The VLT Interferometer

in the context of MIDI

A. Richichi (ESO Garching)

VLTI/MIDI Data reduction, analysis and science school, Leiden 11 October 2004

Overview of current Interferometers

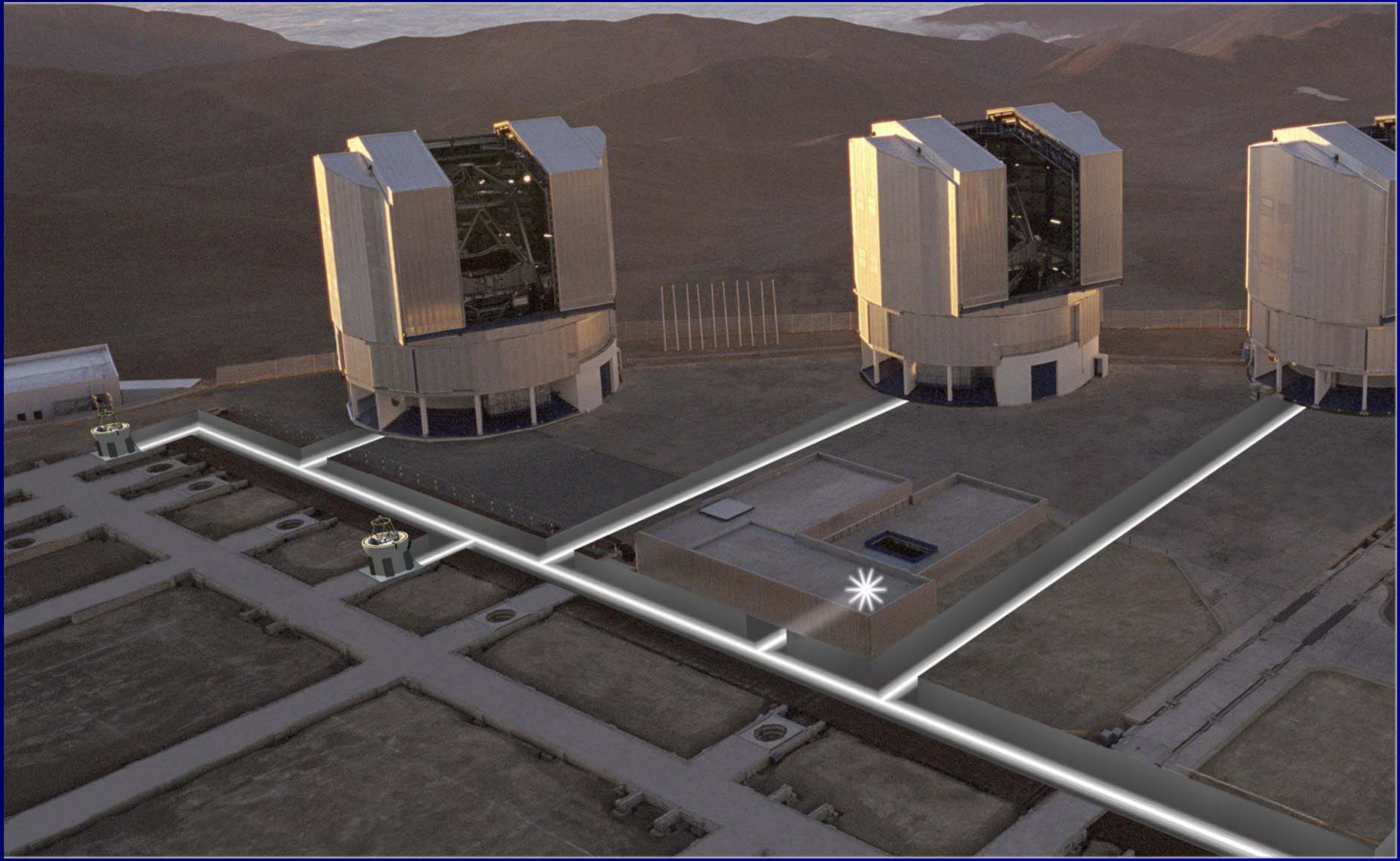
facility	funding	location	n. of apertures	apertures (m) primary	apertures (m) secondary	baseline max (m)	year of first fringes	wavelength range
CHARA	USA	Mt. Wilson	6	1.0		350	1999	vis
COAST	UK	Cambridge	5	0.4		48	1991	vis
GI2T	F	Calern	2	1.5		65	1986	vis, NIR
IOTA	USA, F	Mt. Hopkins	2-3	0.45		38	1993	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 Observatory on Cerro Paranal

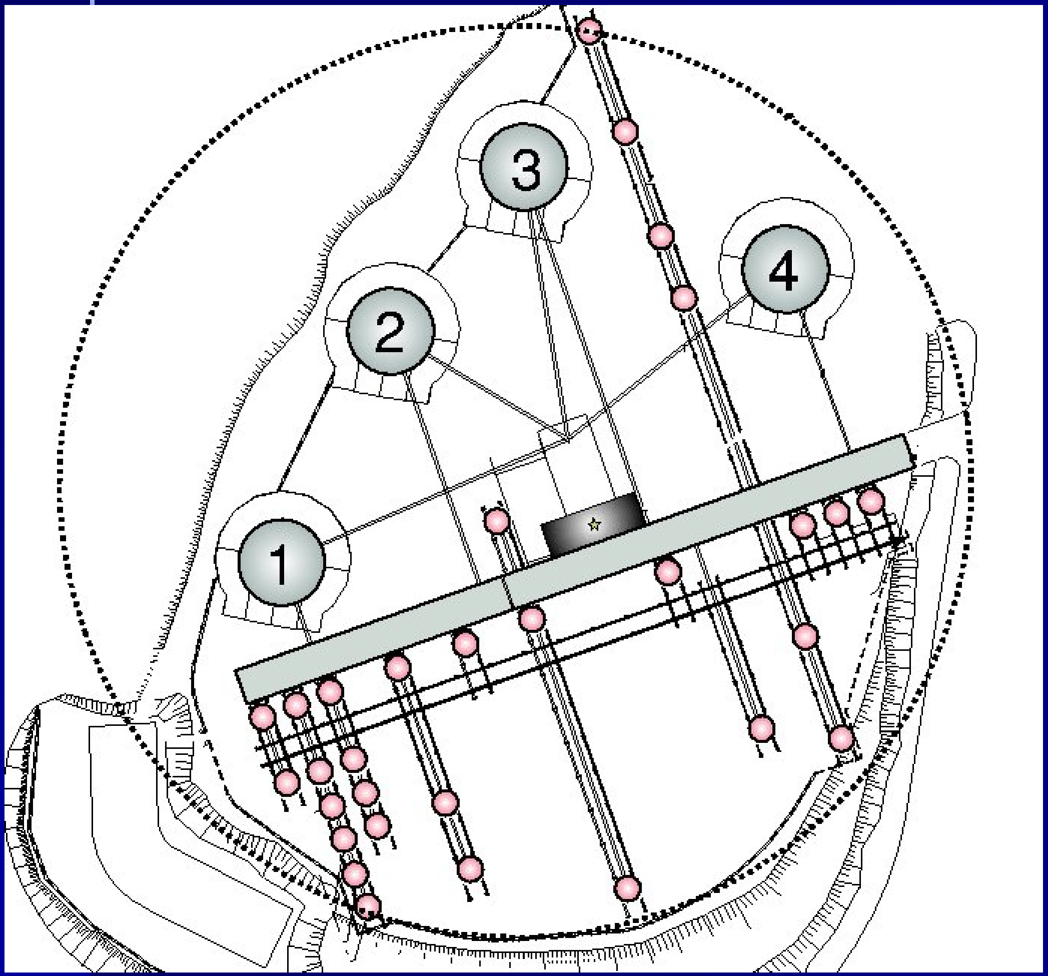
The VLT Interferometer

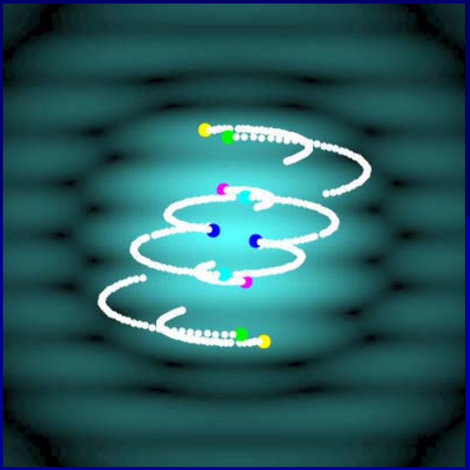
- Four 8.2-m
  Unit Telescopes
  Baselines up to 130m
- Four 1.8-m Auxiliary Telescopes.
  Baselines 8 – 200m
- Field of view: 2 arcsec
- near-IR to MIR (angular resolution 1-20 mas)
- Excellent uv coverage
- Fringe Tracker
- Dual-Feed facility
- Adaptive optics with 60 actuator DM (Strehl >50% in K - Guide Star $m_V < 16$)

The VLTI - close up

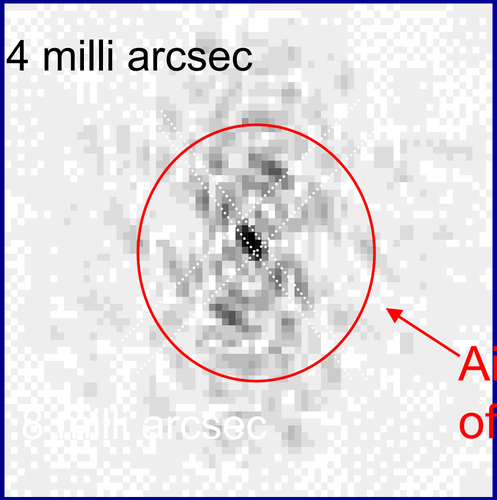


VLTI Main Characteristics





uv coverage after 8 hour observation with all UTs (object at -15°)



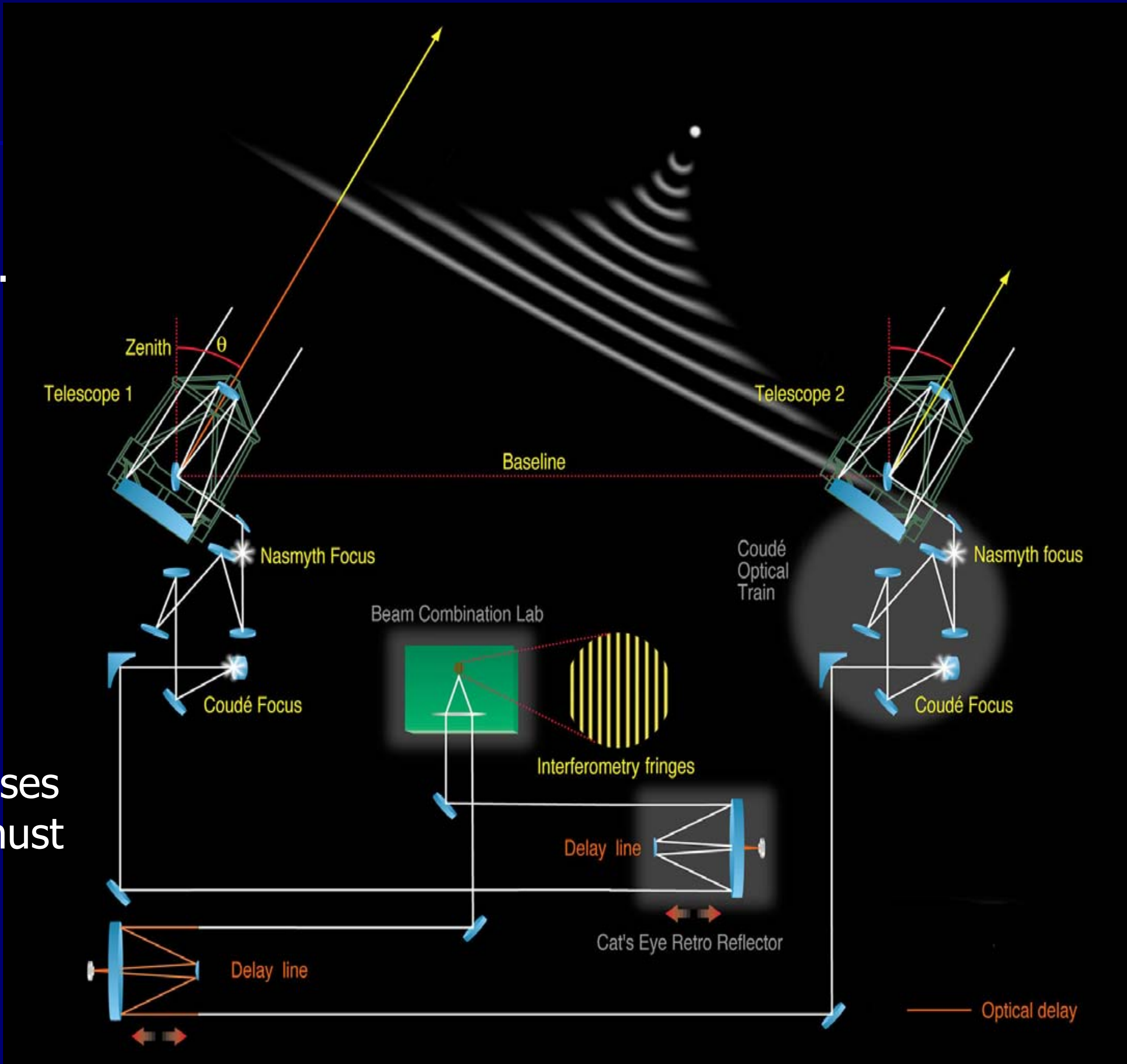
Resulting PSF is the Fourier transform of the visibilities at $\lambda = 2.2\mu m$ (K-band)

VLTI Scheme

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

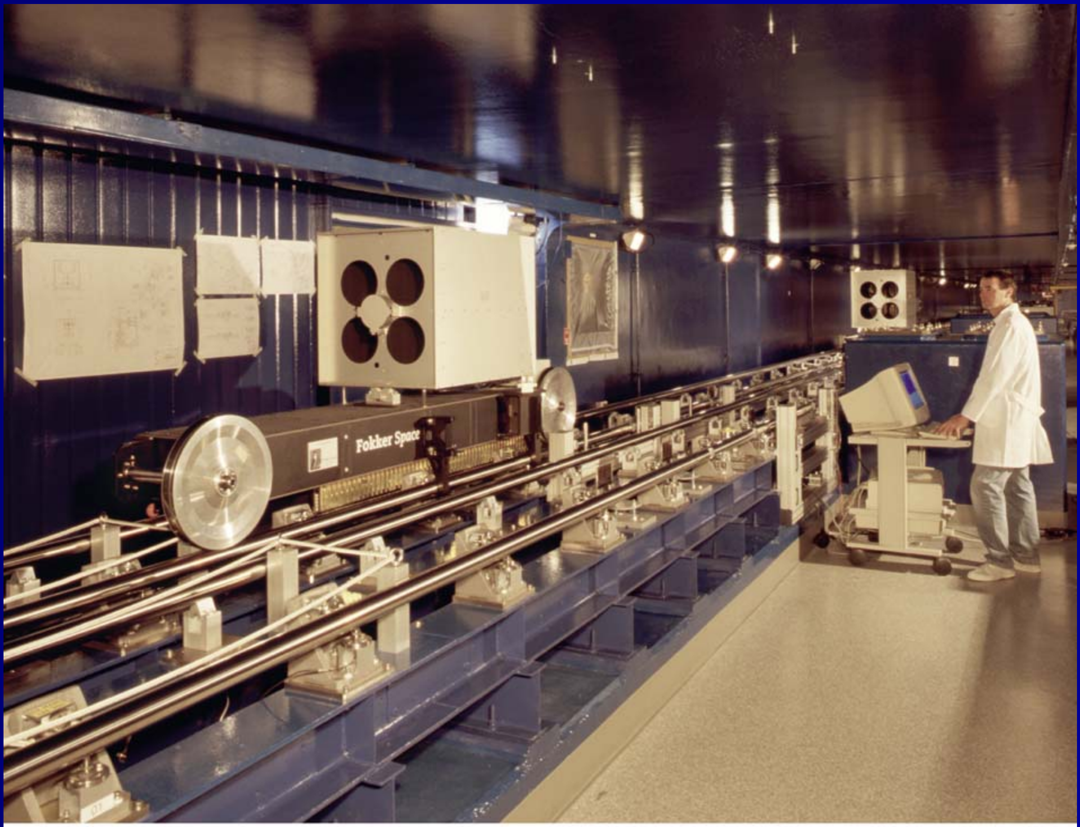
The optical path difference must be continuously compensated by the delay lines.

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



The "Paranal Express"

- six delay lines
- three operational
- three more installed
- combine all UT baselines
- combine almost all AT baselines



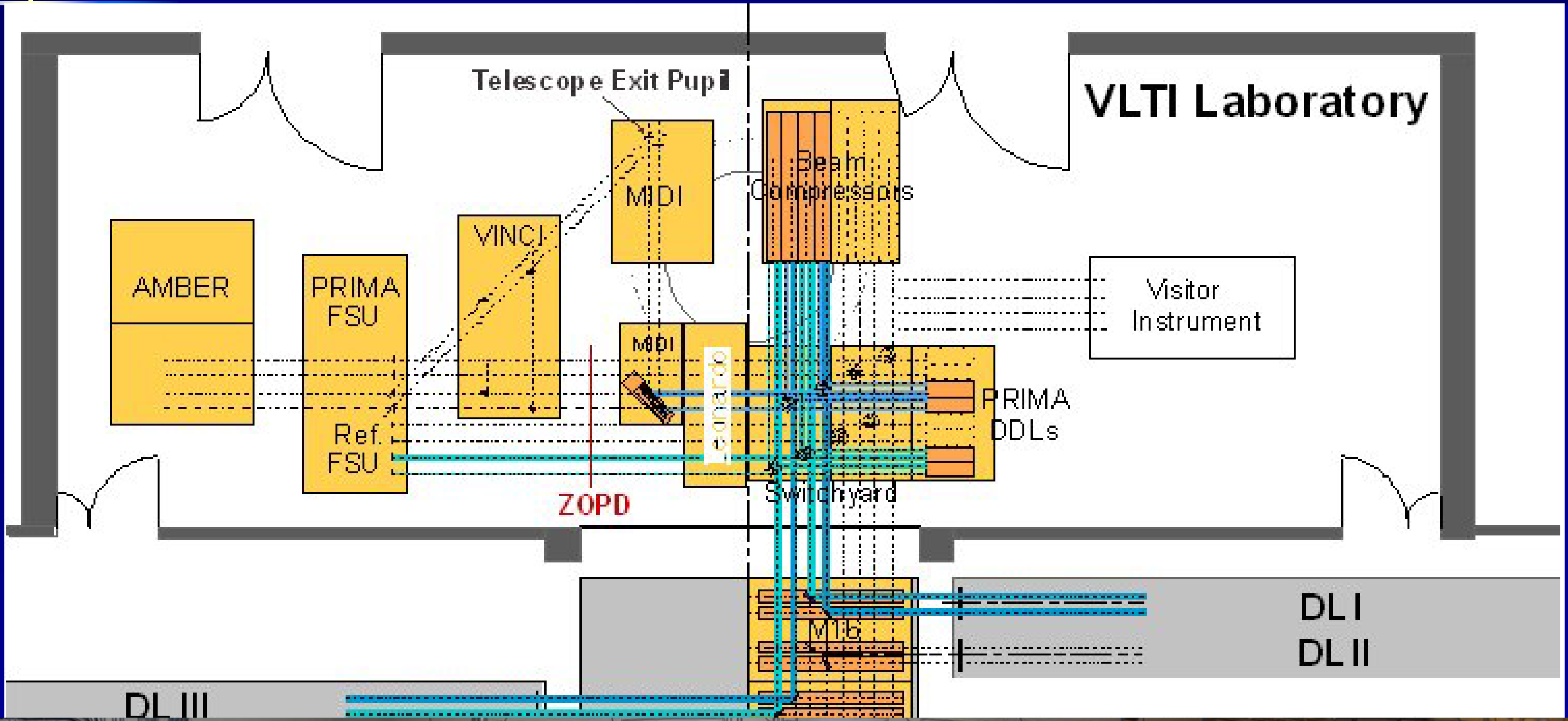
Delay Line Carriage in VLTI Tunnel

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

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
- Fringe tracking in March 2004
  - 200nm rms residual OPD
  - 10sec continuous fringe tracking, recovery after flux loss for 'infinite' tracking
- More testing needed

VLTI Laboratory

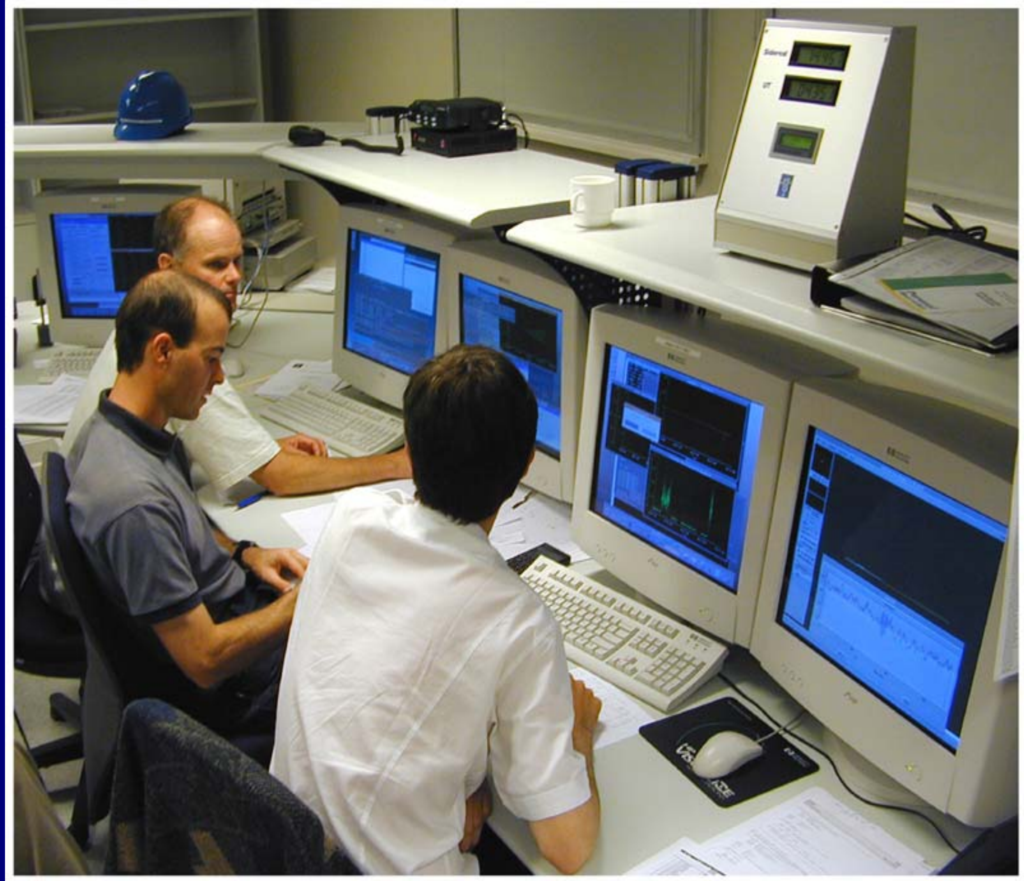


1.8-m Auxiliary Telescopes (ATs)

- increase u-v coverage
- designed for interferometry, optical path same as UT
- Manufactured by AMOS (Liège, Belgium)
- AT1 on site, 2nd Comm
- AT2 Nov 2004
- AT3 & AT4 Europe 2005

Control and operations

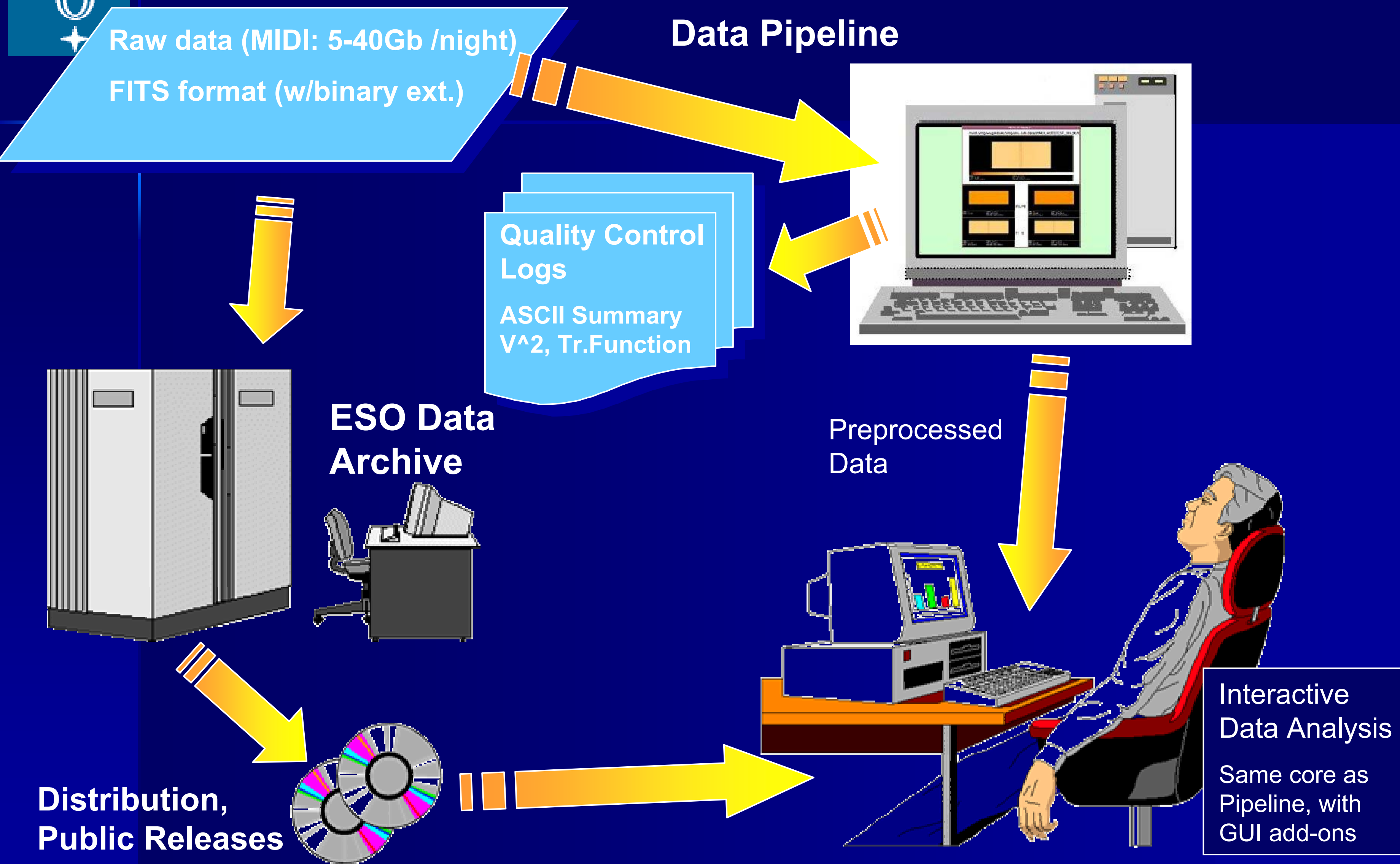
- Remote control
- OB in VLT style
- Data Pipeline
- Data Archive
- Interferometric FITS format



The VLTI Control Consoles

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

VLTI Data Flow System



Instrumentation

TEST

VINCI: K-band 2-way beam combiner

SCIENCE

MIDI: Mid-Infrared 2-way beam combiner

AMBER: Near-Infrared 3-way beam combiner

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

VINCI overview

VINCI

(ESO, France)

Paranal: January 2001

K-band, 2-beam

Visibility Accuracy: 0.1% (so far in commissioning with SID)

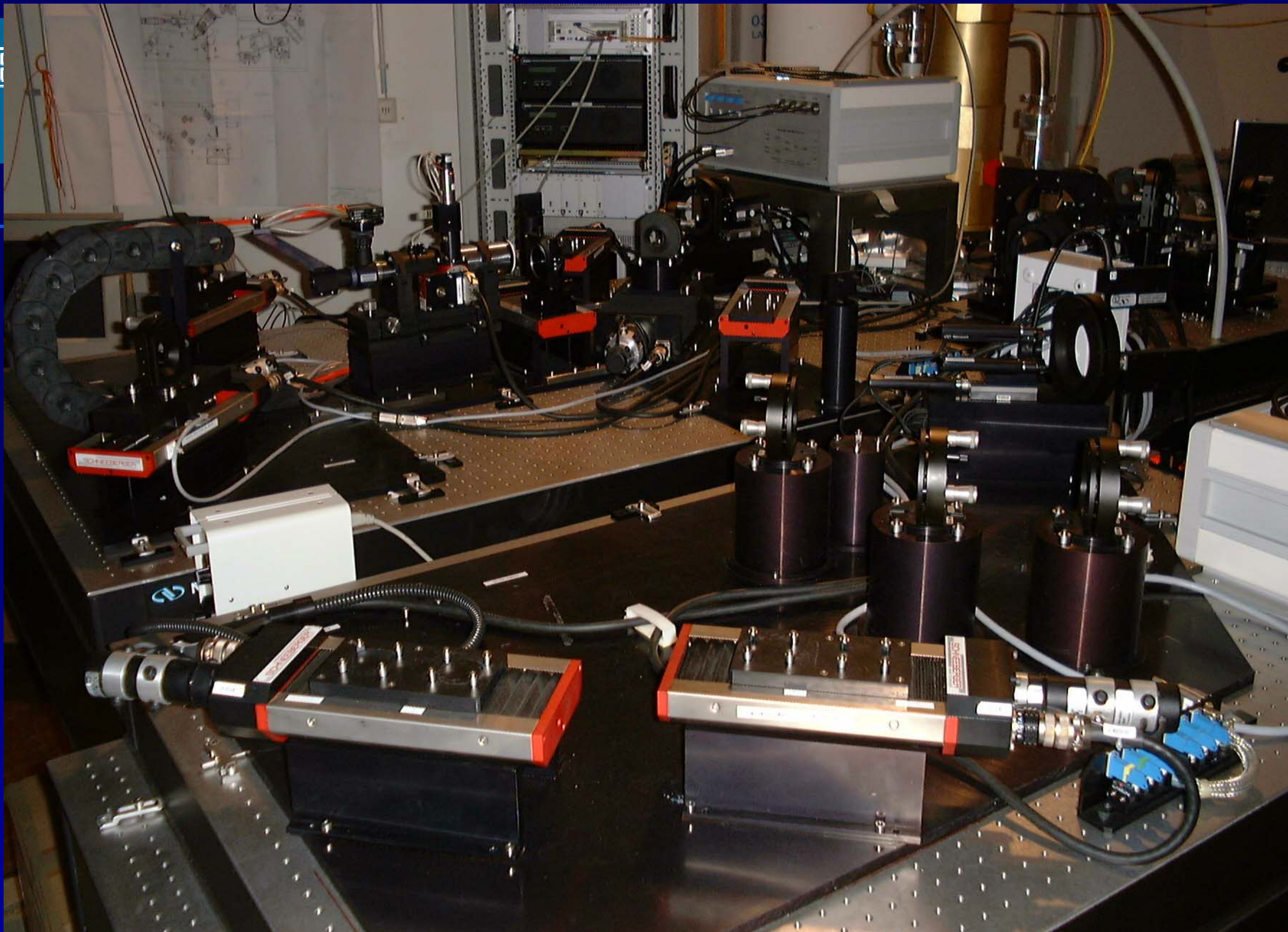
0.01% (goal)

Limiting Magnitude: goal K=6 with SID, K=11 on UT without FT

First Fringes with Siderostats achieved March 2001

First Fringes with UTs achieved October 29, 2001

Main purpose: commissioning, test instrument



MIDI Overview

D/F/NL;   PI: C. Leinert (MPIA Heidelberg)

Paranal: November 2002

First Fringes with UTs: December 2002

Mid IR instrument (10–20 μm) , 2-beam, Spectral Resolution: 30-260

Limiting Magnitude N ~ 4 (1.0Jy, UT with tip/tilt, no fringe-tracker) (0.8 AT)

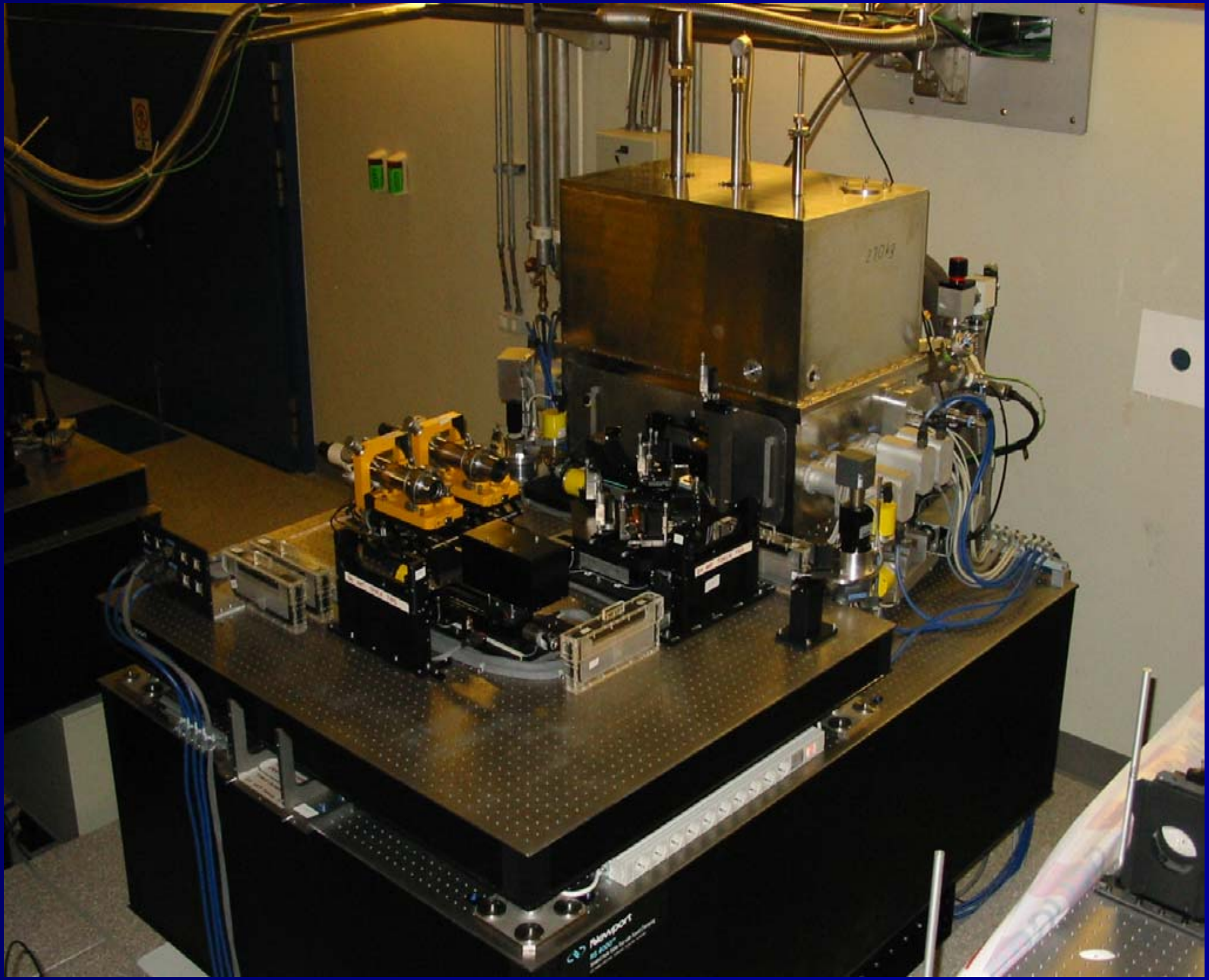
N ~ 9 (10mJ, with fringe-tracker) (5.8 AT)

Visibility Accuracy 1%-5%

Airy Disk FOV 0.26″ (UT), 1.14″ (AT)

Diffraction Limit [200m] 0.01″

MIDI in the VLTI Lab



AMBER Overview

F/D/I; PI: R. Petrov (Nice)

Paranal: February 2004

First Fringes with SIDs: **21 March 2004**

Near IR Instrument (1–2.5 μm) , 3-beam combination (closure phase)

Spectral Resolution: 35-14000 (prism, 2 gratings)

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

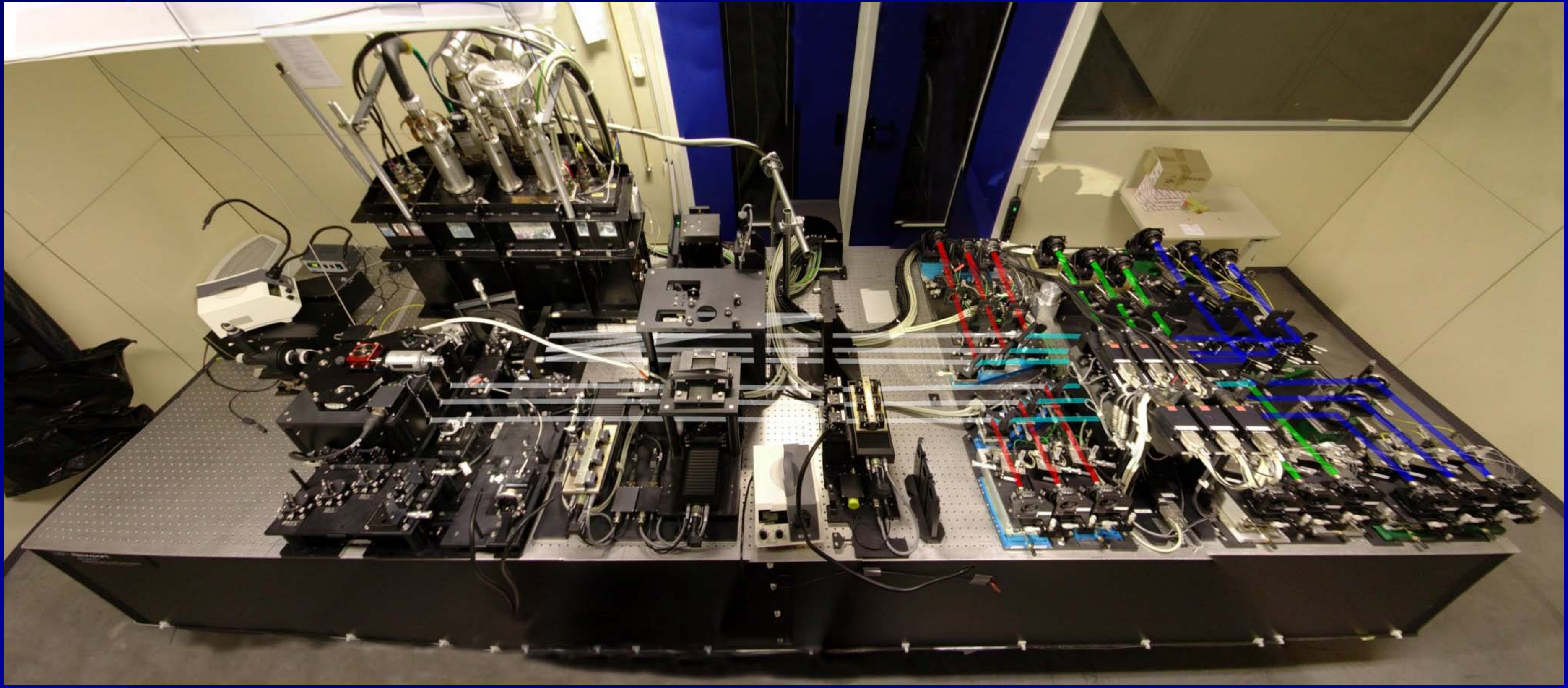
J=19.5, H=20.2, K=20 (goal, FT, AO, PRIMA, 4 hours)

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

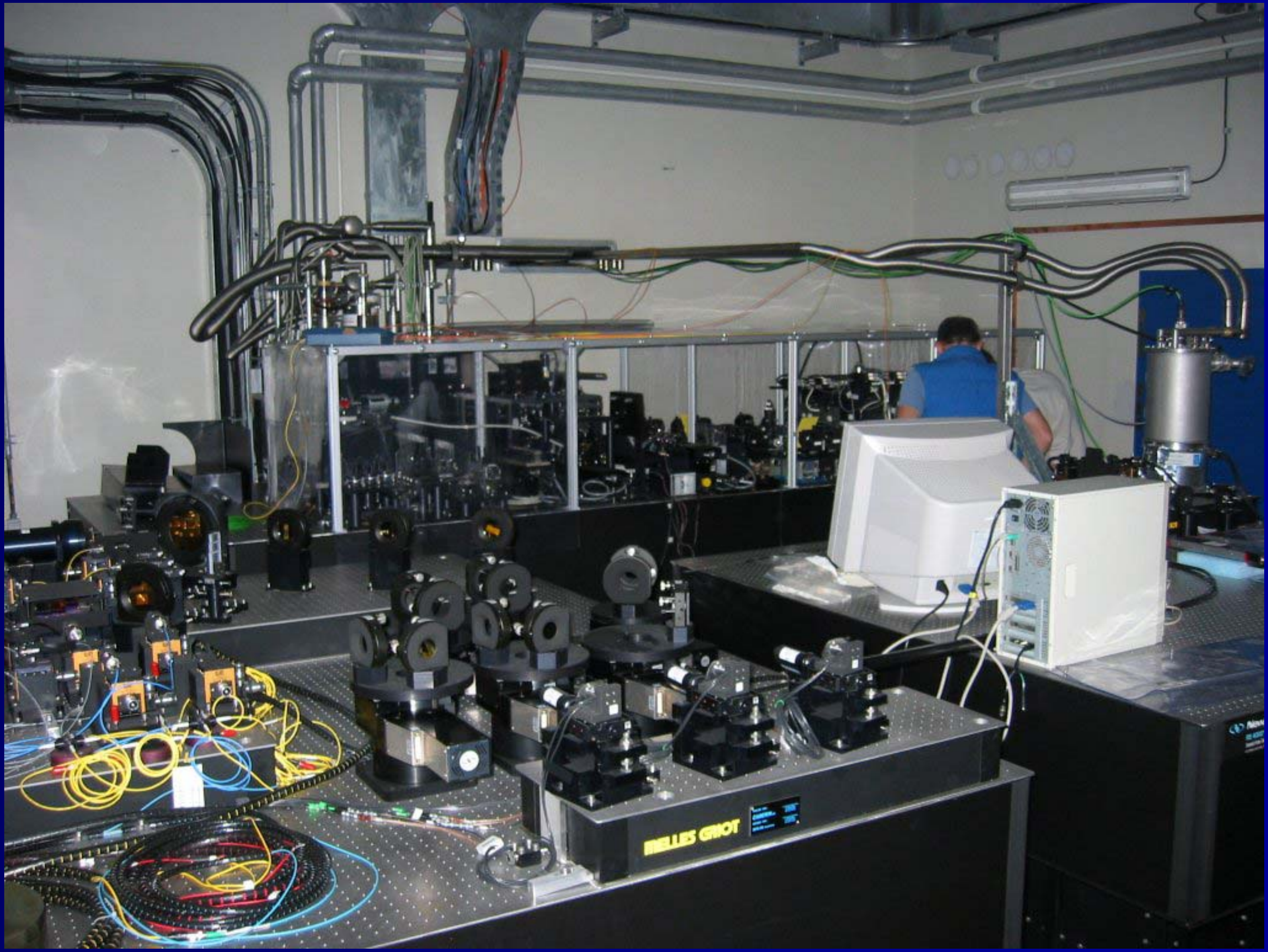
Airy Disk FOV 0.03”/0.06” (UT), 0.14”/0.25” (AT) [J/K band respectively]

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

AMBER in Europe



AMBER in the VLTI Lab



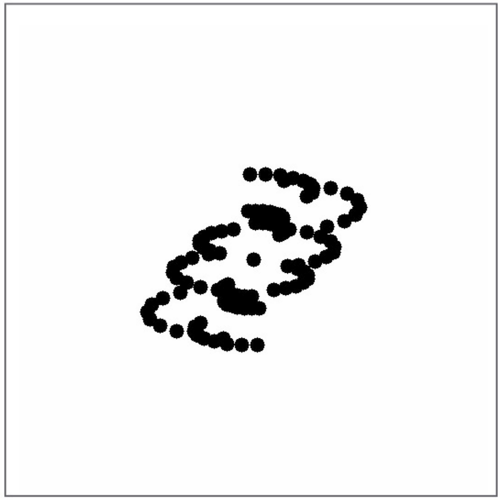
The last two years

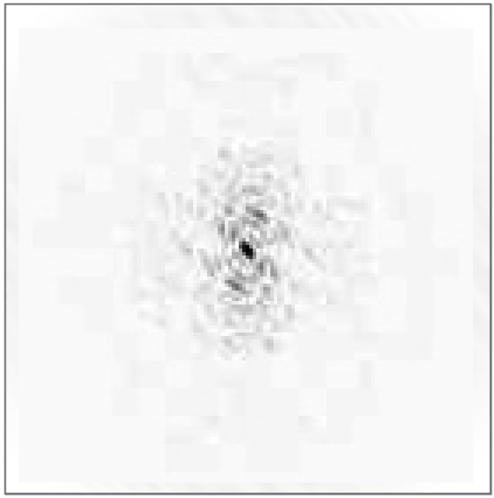
- Scientific results (~30 papers in refereed journals)
- MIDI in science operations
- AMBER First Fringes with 2 UTs and with 3 UTs
- MACAO, adaptive optics on UTs, routinely in operation
- FINITO, on-axis fringe tracker (working, not routinely)
- IONIC, integrated optics beam combiner for VINCI
- Delay Lines #4, 5 and 6 integrated and tested
- AT1 on the sky

Next Steps

- FINITO Fringe Tracker
  Improve performance.
- IRIS
  Tip-Tilt sensor in the Interferometric Lab. End 2004.
- Variable Curvature Mirrors (VCMs)
  2 installed, 4 to be installed.
- PRIMA
  Dual Feed Facility (astrometry, faint-object science). End 2005.
- 2nd Generation Instrumentation
  Proposals due November 2004.
  Already being discussed: Apres-MIDI, MIDI 20μm, GENIE.
- Large VLTI Workshop planned for April 2005.

What is missing?

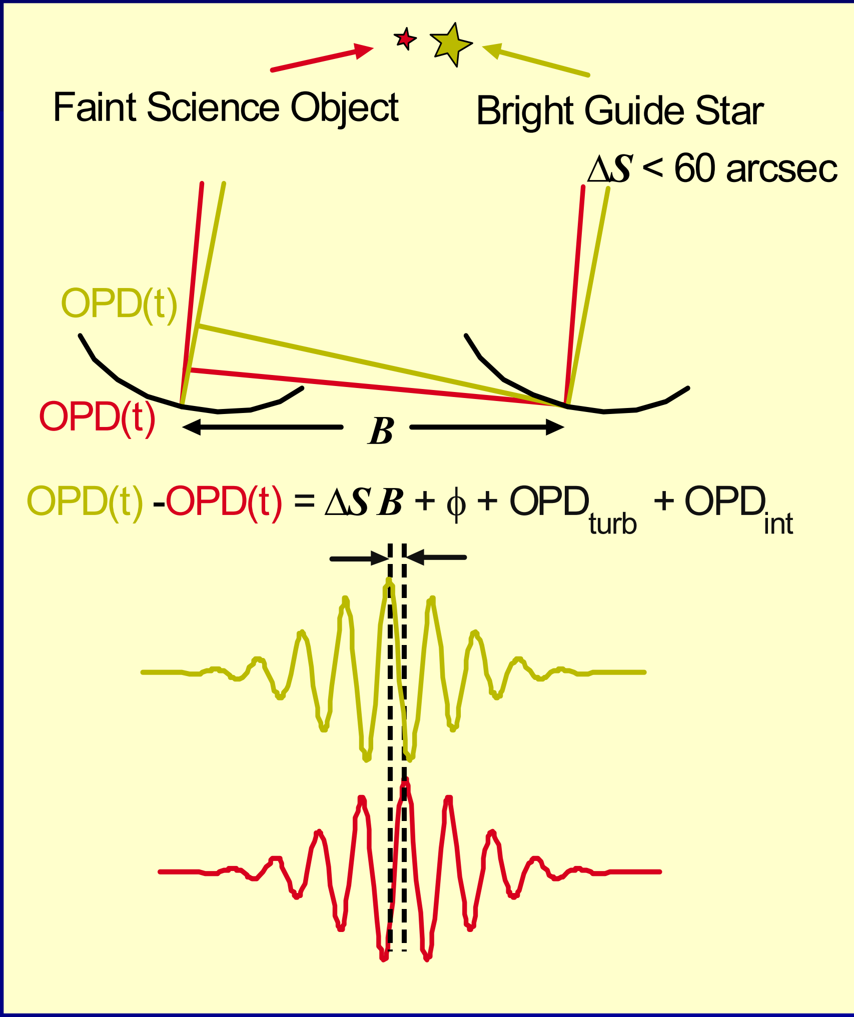




1. **'Easy' (= efficient) imaging**
   - Filling smoothly the uv plane is the key to image quality
   - Restriction to two (MIDI) resp.three (AMBER) beams cumbersome
     ⇨ More telescopes, Delay Lines, and multi way beam combiner
2. **Shorter wavelengths**
   - Angular resolution improves with baseline or shorter wavelength
     Problem is the atmospheric turbulence (both for AO and fringe tracking)
3. **'Large' (= 2 arcsec) field of view**
   - Field of view of one Airy disk with MIDI (250mas) and AMBER (57mas)
   - Although still small, 2 arcsec means 2000 resolution elements
     for milliarcsec resolution

Phase-referencing (PRIMA)

- **Pick up 2 stars in a 2 arcmin field**
- **ΔOPD = ΔSxB + ϕ + OPD_{turb} + OPD_{int}**
  - OPD_{int} measured by laser metrology
  - OPD_{turb} mean tends to 0
  - ΔOPD measured by VINCI / AMBER / MIDI / FSU
  - **ΔS** => object position => astrometry
  - ϕ => object phase => imaging



PRIMA - The Dual Feed Facility

1st Phase:

Faint object imaging with ATs (K~16, N ~ 8) and 100 µarcsec astrometry

Required hardware:

- 2 Fringe Sensor Units (ALENIA Spazio, Italy, 2005)
- 2 star separator systems (STS) (TNO/TPD, Netherlands, 2005)
- Laser metrology (ESO+IMT, Switzerland)

2nd Phase:

Faint object imaging with UTs (K ~ 19, N ~ 11) and 10 µarcsec astrometry

Required hardware:

- 2 STS for the UTs
- Differential Delay Lines (Dutch/Swiss/German consortium)

PRIMA goals

❑ faint object observation (by stabilising the fringes)

- dual-feed / dual-field : 2′ total FoV (2″ FoV for each field)
- K~13 (guide star) - K~20 (object) on UTs
- K~10 (guide star) - K~16 (object) on ATs

❑ phase-referenced imaging

- accurate (1%) measurement of the visibility modulus and phase
- observation on many baselines
- ➢ synthetic aperture reconstruction at 2 mas resolution (2.2 μm)

❑ micro-arcsecond differential astrometry

- very accurate extraction of the astrometric phase:
  - 1st phase ~ 2006 : 100 μas
  - 2nd phase ~ 2008 : 10 μas
- 2 perpendicular baselines
- 2 phase-reference stars (2D-movement of photocenter)

Access Opportunities

- Shared-risk VINCI proposals P70, P71
  Access rules as for normal ESO proposals, in P71 OPC evaluation.
- Public Releases
  Data released to the community after validation thru VLTI web page: ~20000 observations from VINCI commissioning, and two runs of science demonstration with MIDI
- Access to MIDI
  Offered since P73
- Access to AMBER
  Goal P76, depending on progress of commissioning.
- Long term
  Applications, selection, operation of instrument (visitor or service), data release: will be the same as for any other VLT instruments

Early Scientific Results

HARVESTING SCIENTIFIC RESULTS WITH THE VLTI

Andrea Richichi and Francesco Paresce (ESO)

The ESO Very Large Telescope Interferometer (VLTI) has been included for the first time in the official call for proposals requesting ESO telescopes, for the period starting in April 2004. This marks the official start of public interferometric observations open to the community. It is the start of a new approach to interferometry as a standard astronomical technique, and a point of pride and satisfaction for all the people who have been working with this challenging goal for many. But it should not be forgotten that the VLTI has already logged over two years of intensive commissioning, as well as some initial science demonstration runs. Over 16,000 observations of hundreds of objects have been collected and are available publicly over the ESO archive on the web. In 2003, the first scientific results of this remarkable effort have appeared. Already more than a dozen papers based on VLTI data have been submitted or accepted by refereed journals, with a similar volume of contributions to workshops and conferences of a scientific nature. We provide here an overview of this early scientific production of the VLTI, ranging from the determination of fundamental parameters of many classes of stars to the first interferometric measurement of the inner regions of the nucleus of the Seyfert galaxy NGC 1068.

The Messenger, 114 (December 2003)

Science Goals of MIDI and AMBER

MIDI

- Dust Tori in nearby AGN
- Inner disks around stars (low-mass YSO, intermediate mass YSO, Vega-type)
- Massive YSO
- Dusty environment of Hot Stars
- Cool Late-type stars
- Extrasolar planets and brown dwarfs

AMBER

- Cosmology (distance scale)
- Galaxies and Galactic Nuclei
- PMS and stellar parameters
- Disks around low-mass and intermediate mass PMS
- Outflows, stellar jets, HH objects
- Young binaries and young stellar clusters
- Brown Dwarfs
- Extrasolar Planets
- Solar System bodies
- AGB, Post-AGB, Mira stars
- Massive stars, Symbiotic stars, Hot Be B[e] stars
- Stellar fundamental parameters, activity, magnetism

VLTI Commissioning

~2 year effort to provide well-commissioned, user-friendly facility.

VINCI test instrument, mostly with Siderostats, some UT time.

Table 1. Statistics of the VINCI commissioning observations (up to August 2003). A total of 321 independent objects have been observed.

Archive (Raw data)	Number of OBs	Total number of files	Number of nights	Size (Gb)
2001	4827	19308	206	25.2
2002	4966	19864	235	35.9
2003	6125	24500	180	56
Total	15918	63672	621	117.2

VLTI Publications I

1. First radius measurements of very low mass stars with the VLTI, Segransan et al., 2003, A&A, 397, L5

   ESO Press Release 22/02,29 November 2002. How Small are Small Stars Really? VLT Interferometer Measures the Size of Proxima Centauri and Other Nearby Stars

2. The diameters of Alpha Centauri A and B: a comparison of the asteroseismic and VLTI views, Kervella et al., 2003, A&A, 404, 1087

   ESO Press Release 05/03,15 March 2003. A Family Portrait of the Alpha Centauri System: VLT Interferometer Studies the Nearest Stars

3. Interferometry and asteroseismology: The radius of τ Cet, Pijpers et al., 2003, A&A, 406, L15

4. The spinning-top Be star Achernar from VLTI-VINCI, Domiciano de Souza et al., 2003, A&A, 407, L47

   ESO Press Release 14/03. Flattest Star Ever Seen, VLT Interferometer Measurements of Achernar Challenge Stellar Theory

5. The interferometric diameter and internal structure of Sirius A, Kervella et al., 2003, A&A, 408, 681

VLTI Publications II

6. Direct measurement of the size of the star Eta Carinae, Van Boekel et al., 2003, A&A, 410, L37 (astro-ph/0310399)

   ESO Press Release 31/03, Biggest Star in Our Galaxy Sits within a Rugby-Ball Shaped Cocoon , VLT Interferometer Gives Insight Into the Shape of Eta Carinae

7. J-K DENIS photometry of a VLTI-selected sample of bright southern stars, Kimeswenger et al., 2004, A&A, 413, 1037
8. Tests of stellar model atmospheres by optical interferometry: VLTI/VINCI limb-darkening measurements of the M4 giant ψ Phe, Wittkowski et al., 2004, A&A, 413, 711
9. The diameter and evolutionary state of ProcyonA, Kervella et al., 2004, A&A, 413, 251 (astro-ph/0309148)
10. Cepheid distances from infrared long-baseline interferometry I. VINCI/VLTI observations of seven Galactic Cepheids, Kervella et al, 2004, A&A, in press (astro-ph/0311525)

VLTI Publications III

11. Introduction to VINCI/VLTI interferometric data analysis, Kervella et al., 2004, A&A, submitted
12. Interferometric observations of the Mira star o Ceti with the VLT/VINCI instrument in the near IR, Woodruff et al., 2004, A&A, submitted
13. Dust in the nucleus of the active galaxy NGC1068: structure and composition on parsec scales, Jaffe et al., 2004, Nature, 6 May 2004

    ESO Press Release 17/03. A First Look at the Doughnut Around a Giant Black Hole - First detection by infrared interferometry of an extragalactic object
14. Mid-IR interferometry of the Mira variable RR Sco with the VLTI/MIDI instrument, Ohnaka et al., 2004, A&A, submitted
15. Mid-IR sizes of circumstellar disks around Herbig AeBe stars measured with MIDI on the VLTI, Leinert et al., 2004, A&A, submitted

VLTI Publications IV

16. The angular size of the Cepheid l Car: a comparison of the interferometric and surface brightness techniques, Kervella et al., 2004, ApJ, submitted (astro-ph/0402244)
17. VLTI NIR interferometric observations of Vega-like stars,   Di Folco et al., 2004, A&A, submitted
18. VLTI/VINCI Observations of the nucleus of NGC 1068 using the adaptive optics system MACAO, Wittkowski et al., 2004, A&A, submitted
19. Direct observations of the building blocks of planets in the terrestrial region of proto-planetary disks R. van Boekel et al., 2004, Nature, submitted

Fundamental parameters of cool dwarfs

Very few diameters of late-type MS stars available

Made possible by high-accuracy of VLTI/VINCI (partially resolved)

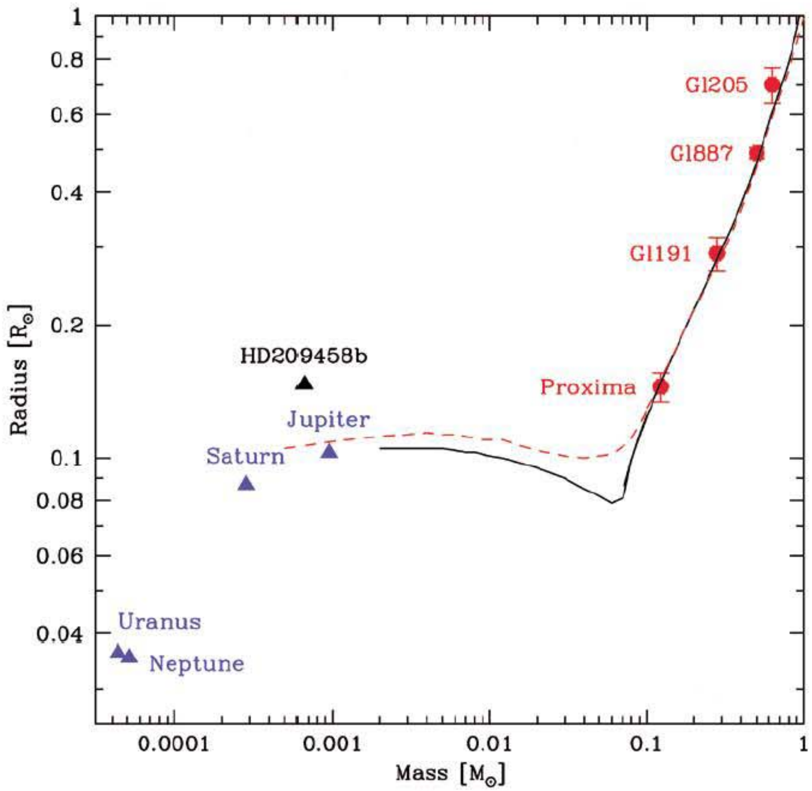
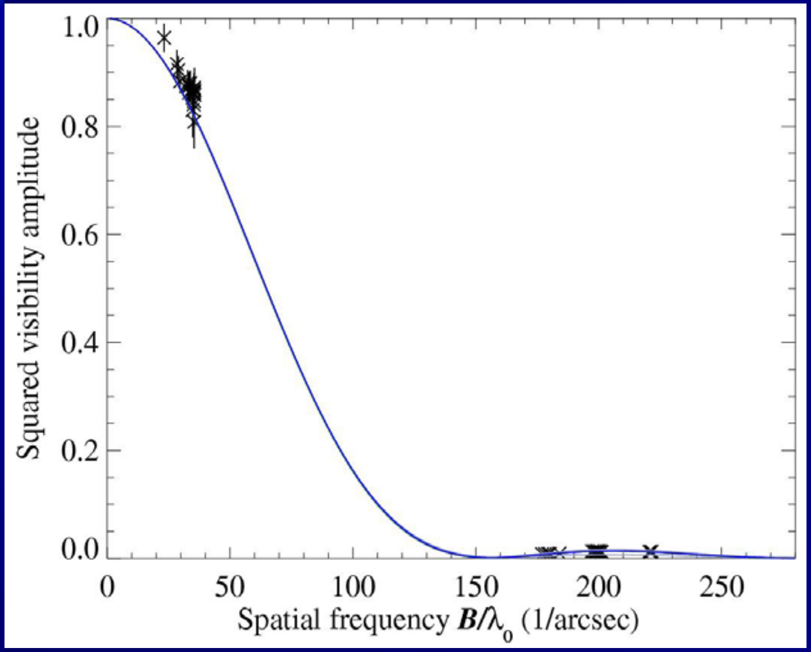


Figure 1: *Radii and masses of the four very-low-mass stars now observed with the VLTI, GJ 205, GJ 887, GJ 191 (also known as "Kapteyn's star") and Proxima Centauri (red filled circles; with error bars). For comparison, the masses and radii of the Solar System planets (blue triangles) and of HD 209458 B (black triangle) are also shown. The two curves represent theoretical models for stars of two different ages (400 million years - red dashed curve; 5 billion years - black fully drawn curve). The VLTI observations are from Ségransan et al. (2003), the models from Baraffe et al. (1998).*

Limb-Darkening

Very difficult measurement, but of great importance for stellar atmospheric models. Needs measurements close to the visibility null.



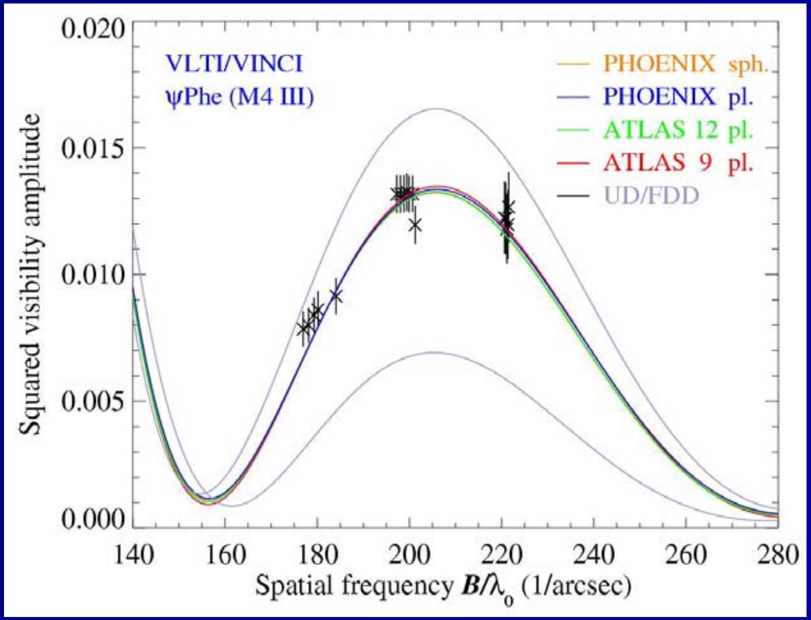


Figure 3: *Measured squared visibility amplitudes of Psi Phe together with predictions by a (solid black line) spherical PHOENIX model atmosphere, (dashed-dotted line) plane-parallel PHOENIX model atmosphere, (dotted line) plane-parallel ATLAS 12 model atmosphere, (dashed line) plane-parallel ATLAS 9 model atmosphere. The models were constructed by comparison to spectrophotometry. The gray lines denote uniform disc and fully darkened disc models. The left panel shows the full range of the visibility function while the right panel is an enlargement of the low squared visibility amplitudes in the second lobe. From Wittkowski et al. (2003)*

Flattening in fast rotators

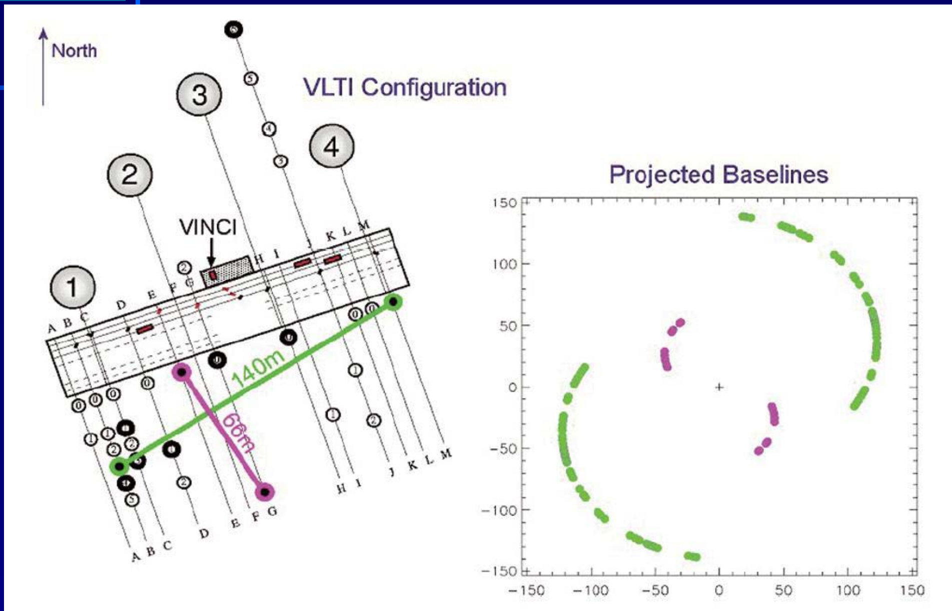
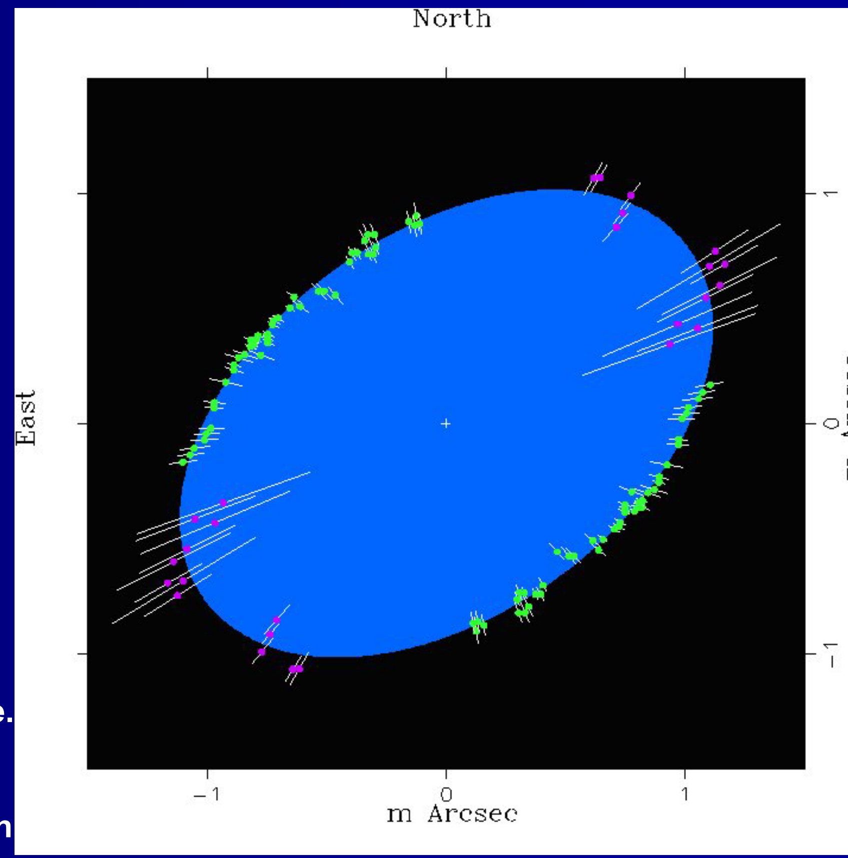


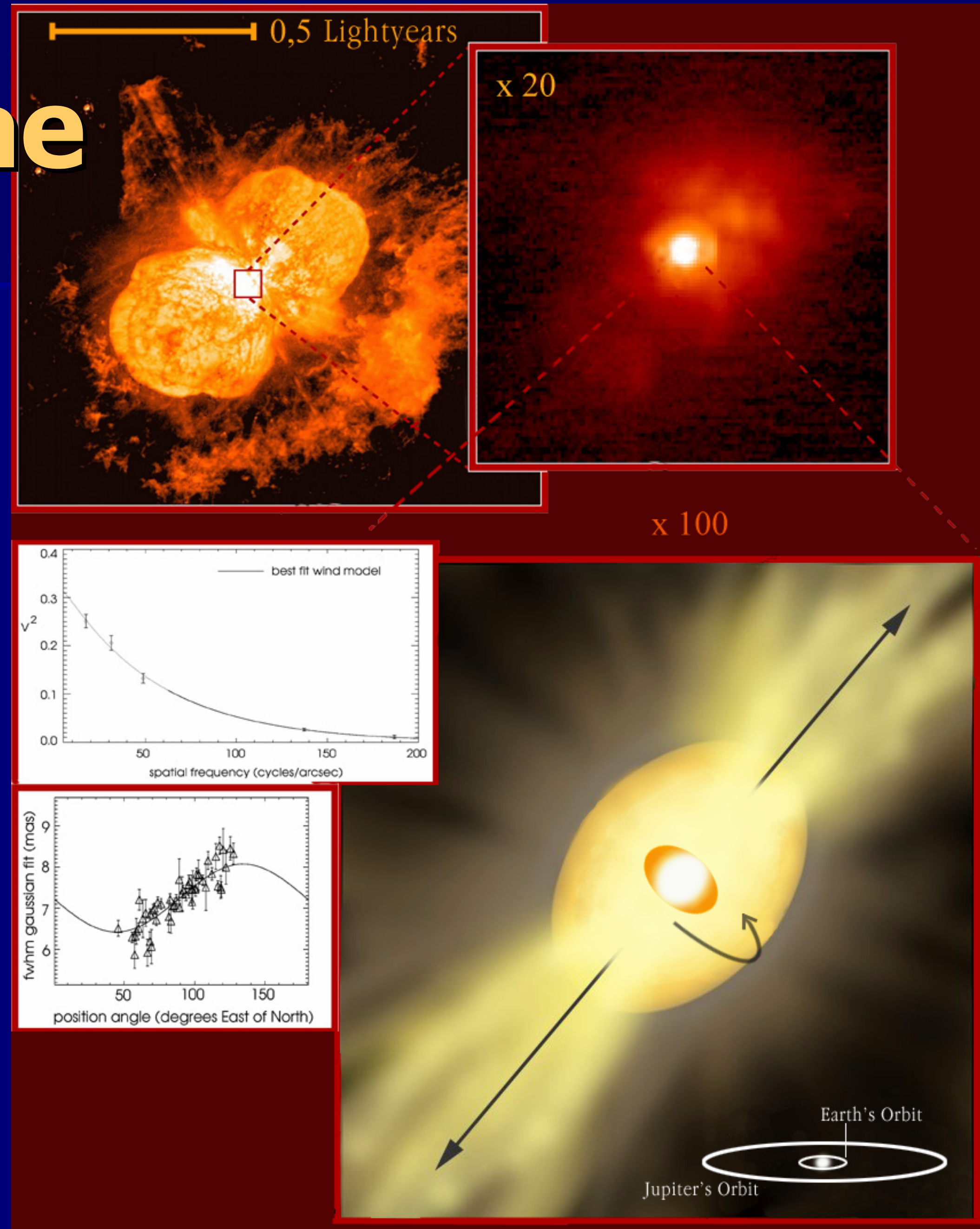
Figure 6: *VLTI ground baselines for Achernar observations and their corresponding projections onto the sky at different observing times. Left, scheme of VLTI baselines for the two pairs of siderostats used for Achernar observations. Color magenta represents the 66 m (E0-G1; azimuth 147°, counted from North to East) and green the 140 m (B3-M0; 58°). Right, Corresponding baseline projections onto the sky (B_{proj}) as seen from the star. Note the very efficient Earth-rotation synthesis resulting in a nearly complete coverage in azimuth angles.*

Fit of an ellipse over the observed V^2 points translated to equivalent uniform disc angular diameters. Magenta points are for the 66m baseline and green points are for the 140m baseline. The fitted ellipse results in major axis 2a=2.53±0.06 milliarcsec, minor axis 2b=1.62±0.01 milliarcsec, and minor-axis orientation α_0=39±1° (from North to East). The points distribution reveals an extremely oblate shape with a ratio 2a/2b = 1.56±0.05. From Domiciano de Souza et al. (2003).



Eta Carinae

Zoom into the η Carinae nebula. *Top left*: WFPC2 image (Morse et al. 1998). *Top right*: NACO observations at 2 μm. Center left : VINCI data reveal an object with size 5 mas. This is not the photosphere of the star, but the radius at which the stellar wind becomes opaque. *Bottom left*: VINCI data, converted to an effective diameter, plotted against the position angle of the baseline. *Bottom right*: the diameter change with position angle implies that the object is elongated; the orientation is the same as that of the large-scale nebula shown in the top left panel. Courtesy R. Van Boekel.



NGC 1068

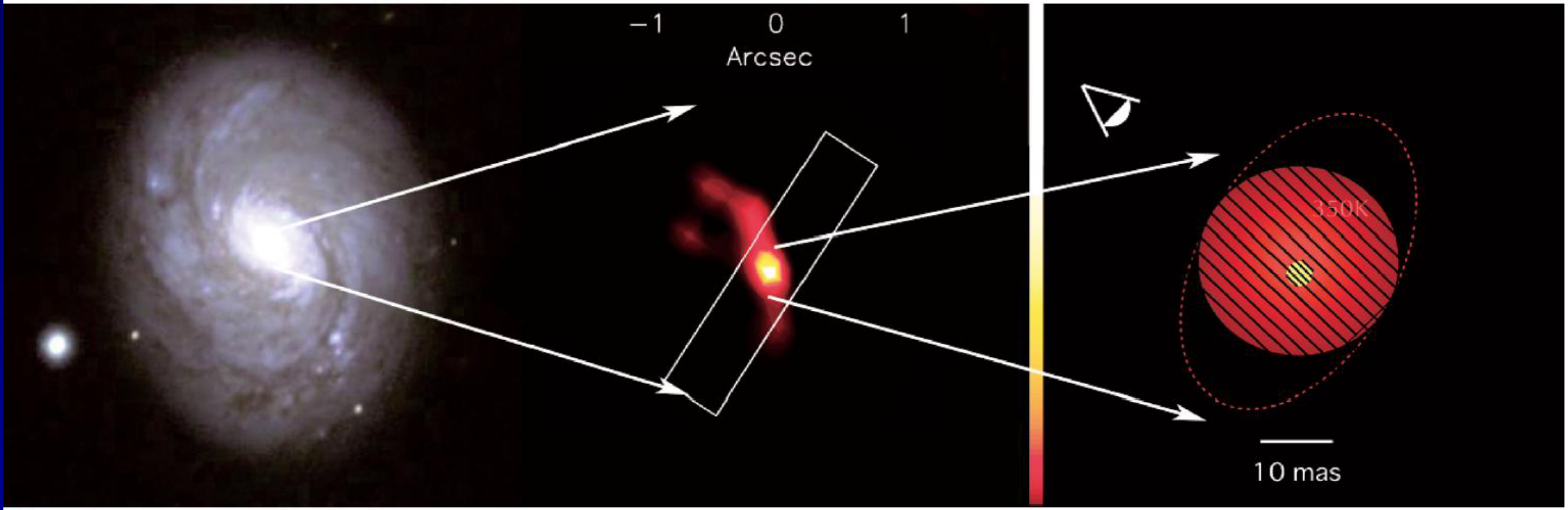
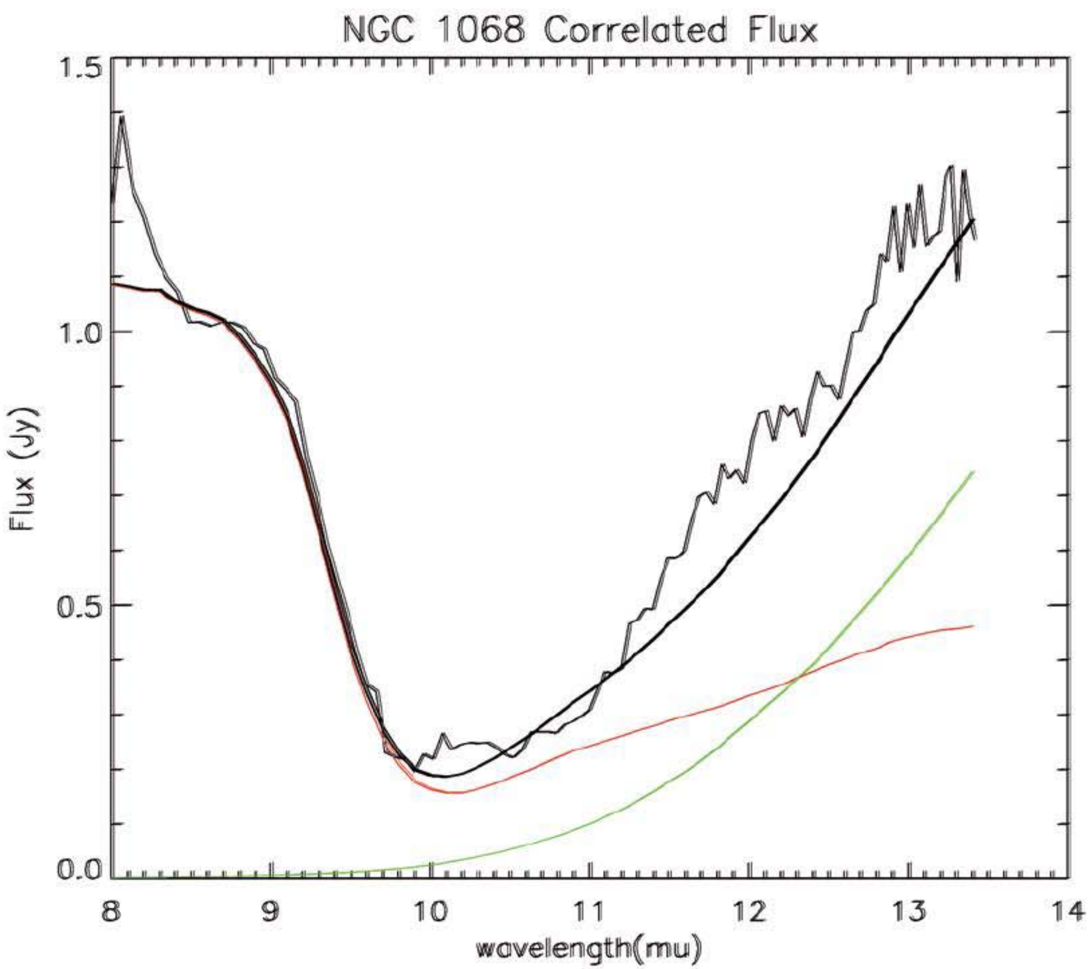


Figure 9: Left: 3.4 × 3.4 arcmin optical image of NGC 1068, (NOAO/AURA/NSF). Centre: non-interferometric acquisition image of NGC 1068 taken by MIDI with a 8.7 micron filter, showing the structures on arcsec scales. Also shown are the position of the spectroscopic slit used in the interferometric observations and the directions of North (toward top left) and East (toward bottom left) on the sky. The projected baseline was essentially North/South and the fringe spacing in this direction was 26.3 mas at 10 micron wavelength. Right: sketch of the dust structure in the nucleus of NGC 1068, as derived from modeling the MIDI observations. It contains a central hot component (T > 800 K, yellow) which is significantly smaller than the interferometric beam, and a much-larger well-resolved warm component (T=330 K, red) of diameter 33±5 mas, corresponding to 2.8 pc at the distance of NGC 1068. From Jaffe et al (2003).

NGC 1068

Figure 10: The interferometric spectrum of NGC 1068 showing the flux on scales of 30 milli-arcsec and smaller. The jagged line shows the data and the smooth line the best fitting two-component gaussian model described in Fig. 9. The red and green lines indicate the individual contributions of the "hot" and "warm" components, respectively. The dip near 10 micron is probably caused by alumino-silicate dust, as opposed to the olivine-type, silicate dust absorption noted in the same spectrum obtained without the interferometric combination. From Jaffe et al. (2003).



The VLTI Science Group

Lots of people have contributed to the VLTI, too many to mention!

Some current or recent SG members:

Pascal Ballester, Emanuel Di Folco, Emanuel Galliano, Andreas Glindemann, Christian Hummel, Pierre Kervella, Sebastien Morel, Francesco Paresce, Isabelle Percheron, Fredrik Rantakyrö, Andrea Richichi, Markus Schöller, Martin Vannier, Markus Wittkowski

Fringes on the WEB

ESO VLTI:

http://www.hq.eso.org/projects/vlti/

AMBER and MIDI:

http://www.obs-nice.fr/amber/

http://www.mpia-hd.mpg.de/MIDI/

Visitors and Students welcome!