visibility modulus and closure phases.

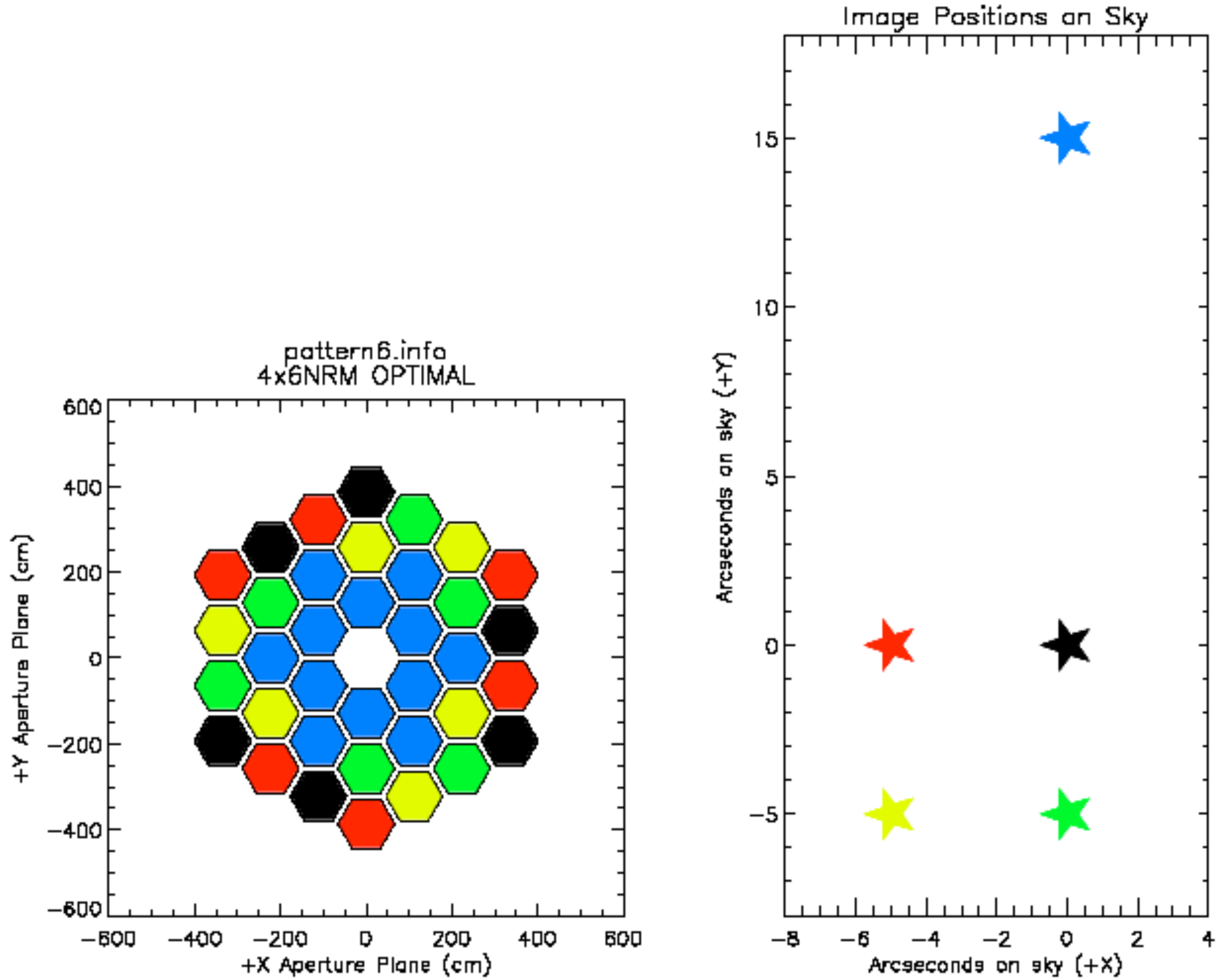
Installation of the Aperture Mask on the Keck I IR Secondary

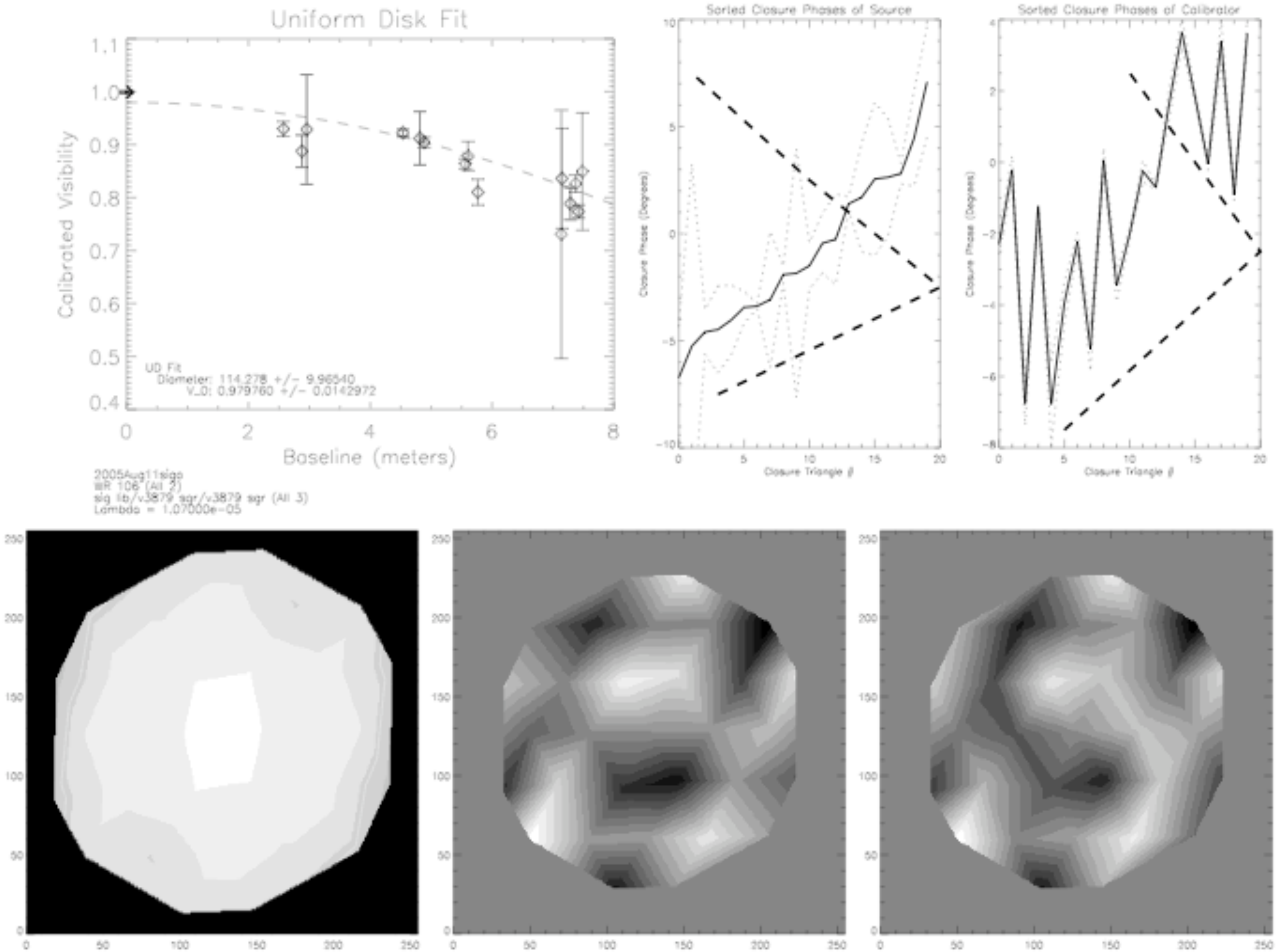


IR Secondary Mirror of Keck I Telescope, with Aperture Masking support stalk installed.



IR Secondary with 21 Hole Golay Aperture Mask installed on support stalk. Note collars prevent mask from falling off and from touching secondary mirror.


pattern6.info
4x6NRM OPTIMAL
+Y Aperture Plane (cm)
+X Aperture Plane (cm)
-600
-400
-200
0
200
400
600
Image Positions on Sky
Arcseconds on sky (+Y)
Arcseconds on sky (+X)
-8
-6
-4
-2
0
2
4
-5
5
10
15



Uniform Disk Fit
Calibrated Visibility
Baseline (meters)
UD Fit
Diameter: 114.278 +/- 9.96540
V_0: 0.979760 +/- 0.0142972
Sorted Closure Phases of Source
Closure Phase (Degrees)
Closure Triangle #
Sorted Closure Phases of Calibrator
Closure Phase (Degrees)
Closure Triangle #
2005Aug11sigo
WR 106 (All 2)
sig lib/v3879 sgr/v3879 sgr (All 3)
Lambda = 1.07000e-05

Segment-tilting results

Observed one target from each class of our VLTI sample

- WR 106 (WC 9 star) is resolved.
- Size is bigger than expected from the VLTI data. Clear evidence for an extended component (resolved out in the VLTI measurement).
- Simple model fits indicate either:

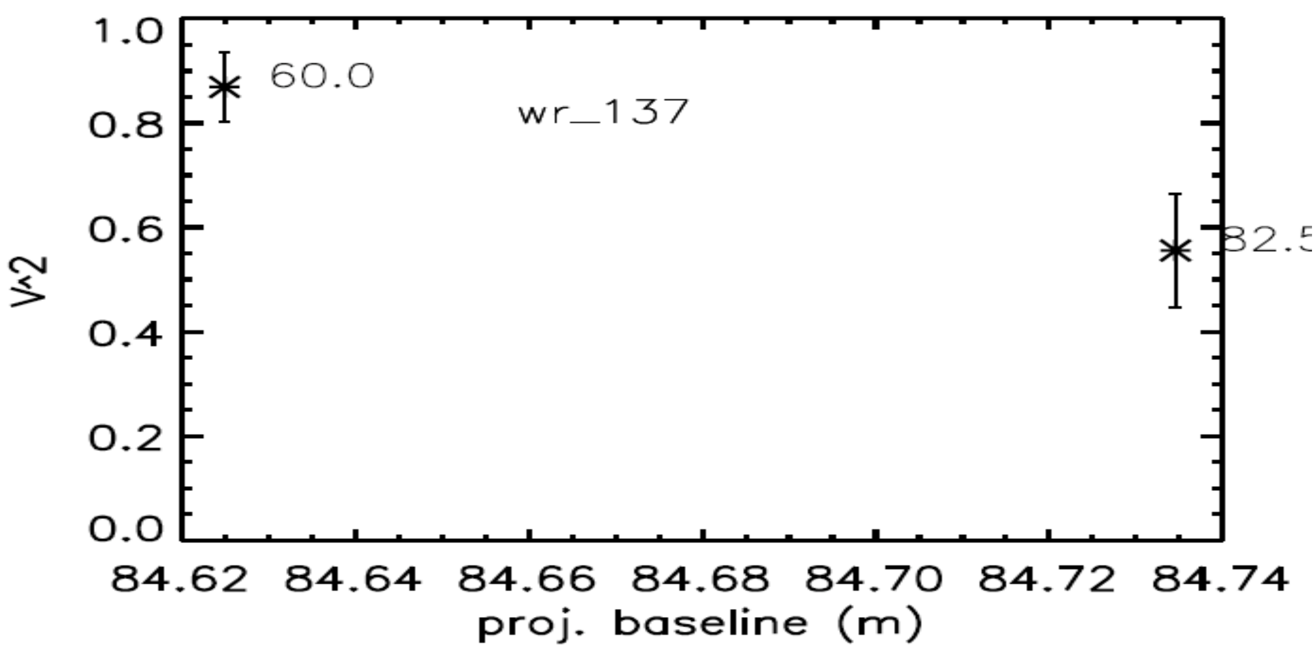
  point source + Gaussian of ~65 mas FWHM

  OR

  Gaussian of ~ 180 mas FWHM
- No asymmetry detected. Closure phases are zero.
- WR 122 (LBV-transition) star was unresolved.

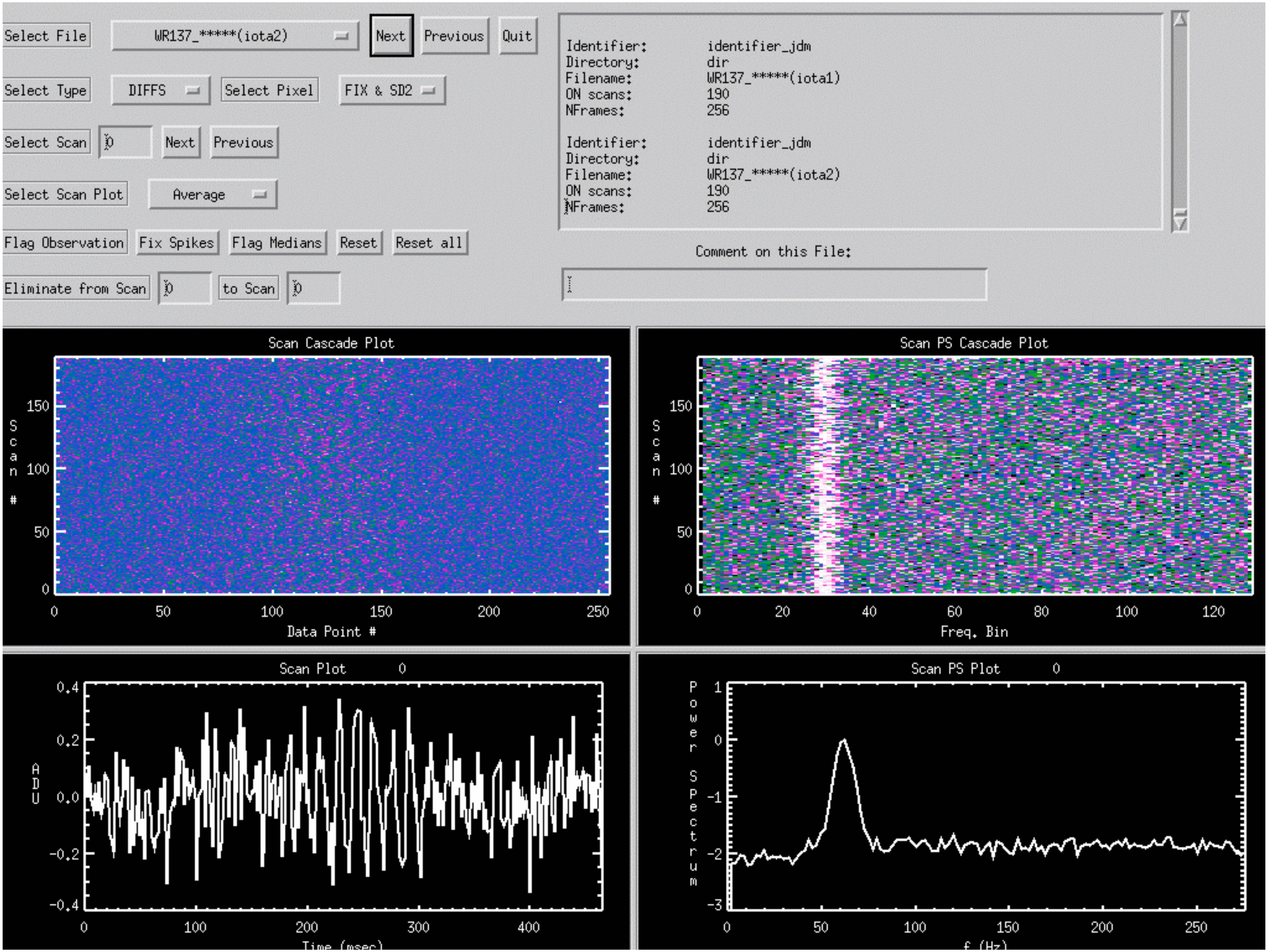
Keck-I and IOTA program

- Late type dusty WC stars, WR 140 and WR 137
- "Periodic" dust: Very long period WR -O star binary systems: dust formed in wind-collision zone. e.g. WR 140 which has fairly well known spectroscopic orbit.
- WR 137 is not a confirmed spectroscopic binary.



Keck-I,

Aug 2003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WR137_*****(iota2)
Next
Previous
Quit
Select Type
DIFFS
Select Pixel
FIX & SD2
Select Scan
Next
Previous
Select Scan Plot
Average
Flag Observation
Fix Spikes
Flag Medians
Reset
Reset all
Eliminate from Scan
to Scan
Identifier: identifier_jdm
Directory: dir
Filename: WR137_*****(iota1)
ON scans: 190
NFrames: 256
Identifier: identifier_jdm
Directory: dir
Filename: WR137_*****(iota2)
ON scans: 190
NFrames: 256
Comment on this File:
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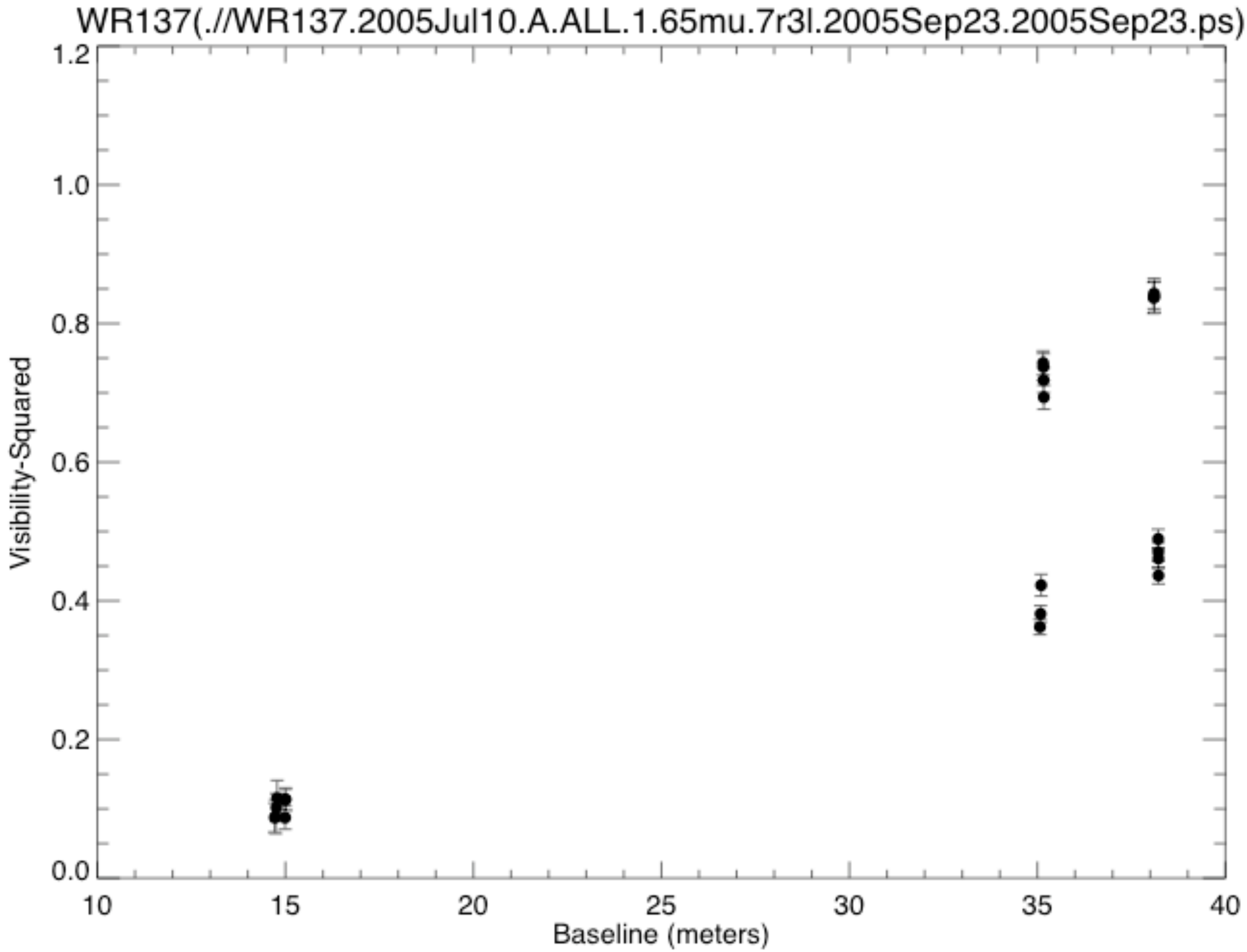
Scan #
Data Point #
Scan PS Cascade Plot
Freq. Bin
Scan Plot 0
ADU
Scan PS Plot 0
Power Spectrum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Visibility-Squared
Baseline (meters)
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0.2
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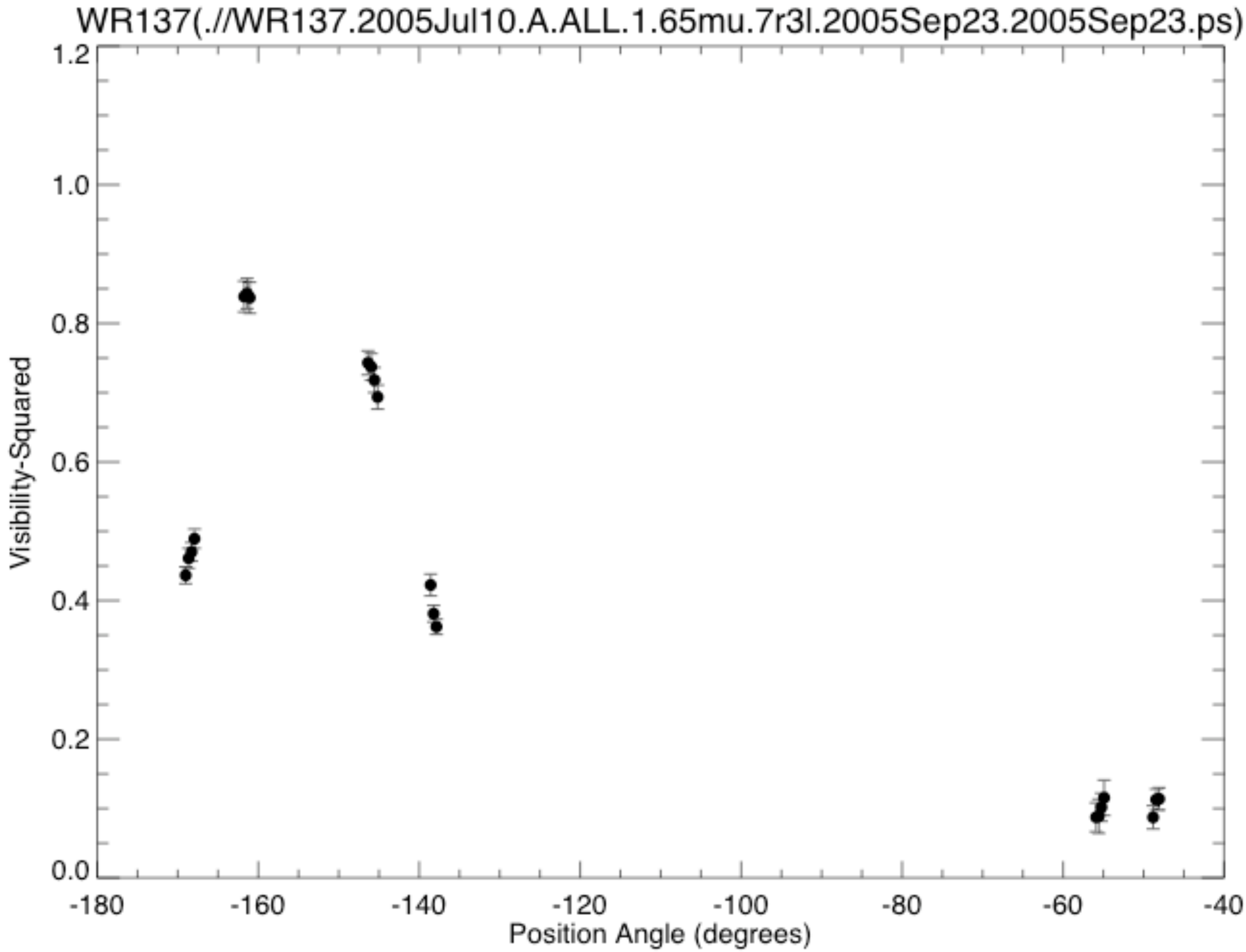
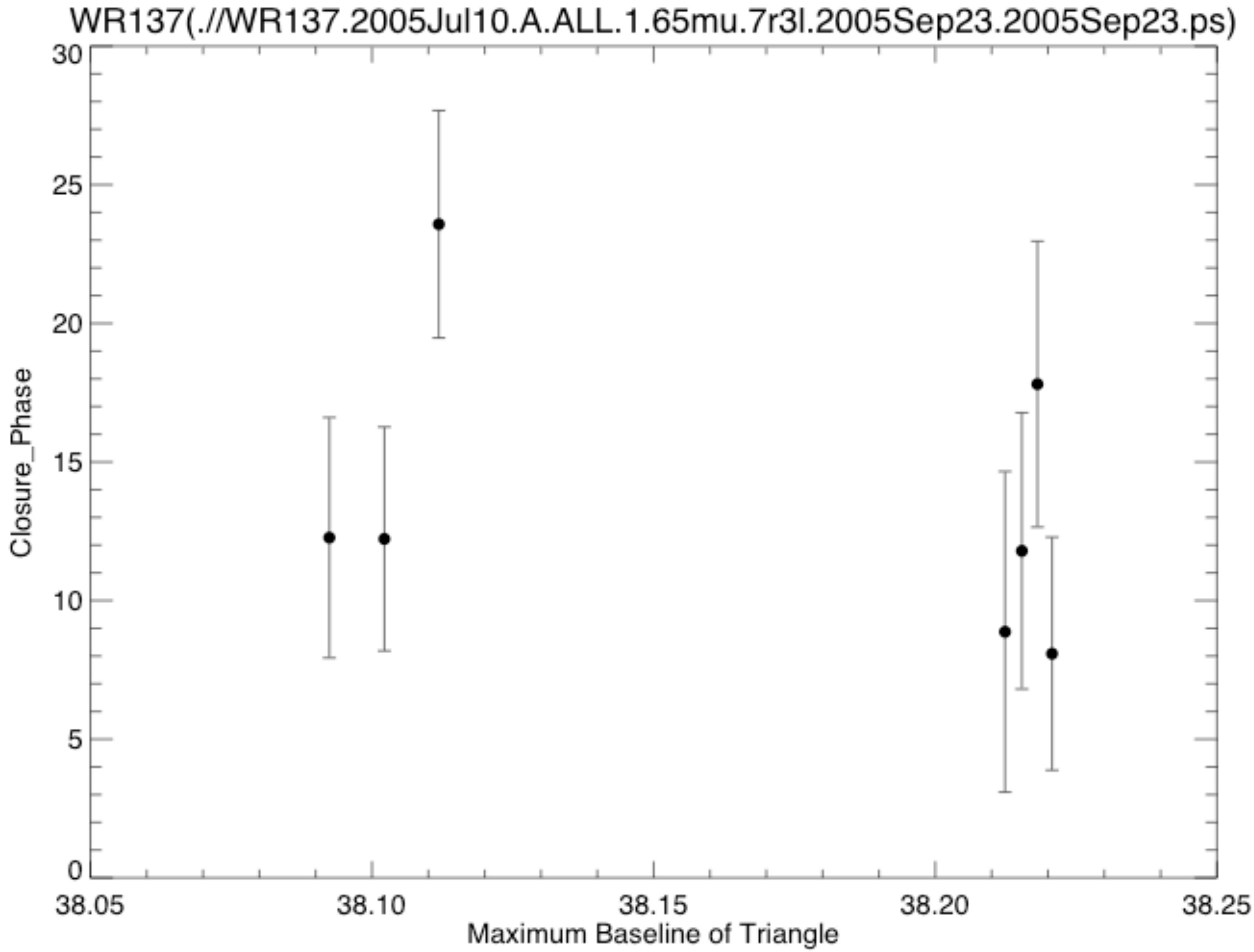
1.2
10
15
20
25
30
35
40



WR137(.//WR137.2005Jul10.A.ALL.1.65mu.7r3l.2005Sep23.2005Sep23.ps)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Visibility-Squared
-180
-160
-140
-120
-100
-80
-60
-40
Position Angle (degrees)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Closure_Phase
Maximum Baseline of Triangle
0
5
10
15
20
25
30
38.05
38.10
38.15
38.20
38.25

WR 137: binary parameters

- Used our Jul 10 ’05 data and Monnier’s Jun 15 ’05 data.
- Separation (mas) : 9.8 (0.6)
- Intensity Ratio : 0.81 (0.2)
- Position Angle (deg E of N, bright to faint) : 295 (1.3)
- The non-zero closure phase helps determine the position angle.

IOTA results summary

- Resolved WR 137 binary. "Static" separation, flux ratio and PA known.
- First time that this system has been resolved.
- Only the second WR + O star binary (after WR 140) to have been resolved.
- Will be able to constrain dust-formation scenario.
- IOTA + Keck-I data + Radial velocities could yield a full astrometric orbit with inclination, masses and distance.

To conclude…

- We have measured for the first time the mid IR sizes of dusty Wolf-Rayet stars. Further u,v sampling (more baselines) will be required for any detailed modeling. Simple models can check consistency with existing SED-bases models of dust extent, mass.
- WR 137 has been resolved into a binary system. We're working on fitting an astrometric orbit.

End