SOFIA multi-wavelength observations of nearby, dense star-forming clusters

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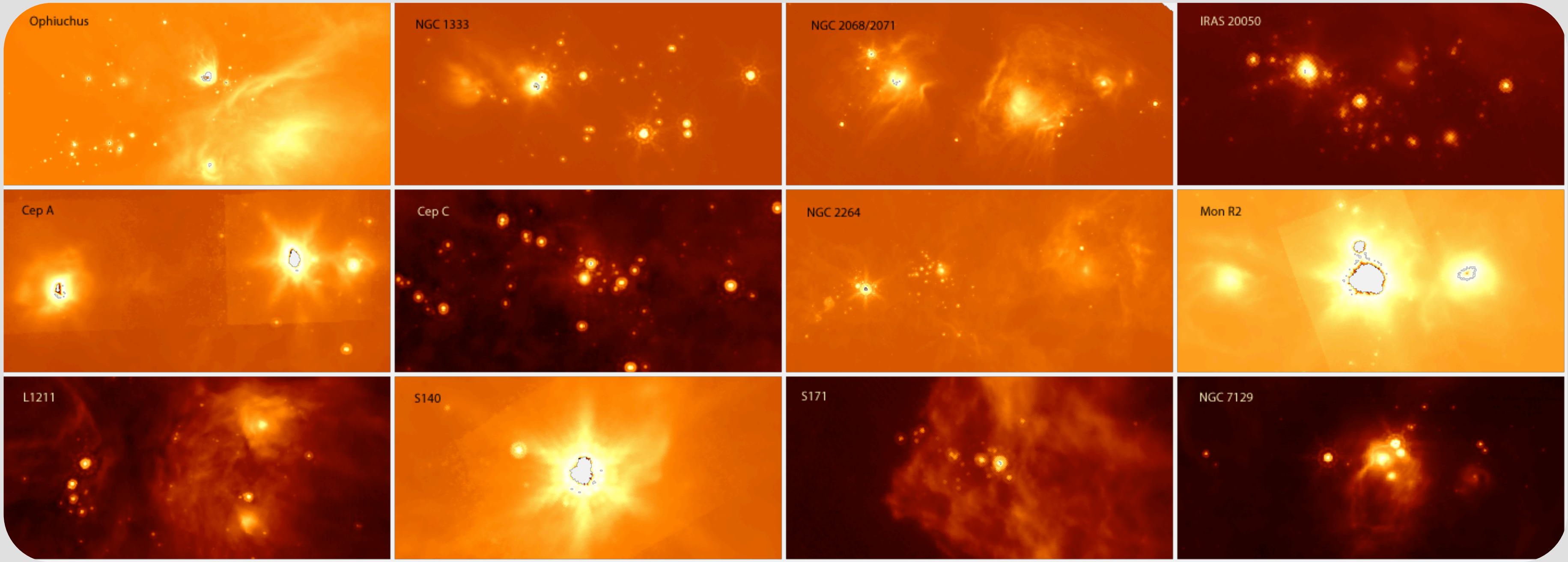
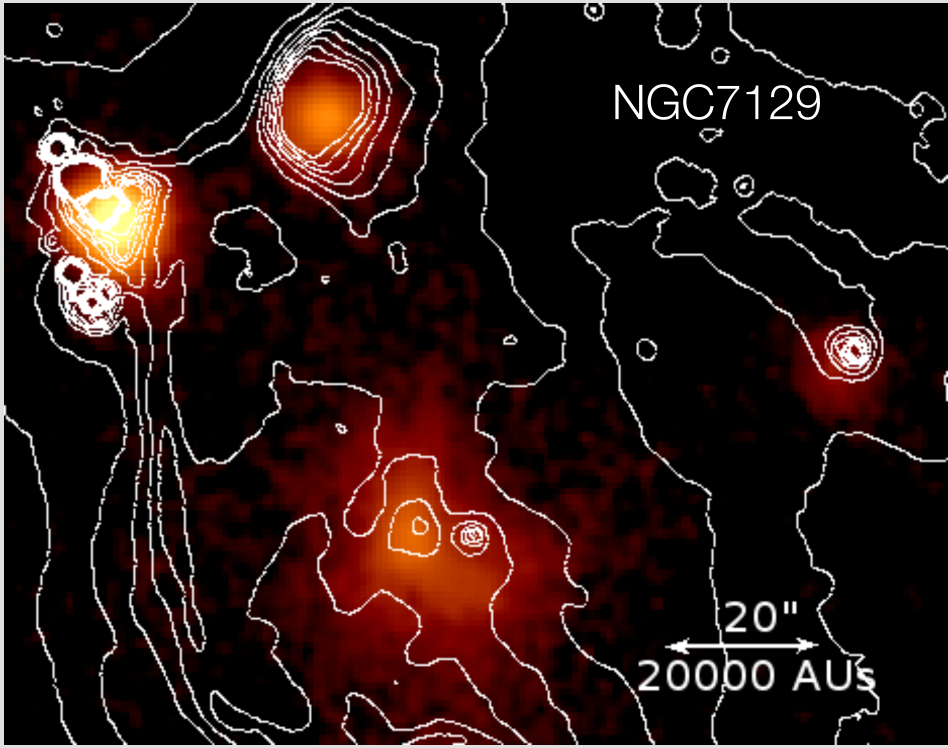


SPITZER MIPS 24um

Outline

1. Project description, goals and status
2. Data reduction & products
3. Preliminary results
   - Typical sources & sample statistics
   - "New" sources
   - Cases of source multiplicity
   - Extended sources
4. Morphology of extended sources
   - NGC1333.1
   - IRAS 20050+2720
   - Ophiuchus WL 16
5. Future work



37 um image (this work), with IRAC 8um contours

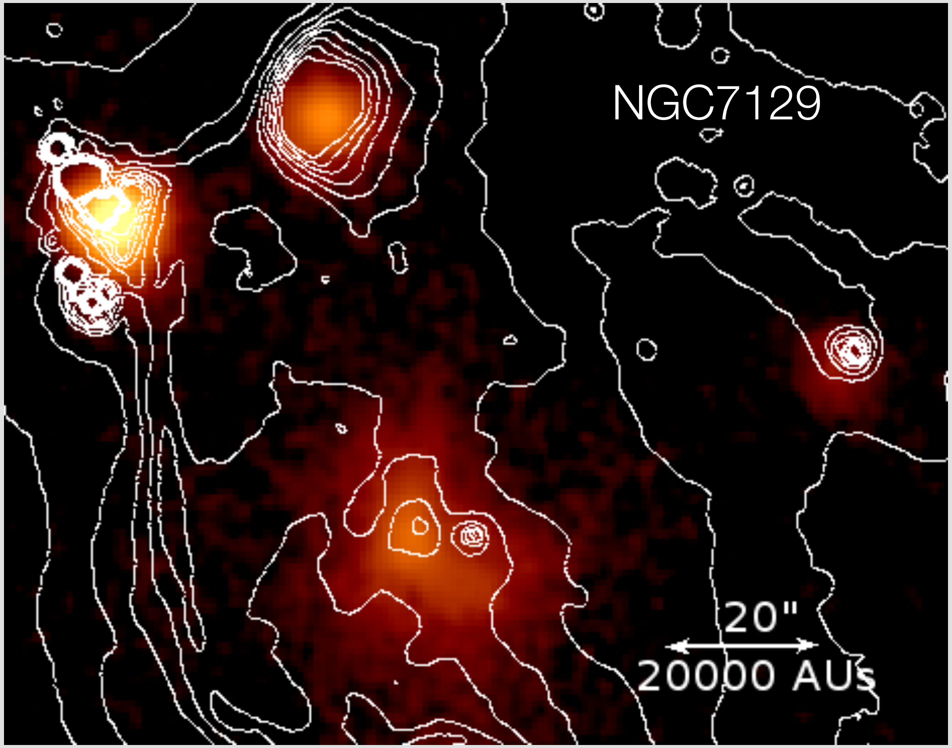
Project description & goals

- Survey of nearby dense cores
  - Saturate Spitzer/WISE
  - Challenge their spatial resolution
  - 12 nearby cluster candidates (50+ fields)
  - 11, 19, 31, 37 um
  - Gap-filling project: short observations

- Goals:
  1. Complete the SED and fill the 10-40um gap for 80+ YSOs
  2. Characterize the spatial extent of the 31 and 37um emission
     - Where does most of the emission come from?
     - Are there multiple protostars contributing to the emission?

Why are dense cores important?

- Clusters are the location where most stars form
- Cores common in the youngest clusters
- Very dense, very bright, multiple heating sources
- Testing grounds for star formation theories

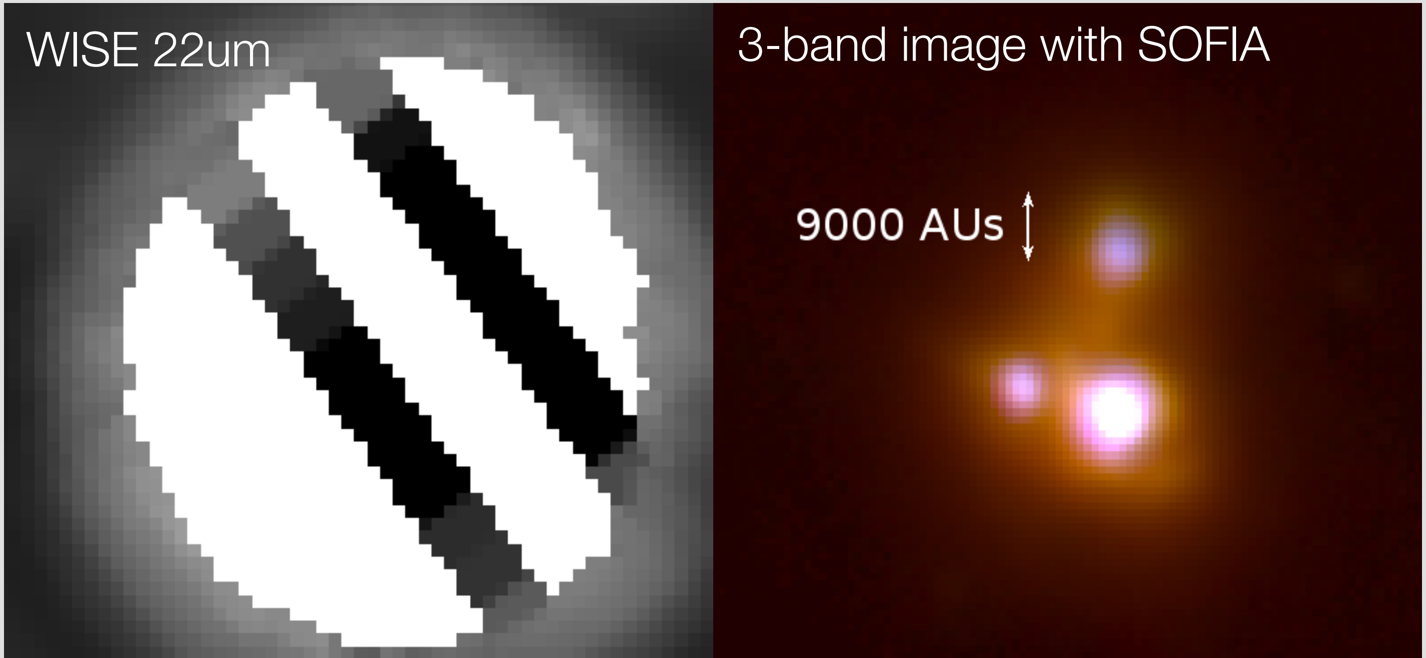


37 um image (this work), with IRAC 8um contours

SOFIA in the big picture

- Why are SOFIA observations unique?
  - Can study sources enshrouded in dusty envelopes: hard to study at shorter wavelengths
  - Provides the necessary angular resolution to resolve many more cores
  - Access to saturated regions

S140

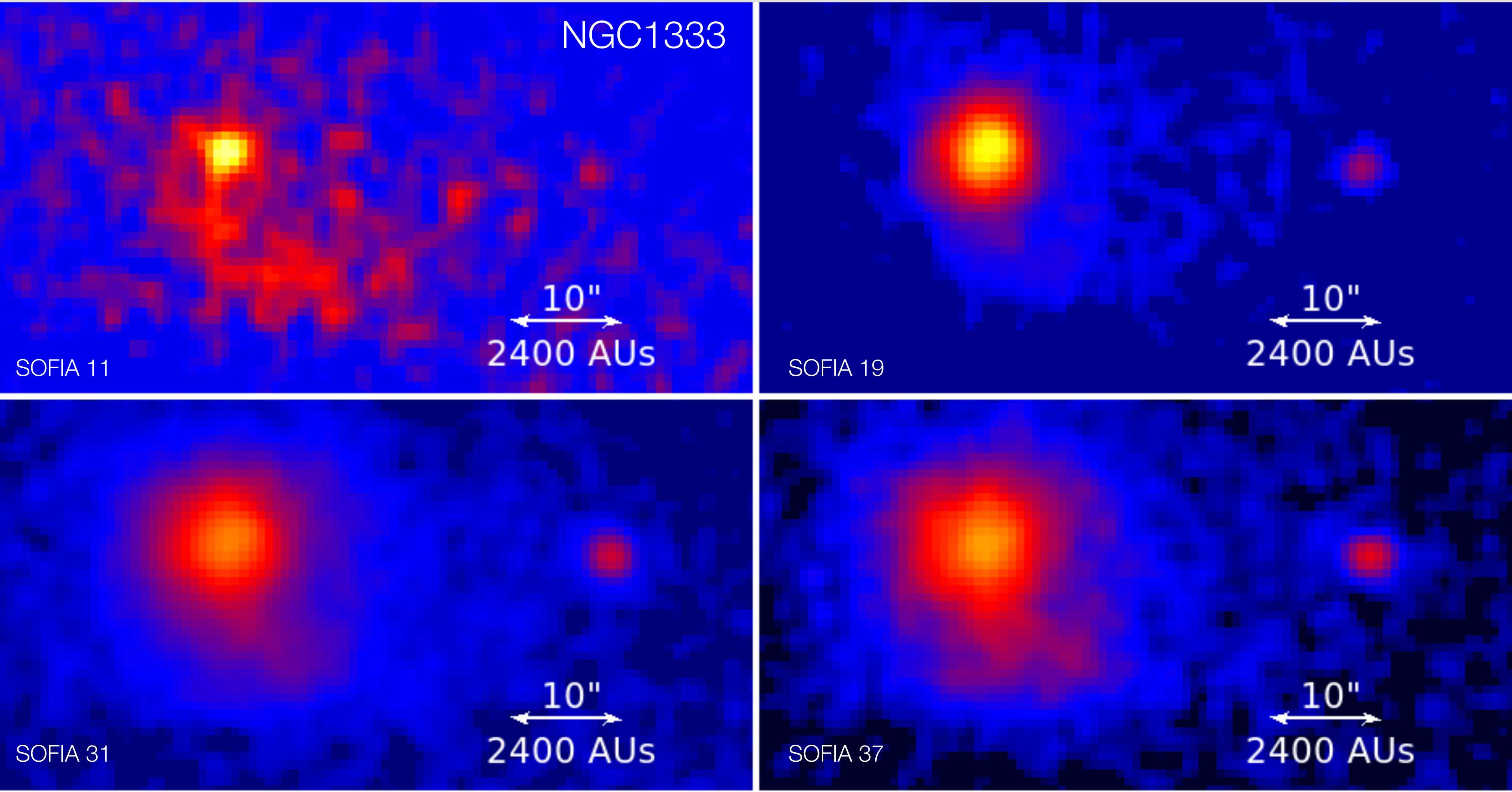


Data reduction

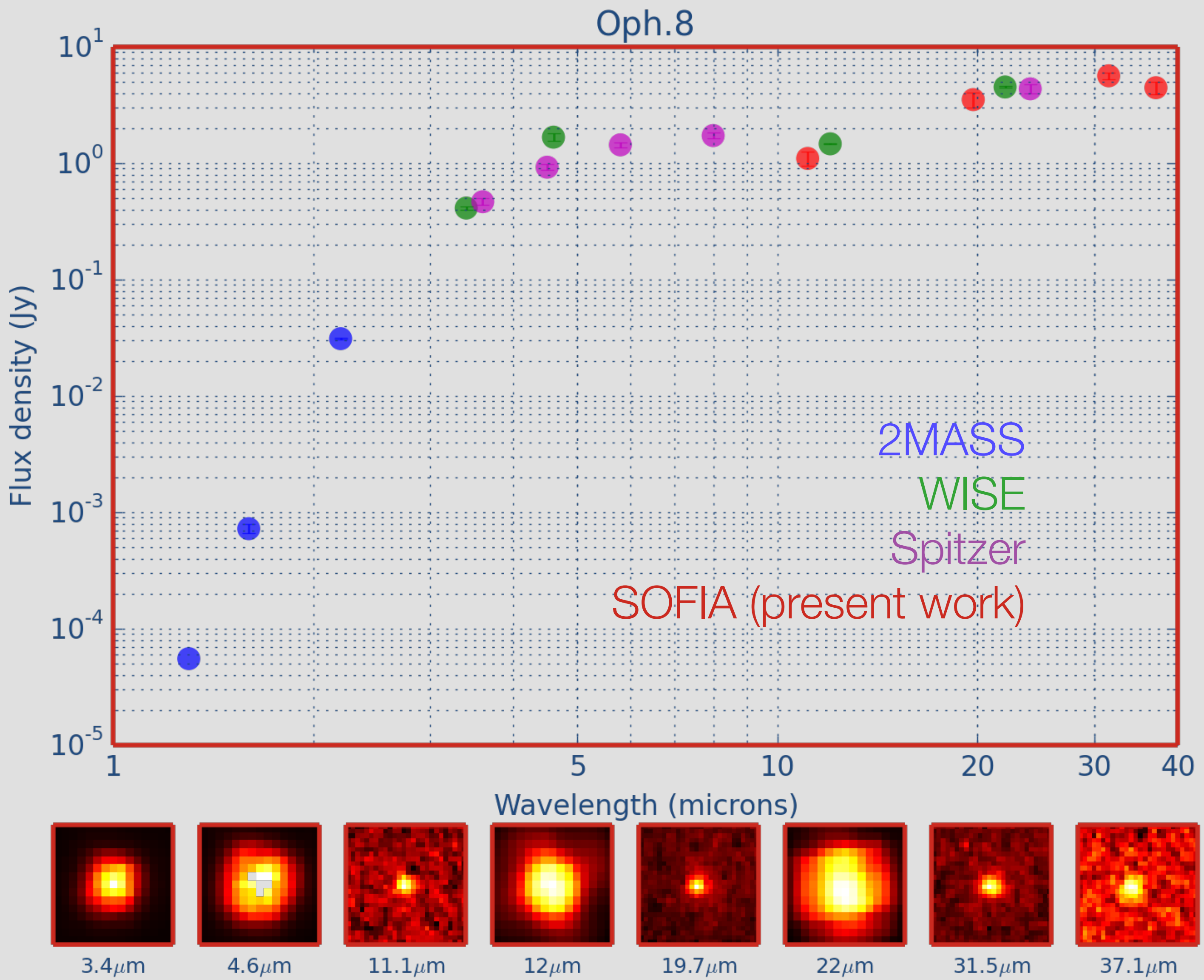
- Steps of data reduction:
  – Use flight calibrators to determine aperture correction
  – Isolate extended sources from the sample, treat with larger aperture (and no correction)
  – Manually align all fields, all wavelengths with WISE WCS reference
    - Some fields without a bright point source could not be aligned!
    - Technique still imperfect: what is the best approach?
  – Background subtraction with median filter (using Python *photutils* package)
  – Aperture photometry

Data products

- Background-corrected, smoothed mosaics in all 4 bands

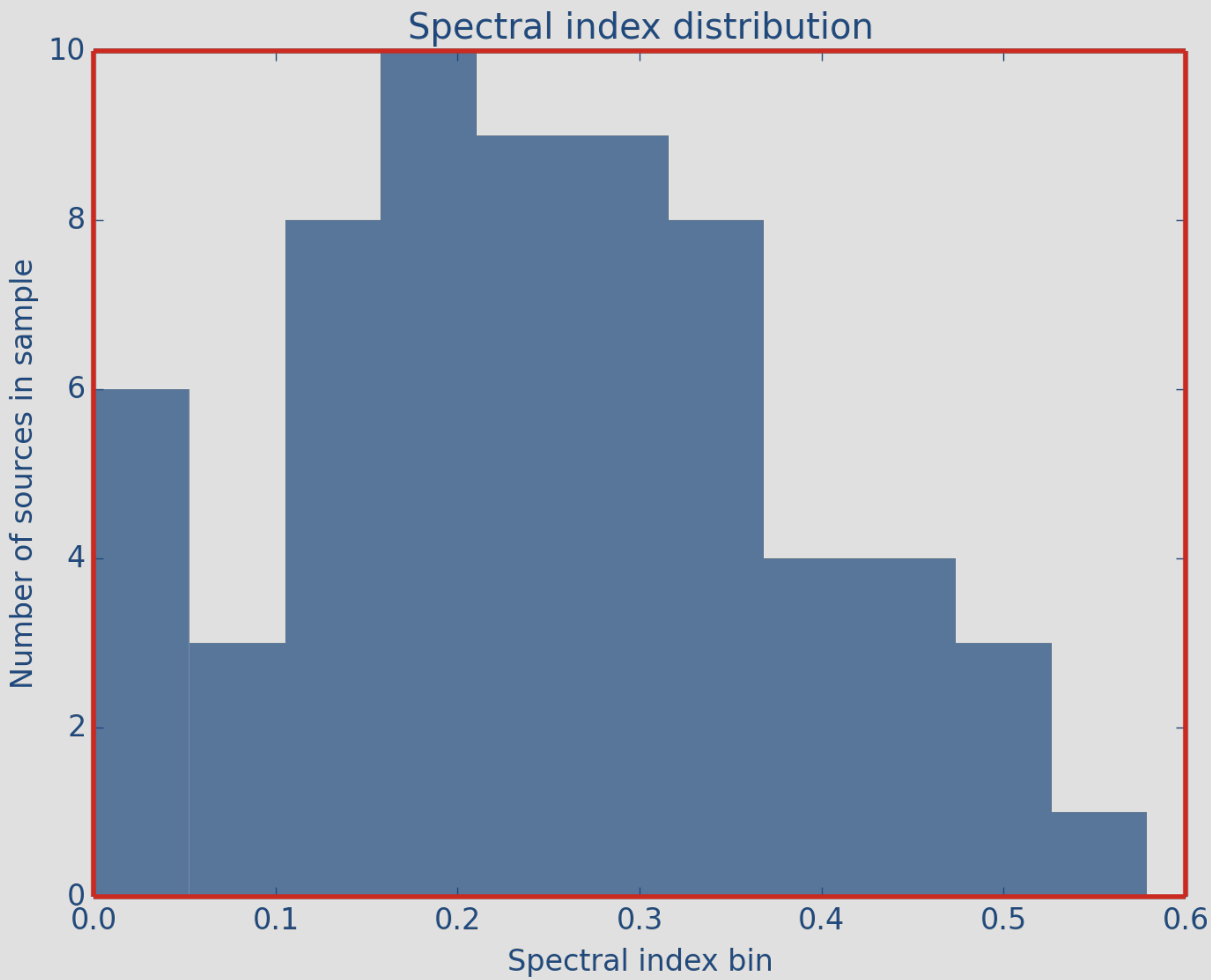


Data products



Data products

- Spectral index distribution over the whole sample



- Fits include our SOFIA data points
- Most sources are "flat" or Class I protostars

Sample statistics

Cluster	Distance (pc)	fields	4-band approximate 5σ sensitivity (Jy)	Point sources	Extended sources	New sources
Ophiuchus	160	9	0.4 | 0.4 | 1.4 | 3.2	9	8	0
NGC 1333	240	4	0.3 | 0.3 | 1.3 | 2.5	4	2	0
IRAS 20050	700	2	0.2 | 0.2 | 1 | 1.6	7	0	6
Cepheus A	730	2	0.2 | 0.2 | 0.8 | 1.5	2	2	0
Cepheus C	730	1	0.2 | 0.2 | 0.8 | 1.5	3	1	1
NGC2264	760	5	0.2 | 0.3 | 1.1 | 1	15	2	2
S140	900	1	-- | 0.1 | 0.5 | 1	5	2	6
S171	850	1	0.1 | 0.2 | 0.6 | 1	2	0	0
NGC 7129	1000	1	0.1 | 0.1 | 0.6 | 0.8	2	2	1
				49	19	16

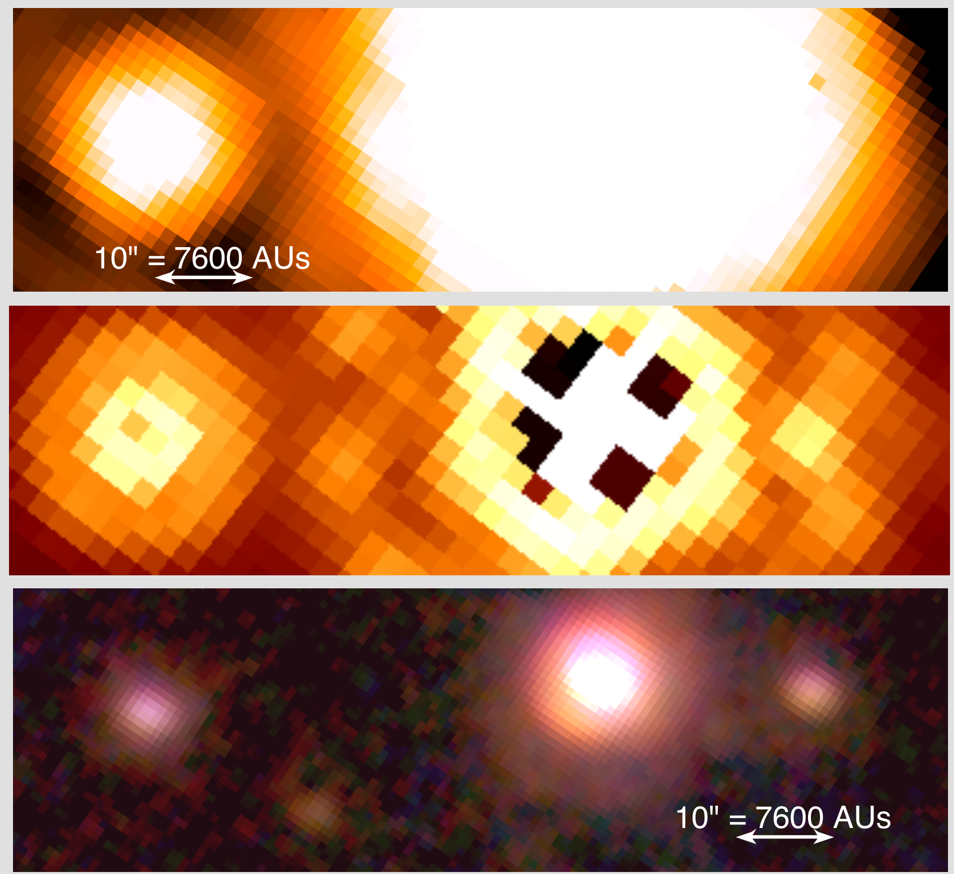
“New” sources?

- Sources previously unresolved by Spitzer/WISE at 24/22um
- Sources saturating Spitzer/WISE

NGC2264 “Cone Nebula”,
WISE, 22um

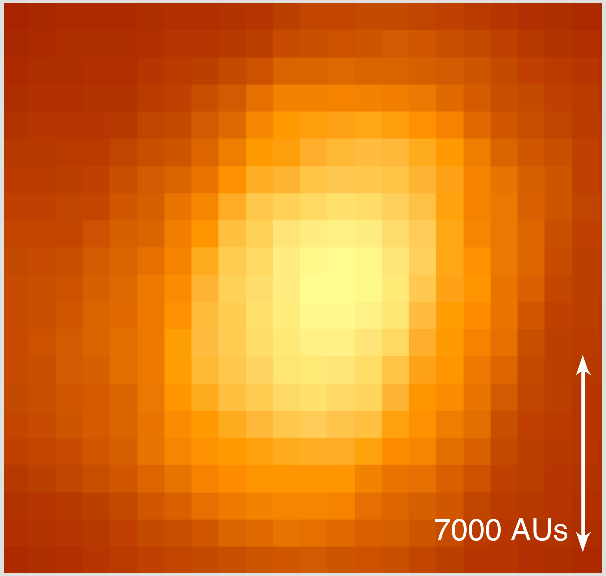
NGC2264 “Cone Nebula”,
MIPS, 24um

NGC2264 “Cone Nebula”,
SOFIA, 3-band

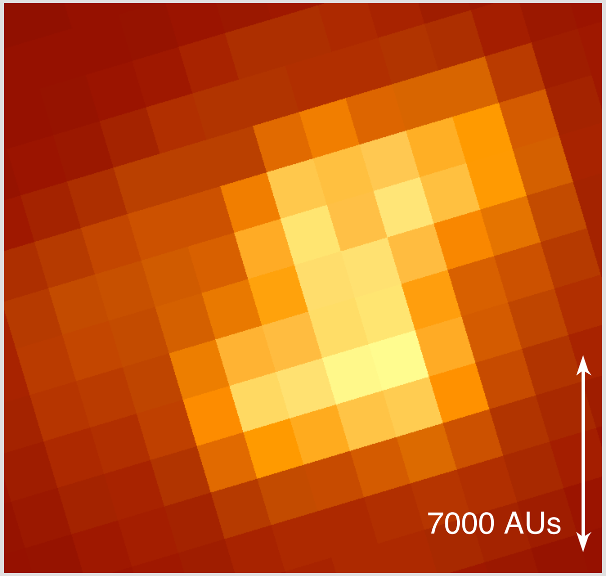


Cases of source multiplicity

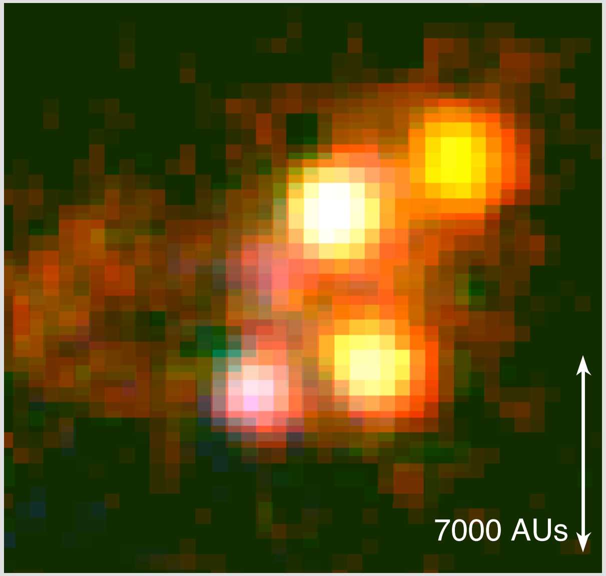
WISE 22 μm



Spitzer 24 μm



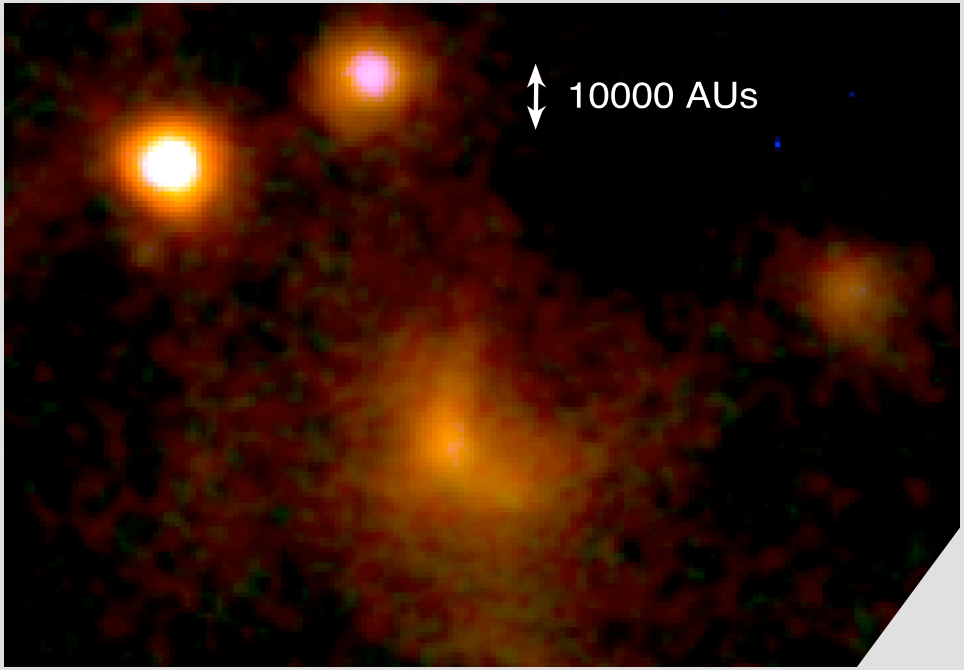
SOFIA 19, 31, 37 μm



IRAS 20050+2720

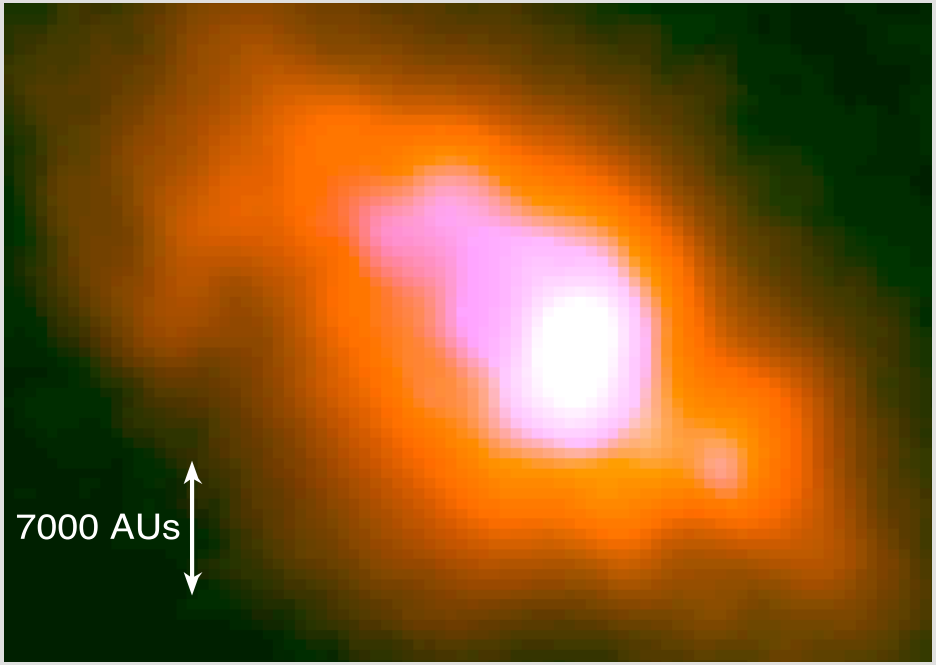
Extended sources

NGC7129 19, 31, 37 μm



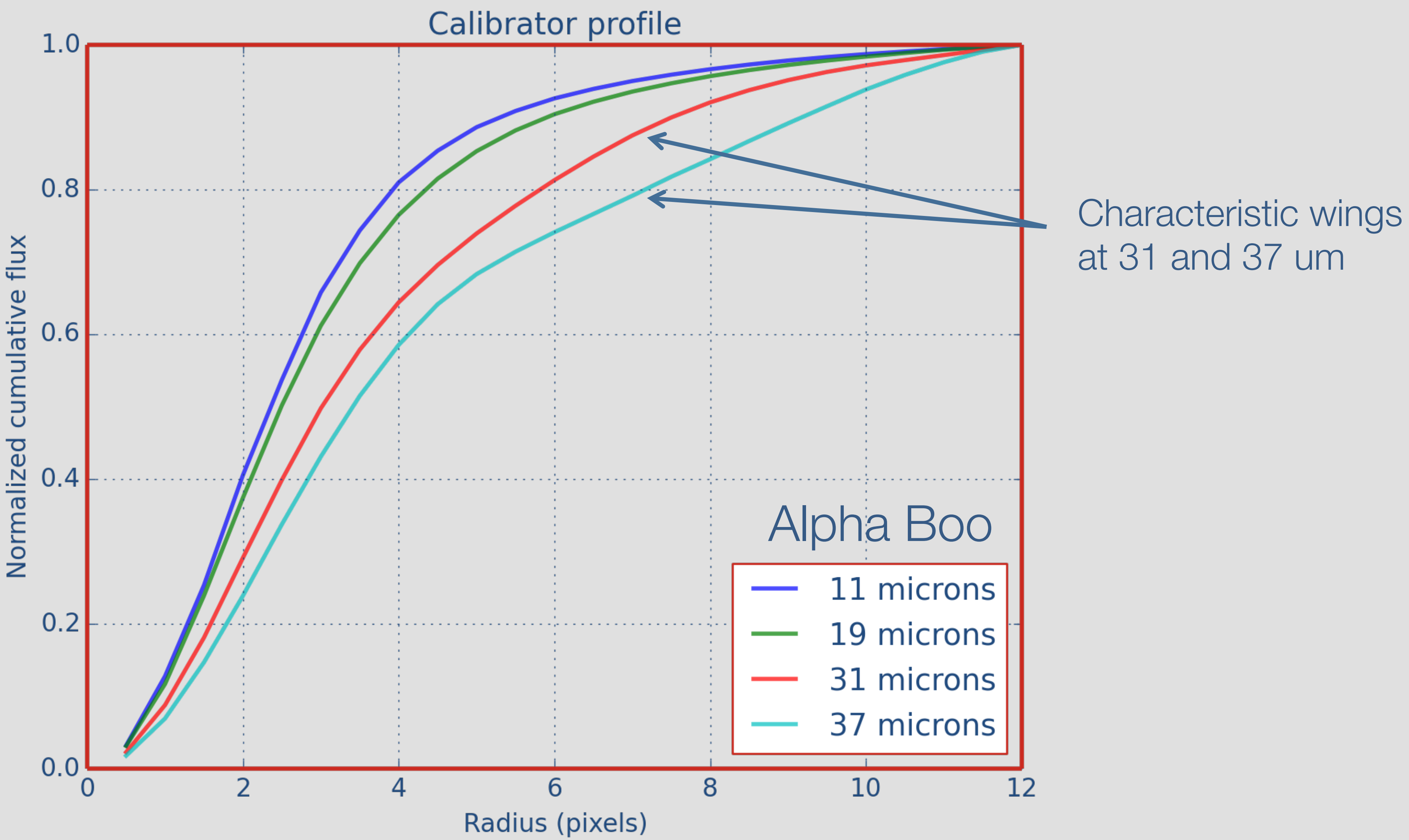
External heating source(s)

Cepheus A 19, 31, 37 μm



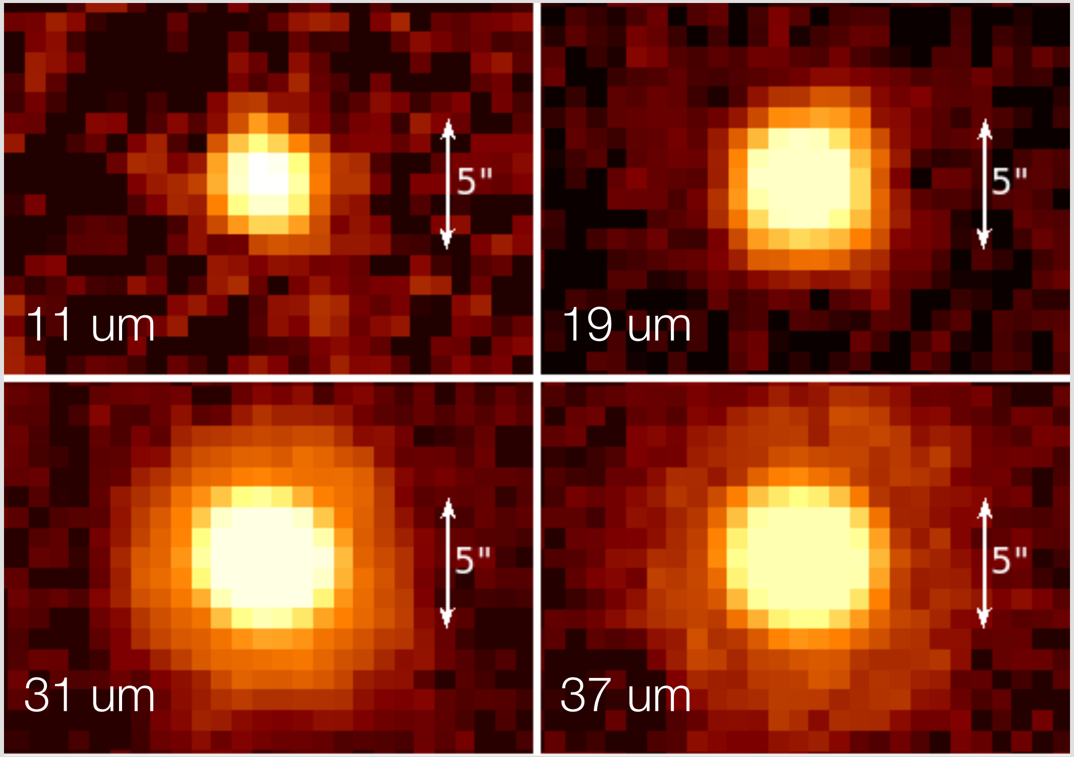
Internal heating source

Understanding SOFIA's PSF

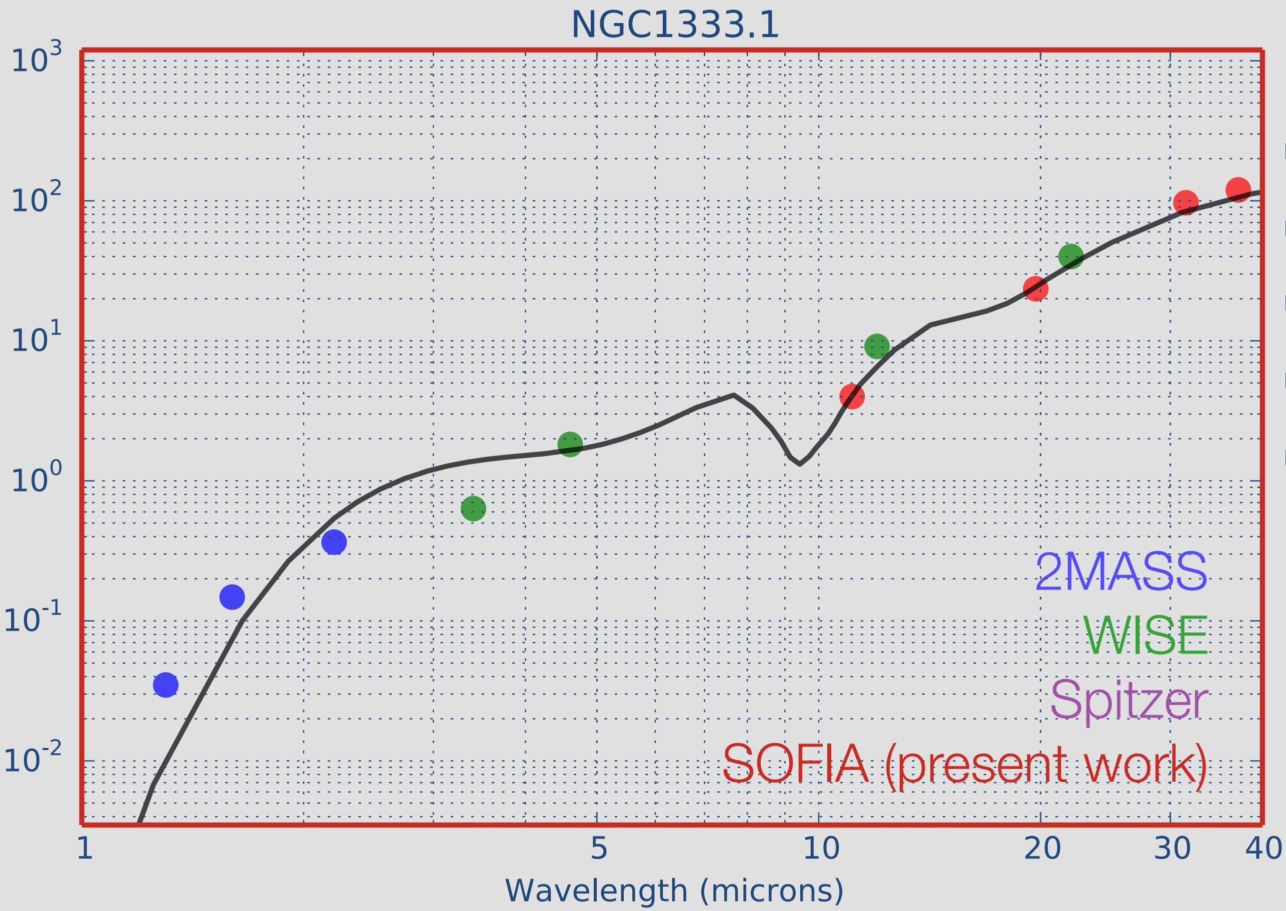


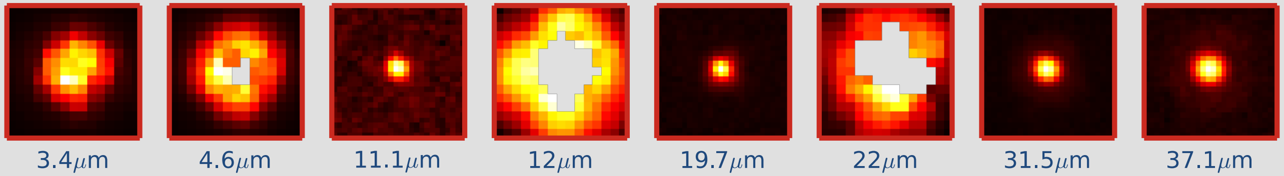
Point sources?

- Example: NGC 1333.1
- Is this an extended source?



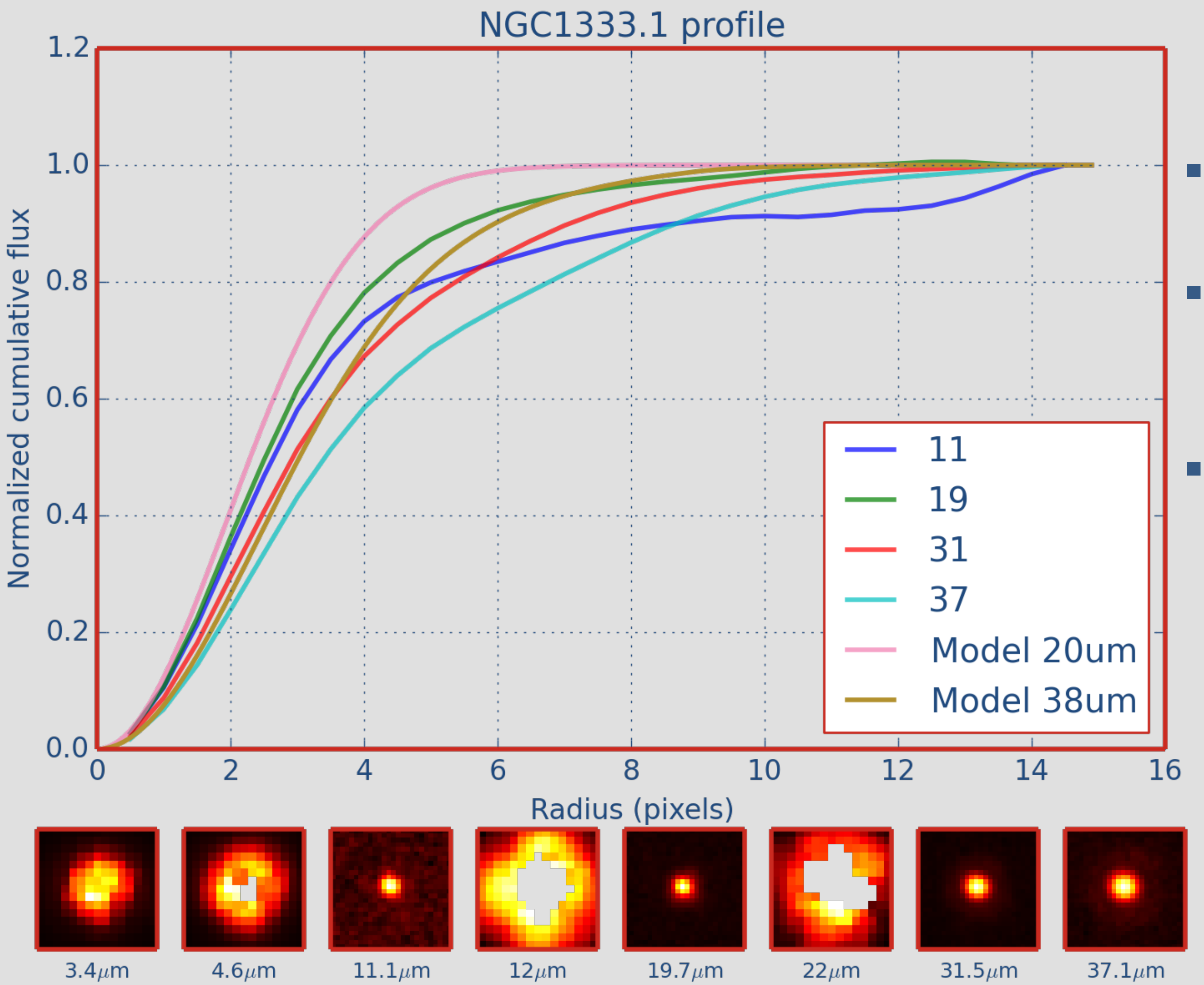
Model fitting





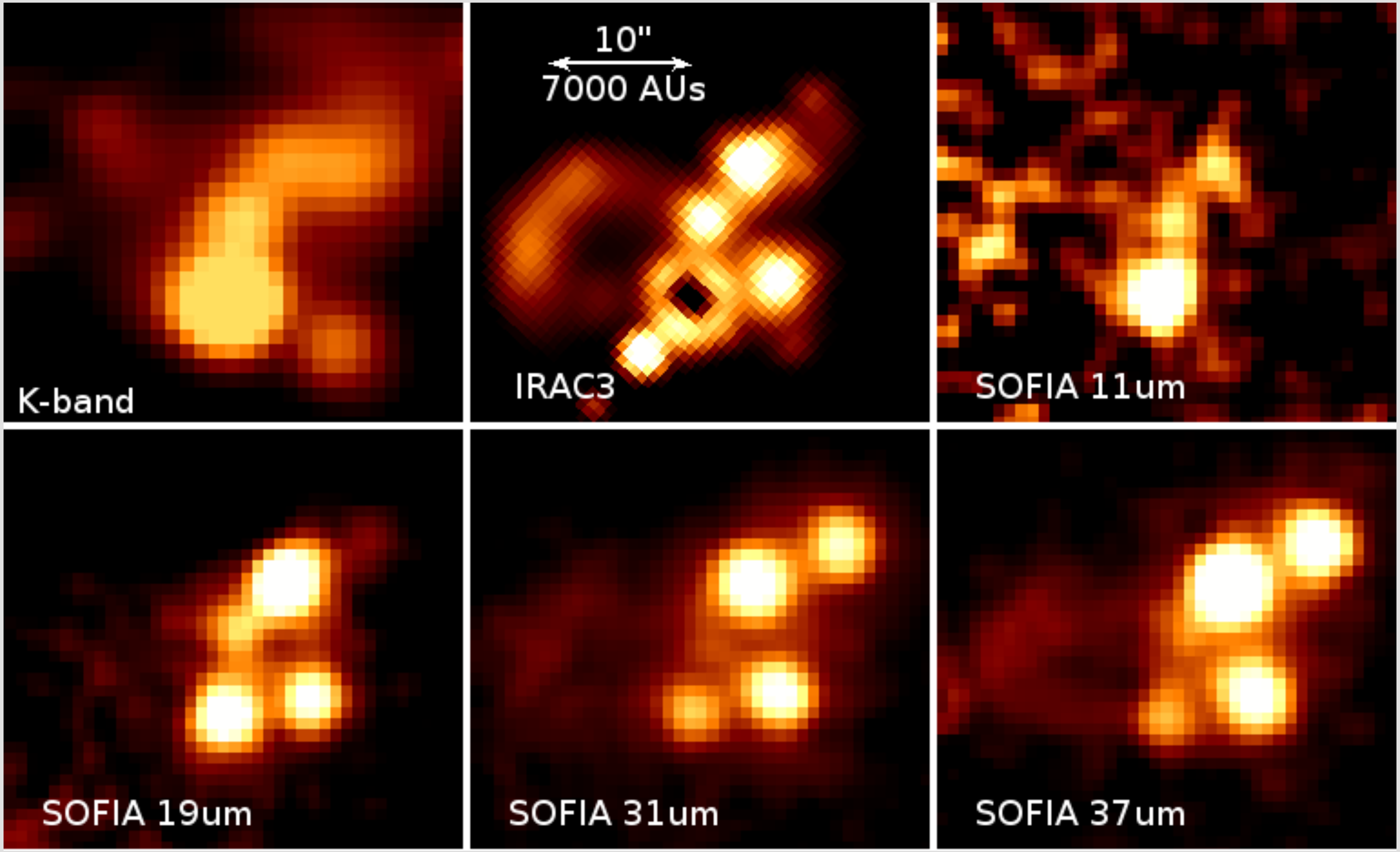
- Distance = 240pc
- L = 32 L_{sun}
- Density law = -0.7
- Envelope mass = 3 M_{sun}
- Inner radius = 30 AU

Point sources?



- Similar wings as calibrator
- Model uses a gaussian PSF to predict radial profile
- Can the calibrator's PSF be trusted?

IRAS 20050 +2720

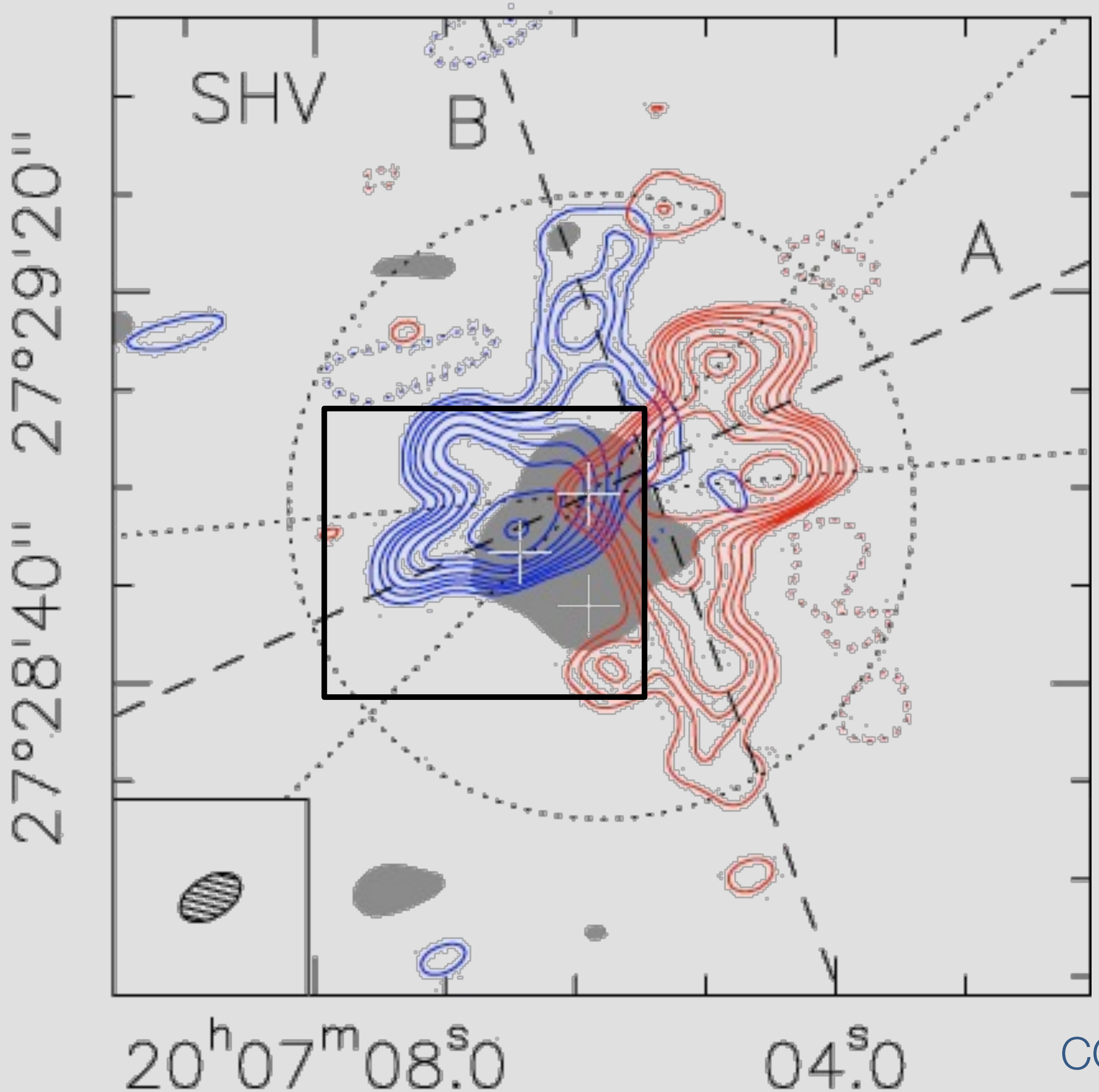


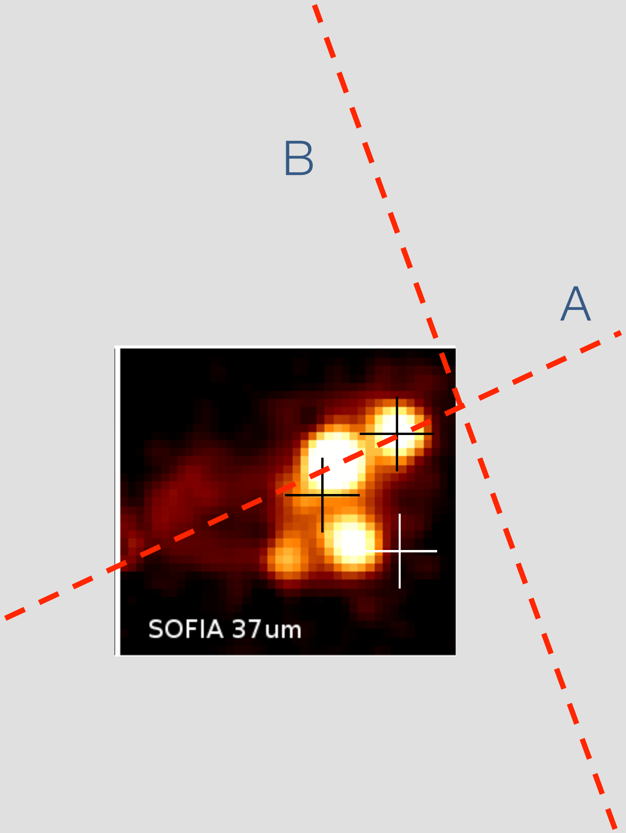
IRAS 20050 +2720

- Typical intermediate-mass star-forming region
- Millimeter continuum sources detected (e.g. Beltran et al. 2008), as well as outflows (e.g. Bachiller et al.1995)
- Identified source multiplicity from interferometry mm data & IRAC maps
- Embedded protostars at different evolutionary stages inferred
  - Intermediate mass YSOs could form after a first generation of low-mass stars has already evolved

- SOFIA allows unprecedented characterization of the evolutionary stage of the deeply embedded protostars

IRAS 20050 +2720

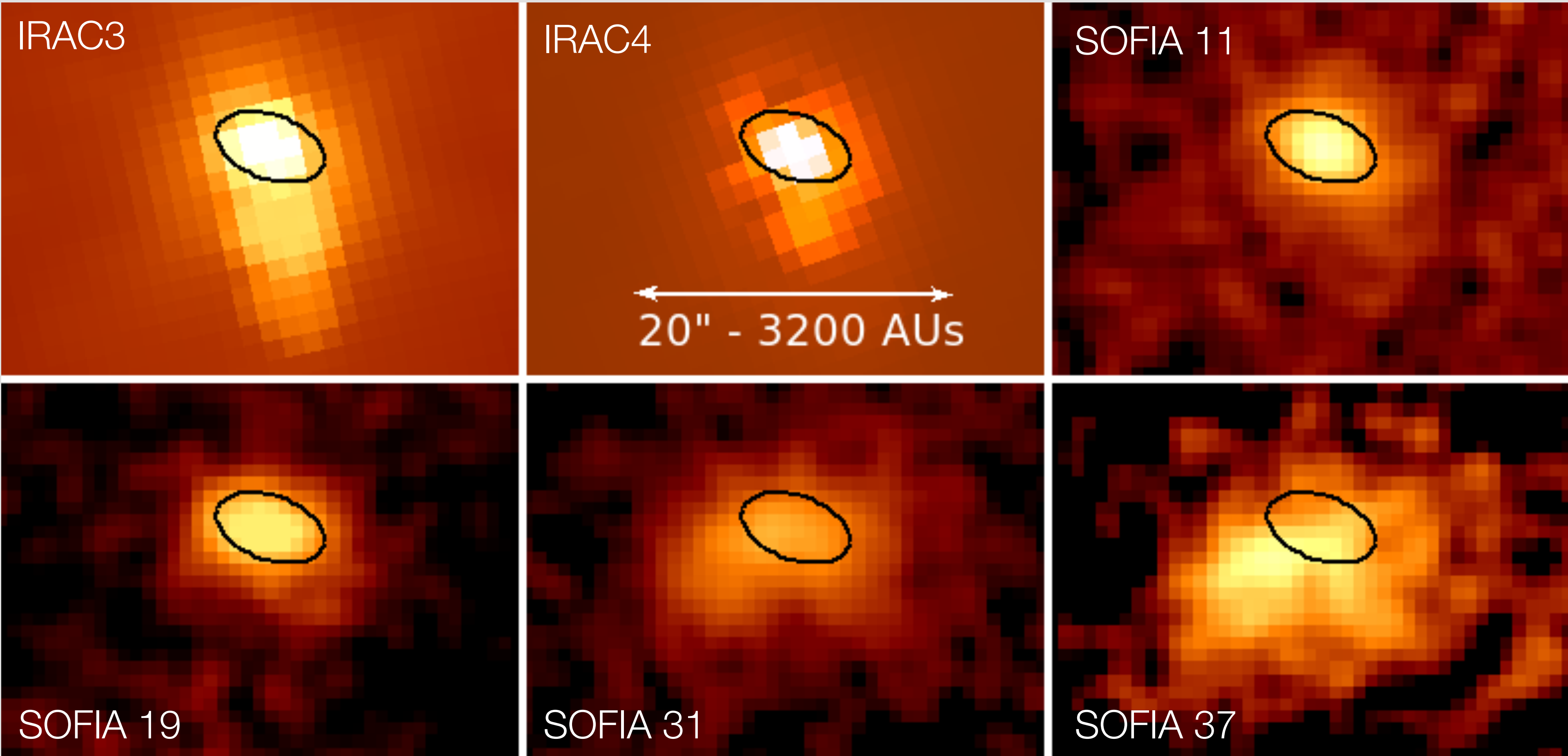




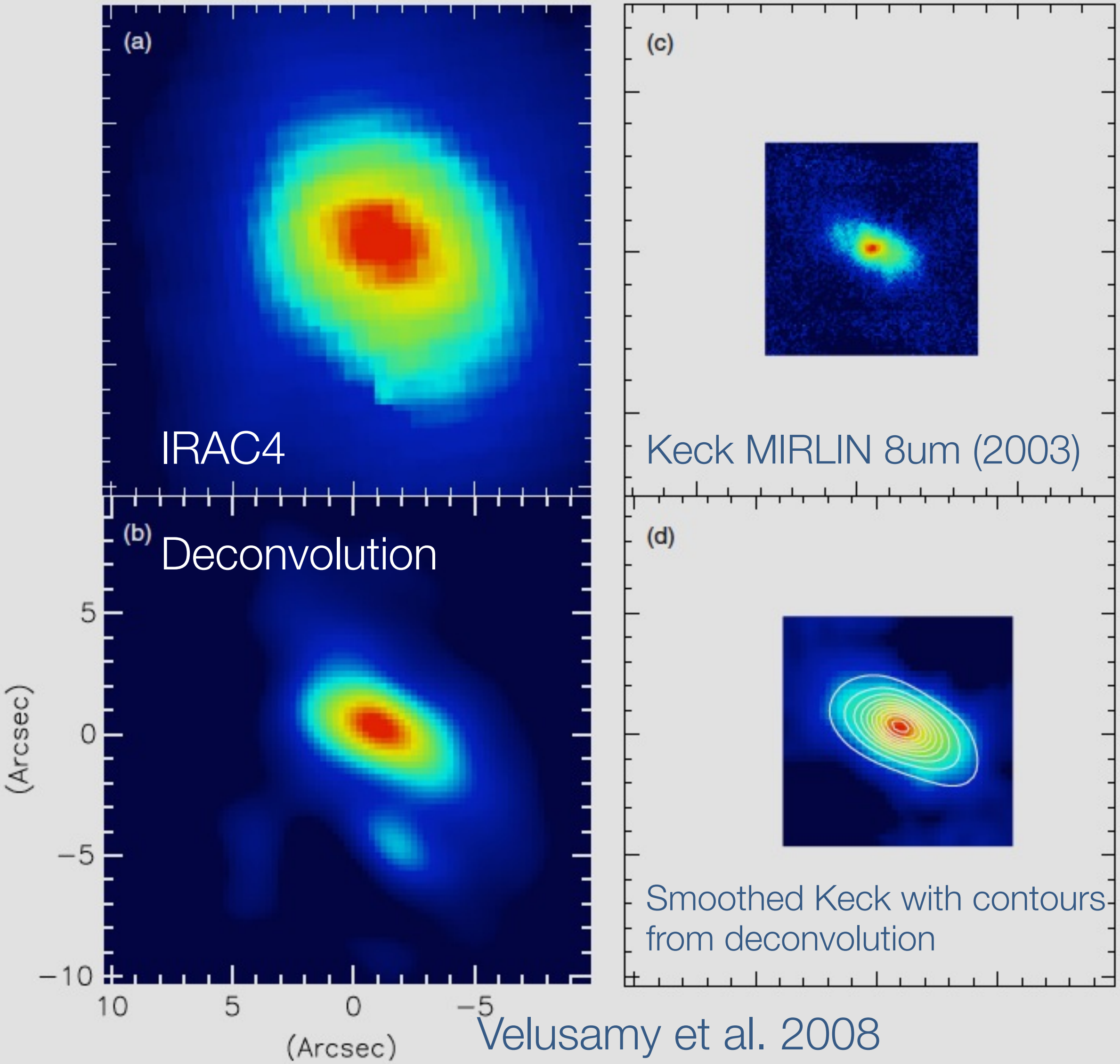
CO (J=1-0), Beltran et al 2008

Ophiuchus WL16

- Classification not clear in the literature (T-Tauri, Herbig Ae/Be, Class I…)
- Presence of mid-IR extended emission attributed to a 800 AUs disk (Ressler 2003)
- Strong PAH emission seen with IRAC and ground-based instruments



Ophiuchus WL16

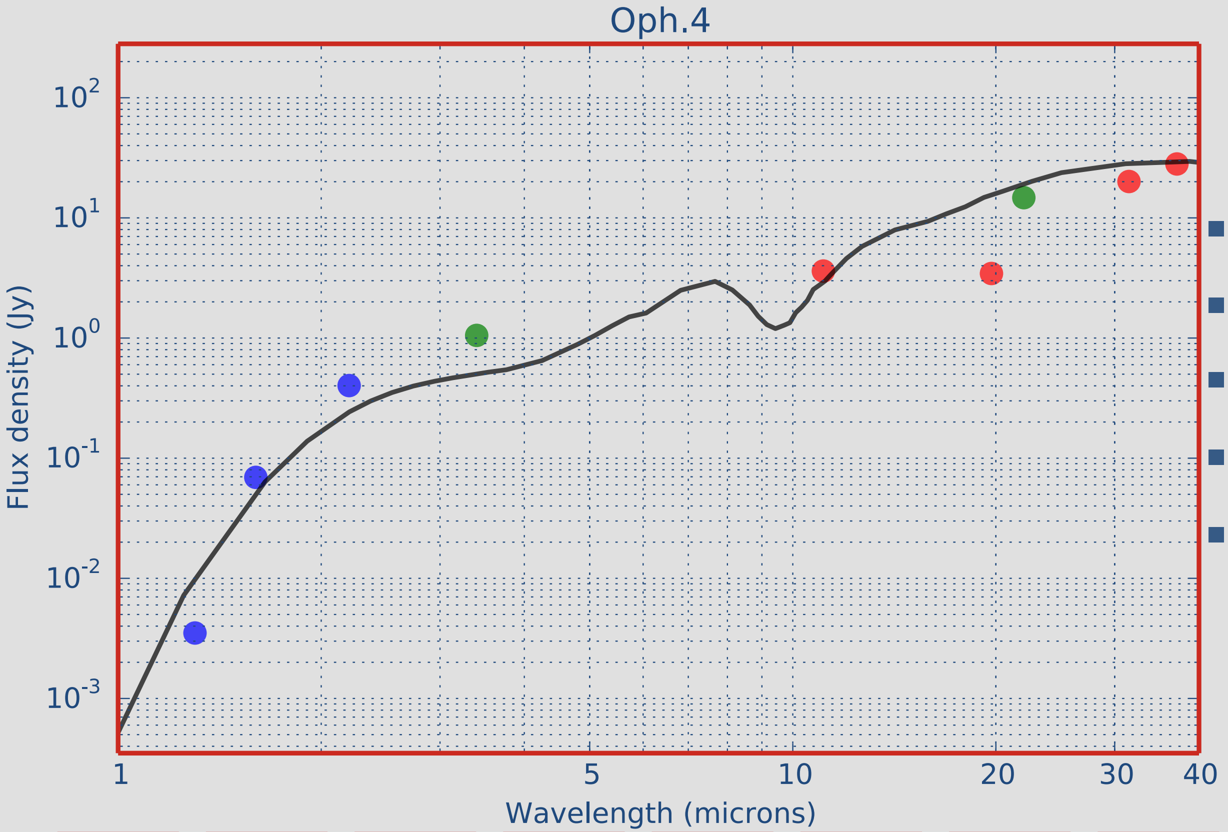


Velusamy et al. 2008

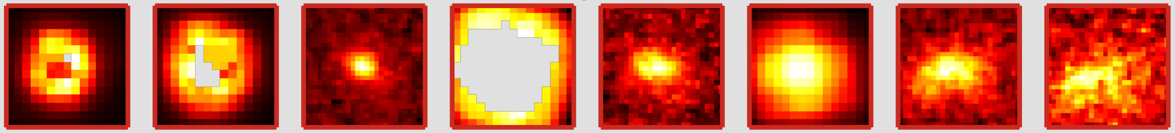
- SOFIA observations show that the extent of long-wavelength emission is much larger, ~3000 AU
- A disk that large is very hard to justify
- Are we seeing a larger envelope, within which the disk has made a cavity?

Ophiuchus WL16

- Can we tell something with SOFIA and modeling?

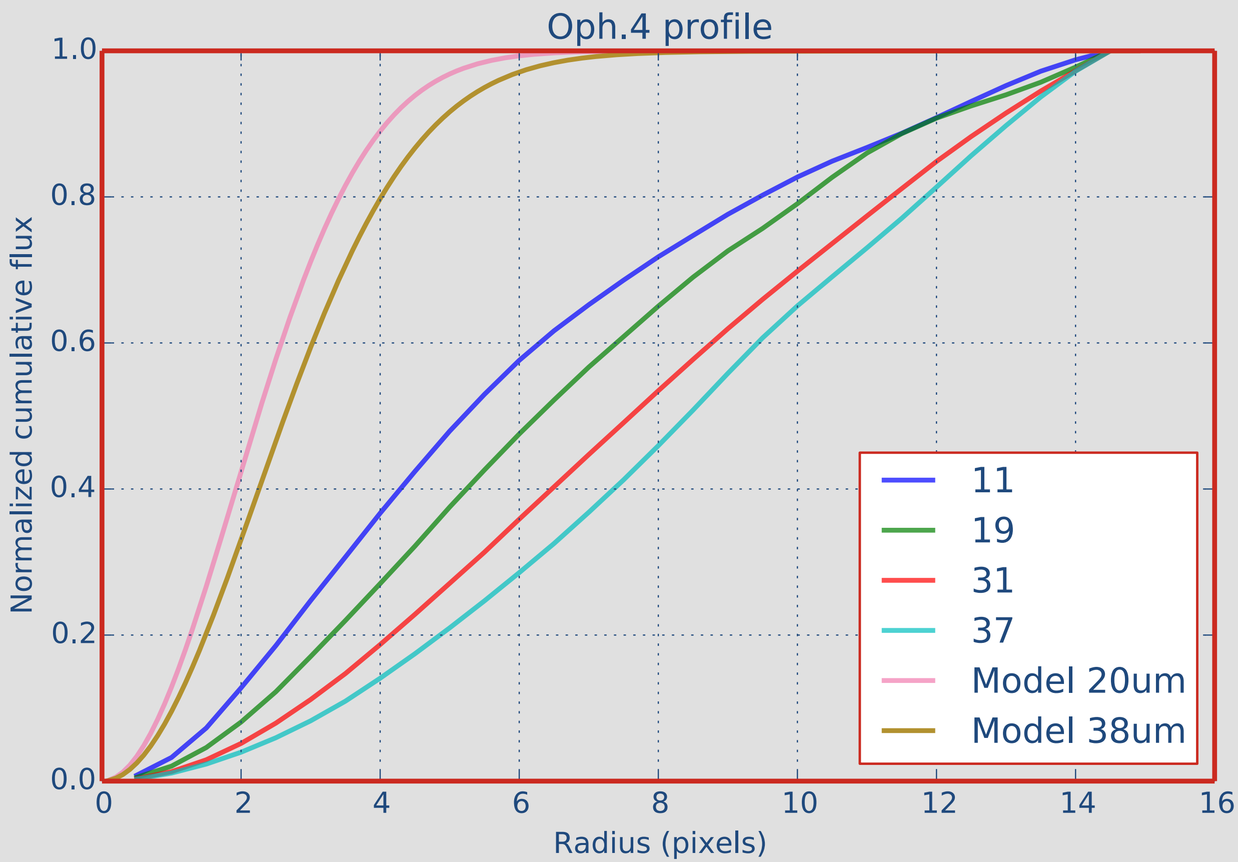


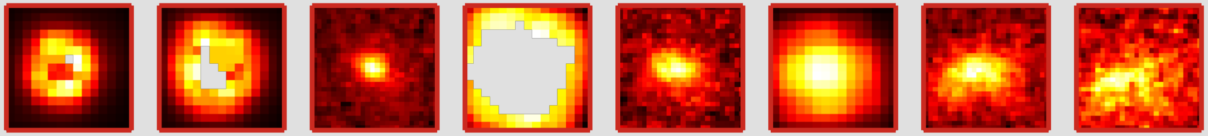
- Distance = 160pc
- L = 4 L_{sun}
- Density law = -1.67
- Envelope mass = 0.08 M_{sun}
- Inner radius = 10 AU



3.4μm | 4.6μm | 11.1μm | 12μm | 19.7μm | 22μm | 31.5μm | 37.1μm

Ophiuchus WL16





- Spherical model can't account for the size of extension
- Actually, hard to find parameters that reproduce the observed profile
- Need to do more modeling – SOFIA's spatial resolution allows a unique look at the object's morphology

A lot is left to do

- Answer remaining questions about data reduction
  - Wings of calibrators?
  - WCS alignment technique (from FITS header maybe)?
- Waiting for new data to be processed as level 3, to complete survey
- Look for more advanced modeling software?
- Look at the sample both in terms of statistics, and in terms of individual objects
  - Most objects are very well studied: need to search extensive literature to find where observations can serve the most

Conclusions and summary

- We identify the SED of ~70 YSOs in nearby clusters, and characterize their spatial extension
- We provide the first far-IR data points of ~16 sources, that were previously either unresolved or saturated
- We use a spherically symmetric model of a dust envelope to fit SEDs and spatial shapes of the objects – but this doesn't work for a large fraction of our sources with complex geometry

Thank you for your attention!