VLT Interferometry, the milliarcsec view at 2 μm

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VLT Interferometry of galactic centers

- Until very recently, observational studies of galactic centers were limited to the diffraction limit of single telescopes, i.e. to about 50 mas at 2 μm, or 4 pc at the distance of NGC 1068.
- There are a few NIR studies at about this resolution.
- Optical to MIR interferometry can reach much higher angular resolution, currently up to the order of 1-2 mas at 2 μm (0.7-1.4 pc at the distance of NGC 1068), but has until very recently been limited to much brighter targets.
- NIR interferometry of GCs requires AO correction (MACAO), and –for many galactic centers- will require a dual feed system (PRIMA) and fast fringe tracking (FINITO).

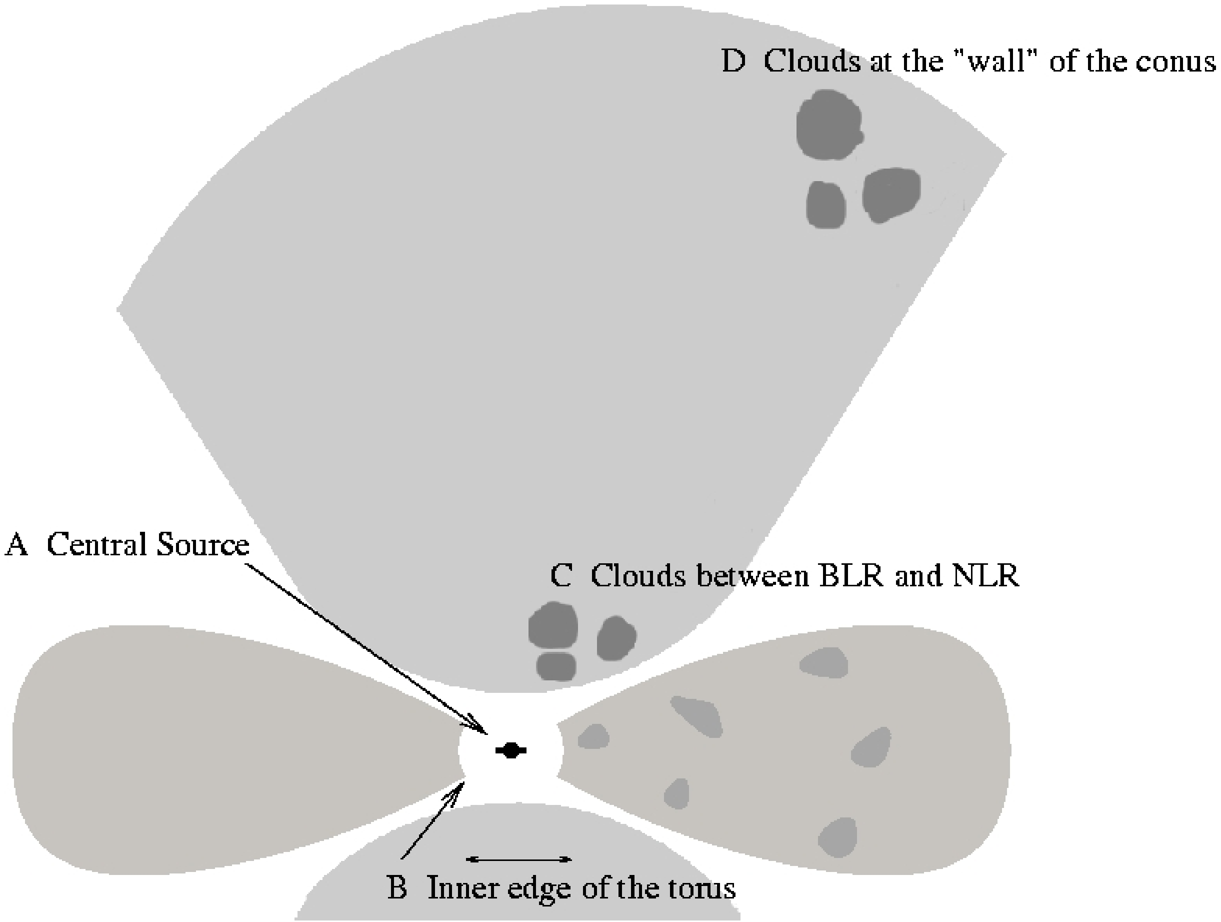
Obtained interferometric observations of (A)GN

- Swain et al. (2003) obtained the first NIR long-baseline interferometry of a galactic center with the Keck interferometer: NGC 4151 (Seyfert 1 nucleus), K-band, baseline 85 m.
- Jaffe et al. (2004) obtained the first MIR long-baseline interferometry of NGC 1068 (Seyfert 2 nucleus): VLT Interferometer, MIDI instrument.
- Wittkowski et al. (2004) obtained the first NIR long-baseline interferometry of NGC 1068: VLT Interferometer, K-band, commissioning instrument VINCI, during MACAO commissioning time, baseline 46 m.

Infrared interferometry of (A)GN, modeling

- AGN show relatively compact structures, but which are still of the order of , and larger than, the interferometric field of view.
- This leads to an uncorrelated flux contribution and a complication of the interpretation.
- Even within the interferometric field of view, relatively complex multi-component structures are expected, which are difficult to probe by a usually sparse uv coverage.
- Combination with single-telescope data, and coherent modeling (radiative transfer) at multi wavelengths needed. Also more detailed theory for very compact sub-pc structures.

The 2 μm view: Structures and scales to be expected



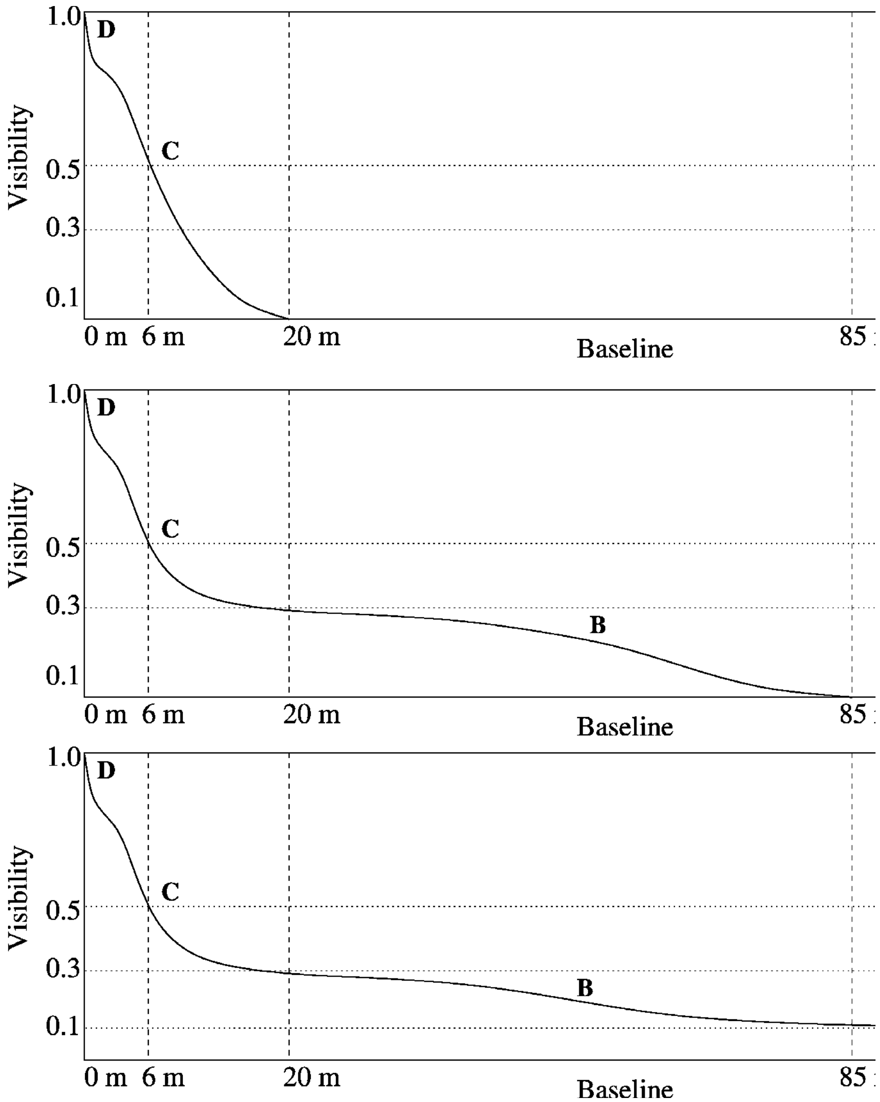
	Scale (pc)	Ang. Scale* (mas)
A	~0.05	~0.7
B	1-2	15-30
C	~2-4	~30-60
D	10-100	150-1500

*at the distance of NGC 1068

Torus clouds	0.2	3

Discussion and references in Wittkowski et al., SPIE 4838, 1378; A&A 418, L39

The 2 μm view: Effect of scales on visibilities



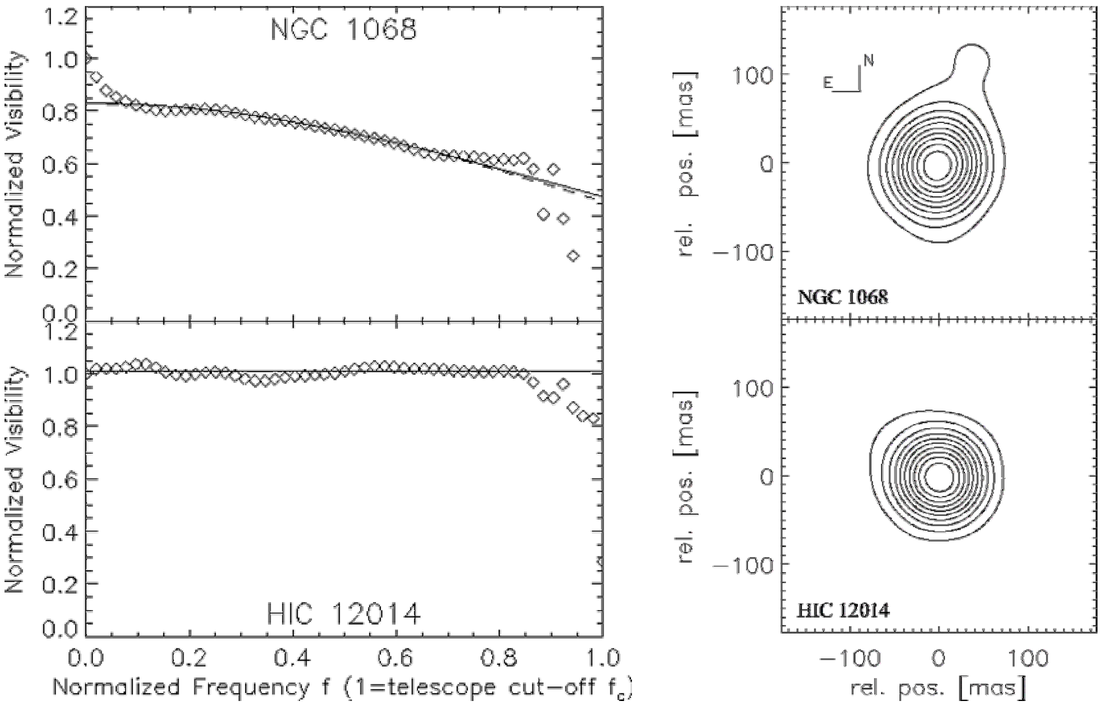
C and ***D*** completely obscure any more compact structures. The visibility decreases to zero at B ~ 20 m.

B has a flux contribution of 30 %; any more compact strucutures are obscured.

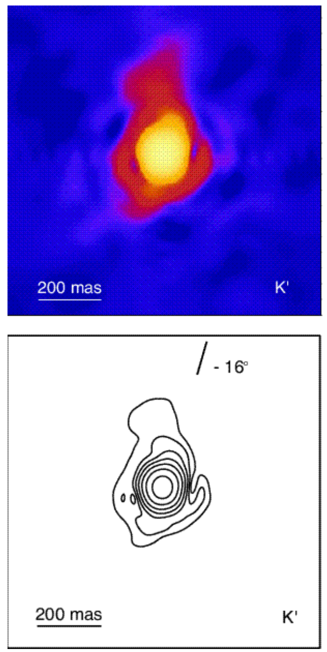
A has 10% of the total flux, and ***B*** 20%.

From Wittkowski et al, SPIE 4838, 1378

Speckle observations at 2 μm



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



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

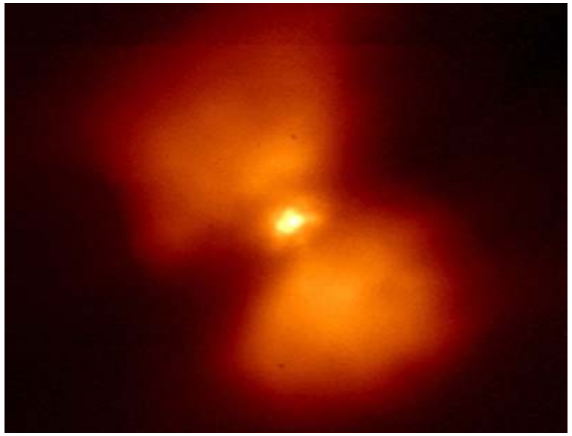
Compact core : ~20x40 mas/ 30x60 mas , 1.5 x 3 pc/ 3 x 6 pc, PA ~ -16 deg.
Extended comp. : N-S, extension ~ 400 mas, 30 pc (~1 % level of peak intens.).

K-band VLT Interferometry of NGC 1068

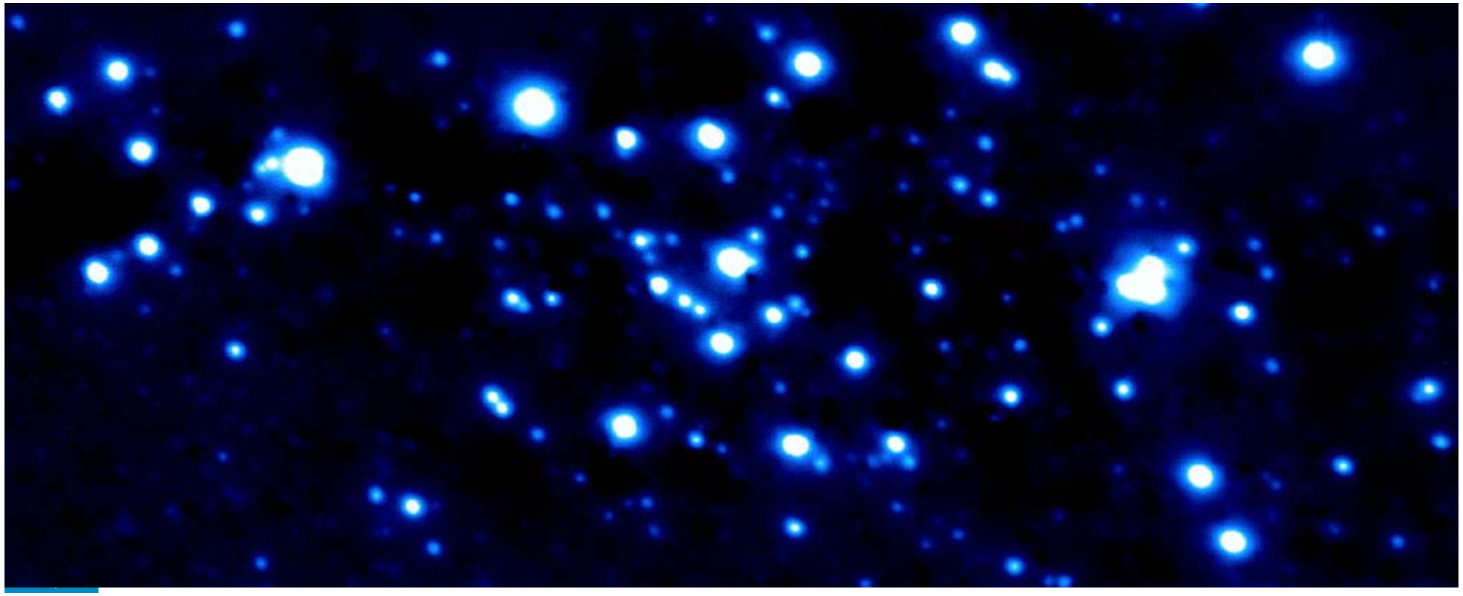
- VLTI commissioning observations with the adaptive optics system MACAO of NGC 1068 on Nov. 4, 2003.
- Baseline UT2 – UT3, 47 m ground length.
- Both MACAO systems (on UT2 and UT3) could guide on the core of NGC 1068. Same control parameters for both systems.
- Interferometric fringes were detected and tracked with the commissioning instrument VINCI in the near-infrared K-band.
- 1000 interferograms were recorded on NGC 1068. Fringe frequency 216 Hz. Effective wavelength approx. 2.18 μm.

Wittkowski et al., 2004, A&A 418, L39

MACAO-VLTI: Results on UT2



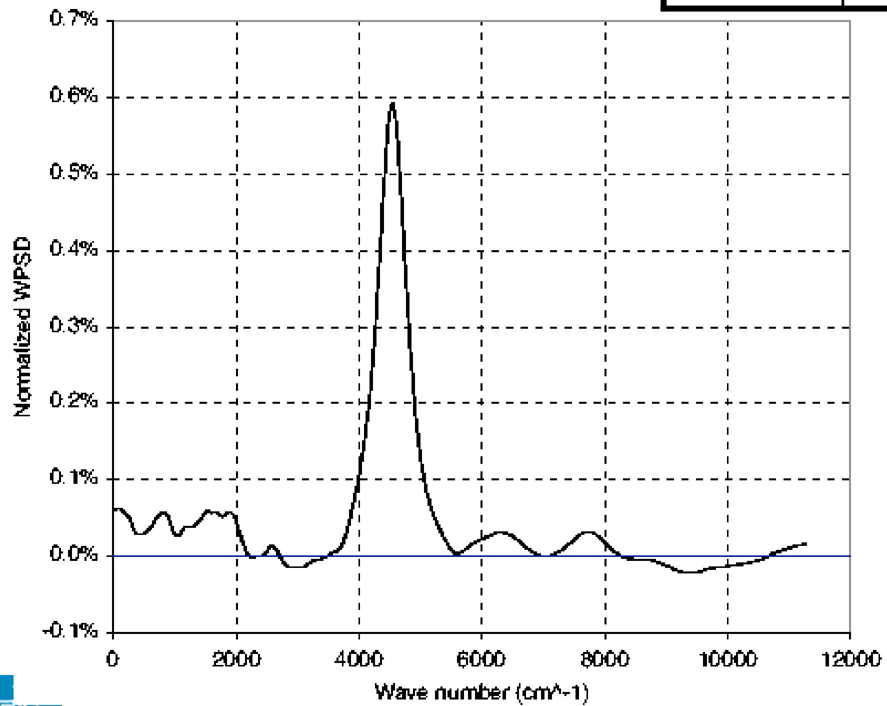
5 x 5 arcsec2 K-band image of **"Frosty Leo"** obtained in 0.7 arcsec seeing. V~ 11, difficult AO target because 3 arcsec in size at visible wavelengths. The corrected image quality is about FWHM 0.1 arcsec.



90-second K-band exposure of the central 6 x 13 arcsec2 around the Galactic Center obtained by under average atmospheric conditions (0.8 arcsec seeing). Although the 14.6 magnitude guide star is located roughly 20 arcsec from the field center the present image is nearly diffraction limited and has a point-source FWHM of about 0.115 arcsec.

Visibility results

JD -2452940	N	B	Az	μ^2	TF	V^2	Target
8.717	250	45.79	44.87	0.054	0.340	0.158 +/- 0.049	NGC 1068
8.722	214	46.00	45.13	0.062	0.340	0.182 +/- 0.091	NGC 1068
8.761	407	46.62	45.40	0.319	0.348		HD 20356
8.767	438	46.64	45.62	0.304	0.331		HD 20356
8.772	416	46.63	45.80	0.315	0.334		HD 20356



Calibrated squared Vis.: V^2=16.3 +- 4.3 %

Baseline : B = 45.84 m

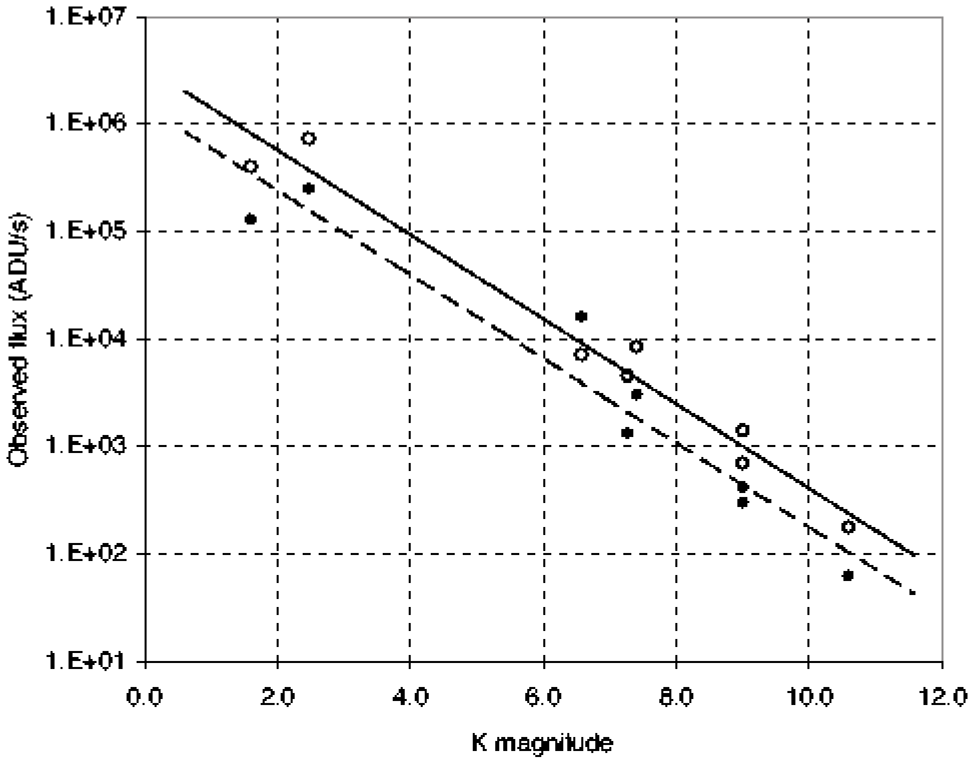
Azimuth (east of north) : Az = -44.9 deg

Effectice wavelength : λ_{eff} = 2.18 μm

Magnitude estimate

Observed flux in the photometric outputs of VINCI as a function of the K-band magnitude of several stars observed with the same VLTI/MACAO configuration.

This is a difficult calibration because of variable flux coupling, but seems to work alright (see Fig.)!



Upper limit for the flux of NGC 1068 in the FOV (might be lower owing to a possible lower performance of MACAO for an extended target as NGC 1068):

$m_K < 9.2 \pm 0.4$; $F_K >$ 130 +/- 60 m Jy

FOV approx. 56 mas (Airy disk of the UTs in K-band).

Discussion of the visibility result

Assumption of a single Gaussian (not consistent with speckle results):

V^2 = 16 % (V~40%) at B = 46m and λ_{eff} = 2.18 μm corresponds to a Gaussian intensity distribution with FWHM of 5.0 +/- 0.5 mas ~ 0.4 +/- 0.04 pc.

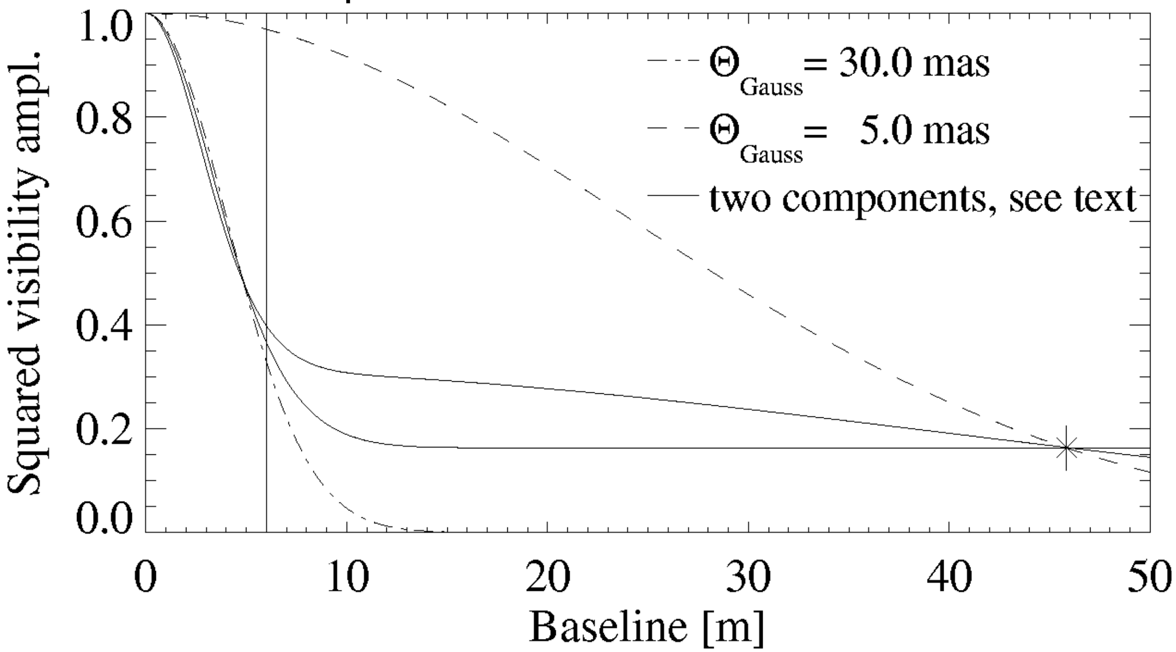
Multi-components (consistent with speckle results):

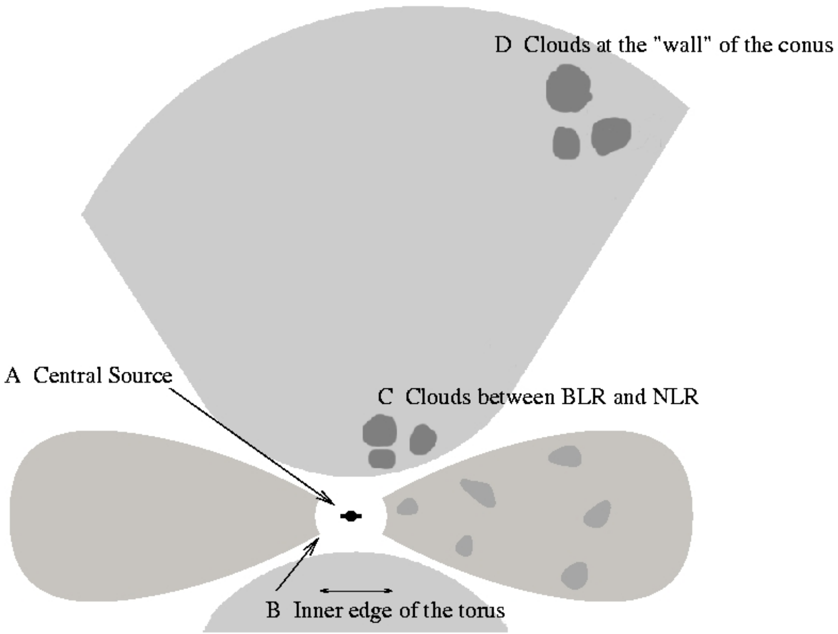
At least 40% of the total detected flux (i.e. >50 mJy) originates from scales clearly smaller than ~ 5 mas ~ 0.3 pc (<6.7 mas at 3σ).

The remaining flux originates from scales larger than ~ 5 mas ~ 0.3 pc but within the ~ 56 mas ~3.3 pc FOV (speckle component).

Discussion of the visibility result

Small components: 3 mas / 0.1 mas.





K-band flux of >~ 50 mJy originates from scales clearly smaller than ~ 5 mas, 0.4 pc.

- Central source viewed through only moderate extinction (A_V 10 ~ A_K 1.2) ?
- Substructure of the torus, such as individual clouds forming the torus ?

Substructure of the torus

- The inner edge of the torus is likely of the order of ~ 2 pc (in diameter), e.g. Dopita et al. 1998. This is rather consistent with the ~ 30-50 mas ~ 2-4 pc K-band speckle component (Wittkowski et al. 1998, Weigelt et al. 2004; also Weinberger et al. 1999, AO results).
- Since the work of Krolik and Begelmann (1988) it has been discussed that the dusty torus may not have a uniform shape but may consist of a large number of clouds/clumps. See Nenkova et al. 2002, Vollmer et al. 2004).
- The radius of single clouds may be ~0.1 pc (Vollmer et al. 2004) which would be consistent with the observed scale.
- Such clouds can also exist in polar direction.
- Also free electrons above and below the BLR could scatter light and could form a sub-pc K-band structure.

Central source

- A fraction of the K-band photons originating directly from the central engine could reach us directly through only moderate extinction. (A_V~10, A_K~1.2) (Wittkowski et al.1998).
- The chance for low extinction toward the central source is even larger with a concept of a clumpy torus.
- The separated compact component should then show a Seyfert 1 spectrum.
- K-band flux from the central engine is possible (see e.g. Wittkowski et al. 1998; Beckert & Duschl 2002; Weigelt et al. 2004)

Comparison to VLTI MIDI results of NGC 1068

- Jaffe et al. (2004): 2 components:
  hot component, T > 800 K, 0.8 x (<1) pc
  warm component, T ~ 320 K, 2.5 x 4 pc
- The warm component has a similar size as the compact K-band speckle component (1.3 x 2.8 pc/ 2 x 4 pc).
- The hot component has a similar size as the very compact K-Band VLTI component (<0.4 pc).
- Emission mechanism unlikely to be the same, especially for the warm component. Scattering at electrons ?

Comparison to K-band Keck observations of NGC 4151

- K-band interferometric Keck observations of NGC 4151 (Swain et al. 2003, ApJ 596, L163) resulted in a calibrated V^2 of 0.84 +- 0.06 at baseline of B= 82.7m, indicating that most of the flux (~90%) originates from scales smaller than 0.1 pc in diameter. Their preferred interpretation is emission from an unresolved central accretion disk.
- The VLTI/VINCI observations of NGC 1068 are also consistent with thermal emission from a central accretion disk, but with larger contributions from larger resolved components (60%) than for NGC 4151 (10%) of the total flux in the FOV.
- This difference might be explained by the different inclination angle, i.e. the Sy 1 and Sy 2 natures of these AGN.

Next steps (NIR)

- More baselines

  -> this resolves easily the uncertainty regarding the size of the very compact component (torus substructure vs. central source).
- Visibility spectra in JHK with resolution ~1000.

  -> detailed modeling (radiative transfer) of the torus

  -> separation of the flux of the central source, if any, and modeling of its spectrum.
- Comparison of GCs with different orientations, luminosities, levels of activity, etc.
- Comparison of GCs at different redshift.
- Consistent modeling of the whole nuclear region, and simultaneous comparison to interferometric data at JHK, and N, as well as to single telescope data.
- Coordinated VLBA and ALMA observations ?

VLTI Observing Periods – past, present, future

- Shared risk science operations with the near-infrared K-band commissioning instrument VINCI in P70 and P71 (2002).
- MIDI and AMBER Science Demonstration Program (since 2003).
- MIDI and AMBER GTO program (since 2003)
- Open time in P73 (2004): 2 UT baselines, SM/VM, MIDI with prism (R~30). 30 proposals received, out of which 20 could be scheduled (12 in service mode and 8 in visitor mode). Catg. B, C, and D. Most OBs successfully completed and data delivered.
- Open time in P74 (2004/5): 3 UT baselines, SM/VM, MIDI with prism and grism (R~230). 30 proposals received, of which again ~20 have been scheduled.
- Open time in P75 (2005): MIDI as in P74, all 6 UT baselines. Proposal deadline was 1 October 2004.
- Later (2005+). AMBER, 2 ATs, FINITO; 4 ATs, PRIMA. Next CfP:1 March 2005; Proposal deadline :1 April 2005.