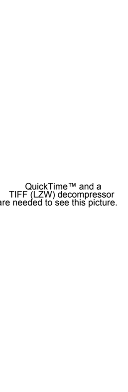
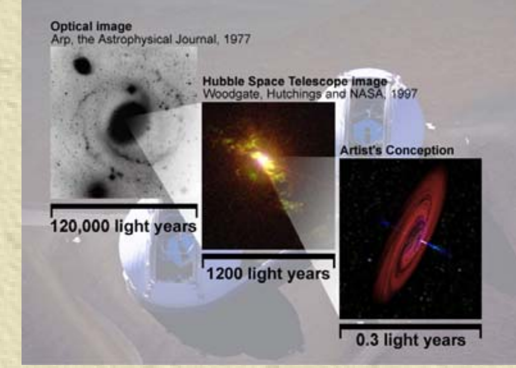




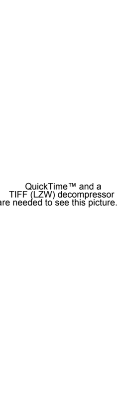
Interferometry and AGN

Michelson Summer Workshop 2006

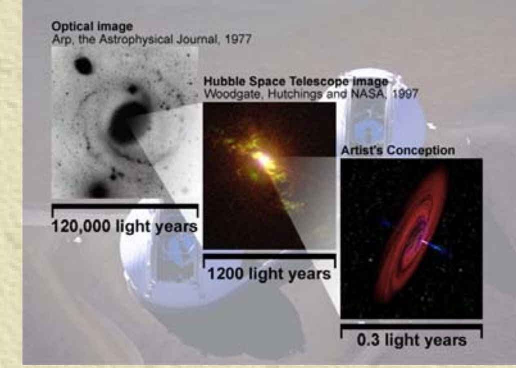
Mark R. Swain

Acknowledgements to:

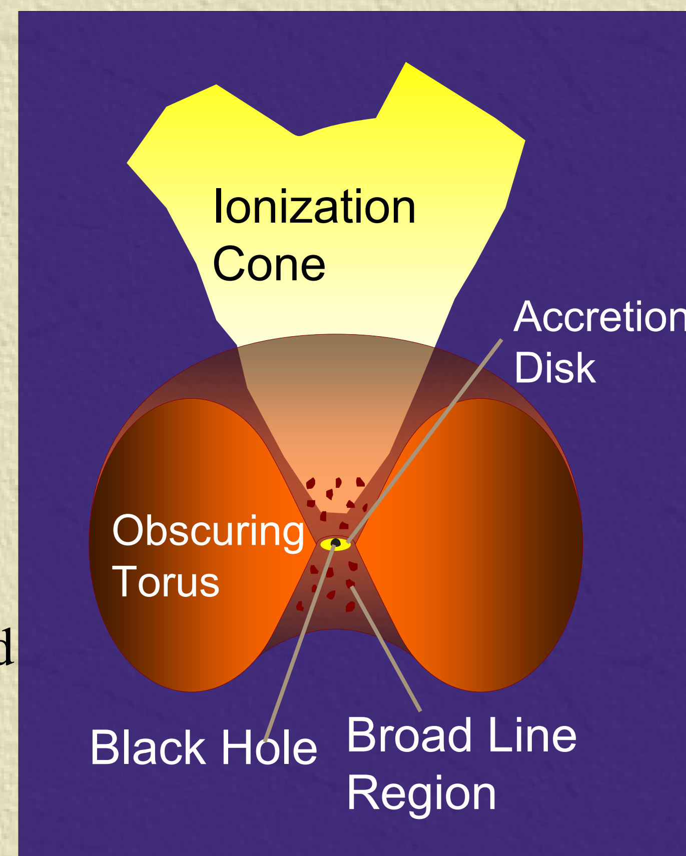
Walter Jaffe, Klaus Meisenheimer, Konrad Tristram, & Markus Wittkowski

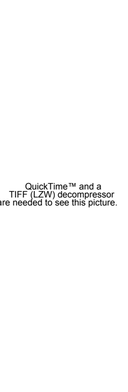


Overview



- Themes
  - Origin of light as a function of wavelength (thermal gas or thermal dust)
  - Structure of the inner tori
  - Mineralogy of the tori
  - Direct test of unification models involving a tori of obscuring material.
  - Determine basic properties of AGN and their environments.
- Results to date:
  - Four observational results papers.
  - Several objects observed (using Keck and VLT Interferometers).
  - Vigorous program in progress with the MIDI instrument on VLTI.
  - Strong support for tori-based unification models.

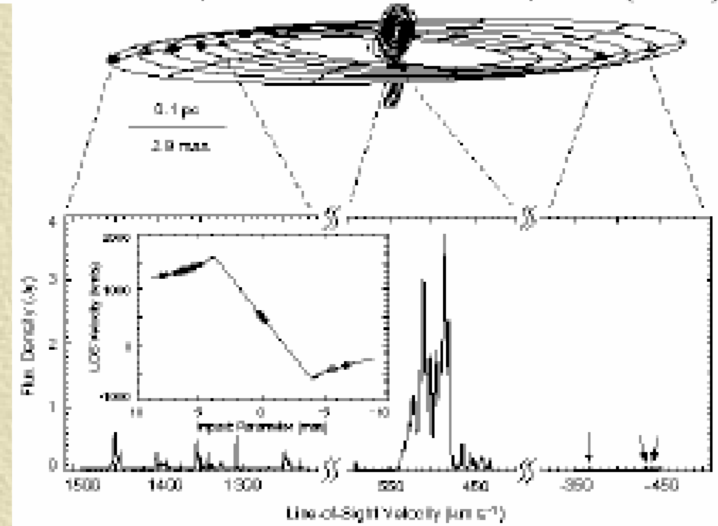




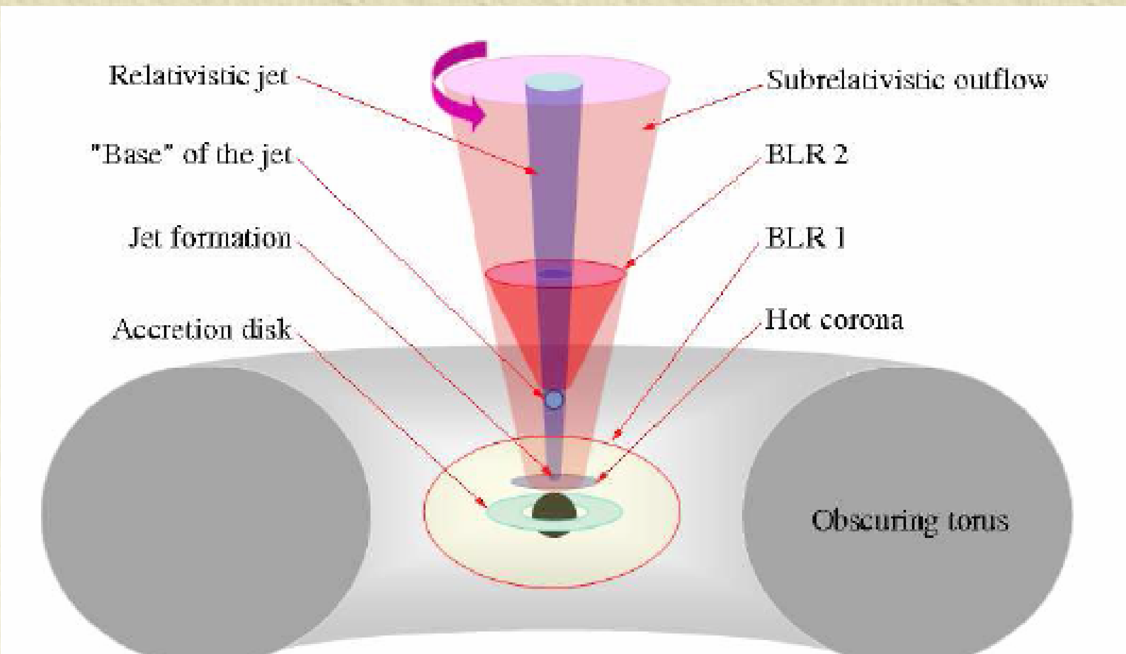
Context

	l [R_g]	l_g [pc]	θ_{Gpc} [mas]	τ_c [yr]	τ_{orb} [yr]
Event horizon:	1–2	10^{-5}	5×10^{-6}	0.0001	0.001
Ergosphere:	1–2	10^{-5}	5×10^{-6}	0.0001	0.001
Accretion disk:	10^1–10^3	10^{-4}–10^{-2}	0.005	0.001–0.1	0.2–15
Corona:	10^2–10^3	10^{-3}–10^{-2}	5×10^{-3}	0.01–0.1	0.5–15
Broad line region:	10^2–10^5	10^{-3}–1	0.05	0.01–10	0.5–15000
Molecular torus:	$>10^5$	>1	>0.5	>10	>15000
Narrow line region:	$>10^6$	>10	>5	>100	>500000
Jet formation:	$>10^2$	$>10^{-3}$	$>5 \times 10^{-4}$	>0.01	>0.5
Jet visible in the radio:	$>10^3$	$>10^{-2}$	>0.005	>0.1	>15

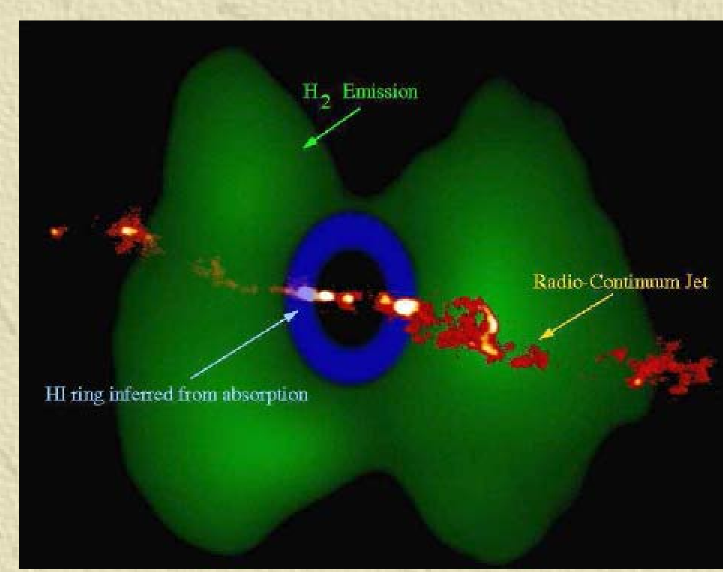
J.R. Herrnstein, J.M. Moran, L.J. Greenhill, et al.: Nature 400, 539 (1999)



NGC 4258 VLBI maser observations

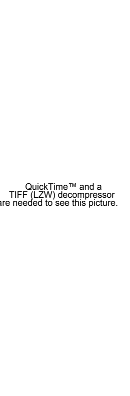


from Lobanov & Zensus 2006

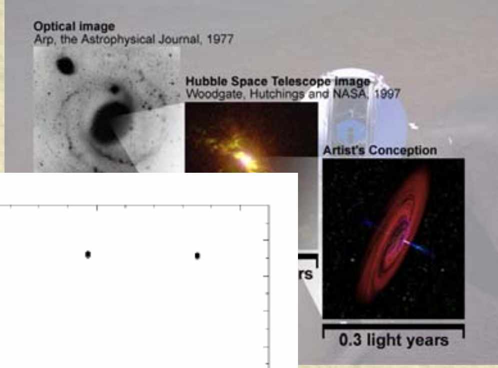


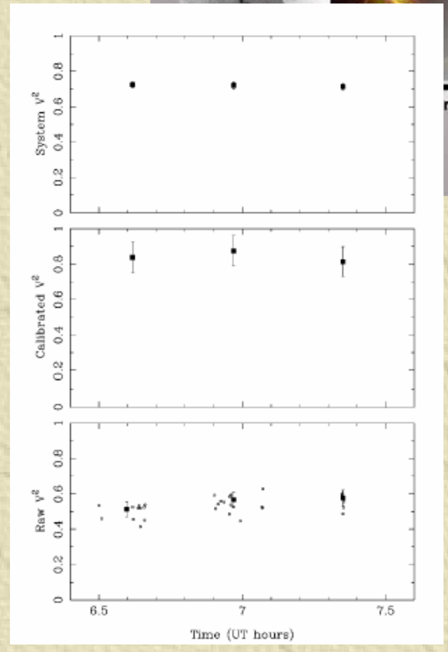
NGC 4152 inner 250 pc “montage”

C.G. Mundell, J.M. Wrobel, A. Pedlar, J.F. Gallimore: ApJ 583, 192 (2003)

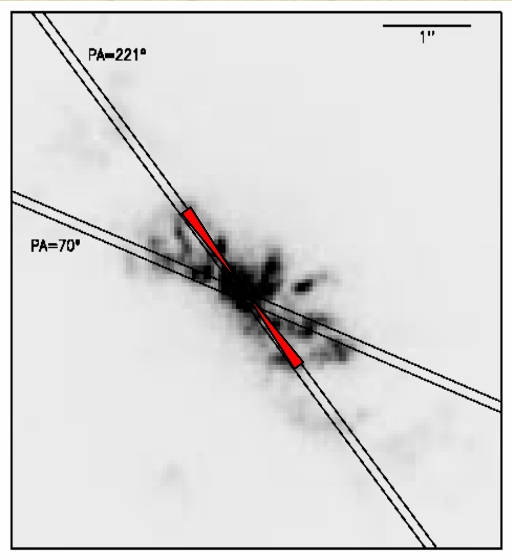


NGC 4151 - gas or dust?





- First extragalactic object observed with an optical/IR interferometer.
- Measured 2 micron emission to be very compact ≤ 0.1 pc.
- *The measurements rule out models in which the majority of the K-band nuclear emission is produced on scales larger than 0.1 pc for this P.A.*
- Results interpreted as 2 micron light originating from thermal gas.
- Dust a possible origin according to author authors (see later slides).



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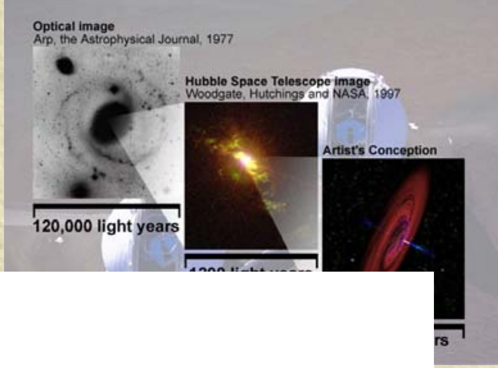
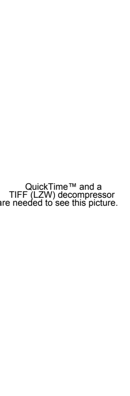


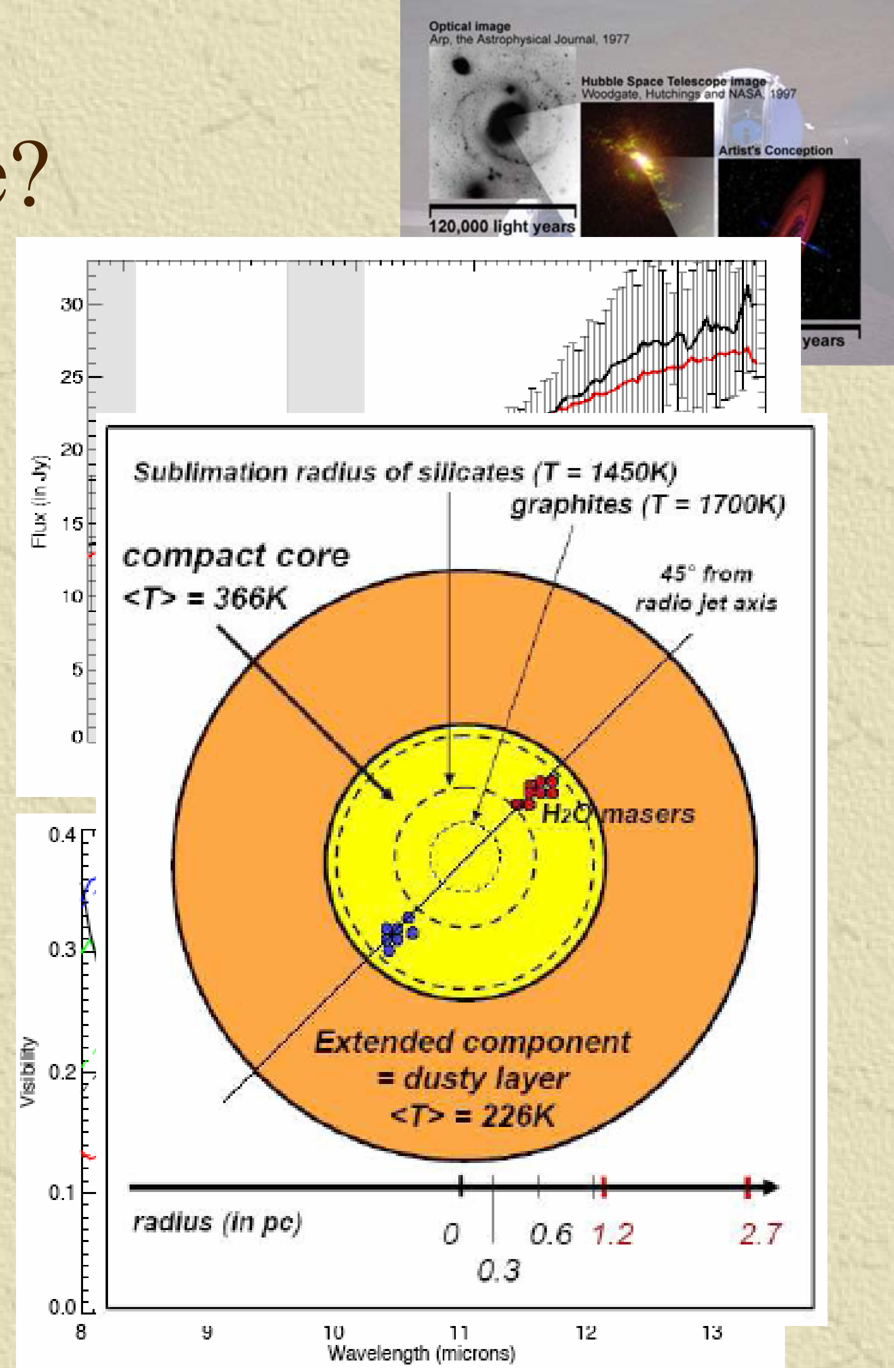
NGC 1068 at N band- torus?

- Resolve a 3.4 pc diameter warm (320) dust feature.
- Find dust feature is thick (h/r ≥ 0.6).
- Conclude central support for thick dust feature is required.
- Identify central feature as obscuring torus in agreement with Seyfert 2 models.
- Detection of silicate absorption feature.
- Detect central hot (>800) feature < 1 pc in diameter.
- Jaffe et al. 2004 Nature 429, 31.

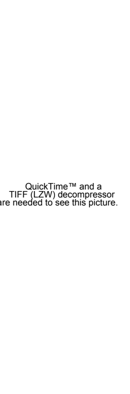
QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.



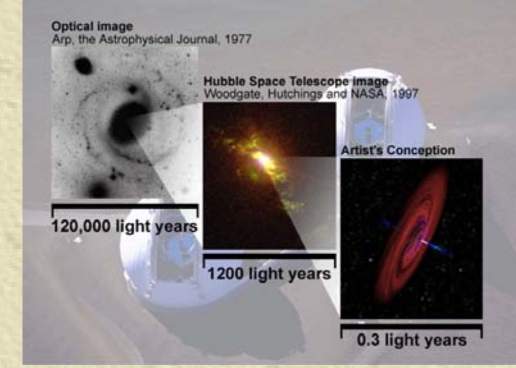
NGC 1068 - or sphere?



- New analysis of MIDI 1068 data using a radiative transfer model.
- Two spherical components found to fit the spectral visibility data well across the MIDI pass band.
- Inner: r = 17 ± 2 mas & T=361 ± 12 K.
- Outter: r = 41 ± 3 & T 226 ± 8 K.
- Proposed picture consistent with maser results.
- Poncelet et al 2006 A&A.



Silicate feature in NGC 1068 - how much and where?



- Two groups undertake high angular resolution spectroscopy with 8 m class telescopes.
- Find that silicate absorption feature and continuum vary substantially in immediate region of presumed torus.
- Silicate absorption found in inner 0.25 arcseconds.
- Mason et al. 2006 ApJ, 640, 612.

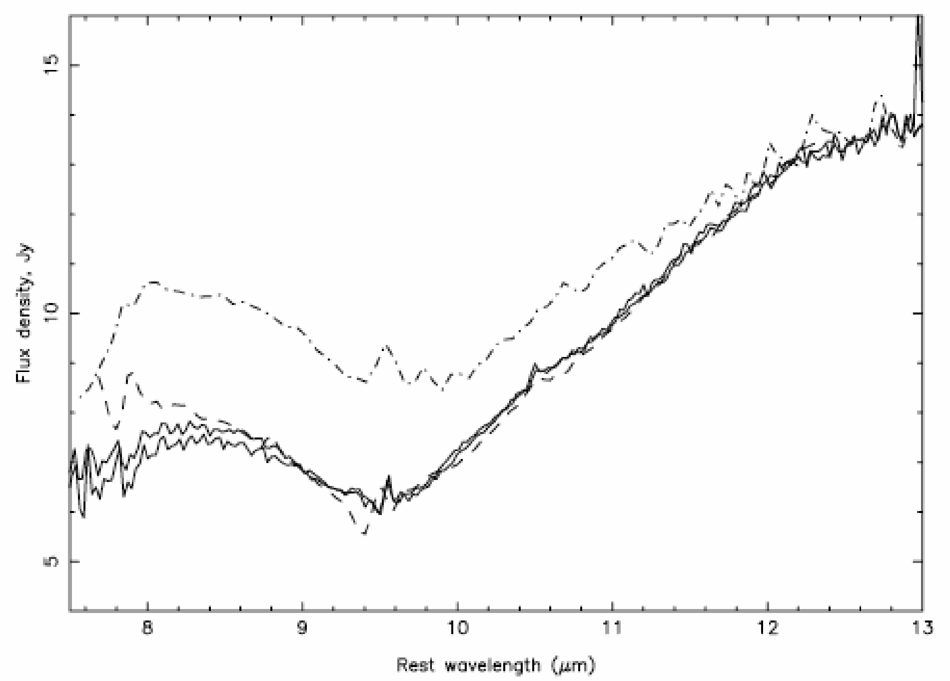
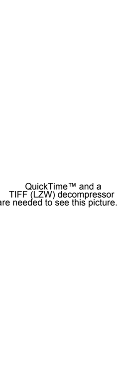
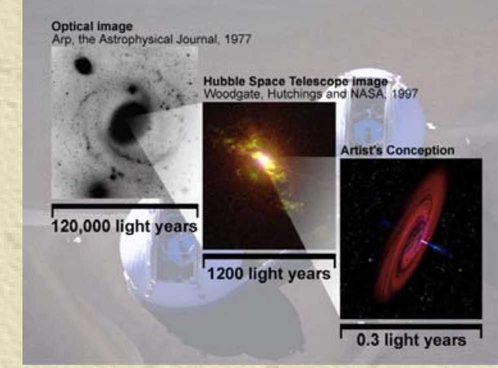


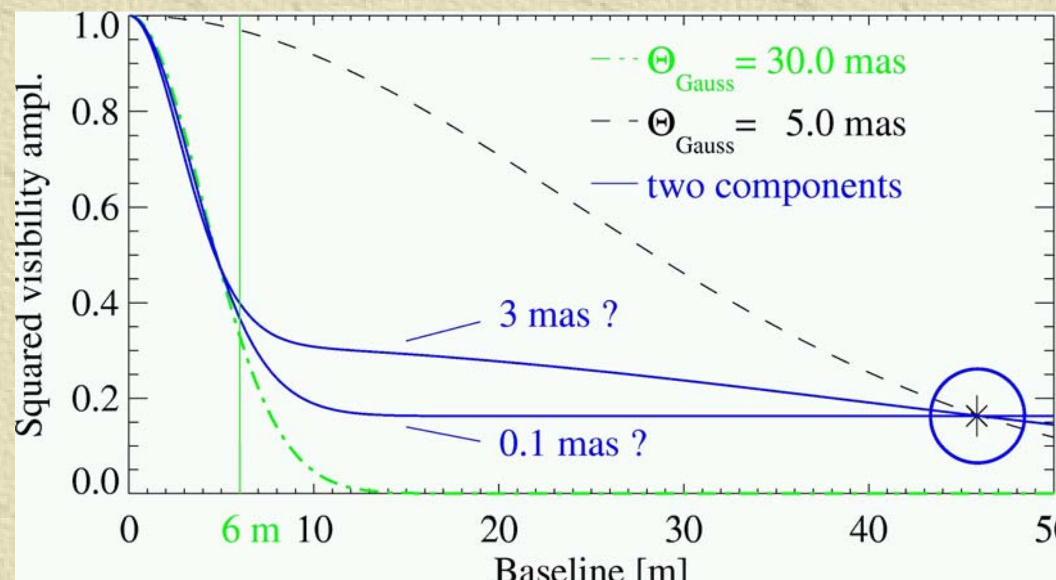
FIG. 3.—Spectra extracted from a 0″.4 × 0″.4 region centered on the flux peak (epoch 2, *black*; epoch 1 × 1.4, *gray*). Also shown are the Rhee & Larkin (2006) spectrum of the central 0″.25 × 0″.25 of NGC 1068 (*dashed line*; scaled to match the Michelle spectrum around 12 μm) and the single-dish MIDI spectrum of Jaffe et al. (2004; *dash-dotted line*).

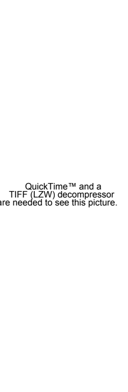


NGC 1068 in K - gas or dust?

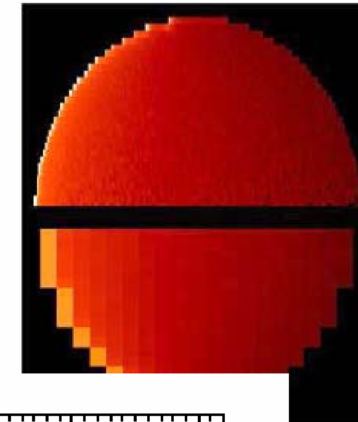


- Find a component of the flux probably originates on scales ≤ 0.4 pc.
- Component could be from the accretion region or from a substructure (hot clump) in the torus.
- Wittkowski et al. 2004 A&A 419, L39.

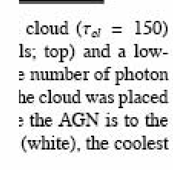




NGC 1068 in K - dust … according to some



- Clumpy model of torus includes lots of effects.
- Clouds are small enough to appear as point sources to VLTI.
- Authors claim good reproduction of visibility measurements and SED.
- Authors conclude VLTI K band observations are likely a single hot clump in the torus.
- However, inferred inclination angle is unexpected.
- Hönig et al. 2006, A&A.



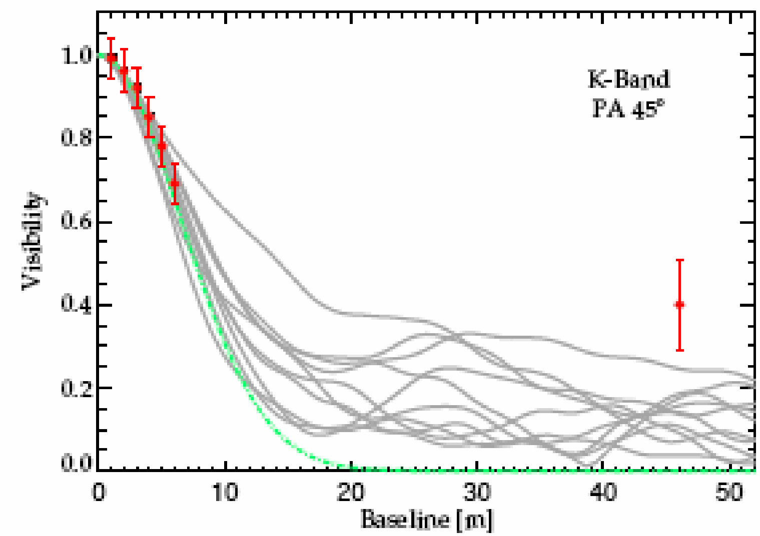
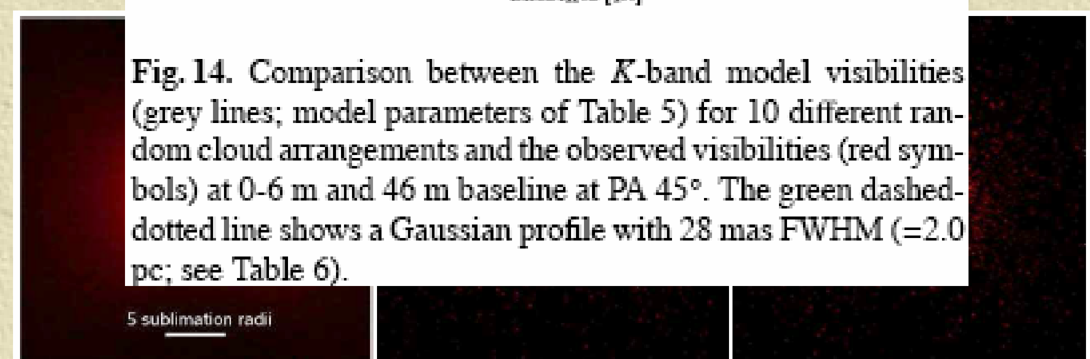
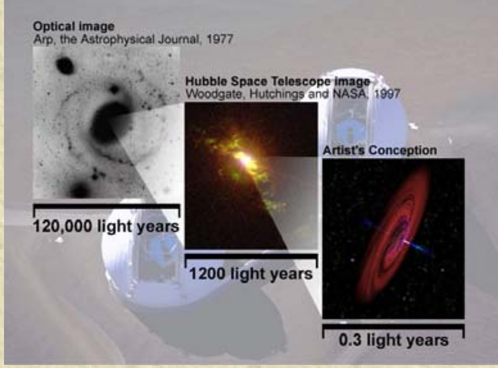


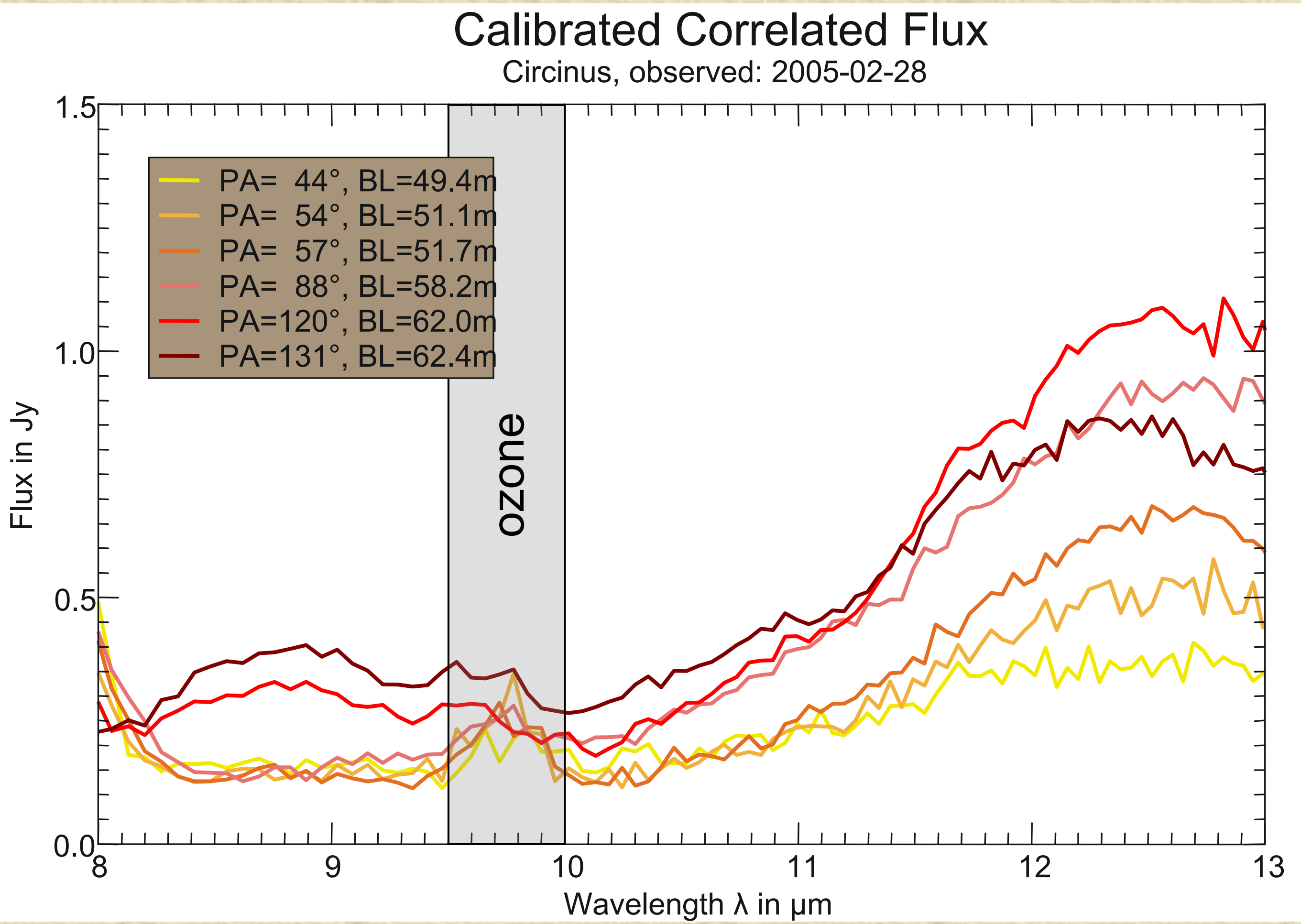
Fig. 14. Comparison between the K-band model visibilities (grey lines; model parameters of Table 5) for 10 different random cloud arrangements and the observed visibilities (red symbols) at 0-6 m and 46 m baseline at PA 45°. The green dashed-dotted line shows a Gaussian profile with 28 mas FWHM (=2.0 pc; see Table 6).

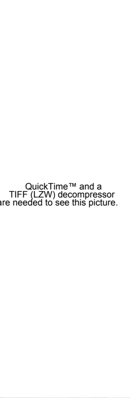


Circinus - VLTI/MIDI

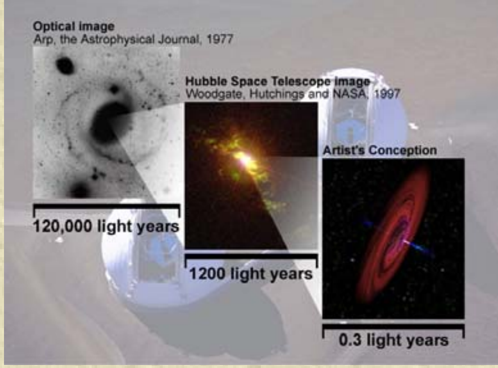


- Orientation dependence detected.
- Possible ozone feature?

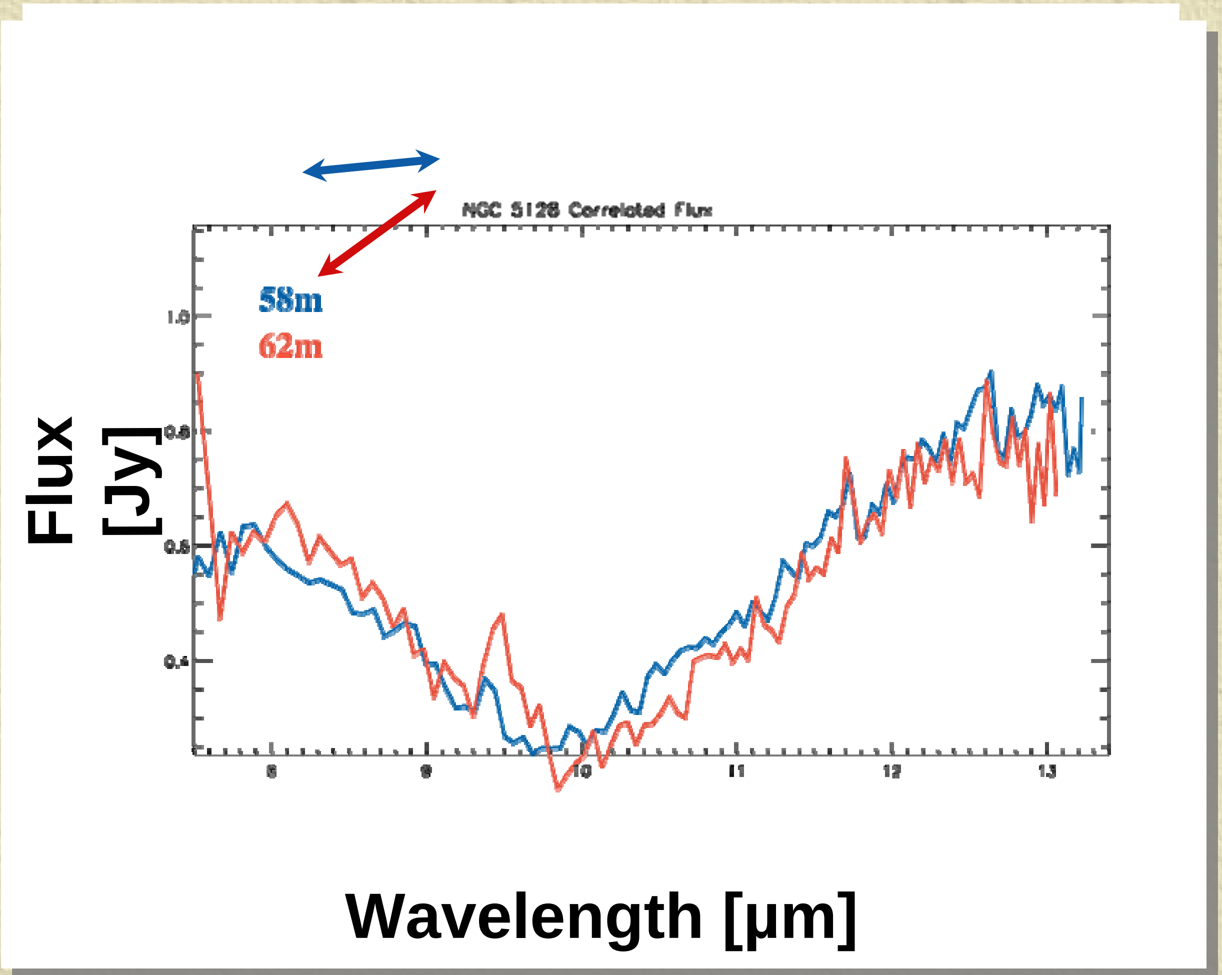


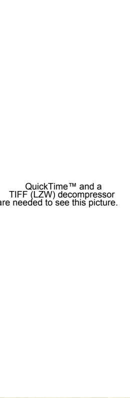


Centaurus A - VLTI/MIDI

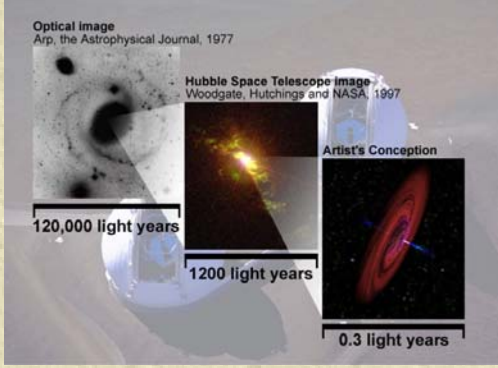


- Similar correlated flux spectrum as long baseline measurements for NGC 1068.





Questions about dust - and unification models

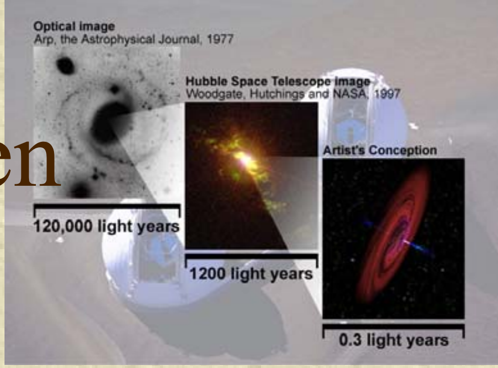


- How is the dust distributed?
- Where is the inner edge of the torus?
- How clumpy is the torus?
- What emission originates in the torus and what originates from thermal gas?

- We need to answer the last question first.

QuickTime™ and a
TIFF (LZW) decompressor
re needed to see this picture.

How can we distinguish between thermal gas and dust emission?



- Look for a signature of torus (dust emission) – the “infrared bump”.
- Determine whether IR nucleus size is a function of wavelength.
  - IR nucleus size invariant with wavelength consistent with inner edge of an optically thick dust torus.
  - IR nucleus size decreasing with wavelength consistent with centrally heated thermal gas (accretion disk) or clumpy dust.
- Clumpy dust is expected and included in many models.
- Resolving the torus region at multiple wavelengths probably required.

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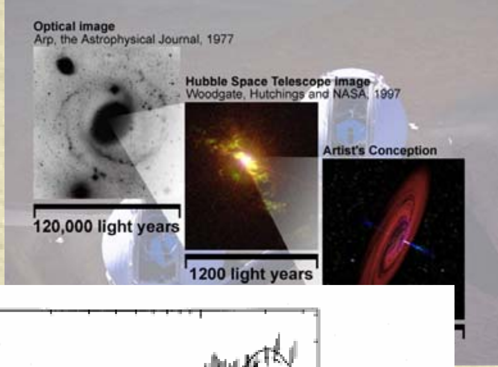
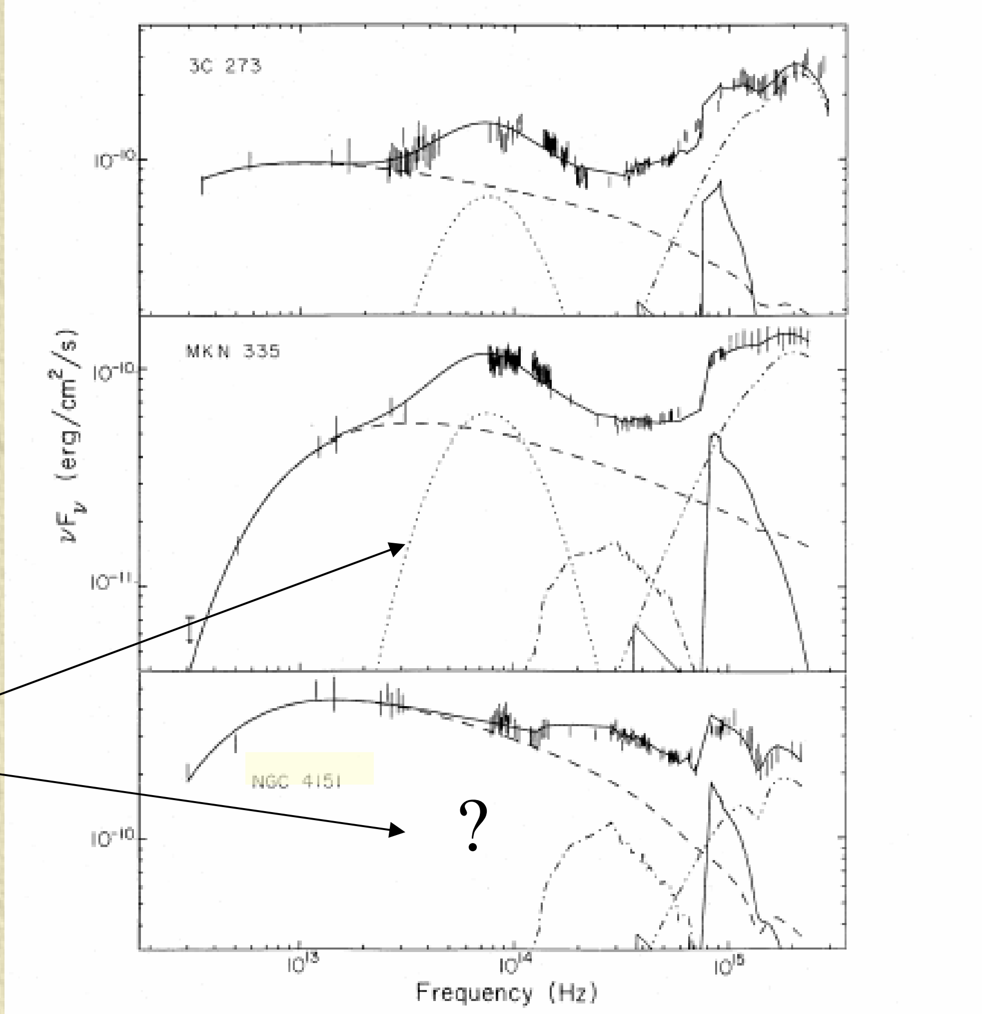
Infrared Bump Measurements

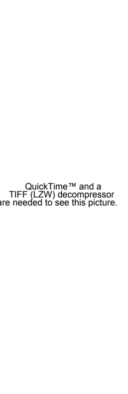


- Near IR bump not detected in NGC 4151.
- 3C 273 and MKN 335 shown for comparison

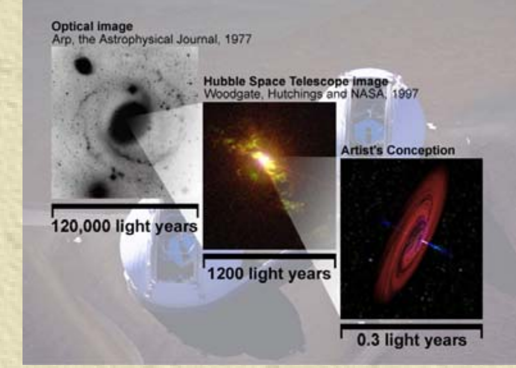


Near-IR bump component not present in NGC 4151.

Edelson & Malkon 1986, ApJ, 308, 59



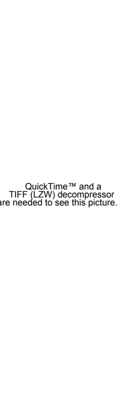
IR-Optical Correlations



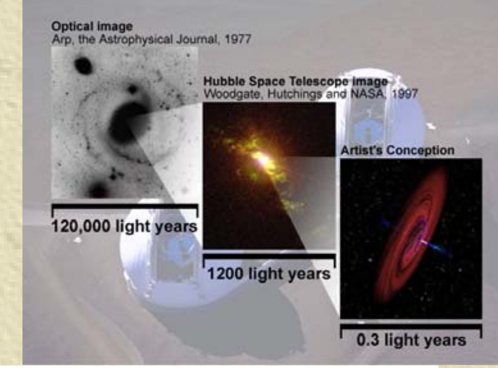
- The Minezaki et al. result corresponds to a features size of ~0.08 pc diameter.
- K band results broadly consistent over 30 years.
- The multi-wavelength correlation analysis has an interesting trend.

Δt (days)	Band	Reference
~ 30 to 60	K(UVB)	Penston 1974
18 ± 6	K(U)	Oknyanskij 1993
97 ± 10	L(UVB)	Oknyanskij 1999
38 ± 8	K(UVB)	"
8 ± 4	H(UVB)	"
~ 6	J(UVB)	"
48 +2/-3	K(V)	Minezaki 2003

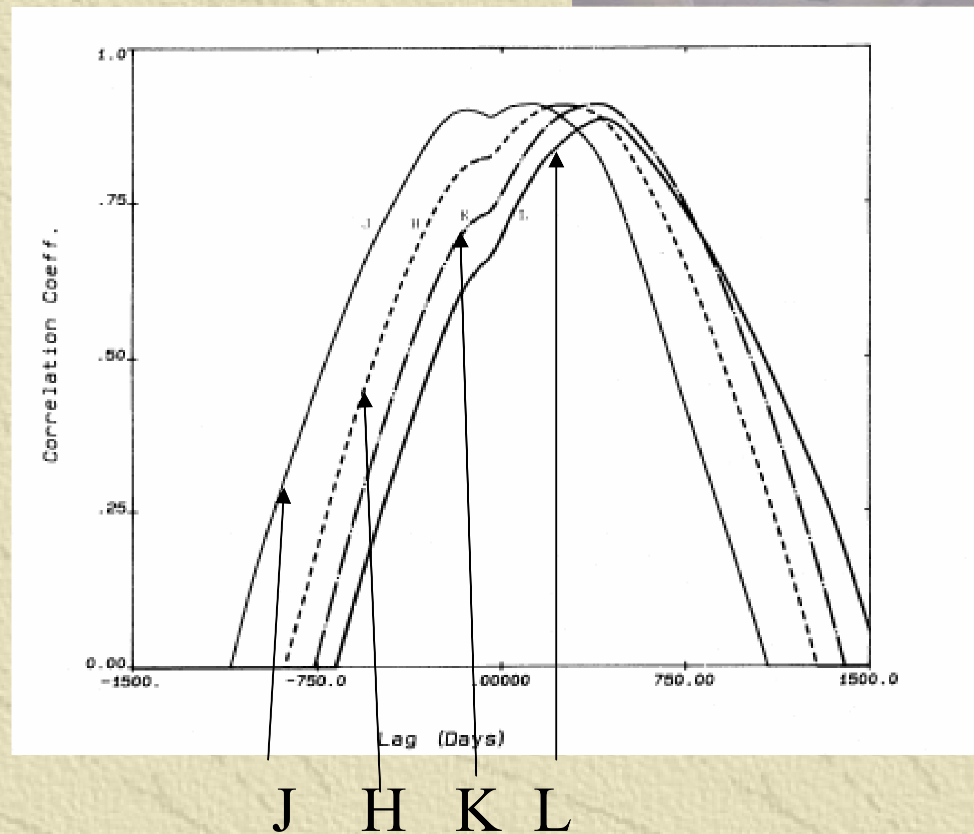
Excellent data set – 49 samples in 11 months



The Seyfert 1 Fairall 9



- Correlation analysis line and continuum.
- BLR ~ 300 lt-days
- Time lags (lt-days)
  - J: –20 ± 100
  - H: 250 ± 100
  - K: 310 ± 105
  - L: 410 ± 110
- T_{dust} = 1730 ± 230
- Data interpreted as consistent with optically thin dust torus by Barvainis (1992).



Clavel & Wamsteker 1989, ApJ, 337, 236

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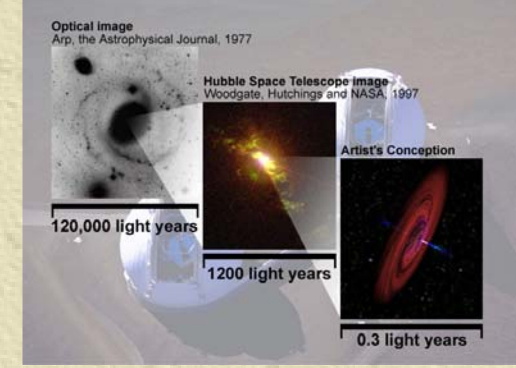
The Radio Quiet Quasar GQ Comae II



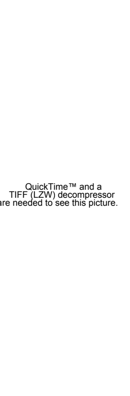
- IR(UV) time delay analysis (Stiko et al. 1993) and dust model fit to data

  H: ~100 days

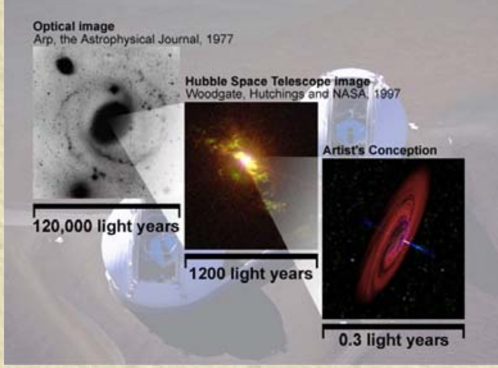
  K: ~250 days

  L: ~ 700 days

  T_{dust} = 1700 K
- Note that no time delay dependence on wavelength should exist for wavelengths shorter than ~2.5 μm.
  - Assumes dust grains destroyed at ~1800 K.
  - Interprets the H(UV) and K(UV) time delay difference in their data as not significant (1.3 σ level).



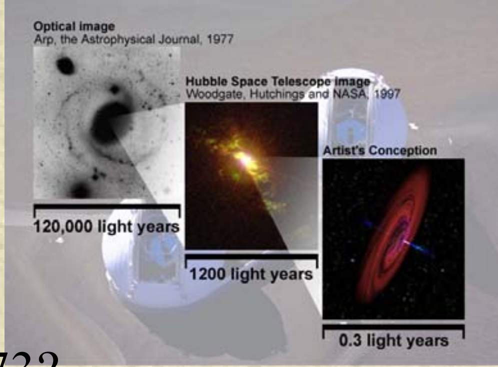
The Near Future



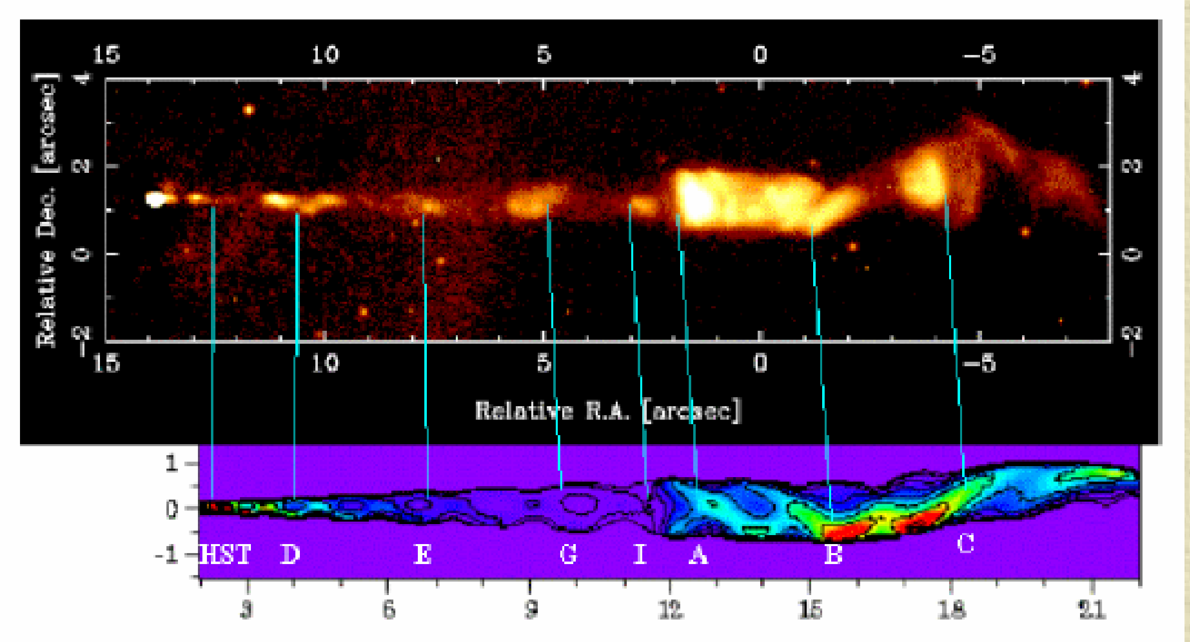
- Selected Questions
  - What is the structure of the gas-dust transition region?
  - Are the chemical properties of inner dust features similar?
  - Can we detect time variability in spatially resolved features (NGC 4151)?
  - How is material organized in the BLR?
- These and related topics can be addressed with existing instruments coming on line (AMBER at VLTI and 3 micron FATCAT at the Keck Interferometer).

QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.

Middle Future



- Selected jet related questions
  - What is the structure of the central feature in 3C 273?
  - Can we detect time variability (evidence for jet launch or evolution) in spatially resolved central features?
- These topics require upgrades to existing instruments (planned at VLTI)



E.S. Perlman, J.A. Biretta, F. Zhou, W.B. Sparks, F.D. Macchetto: AJ **117**, 2185 (1999)

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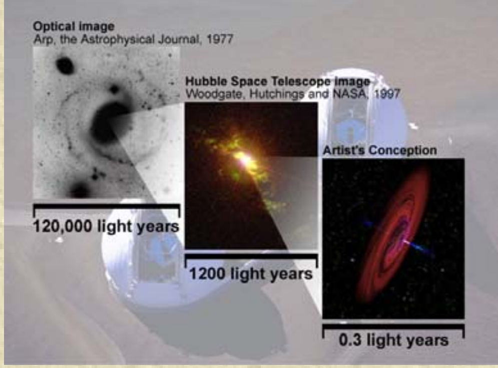
Conclusions



- Lots of new things to be learned about the AGN phenomena in the infrared on these spatial scales.
- Interferometry is making a unique contribution to this field.
- VLTI is a remarkable instrument for AGN.
- Recent news: MIDI measures 2 more AGN.
- There are now at least 6 AGN observed in the infrared with interferometers.