Hypercat - Hypercube of AGN tori

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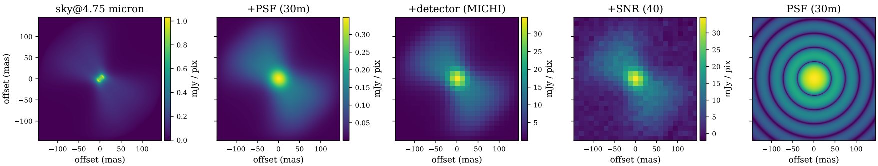
TORUS2018, December 2018, Puerto Varas / Chile



CLUMPY torus model

single cloud optical depth τ_V

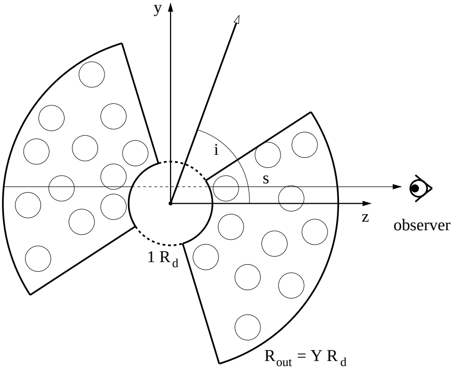
clouds/ray in equatorial plane N_0

angular torus width σ

torus thickness $Y = R_o/R_d$

radial cloud distribution r^{-q}

observer viewing angle i

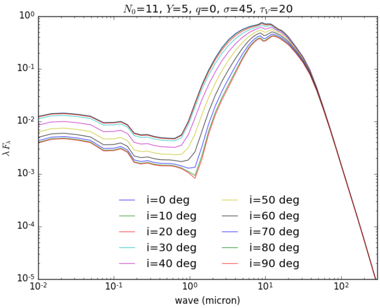


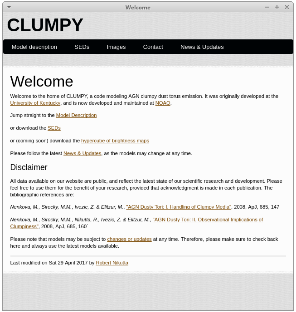
CLUMPY so far: SEDs

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

Model SEDs brought to you since 2008

www.clumpy.org





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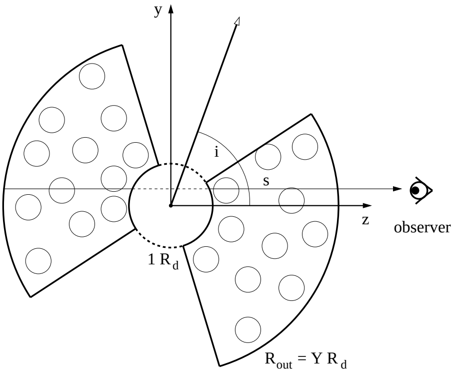

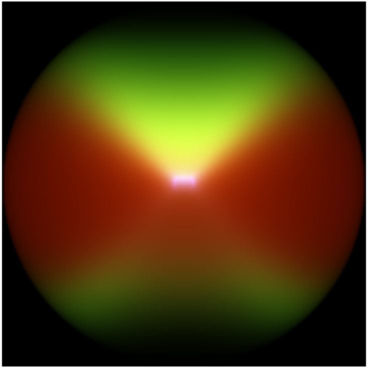

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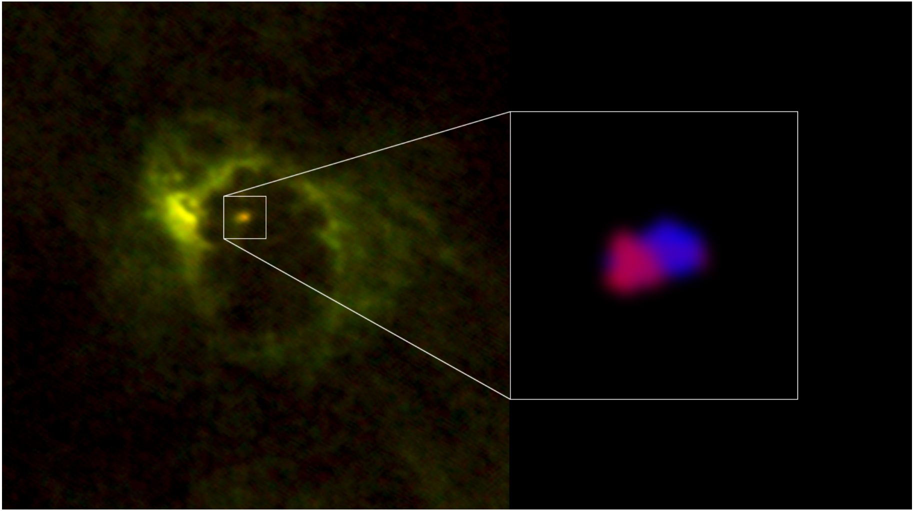
Vector of parameters

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

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

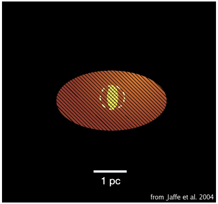


Imanishi+2018

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

Resolved dust emission in the Mid-IR (VLTI)

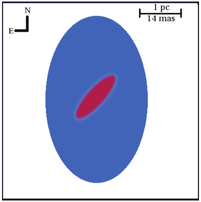
NGC1068



Jaffe+2004,

2 uv points

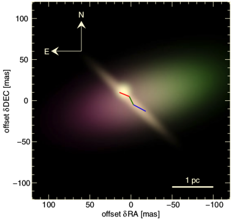
NGC1068



Raban+2009,

16 uv points

Circinus

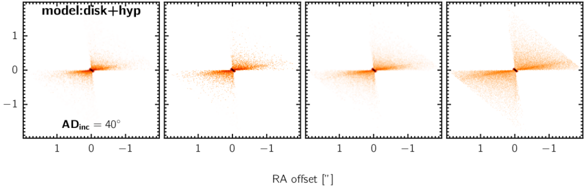


Tristram+2014
polar dust emission?

- 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

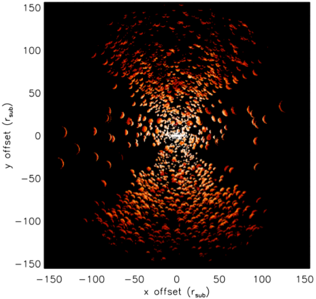
Some proposed solutions

Tilt the illuminating disk, use hollow cone...



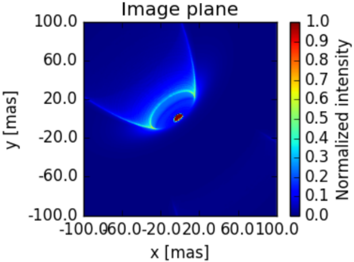
Stalevski+2017 (see also M. Kishimoto talk yesterday)

Re-arrange the clouds...



Hoenig & Kishimoto 2017

Disk+wind



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, $N_\lambda = 119 \longrightarrow$ **0.5 GB**
- Image hypercube w/ same parameter sampling would be **15-50 TB!!**
- Limit sampling (336k) & $N_\lambda = 25 \longrightarrow$ **0.9 TB** (271 GB compressed)

Get the hypercubes today!

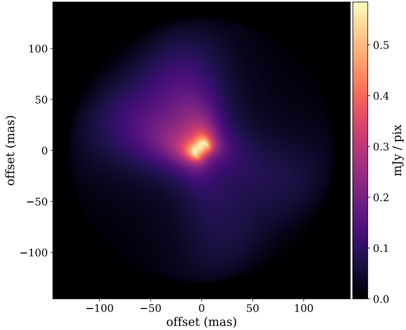
- FTP: `ftp://noao.edu/pub/nikutta/hypercat/`
- Straight from your local dealer *[ask me for my external HDD ;-)]*

$\longrightarrow$ **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')
```

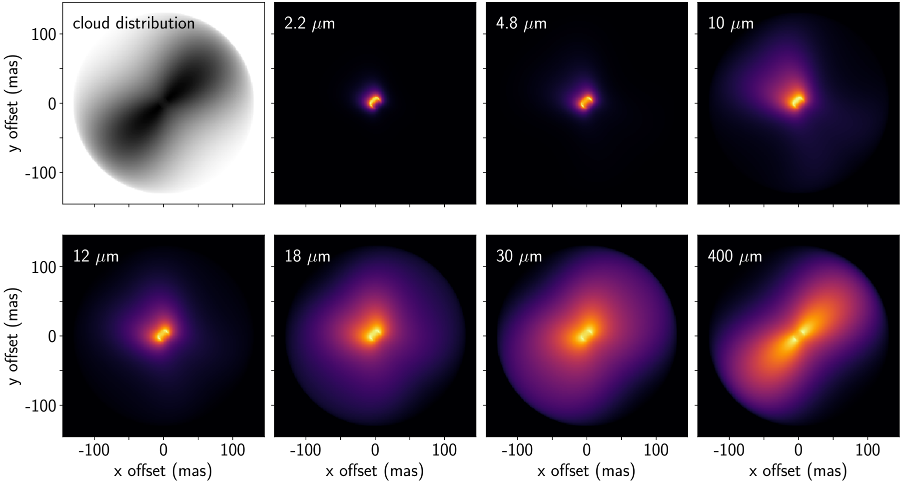
- IR radiative transfer is self-similar; L set scale: $R_{\rm dust} \propto \sqrt{L}$
- Interpolates image on n-dim hypercube for the vector of parameters



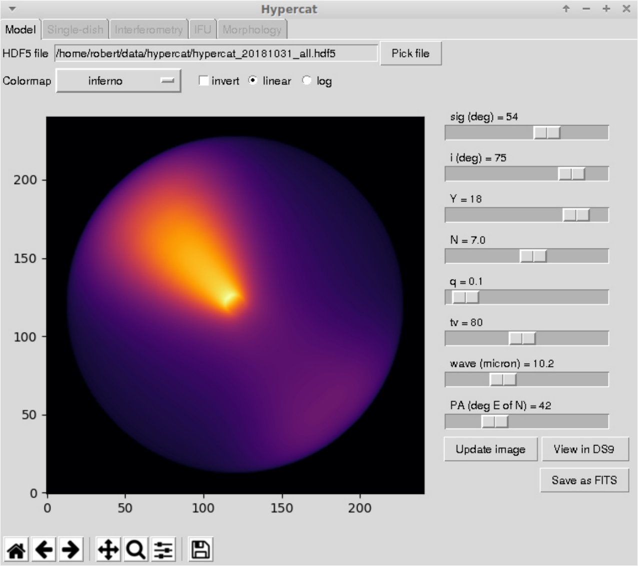
Multi-wavelength view

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

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

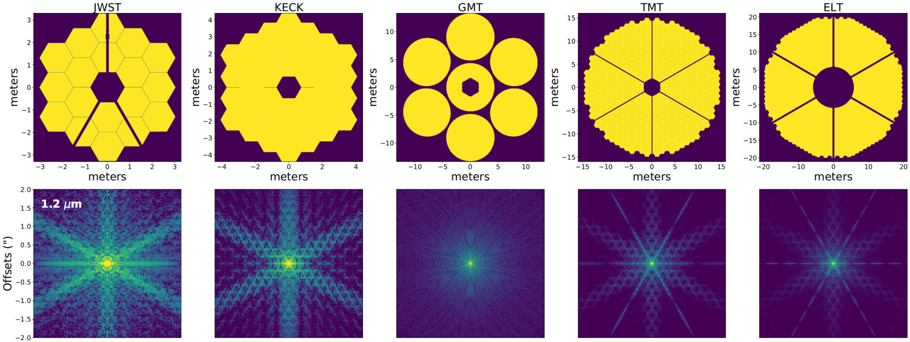


Hypercat GUI (very basic for now)

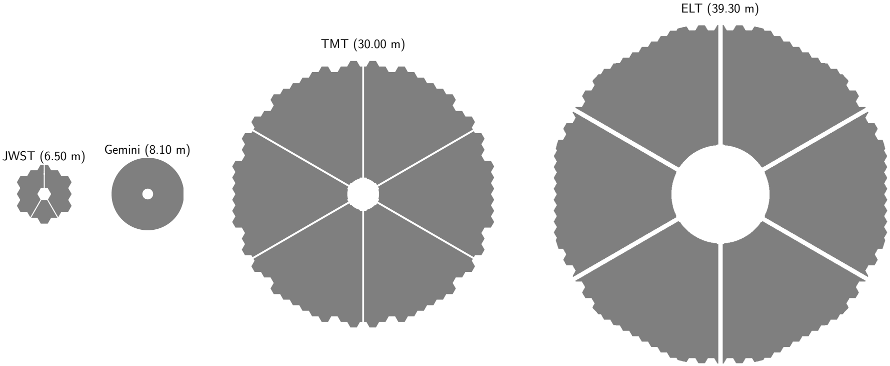


Simulate observations - PSFs from pupils

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

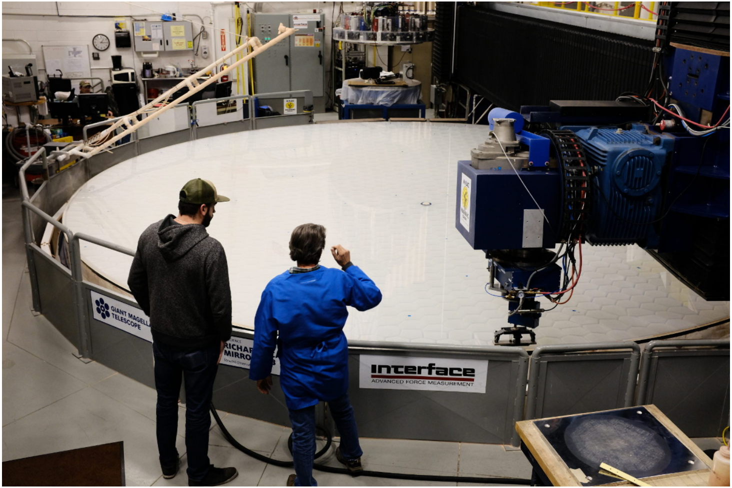


Pretty big pupils...



Last week...

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



Realistic observation simulations

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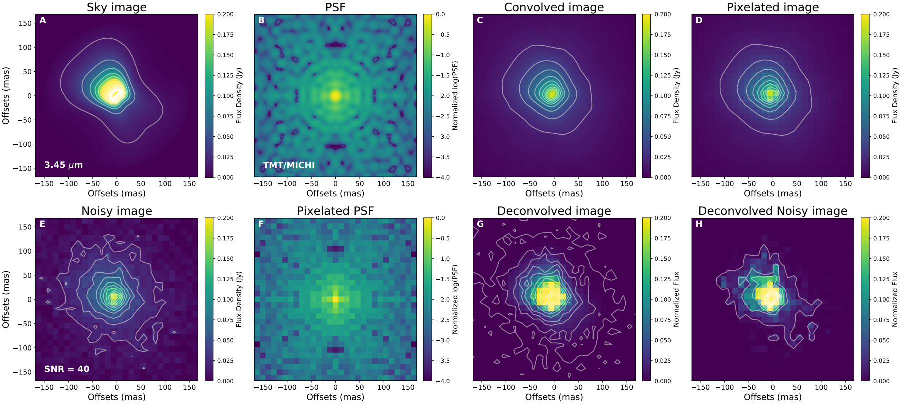
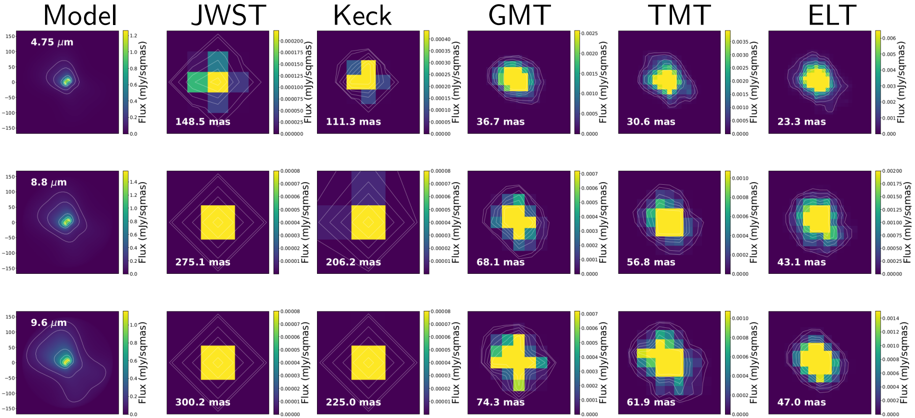


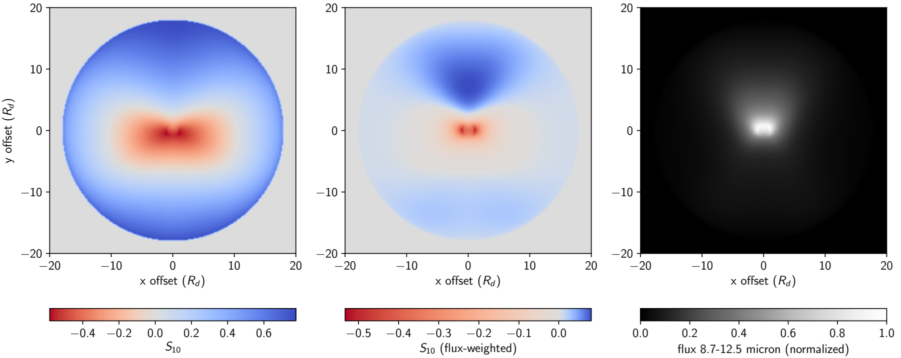
PSF convolution + detector pixelization + noise

Realistic observation simulations



IFU-like observations

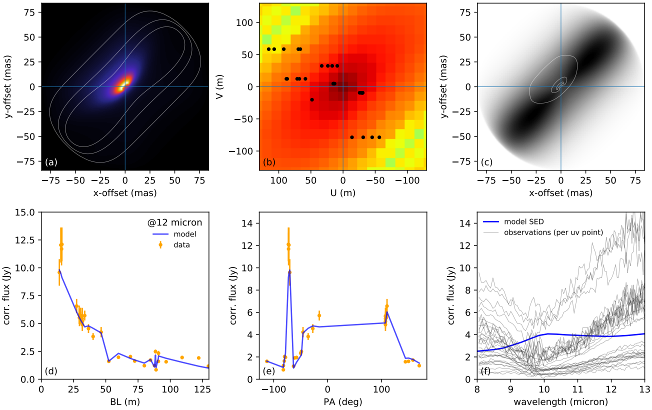
10μm silicate feature strength $S_{10} = \ln \frac{F(10\mu\text{m})}{F(cont)}$



Moderate absorption at the center, mild emission in polar region

Interferometric observations

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



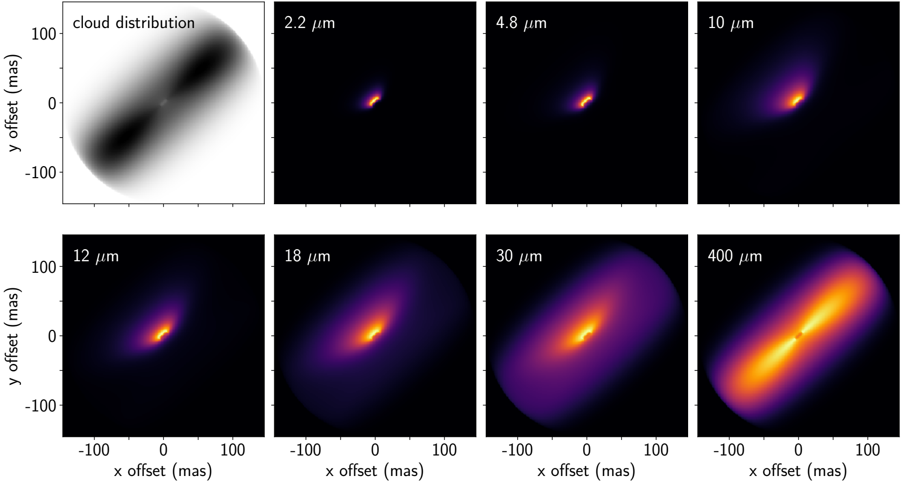
Best fit (@12 μm):

- $\sigma = 21\,\mathrm{deg}$
- $i = 73\,\mathrm{deg}$
- $Y = 20$
- $N_0 = 7$
- $q = 0.1$
- $\tau_V = 75$
- $D = 13.1\,\mathrm{Mpc}$
- $L = 4.4\mathrm{e}44\,\mathrm{erg/s}$
- axis $PA = 42\,\mathrm{deg}$

Multi-wavelength view

Best-fit parameters from interferometry fitting

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



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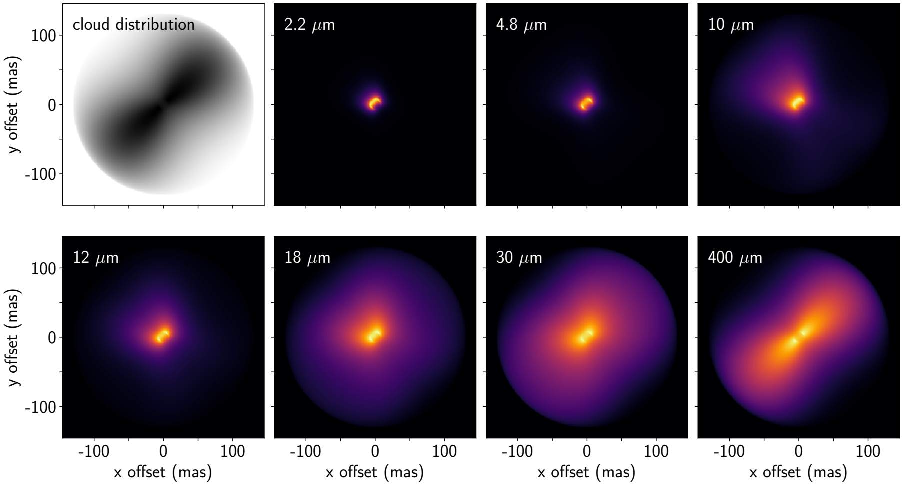


Quantifying morphology - Example: measure size

- Half-light radius

$$\frac{1}{F_{\mathrm{tot}}} \int_0^{R_{1/2}} \mathrm{d}r \, I \, 2\pi \, r = \frac{1}{2}$$

- Gini coefficient

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

- Radii of gyration

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

Quantifying morphology

Image moments

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

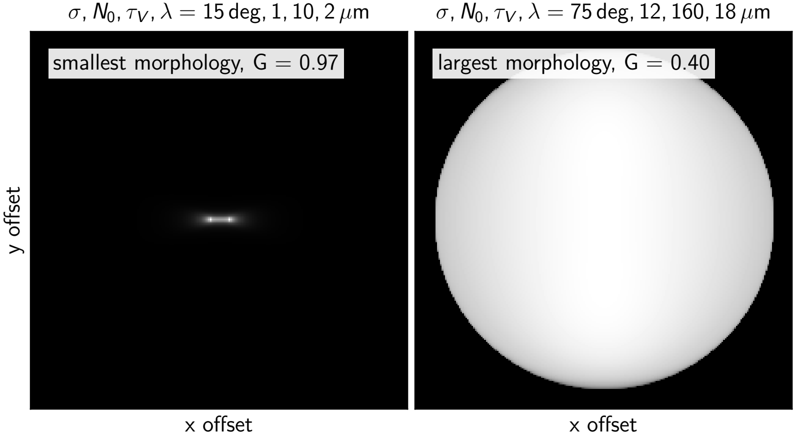
where $\bar{x}$, $\bar{y}$ are the image centroid coordinates, and p, q are integers $>= 0$.

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



Radii of gyration

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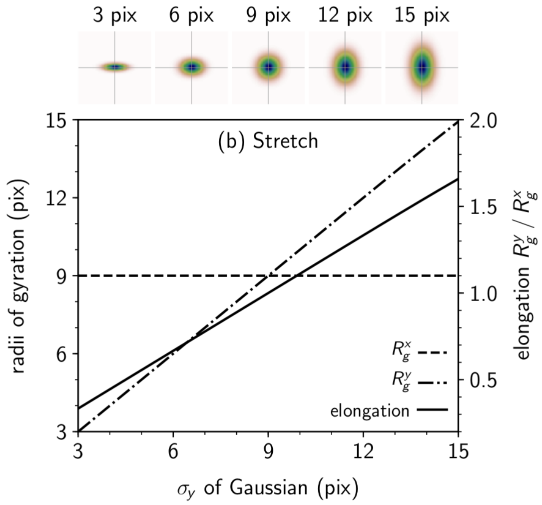
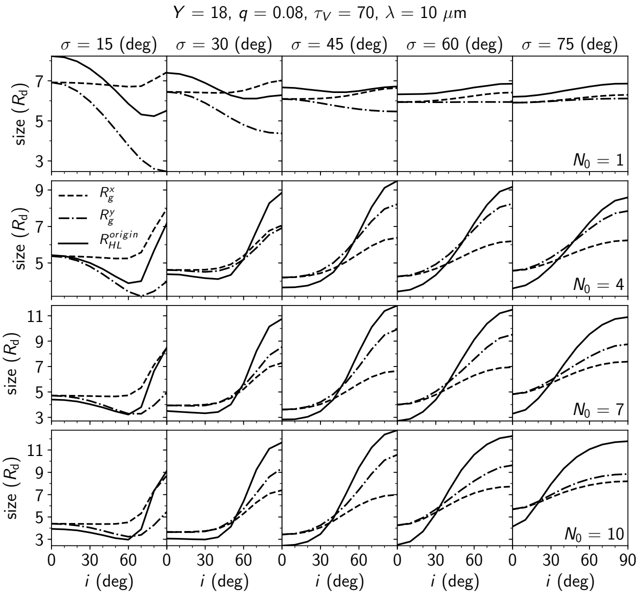
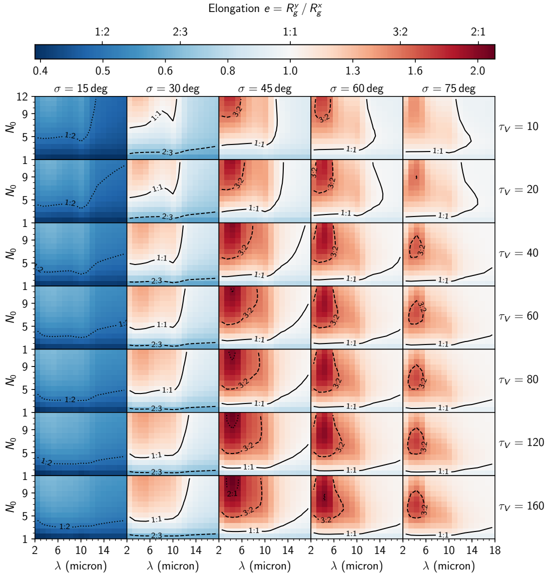


Half-right radius & radii of gyration



Morphology elongation



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

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

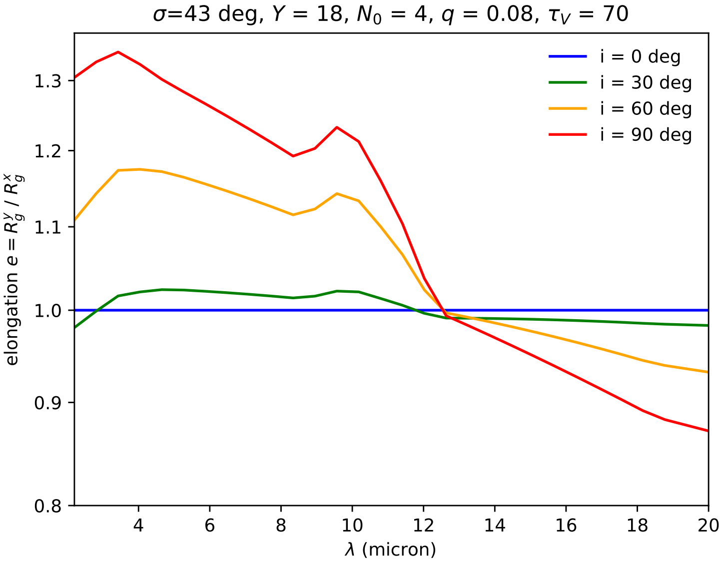
Measured elongations in N-band (Burtscher+2013)

- 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

Elongation as function of wavelength



Summary & Future

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- 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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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!

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www.clumpy.org

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