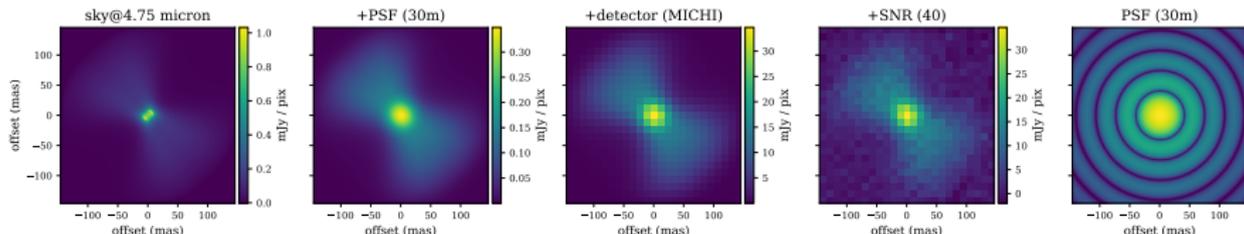


Hypercat - Hypercube of AGN tori

Robert Nikutta (NOAO)

Enrique Lopez-Rodriguez (SOFIA), Kohei Ichikawa (Tohoku Univ.)
Nancy Levenson (STScI), Chris Packham (UTSA)

TORUS2018, December 2018, Puerto Varas / Chile



CLUMPY torus model

single cloud optical depth τ_v

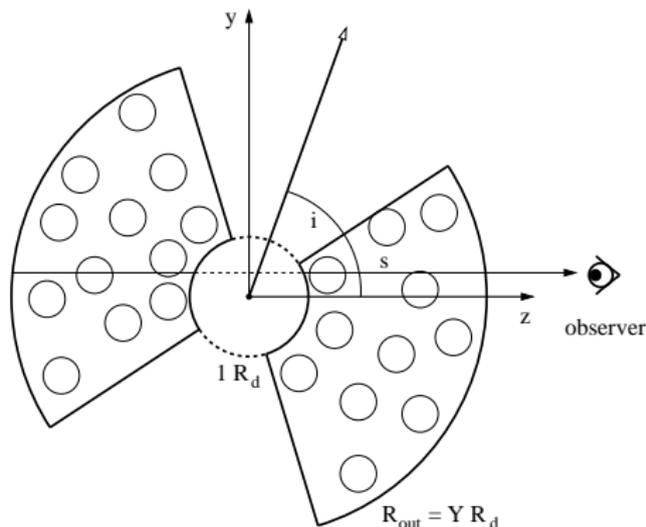
clouds/ray in equatorial plane N_0

angular torus width σ

torus thickness $Y = R_o/R_d$

radial cloud distribution r^{-q}

observer viewing angle i

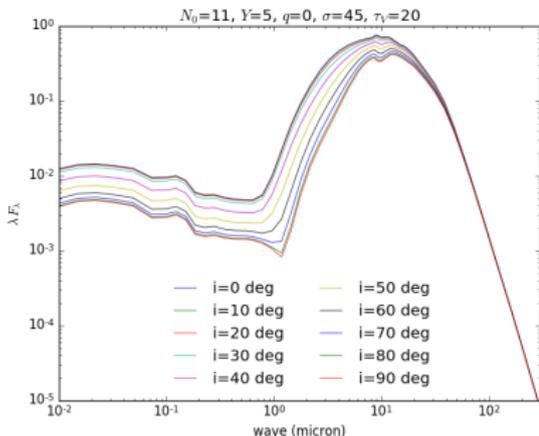


CLUMPY so far: SEDs

Most *du jour* torus models; Nenkova+2002, 2008a&b; 1100 citations

Model SEDs brought to you since 2008

www.clumpy.org



Welcome

CLUMPY

Model description SEDs Images Contact News & Updates

Welcome

Welcome to the home of CLUMPY, a code modeling AGN clumpy dust torus emission. It was originally developed at the [University of Kentucky](#), and is now developed and maintained at [UPAO](#).

Jump straight to the [Model Description](#)
or download the [SEDs](#)
or (coming soon) download the [topographic brightness maps](#)

Please follow the latest [News & Updates](#), as the models may change at any time.

Disclaimer

All data available on our website are public, and reflect the latest state of our scientific research and development. Please feel free to use them for the benefit of your research, provided that acknowledgment is made in each publication. The bibliographic references are:

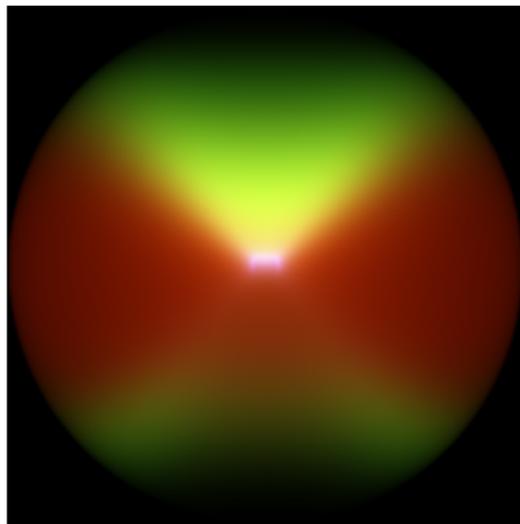
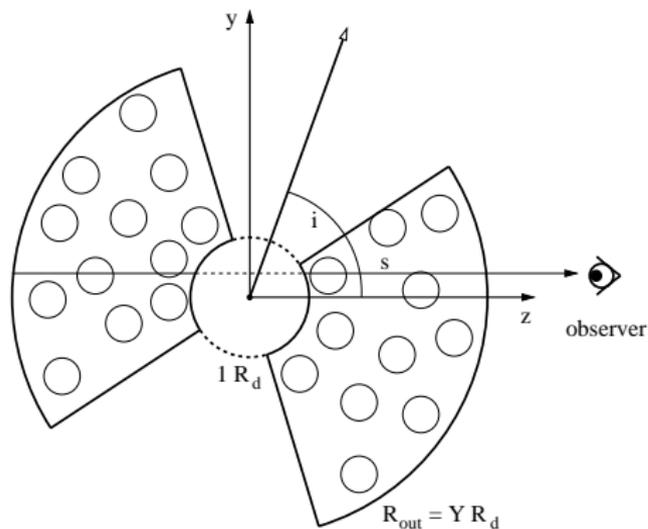
Nenkova, M., Stacey, M.H., Ivezić, Z. & Elitzur, M., "AGN Dusty Tori. I. [Handbook of Clumpy Media](#)", 2008, Apr. 685, 147

Nenkova, M., Stacey, M.H., Nikutta, R., Ivezić, Z. & Elitzur, M., "AGN Dusty Tori. II. [Observational Implications of Clumpiness](#)", 2008, Apr. 685, 160

Please note that models may be subject to [changes or updates](#) at any time. Therefore, please make sure to check back here and always use the latest models available.

Last modified on Sat 23 April 2017 by [Robert Nenkova](#)

CLUMPY torus model

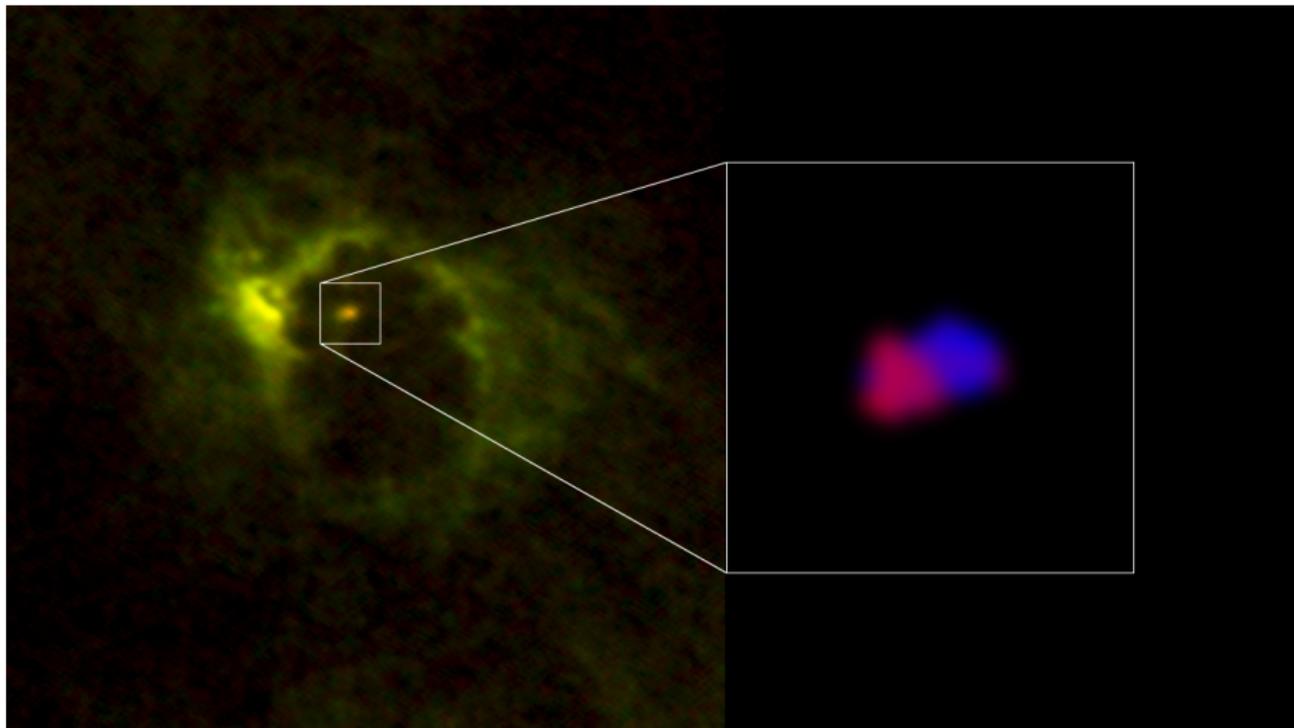


- single cloud optical depth τ_V
- clouds/ray in equatorial plane N_0
- angular torus width σ
- torus thickness $Y = R_o/R_d$
- radial cloud distribution r^{-q}
- observer viewing angle i

Vector of parameters

$$\vec{\theta} = (\sigma, i, Y, N_0, q, \tau_V, \lambda)$$

Torus now resolvable, VLT, ALMA, and TMT, GMT, ELT

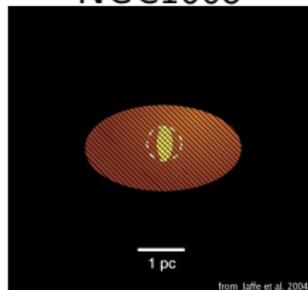


Imanishi+2018

(see also Garcia-Burillo+2016, Gallimore+2016)

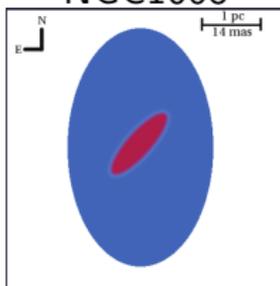
Resolved dust emission in the Mid-IR (VLT)

NGC1068



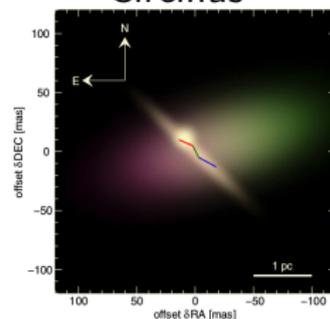
Jaffe+2004,
2 uv points

NGC1068



Raban+2009,
16 uv points

Circinus

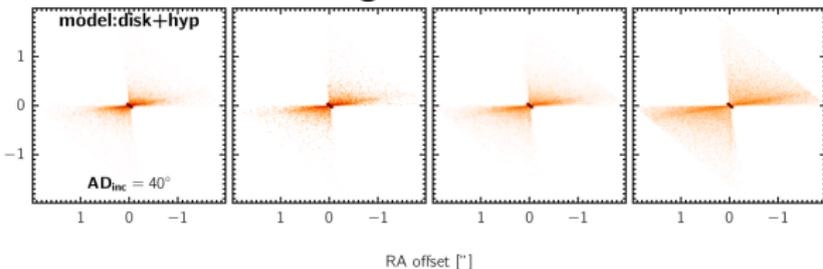


Tristram+2014
polar dust emission?

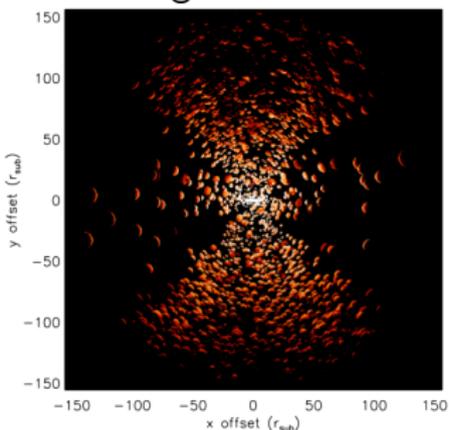
- ▶ More AGN with polar elongation MIR emission observed (see e.g. Hoenig+2013, Lopez-Gonzaga+2016, Leftley+2018)
- ▶ Non-physical, direct modeling of the brightness distribution seen by the interferometer

Some proposed solutions

Tilt the illuminating disk, use hollow cone...

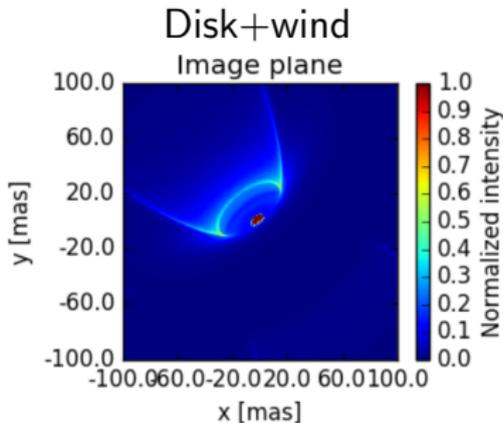


Re-arrange the clouds...



Hoening & Kishimoto 2017

Stalevski+2017 (see also M. Kishimoto talk yesterday)



Vollmer+2017

HYPERCAT in nutshell

HYPERCAT is...

- ▶ Very large **hypercube** of AGN torus images
(here the CLUMPY model, but you can plug in your own)
- ▶ A suite of Python **tools** to easily interact with the hypercube
(slicing, loading, n-dim interpolation)
- ▶ Tools to **simulate** observations (to 1st order, 2nd maybe...)
(single-dish giant telescopes and interferometers)
- ▶ Methods to **analyze** image morphology
(“traditional” techniques, image moments, *wavelets*, ...)
- ▶ HYPERCAT also has the 2-d **projected cloud maps**
(compare dust and light morphologies)

... all while hiding the complexity of the problem from the user.

Image hypercube

- ▶ CLUMPY SEDs, $1.2e6$ param. combos, $N_\lambda = 119 \rightarrow$ **0.5 GB**
- ▶ Image hypercube w/ same parameter sampling would be **15-50 TB!!**
- ▶ Limit sampling (336k) & $N_\lambda = 25 \rightarrow$ **0.9 TB** (271 GB compressed)

Get the hypercubes today!

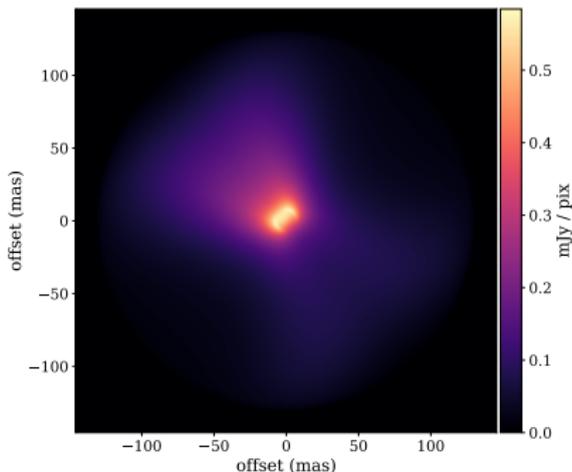
- ▶ FTP: <ftp://noao.edu/pub/nikutta/hypercat/>
- ▶ Straight from your local dealer [*ask me for my external HDD ;-)*]

\rightarrow **3.2 CPU-years** to compute images (*once...*)
(245 billion voxels in 9-dim space, plus dust maps)

Generate ideal image of the source

```
ngc1068 = Source(cube,luminosity='1.6e45 erg/s',\  
                 distance='14.4 Mpc',pa='42 deg')\  
vec = (43,75,18,4,0.08,70,10) # sig,i,Y,N0,q,tv,wave\  
sky = ngc1068(vec,total_flux_density='2700 mJy')
```

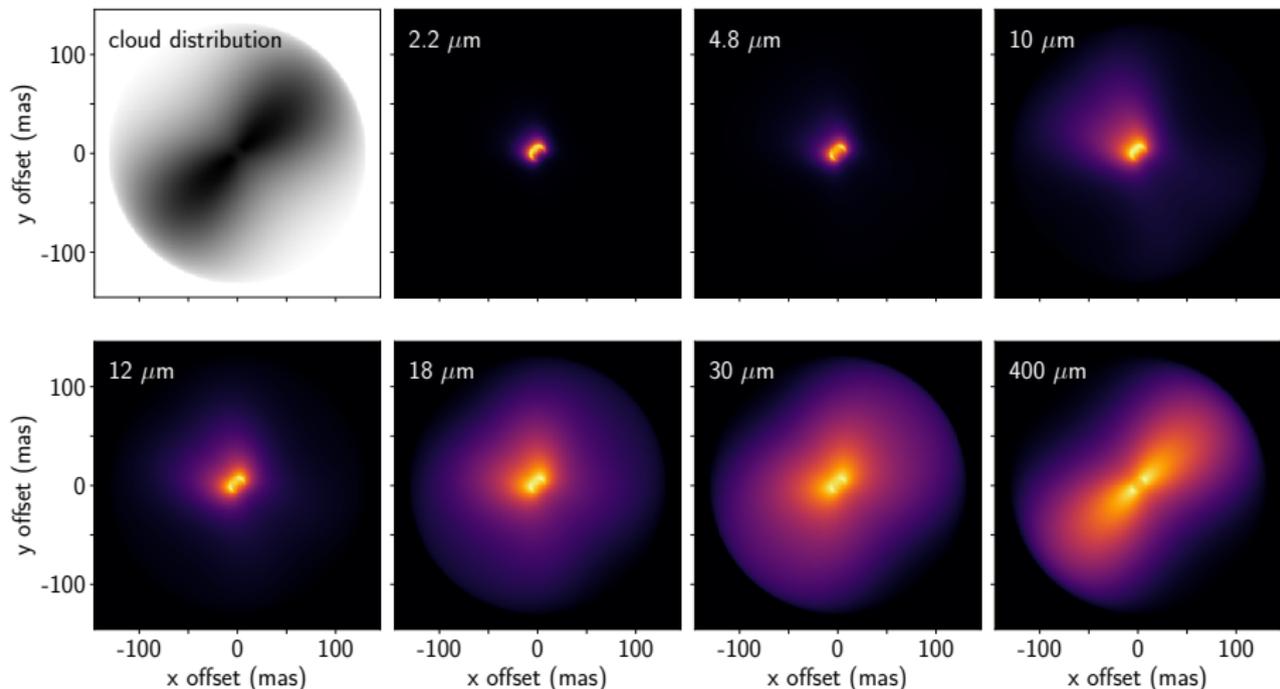
- ▶ IR radiative transfer is self-similar; L set scale: $R_{\text{dust}} \propto \sqrt{L}$
- ▶ Interpolates image on n-dim hypercube for the vector of parameters



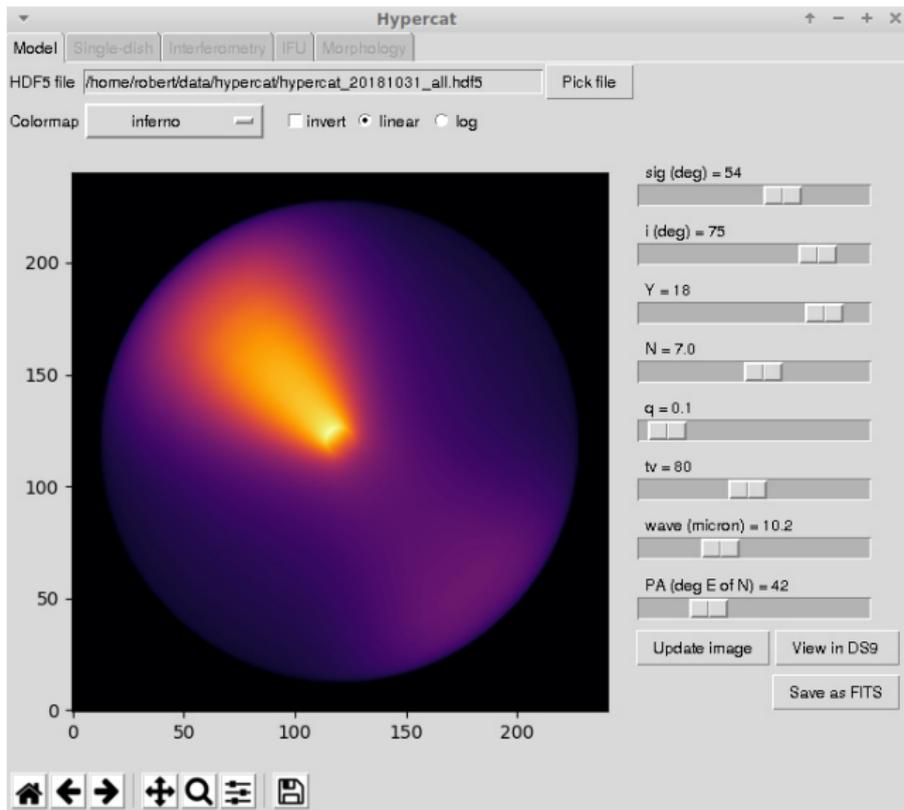
Multi-wavelength view

NGC1068 best-fit parameters from SED fitting (Lopez-Rodriguez+2018)

$$\sigma = 43, i = 75, Y = 18, N_0 = 4, q = 0.08, \tau_V = 70$$

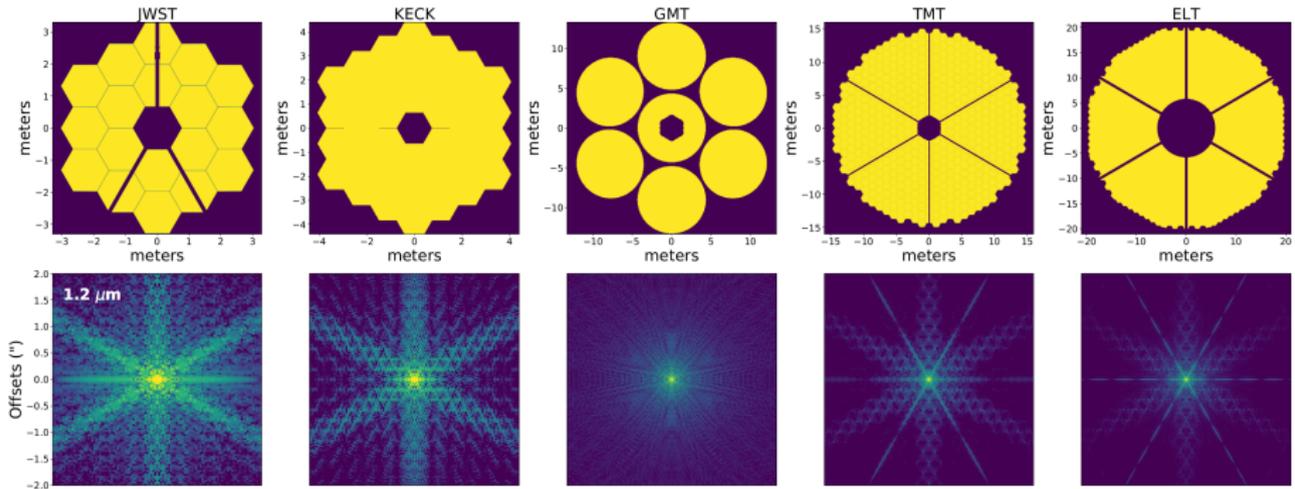


Hypercat GUI (very basic for now)



Simulate observations - PSFs from pupils

PSFs from pupil images (*thank you, telescope consortia!*)



Pretty big pupils...

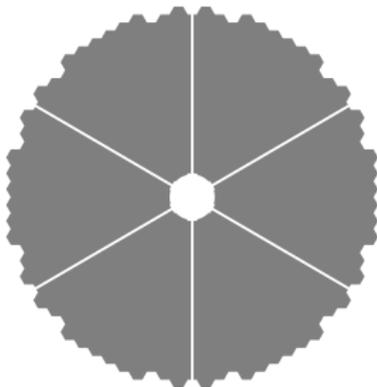
JWST (6.50 m)



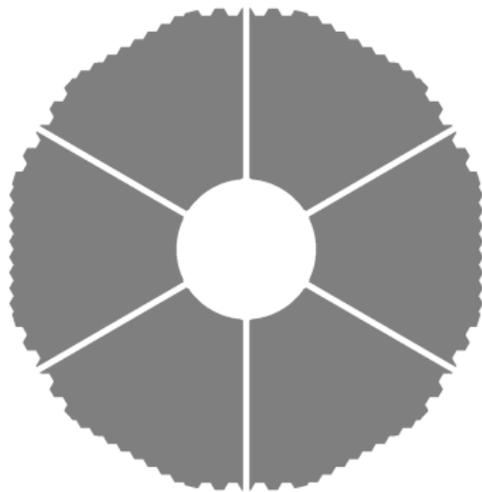
Gemini (8.10 m)



TMT (30.00 m)

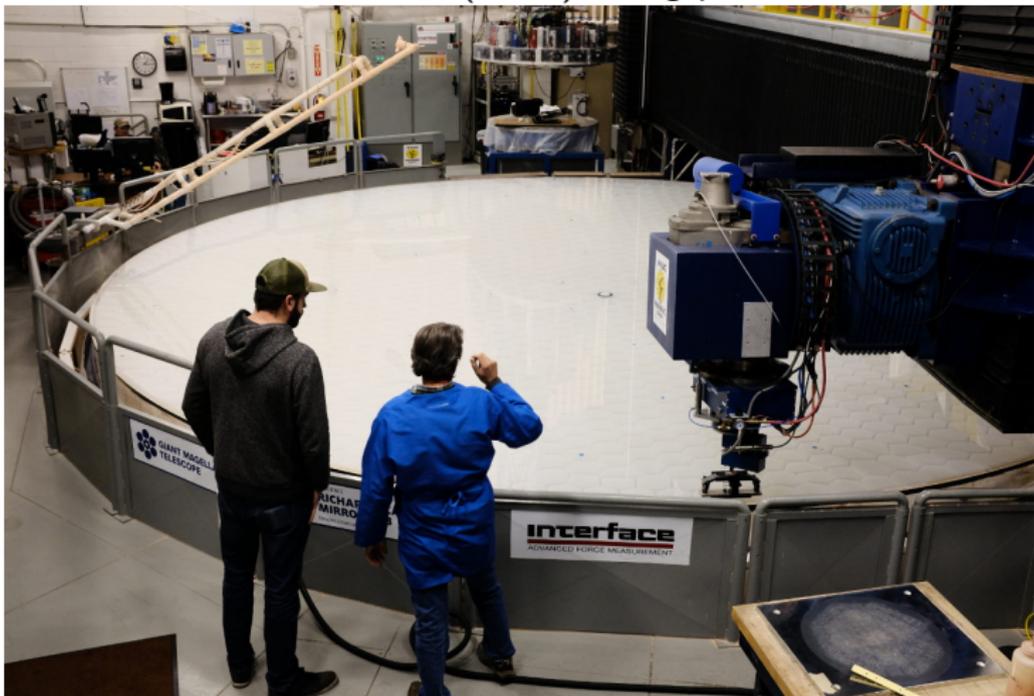


ELT (39.30 m)



Last week...

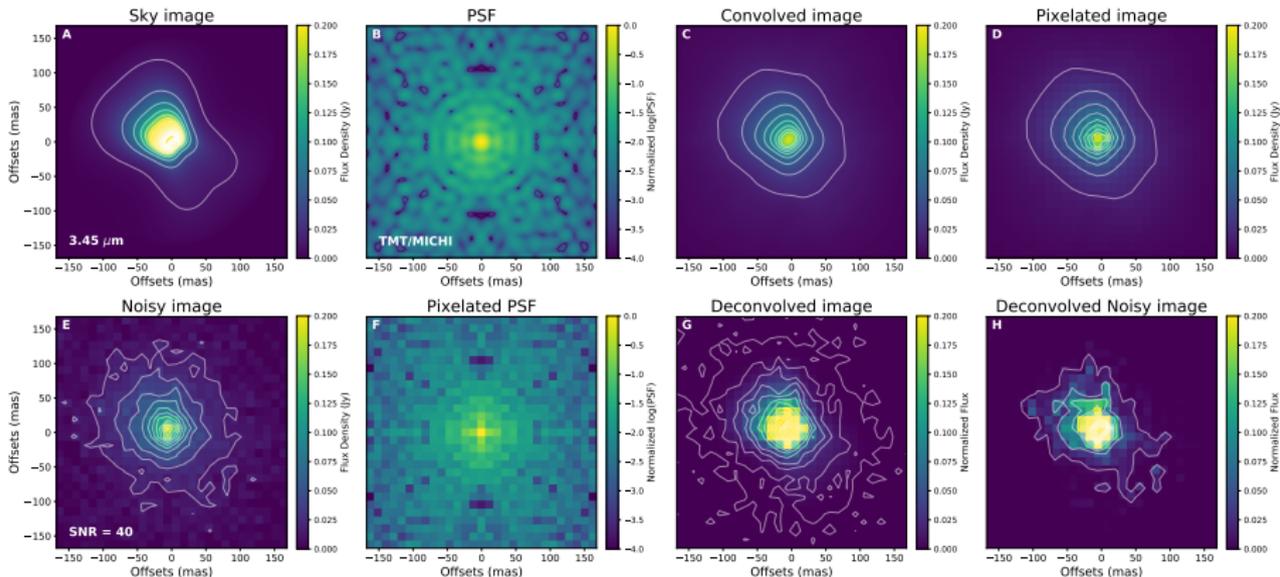
One of the GMT mirrors (8.4m) being polished in Tucson



Realistic observation simulations

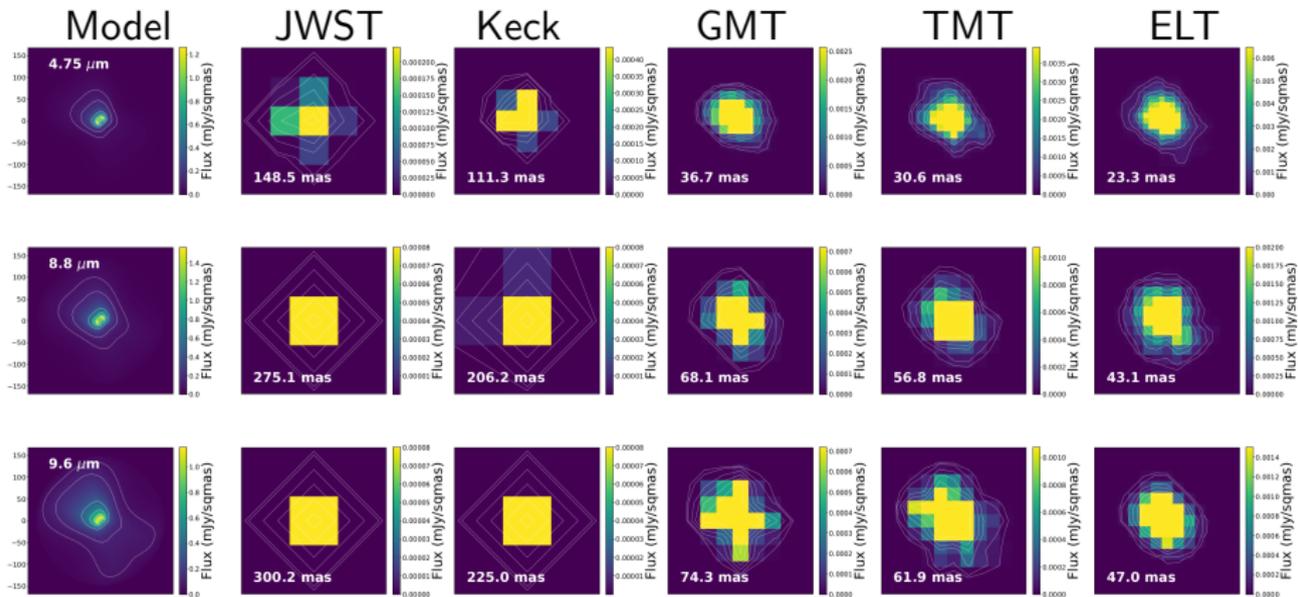
NGC1068 best-fit parameters from SED fitting (Lopez-Rodriguez+2018)

$$\sigma = 43, i = 75, Y = 18, N_0 = 4, q = 0.08, \tau_V = 70$$



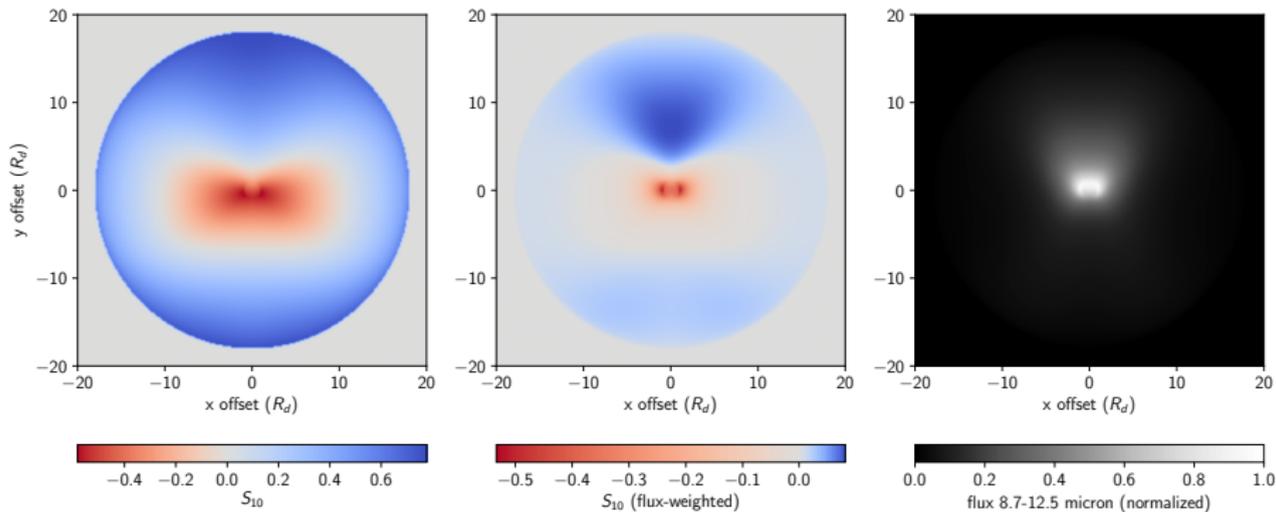
PSF convolution + detector pixelization + noise

Realistic observation simulations



IFU-like observations

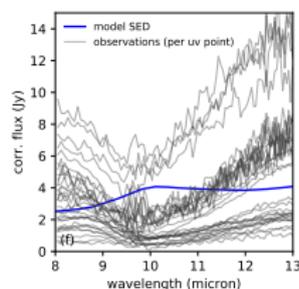
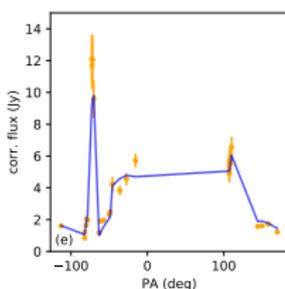
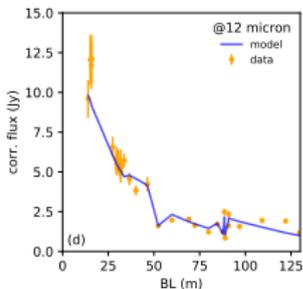
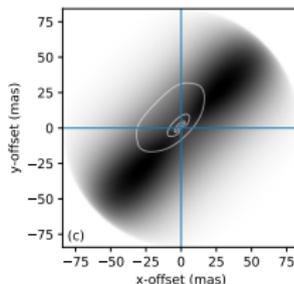
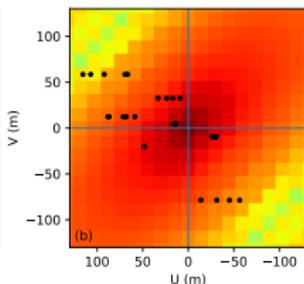
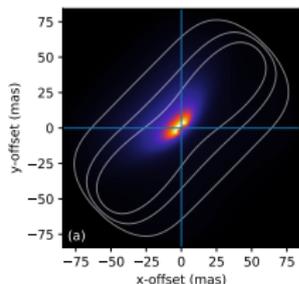
$$10\mu\text{m silicate feature strength } S_{10} = \ln \frac{F(10\mu\text{m})}{F(\text{cont})}$$



Moderate absorption at the center, mild emission in polar region

Interferometric observations

Extract visibilities from model images,
compare to data (VLTI, ALMA)



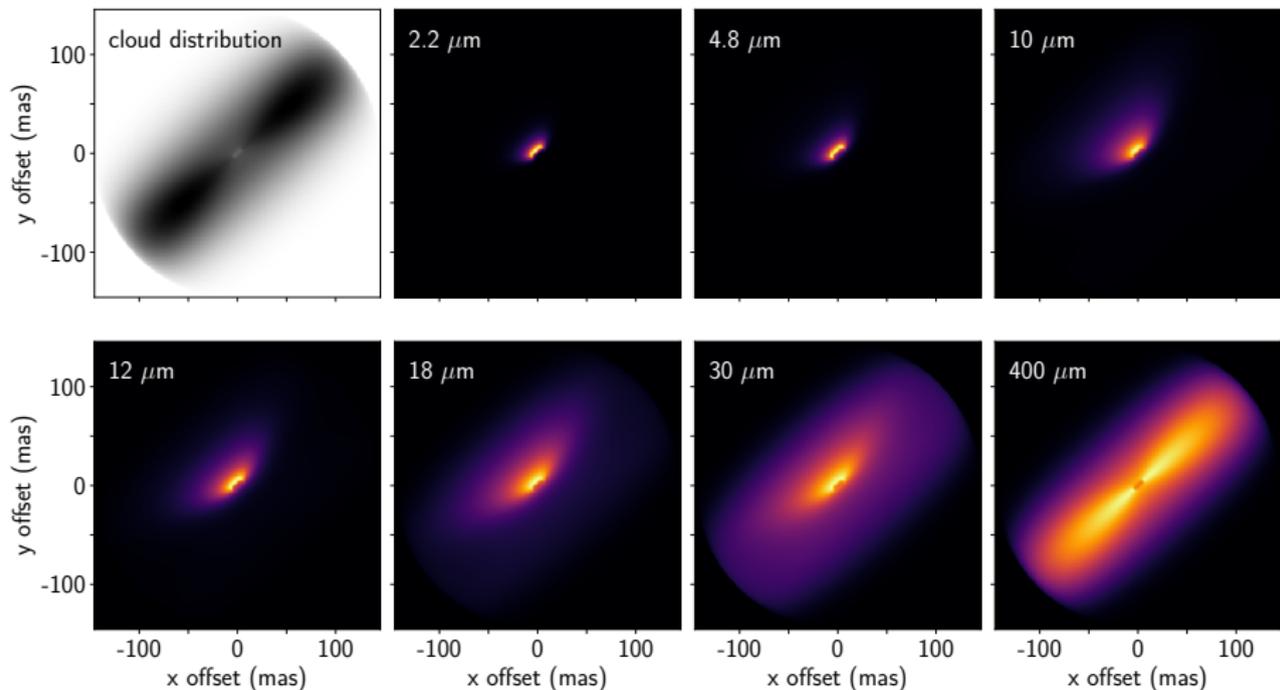
Best fit (@12 μm):

- ▶ $\sigma = 21$ deg
- ▶ $i = 73$ deg
- ▶ $Y = 20$
- ▶ $N_0 = 7$
- ▶ $q = 0.1$
- ▶ $\tau_V = 75$
- ▶ $D = 13.1$ Mpc
- ▶ $L = 4.4e44$ erg/s
- ▶ axis $PA = 42$ deg

Multi-wavelength view

Best-fit parameters from interferometry fitting

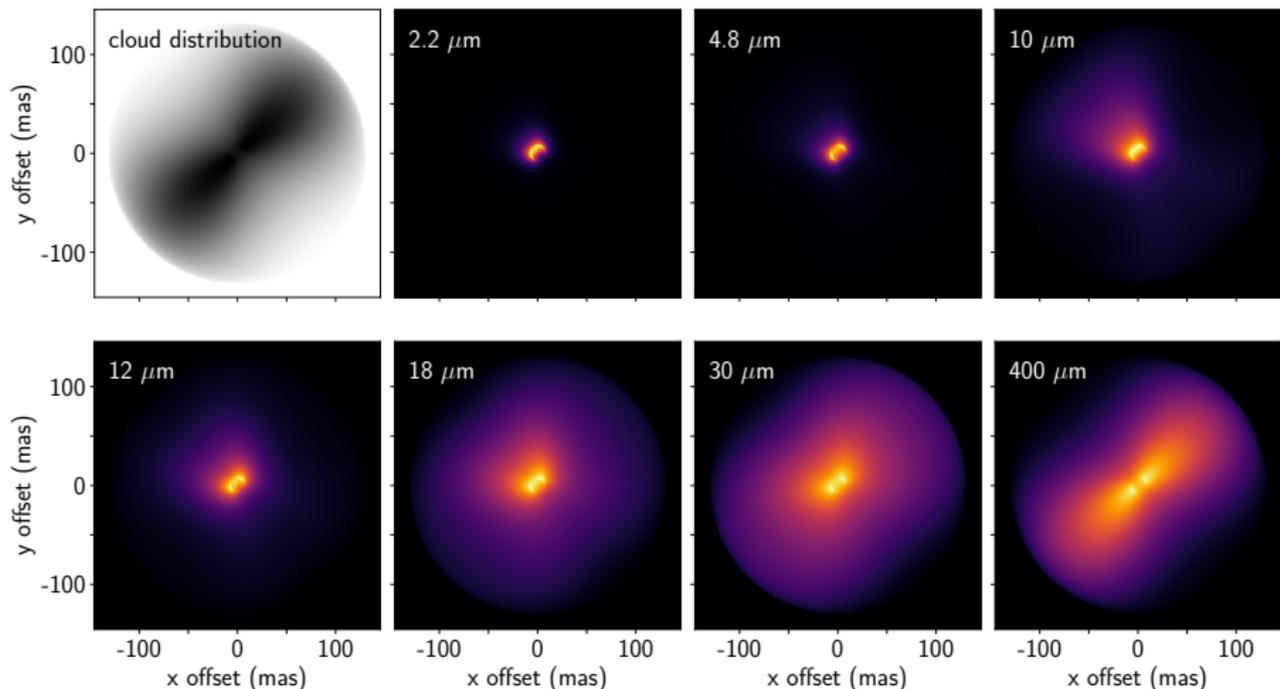
$$\sigma = 21, i = 73, Y = 20, N_0 = 7, q = 0.08, \tau_V = 75$$



Multi-wavelength view

NGC1068 best-fit parameters from SED fitting (Lopez-Rodriguez+2018)

$$\sigma = 43, i = 75, Y = 18, N_0 = 4, q = 0.08, \tau_V = 70$$



Quantifying morphology - Example: measure size

- ▶ Half-light radius

$$\frac{1}{F_{\text{tot}}} \int_0^{R_{1/2}} dr \, l \, 2\pi r = \frac{1}{2}$$

- ▶ Gini coefficient

$$G = \frac{\sum_i (2i - n - 1) \cdot l_i}{n \sum_i l_i}$$

- ▶ Radii of gyration

$$R_{gx} = \sqrt{\mu_{20}/\mu_{00}}, \quad R_{gy} = \sqrt{\mu_{02}/\mu_{00}}$$

Quantifying morphology

Image moments

$$\mu_{pq} = \sum_x \sum_y I(x, y) (x - \bar{x})^p (y - \bar{y})^q$$

where \bar{x} , \bar{y} are the image centroid coordinates, and p , q are integers ≥ 0 .

Some beneficial features of moments:

- ▶ independent of magnitude
- ▶ translation-invariant
- ▶ moment definitions exist that are scale- or rotation-invariant
- ▶ very easy to measure offsets, sizes, elongations, rotations, asymmetry (skew), peakedness (kurtosis)

Morphology size: Gini coefficient

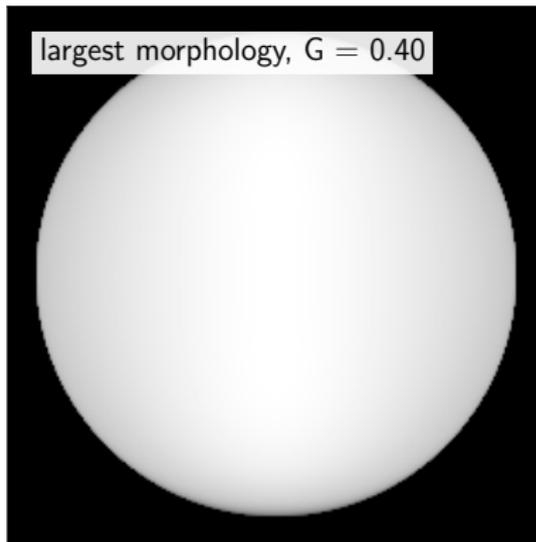
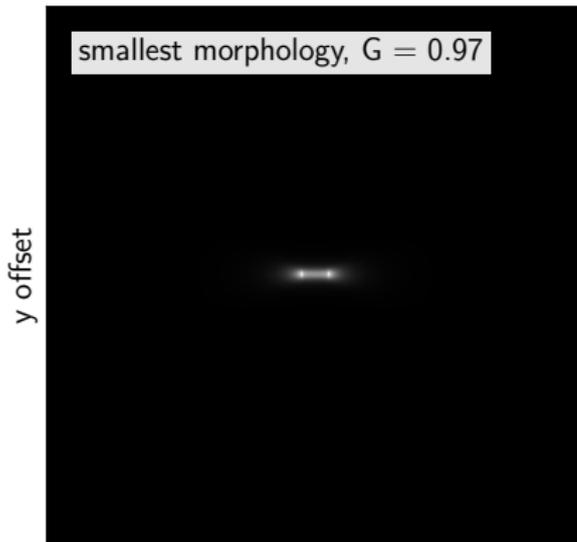
All pixels same value: $G = 0$

A single pixel non-zero: $G = 1$

Uniform random: $G = 1/3$

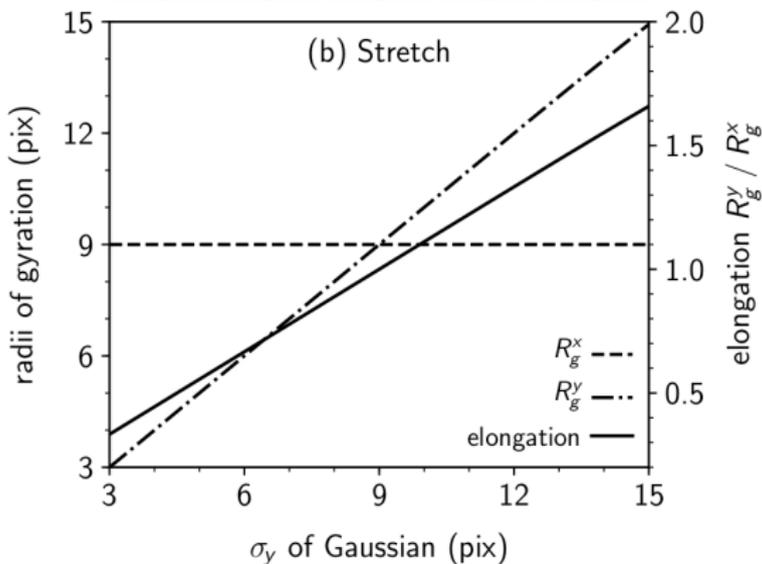
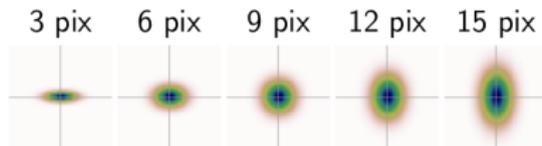
$\sigma, N_0, \tau_V, \lambda = 15 \text{ deg}, 1, 10, 2 \mu\text{m}$

$\sigma, N_0, \tau_V, \lambda = 75 \text{ deg}, 12, 160, 18 \mu\text{m}$



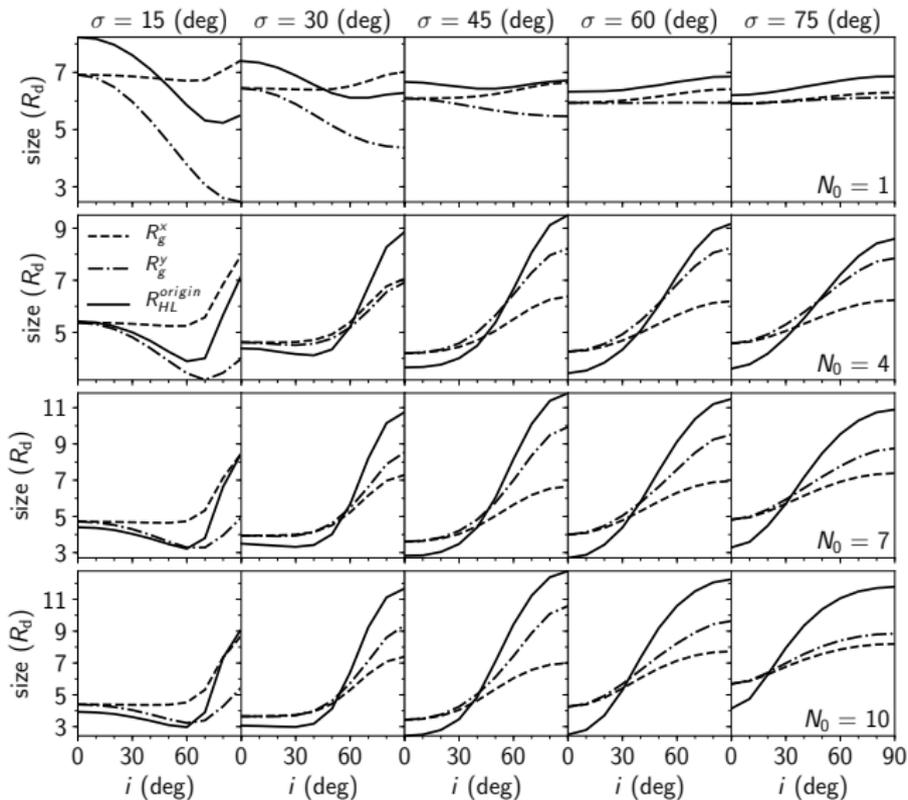
Radii of gyration

$$R_{gx} = \sqrt{\mu_{20}/\mu_{00}}, \quad R_{gy} = \sqrt{\mu_{02}/\mu_{00}}$$

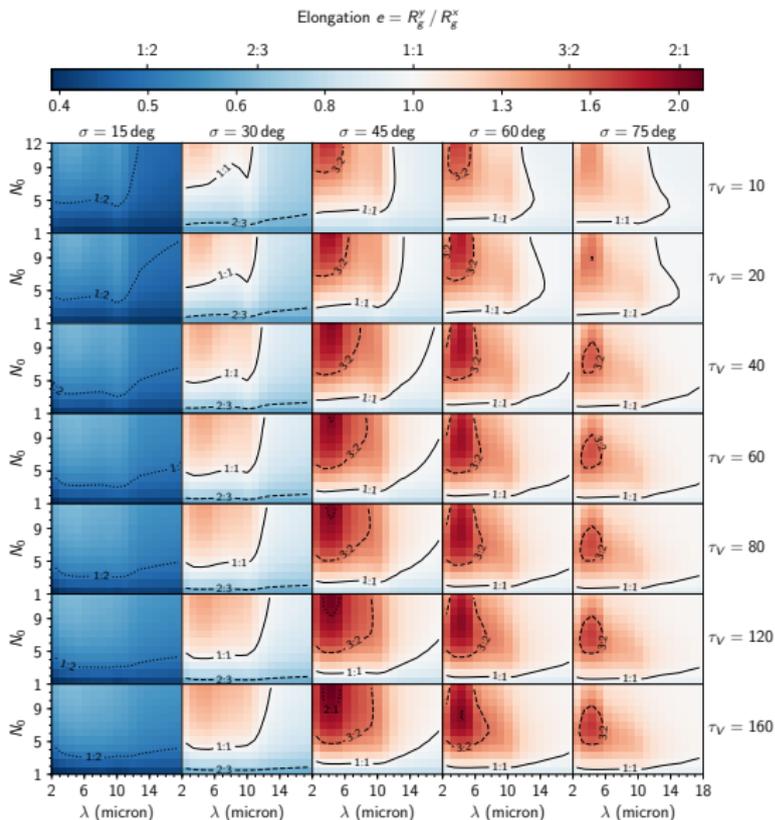


Half-right radius & radii of gyration

$$Y = 18, q = 0.08, \tau_V = 70, \lambda = 10 \mu\text{m}$$



Morphology elongation



$$e = R_g^y / R_g^x$$

Measured elongations in N-band (Burtscher+2013)

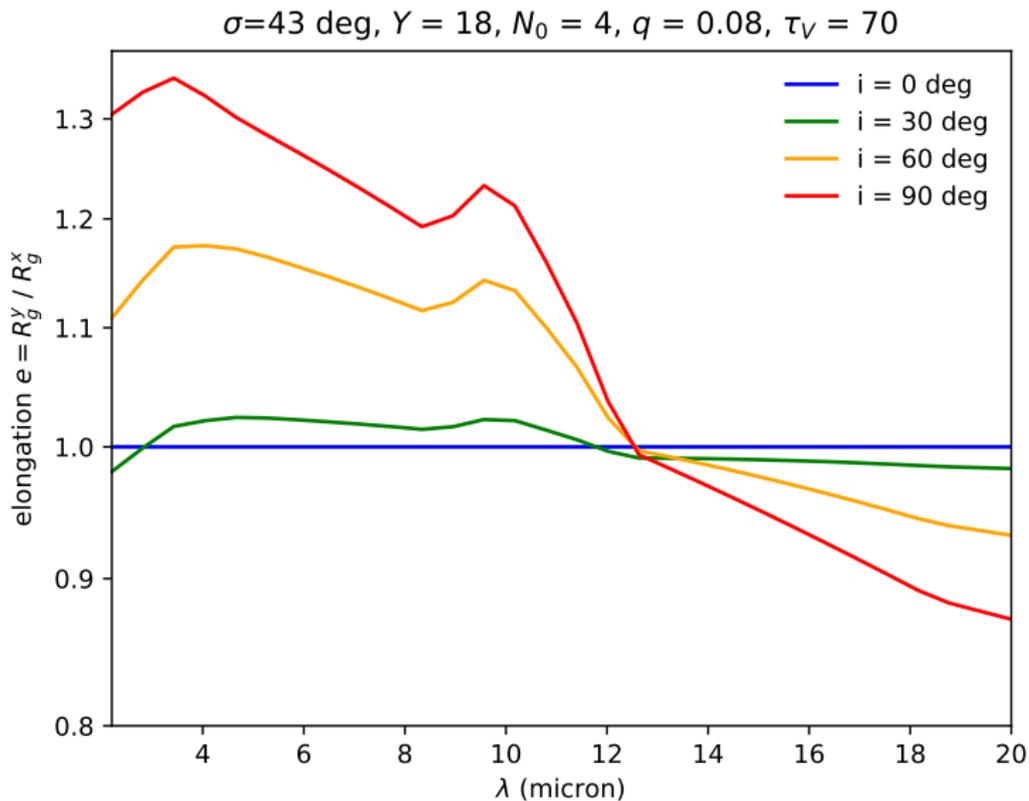
- ▶ NGC 1068: 1.3
- ▶ NGC 424: 1.3
- ▶ NGC 3783: 1.5
- ▶ Circinus: 2

CLUMPY models (@10 μm)

- ▶ Can produce $e \approx 1.5$
- ▶ $e > 2$ possible closer to edge-on views

($i = 75$ deg, $Y=18$, $q=0.08$ fixed here)

Elongation as function of wavelength



Summary & Future

Summary

- ▶ Must model 3-d dust distros to produce physical 2-d brightness maps
- ▶ HYPERCAT empowers you to study resolved AGN imagery, **pain-free**
- ▶ Simple CLUMPY torus models can produce **significant polar elongations** (torus inner wall)
- ▶ NGC1068: the same model can give **perpendicular orientations** in N band and ALMA frequencies
- ▶ Models can **fit SEDs well**, and **visibilities too**; now must fit both simultaneously

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- ▶ Models can **fit SEDs well**, and **visibilities too**; now must fit both simultaneously

Near future

- ▶ Submit paper 1 (January?)
- ▶ Assess detectability and resolvability of all nearby AGN, with all instruments (lead: **Kohei Ichikawa**)
- ▶ Compare models and all current + future resolved observations (lead: **Enrique Lopez-Rodriguez**)

Thank you! Gracias!

nikutta@noao.edu

www.clumpy.org

<ftp://noao.edu/pub/nikutta/hypercat/>