Infrared interferometry of AGN: present results and future goals

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- **Bispectrum speckle interferometry: 1.6 and 2.1 μm**
- **VLTI-VINCI long-baseline interferometry: 2.2 μm, and**
- **VLTI-MIDI long-baseline interferometry: 8-13 μm**

Infrared Interferometry

- Resolution of conventional imaging (atmosphere-limited resolution): ~ 1 ”
- Hubble Space Tel. (2.4 m; diffraction-limited resolution): 87 mas at λ= 1 μm

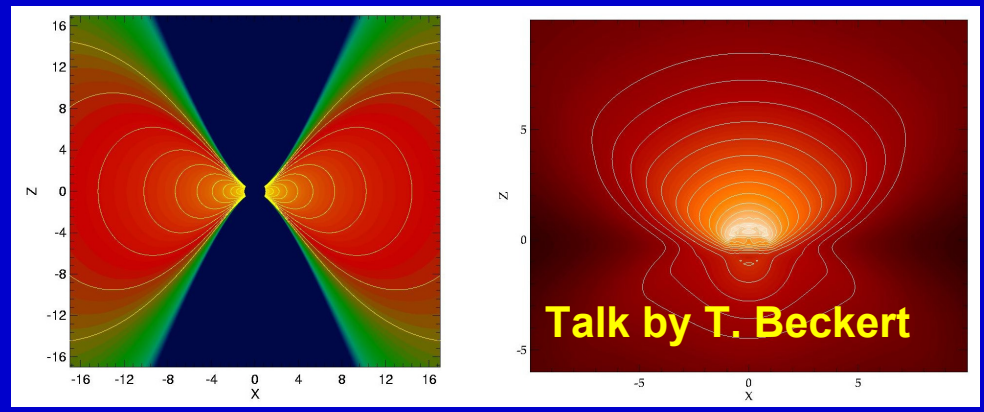
Resolution (λ/D) achievable with bispectrum speckle interferometry and infrared long-baseline interferometry:

- 6 m telescope / bispectrum Speckle Interferometry: 35 mas at λ= 1 μm
- 10 m telelescope / bispectrum Speckle Interferometry: 21 mas at λ= 1 μm

- IOTA interferometer (30 m baseline): 7 mas at λ= 1 μm
- Large Binocular Telescope (LBT) 9 mas at λ= 1 μm
- ESO VLT Interferometer (200 m baseline): 1 mas at λ= 1 μm

~100 times Hubble resolution

Goals of infrared interferometry



Activity in the centers of galaxies:

- non-stellar activity - BH, accretion disk, BLR, torus, NLR
- and of circumnuclear star formation (starburst).

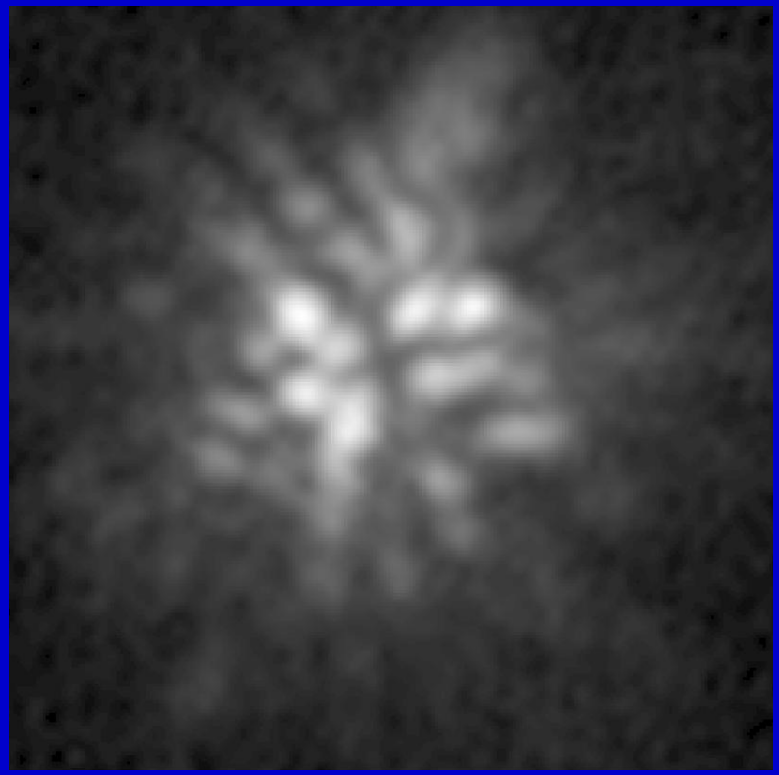
Combining interferometric observations and theoretical studies, we can investigate how accretion processes at different length scales work and how they relate to each other. The length scales of interest are:

- 10-100 pc, where starbursts may dominate the appearance:
  HST, speckle imaging, AO

- a few pc, where the torus is the main component:
  speckle, AO, MIDI / VLTI, AMBER / VLTI

- the Broadline Region (approx. 0.1 mas in nearby QSOs): AMBER / VLTI

Observations: Bispectrum speckle interferometry of NGC 1068 with the SAO 6 m telescope



1.8”

K-band speckle interferogram of NGC 1068:

exposure time 200 ms,
FOV 1.8 x1.8 ”

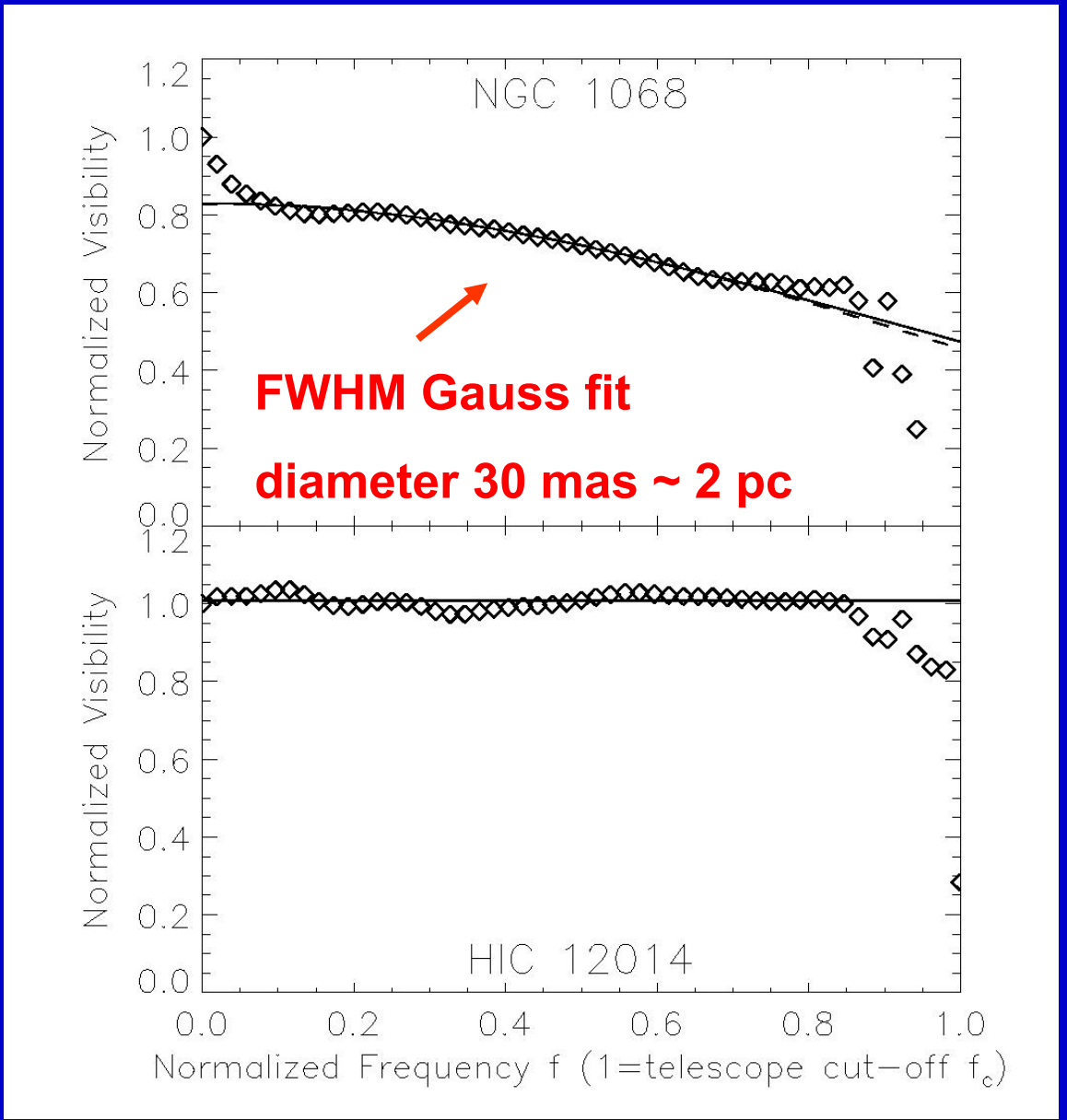
Unresolvable point source?

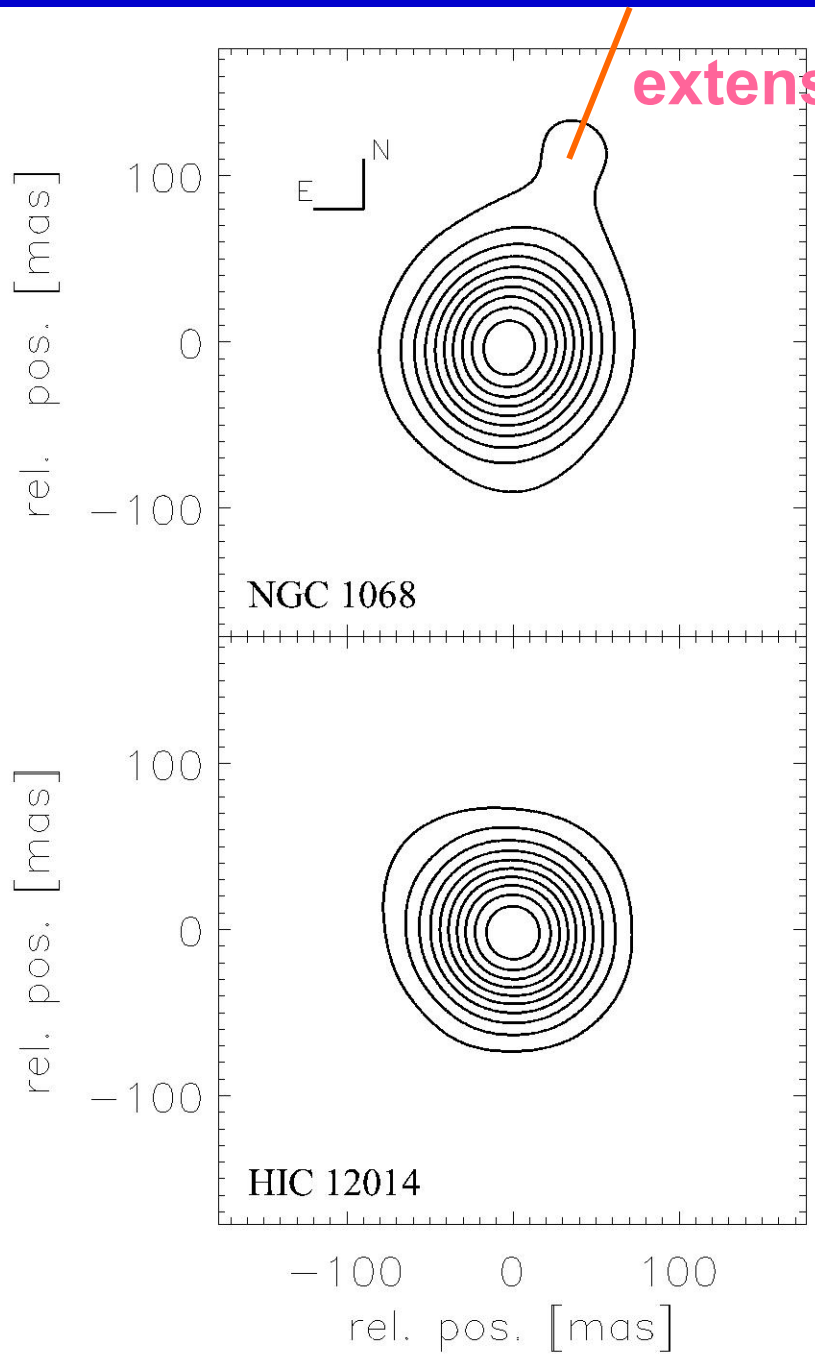
First resolution of NGC 1068

Azimuthally averaged visibility of NGC 1068 (top) and an unresolved reference star (bottom)

Wittkowski et al., 1998
A&A 329, L45

1999: Weinberger et al. confirmed this result (AJ 117, 2748)





Bispectrum speckle interferometry of NGC 1068:

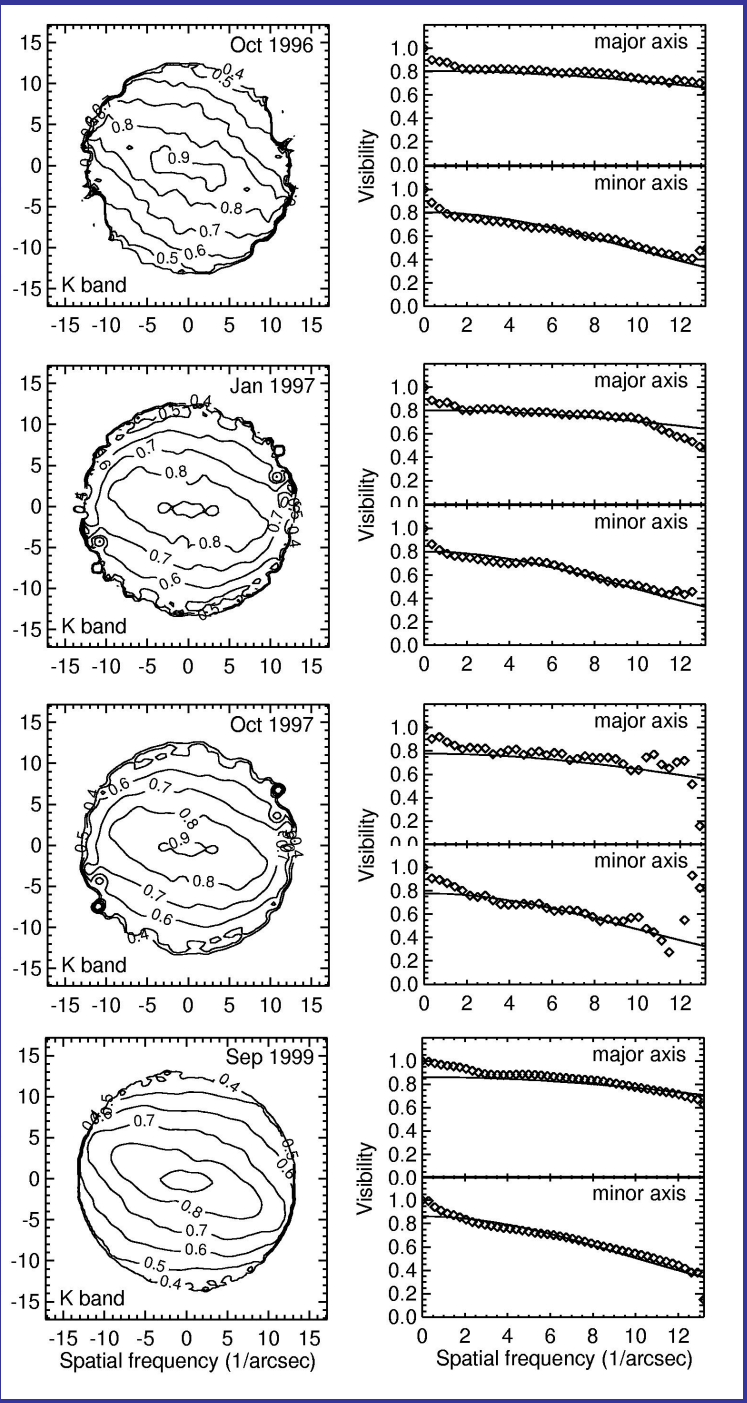
First diffraction-limited, elongated K-band image of NGC 1068

(Wittkowski et al. 1998, A&A 329, L45)

NGC 1068:

visibility functions derived from 4 different data sets

Weigelt et al. 2004, A&A 425, 77



major axis

19 x 40 mas

minor axis

20 x 40 mas

24 x 40 mas, 600 frames, 2'' K-band seeing

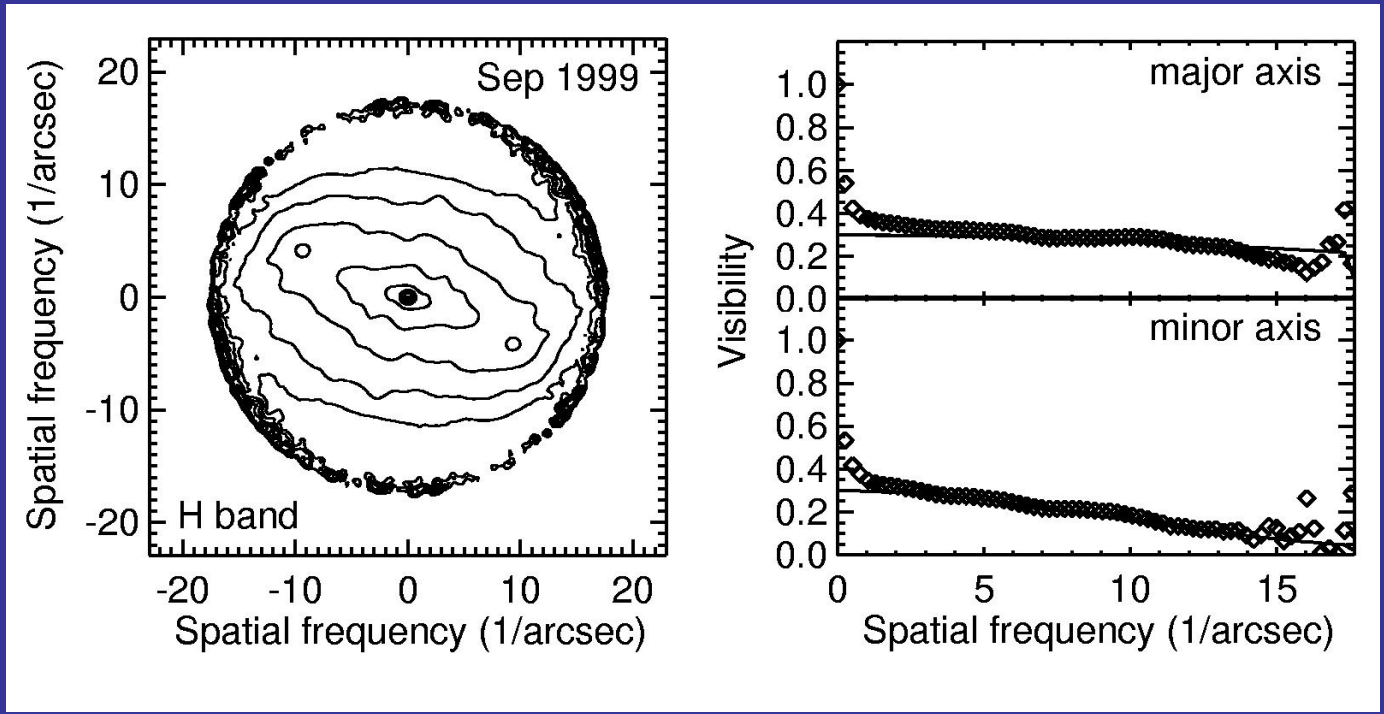
18 x 38 mas ~ 1.5 x 3 pc

error +/- 3 mas

11 000 frames,

1.2'' seeing

H-band visibility of NGC 1068



FWHM Gauss fit diameter: **18 x 45 mas (+/- 4 mas)**

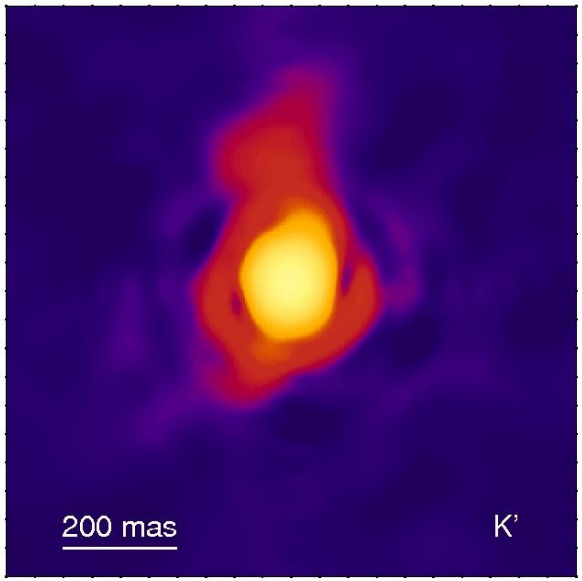
Reconstruction of true images at 1.6 and 2.1 micron?

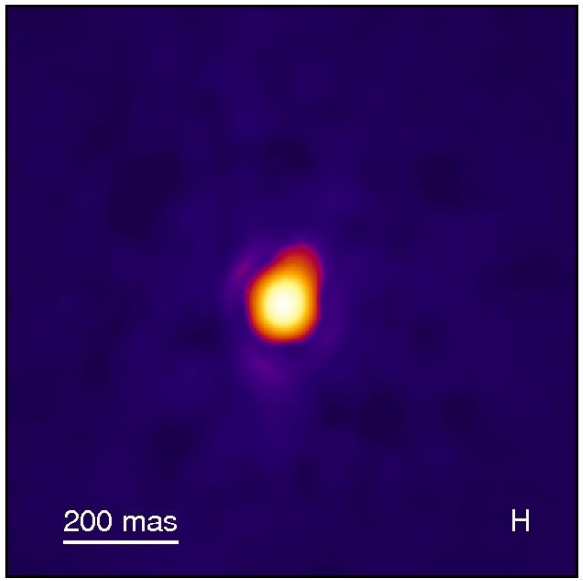
Bispectrum Speckle Interferometry

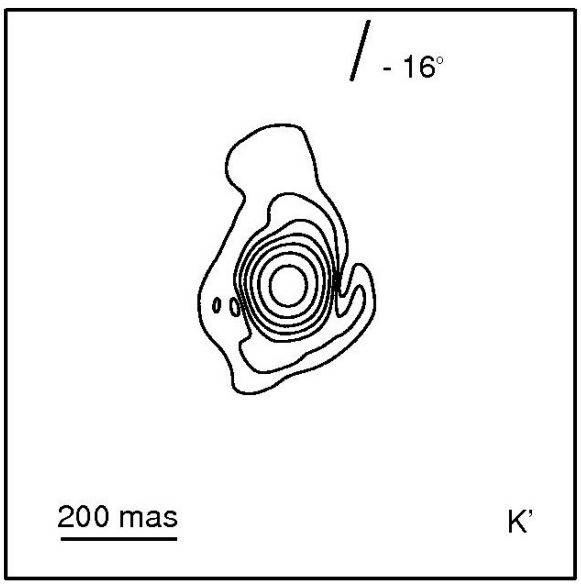
Real-time image reconstruction:

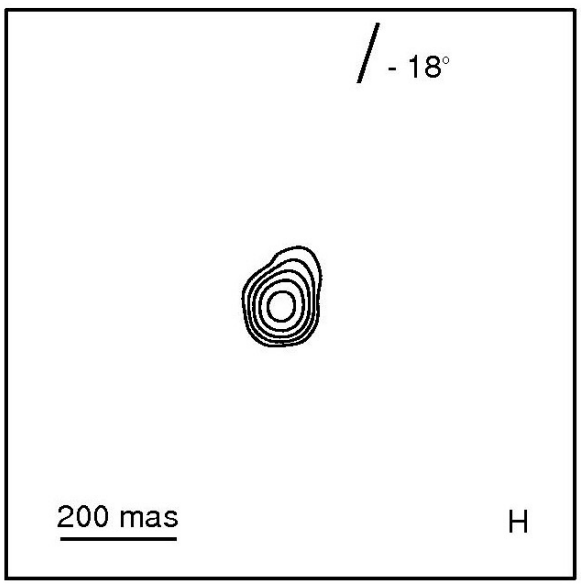
SAO 6 m telescope, 2 arcsec K-band seeing

- ..\0-Movies\hip4849.SAO+++.mov









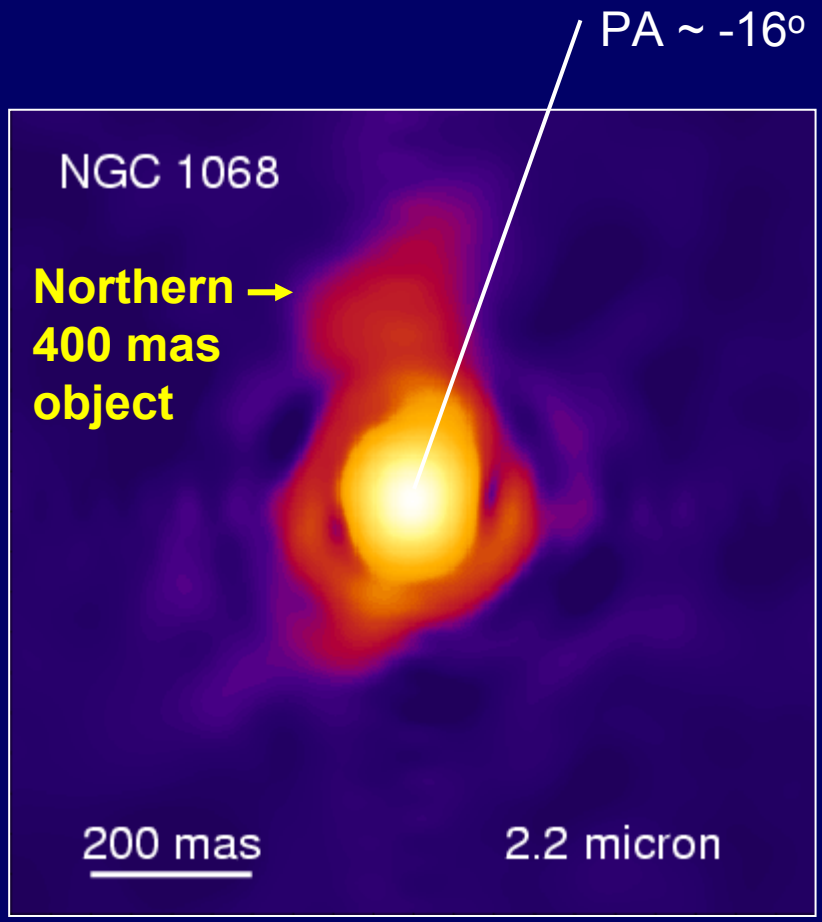
Weigelt et al. 2004, A&A 425, 77

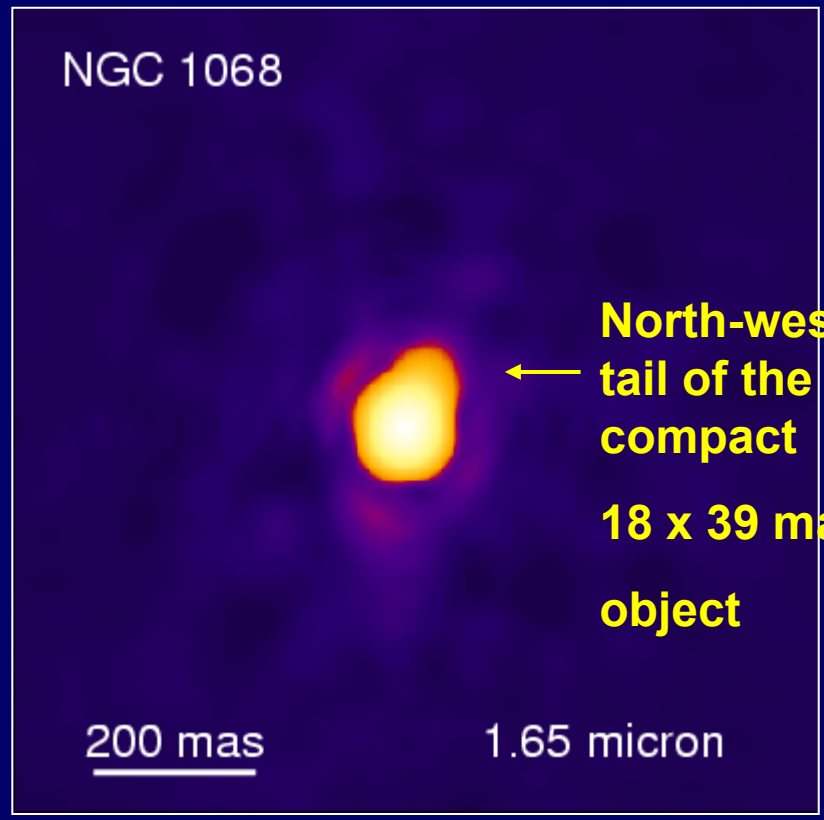
Bispectrum speckle interferometry of NGC 1068:

First diffraction-limited K'- and H-band images of the resolved 18 x 39 mas core of NGC 1068

The images show the compact core with its tail-shaped, north-western extension at PA -16/18° as well as the northern and south-eastern extended components.

First diffraction-limited K'- and H-band images of NGC 1068





Compact component: 18 x 39 mas ~ 1.3 x 2.8 pc

Northern component: 400 mas

Summary:
H- and K-band bispectrum speckle interferometry of NGC 1068:

57 mas / 74 mas resolution images

- A diffraction-limited K'-band image with 74 mas resolution and the first H-band image with 57 mas resolution were reconstructed from speckle interferograms obtained with the SAO 6 m telescope.

- The resolved compact core has a north-western, tail-shaped extension

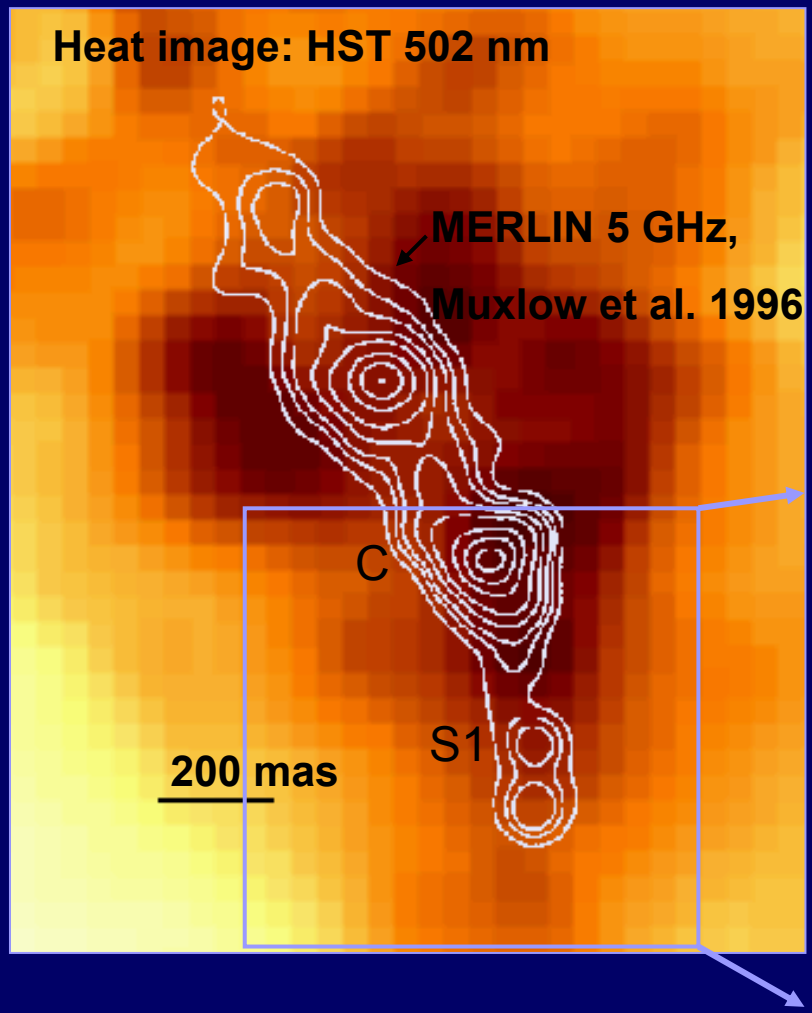
Bispectrum speckle interferometry method: Weigelt, Optics Com. 21, 55, 1977; Lohmann et al. Appl. Opt. 22, 4028, 1983

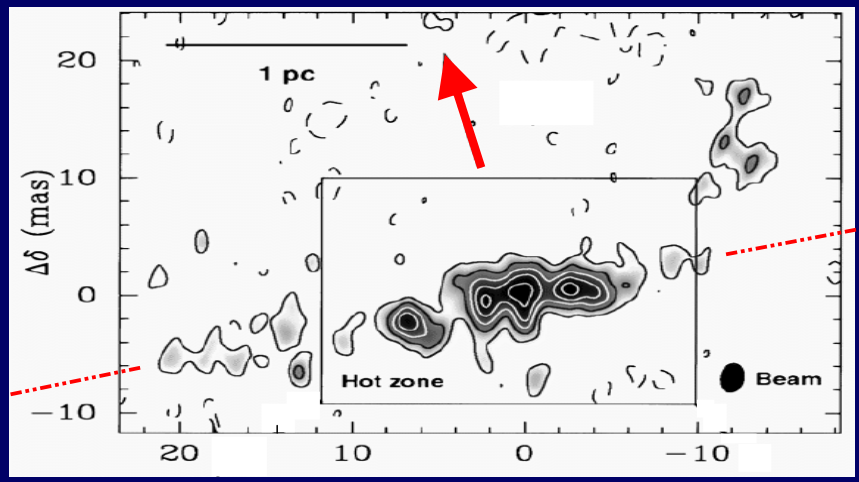
Summary: Bispectrum speckle interferometry of NGC 1068:

1.3 x 2.8 pc core

- The K'-band FWHM diameter of the resolved compact core is 18 x 39 mas or 1.3 x 2.8 pc (FWHM of a Gaussian fit).
- The PA of the north-western extension is -16 ± 4^{o}.
- In the H band, the FWHM diameter of the compact core is 18 x 45 mas ($\pm$ 4 mas), and the PA is -18 ± 4^{o}.
- The K'- and H-band fluxes of the compact core are 350 ± 90 mJy, or **K' = 8.2,** and 70 ± 20 mJy, or **H = 10.4**, respectively.

Comparison with HST, Merlin, and VLBA images

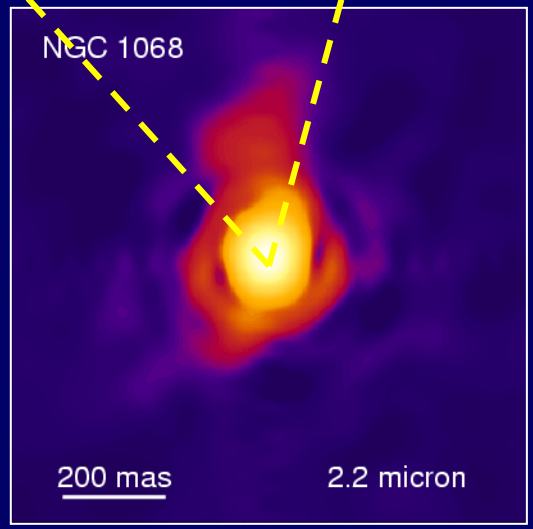


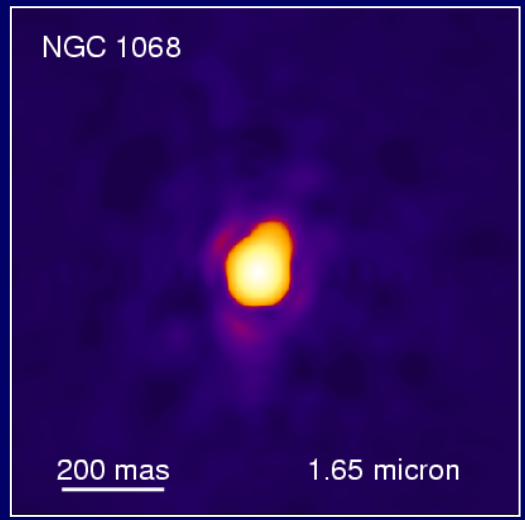


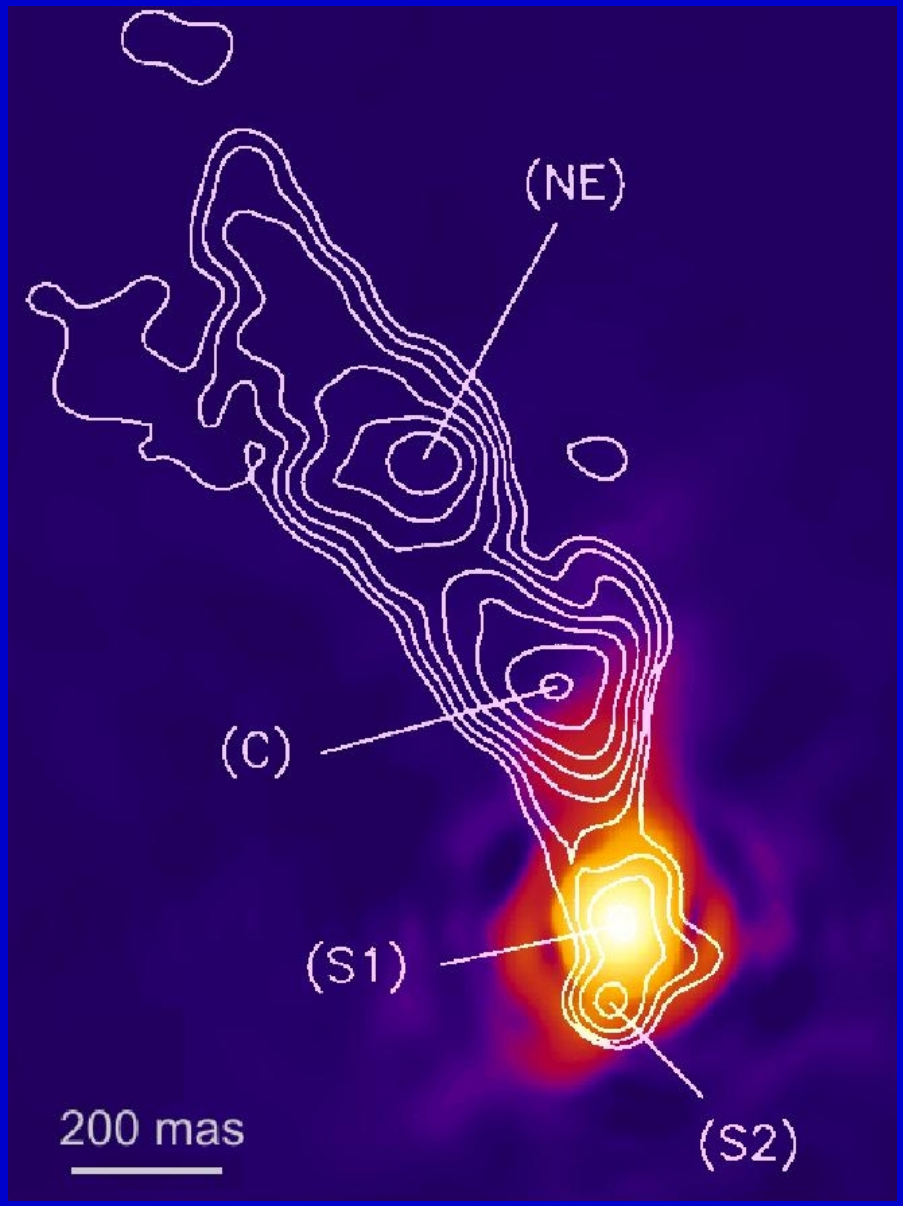
100 mas

VLBA 8.4 GHz radio continuum; Gallimore et al. 1997: ~ 5 x 20 mas

Ionization cone







MERLIN 5 GHz contour map (Gallimore et al.1996) superposed on our K'-band image.

- The center of the radio component S1 coincides with the center of the K'-band peak.
- The PA of –16^{o} of the 18 x 39 mas K'-band core is very similar to that of the western wall (PA -15^{o}) of the ionization cone.
- The northern extended 400 mas structure (red) aligns with the direction of the inner radio jet (S1 - C).

Interpretation 1.3 x 2.8 pc core and the northern extended 400 mas structure

- The PA of -16° of the compact **1.3 x 2.8 pc core** is very similar to that of the western wall (PA = -15°) of the ionization cone.
The **dust sublimation radius** of NGC 1068 is approximately **0.2 - 1 pc**.

⟶ This suggests that the H- and K'-band emission from the 1.3 x 2.8 pc core is both thermal emission and scattered light from

- dust near the **western wall of a low-density, conical outflow cavity**
- or from the innermost region of a **pc-scale dusty torus**.

- The northern extended 400 mas structure lies near the western wall of the ionization cone and coincides with the inner **radio jet** (PA = 11°). The large distance from the core suggests that the K'-band emission of this component is scattered light from the western cavity region and the radio jet region.

Interpretation:
Flux and structure predicted by various torus models

- For a quantitative analysis of the K'-band flux emerging from the optically thick torus, accurate radiative transfer modeling is necessary. A number of models have been published for NGC 1068 (e.g., Pier & Krolik1992, 1993, Granato et al. 1997, Nenkova et al. 2002).

All these models try to fit the SED of Rieke & Low (1975) with a K-band flux of 0.3 Jy.

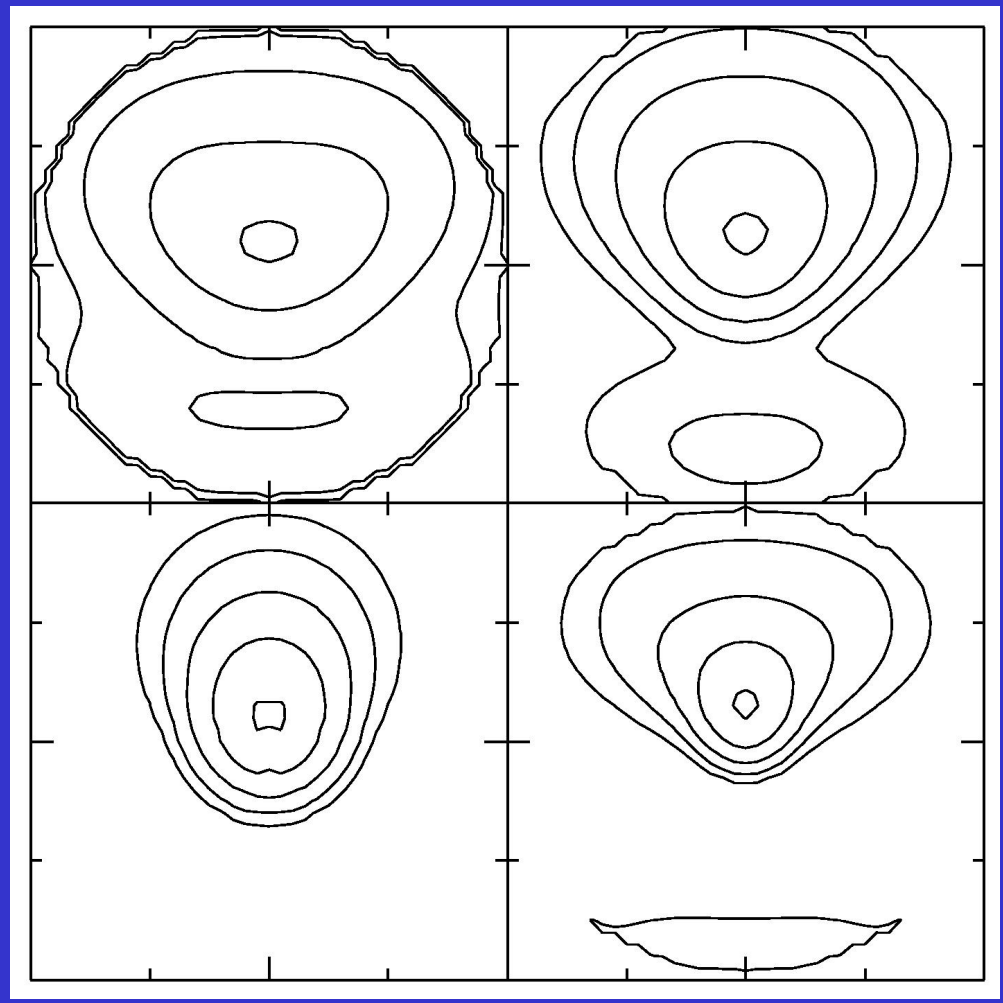
- Model images reported by Granato et al. (1997) shows an elongated shape along the direction with low absorption. The model images are somewhat larger than the dust sublimation radius. As discussed above, our images of the compact core also have a size which is similar to the dust sublimation radius.

Brightness contours of torus models

(Granato et al. 1997; ApJ 486, 147; NGC 1068 SED; 4 different wavelengths)

25 μm

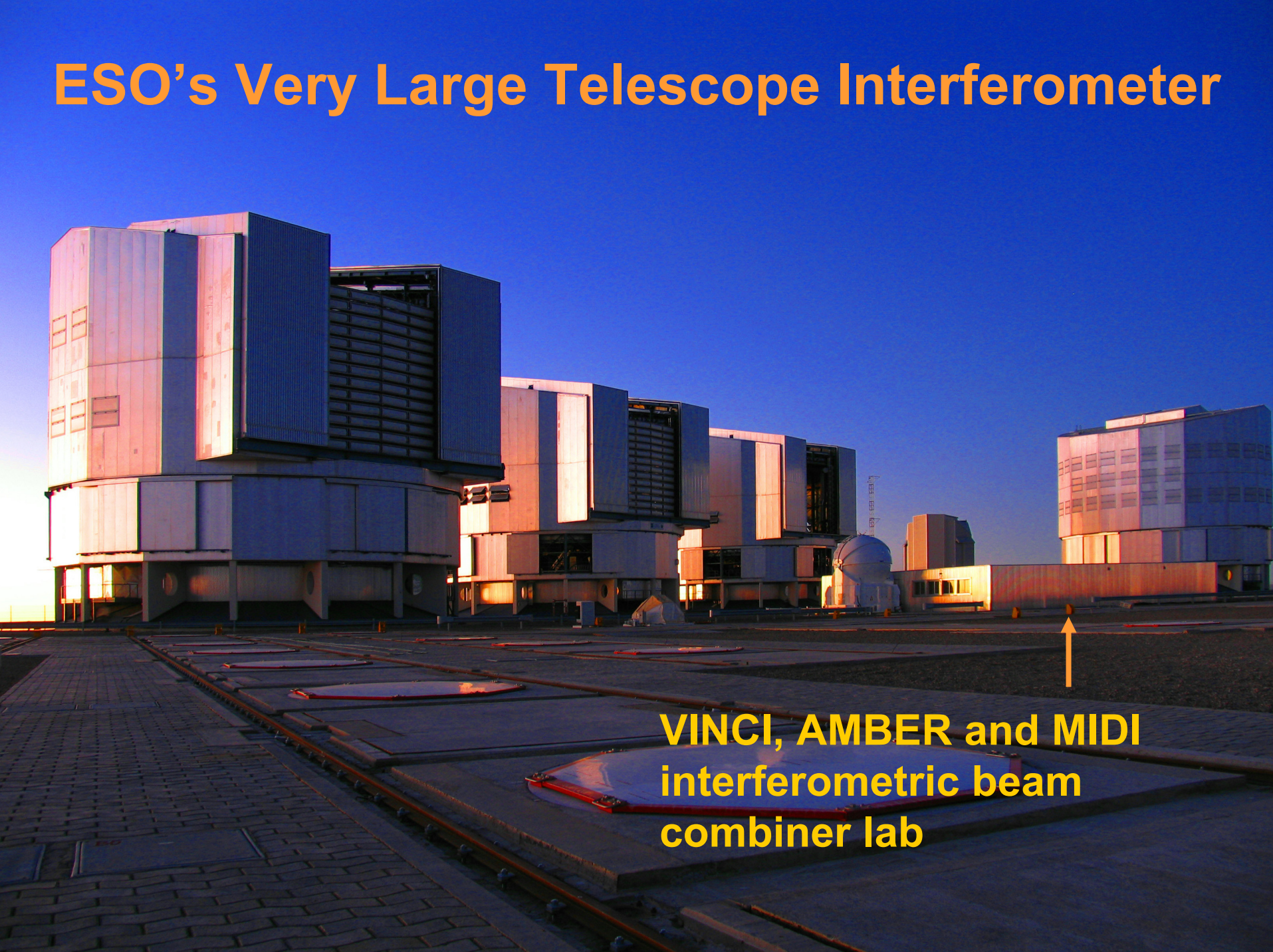
10 μm



3.5 μm

2.2 μm

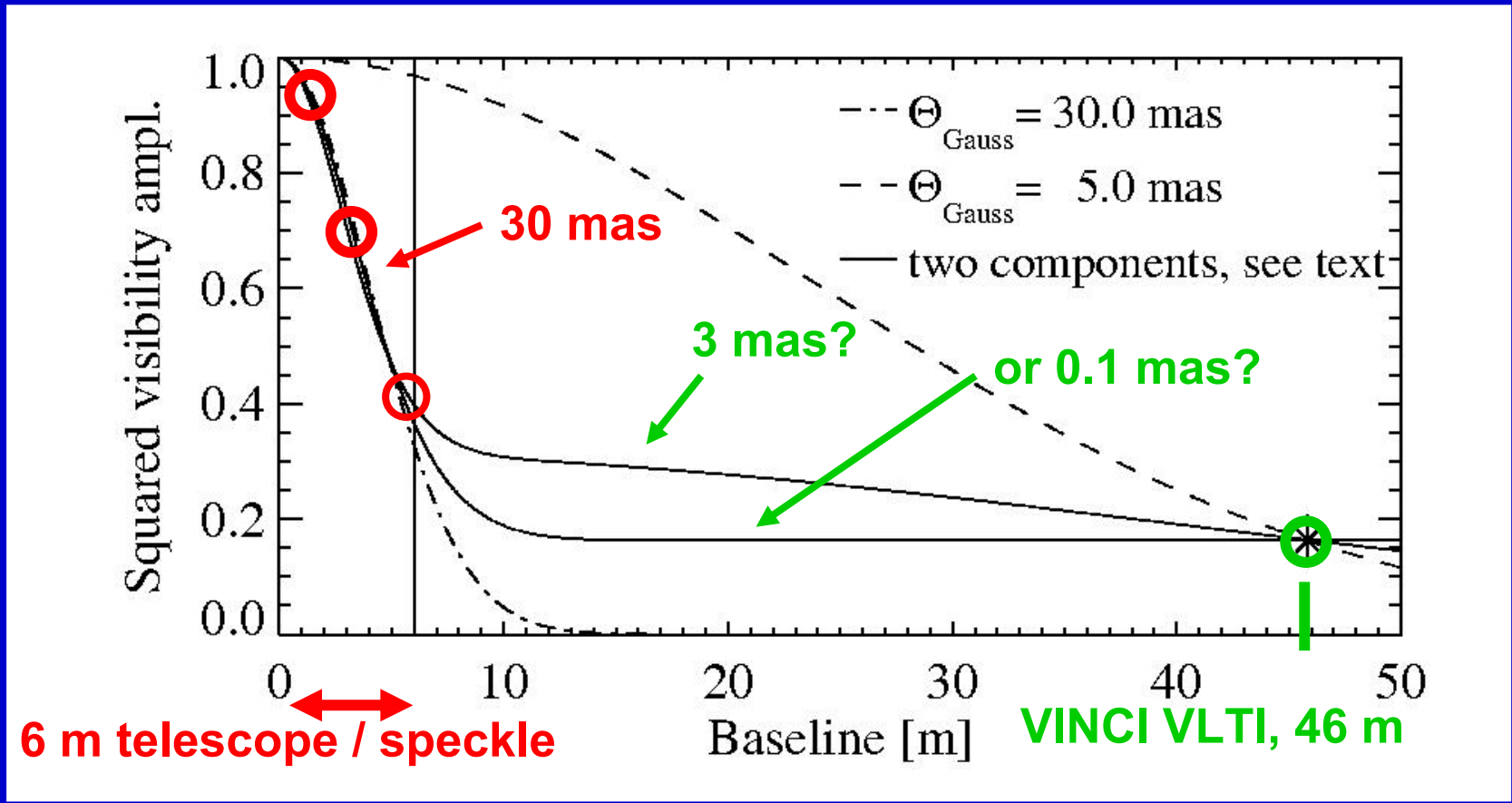
ESO's Very Large Telescope Interferometer



First VINCI-VLT NIR interferometry of NGC 1068:

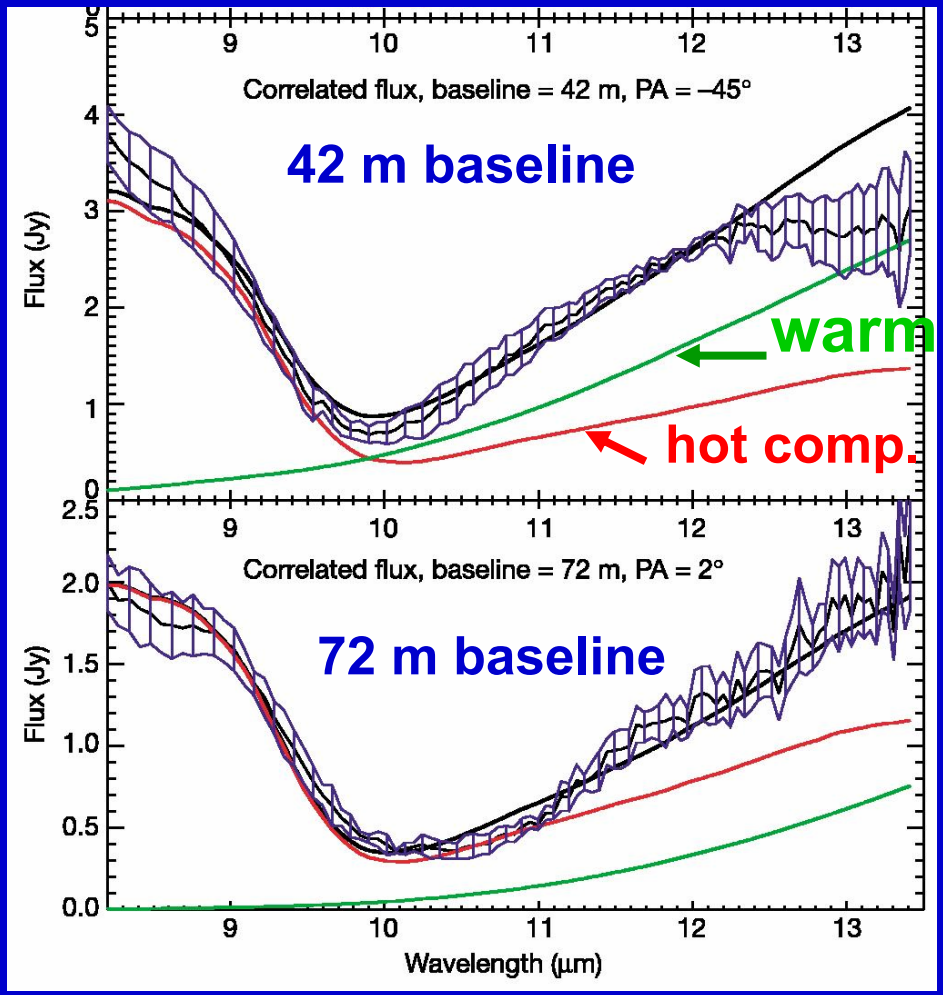
resolution of a new 0 - 3 mas structure (46 m baseline, K band):

< 3 mas clumps in the torus? Accretion disk?



Wittkowski, Kervella, Arsenault, Paresce, Beckert, Weigelt 2004, A&A 418, L39

First MIDI-VLT interferometry of NGC 1068



Silicate dust absorption dip near 10 µm

Resolution of two components:

- Central hot component:

  Dust temperature T > 800 K

  Size: 0.7 x <1 pc (0.7 pc parallel jet)

- Large warm component:

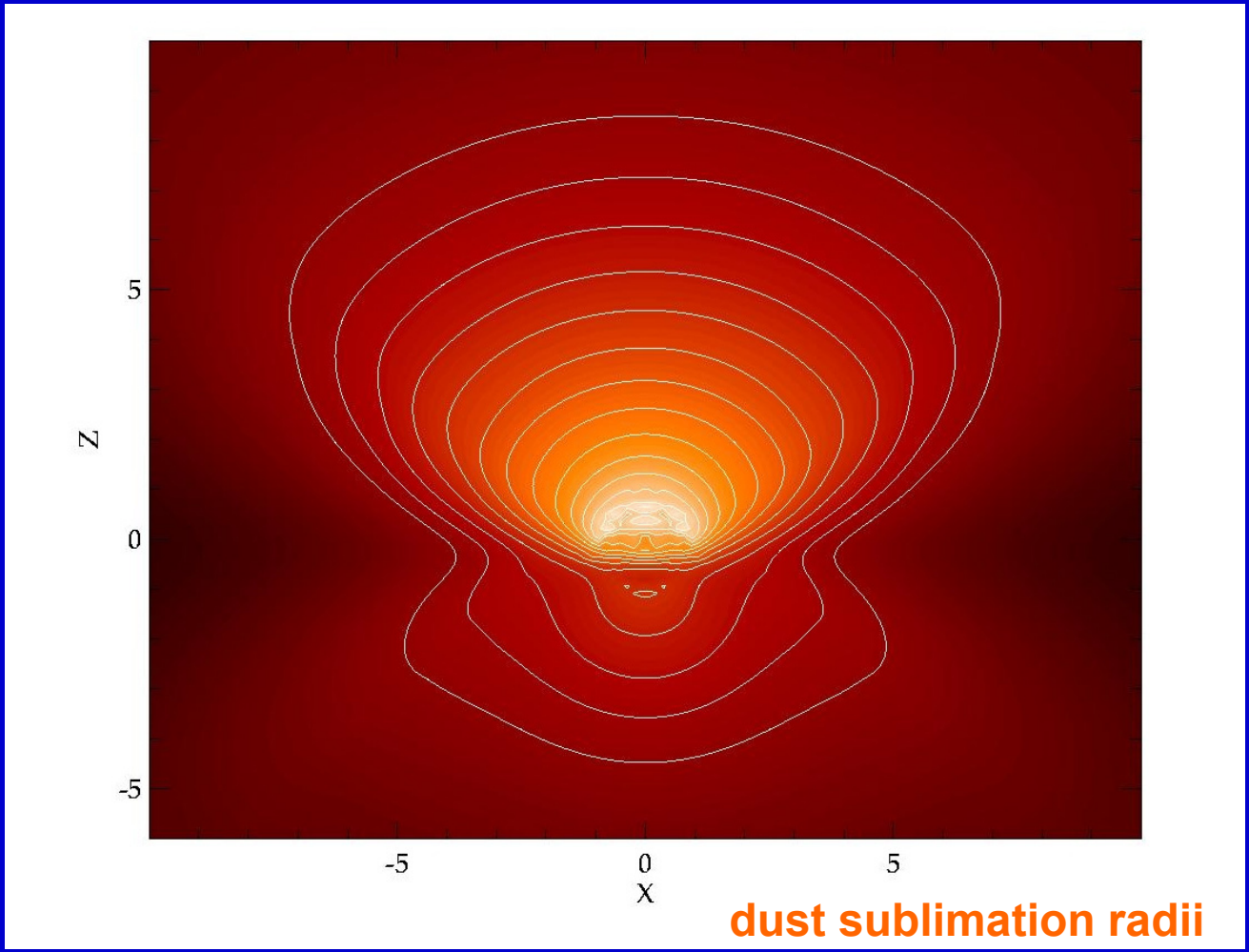
  T = 320 K

  Size 2.1 x 3.4 pc (2.1 pc parallel jet)

  (= 30 x 49 mas)

Jaffe et al. 2004, Nature 429, May 6

Future goals



Talk by

T. Beckert

K-band brightness distribution of our radiative transfer calculations based on the method of Nenkova et al. (2002) (Beckert et al. 2004).

The inclination is 20° from the midplane (contour range of 2^{13}).

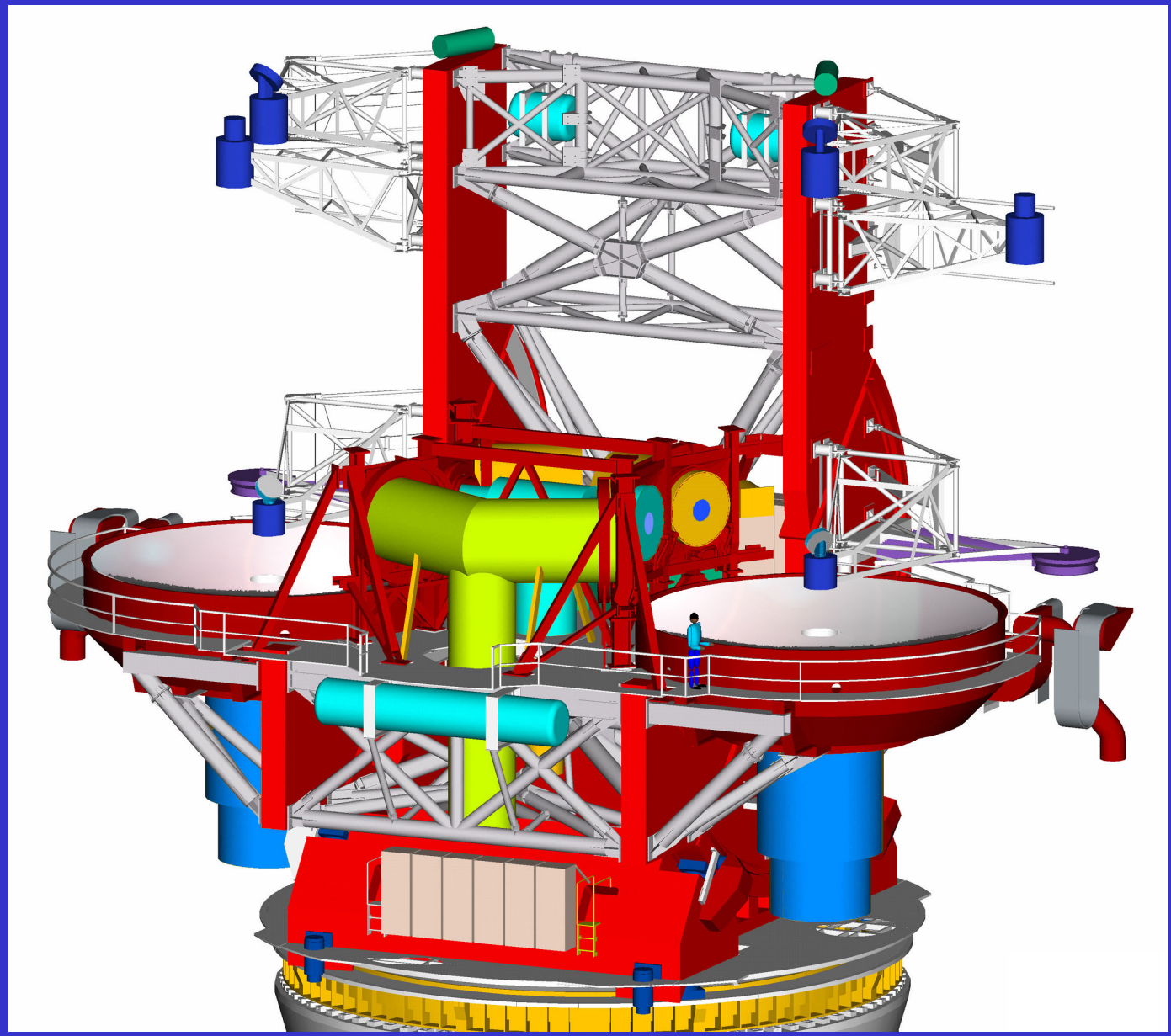
LBT Interferometry: Beam combiner instrument LINC

Collaboration:

MPI for Astronomy (PI T. Herbst), Arcetri Obs.,Univ. Cologne, MPI for Radio Astronomy

Wavelength range: 0.5 - 2.4 μm

Very large field of view (60 arcsec) → availability of reference stars → imaging of very faint objects




VLTI phase-closure
instrument AMBER

AMBER

Observation of 51 Hya:

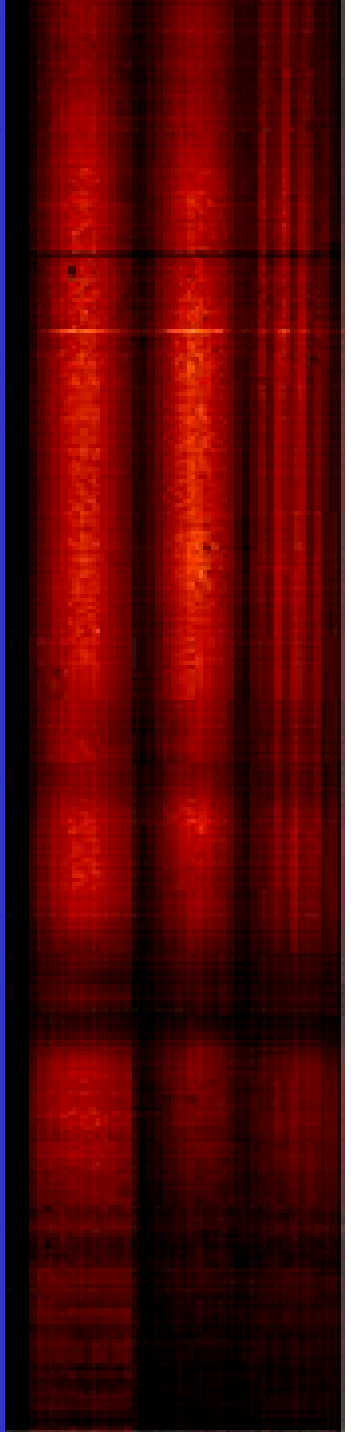
Commissioning May 2004

Medium spectral resolution R=1200

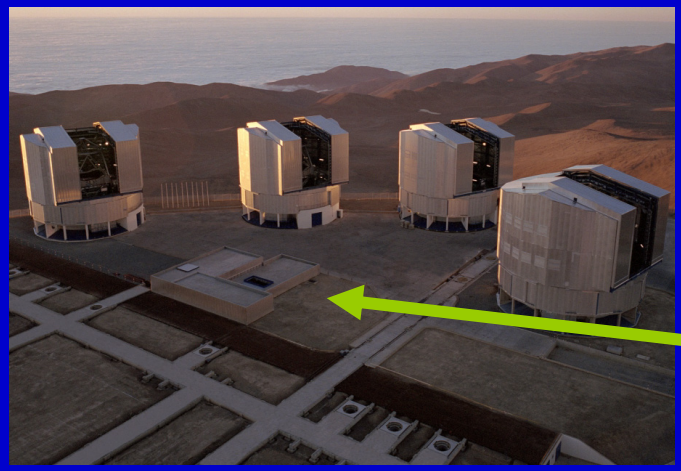
K‘ band (2.0-2.3 µm)

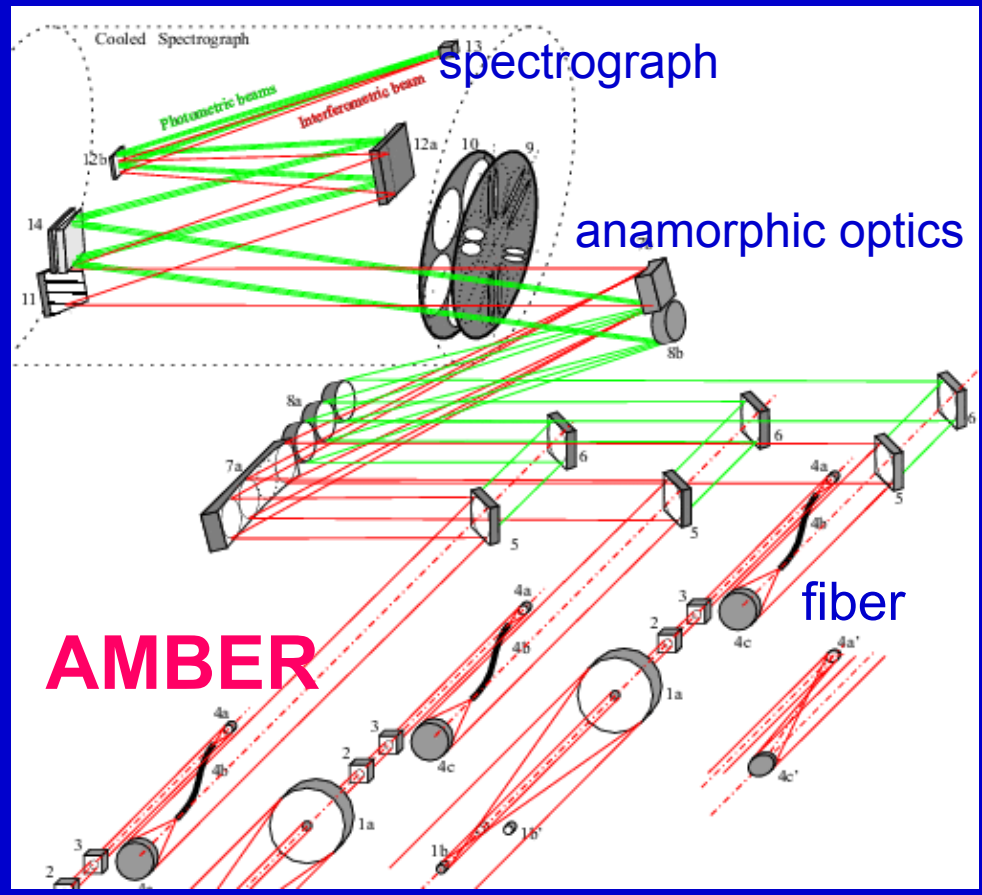
Two 8.2 m UTs equipped with MACAO AO

46 m baseline



VLTI phase-closure instrument AMBER





AMBER Consortium: Univ. of Nice, Univ. of Grenoble, Arcetri Observatory, MPIfR

- **Angular resolution: 1 mas at wavelength 1 μm —— 100 times Hubble resolution**
- **Spectral resolution: 30 to 10 000**
- **Limiting magnitude: K = 14; visibility accuracy: 0.1 % (λ differential accuracy 0.01%)**
- **Scientific goals: YSOs, evolved stars, AGN (torus, BLR), extra-solar planets (first light 2/04)**