FORCAST Studies of High-Mass Star Formation on Small and Large Scales

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We know so little about massive star formation because it is harder to observe

- Generally FAR away (few kpc, not 10s of pc)
- Optical (and often NIR) imaging is not viable because high extinction (locally and globally)
- Radio continuum emission only arises from the HII region or collisionally-ionized jets later in evolution (~$10^{5\text{-}6}$ yrs)
- Direct continuum observations of the pre-HII phase can only be performed from the mid-infrared (~10µm) to millimeter (~3 µm)

IR facilities like SOFIA are key to learning about the detailed properties of massive star formation

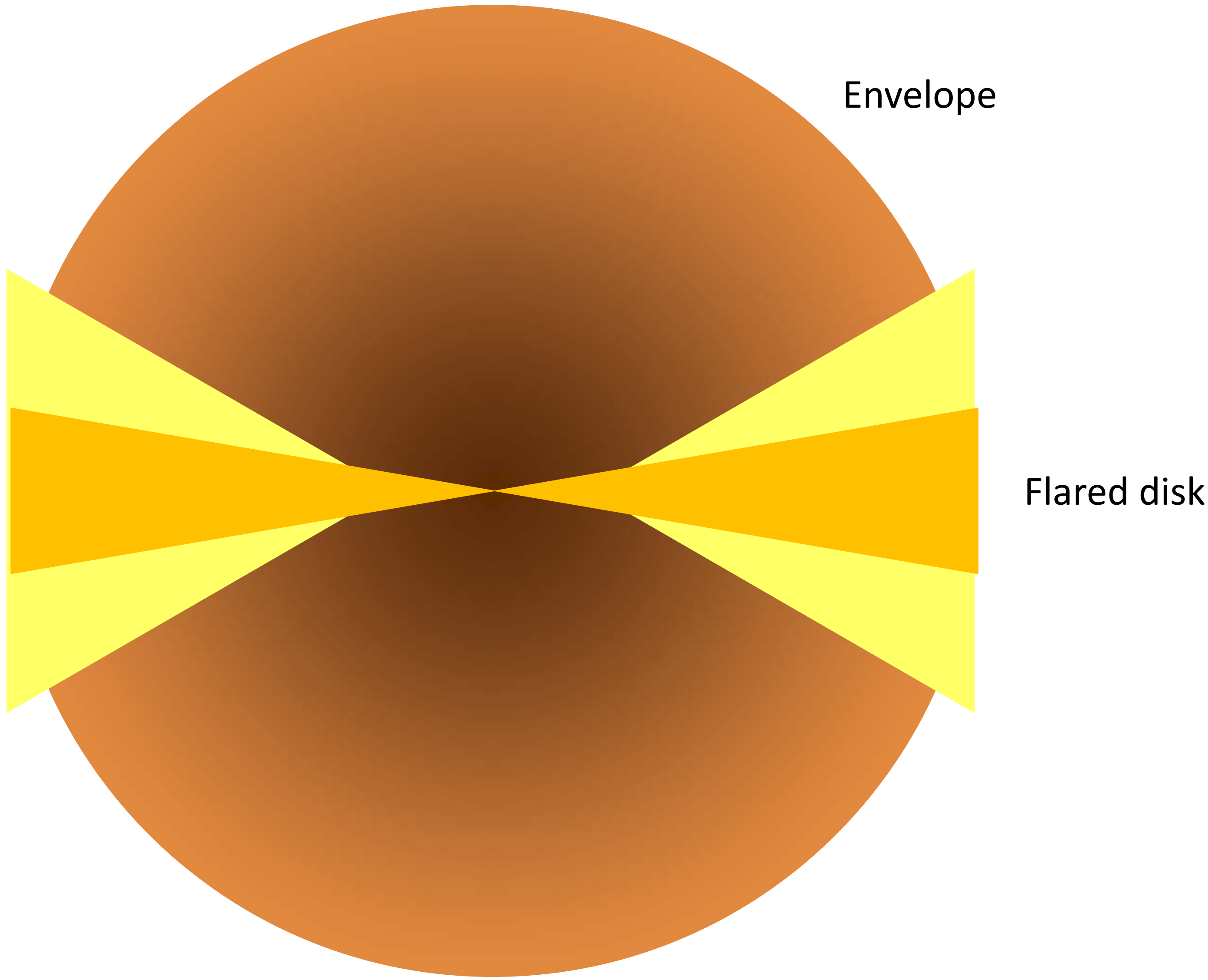
Small-scale:

- IR allows one to peer through global extinction
- MIR continuum emission traces the warm circumstellar dust (~200 K) heated close to massive stellar sources

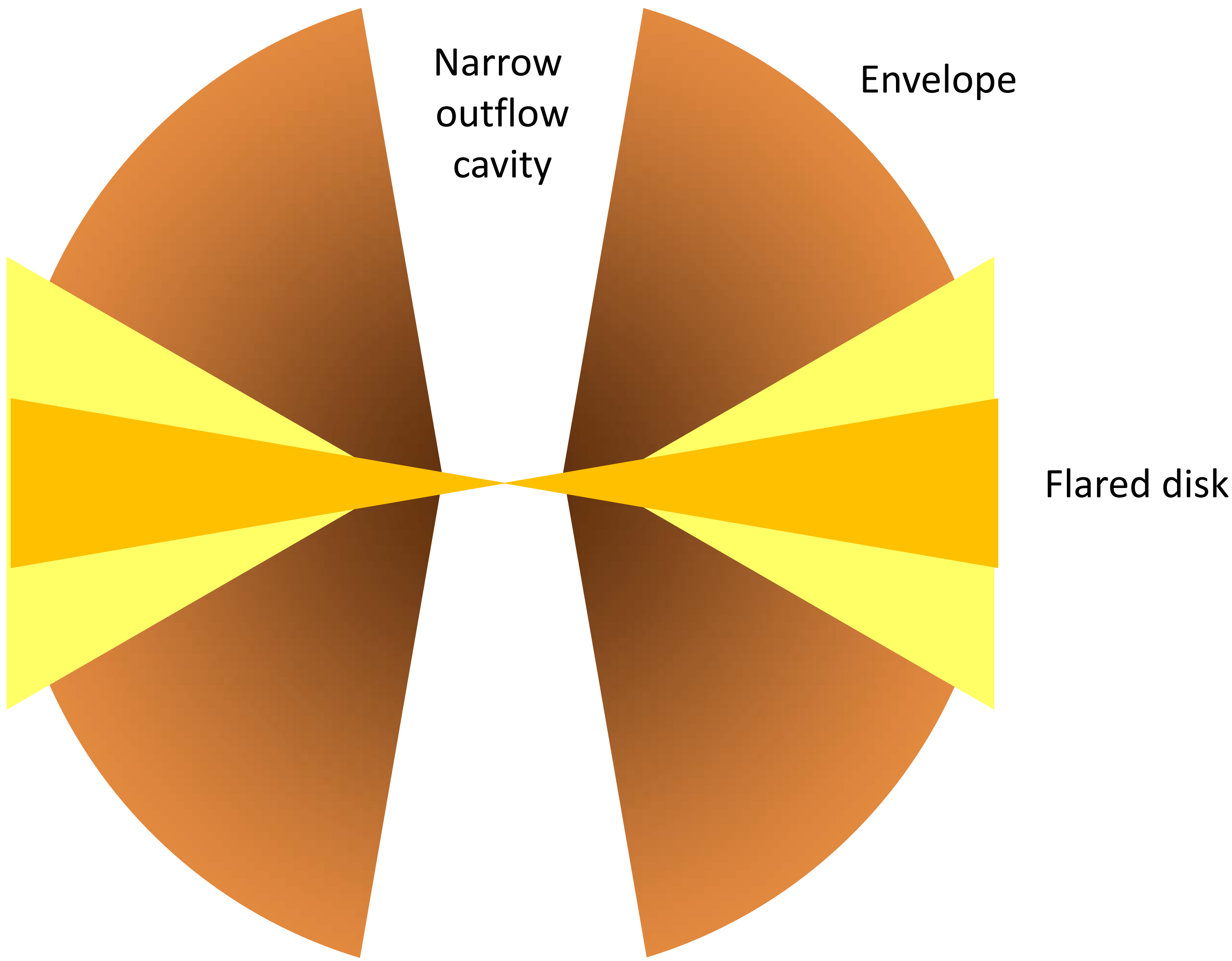
Large-scale:

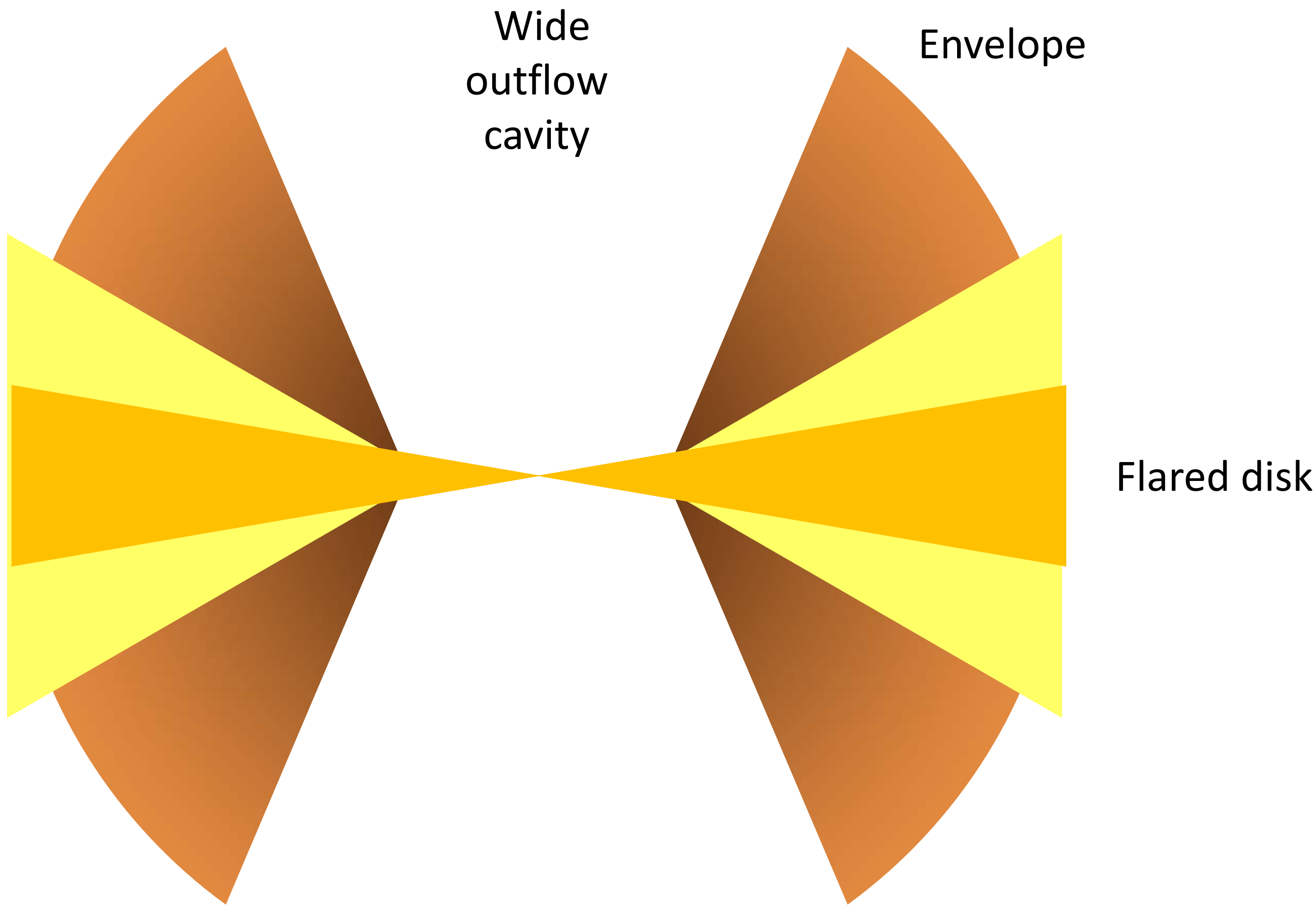
- The energy produced globally by all stars and protostars in a GMC help heat up the dust, allowing the environment of star formation to be studied in the IR

High-Mass Star Formation on **Small Scales**

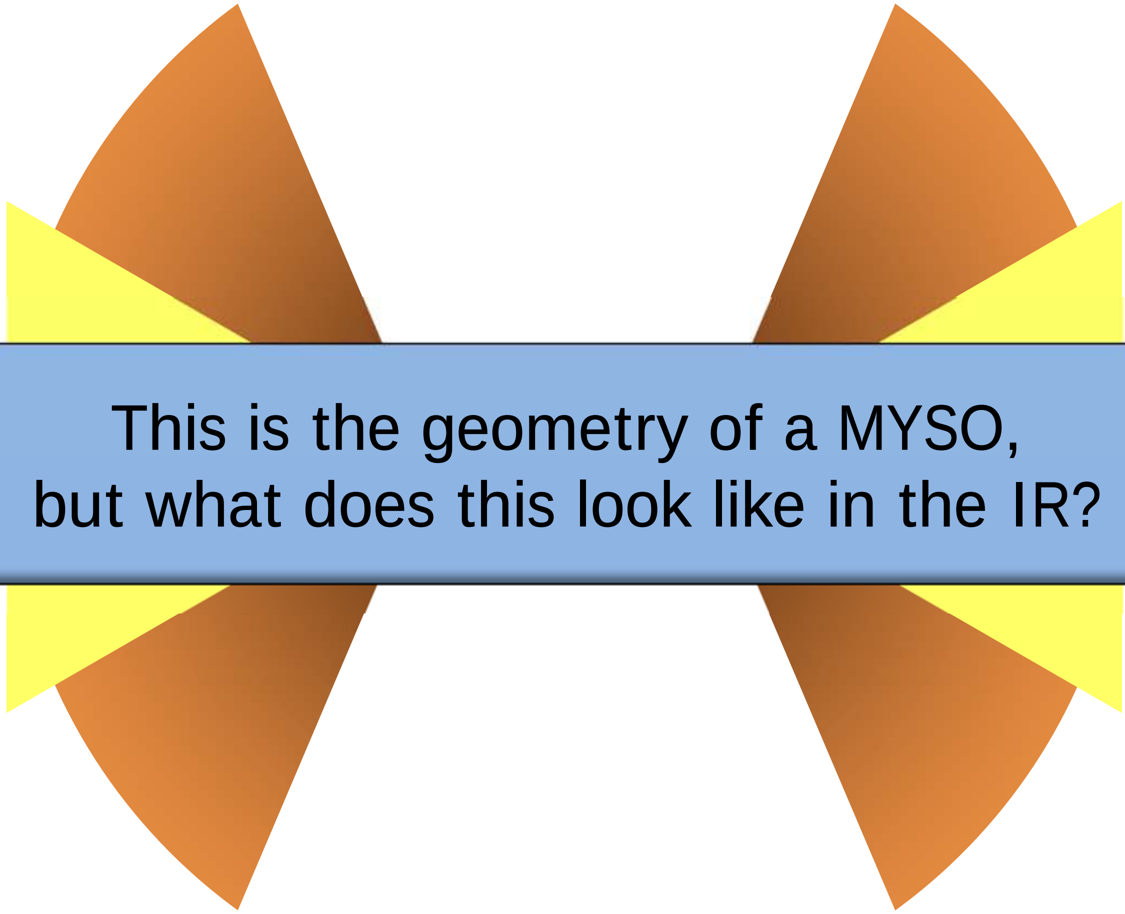


Disk is optically thick in IR, and envelope could be as well


Narrow
outflow
cavity
Envelope
Flared disk

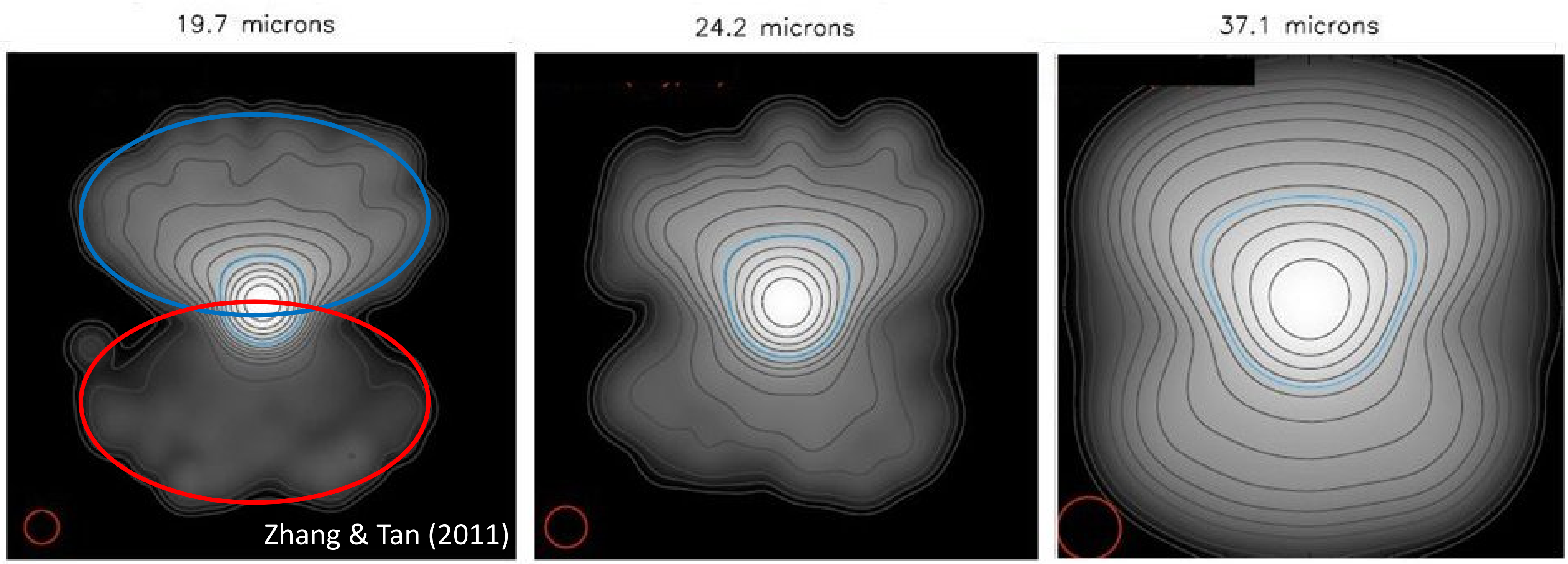


Widening of the outflow may be related to the evolution of the young stellar object, or to the envelope accretion and/or density



This is the geometry of a MYSO,
but what does this look like in the IR?

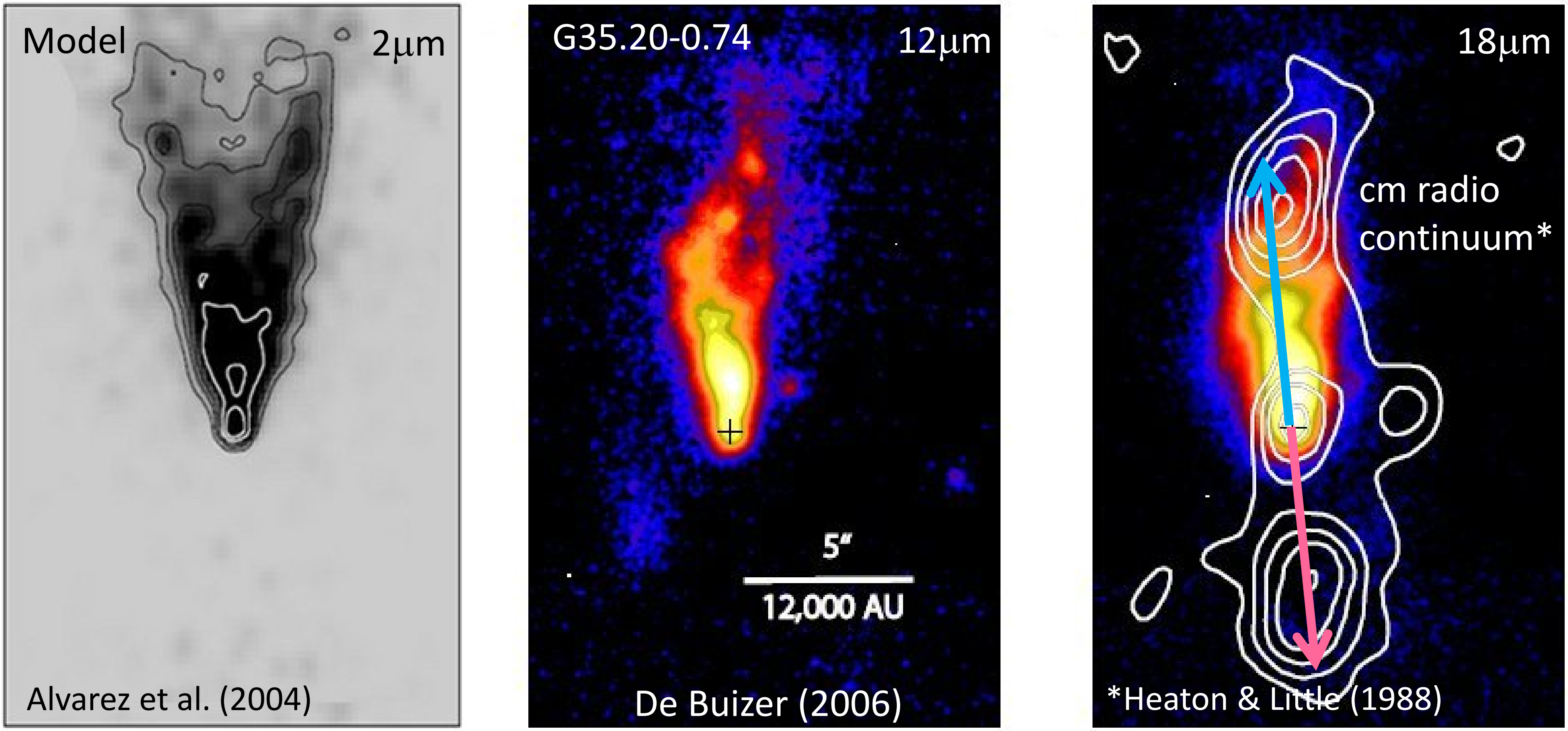
More sophisticated radiative transfer models show the same gross features as our toy model



Model with i=60^o, thin disk, with 60^o outflow/disk opening angle, with SOFIA resolutions

- These models demonstrate the wavelength dependence of emission as well

High-res MIR images of massive young stellar objects also corroborate this model



Dust continuum from outflow cavity dominates the MIR emission

We even detect the red-shifted outflow cavity at the longer wavelengths available to FORCAST!

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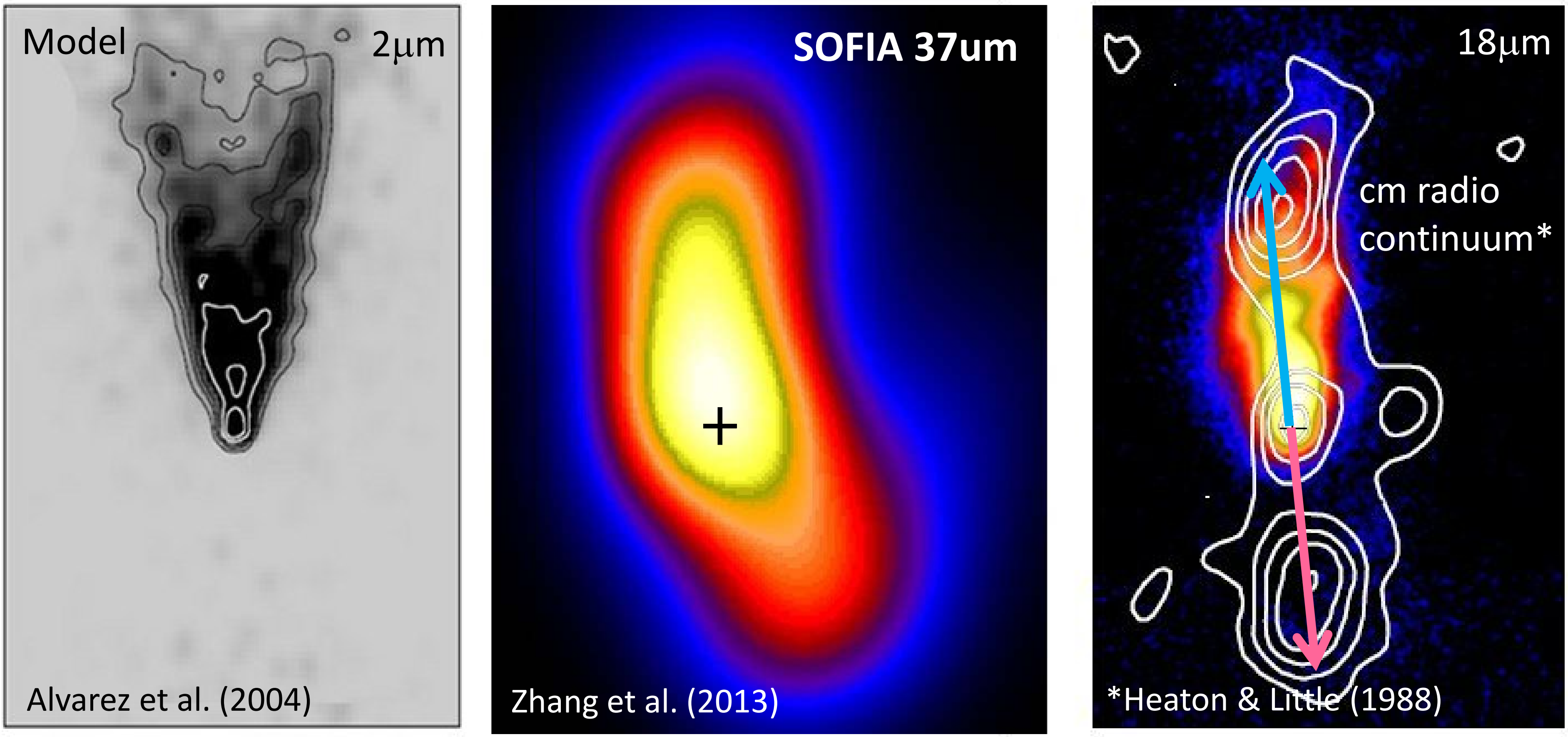

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The SOFIA Massive Star Formation (SOMA) Survey

Designed to look at more (~50) young high (and intermediate) mass protostars

Initial sample of 8 sources from Cycles 1-3 have been analyzed and pooled into a paper (De Buizer et al. submitted)

Motivation 1: How wide-spread is the evidence in our sample that the MIR morphologies are influenced by the presence of outflow cavities?

Motivation 2: Can SEDs be reasonably fit by 3D radiative transfer turbulent core models?

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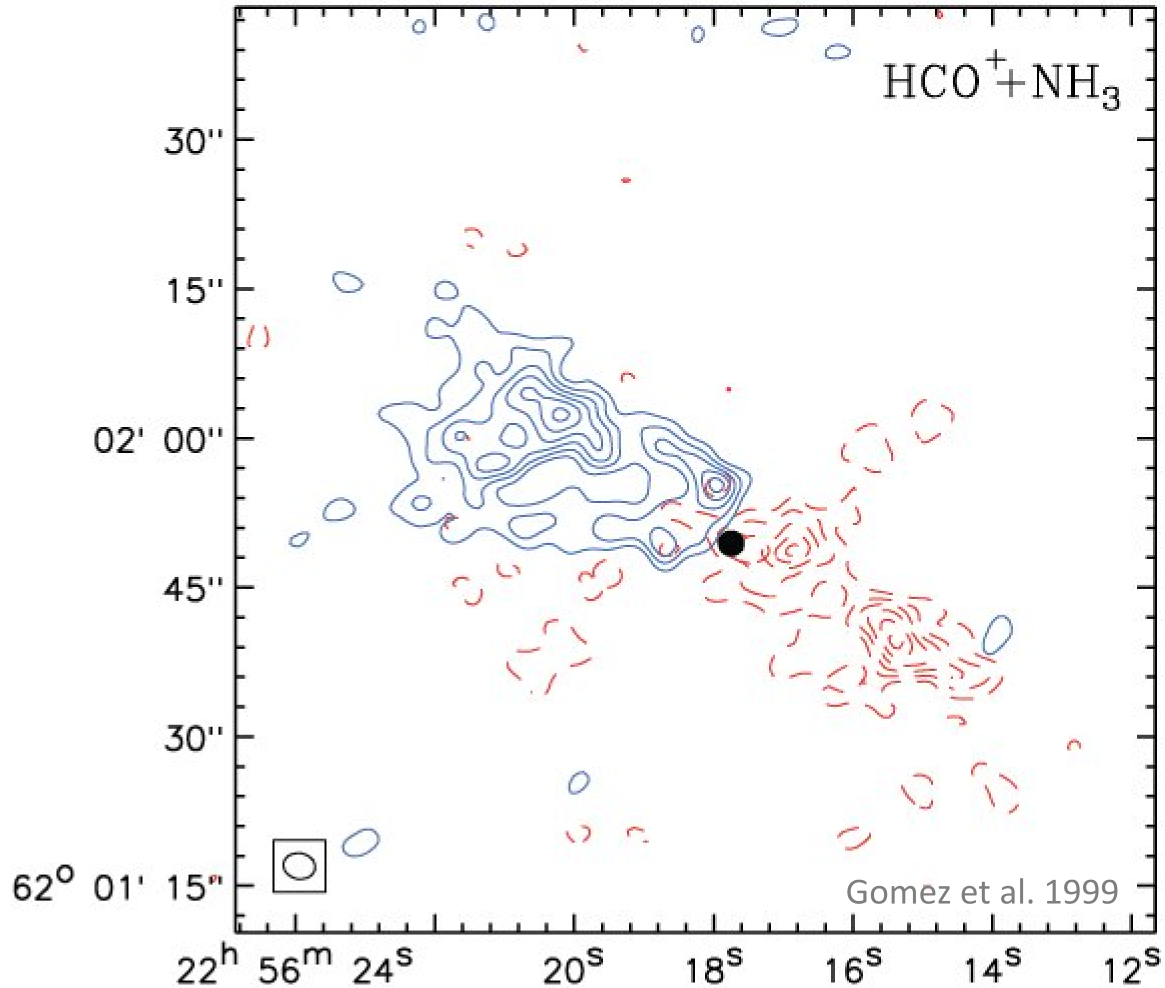
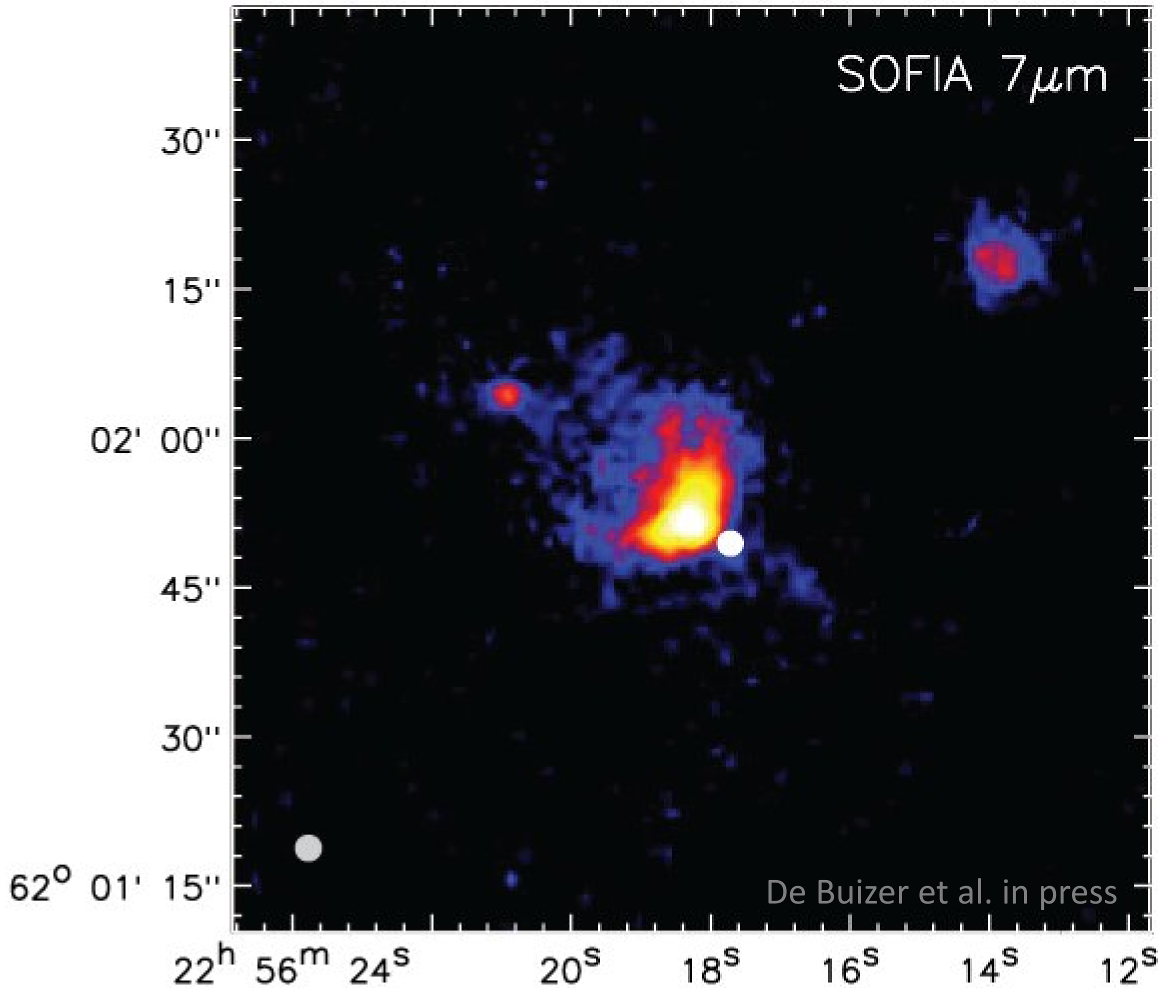
Cepheus A



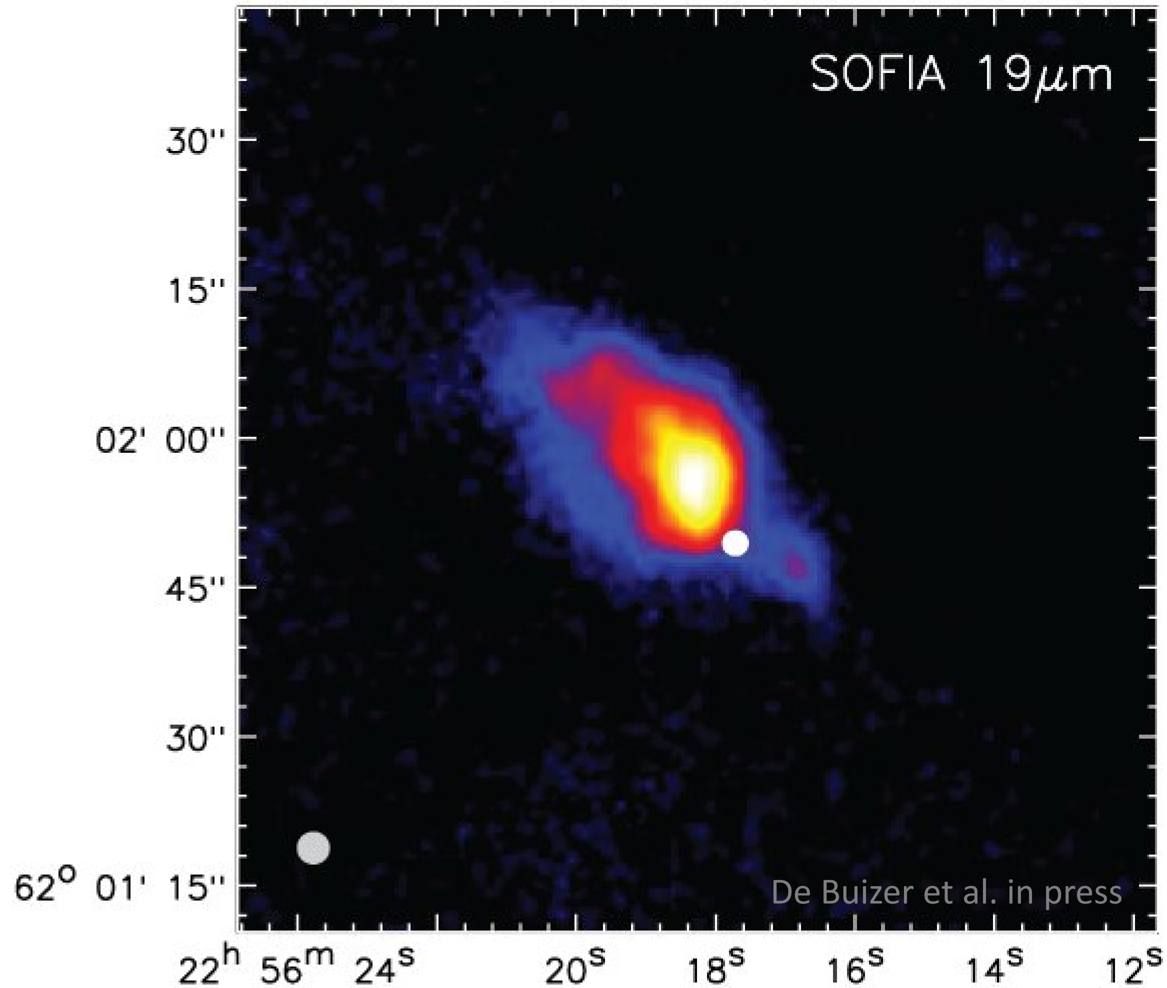
● HW2 (cm continuum source)

Cepheus A



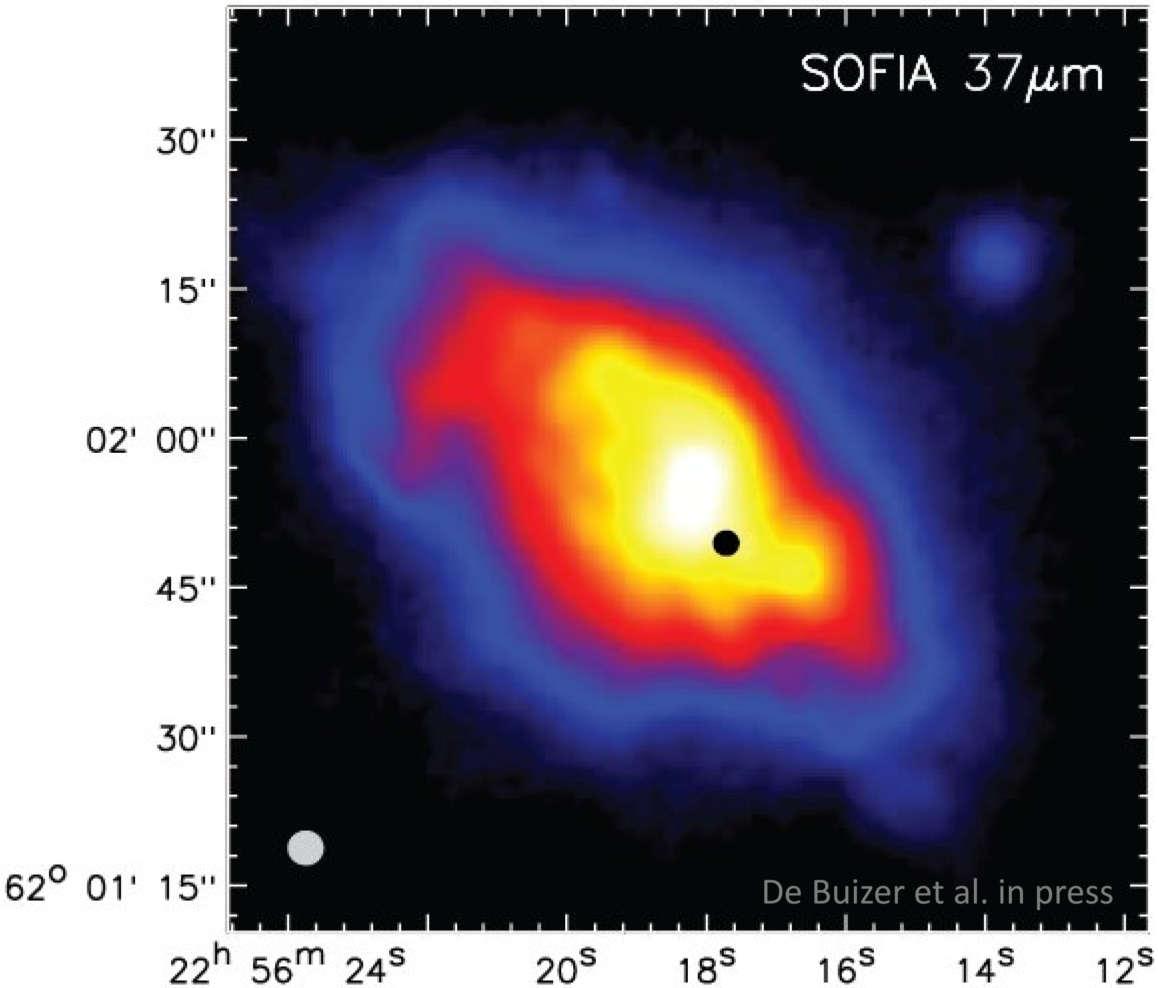
Shorter FORCAST wavelengths trace blue-shifted outflow cavity

Cepheus A



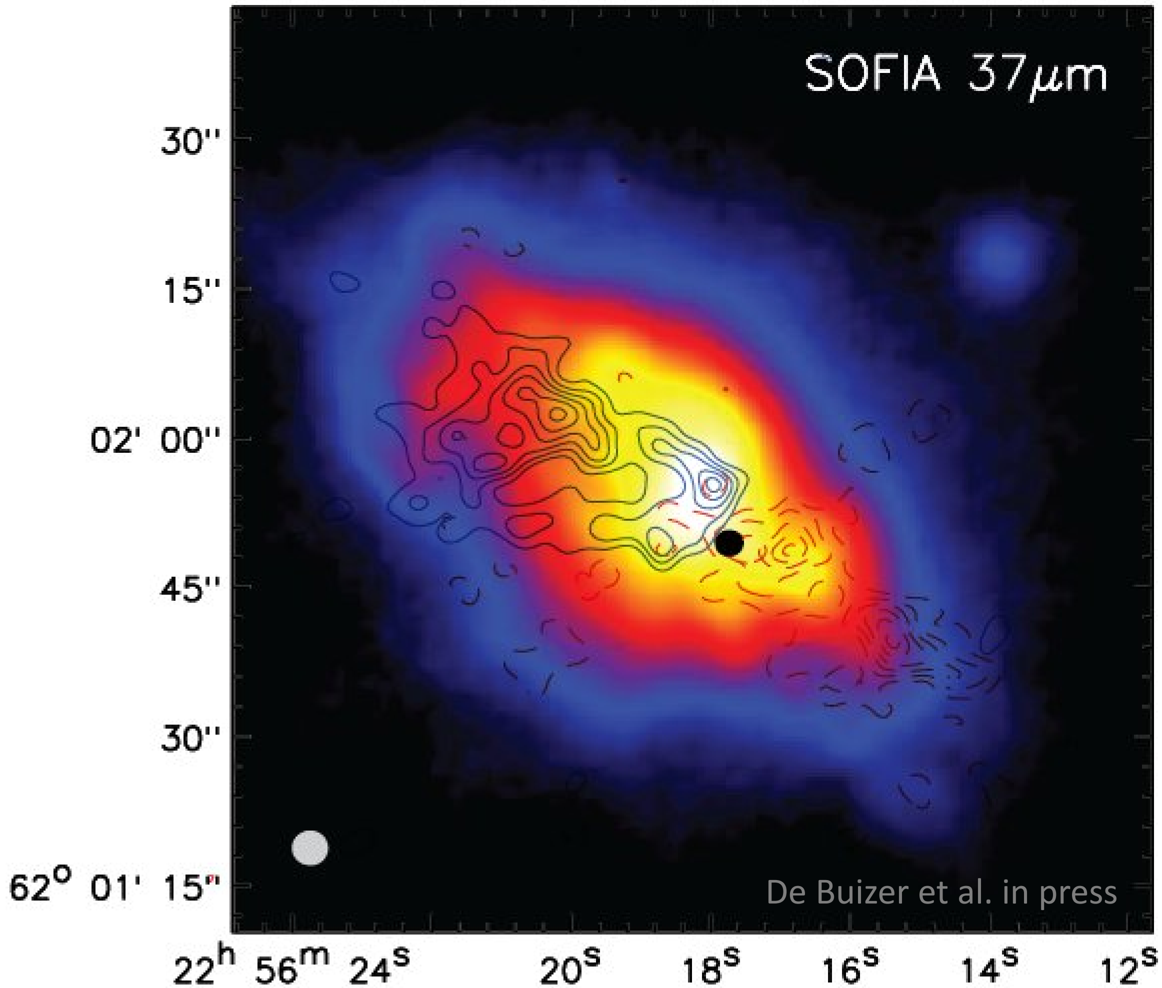
Start to pick up the red-shifted outflow cavity around 20um

Cepheus A



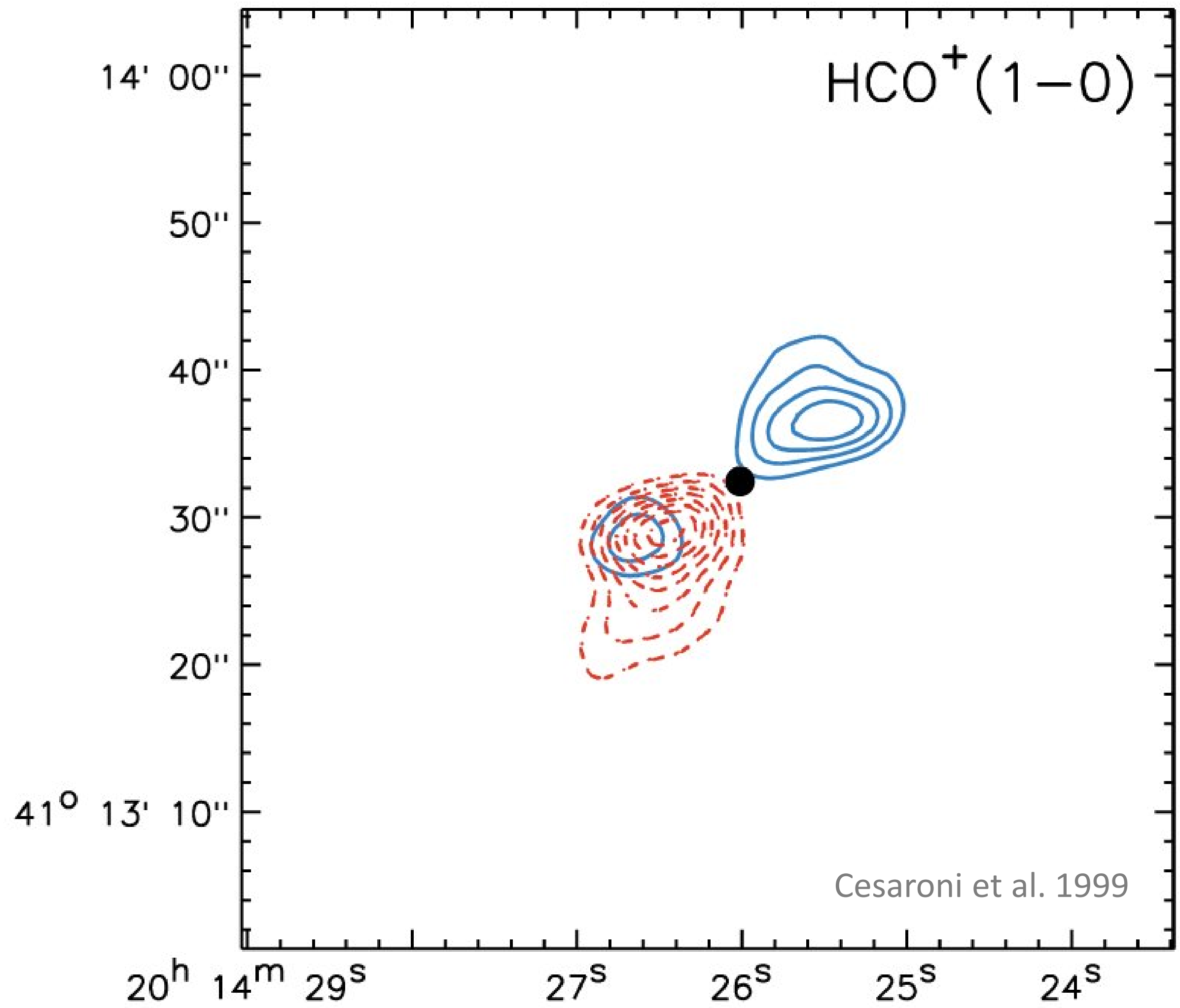
Substantial red-shifted outflow cavity emission seen at 37um

Cepheus A



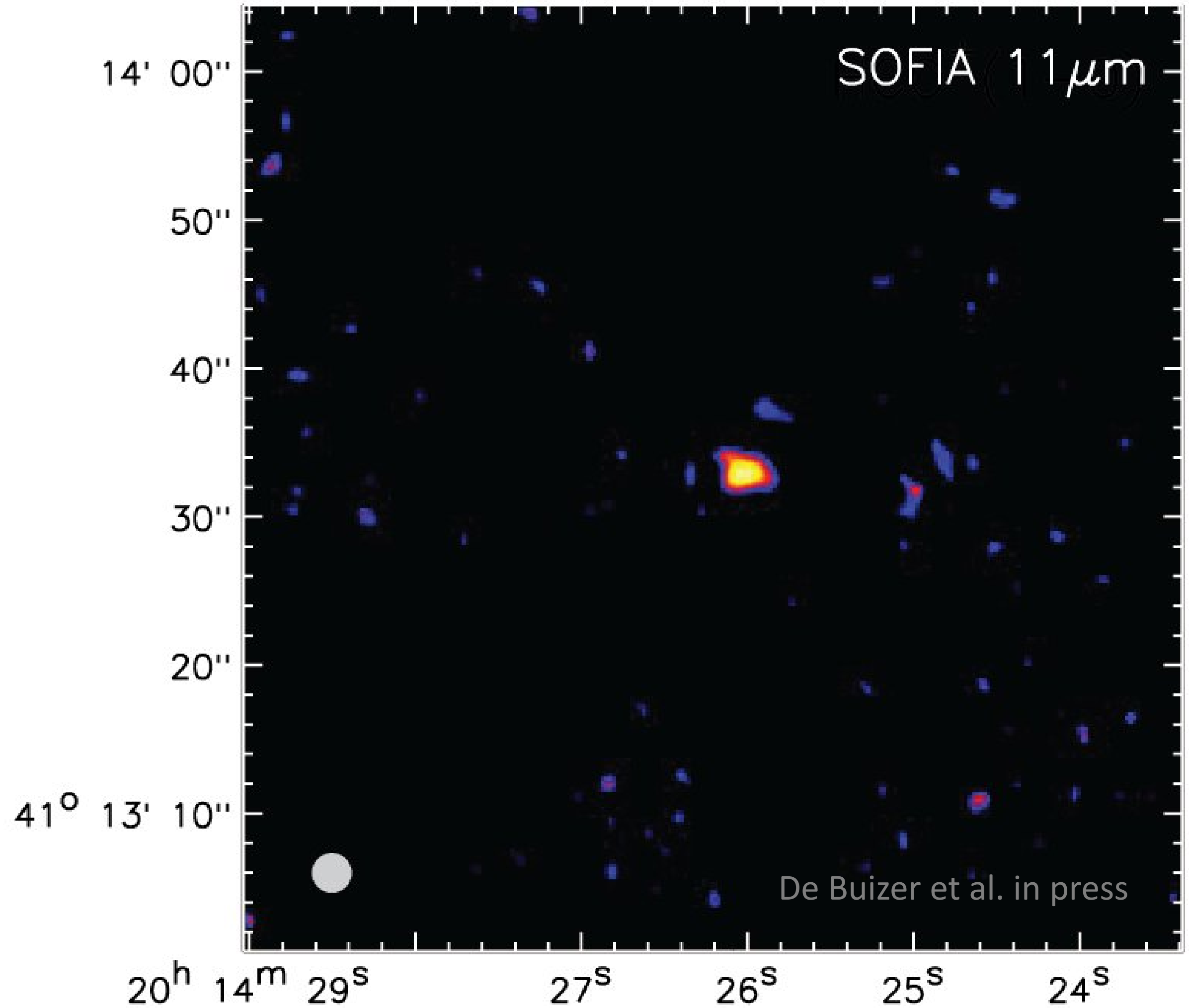
Substantial red-shifted outflow cavity emission seen at 37um

IRAS 20126+4104



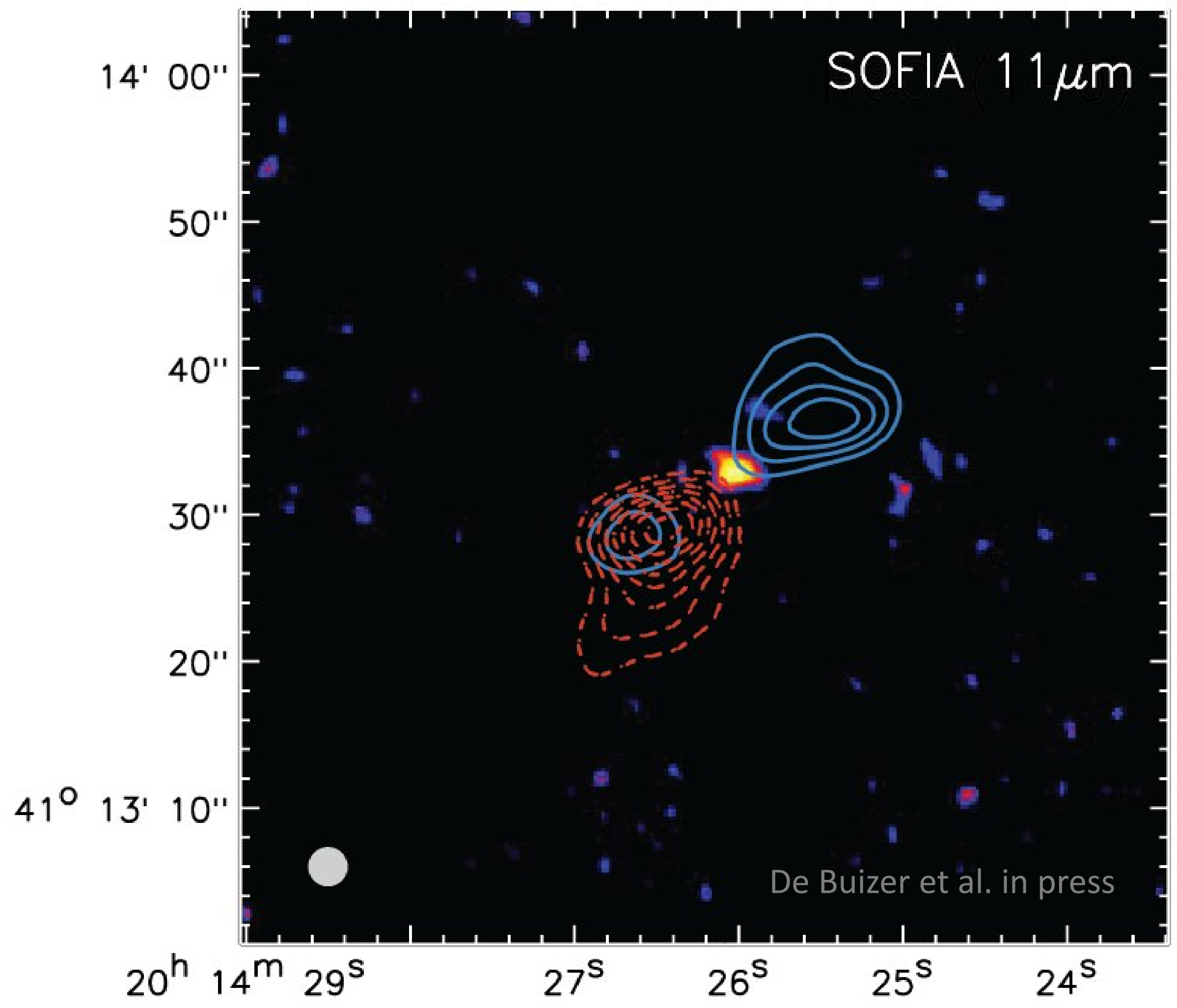
● Water masers marking outflow source

IRAS 20126+4104



Shorter FORCAST wavelengths trace emission near outflow source

IRAS 20126+4104



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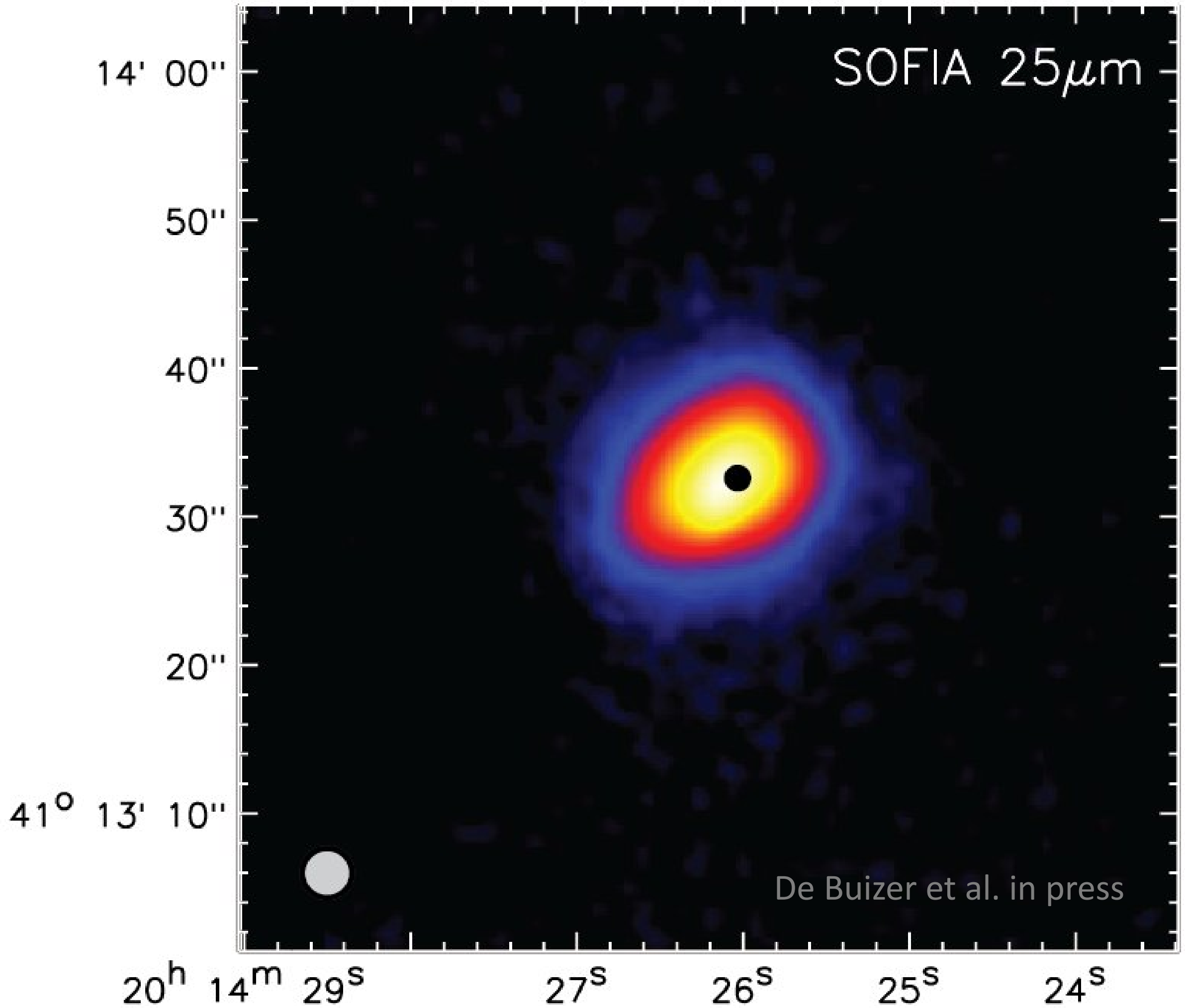
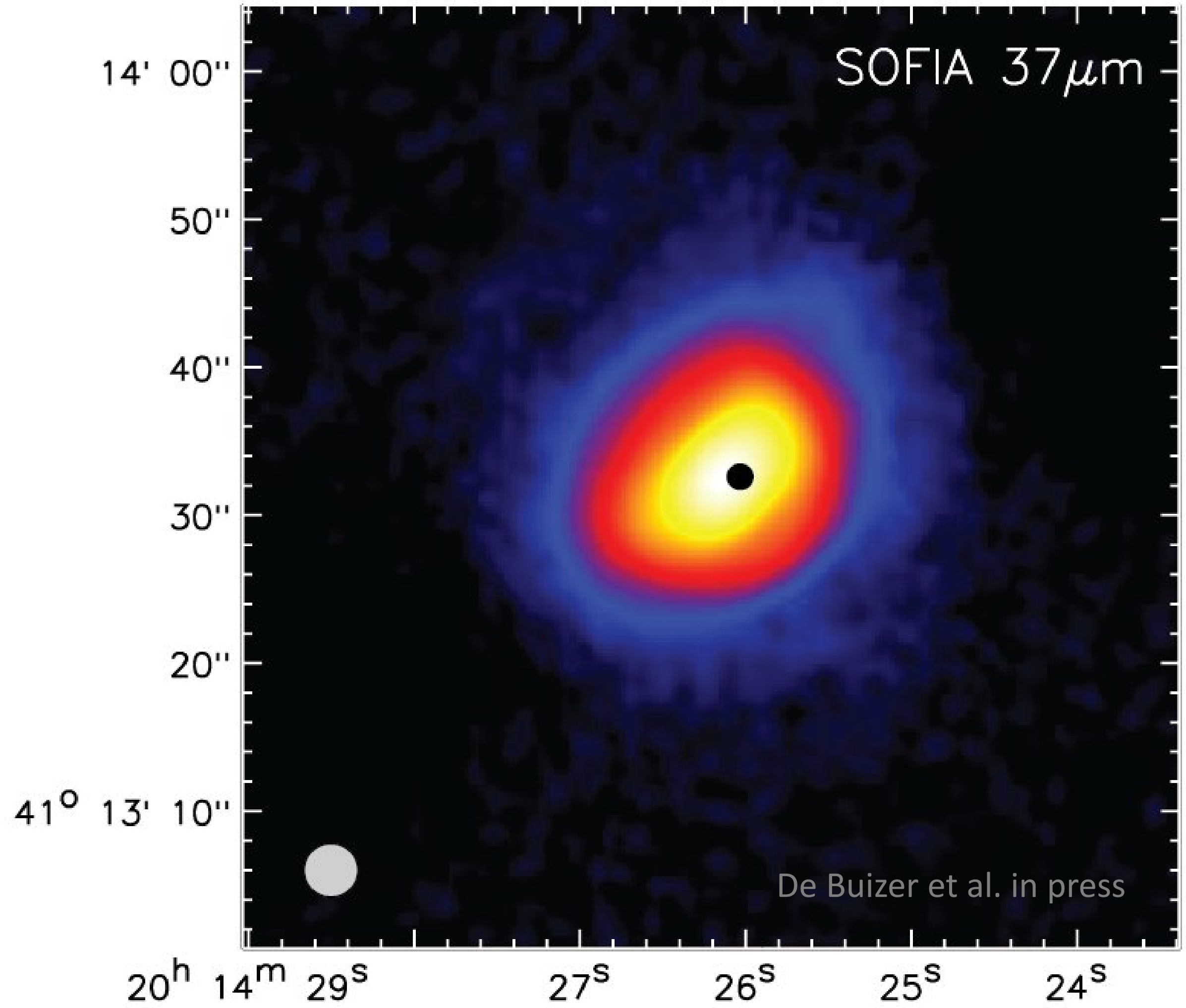


By 25um we are picking up extended emission along the outflow axis

IRAS 20126+4104



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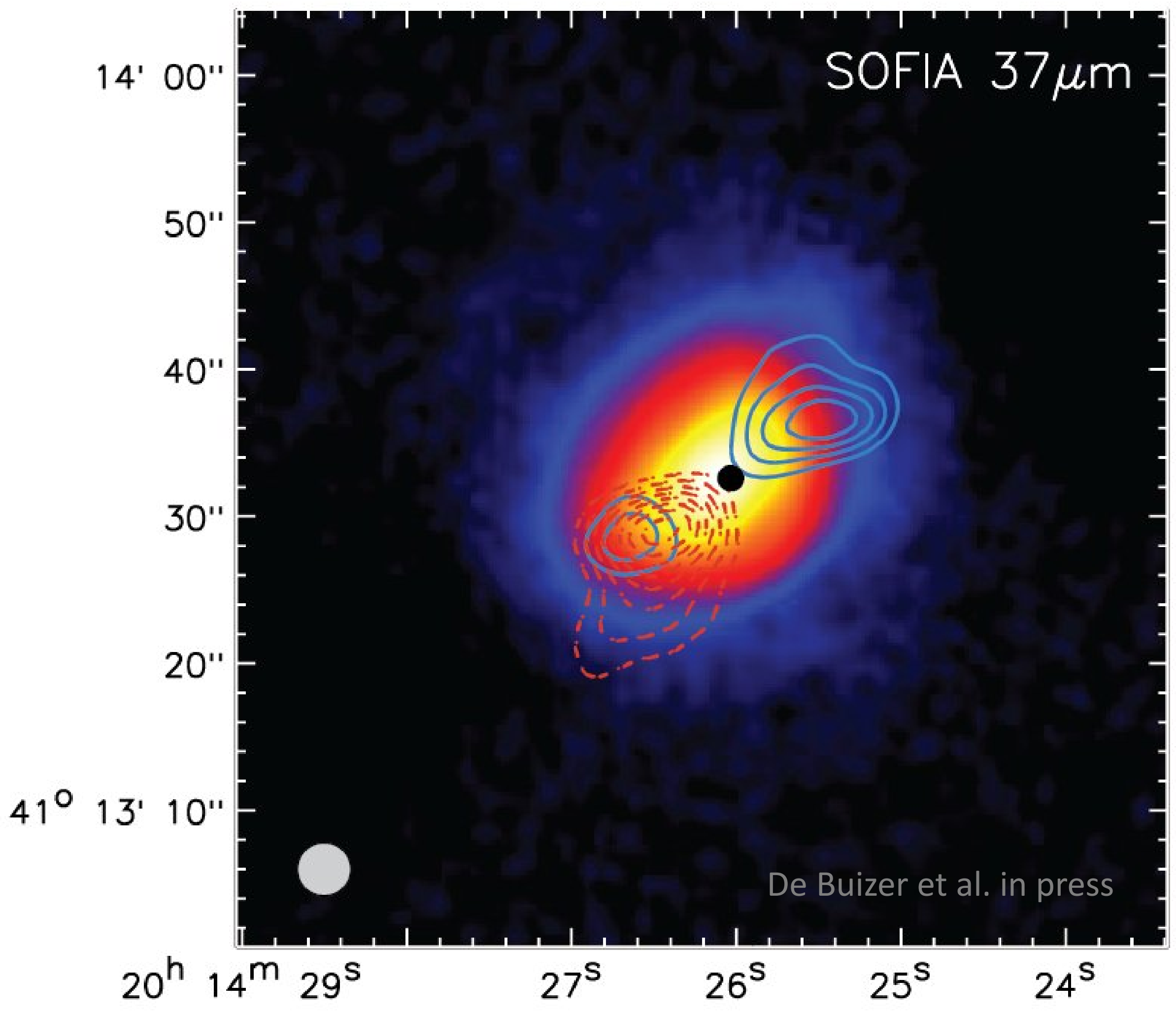

Source morphology is heavily dependent on outflow axis orientation

Are MIR morphologies influenced by the presence of outflow cavities?

From our initial sample of 8 sources:

- Only the intermediate-mass source, AFGL 437 does not show clear signs of extended MIR/FIR emission
- Of the remaining seven high-mass sources, six are extended in MIR/FIR at a position angle comparable to their outflow axes
- High-mass source IRAS 07299-1651 has extended emission at multiple wavelengths, but outflow info for comparison

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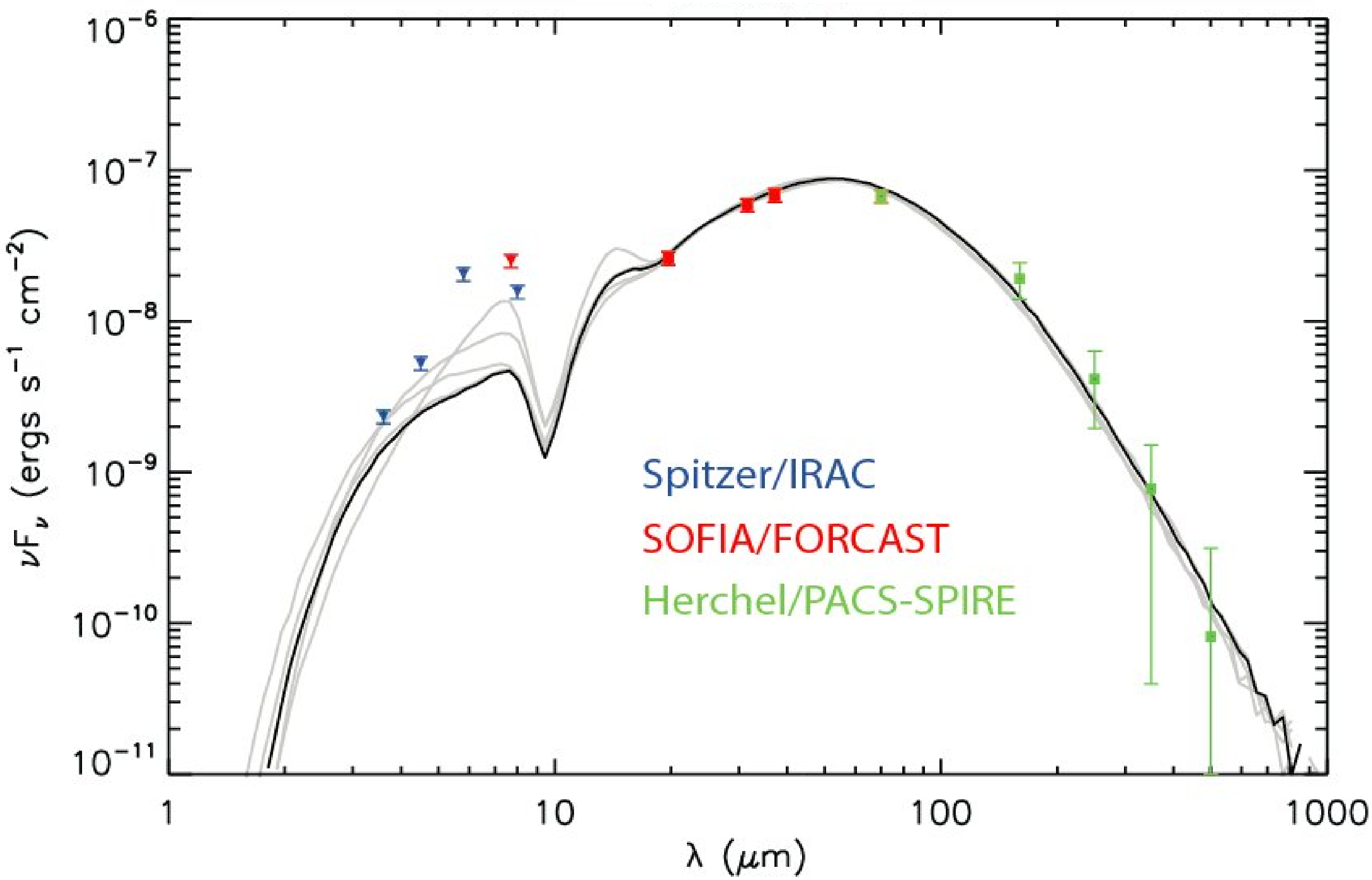
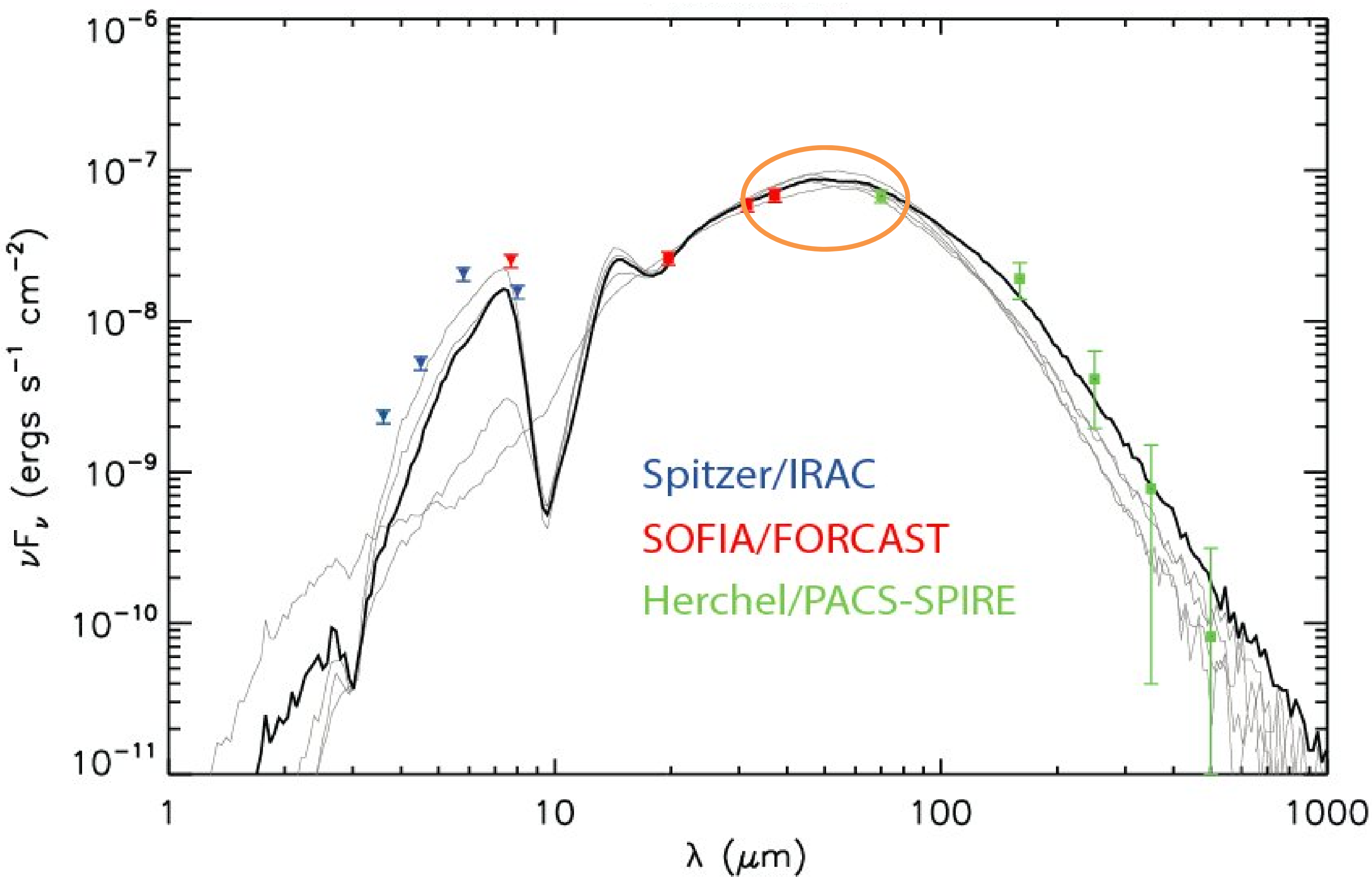
NGC 7538 IRS9



Robitialle Model

De Buizer et al. in press

NGC 7538 IRS9



Zhang & Tan Model

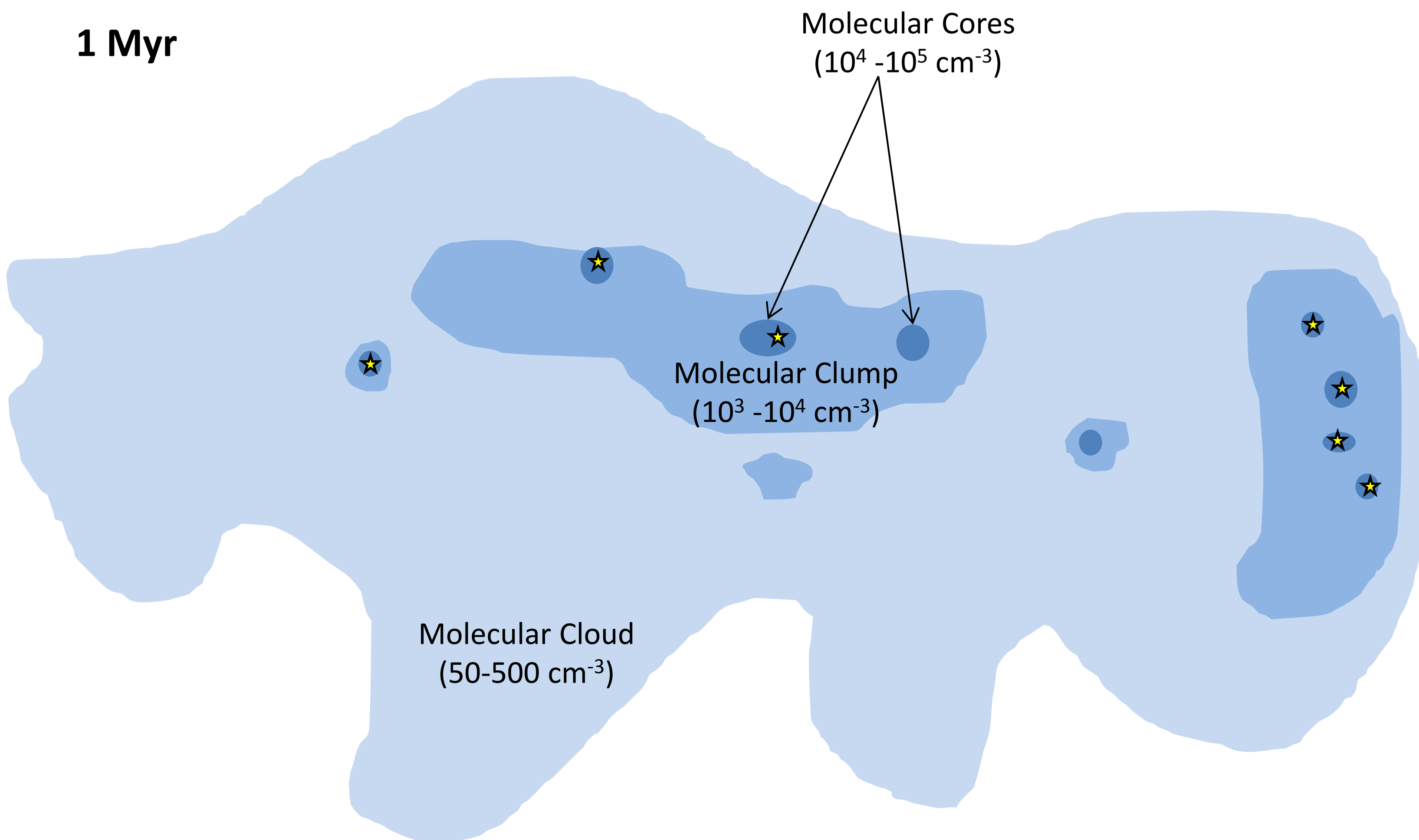
De Buizer et al. in press

Can SEDs be reasonably fit by ZT models?

- FORCAST 37μm and Herschel 70μm data crucial to constraining SED
- The Zhang & Tan models fits of all sources yield:
  - Protostellar masses between 10 – 30 M_{sun}
  - Accretion rates between 10^{-4} – 10^{-3} M_{sun}/yr
  - Initial core masses between 30 – 500 M_{sun}
  - Clump mass surface densities between 0.1 – 3 g/cm^2
- Robitaille et al. models typically lead to slightly higher protostellar masses, and disk accretion rates about 100x smaller

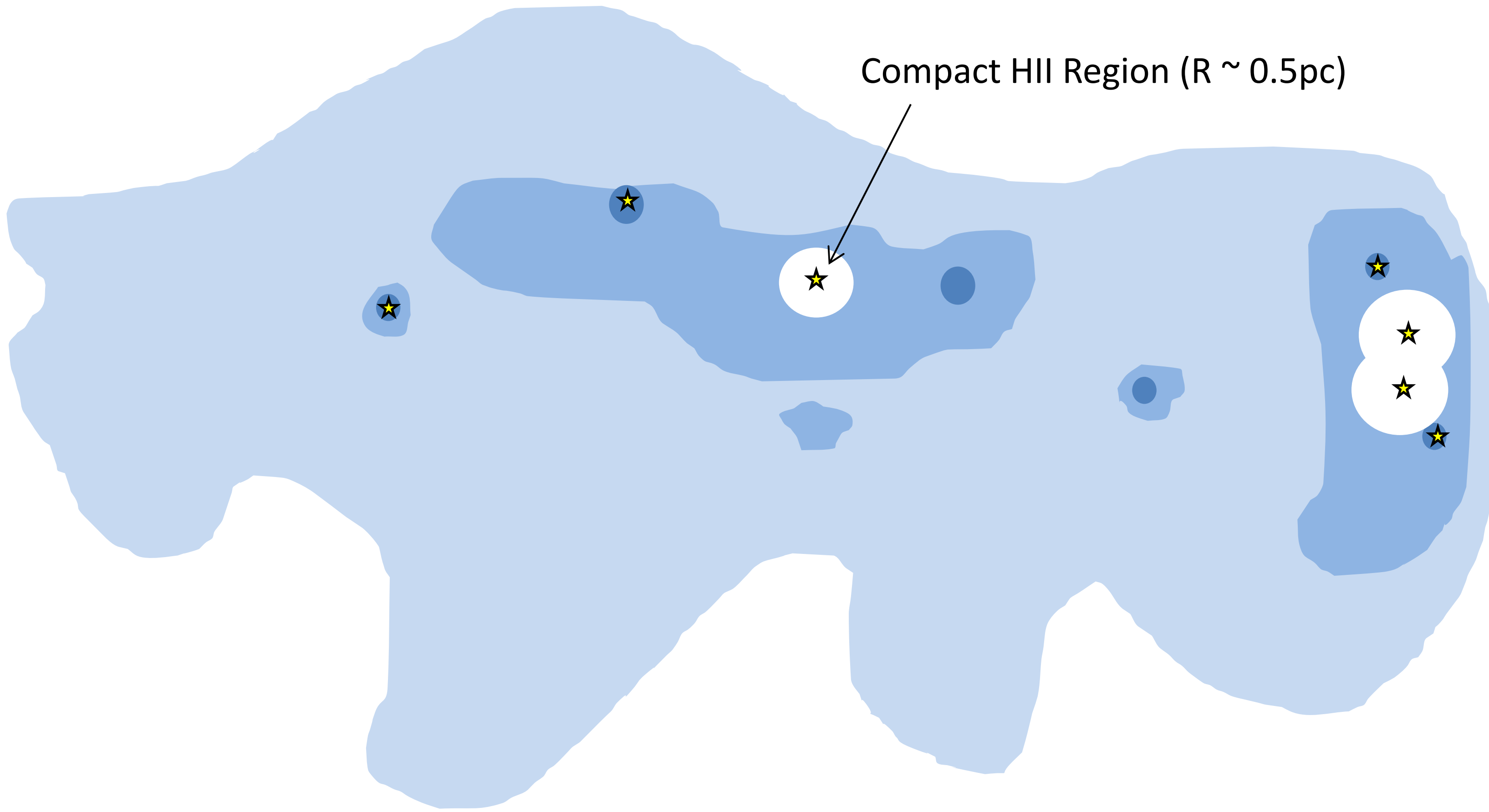
See Mengyao Liu's poster for more details

High-Mass Star Formation on **Large Scales**



Evolution of a Giant Molecular Cloud

2 Myr



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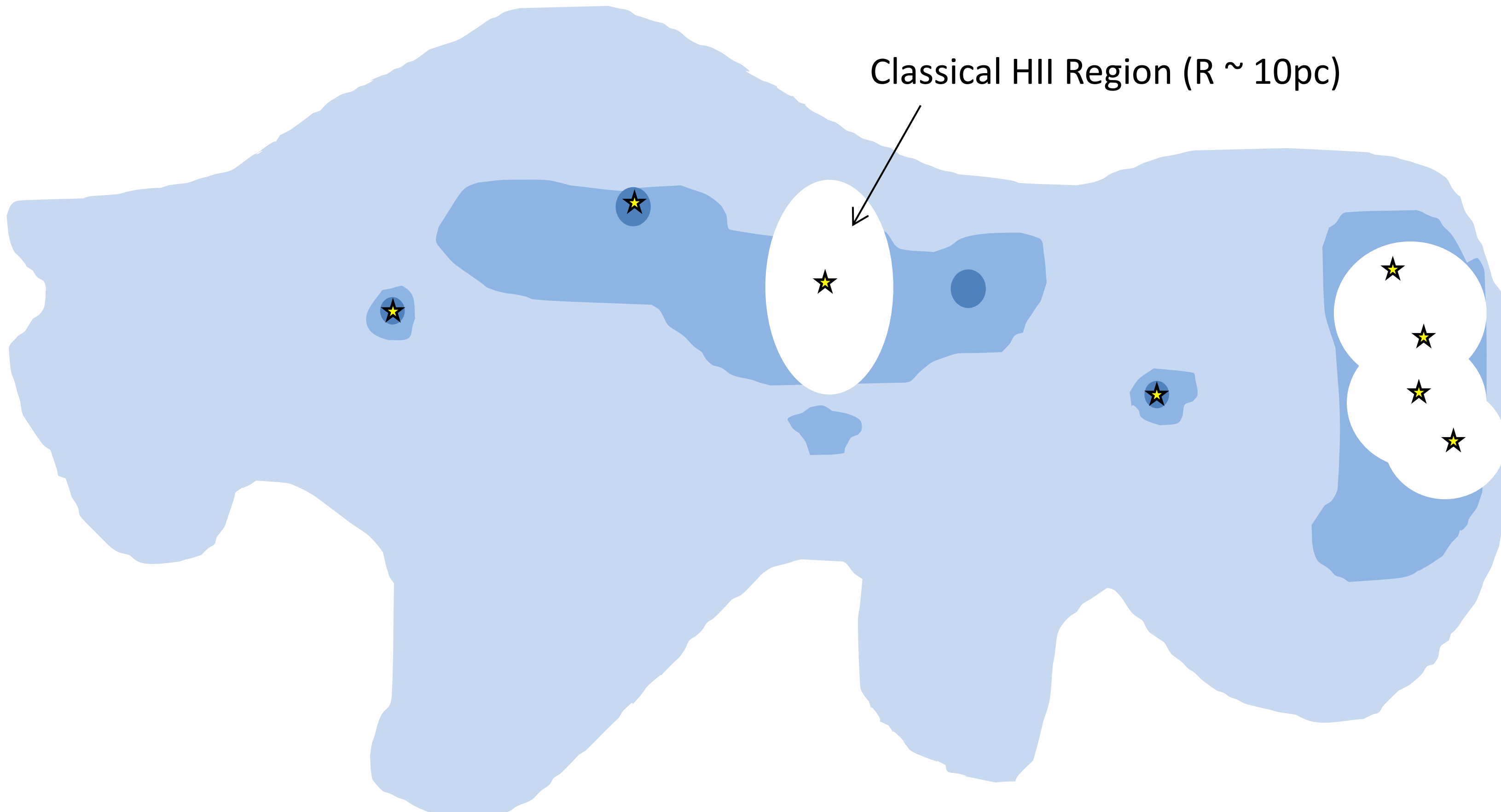

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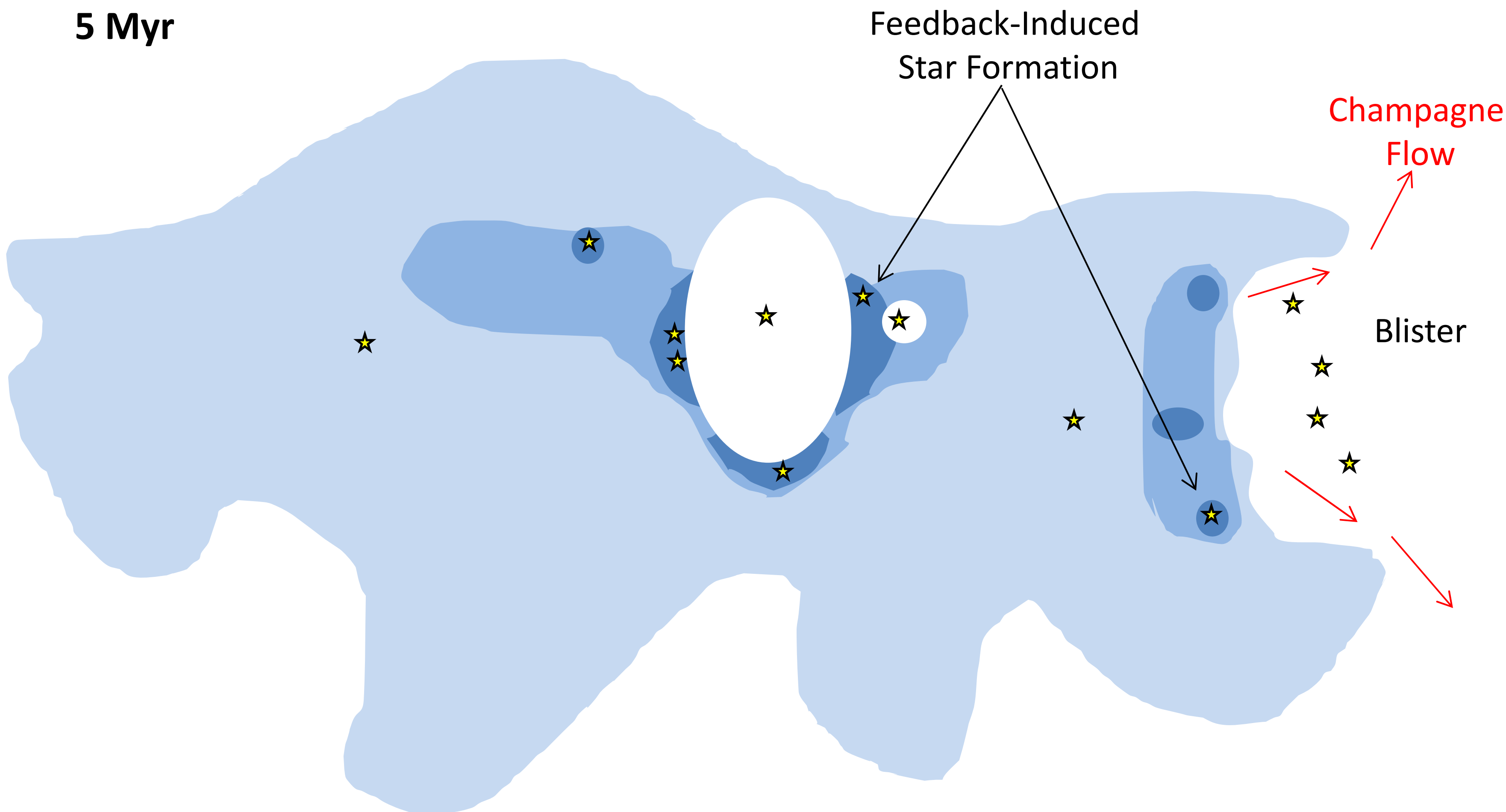

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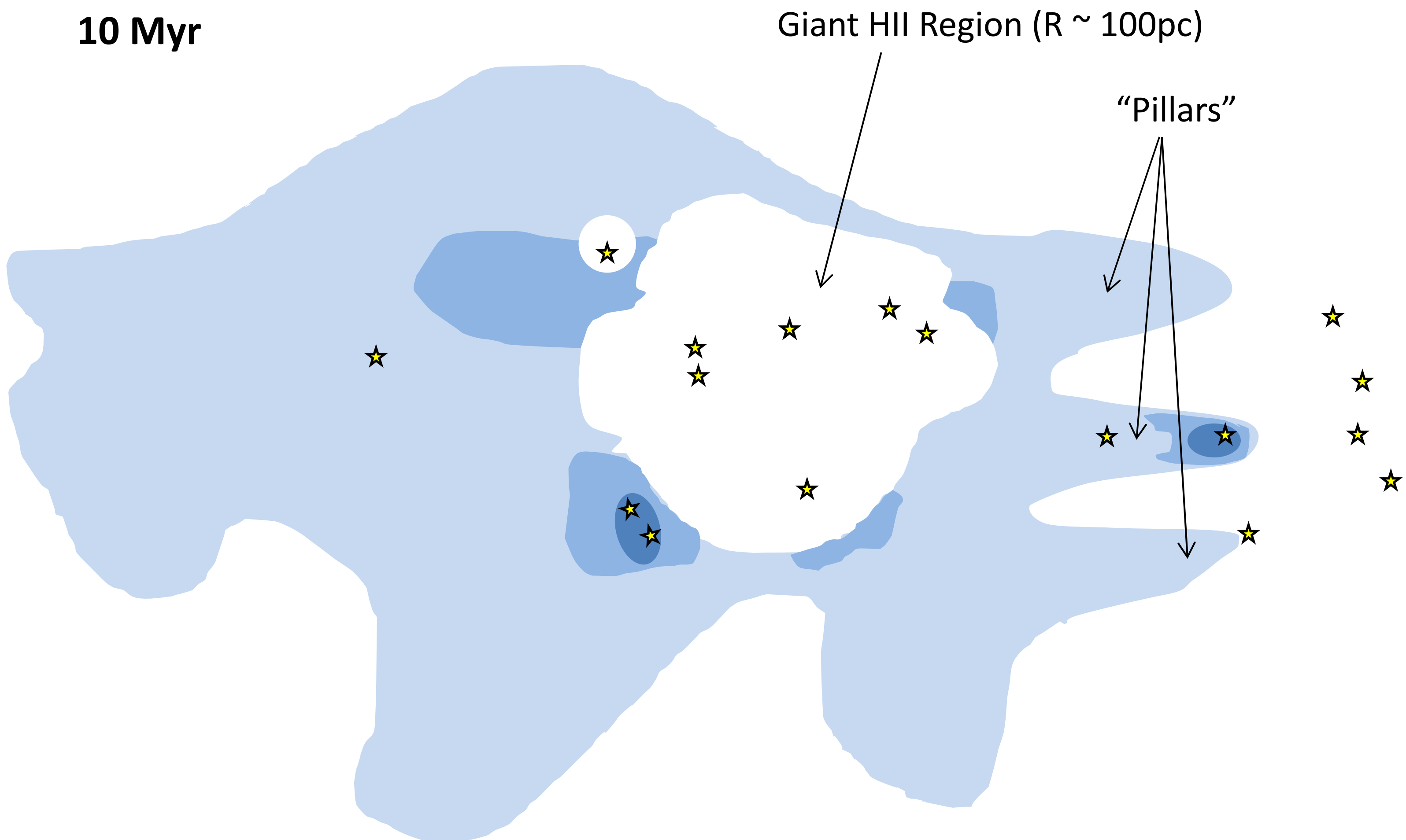


Evolution of a Giant Molecular Cloud

Imaging Galactic Giant HII regions with FORCAST

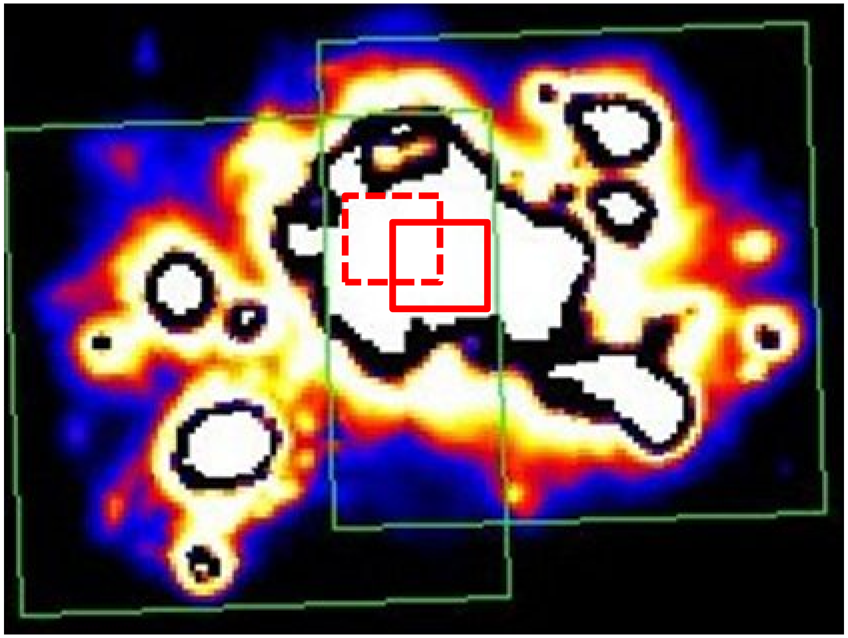
- Only 56 bona fide exist in our galaxy (Conti & Crowther 2004)
- Laboratories for extreme clustered star formation
- Analogs to “mini” star-burst regions in external galaxies
- Mostly Cycle 3 data; Preliminary results only

(i.e pretty picture time)

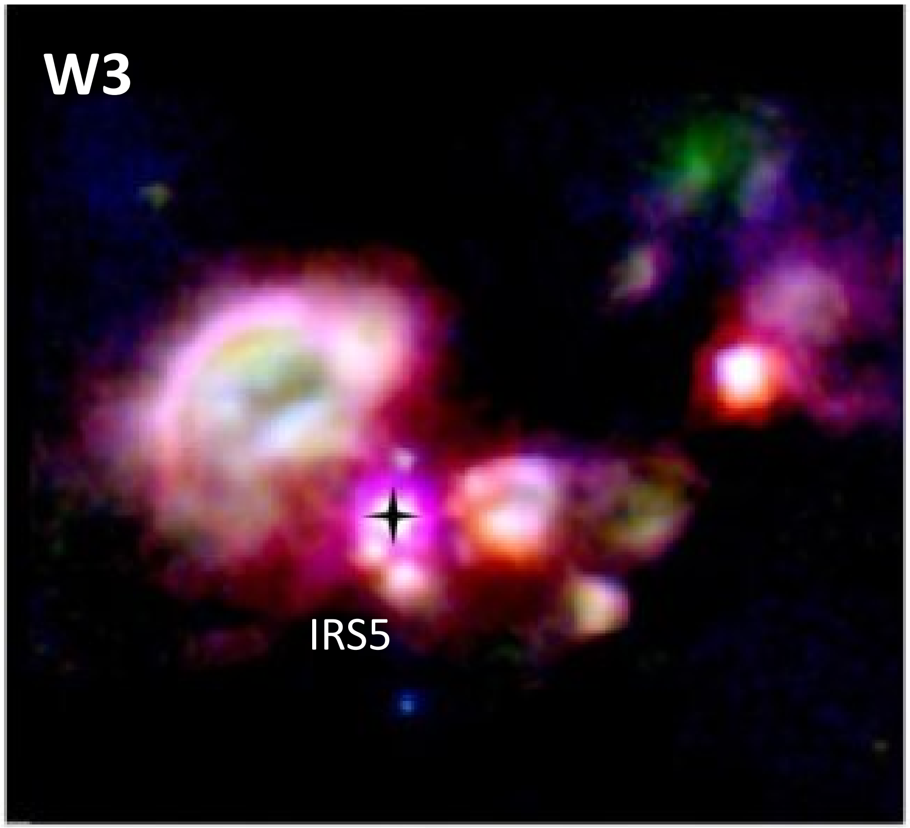
Spitzer - Credit: NASA, JPL/Caltech, and K. Gordon (STScI)

This is a unique dataset!

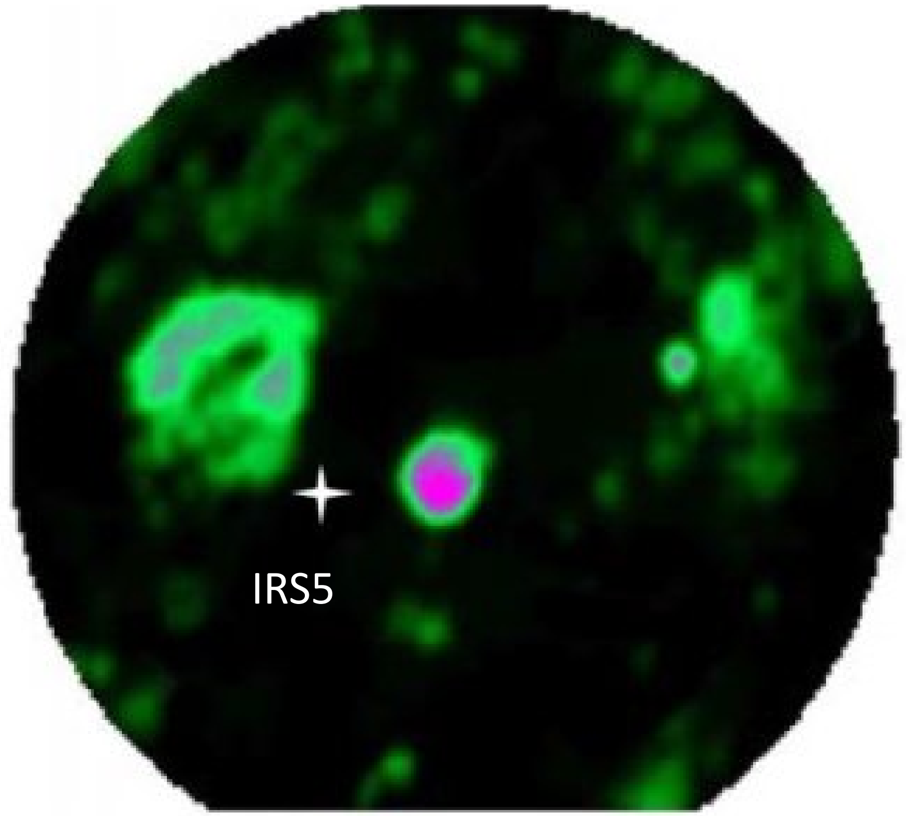
- Can’t image >25μm from ground
- Saturated in Spitzer data
- Even <25μm can’t be done on ground (can’t chop far enough)
- SOFIA enables best-ever resolution MIR images of these regions at λ>25μm



SOFIA can detect an embedded population of pre-UCHII sources



SOFIA 6µm, 19µm, 37µm



VLA 2cm

IRS5 L_{IR}= 500,000 L_{sun}

FORCAST Studies of High-Mass Star Formation on Small and Large Scales

- Small scales:
  - IR morphology seems to be highly dependent upon outflow cavity opening angle and orientation
  - New ZT Model fitting yields reasonable physical parameters
  - SOFIA wavelengths ≥25μm have proven to be extremely helpful (constraining SED and allowing us to see red-shifted outflow cavities)
- Large scales:
  - SOFIA and FORCAST facilitate observations of GHII regions unobservable by other means
  - Analysis just beginning, but beautiful and unique dataset
  - An embedded population of pre-UCHII sources can be studied where they are saturated in Spitzer data