THE EMISSION AND DISTRIBUTION OF DUST OF THE TORUS OF NGC 1068

ENRIQUE LOPEZ RODRIGUEZ

Instrument Scientist (HAWC+)

Stratospheric Observatory For Infrared Astronomy (SOFIA) / NASA

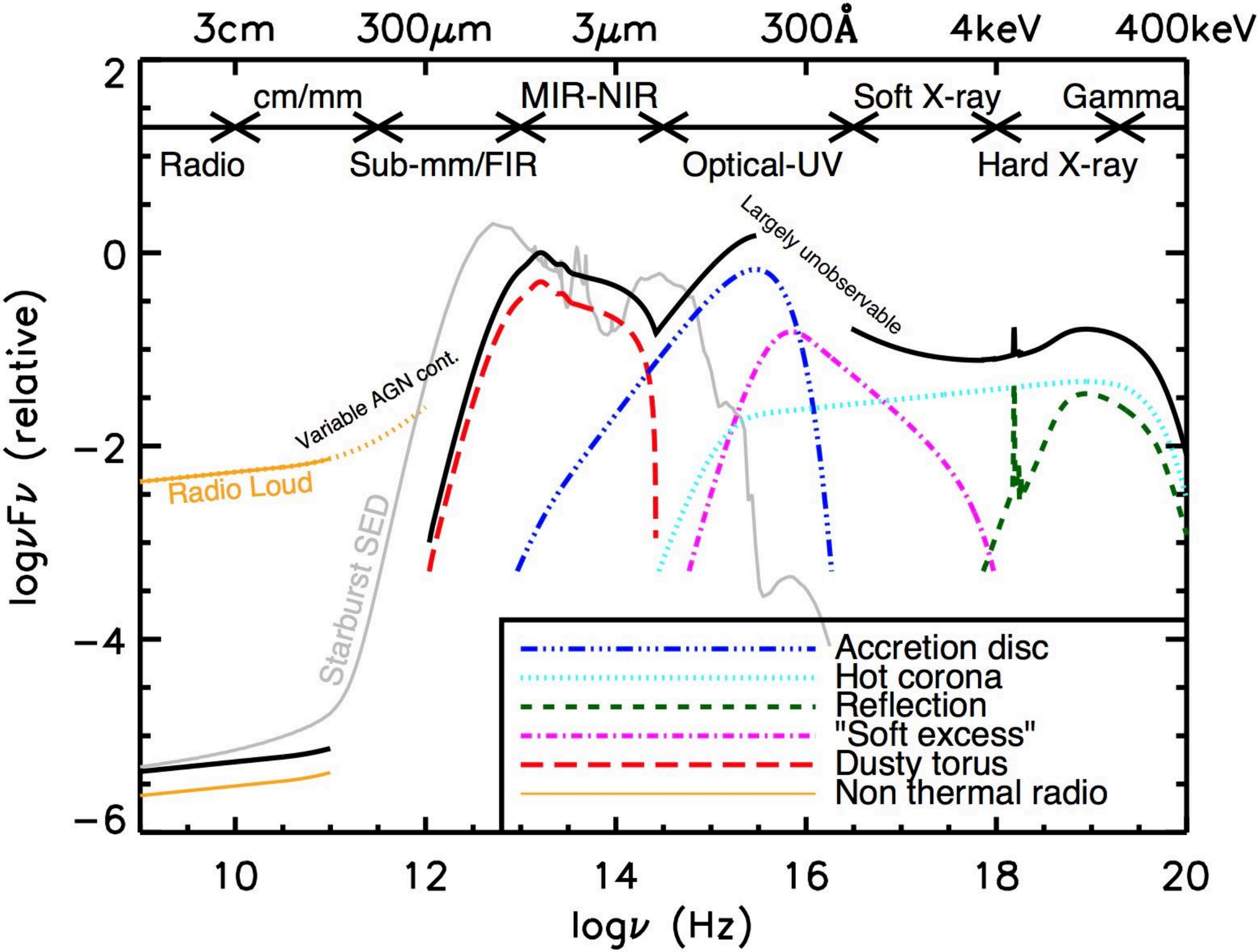
elopezrodriguez@nasa.gov

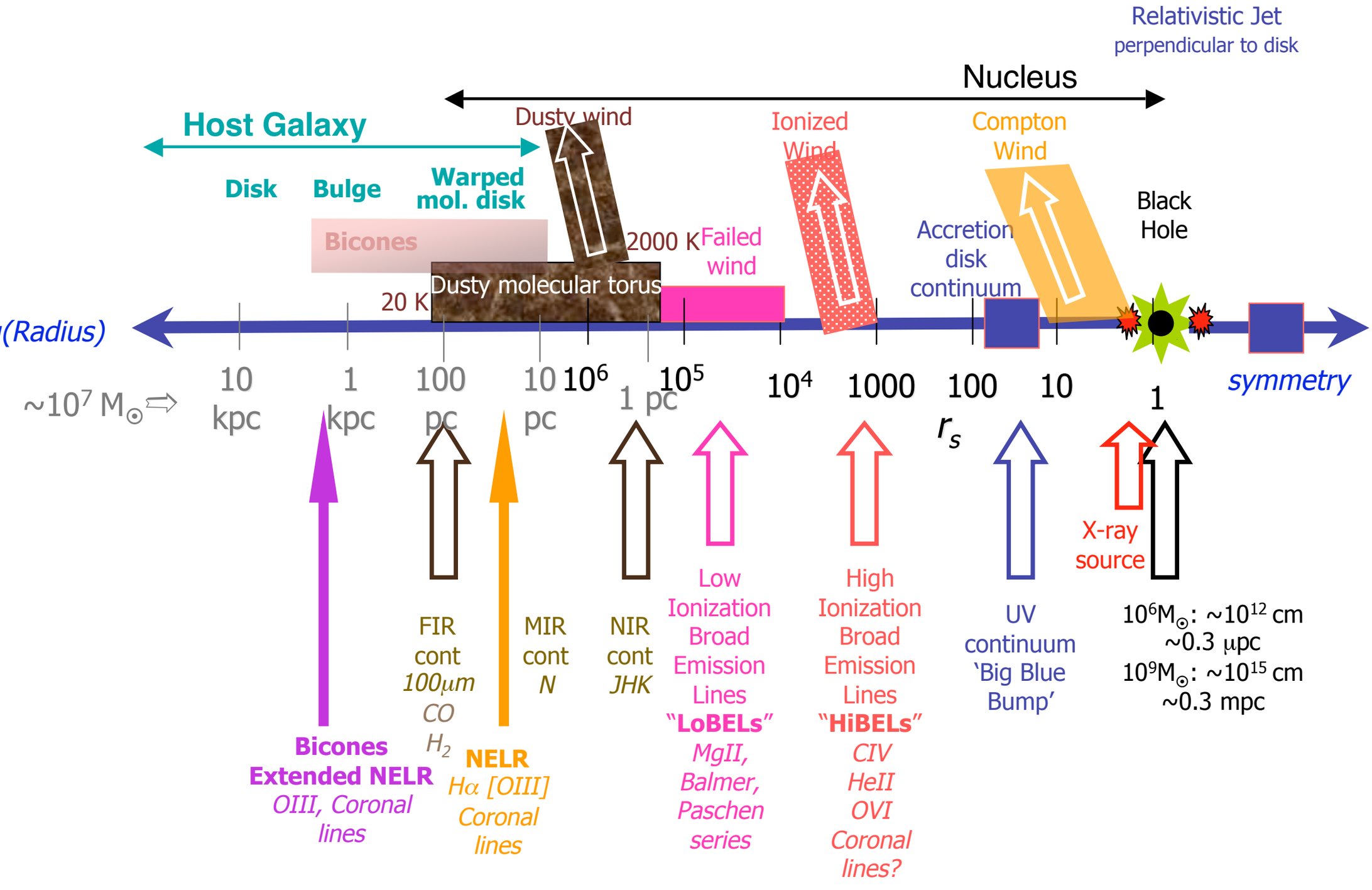
COLLABORATORS:

Alonso-Herrero, A. (CSIC)
Efstathiou, A. (U. of Cyprus)
Fuller, L. (UT San Antonio)
Ichikawa, R. (Columbia U.)
Levenson, N. (STScI)
Nikutta R. (NOAO)
Packham, C. (UT San Antonio)
Radomski, J. (SOFIA)
Ramirez, E. (INAOE)
Ramos Almeida C. (IAC)
and HAWC+ Science Team

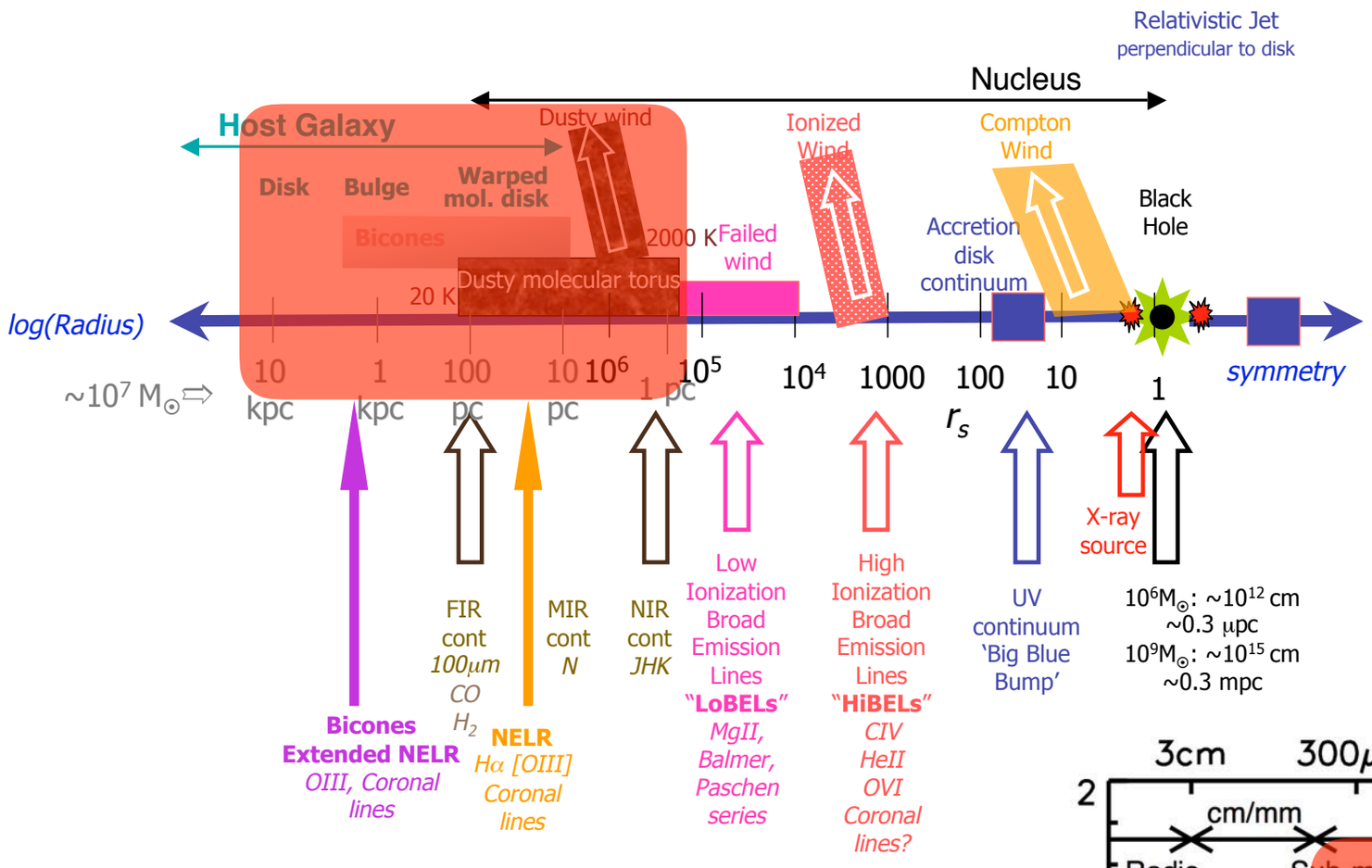
THE TORUS

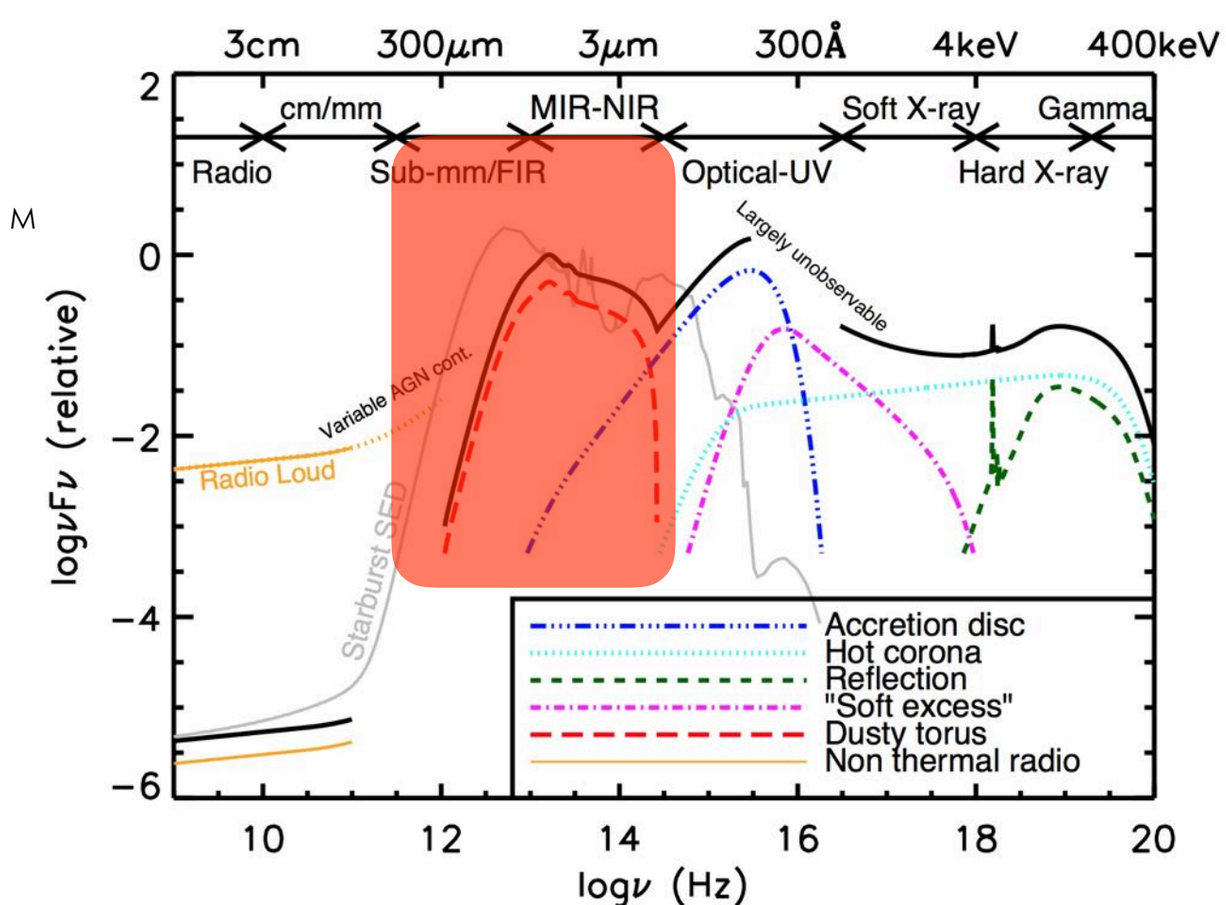
ACTIVE GALACTIC NUCLEI


3cm
300μm
3μm
300Å
4keV
400keV
cm/mm
MIR-NIR
Soft X-ray
Gamma
Radio
Sub-mm/FIR
Optical-UV
Hard X-ray
Largely unobservable
Variable AGN cont.
Radio Loud
Starburst SED
Accretion disc
Hot corona
Reflection
"Soft excess"
Dusty torus
Non thermal radio
2
0
−2
−4
−6
10
12
14
16
18
20
logνFν (relative)
logν (Hz)



Martin Elvis, September 2007


Relativistic Jet
perpendicular to disk
Nucleus
Host Galaxy
Disk
Bulge
Warped mol. disk
Bicones
Dusty wind
Dusty molecular torus
2000 K
20 K
Failed wind
Ionized Wind
Compton Wind
Accretion disk continuum
Black Hole
log(Radius)
~10^7 M⊙
10 kpc
1 kpc
100 pc
10 pc
10^6
1 pc
10^5
10^4
1000
100
10
1
r_s
symmetry
FIR cont 100μm CO
MIR cont N
NIR cont JHK
Low Ionization Broad Emission Lines "LoBELs" MgII, Balmer, Paschen series
High Ionization Broad Emission Lines "HiBELs" CIV HeII OVI Coronal lines?
UV continuum 'Big Blue Bump'
X-ray source
10^6M⊙: ~10^12 cm ~0.3 μpc
10^9M⊙: ~10^15 cm ~0.3 mpc
Bicones
Extended NELR
OIII, Coronal lines
H2
NELR
Hα [OIII]
Coronal lines


3cm
300μm
3μm
300Å
4keV
400keV
cm/mm
MIR-NIR
Soft X-ray
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Radio
Sub-mm/FIR
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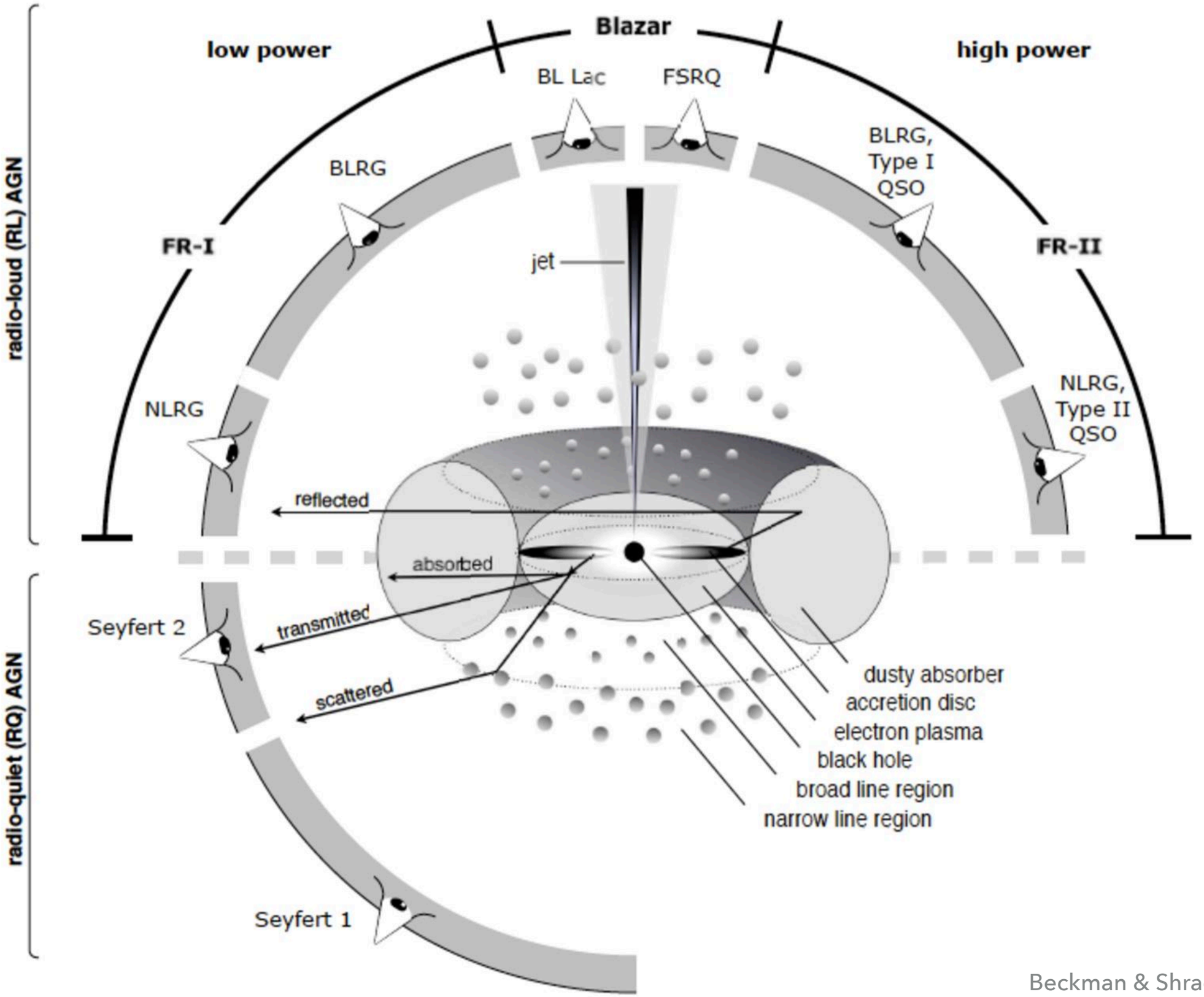
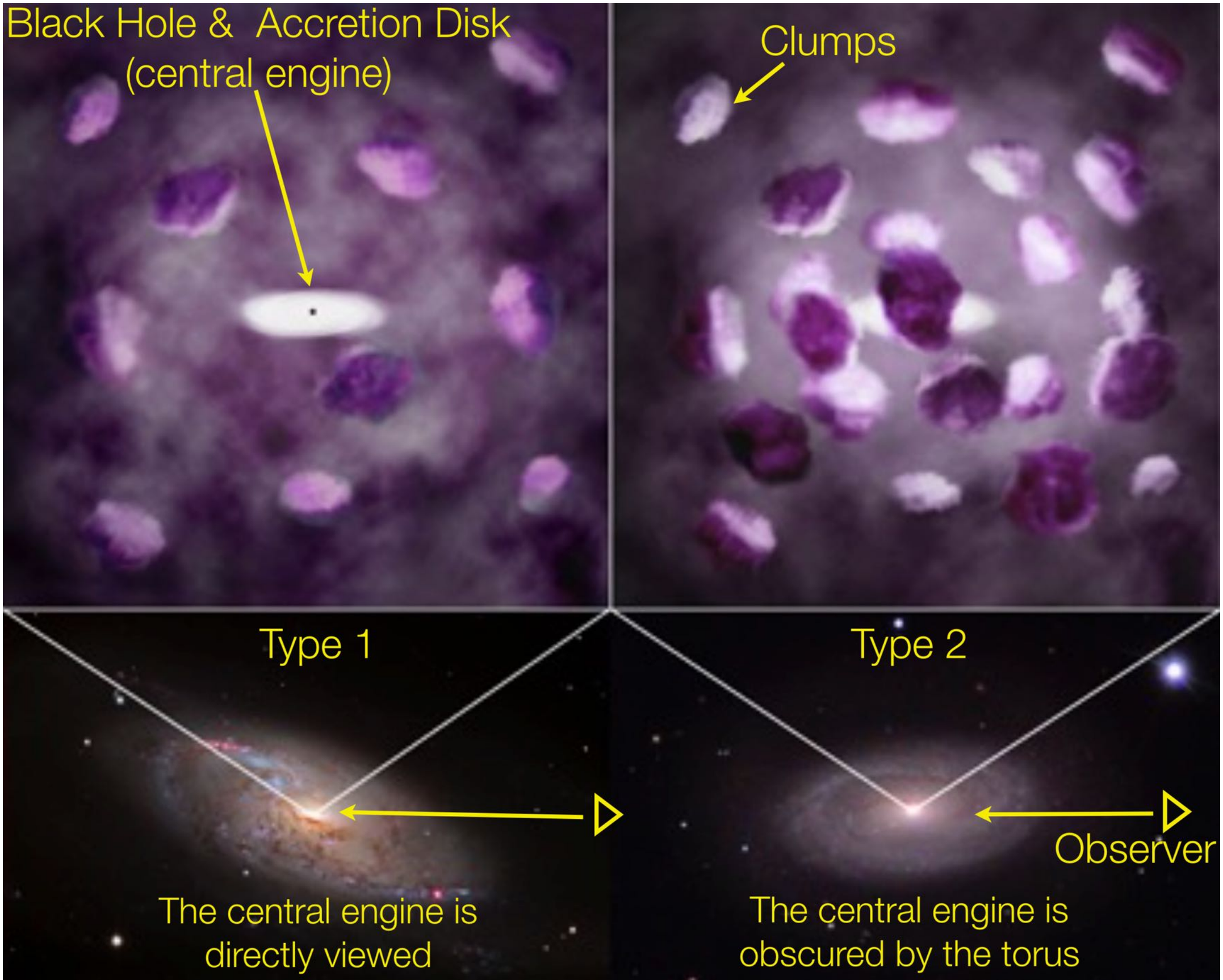
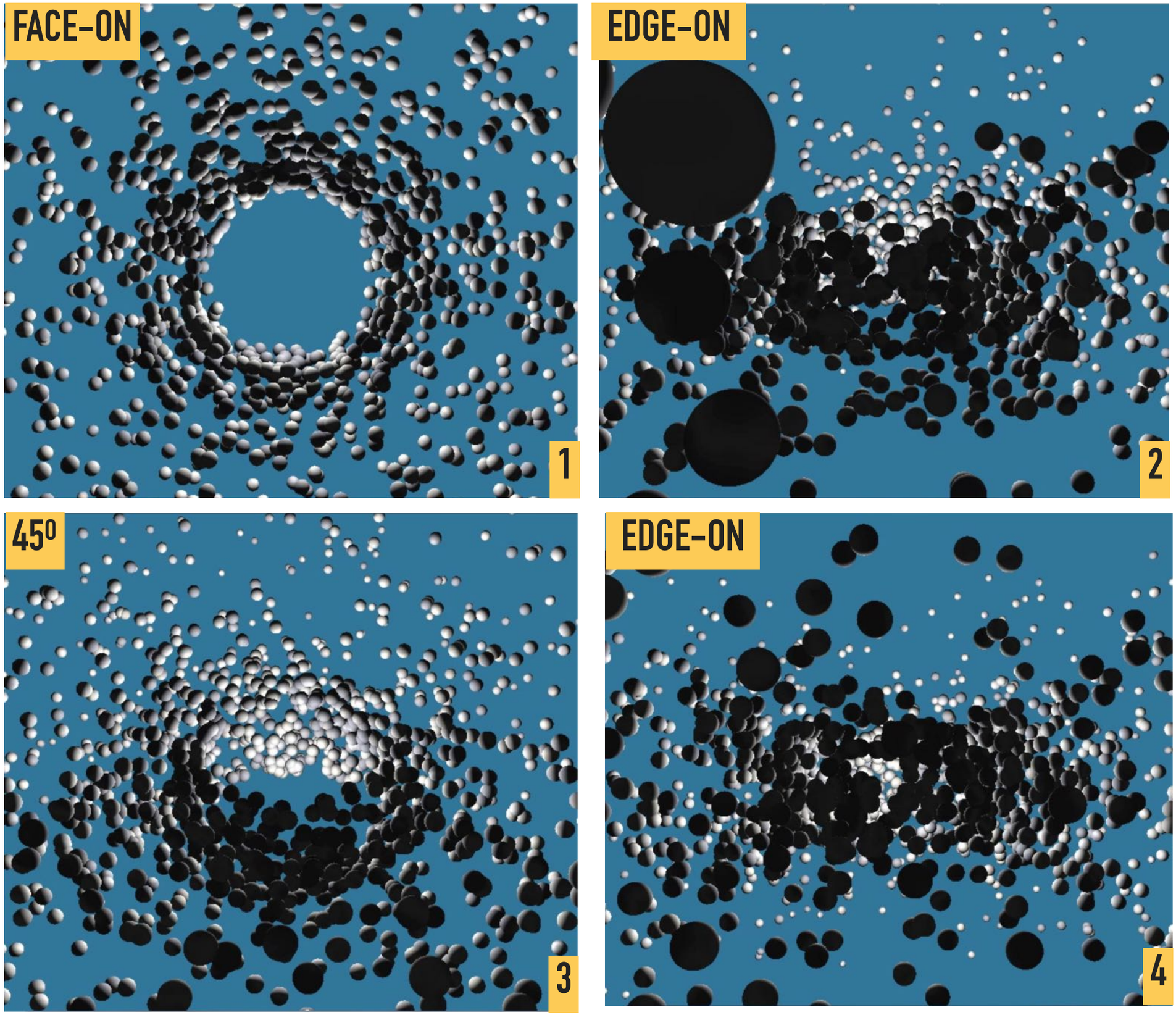
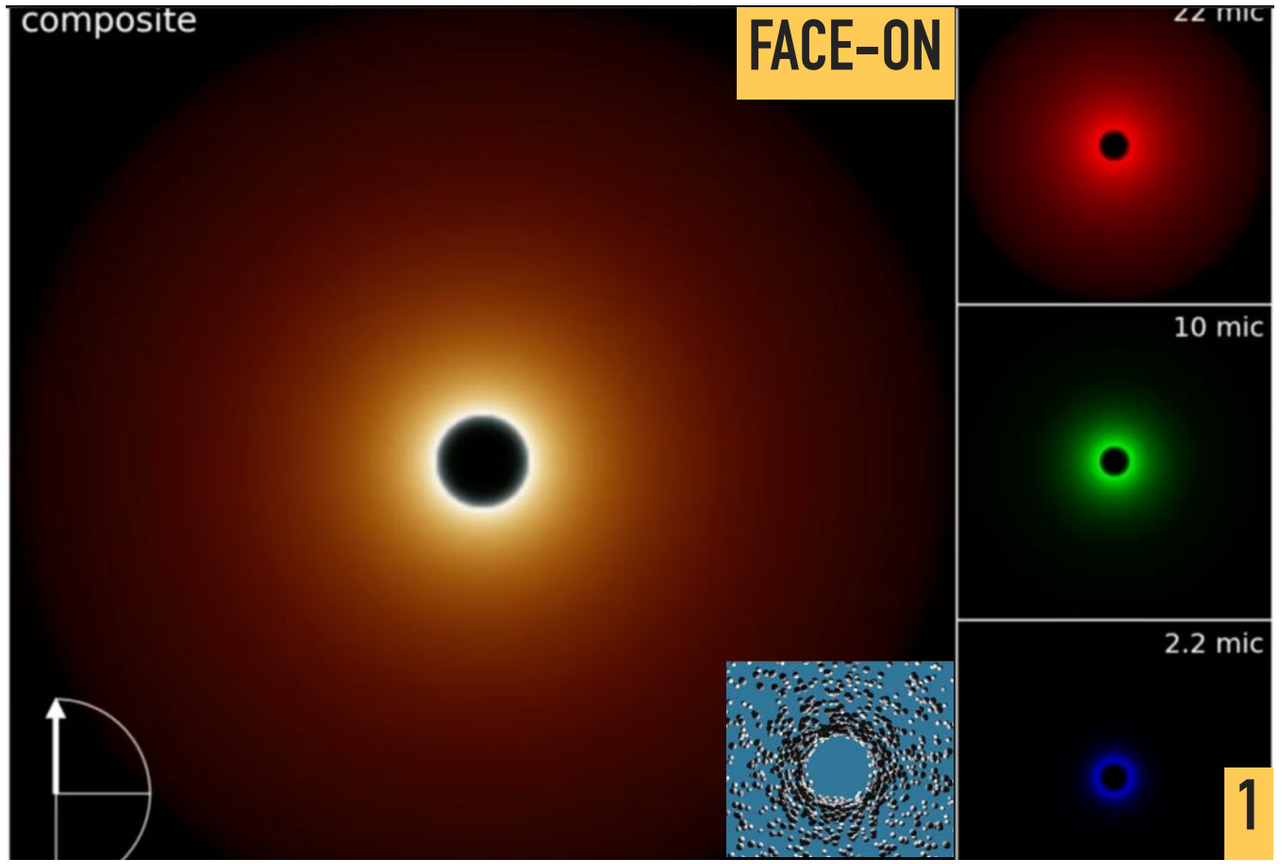


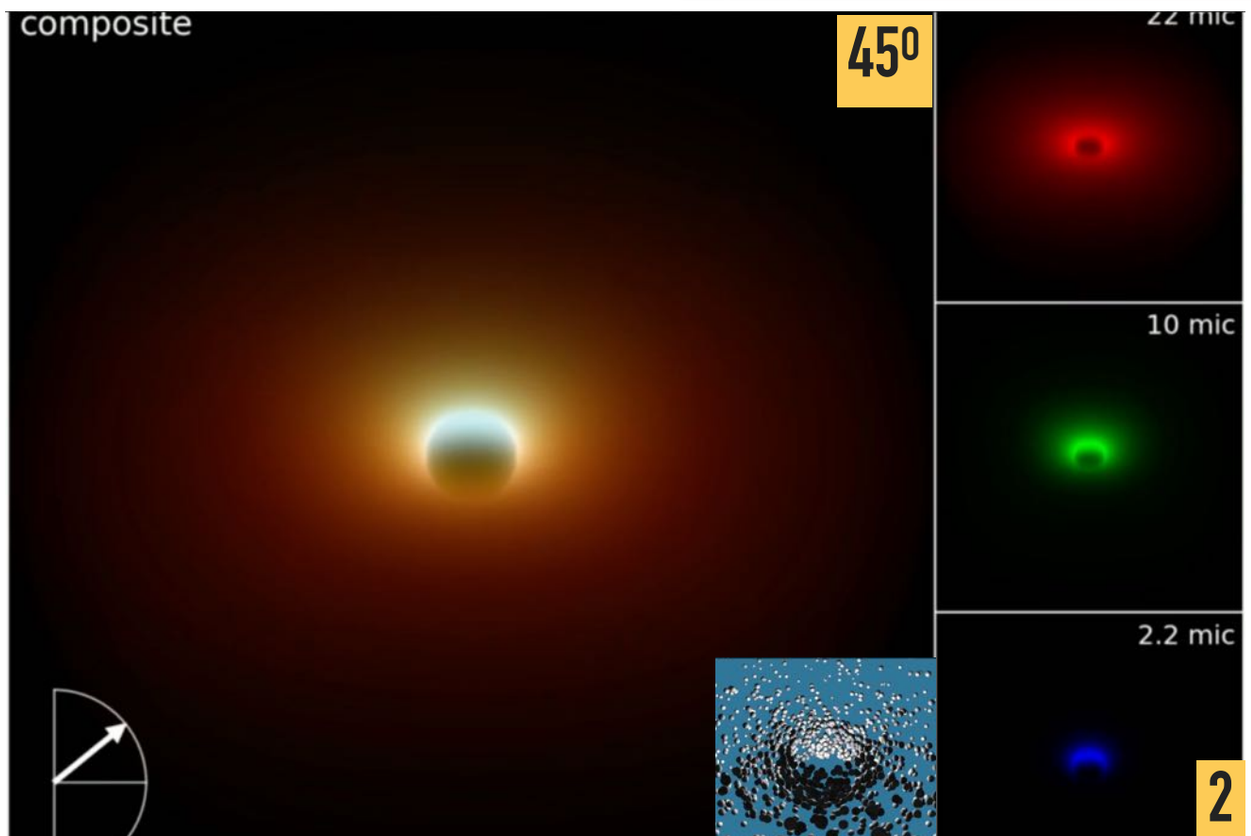
Beckman & Shrader et al. (2012)

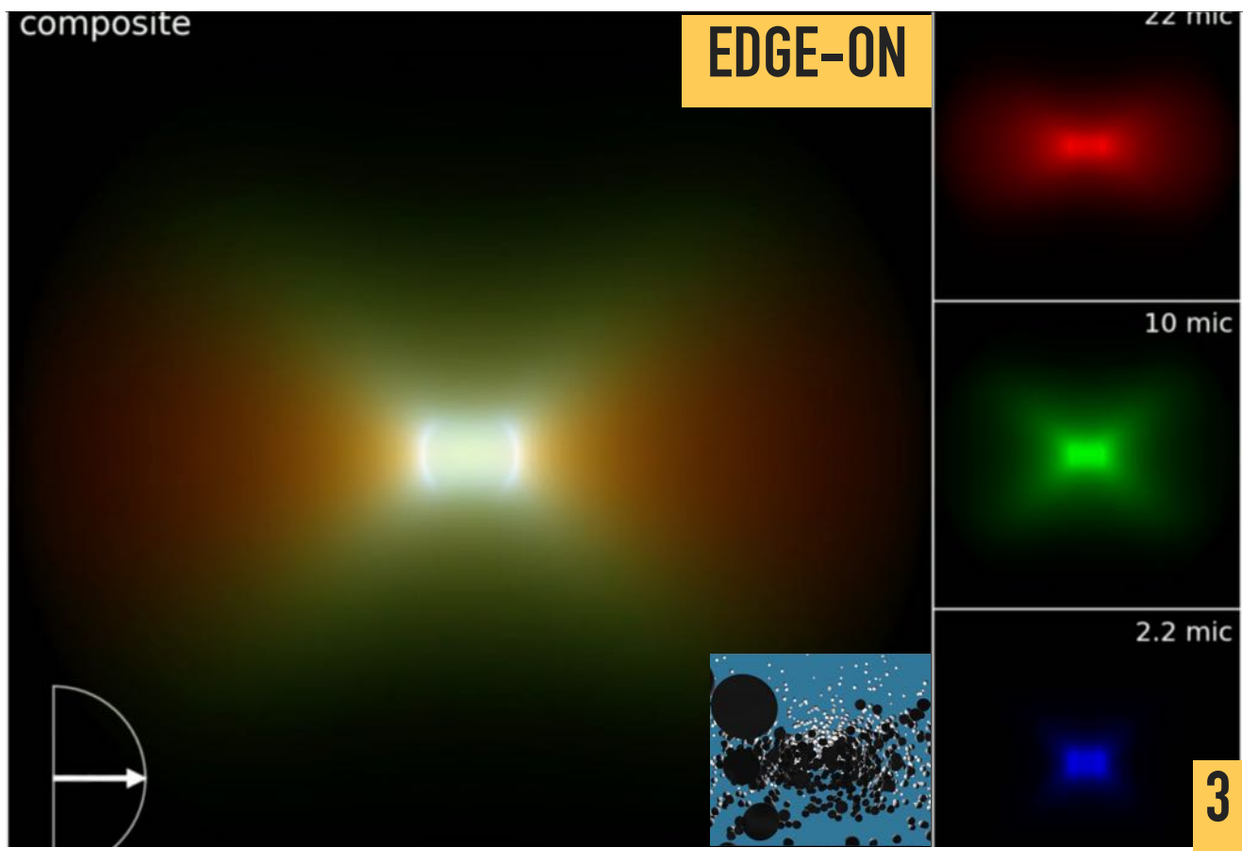

Black Hole & Accretion Disk
(central engine)
Clumps
Type 1
Type 2
Observer
The central engine is
directly viewed
The central engine is
obscured by the torus



Credit: Nikutta R.

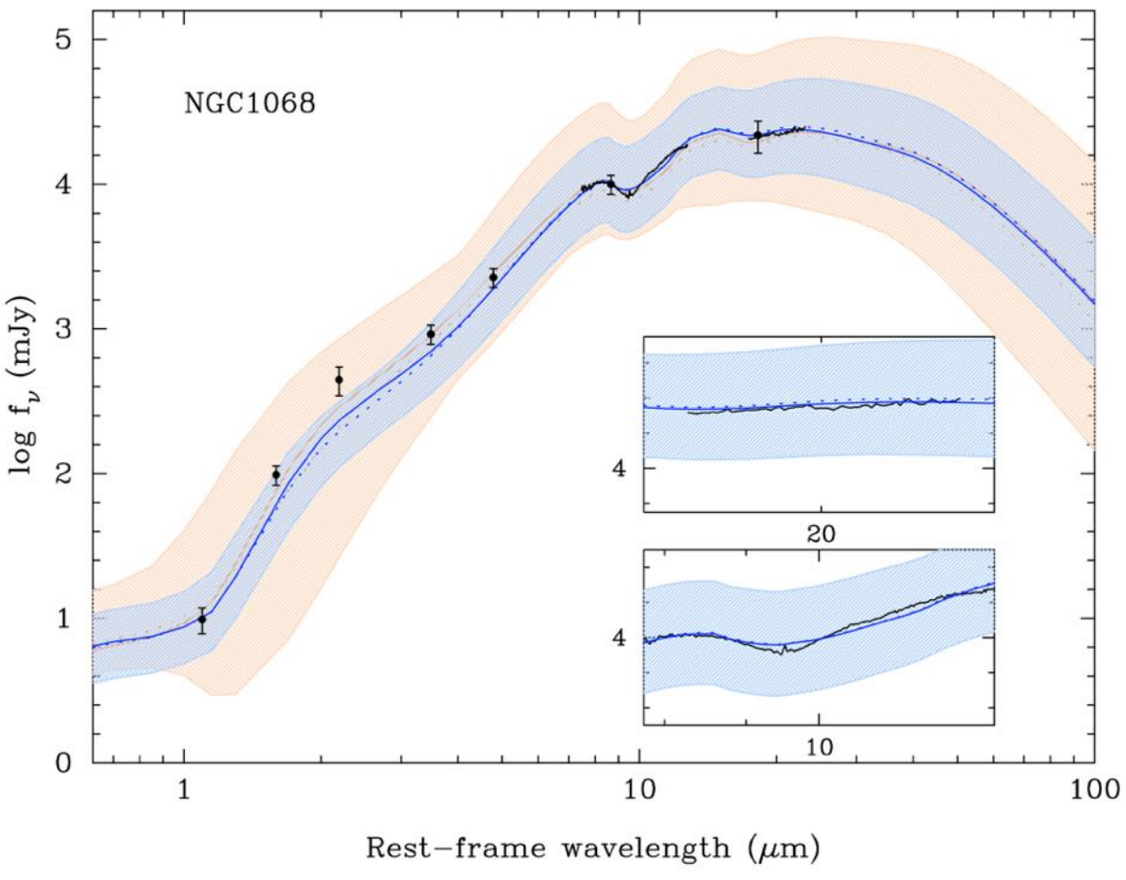


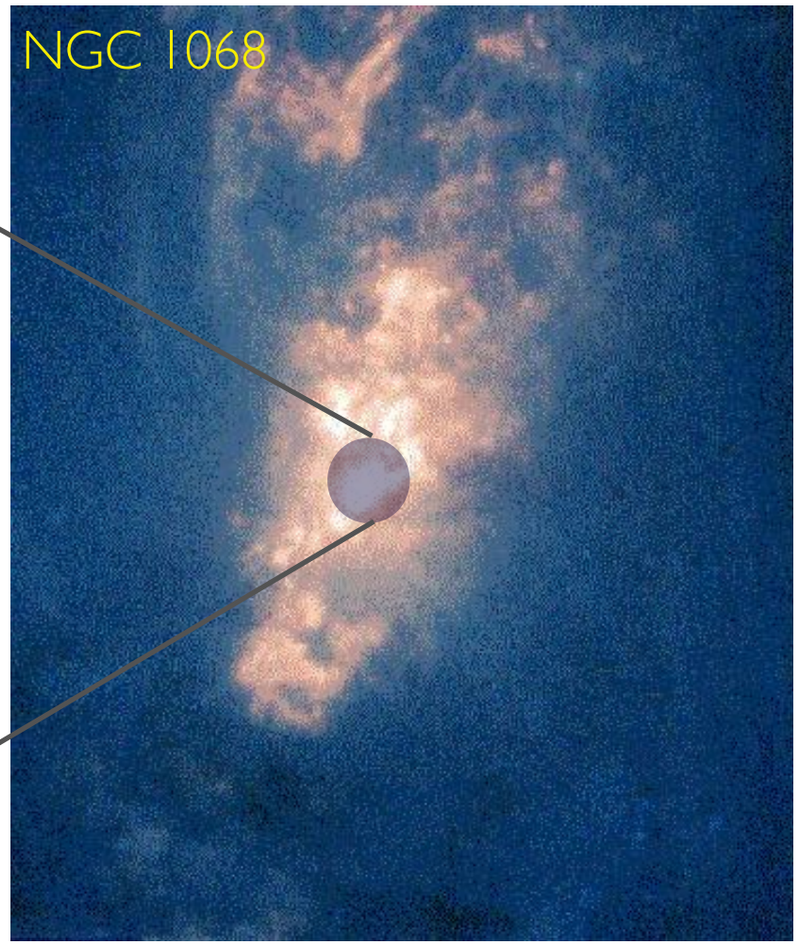




Credit: Nikutta R.

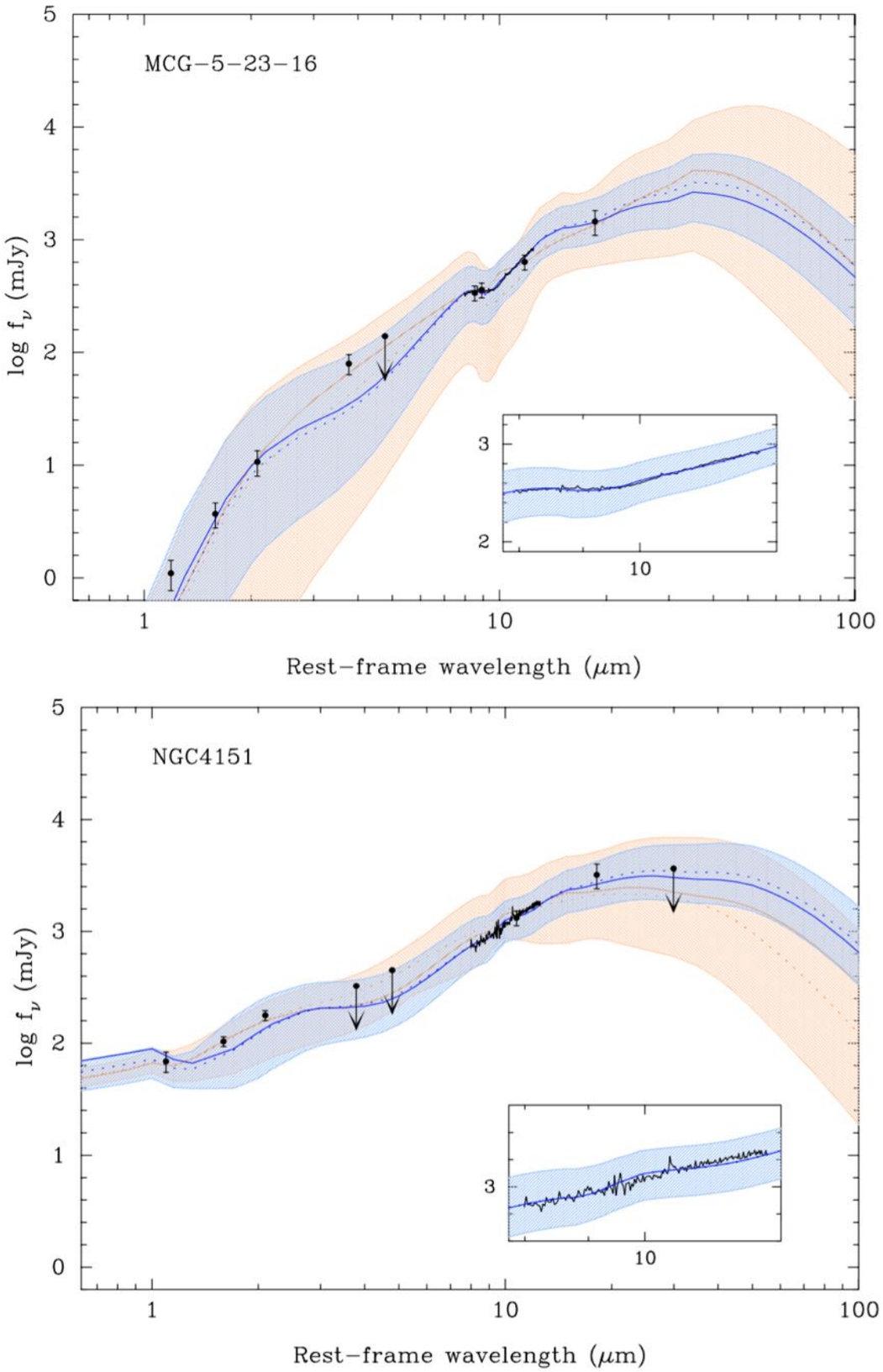
- The isolated emission from the nucleus using 10-m class telescopes can be reproduced using CLUMPY torus models.

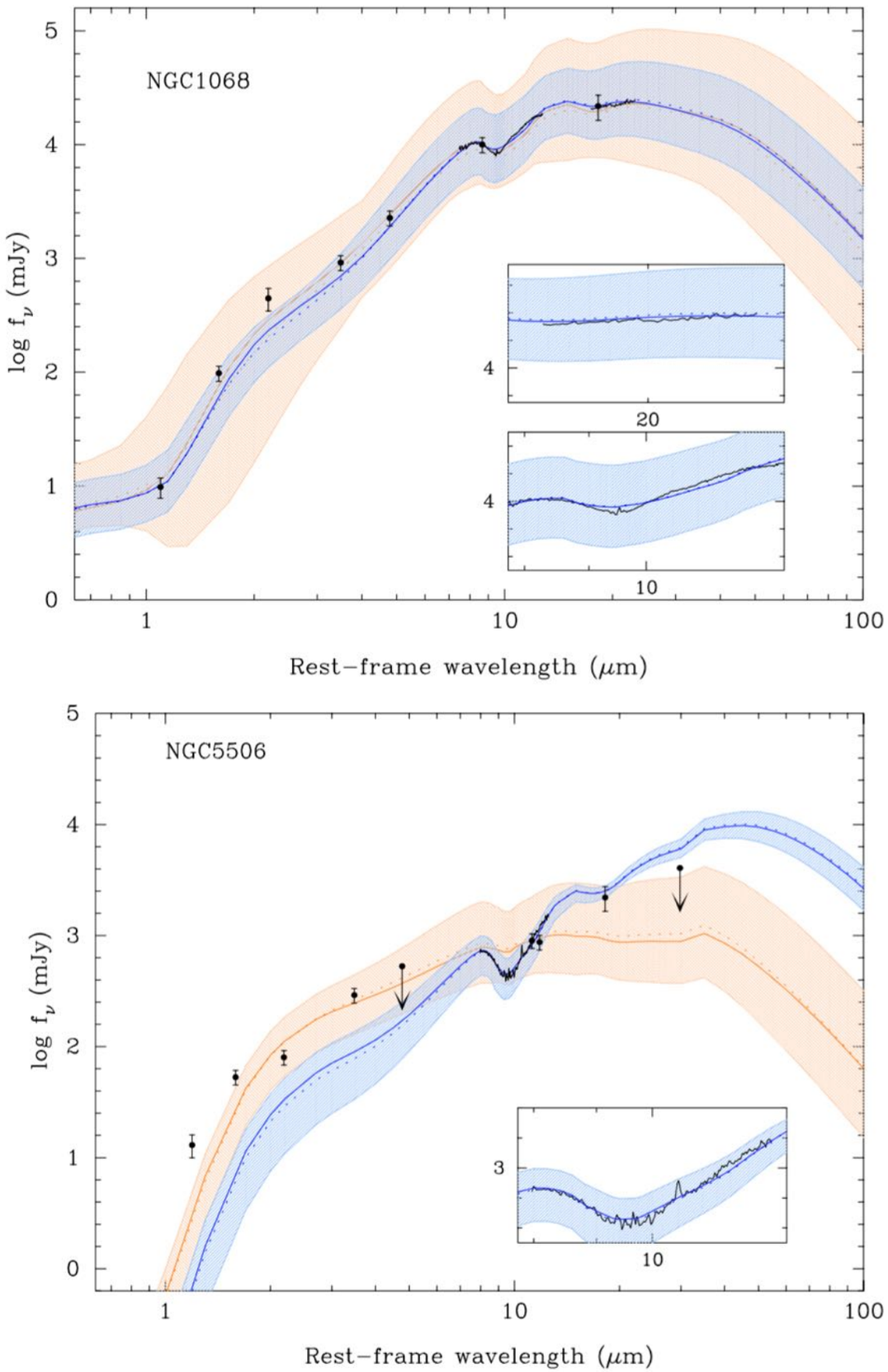




Alonso-Herrero et al. (2011)

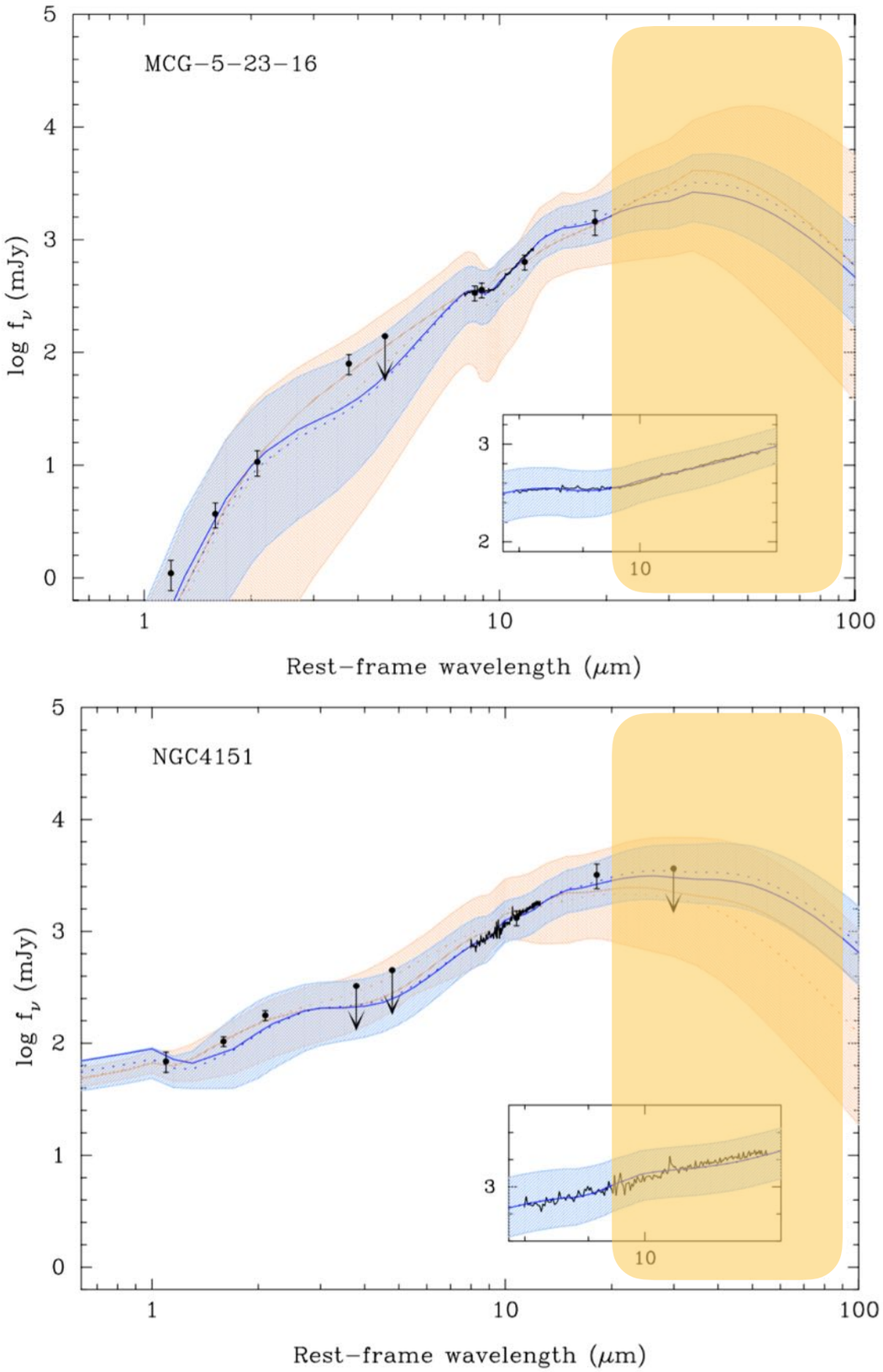
Torus models using CLUMPY (Nenkova et al. 2002, 2008a,b)

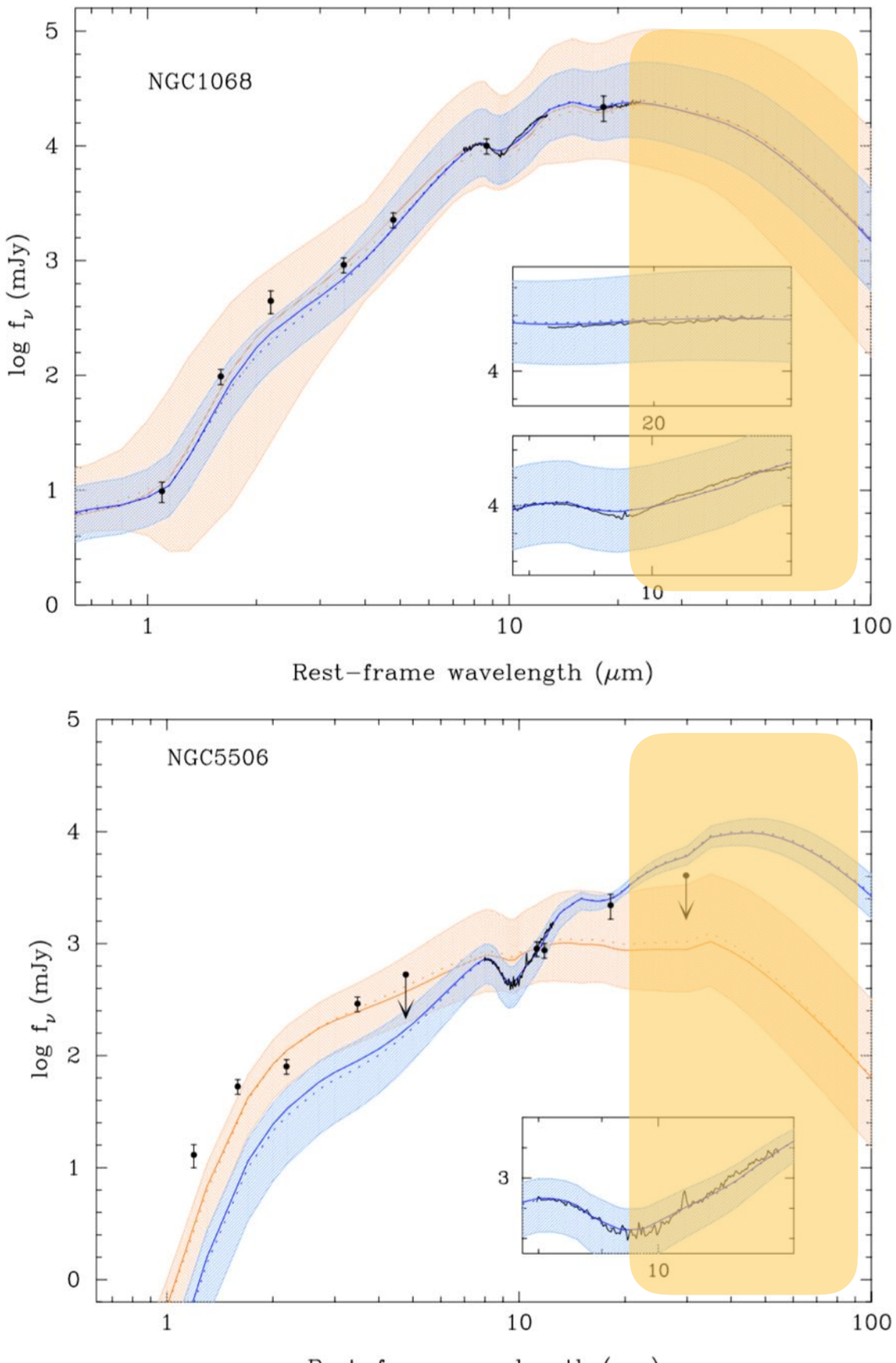




Alonso-Herrero et al. (2011)

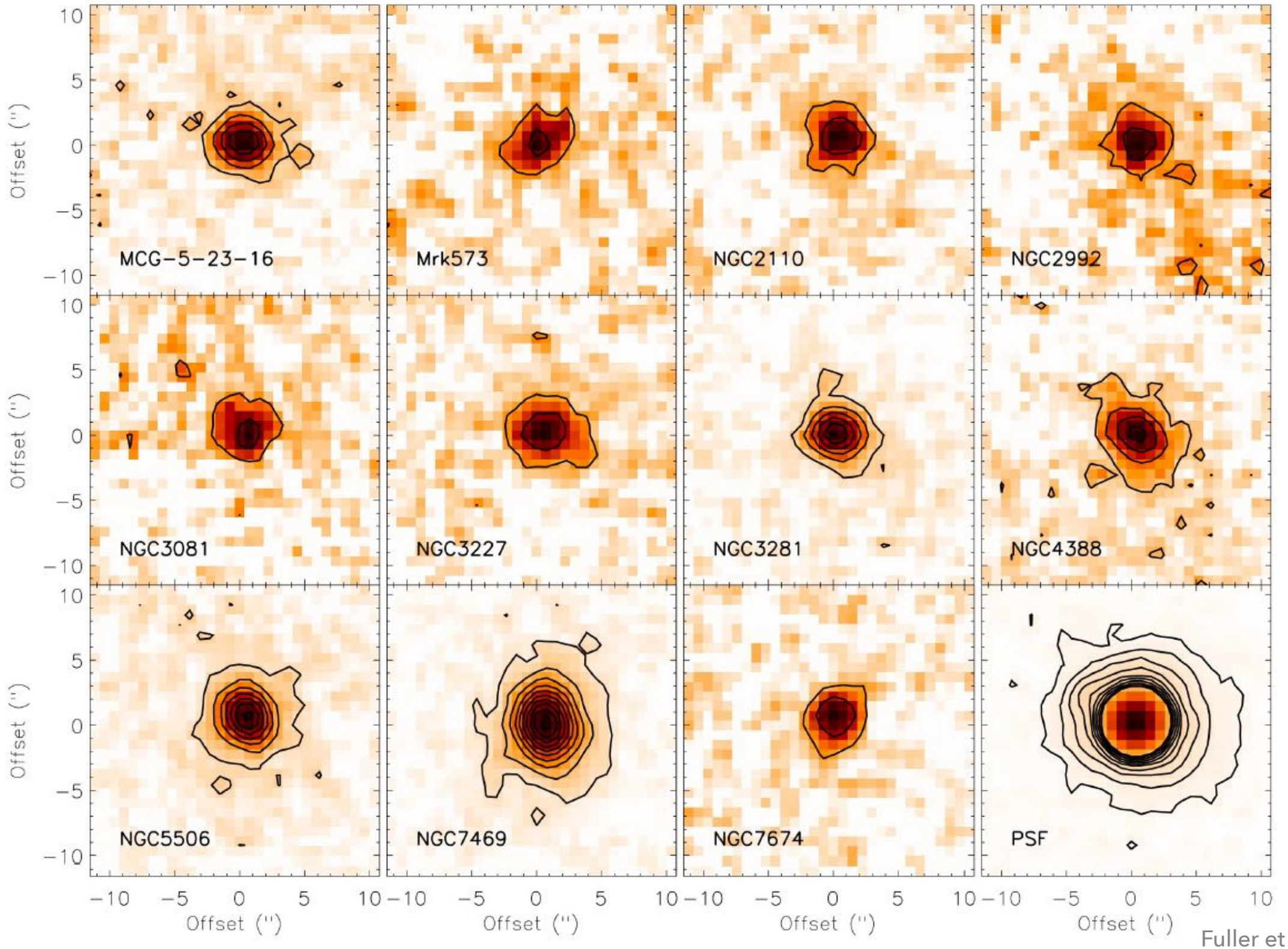
AGN SED: LACK OF FIR OBSERVATIONS WITH MODERATED RESOLUTIONS





Alonso-Herrero et al. (2011)

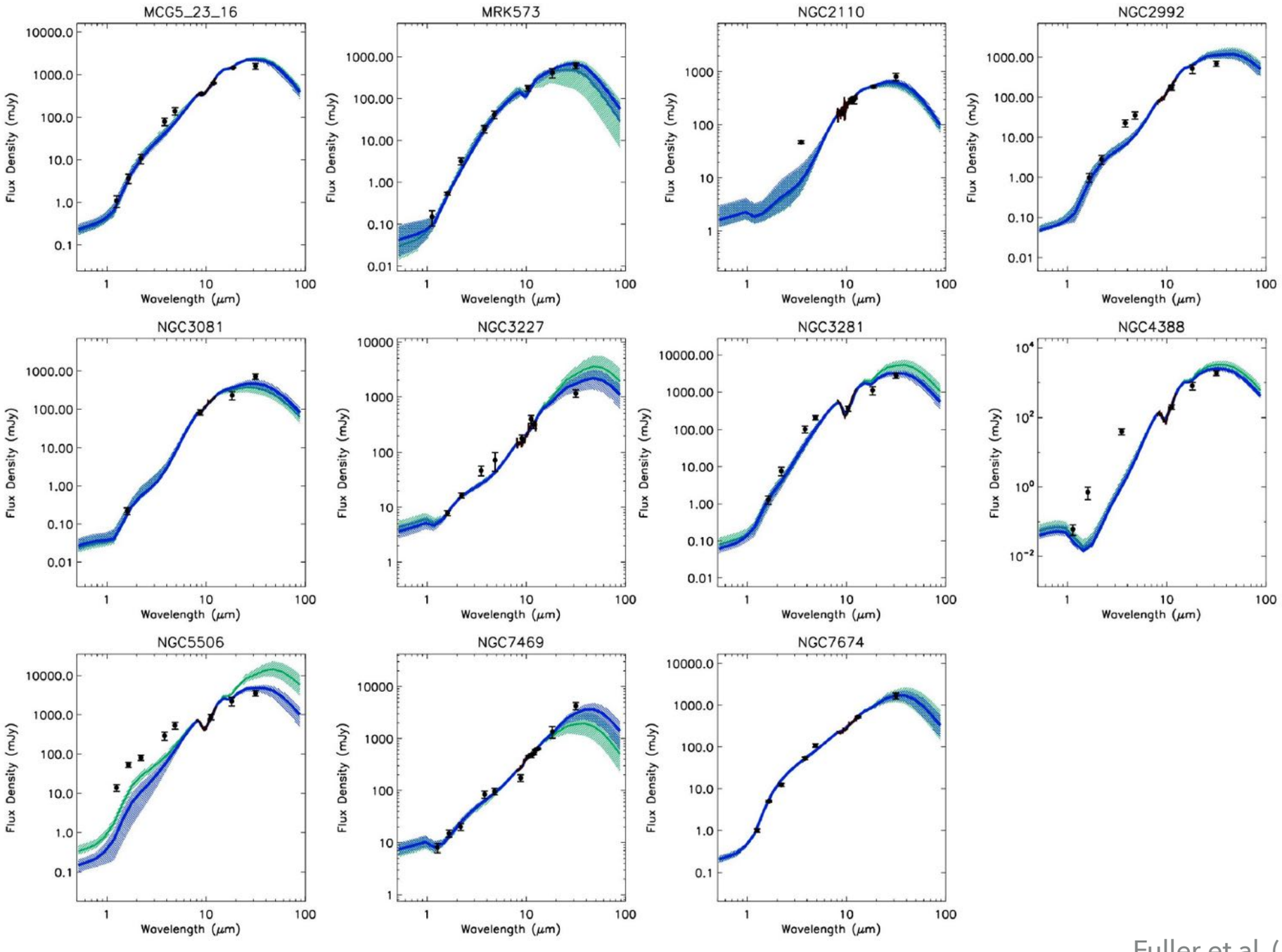
31.5 um imaging observations of AGN using FORCAST



Fuller et al. (2016)

31.5 um observations:

- Characterize the warm dust of the torus.
- Sample the peak emission of the torus, suggesting to occurs in the 30-40 um range.
- Reduce the uncertainties of the inferred family of CLUMPY torus models

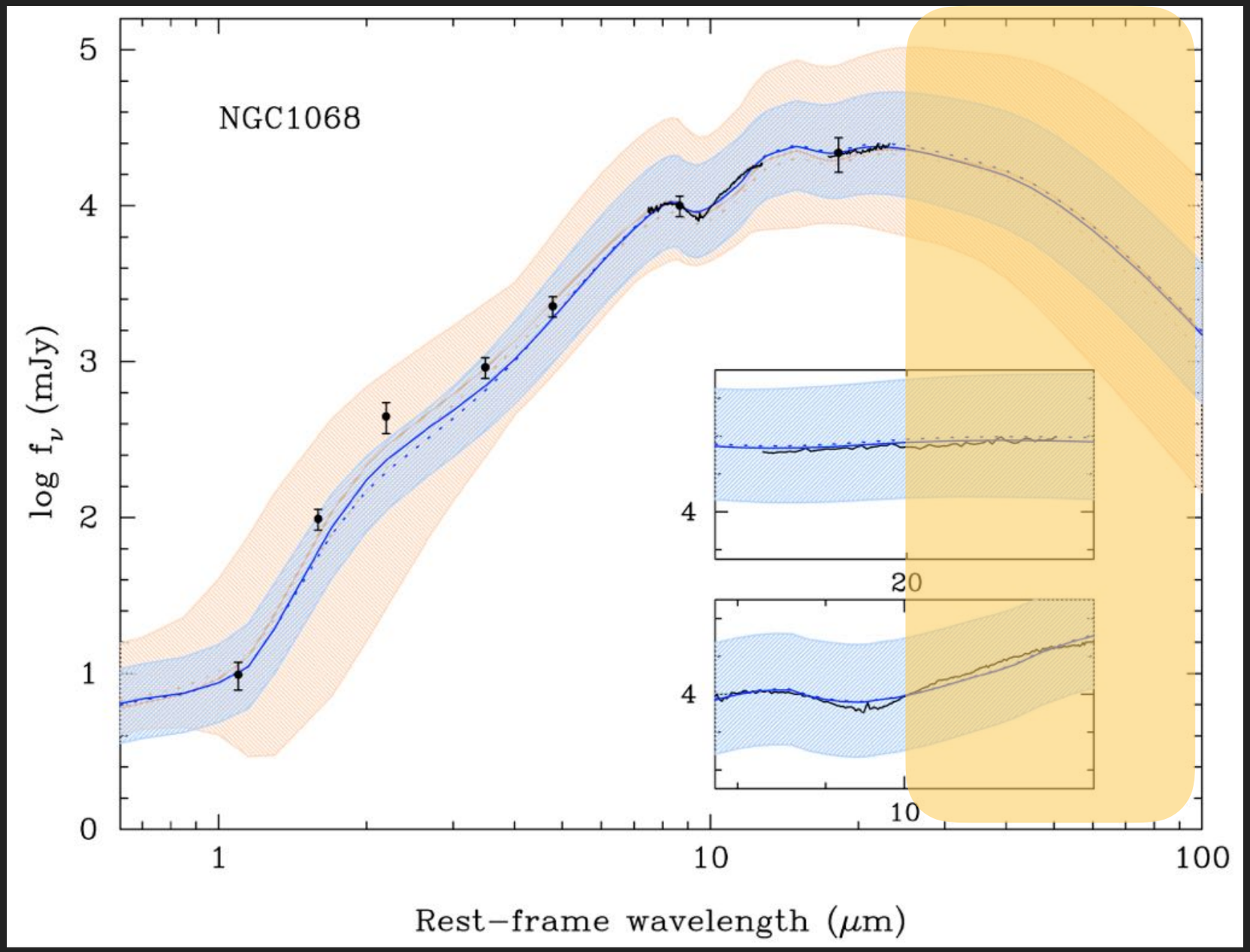


Fuller et al. (2016)

Characterizing the warm/cold dust in the AGN torus:

Lack of 20-100 um coverage at moderate angular resolutions:

- Missing warm and cold dust in the torus
- How this affect the torus emission and morphology?



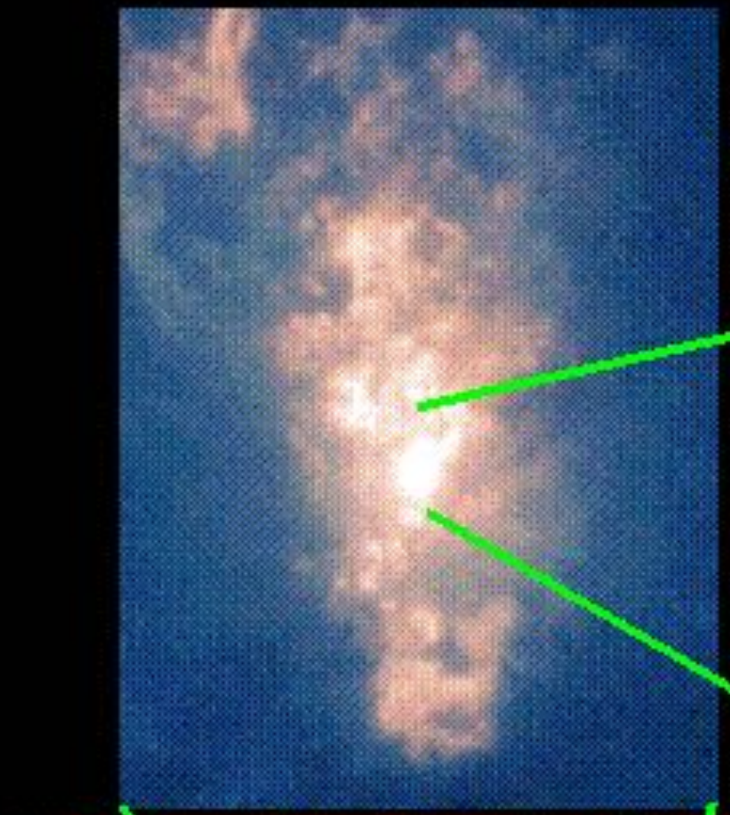
FORCAST & HAWC+ IMAGING OBSERVATIONS

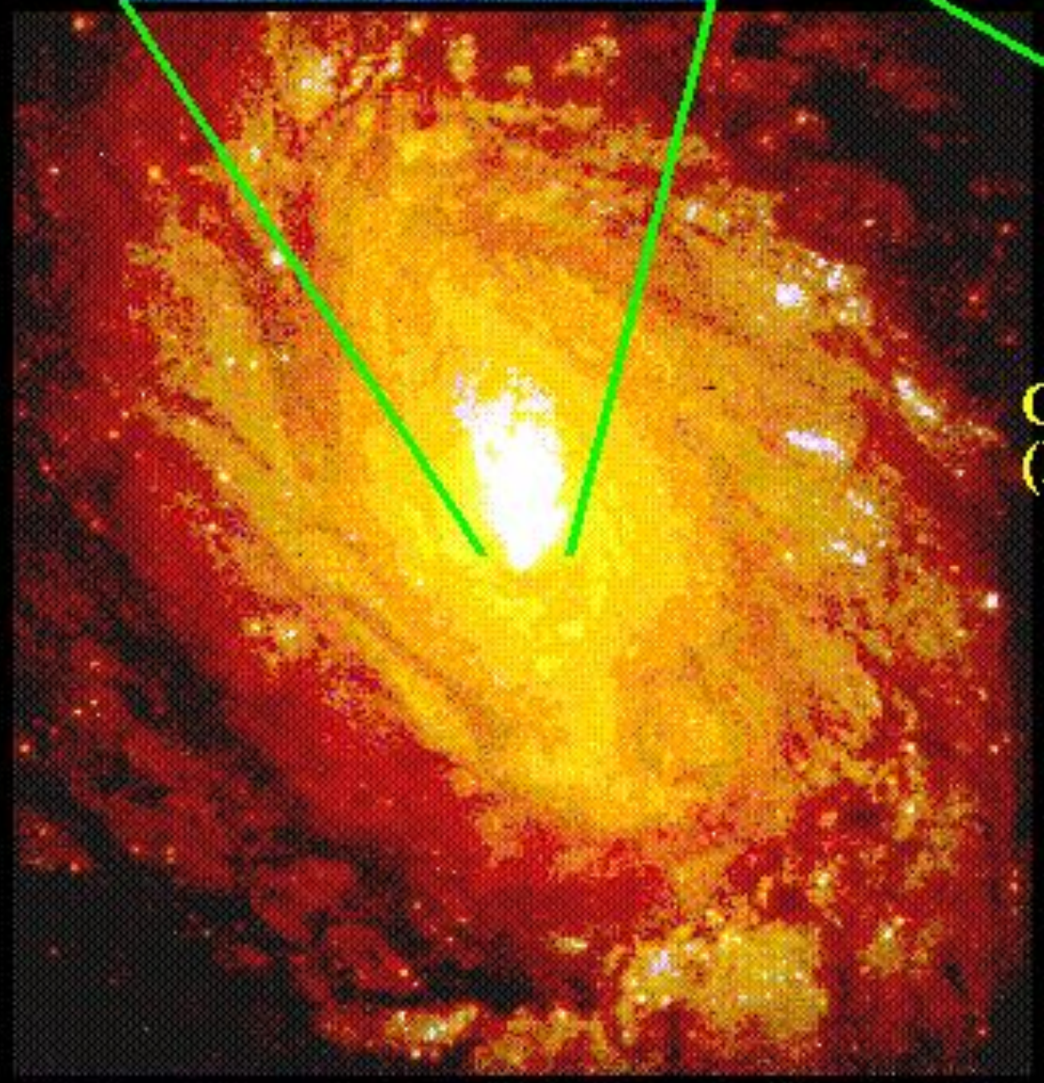
EMISSION AND DISTRIBUTION OF DUST IN THE TORUS OF NGC 1068

Lopez-Rodriguez et al. (2018, ApJ, 859, 99)

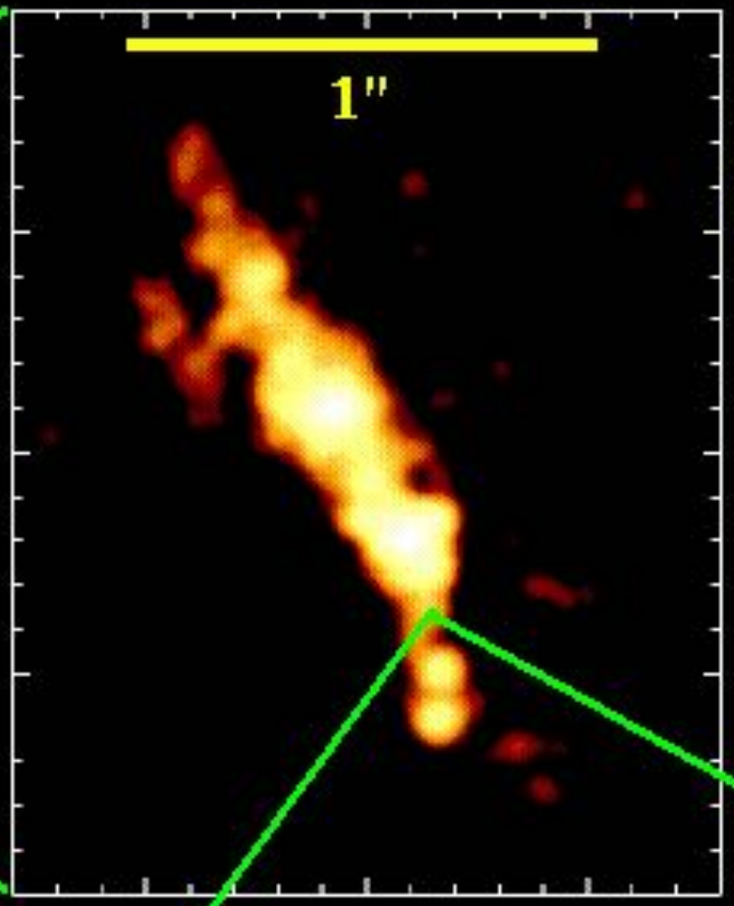
NGC 1068

Nuclear reflection cone (HST/FOC)



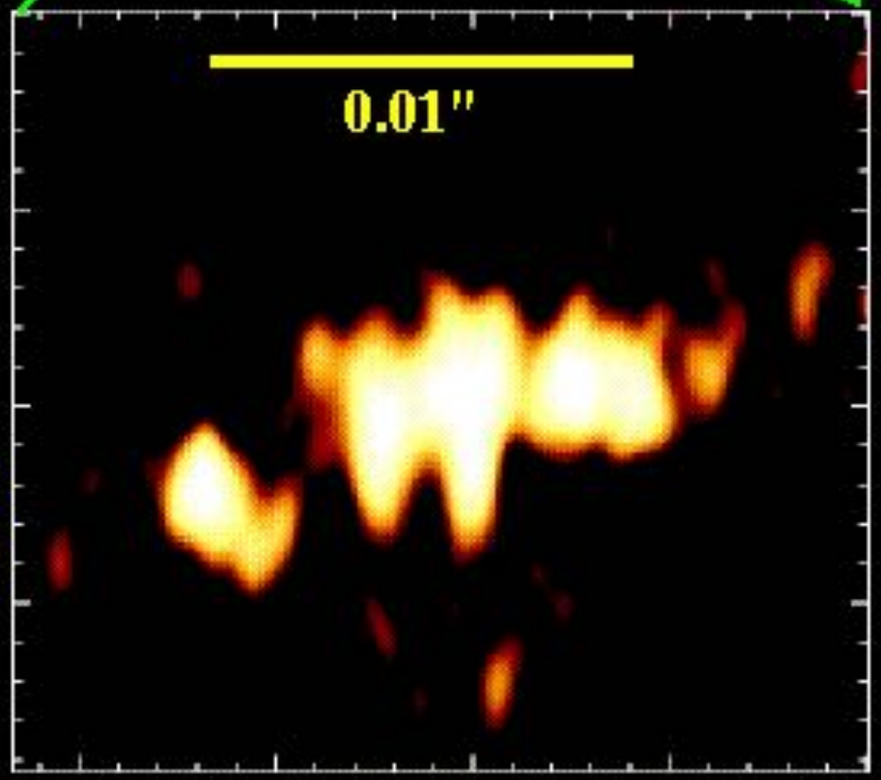


Optical galaxy (HST)



Radio jet (MERLIN)

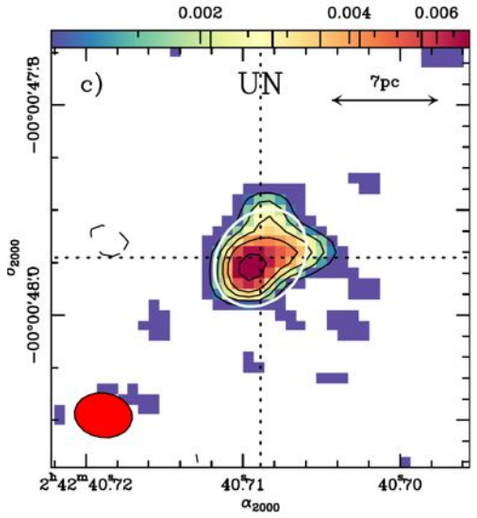
Obscuring torus ? (VLBA)



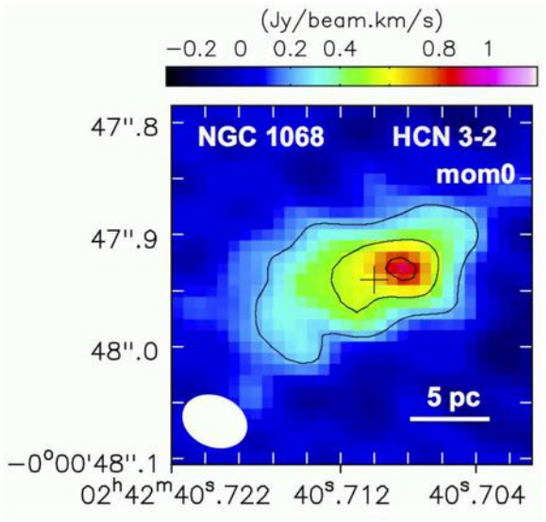
Torus size ~ 12x5 pc

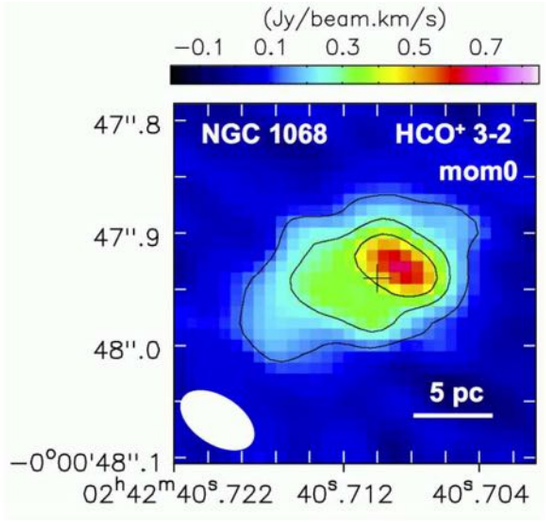
Orientation of the torus ~ 110°

Highly inhomogeneous molecular torus

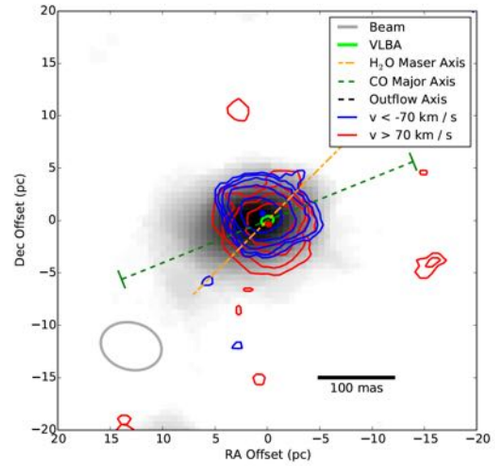


Garcia-Burrillo et al. (2016)

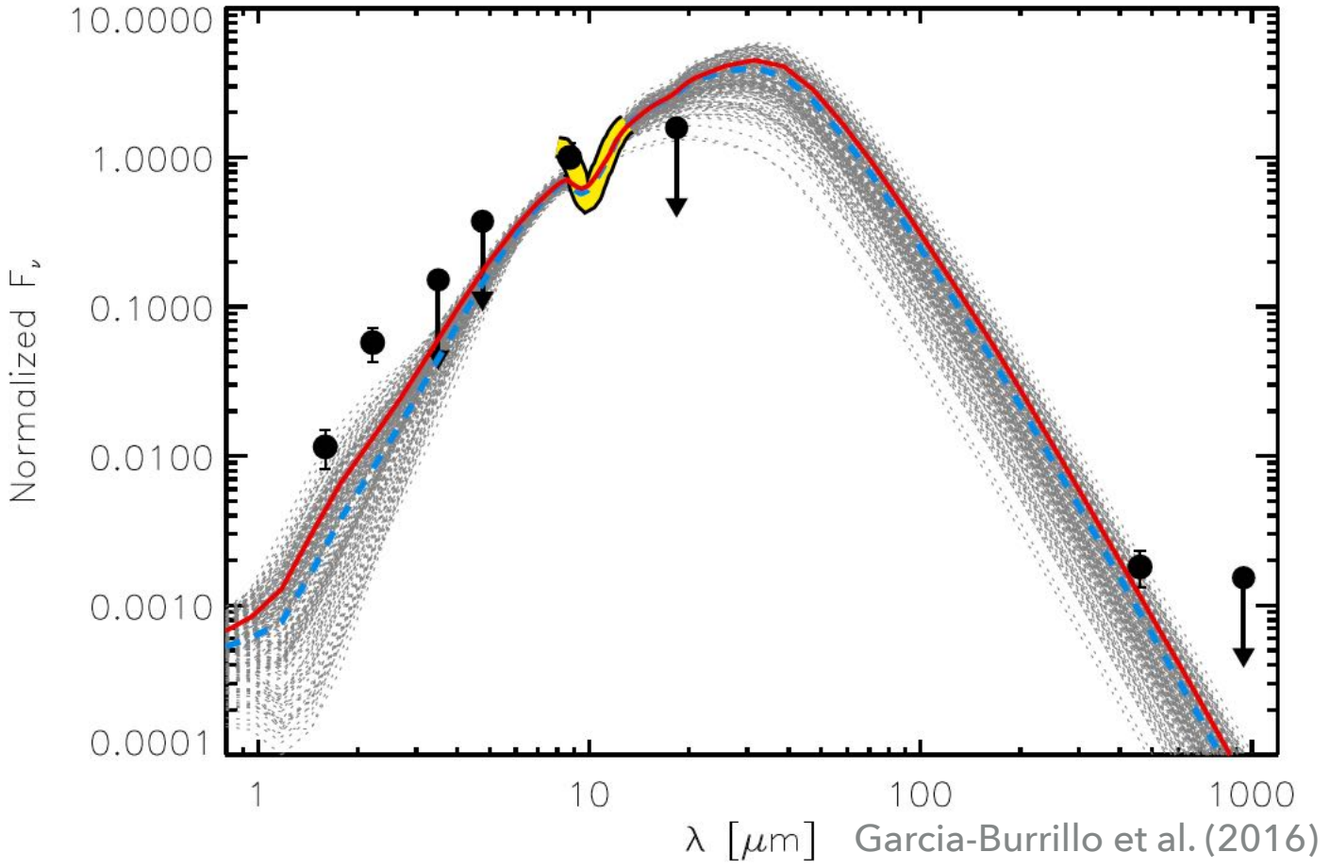




Imanishi et al. (2018)



Gallimore et al. (2016)



Garcia-Burrillo et al. (2016)

Torus size ~ 12x5 pc

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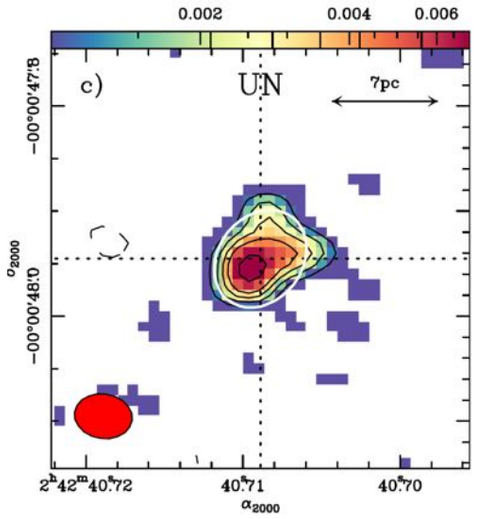
Highly inhomogeneous molecular torus



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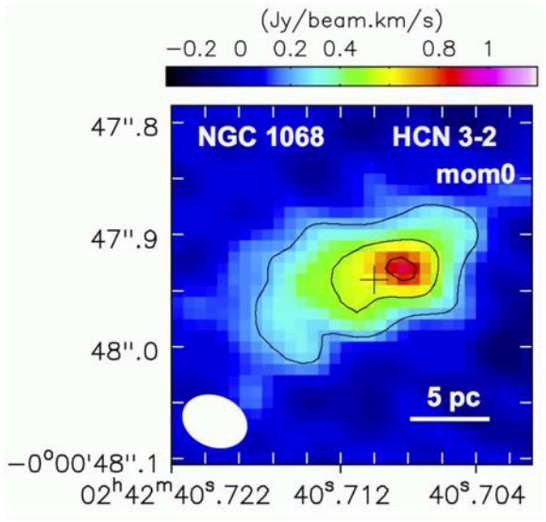

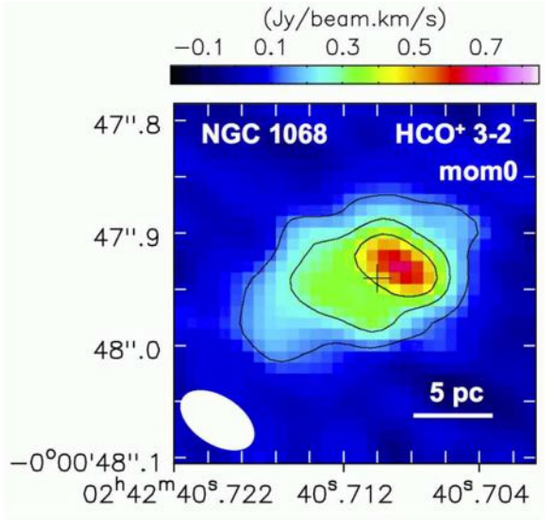

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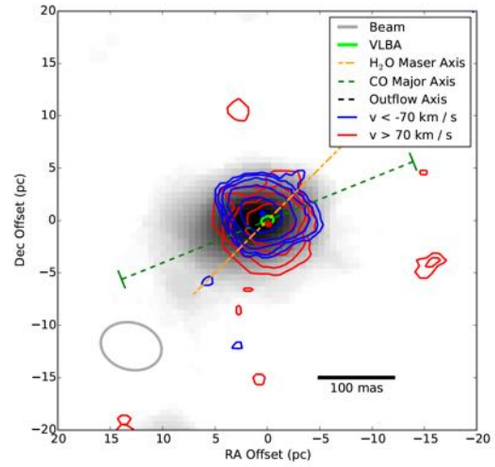

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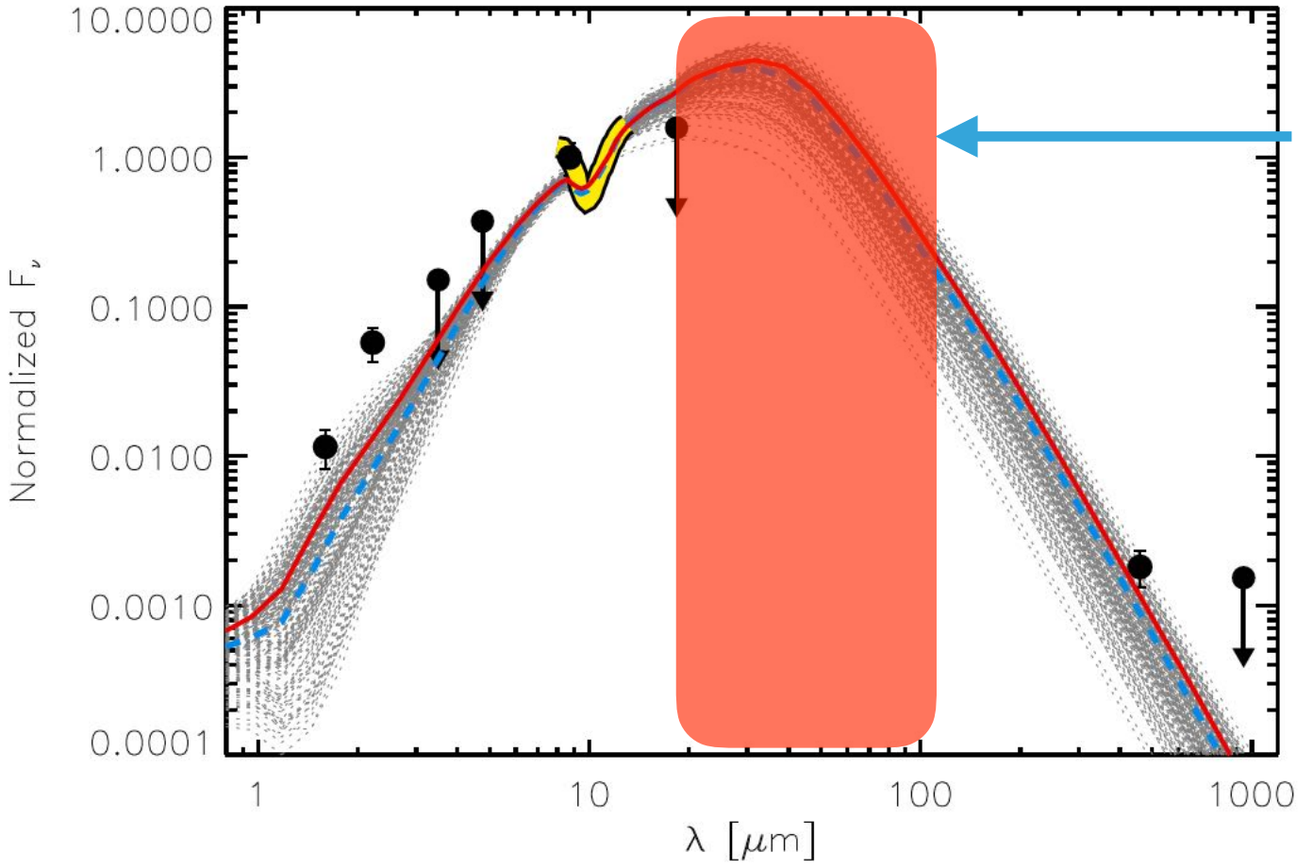
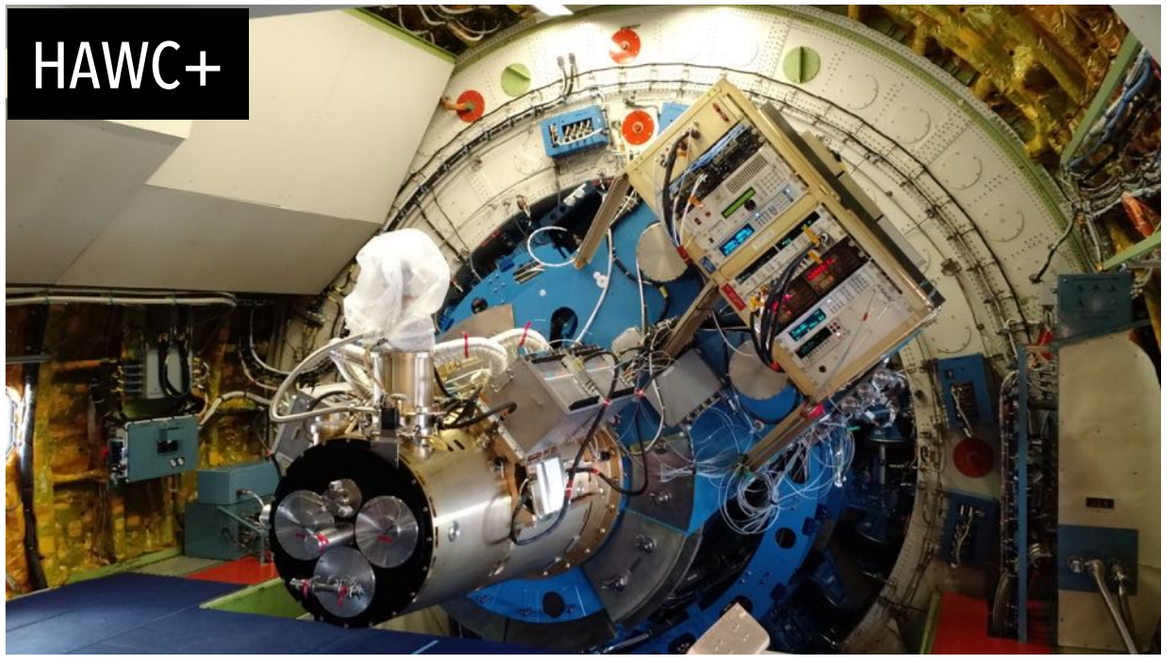


Lack of moderate angular resolution observations in the FIR.

SOFIA: 2.5-m telescope
WAVELENGTH RANGE: 0.3-300 microns
INSTRUMENTS: 7 First generation instruments: cameras, spectrometers & high-spectrometers. New instrument: imager-polarimeter at 50-250 microns (HAWC+)
AIRSPEED: Mach 0.85 (560 mph ~ 901 kmh)
OBSERVING ALTITUDE: 37,000 - 45,000 ft
ONBOARD STAFF: Flight crew 3; Mission crew 2-6, Scientist 1-3, Educators 5-15
AVERAGE SCIENCE FLIGHT LENGTH: 10 hours overnight



PI: Darren Dowell (JPL)

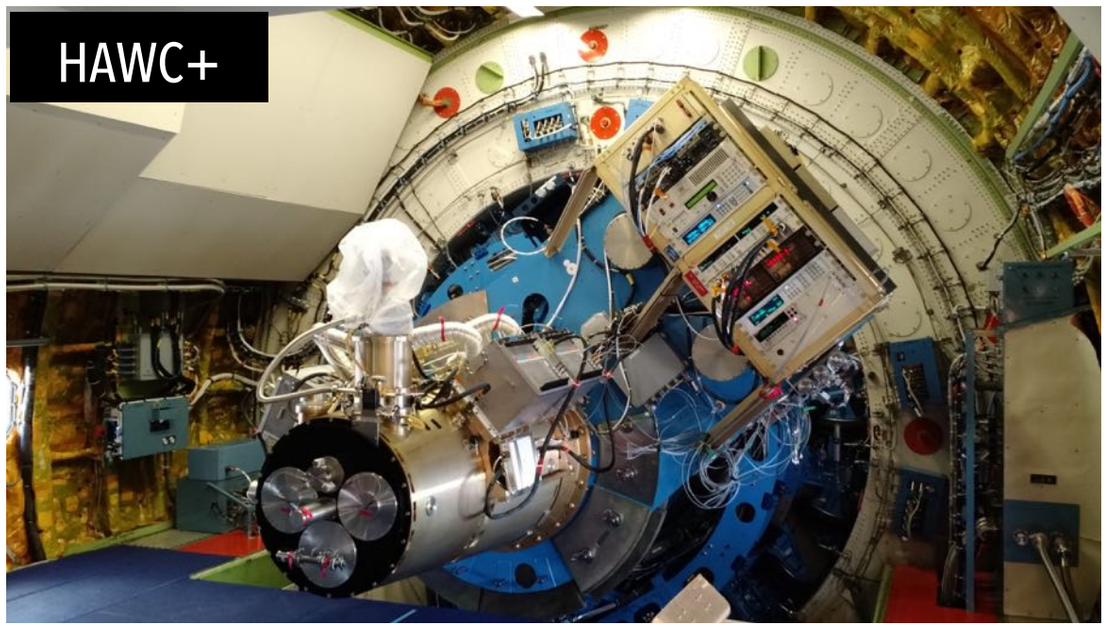
HAWC+ observes total and polarized emission of dust grains at four different wavelengths in the range of 50-250 micrometers.

The far-infrared emission, detected by HAWC+, samples different dust temperatures in the range of 10K to 100K.

FORCAST observes total emission of dust grains in the range of 5-40 micrometers.

The infrared emission, detected by FORCAST, samples different dust temperatures in the range of 100K to 600K.

PI: Terry Herter (Cornell University)

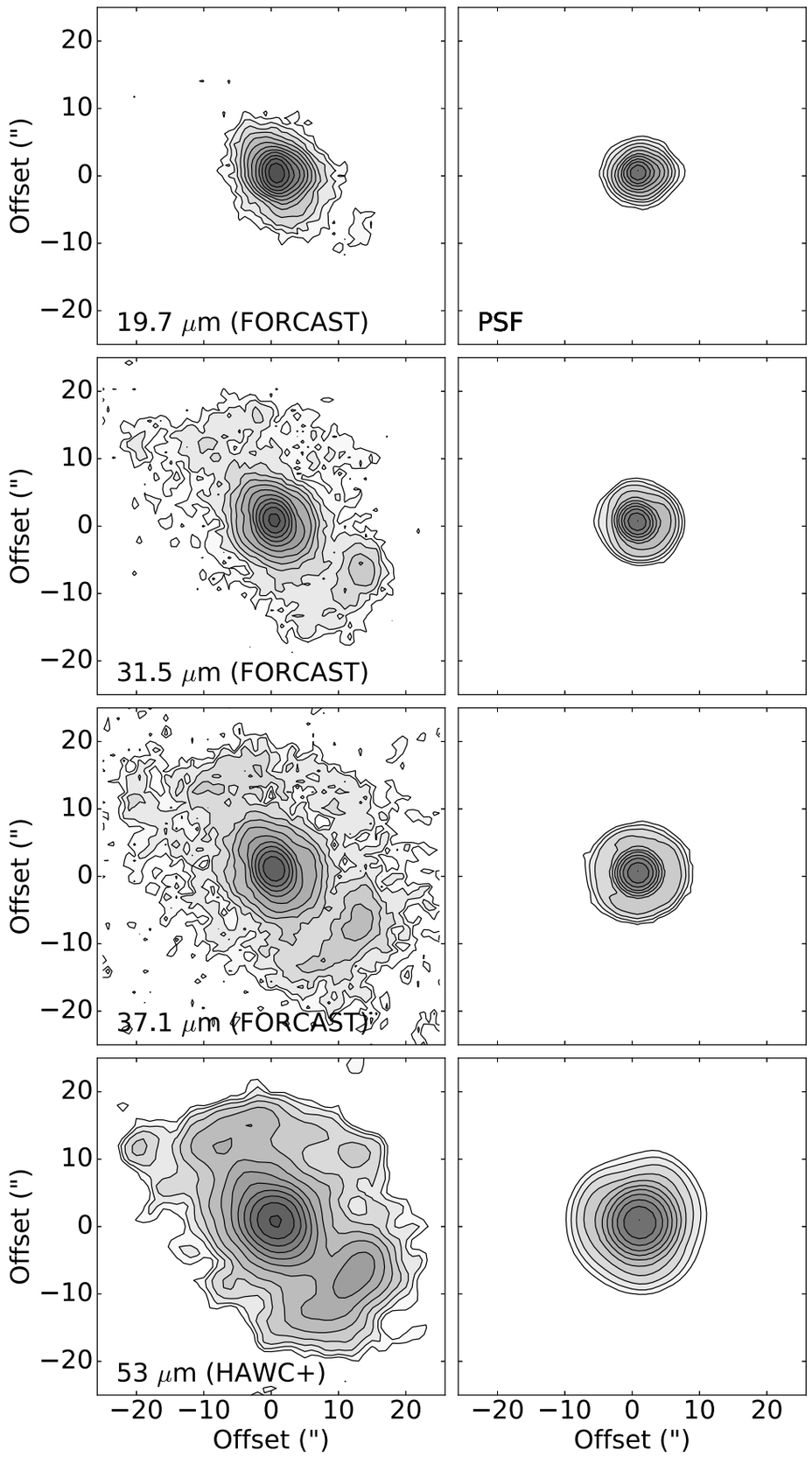


PI: Darren Dowell (JPL)

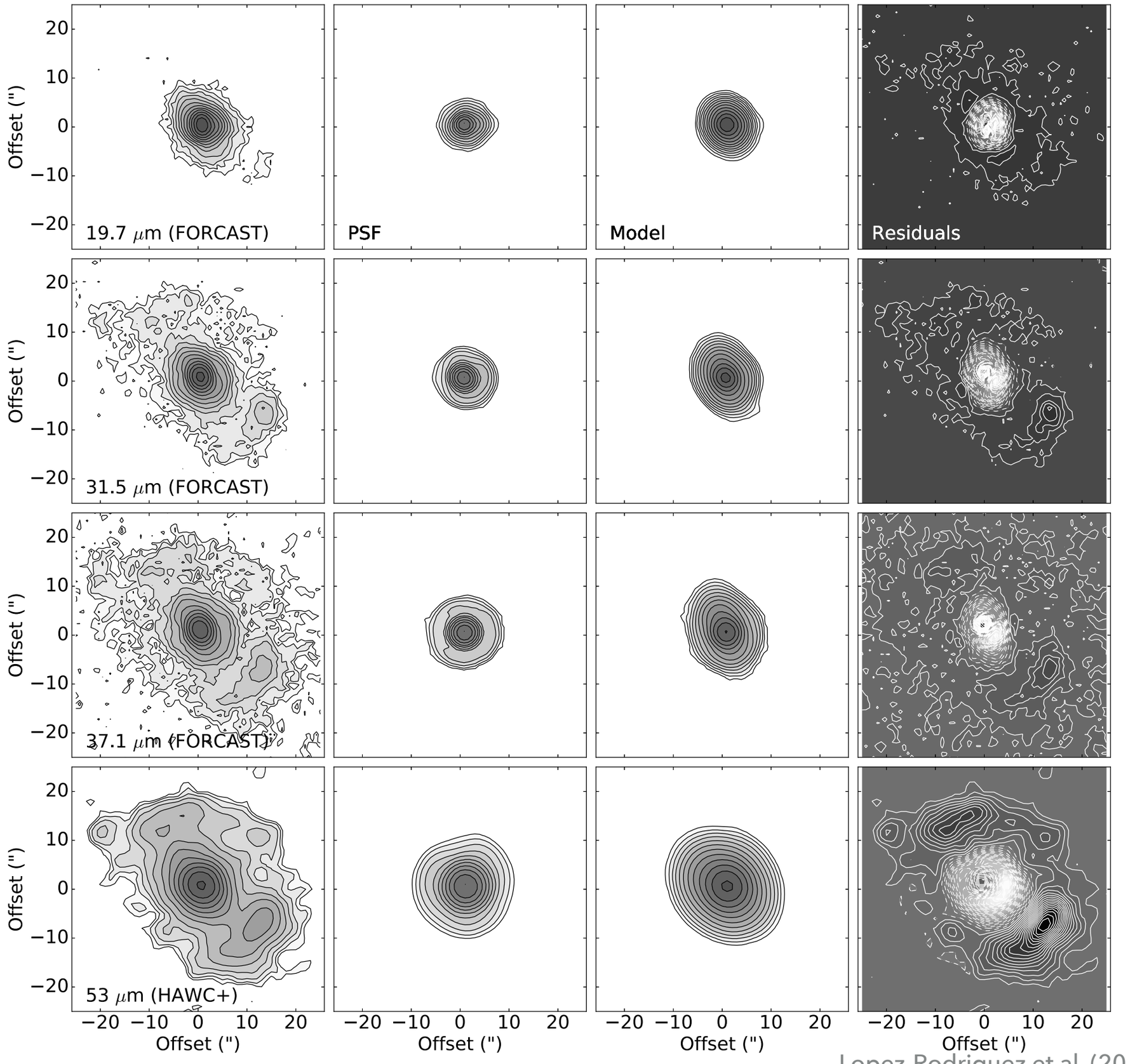
Band / Wavelength	Δλ/λ	Angular Resolution	Total Intensity FOV (arcmin)	Polarization FOV (arcmin)
A / 53 µm	0.17	4.7” FWHM	2.7 x 1.7	1.3 x 1.7
~~B[a] / 63 µm~~	~~0.15~~	~~5.8” FWHM~~	~~4.2 x 2.6~~	~~2.1 x 2.6~~
C / 89 µm	0.19	7.8” FWHM	4.2 x 2.6	2.1 x 2.6
D / 154 µm	0.22	14” FWHM	7.3 x 4.5	3.6 x 4.5
E / 214µm	0.20	19” FWHM	8.0 x 6.1	4.0 x 6.1

PI: Terry Herter (Cornell University)

SWC Filters		LWC Filters	
λ_{eff} (µm)	Δλ (µm)	λ_{eff} (µm)	Δλ (µm)
5.4	0.16	24.2	2.9
5.6	0.08	25.3	1.86
6.4	**0.14**	**31.5**	**5.7**
6.6	**0.24**	**33.6**	**1.9**
7.7	**0.47**	**34.8**	**3.8**
8.6	0.21	**37.1**	**3.3**
11.1	**0.95**		
11.3	0.24		
11.8	0.74		
19.7	**5.5**		
25.4	**1.86**		



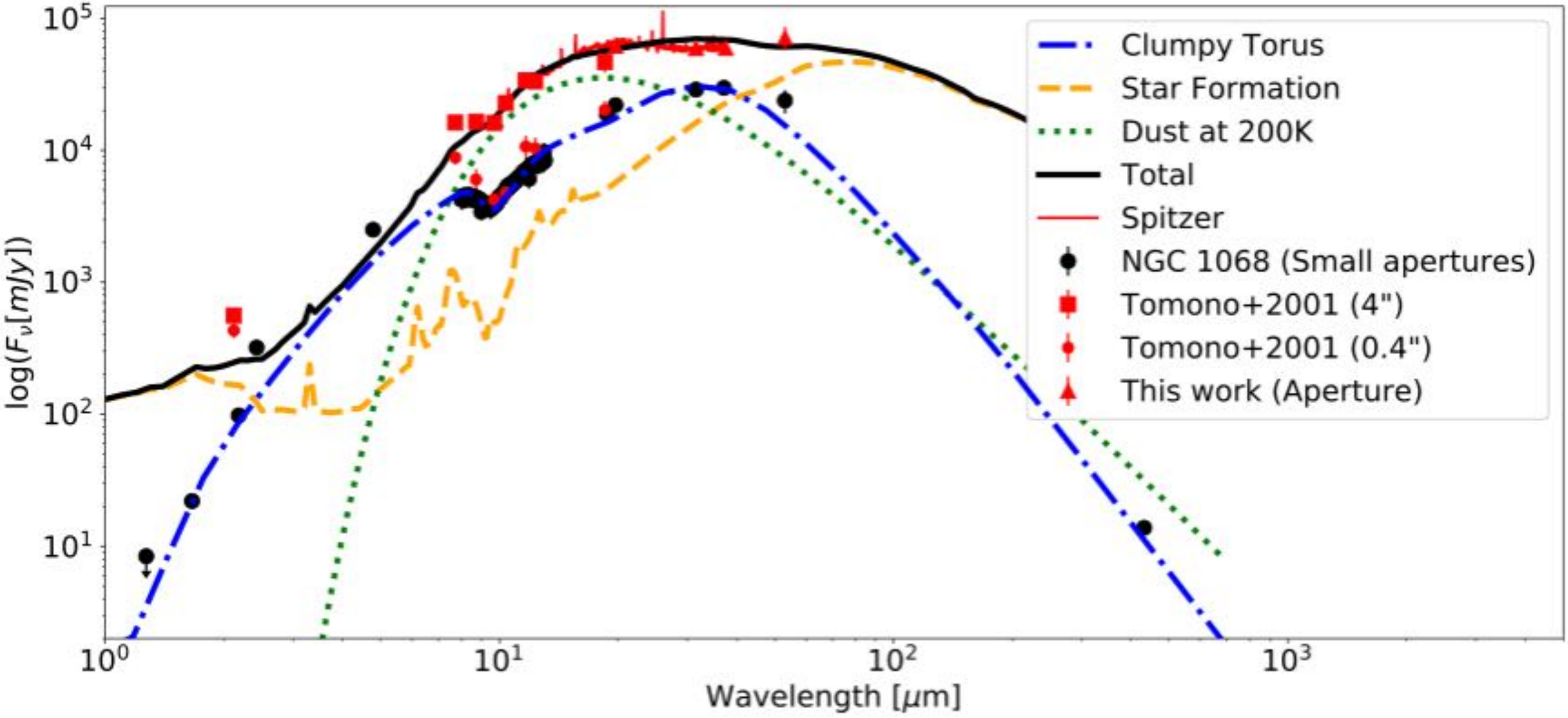
Lopez-Rodriguez et al. (2018, ApJ, 859, 99)



Lopez-Rodriguez et al. (2018, ApJ, 859, 99)

We combined SOFIA (FORCAST & HAWC+) observations with 1-20 um imaging and spectroscopy, ALMA, and *Spitzer* observations.

- SED using 'moderate' (>1") and 'high' (PSF-fitting) angular flux measurements of the core of NGC 1068

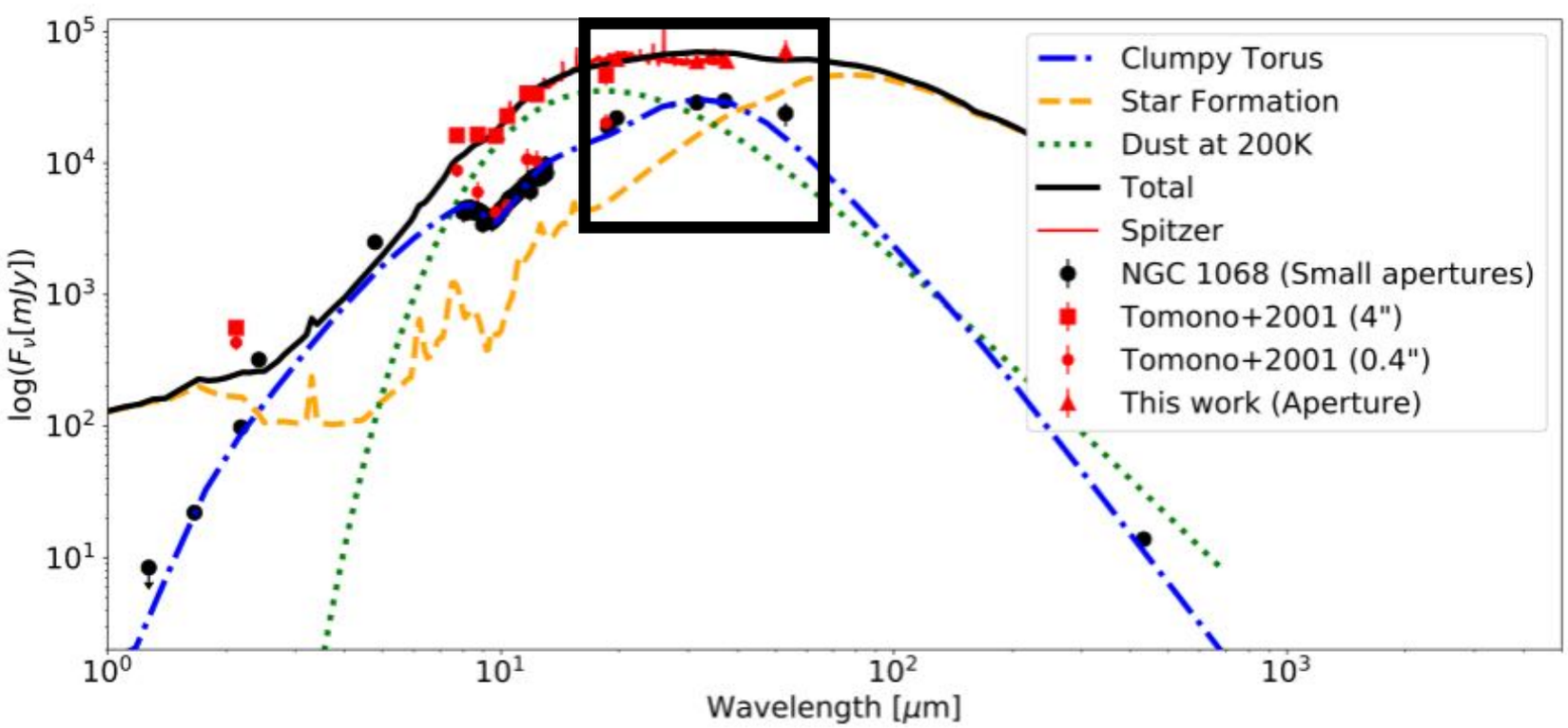


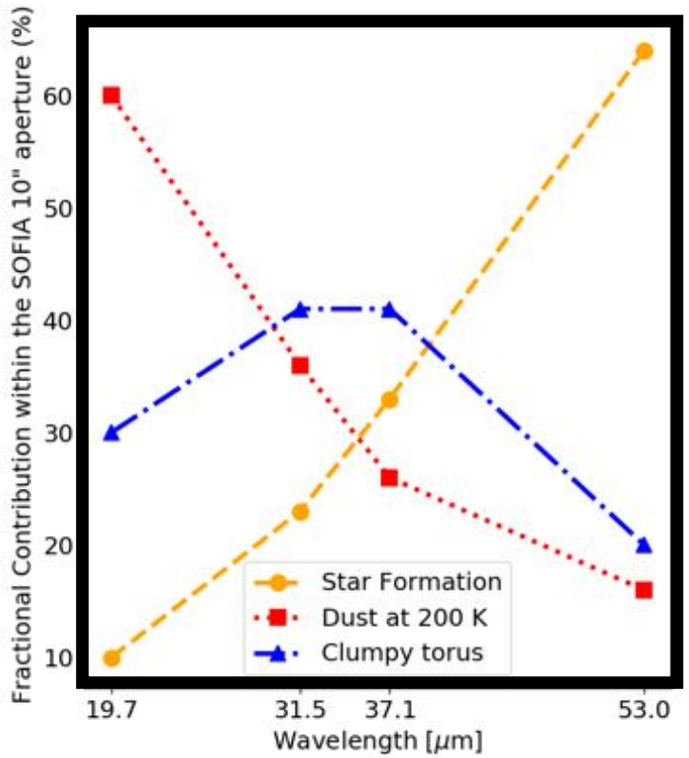
Lopez-Rodriguez et al. (2018, ApJ, 859, 99)

Star forming regions dominates at wavelengths > 50 um.

Dust emission at ~10 um arises from polar emission and its characterized with a blackbody components dominating at ~200 K at scales > 10 pc.

The torus emission of the torus peaks in the 30-40 um range.
- This is the first detection and characterization of the AGN torus peak emission.





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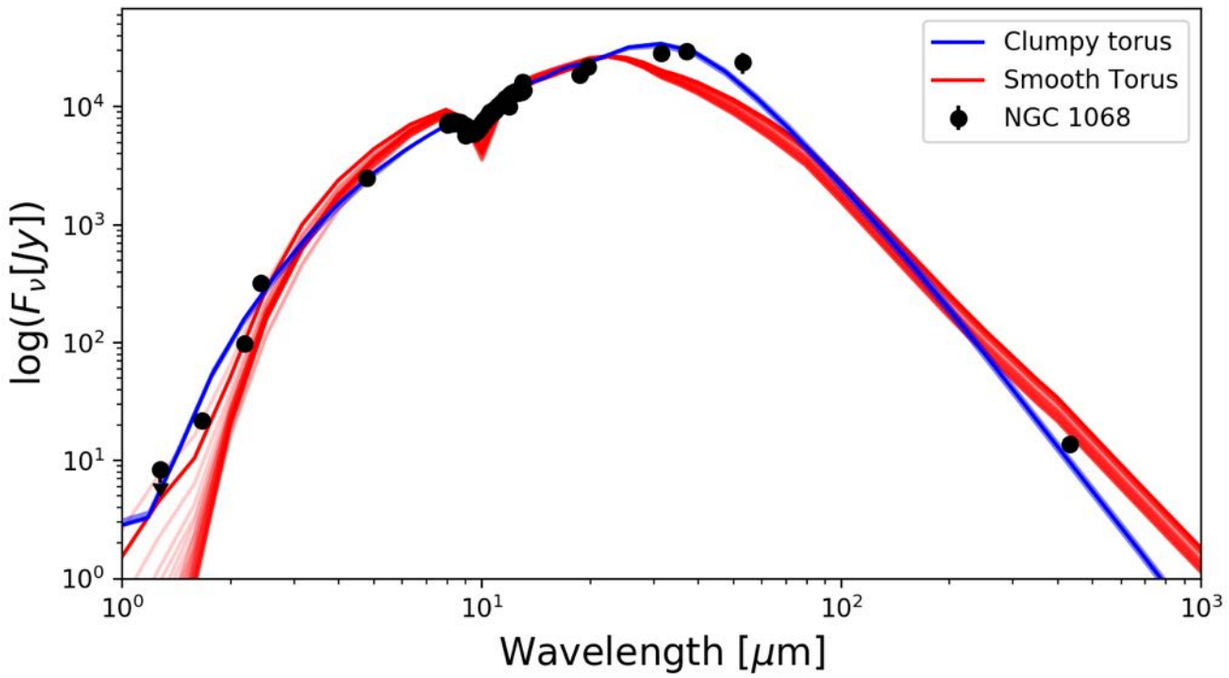
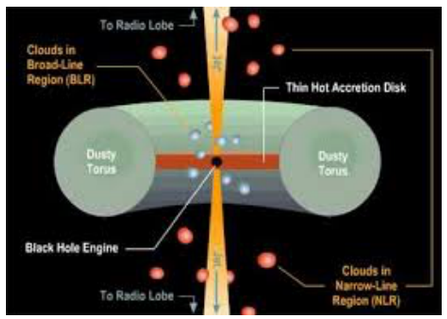
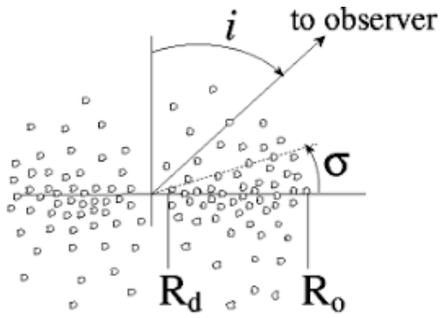


CLUMPY torus models best describe the high-resolution 1-432 um observations

Smooth



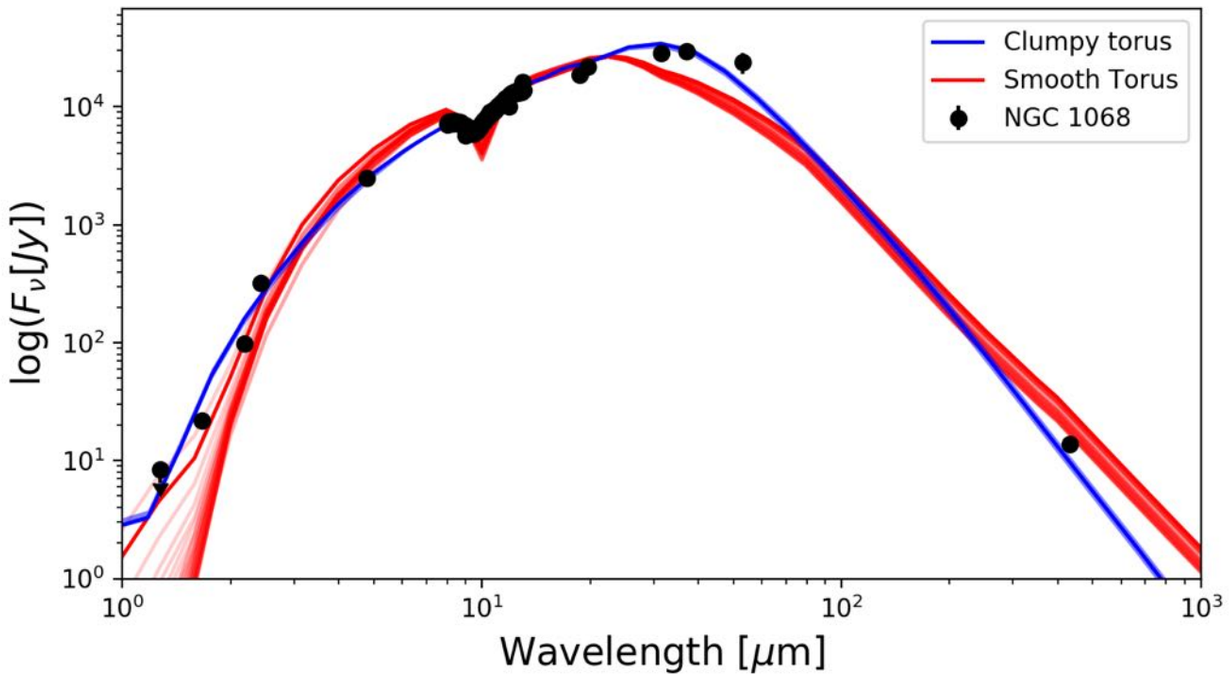
CLUMPY



Smooth torus model under-estimates the FIR emission.

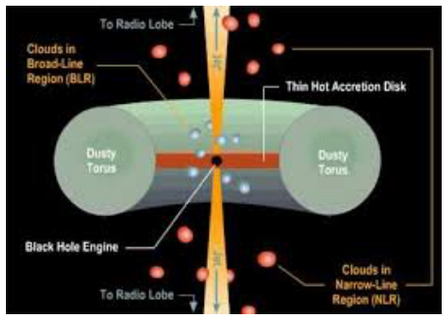
- If we force the smooth torus models to go through the FIR emission, then smooth models over-estimate the torus size and cold dust emission.

Lopez-Rodriguez et al. (2018, ApJ, 859, 99)

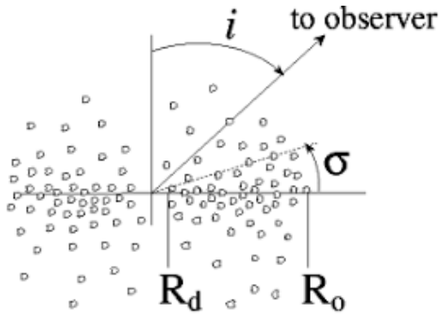


CLUMPY torus models best describe the high-resolution 1-432 um observations

Smooth



CLUMPY



Smooth torus model under-estimates the FIR emission.

- If we force the smooth torus models to go through the FIR emission, then smooth models over-estimate the torus size and cold dust emission.

Table 2. CLUMPY and Smooth torus model parameters.

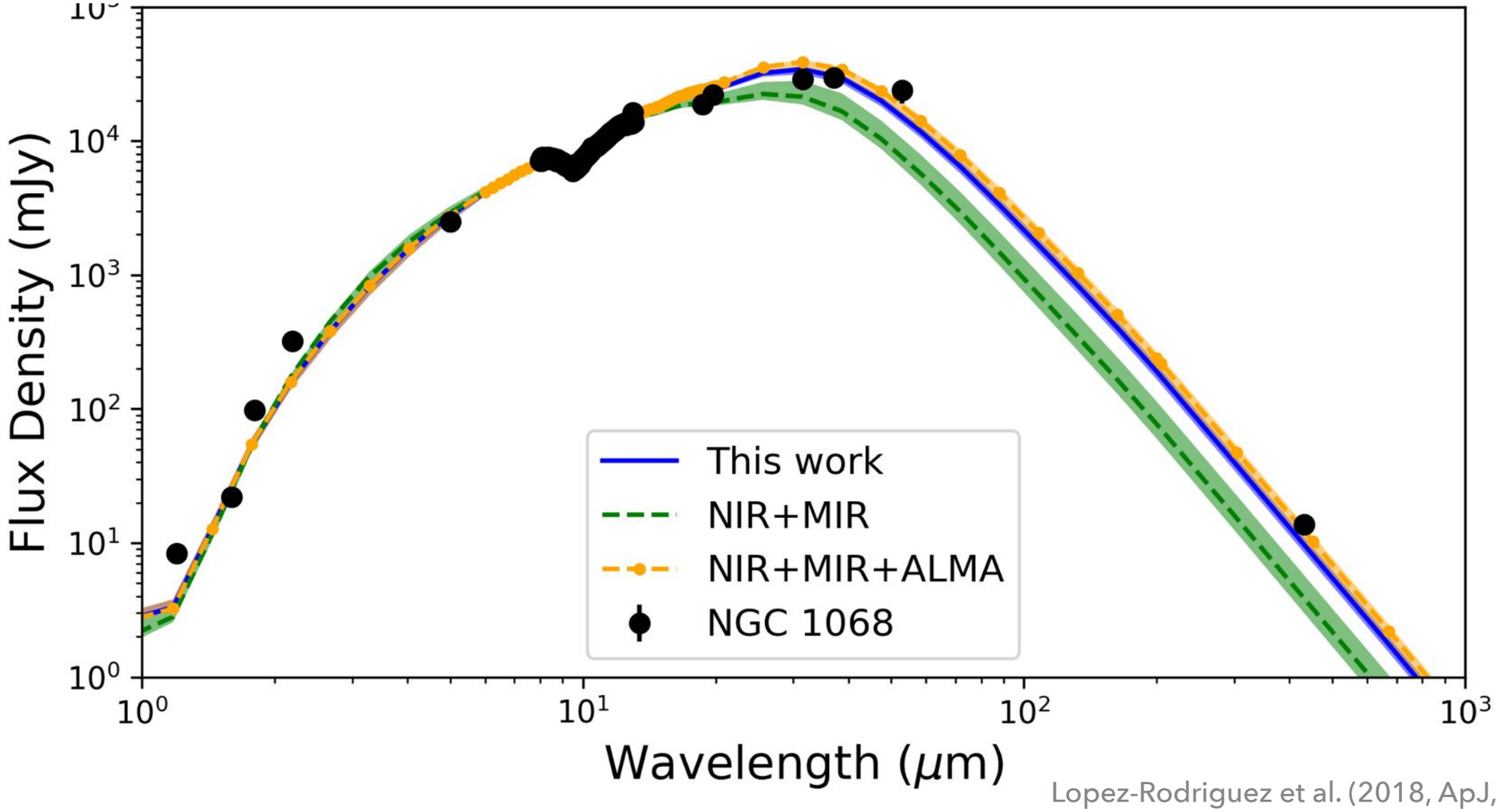
CLUMPY torus			Smooth torus		
Parameter	Symbol	Value	Parameter	Symbol	Value
Angular width	σ	$43^{+12\circ}_{-15}$	Opening angle	θ_{OA}	$37^{+23\circ}_{-8}$
Radial thickness	Y	18^{+1}_{-1}	Radial thickness	Y_s	20^{+4}_{-4}
Number clouds along the equatorial plane	N_0	4^{+2}_{-1}	-	-	-
Index of the radial density profile	q	$0.08^{+0.19}_{-0.06}$	Index of the radial density profile	q_s	1 (fixed)
Optical depth of each cloud	τ_v	70^{+6}_{-14}	Optical depth of the torus, LOS	$\tau_{v,s}$	250^{+20}_{-10}
Viewing angle	i	$75^{+8\circ}_{-4}$	Viewing angle	i_s	$79^{+7\circ}_{-10}$
Inner radius	r_{in}	$0.28^{+0.01}_{-0.01}$ pc		$r_{in,s}$	$0.41^{+0.05}_{-0.02}$ pc
Outer radius	r_{out}	$5.1^{+0.4}_{-0.4}$ pc		$r_{out,s}$	$8.5^{+7.9}_{-0.7}$ pc
Height	H	$3.5^{+1.0}_{-1.3}$ pc		H_s	$4.2^{+0.5}_{-0.2}$ pc
Bolometric luminosity (erg s^{-1})	L_{bol}	$5.02^{+0.15}_{-0.19} \times 10^{44}$		$L_{bol,s}$	$1.11^{+0.28}_{-1.23} \times 10^{44}$

Lopez-Rodriguez et al. (2018, ApJ, 859, 99)

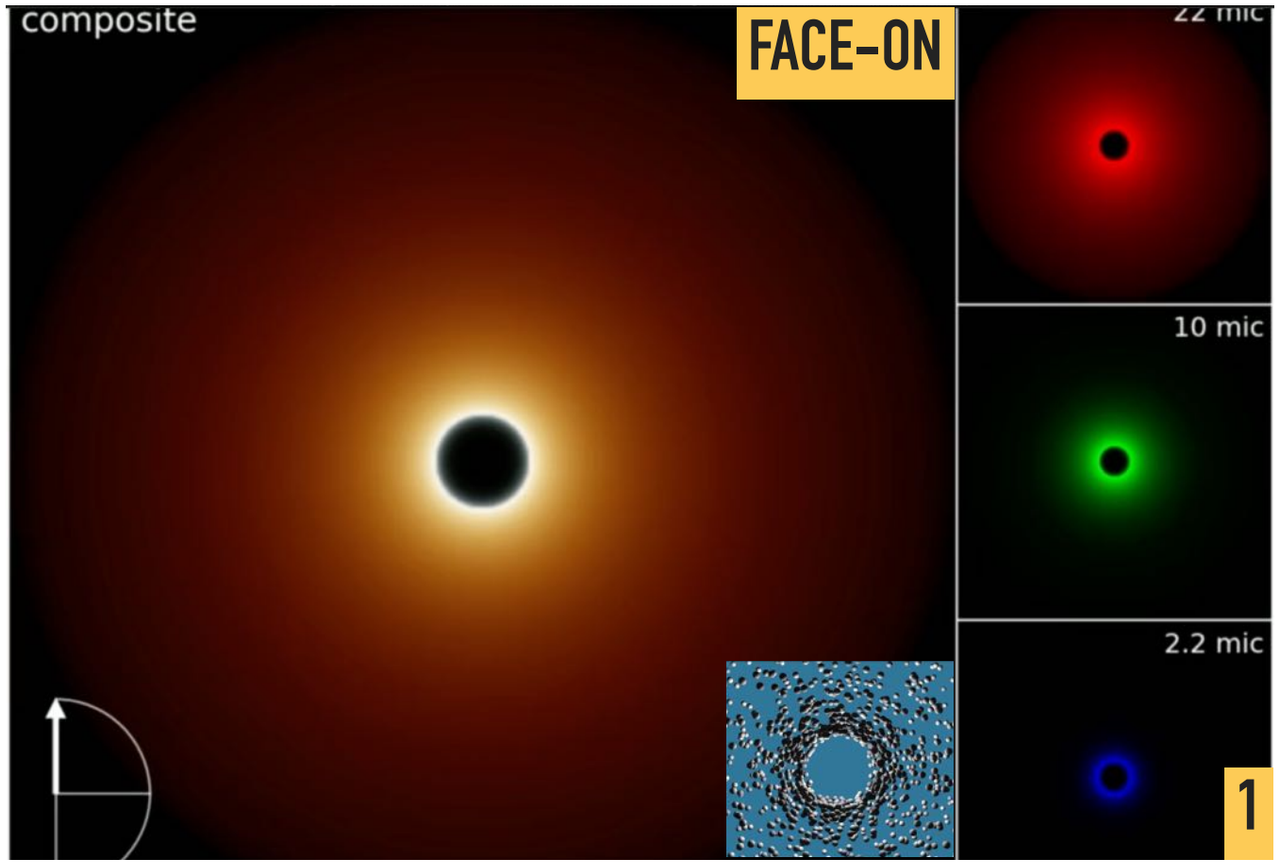
We inferred the best CLUMPY torus model using different SED coverages.

- 1-20 um: The full extend of the torus cannot be constrained.
- 30-40 um: Turn-over of the torus emission occurs.
- 20-500 um: Probe the full bulk of dust emission in the torus by accounting the warm/cold dust.

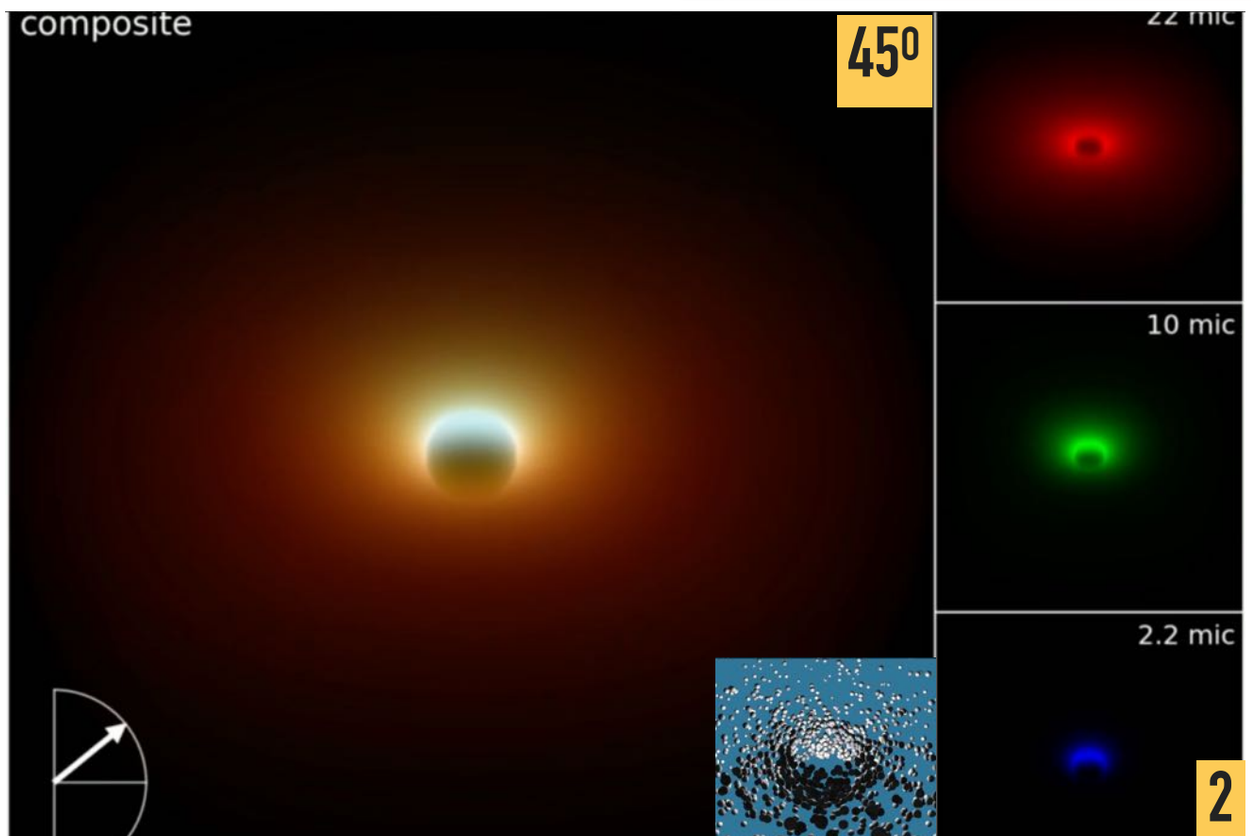
σ (°)	Y	N_0	q	τ_v	i (°)	r_{out} (pc)	SED
20^{+5}_{-3}	13^{+4}_{-3}	11^{+2}_{-3}	$0.22^{+0.20}_{-0.13}$	28^{+10}_{-6}	75^{+4}_{-6}	$3.5^{+1.3}_{-0.9}$	1−20 μm SED+MIR Spectroscopy
31^{+20}_{-8}	19^{+1}_{-1}	5^{+3}_{-2}	$0.06^{+0.08}_{-0.04}$	59^{+16}_{-13}	71^{+5}_{-3}	$5.5^{+0.4}_{-0.4}$	1−20 μm SED+MIR Spectroscopy+ALMA

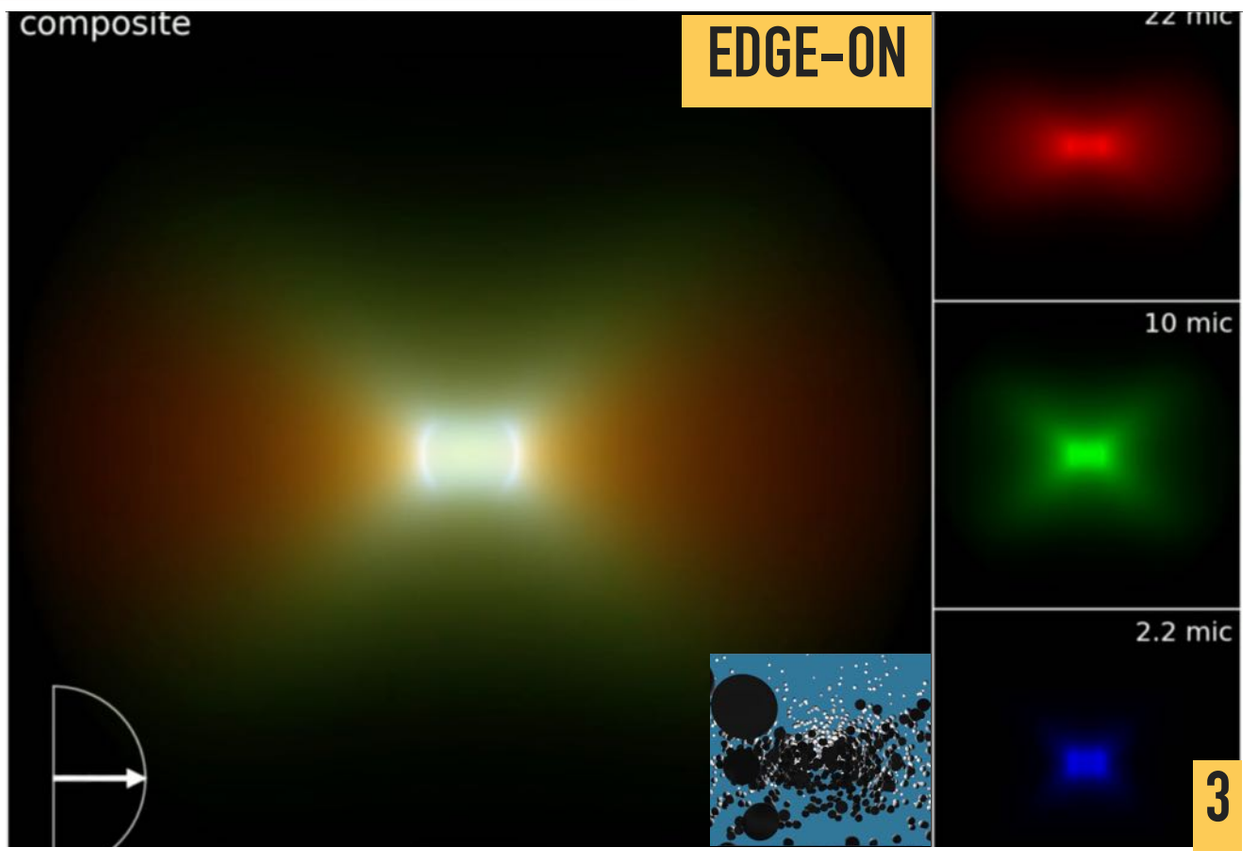


Lopez-Rodriguez et al. (2018, ApJ, 859, 99)



Credit: Nikutta R.





1-20 um SED coverage underestimates the cold dust in the torus —-> Torus is small and very compact, and the SED underestimates the FIR and sub-mm observations.

1-20 um + ALMA SED coverage overestimates the cold dust in the torus —-> Torus is slightly bigger and has small angular width.

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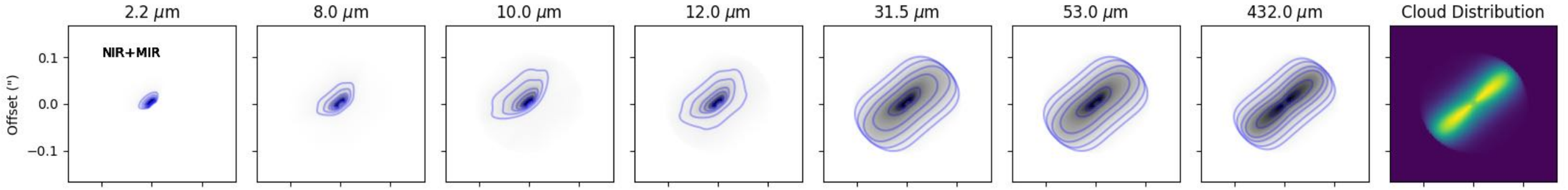

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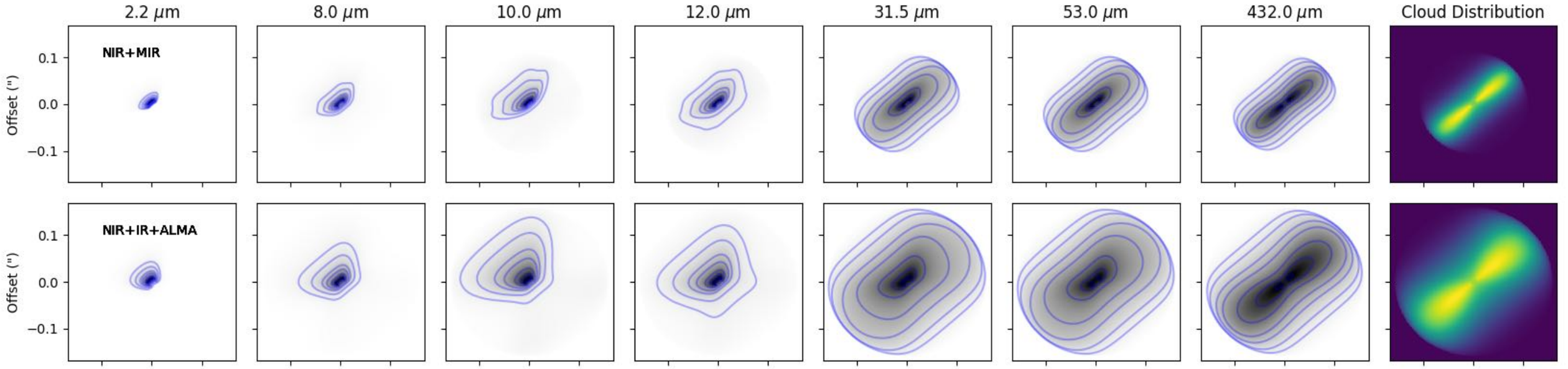

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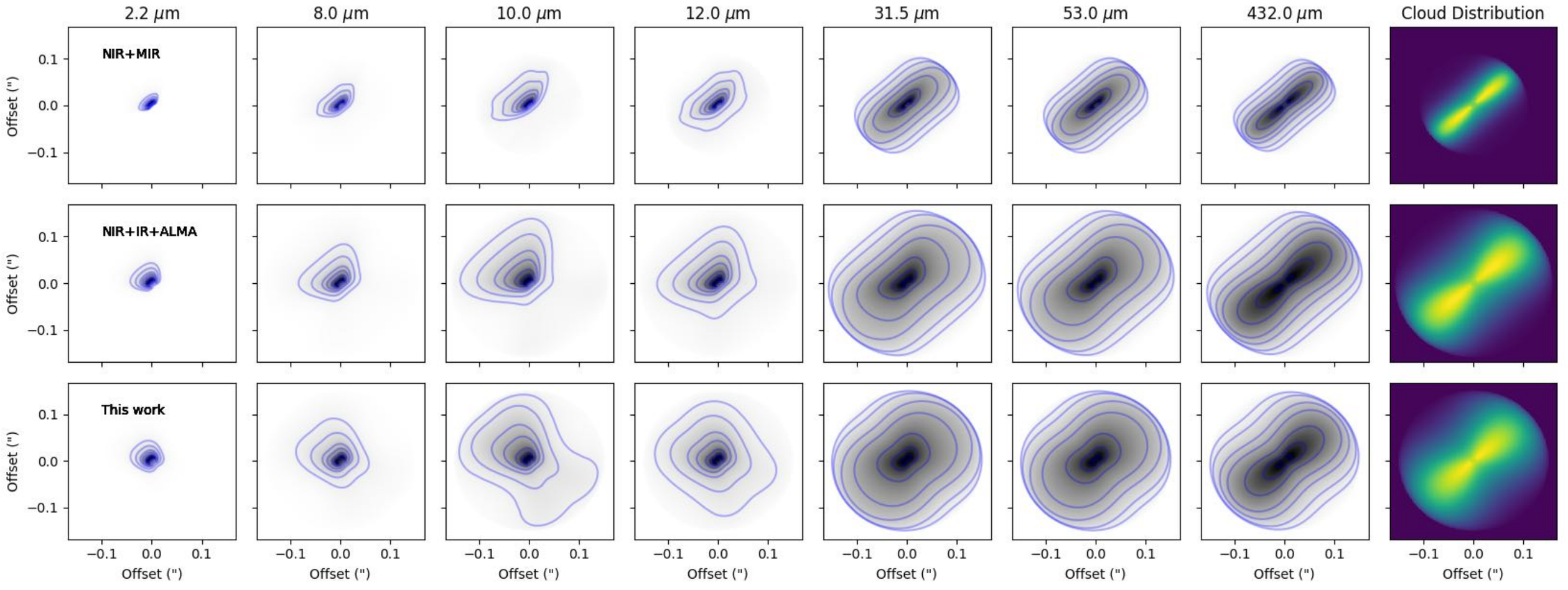
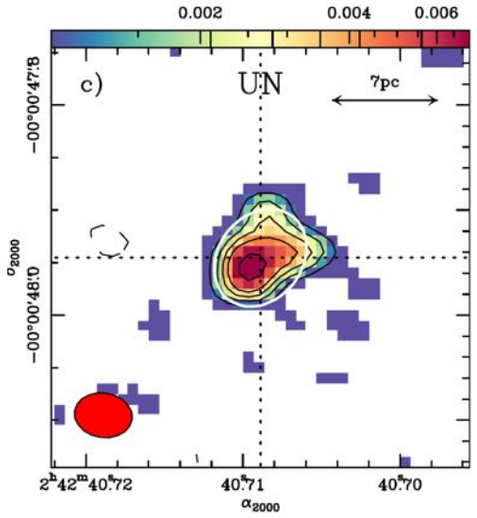


Lopez-Rodriguez et al. (2018, ApJ, 859, 99)

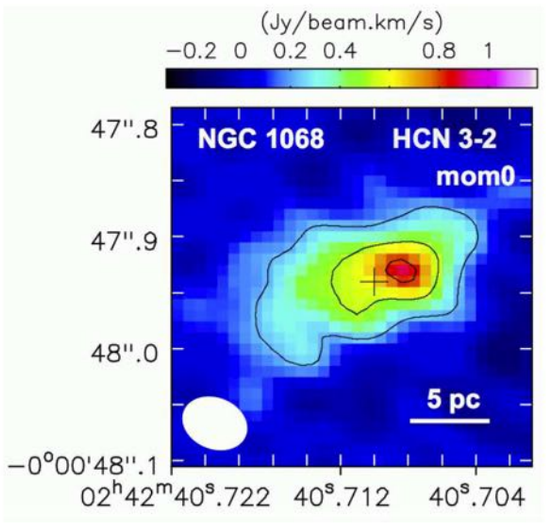
Torus size ~ 12x5 pc

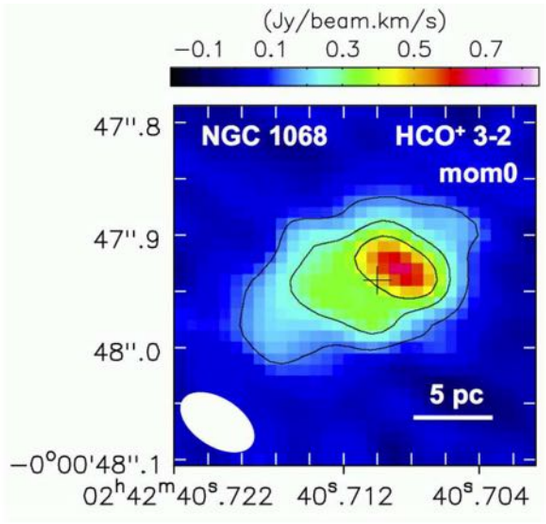
Orientation of the torus ~ 110°

Highly inhomogeneous molecular torus

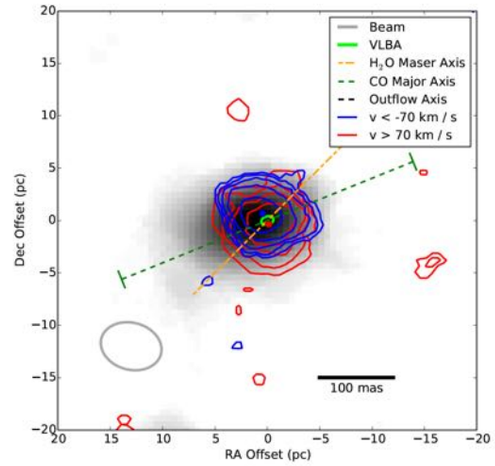


Garcia-Burrillo et al. (2016)



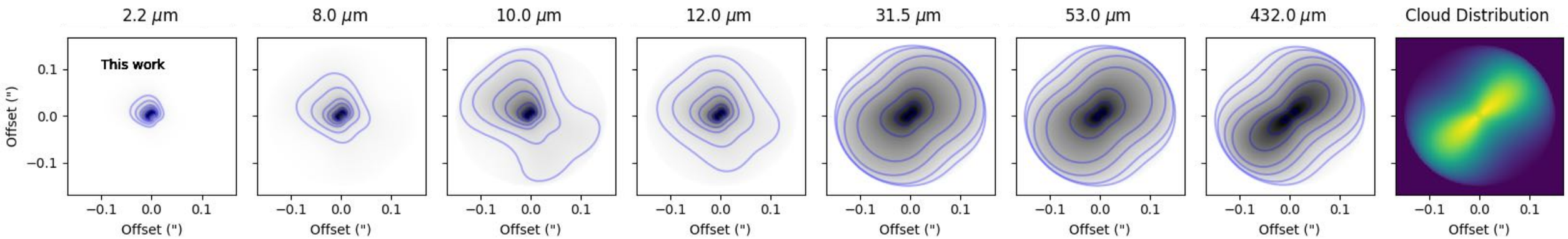


Imanishi et al. (2018)



Gallimore et al. (2016)

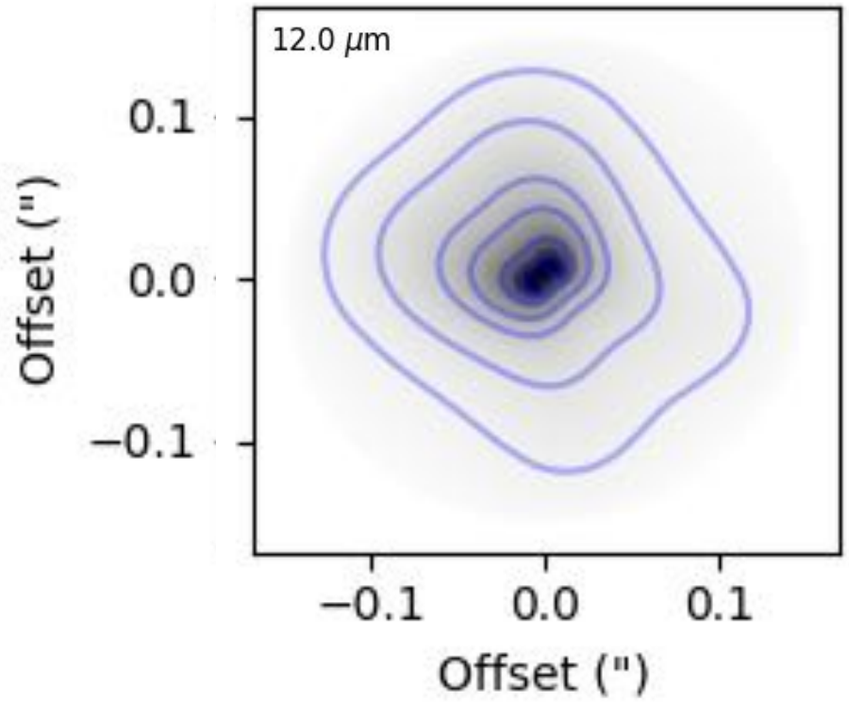
Inferred torus using CLUMPY torus models



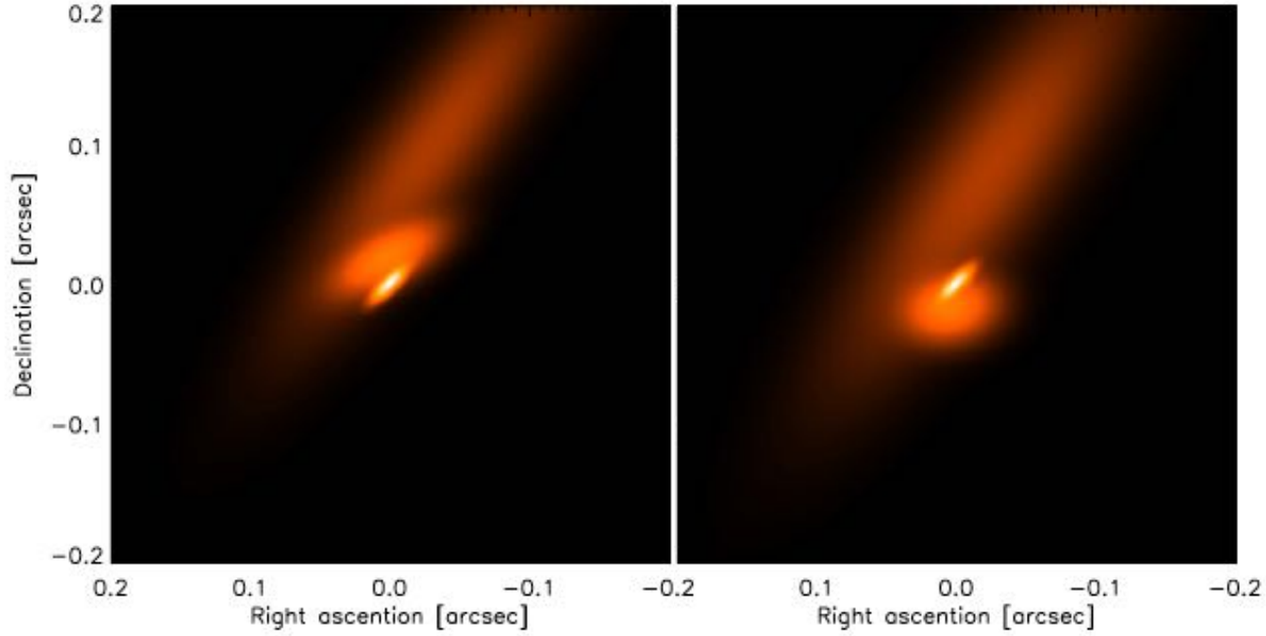
Results:

- The inferred torus size, dust distribution and dust emission is well described by the 1-432 um SED.
- Dust distribution is best described by the 432 um observations

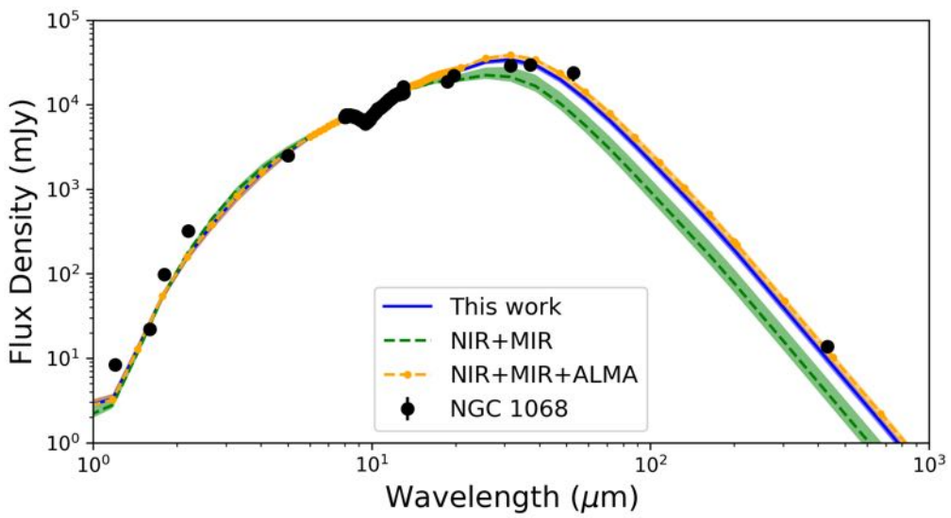
Best inferred dust emission using CLUMPY torus models (Lopez-Rodriguez+2018)



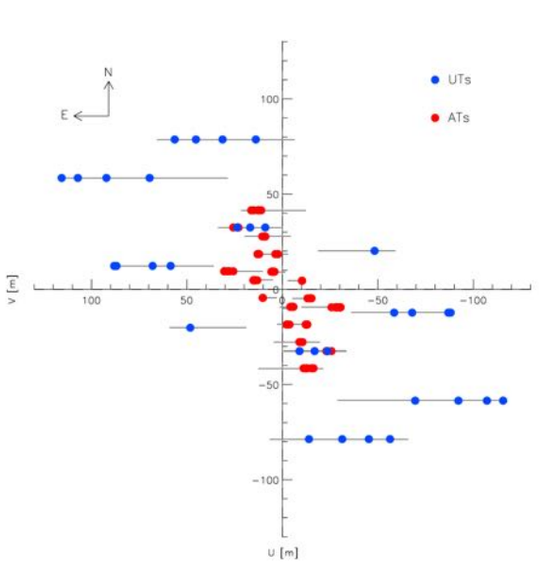
Best inferred dust emission using IR interferometry (Lopez-Gonzaga+2014)

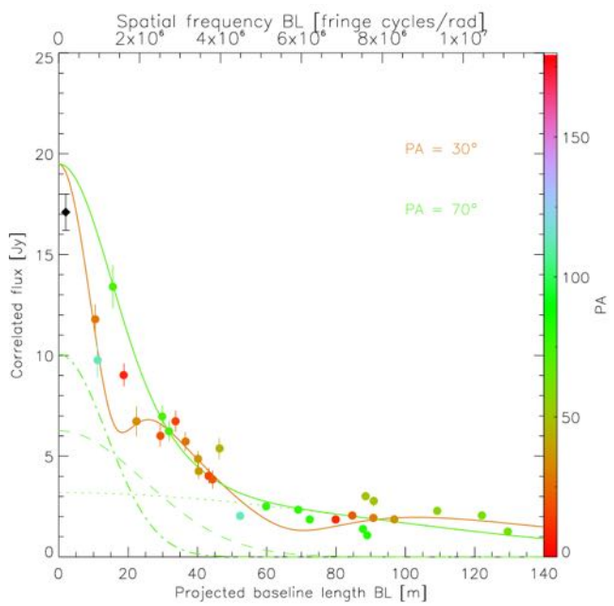


1-432 um nuclear SED



12 um MIDI/VLTI uv-plane and correlated flux





SUMMARY

- The torus is the cornerstone of the unification model of active galaxies.
  - The torus absorbs radiation from the active nucleus and re-emits it at IR wavelengths.
  - This structure has been extensively study in the 1-13 um (1500K-100K) and recently in the sub-mm range with ALMA.
  - The torus is thought to be clumpy, dusty and with sizes <10 pc. This structure is not resolved with current single-dish telescopes.

- Current studies lack of moderate resolution observations in the range of 30-70 um.
  - This wavelength range is thought to be where the peak emission of the torus occurs and where the warm/cold dust of the torus can be traced.

- We report 20-53 um imaging observations of NGC 1068 using FORCAST AND HAWC+ onboard SOFIA.
  - Star forming regions dominate at scales of 700 pc at >100 um.
  - Dust emission at scales > 10 pc in the polar direction dominates at 10 um.
  - The torus emission is isolated from these two regions and their peak is found to be in the 30-40 um range.

- Using CLUMPY torus models, we found that:
  - The 1-20 um range is not able to probe the full extent of the torus.
  - The morphology of the emission in the 1-20 um range shows an elongated morphology perpendicular to the cloud distribution.
  - The cloud distribution is characterized by observations in the sub-mm range.


Thank you