Resolving the dust structures in AGNs using thermal-infrared Interferometry

Leo Burtscher, Konrad Tristram, Klaus Meisenheimer, Walter Jaffe, Noel Lopez Gonzaga, **Violeta Gámez Rosas, Jacob Isbell**, Ric Davies, Sebastian Hönig, Makoto Kishimoto, Jörg-Uwe Pott, Huub Röttgering, Marc Schartmann, Gerd Weigelt et al.

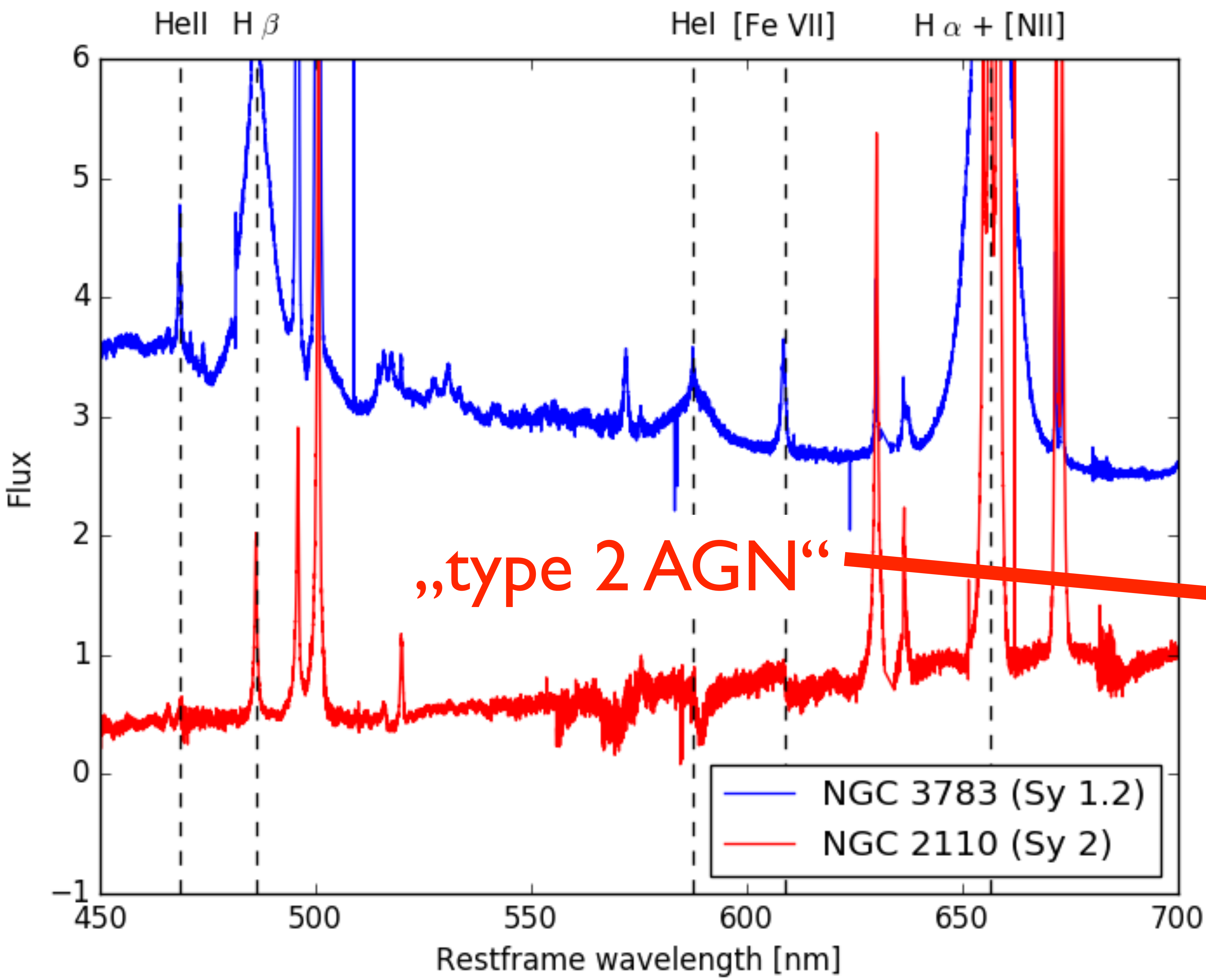
see their talks at this conference!

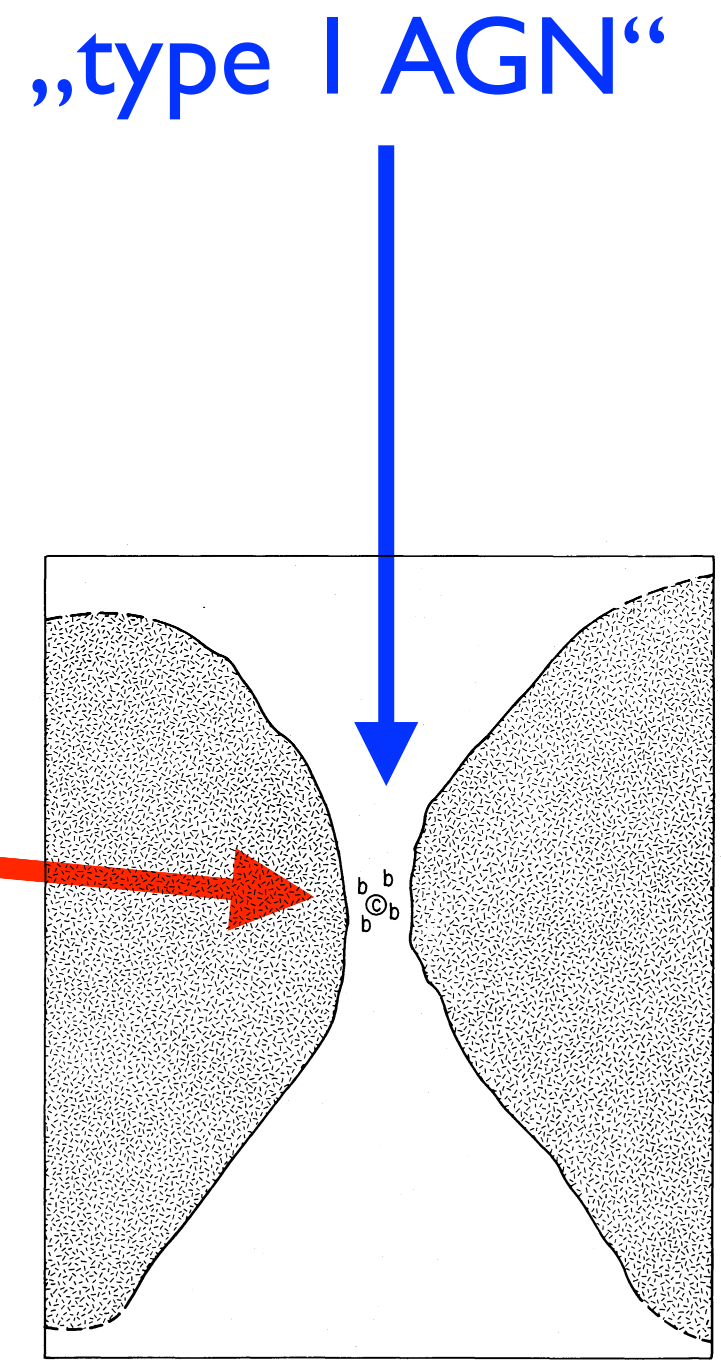
IR 2020
14 Oct 2020

Universiteit Leiden

The „torus“: originally invented to explain type 1/2 dichotomy

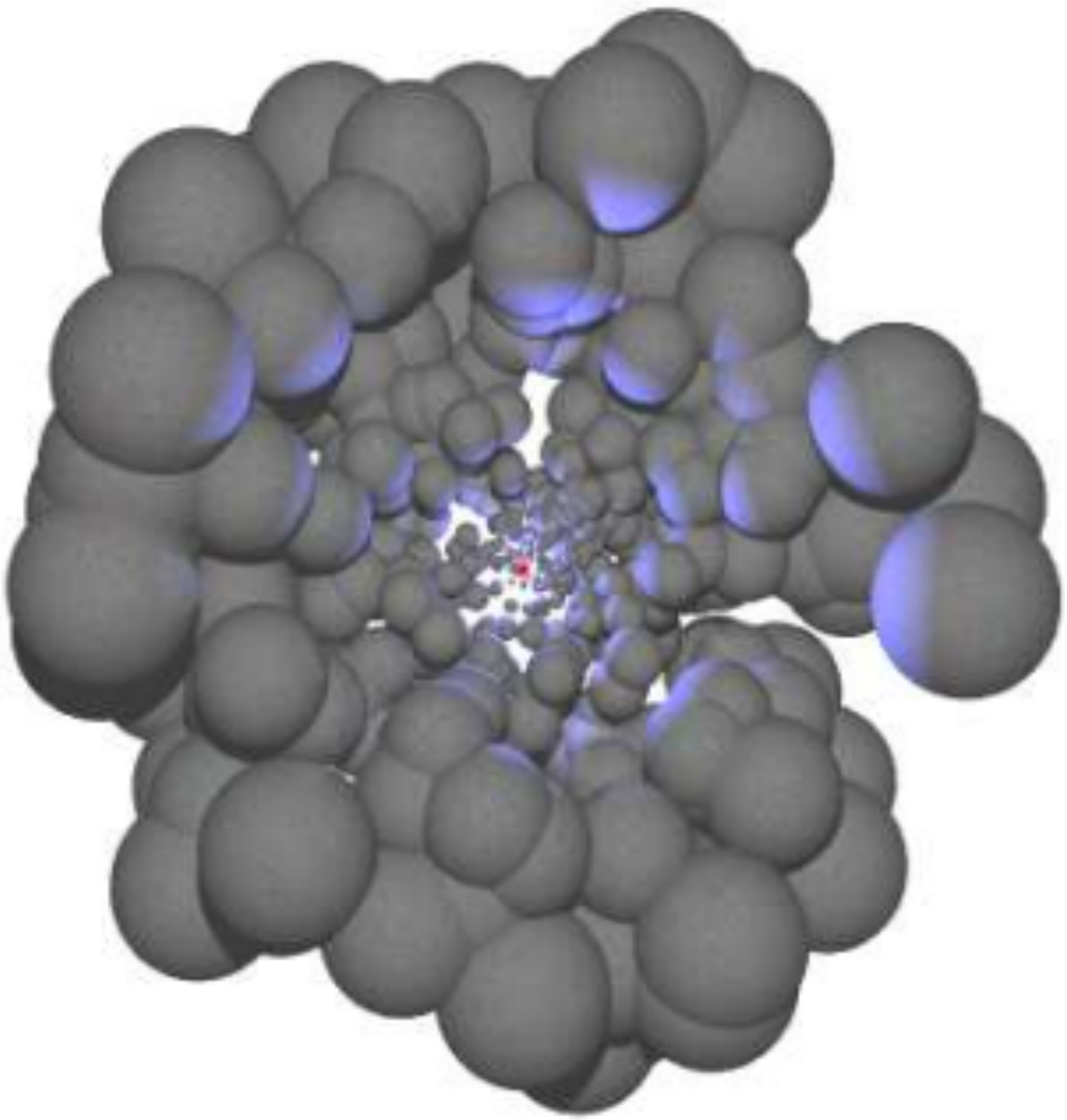
The Seyfert dichotomy



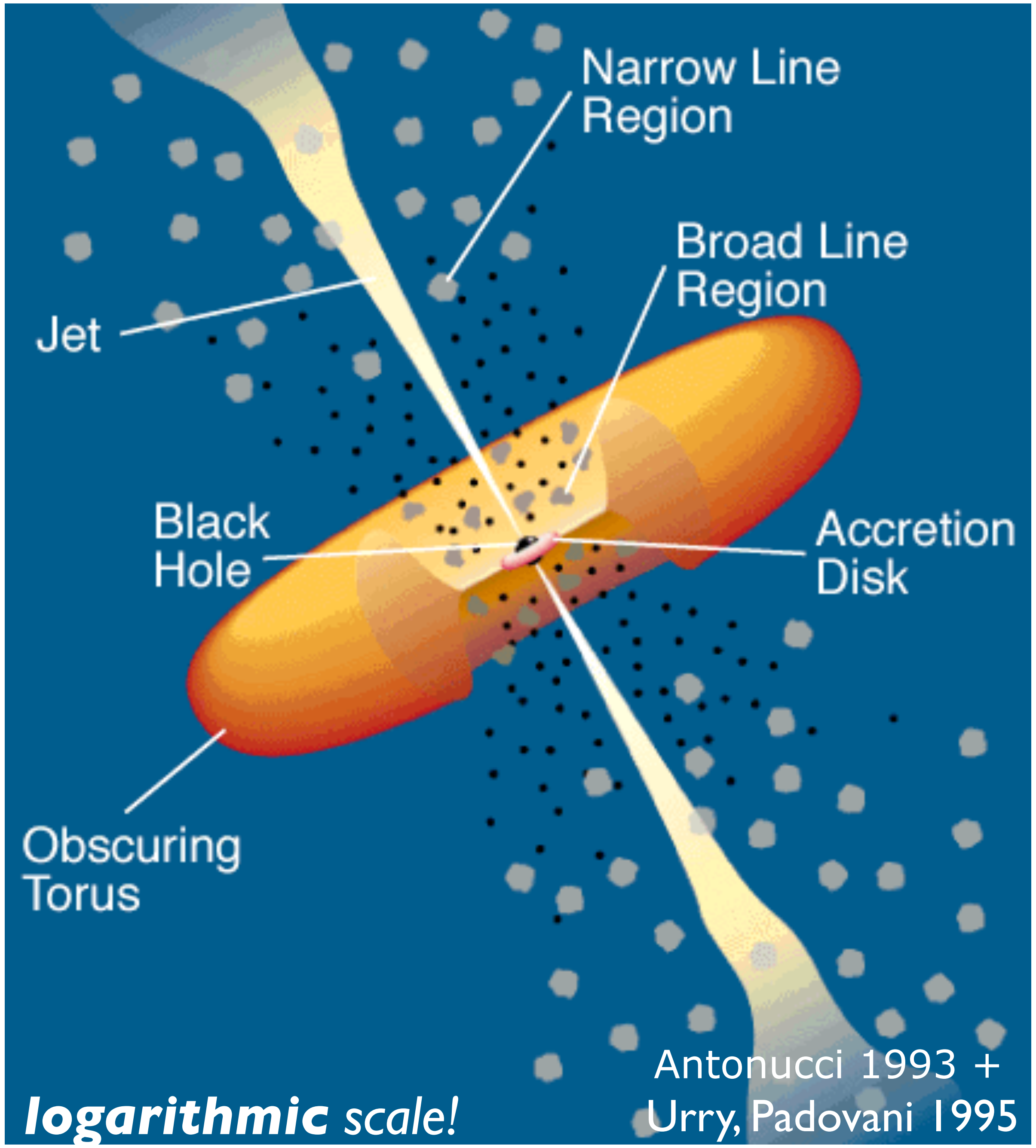


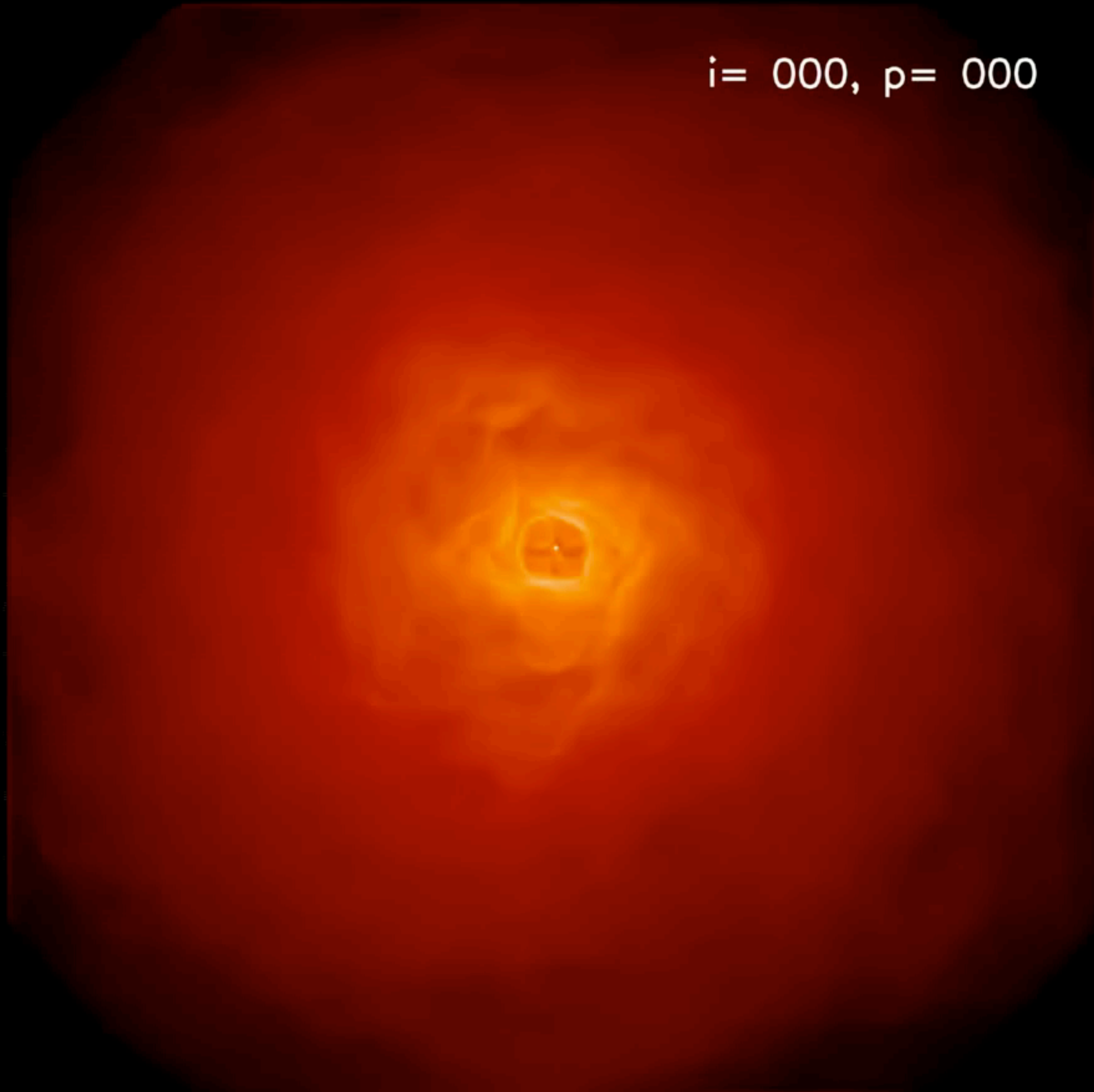
Antonucci & Miller 1985

The AGN (clumpy) "torus"



e.g. Nenkova+ 2002, Hönig+ 2006, Schartmann+ 2008, Stalevski+ 2008, Hönig+ 2017





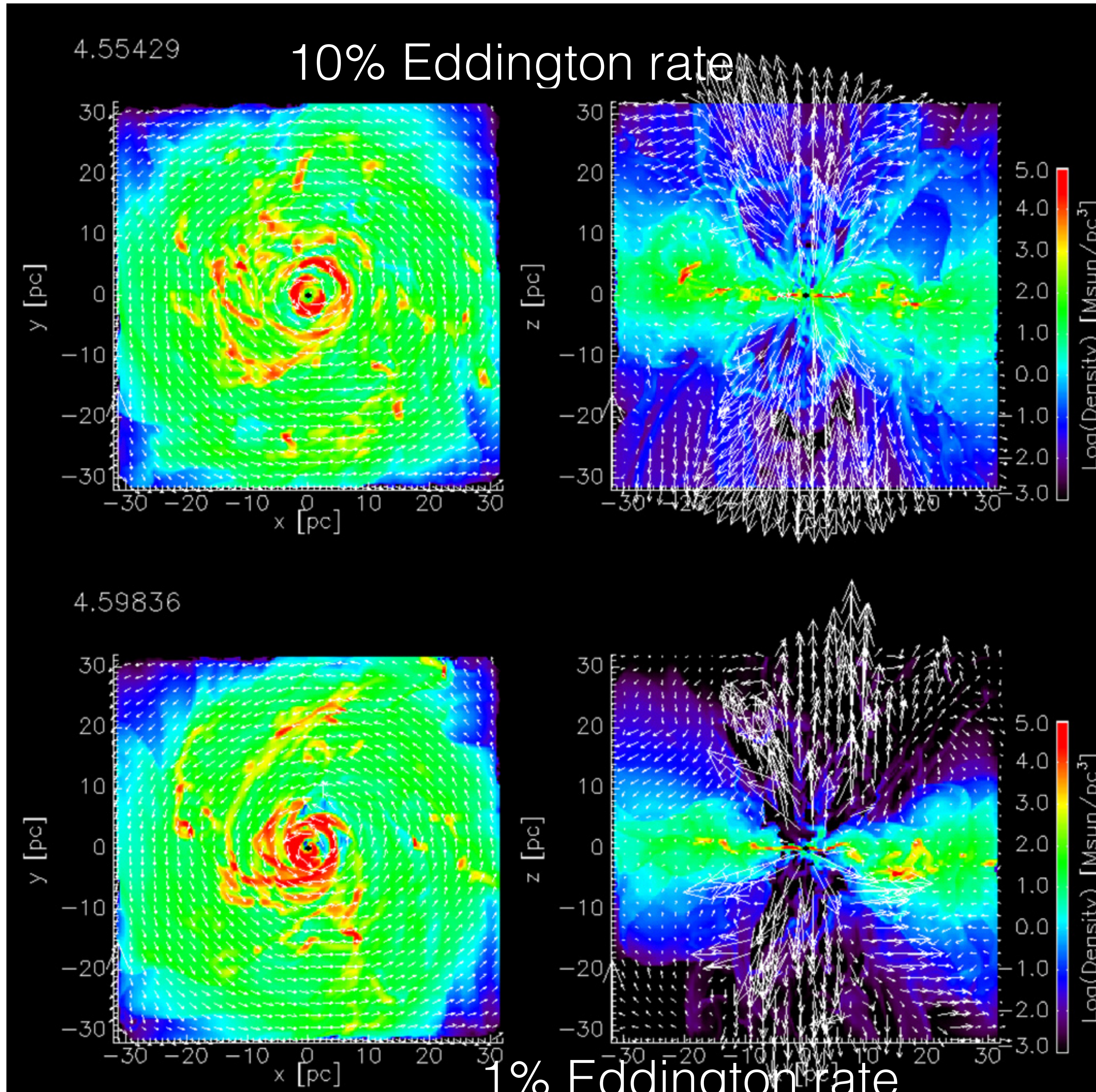
Wada+ 2012

Connecting physical torus models to observables

Eddington rate – outflow connection

Accretion efficiency – torus structure

Nuclear star formation rate – torus structure



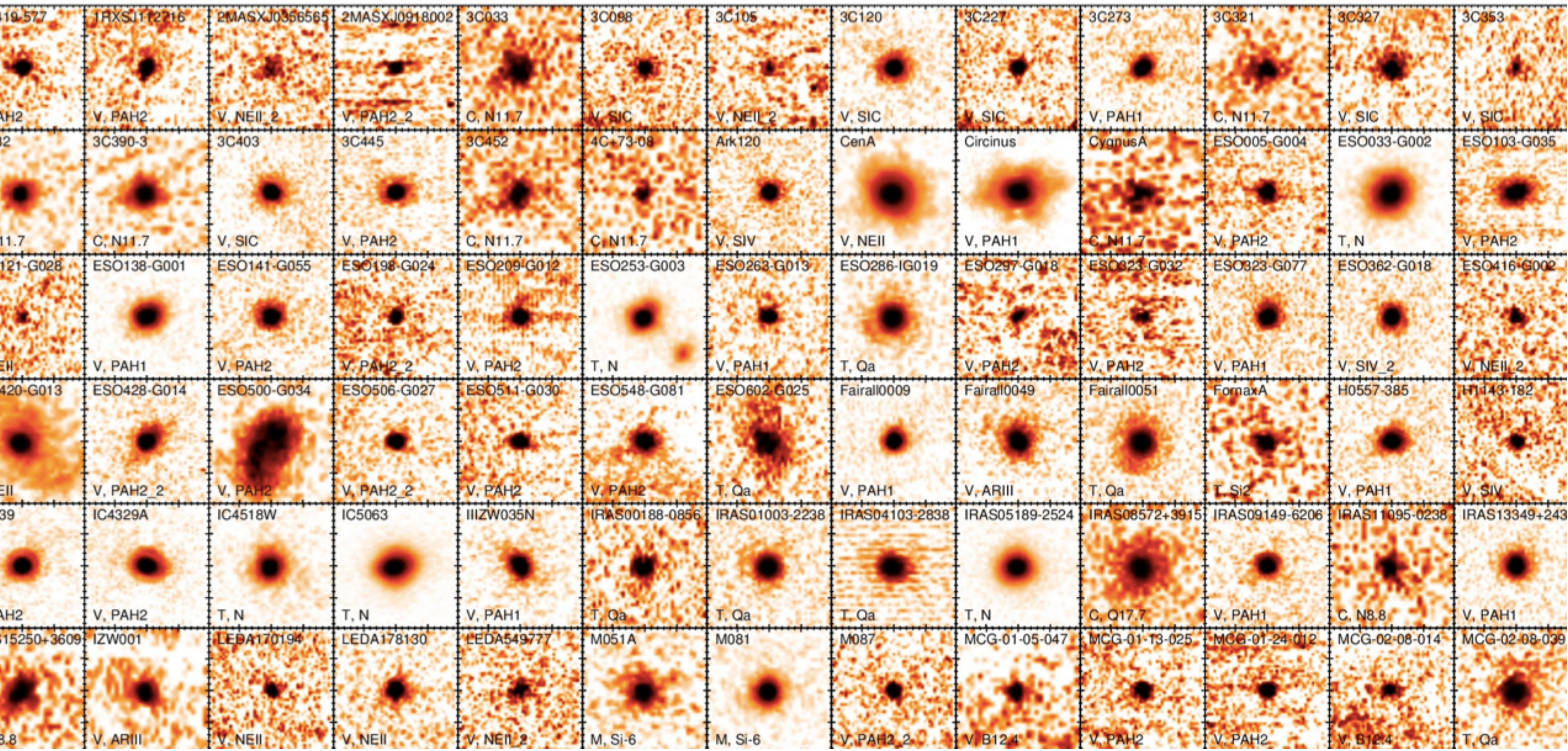
Wada+ 2012, 2016

More 3D (radiation) hydrodynamical simulations of the central regions of AGNs: e.g. Schartmann et al. 2009, 2010, 2014, 2018, Williamson et al., 2019, 2020
More radiative transfer calculations: see Marko Stalevski's talk

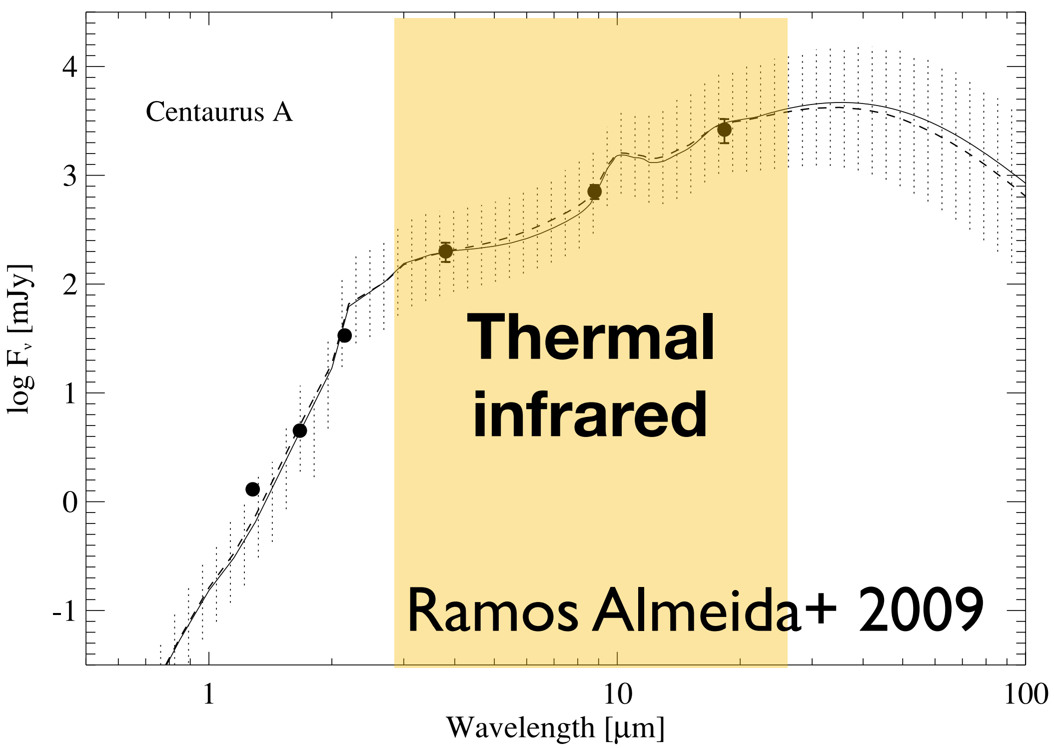
AGN tori in the mid-IR

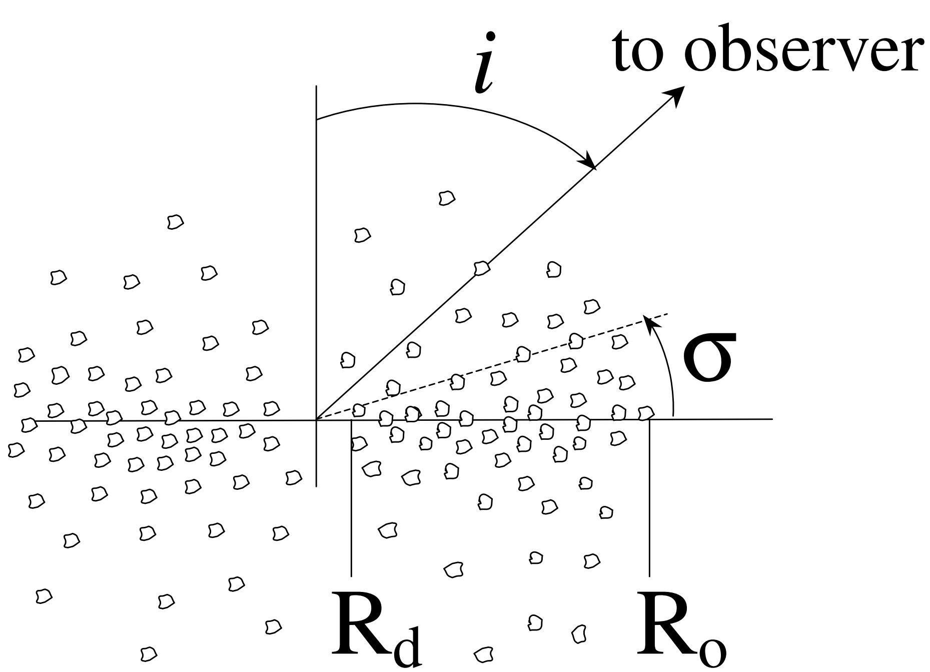
Spatial resolution matters

Asmus+ 2013



SED models for AGN tori

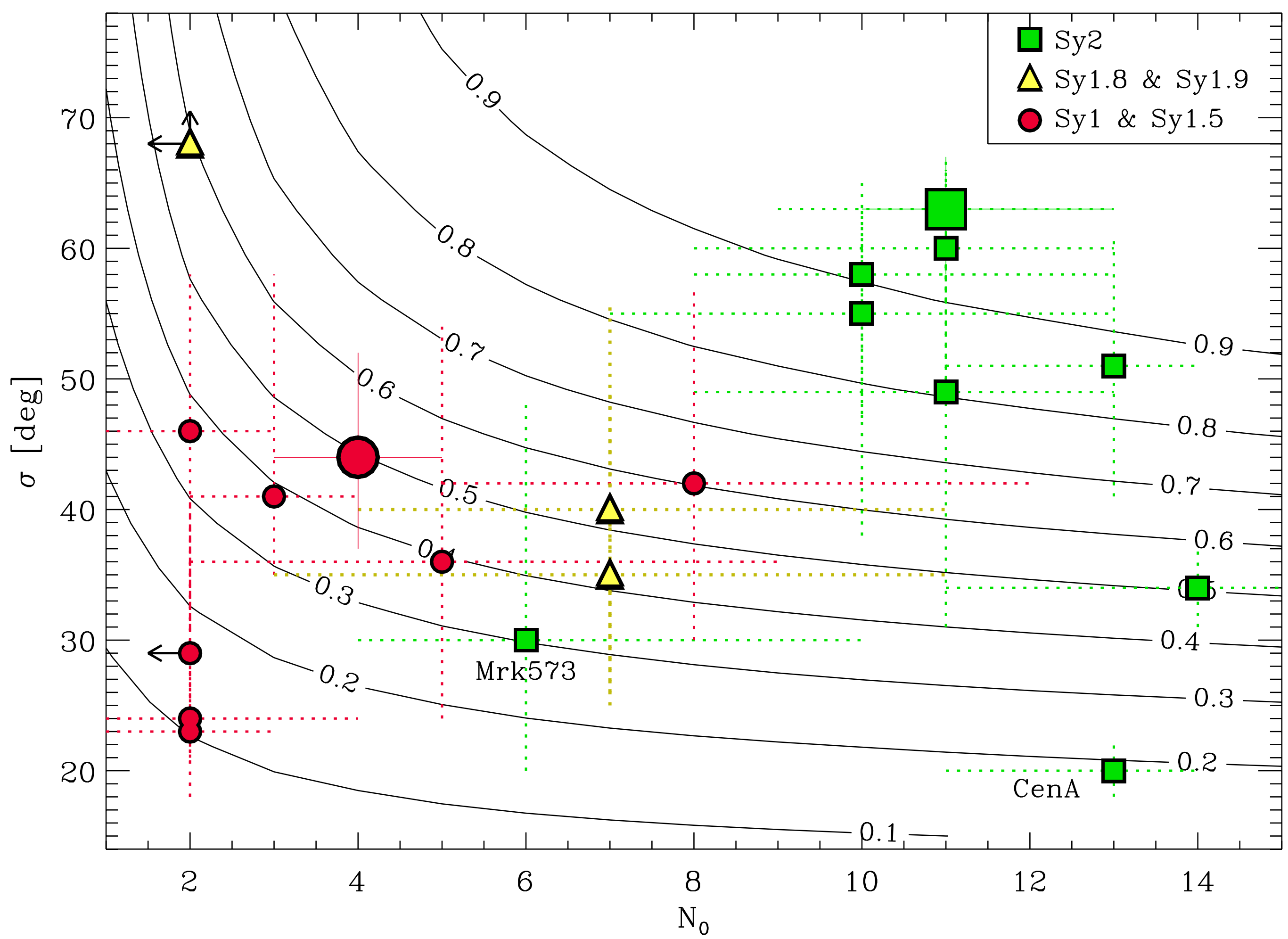




Nenkova+ 2008b

Ramos Almeida+ 2011

Half-opening angle of torus



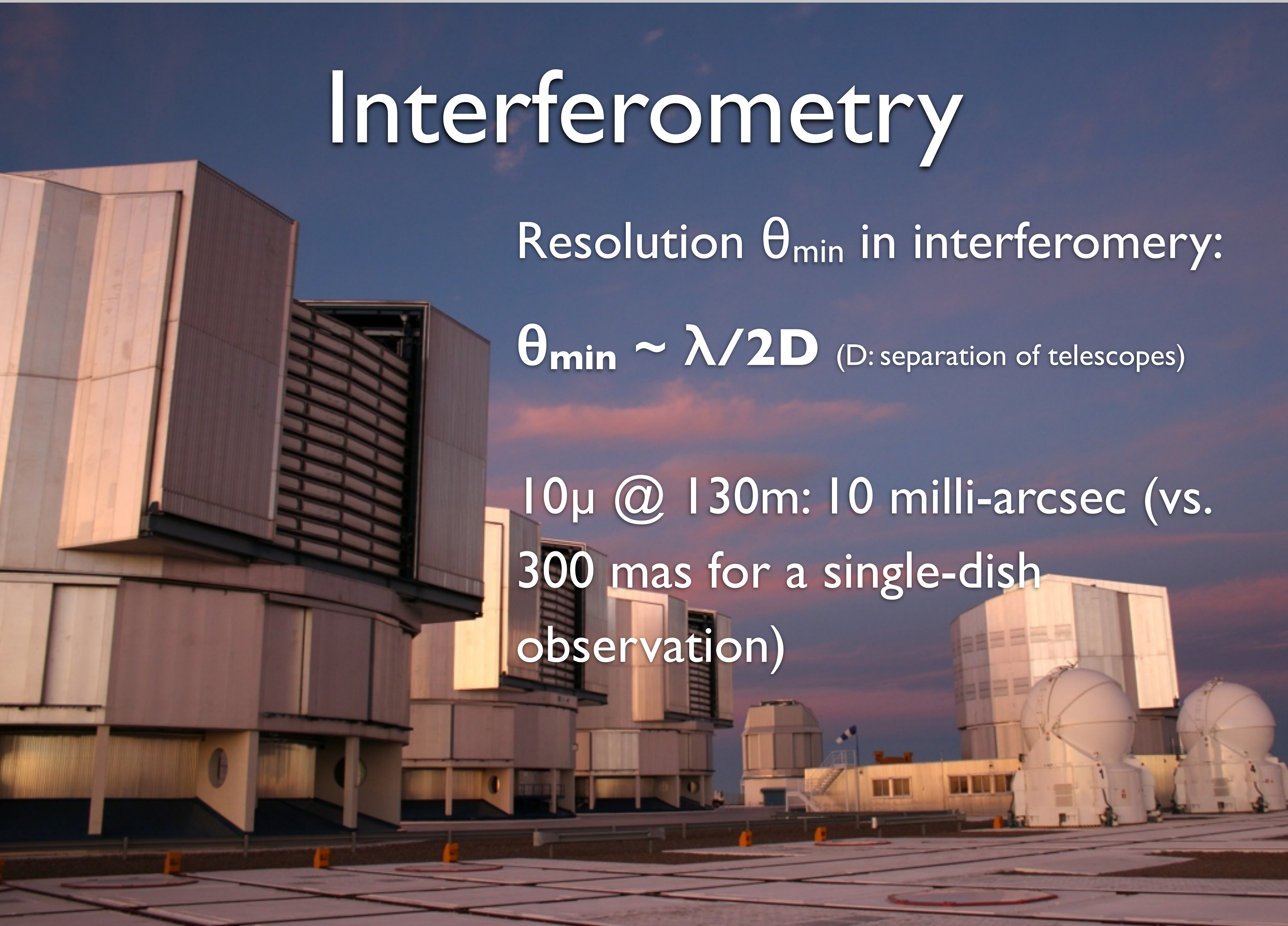
Number of clumps along line of sight

Interferometry

Resolution θ_{min} of a single dish telescope:

$\boldsymbol{\theta_{min} \sim \lambda/D}$ (D: diameter of primary mirror)

(10μ @ 8m: 300 milli-arcsec)



Interferometry

Resolution θ_{min} in interferomery:

$\boldsymbol{\theta_{min} \sim \lambda/2D}$ (D: separation of telescopes)

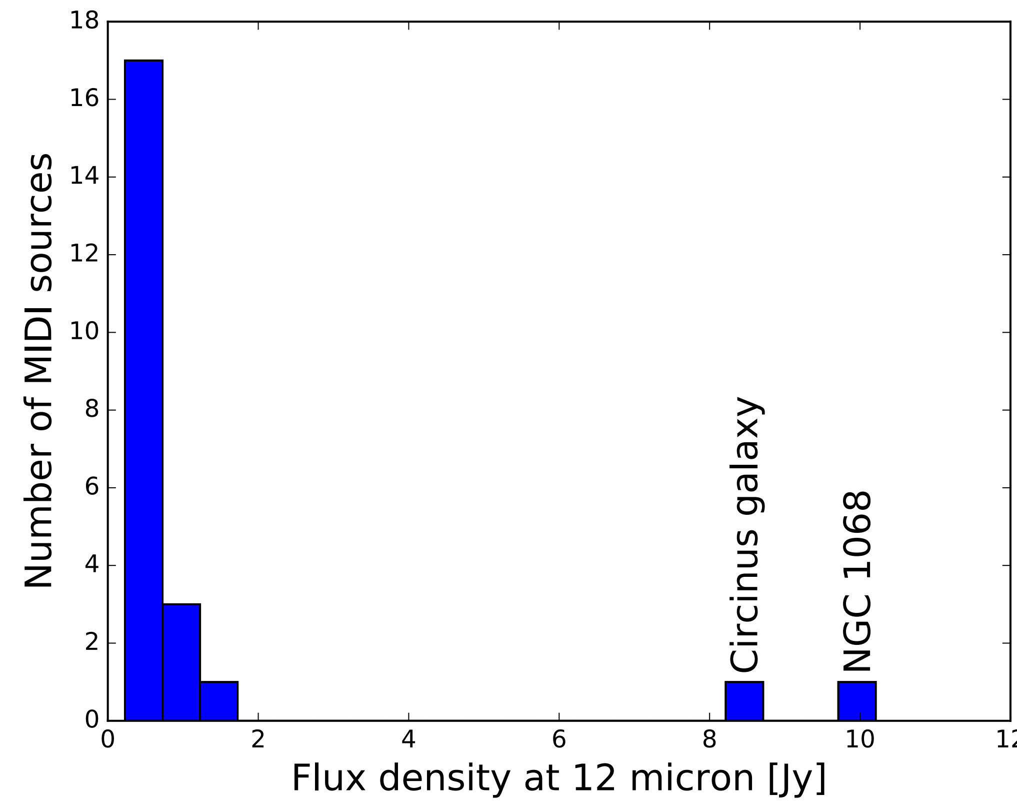
10µ @ 130m: 10 milli-arcsec (vs. 300 mas for a single-dish observation)

Infrared Interferometry of AGNs

Reference	Interferometer	#	summary of result
Swain et al. 2003[25]	KI	1	Marginally resolved emission in NGC 4151
Wittkowski et al. 2004[26]	VINCI	1	Low near-IR visibility for NGC 1068 argues for two-component model
Jaffe et al. 2004[27]	MIDI	1	Resolved two components of warm and hot dust in NGC 1068
Poncelet et al. 2006[28]	MIDI	1	Re-analysis of the Jaffe et al. 2004 MIDI data, find no hot dust
Meisenheimer et al. 2007[29]	MIDI	1	Nucleus of Centaurus A: a dusty disk and synchrotron emission
Tristram et al. 2007[30]	MIDI	1	Two-component structure of nuclear dust in Circinus, disk component is warm and co-aligned with maser disk
Beckert et al. 2008[31]	MIDI	1	Nuclear dust in NGC 3783 consistent with clumpy torus model
Kishimoto et al. 2009a[32]	MIDI & KI	4	Evidence for a common radial structure in AGN tori
Raban et al. 2009[33]	MIDI	1	Two-component structure of nuclear dust in NGC 1068, disk component is hot and co-aligned with maser disk
Tristram et al. 2009[34]	MIDI	8	Mid-IR sizes roughly scale with $\sqrt{L}$, no clear distinction between type 1 and type 2 sources
Burtscher et al. 2009[35]	MIDI	1	The nuclear dust in the Seyfert 1 galaxy NGC 4151 has similar properties as in Seyfert 2 galaxies
Kishimoto et al. 2009b[36]	KI	4	Interferometrically derived near-IR radii are slightly larger than reverberation-based radii and therefore likely probing the sublimation radius
Pott et al. 2010[37]	KI	1	No change in near-IR size of circum-nuclear dust in NGC 4151 despite variable luminosity
Burtscher et al. 2010[38]	MIDI	1	New mid-IR visibilities of Cen A do not fit well to a dust disk
Kishimoto et al. 2011a[39]	KI	8	Sublimation radius scales with $\sqrt{L}$
Tristram & Schartmann 2011[40]	MIDI	10	Differences in mid-IR sizes between type 1 and type 2 sources, expected from models, are not seen observationally.
Kishimoto et al. 2011b[41]	MIDI	6	Half-light radius in the mid-IR independent of luminosity
Weigelt et al. 2012[42]	AMBER	1	Marginally resolved near-IR emission in NGC 3783
Hönig et al. 2012[43]	MIDI	1	Majority of mid-IR emission originates from optically thin dust in the polar region in NGC 424 and is part of the outflow
Hönig et al. 2013[44]	MIDI	1	Detection of dust in the polar region of NGC 3783
Burtscher et al. 2013[45]	MIDI	23	MIDI AGN Large Programme results: half-light radius in the mid-IR scales with luminosity, but with large scatter; tori show a large diversity in intrinsic structure
Kishimoto et al. 2013[46]	KI	7	Evidence for a receding dust sublimation region in NGC 4151
Tristram et al. 2014[47]	MIDI	1	Updated model for the Circinus galaxy including data from shorter AT baselines; two-component structure confirmed with larger structure in the polar direction; SED model predicts sub-mm flux precisely as measured with ALMA; no evidence for large amounts of cold gas
Lopez-Gonzaga et al. 2014[48]	MIDI	1	Updated model for NGC 1068 including data from shorter AT baselines; two component structure confirmed with larger structure in the polar direction
Lopez-Gonzaga et al. 2016[18]	MIDI	23	Modeling shows that the observed (u, v) coverages only allow to detect elongations in 7/23 sources. 5/7 are found to be significantly elongated, all in polar direction.

Table 1: Summary of all publications using long-baseline interferometry for studying AGNs (either data publication or new analysis). The third column gives the number of sources involved in the particular study.

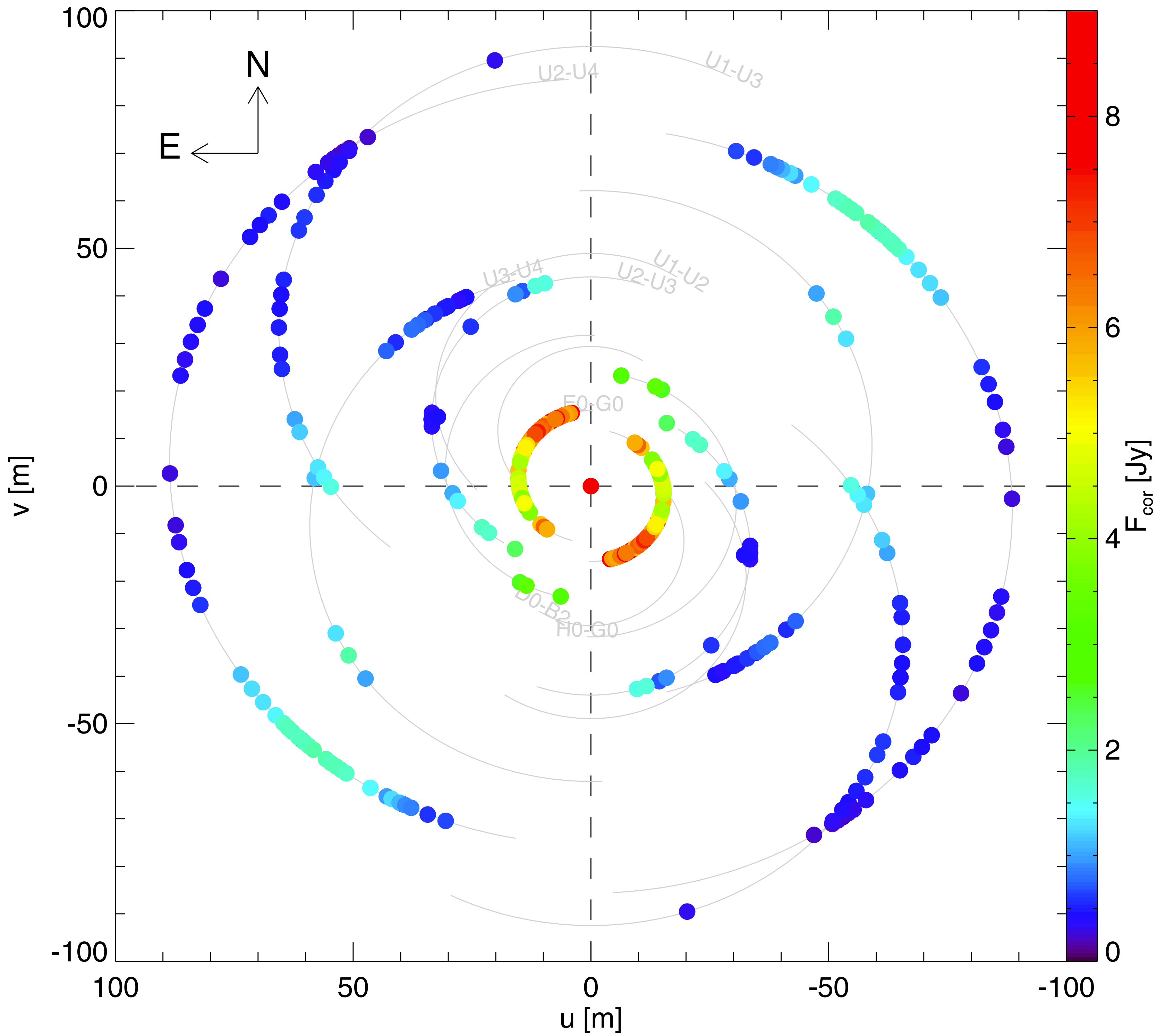
Burtscher+ 2016



- Lopez-Gonzaga, 2017, MIDI, 1, no change in mid-IR torus structure in NGC 1068 despite X-ray variability
- Leftley+ 2018, MIDI, 1, polar elongation in ESO 323-G77
- Gravity Collab. 2018, GRAVITY, 1, spatially resolved rotation of the BLR of 3C 273
- Leftley+ 2019, MIDI, 33, a relation between extended emission and Eddington ratio of AGN
- Gravity Collab. 2019, GRAVITY, 8, size-luminosity relation and a possible deviation thereof in nearby Seyfert galaxies
- Gravity Collab. 2019, GRAVITY, 1, An image of the dust sublimation region in NGC 1068

MIDI observations of the Circinus galaxy

The best extragalactic case for infrared interferometry



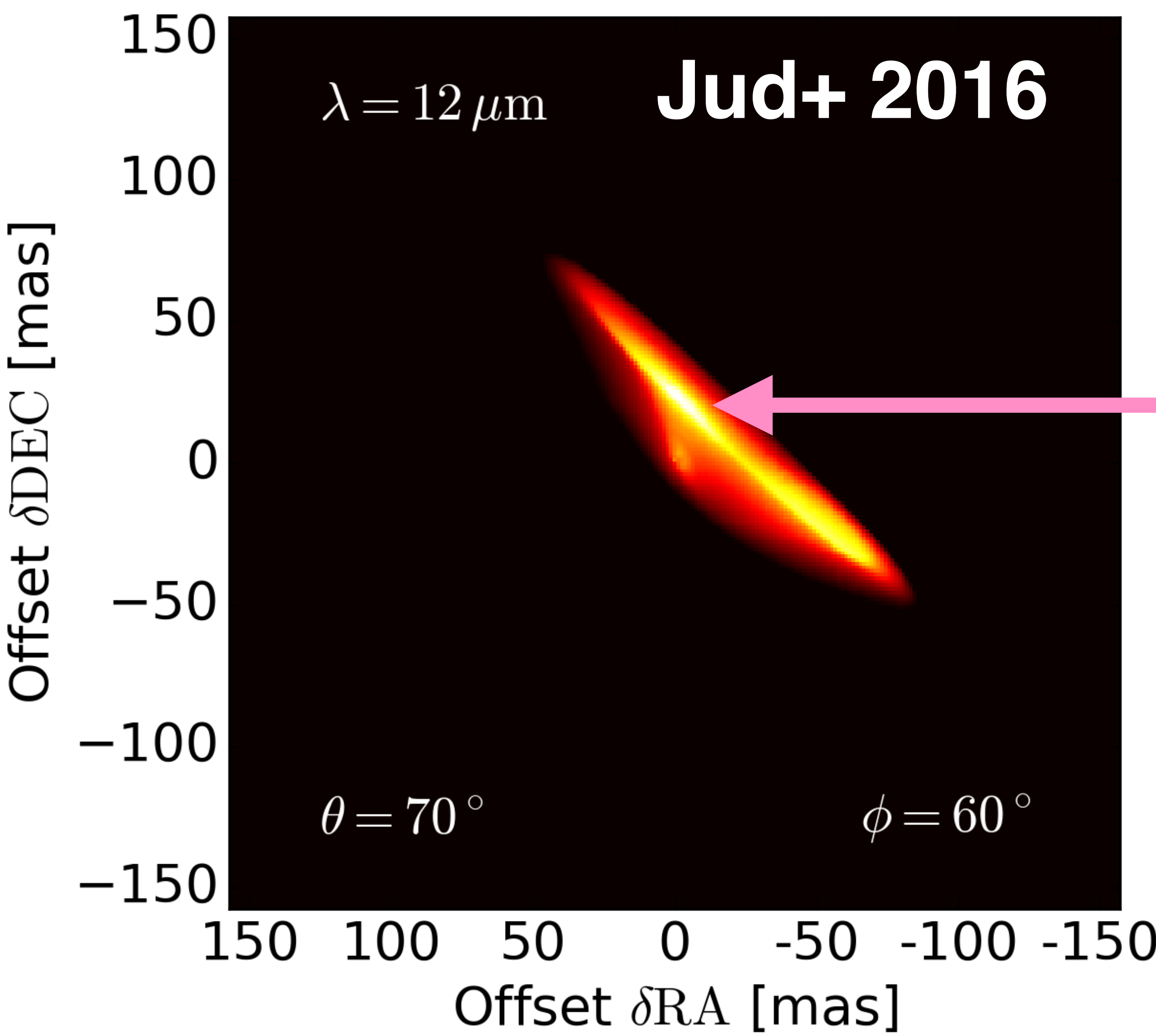
$F_{cor} = V * F_{tot}$

Carried out over 10 years at the VLTI using both 8m (UT) and 1.8m (AT) telescopes

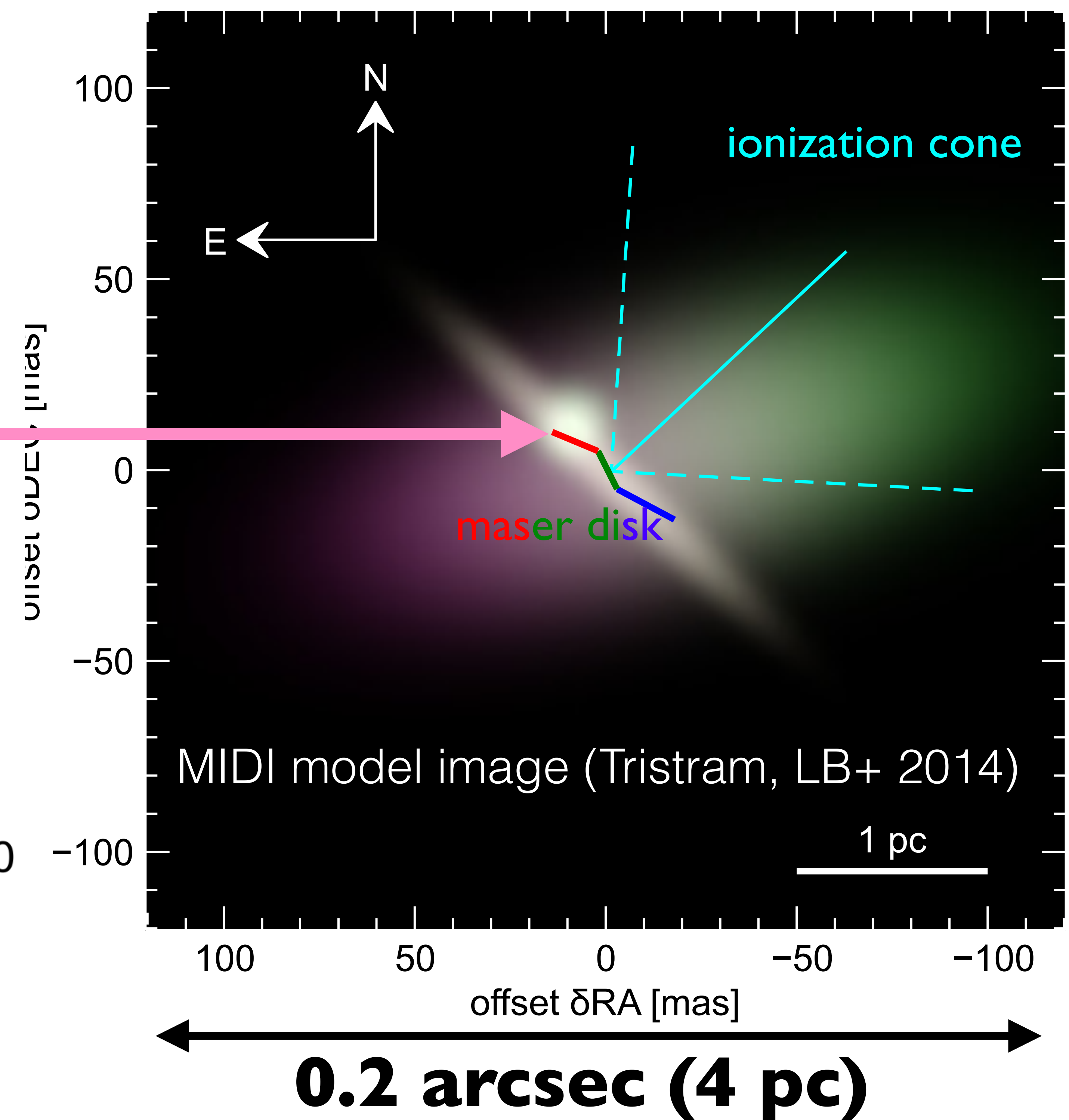
Tristram et al. 2014

The Circinus galaxy on sub-parsec scale

Starting to resolve "sub-structure"

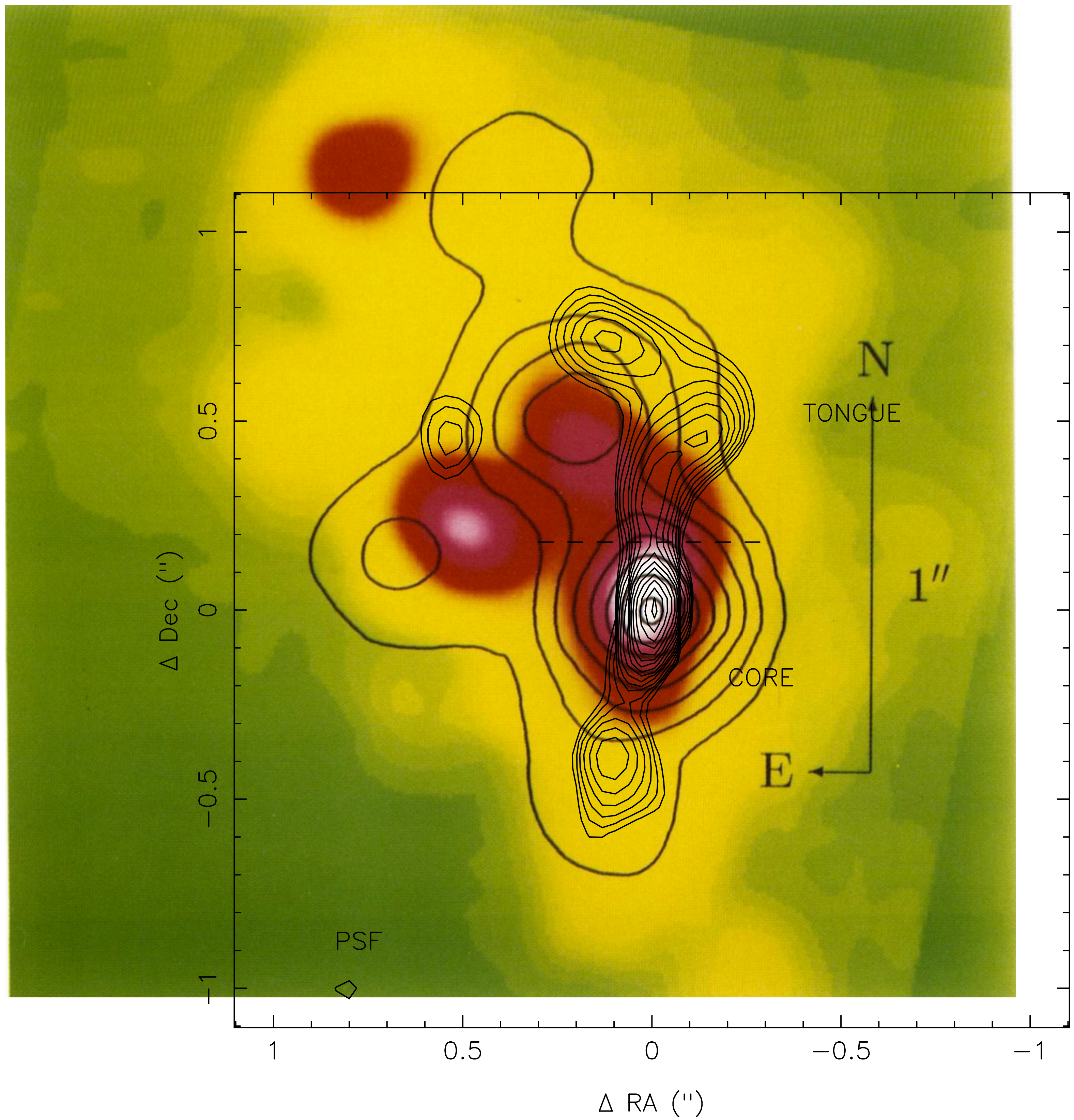


3 component model of the dust emission in the Circinus galaxy



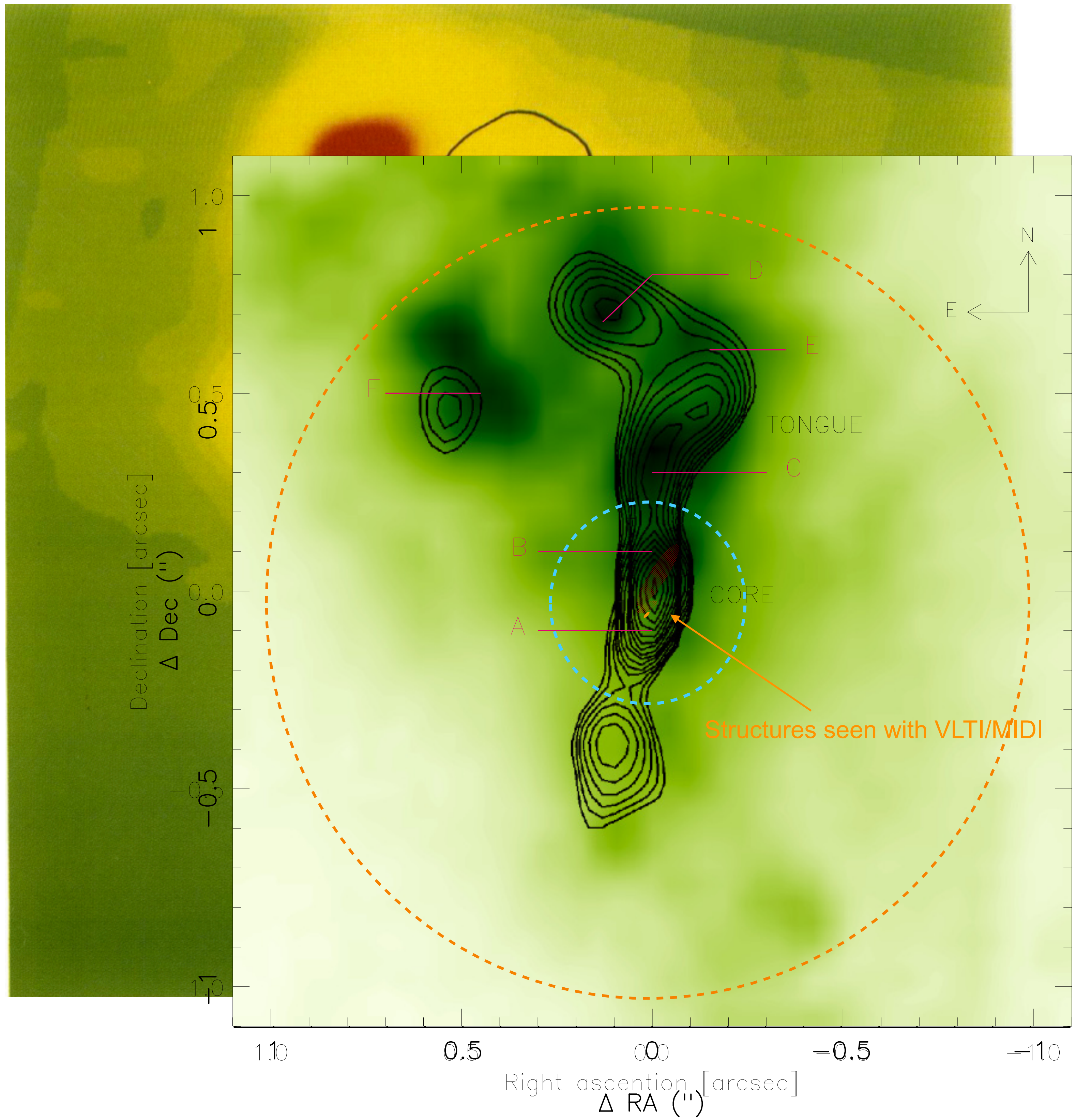
NGC 1068

Cameron+ 1993 (MIRACLE @ UKIRT)



Bock+ 2000 (MIRLIN @ Keck 2)

NGC 1068

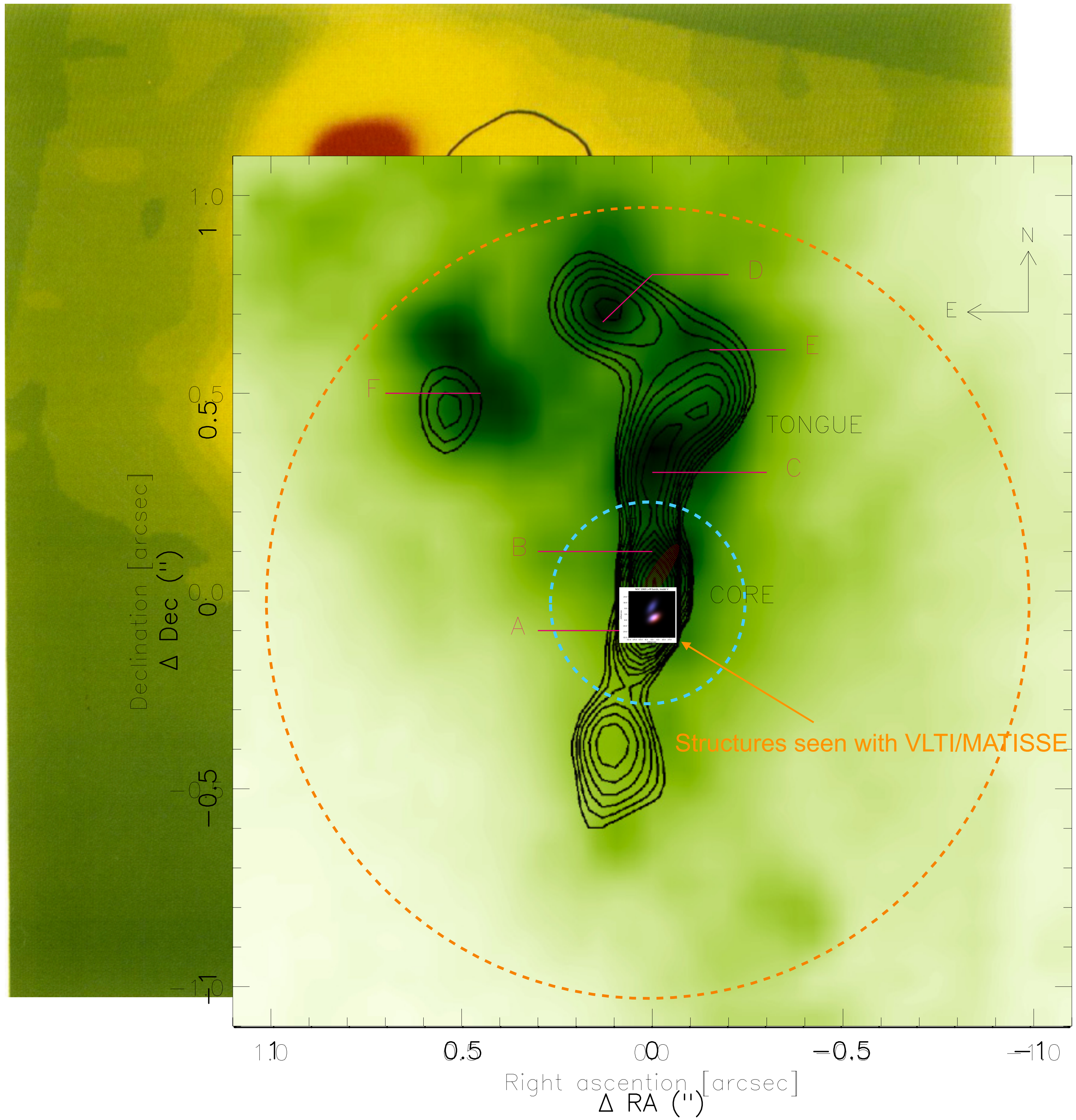


Cameron+ 1993 (MIRACLE @ UKIRT)

Bock+ 2000 (MIRLIN @ Keck 2)

Lopez-Gonzaga+ 2014

NGC 1068



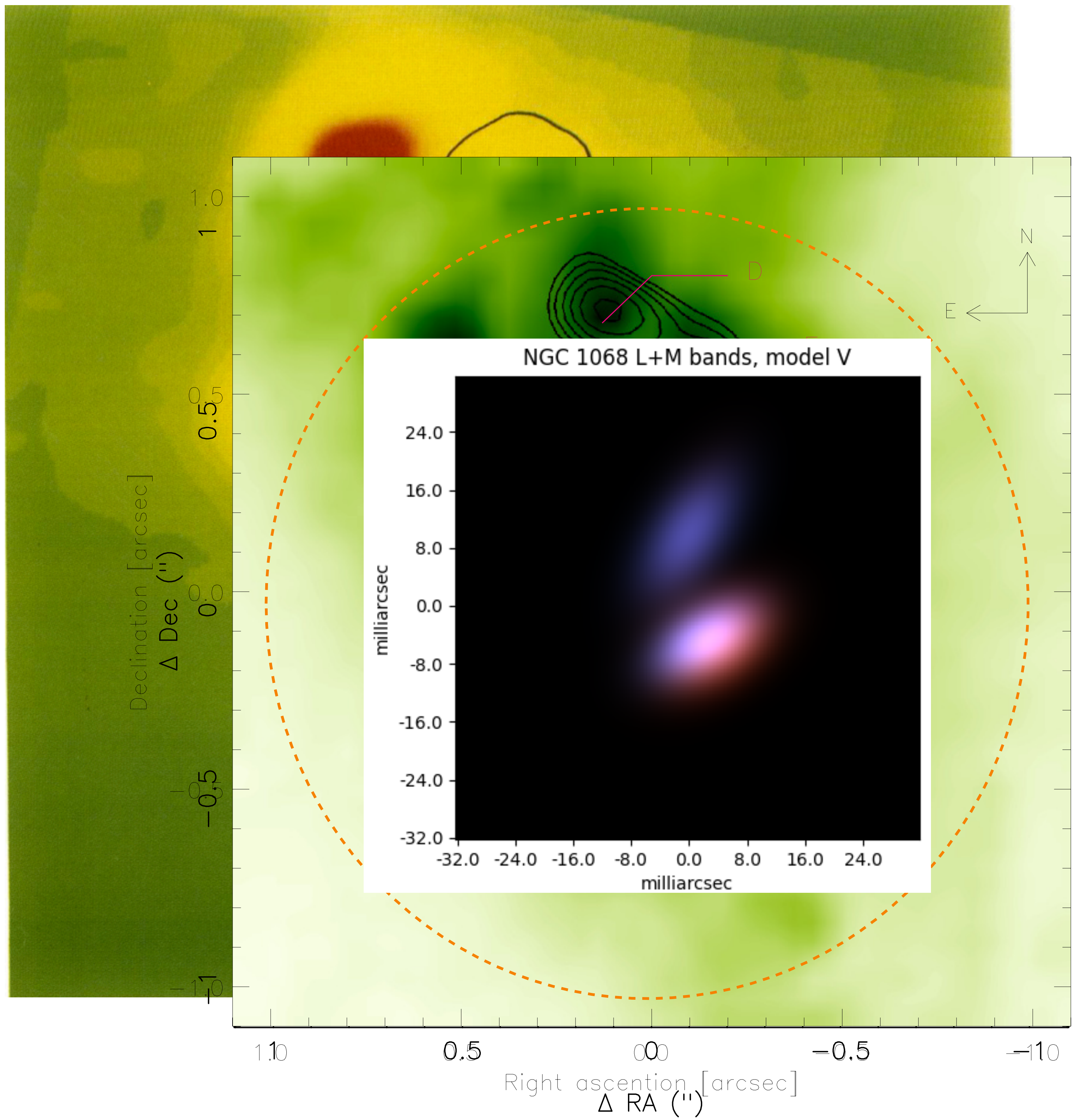
Cameron+ 1993 (MIRACLE @ UKIRT)

Bock+ 2000 (MIRLIN @ Keck 2)

Lopez-Gonzaga+ 2014

Gámez Rosas+ (in prep.) – **see Violeta's talk for more!**

NGC 1068



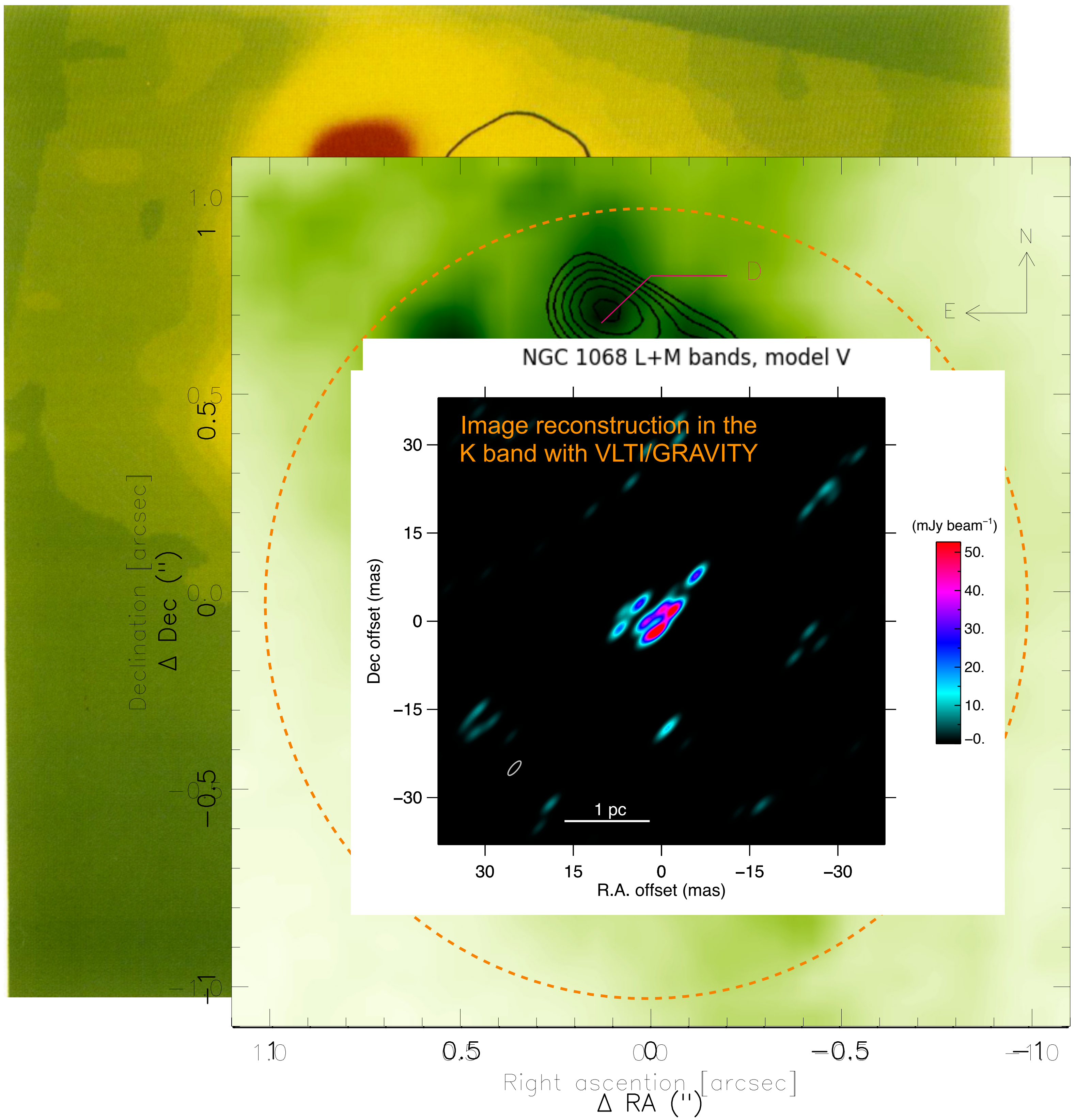
Cameron+ 1993 (MIRACLE @ UKIRT)

Bock+ 2000 (MIRLIN @ Keck 2)

Lopez-Gonzaga+ 2014

Gámez Rosas+ (in prep.) – **see Violeta's talk for more!**

NGC 1068



Cameron+ 1993 (MIRACLE @ UKIRT)

Bock+ 2000 (MIRLIN @ Keck 2)

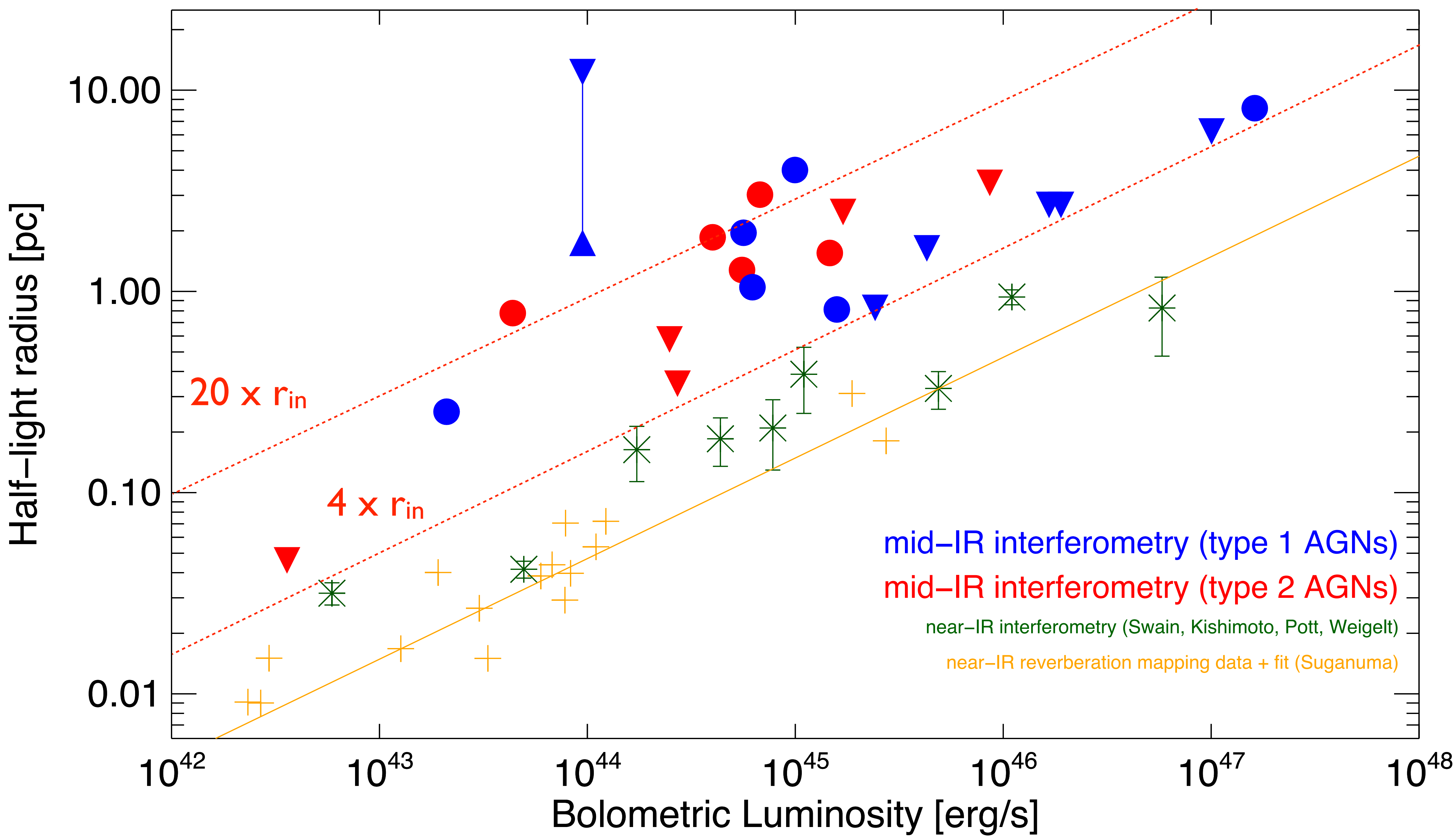
Lopez-Gonzaga+ 2014

Gámez Rosas+ (in prep.) – **see Violeta's talk for more!**

GRAVITY Collab. 2019

The torus size-luminosity relation

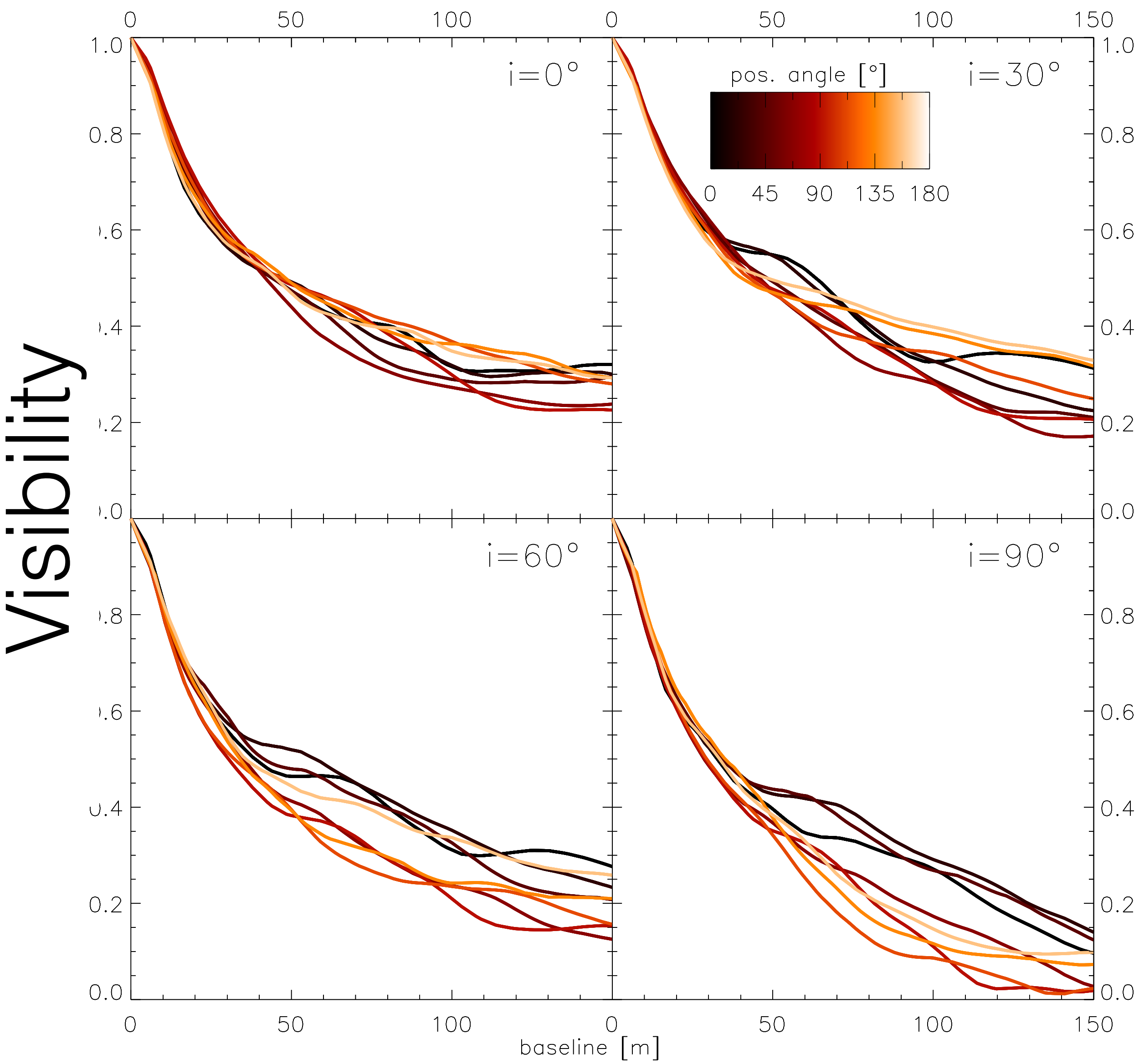
23 AGNs observed with VLTI/MIDI



Burtscher+ 2013

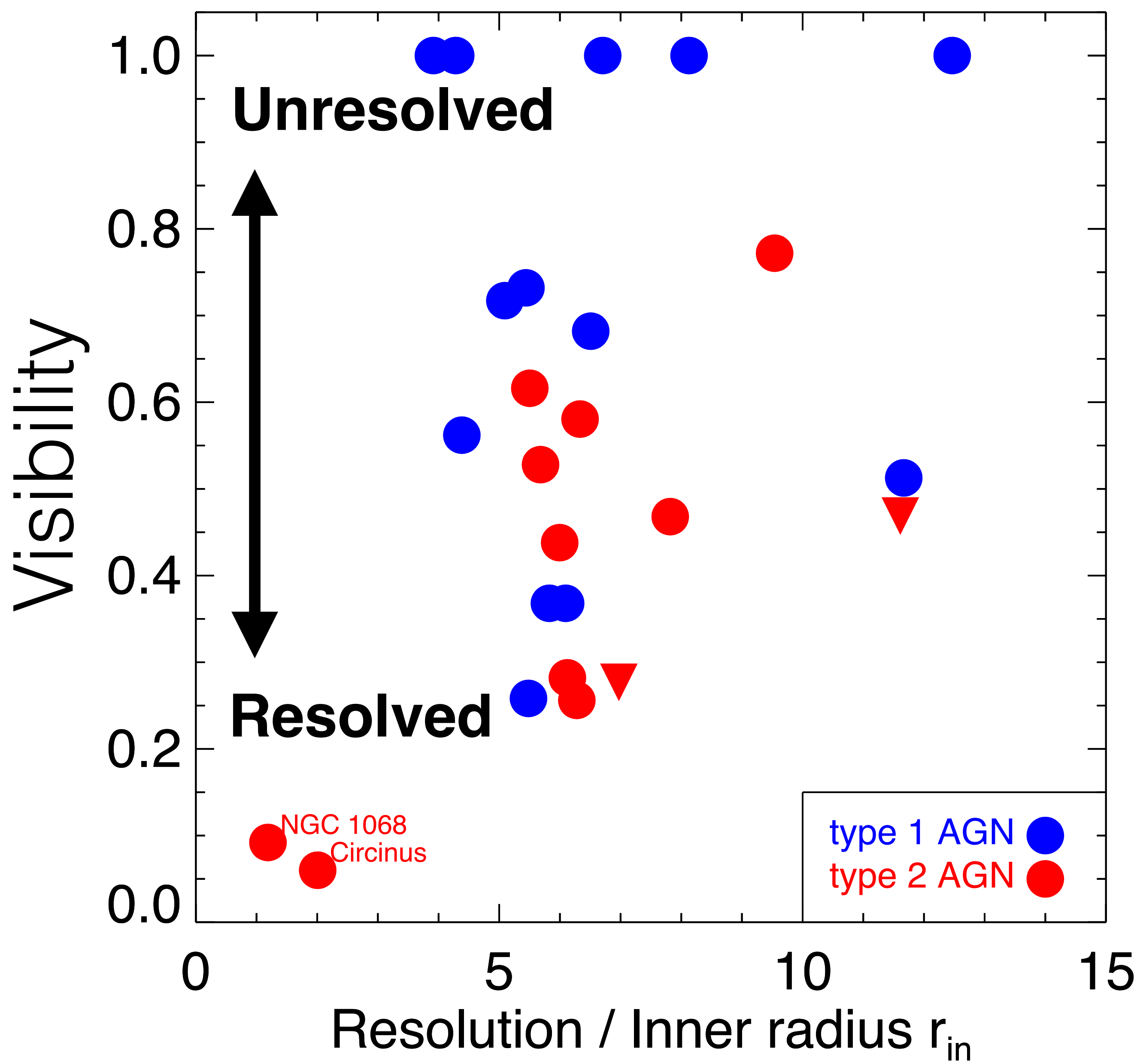
The fraction of unresolved flux

…does not depend much on inclination or position angle



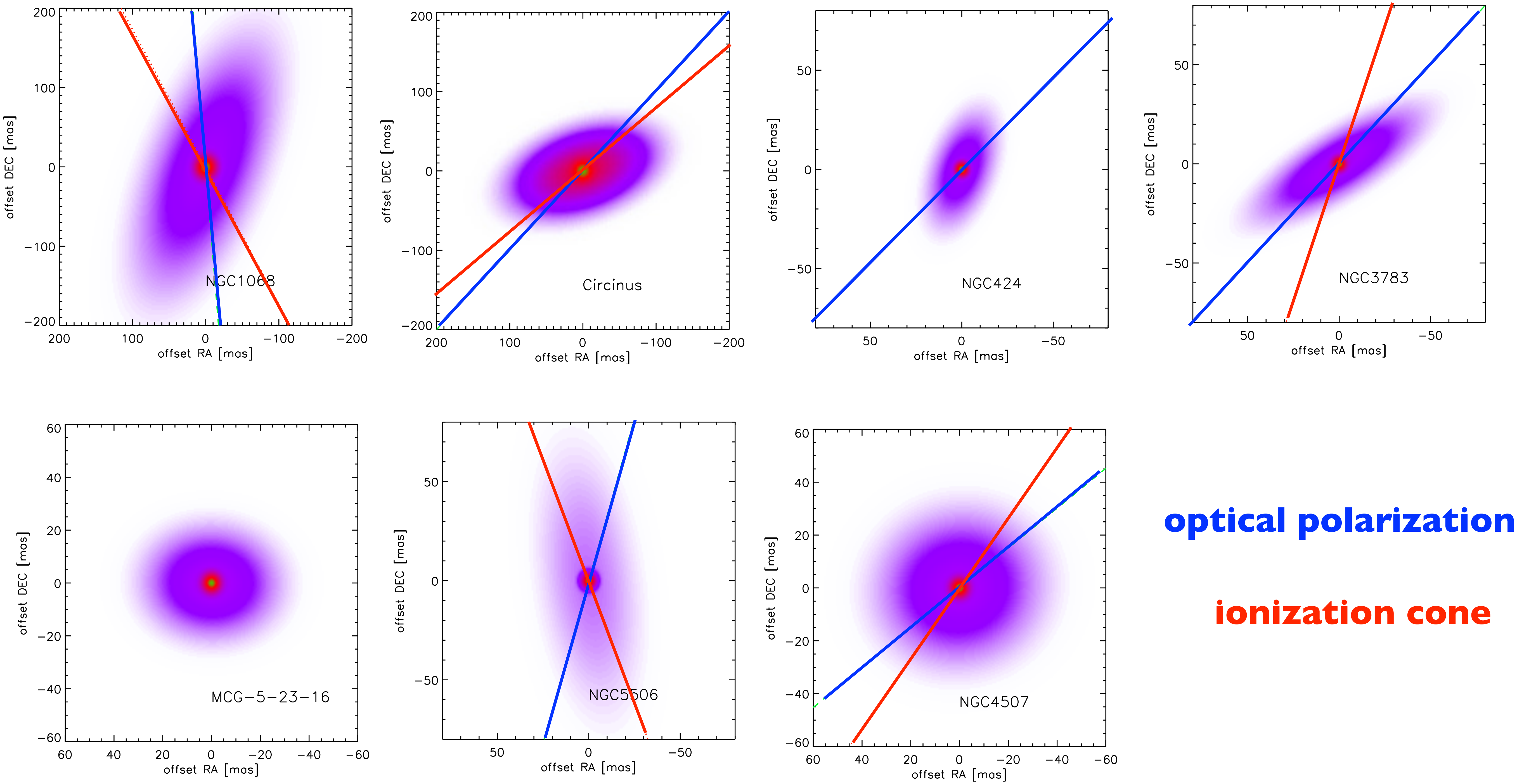
Schartmann+ 2008

But tori aren't alike, even when observed at similar resolution



Burtscher+ 2013

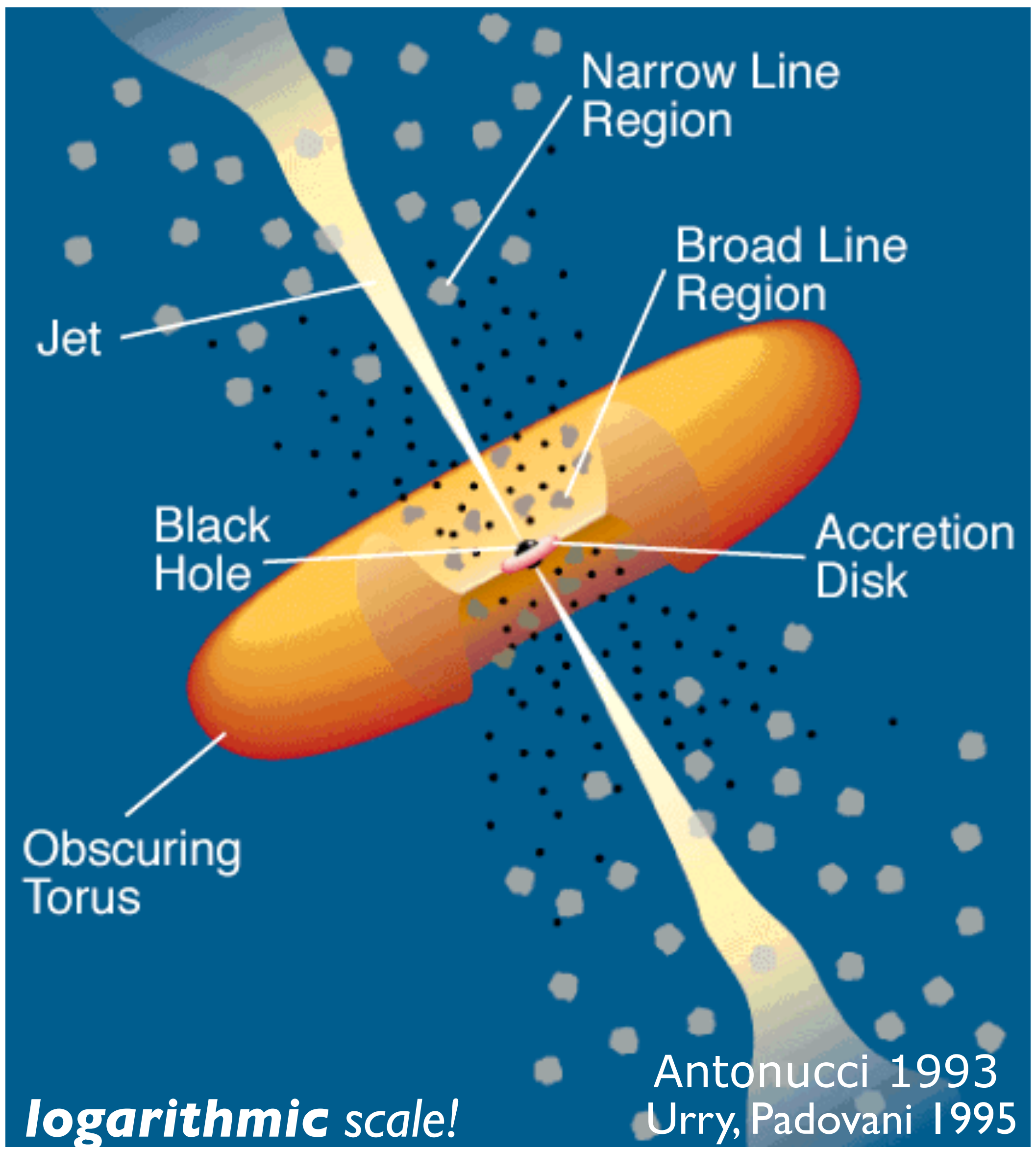
Most AGN „tori“ are oriented along the polar axis

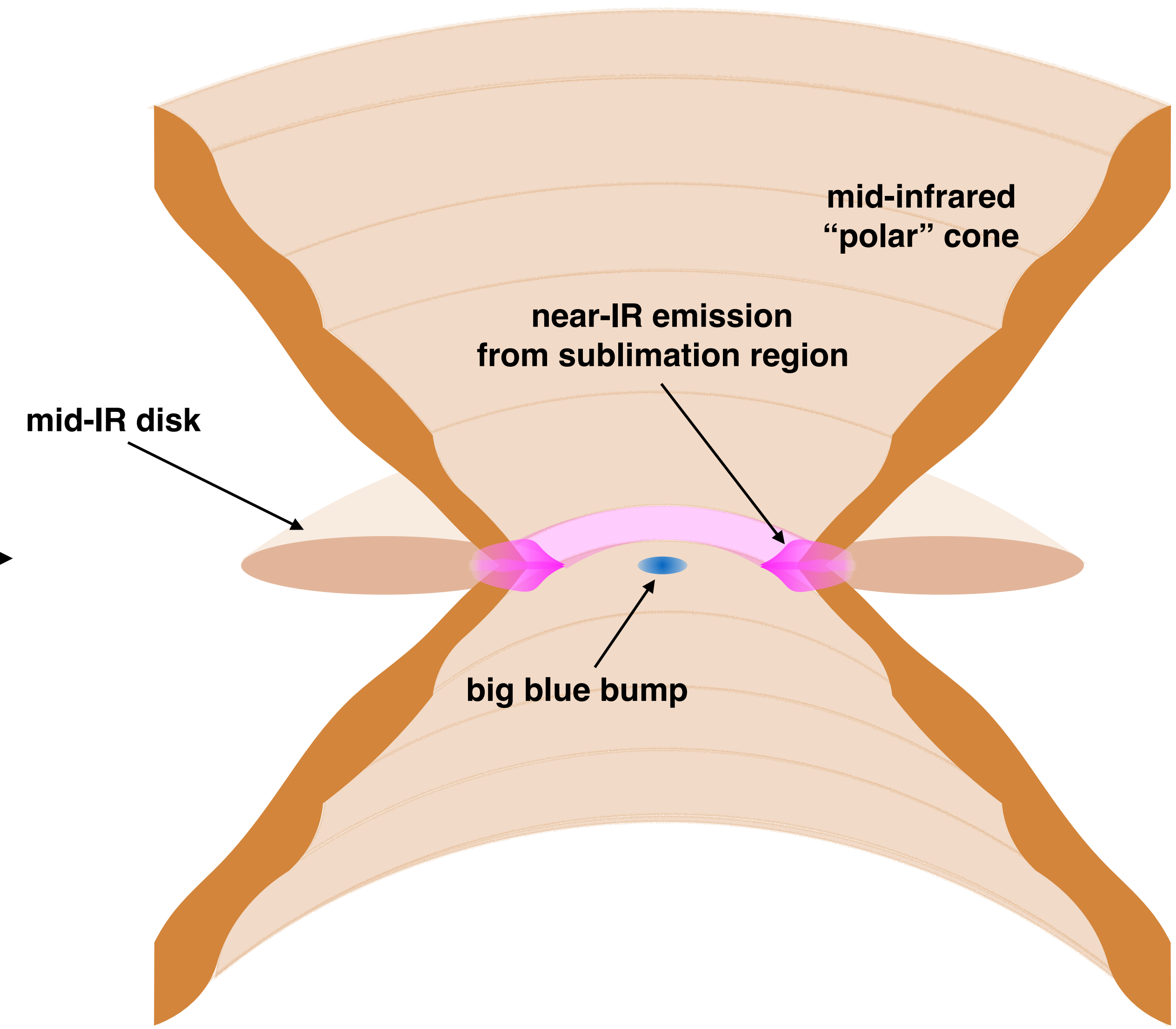


Lopez-Gonzaga et al. 2016; see also Hönig+ 2012, 2013, Tristram+ 2014, Lopez-Gonzaga+ 2014, Leftley+ 2018

A new view of AGN-heated dust

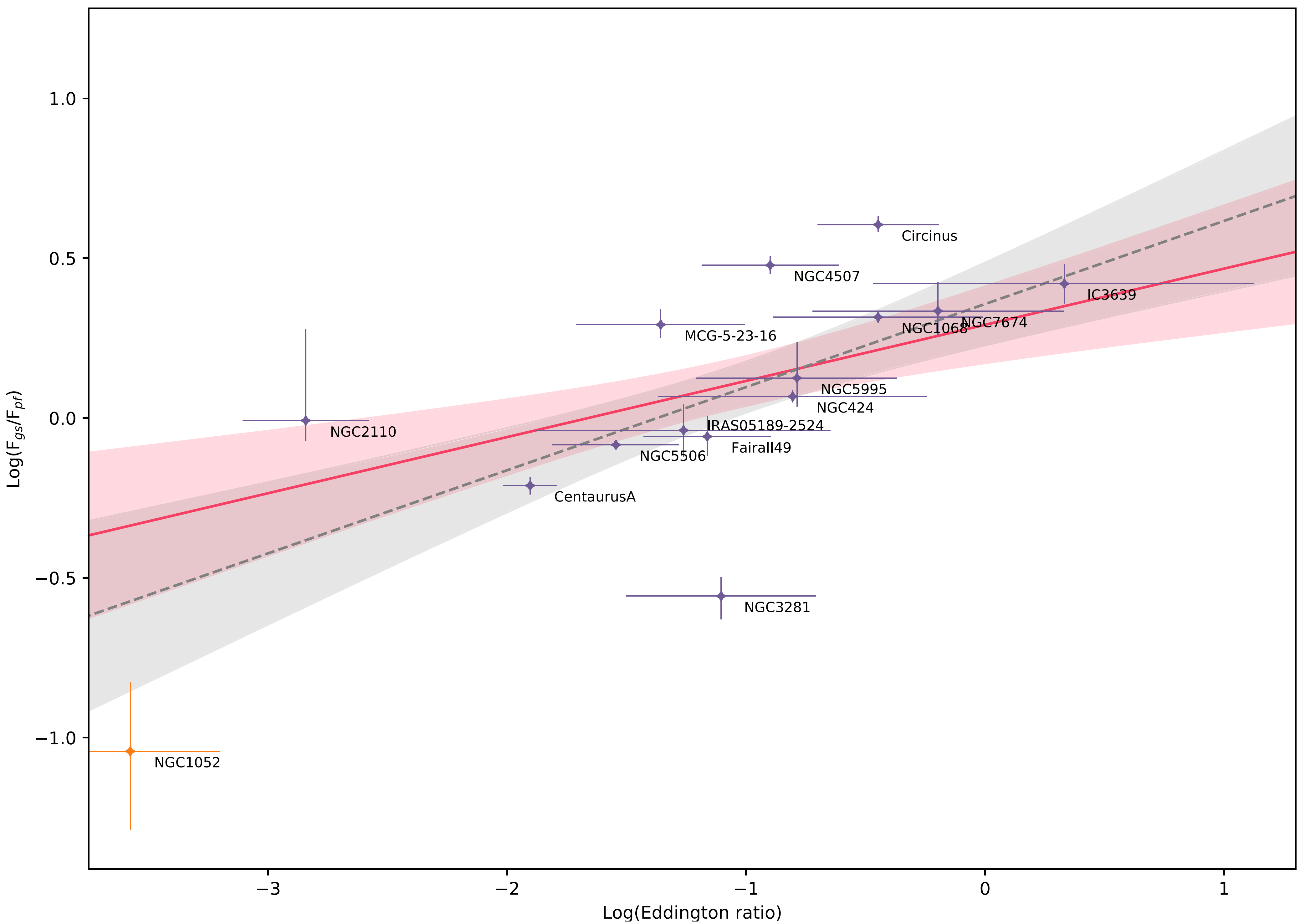
Thanks to mid-IR interferometry & imaging!





Hönig 2019

A correlation between extended extended flux and Eddington ratio?

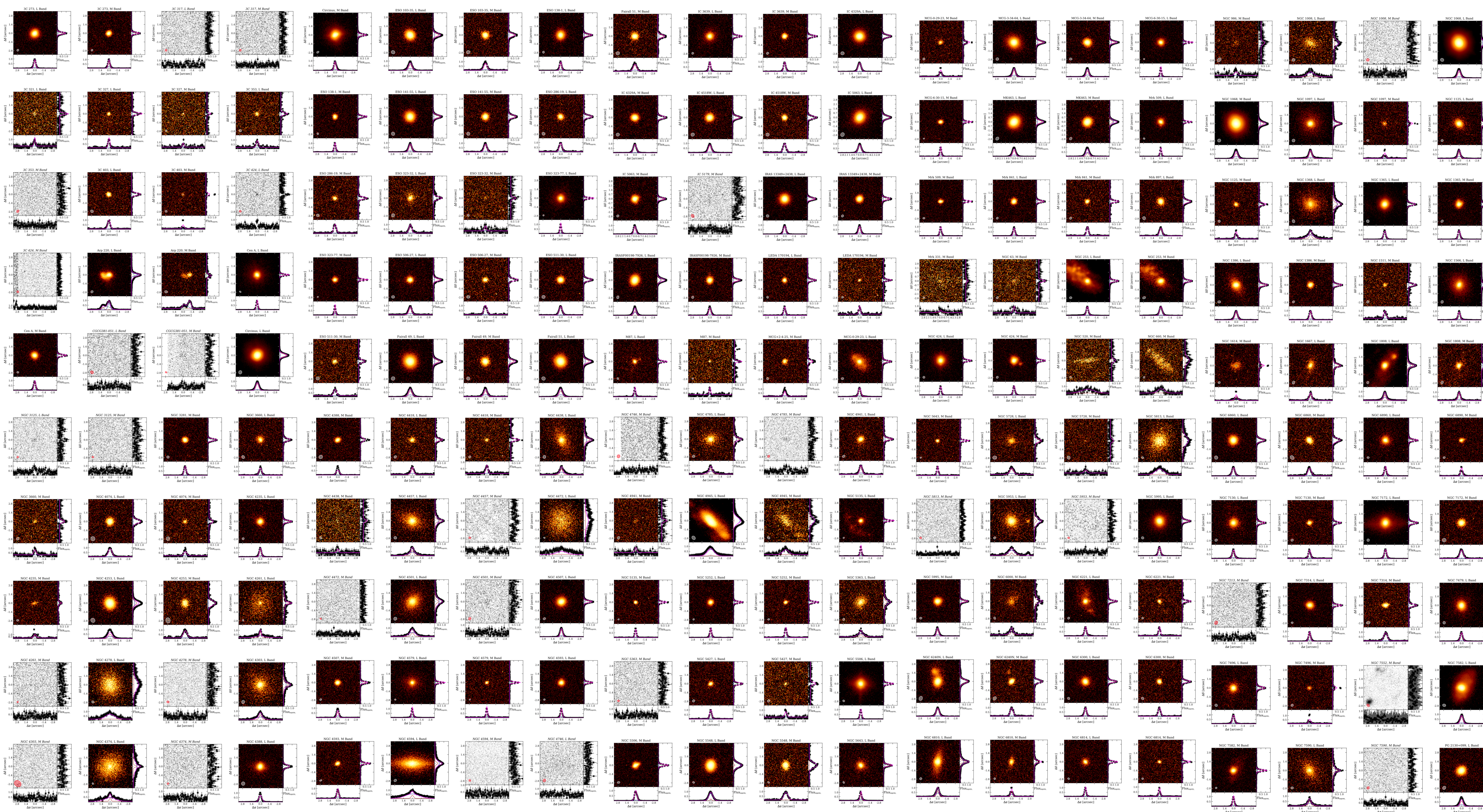


Leftley+ 2019

More sources dearly needed!

A complete census of all archival ISAAC L' band observations of AGNs

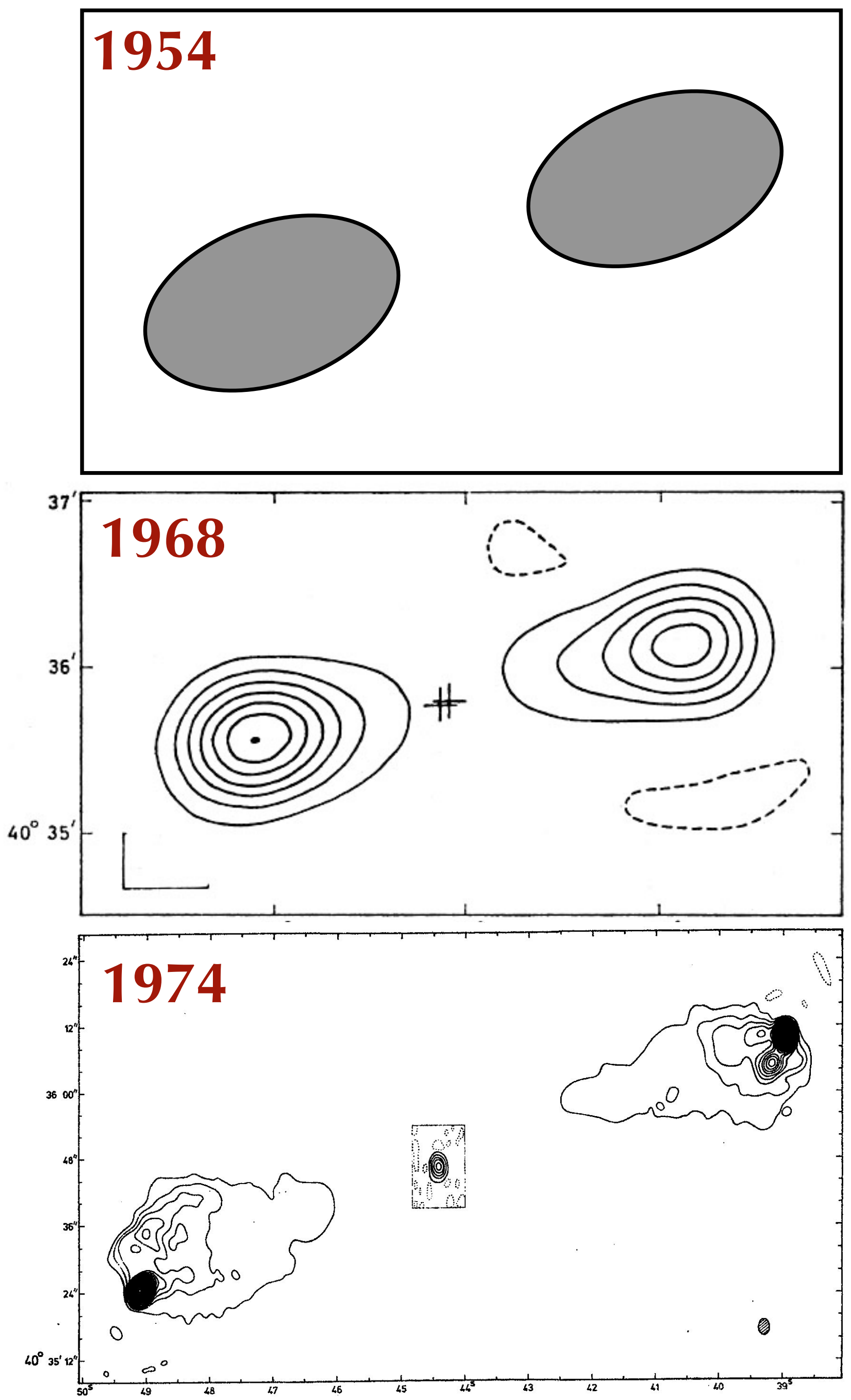
see Jacob's talk



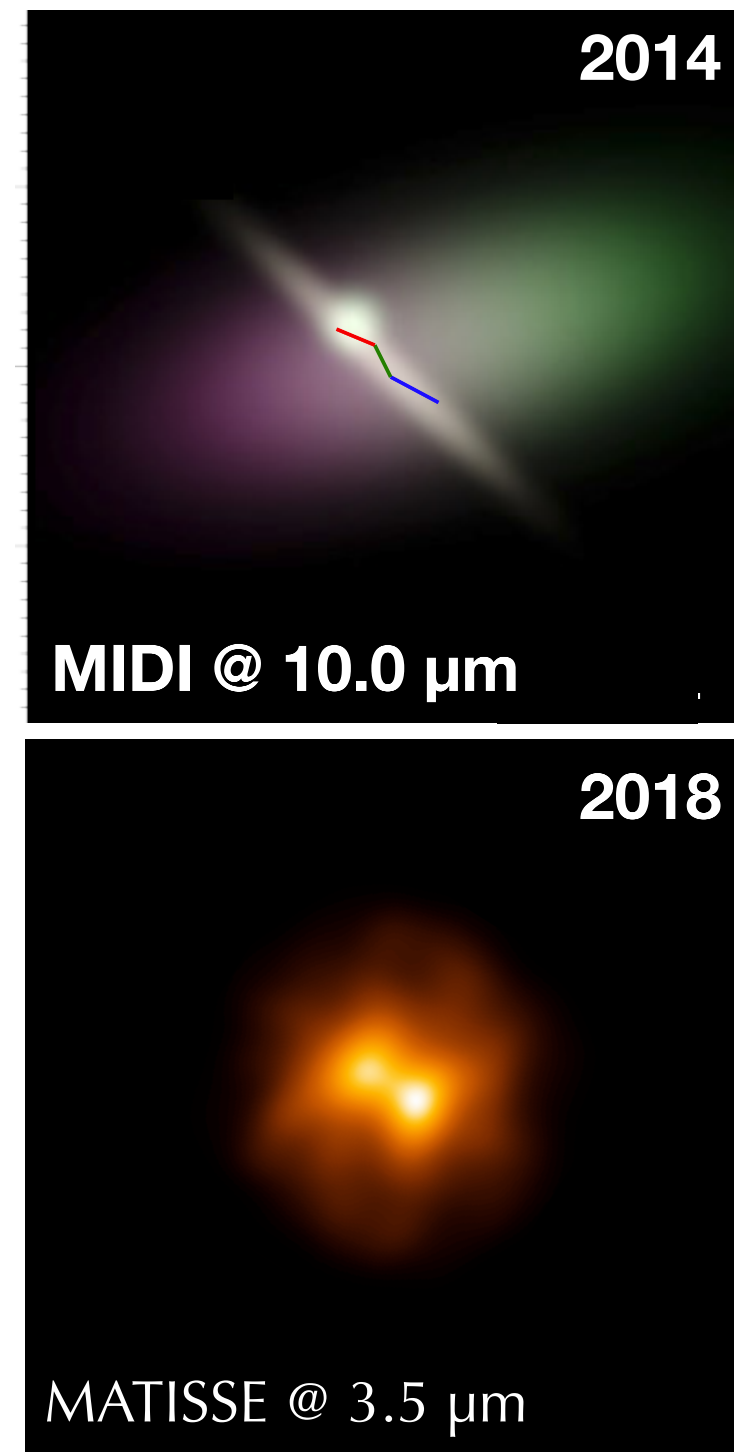
Isbell+ 2020 (submitted)

MATISSE is the next big step in IR interferometry

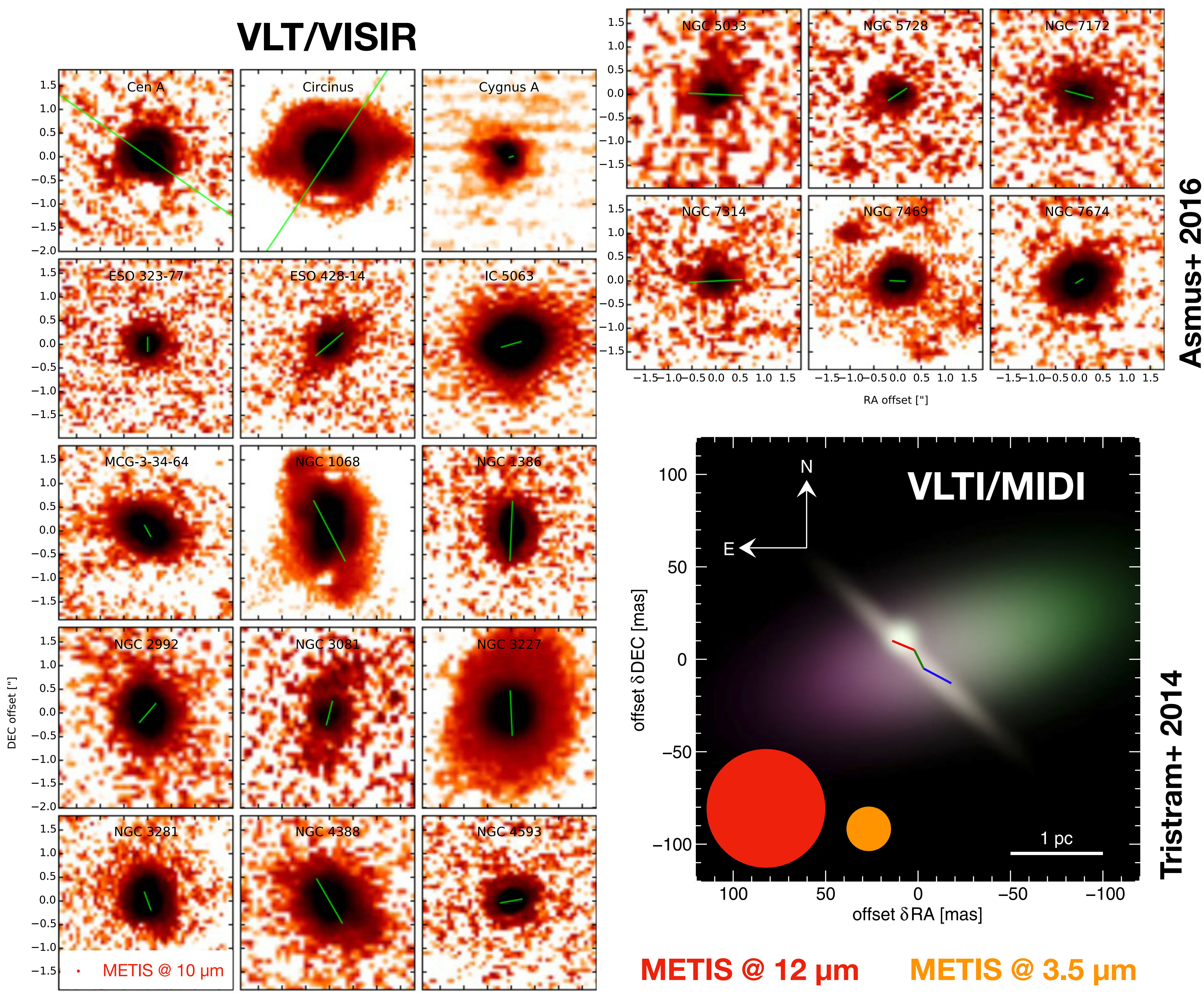
Cygnus A



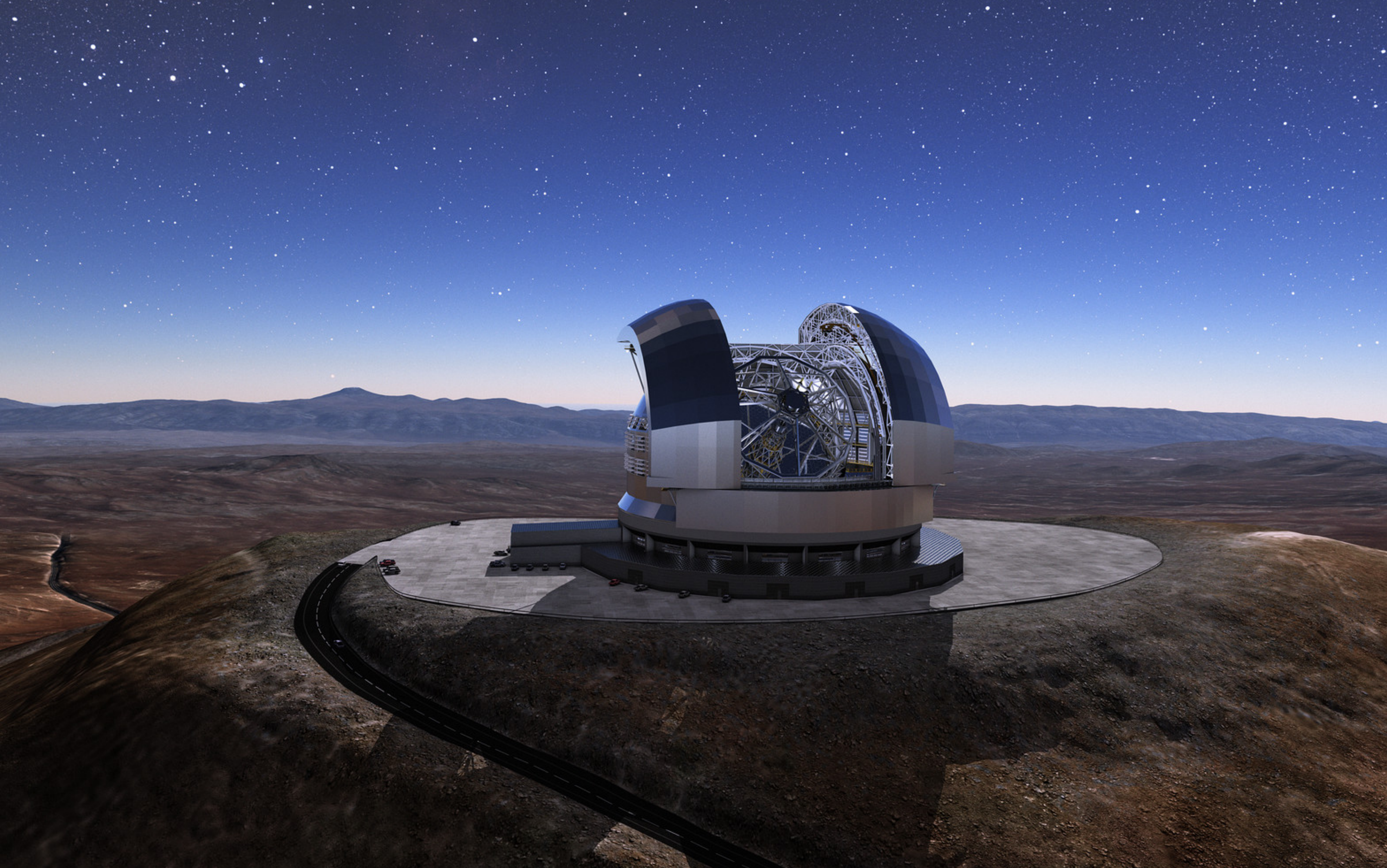
The Circinus galaxy

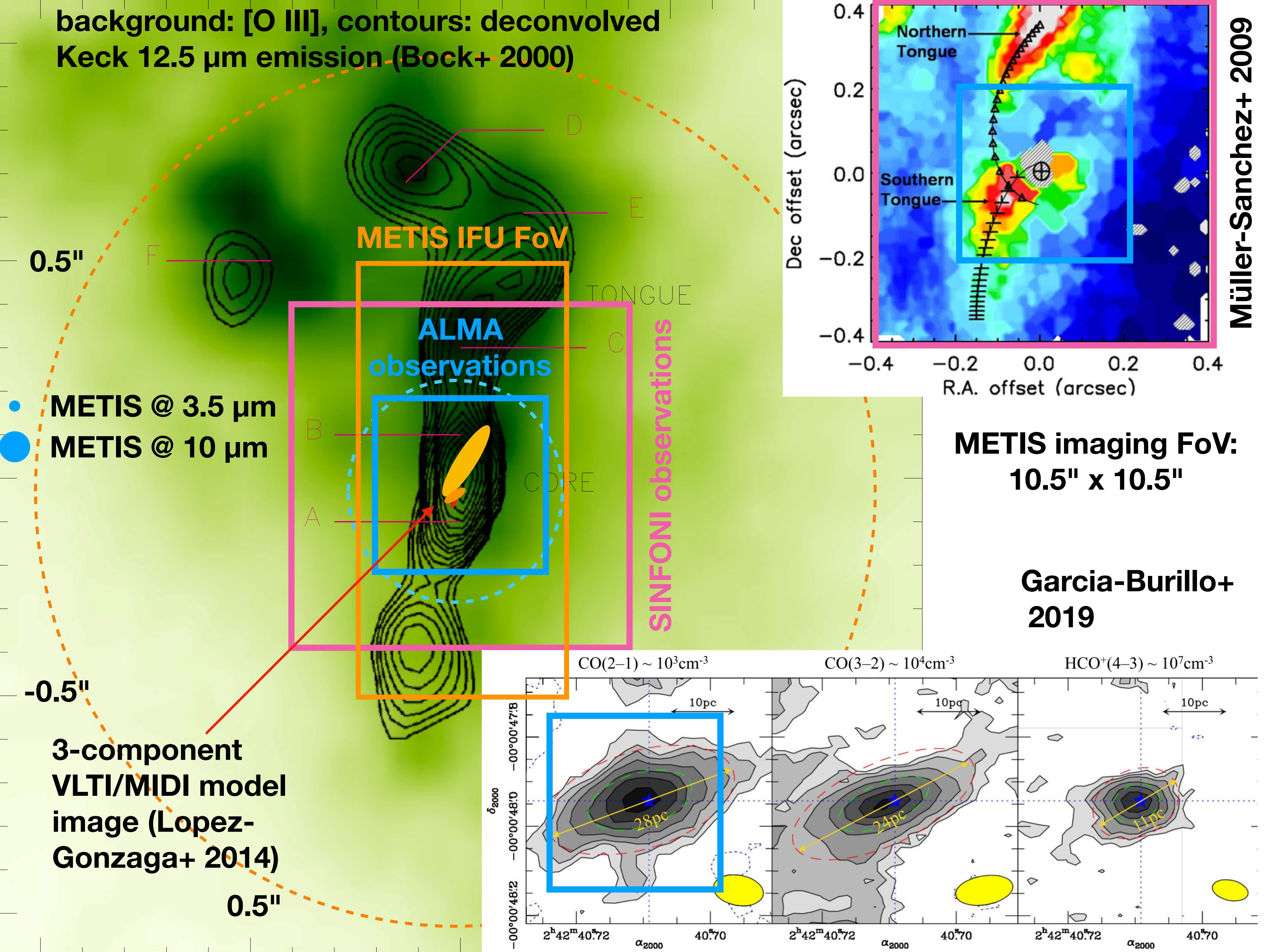


adapted from
Meisenheimer 2008


VLT/VISIR
Cen A
Circinus
Cygnus A
ESO 323-77
ESO 428-14
IC 5063
MCG-3-34-64
NGC 1068
NGC 1386
NGC 2992
NGC 3081
NGC 3227
NGC 3281
NGC 4388
NGC 4593
METIS @ 10 μm
DEC offset ["]
NGC 5033
NGC 5728
NGC 7172
NGC 7314
NGC 7469
NGC 7674
RA offset ["]
Asmus+ 2016
VLTI/MIDI
N
E
1 pc
offset δDEC [mas]
offset δRA [mas]
Tristram+ 2014
METIS @ 12 μm
METIS @ 3.5 μm

ELT/METIS + AGNs





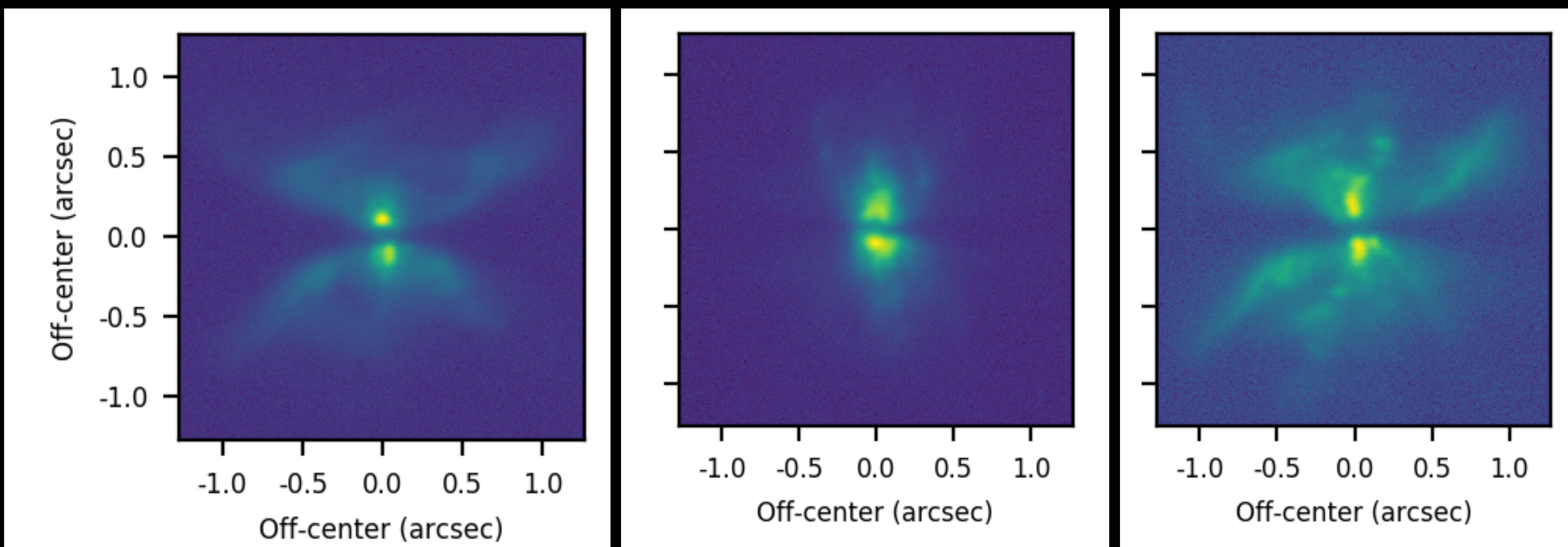
background: [O III], contours: deconvolved
Keck 12.5 µm emission (Bock+ 2000)
D
E
F
METIS IFU FoV
0.5"
TONGUE
C
ALMA
observations
SINFONI observations
METIS @ 3.5 µm
METIS @ 10 µm
B
CORE
A
-0.5"
3-component
VLTI/MIDI model
image (Lopez-
Gonzaga+ 2014)
0.5"
Northern
Tongue
Southern
Tongue
Dec offset (arcsec)
R.A. offset (arcsec)
0.4
0.2
0.0
−0.2
−0.4
Müller-Sanchez+ 2009
METIS imaging FoV:
10.5" x 10.5"
Garcia-Burillo+
2019
CO(2–1) ~ 10³cm⁻³
CO(3–2) ~ 10⁴cm⁻³
HCO⁺(4–3) ~ 10⁷cm⁻³
10pc
28pc
24pc
11pc
δ2000
α2000
−00°00'47.8
−00°00'48.0
−00°00'48.2
2h42m40.72
40.70

SimMETIS simulations

Radiation driven AGN feedback as seen by METIS

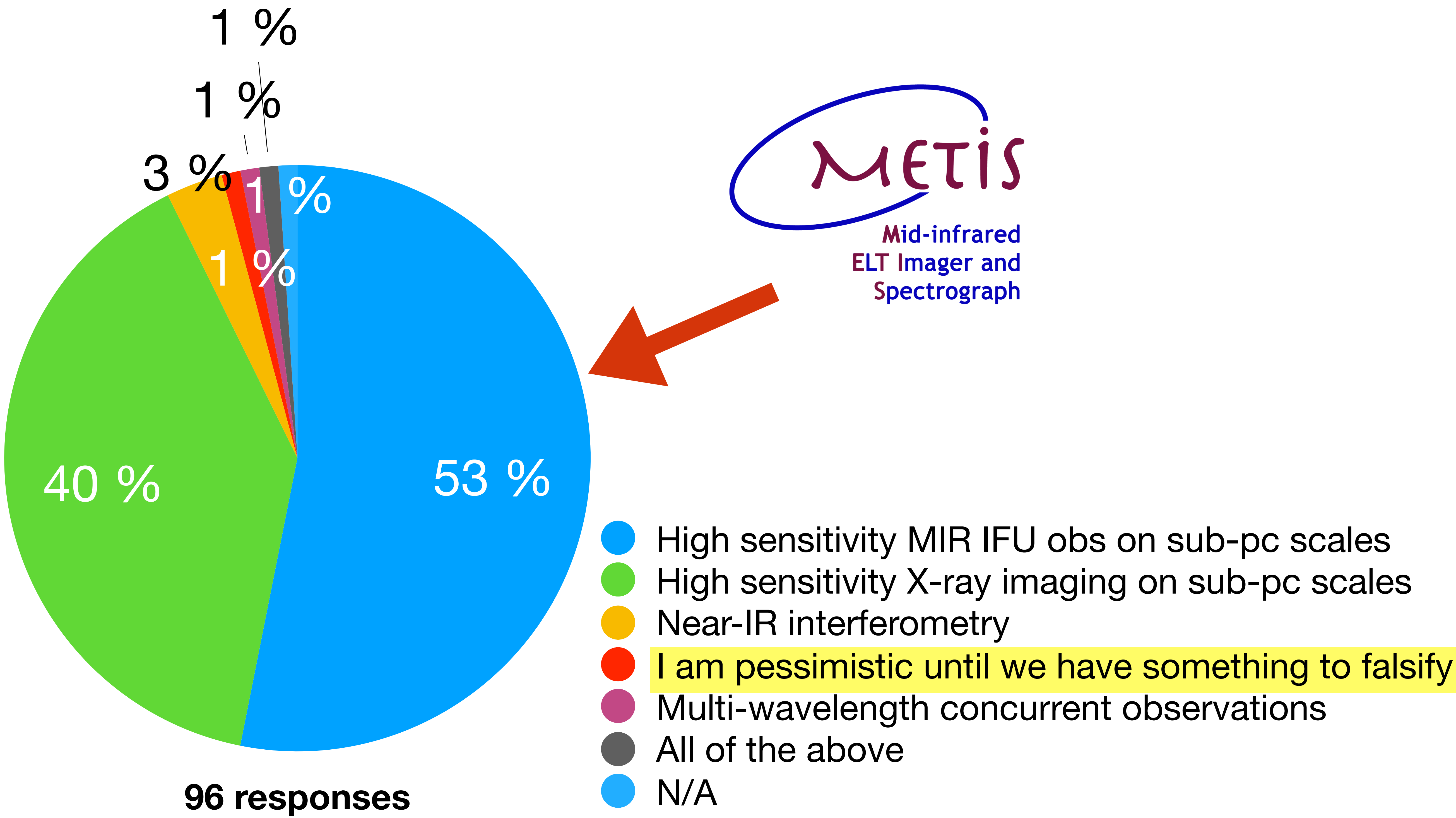
Eddington ratio

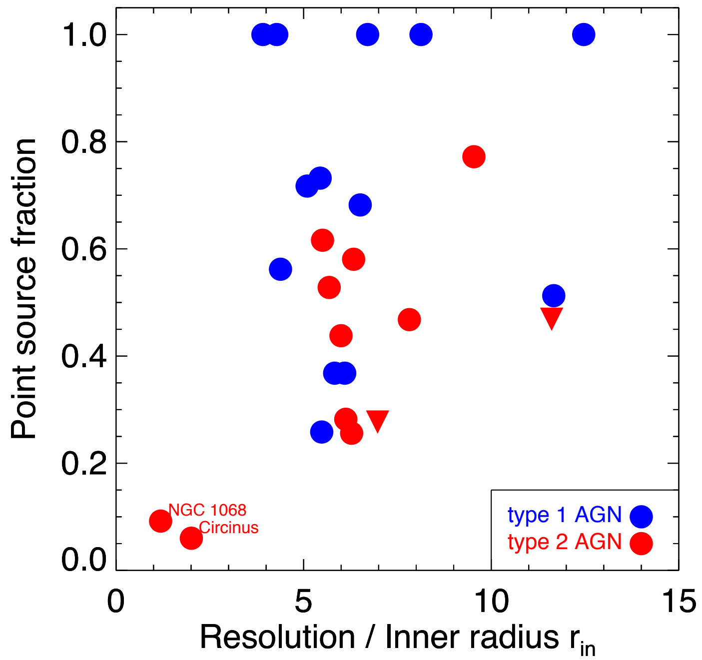
λ = 1% **λ = 10%** **λ = 20%**

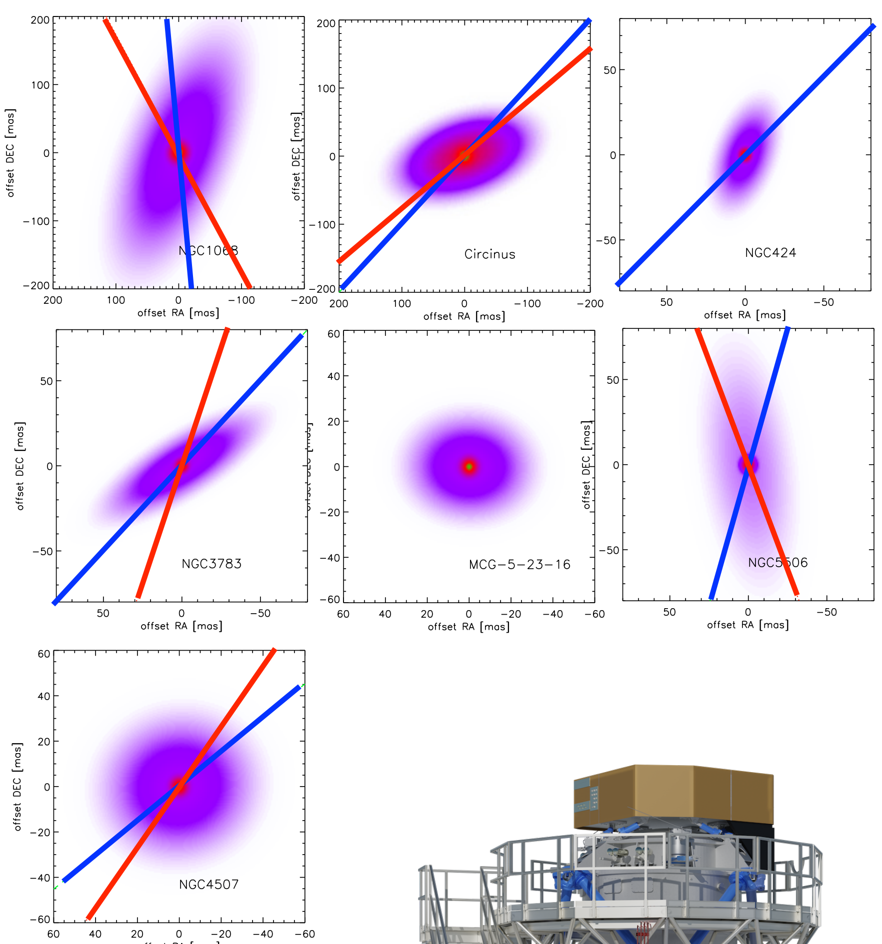


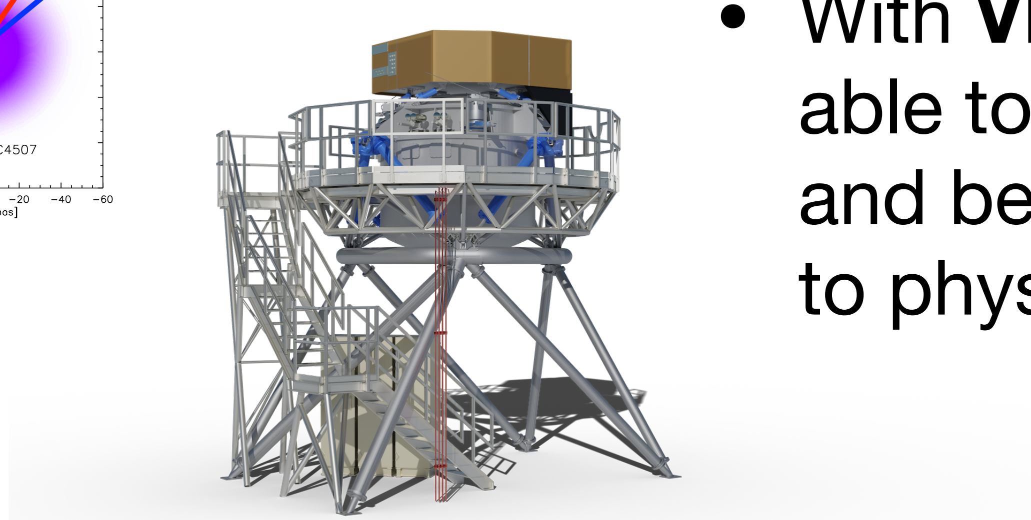
hydrodynamical model: Schartmann + 2014
SimMETIS simulation by Violeta Gamez-Rosas

Poll at TORUS 2018: What do you think is the single most fundamental missing future (~30 yr window) observation that would help us better understand the torus and its environment?









Summary

Mid-Infrared Interferometry of AGNs

- Using **mid-IR interferometry** we have resolved the nuclear dust structures in ~ 30 nearby AGNs. On parsec-scale, AGN "tori" structurally differ from each other.

- In a handful of bright sources with good (u,v) coverage we can constrain elongated Gaussian components; most of them are oriented in the **polar direction**.

- With **VLTI/MATISSE** and **ELT/METIS** we will be able to resolve the base of the AGN outflow and begin to relate the torus phenomenology to physical parameters of the AGN.