Studies of Active Galactic Nuclei

with the VLT Interferometer

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Max-Planck-Institut für Astronomie

VLTI Summer School

Torun – September 5/6, 2007

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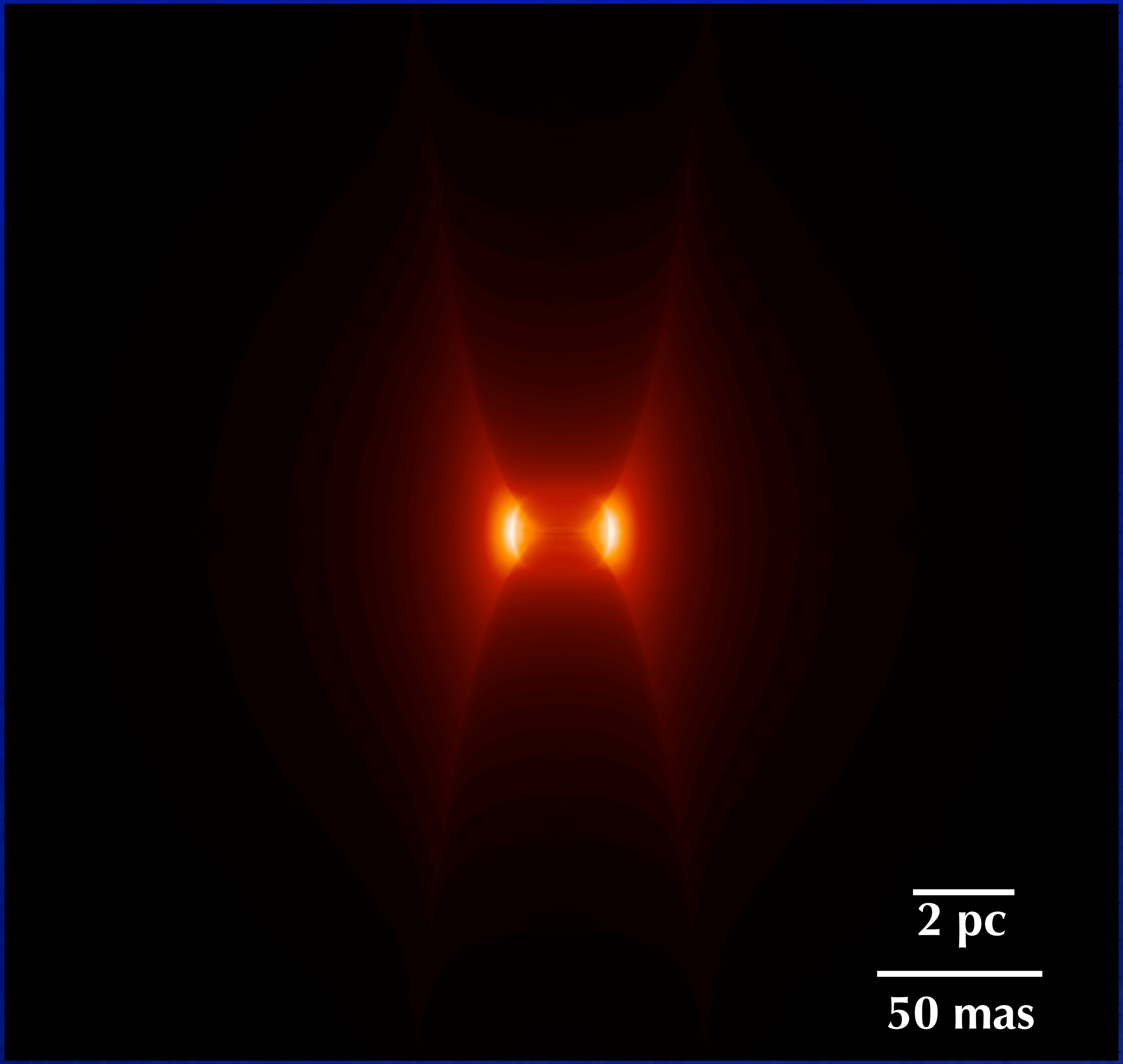
with the VLT Interferometer

Overview:

1. Introduction and Goal of this Lecture
2. MIDI+VLTI observations of the closest Seyfert 2 galaxies
3. Models of the torus
4. MIDI+VLTI observations of the radio galaxy Centaurus A
5. Outlook: More luminous and distant AGN
6. The Future: New instruments at the VLTI
7. Summary

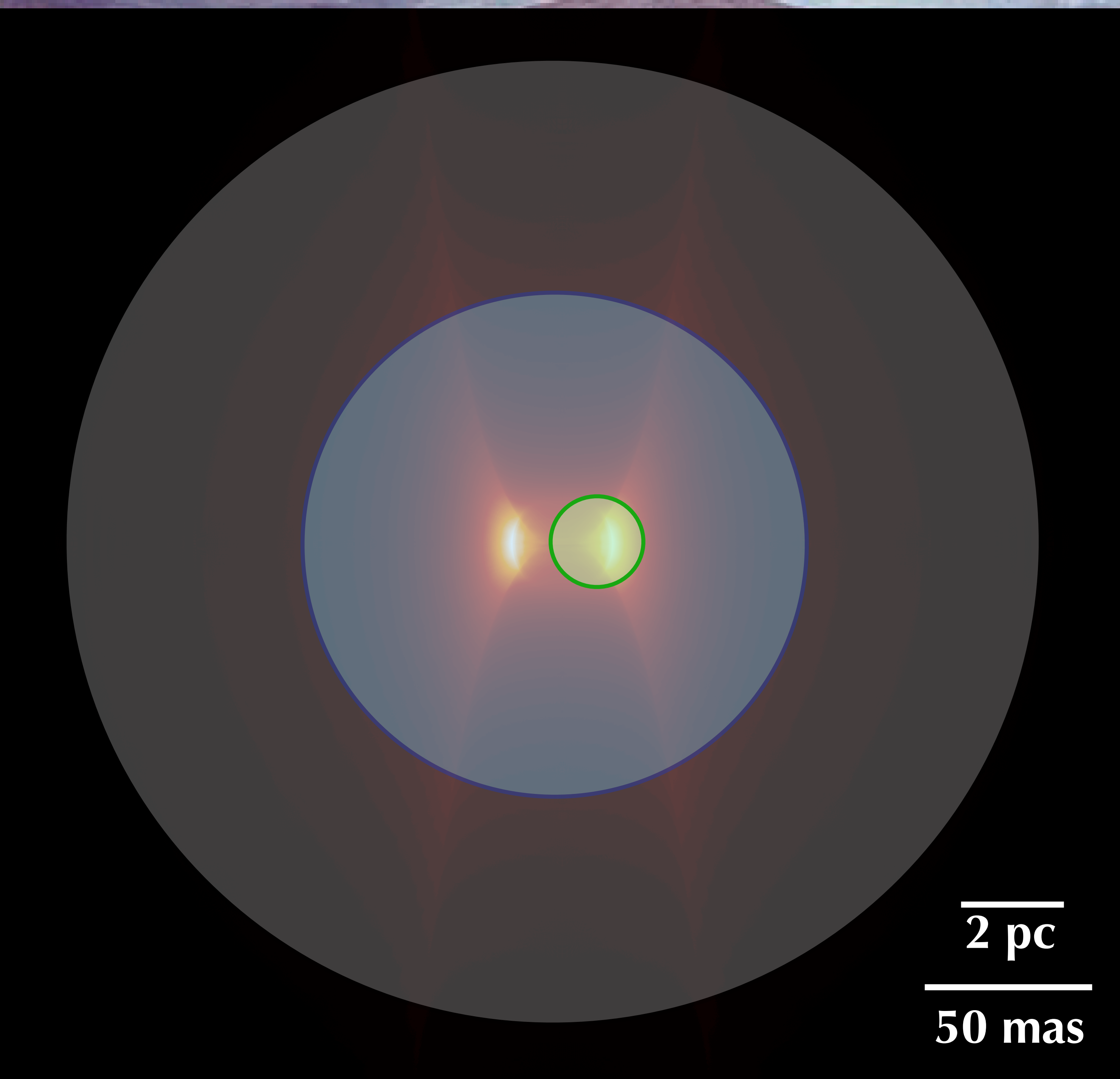
Introduction: Resolving the dust torus in AGN



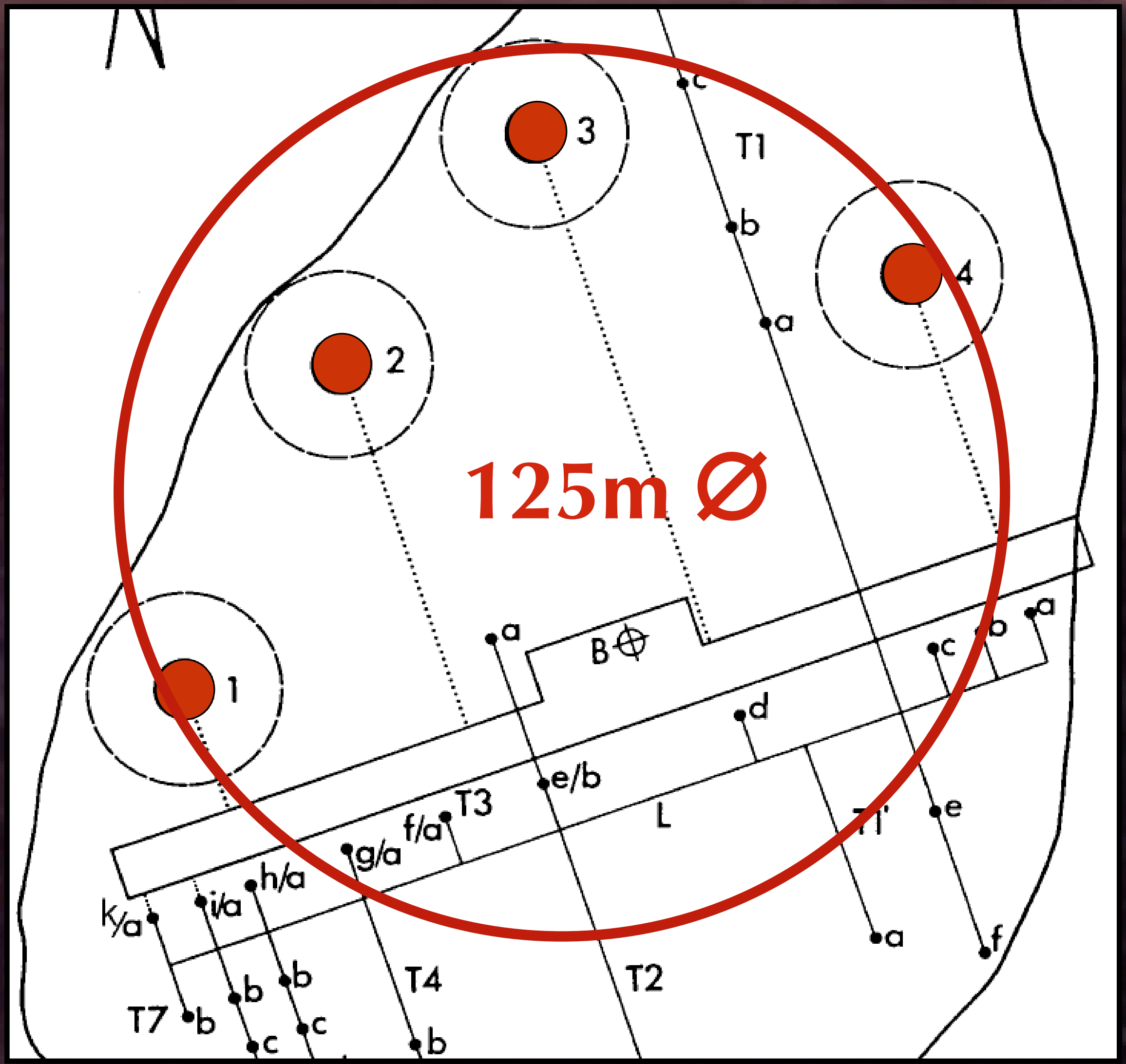
For nearby Seyfert's, e.g. NGC 1068, NGC 4151

Schartmann, Meisenheimer, Camenzind, Wolf, Henning: A&A 437, 861 (2005)

Introduction: Resolving the dust torus in AGN



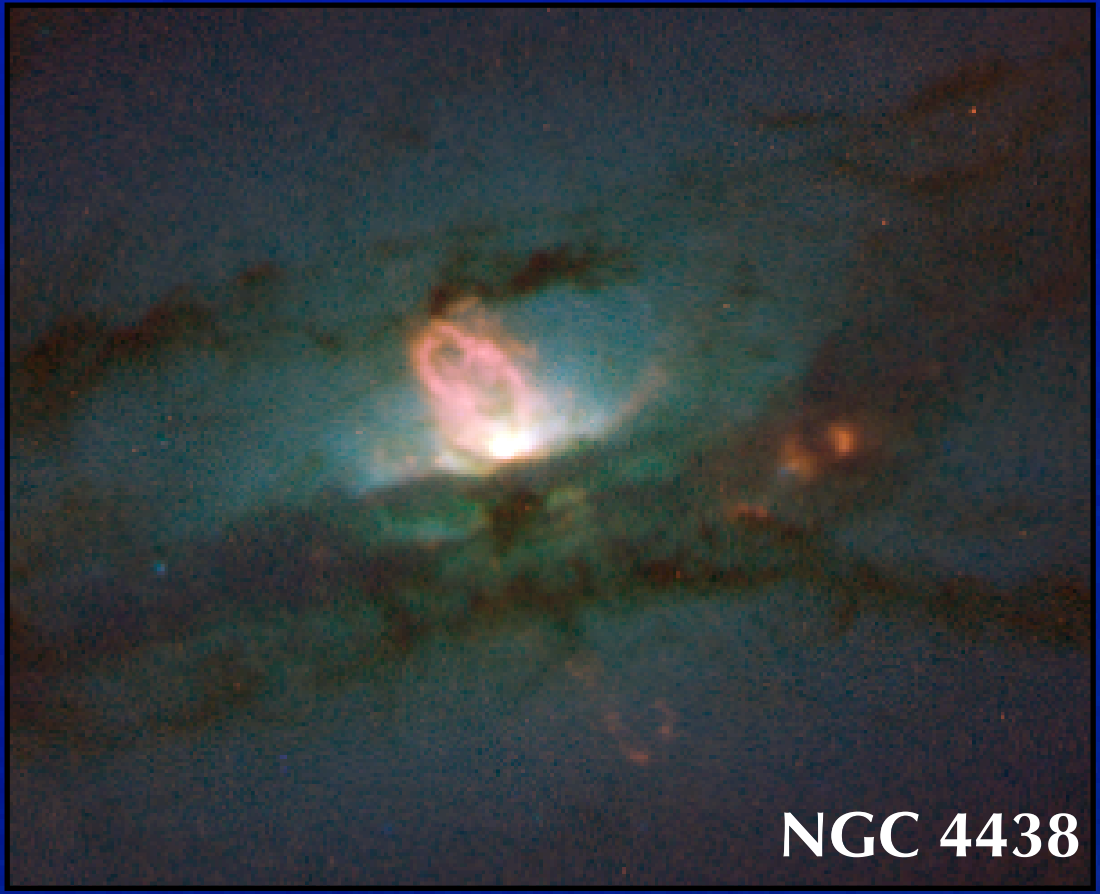
8m ∅, 4.5 μm
8m ∅, 10 μm
100m ∅, 10 μm



Introduction: Resolving the dust torus in AGN

Scientific Questions to address:

- Generic question:
  How are Active Nuclei fueled ?
- What role plays the torus of gas and dust in this ?
- Do all AGN contain a dust torus ?
- What is the structure of the dust torus ?



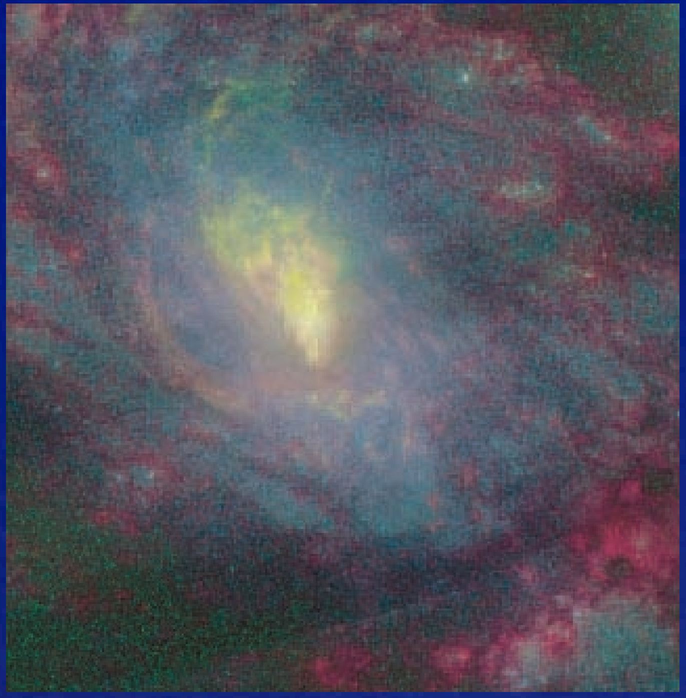
Goals of this Lecture

- ✦ Present first results obtained with VLTI and MIDI
- ✦ Confront observations with models of dust torus
- ✦ Current observational limits (examples)
- ✦ Outlook on the immediate next steps
- ✦ Further AGN observations with the current VLTI
- ✦ New VLTI instruments and their capabilities

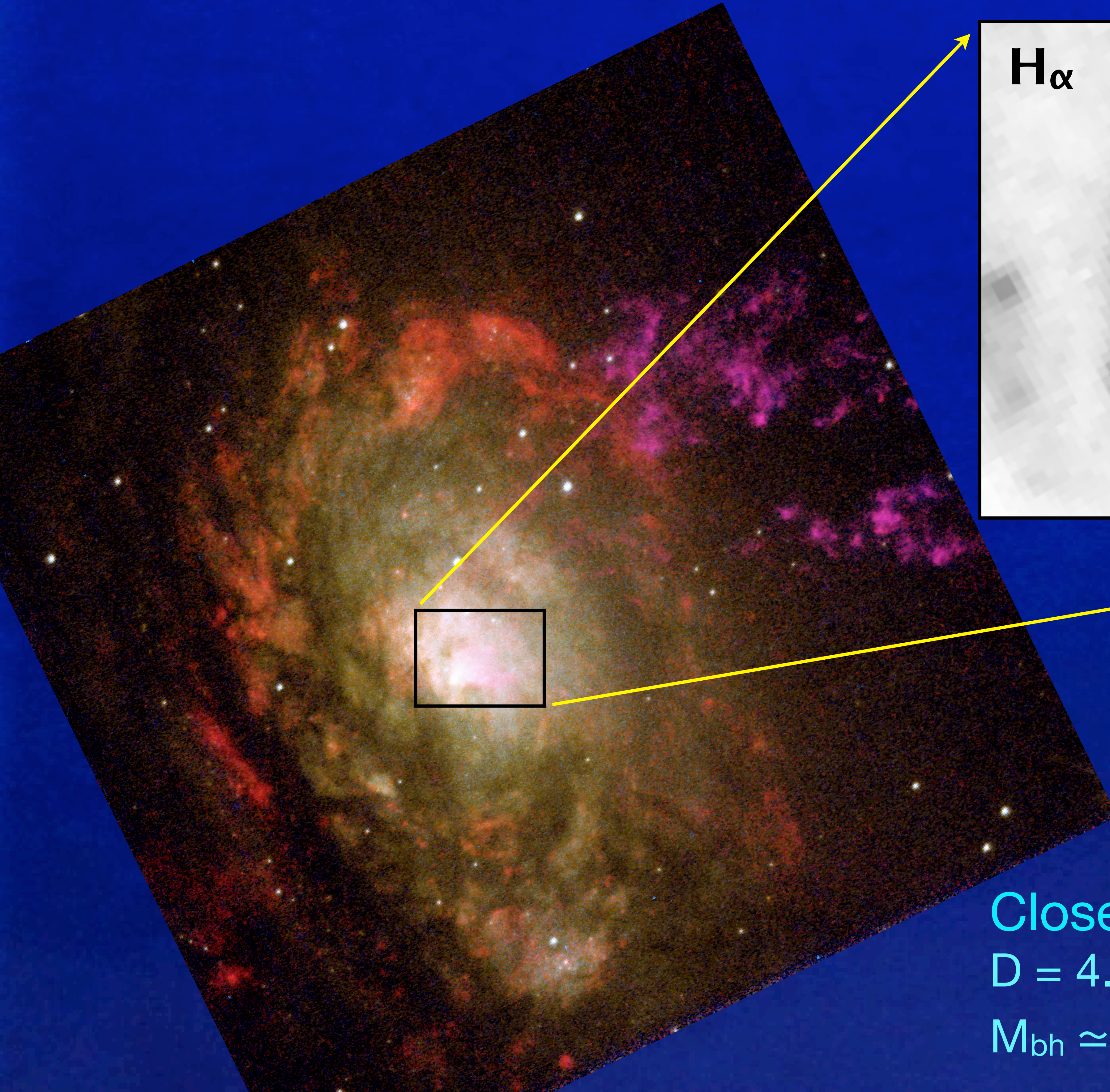
2. MIDI + VLTI observations of the dust tori in the closest Seyfert 2 galaxies

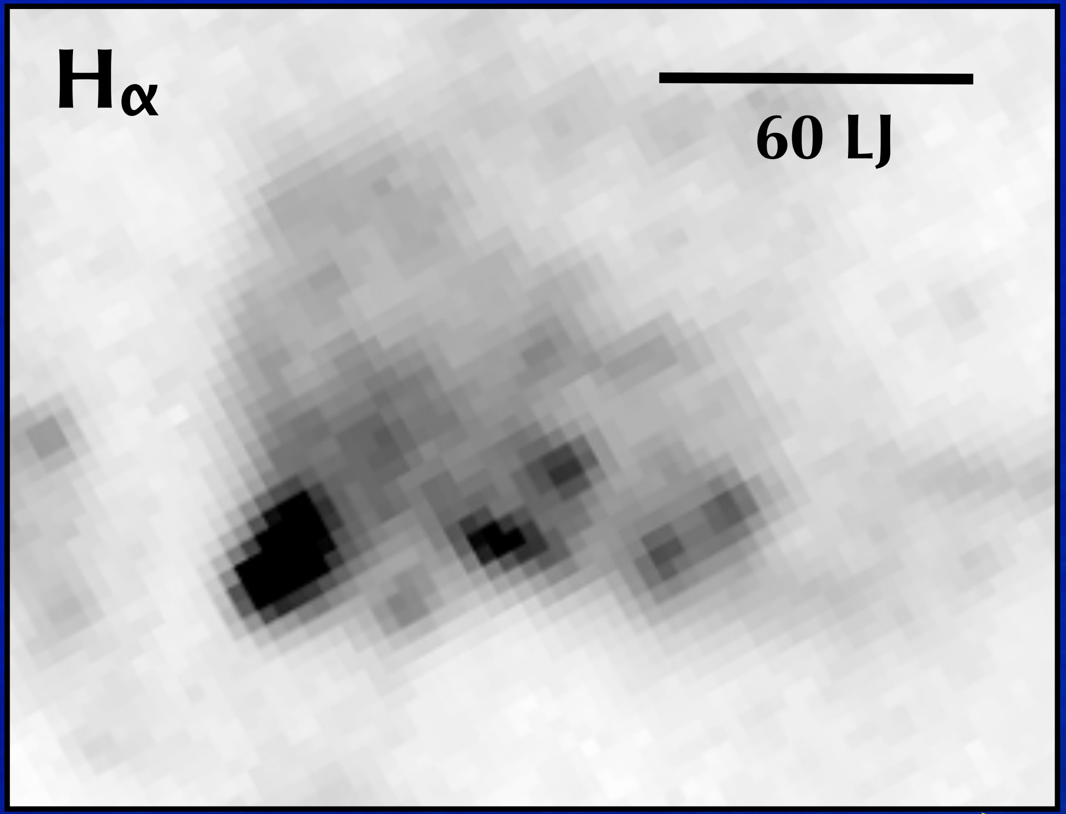
2.1 Dust torus in the Circinus galaxy

2.2 Dust torus in NGC 1068



2.1 Dust torus in the Circinus galaxy





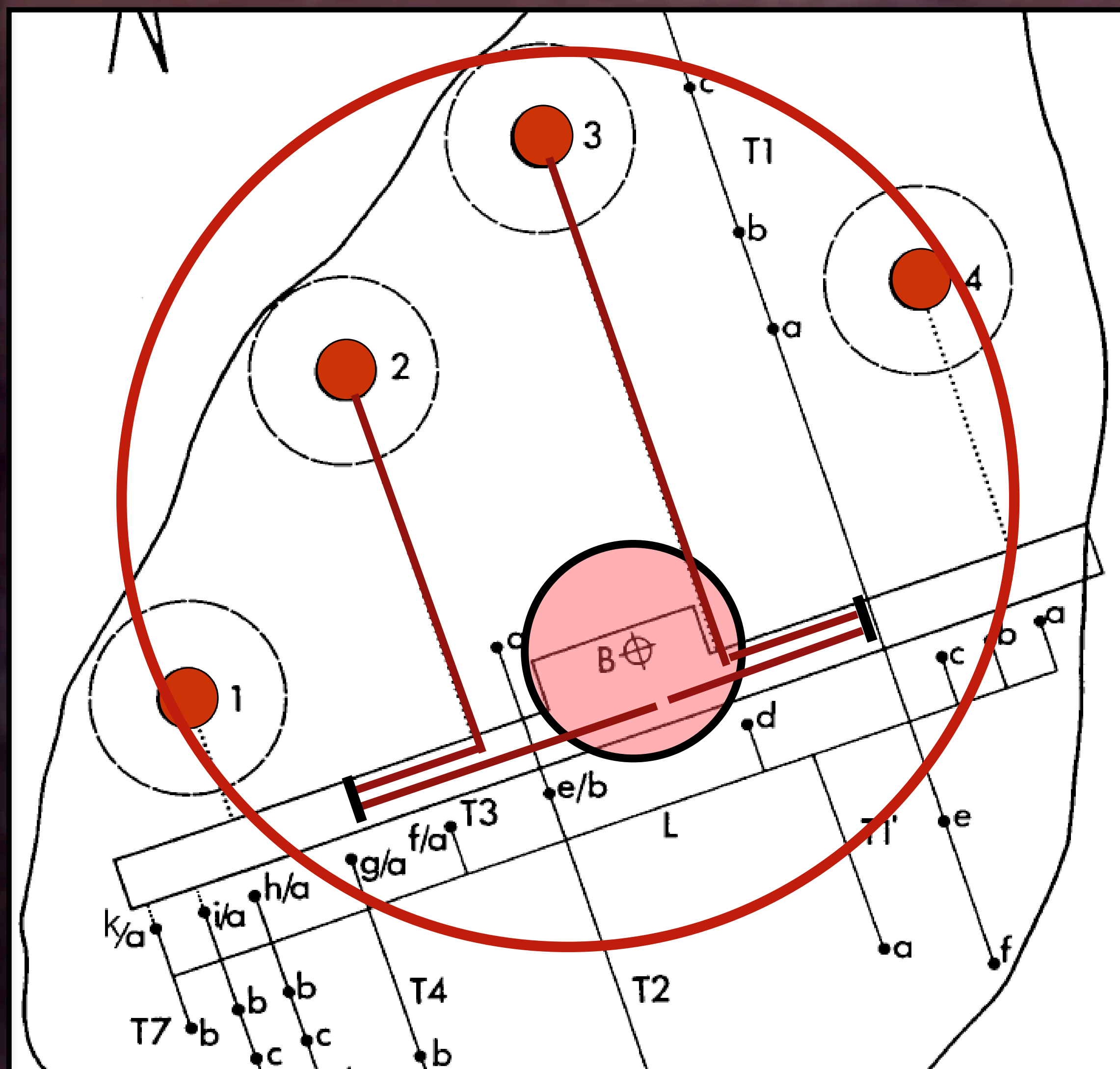
Closest Seyfert 2 galaxy

D = 4.0 Mpc → 1 pc = 50 mas

$M_{bh} \simeq 10^6\ M_{sun}$

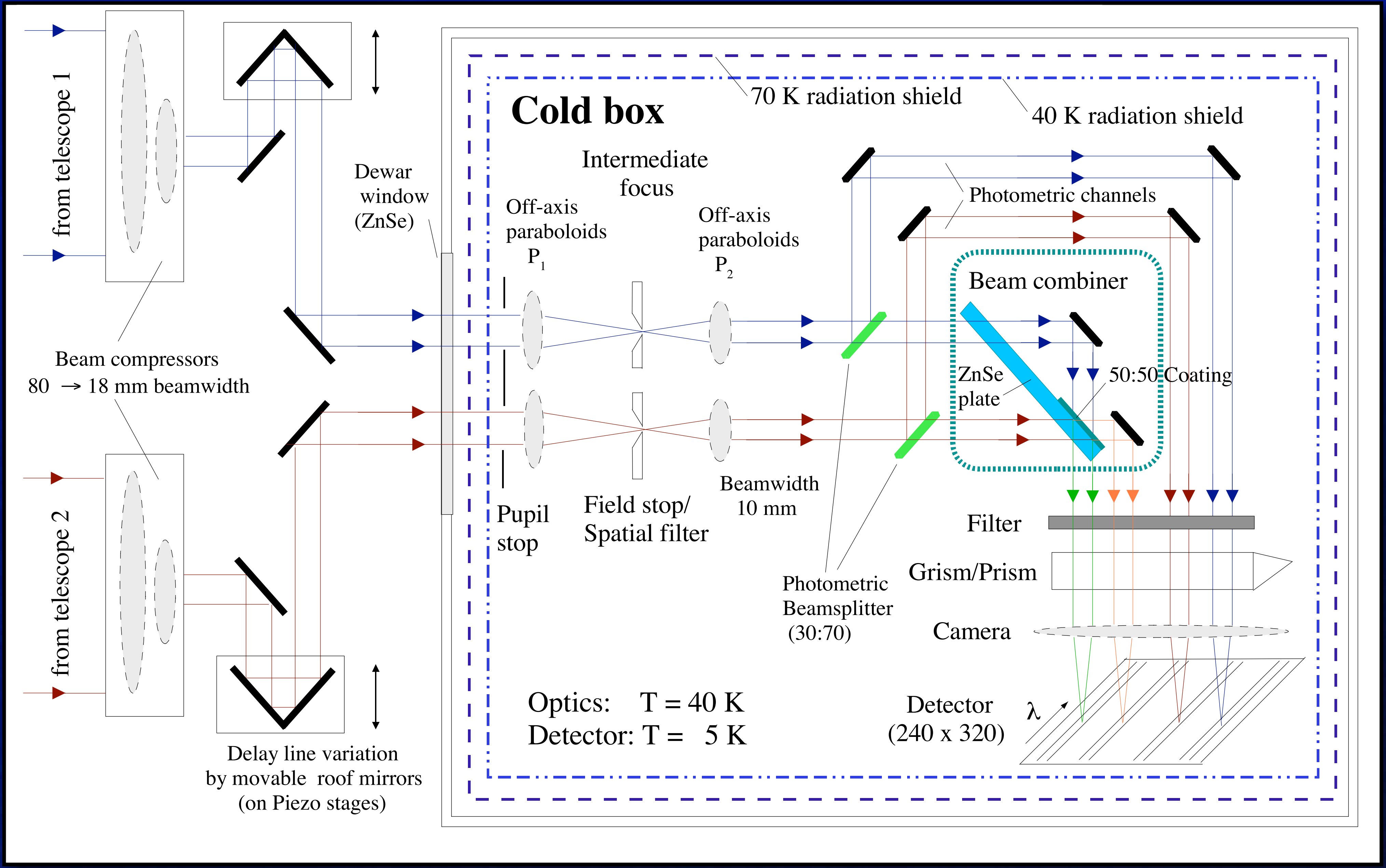
Very Large Telescope Interferometer

MIDI – MID-infrared Interferometer



The MID-infrared Interferometer MIDI

Schematic Setup:

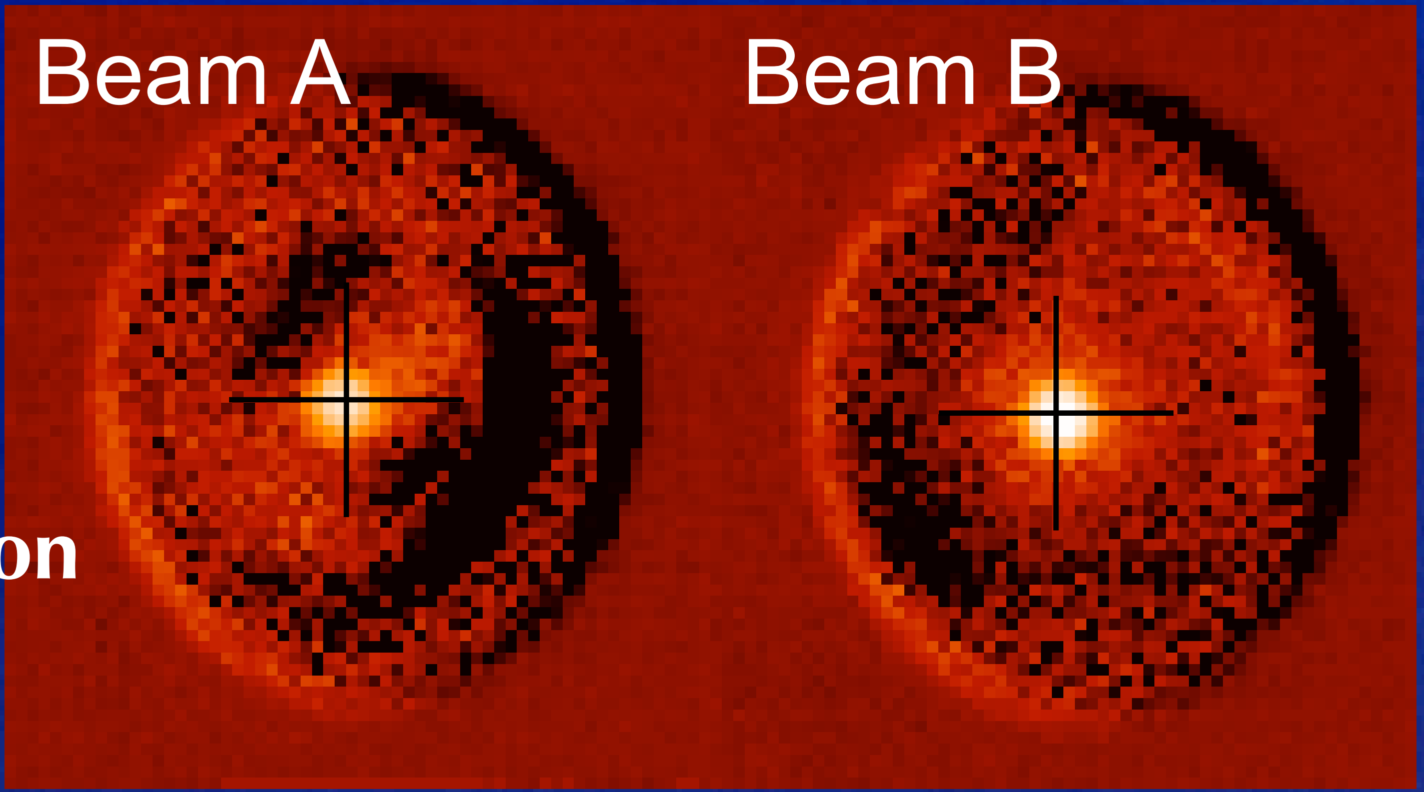


Observations with VLTI & MIDI on Paranal

The MID-infrared Interferometer MIDI

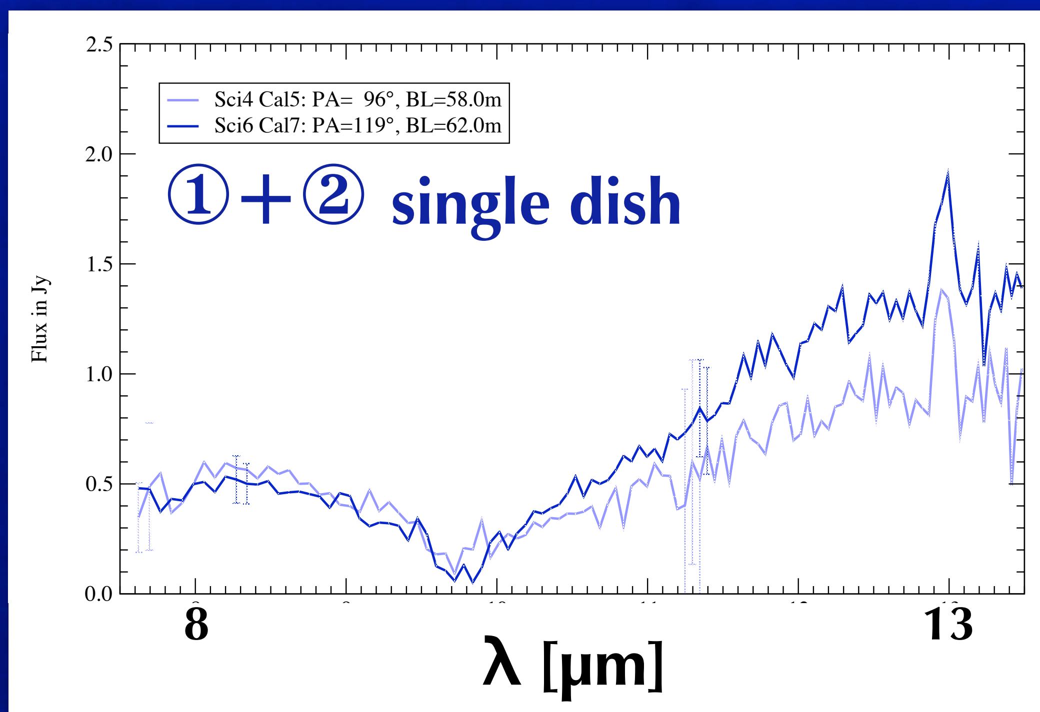
Observations:

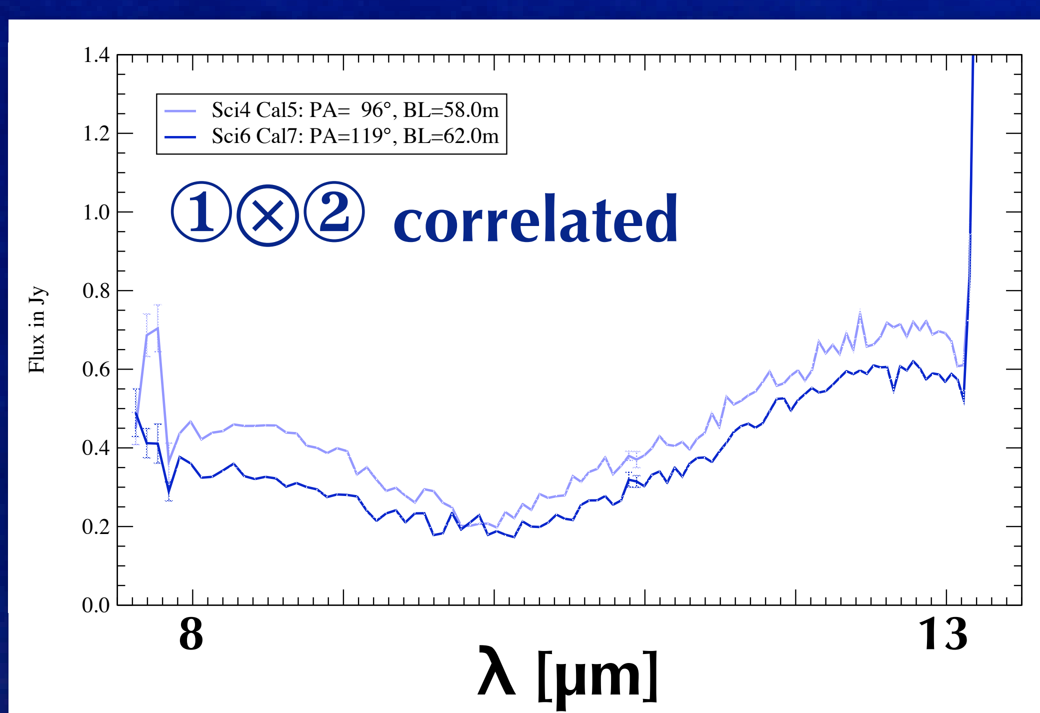
1. point both unit telescope to same source
2. find guide-stars, close telescope loop
3. close loop of AO system (MACAO) on target (or nearby star)
4. identify target in both MIDI beams
5. center target in both MIDI beams
6. search for “fringes” OPD = 0
7. interferometric integration
8. photometric integration

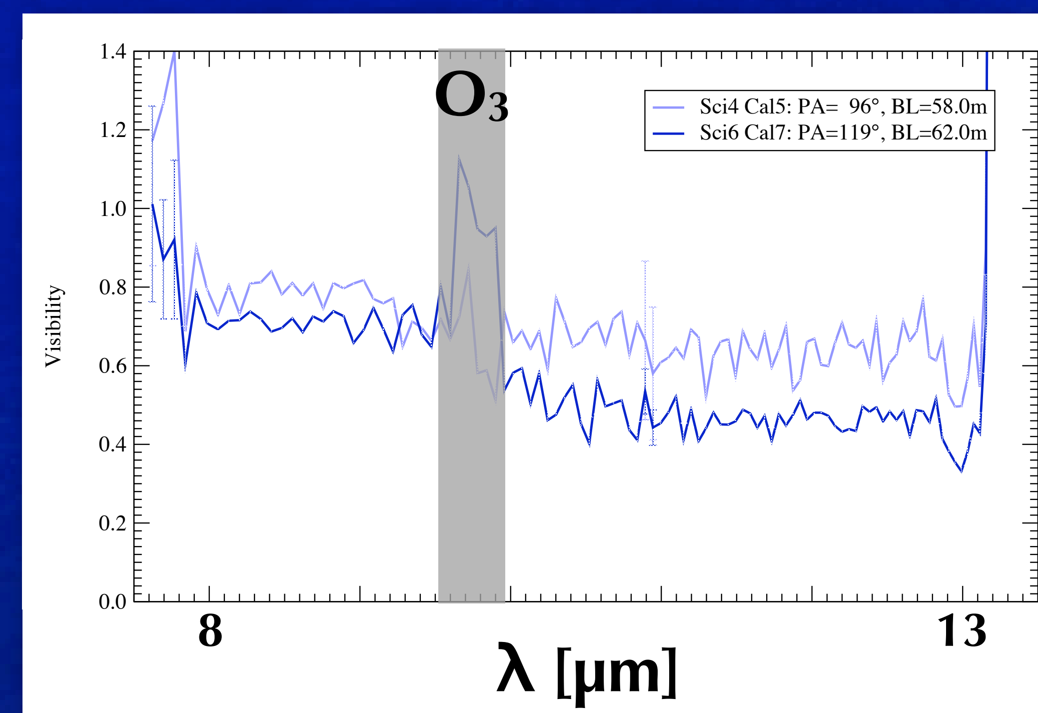


The MID-infrared Interferometer MIDI

Output from the instrument

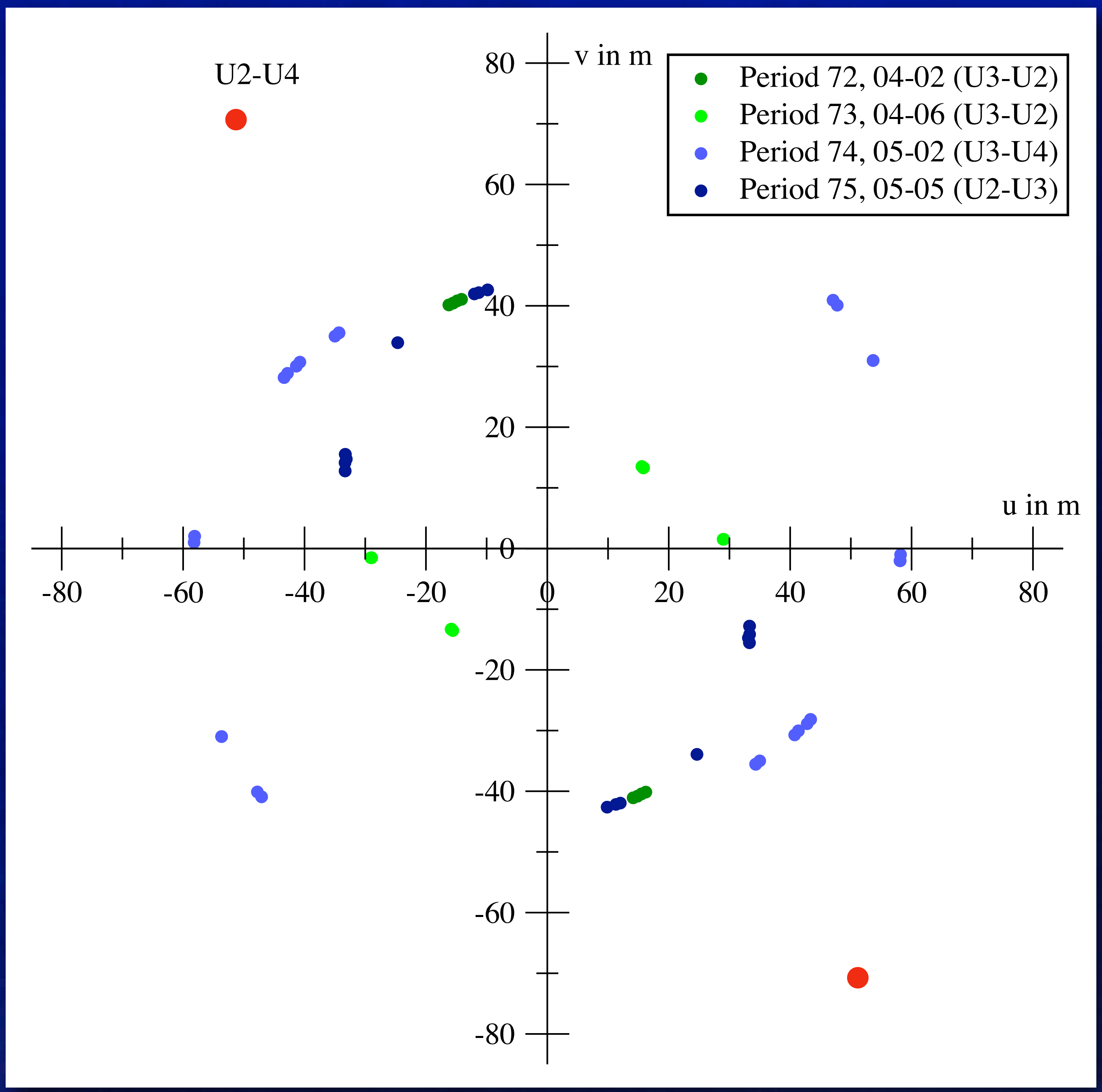


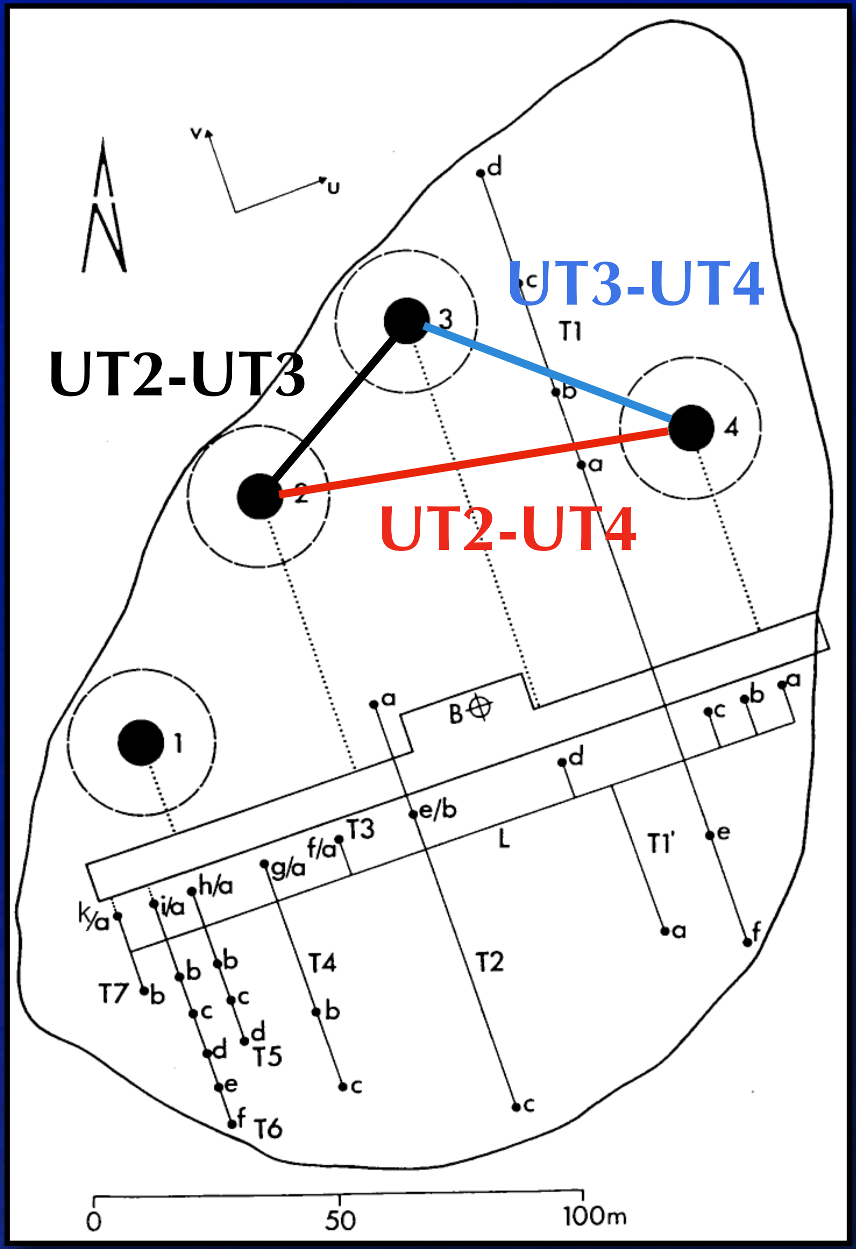




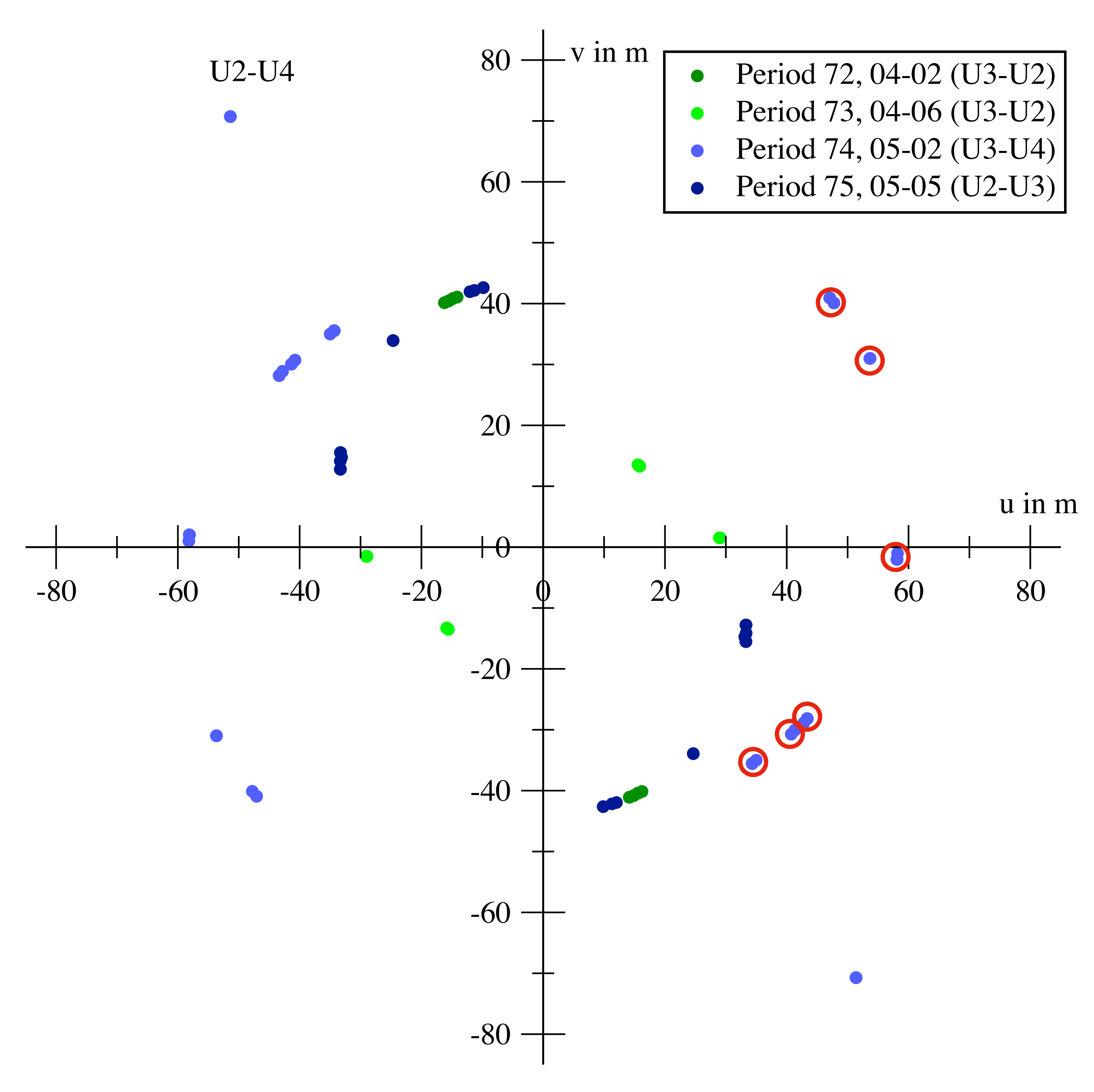
Dust torus in the Circinus galaxy

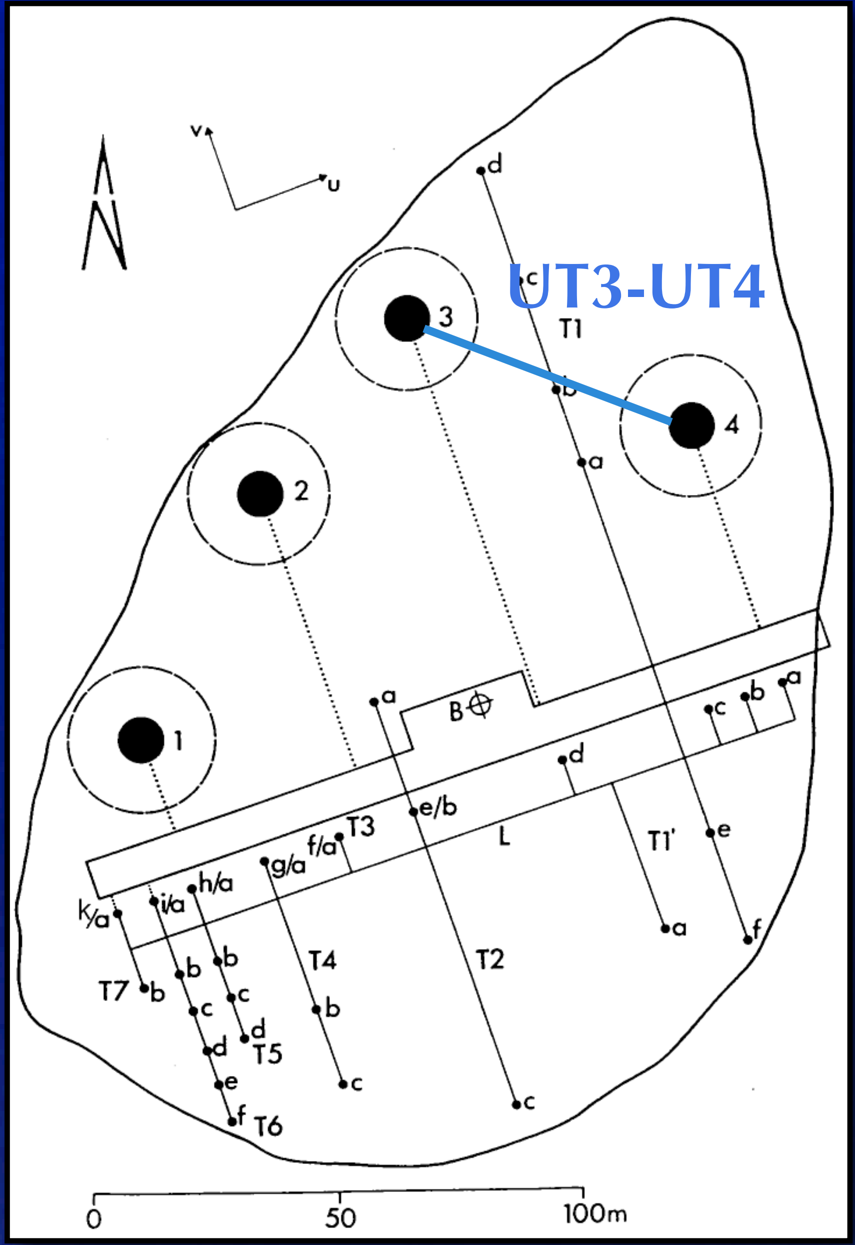
Konrad Tristram, K. M., Walter Jaffe, et al. 2007



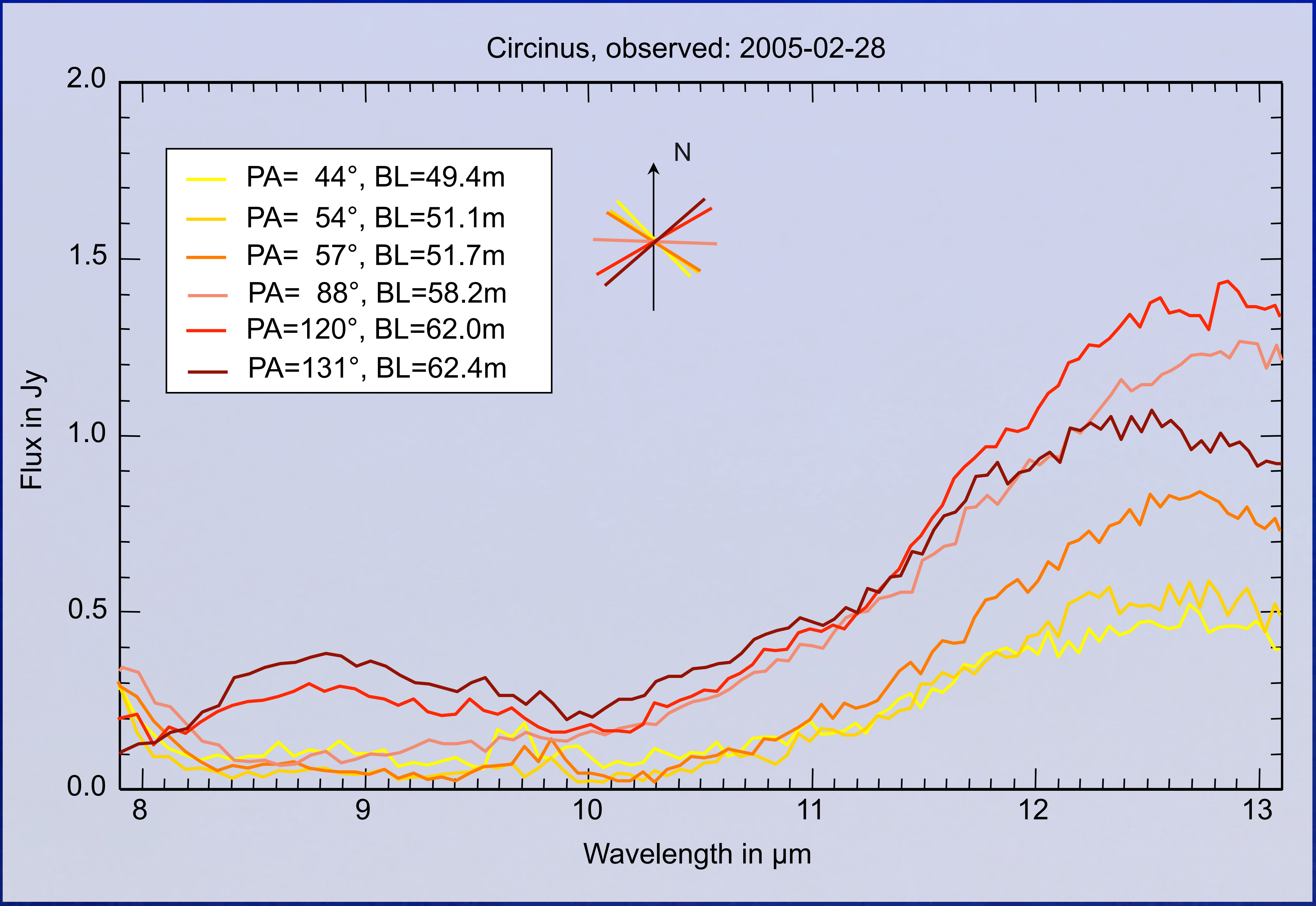


Dust torus in the Circinus galaxy



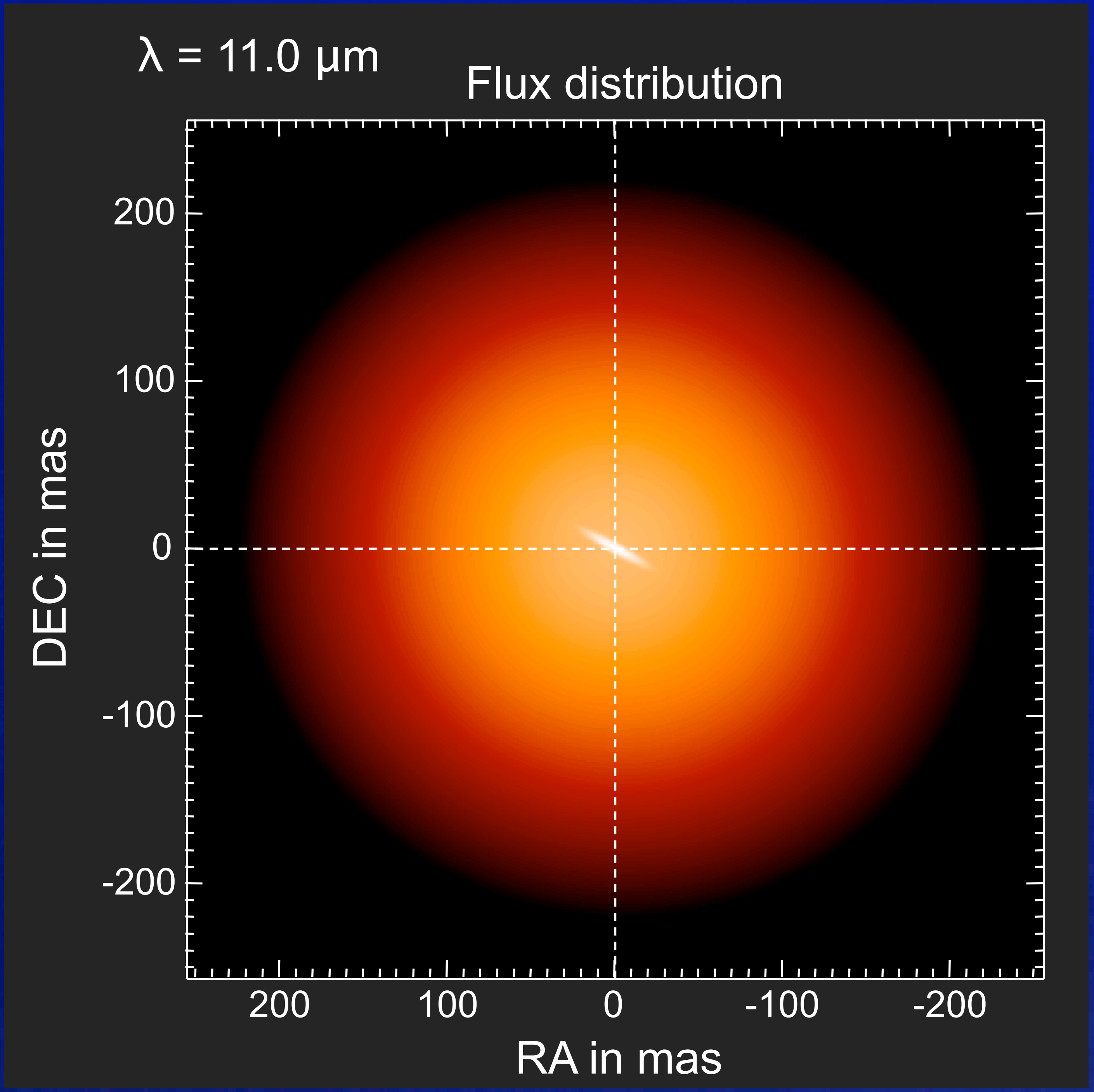


Dust torus in the Circinus galaxy



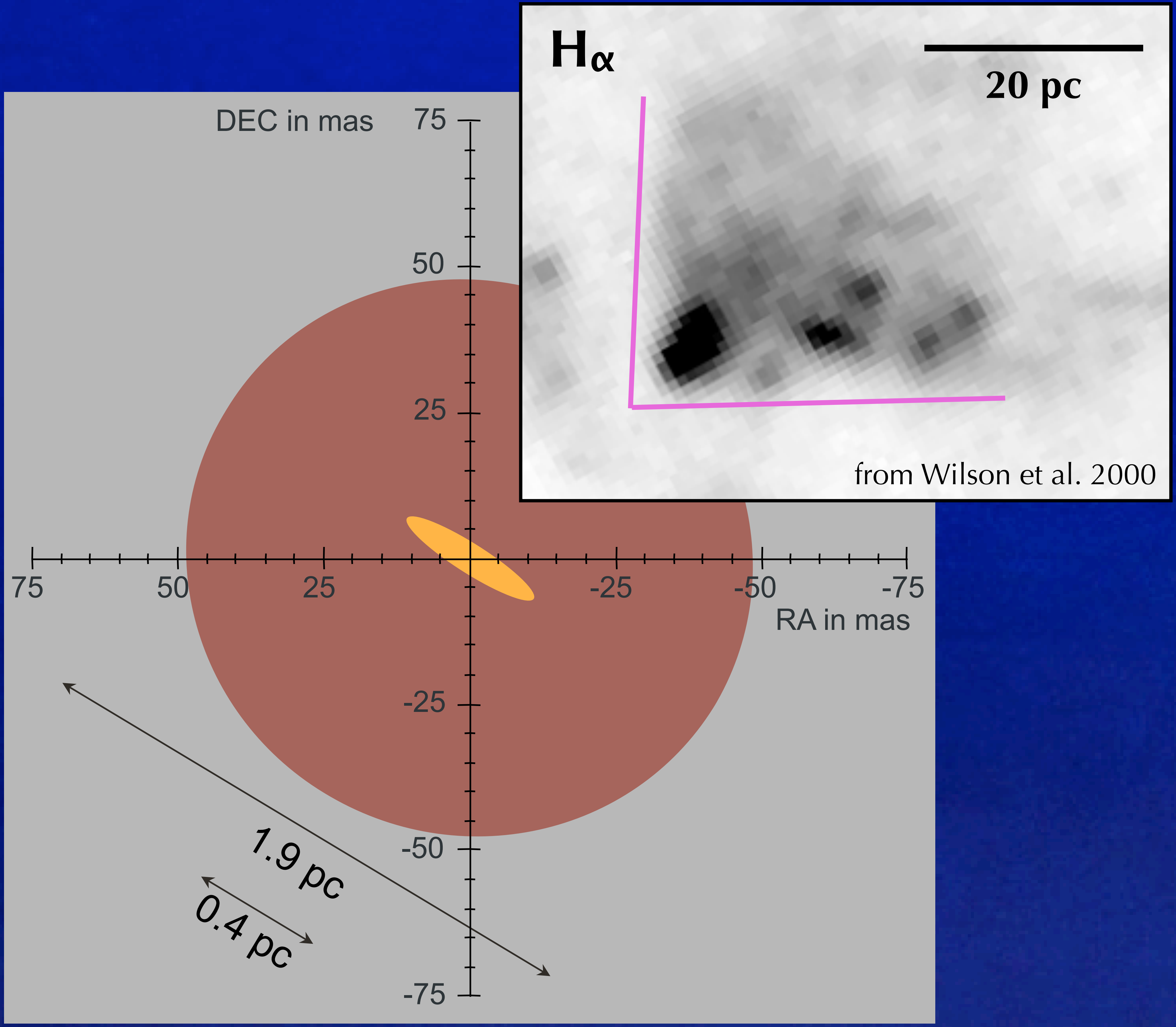
Dust torus in the Circinus galaxy

Observational Model: Gaussian fit

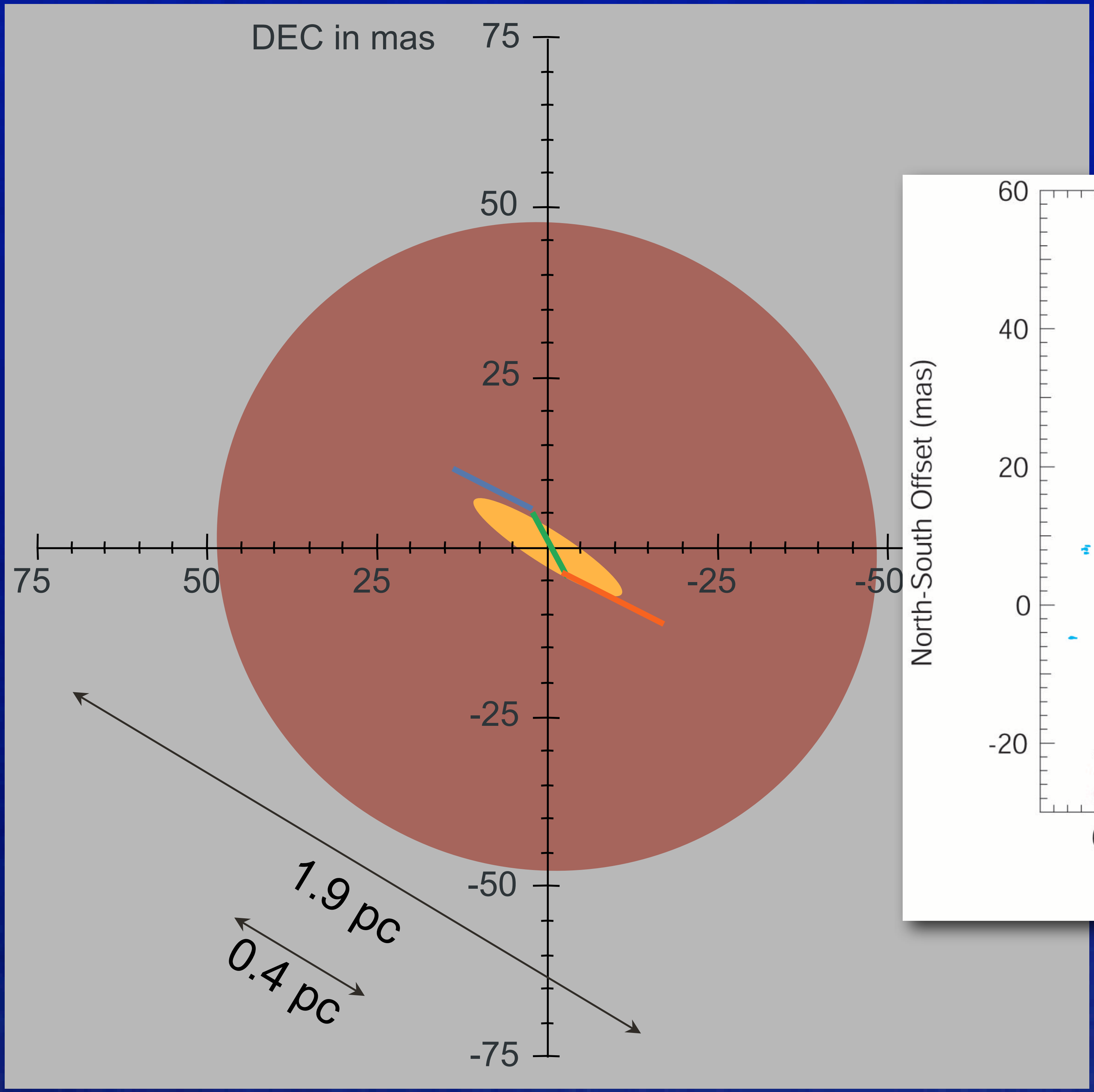


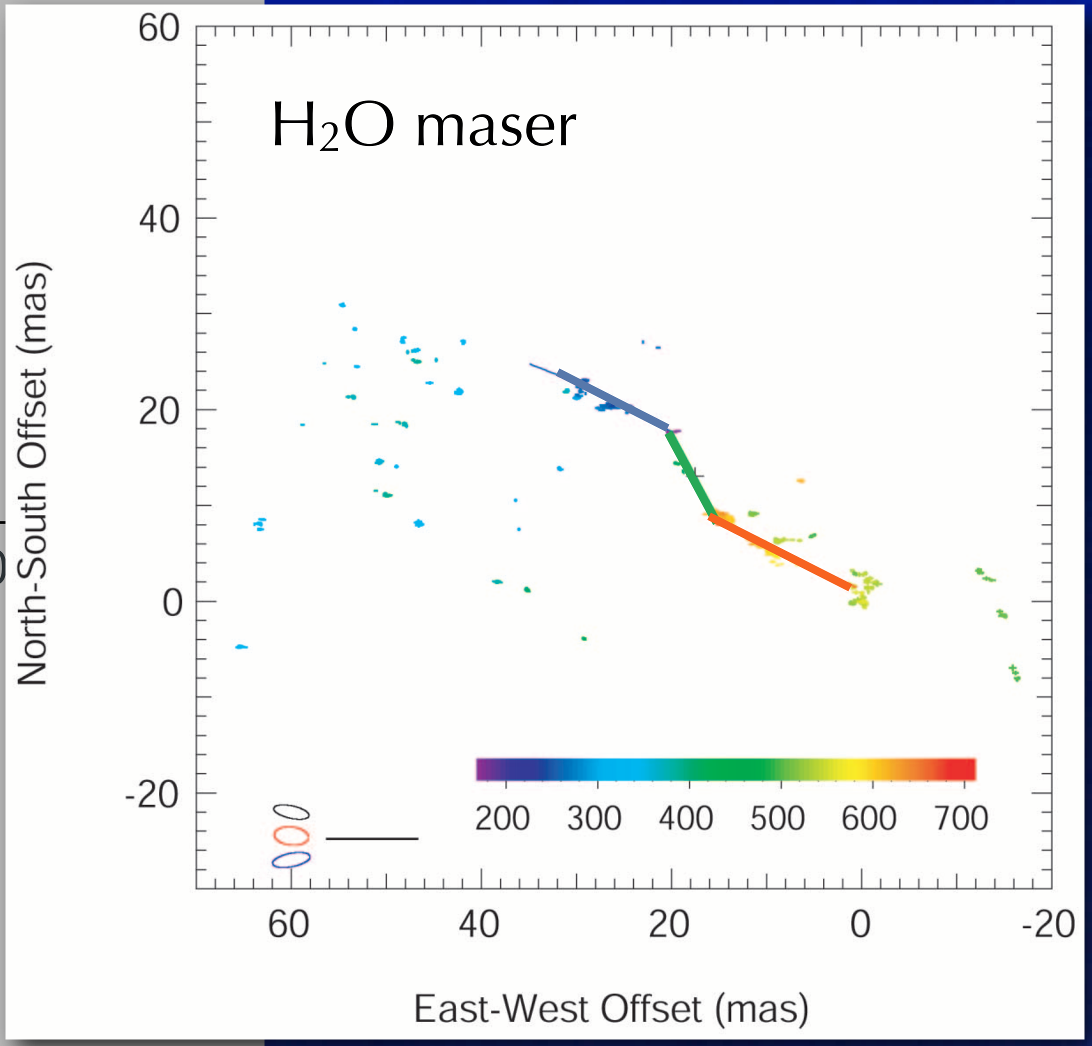
Size:	Δ_1 = 21 mas
Axis ratio:	r_1 = 0.21
Silicate depth:	τ_1 = 1.18
Temperature:	T_1 = 334 K
Covering factor:	f_1 = 1.0
Size:	Δ_2 = 97 mas
Axis ratio:	r_2 = 0.97
Silicate depth:	τ_2 = 2.21
Temperature:	T_2 = 298 K
Covering factor:	f_2 = 0.20
Position angle:	α = 61°

Dust torus in the Circinus galaxy



Dust torus in the Circinus galaxy



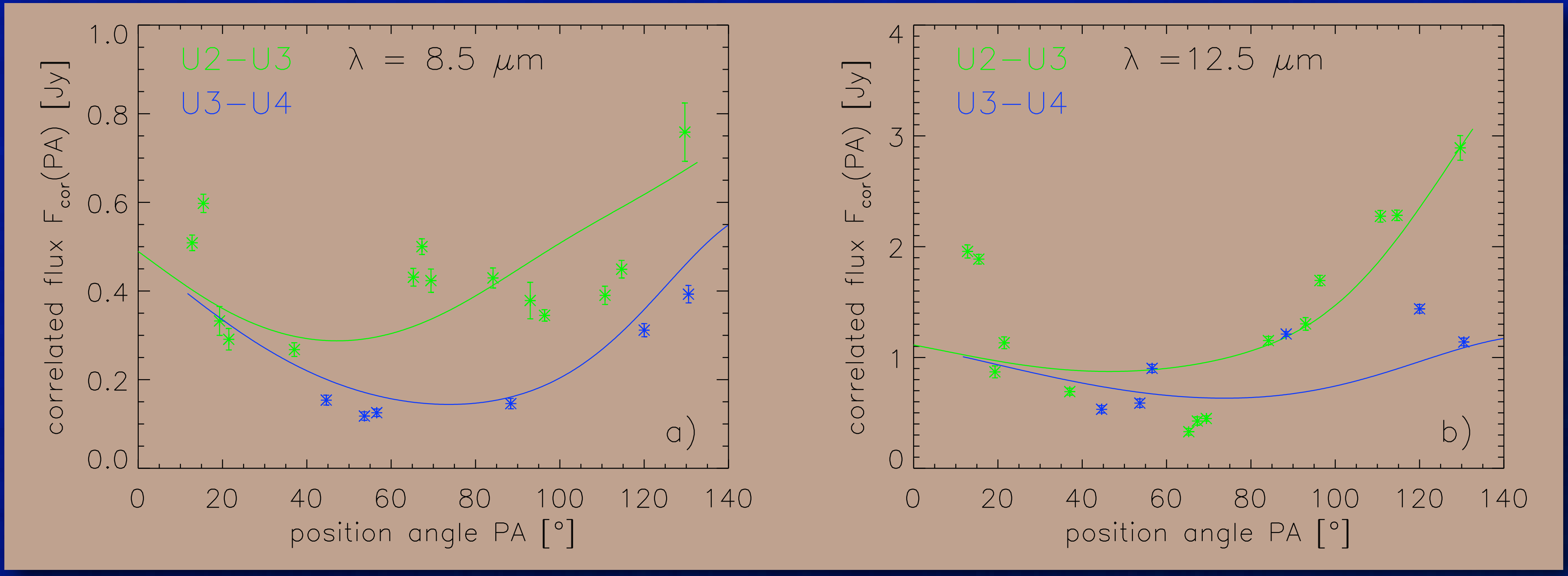


Greenhill et al. 2003

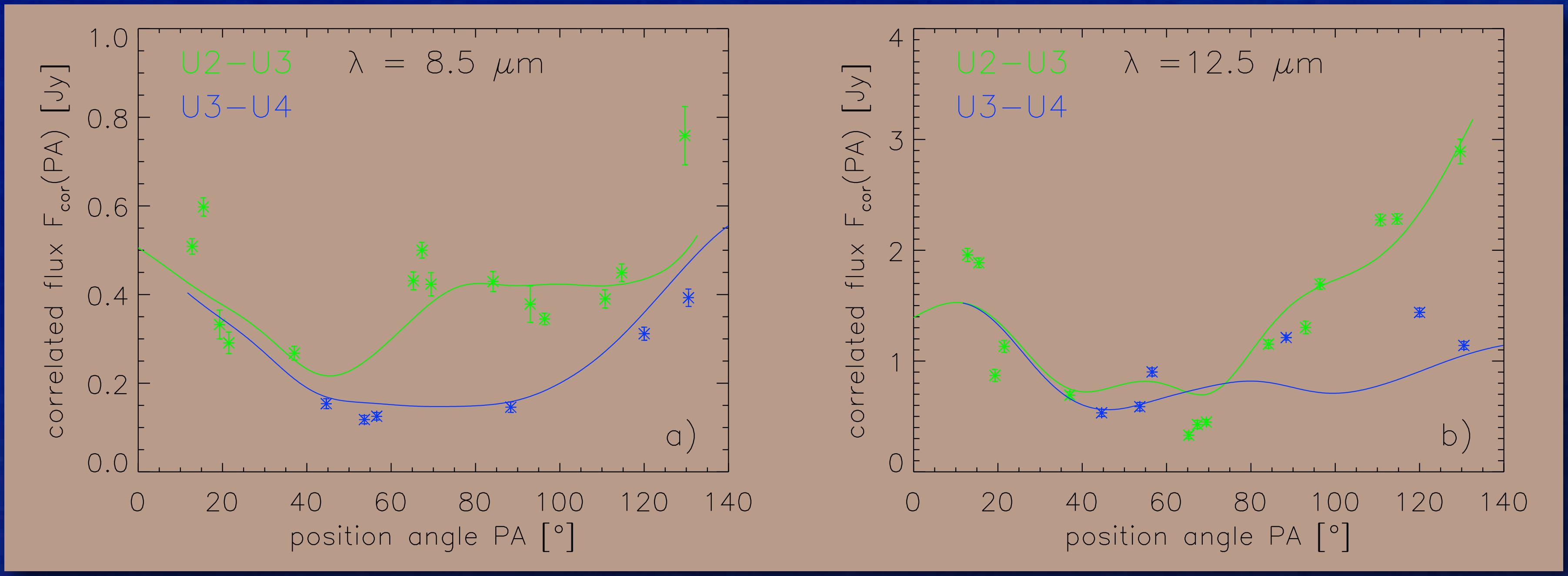
Dust torus in the Circinus galaxy

BUT ...

the smooth model is a rather poor fit to the visibilities:

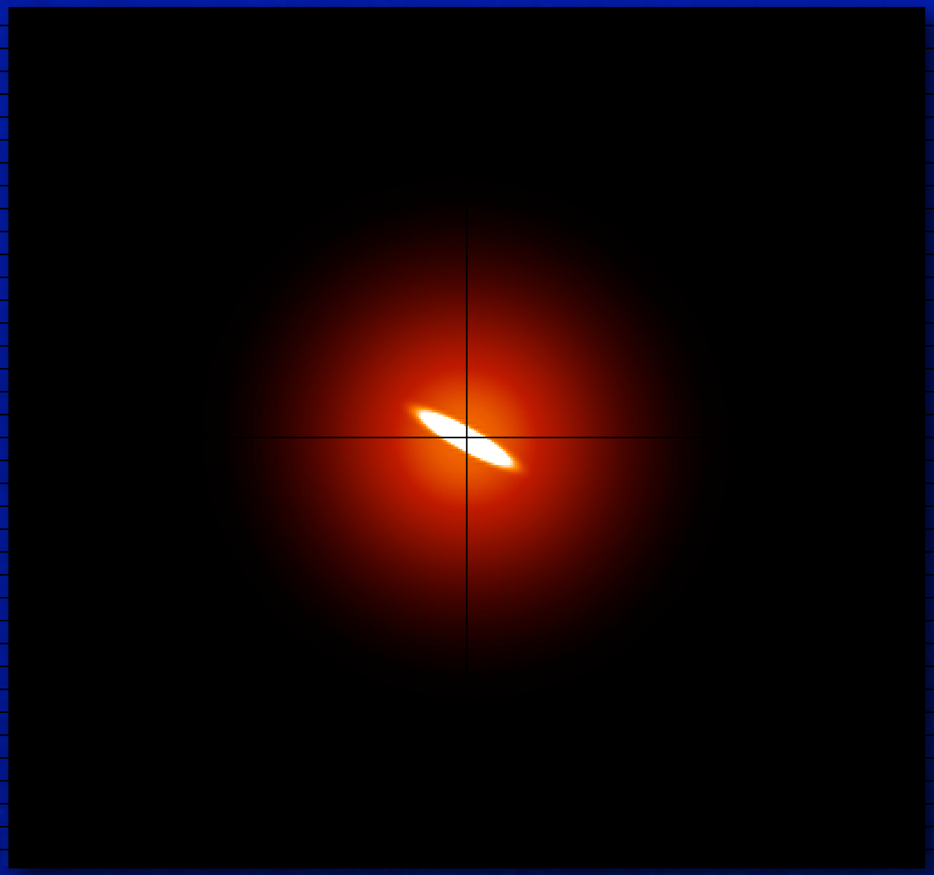


modify model by irregular screen:

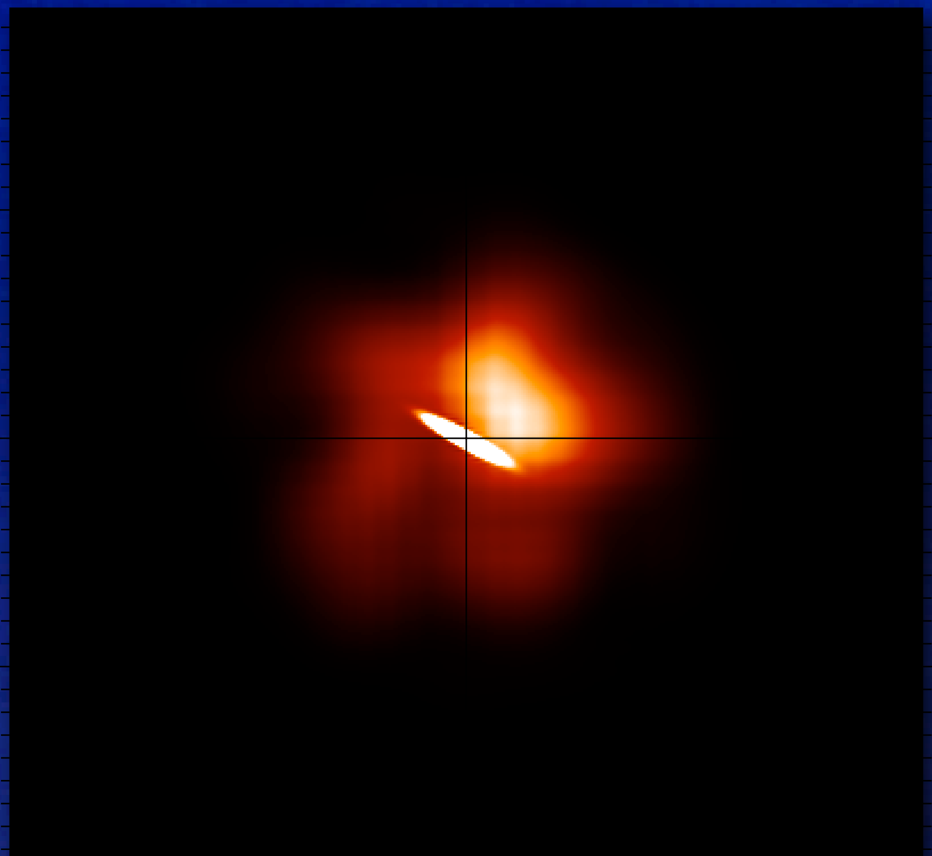


Dust torus in the Circinus galaxy

Images: smooth model



irregular/clumpy model



Dust torus in the Circinus galaxy

More than a dozen people helped to get these results

Resolving the complex structure of the dust torus in the active nucleus of the Circinus galaxy★

Konrad R. W. Tristram[1], Klaus Meisenheimer[1], Walter Jaffe[2], Marc Schartmann[1], Hans-Walter Rix[1], Christoph Leinert[1], Sébastien Morel[3], Markus Wittkowski[4], Huub Röttgering[2], Guy Perrin[5], Bruno Lopez[6], David Raban[2], William D. Cotton[7], Uwe Graser[1], Francesco Paresce[4], Thomas Henning[1]

[1] Max-Planck-Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany
[2] Leiden Observatory, Leiden University, Niels-Bohr-Weg 2, 2300 CA Leiden, The Netherlands
[3] European Southern Observatory, Casilla 19001, Santiago 19, Chile
[4] European Southern Observatory, Karl-Schwarzschild-Strasse 2, 85748 Garching bei München, Germany
[5] LESIA, UMR 8109, Observatoire de Paris-Meudon, 5 place Jules Janssen, 92195 Meudon Cedex, France
[6] Laboratoire Gemini, UMR 6203, Observatoire de la Côte d'Azur, BP 4229, 06304 Nice Cedex 4, France
[7] NRAO, 520 Edgemont Road, Charlottesville, VA 22903-2475, USA

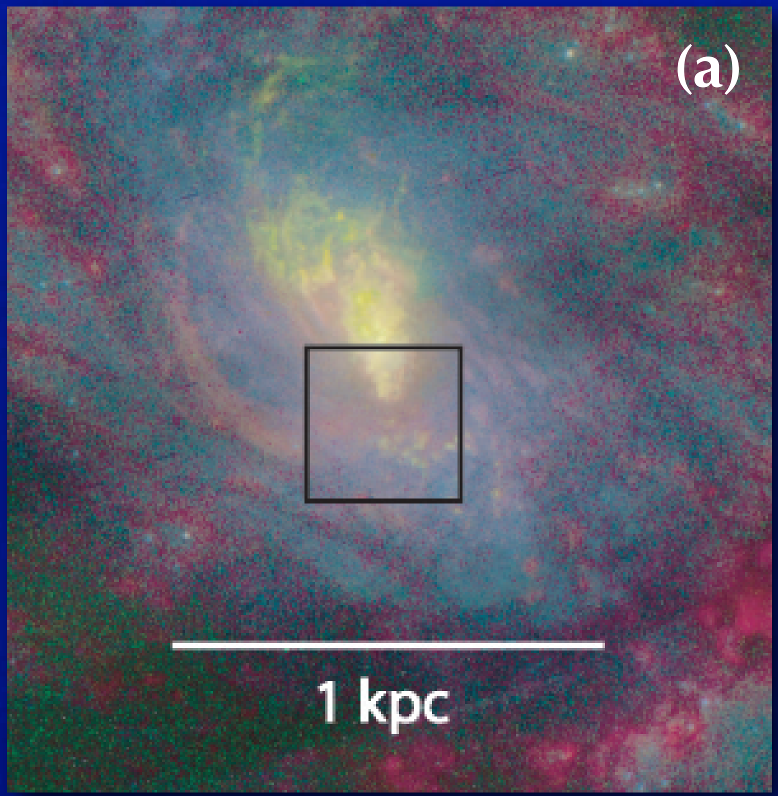
MIDI GTO team for AGN studies

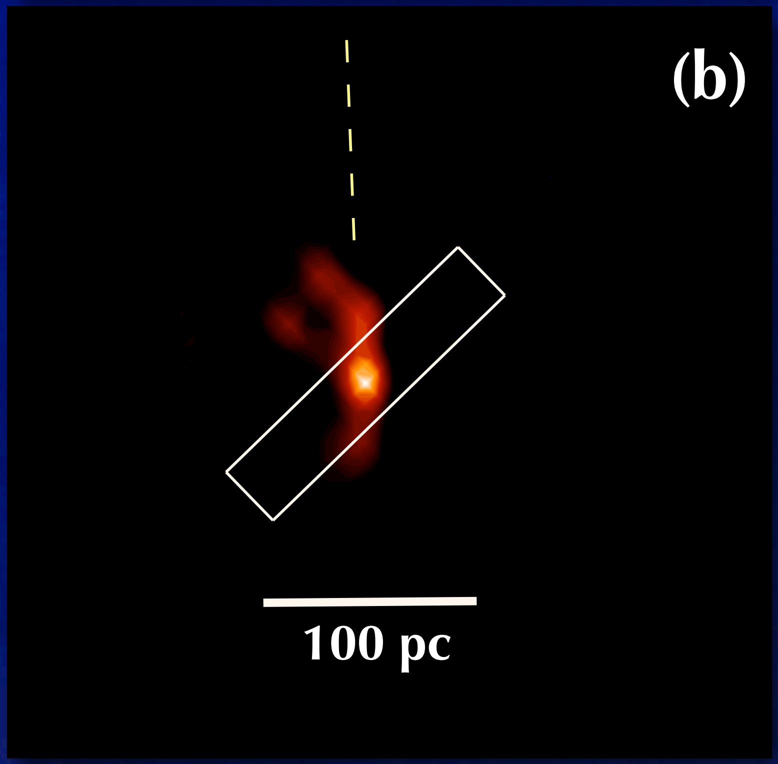
ESO VLTI team

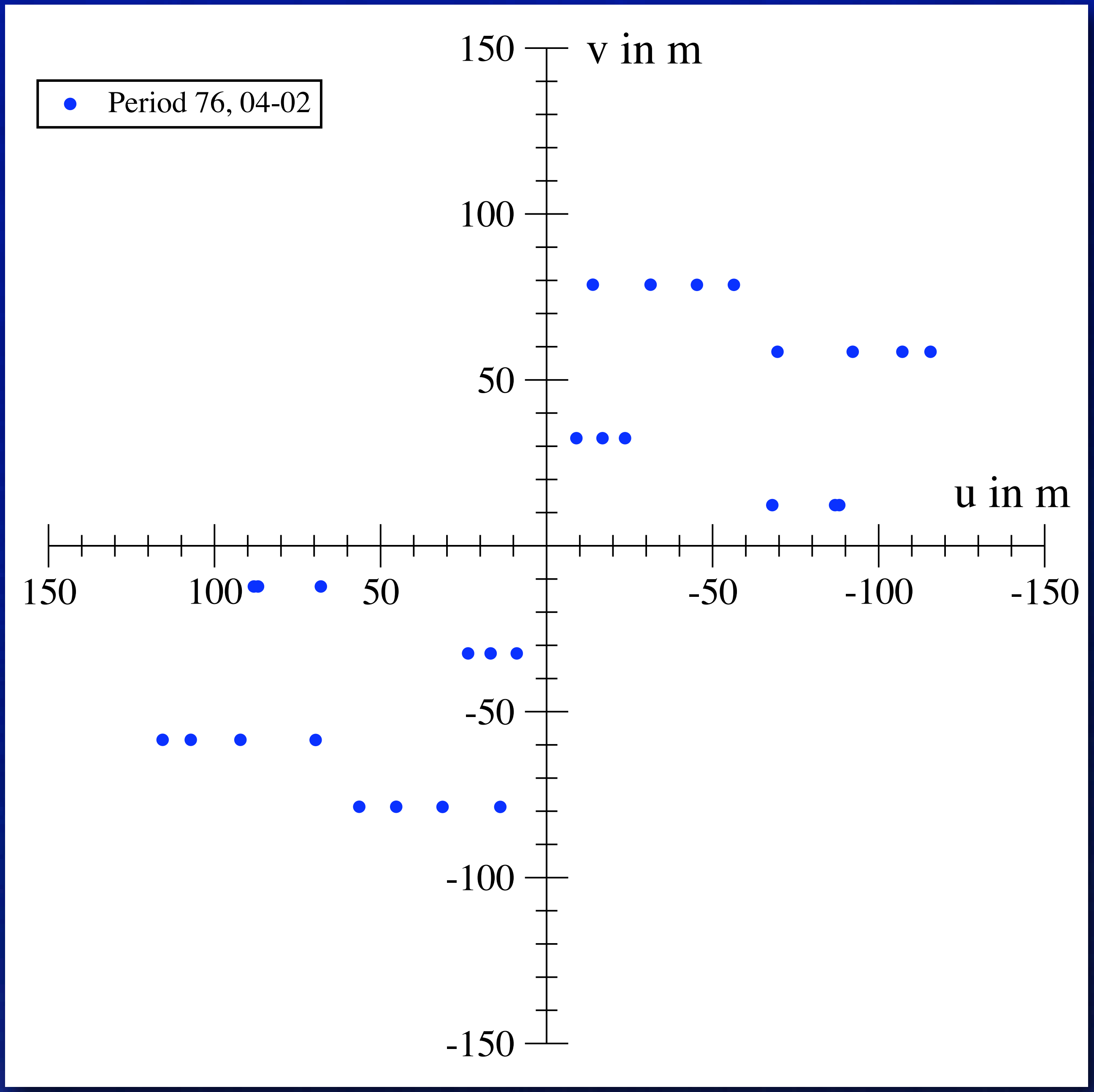
A&A, accepted August 31, 2007

= arXiv:0709.0209

2.2 Dust torus in NGC 1068

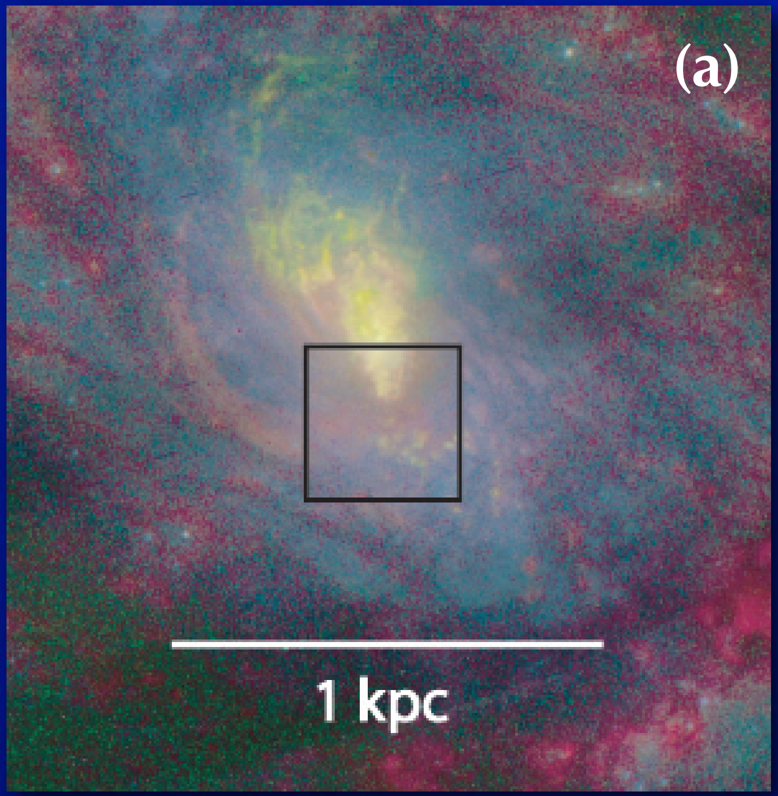


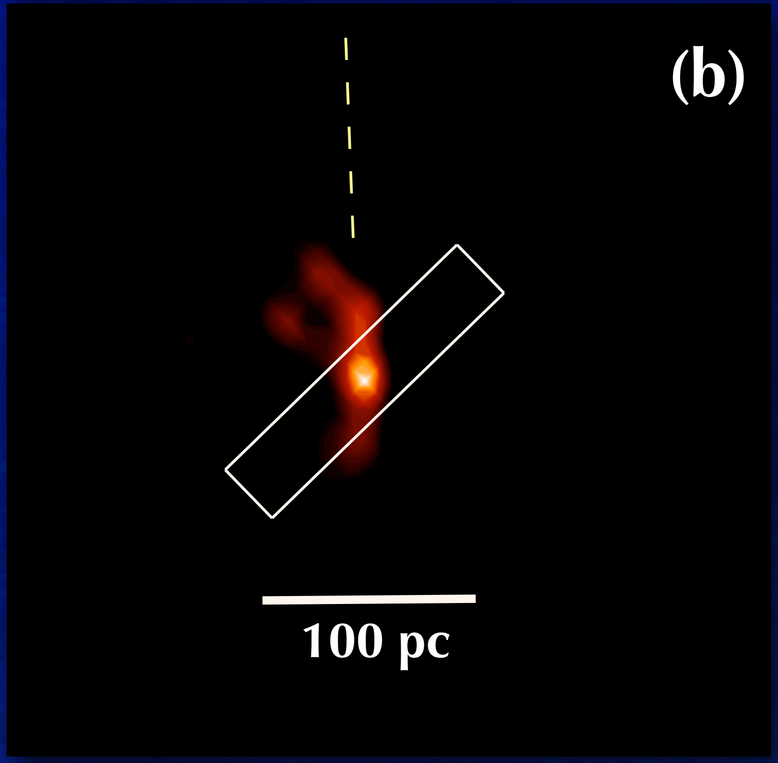


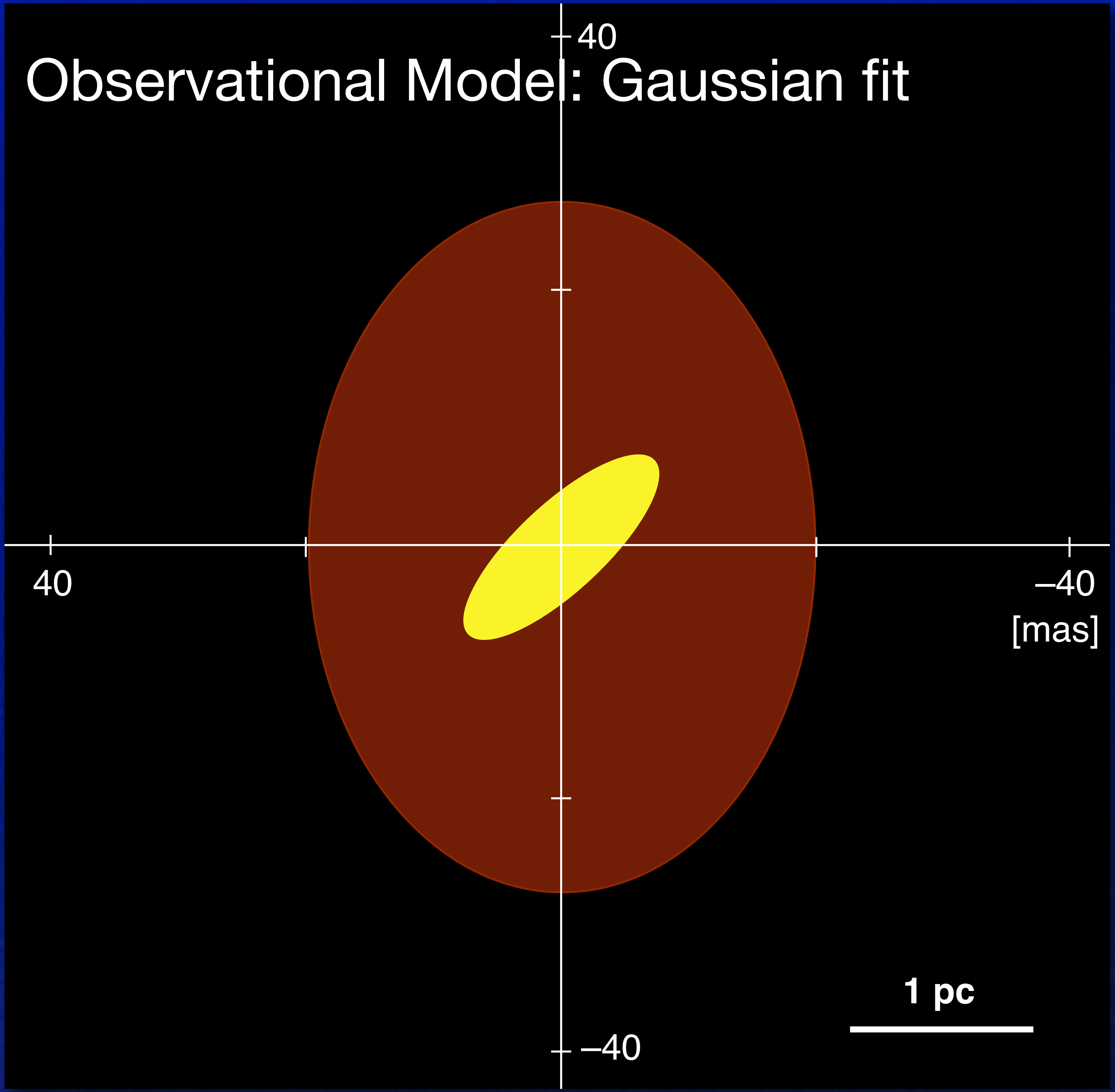


David Raban, Walter Jaffe et al. 2007

2.2 Dust torus in NGC 1068

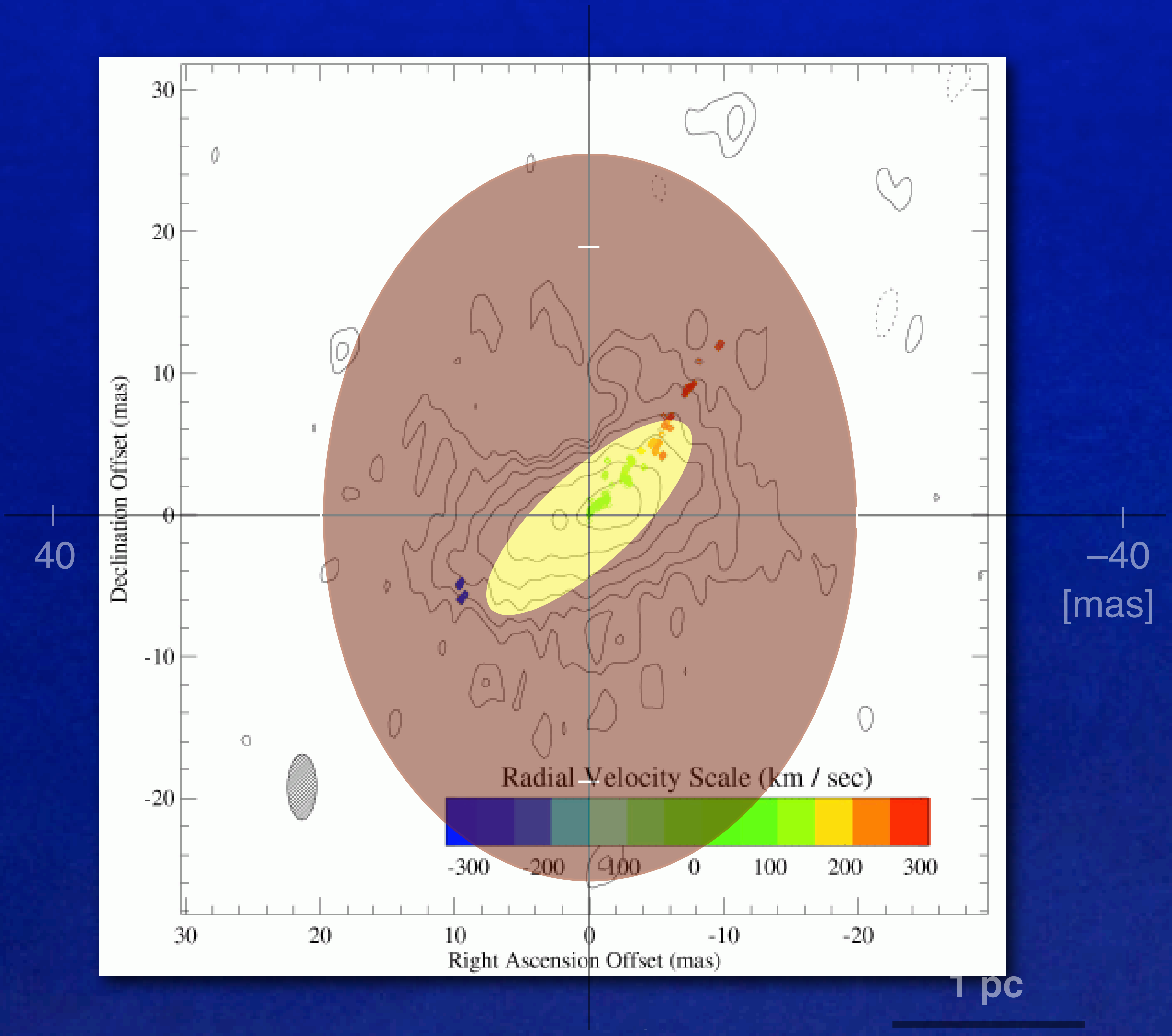






2.2 Dust torus in NGC 1068

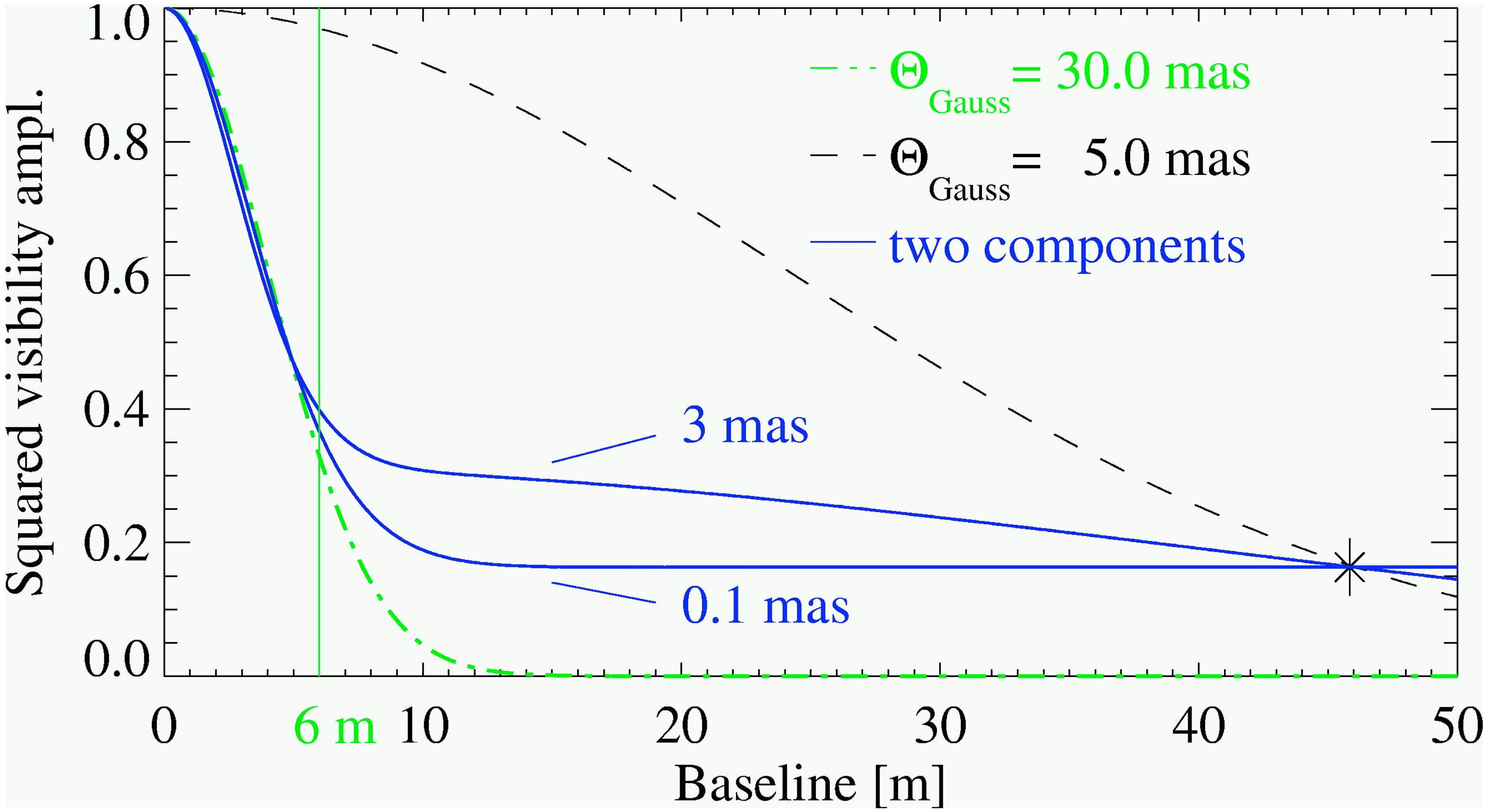
Comparison with radio continuum and water masers

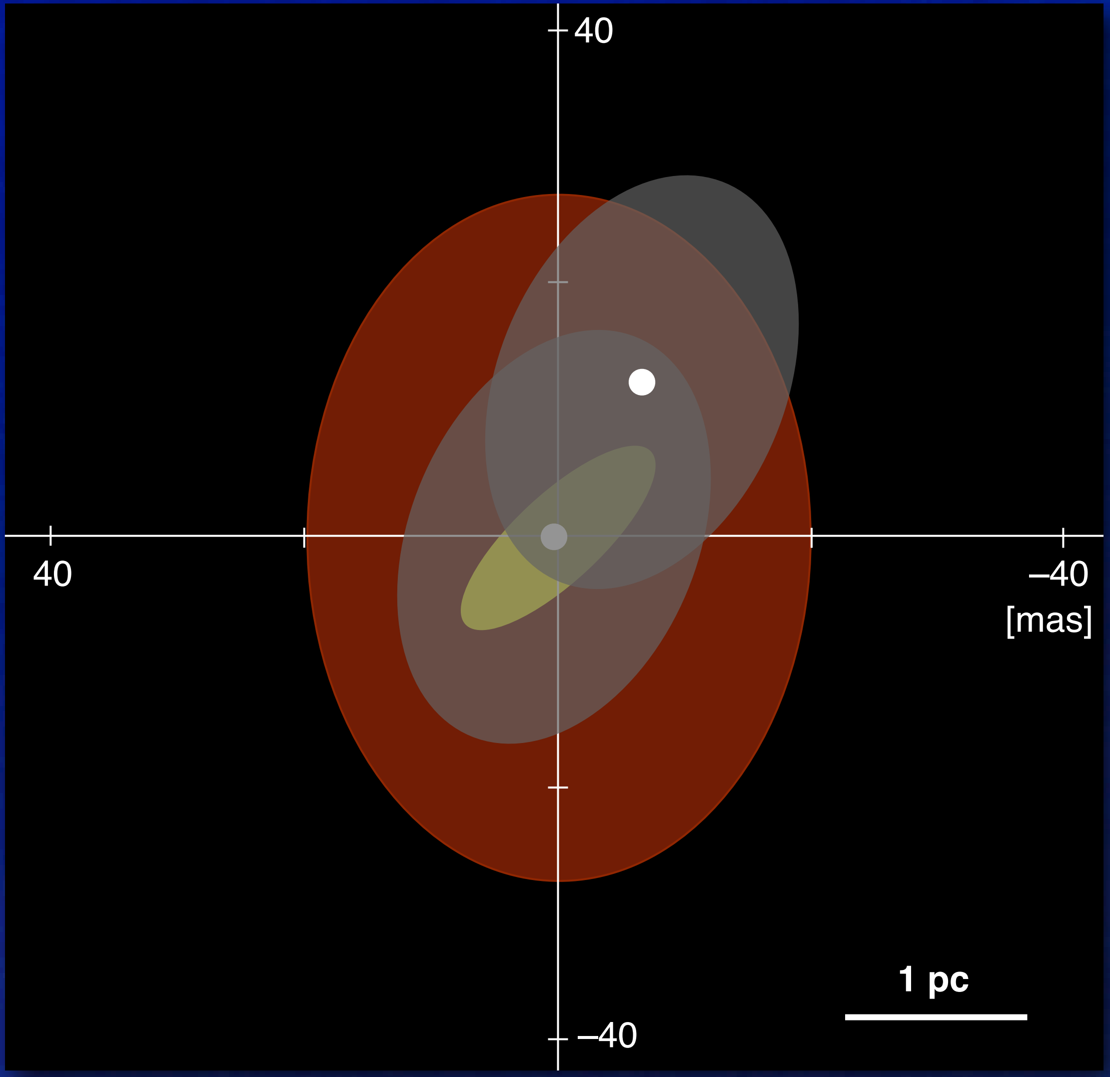


2.2 Dust torus in NGC 1068

K-band interferometry from VINCI @ VLTI

Wittkowski *et al.* 2004:





Studies of Active Galactic Nuclei

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Lecture Part II

1. Introduction and Goal of this Lecture
2. MIDI+VLTI observations of the closest Seyfert 2 galaxies
3. Models of the torus
4. MIDI+VLTI observations of the radio galaxy Centaurus A
5. Outlook: More luminous and distant AGN
6. The Future: New instruments at the VLTI
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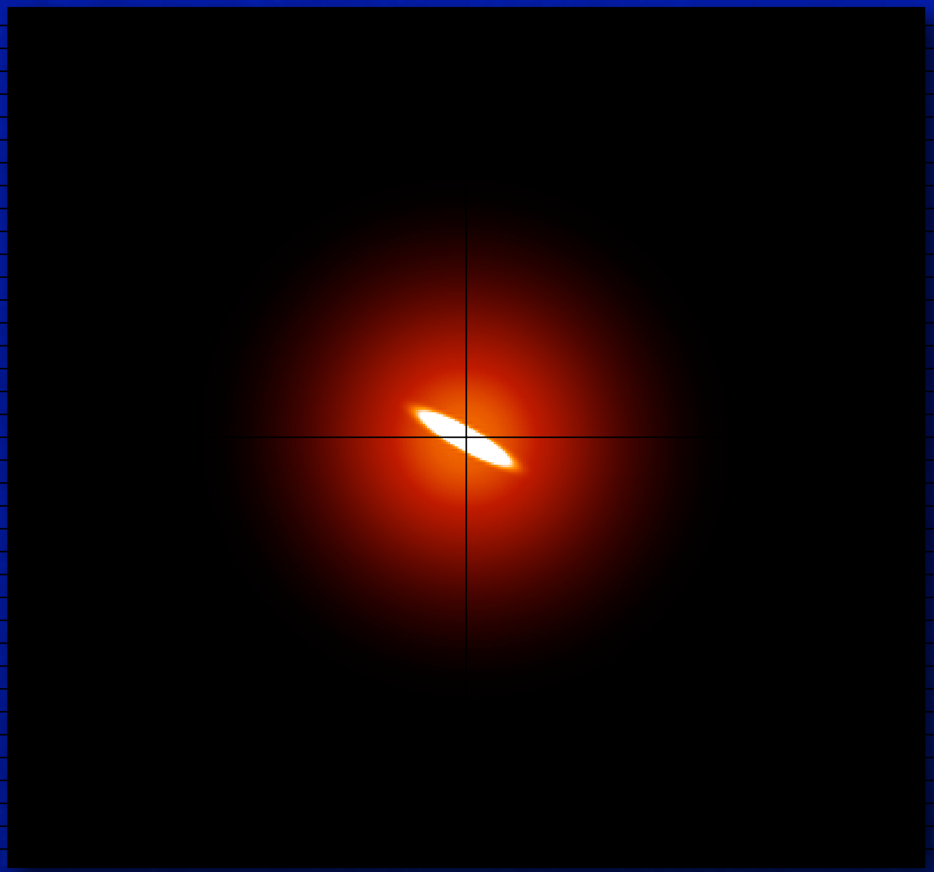
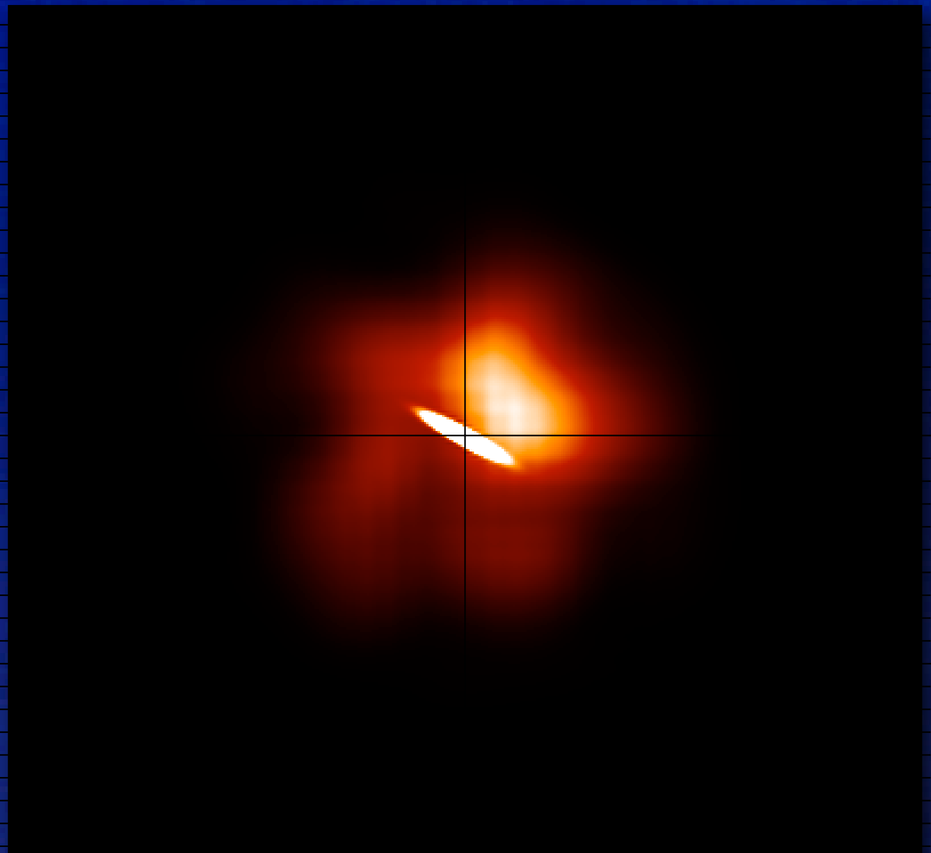
Reminder:Dust torus in the Circinus galaxy

Images: smooth model

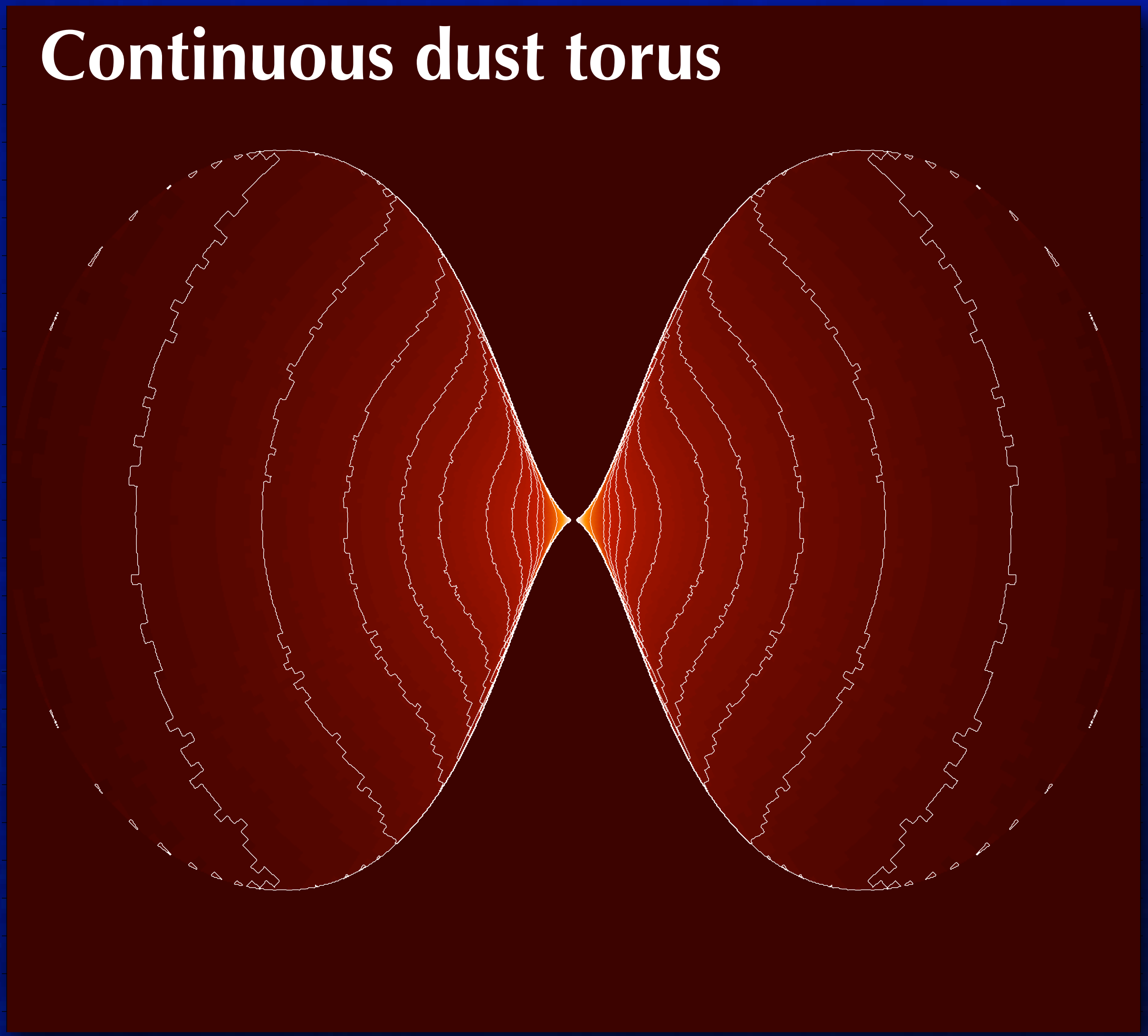


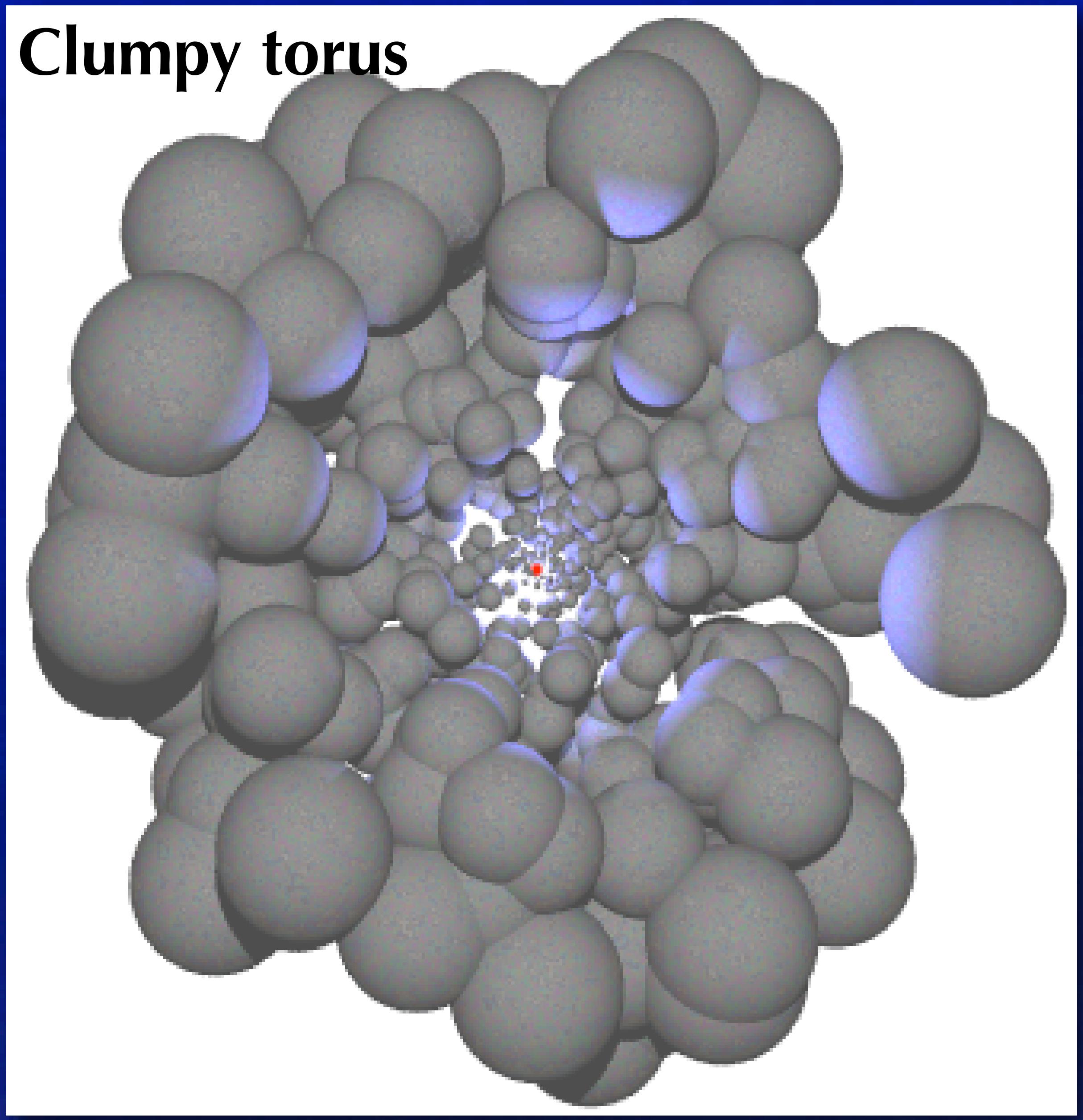
irregular/clumpy model



3. Models of the dust torus

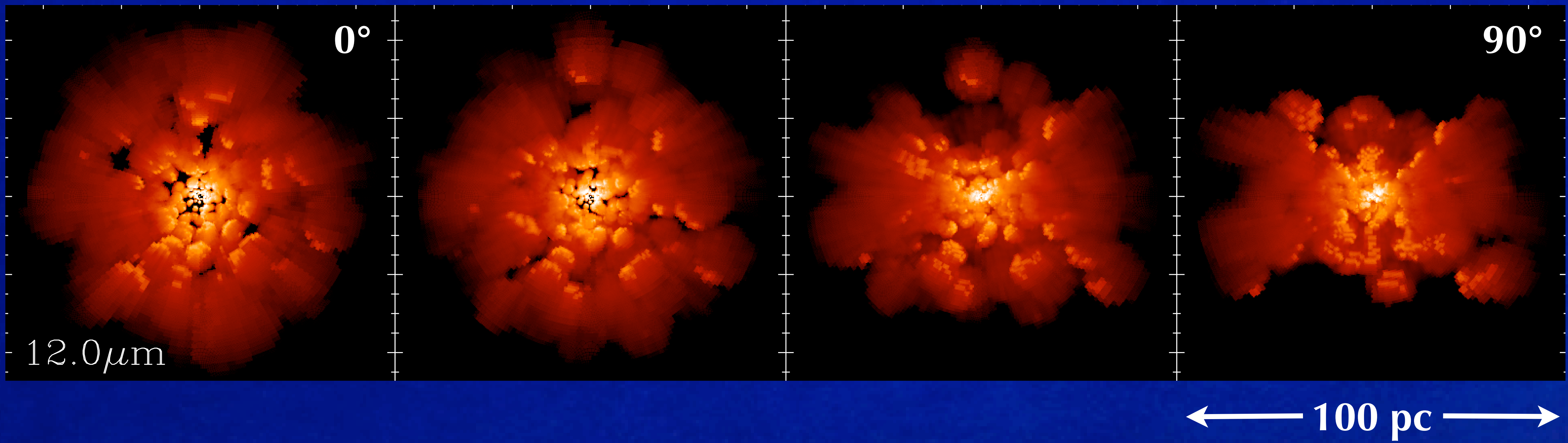
What do we see ? – Variations on Moshe's theme

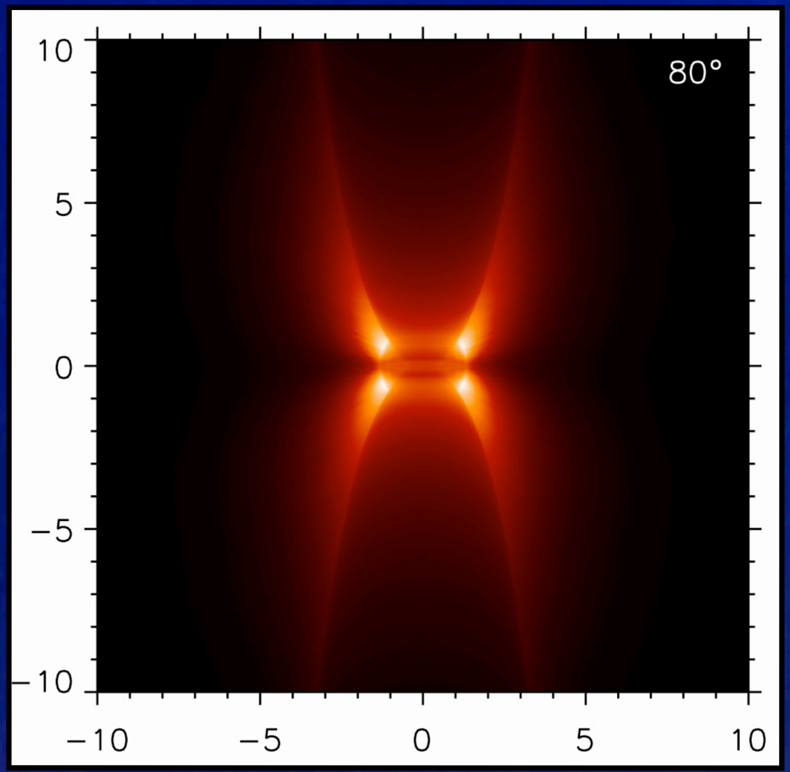




Nuclear dust in Seyfert galaxies

What do we see ? – Models of clumpy tori

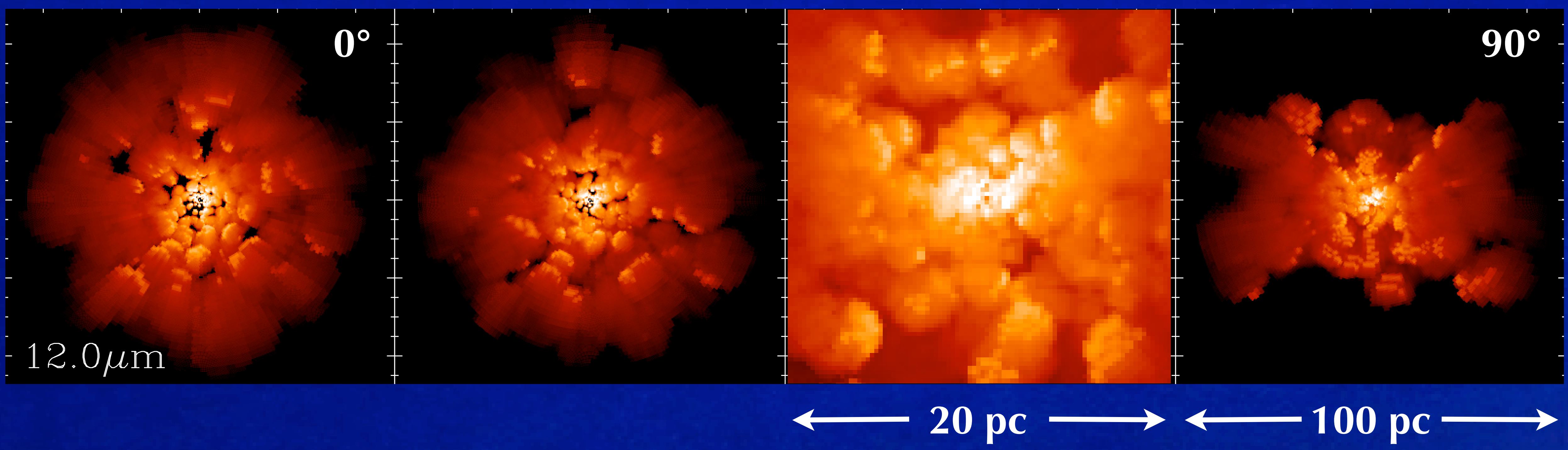


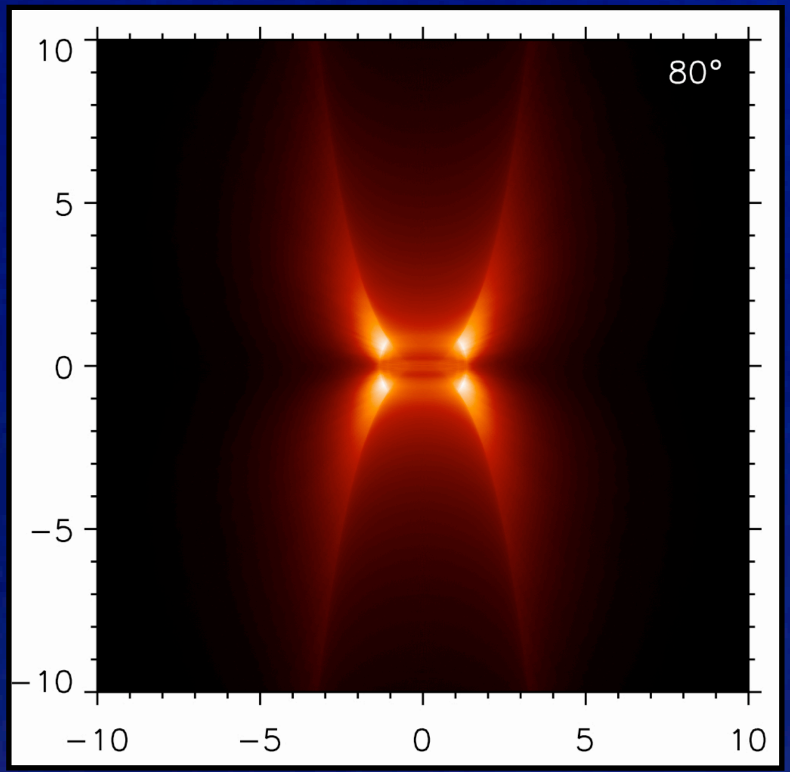


Marc Schartmann, K.M., Max Camenzind et al. 2007

Nuclear dust in Seyfert galaxies

What do we see ? – Models of clumpy tori

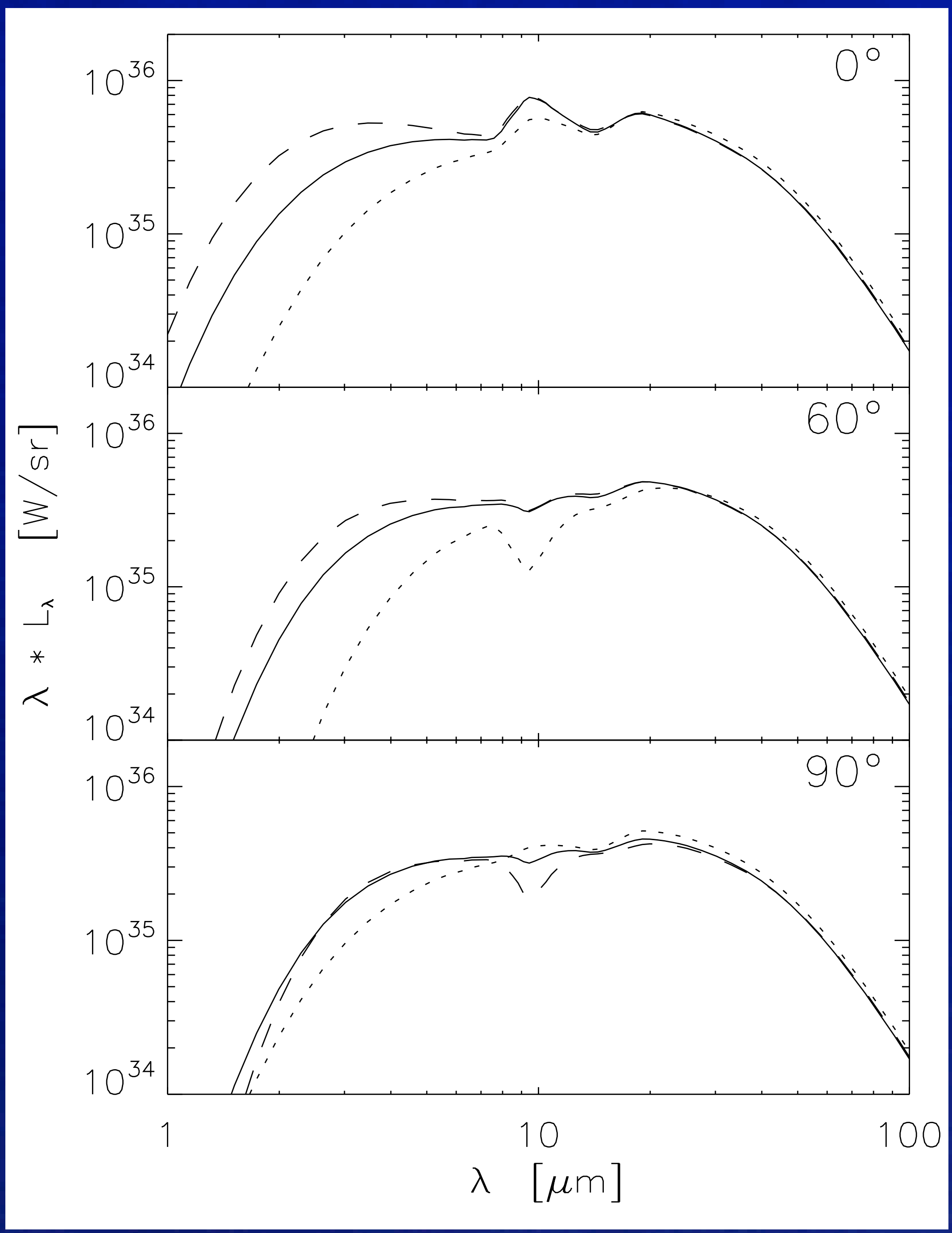


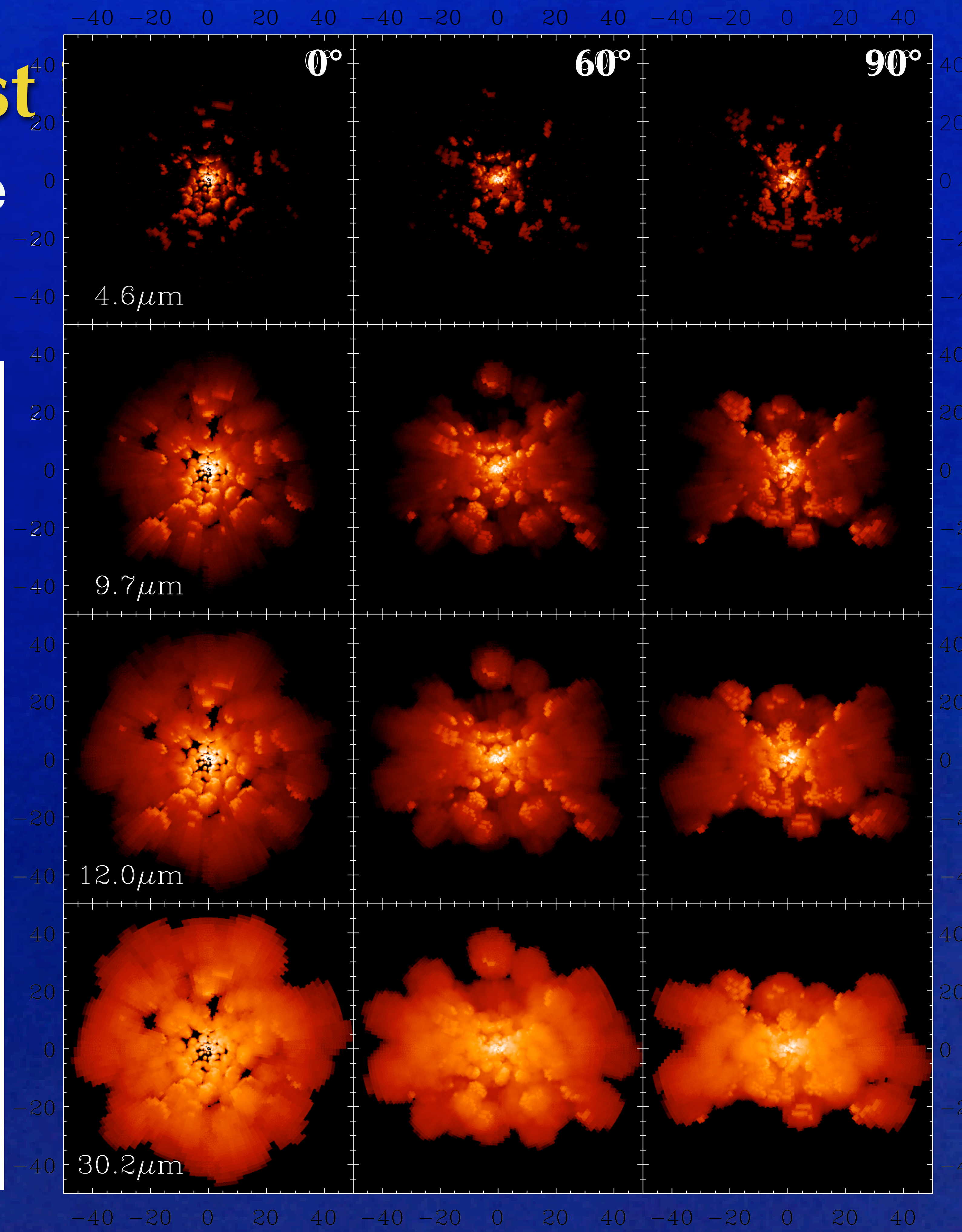


Marc Schartmann, K.M., Max Camenzind et al. 2007

Nuclear dust

Wavelength dependance





Nuclear dust in Seyfert galaxies

What do we see ?

Hydrodynamical Torus Models

Ingredients:

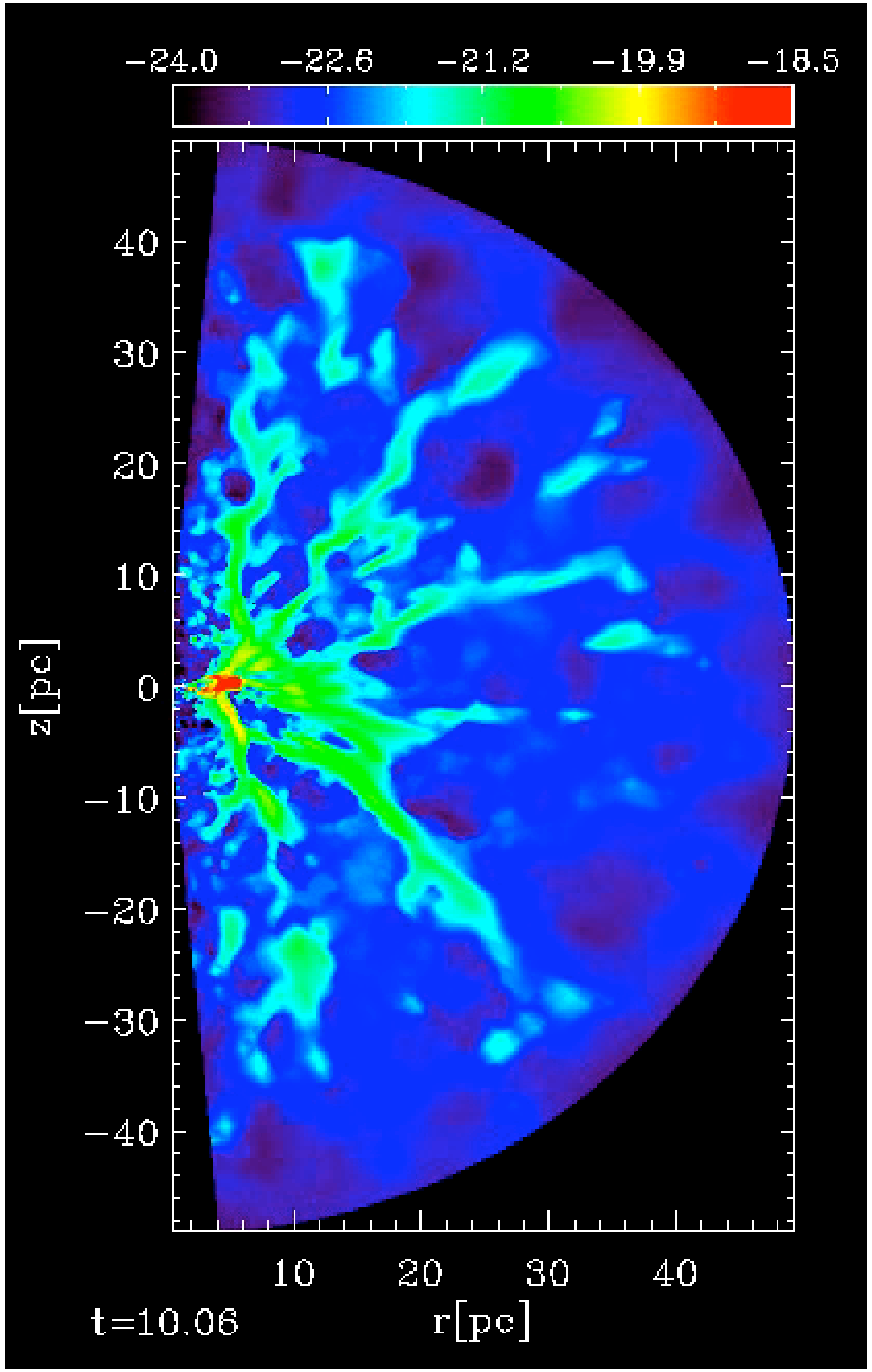
– black hole + star cluster potential

– young star cluster (> 40 Myrs)

– mass input: PNe

– energy input: SNe

– radiative cooling



unit time: 120 000 yrs = 1 orbit @ r = 5pc

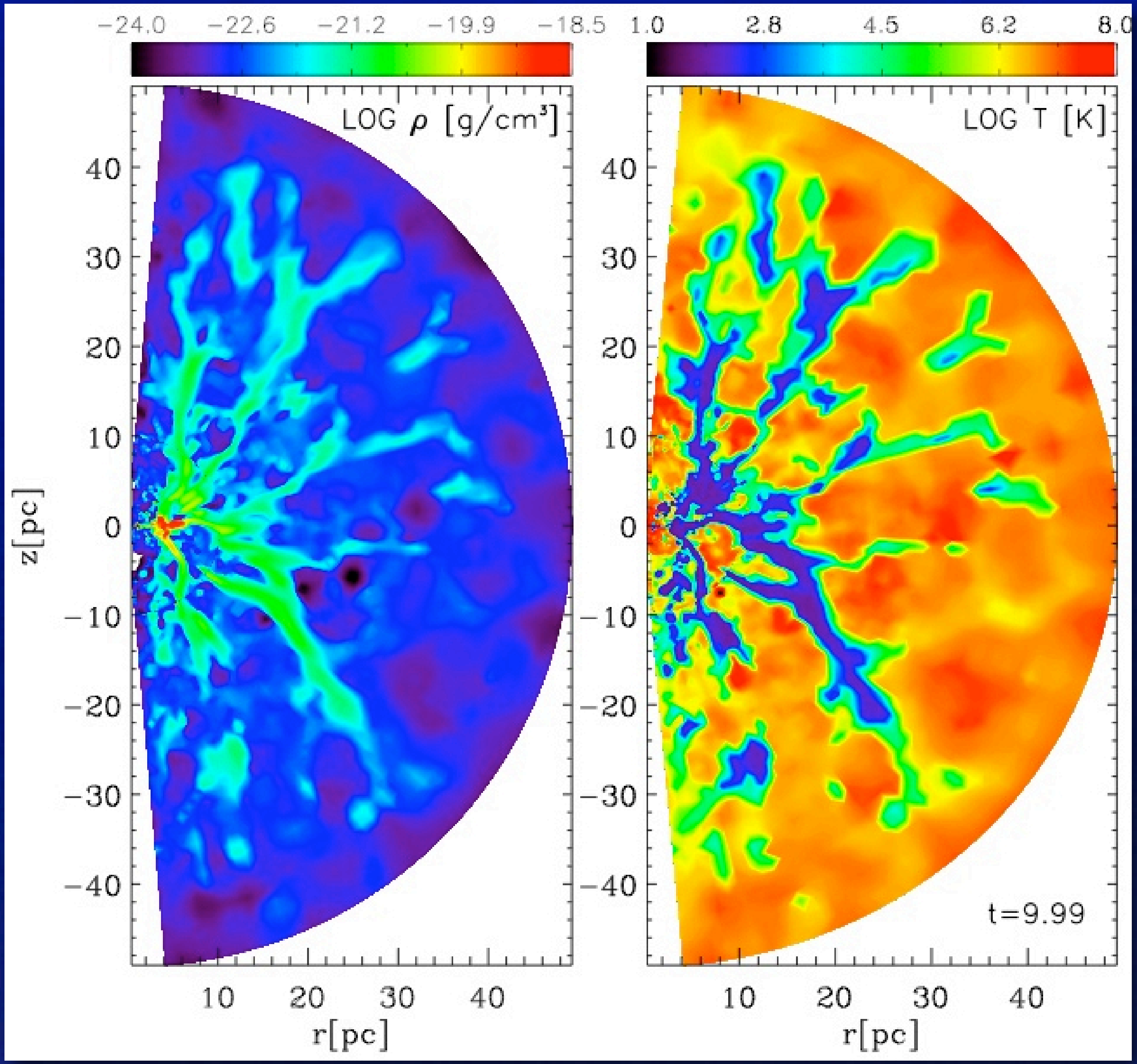
Nuclear dust in Seyfert galaxies

Hydrodynamical Torus Models

Marc Schartmann, KM, Max Camenzind, Hubert Klahr et al.

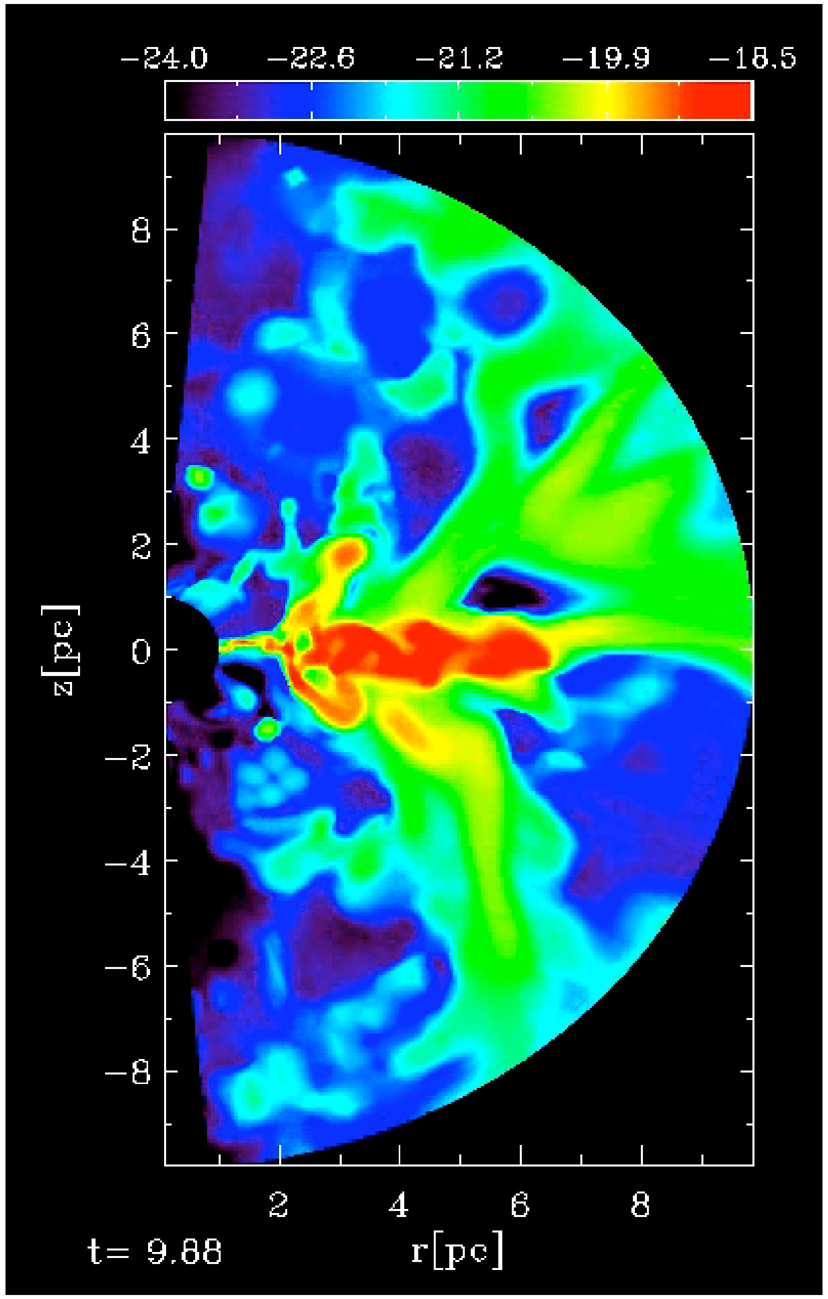
Density

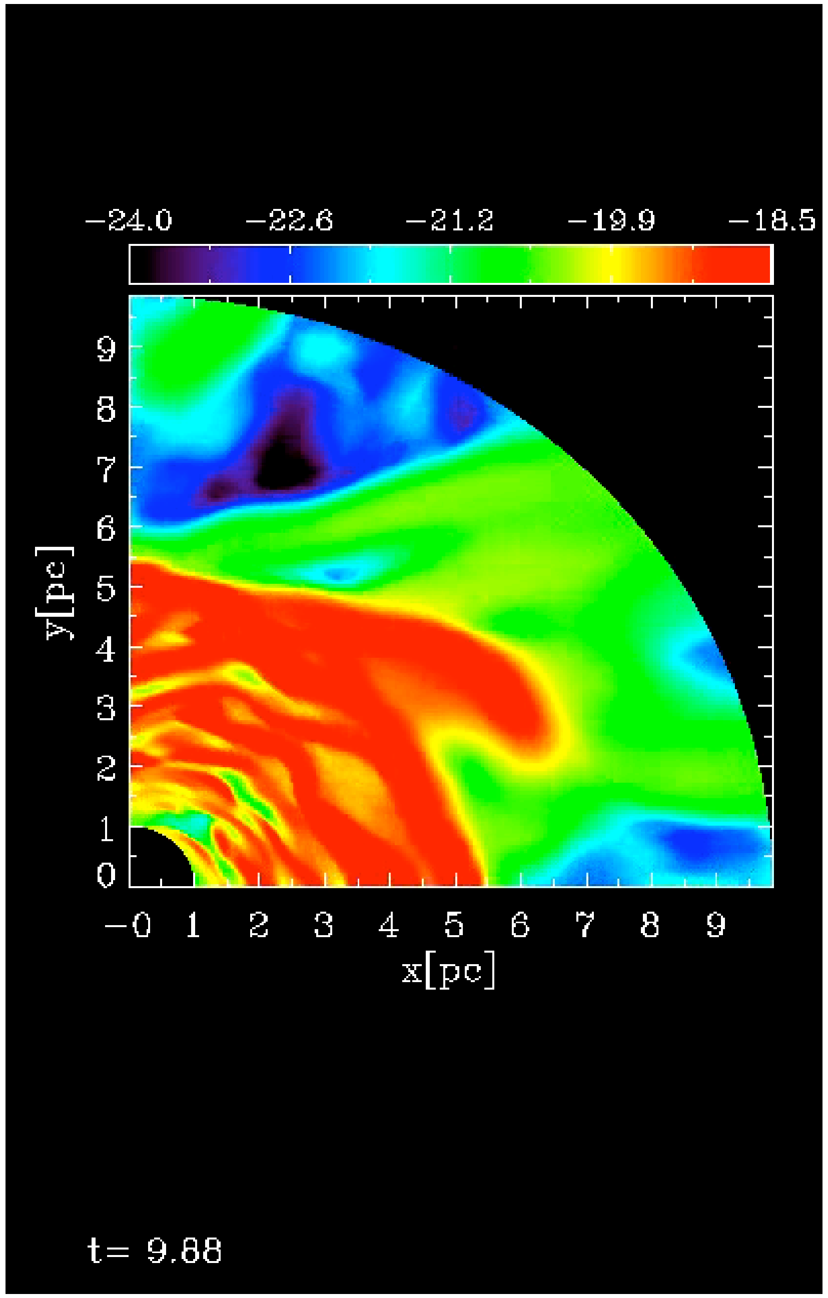
Temperature



Nuclear dust in Seyfert galaxies

Hydrodynamical Torus Models

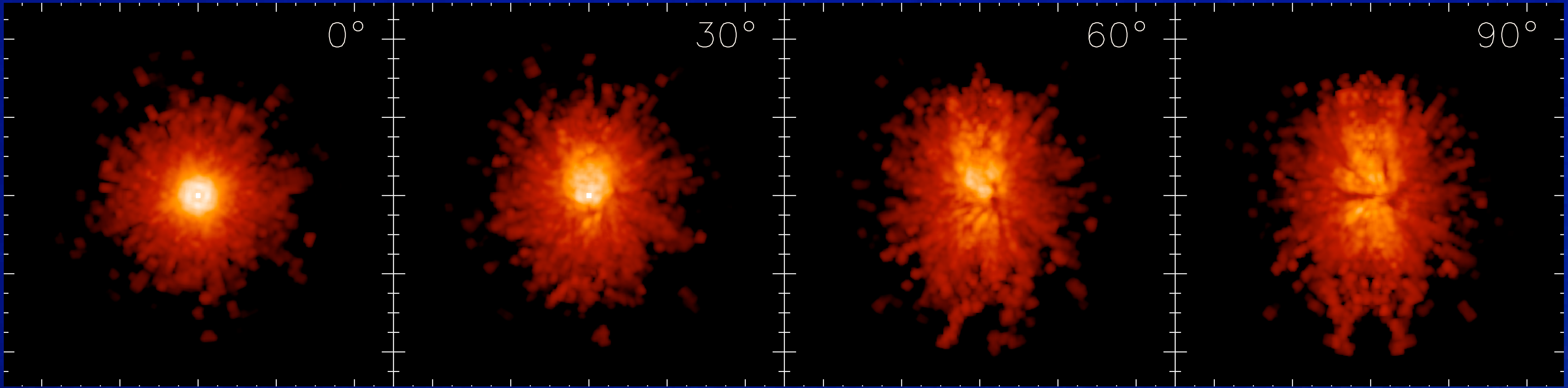




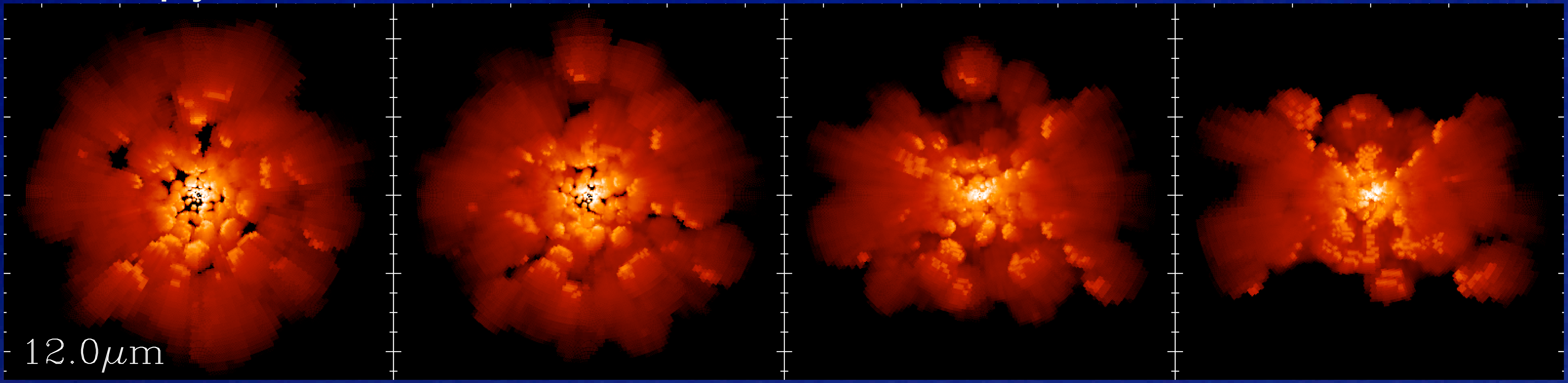
Nuclear dust in Seyfert galaxies

What do we see ? – Models of the torus

hydrodynamical torus model:



“clumpy” torus model:

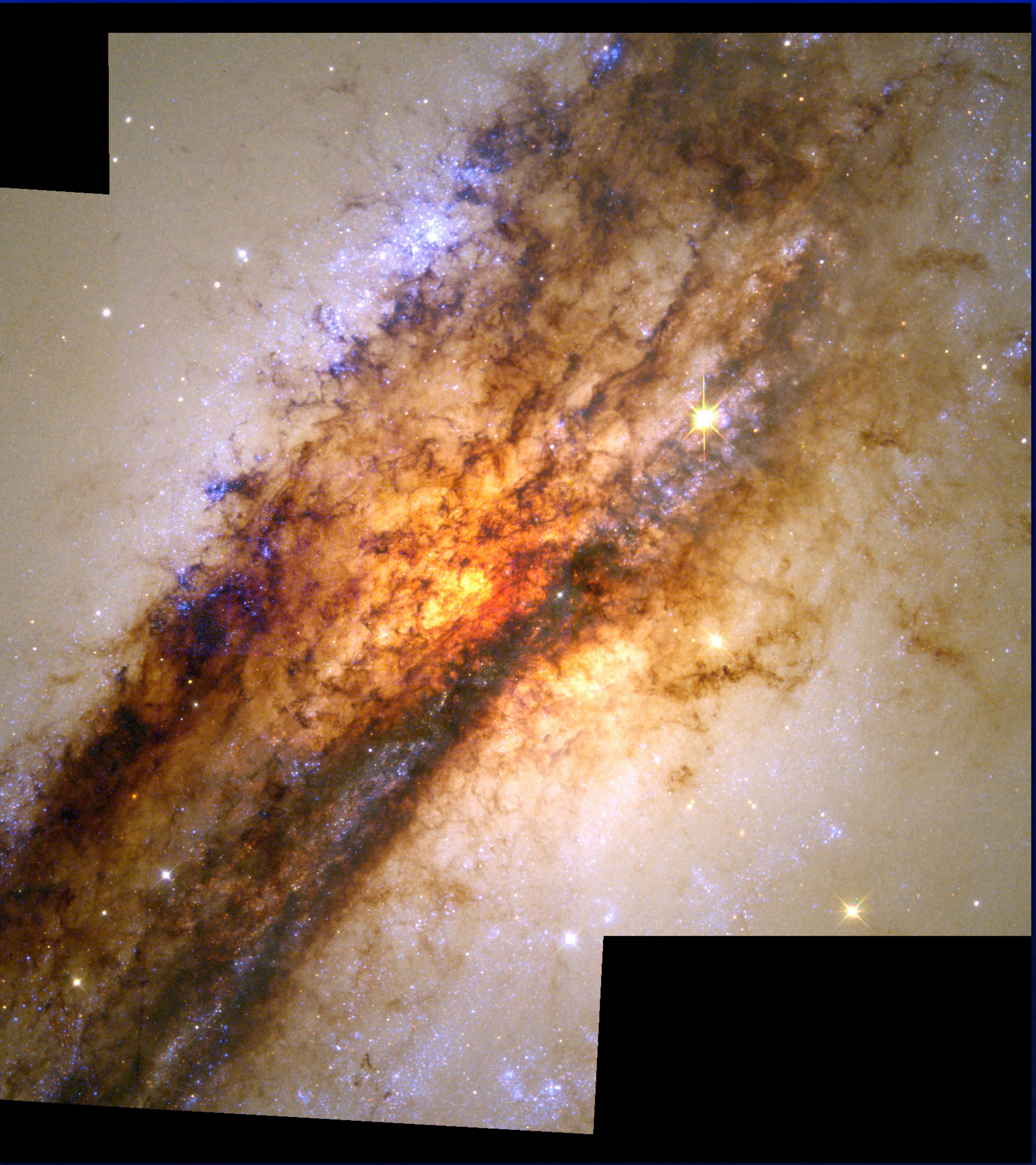


Dust Tori in Seyfert Galaxies

Conclusions

- VLTI + MIDI resolve pc-scale structures in nearby AGN.
- Seyfert 2 galaxies contain compact dust tori (d = 2... 10 pc).
- Hot inner dust (disk) and maser disk coincide.
- Torus models do already explain some of the structures.

The nucleus of Centaurus A



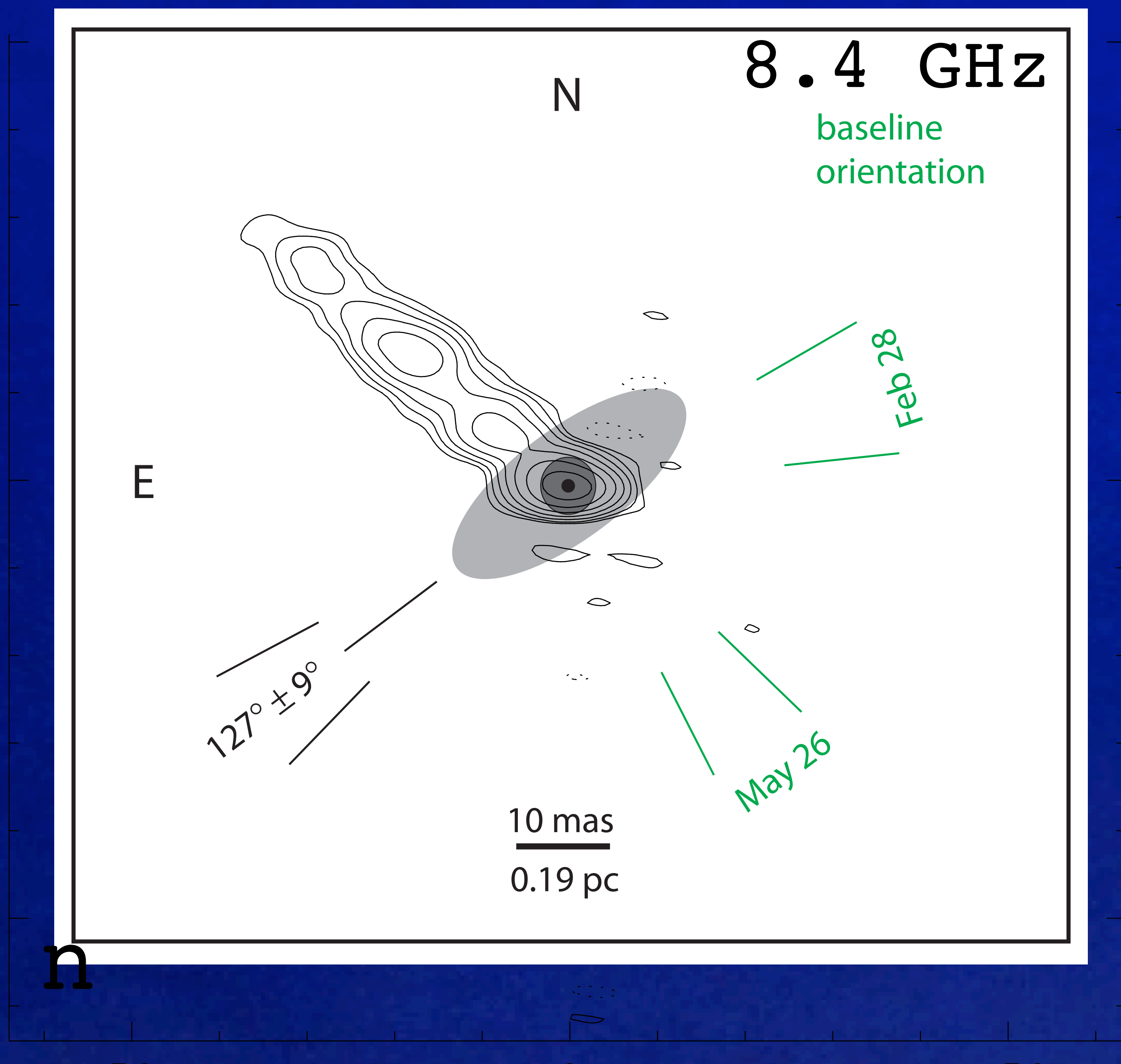
Centaurus A =

- The nearest merger (3.8 Mpc)
- The nearest radio galaxy
- Contains black hole of $M_{bh} = 7 \times 10^7 M_{sun}$

K.M., Konrad Tristram, Walter Jaffe et al. arXiv:0707.0177

MIDI - VLTI observations of Centaurus A

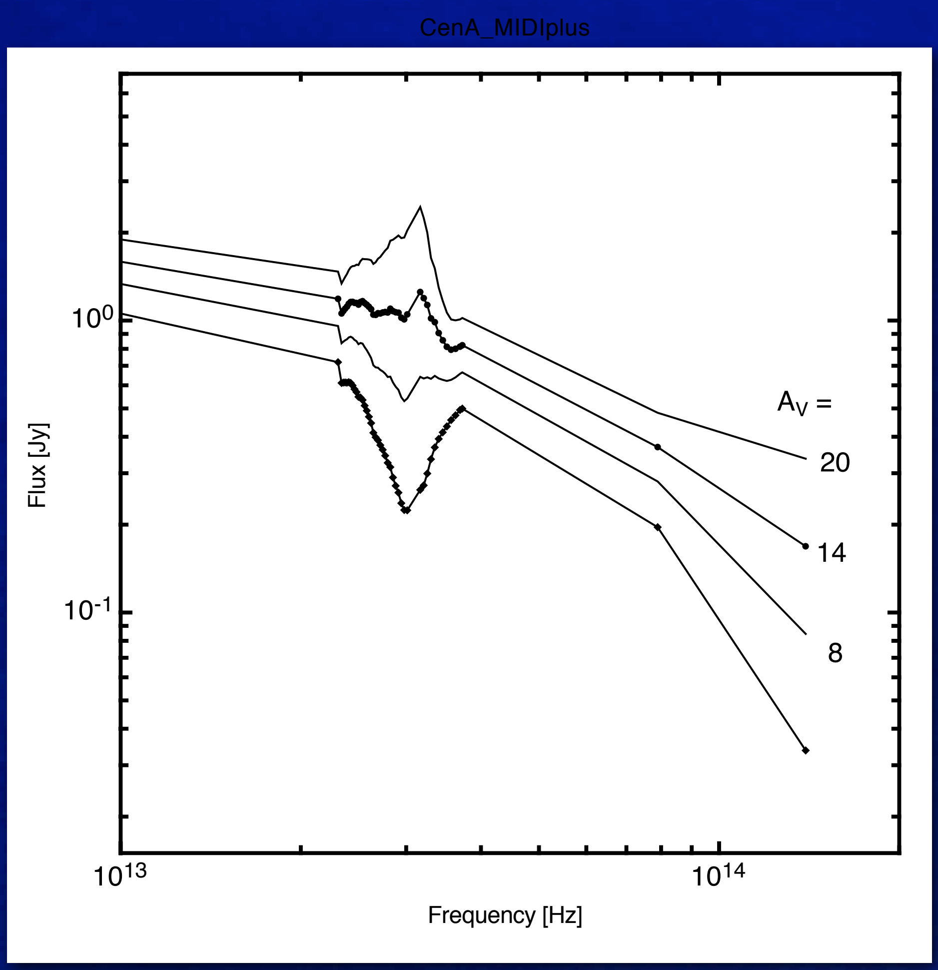
Basic result:

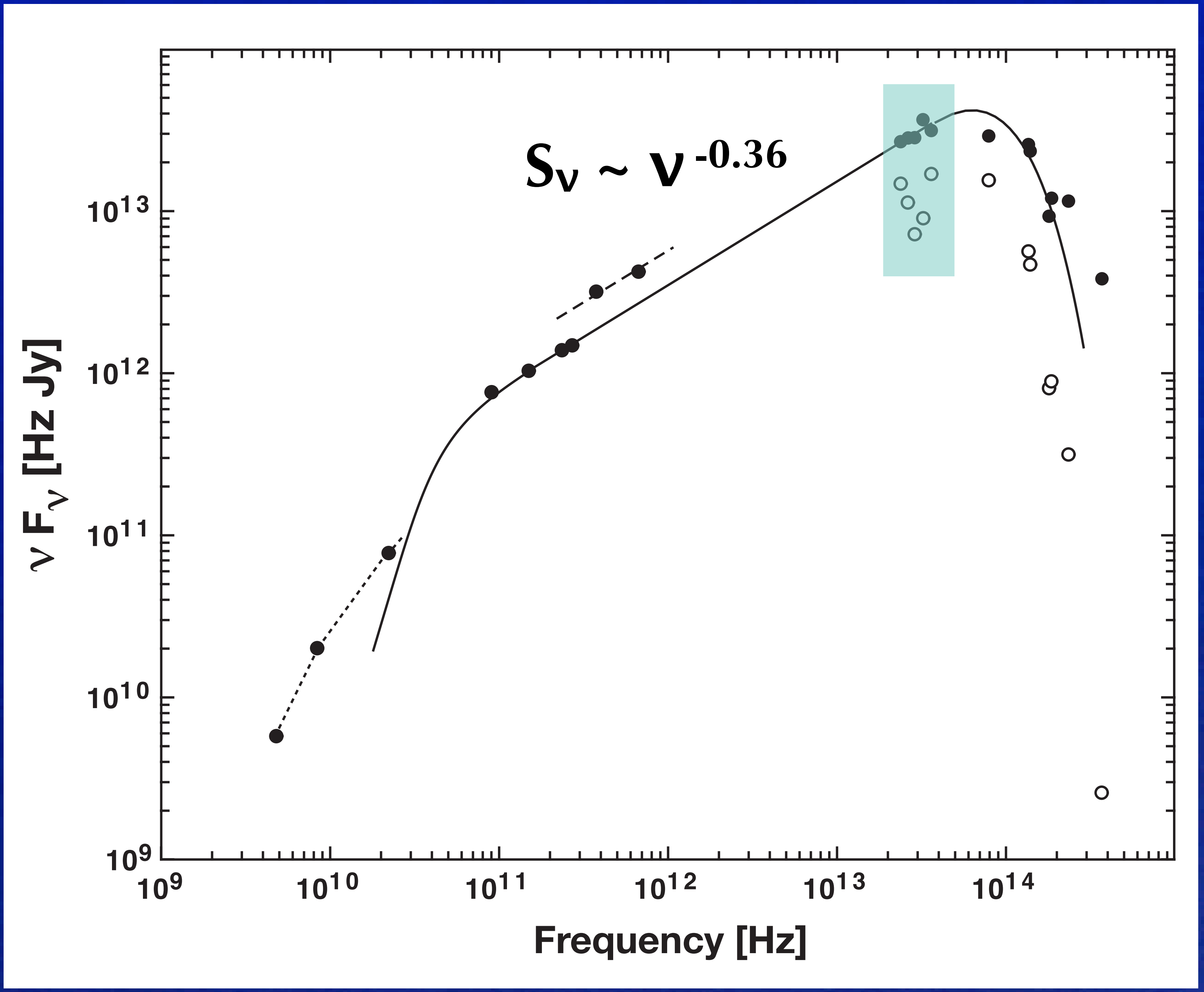


1. Unresolved **core:**
   80–60% of 8...13 μm flux
2. **Dust disk:** d ≃ 0.6 pc,

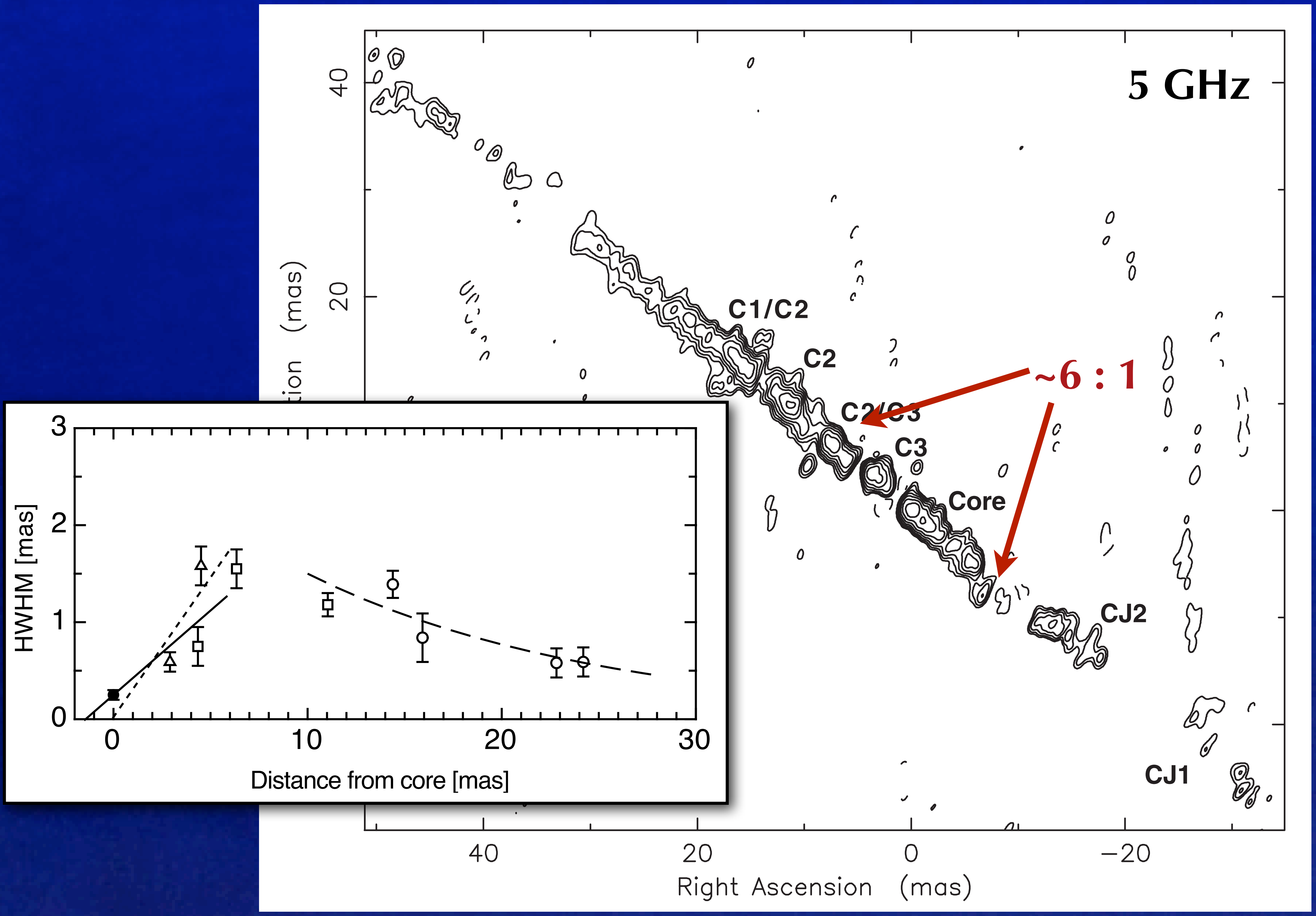
   b:a = 1:3 (i = 66° ?),
   T = 240 K

The core spectrum of Centaurus A

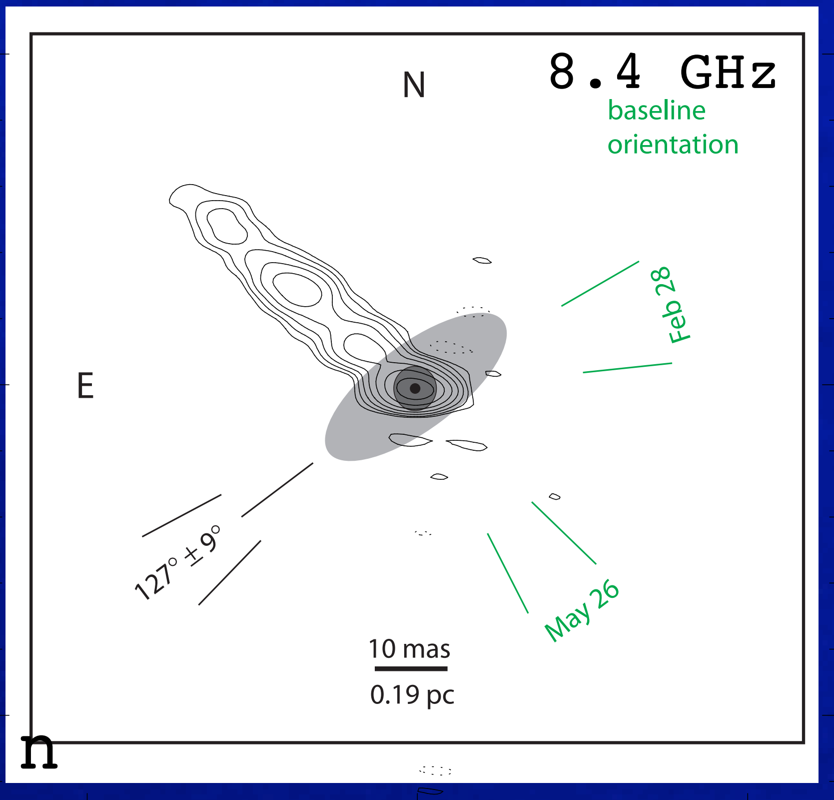


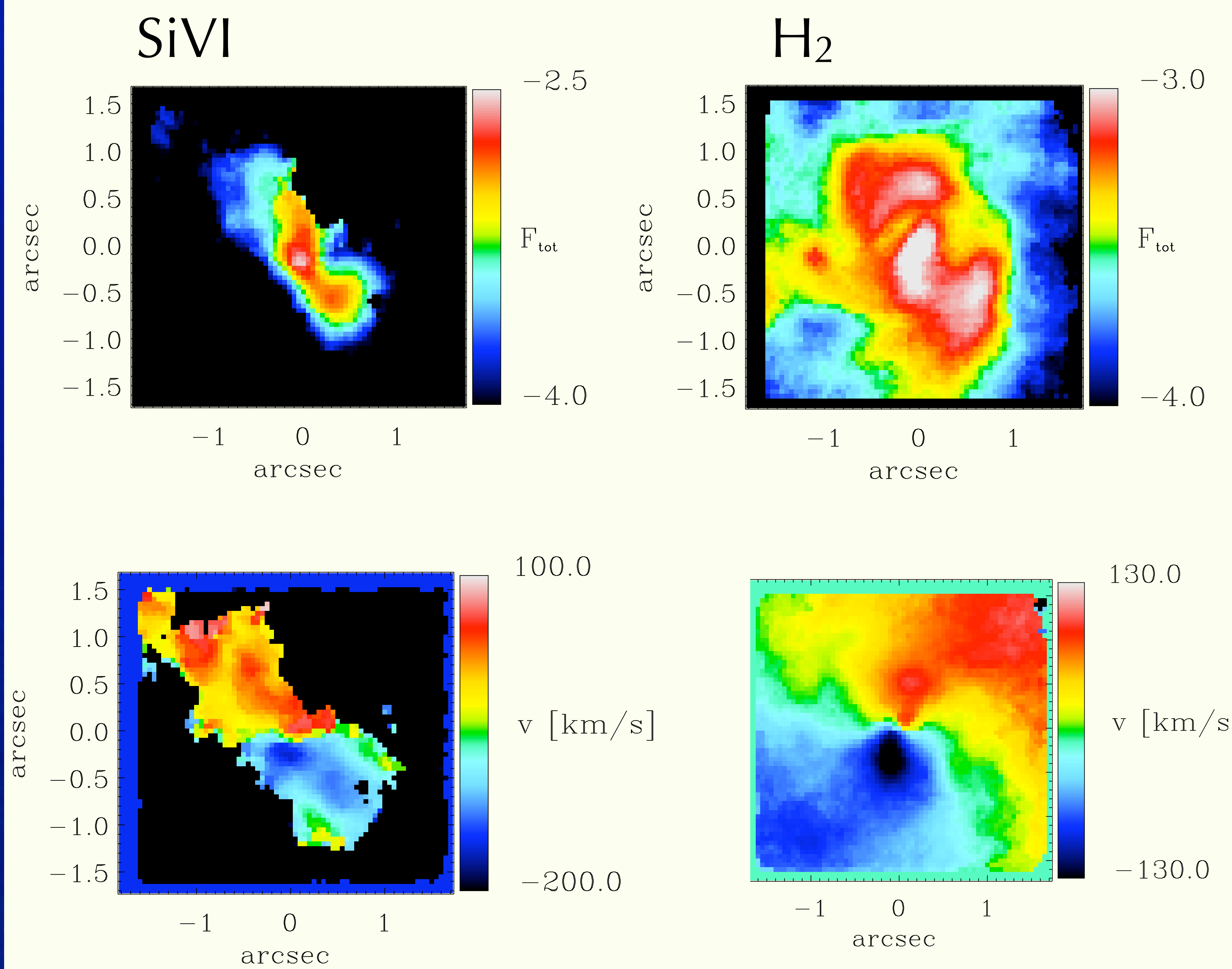


The VLBI Jet of Centaurus A



Circum-nuclear gas in Centaurus A





SINFONI observations (Nadine Neumayer)

$P_{dust} = 3x10^{34}$ W

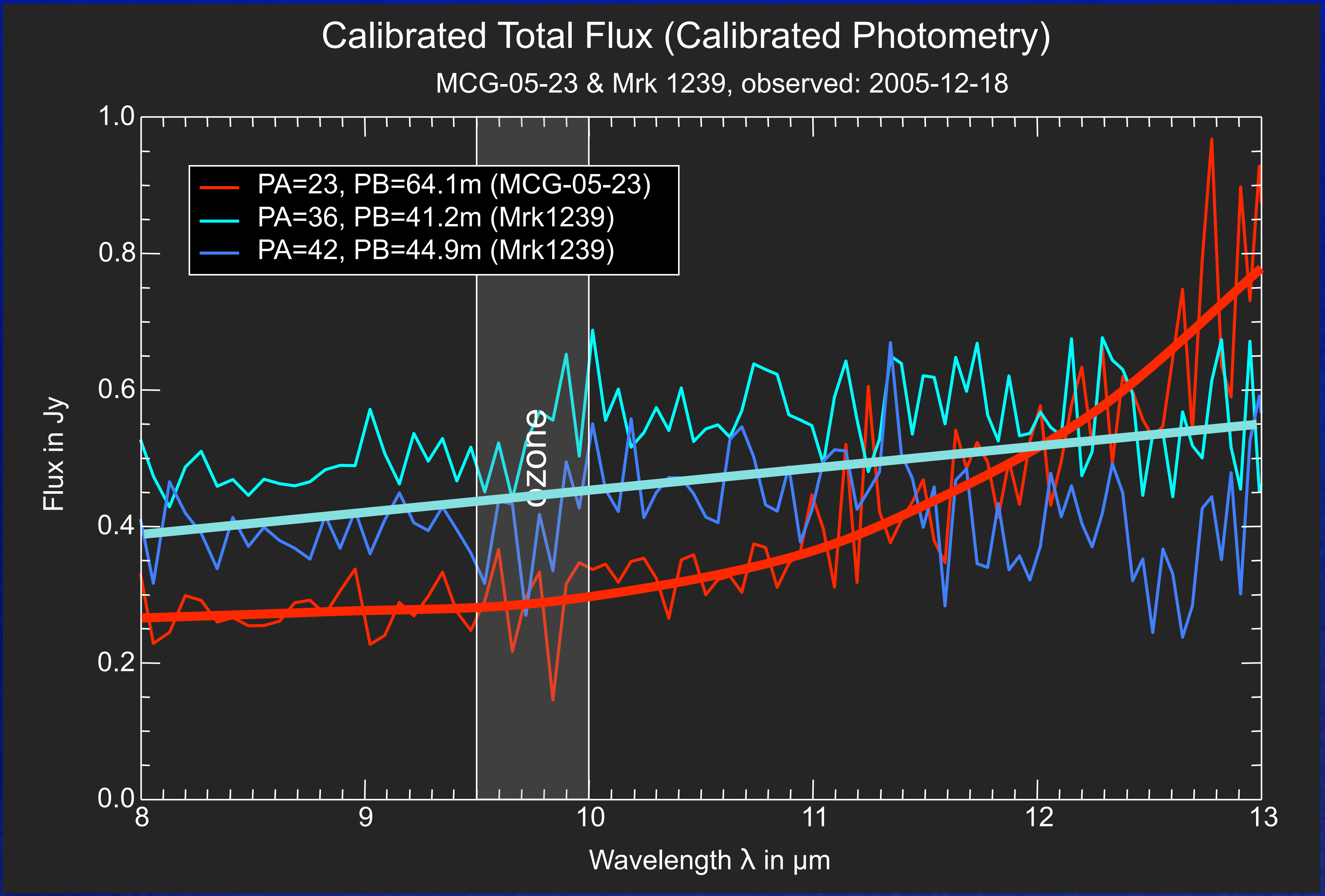
$P_{heat} > 10^{35}$

$P_{Xray} \simeq 2x10^{35}$ W

$= 0.0002\ P_{Edd}$

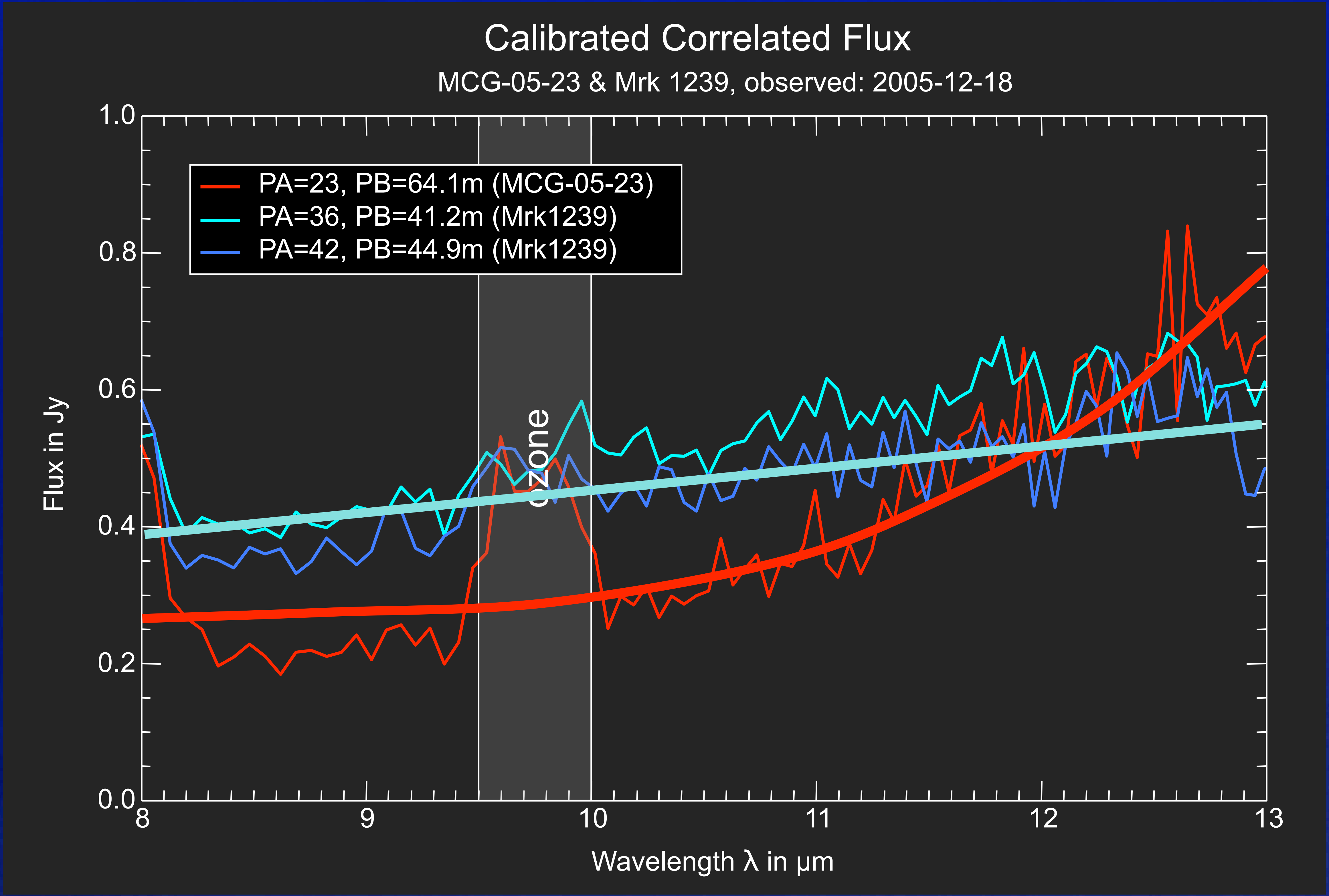
Outlook: more distant AGN

MCG-05-23 (Sy 2, D = 38 Mpc), Mrk 1239 (Sy 1, D = 92 Mpc)



Outlook: more distant AGN

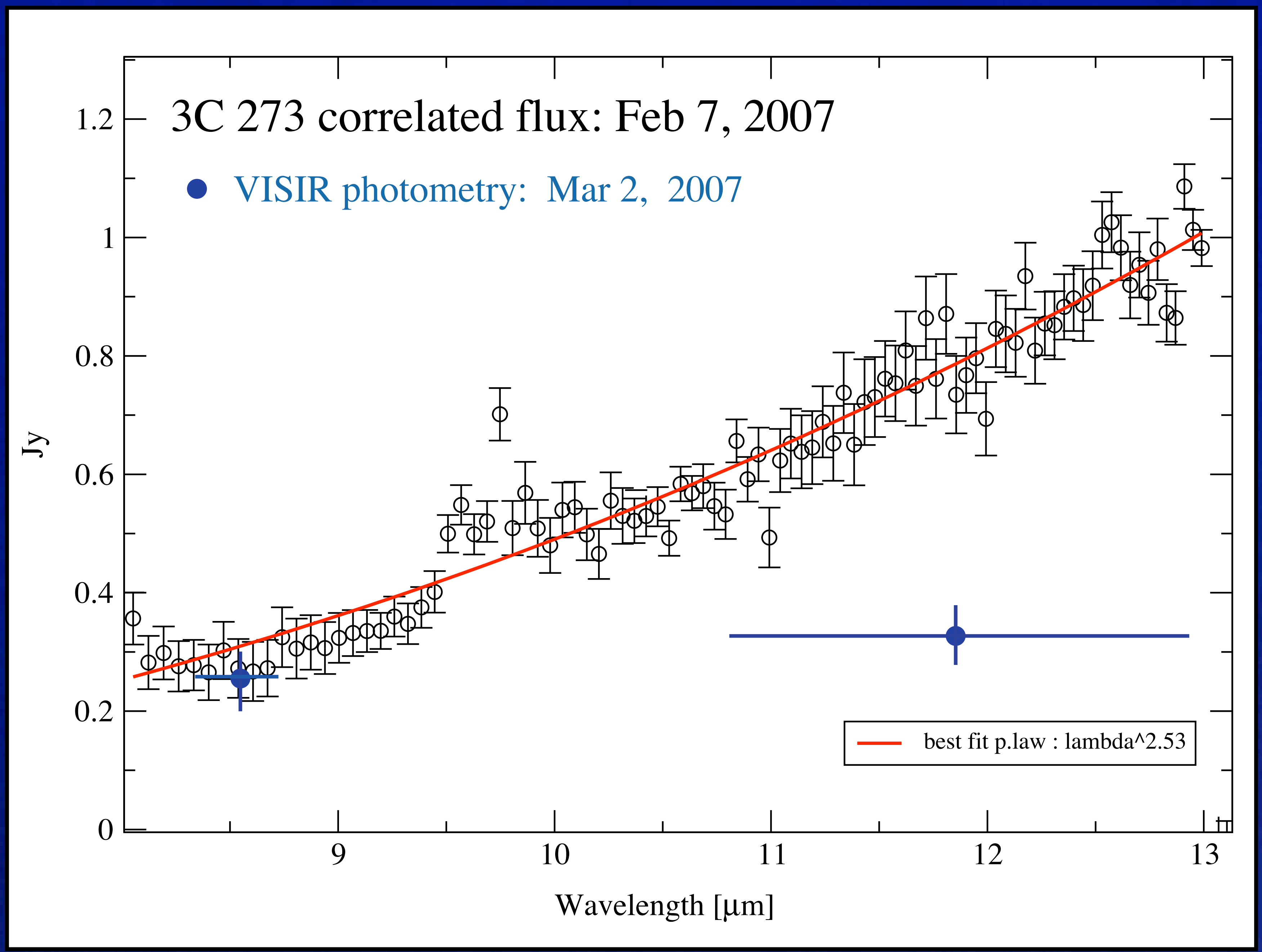
MCG-05-23 (Sy 2, D = 38 Mpc), Mrk 1239 (Sy 1, D = 92 Mpc)



Outlook: a very distant AGN !

MIDI observations of the quasar 3C 273

(z = 0.158, D_A = 550 Mpc)



Outlook: Next steps with MIDI & AMBER

Our immediate plans:

- Finish the investigation of the Circinus galaxy with MIDI → use baselines UT2–UT4 and UT1-UT3
- Extend the study of NGC 1068 → try to use the ATs for better uv coverage
- Resolve Centaurus A properly
- Get a proper measurement of 3C 273
- Try to observe the nearest Seyfert 1, NGC 4151 ($\delta = +40°$)
- Try to resolve more distant Seyfert 1s with longest baselines

David Raban, Walter Jaffe (Leiden)
Konrad Tristram, Leonard Burtscher, KM (Heidelberg)

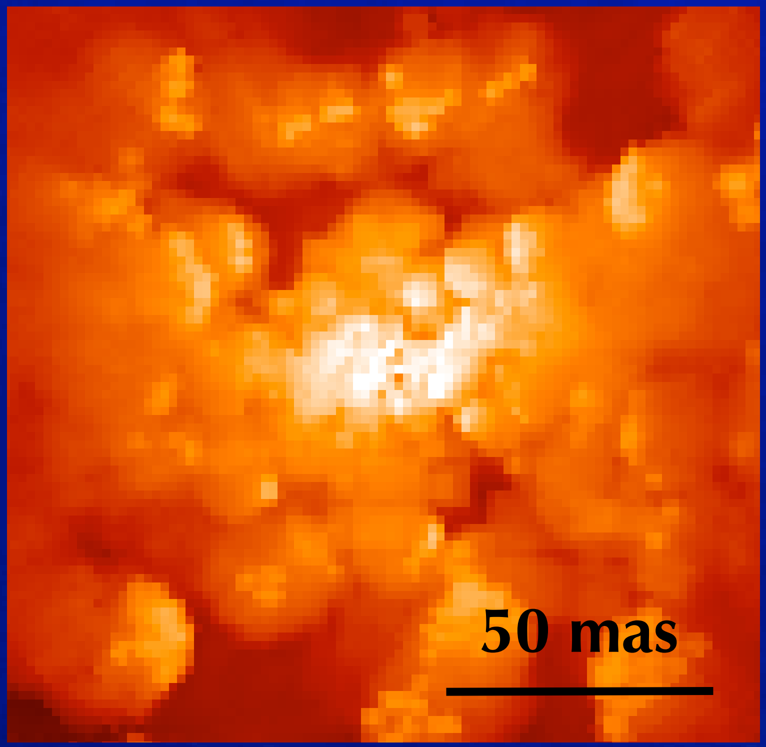
Outlook: Next steps with MIDI & AMBER

But a lot more can be done !

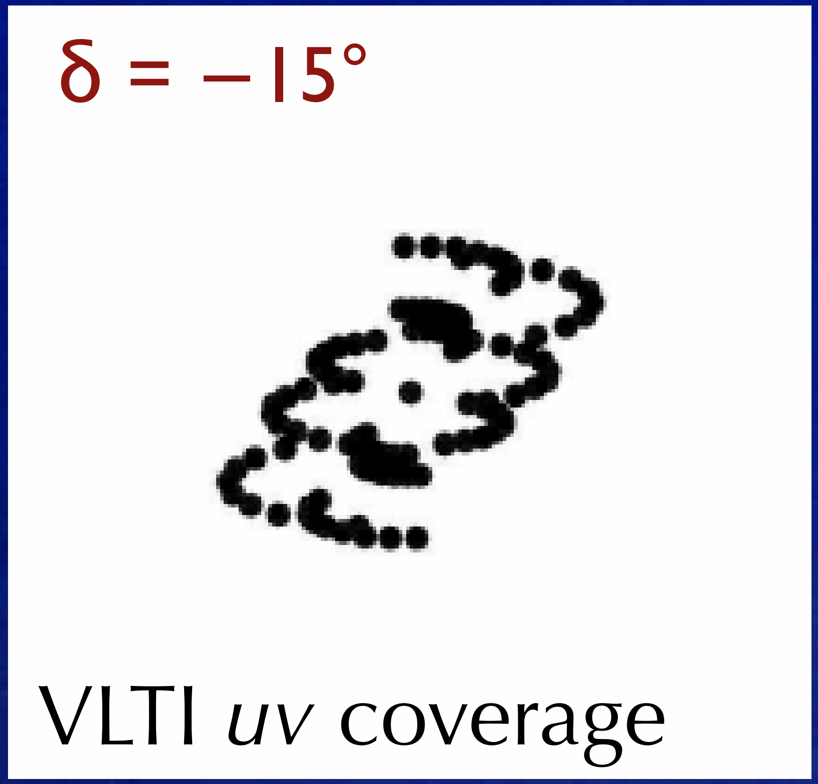
Name	α(J2000)	δ(J2000)	Type	z	Dist [Mpc]	Δ(1pc) [mas]	S_N(core) [mJy]	beam	Imme
NGC 1068	02 40 40.7	-00 00 48	S2	0.00379	17.4	11.9	3400	0″.2	torus,
✔ NGC 1365	03 33 36.4	-36 08 25	S1.8	0.00546	25.2	8.2	610	0″.5	torus,
? IRS 0518-25	05 21 01.7	-25 22 14	S2	0.0425	196.4	1.0	550	0″.5	size ?
MCG-5-23-16	09 47 40.2	-30 56 54	S2	0.00827	38.1	5.4	650	0″.5	size, o
Mrk 1239	09 52 19.1	-01 36 43	S1	0.0199	91.9	2.2	640	0″.5	size ?
NGC 3256	10 27 51.8	-43 54 09	HII	0.00913	42.1	4.9	550	0″.5	size ?
NGC 3281	10 31 52.1	-34 51 13	S2	0.01067	49.2	4.2	620	0″.5	size ?
NGC 3783	11 39 01.8	-37 44 19	S1	0.00973	44.9	4.6	590	0″.5	size ?
NGC 5128	13 25 27.6	-43 01 09	RG	0.00182	8.4	24.6	1220	0″.5	size, o
✔ IC 4329A	13 49 19.3	-30 18 34	S1	0.01605	74.0	2.8	350-500	0″.5	detect
Mrk 463	13 56 02.9	+18 22 19	S1	0.0504	232.3	0.9	340	0″.5	detect
Circinus	14 13 09.3	-65 20 21	S?	0.00145	6.6	31.3	9700	0″.5	size, t
? NGC 5506	14 13 15.0	-03 12 27	S2	0.00618	28.5	7.2	910	0″.5	size, o
✔ NGC 7469	23 03 15.6	+08 52 26	S1	0.01631	75.2	2.7	410	0″.5	detect
NGC 7582	23 18 23.5	-42 22 14	S2	0.00539	24.8	8.3	320	0″.5	detect
3C 273	12 29 06.7	+02 03 08	RQ	0.1583	731.0	0.3	350var	0″.5	detect
NGC 253 core	00 47 33.1	-25 17 17	LE	0.00080	3.6	57.3	380-1160	0″.5	detect

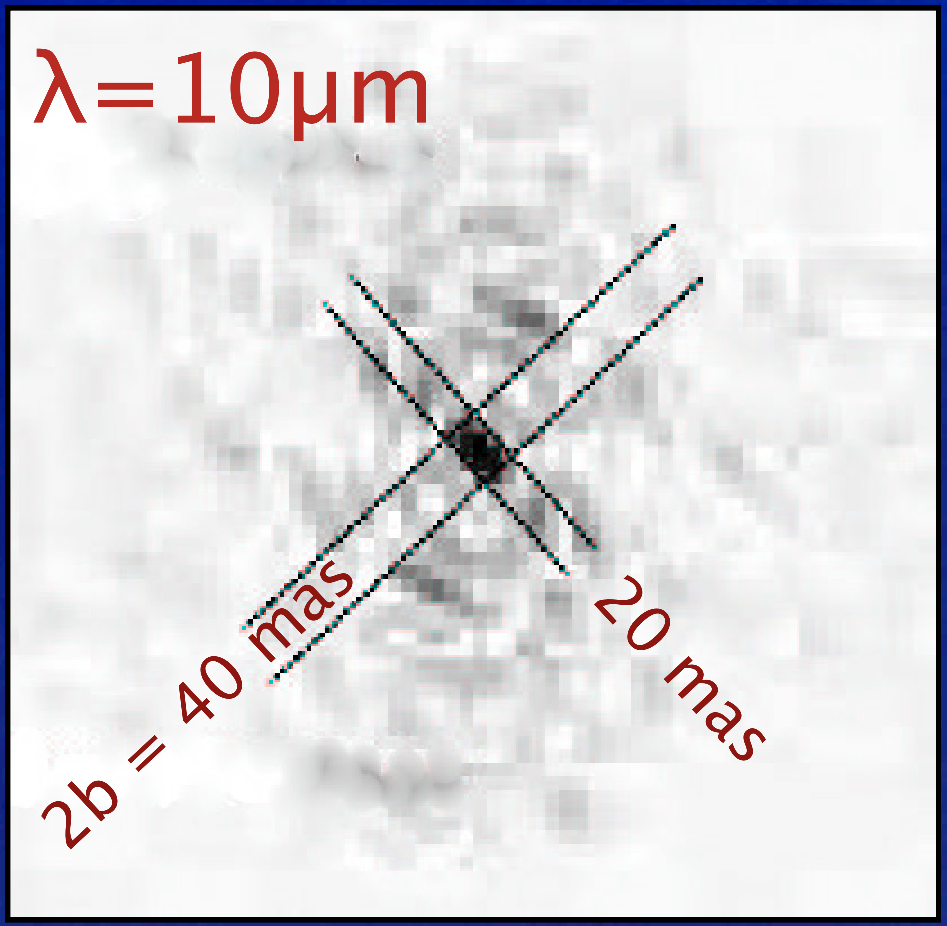
The Future: New instruments at the VLTI

PRIMA referenced imaging with MIDI & AMBER



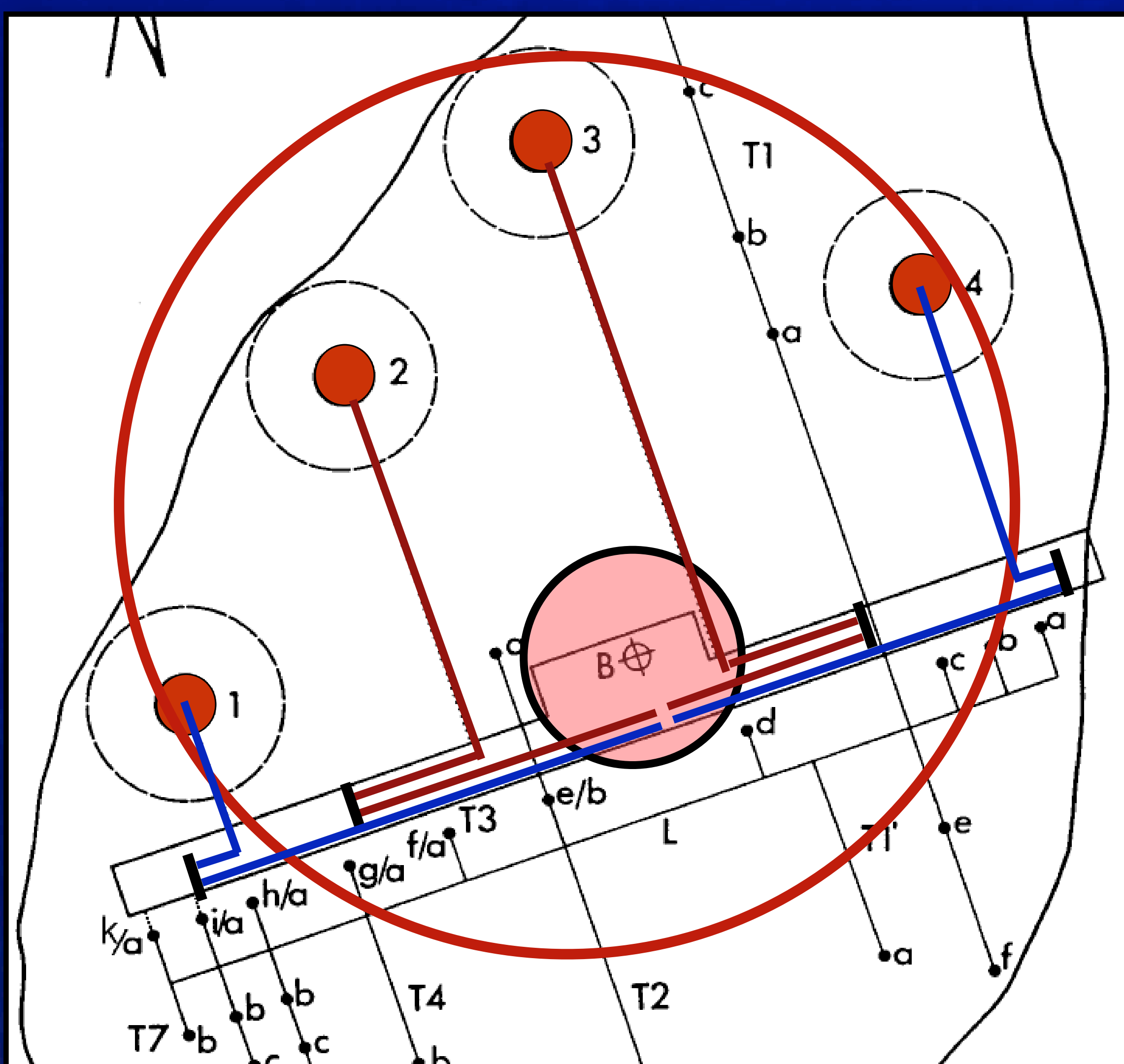
Imaging is needed !

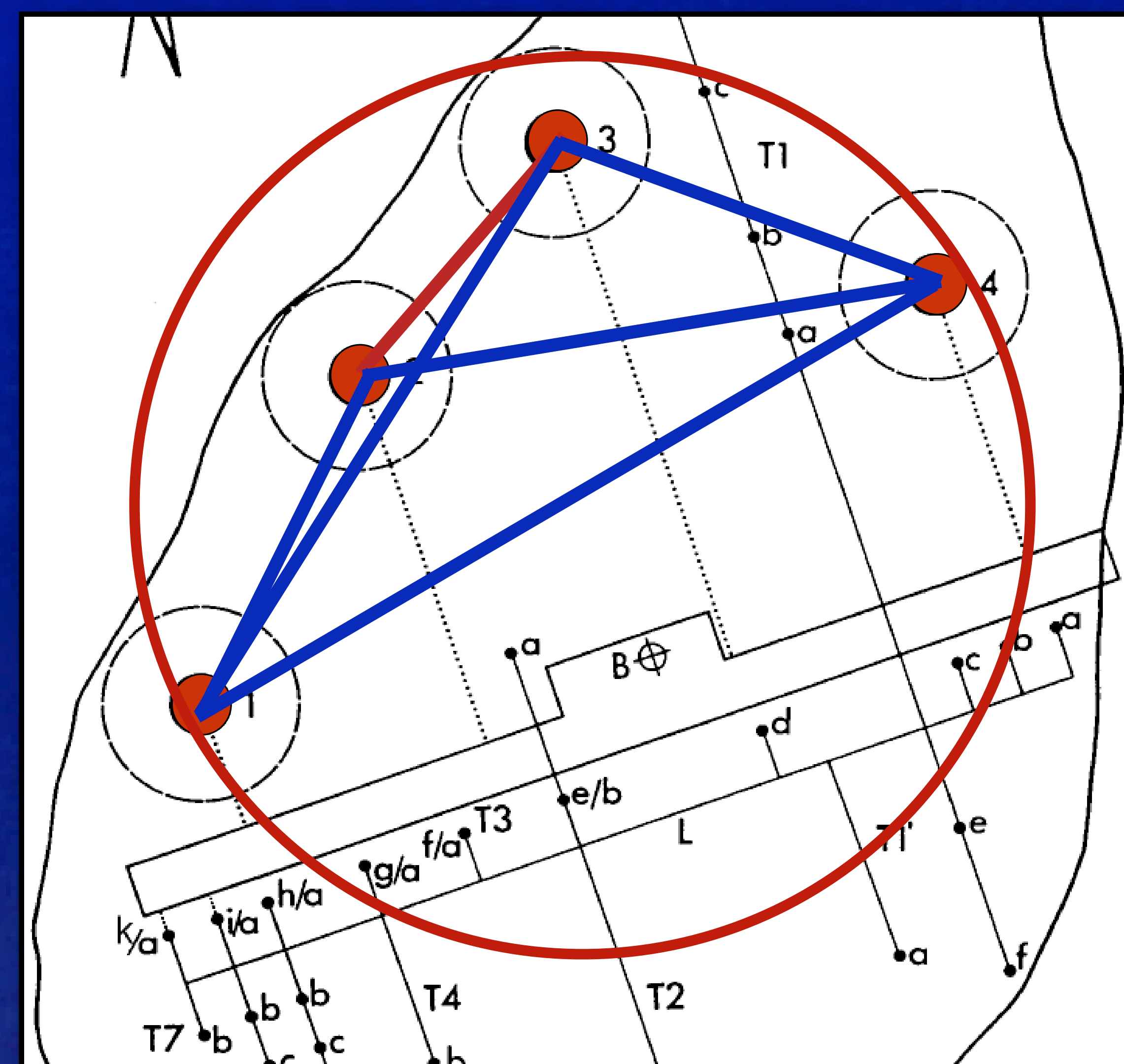




The Future: New instruments at the VLTI

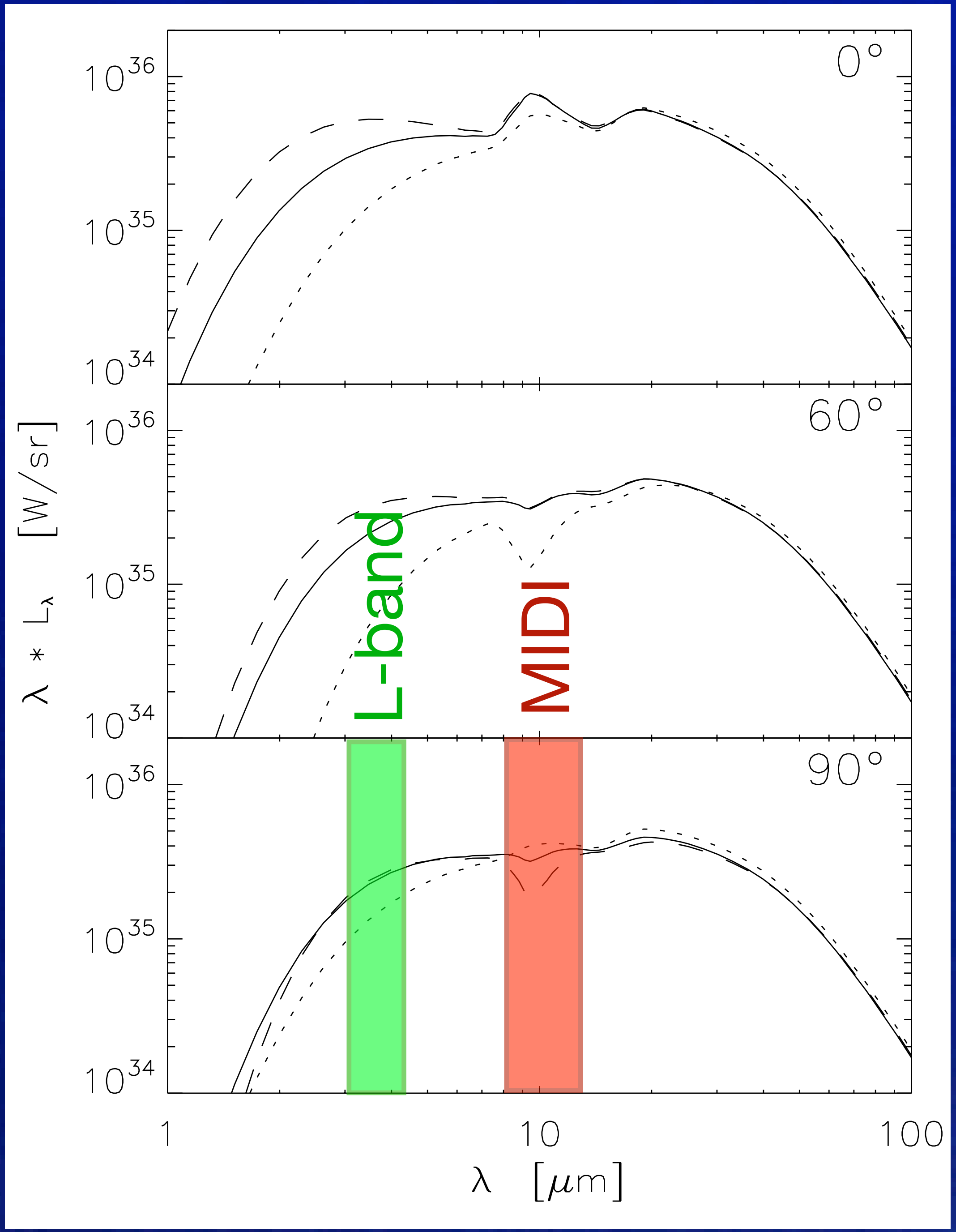
MATISSE





The Future: New instruments at the VLTI

MATISSE



MATISSE will allow to observe at 10 µm (as MIDI) and in L-band (3.6 µm)

This will give:

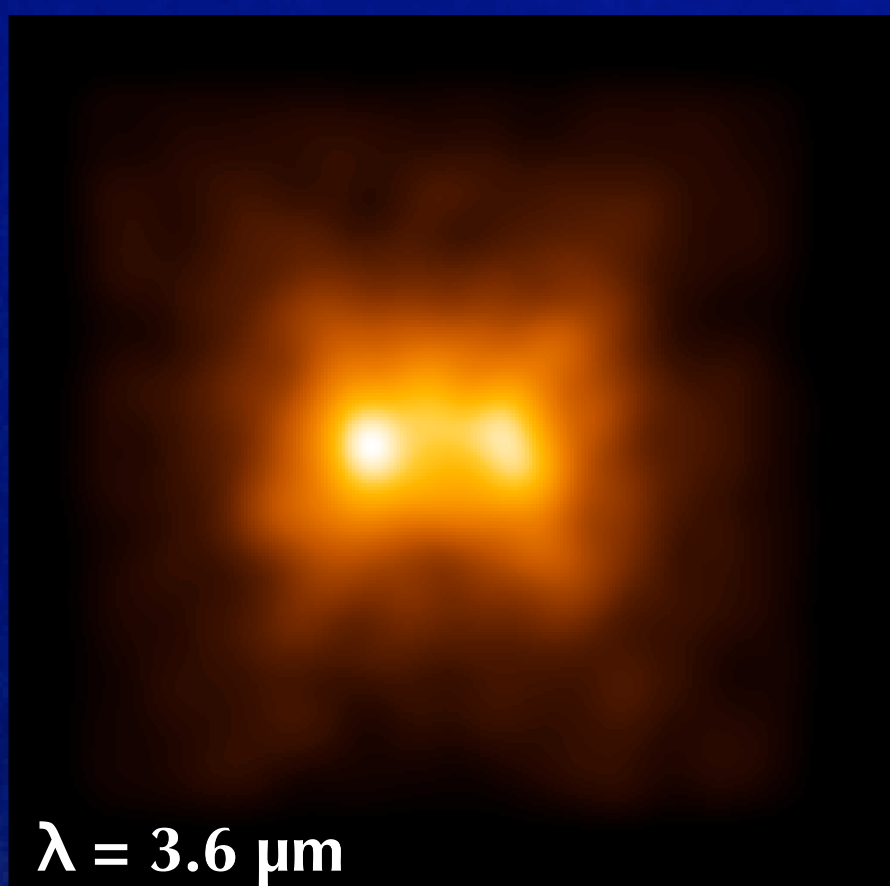
- **3x better resolution,**
- **much better temperature measurements,**
- **higher sensitivity = more AGN**

The Future: New instruments at the VLTI

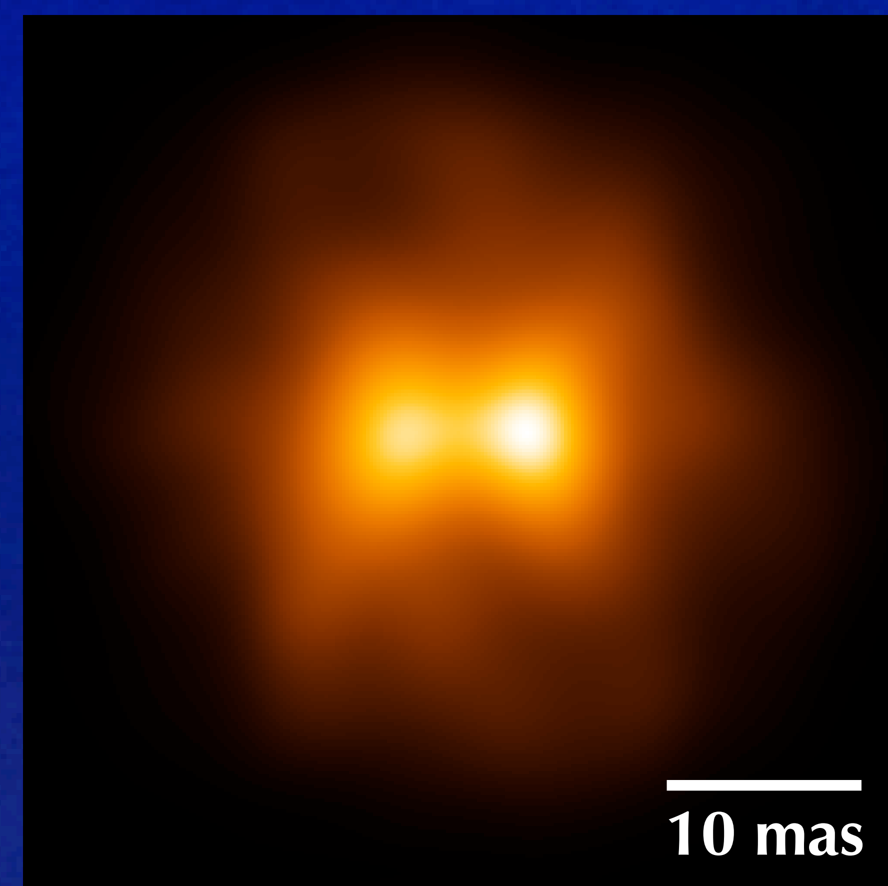
MATISSE

Image reconstruction

Input image:



Reconstructed image:



from K.-H.Hofmann, MPIfR

Studies of Active Galactic Nuclei

with the VLT Interferometer

Summary

- Currently, MIDI @ VLTI allow us to study the dust distribution in Seyfert galaxies with 15 mas (~ 1pc) resolution.
- We see fine structure (disks, clumpiness) !
- No Seyfert 1 galaxy has been resolved yet – so we still have to test the unification scheme: longer baselines !
- Models for this dust distribution ("torus") are rapidly evolving and are able to guide the observations.
- The next generation of IMAGING instruments at the VLTI will give a much clearer view.