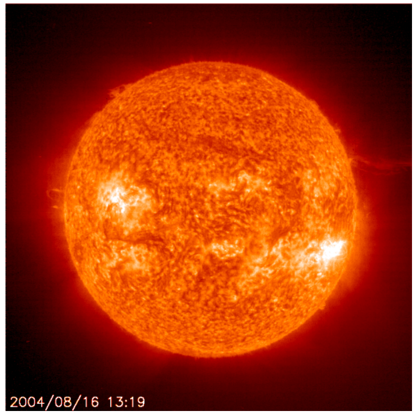
Stellar Astrophysics based on optical long-baseline interferometry -present and future-



Markus Wittkowski (ESO)

1st Joint ARENA/OPTICON JRA4 Workshop
Interferometry
10-12 May, 2006
Maison du Seminaire, Nice, France

Outline of the talk

- Current interferometric facilities
- Current stellar astrophysics based on interferometry
- Planned upgrades and their science cases
- Remaining science cases

Proceedings of the 37th Liege International Astrophysical Colloquium, “Science Cases for Next Generation Optical/Infrared Interferometric Facilities”, 23-25 August 2004.

olbin.jpl.nasa.gov by Peter Lawson.

Thanks to Andrea Richichi (ESO) for providing some figures/slides.

Currently used interferometric facilities

CHARA	Mt. Wilson, California	6 x 1.0 m	350 m	0.5-0.8 µm, 2.0-2.4 µm
IOTA	Mt. Hopkins, Arizona	3 x 0.4 m	38 m	0.7-2.2 µm
Keck-I	Mauna Kea, Hawaii	2 x 10.0 m +?	80 m +?	2 mm,10 µm nulling
NPOI	Flagstaff, Arizona	6 x 0.5 m	66m (437m)	0.4-0.9 µm
SUSI	Narrabi, Australia	2 x 0.14 m	640 m	0.4-0.9 µm
VLTI	C. Paranal, Chile	4 x 8.2 m + 4 x 1.8 m	200 m	1-2.5 µm, 8-13 µm

The VLT Interferometer

- Four 8.2-m Unit Telescopes. Baselines up to 130m
- Four 1.8-m Auxiliary Telescopes. Baselines 8 – 200m
- Near-IR to MIR (angular resolution 1-20 mas)
- Excellent uv coverage
- 1st Gen Instruments
- IR tip-tilt in lab (IRIS)
- Adaptive optics with 60 actuator DM, Strehl >50% in K - Guide Star $m_V < 16$ (MACAO)
- Fringe Tracker
- Dual-Feed facility (PRIMA)
- 2nd Gen Instruments

1.8-m Auxiliary Telescopes (ATs) of the VLTI

- increase u-v coverage
- movable
- designed for interferometry, optical path same as UT
- Manufactured by AMOS (Liège, Belgium)
- First fringes 2T Feb05
- AT3 late 2005
- AT4 mid-2006

Facility Instrumentation of the VLTI

VINCI: K-band

MIDI: Mid-Infrared (8-13 μm) 2-way beam combiner.

Spectral resolution R=30 (prism), R=230 (grism).

AMBER: Near-Infrared (J, H, K; 1-2.5 μm) 3-way beam combiner.

Spectal resolution R=30 (low resolution), 1500 (medium r.), 12000 (high r.).

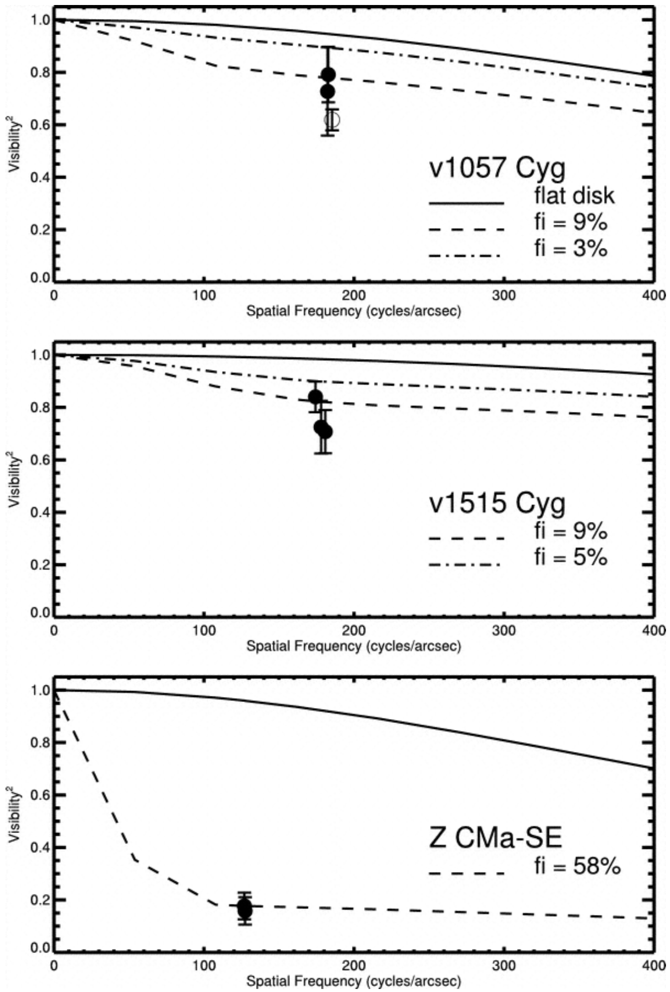
VLTI instruments and their operation are designed along the same lines of VLT instruments, in particular for what concerns standards, operation, data management.

Both instruments represent first-timers in their areas. ESO approach to provide interferometry at the same level as any other astronomical observation also represents a first-timer.

Current topics of interferometry-based stellar astrophysics

- Young stellar objects (Herbig Ae/Be, T Tauri, FU Orionis stars)
- (Protoplanetary) Disk structure around Herbig stars
- Stars with debris disks, Vega-like stars
- Cool dwarfs
- Be stars
- Rapid Rotators
- Limb-darkening
- Cepheid variables
- Mira variables (pulsation mechanism)
- Circumstellar environment of evolved stars
- Post-AGB stars, PNe
- Binary and multiple stars
- LBVs (Eta Car), exotic stars

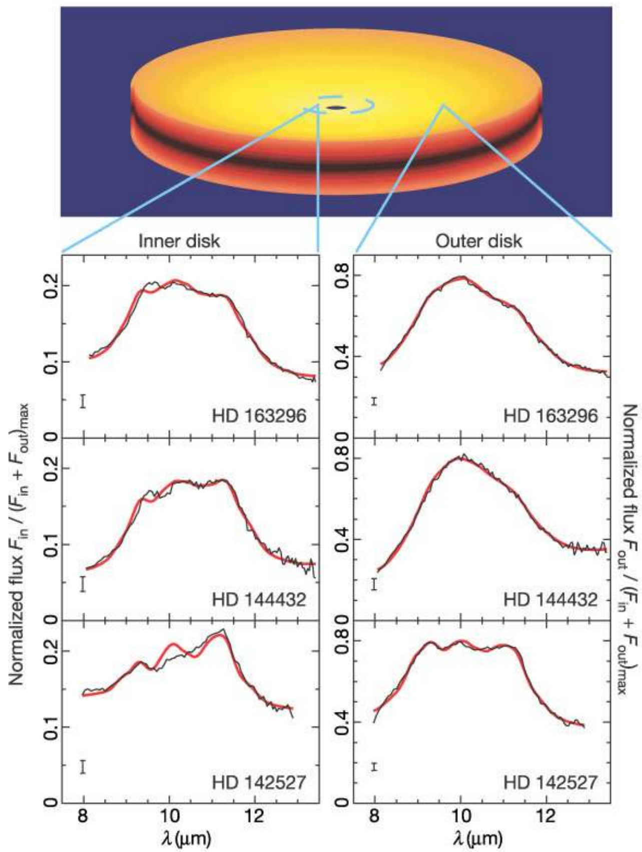
FU Orionis objects with the Keck Interferometer



Millan-Gabet et al. (2006)

- V1057 Cyg, V1515 Cyg, Z CMA-SE
- NIR emission is resolved, 0.4-4.5 AU
- More resolved than expected based on spectro-photometry
- Explained by additional large-scale envelopes.

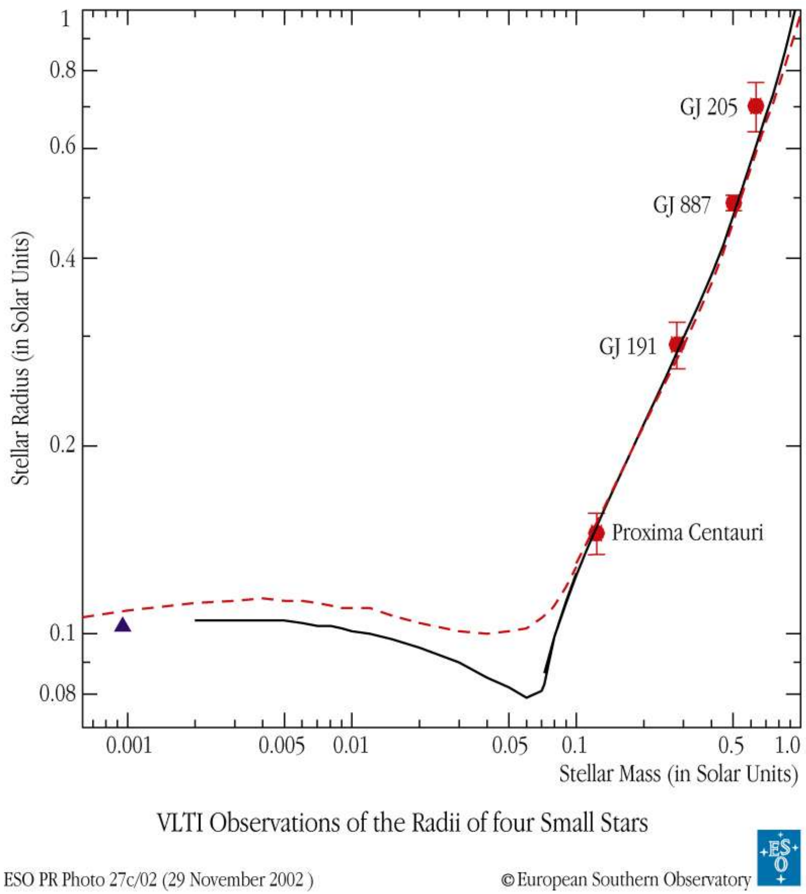
Protoplanetary disks around Herbig stars (VLTI)



Van Boekel et al. (2004)

- Three Herbig Ae stars observed with VLTI/MIDI.
- Separation of total disk, inner disk, and outer disk spectra.
- The inner-disk regions have a substantially higher degree of crystallinity than the outer regions (more "processed dust" closer to the star).
- Implications on the formation of planetary system.

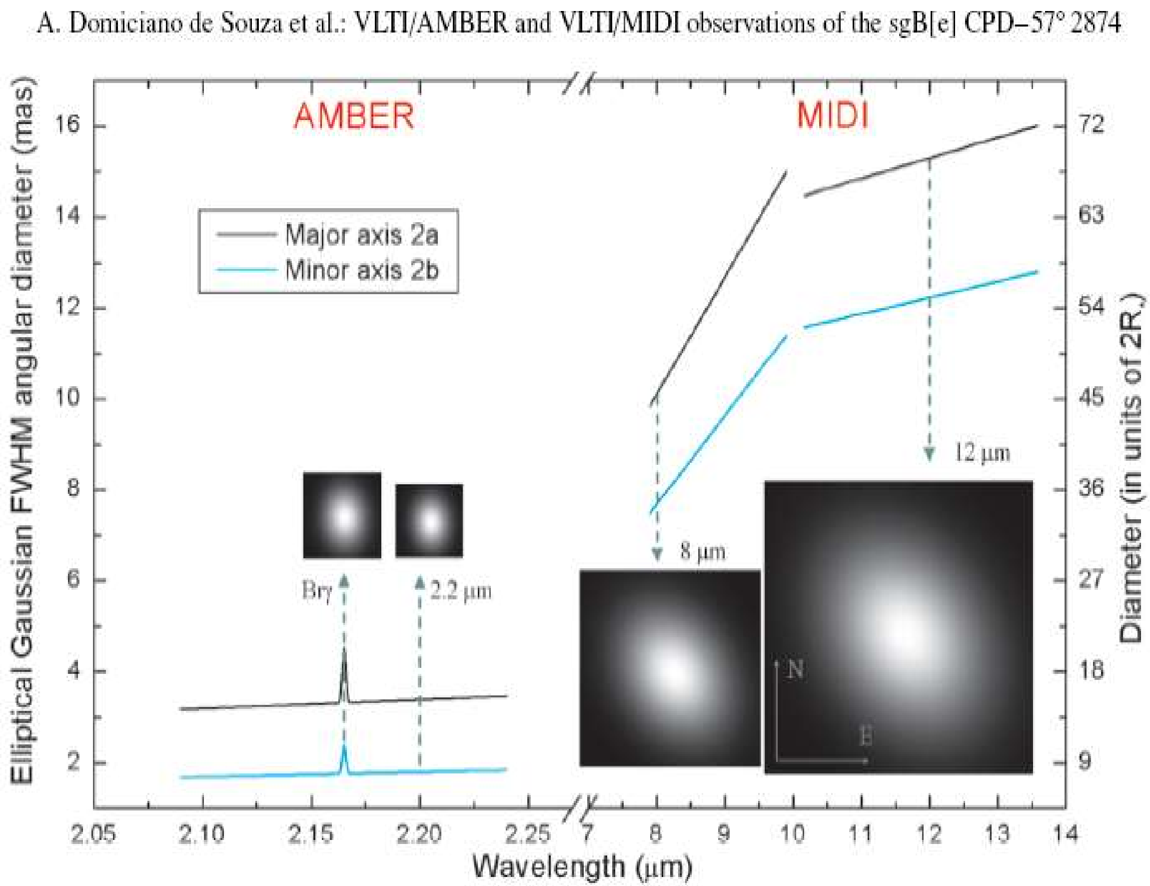
M-R relation of cool dwarfs compared to models



Segransan et al. (2003)

- 4 very low mass stars measured with VLTI/VINCI
- Angular diameters of 0.7-1.5 mas with precisions of 0.04-0.11 mas.
- Absolute radii with Hipparcos parallax; masses from empirical K-band mass-luminosity relation.
- Compared to theoretical isochrones from Baraffe et al (1998) for 5 Gyr and 0.4-1 Gyr.

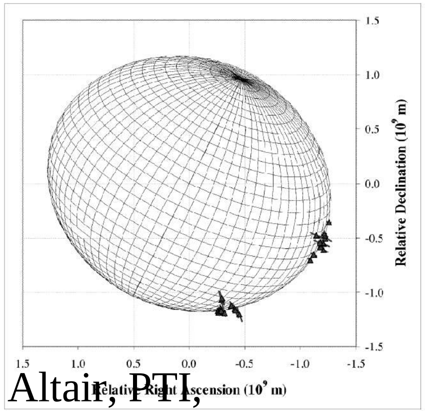
B[e] supergiant CPD-57 2874 observed with AMBER and MIDI



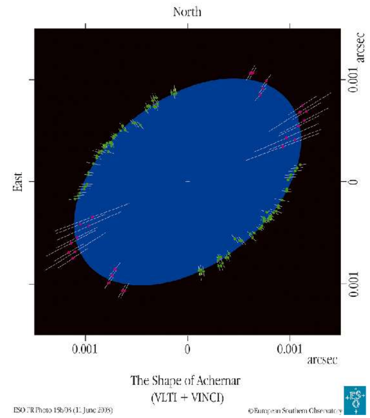
Domiciano de Souza et al. (2006)

- Spectra, visibilities and closure phases obtained with MIDI and AMBER.
- Consistent with elliptical Gaussian models with FWHM 1.8x3.4 mas at 2.2μm to 4.5x8.5 mas at 12μm.
- Brγ emitting region: 2.8x5.2 mas.
- Hints to a non-spherical disk-like structure.

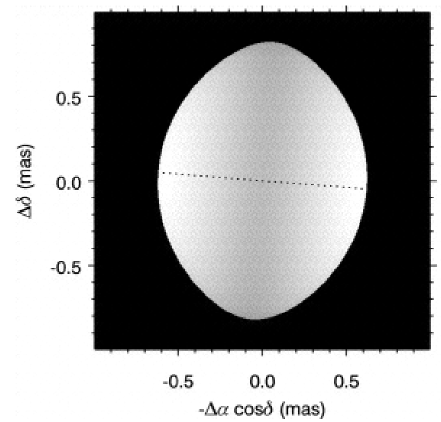
Rapid rotators



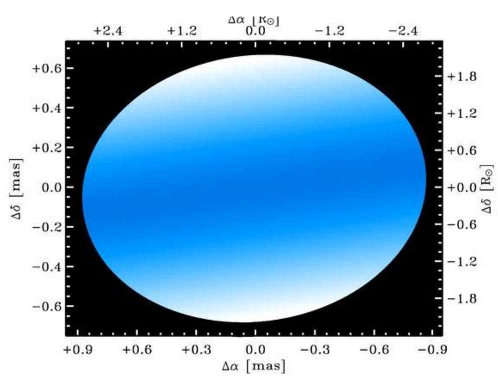
Altair, PTI,
van Belle et al. (2001)



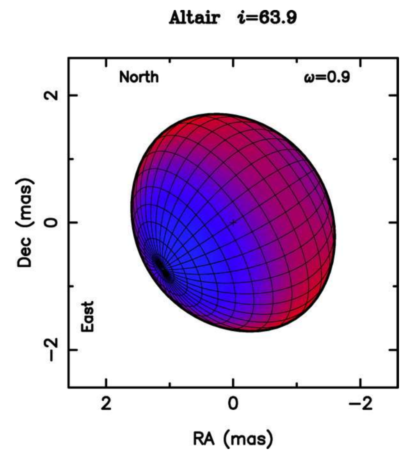
Achernar, VLTI/VINCI,
Domiciano et al. 2003



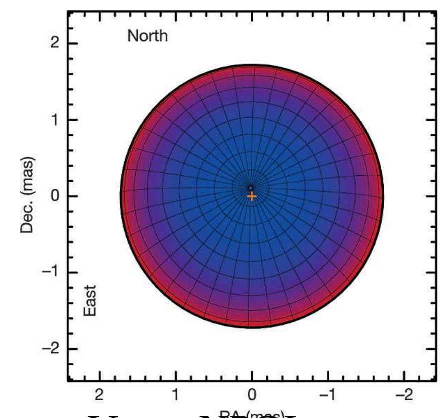
Regulus, CHARA,
McAlister et al. 2005



Aldemarin, CHARA,
Van Belle et al. (2006)

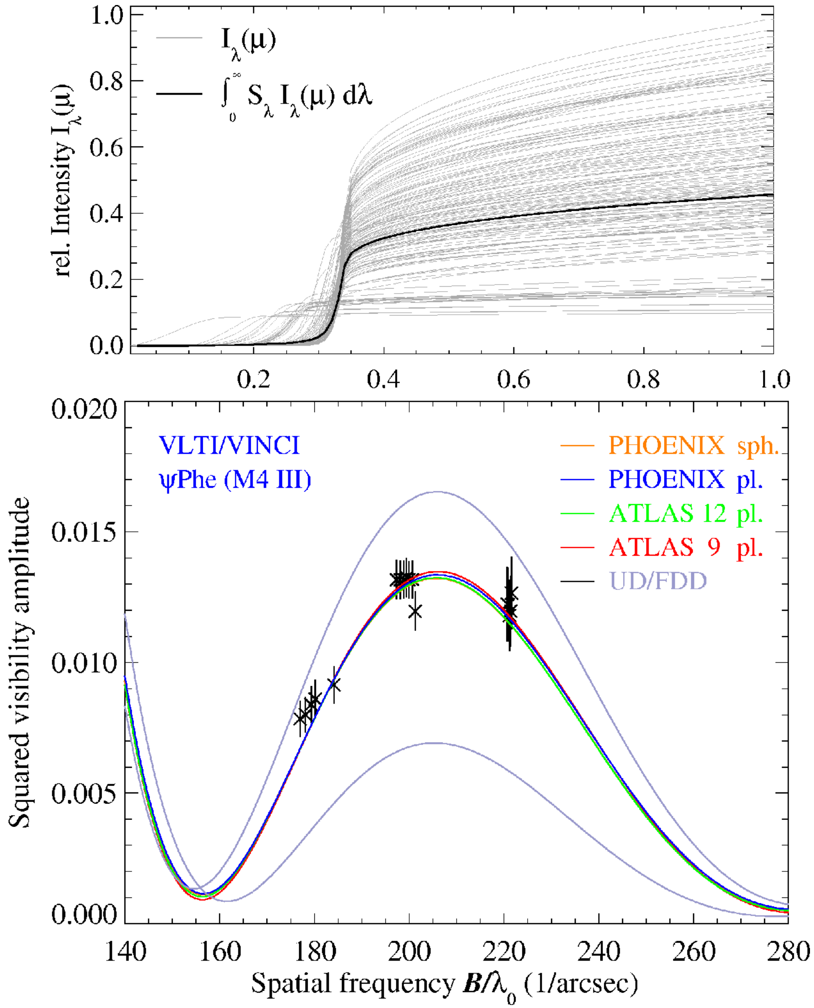


Altair, NPOI,
Peterson et al. 2006



Vega, NPOI
Peterson et al. 2006

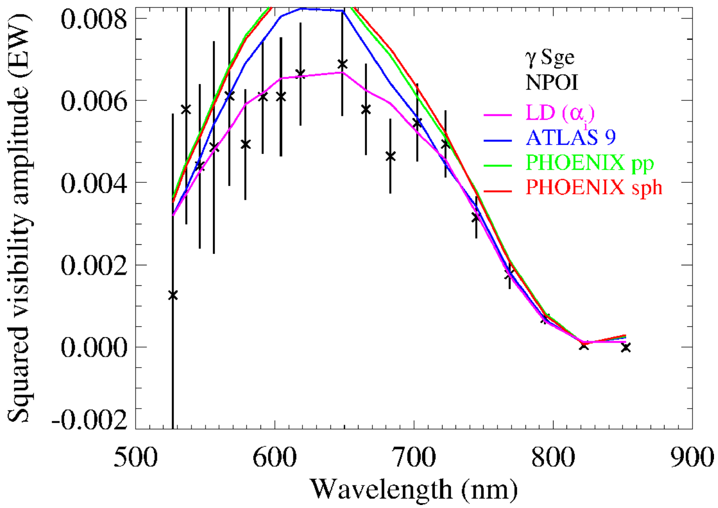
VLTI limb-darkening observations of Psi Phe

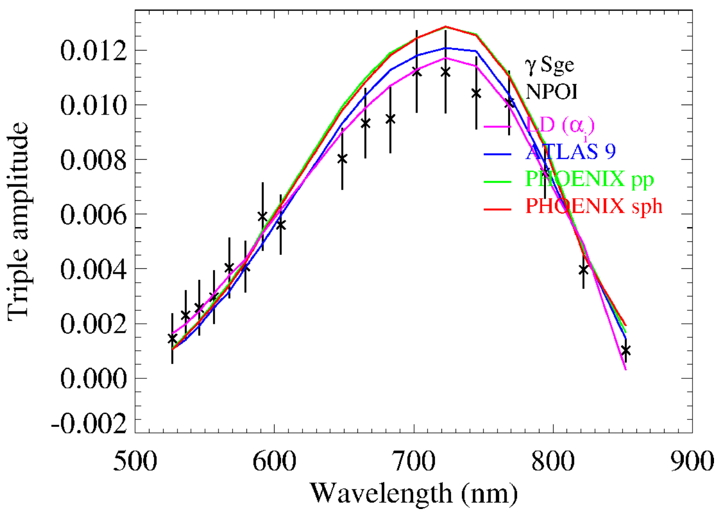


Wittkowski et al. (2004)

- Limb-darkening observations in the first and second lobe with VLTI/VINCI.
- Comparison to ATLAS9 (pp), ATLAS 12 (pp) and PHOENIX (pp, sph.) models.
- Visibility consistent with all considered models.
- High-precision fundamental parameters derived.

NPOI and VINCI observations of gam Sge (M0 III)

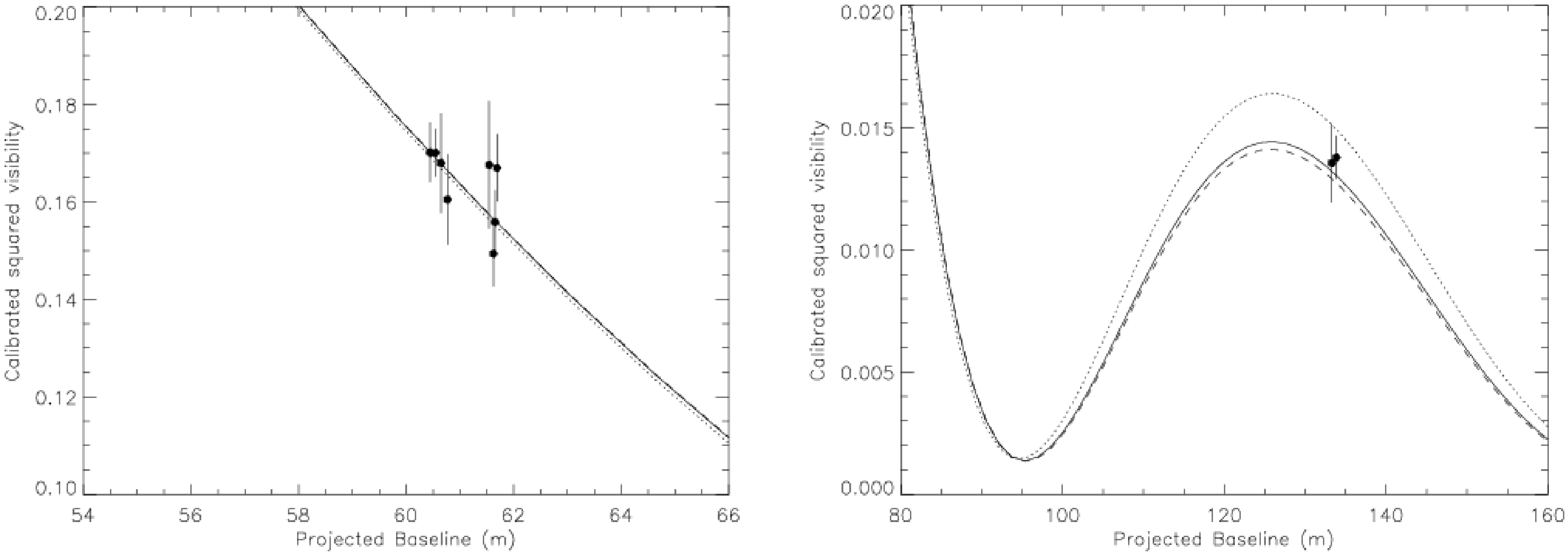




Wittkowski et al. (in preparation)

- NPOI limb darkening observations in the first and second lobes covering 526-852 nm.
- VLTI diameter measurements at 2.2μm.
- Different models differ for visual wavelengths and narrower spectral channels.
- Comparison of NPOI & VLTI.

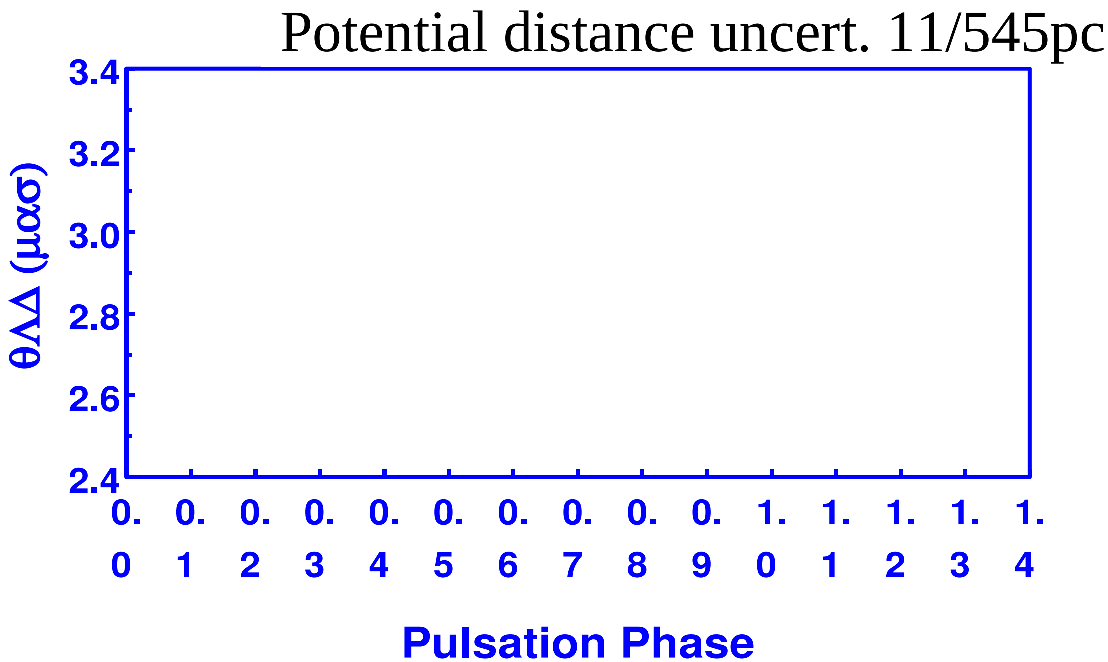
Limb-darkening observations of α Cen B (K1 V)



Bigot et al. (2006)

- Obtained with VLTI/VINCI.
- Compared to ATLAS 9 and a 3-D hydrodynamical radiative transfer model.

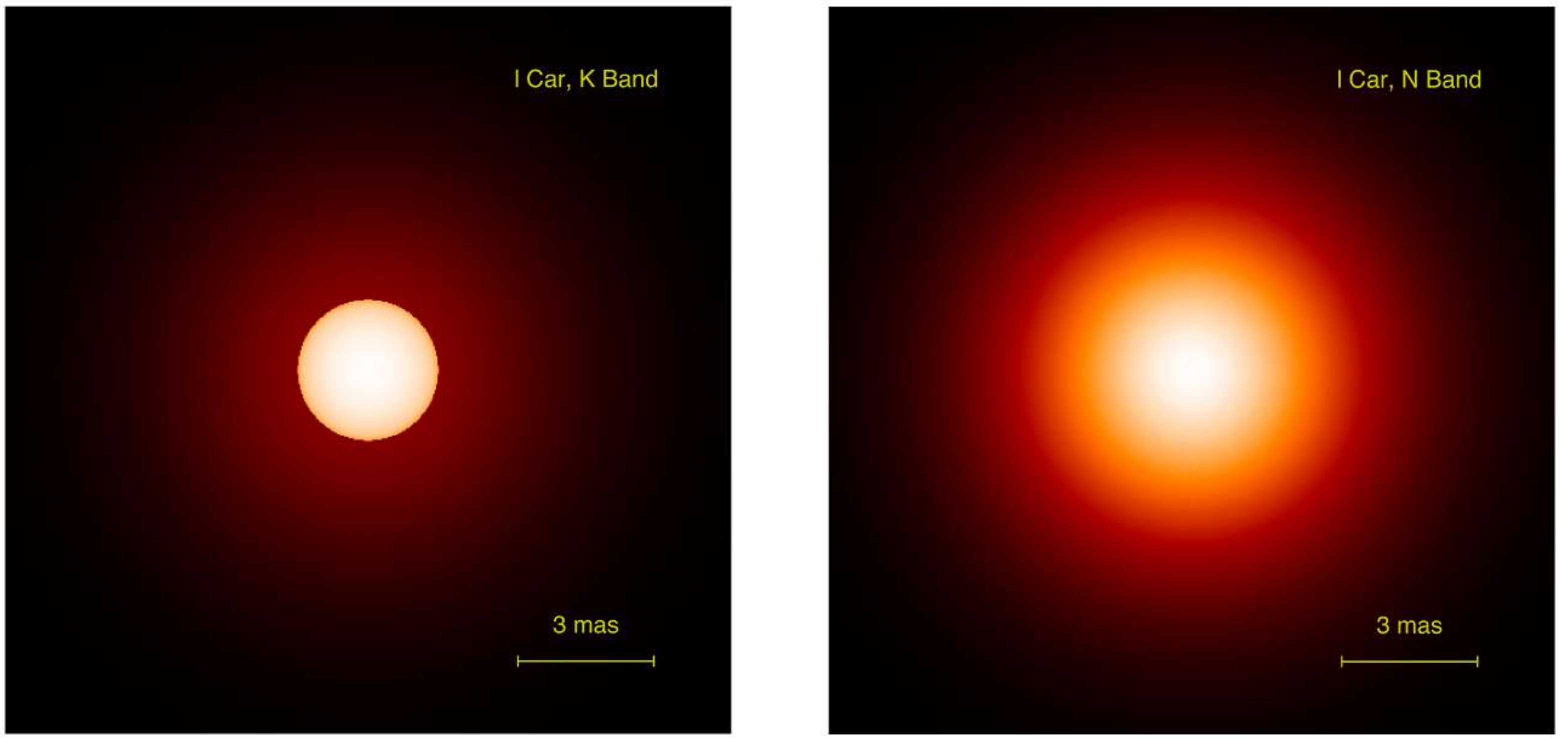
l Car



From J. Davis (2005)

Envelope around l Car

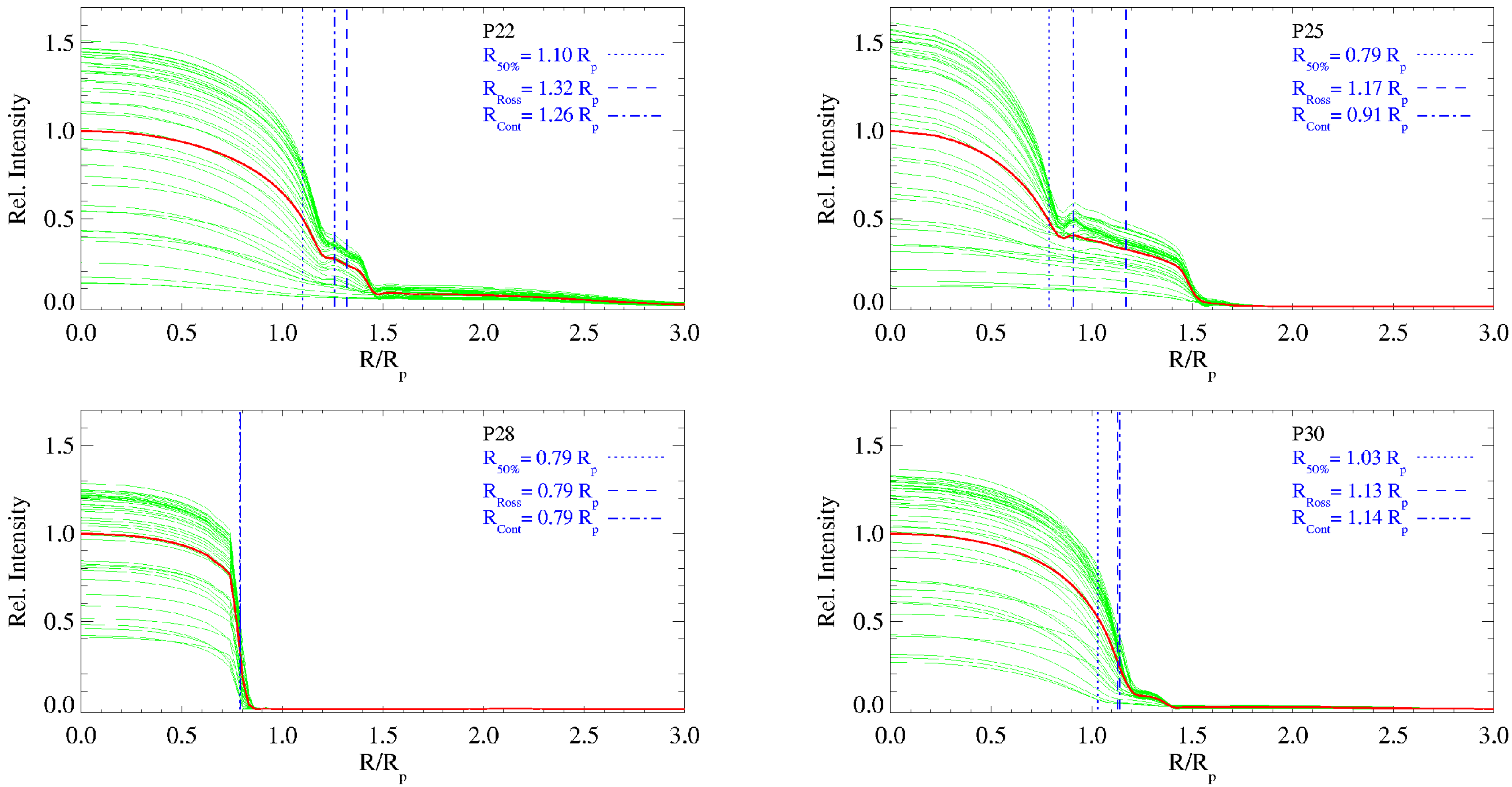
From ESO PR 09/06 (Kervella et al. Merand et al)



Model Image of Cepheid L Carinae
(VINCI, MIDI/VLTI)

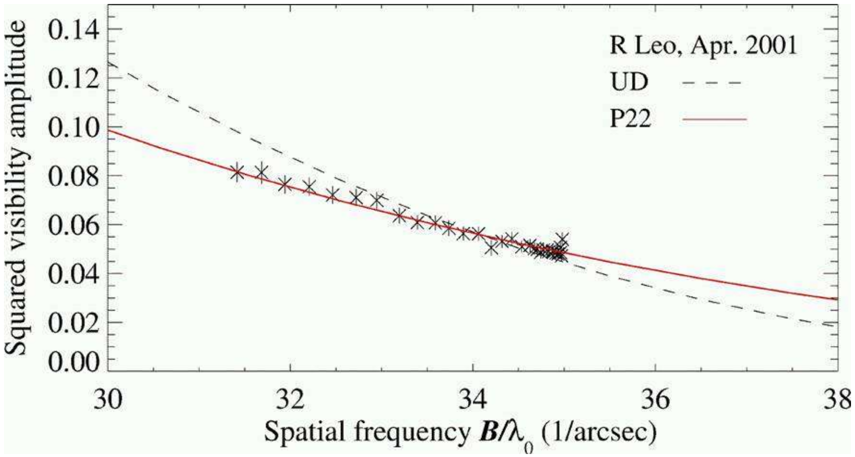
ESO PR Photo 09/06 (28 February 2006)

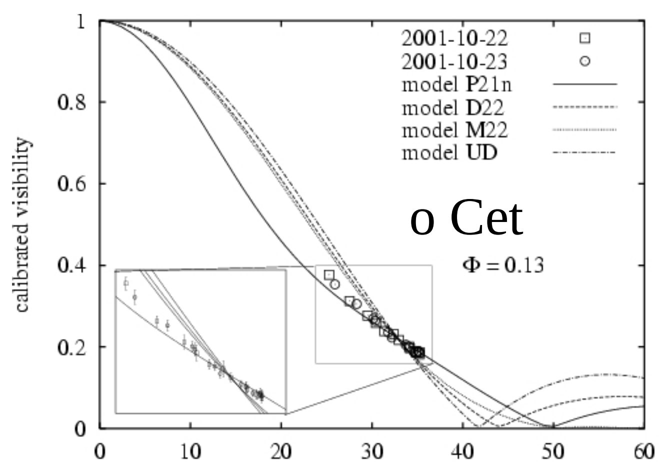
Mira CLVs (Hofmann et al., Tej et al., Ireland et al.)



Scholz & Wood (2004), private communication.

VINCI observations of the Miras o Cet and R Leo

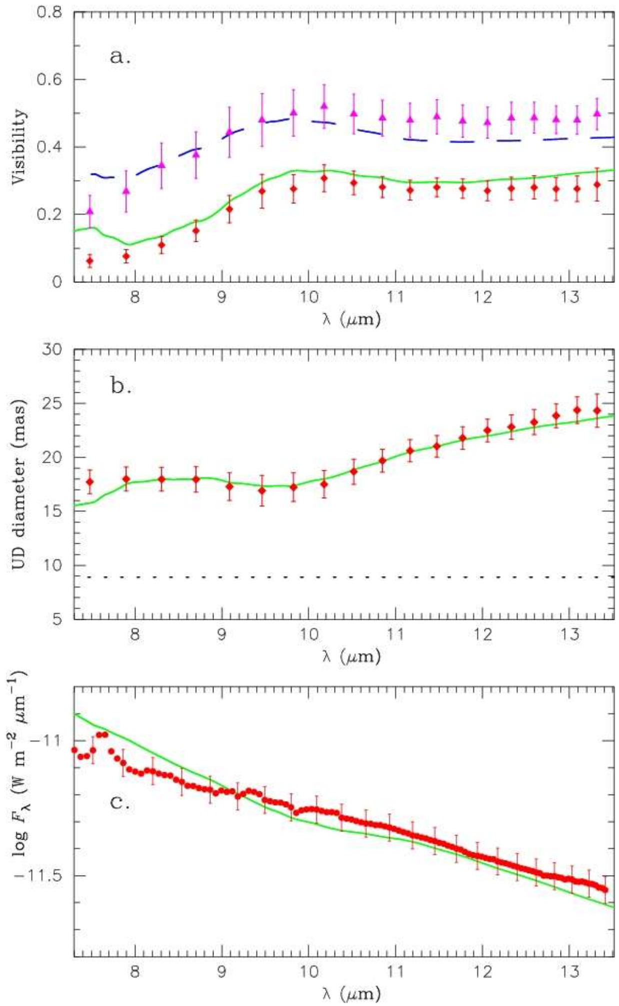




Woodruff et al. (2004);
Fedele et al. (2005)

- 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.

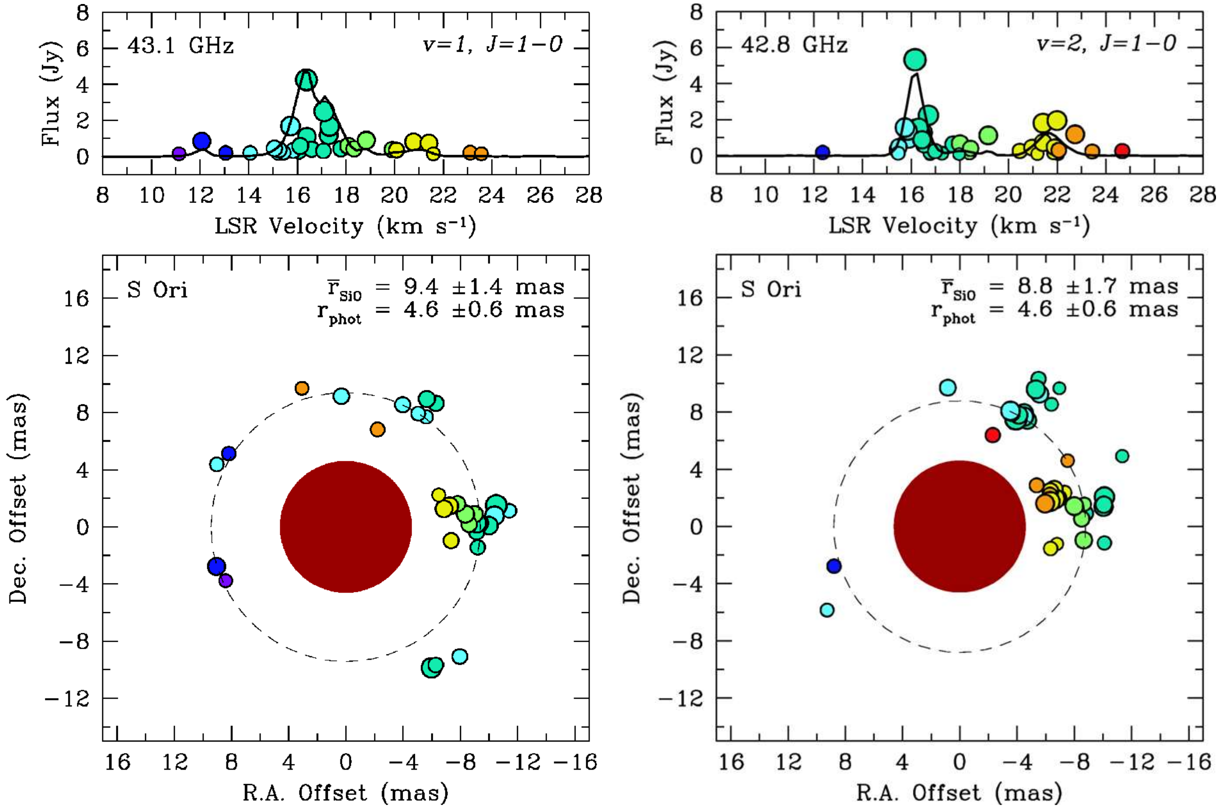
MIDI observations of the Mira star RR Sco



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).

Joint VLBA/VINCI observations of S Ori

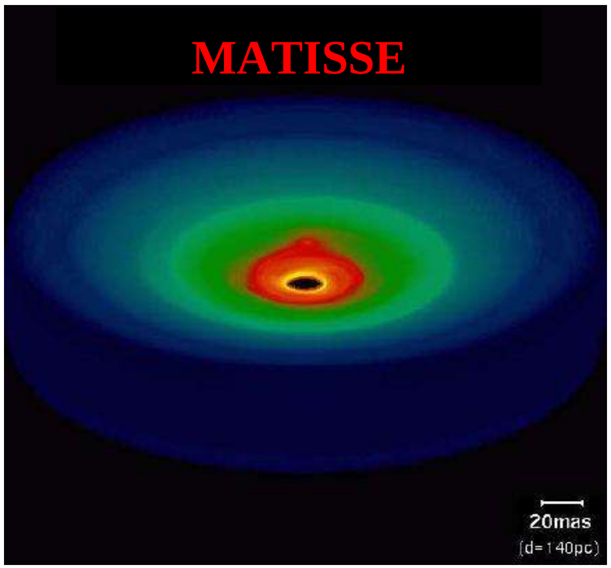


Boboltz & Wittkowski (2005)

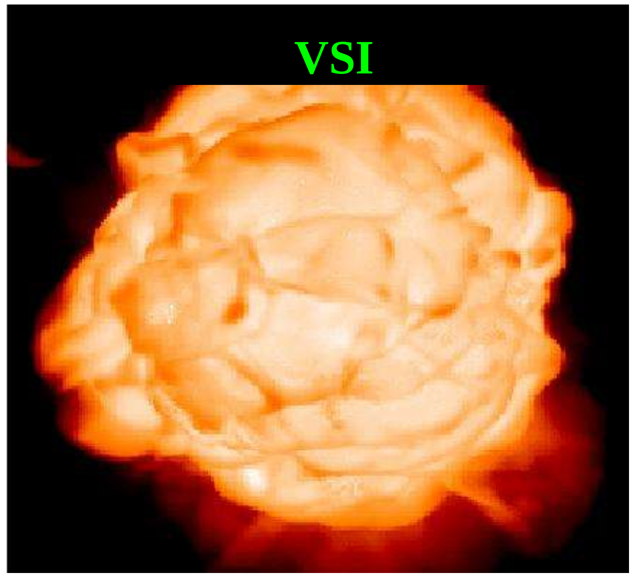
- Coordinated VLBA/VLTI observations of the Mira variable S Ori.

2nd Generation VLTI Proposed Instruments

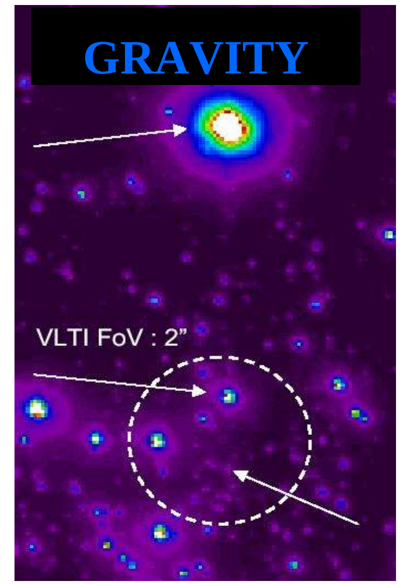
3-20µm, 4 beams



1-2.5µm, 4-6 beams



K-band, 4x2 beams



Three proposals at a glance

Table 1. Summary of VLTI 2nd Generation Instrument Proposals

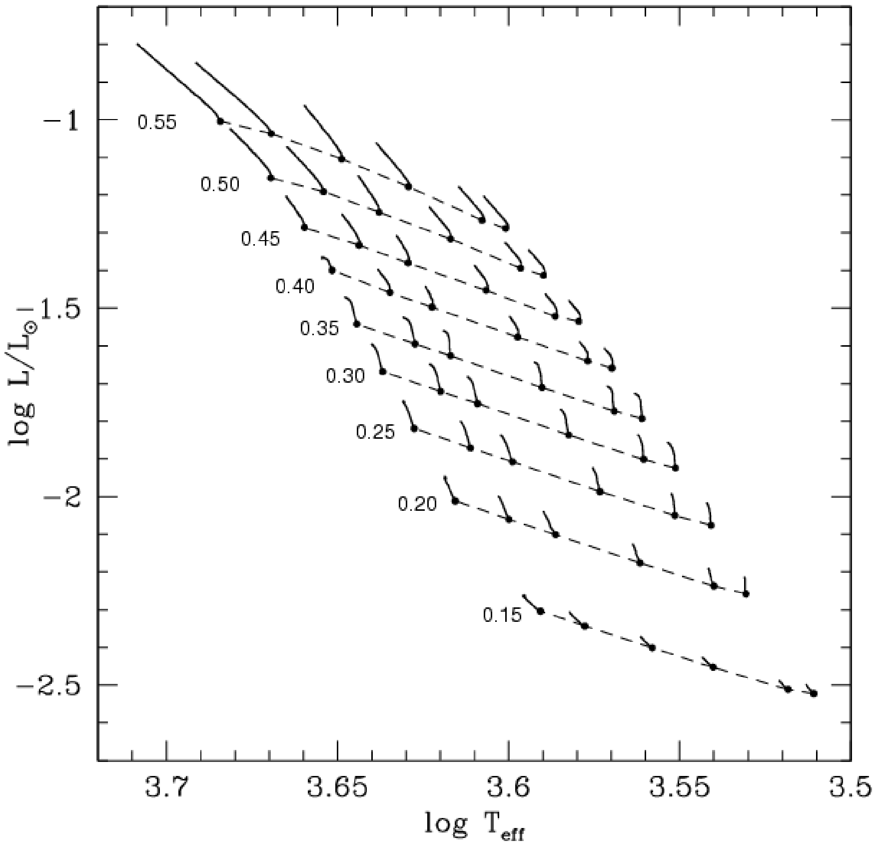
(from ESO/STC-402)

Project	MATISSE	GRAVITY	VSI
P.I.	B. Lopez	F. Eisenhauer	F. Malbet
P.I. Affiliation	Nice	MPE Garching	Grenoble
Participating countries	F, D, NL, PL, HU	D, F	F, UK, D, P, I, A, B
Max No. of Beams	4	4	4-6
λ range (μm)	3.5-20	1.9-2.5	1-2.5
Imaging	Yes	Yes	Yes
Spectr ($\lambda/\Delta\lambda$)	30, 100, >500	30-500	$10^2 - 10^4$
Lim. magnitude UT	0.2Jy R=30 SNR=10 in 2s	19.5 1hr w/FT	18-20 100s w/FT
Internal fringe tracker	No	Yes, +ownWFS	Yes

Stellar science cases for the post-VLTI era

- Precise effects on the main sequence.
- Metal-poor stars.
- Low-mass stars.
- High-mass stars, mass-loss on the main sequence.
- Magnetic activity.
- Stellar rotation.
- Improved physical description of convection, turbulent mixing, etc.
- Binaries and multiple stars: Initial distrubution of mass ratios and orbital periods, larger diversity.
- Stellar imaging.
- Star and planet formation process (structure of the disk region, interaction between star and disk).
- Extragalactic stars (SMC, LMC).
- Extrasolar planets/planetary systems.

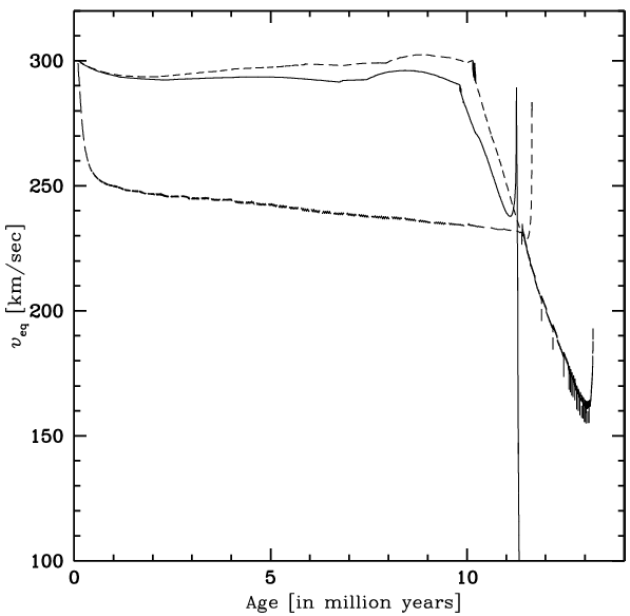
Effects on the main sequence

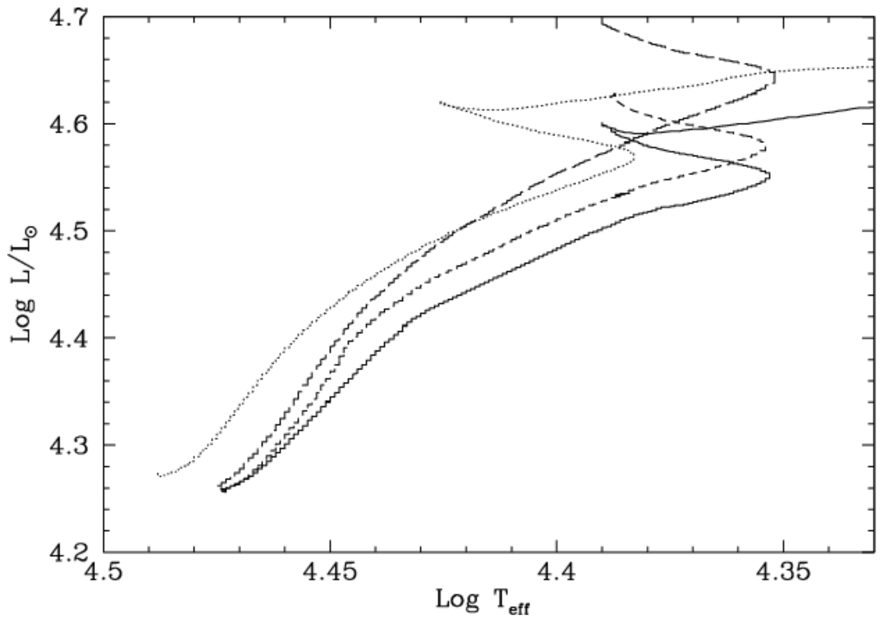


Girardi et al. (2000)

- Example from Girardi et al. (2000), for low-mass stars.
- From ZAMS up to 25 Gyr.
- From left to right metallicity Z=0.0004, 0.001, 0.008, 0.019, 0.030.
- Evolution starts at the full dot.

Effects of rotation and magnetic fields





Examples from Maeder & Meynet (2004), "Stellar evolution with rotation and magnetic fields". Surface rotational velocity versus age, and evolutionary tracks, both for different models including rotation and magnetic fields.

Stellar radii and stellar surfaces

- The radius is not well defined. Stars are gaseous spheres, and do not have a well-defined “edge”. Observable is the intensity profile across the stellar disk, which depends on the stellar atmospheric structure.
- The intensity profile may include molecular shells and/or dust shells outward the photosphere (circumstellar environment).
- The vertical temperature profile may be superimposed by horizontal inhomogeneities (temperature, abundance…).
- Intensity profiles change with time (pulsation, variable features, etc.).
- Distance is often not well known (absolute radii).

Mass estimates

- Binary stars are the main source for measurements of high-precision masses:
- Double-lined astrometric-spectroscopic binaries (radial velocities of both components + relative orbit).
- Absolute astrometry (absolute orbits of both stars).
- Single-lined spectroscopic binary (radial velocity plus relative orbit plus distance).
- Next generation interferometry can improve mass estimates by higher-precision orbits of more (closer and fainter) binaries.
- The mass can also be estimated by comparison of interferometric data with models of atmospheres and evolution

Luminosity

- Apparent bolometric flux plus distance estimate.
- Improved measurements require higher-precision bolometric fluxes and higher-precision distances, of the same sources that are studied by interferometry.
- Contemporaneous photometric measurements of variable stars are needed.

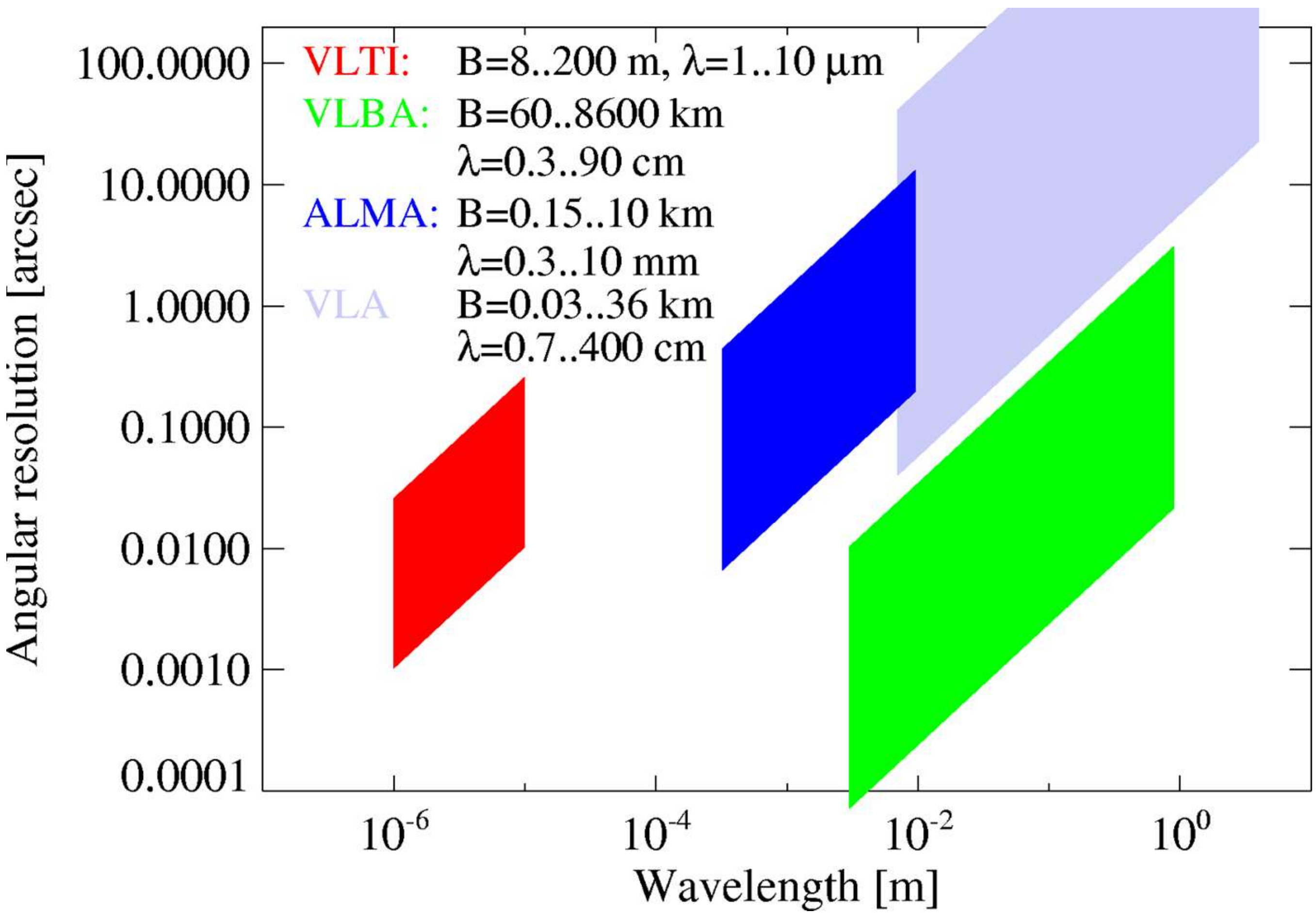
Limiting case: very low mass stars at the bottom of the main sequence

- Evolutionary calculations by Chabrier et al. (2000):
- Star at the limit to a brown dwarf (mass 0.08 M_{sun}), age 5 Gyr
- Radius 0.1 R_{sun}
- Luminosity log L/L_{sun} = -3.6
- $M_V \sim 19$, $M_K \sim 11$, $M_M \sim 10$.
- At 10 pc: $\Theta = 0.1$ mas, $m_V \sim 24$, $m_K \sim 16$, $m_M \sim 15$ for V=1%
- To sample with 3-5 resolution elements: B ~ 6 – 10 km.

Synergies with other facilities

- Existing optical interferometers (will they be operating at the same time?, can the same sources be observed, can data be combined ?)
- ELT (combination of data ?)
- Radio interferometers (ALMA, VLBA): combination of data ?
- Contemporaneous high-precision flux measurements ?
- High-precision distances ?
- Calibration strategies for improved accuracies ?

Comparison of VLTI, VLBA, and ALMA



- VLTI, VLBA, and ALMA can observe the same targets in terms of angular resolution and sensitivity.
- They provide complementary information on different components and regions.

Telescopes:

VLTI : 4 x 8m + 4 x 1.8 m
VLBA : 10 x 25 m
ALMA : 64 x 12 m
VLA : 27 x 25 m