Observing Cool Dust Around Active Galactic Nuclei Using the SOFIA Telescope

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Overview

- AGN Background
  - Mid-infrared emission source in AGN
- Two main projects:
  - Cycle 2 Observations
    - Modeling using Bayesian inference tool
    - How do SOFIA observations improve the model?
  - Cycle 4 Observations
    - Observational results
    - Resolving 100 pc scale MIR emission

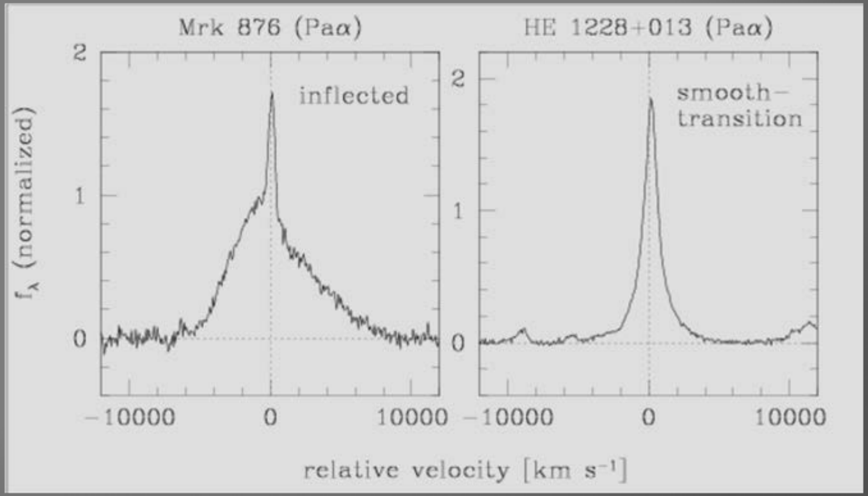
Introduction to Active Galaxies

Credits: NASA/SOFIA/Lynette Cook.
Press Release, Fuller et al. 2016

- Active galaxy - nucleus is more luminous than the galaxy itself
  - Most consistently luminous sources of radiation in the universe
- Mechanism that drives the high energies is accretion onto supermassive black hole, causes friction and radiation

Spectral Features

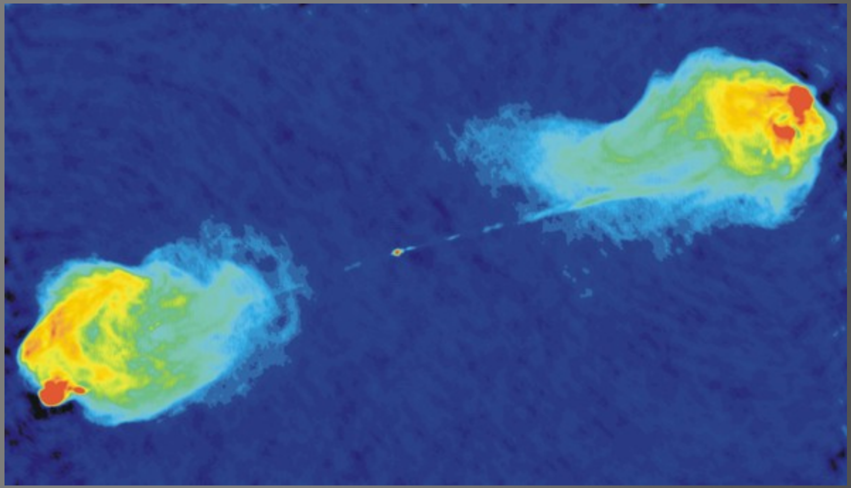
- Rotation from accretion process causes velocity dispersion/Doppler broadening of emission lines
- Broad permitted and forbidden emission lines
  - Hallmark of AGN identification
  - FWHM ~ 10^3 – 10^4 km/s
- Narrow forbidden emission lines
  - FWHM < 10^3 km/s



Plot from Landt et al. (2014) shows a broadened Pa α line

Classification

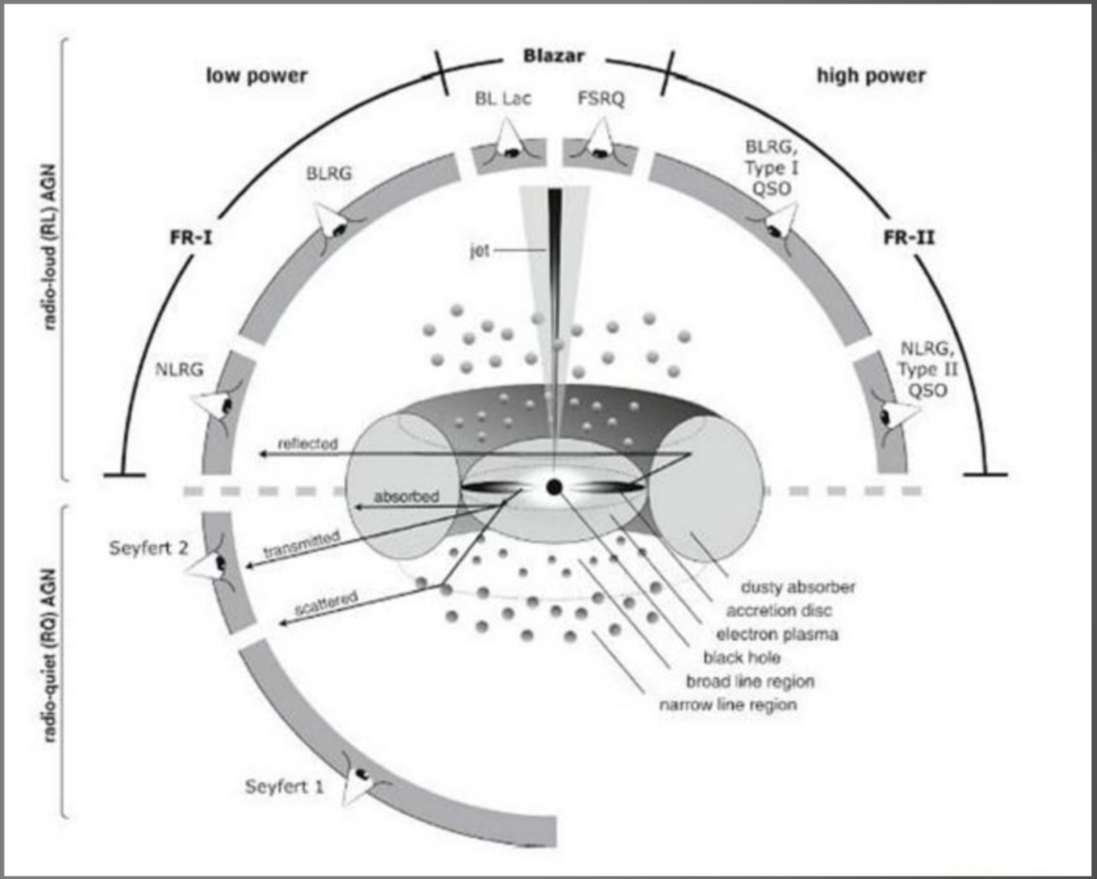
- Radio Quiet
  - Relatively weak radio emission
  - Primarily spiral galaxy hosts
  - Seyfert galaxies
    - Moderate Luminosity: $42 < \log L_{bol} < 44$ erg/s
    - Type 1: Broad and narrow emission lines
    - Type 2: Narrow lines only
- Radio Loud
  - Generally have prominent radio jet
  - Primarily elliptical host
  - Can also be Type 1 or 2
  - Only about 10 % of AGN



Cygnus A. Image credit: NRAO/AUI; R. Perley, C. Carilli, J. Dreher

Unified Model

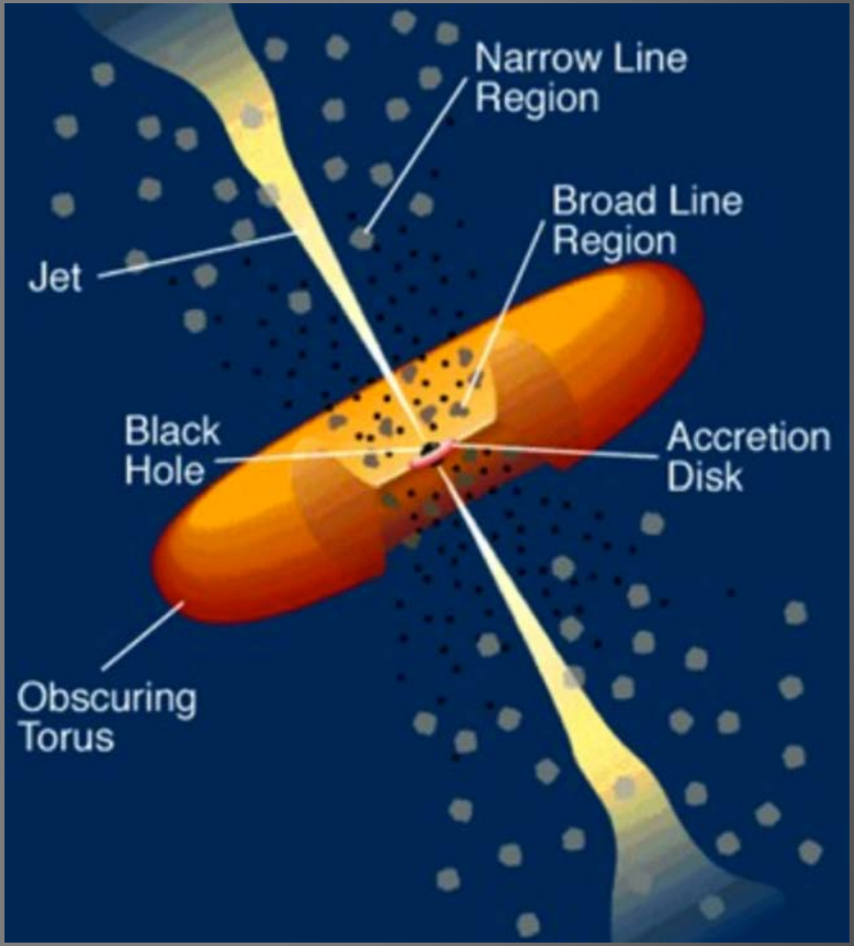
- Requires obscuration by optically and geometrically thick dust torus
- Type 1 and 2 are essentially the same, seen in different orientations



Adapted from Beckmann and Schrader (2012), Page 132, Figure 4.16

AGN components

- Supermassive Black Hole
- Accretion disk
- Broad line region
- Narrow line region
- Dust torus – absorbs optical/UV radiation, emits in IR
- Radio jets (possibly)

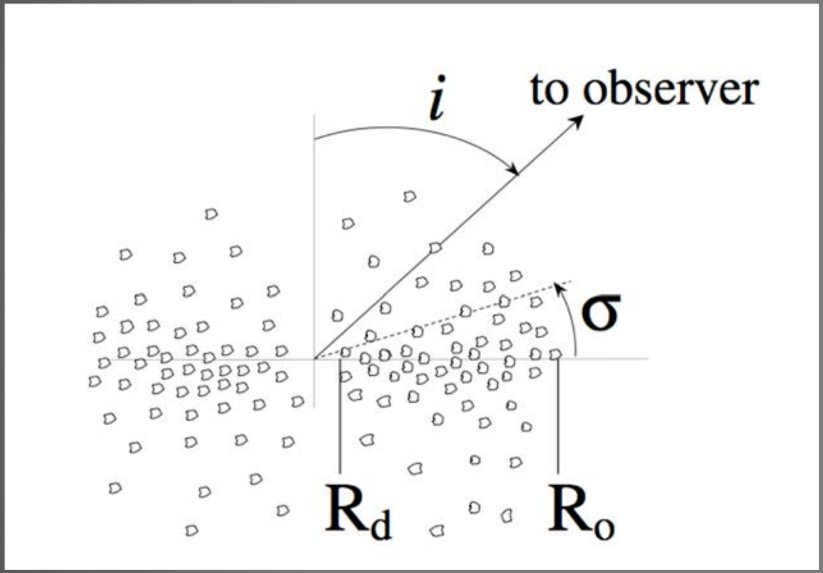


Adapted from Urry & Padovani, 1995

The AGN Torus

- Originally modeled as homogeneous, which saw observational inconsistencies
  - Homogeneous models predict large radii (~100 pc)
  - High resolution (subarcsecond) observations on 8m telescopes ruled out large radii, upper limit ~ 10 pc
- Successful models used “clumpiness” to explain observational inconsistencies
  - Size
  - 10 μm feature
- If the dust is distributed in clouds, dust of differing temperatures can exist at similar radii

Model described by six parameters



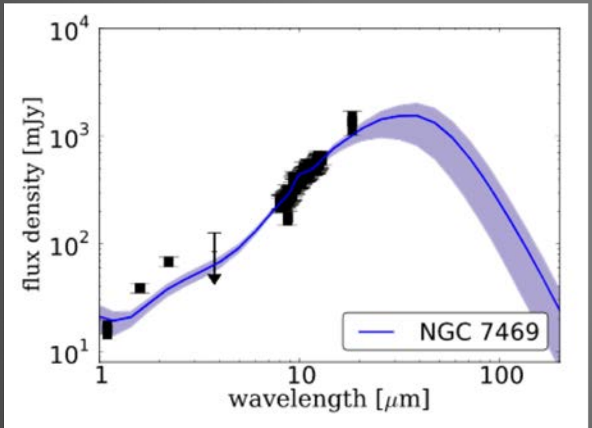
Nenkova et al. (2008b)

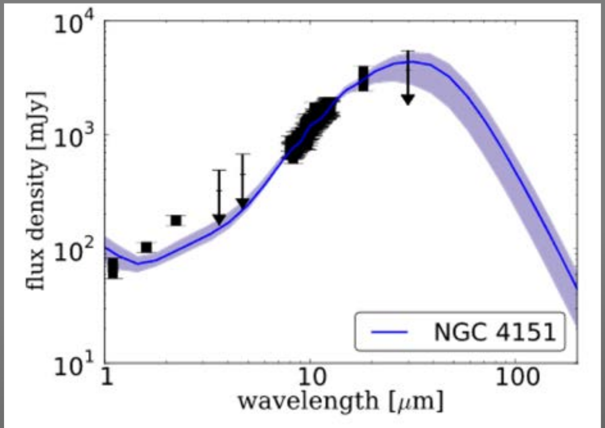
Model formalism of Nenkova et al. (2008)

- σ : Torus angular width
- $Y = R_o/R_i$: Torus outer to inner ratio
- N_0 : Number of clouds in LOS
- r^{-q} : radial distribution power law
- τ_V : optical depth
- i : torus inclination angle

Torus SED

- Spectral energy distributions have been computed using subarcsecond-resolution, ground based telescopes between 1 – 20 μm
  - Ex: Ramos-Almeida et al. 2009, 2011; Alonso-Herrero et al. 2011
- Lack of high-resolution observations at wavelengths > 20 μm leaves the SED largely unconstrained
- SOFIA provides a solution to SED coverage at wavelengths > 20 μm



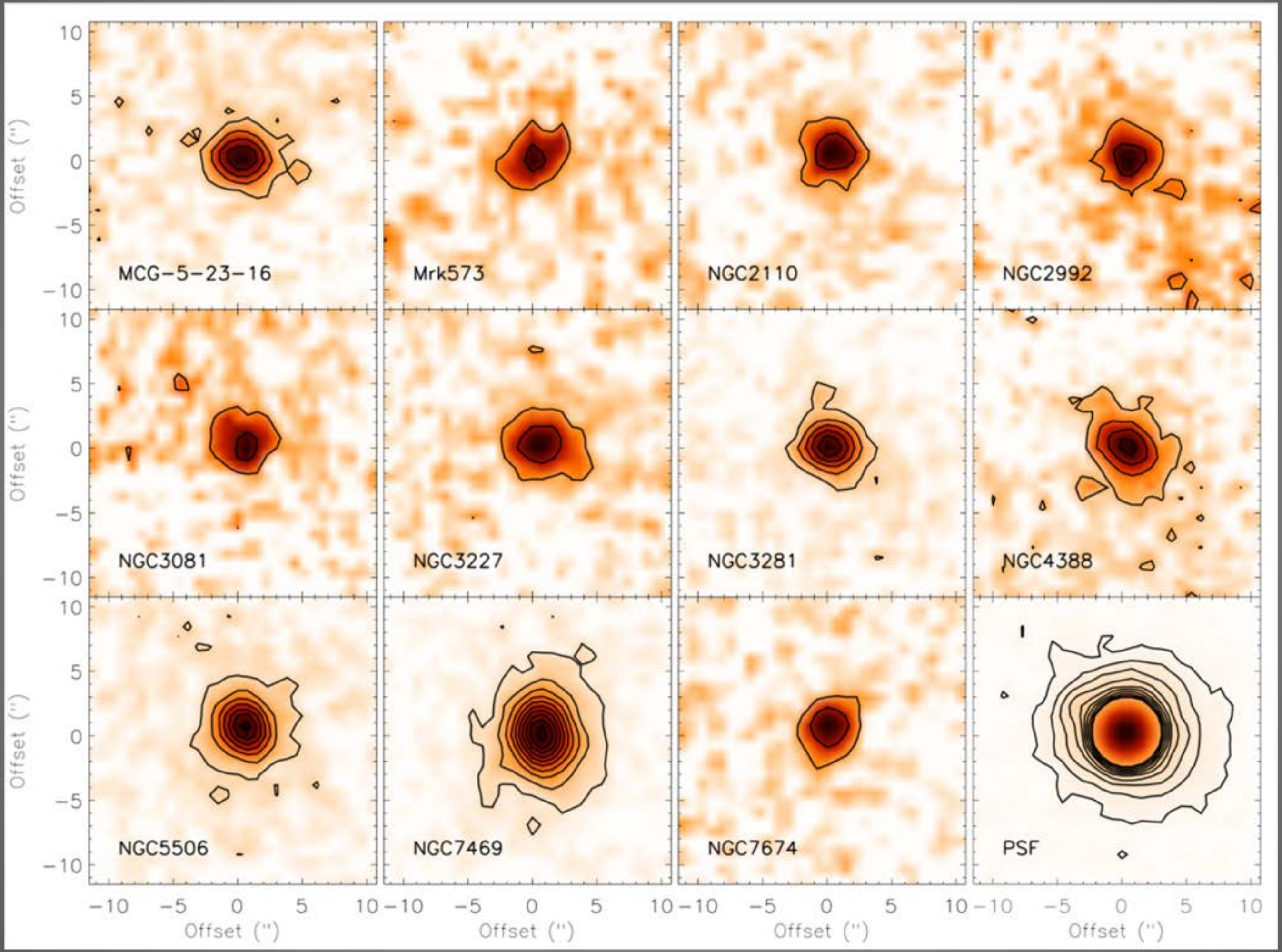


Ichikawa et al. (2015): When available, 30 μm *Spitzer* data used as an upper limit, no wavelength coverage beyond 30 μm

Cycle 2 Observations

- Eleven Objects observed during SOFIA's 2nd observing cycle (in 2014)
- Well-known, bright, nearby Seyferts that are well-sampled between 1 – 18 μm with subarcsecond resolution.
- Bolometric luminosities $42 \leq \log L_{bol} \leq 45$ erg/s
- Redshifts < 0.03
  - <120 Mpc
- SOFIA provides a solution to SED coverage at wavelengths > 20 μm….but resolution is 3 – 4" (hundreds of parsecs), where the dust torus is 1 – 10 pc scale

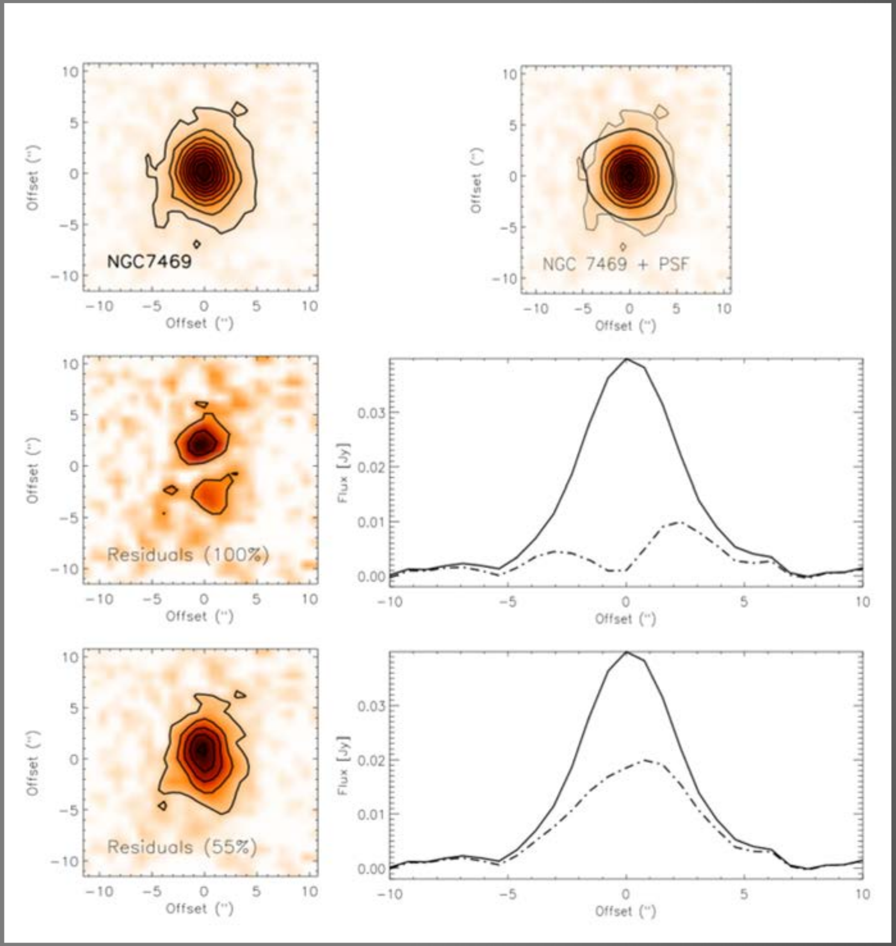
Cycle 2 Images



31.5 μm images, Fuller et al. (2016)
Contours start at 3σ with 5σ steps

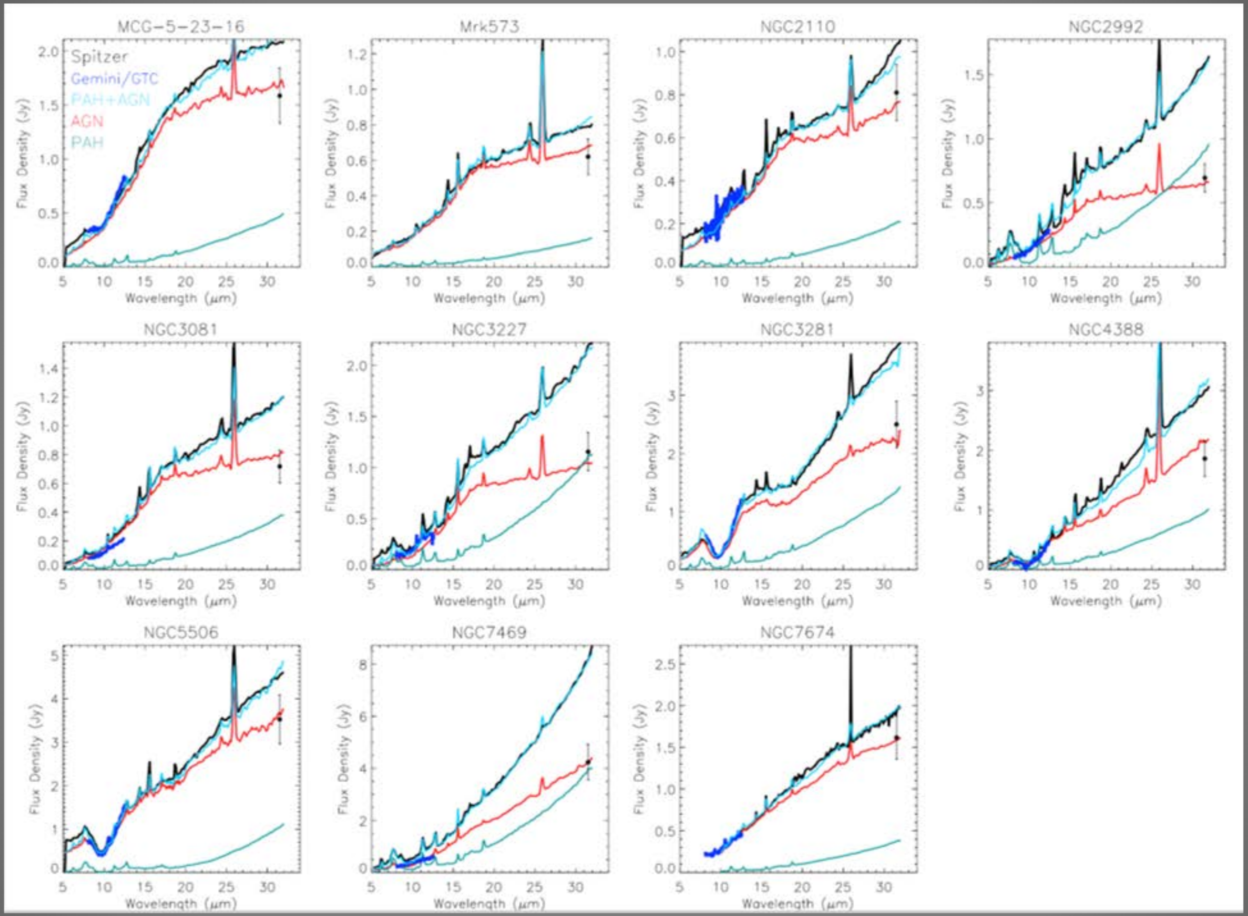
Extracting Torus Emission: PSF Scaling

- The PSF represents unresolved torus emission
- Scaled to 100% of the peak of AGN emission
- The PSF is scaled until the *residual* shows a smooth profile



Top: AGN image and AGN with PSF overlaid. Middle: Residual after 100% PSF scaling and subtraction. Bottom: Residual after 55% PSF scaling and subtraction.

Spectral Decomposition

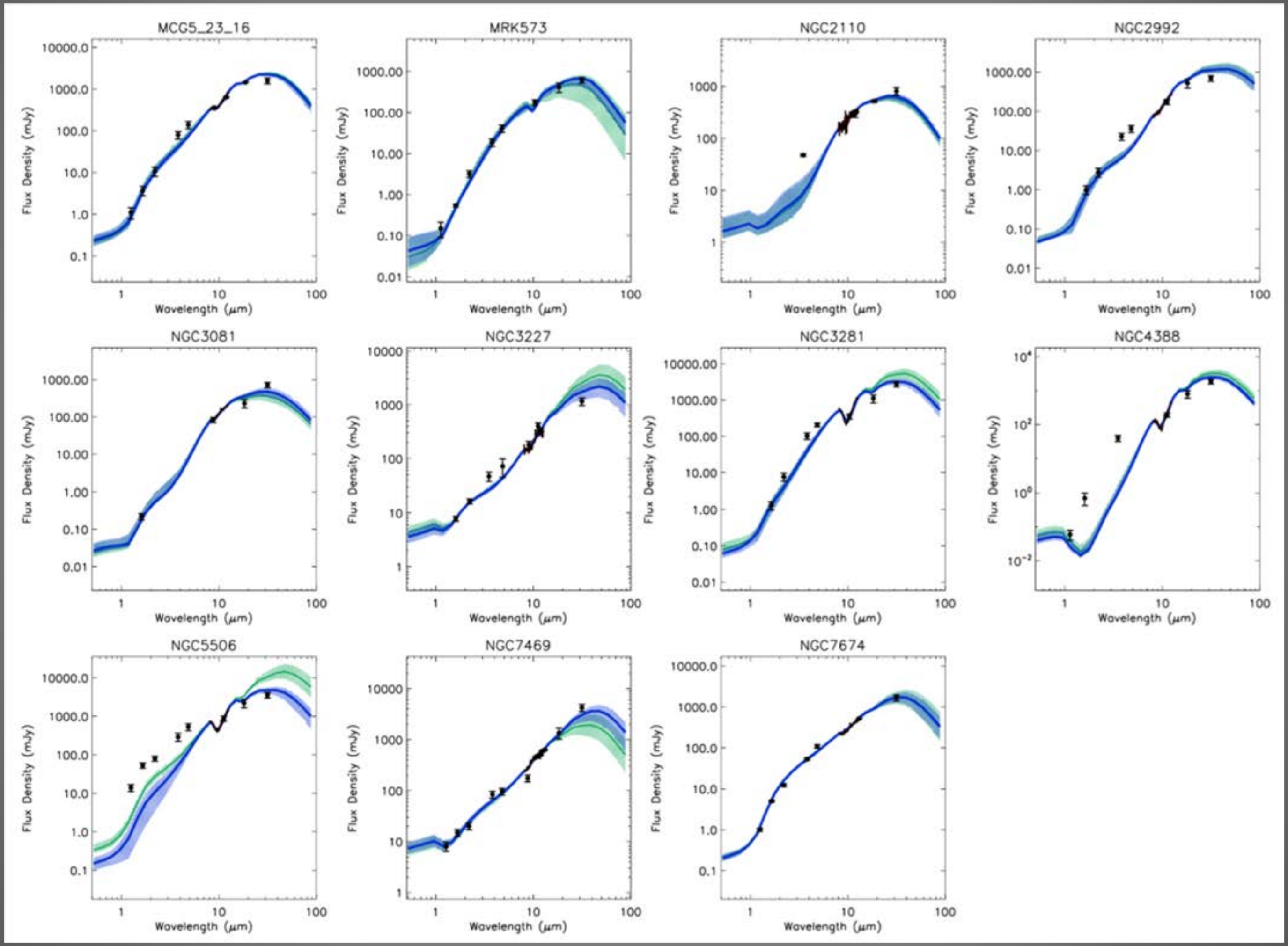


- DeblendIRS (Hernan-Caballero et al. 2015)
- IDL routine that separates Spitzer spectra into AGN and stellar components

Clumpy Torus Modeling

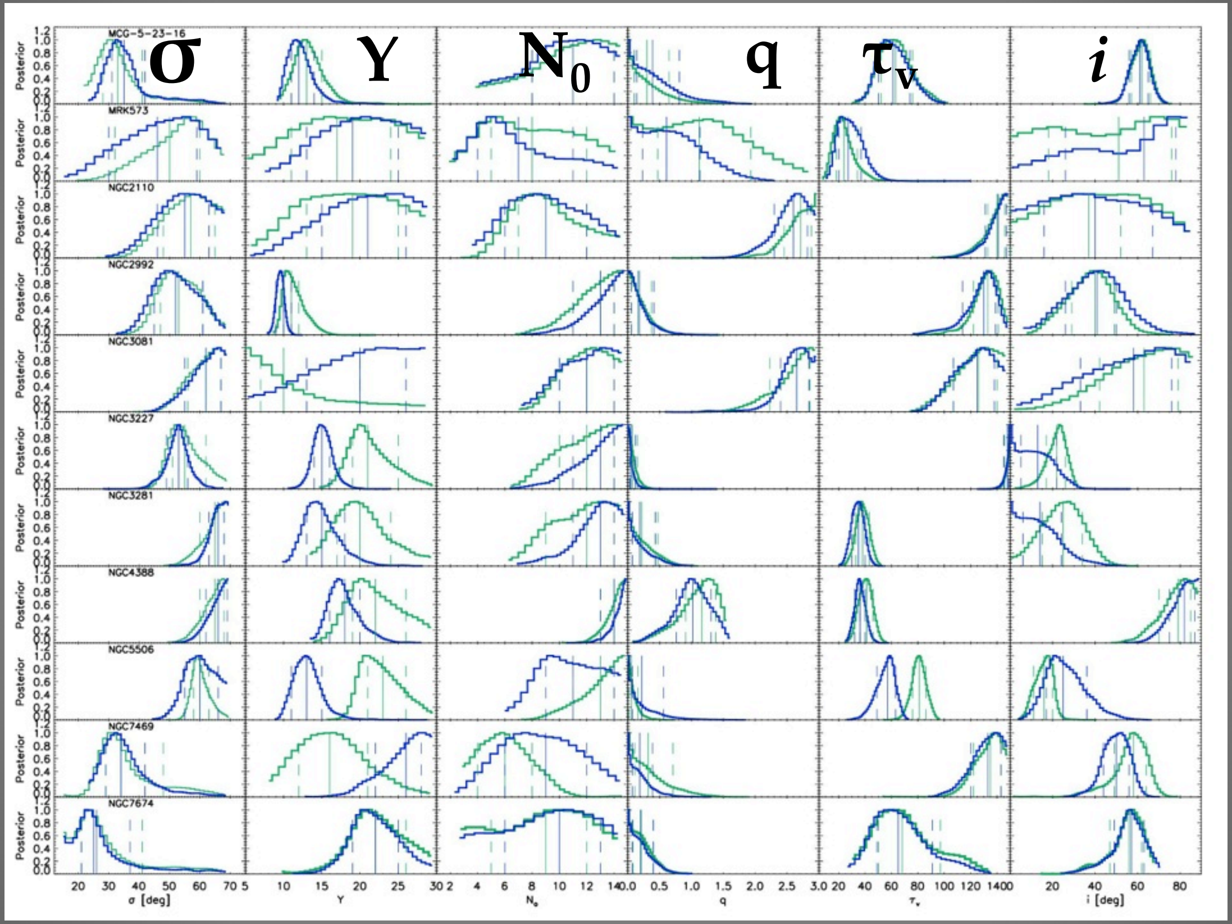
- Bayesian inference tool BayesClumpy
  - (Asensio Ramos & Ramos Almeida, 2009)
- Input: photometry and spectroscopy data, distance, Sy1 or Sy2
- Output: Most probable SED, probability distributions representing the most likely parameter outputs
- Asensio Ramos & Ramos-Almeida 2014: SOFIA provides largest constraining power for Clumpy models
  - We put this to the test!

BayesClumpy Output SEDs



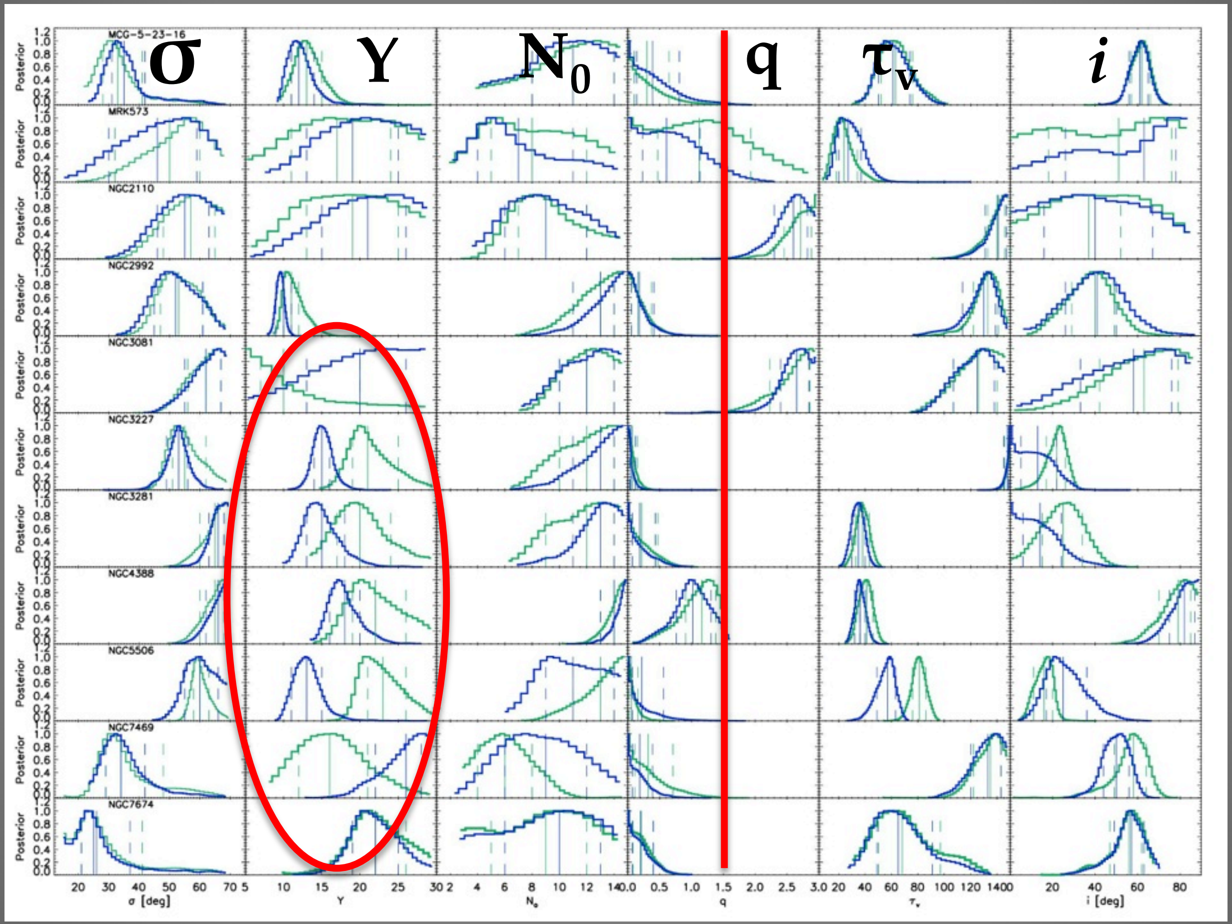
Green: BayesClumpy output before adding SOFIA data
Blue: BayesClumpy output after adding SOFIA data

BayesClumpy Posterior Outputs



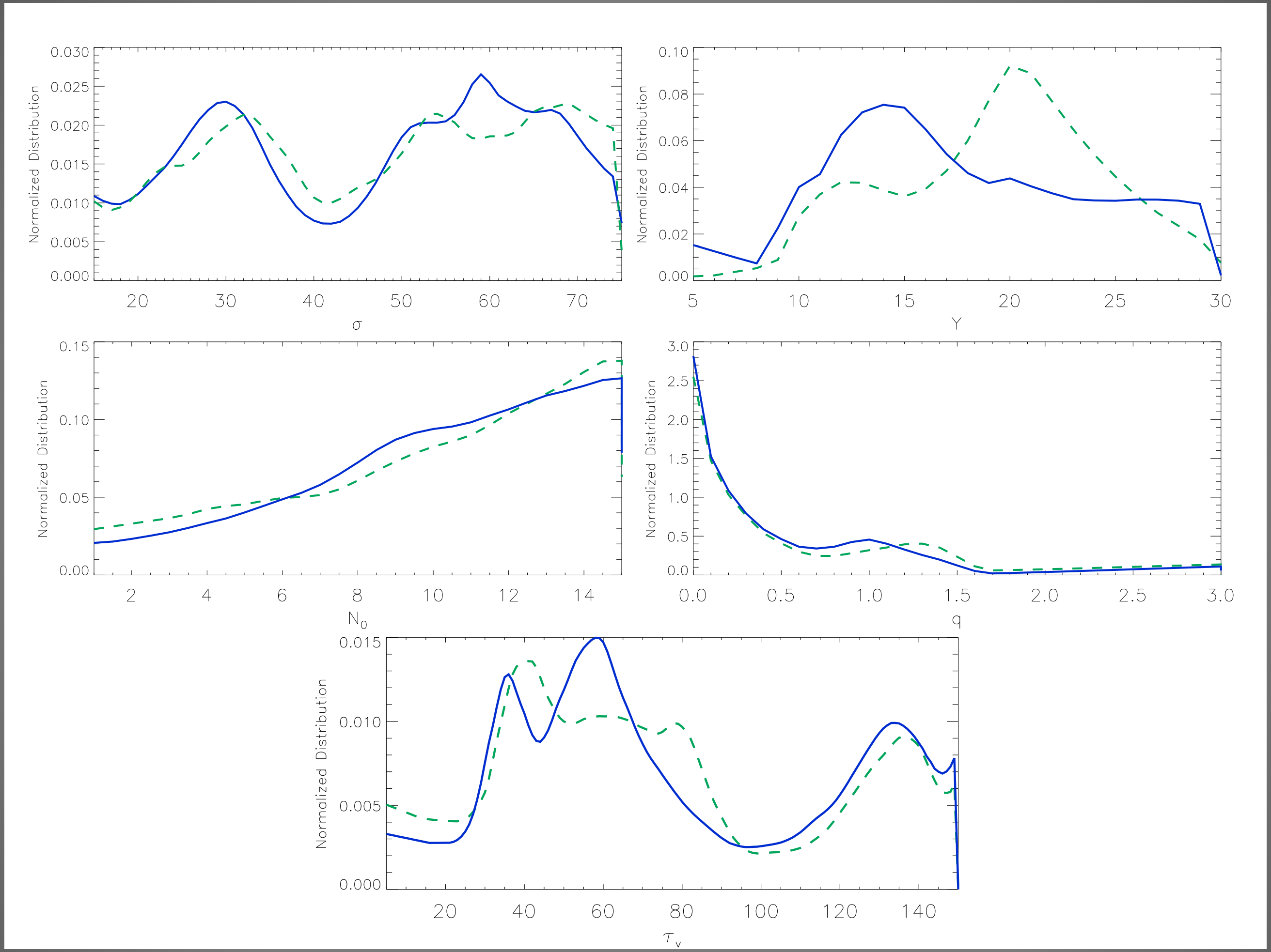
Green: BayesClumpy output before adding SOFIA data
Blue: BayesClumpy output after adding SOFIA data

BayesClumpy Posterior Outputs



Green: BayesClumpy output before adding SOFIA data
Blue: BayesClumpy output after adding SOFIA data

Global Posterior Distributions



Only AGN with NIR data and spectroscopic data were used
Green: Global posterior distribution before incorporating SOFIA data
Blue: Global posterior distribution after incorporating SOFIA data

Assessment of Cycle 2 Observations

- The wavelength of peak emission does not occur <31.5 μm
  - supported by Audibert et al., 2017

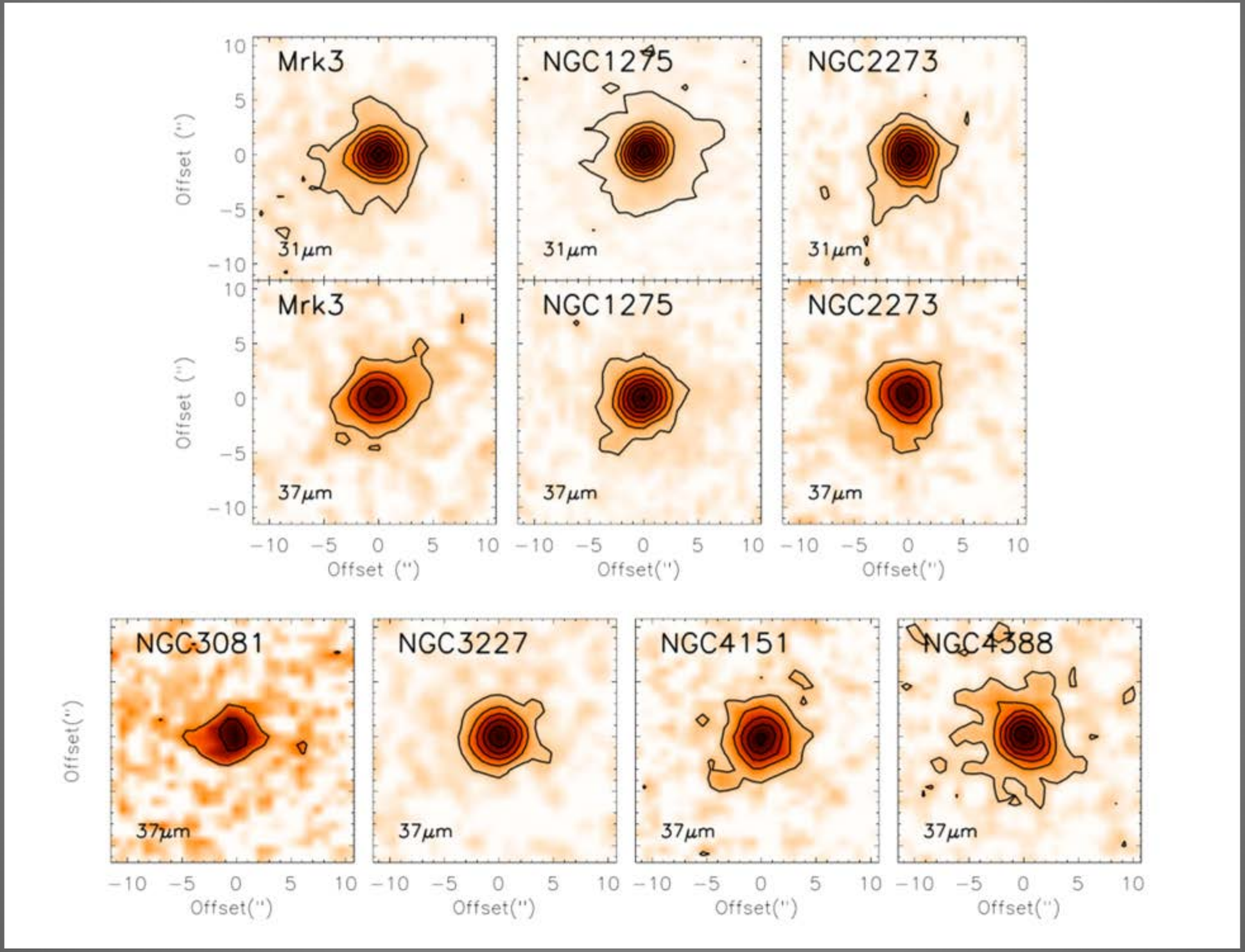
- The radial extent predicted by the clumpy model is either underestimated or overestimated for 10 of 11 objects.
  - Six objects show an overestimation
  - Four show an underestimation.
  - The average global posterior of Y decreases from 20 to 17, showing that the model generally overestimates torus size without 30 μm data

- We want to know where the spectral turnover occurs
  - Next project: 37.1 μm SOFIA observations

Cycle 4 Observations

- Three AGN observed at 31.5 and 37.1 μm
- Four observed at only 37.1 μm
- Spectral atlas of Alonso-Herrero et al. 2016
  - Observations carried out under guaranteed time on the Gran Telescopio de Canarias using CanariCam granted to Los Piratas
- Z < 0.02 (D < 75 Mpc)
- $43 \leq \log L_{bol} \leq 46$ erg/s

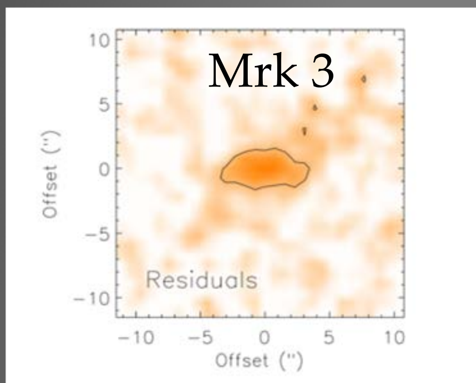
Cycle 4 Images

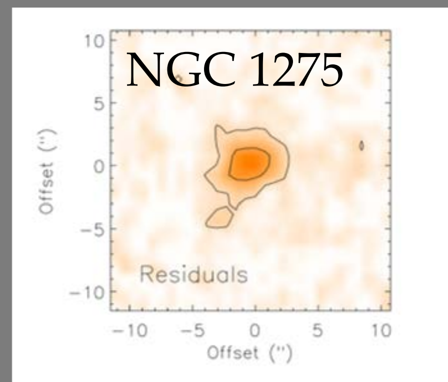


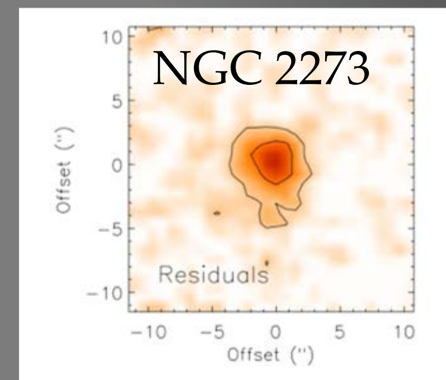
31.5 and 37.1 μm images

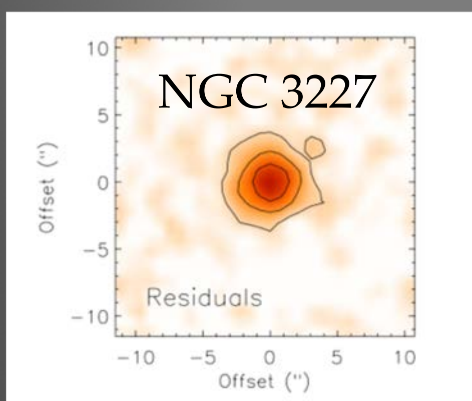
Lowest contour is 3σ, increase in steps of 5σ

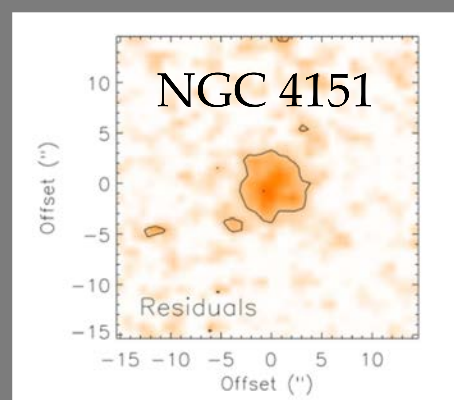
37.1 μm Residual Emission

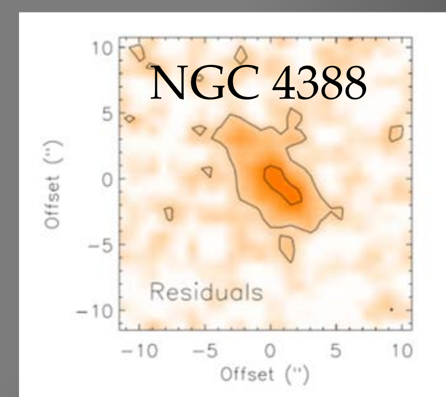












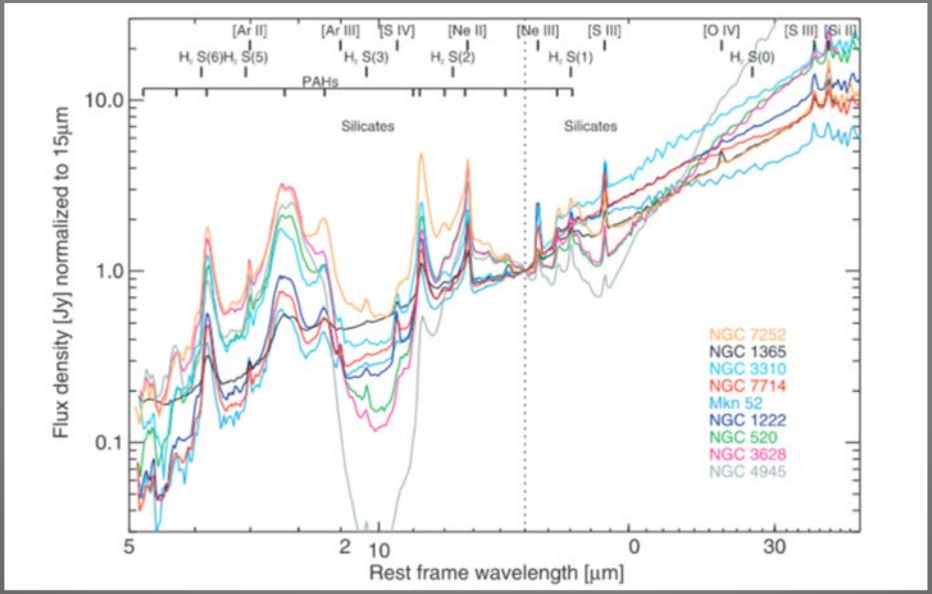
- AGN torus is on the order of ~10 pc, SOFIA resolution is 0.1 – 1 kpc, so knowing emission components and scales is crucial

Individual MIR Contributors

- Using Spitzer/IRS arcsecond scale spectra:
  - Fritz et al. 2006:
    - AGN – anything heated by AGN (primarily torus?)
    - Starburst – major contributor to emission at $\lambda > 50$ μm
  - Mullaney et al. 2011:
    - AGN – could be several dust sources
    - "Host Galaxy" (or anything non-AGN heated…probably stellar)
  - Mor et al. 2009, 2012:
    - Hot AGN component
    - Torus
    - Starburst
    - Cool NLR component

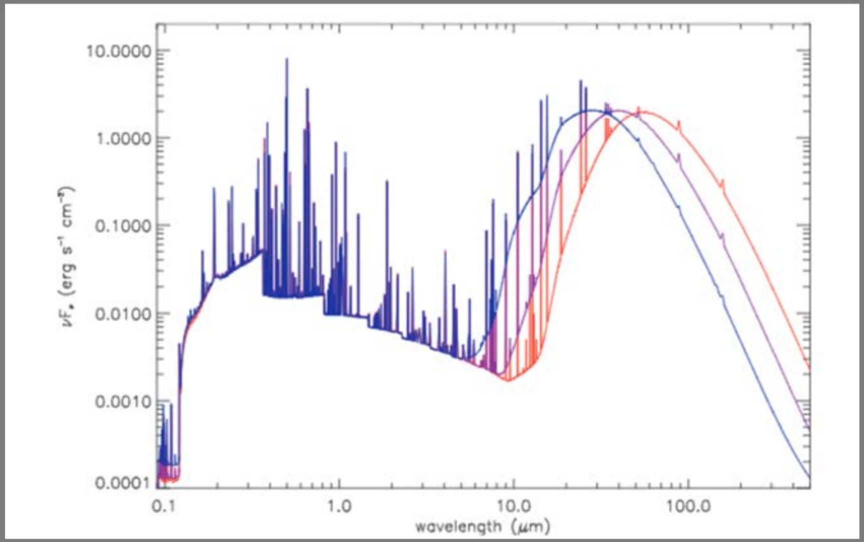
PAH Features

- Star Formation
  - Polycyclic Aromatic Hydrocarbons (PAHs)
  - Present in spectra of HII regions and starburst galaxies
    - Effective tracer of star formation
  - 3.3, 6.2, 7.7, 8.6, 11.2, 12.7, 17 μm (There is a [Ne II] 12.8 line as well as H_2 at 17.1 μm)



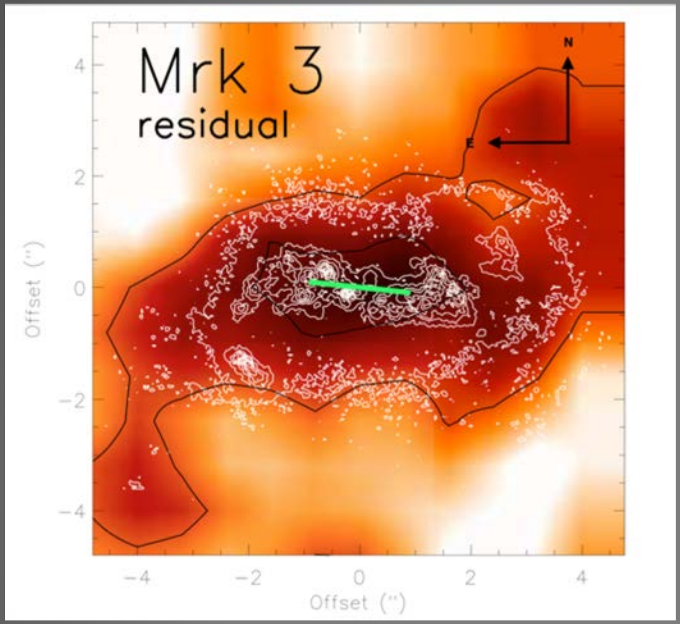
Starburst spectra from Brandl et al., 2006

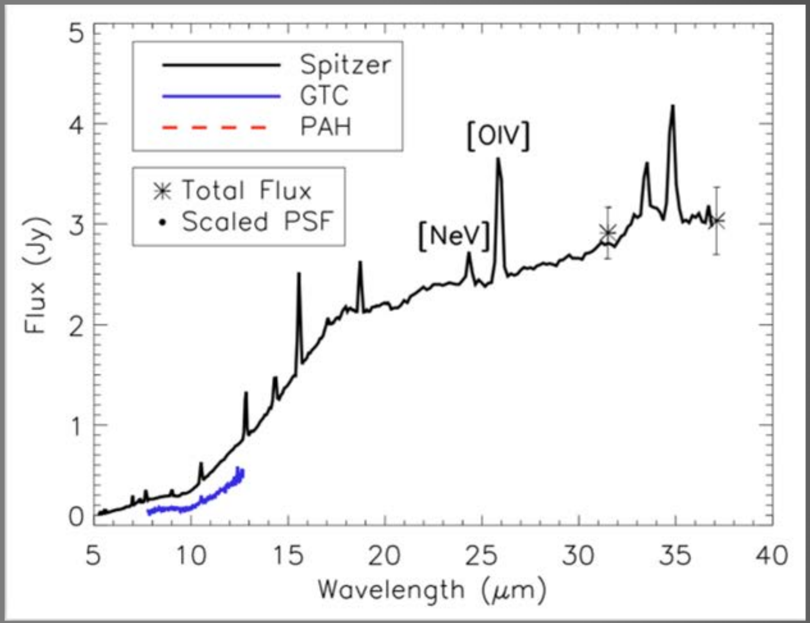
NLR MIR Spectral Features



- NLR model SED of Groves et al. 2006
- Narrow Line Region Emission Lines
  - Ionization potentials are too high to be caused by stellar heating
  - [O IV] 25.9 μm (~55 eV)
  - [Ne V] 14.3, 24.3 μm (~97 eV)
- To determine emission source, we looked at Spitzer spectra and also compared extended emission to optical and radio axes

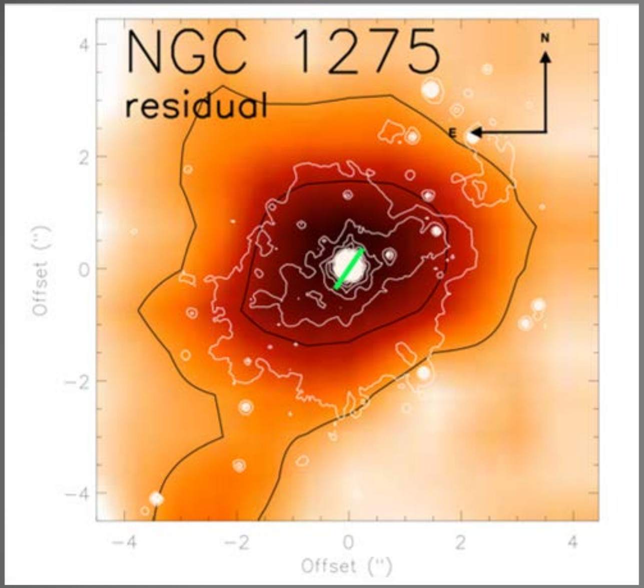
Mrk 3

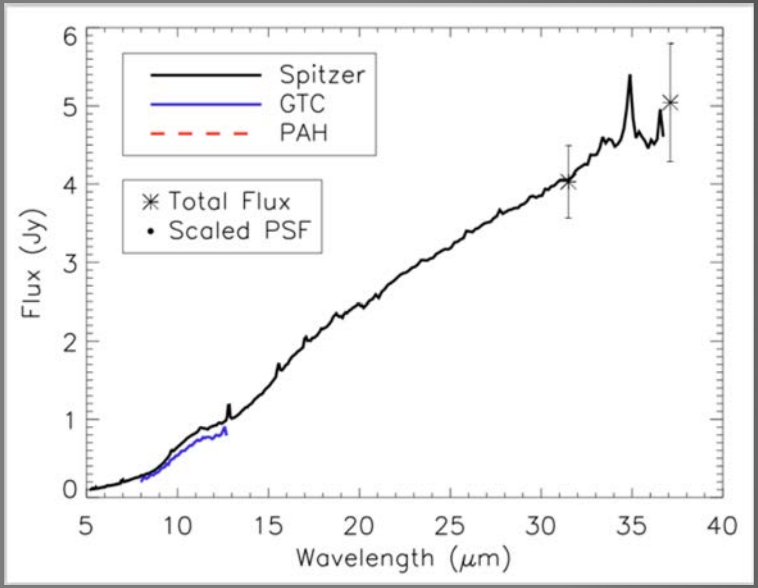




- Optical [OIII] (Capetti et al. 1995) and radio (Kukula et al. 1993) axes are coincident with 37 μm residual
  - Radio axis shown in green at 500 pc scale
- Radio axis at PA 84 in close alignment to NLR at PA 80
- No PAH, prominent [OIV] and [NeV]
- Residual emission consistent with NLR
-

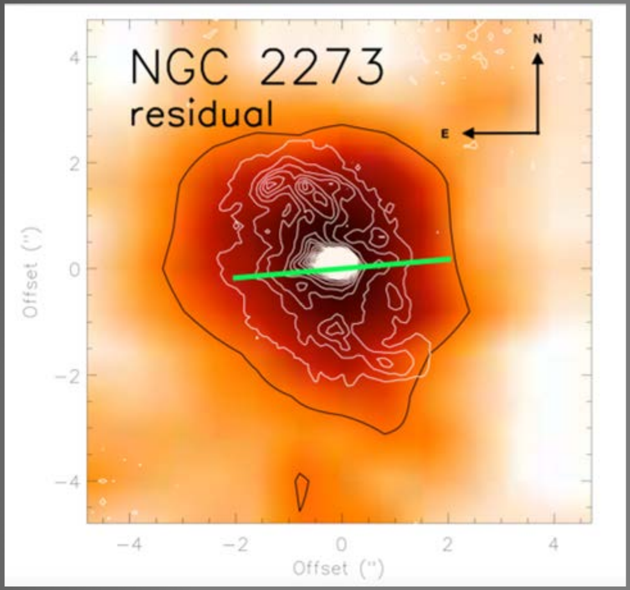
NGC 1275

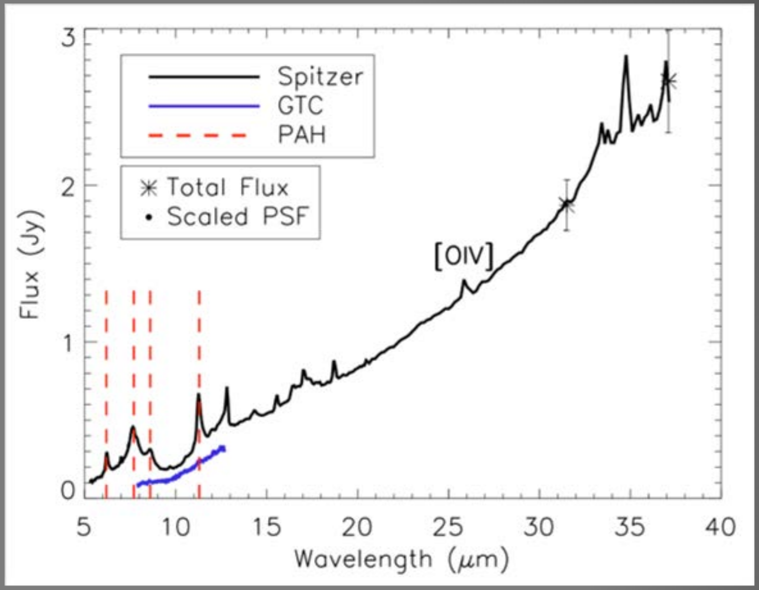




- No clear connection to radio axis (Asmus et al. 2016), optical emission is point-like. Radio axis in green at 500 pc scale
- Almost featureless spectrum
- Silicate in emission
- No clear determination of residual source

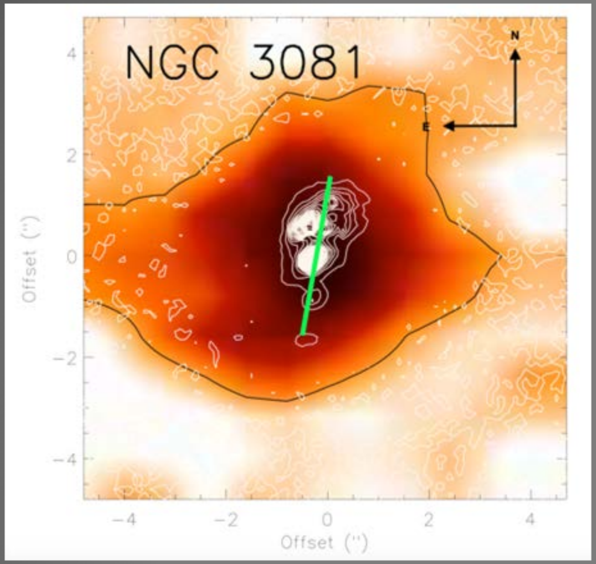
NGC 2273

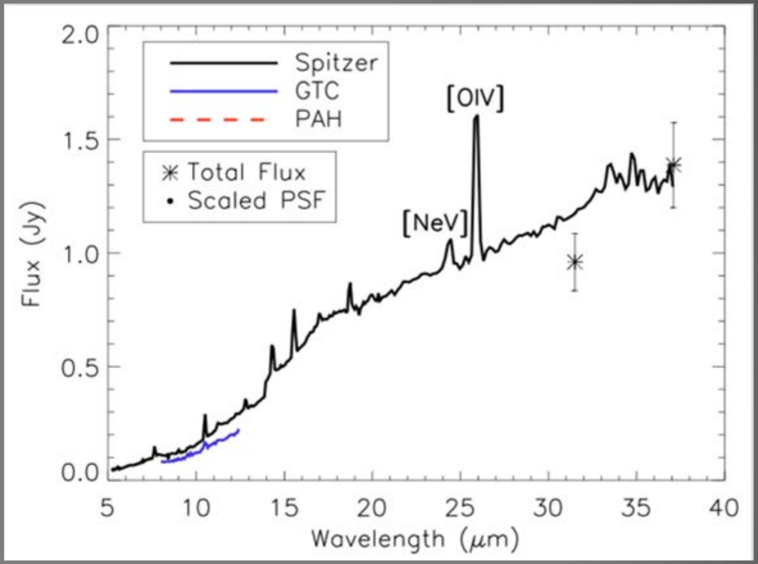




- Residual not consistent with radio axis (Nagar et al. 1999)
- Optical contours (Ferruit et al. 2000) consistent with star forming regions
- Significant PAH features, little to no NLR features
- Residuals attributed to dust from star formation

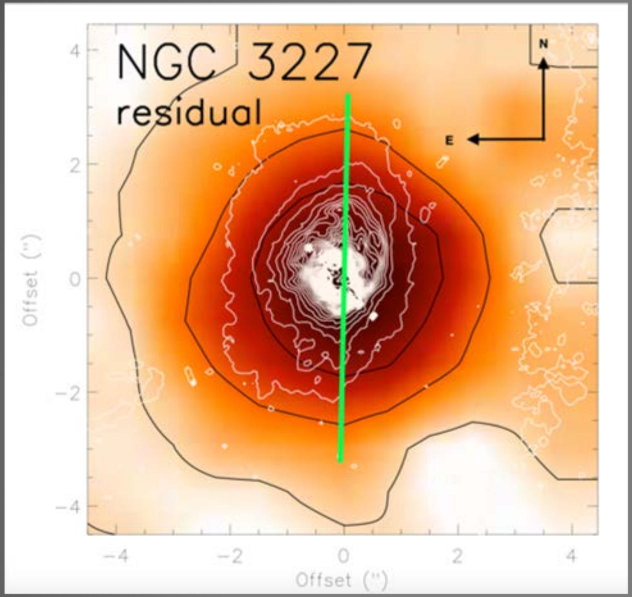
NGC 3081

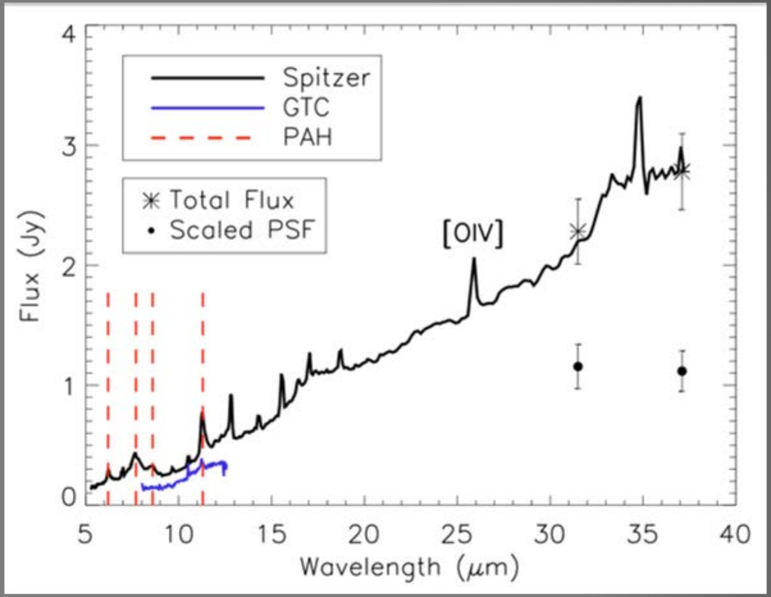




- Unable to perform the PSF-scaling, residual unavailable
- Optical contours (Ferruit et al. 2000) show AGN-like emission 1" north of the nucleus
- No PAH with strong [OIV] emission
- If there were residual emission, I would attribute to NLR

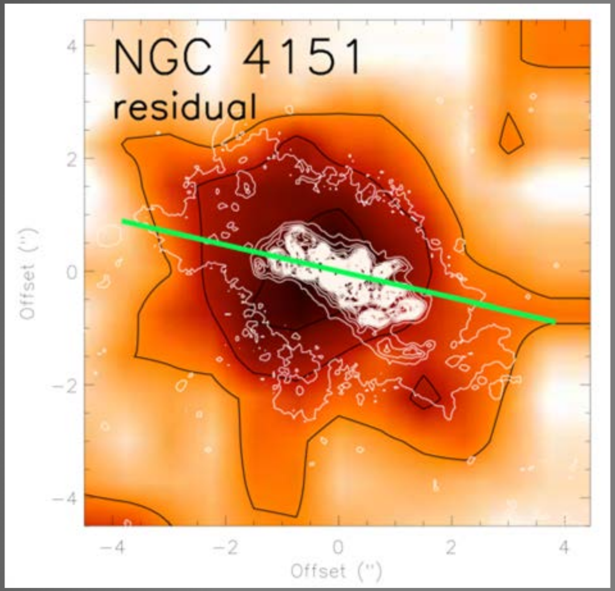
NGC 3227

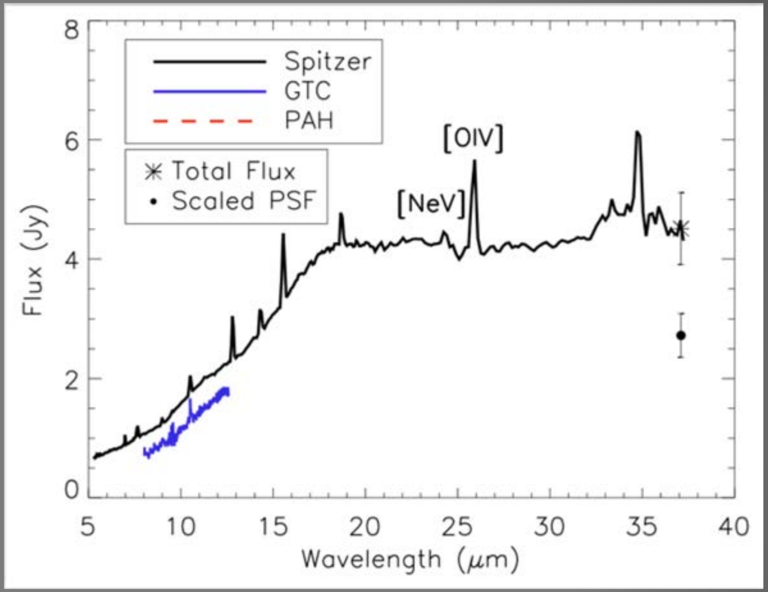




- Optical emission (Malkan et al. 1998) fits well within residual emission. Not coincident with radio axis.
- Significant PAH with (relatively) weak [OIV]
- Residuals attributed to star formation with NLR contribtuion

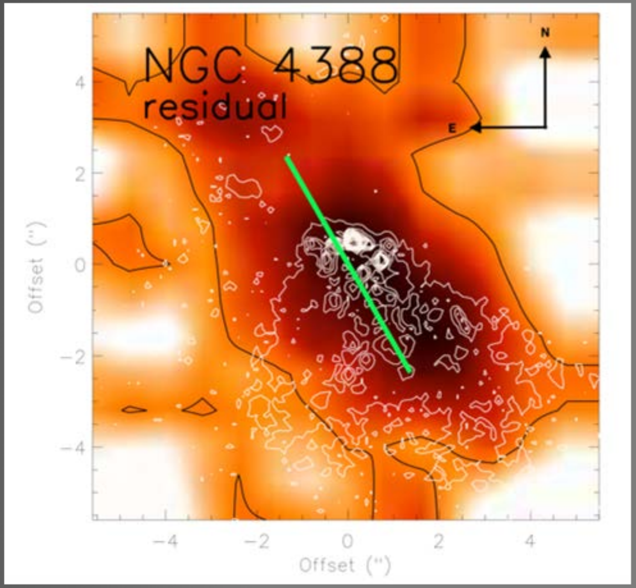
NGC 4151

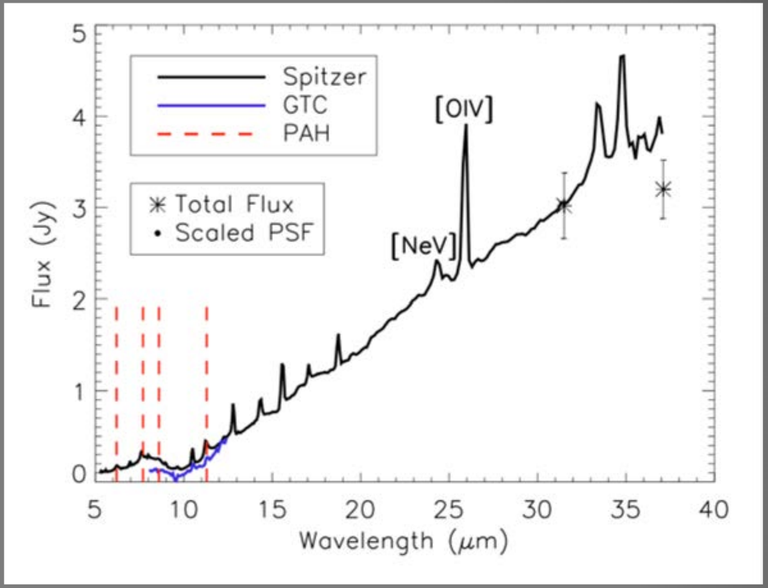




- Residual emission is somewhat coincident with optical (Kaiser et al. 2000) and radio (Pedlar et al. 1998) axes.
- Spectrum shows no PAH, strong [OIV] and weak [NeV]
- Residual emission is consistent with NLR

NGC 4388



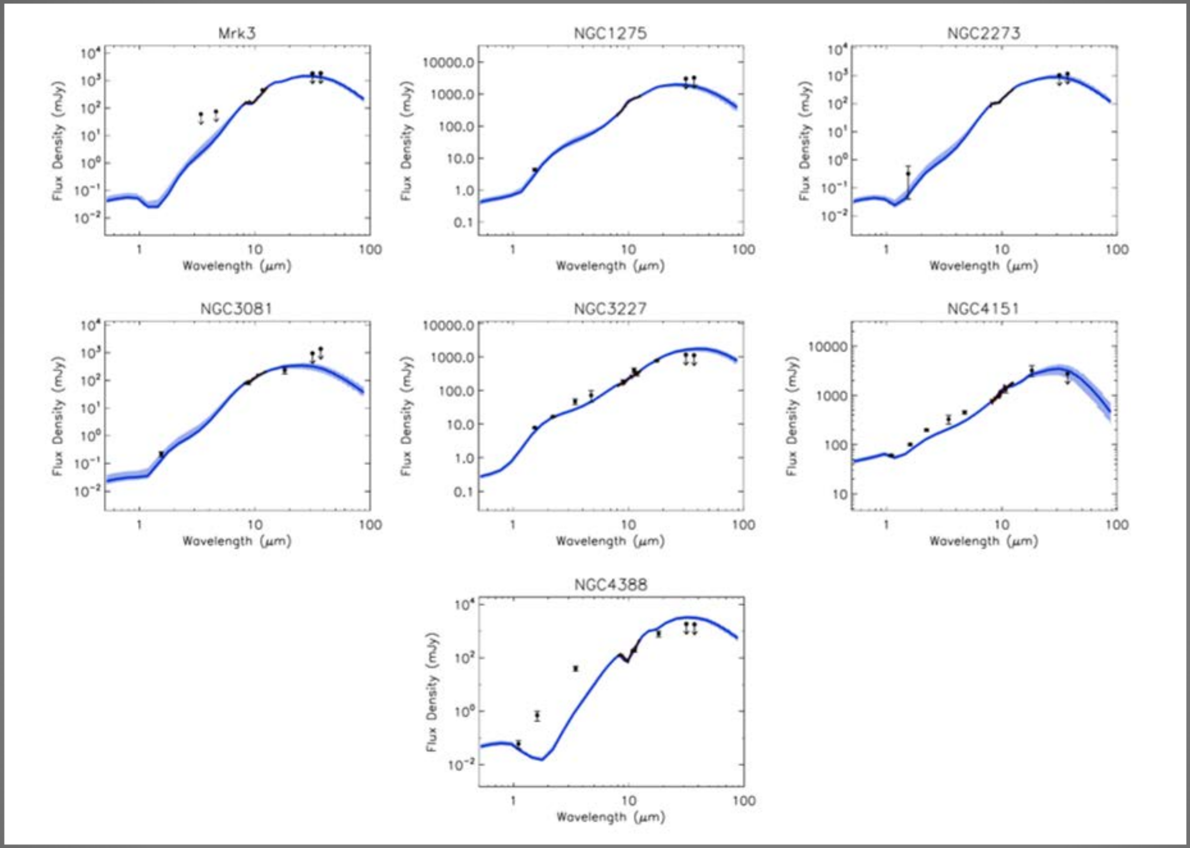


- Residual emission consistent with optical (Falcke 1998) and radio axes, with some extinction due to host galaxy
- Spectrum shows some weak PAH, strong [OIV]
- Residual emission attributed primarily to NLR with some SF

A Dusty NLR

- Implication is a dusty NLR on 3 – 4" scales
- Subarcsecond scale polar MIR emission
  - (Honig et al., 2012, 2013; Tristram et al., 2014; Lopez-Gonzaga et al. 2016)
- Extended polar dust emission out to hundreds of parsecs
  - 18 Seyferts (of 149)
  - (Asmus et al. 2016)
- Other models and observations indicate that dust may exist on scales of hundreds of parsecs
  - (Groves et al. 2004, 2006; Schweitzer et al. 2008; Mor et al. 2009, 2012; Richardson et al., 2014)
- NLR contribution and SED unknown so we use upper limits on our fluxes (could not do decomposition again)

BayesClumpy SEDs

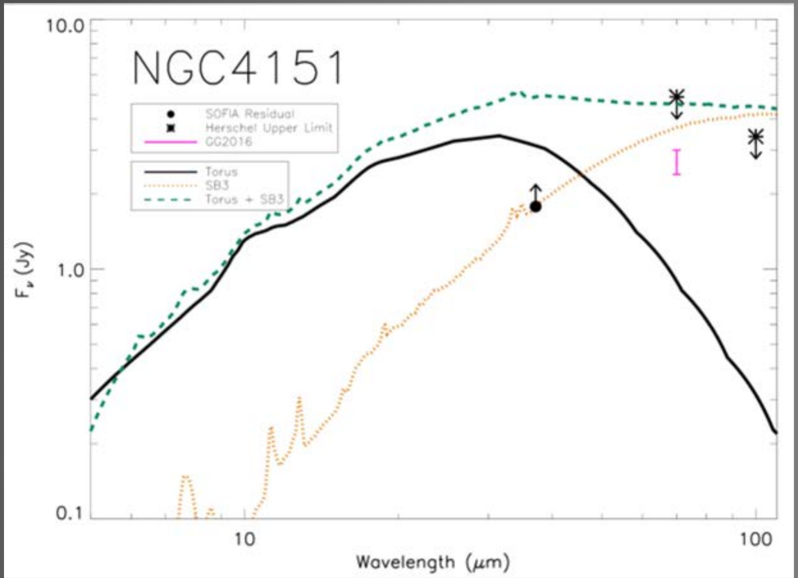


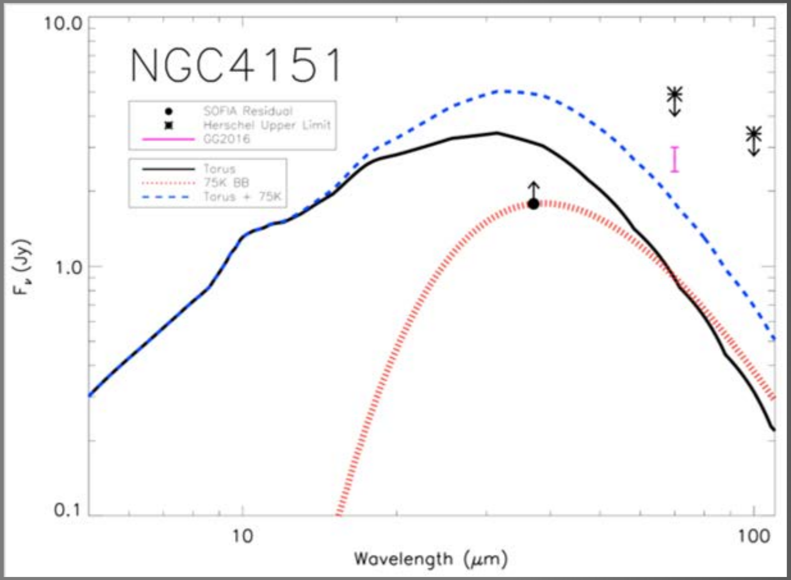
- Even when the 31.5 and 37.1 μm data is set as an upper limit, the model overestimates 30 – 40 μm flux in NGC 3227 and NGC 4388
- Three AGN show tentative turnover between 30 – 40 μm

Blackbody Temperatures

- 31.5 and 37.1 μm residual fluxes increase
  - 2 – color fit to blackbody
  - (Yes, two data points aren't ideal)
- T ~ 70 – 80 K dust for Mrk 3 and NGC 4388
  - Consistent with NLR models
  - Temperatures consistent with dust heated at radii of hundreds of parsecs
- T ~ 50 – 60 K in NGC 2273 and NGC 3227
  - Consistent with star formation temperatures
- Is FIR emission in AGN-dominated objects consistent with observations?

FIR Emission





- 70 and 100 μm *Herschel* fluxes within 13" from Mullaney et al., 2011 used as upper limits
- The data in pink (Garcia-Gonzalez et al. 2016) is the AGN contribution at 1 kpc
- Left: BayesClumpy SED (black) with starburst template (orange) SB3 from Mullaney et al. 2011, and total emission (green)
- Right: BayesClumpy SED (black) with 75 K blackbody (red) and total emission (purple)
- The 75 K blackbody better represents total emission

Assessment of Cycle 4 Observations

- Tentative observational SED turnover in 3 AGN
- Resolved extended emission in the NLR is tentatively detected in Mrk 3, NGC 4388, and NGC 4151.
- NLR dust possibly emits ~ 70 – 80 K
- A 75 K blackbody describes FIR emission in NGC 4151 better than a starburst.
  - FIR SED can likely be described as a combination of both sources, further knowledge on the NLR SED is needed

General Conclusions

- Without 31.5 μm data, the model tends to overestimate torus SED (and radial size)
- AGN tentatively show emission turnover between 30 – 40 μm
- Outer torus radii ~ 1 – 8 pc
- Extended residual emission coincident with NLR for 2 (possibly 3) AGN
  - Must take polar/NLR dust when modeling AGN at the resolution of SOFIA

More SOFIA observations of AGN

- Lopez-Rodriguez et al. (2018) show observations of NGC 1068 using FORCAST and HAWC+
  - The torus SED covers wavelengths 1 – 432 μm!!
- Cycle 6 Observing Proposal approved for observations 37 – 90 μm

- Thank you!