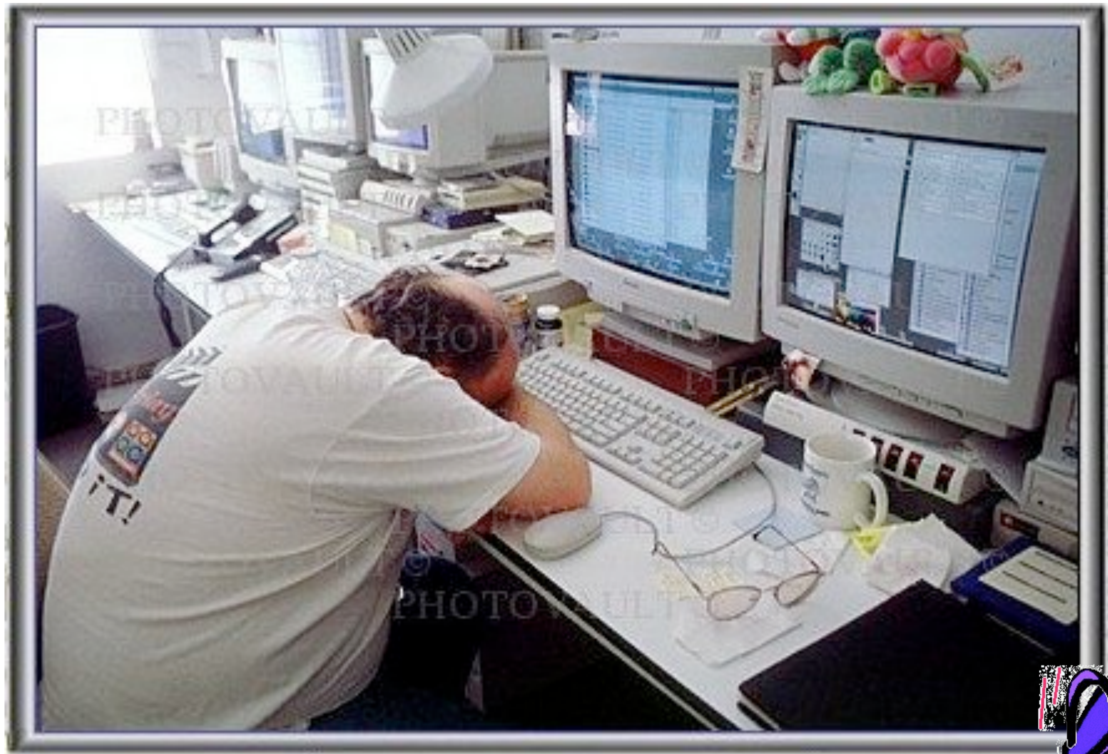
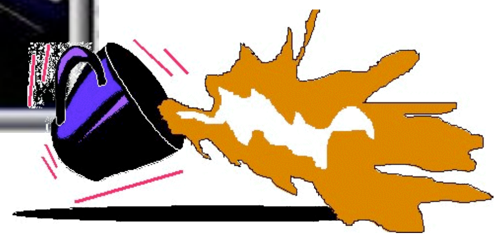
Good Morning !





An introduction to the VLT Interferometer

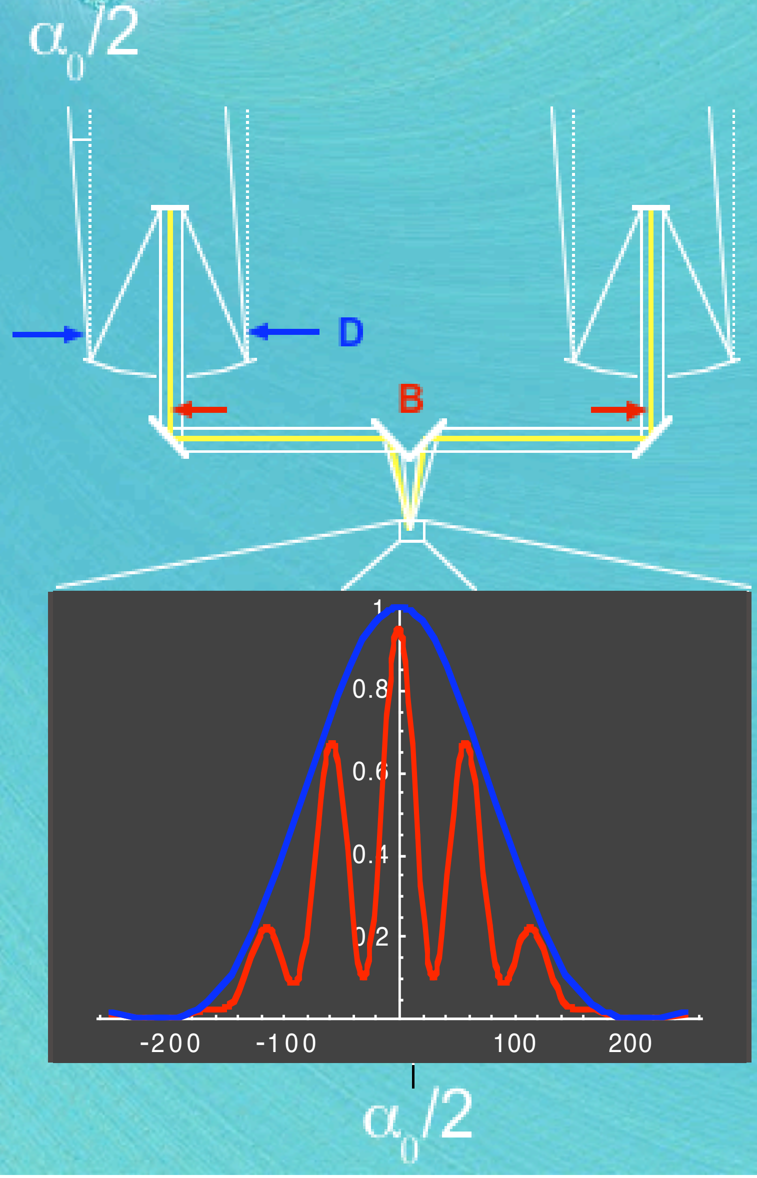
A. Richichi – ESO Garching

List of topics

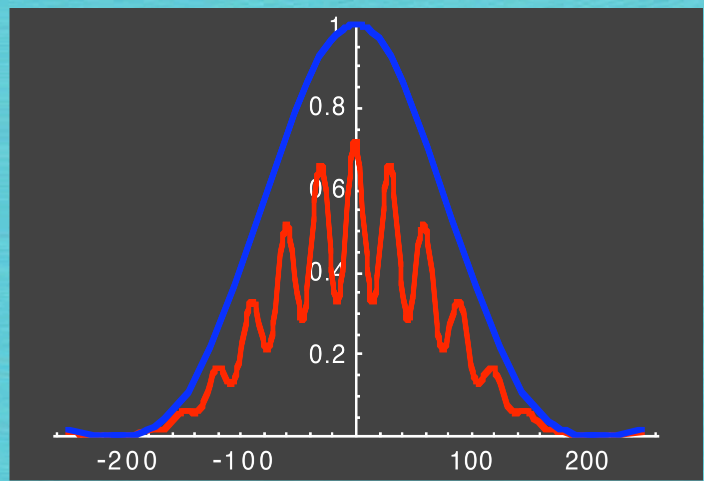
-
- A few notions about interferometry
- What interferometers look like, and where they are
- A tour of the VLTI
- What is an interferometer good for? Some science with the VLTI

-
- Future developments
- VLTI Data and Analysis
- Where are the data?
- How to get your own data

Michelson Stellar Interferometer

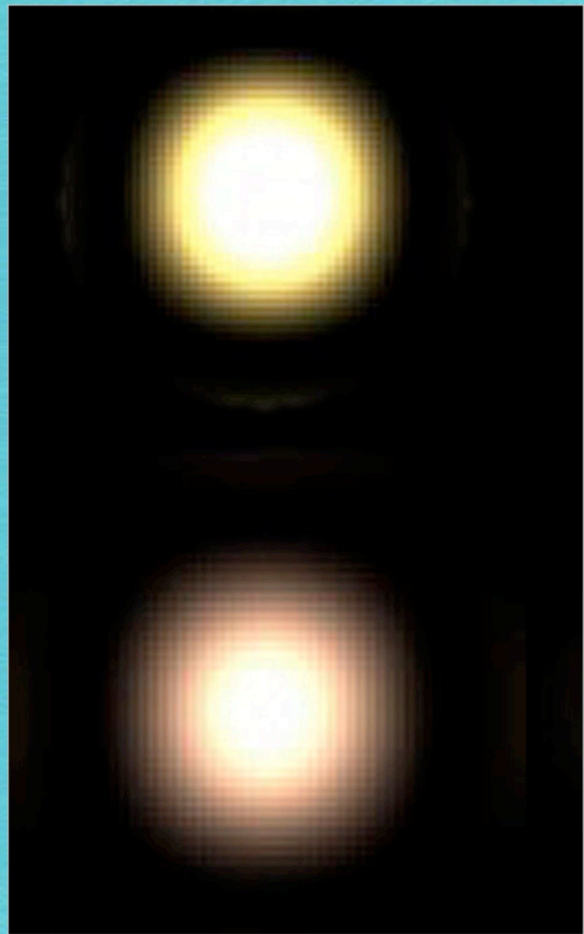


- Stellar source with angular size α_0
- Add fringe patterns (i.e. intensities) between $\pm\,\alpha_0/2$
- Resulting fringe pattern shows reduced contrast.
- Reduced contrast depends on B – and on α_0 .

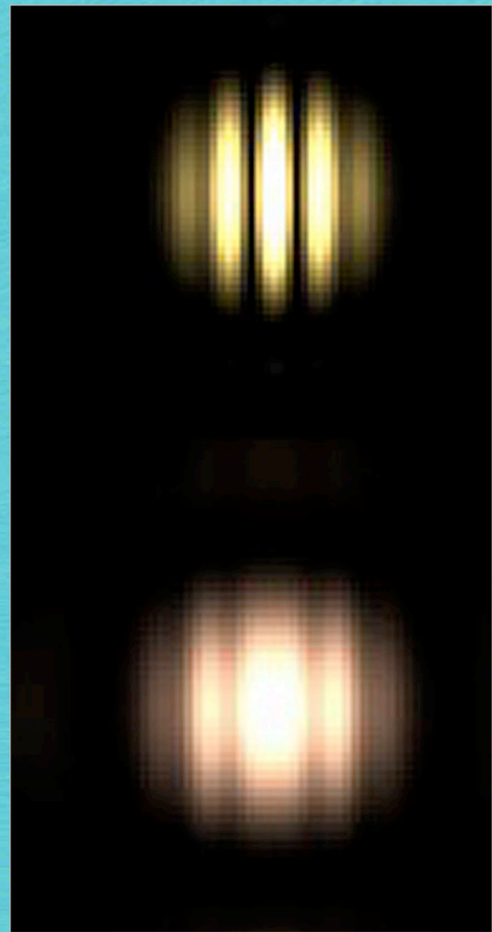


Interferometry at work

Objects

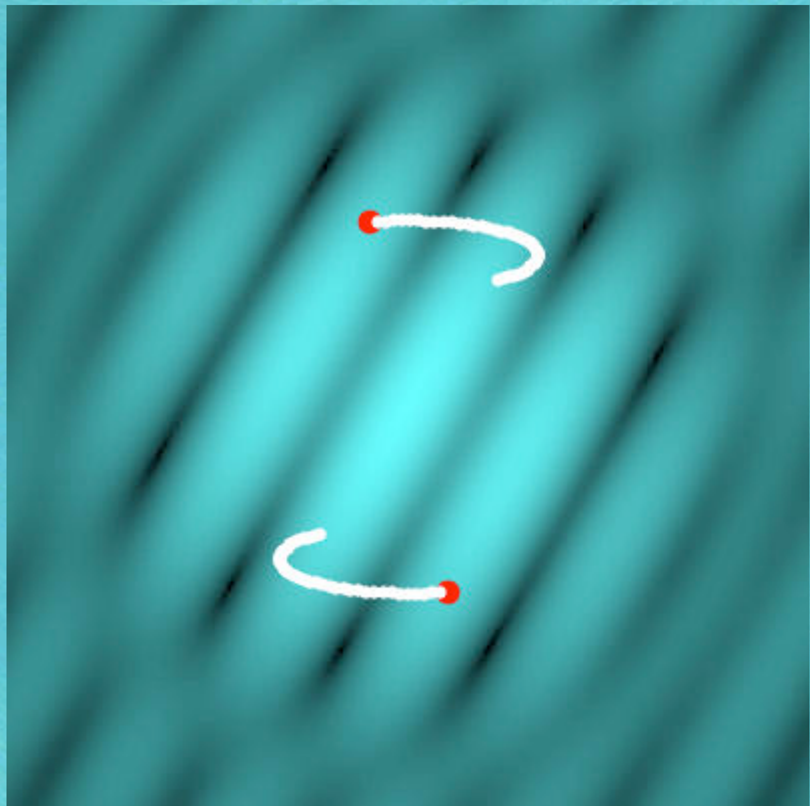


Single Telescope



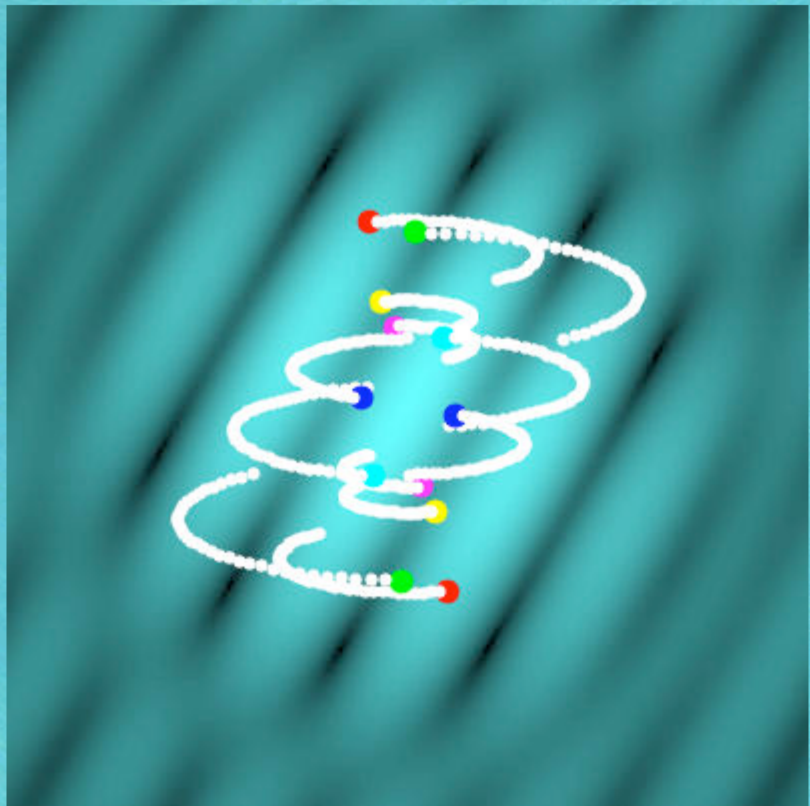
Interf. Fringes

Visibility of a binary star



Interferometry measures along "u-v tracks" (due to Earth's rotation).

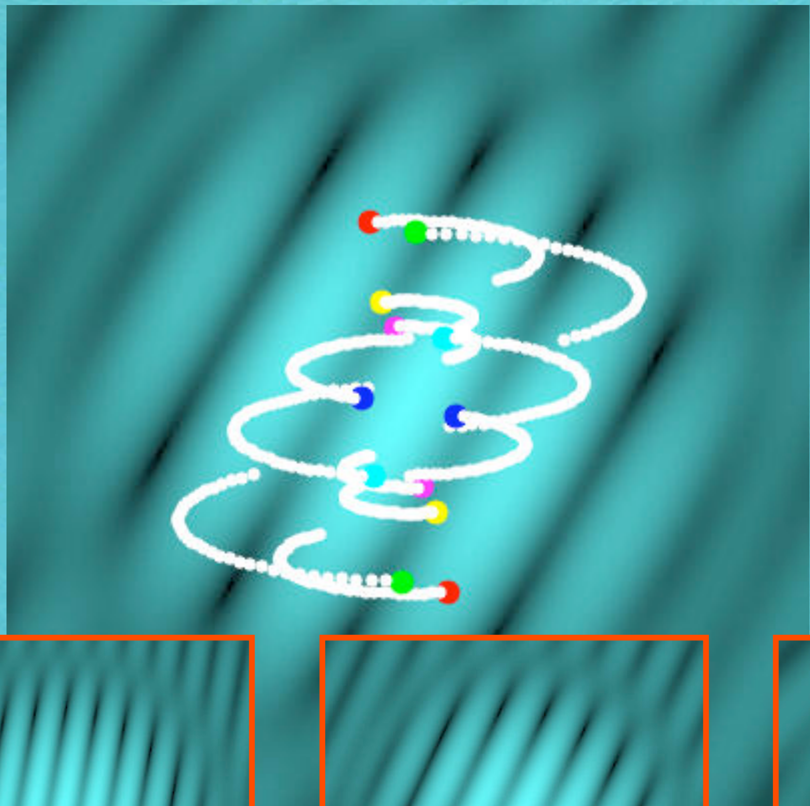
Visibility of a binary star



Interferometry measures along "u-v tracks" (due to Earth's rotation).

Each baseline adds a u-v track.

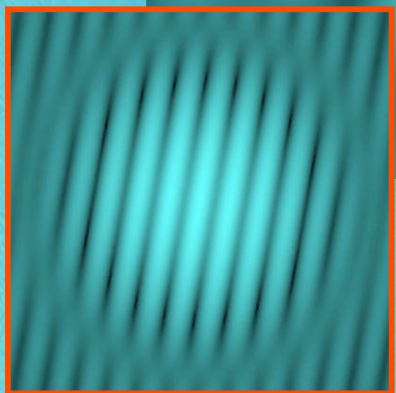
Visibility of a binary star

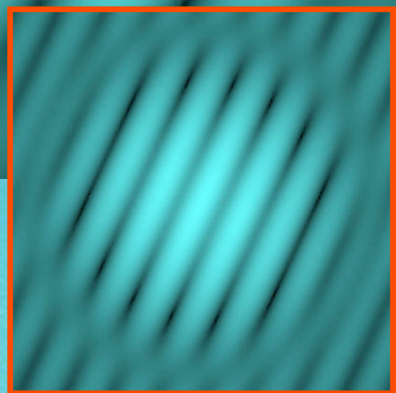


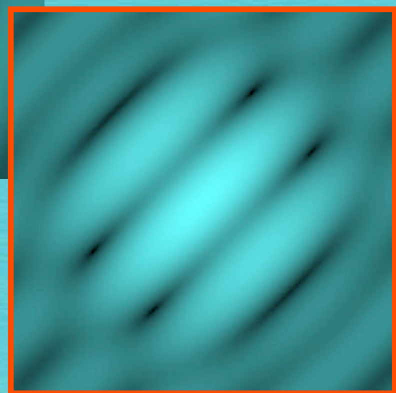
Interferometry measures along "u-v tracks" (due to Earth's rotation).

Each baseline adds a u-v track.

Usually results are based on model fitting, not image reconstruction.



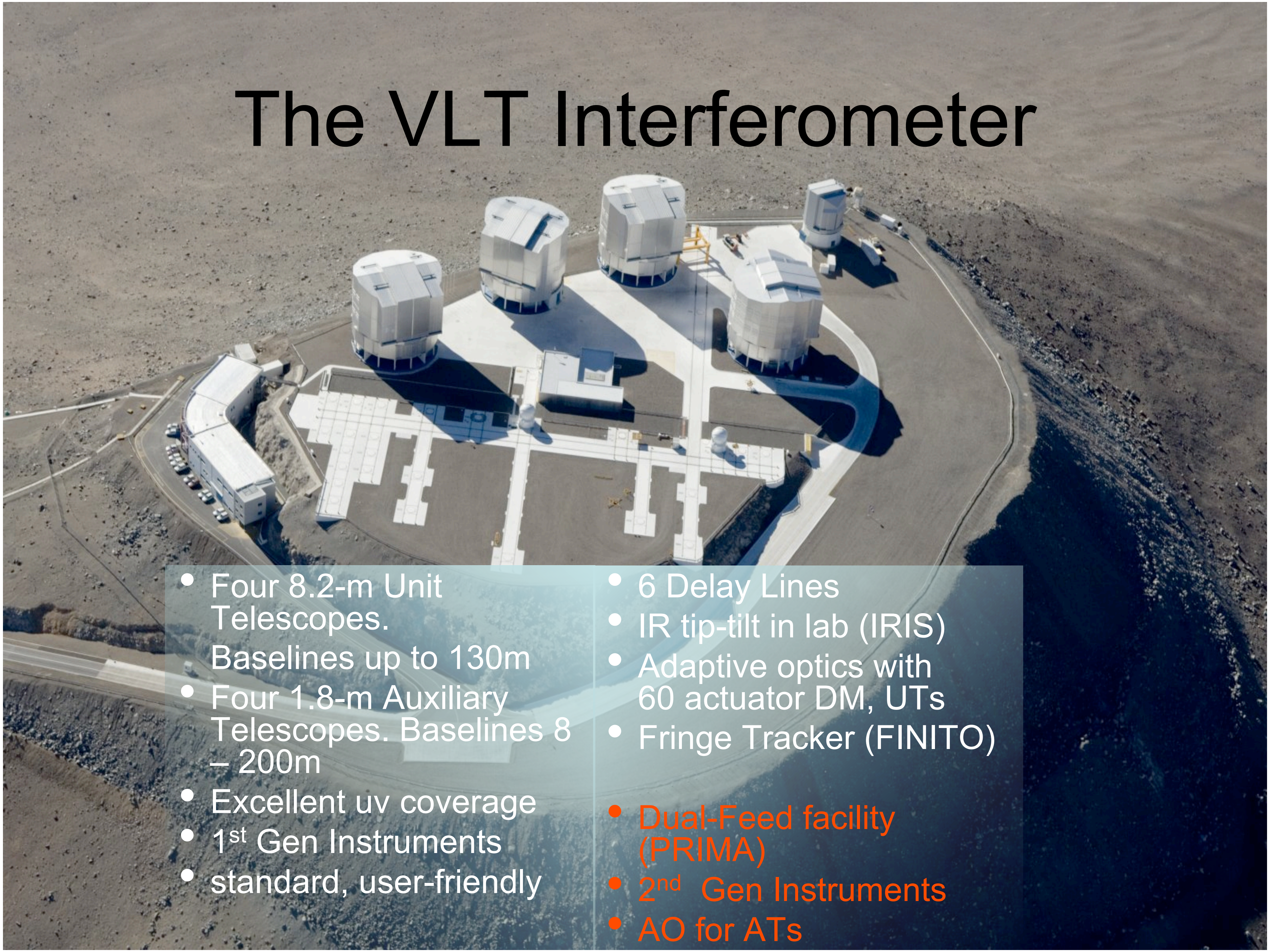




Overview of current Interferometers

facility	funding	location	n. of apertures	apertures (m) primary	apertures (m) secondary	baseline max (m)	year of first fringes	wavelength range
CHARA	USA	Mt. Wilson	6	1.0		350	1999	vis
COAST	UK	Cambridge	5	0.4		48	1991	vis
GI2T	F	Calern	2	1.5		65	1986	vis, NIR
IOTA	USA, F	Mt. Hopkins	2-3	0.45		38	1993	VRI, JHKL
ISI	USA	Mt. Wilson	2-3	1.65		75	1988	M
KECK	USA	Mauna Kea	2(4)	10	(1.8)	85(140)	2001	IR
LBT	USA, D, I	Mt. Graham	2	8.4		23	2005	vis, NIR
MIRA-I.2	J	Tokyo	2	0.30		6	2001	vis
MRO	USA	New Mexico	3-10?	2?		100?	funded	vis, NIR
NPOI	USA	Arizona	3-6	0.35		64	1994	vis, NIR
OHANA	USA, F	Mauna Kea	2-7	3-10		85-800	2004	NIR
PTI	USA	Mt. Palomar	3	0.40		110	1995	K
SUSI	AUS	New South Wales	2	0.14		640	1993	B, R
VLTI	ESO	Paranal	4+4	8.2	1.8	130-205	2001	JHK, NQ

The VLT Interferometer



- Four 8.2-m Unit Telescopes.
  Baselines up to 130m
- Four 1.8-m Auxiliary Telescopes. Baselines 8 – 200m
- Excellent uv coverage
- 1st Gen Instruments
- standard, user-friendly

- 6 Delay Lines
- IR tip-tilt in lab (IRIS)
- Adaptive optics with 60 actuator DM, UTs
- Fringe Tracker (FINITO)

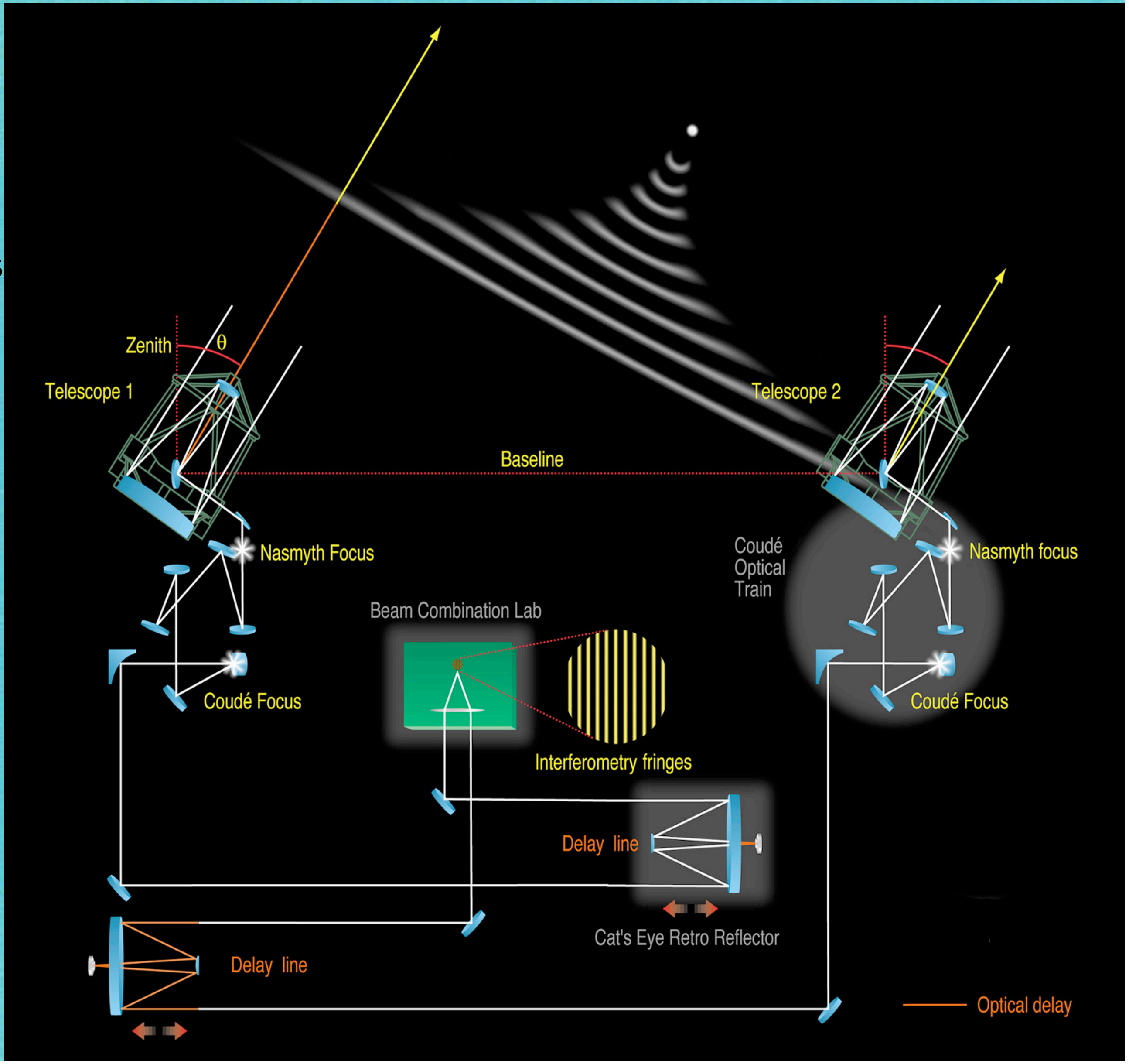
- Dual-Feed facility (PRIMA)
- 2nd Gen Instruments
- AO for ATs

VLTI Scheme

The wavefronts must be "clean", i.e. adaptive optics needed for large telescopes

The optical path difference must be continuously compensated by the delay lines.

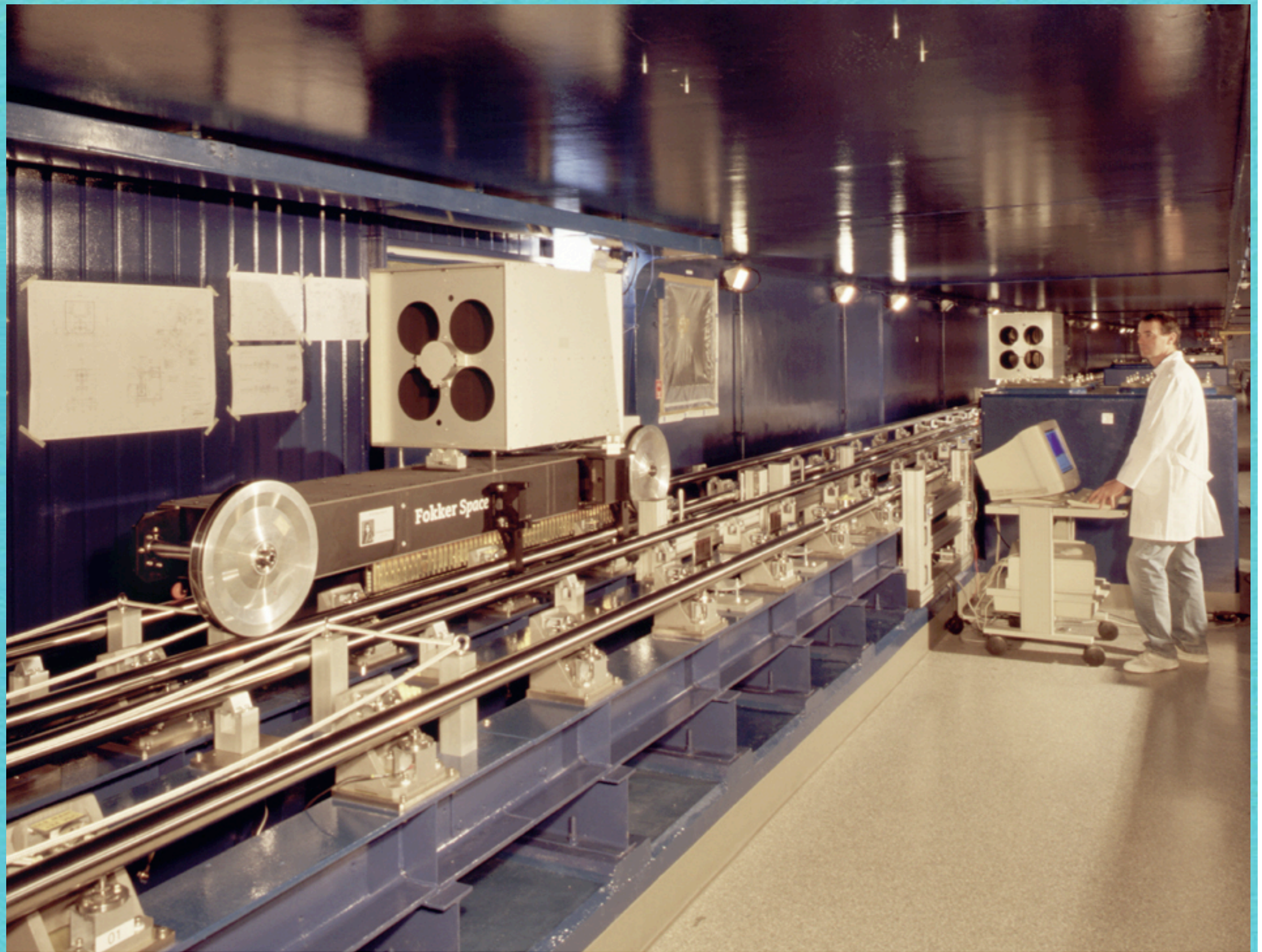
Atmospheric turbulence causes rapid fringe motion which must be "frozen" by a so-called fringe tracker.




• increase u-v coverage
• movable
• optimized for interferometry
• First fringes 2T Feb05
• AT3 late 2005
• AT4 mid-2006

The “Paranal Express”

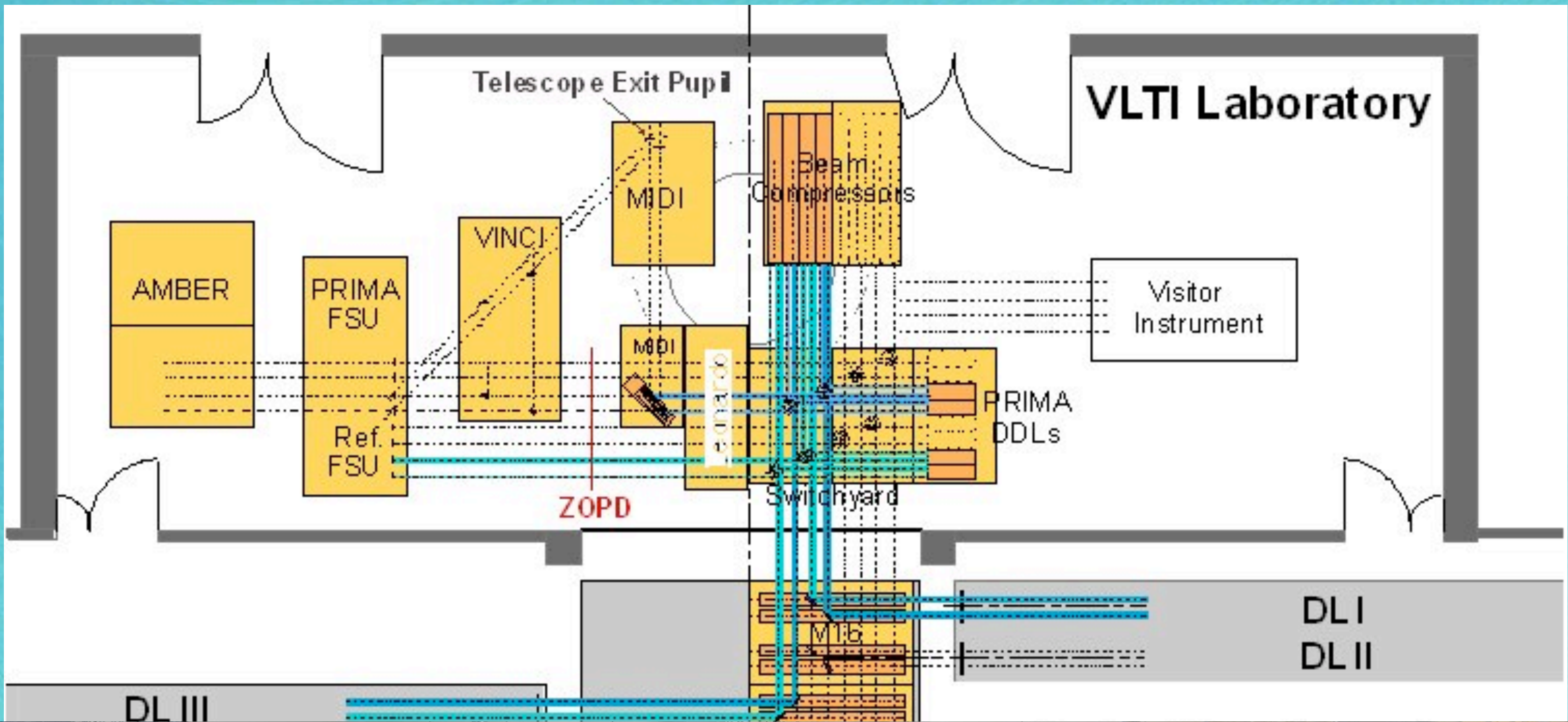
- correct sidereal path difference
- six delay lines
- combine all UT baselines
- combine almost all AT baselines
- laser metrology

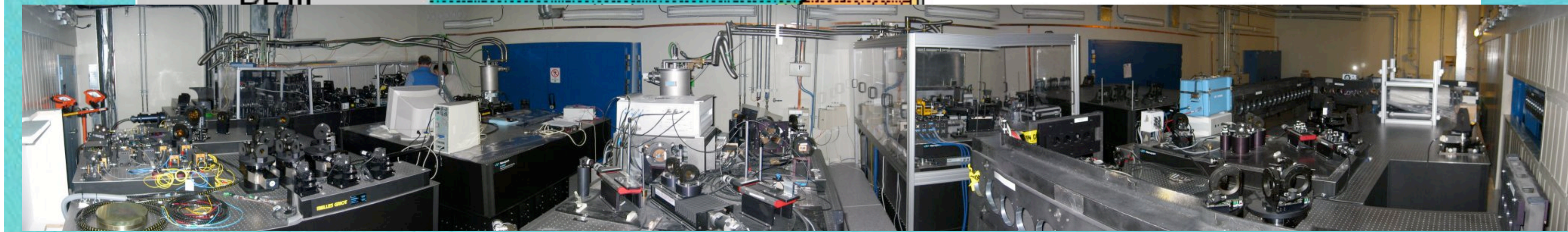


Delay Line Carriage in VLTI Tunnel

ESO PR Photo 10j/01 (18 March 2001)

VLTI Laboratory



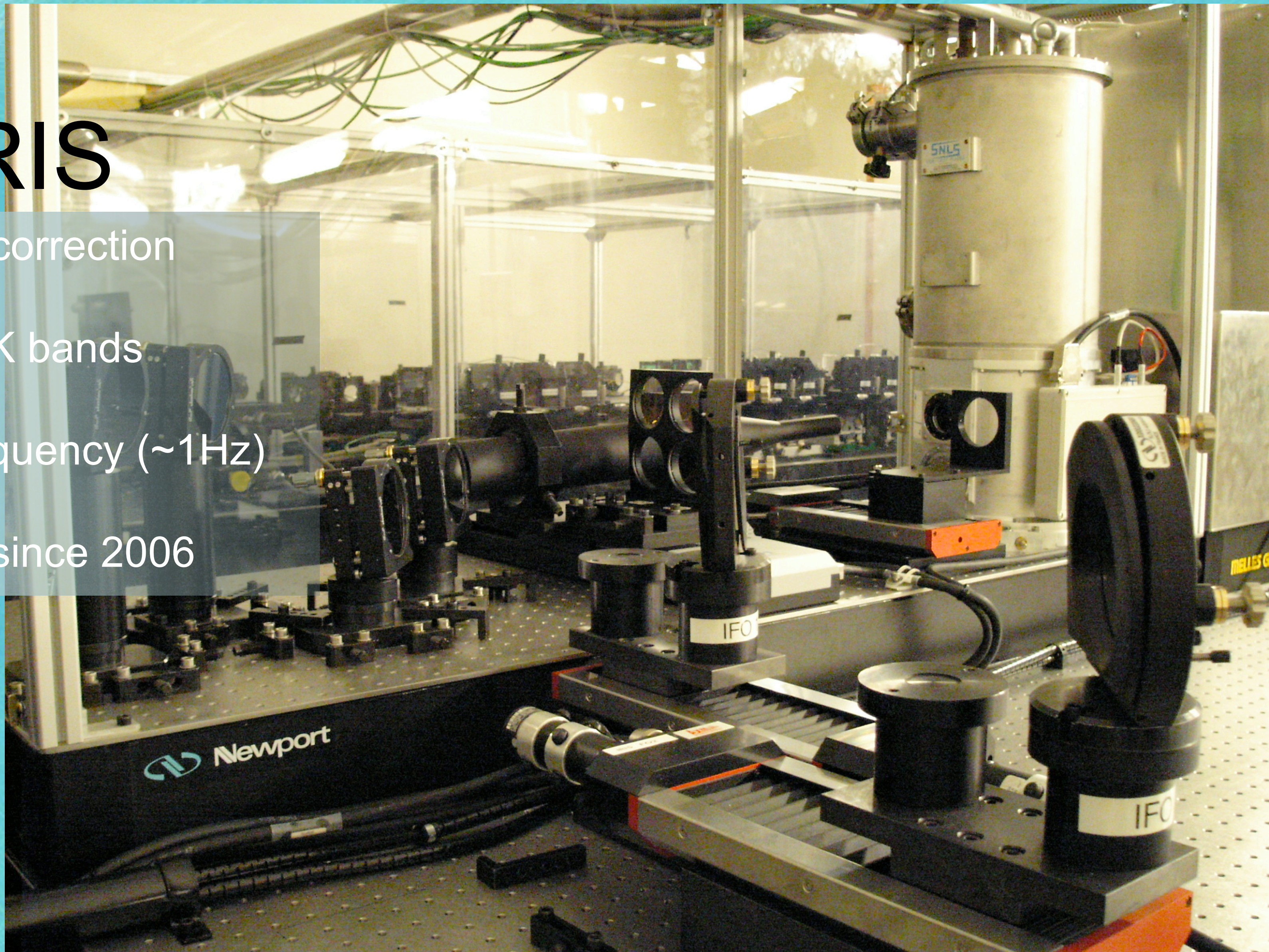


FINITO

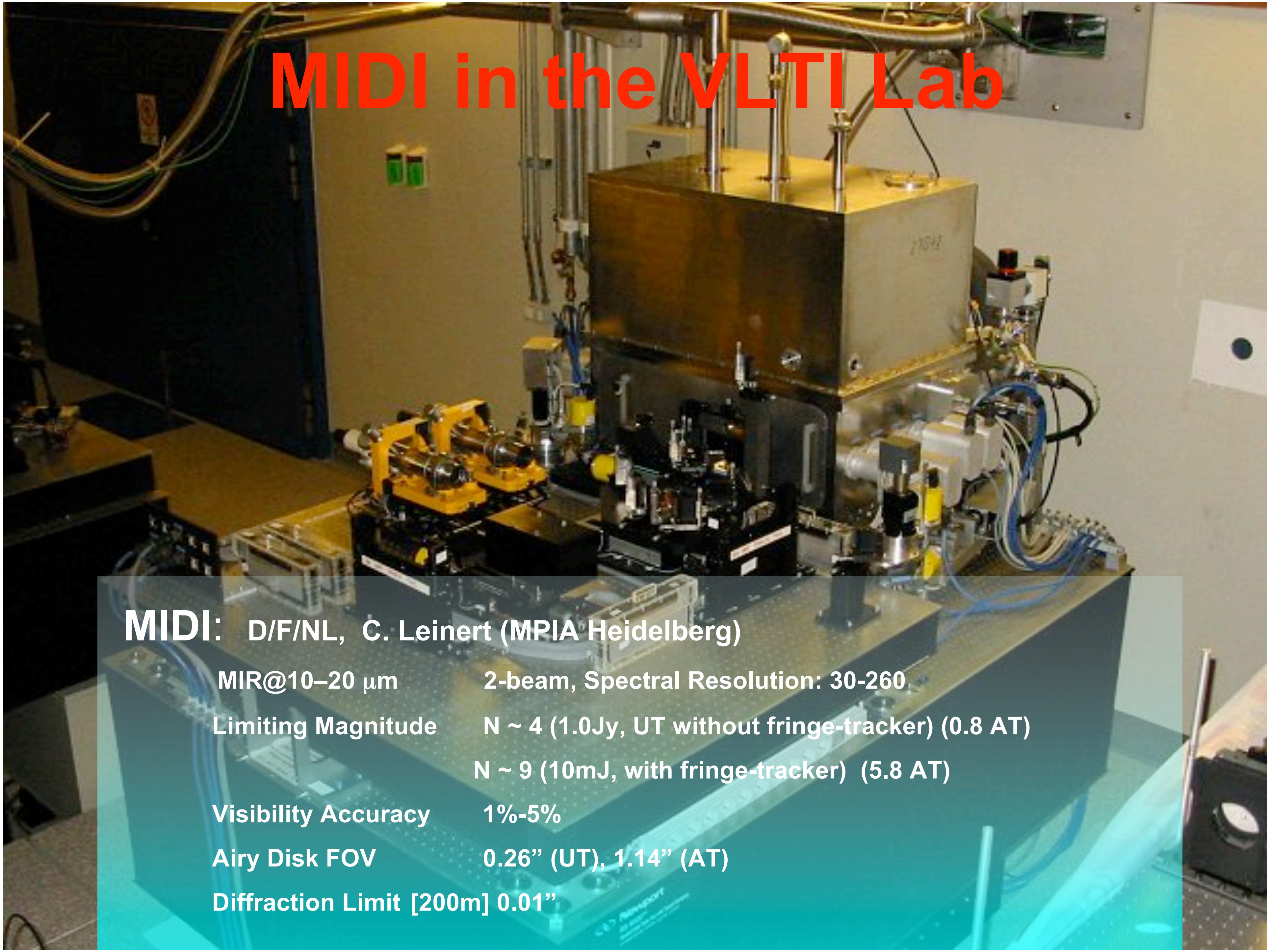
- On-axis fringe tracker
- H-band, three beams, H = 11
- First Fringes at Paranal in July 2003
  - Problem: extreme flux fluctuations
  - open loop only
- Problems understood by 2005, fixing in progress
  - 400nm rms residual OPD on UTs
  - 100nm on ATs
  - goal: offered from 2007

IRIS

- Tip-tilt correction
- H and K bands
- low frequency (~1Hz)
- In use since 2006



MIDI in the VLTI Lab



MIDI: D/F/NL, C. Leinert (MPIA Heidelberg)

MIR@10–20 μm	2-beam, Spectral Resolution: 30-260
Limiting Magnitude	N ~ 4 (1.0Jy, UT without fringe-tracker) (0.8 AT)
	N ~ 9 (10mJ, with fringe-tracker) (5.8 AT)
Visibility Accuracy	1%-5%
Airy Disk FOV	0.26” (UT), 1.14” (AT)
Diffraction Limit [200m]	0.01”

AMBER at the VLTI

AMBER: F/D/I, R. Petrov (Nice)

NIR @1–2.5 μm 3-beam, Spectral Resolution:: 35-14000 (prism, 2 gratings)

Limiting Magnitude K =11 (specification, 5 σ, 100ms self-tracking)

J=19.5, H=20.2, K=20 (goal, FT, AO, PRIMA, 4 hours)

Visibility Accuracy 1% (specification), 0.01% (goal)

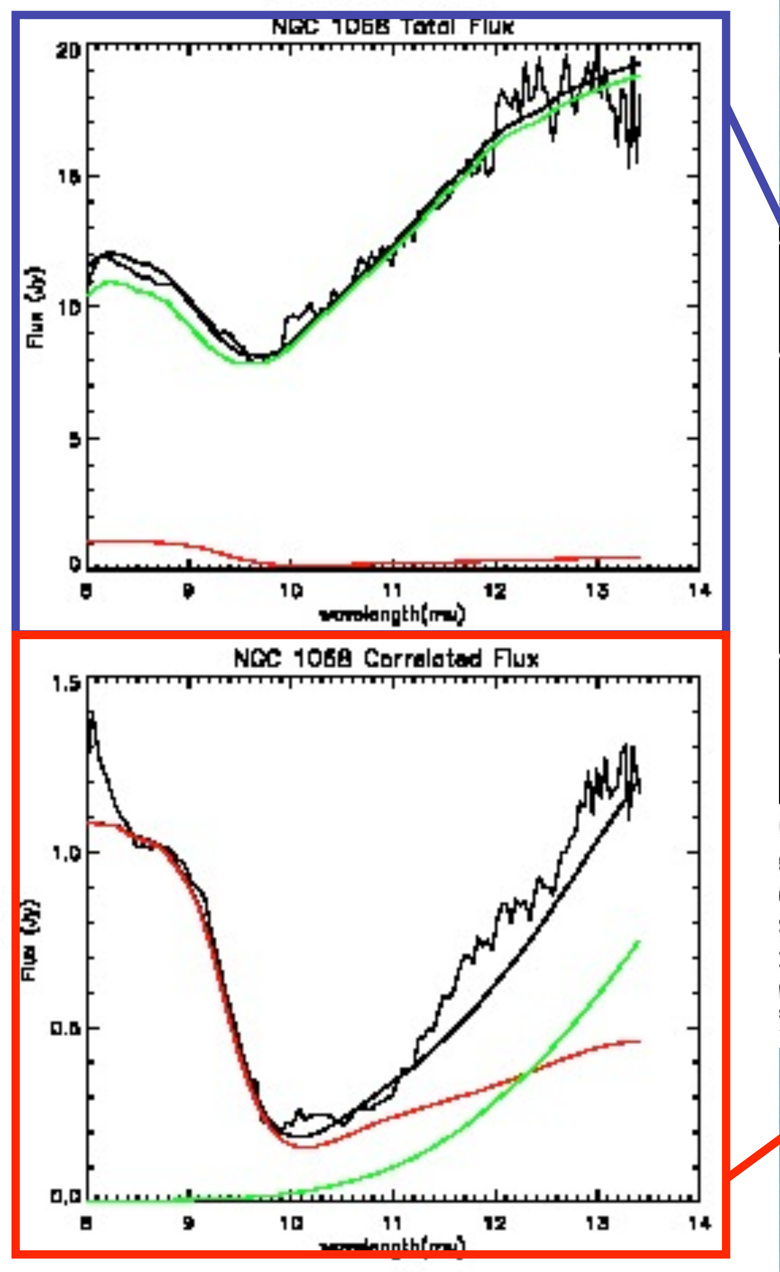
Airy Disk FOV 0.03”/0.06” (UT), 0.14”/0.25” (AT) [J/K band respectively]

Diffraction Limit [200m] 0.001” J, 0.002” K”

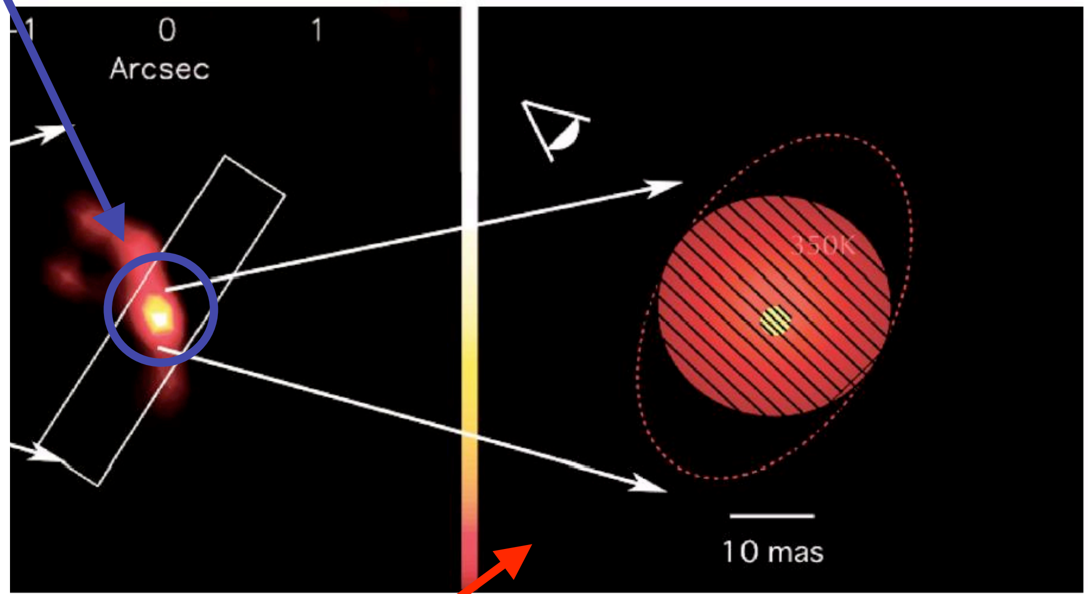
Interferometric Science Highlights

- AGNs (dust tori)
- Hot stars; massive stars; star formation
- Evolved stars; dust in giants; AGBs
- Stellar pulsation
- Binary stars
- MS stars and fundamental parameters
- Search for exoplanets (direct detection)

NGC 1068



Incoherent combination



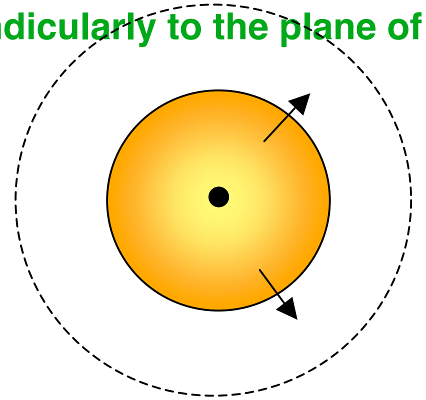
68, (NOAO/AURA/NSF). Centre: non-interferometric acquisition image of NGC 1068 es on arcsec scales. Also shown are the position of the spectroscopic slit used in the oward top left) and East (toward bottom left) on the sky. The projected baseline was tion was 26.3 mas at 10 micron wavelength. Right: sketch of the dust structure in the observations. It contains a central hot component (T > 800 K, yellow) which is signif- larger well-resolved warm component (T=330 K, red) of diameter 33±5 mas, corre- fe et al (2003).

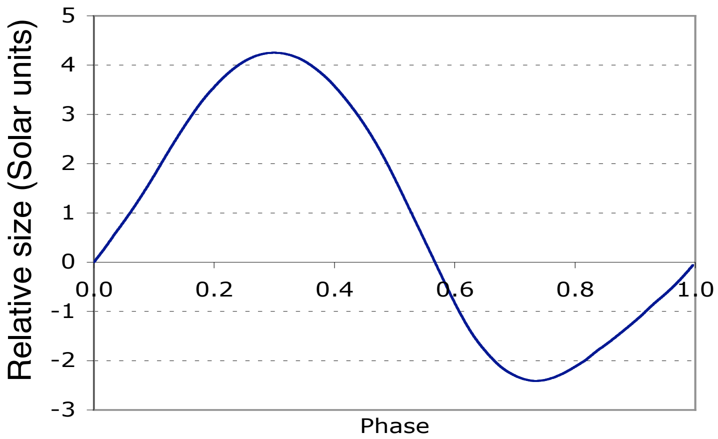
2 Tel coherent combination

Cepheid Stars

- **Radial velocity data (spectroscopy)**

Perpendicularly to the plane of the sky

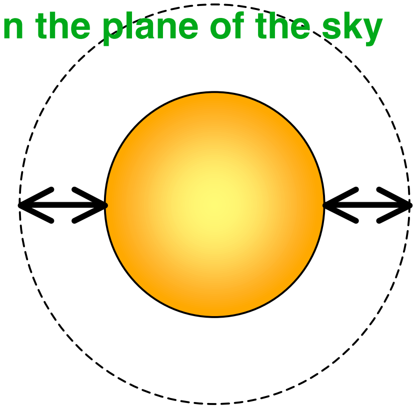


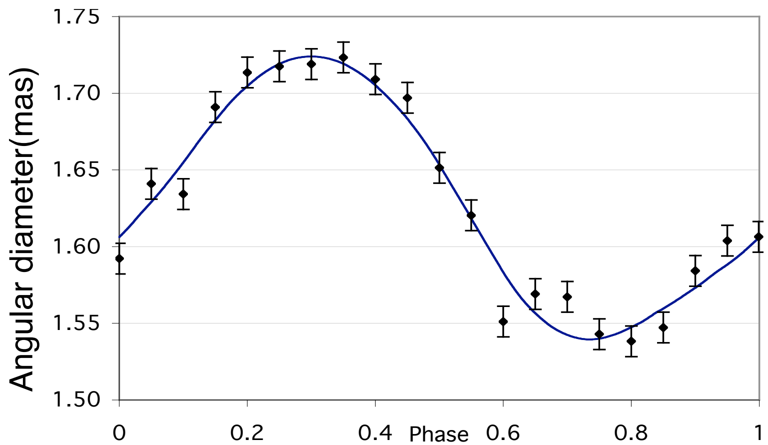


Distance

- **Angular diameter (interferometry)**

In the plane of the sky

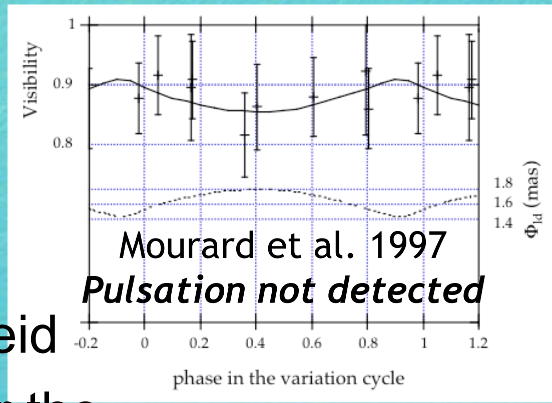


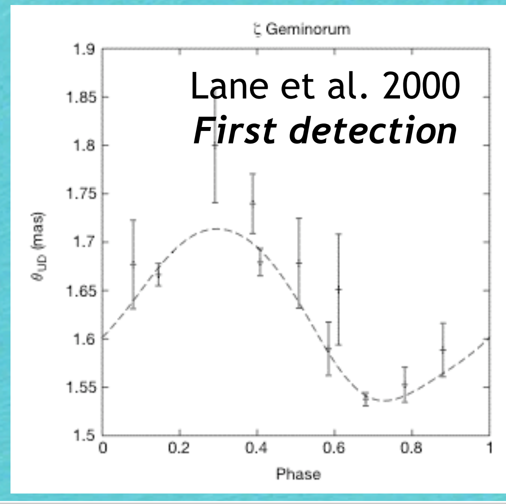


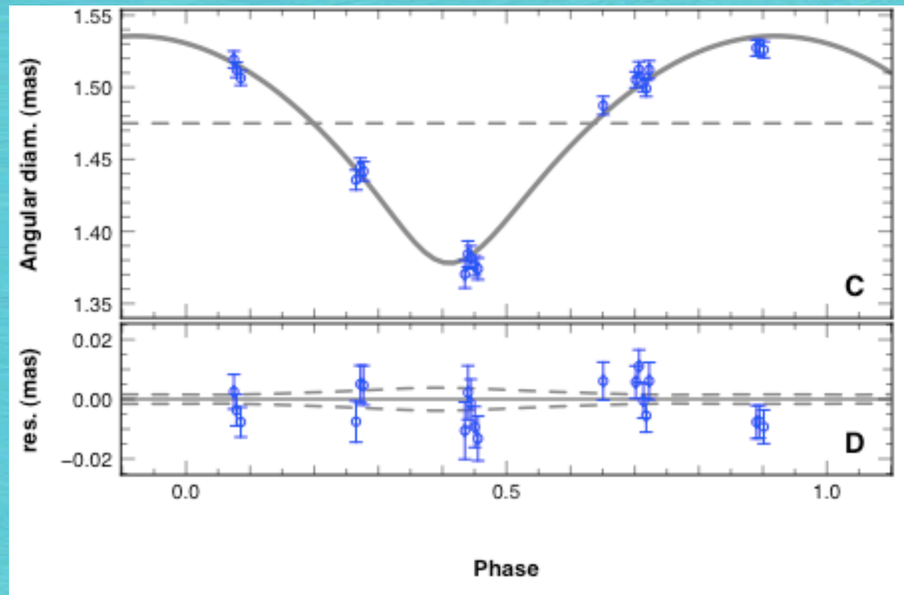
From P. Kervella (2005)

δ Cep

<u>Evolution of the IBW method at a glance:</u>







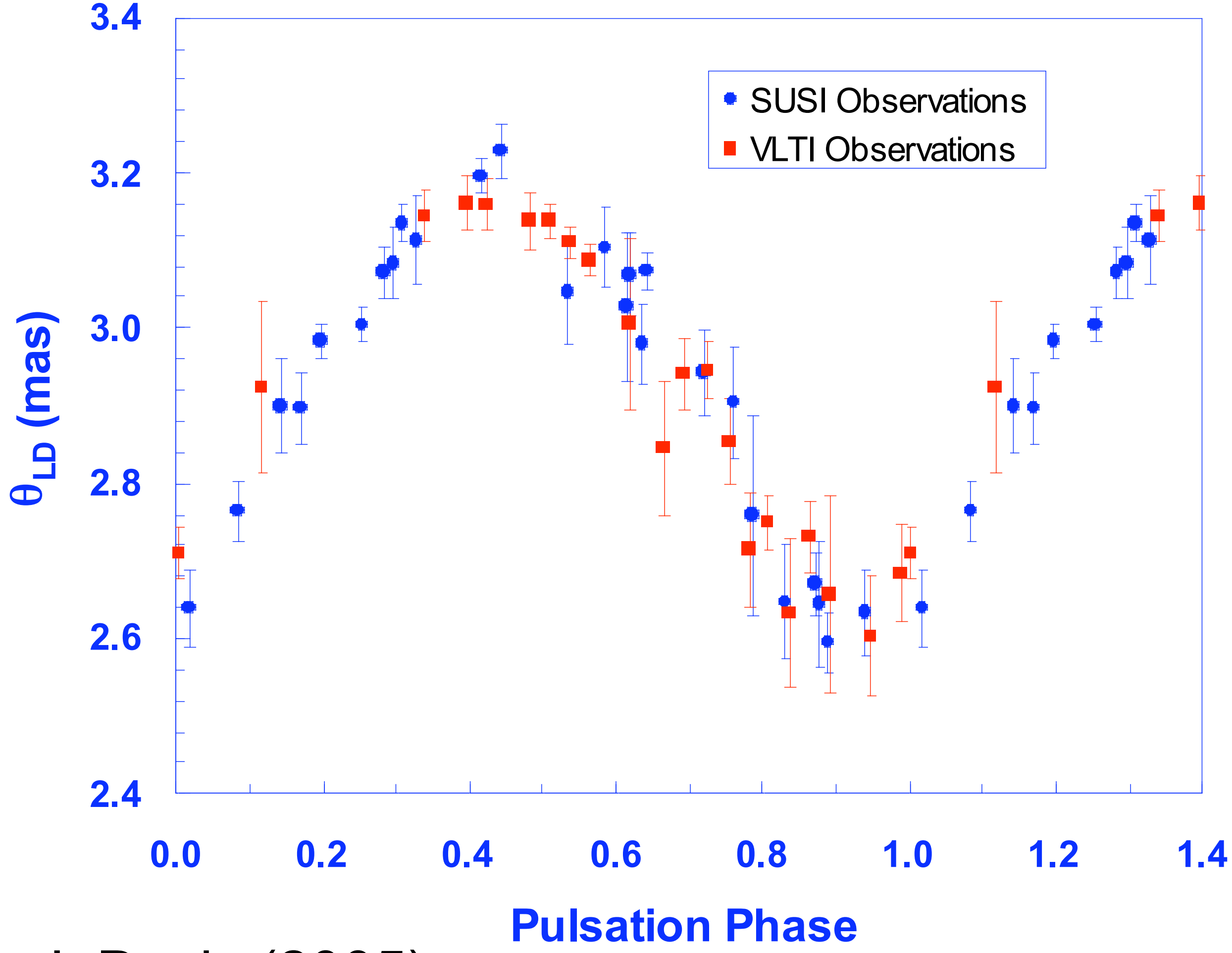
- Prototype Classical Cepheid
- Interferometry is no longer the limitation to the IBW method
- Individual V2 lead to $\sigma\theta/\theta$ < 0.5%
- Potentially*, the distance is determined at the 2% level

* *How well do we trust LD & p-factor models ???*

From A. Mérand (2005)

l Car

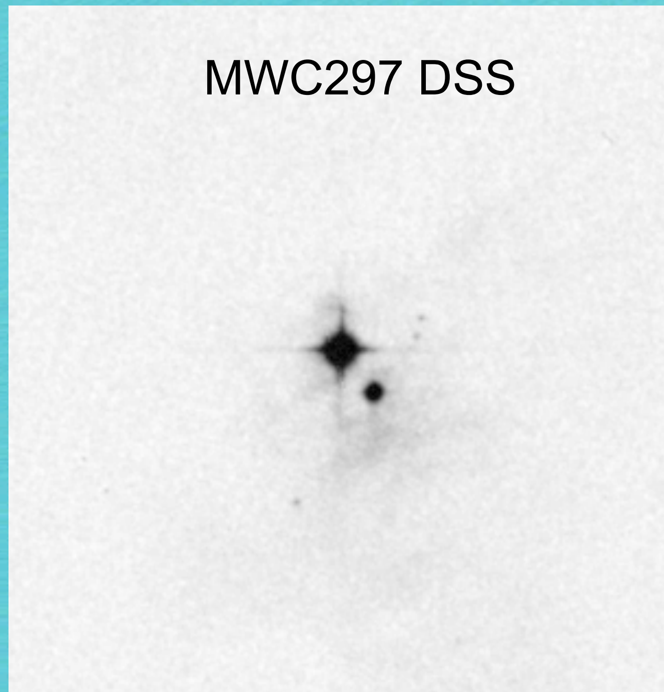
Potential distance uncert. 11/545pc



From J. Davis (2005)

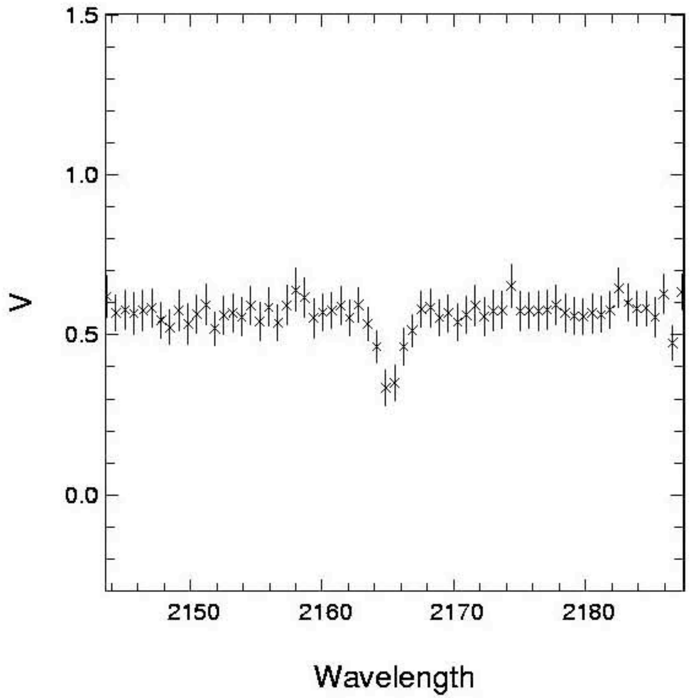
Wind and disk interaction in the Herbig Be star MWC 297

- HAeBe: intermediate mass pre main sequence star
- Original list 1960 of G.Herbig
- Strong emission line spectrum
- Surrounded by circumstellar material
- Early-type Herbig Be star
- Drew et al, 1997:
  - *D=250 pc ± 50*
  - *B1.5 ZAMS*
  - *10 Msun, 6.12Rsun, Teff=23700K*
  - *Av = 8mag*
- AMBER 2T observations



AMBER interferometry of MWC 297

Visibility; baseline 45 m; Br Gamma emission line; medium spectral resolution 1500



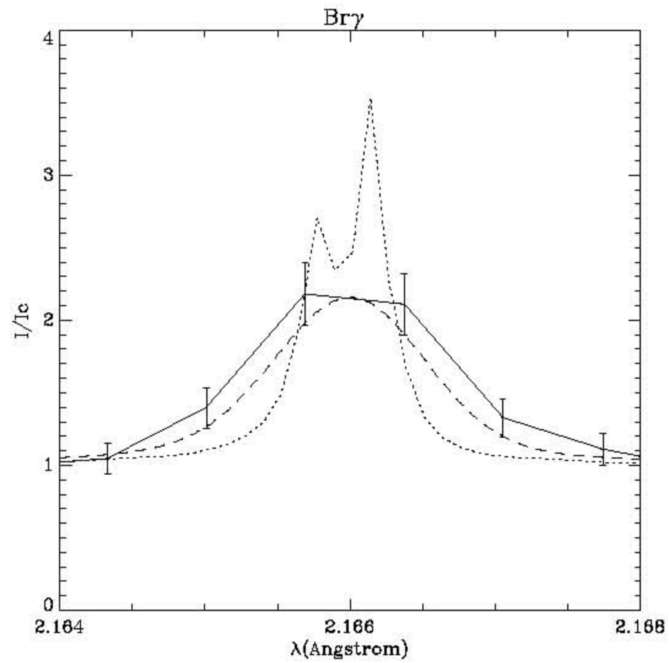


Fig. 1. Left: spectral dependence of the MWC 297 visibilities. Right: comparison of Brγ observed with AMBER (full line) and ISAAC (dotted line). The dashed line corresponds to the ISAAC spectrum convolved at the AMBER spectral resolution.

F. Malbet

Modelling of MWC297 environment

Continuum

- uv to mm→SED (Pezzuto97)
- AMBER K band
- IOTA H band (Millan-Gabet 2001)
- PTI K band (Eisner04)

Geometrically-thin optically-thick accretion disk model + irradiation

(Malbet & Bertout 95)

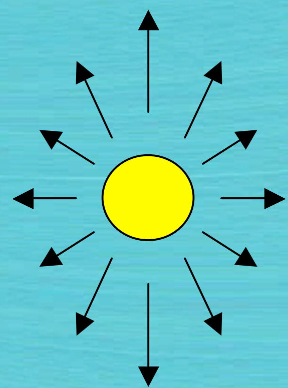
Disk

Emission lines

- Hα, Hβ *R=5000* (Drew97)
- ISAAC Brγ *R=8900*
- Brγ visibility with AMBER *R=1500*

SIMECA code (Stee95)

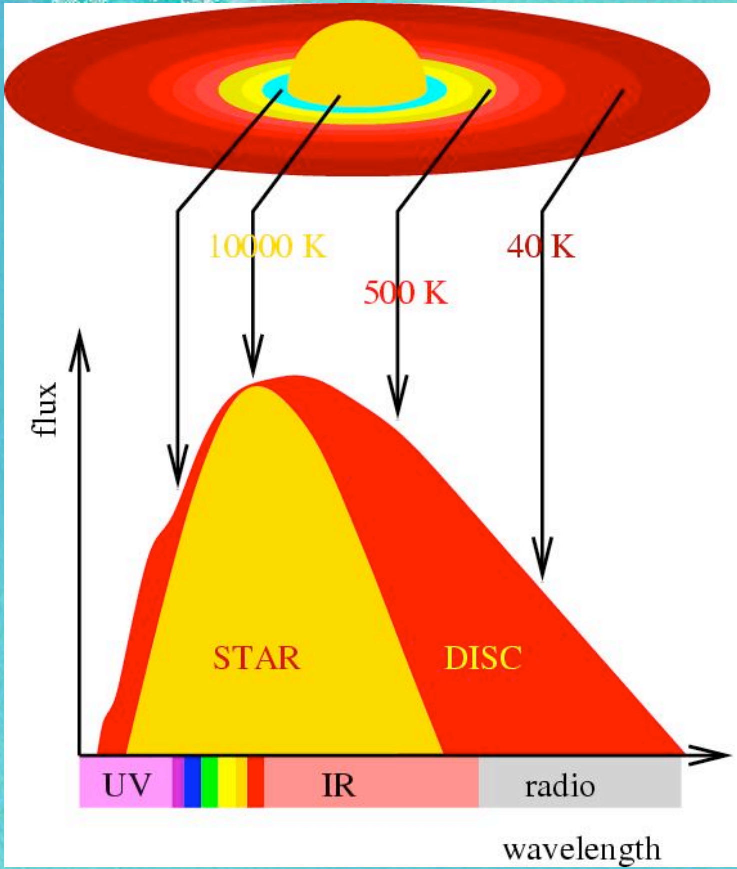
+

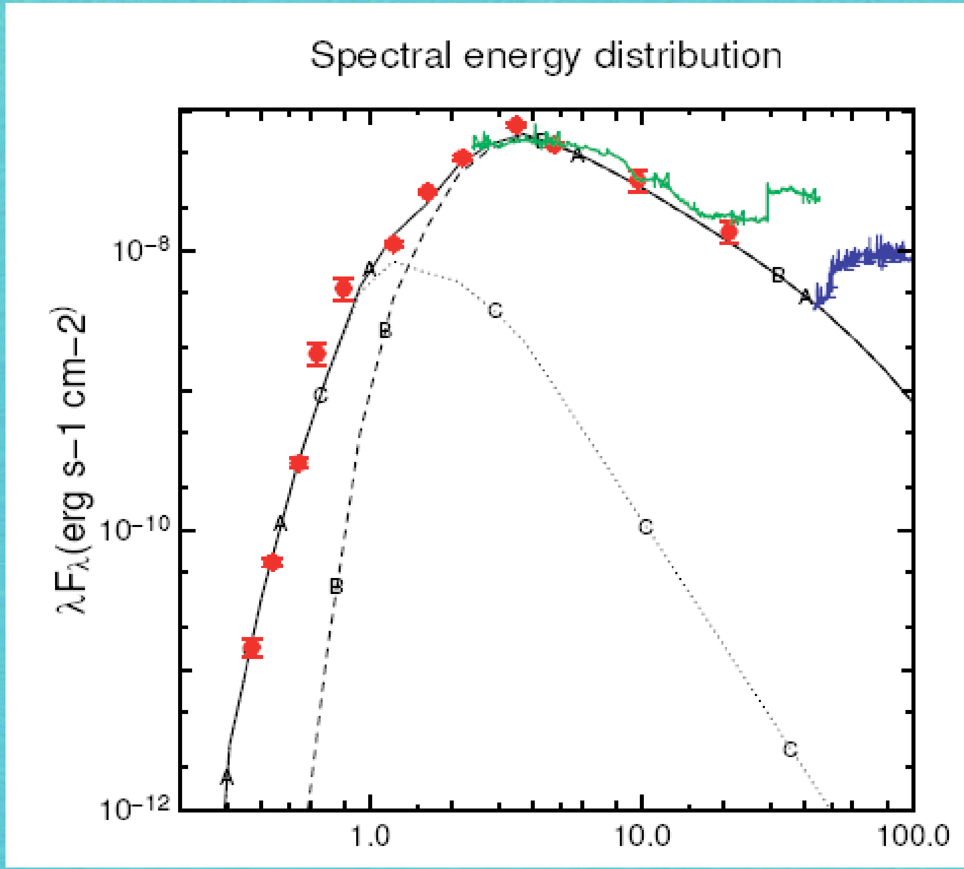


Wind

= ?

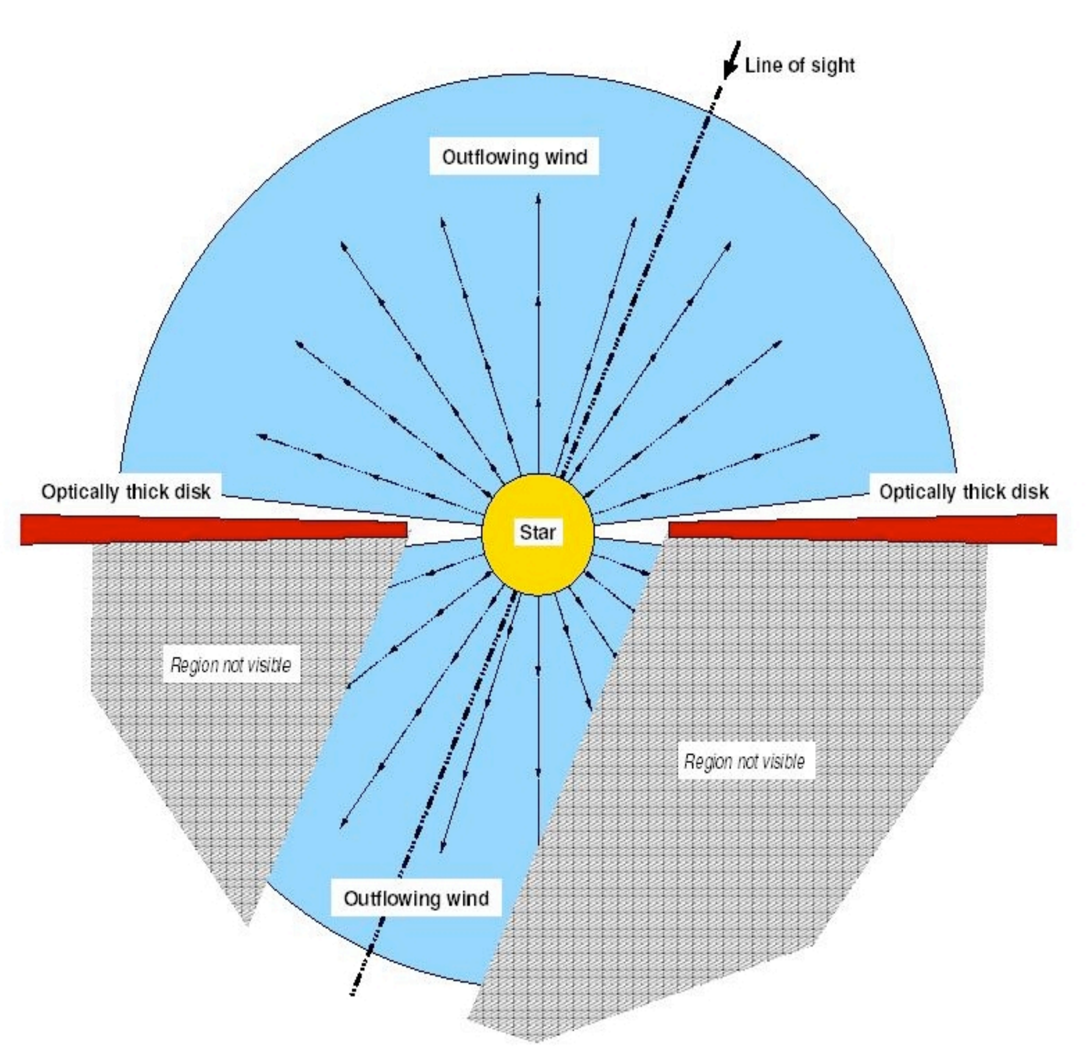
Spectral energy distribution





Geometrically thin optically thick accretion disk + irradiation
= « classical » accretion disk model (Malbet & Bertout 95)

The wind model



- Outflowing wind
- Optically thick disk
- 4° disk thickness
- Part of incoming jet hidden by the disk

Summary of MWC297 results

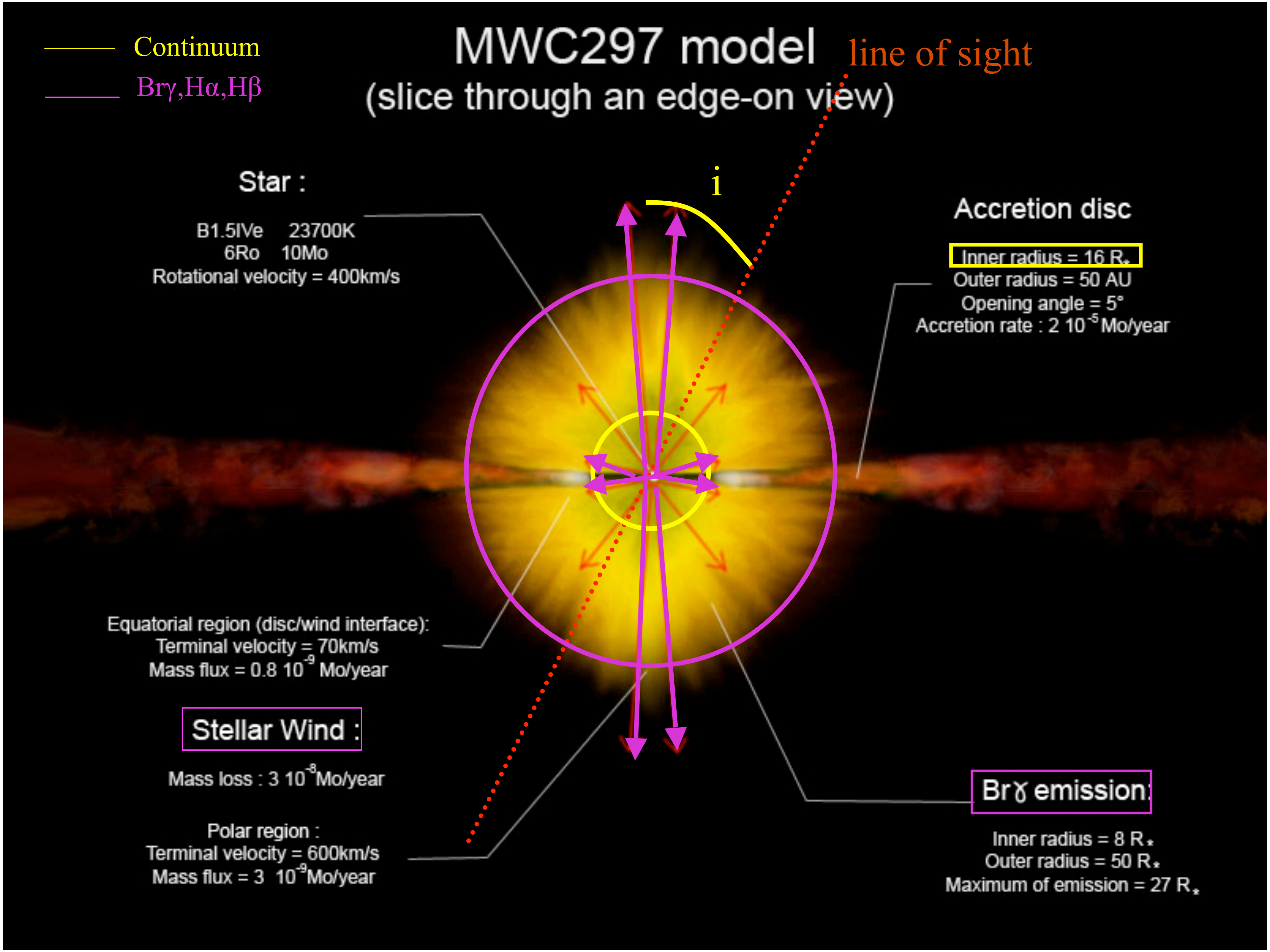
- Simultaneous fit to the continuum visibilities and SED lead to a consistent disk model for the continuum emission.
- Simultaneous fit to the line visibility and emission line profiles lead to a consistent wind model for the line emission.
- Models have been « glued »

Table 3. The best-fit accretion disk model parameter
taneous fitting of SED and visibilities.

Accretion rate ($\dot{M}_{acc}$)	$0 - 1 \times 10^{-5}\ M_{\odot}$
Inner radius (R_{in})	0.5 ± 0.1 AU
Outer radius (R_{out})	55 ± 5 AU
Inclination (i)	$15 \pm 5°$
Position angle (θ)	$56 \pm 7°$

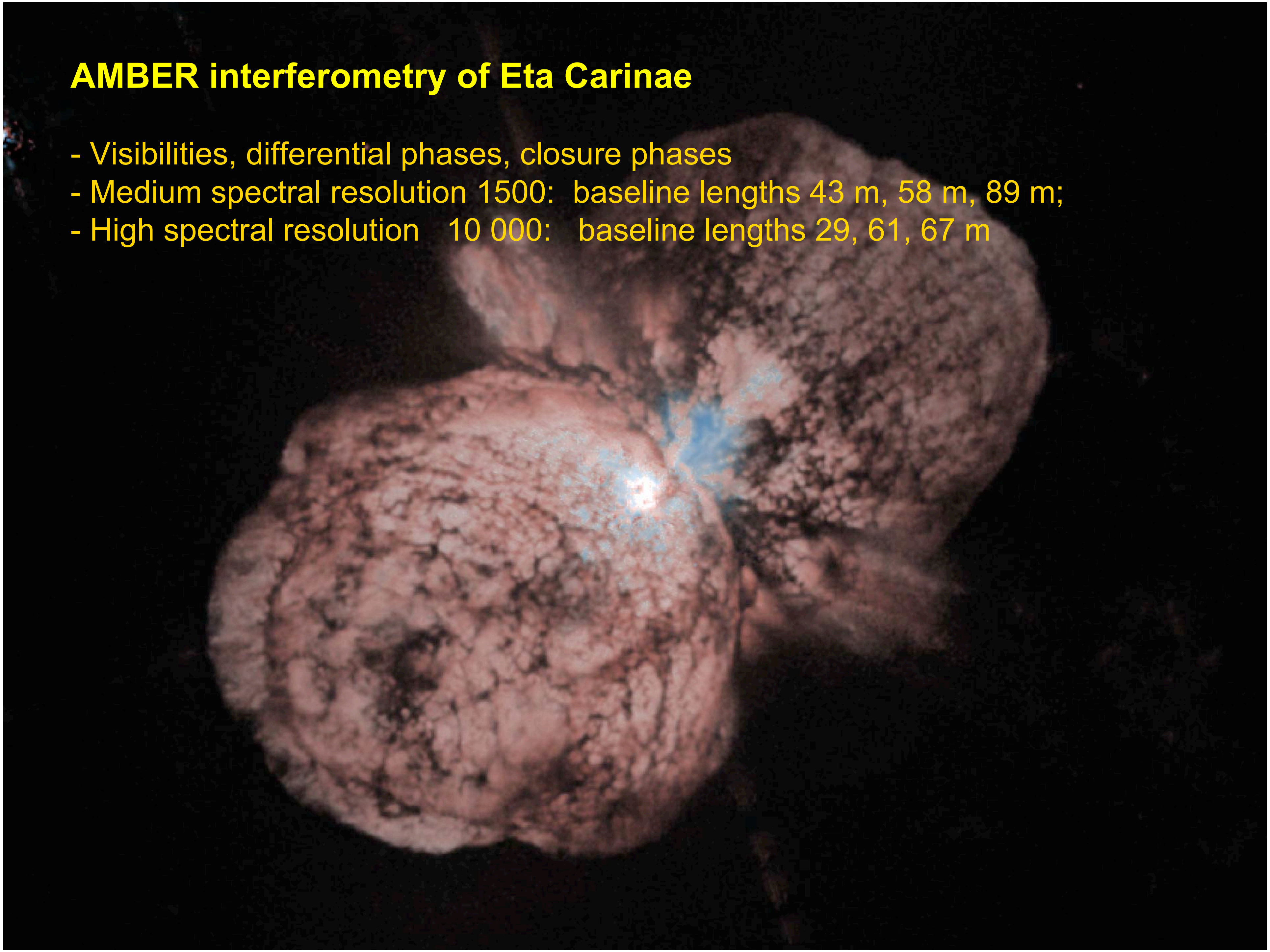
Table 4. The best-fit model parameters for the outflowing wind model. Most parameters are self-explanatory **(see Appendix A for details)**. C_1 is the ratio between the polar and equatorial mass flux; m_1 is the exponent of the mass flux law as function of latitude; m_2 is the exponent of the latitude dependent terminal velocity law.

Photospheric density	$1 \pm 0.5 \times 10^{12}$ cm^{-3}
Equatorial rotational velocity	400 ± 50 km s^{-1}
Polar terminal velocity	600 ± 50 km s^{-1}
Terminal velocity above disk	70 ± 20 km s^{-1}
Polar mass flux	$3.2 \pm 0.2 \times 10^{-9}\ M_{\odot}$ yr^{-1}
C_1	0.25 ± 0.05
m_1	30 ± 10
m_2	10 ± 2
Inclination angle (i)	$25 \pm 5°$


Continuum
Brγ,Hα,Hβ
MWC297 model
(slice through an edge-on view)
line of sight
i
Star :
B1.5IVe 23700K
6Ro 10Mo
Rotational velocity = 400km/s
Accretion disc
Inner radius = 16 R*
Outer radius = 50 AU
Opening angle = 5°
Accretion rate : 2 10-5 Mo/year
Equatorial region (disc/wind interface):
Terminal velocity = 70km/s
Mass flux = 0.8 10-9 Mo/year
Stellar Wind :
Mass loss : 3 10-8 Mo/year
Polar region :
Terminal velocity = 600km/s
Mass flux = 3 10-9 Mo/year
Brγ emission:
Inner radius = 8 R*
Outer radius = 50 R*
Maximum of emission = 27 R*

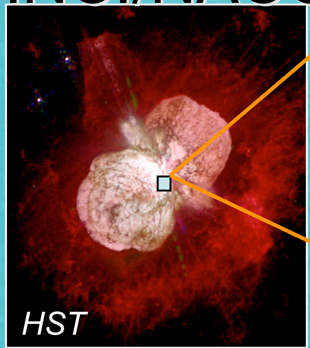
AMBER interferometry of Eta Carinae

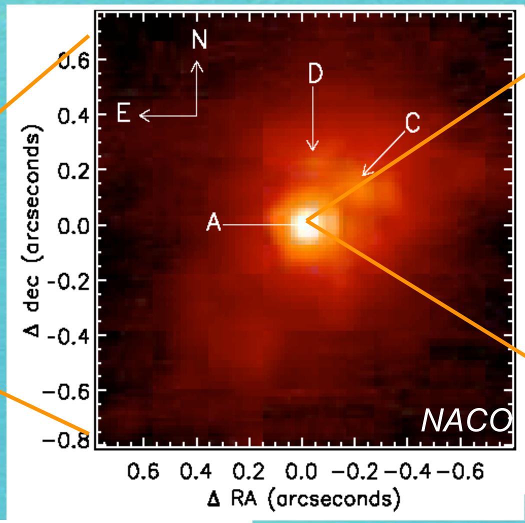
- Visibilities, differential phases, closure phases
- Medium spectral resolution 1500: baseline lengths 43 m, 58 m, 89 m;
- High spectral resolution   10 000:   baseline lengths 29, 61, 67 m

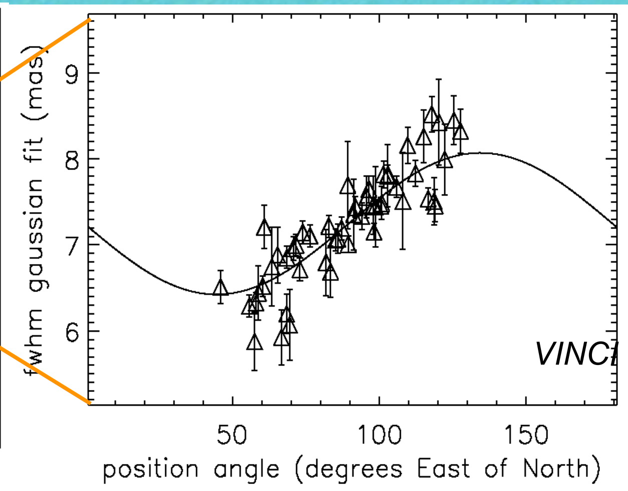


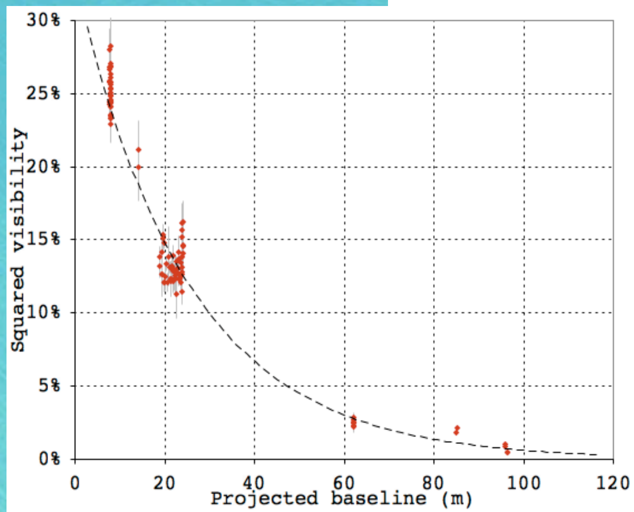
The close environment of the Luminous Blue Variable η Carinae

VINCI/NACO

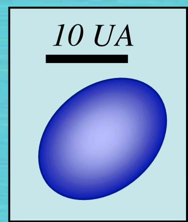


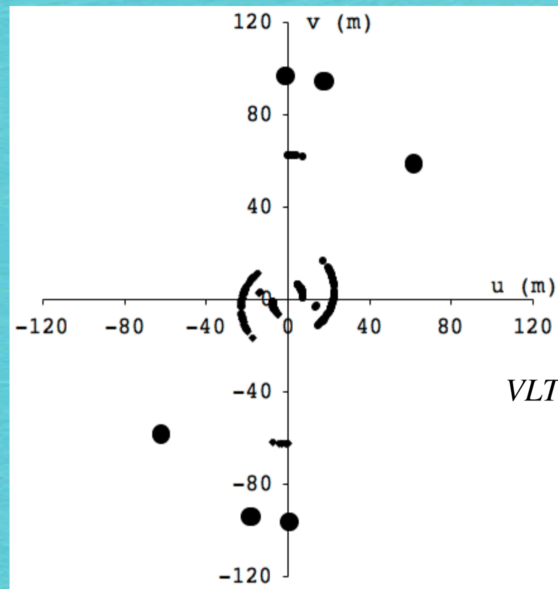






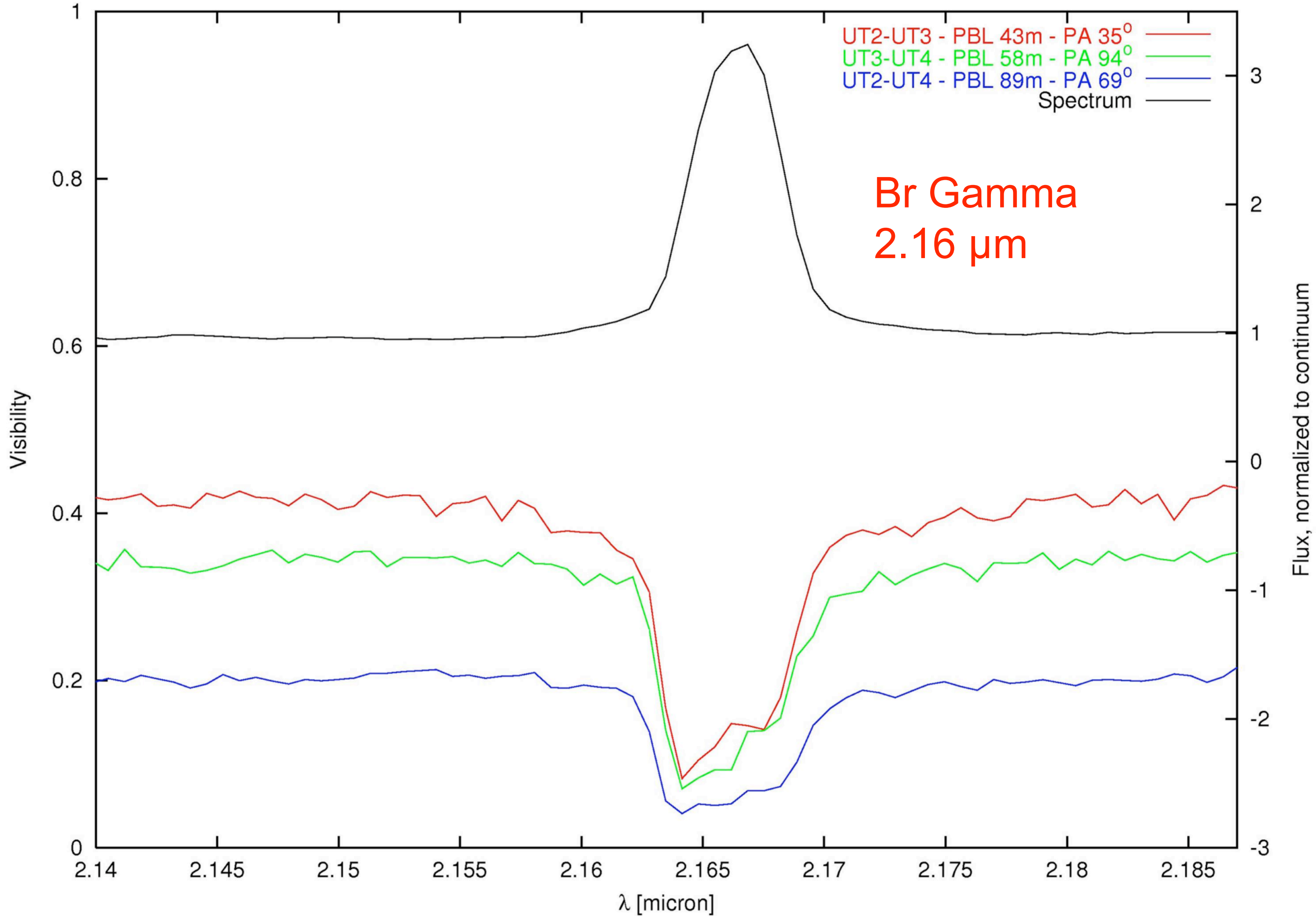
VINCI





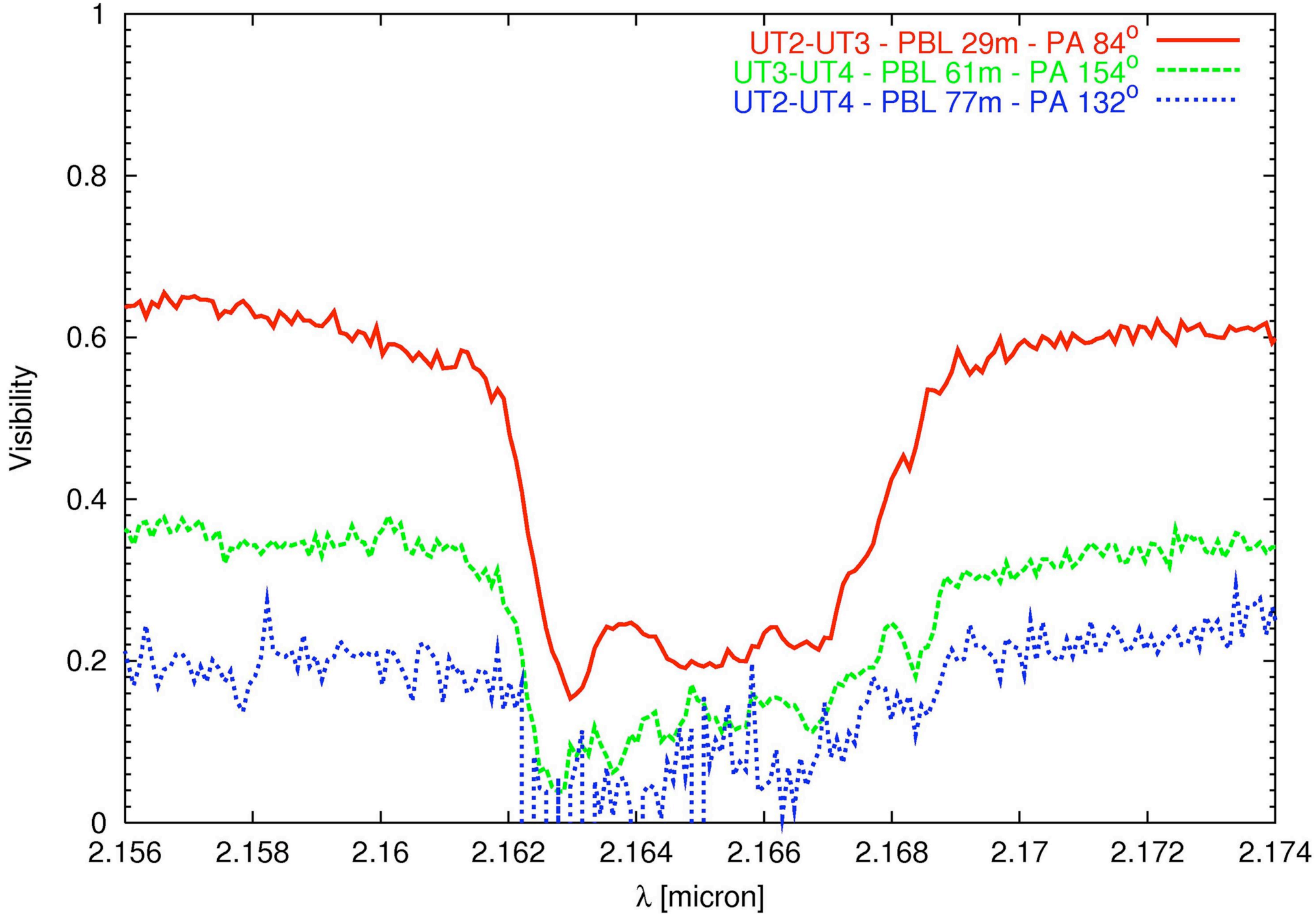
Van Boekel *A&A*, **410**, L37 (2003)

Visibilities; baseline lengths 43 m, 58 m, 89 m; medium spectral resolution 1500

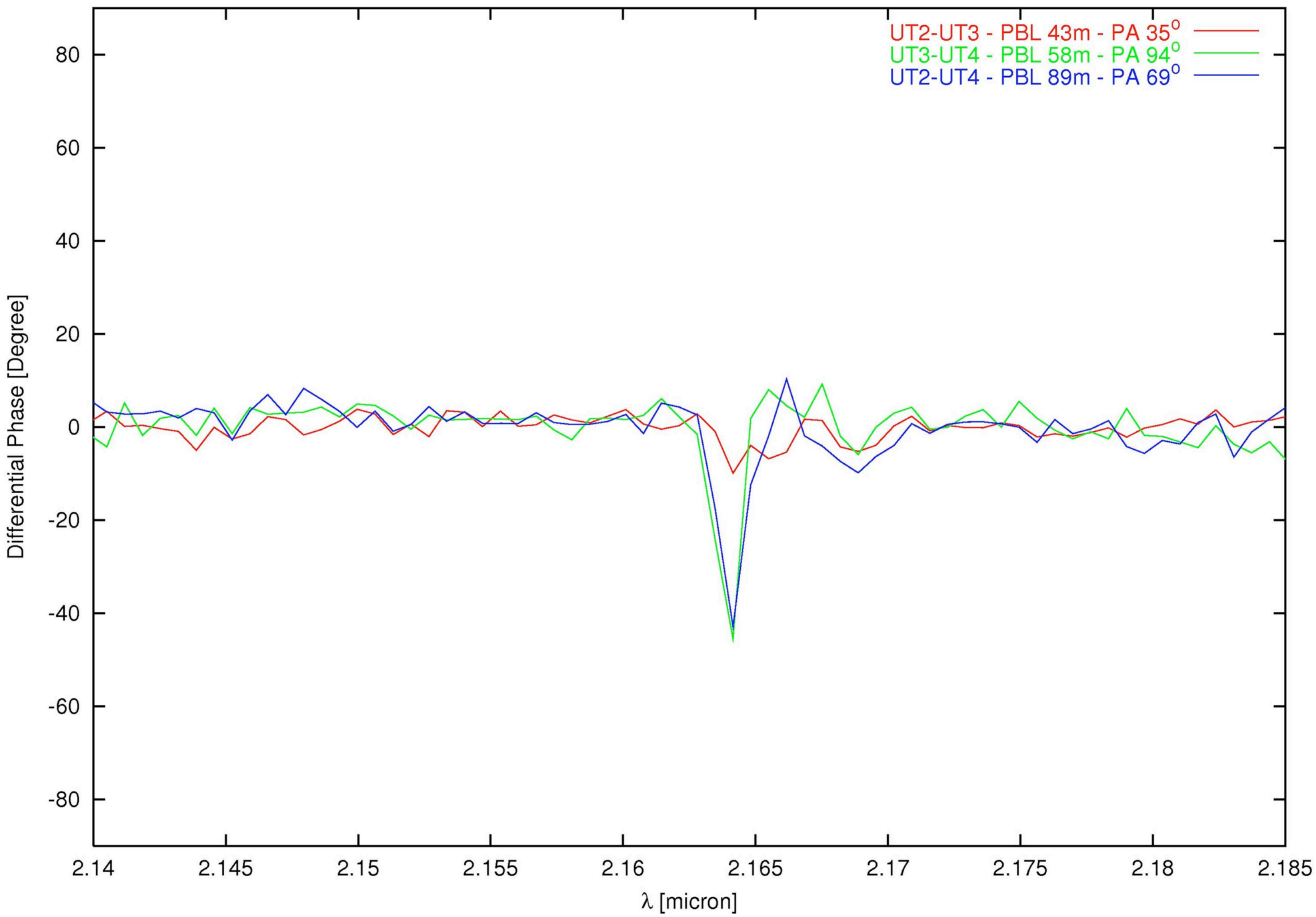


R. Petrov

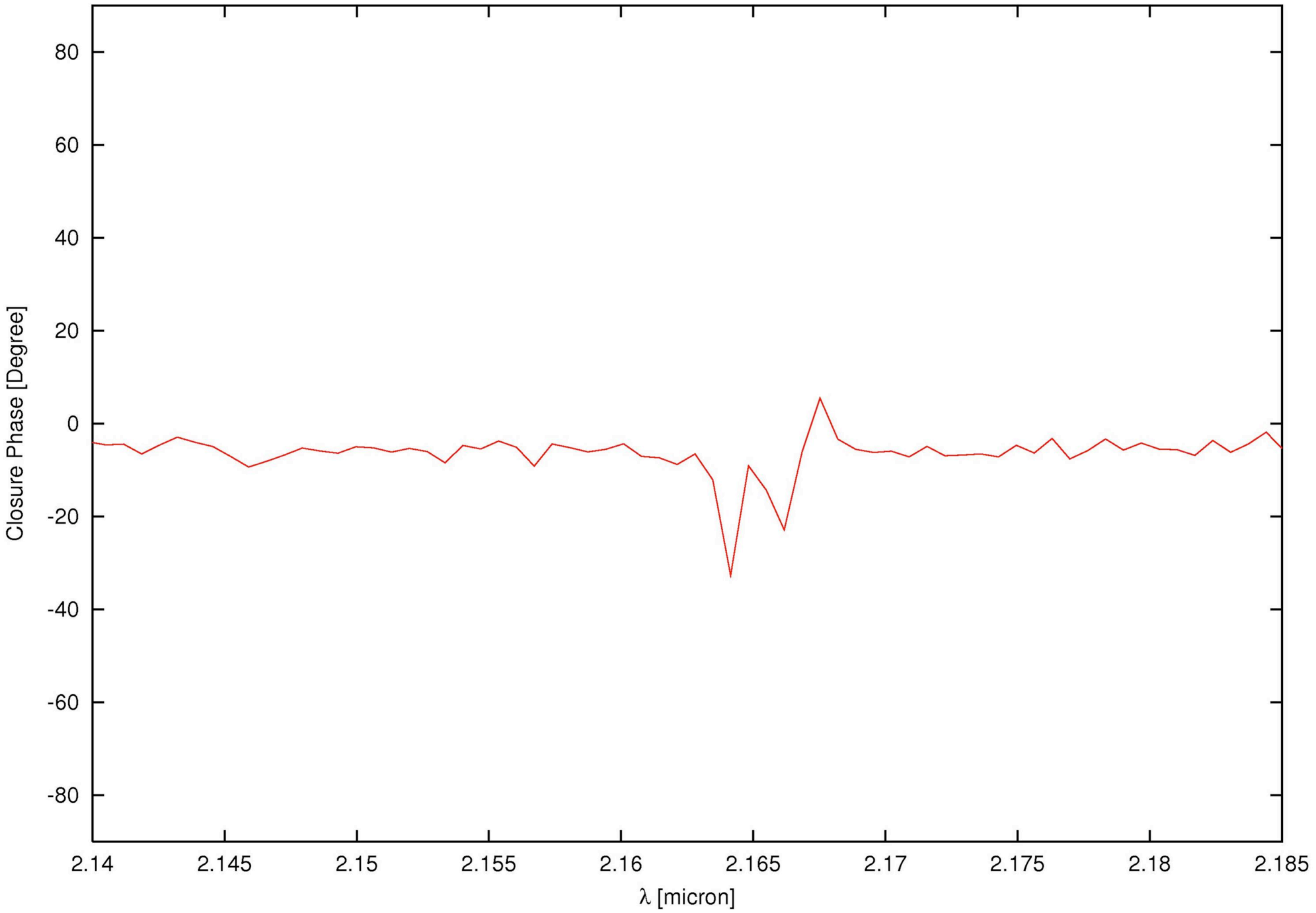
Visibilities; baseline lengths 29, 61, 67 m; high spectral resolution 10 000

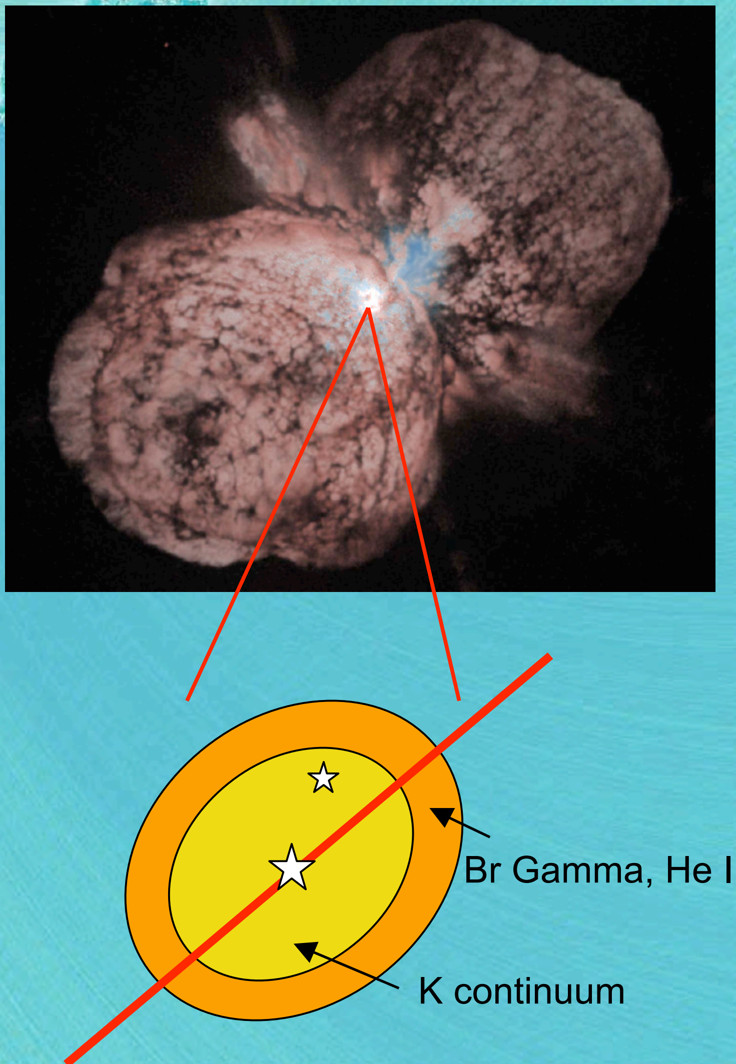


Differential phases; baseline lengths 43 m, 58 m, 89 m; medium spectral resolution1500



Closure phase; baseline lengths 43 m, 58 m, 89 m; medium spectral resolution1500





Polar axis of optically thick wind:

Axis ratio approx. 1:1.2

diameter 5 mas/7mas in continuum/Br Gamma, He I

Summary: VINCI interferometry revealed that η Car's optically thick, non-spherical wind region has a size of ~ 5 mas (axis ratio 1.2, PA 130°) (van Boekel et al. 2003). This non-spherical wind can be explained by models for line-driven winds from luminous hot stars rotating near their critical speed (Owocki et al. 1996, Dwarkadas & Owocki 2002, von Zeipel 1924). The models predict a higher wind speed and density along the polar axis than in the equatorial plane.

AMBER observations of Eta Car (K continuum, He I 2.06 µm, Br Gamma 2.16 µm emission lines) allowed the study of Eta Car's aspheric wind with high spatial and high spectral resolution. Future goals:

- Study of the wavelength dependence the optically thick aspheric wind and comparison of the observations with the predictions of the Hillier model (non-LTE line blanketing code of Hillier & Miller 1998).

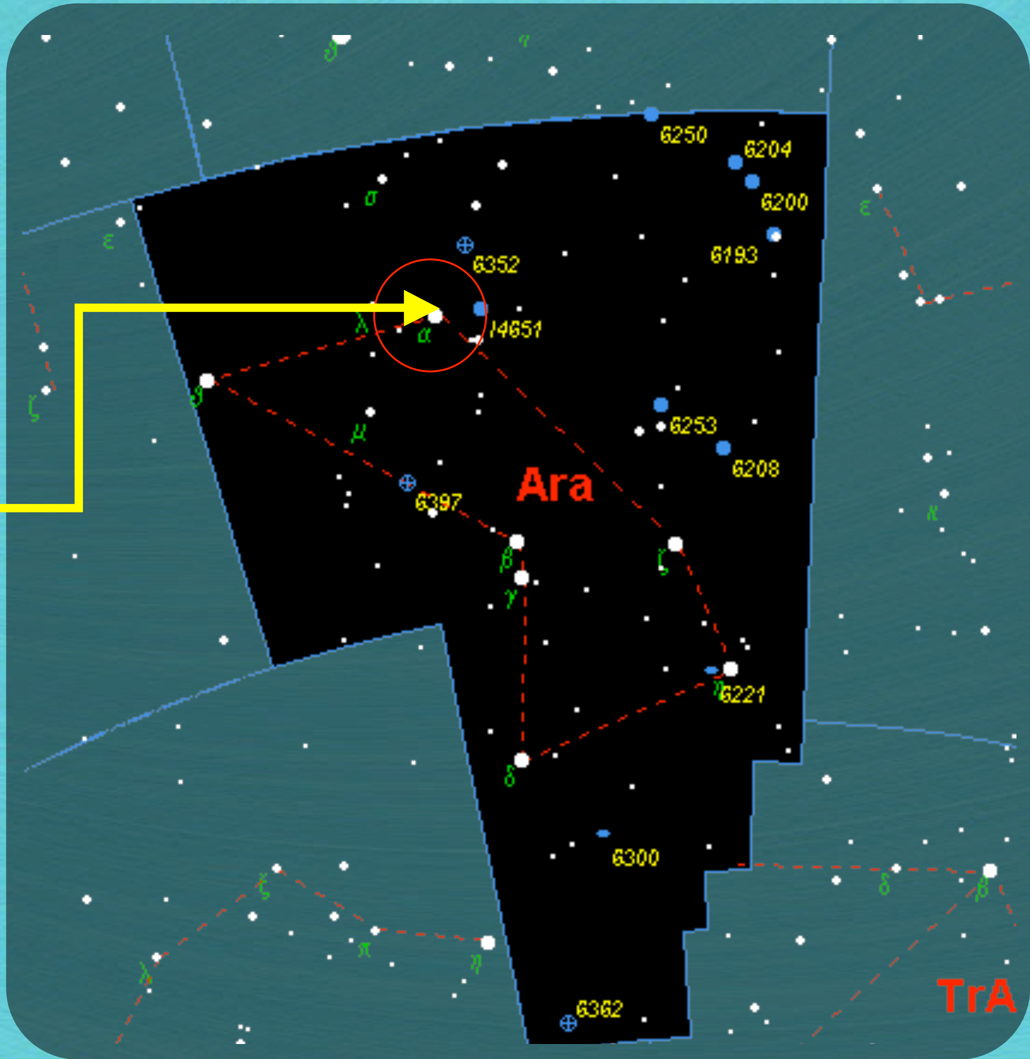
- Is the 5.5 yr periodicity of spectroscopic events caused by a companion or can it be explained by periodic shell eruptions?

Kinematics of the disk around the Be star α Arae

Stellar parameters

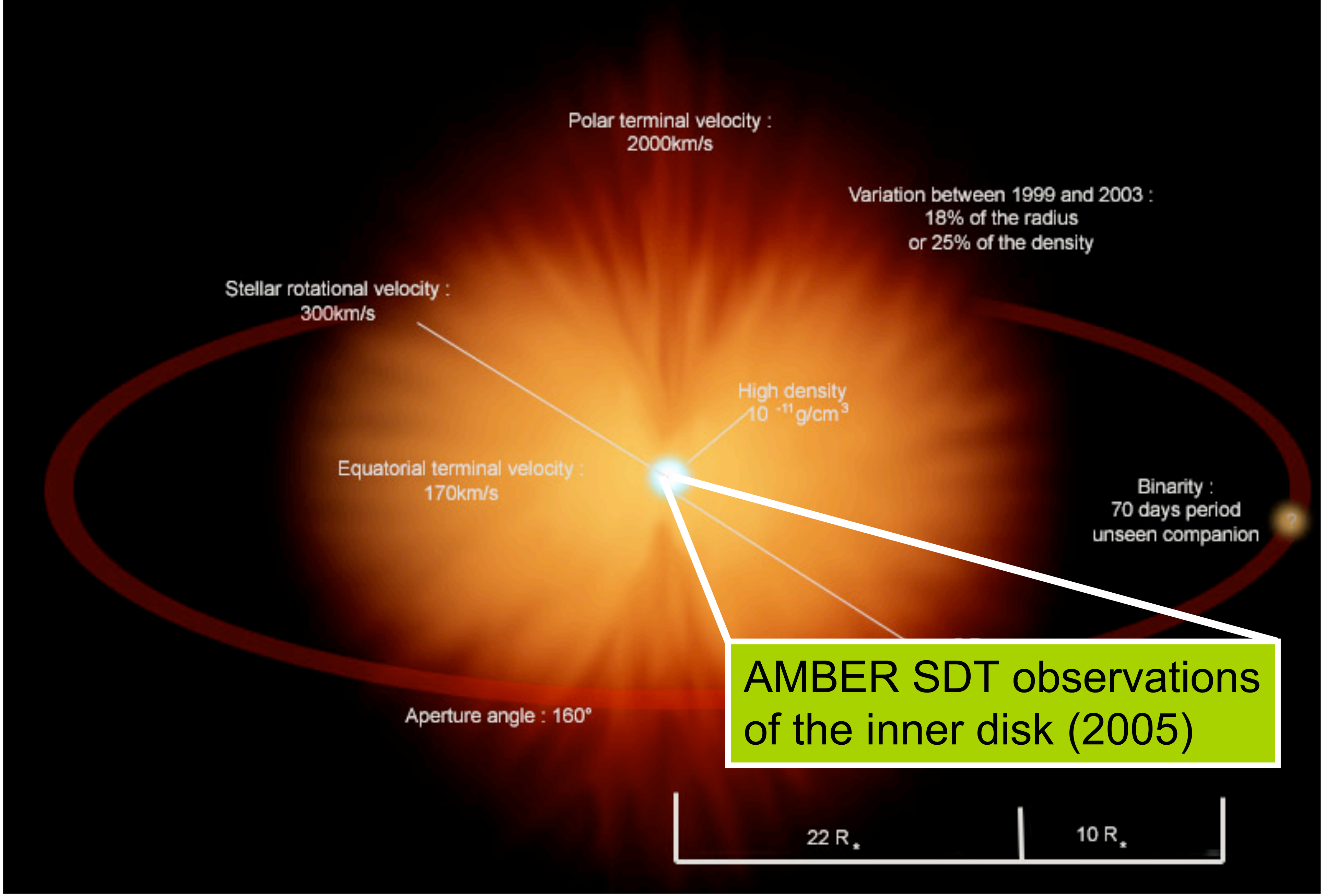
α Ara

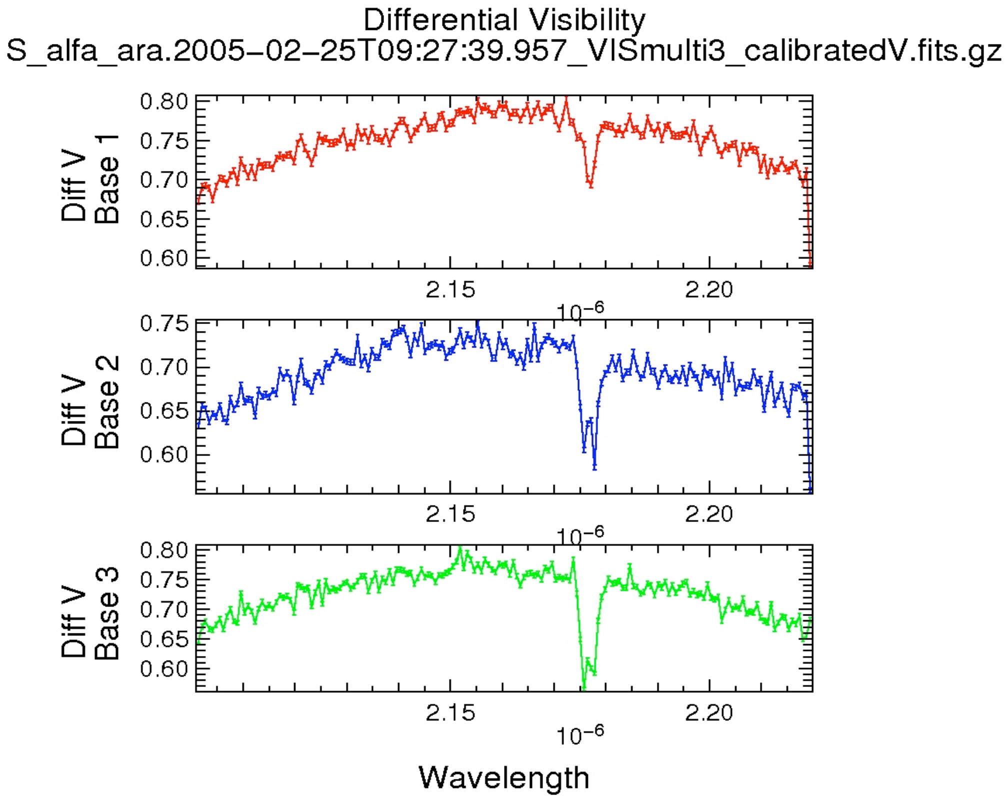
B3Vne
m_V=2.8
m_K=3.8
Teff = 18000 K
$R_* = 4.8\ R_o$
$M_* = 9.6\ M_o$
Vsin i = 220-300 km/s
Distance : 74 pc
Polarization : 172°



Courtesy Ph. Stee 2005

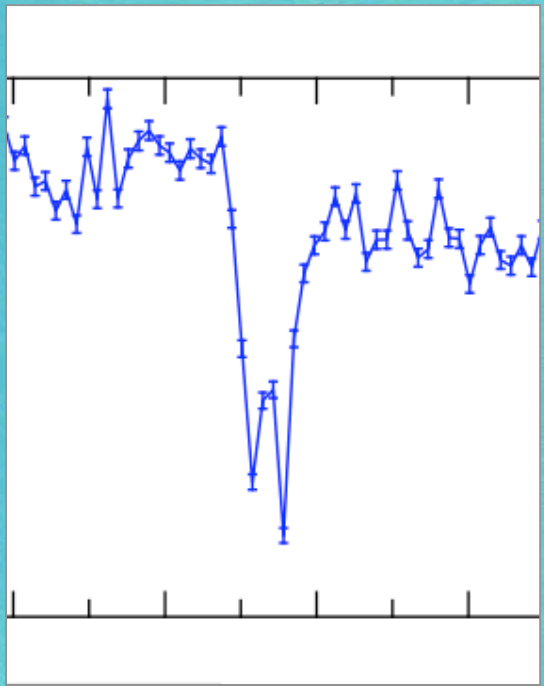
Schematic view of the α Arae circumstellar environment



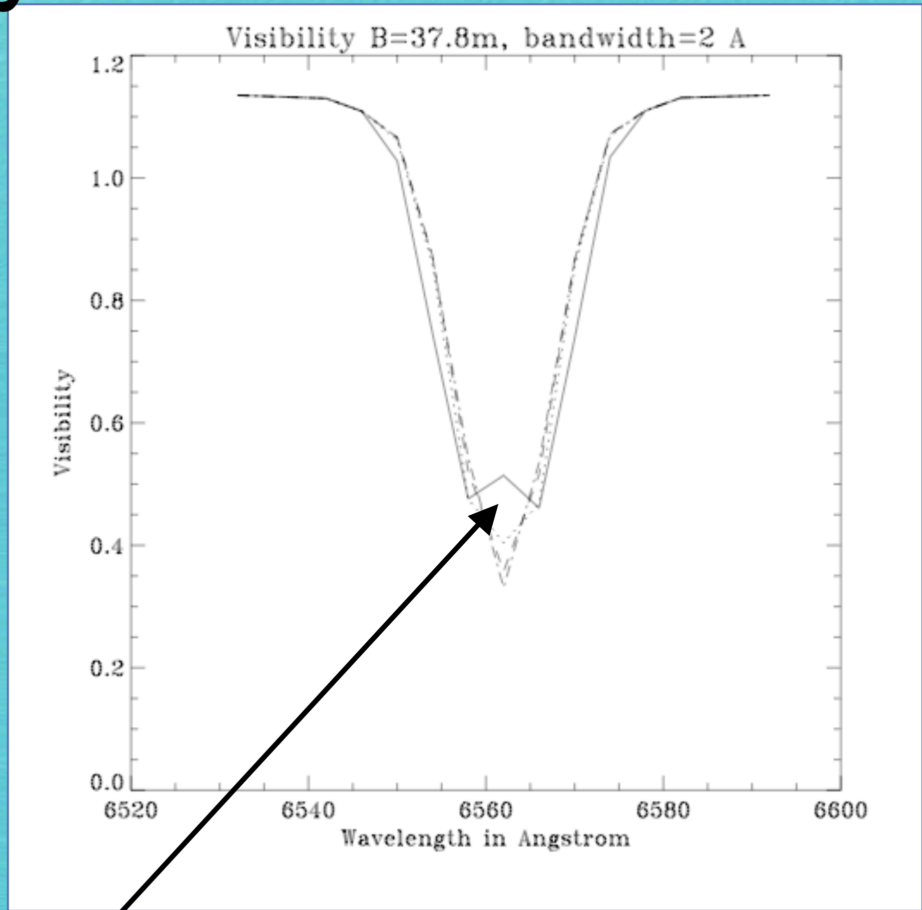


Spectraly resolved visibilities across the Brγ line

Visibility Modulus

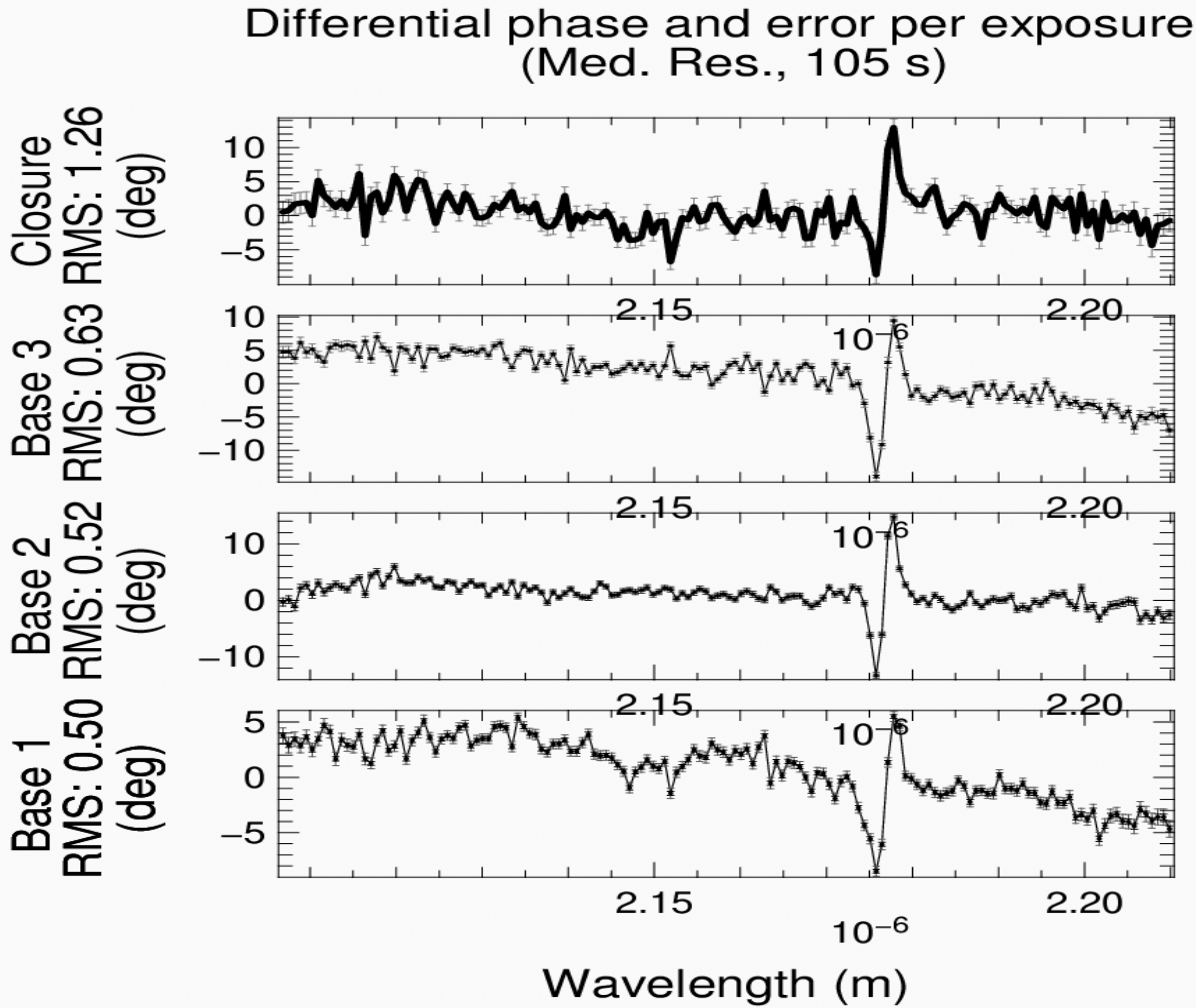


Visibility



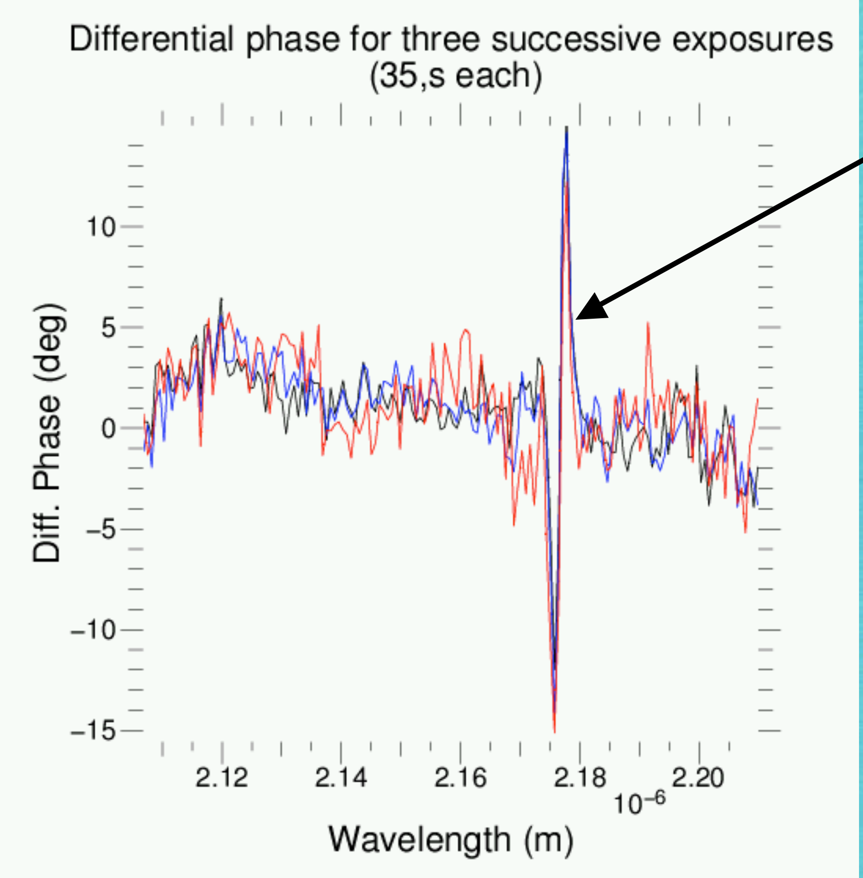
Keplerian rotation

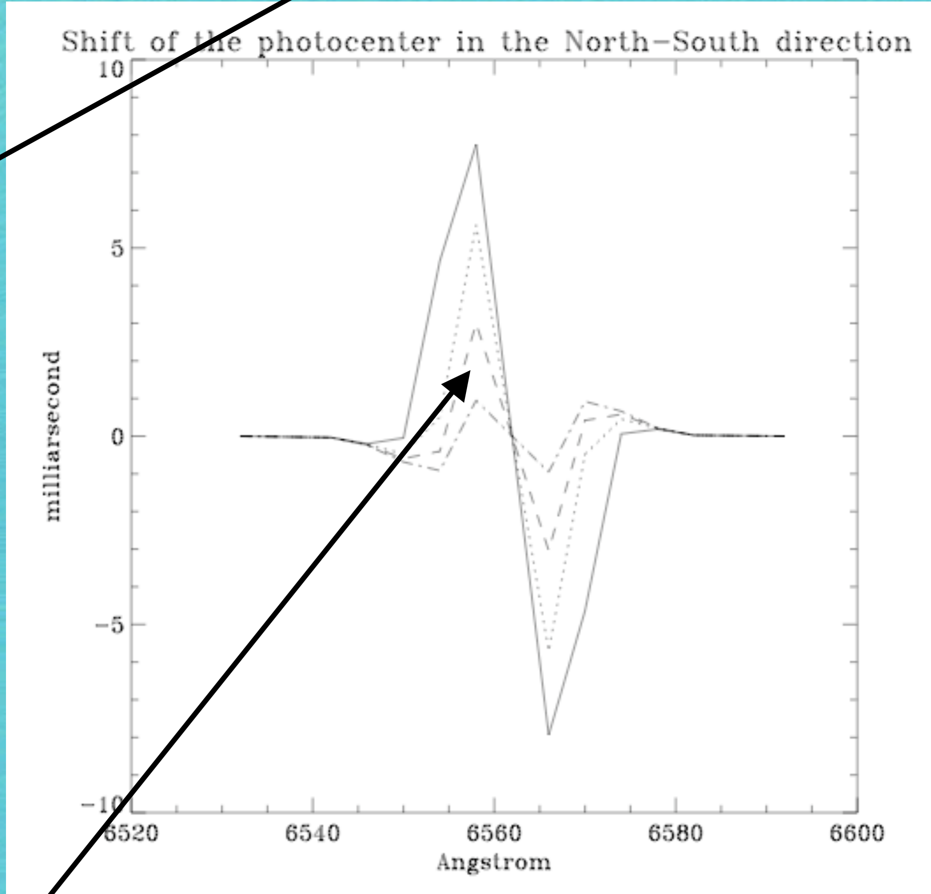
Theoretical visibilities using the SIMECA code
from Stee 1996, A&A, 311



Differential phase and error per exposure
(Med. Res., 105 s)
Closure
RMS: 1.26
(deg)
Base 3
RMS: 0.63
(deg)
Base 2
RMS: 0.52
(deg)
Base 1
RMS: 0.50
(deg)
2.15
2.20
10^{-6}
Wavelength (m)

Amplitude ≈ 20° ≈ 0.42 mas





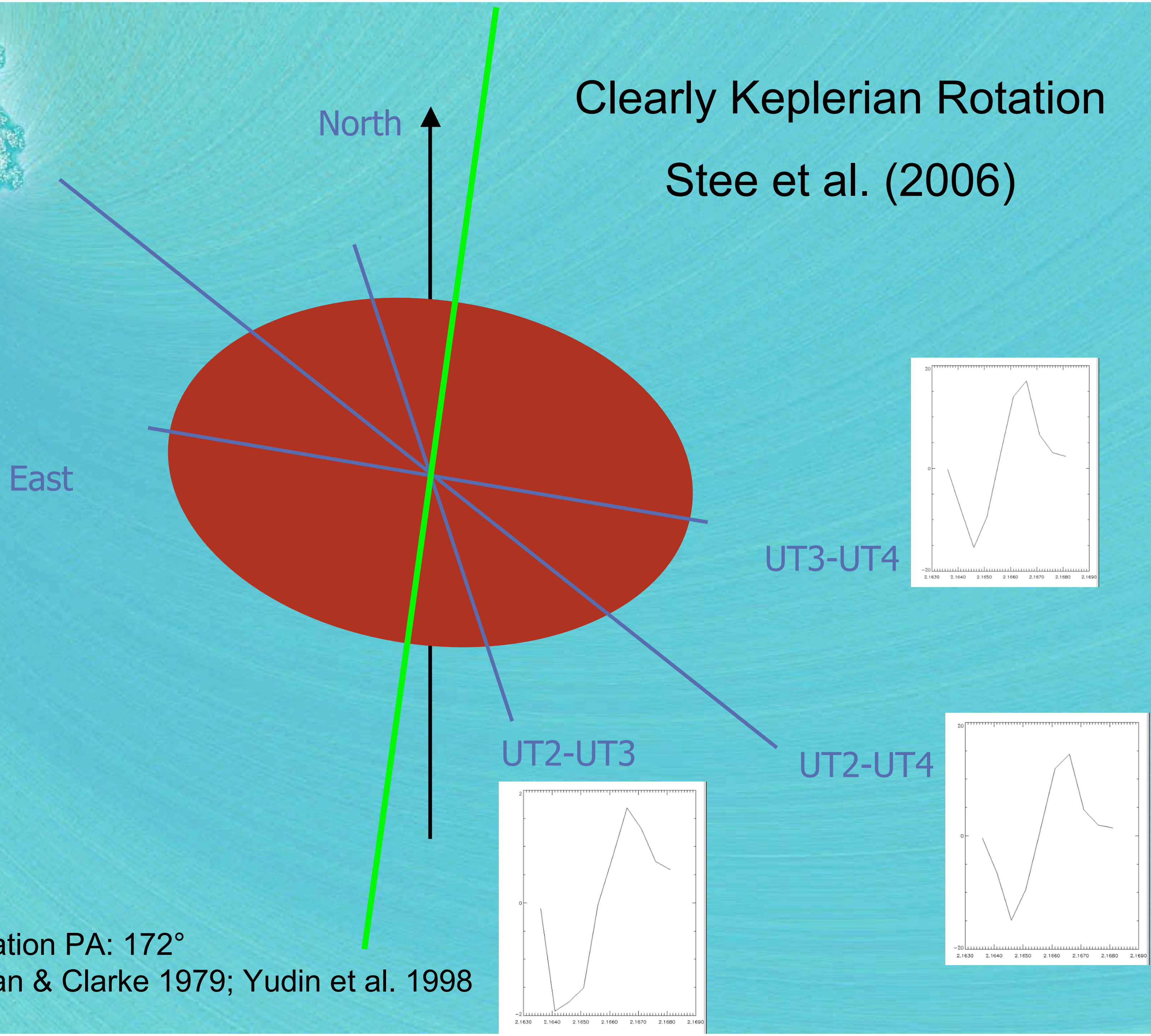
AMBER phase

Keplerian rotation

Theoretical phase using the SIMECA code
from Stee 1996, A&A, 311

Clearly Keplerian Rotation

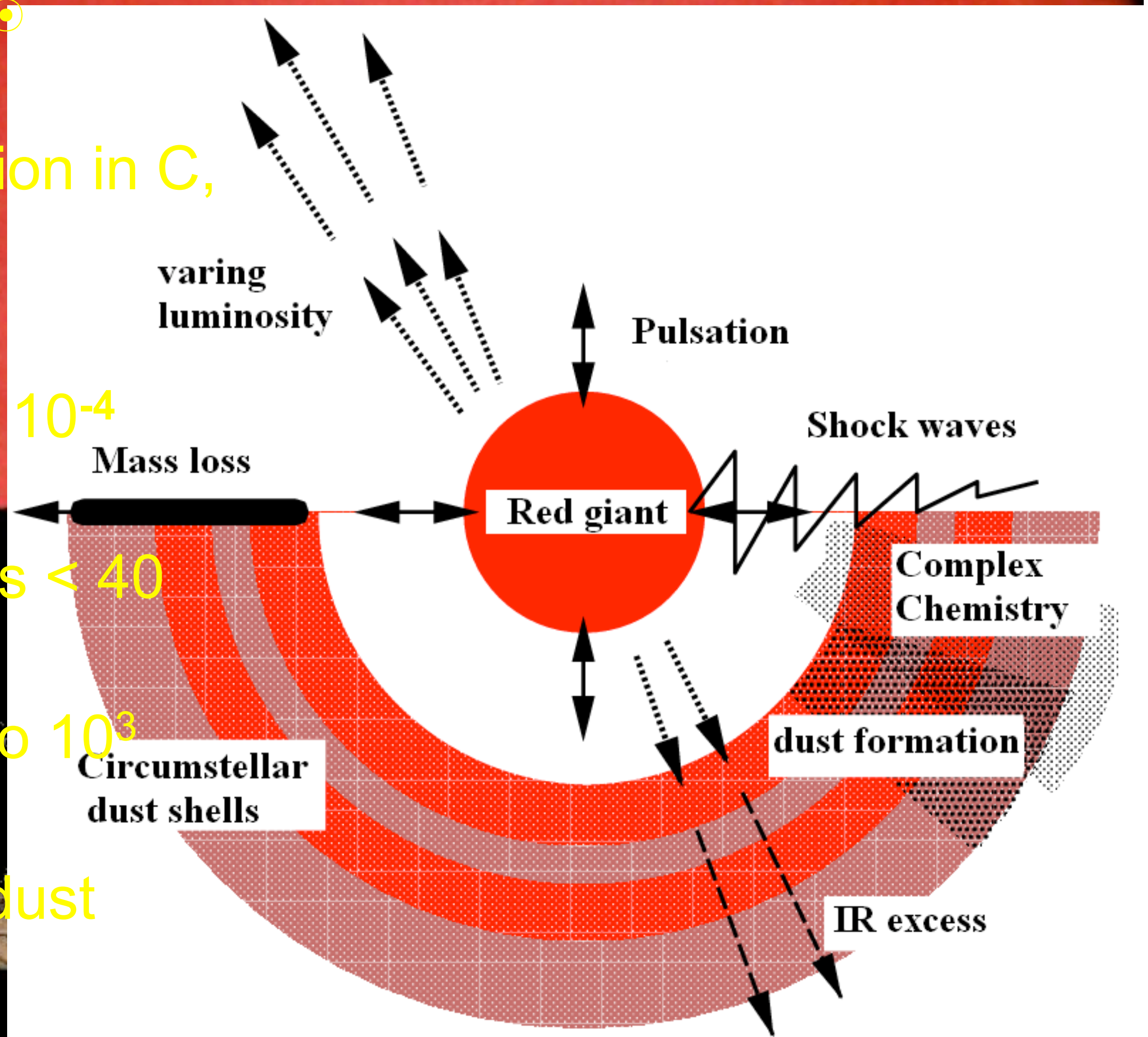
Stee et al. (2006)



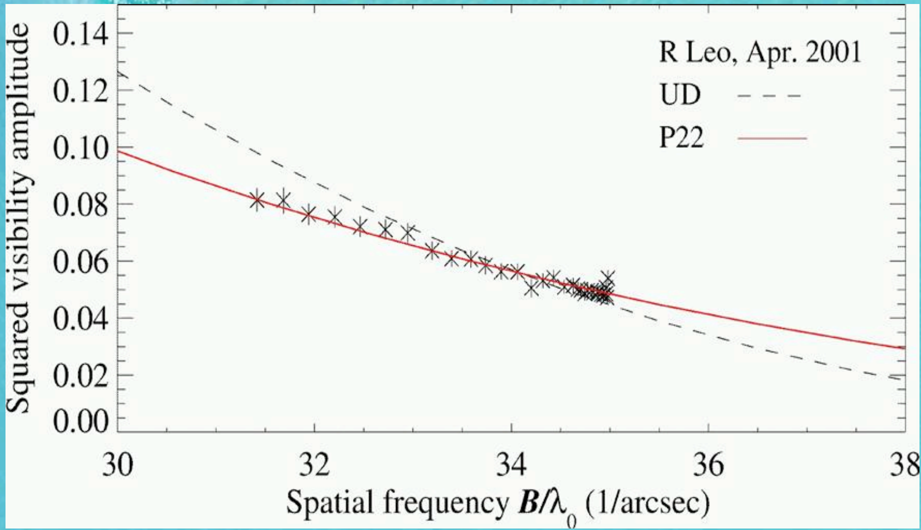
Polarization PA: 172°
(Mc Lean & Clarke 1979; Yudin et al. 1998

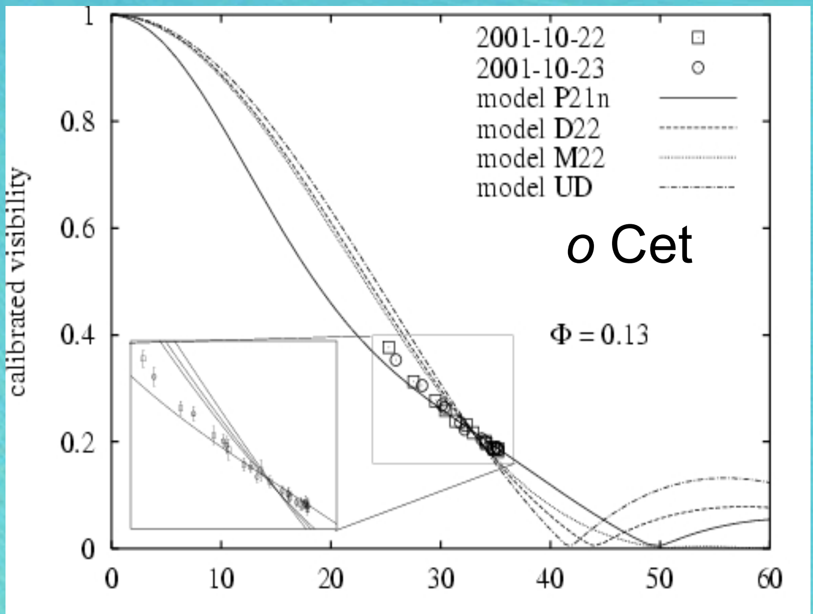
Miras & LPVs

- Luminosities ~ 10^4 $L_\odot$
- T_{eff} < 3000 K
- "Chemical" classification in C, M, and S stars
- Dust formation
- Mass loss rates up to 10^{-4} $M_\odot$/yr
- Final outflow velocities < 40 km/s
- Pulsation period 10^2 to 10^3 days
- Correlation between dust shell and variability



VINCI observations of the Miras *o* Cet and R Leo

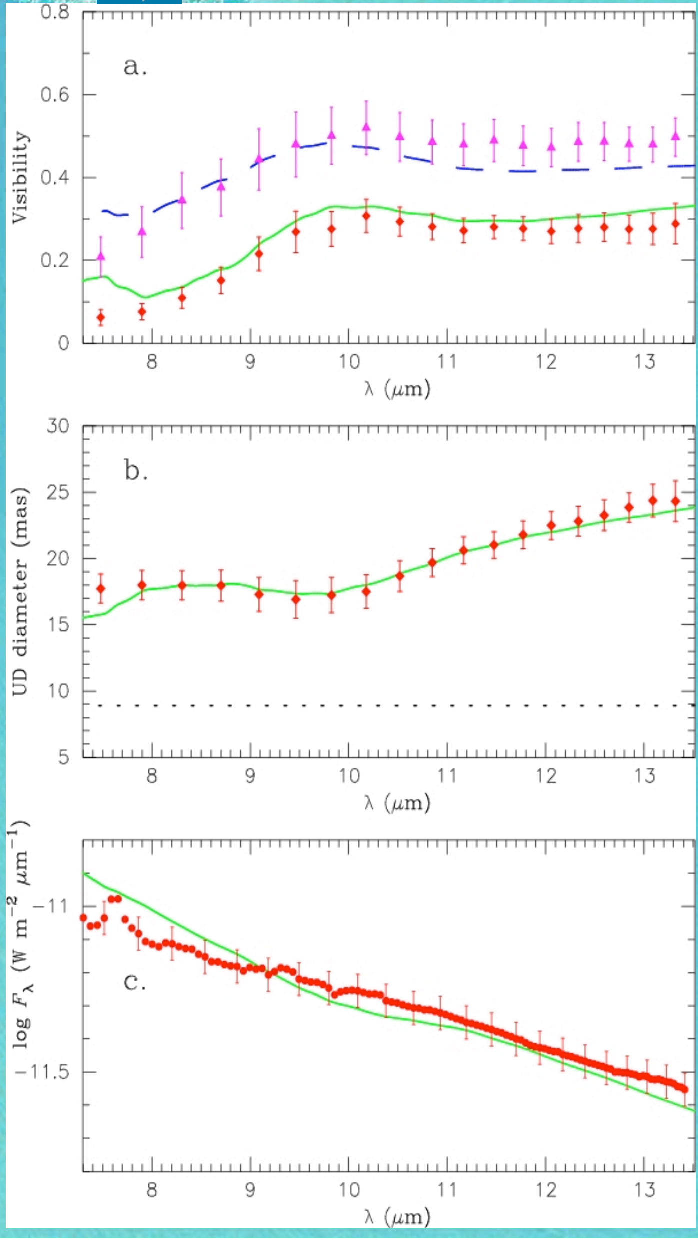




Woodruff et al. (2004); Fedele et al. (2005)

- VLTI/VINCI observations of the prototype Mira stars o Cet and R Leo.
- The CLVs are different from a UD model already in the first lobe, and consistent with predictions by dynamic atmosphere models that include effects by close molecular layers.

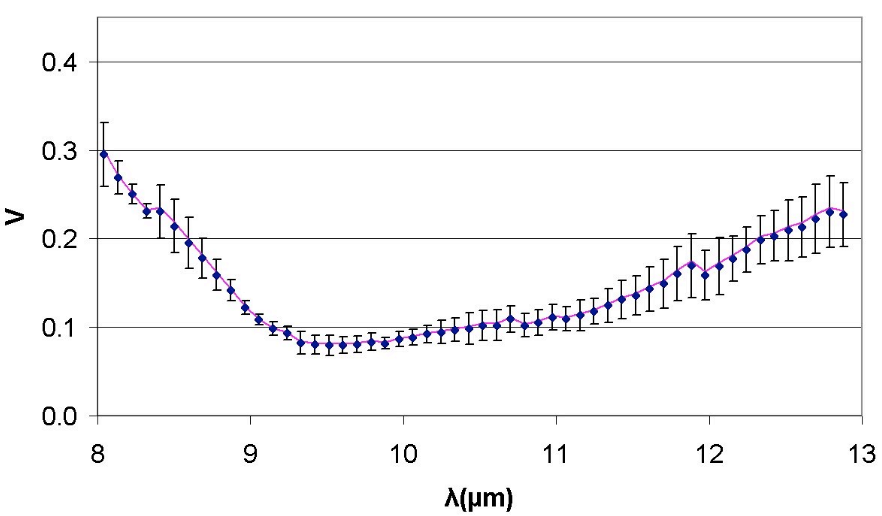
MIDI observations of the Mira star RR Sco

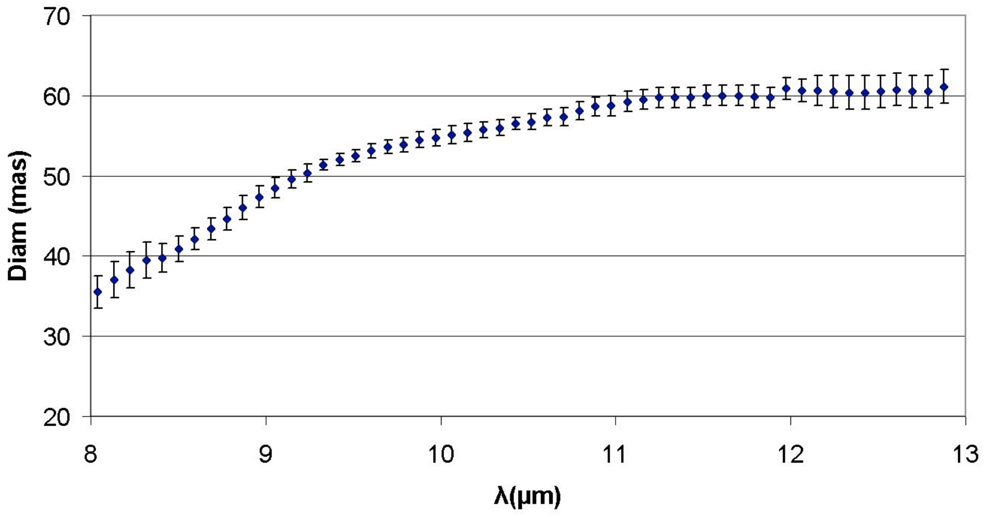


Ohnaka et al. (2005)

- Visibility from 7-13 microns with a spectral resolution of 30.
- Equivalent uniform disk diameter increases from 15 mas @ 7 microns to 24 mas @ 13microns.
- Equivalent UD diameter in the K-band at about same time is 9 mas (VINCI).
- Molecular layer of SiO and water extending to 2.3 stellar radii with a temperature of 1400 K (opt. thick).
- Dust shell of silicate and corundum. Inner radius 7-8 stellar radii (opt. thin).

IW Hya with VLTI/MIDI

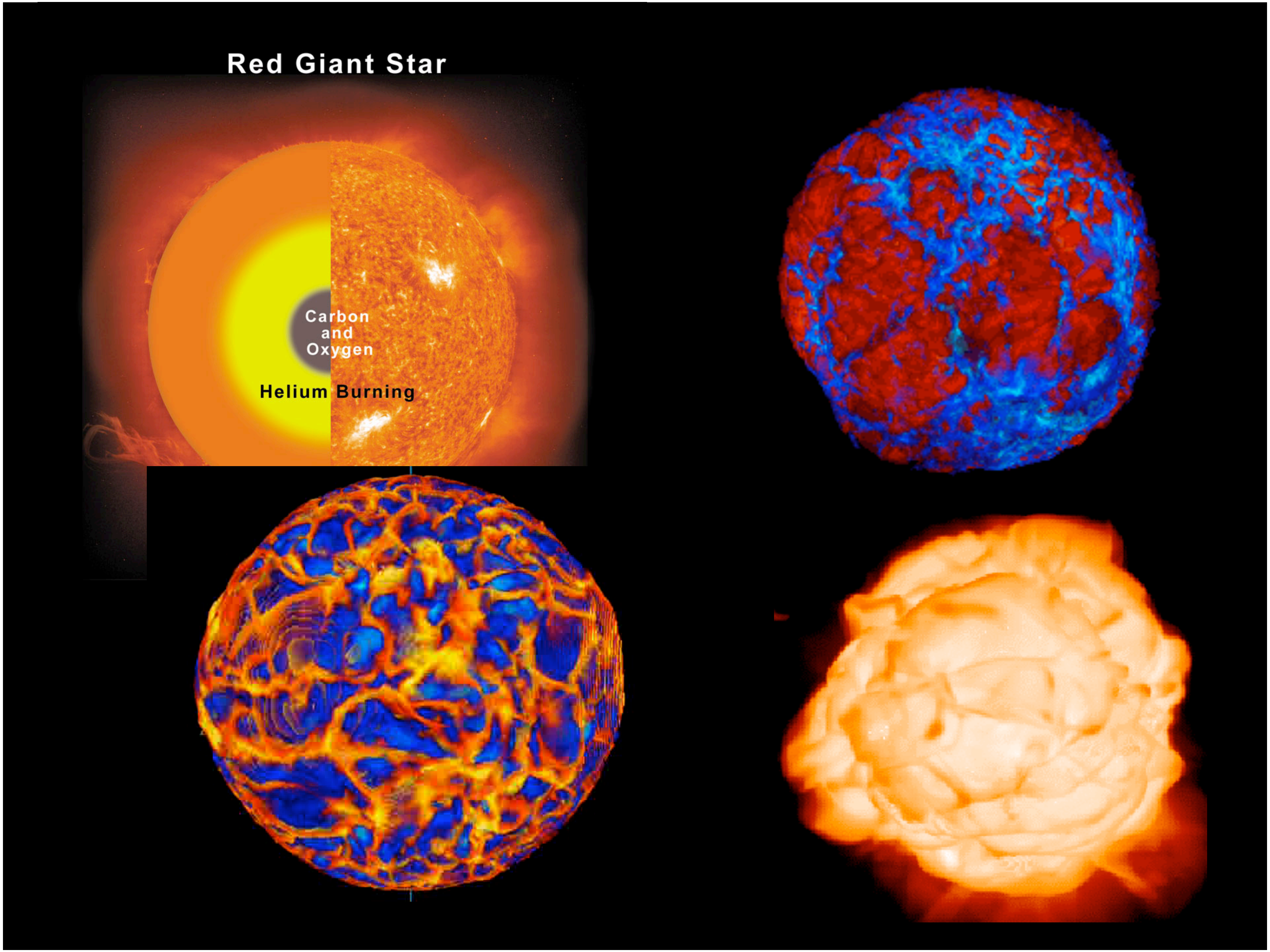




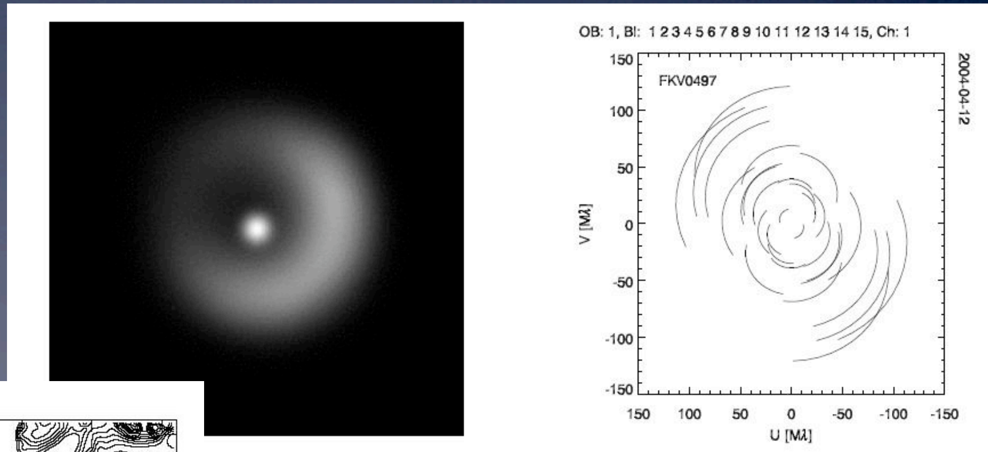
More observations (MIDI/AT, AMBER/UT) for P77

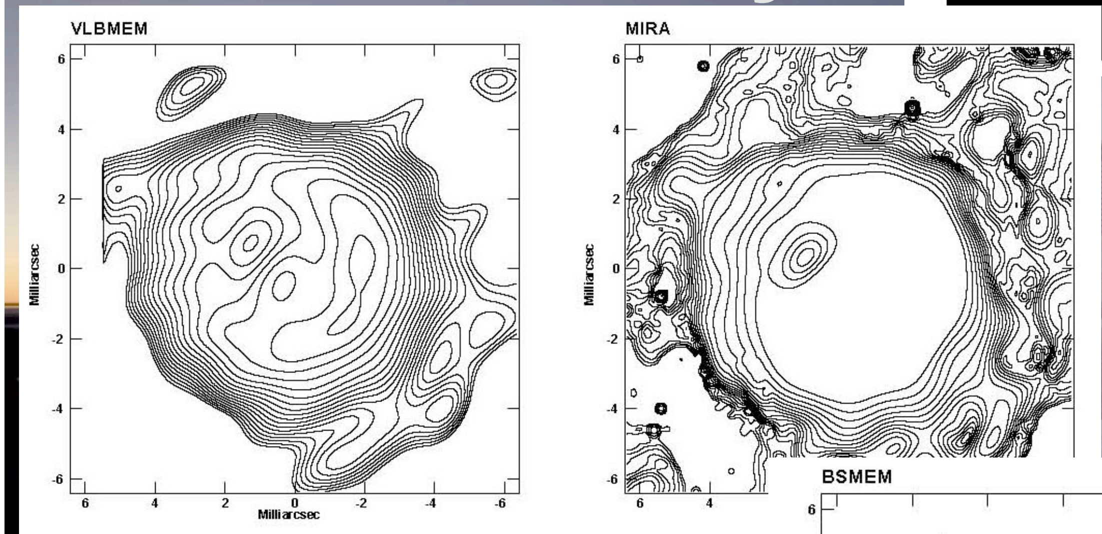
- improve span in PA & baseline
- investigate central star (diameter, T_{eff})
- follow pulsation cycle (~2 years)

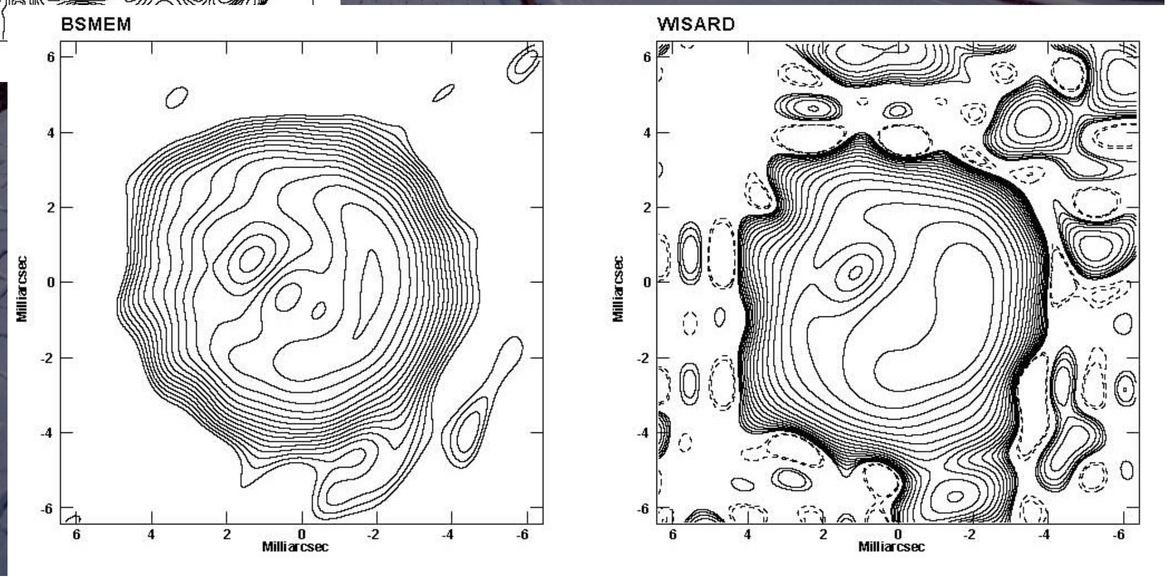
Preliminary results by Jeong & Richichi (2005)


Red Giant Star
Carbon
and
Oxygen
Helium Burning

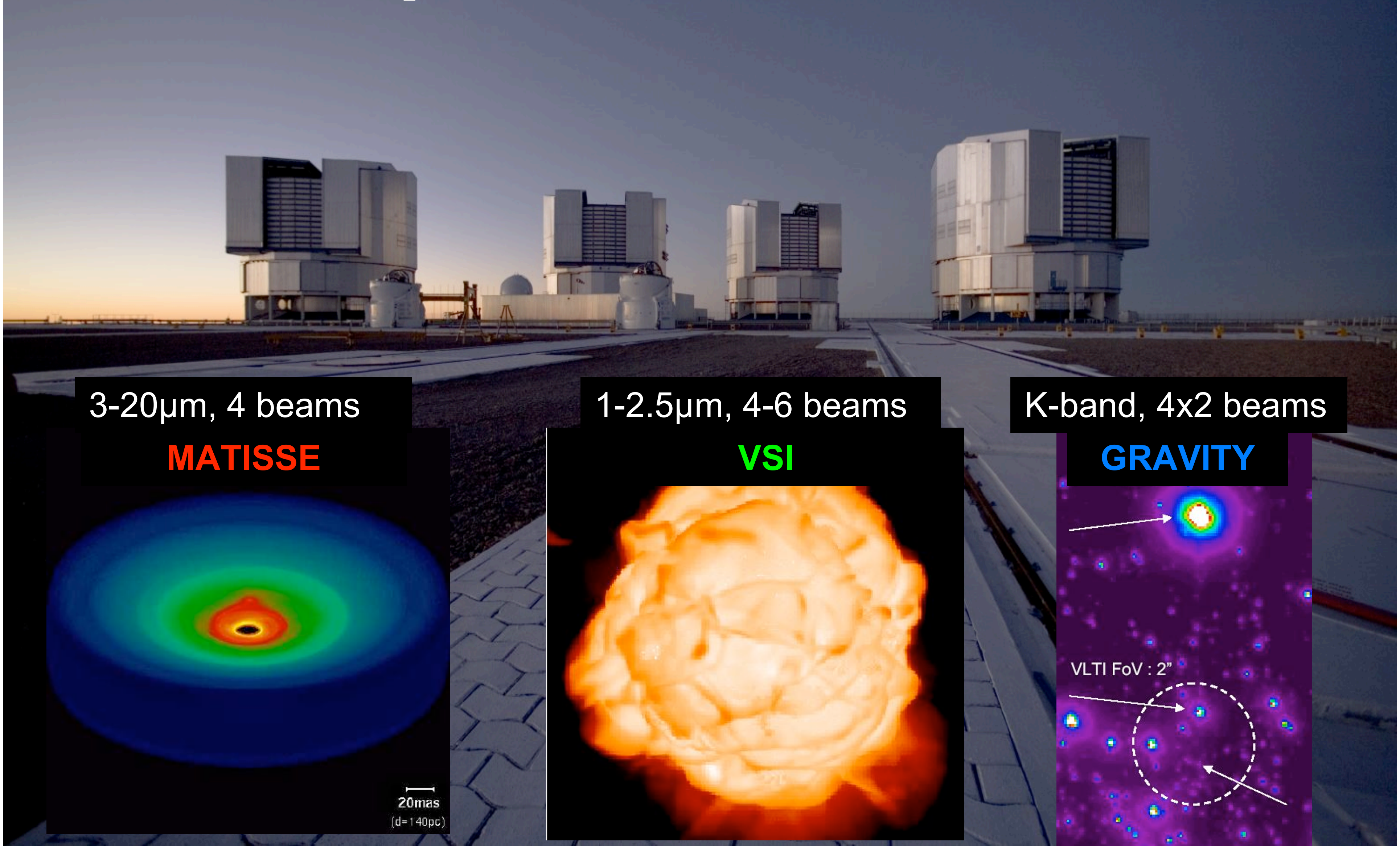
Imaging in Optical Interferometry







2nd Generation VLTI Proposed Instruments



How to obtain and use VLTI data

- Public Archive (VINCI~20000 OBs, SDT, MIDI, AMBER): register as an Archive user
- Write your own proposal
- VINCI: pipeline
- MIDI: MIA/EWS software (IDL)
- AMBER: Ammyorick, Reflex

Conclusions

- VLTI is well-developed, open, user-friendly facility
- Flexible baseline system gives wide *uv* coverage
- Most powerful combination of long baselines and large telescopes
- Standard system of observation, data quality and data analysis
- Several diverse scientific issues can be addressed with 0.001” resolution
- 2nd Generation of Instruments by 2010

www.eso.org/vlti