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The SOMA Survey:

Probing massive star formation across Galactic environments

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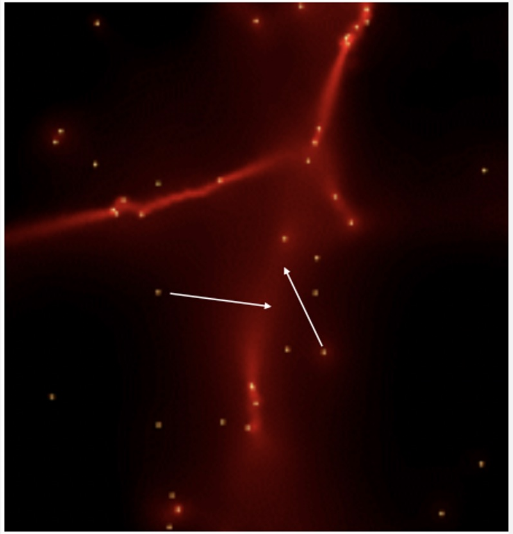
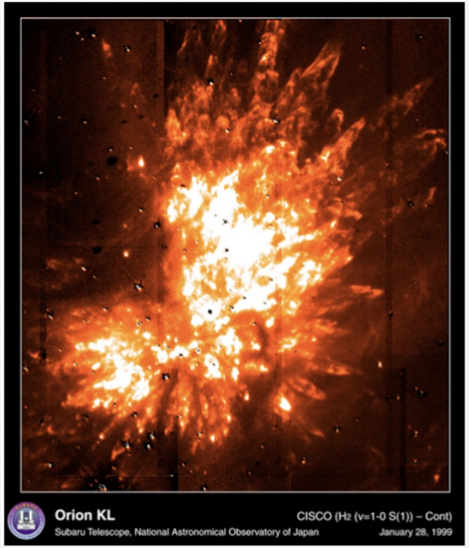
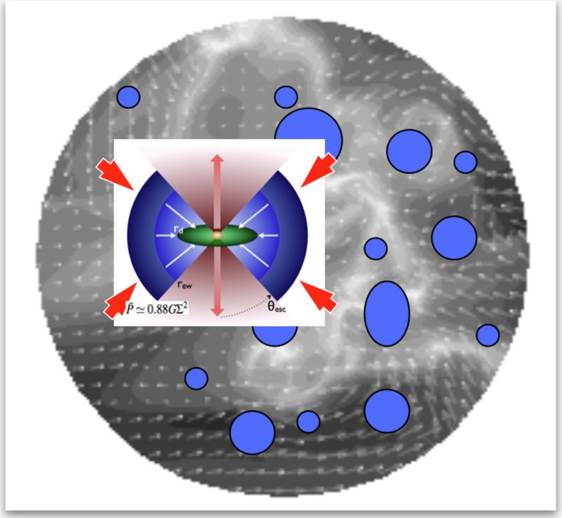
Massive Star Formation Theories







Competitive Accretion (e.g. Bonnell, Clarke, Bate, Pringle 2001; Grudić et al. 2022)

Protostellar Collisions (e.g. Bonnell, Bate & Zinnecker 1998; Bally & Zinnecker 2005; Bally et al. 2011)

Core Accretion (e.g. Myers & Fuller 1992; Caselli & Myers 1995; McLaughlin & Pudritz 1997; Osorio+ 1999; Nakano+ 2000; Behrend & Maeder 2001; McKee & Tan 2002)

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SOFIA Massive (SOMA) Star Formation Survey: Overview

- **SOMA Project Goal**: To observe ~50 protostars with *SOFIA*-FORCAST from 7-37 μm, with sources spanning a range of environments, evolutionary stages, and core masses, to test theoretical models of star formation
- **Paper I:** 8 massive protostars (De Buizer et al. 2017)
- **Paper II:** 7 high luminosity sources (Liu et al. 2019)
- **Paper III:** 14 intermediate mass protostars (Liu et al. 2020)
- **Paper IV:** 10 relatively isolated sources (Fedriani et al., in prep 2022)
- **Paper V:** 8 clustered regions (Telkamp et al., in prep 2022)

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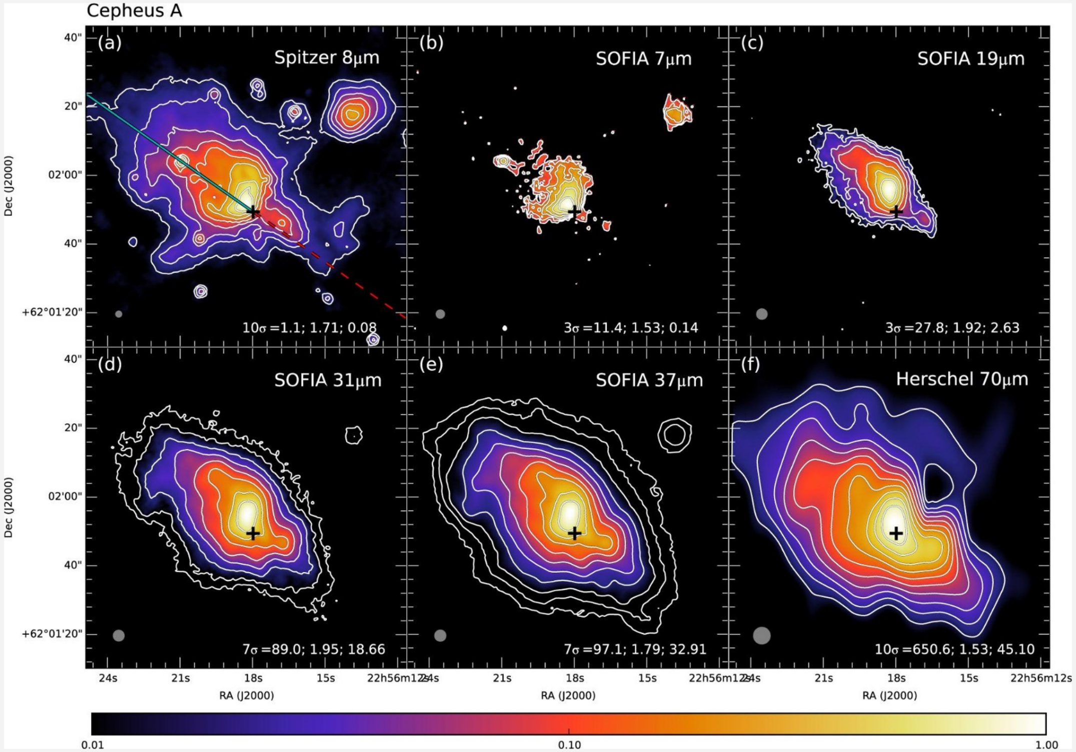
SOFIA Massive (SOMA) Star Formation Survey: Methods

- **Observations:** *SOFIA*-FORCAST 7, 19, 31, 37 μm data, along with *Spitzer* 3.6-8.0 μm and *Herschel* 70-500 μm archival data
- **RGB images** constructed using SOFIA data enable examination of image morphologies + testing of Turbulent Core Accretion model predictions
- **Spectral Energy Distributions (SEDs)** are built by performing aperture photometry on images to measure flux densities



De Buizer et al. 2017

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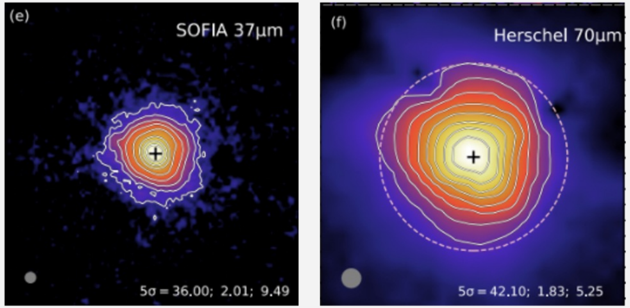
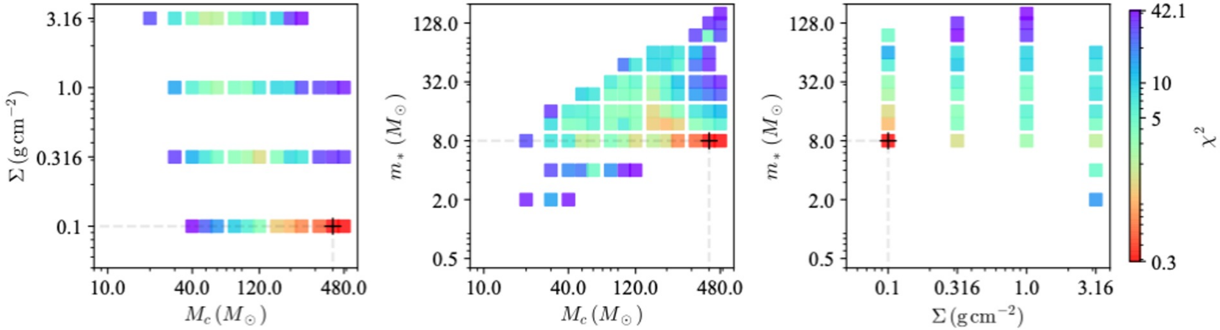
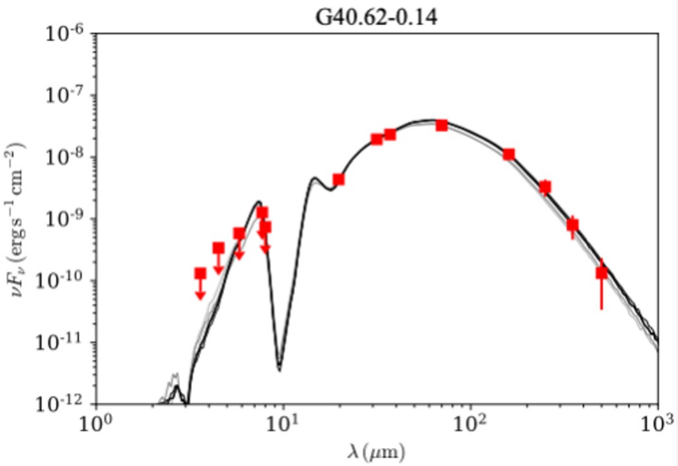
SOFIA Massive (SOMA) Star Formation Survey: Methods







- **Zhang and Tan (ZT) Radiative Transfer Models:**
  - Based on the Turbulent Core Accretion model
  - Three main free parameters (M_c, Σ_{cl}, m_*), two secondary parameters (Θ_{view}, A_V)
- **SED Fitting**: Use χ^2 minimization to fit the grid of models to the observations and consider the best-fitting models

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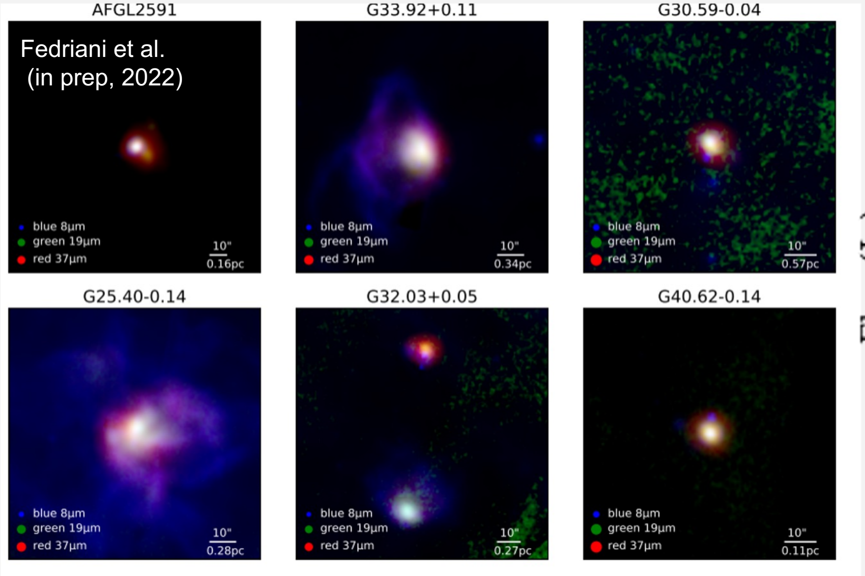
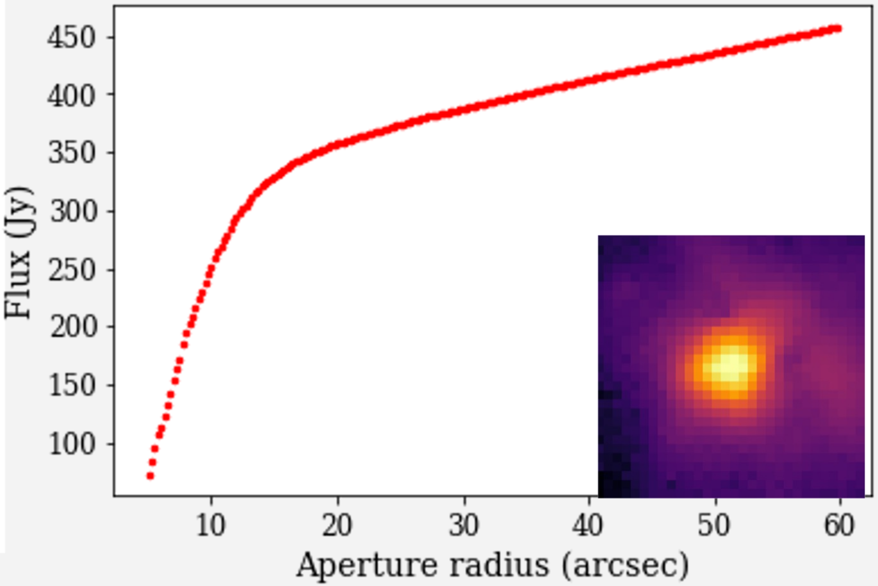
SOMA IV: Isolated Sources and New Methods





Introduces…

- Algorithm to automatically select aperture radii
- Sedcreator Python package for automated aperture photometry and SED fitting
- Averaging of best-fit models to account for degeneracies in SED fitting results

Re-analyzes SOMA I-III sources with new methods

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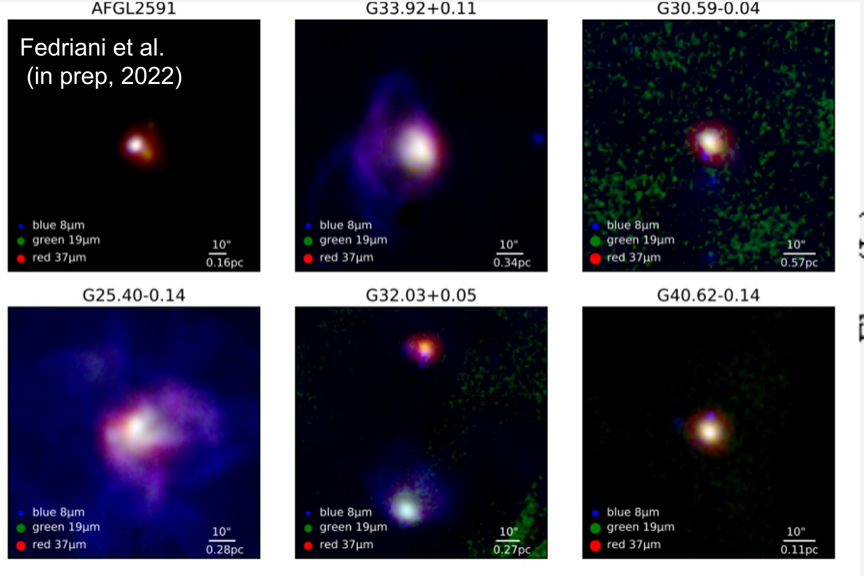

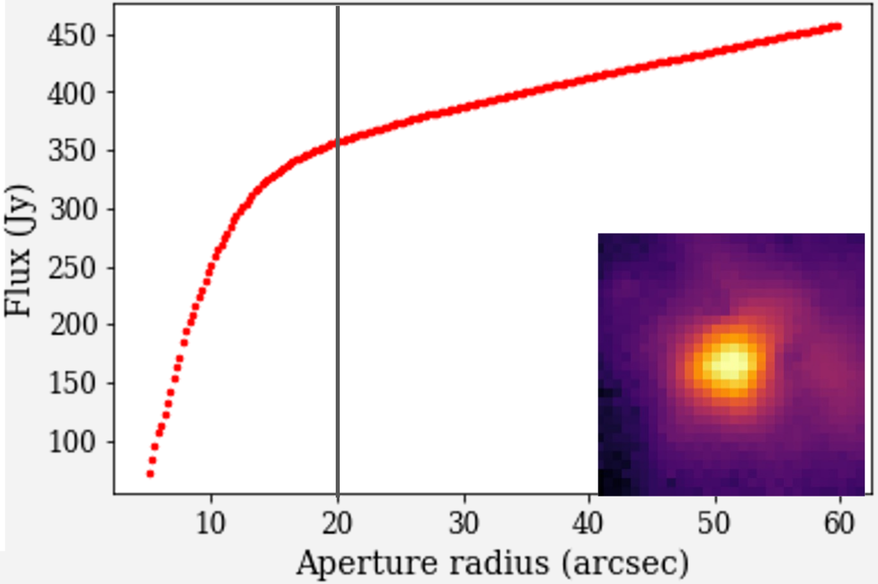

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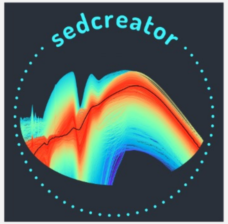
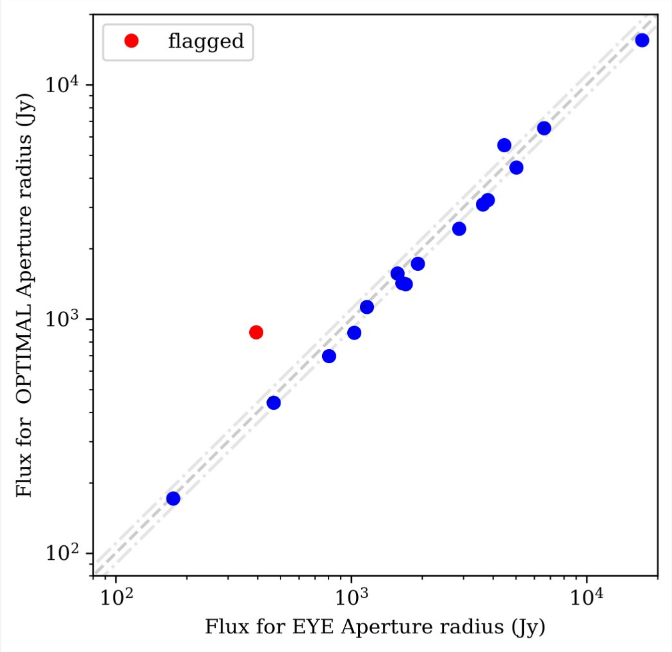
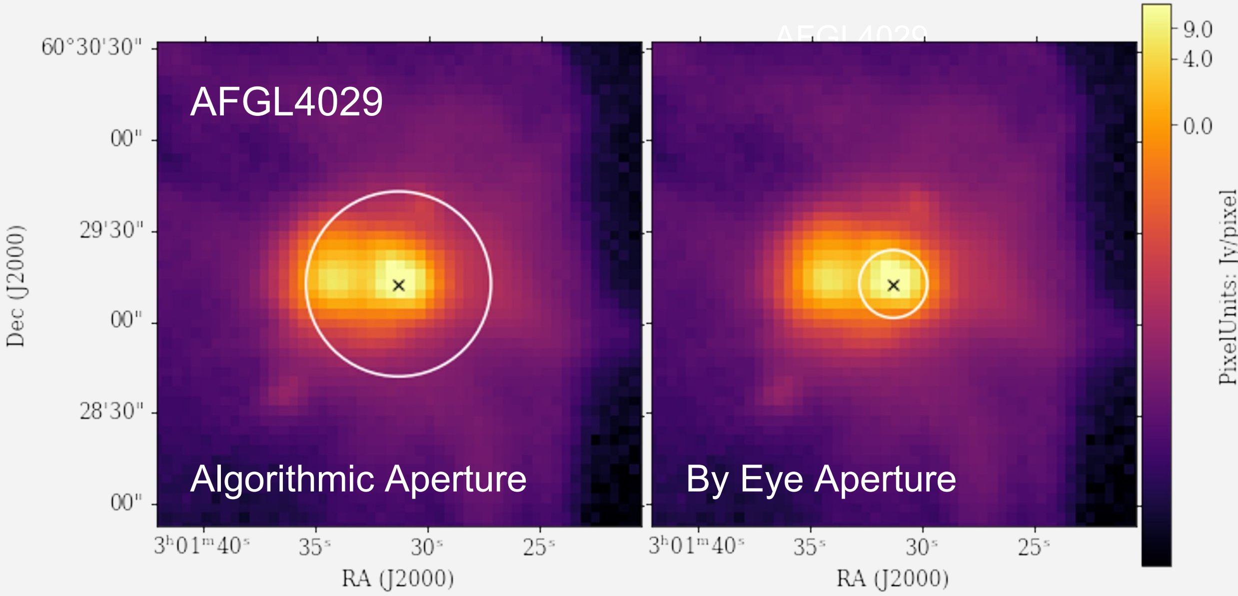


Comparing Algorithmic to By-Eye Results





- Flux measurements are typically within ~10% when using the “optimal” radius v.s. choosing aperture radius by eye
- Algorithm returns radii that are too large in crowded regions

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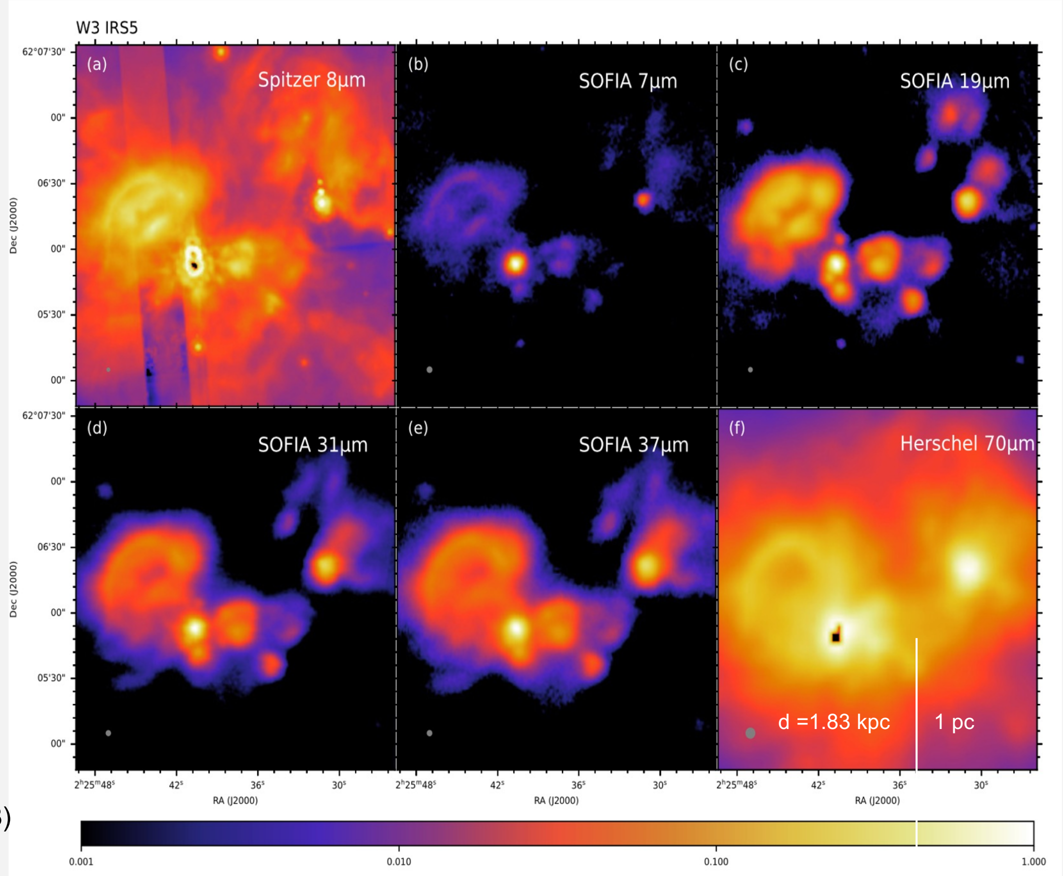
SOMA V: Clustered Environments

- Presents 8 clustered regions, each one with multiple sources
- Adds ~**30-40** sources to the SOMA survey, providing better constraints on environmental trends of massive star formation
- Presents **automated aperture radius selection** algorithm for crowded regions



W3 IRS5: Protostellar number density of ~ 10^6 pc^{-3} (Rodón et al. 2008)

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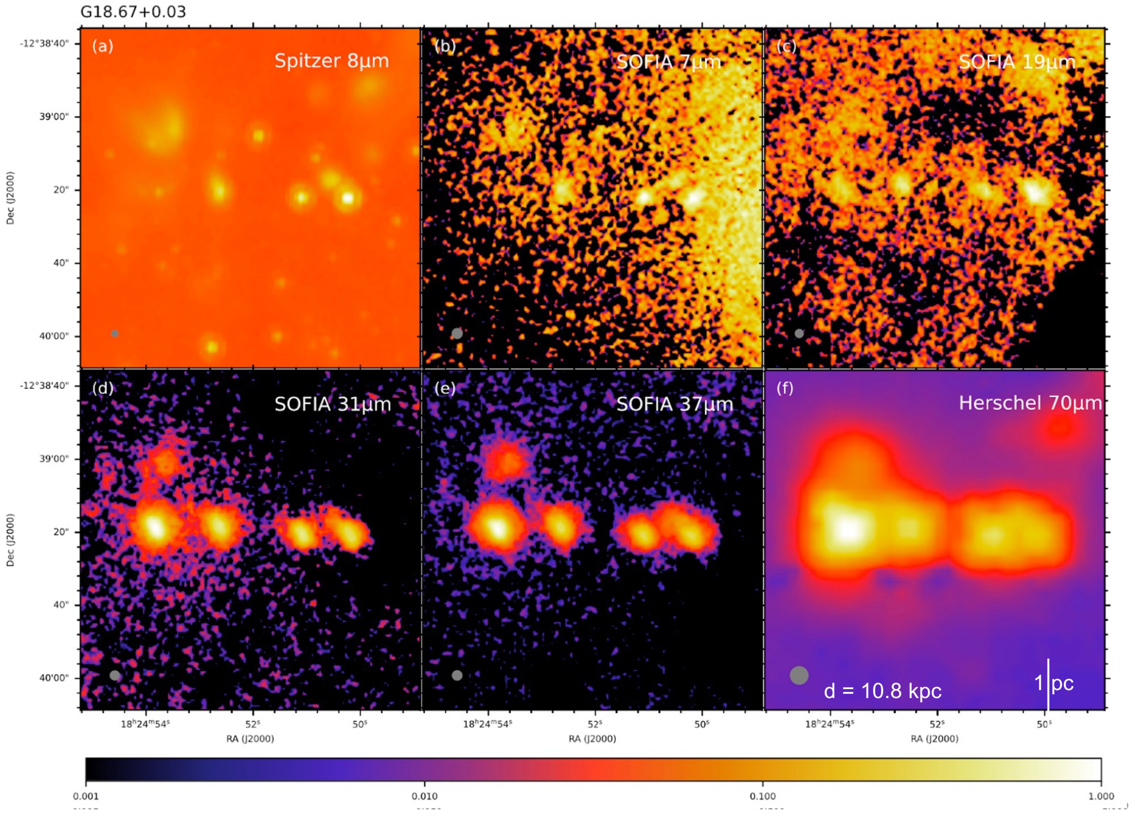
SOMA V: Clustered Environments

Automated aperture radius selection in crowded regions:

- Iteratively cycles through sources and calculates "optimal" radii
- Excludes flux that belongs to another source when determining the optimal aperture radius of a target



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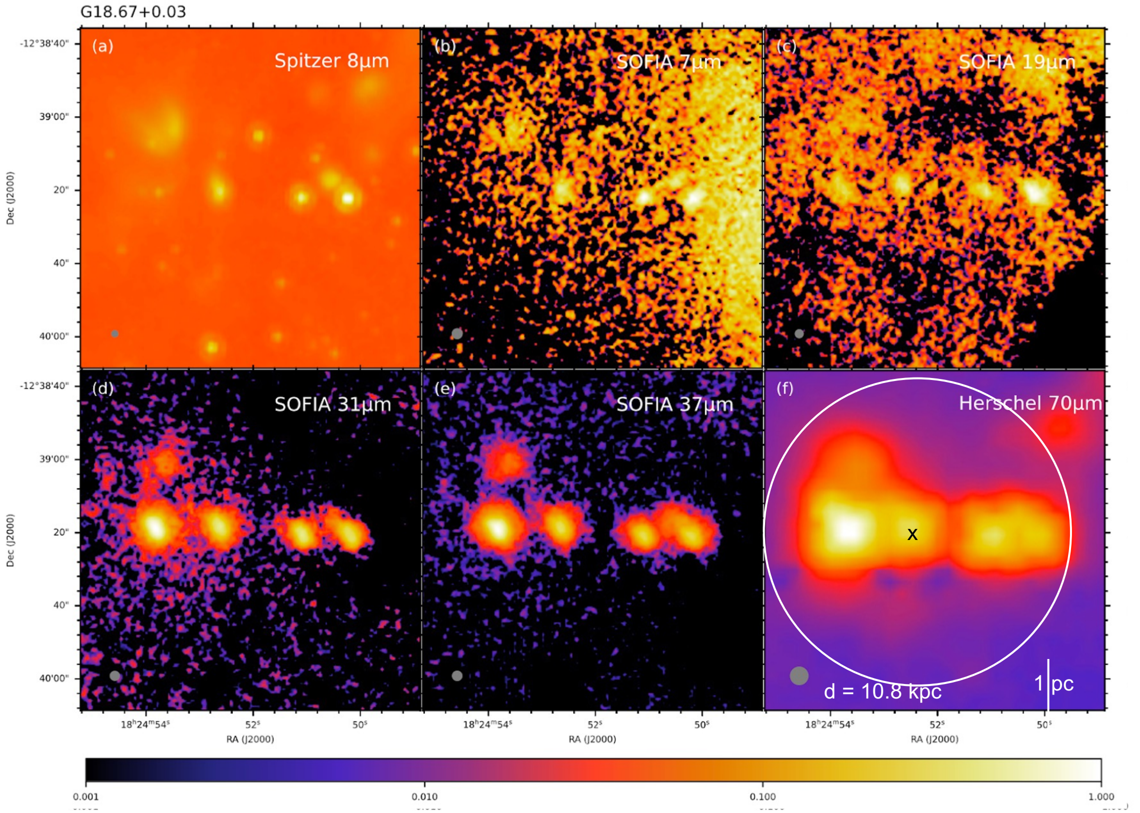

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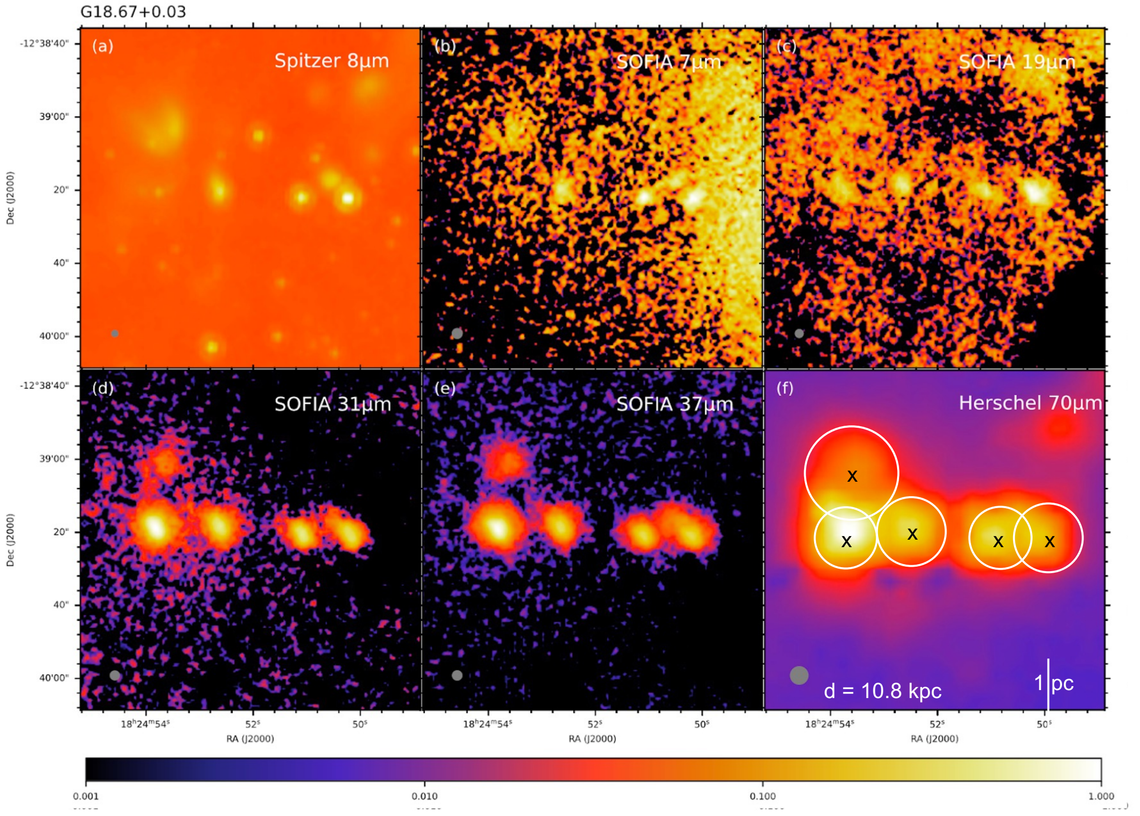

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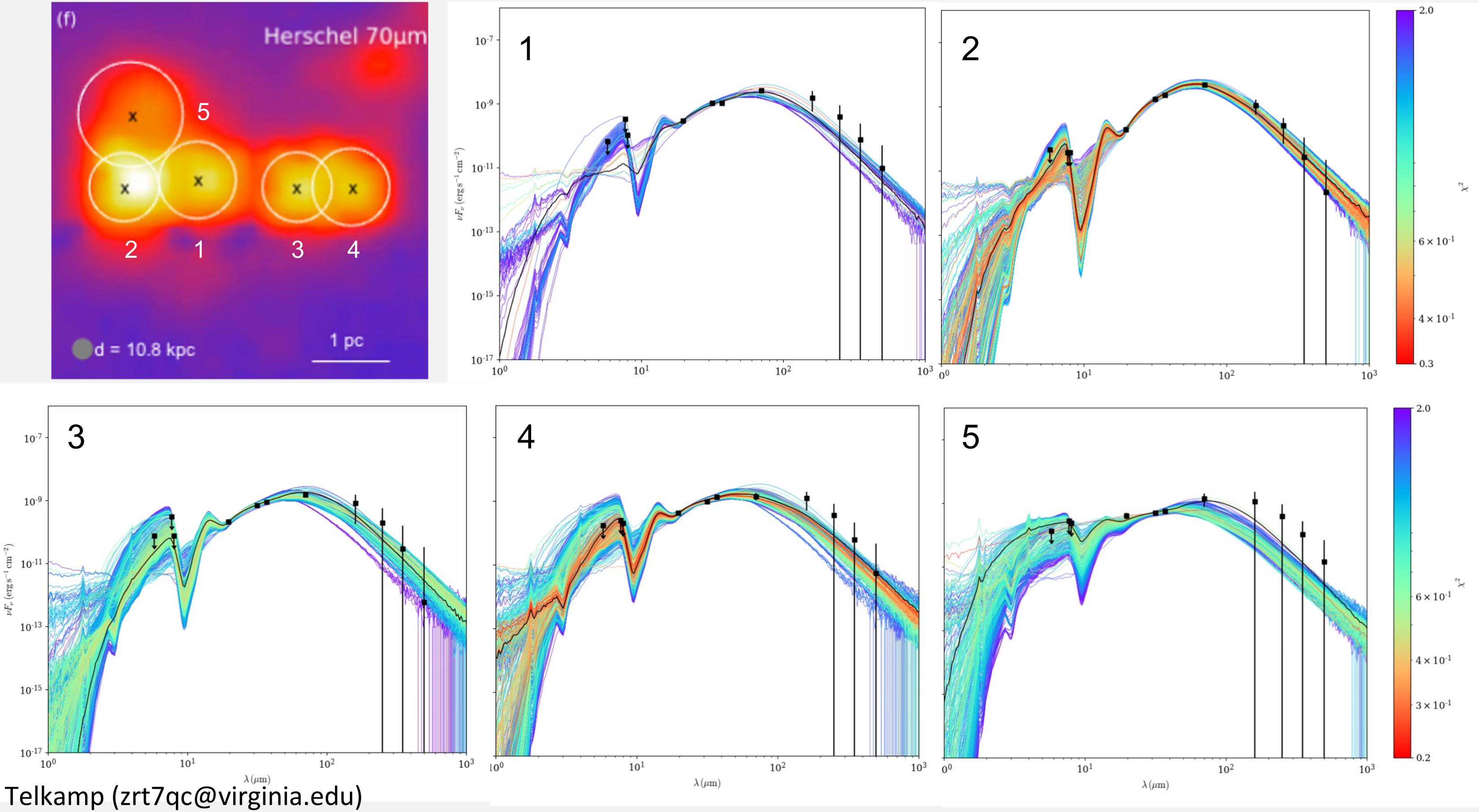
Results from SOMA I-V…

Results for Clustered Region G18.67



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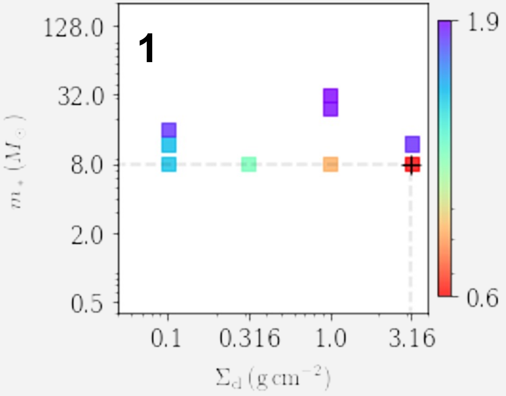
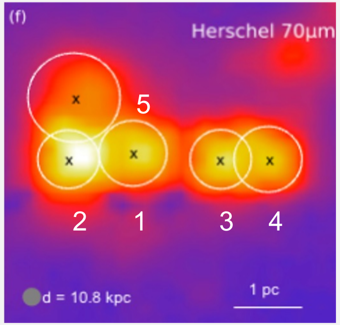
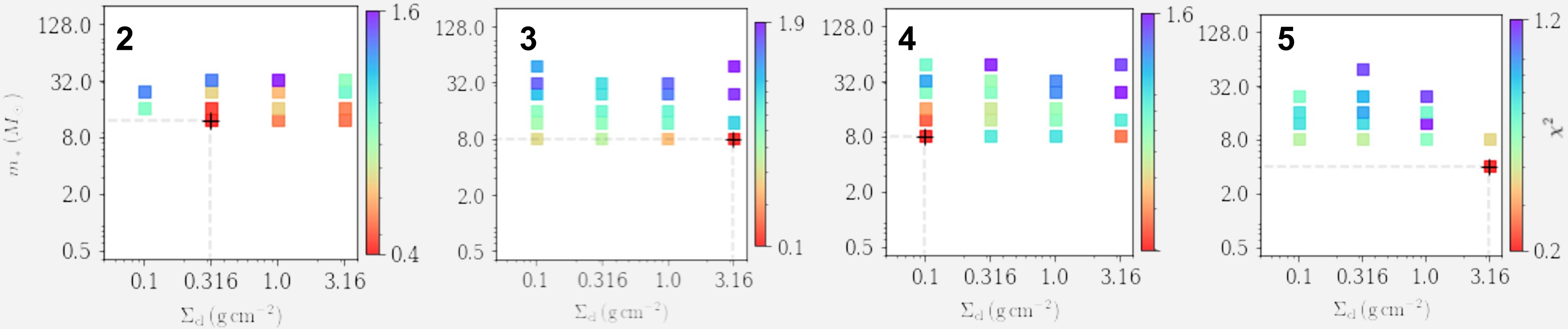
Results for Clustered Region G18.67

- Four 8 M_{sun} stars forming in a "line"
- One lower luminosity, 4 M_{sun} source
- Most sources display similar Σ_{cl} (all have low χ^2 fits at Σ_{cl} = 3.16 g/cm²)







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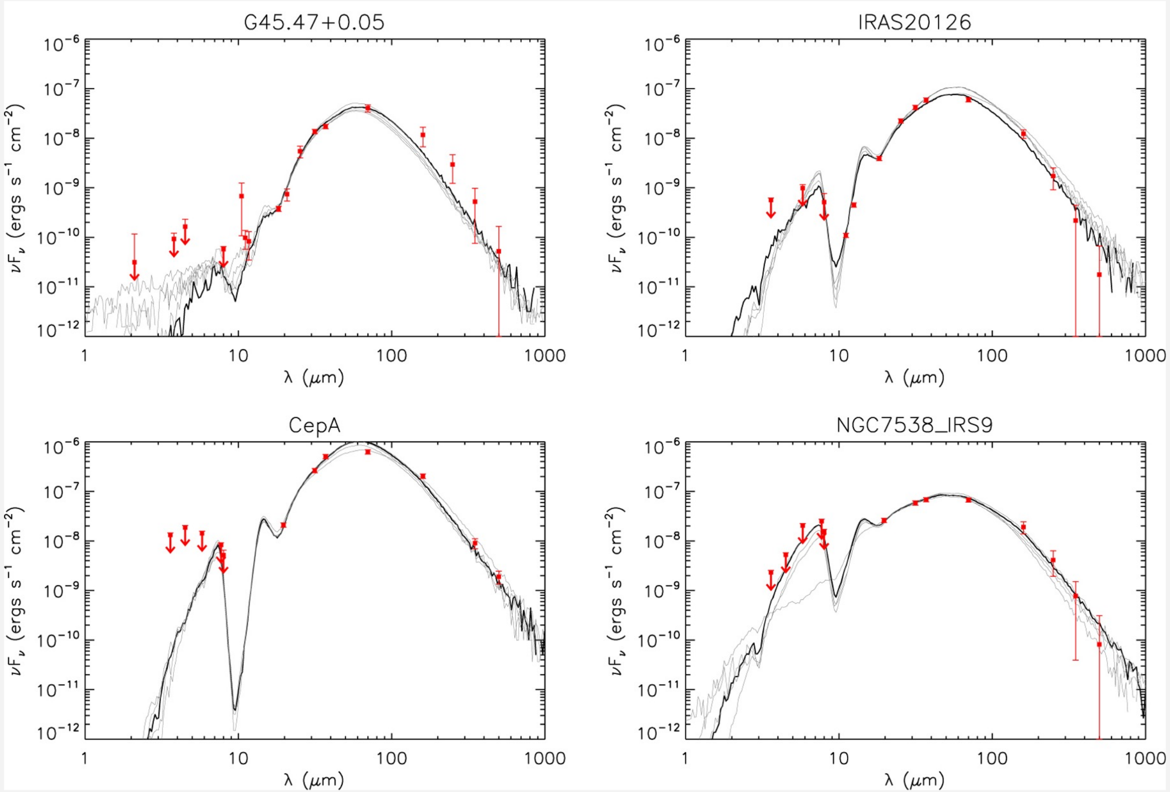
SOMA I-IV SED Fitting Results

- Reasonable fits found for most sources
- Some degeneracies present when using only MIR to FIR SEDs to drive protostellar properties
- Some degeneracies can be broken using internal self-consistency checks and external observations



De Buizer et al. 2017

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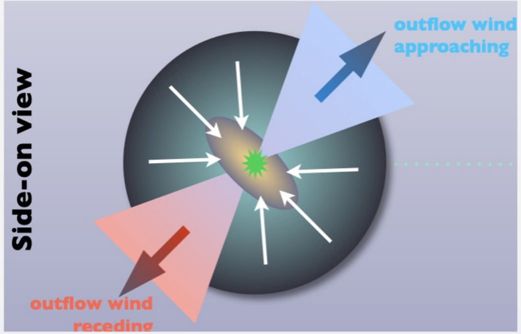
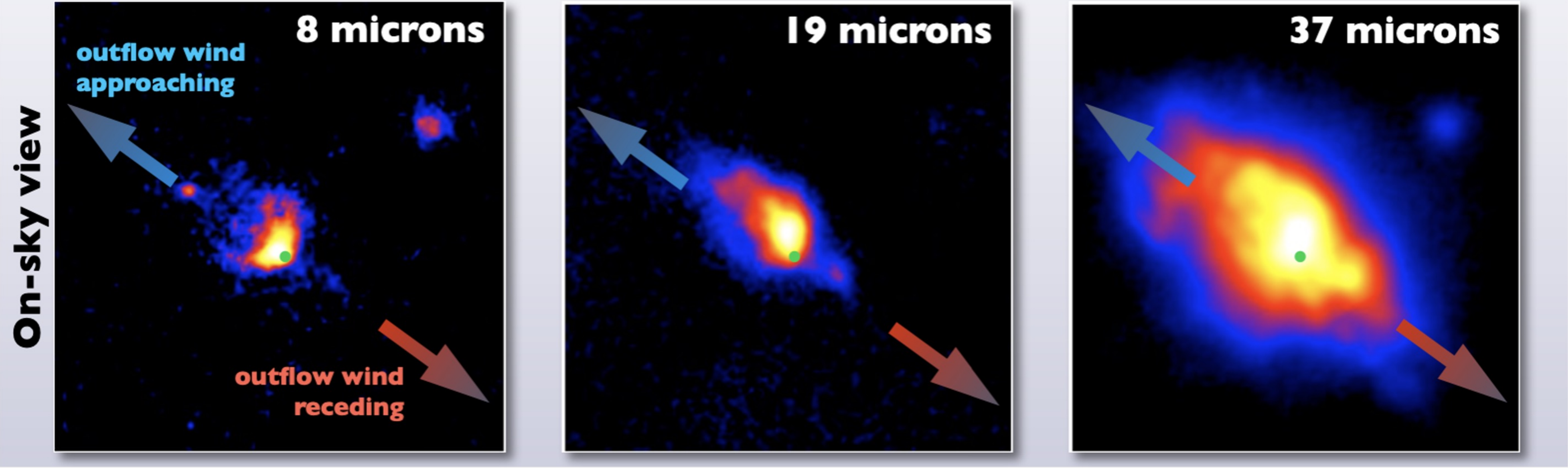
SOMA I-IV SOFIA Imaging Results

- Shorter wavelengths point to blueshifted outflow cavities, as predicted by the Turbulent Core Accretion model

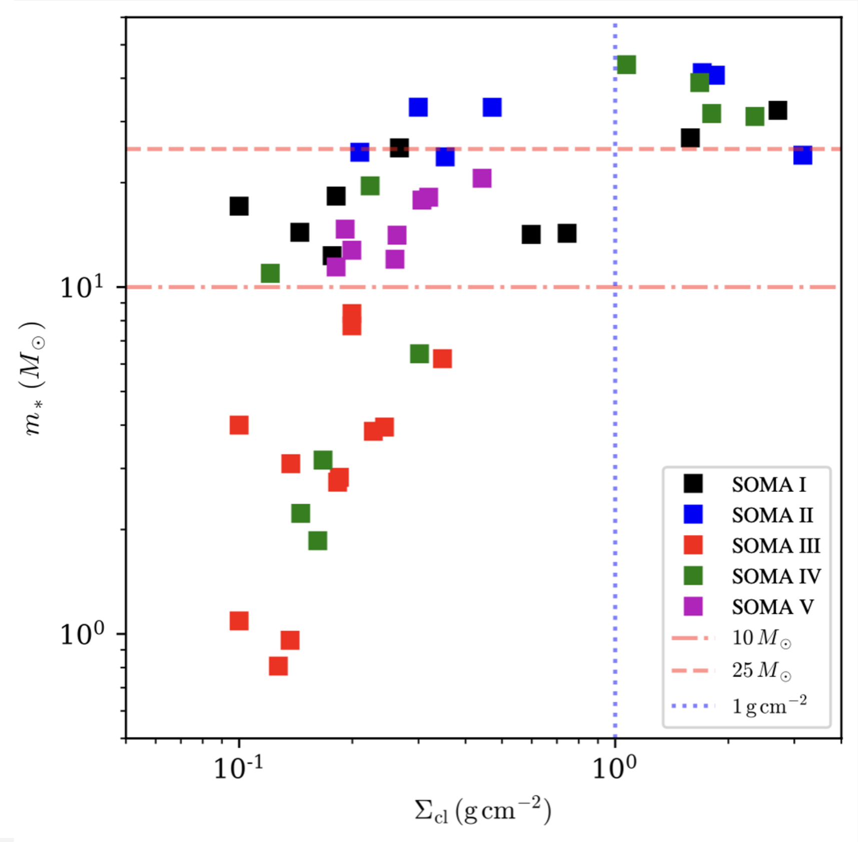


Cepheus A



Spectral Energy Distribution Fitting Results

- SOMA data is inconsistent with the Krumholz & McKee (2008) prediction that 10 M_{sun} stars require $\Sigma_{cl} > 0.3$ g cm^{-2} to form
- The most massive ($\gtrsim$25 M_{sun}) stars are predicted to form more efficiently in $\Sigma_{cl} \gtrsim 1$ g cm^{-2} protostellar clump environments
- This is indicative of special conditions needed to form massive stars, consistent with the Turbulent Core Accretion model



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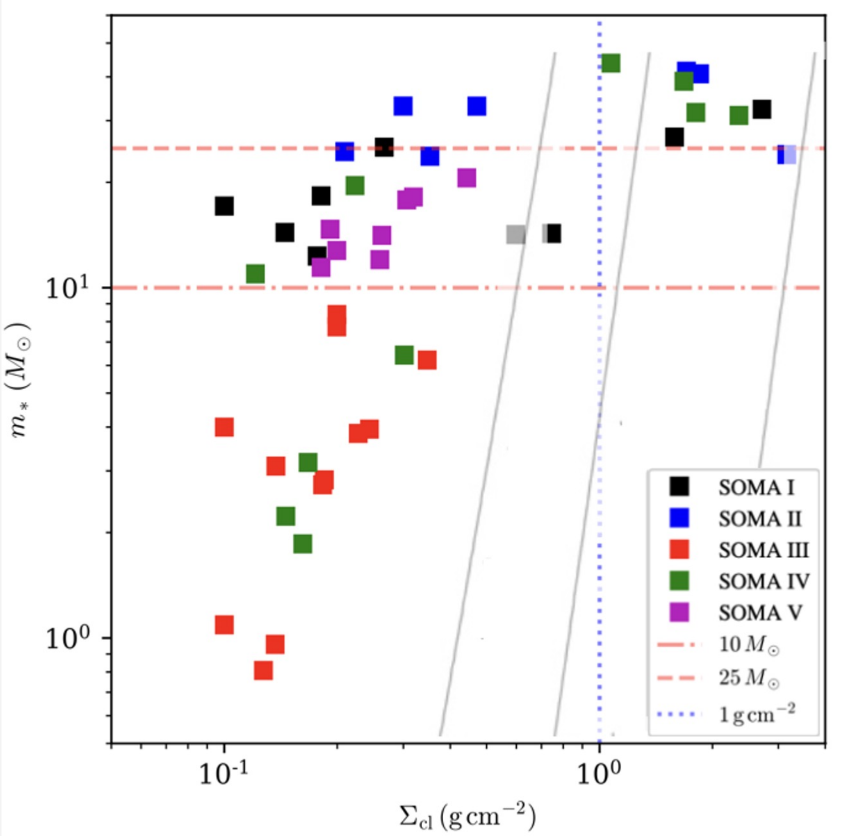

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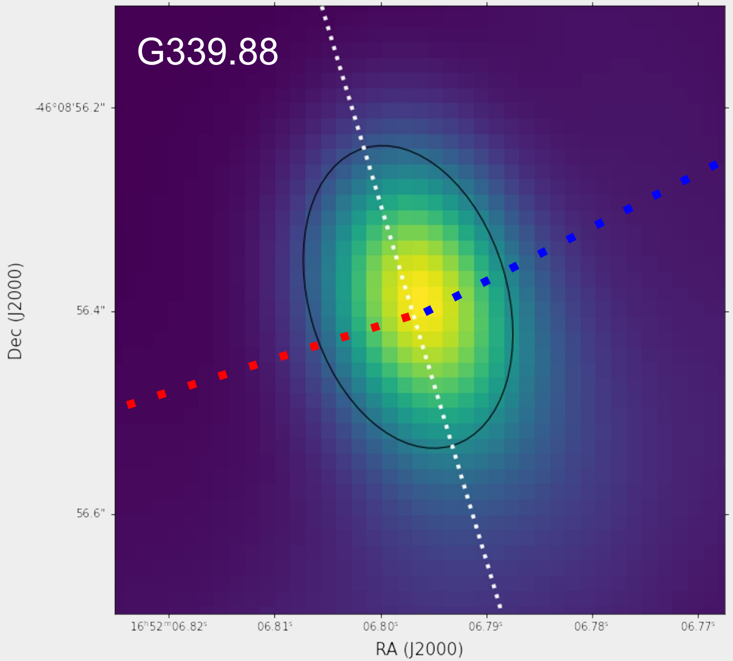
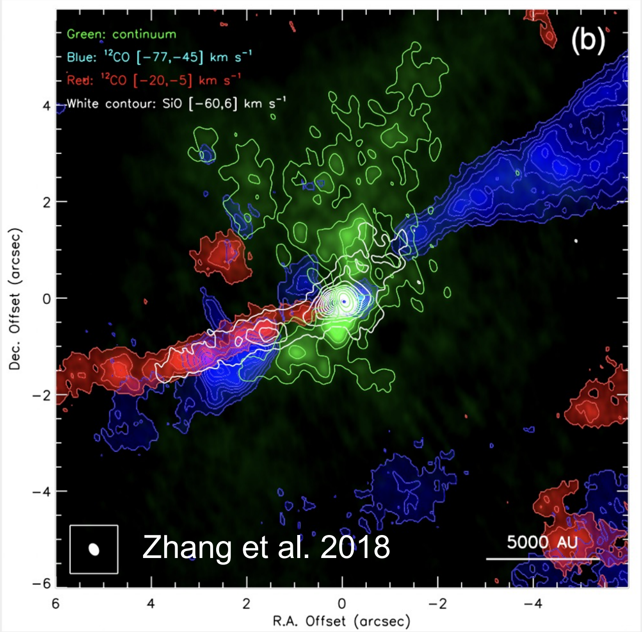
Using ALMA Archival Data to Probe the Disk Scale





- Use high-resolution continuum long-baseline ALMA archival data to measure fluxes within ~100 AU and probe the disk scale
- Fit 2D Gaussians to estimate projected disk orientations

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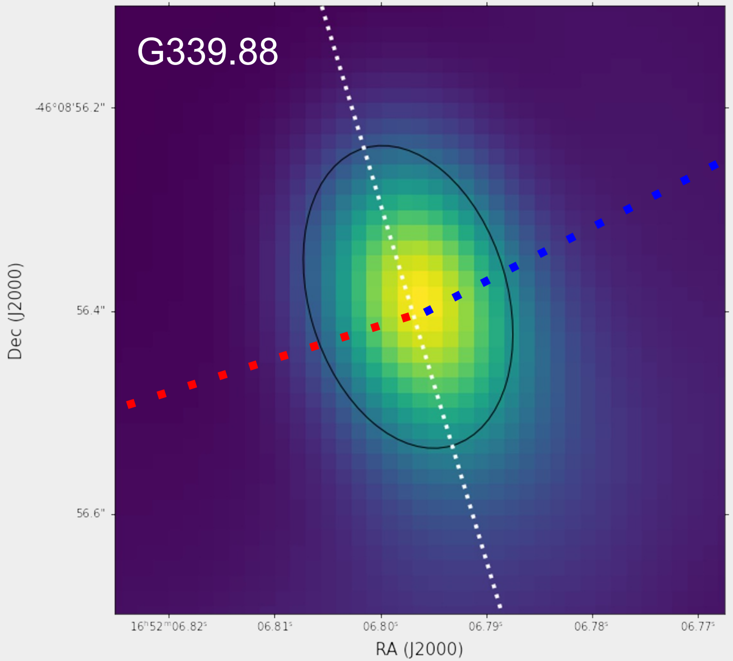
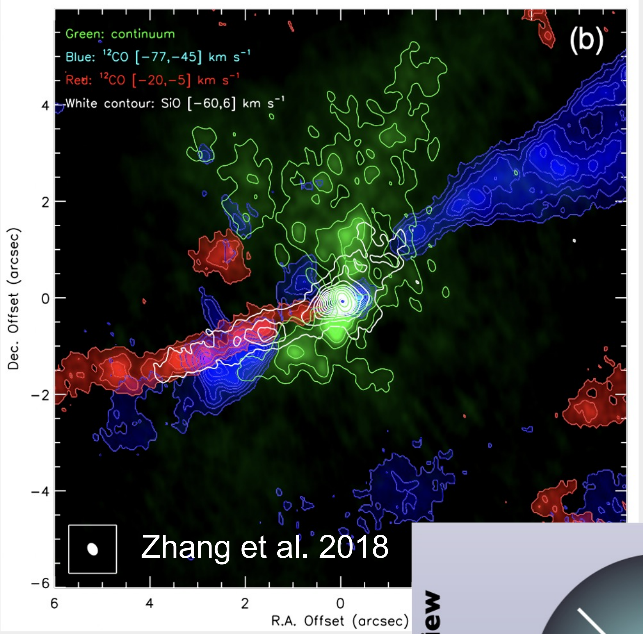
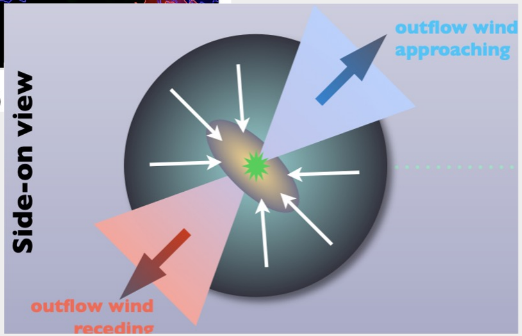
Using ALMA Archival Data to Probe the Disk Scale







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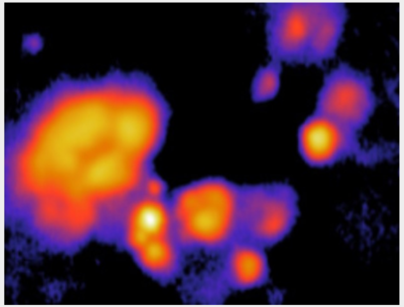
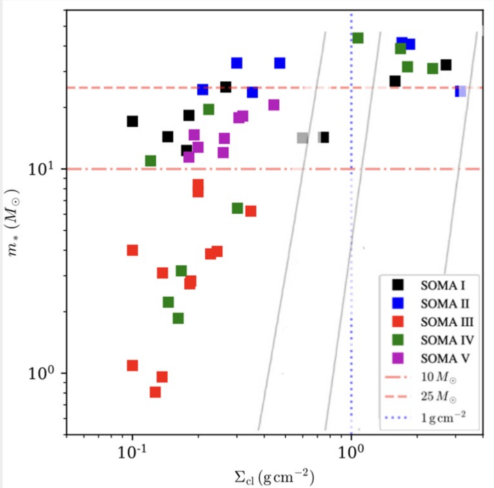
Summary and Conclusions





- The SOMA survey has uniformly observed ~50 protostars with ***SOFIA*-FORCAST** spanning a range of core masses, evolutionary stages, and environments
- SOMA I-IV show that we can fit the SEDs with the ZT radiative transfer models, based on the Turbulent Core Accretion model, with some degeneracies
- Some models, such as the Krumholz & McKee (2008) model, are challenged by the initial SOMA results
- SOMA V (Telkamp et al., in prep. 2022) will…
  - Roughly double the size of the SOMA survey
  - Present new algorithms for protostellar analysis in clustered environments
  - Enable detailed exploration of how massive stars form in clustered environments

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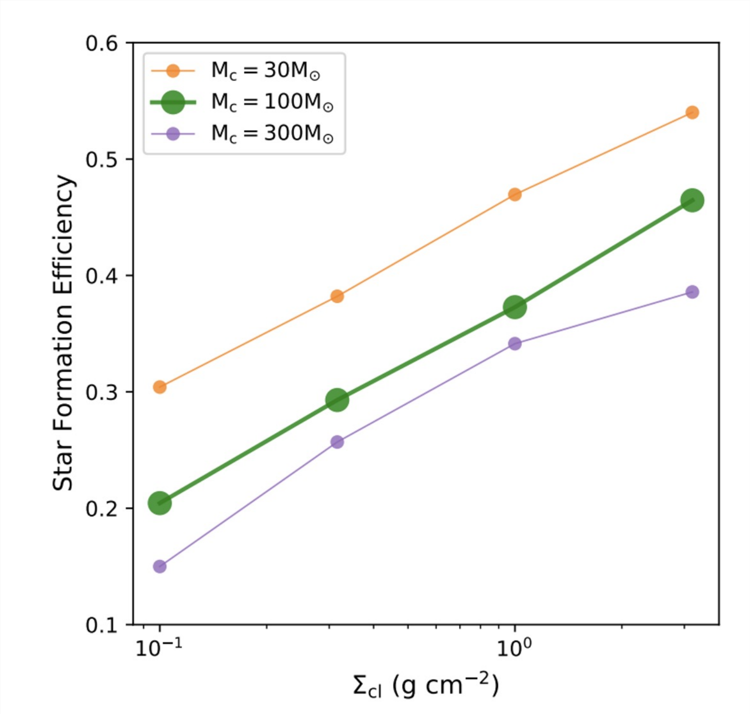
Extra Slides



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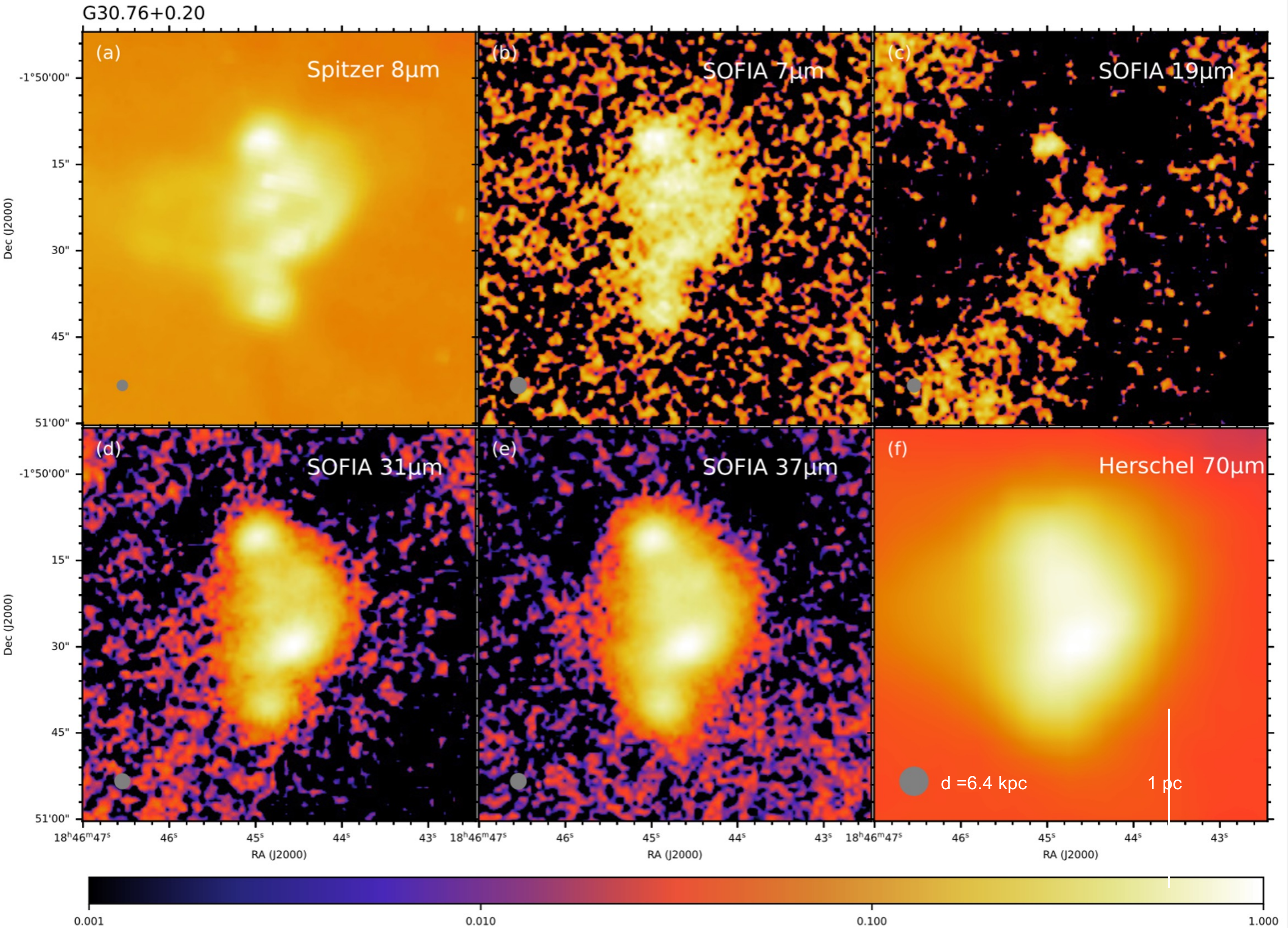
G30.76+0.20
(a)
Spitzer 8μm
(b)
SOFIA 7μm
(c)
SOFIA 19μm
(d)
SOFIA 31μm
(e)
SOFIA 37μm
(f)
Herschel 70μm
d =6.4 kpc
1 pc
Dec (J2000)
-1°50'00"
15"
30"
45"
51'00"
RA (J2000)
18h46m47s
46s
45s
44s
43s
0.001
0.010
0.100
1.000

χ^2 Metric (Zhang & Tan

$$\chi^2 = \frac{1}{N_{\text{total}}} \left\{ \sum_{F_{\nu,\text{mod,ext}} > F_{\nu,\text{fit}}} \left[\frac{\log F_{\nu,\text{mod,ext}} - \log F_{\nu,\text{fit}}}{\sigma_u(\log F_{\nu,\text{fit}})} \right]^2 + \sum_{F_{\nu,\text{mod,ext}} < F_{\nu,\text{fit}}} \left[\frac{\log F_{\nu,\text{mod,ext}} - \log F_{\nu,\text{fit}}}{\sigma_l(\log F_{\nu,\text{fit}})} \right]^2 \right\},$$

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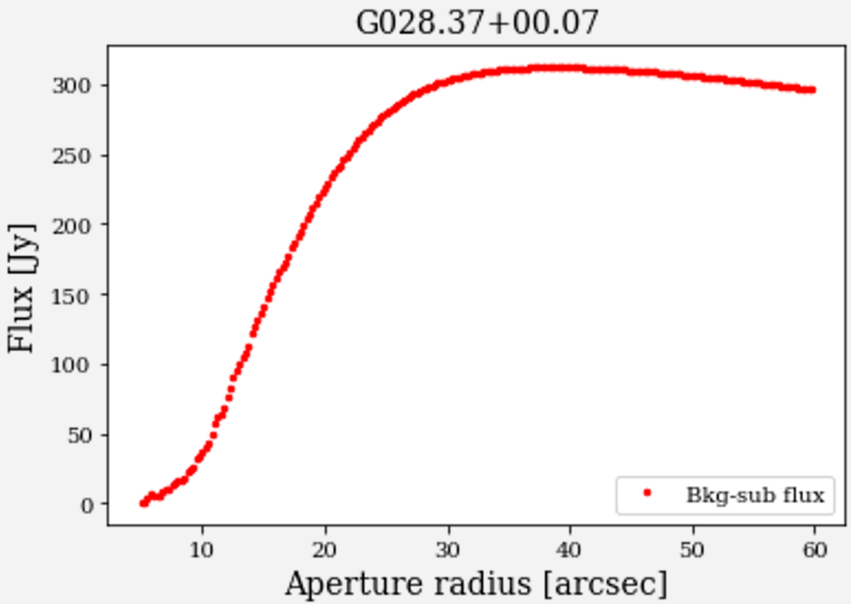
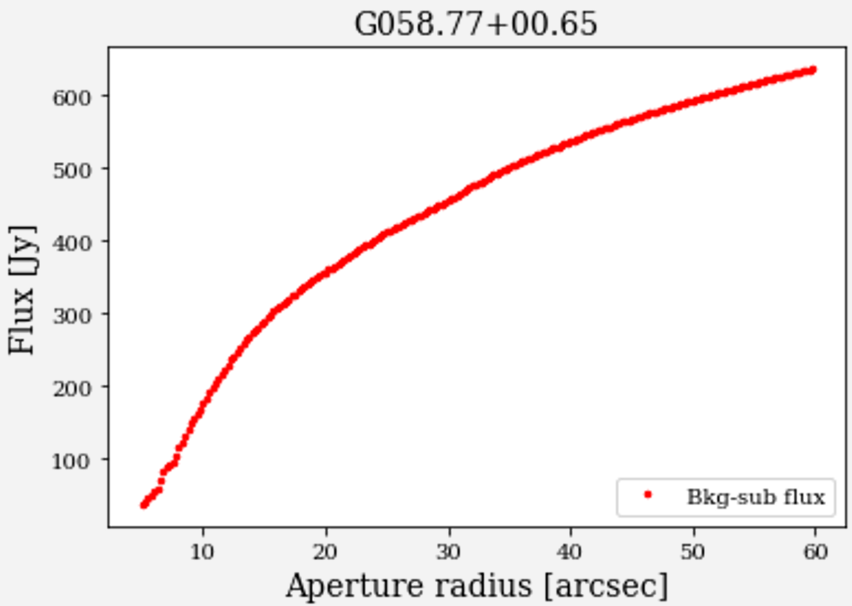
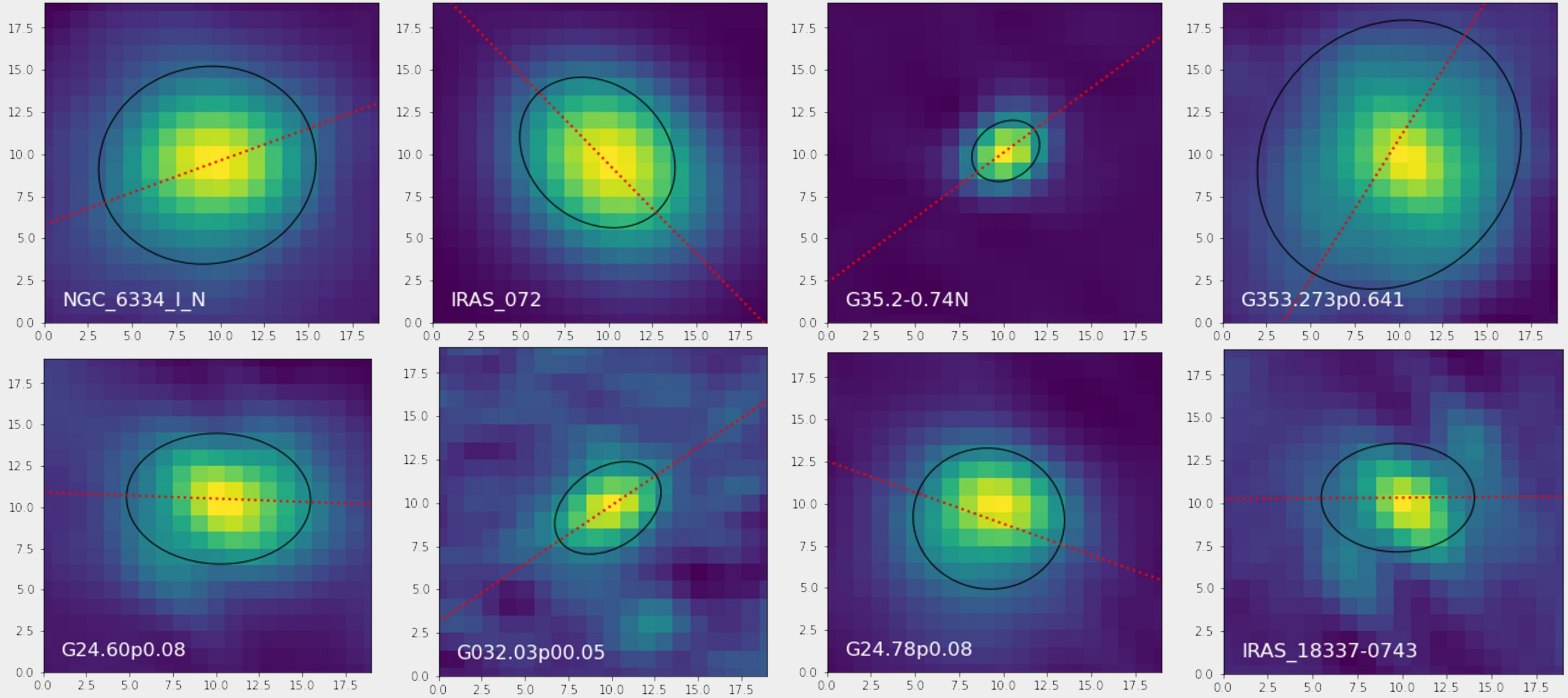
Automating the Aperture Finding Process





- Calculate the background-subtracted flux enclosed for a range of aperture radii
- Find the point at which a 30% increase in aperture radius results in a 10% or smaller increase in flux

Using ALMA Archival Data to Probe the Disk Scale



- Goal: Use high-resolution continuum long-baseline ALMA archival data to measure fluxes within ~100 AU and probe the disk scale
- Want to select relatively simple sources and fit 2D Gaussians