The SOFIA Massive (SOMA) Star Formation Survey - Tests of Massive Star Formation Theories

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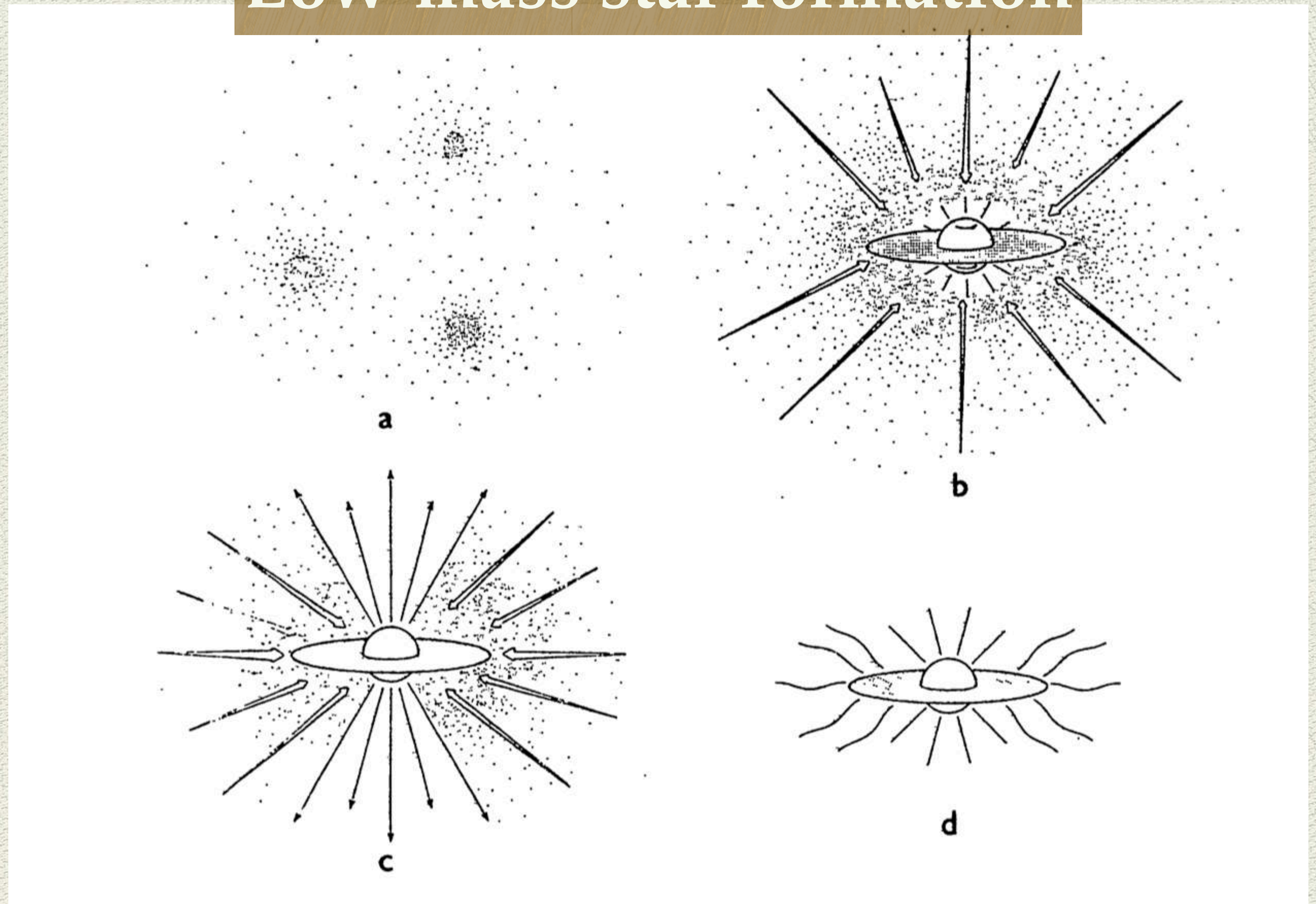
Massive Star Formation

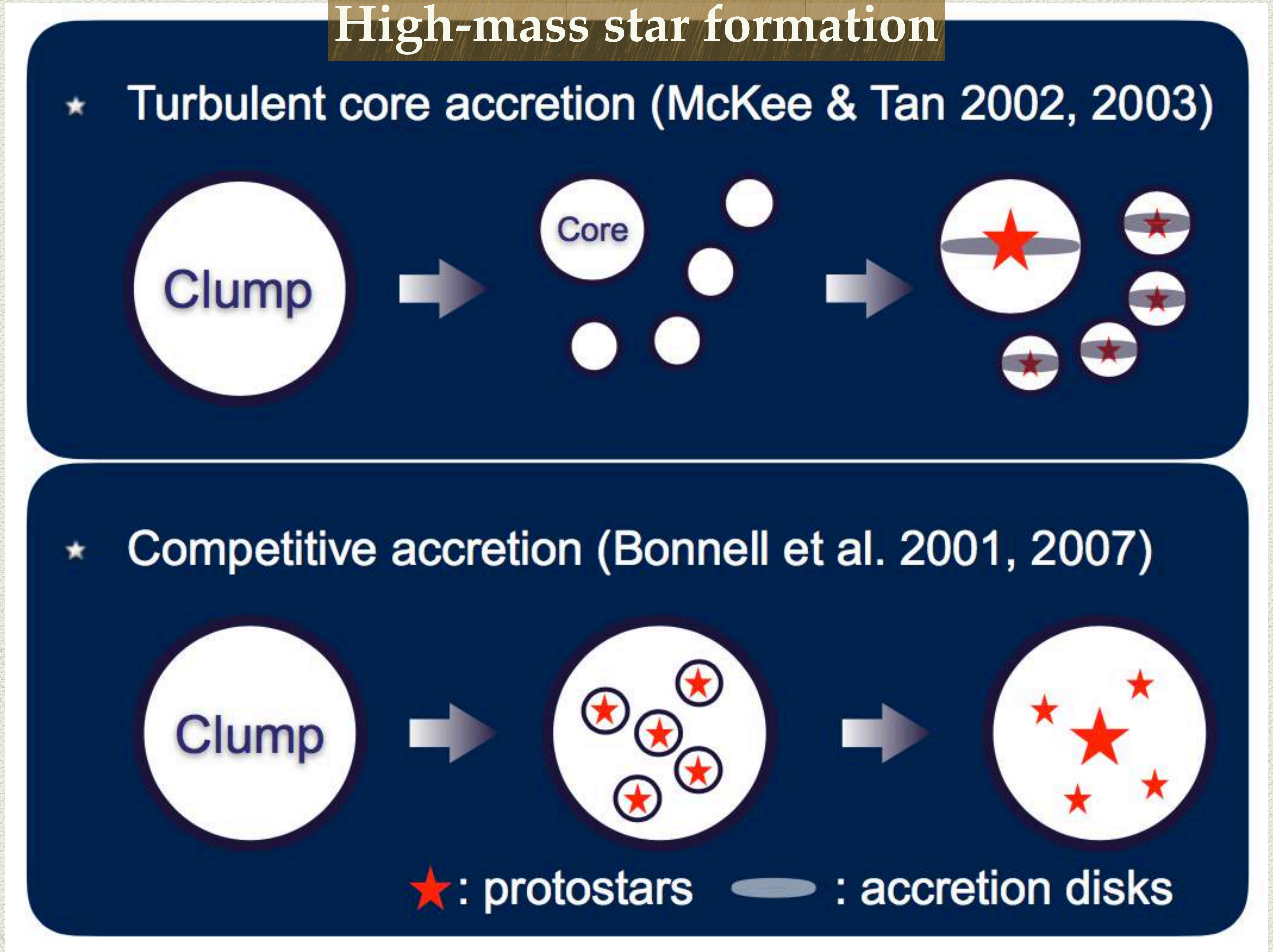
Low-mass star formation



(Shu+ 1987)

?

High-mass star formation



- Turbulent core accretion (McKee & Tan 2002, 2003)

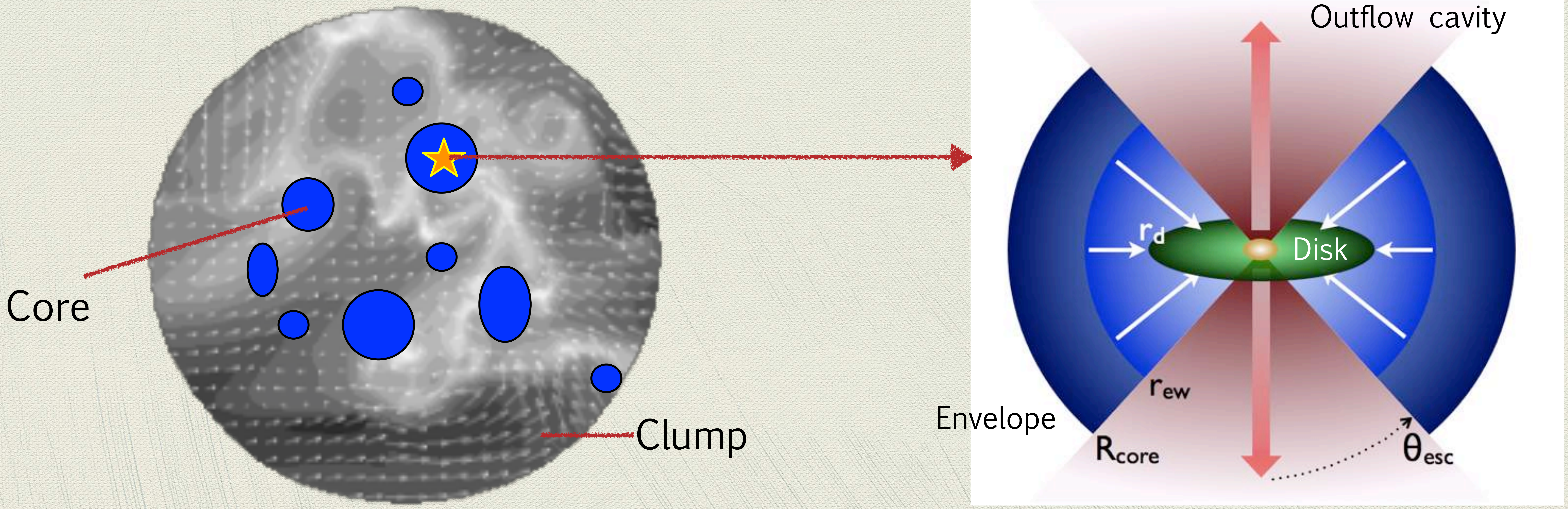
- Competitive accretion (Bonnell et al. 2001, 2007)

★ : protostars ▬ : accretion disks

- Difficulty in observation:
  - Far away (~ a few kpc)
  - High extinction (locally and globally) at optical and NIR wavelengths

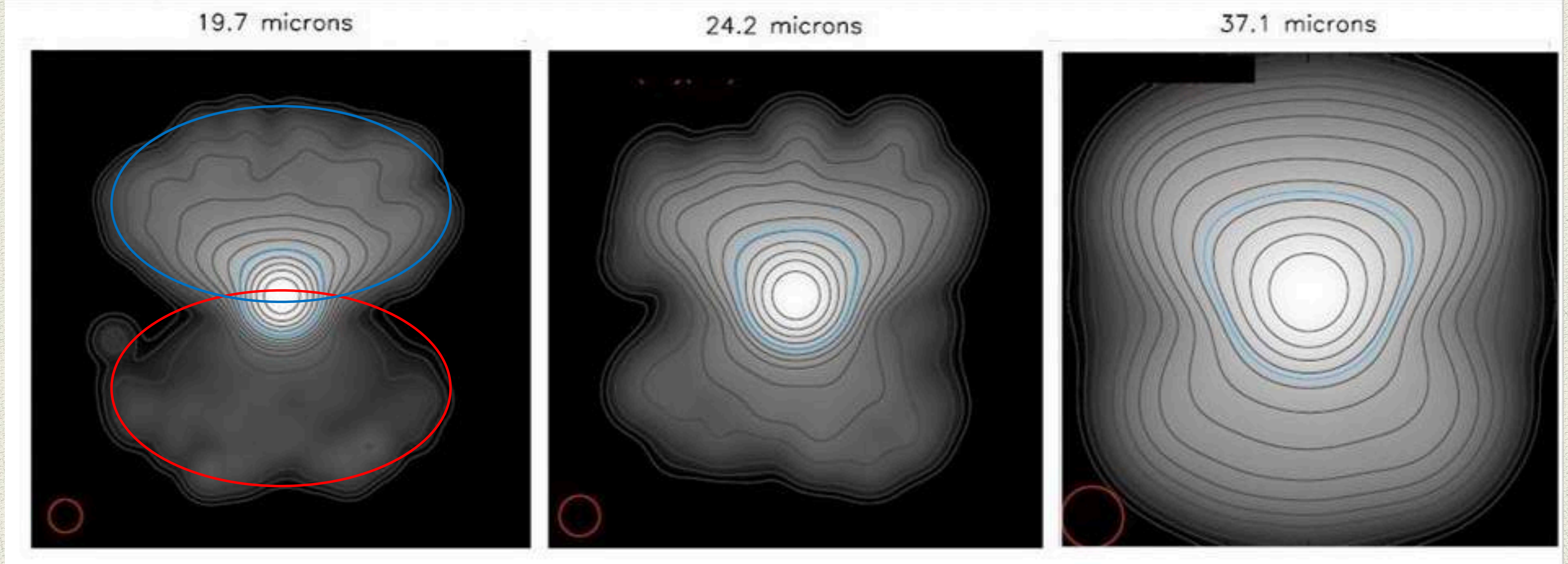
Massive Star Formation

- Turbulent Core Accretion
  - Stars form from massive cores in approximate pressure & virial equilibrium



Theoretical Expectations

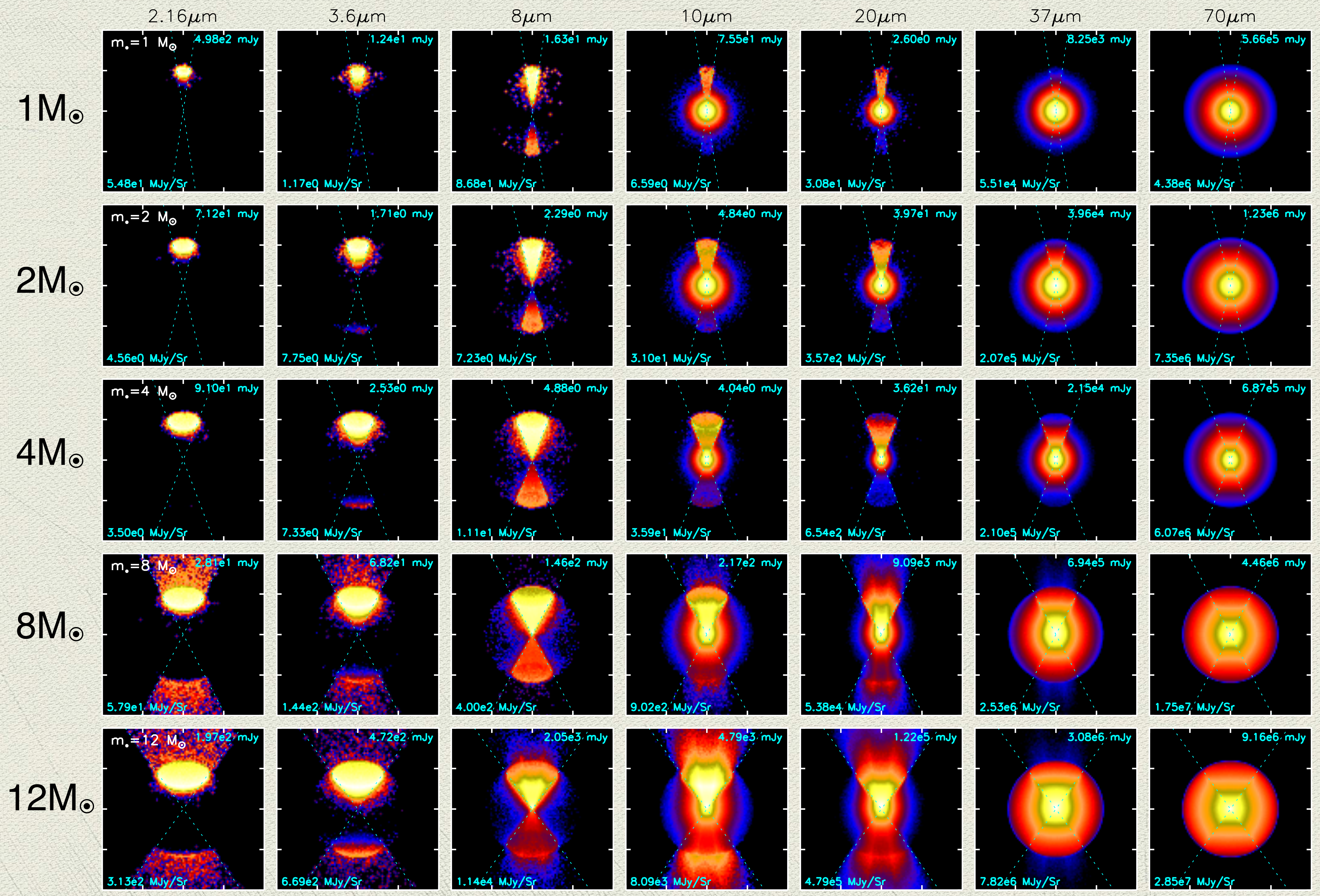
- Extended MIR emission that aligns with known outflows
- Highly asymmetrical shorter wavelengths, being brighter along the near-facing outflow cavity
- More symmetric at longer wavelengths



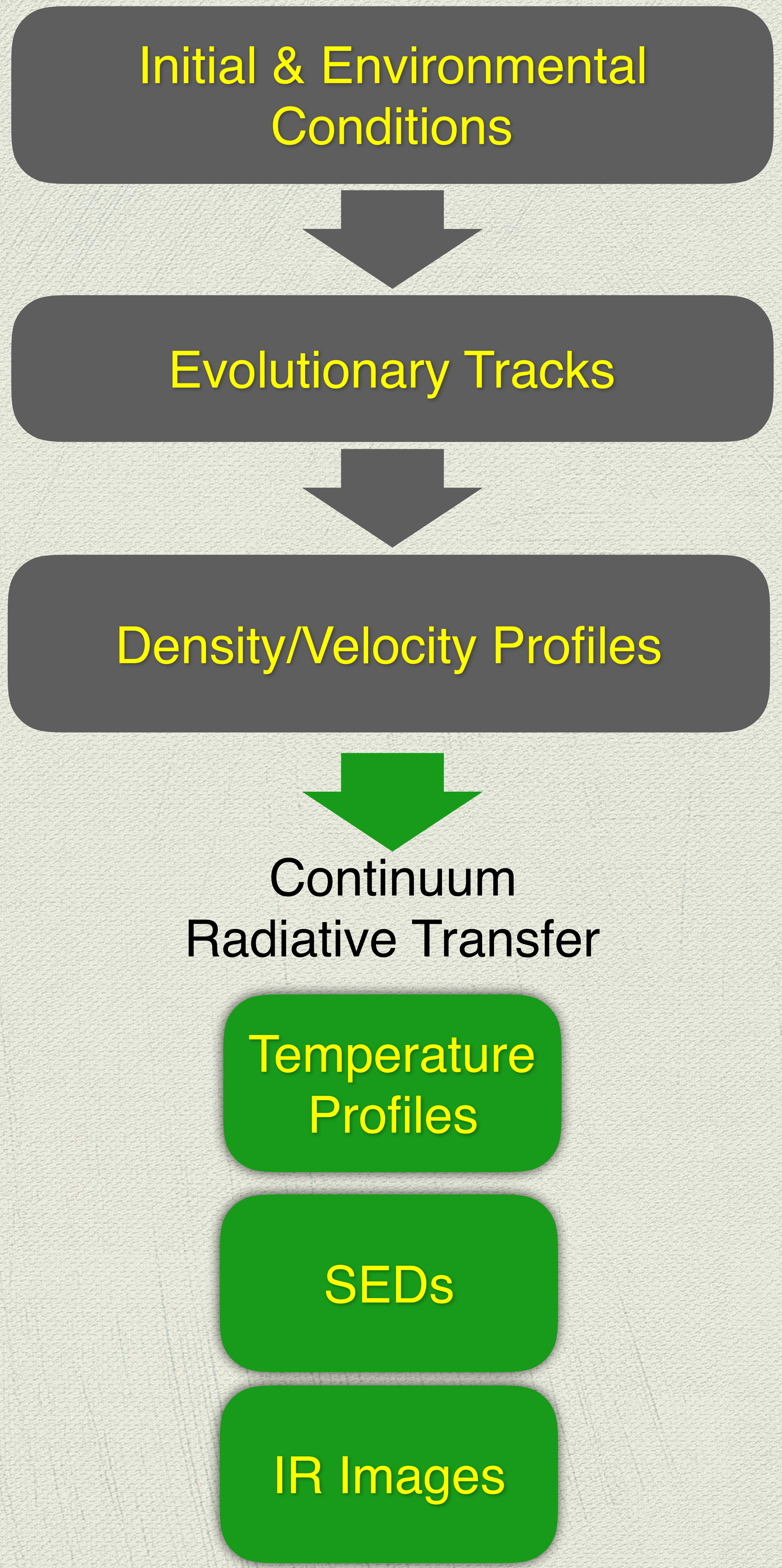
Model with ***i***=60°, thin disk, 60° outflow/disk opening angle, with SOFIA resolutions. (Zhang & Tan 2011)

Zhang & Tan Radiative Transfer (RT) Models

- Based on Turbulent Core Accretion (McKee & Tan 2003).
- Describe one protostar forming through monolithic collapse from the parent core.



Increasing symmetry from MIR to FIR



Initial & Environmental Conditions

Evolutionary Tracks

Density/Velocity Profiles

Continuum Radiative Transfer

Temperature Profiles

SEDs

IR Images

Physical Model Grid

5 free parameters, 432 physical models, 8640 model SEDs.

$$M_c,\ \Sigma_{\rm cl},\ m_*,\ \theta_{\rm view}\ \text{and}\ A_V$$

Evolutionary tracks

Current stage

How the source is observed.

Σ_{cl} : 0.1 ~ 3.2 g cm^{-2}

M_c : 10 ~ 500 $M_\odot$

m_{star}: 0.5 ~ 100 $M_\odot$

Initial & Environmental Conditions

Evolutionary Tracks

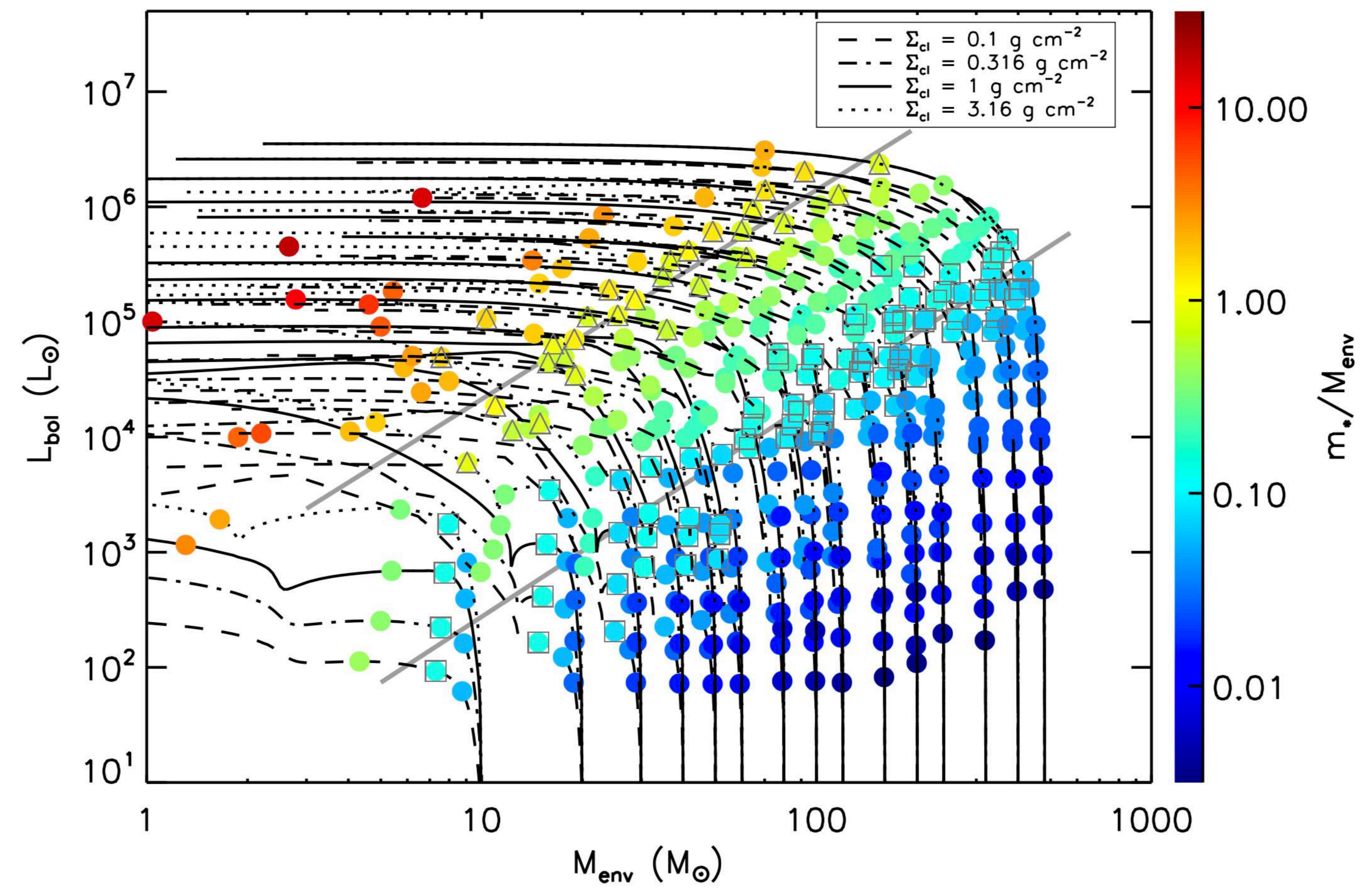
Density/Velocity Profiles

Continuum Radiative Transfer

Temperature Profiles

SEDs

IR Images



(Zhang & Tan 2018)

Initial & Environmental Conditions

Evolutionary Tracks

Density/Velocity Profiles

Continuum Radiative Transfer

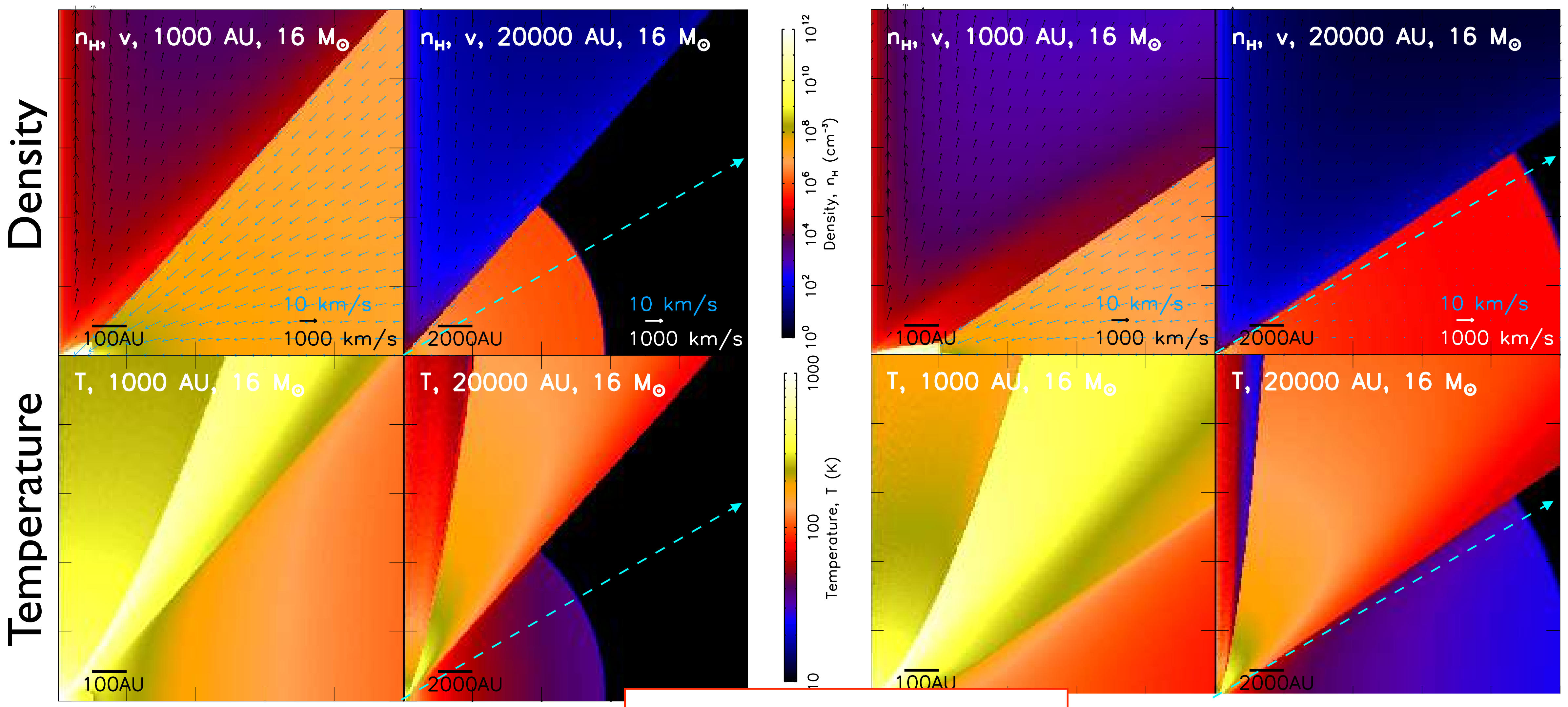
Temperature Profiles

SEDs

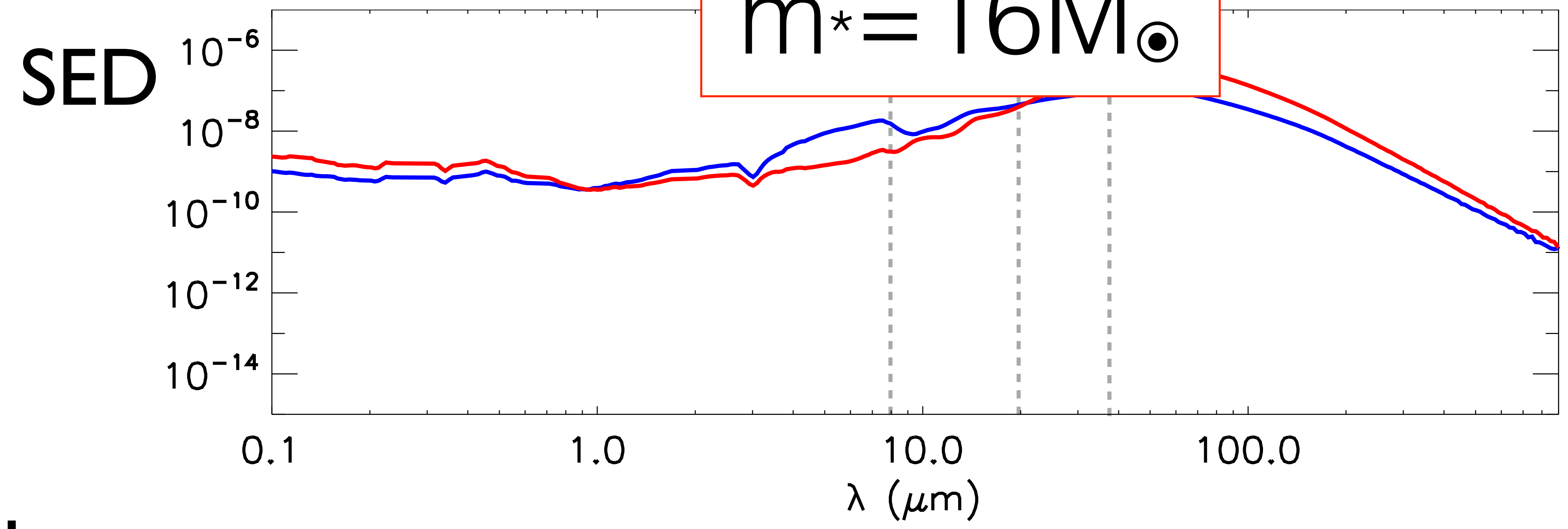
IR Images

$M_c = 60\ M_\odot$, $\Sigma_{cl} = 1\ \mathrm{g/cm^2}$, $\beta_c = 0.02$

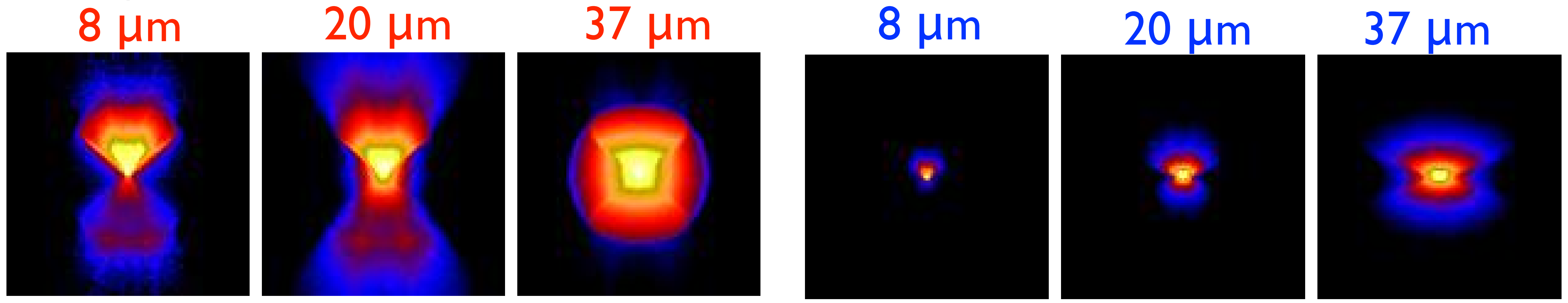
$M_c = 60\ M_\odot$, $\Sigma_{cl} = 0.3\ \mathrm{g/cm^2}$, $\beta_c = 0.02$



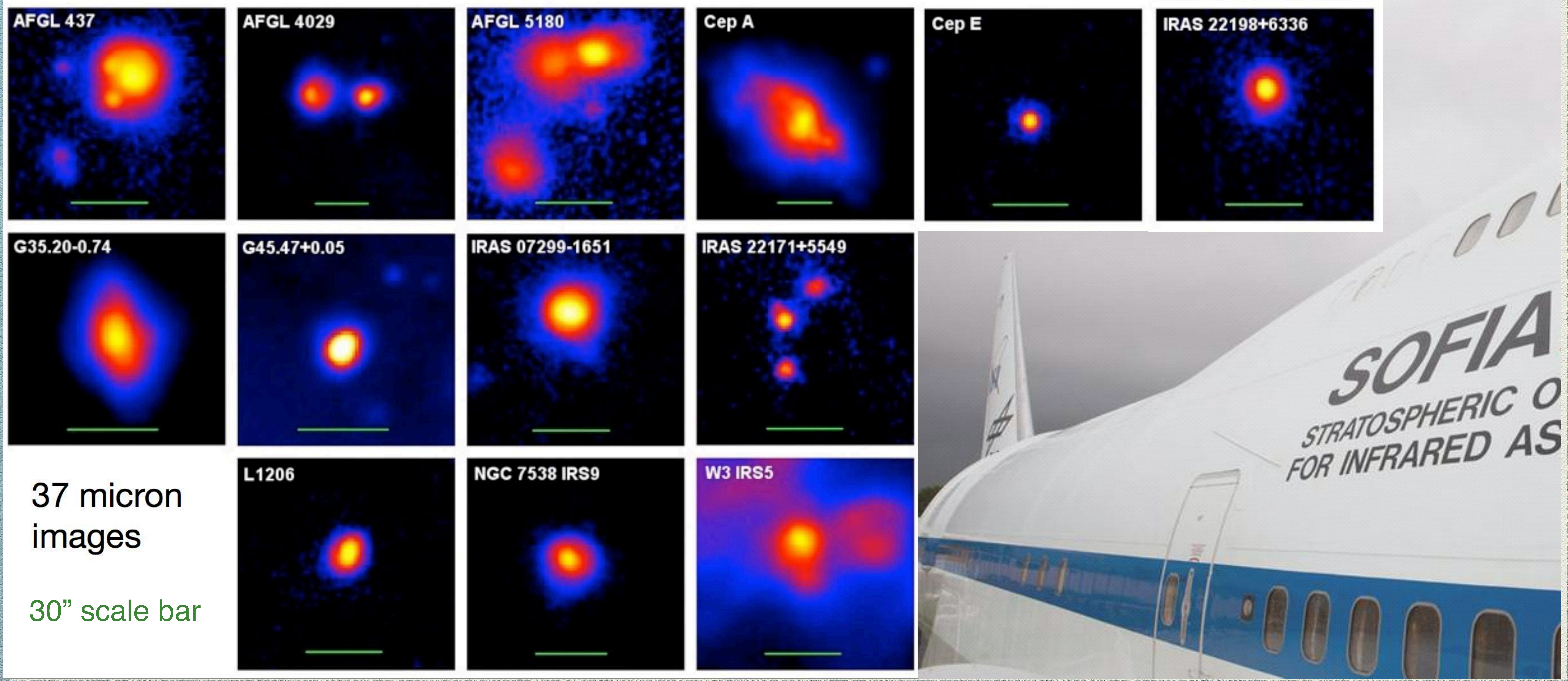
$m_* = 16 M_\odot$



Images



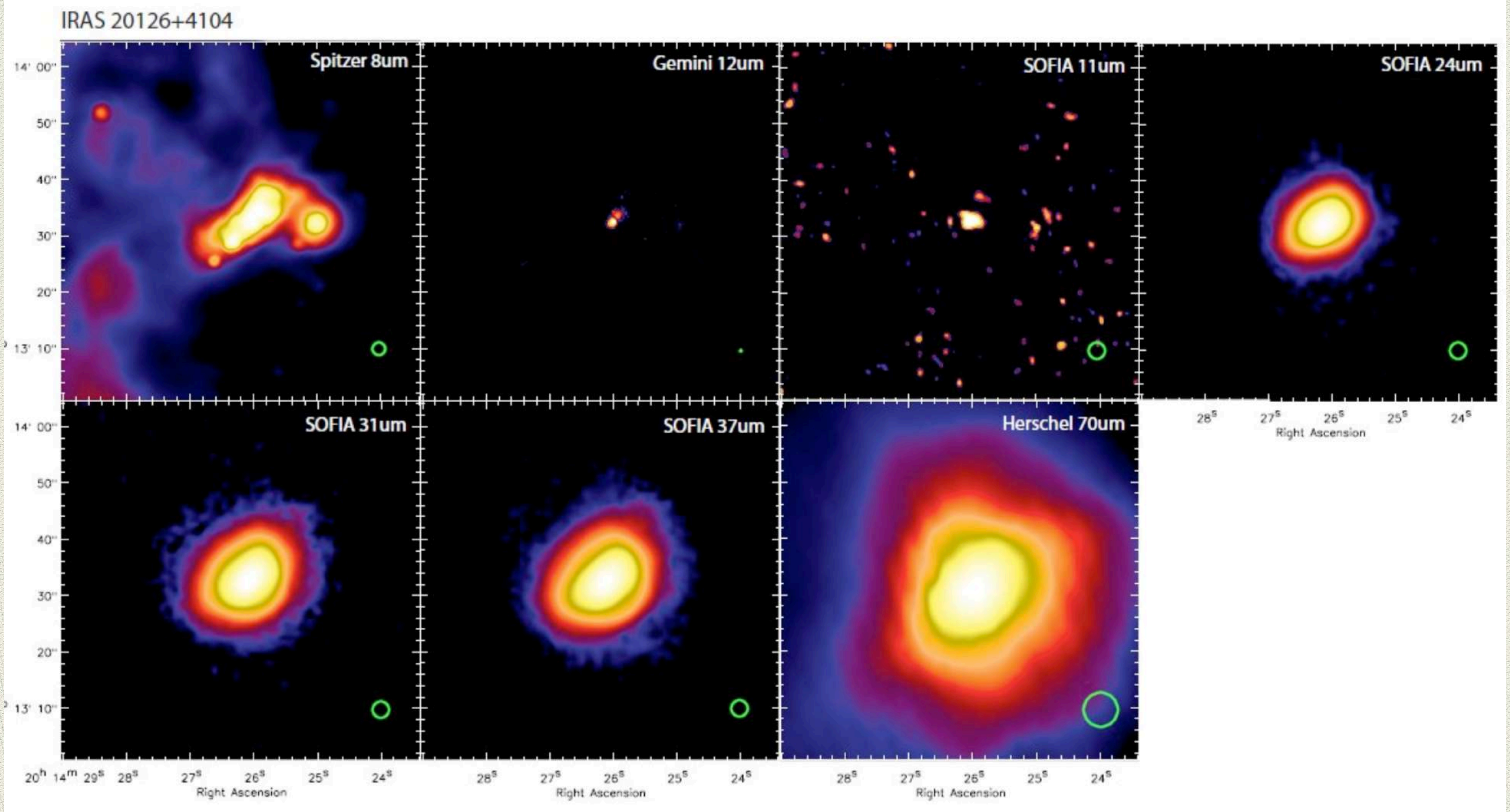
The SOFIA Massive (SOMA) Star Formation Survey



37 micron images

30” scale bar

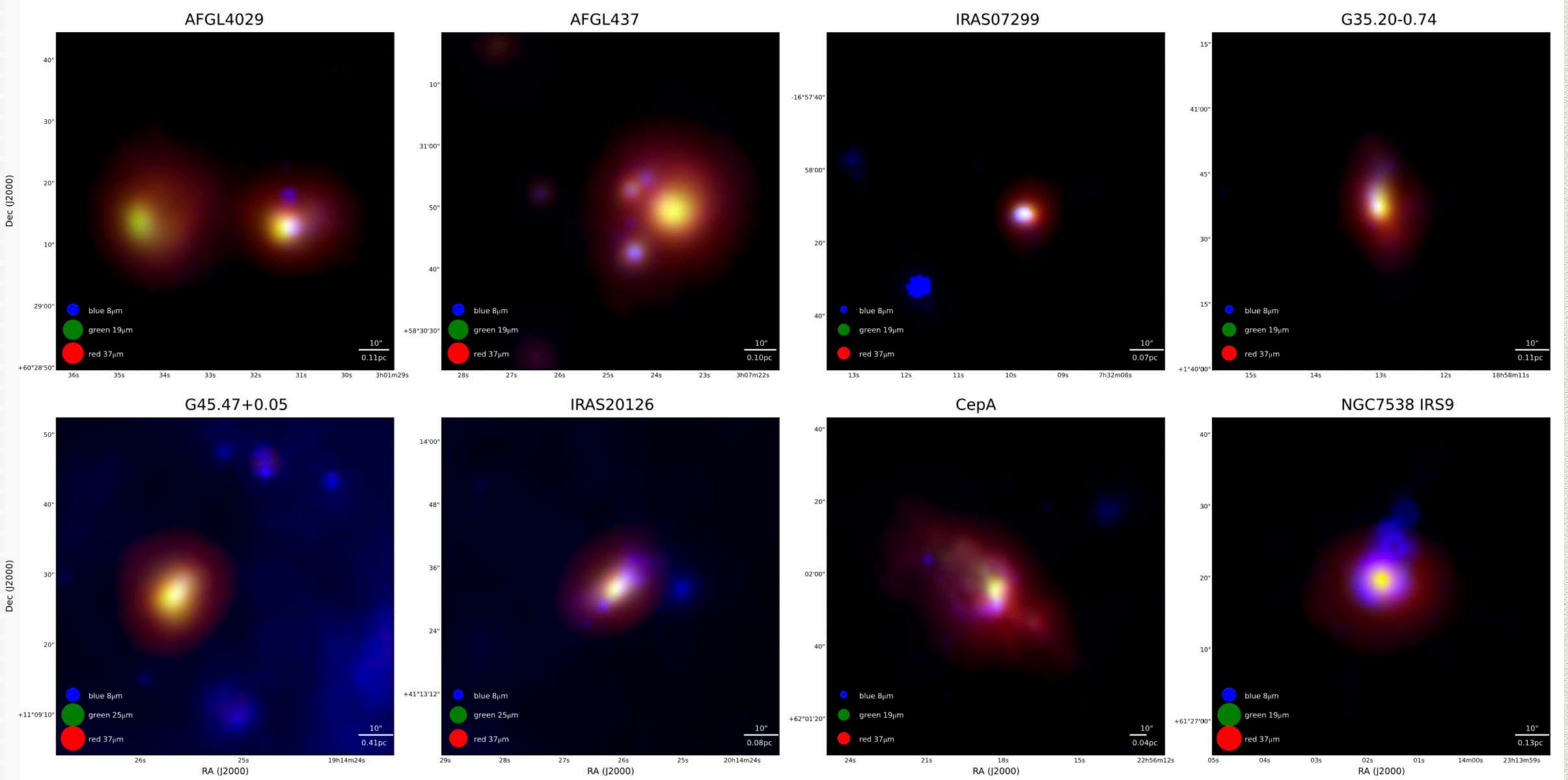
Multi-wavelength Images

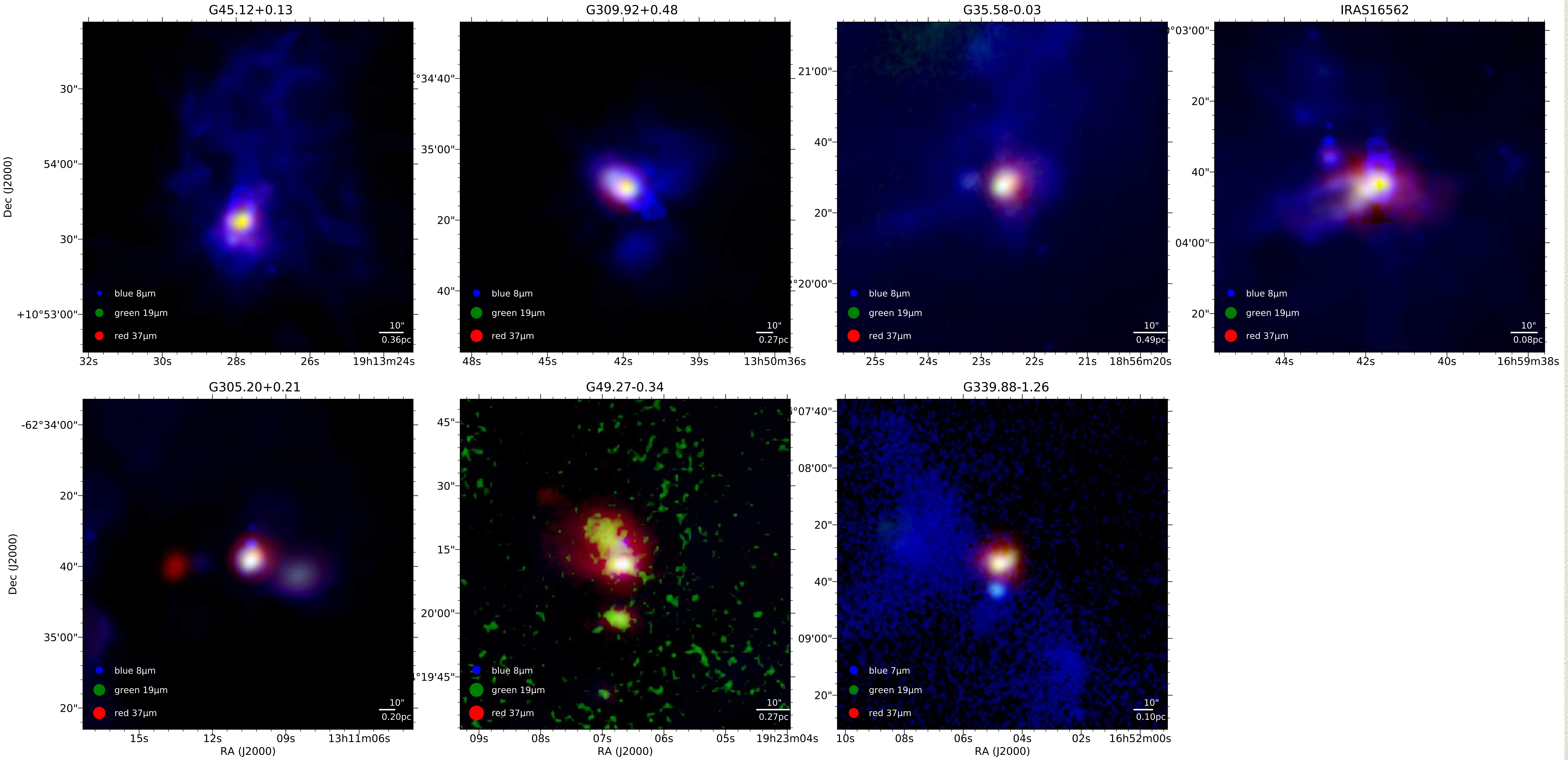


The SOFIA Massive (SOMA) Star Formation Survey

- Obtain **~10 to 40 μm** images of a statistically significant sample of about 50 **high- and intermediate-mass** protostars.
  - 41 sources observed, 15 sources published.
- 4 types of sources spanning a range of **environments** and **evolutionary stages**.
  - Type I: MIR sources in IRDCs; Type II: Hyper-compact; Type III: Ultra-compact; Type IV: Clustered sources.
  - Aim to have >10 sources for each type
- Test massive star formation theories.
  - Influence of outflow cavities on MIR to FIR morphologies
  - SED fitting with radiative transfer (RT) models

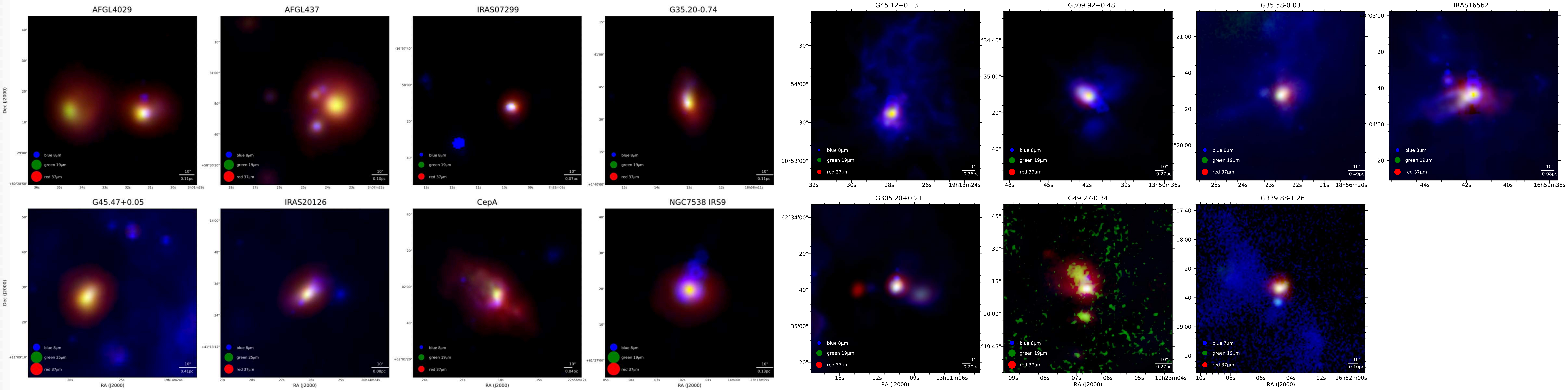
SOFIA
Southern Deployment
Christchurch New Zealand 2016


AFGL4029
AFGL437
IRAS07299
G35.20-0.74
G45.47+0.05
IRAS20126
CepA
NGC7538 IRS9
blue 8μm
green 19μm
green 25μm
red 37μm
10"
0.11pc
0.10pc
0.07pc
0.41pc
0.08pc
0.04pc
0.13pc
Dec (J2000)
RA (J2000)
+60°28'50"
29'00"
3h01m29s
+58°30'30"
31'00"
3h07m22s
-16°57'40"
58'00"
7h32m08s
+1°40'00"
41'00"
18h58m11s
+11°09'10"
19h14m24s
+41°13'12"
14'00"
20h14m24s
+62°01'20"
02'00"
22h56m12s
+61°27'00"
14m00s
23h13m59s


G45.12+0.13
30"
54'00"
30"
+10°53'00"
Dec (J2000)
32s
30s
28s
26s
19h13m24s
blue 8μm
green 19μm
red 37μm
10"
0.36pc
G309.92+0.48
°34'40"
35'00"
20"
40"
48s
45s
42s
39s
13h50m36s
blue 8μm
green 19μm
red 37μm
10"
0.27pc
G35.58-0.03
21'00"
40"
20"
°20'00"
25s
24s
23s
22s
21s
18h56m20s
blue 8μm
green 19μm
red 37μm
10"
0.49pc
IRAS16562
°03'00"
20"
40"
04'00"
20"
44s
42s
40s
16h59m38s
blue 8μm
green 19μm
red 37μm
10"
0.08pc
G305.20+0.21
-62°34'00"
20"
40"
35'00"
20"
Dec (J2000)
15s
12s
09s
13h11m06s
RA (J2000)
blue 8μm
green 19μm
red 37μm
10"
0.20pc
G49.27-0.34
45"
30"
15"
20'00"
°19'45"
09s
08s
07s
06s
05s
19h23m04s
RA (J2000)
blue 8μm
green 19μm
red 37μm
10"
0.27pc
G339.88-1.26
°07'40"
08'00"
20"
40"
09'00"
20"
10s
08s
06s
04s
02s
16h52m00s
RA (J2000)
blue 7μm
green 19μm
red 37μm
10"
0.10pc

First Results

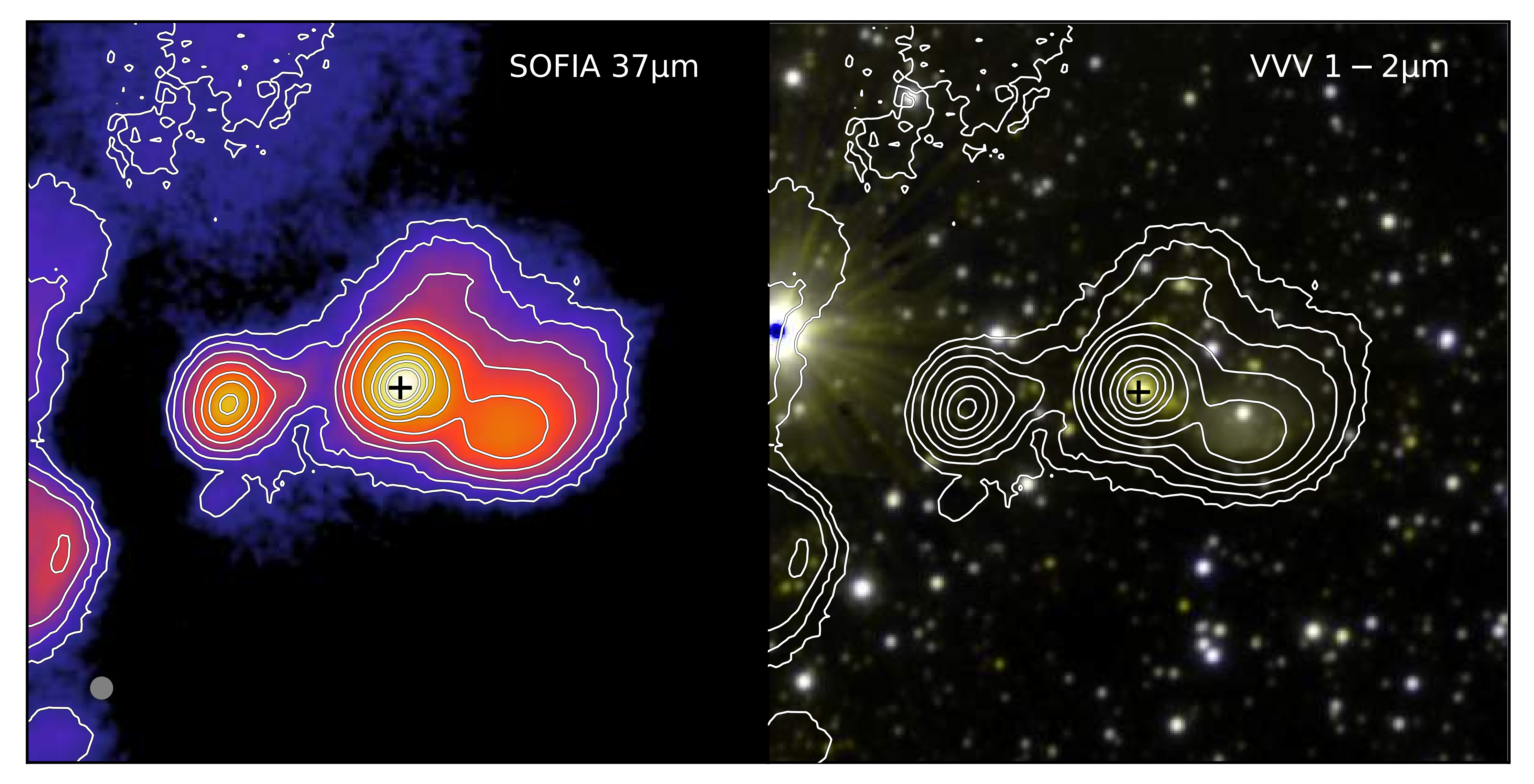
- How and how common are MIR morphologies influenced by outflow cavities?
- Can the SEDs be well fit by ZT radiative transfer models via an axisymmetric, ordered collapse?
- Threshold in Σ_{cl} to form massive stars (e.g., 1 g cm^{-2} in Krumholz & McKee 2008)?

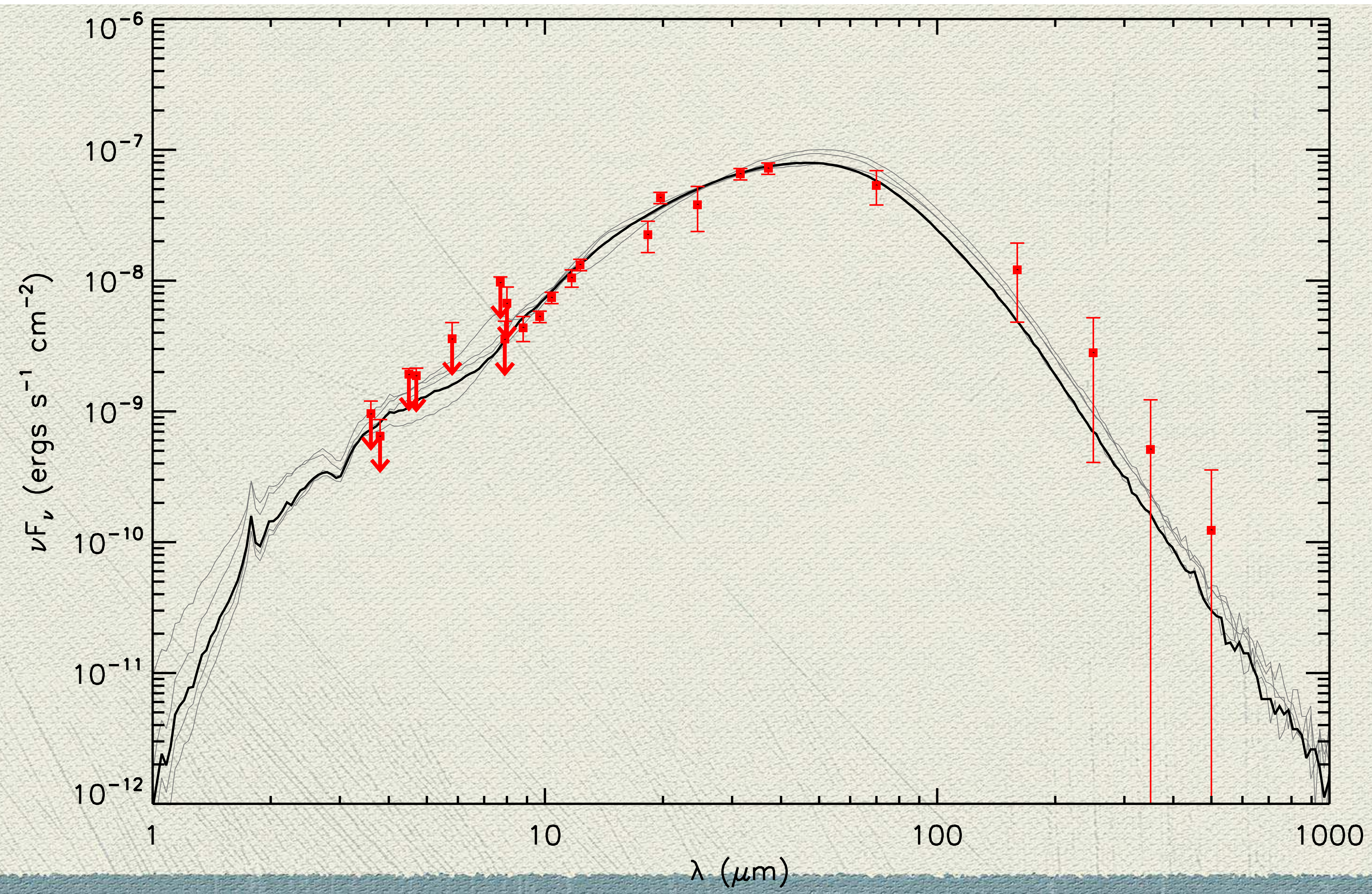


High-mass YSO G305.20+0.21

Parameters of the Best Five Fitted Models

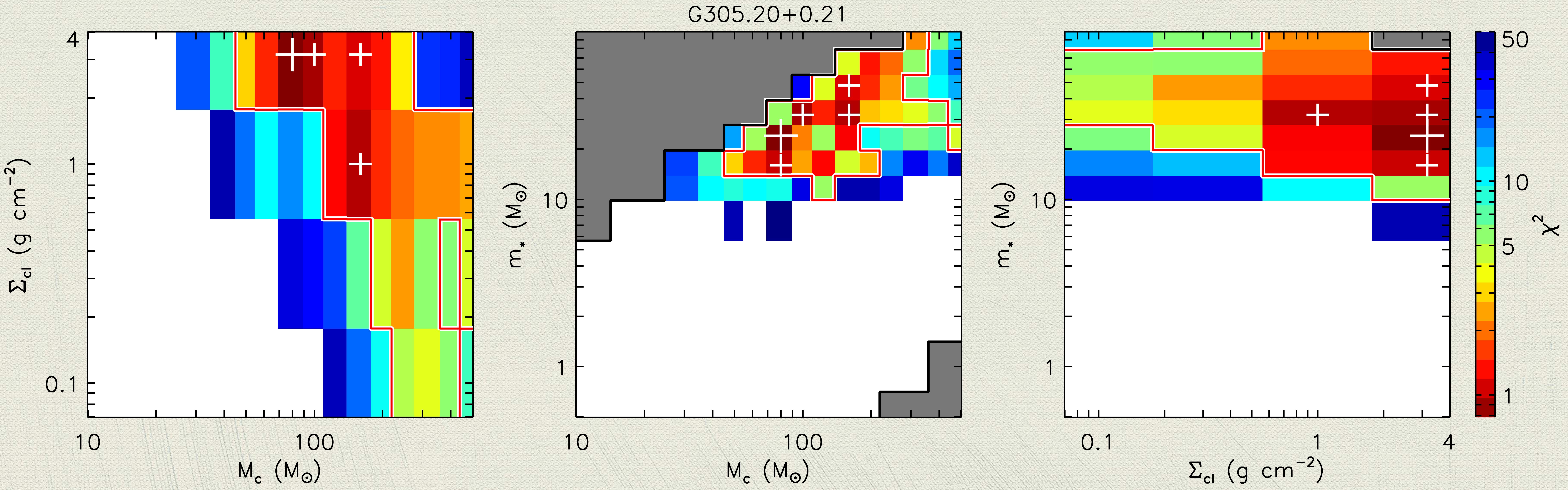
Source	χ^2/N	M_c ($M_\odot$)	Σ_{cl} (g cm^{-2})	R_{core} (pc) ($''$)	m_* ($M_\odot$)	θ_{view} (°)	A_V (mag)	M_{env} ($M_\odot$)	$\theta_{w,esc}$ (deg)	$\dot{M}_{disk}$ ($M_\odot$ yr^{-1})	$L_{bol,iso}$ ($L_\odot$)	L_{bol} ($L_\odot$)
G305.20+0.21	0.79	80	3.2	0.037 (2)	24.0	48	14.1	35	37	1.1×10^{-3}	7.5×10^4	2.6×10^5
d = 4.1 kpc	0.92	100	3.2	0.041 (2)	32.0	51	18.2	37	42	1.2×10^{-3}	7.9×10^4	3.5×10^5
$R_{ap} = 16''$	0.97	160	1.0	0.093 (5)	32.0	44	13.1	88	39	5.9×10^{-4}	8.2×10^4	2.3×10^5
=0.32 pc	1.04	80	3.2	0.037 (2)	16.0	34	8.1	50	27	9.5×10^{-4}	7.2×10^4	1.1×10^5
	1.11	160	3.2	0.052 (3)	48.0	58	16.2	59	45	1.6×10^{-3}	9.0×10^4	6.4×10^5



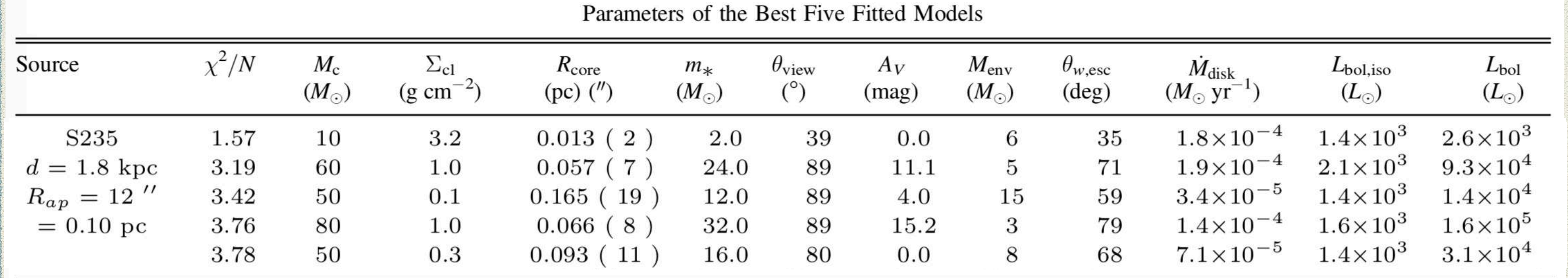


High-mass YSO G305.20+0.21

χ^2 Distribution

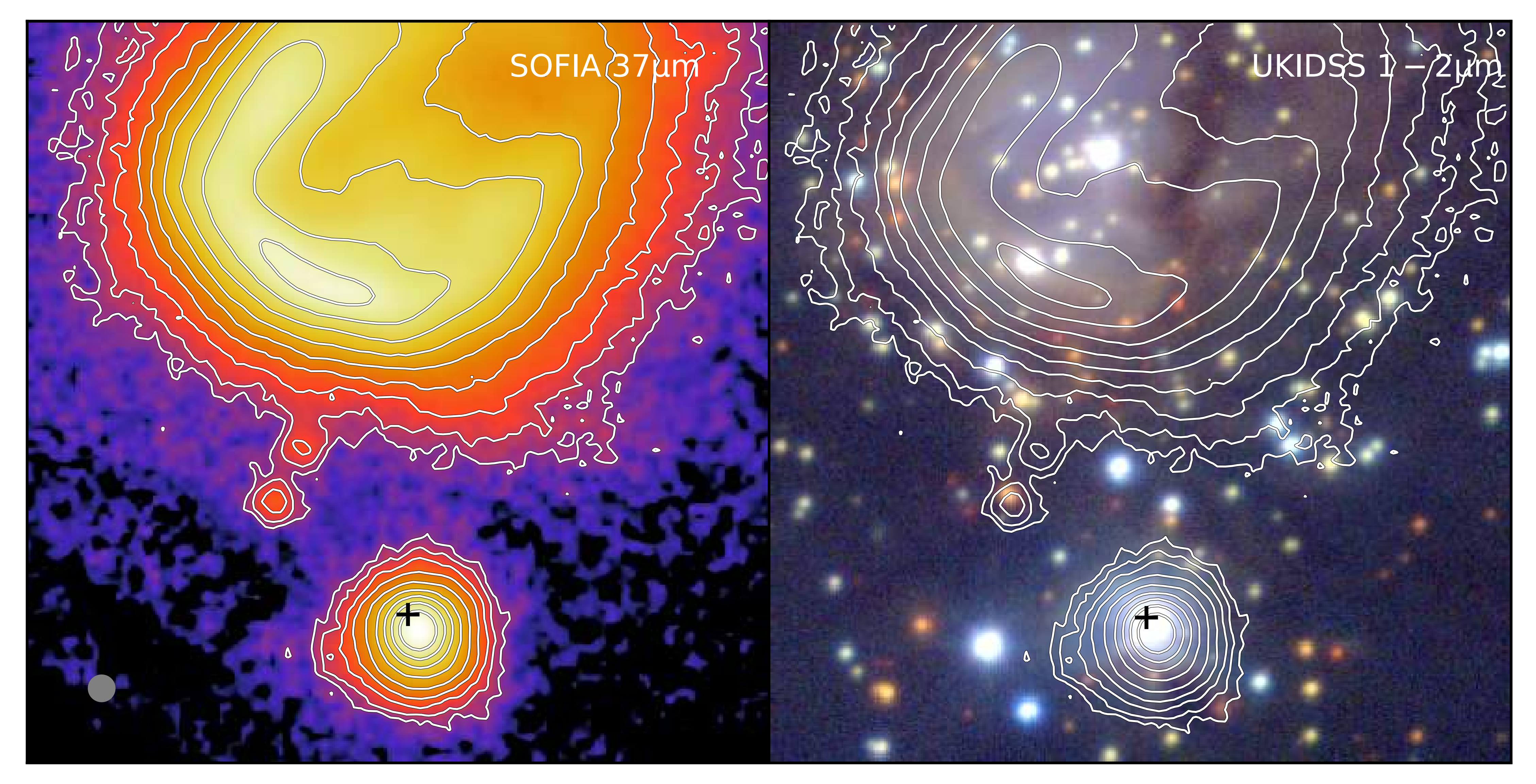


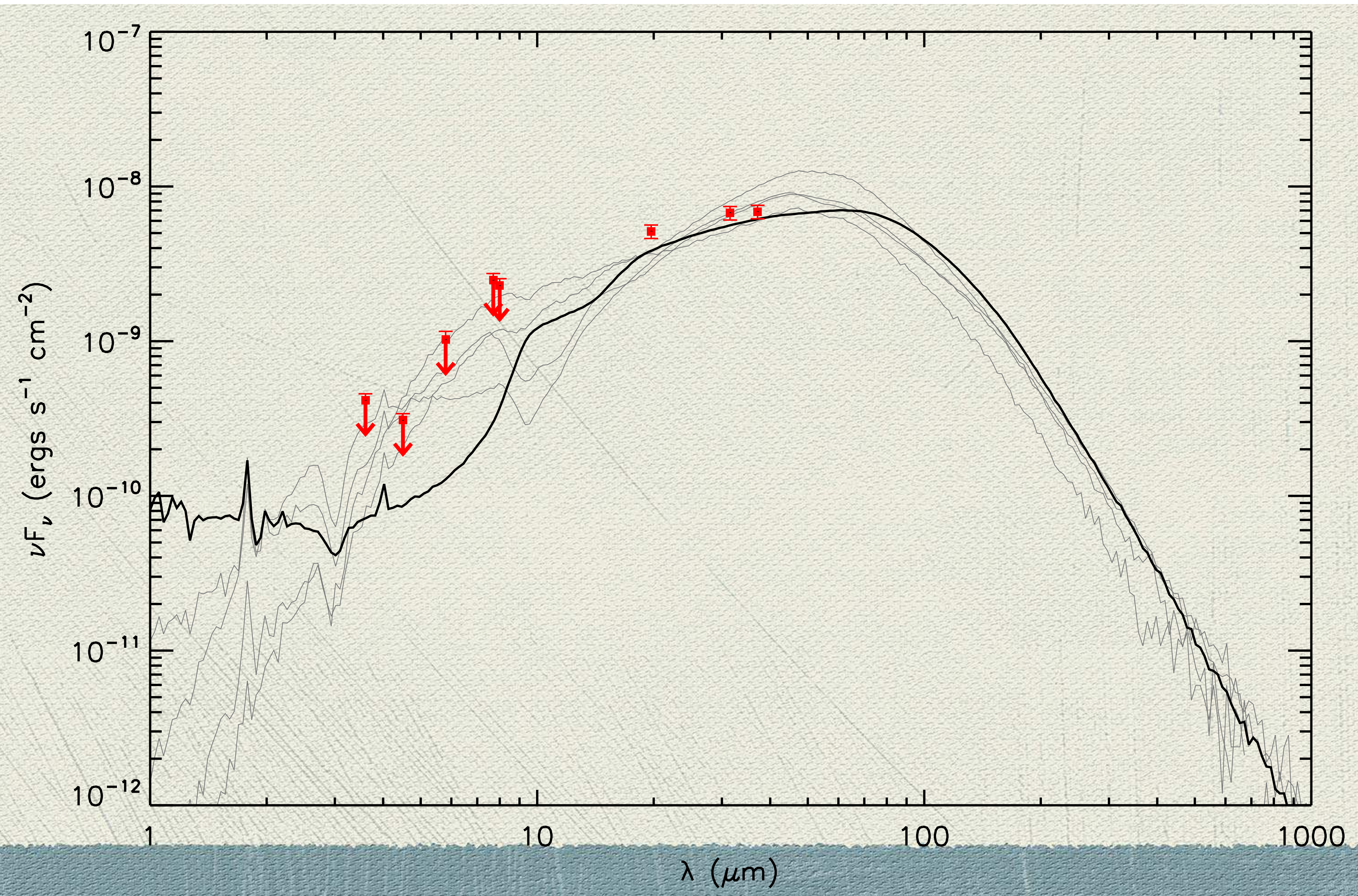
Intermediate-mass YSO S235



Parameters of the Best Five Fitted Models

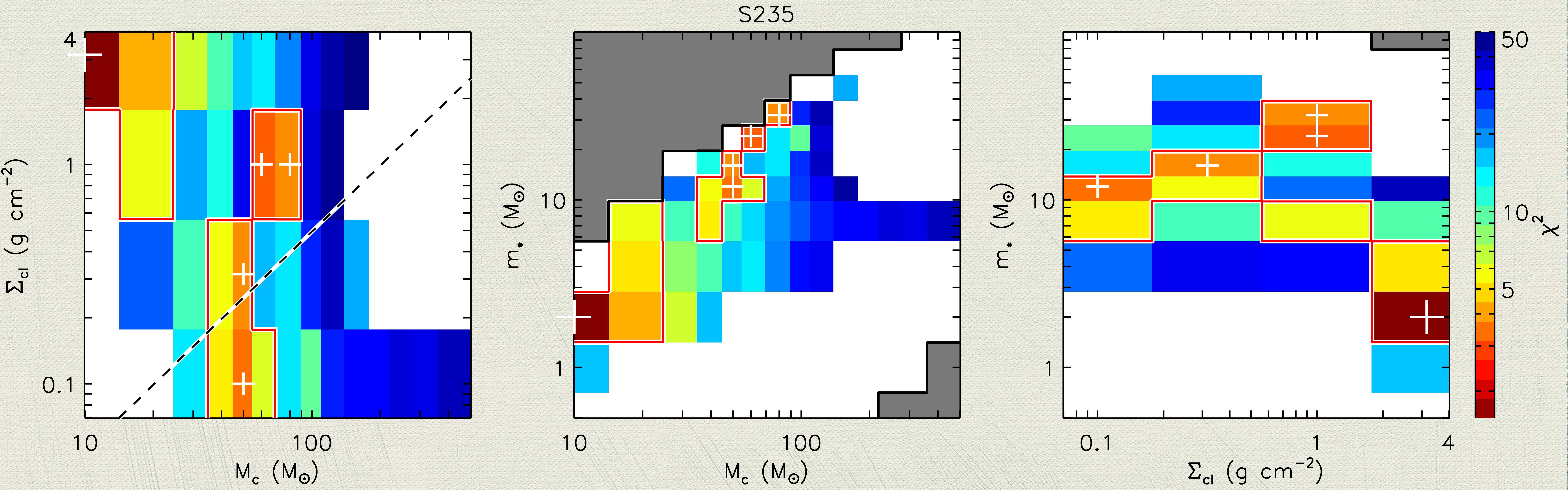
Source	χ^2/N	M_c ($M_\odot$)	Σ_{cl} (g cm^{-2})	R_{core} (pc) ($''$)	m_* ($M_\odot$)	θ_{view} ($^\circ$)	A_V (mag)	M_{env} ($M_\odot$)	$\theta_{w,esc}$ (deg)	$\dot{M}_{disk}$ ($M_\odot$ yr^{-1})	$L_{bol,iso}$ ($L_\odot$)	L_{bol} ($L_\odot$)
S235	1.57	10	3.2	0.013 (2)	2.0	39	0.0	6	35	1.8×10^{-4}	1.4×10^{3}	2.6×10^{3}
d = 1.8 kpc	3.19	60	1.0	0.057 (7)	24.0	89	11.1	5	71	1.9×10^{-4}	2.1×10^{3}	9.3×10^{4}
$R_{ap} = 12''$	3.42	50	0.1	0.165 (19)	12.0	89	4.0	15	59	3.4×10^{-5}	1.4×10^{3}	1.4×10^{4}
= 0.10 pc	3.76	80	1.0	0.066 (8)	32.0	89	15.2	3	79	1.4×10^{-4}	1.6×10^{3}	1.6×10^{5}
	3.78	50	0.3	0.093 (11)	16.0	80	0.0	8	68	7.1×10^{-5}	1.4×10^{3}	3.1×10^{4}





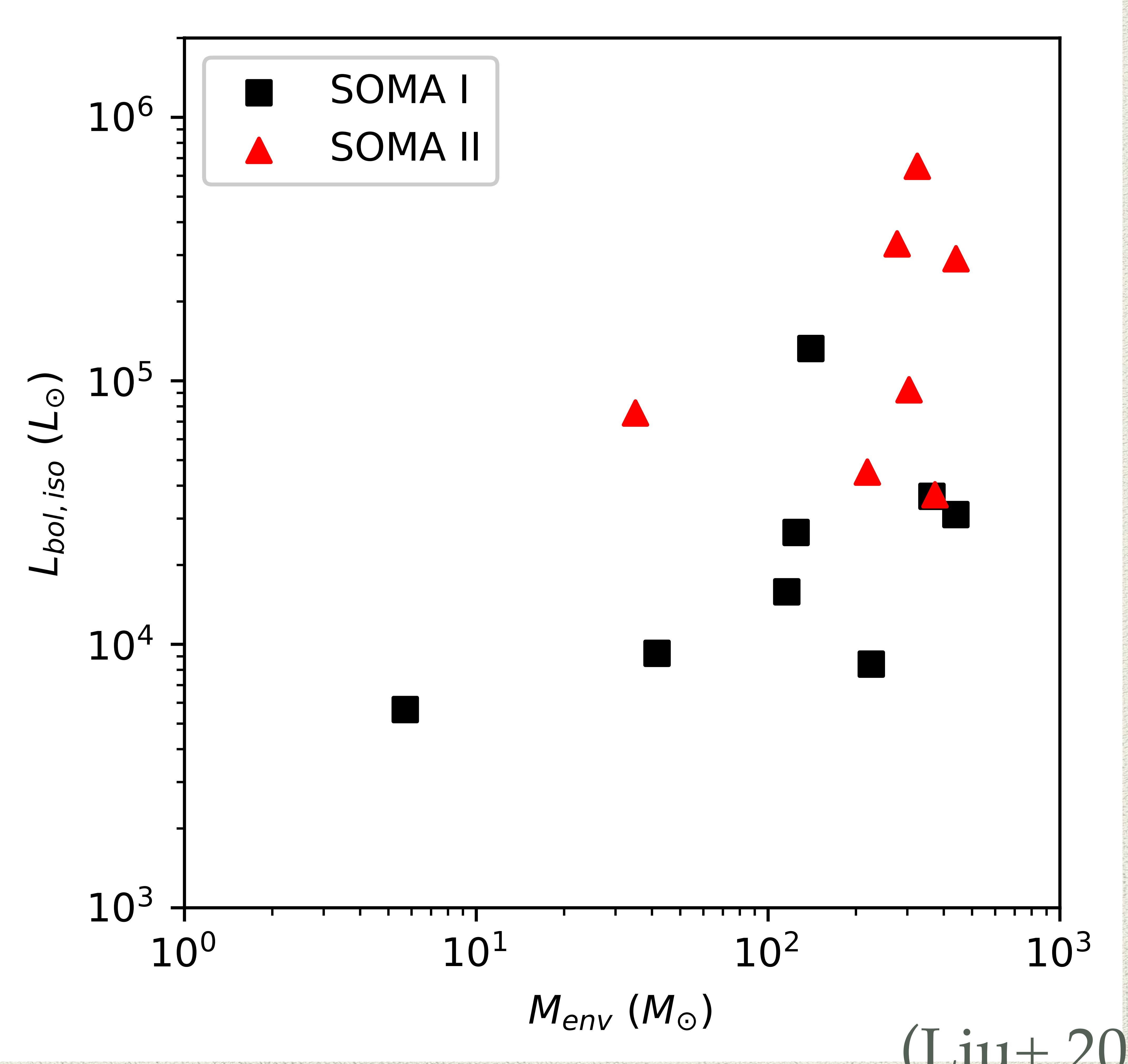
Intermediate-mass YSO S235

χ^2 Distribution



High-mass Sample

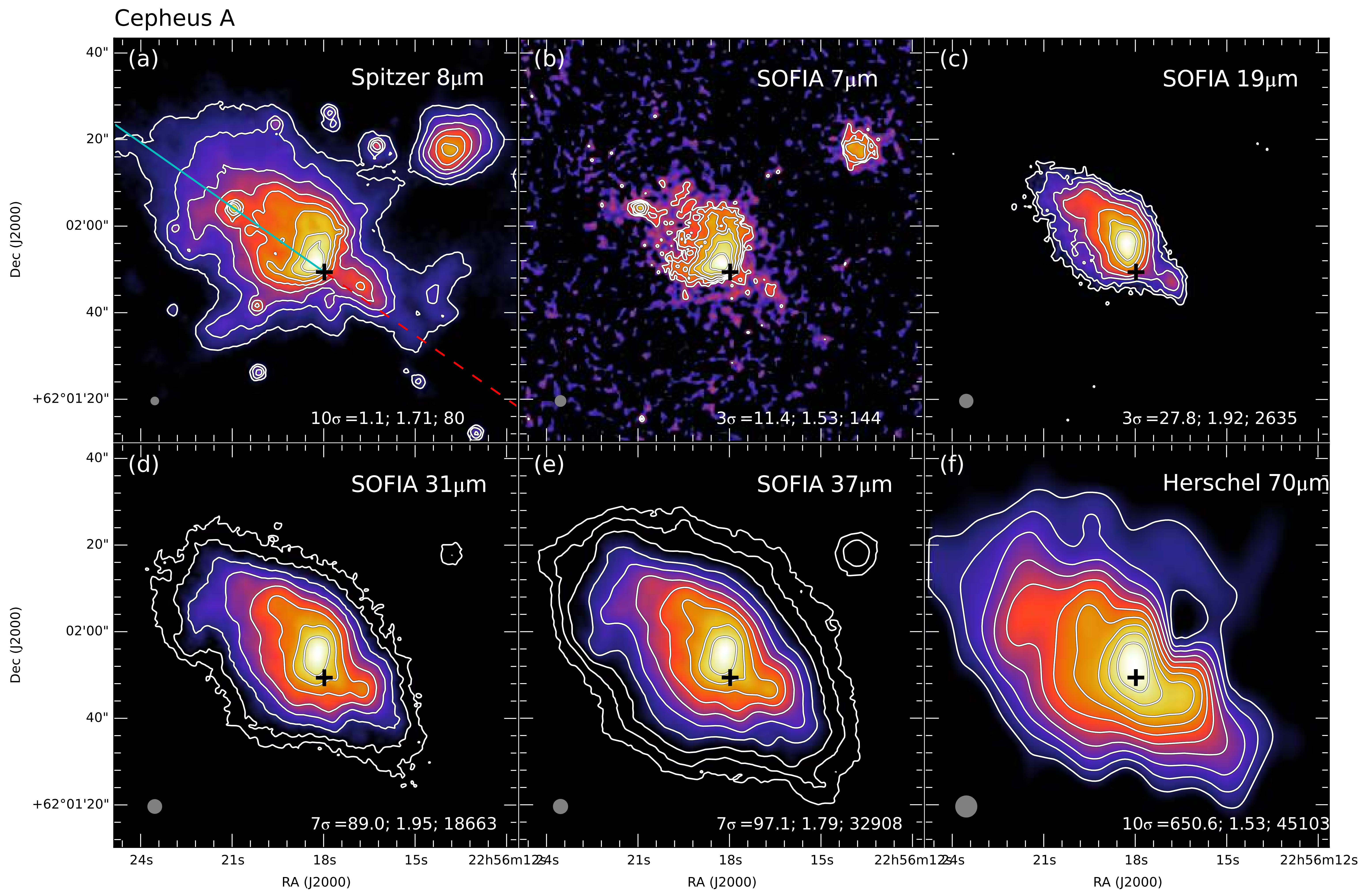
- Isotropic luminosity
  $L_{bol} \sim 10^3 - 10^6\ L_\odot$
- Initial core masses
  $M_c \sim 30 - 500\ M_\odot$
- Clump mass surface densities
  $\Sigma_{cl} \sim 0.1 - 3\ g\ cm^{-2}$
- Protostellar masses
  $m_* \sim 10 - 64\ M_\odot$
- Accretion rates
  $\dot{m}_* \sim 10^{-4} - 10^{-3}\ M_\odot/yr$



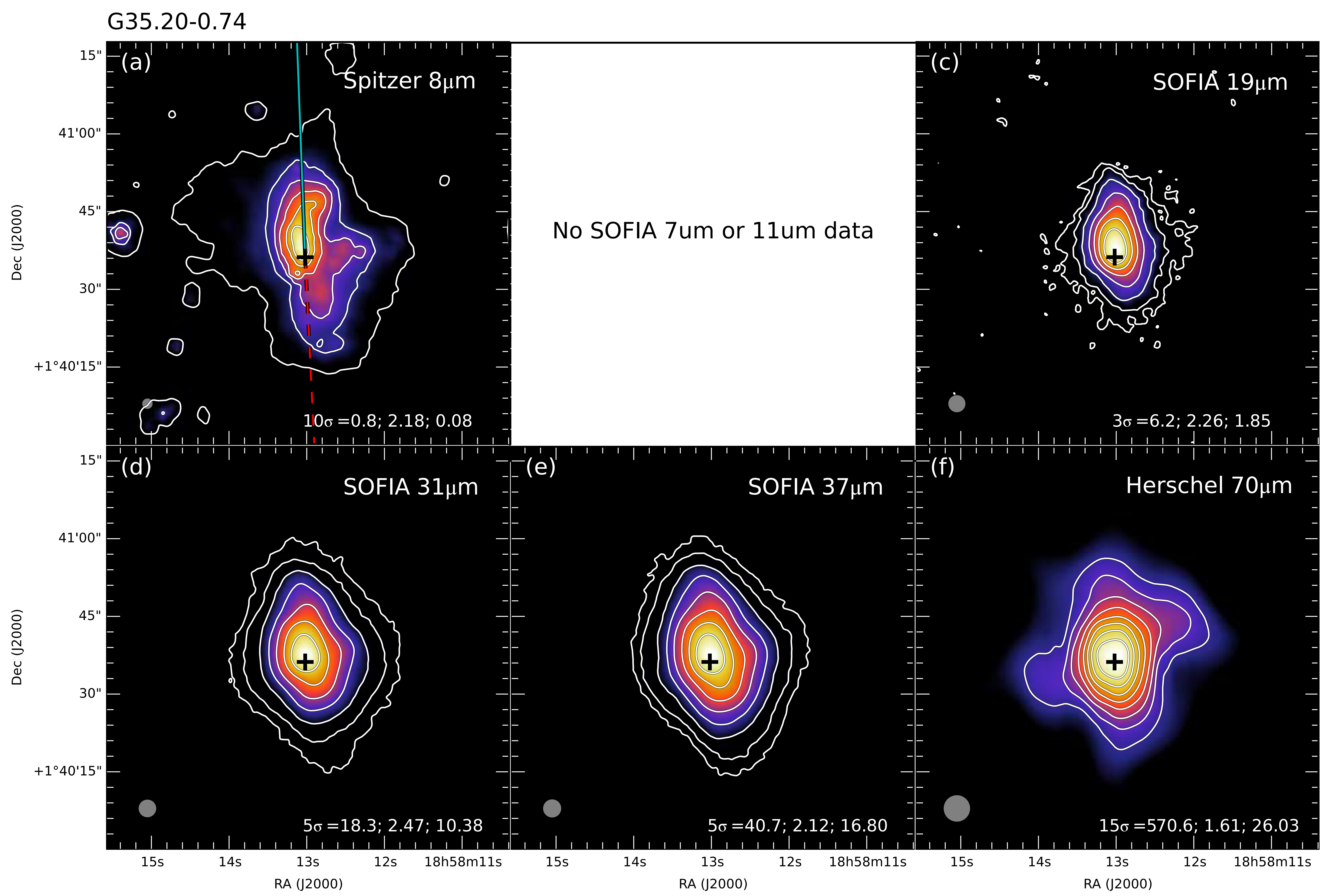
(Liu+ 2019)

What sets the morphology of MIR/FIR emission?

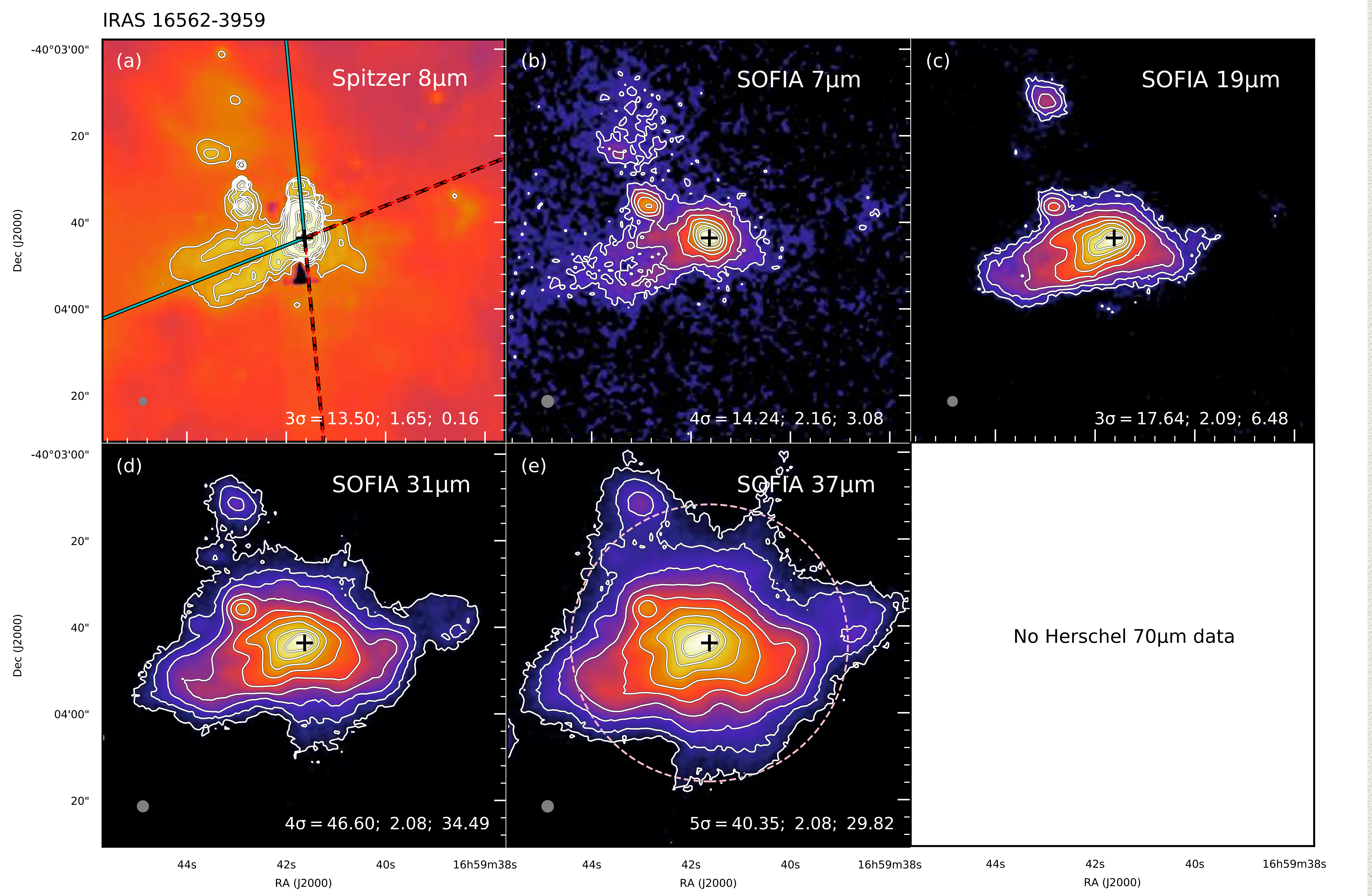
Outflow Cavity



Outflow Cavity



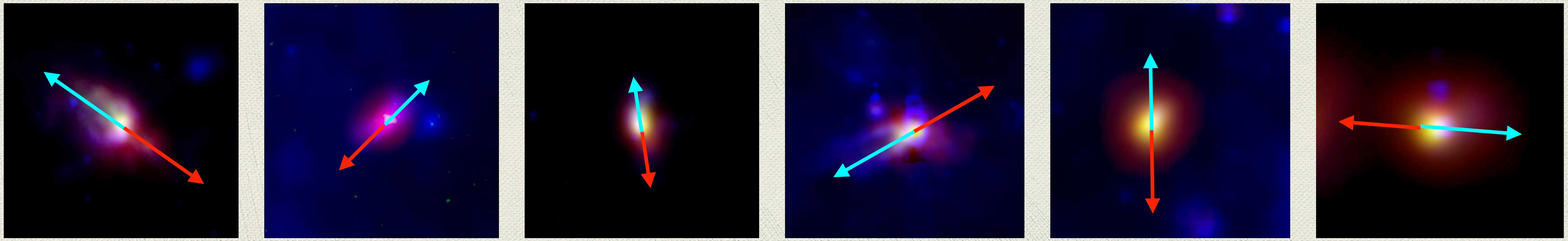
Outflow Cavity



Outflow Cavity

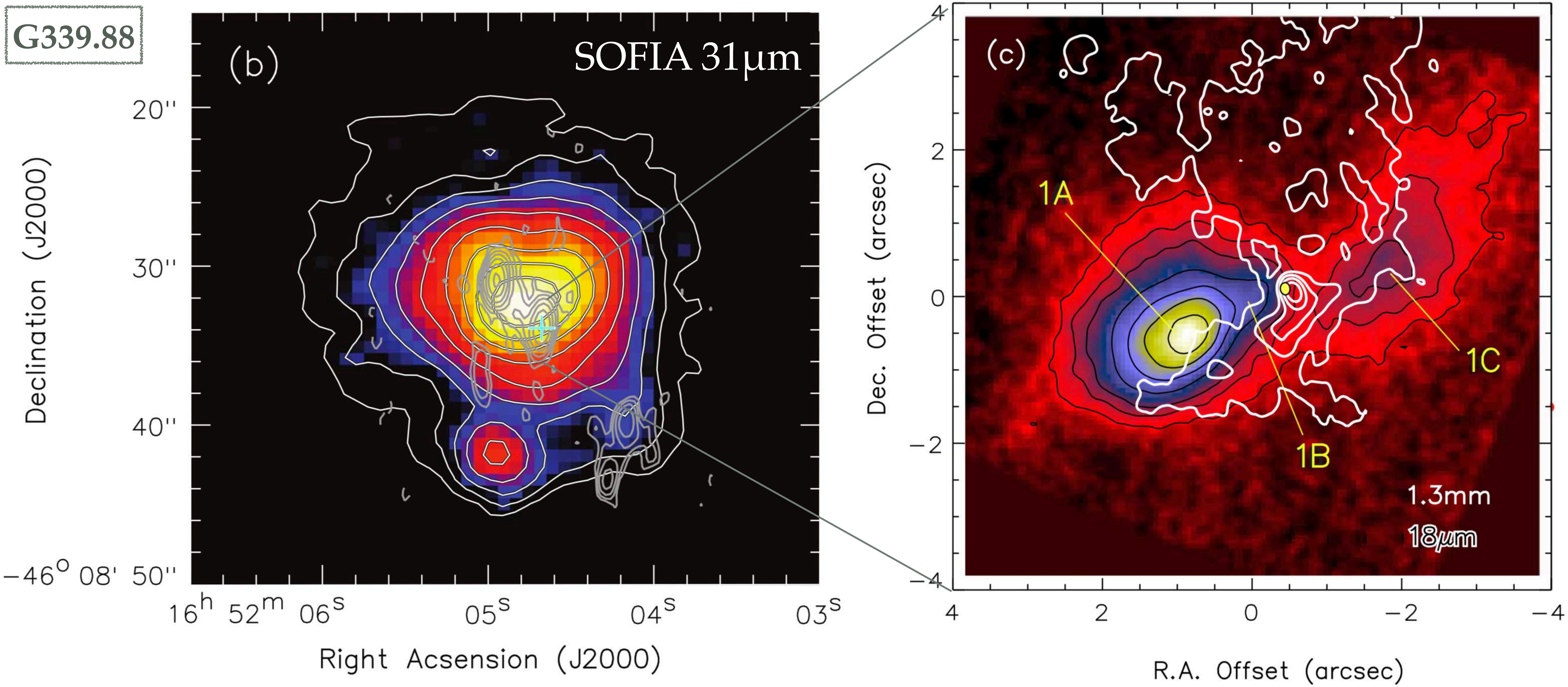
6 out of the 10 sources with known outflows:

- MIR/FIR extension aligns with outflows.
- Brighter emission at the blue-shifted side at short wavelengths.



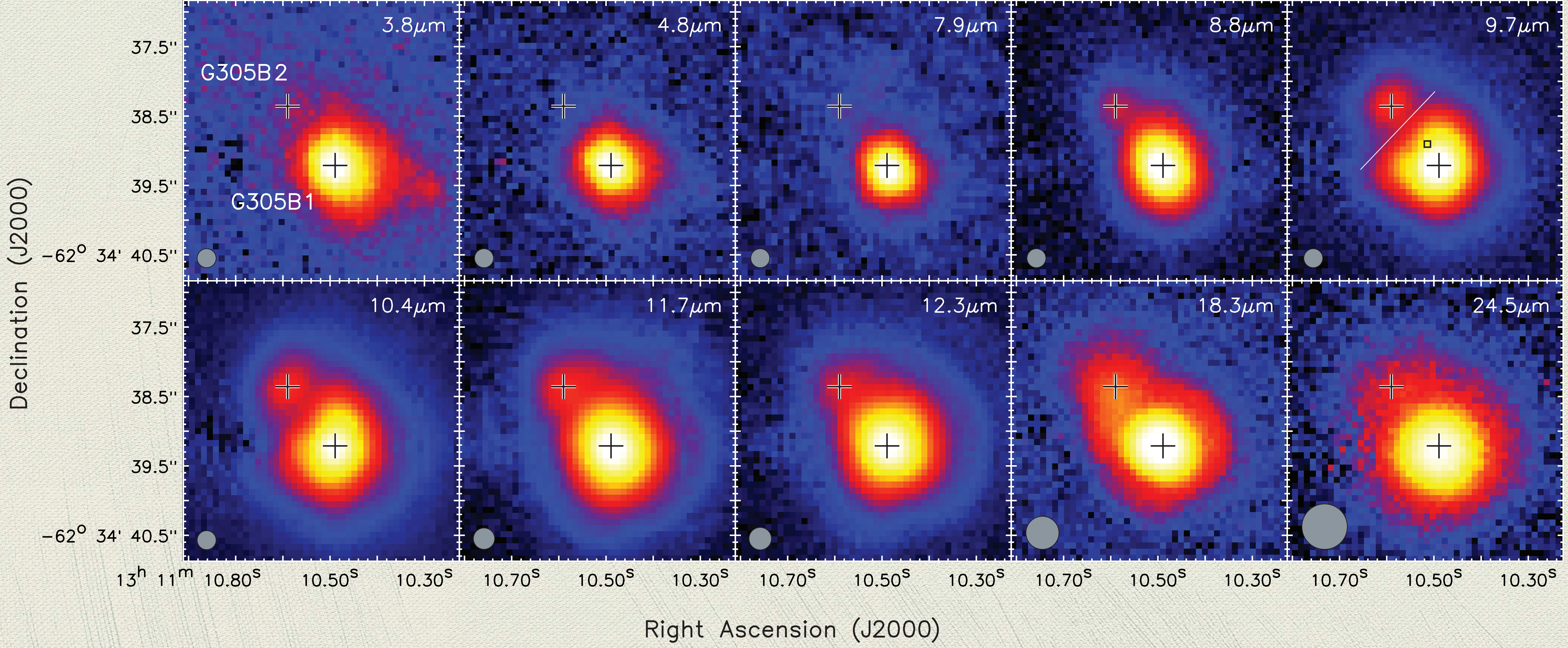
Extinction

G339.88



Flared Disk Surface?

G305.20



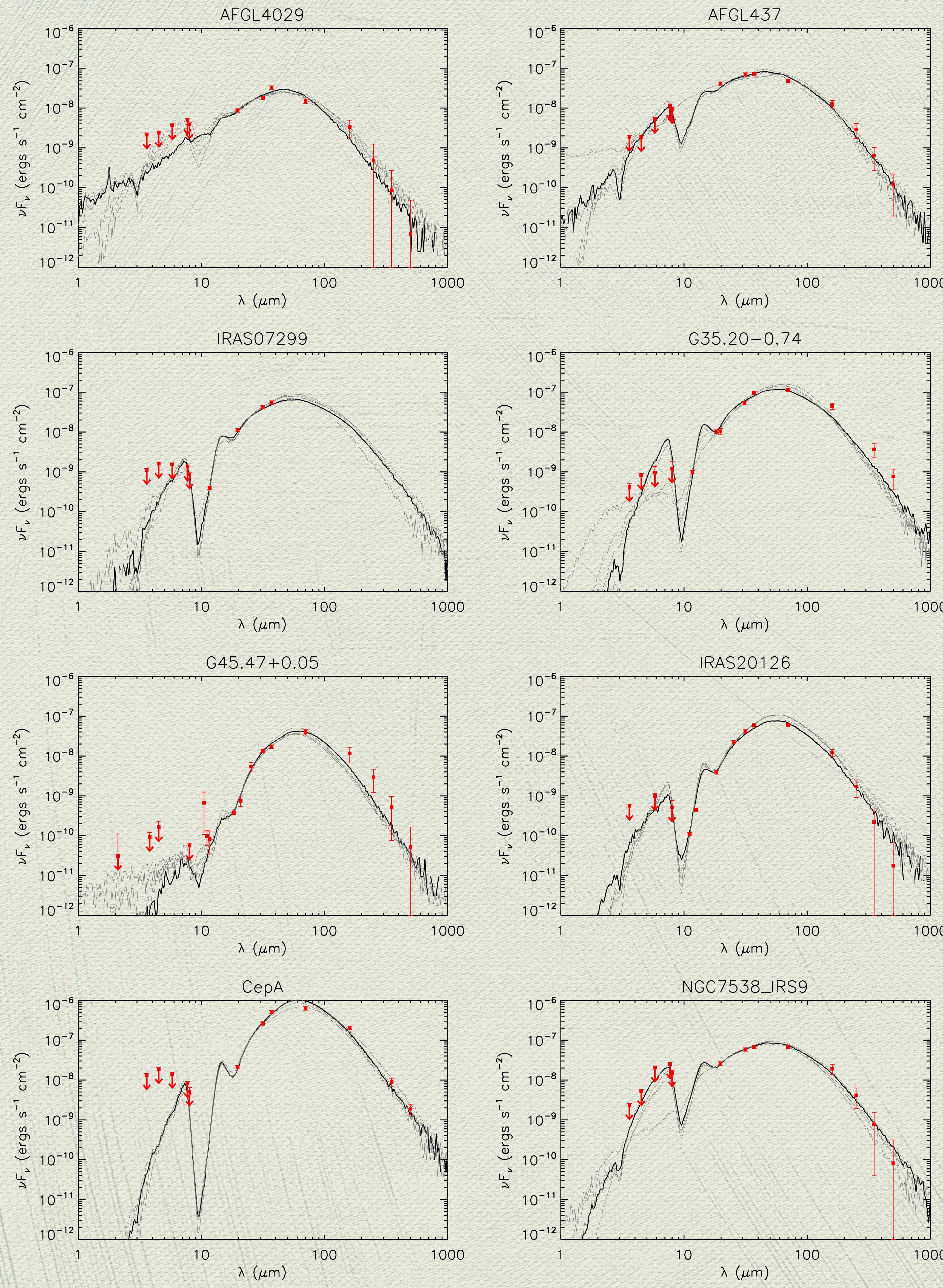
Do massive stars always form in clusters?

Multiplicity

14 MYSOs + 2 intermediate-mass YSOs

- Cluster: AFGL 437, Cep A, NGC7538-IRS9, G45.12, IRAS 16562, S235
- Binary: AFGL 4029, IRAS 07299
- Fragmentation: G35.20, G45.47
- Radio/IR companion: G309.92, G35.58, G305.20, G49.27, G339.88
- Multiple outflows (?): G45.12, IRAS 16562, G339.88

Validity of the SED fitting?


AFGL4029
AFGL437
IRAS07299
G35.20−0.74
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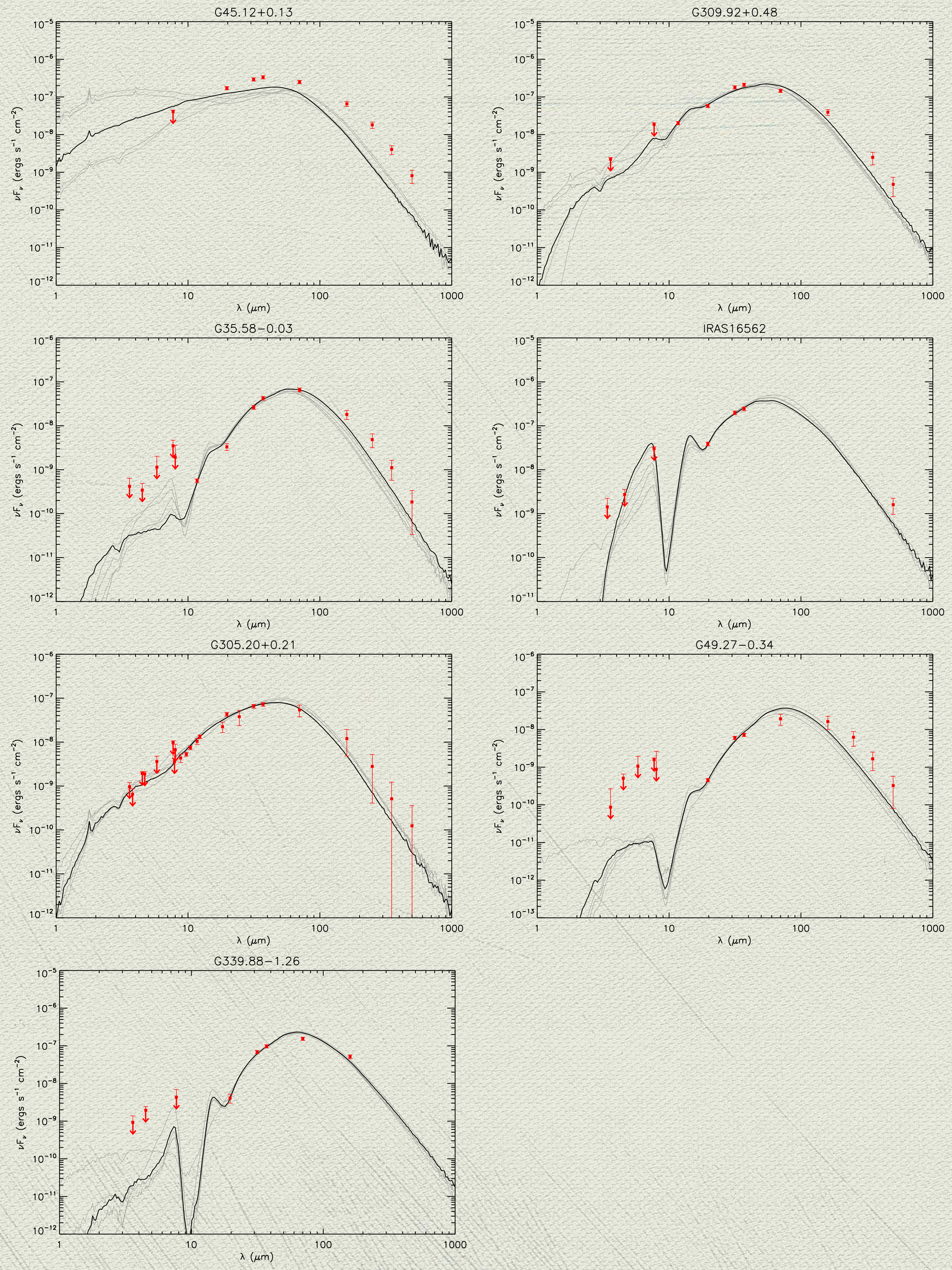
NGC7538_IRS9
νF_ν (ergs s^{-1} cm^{-2})
λ (μm)
1
10
100
1000
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}

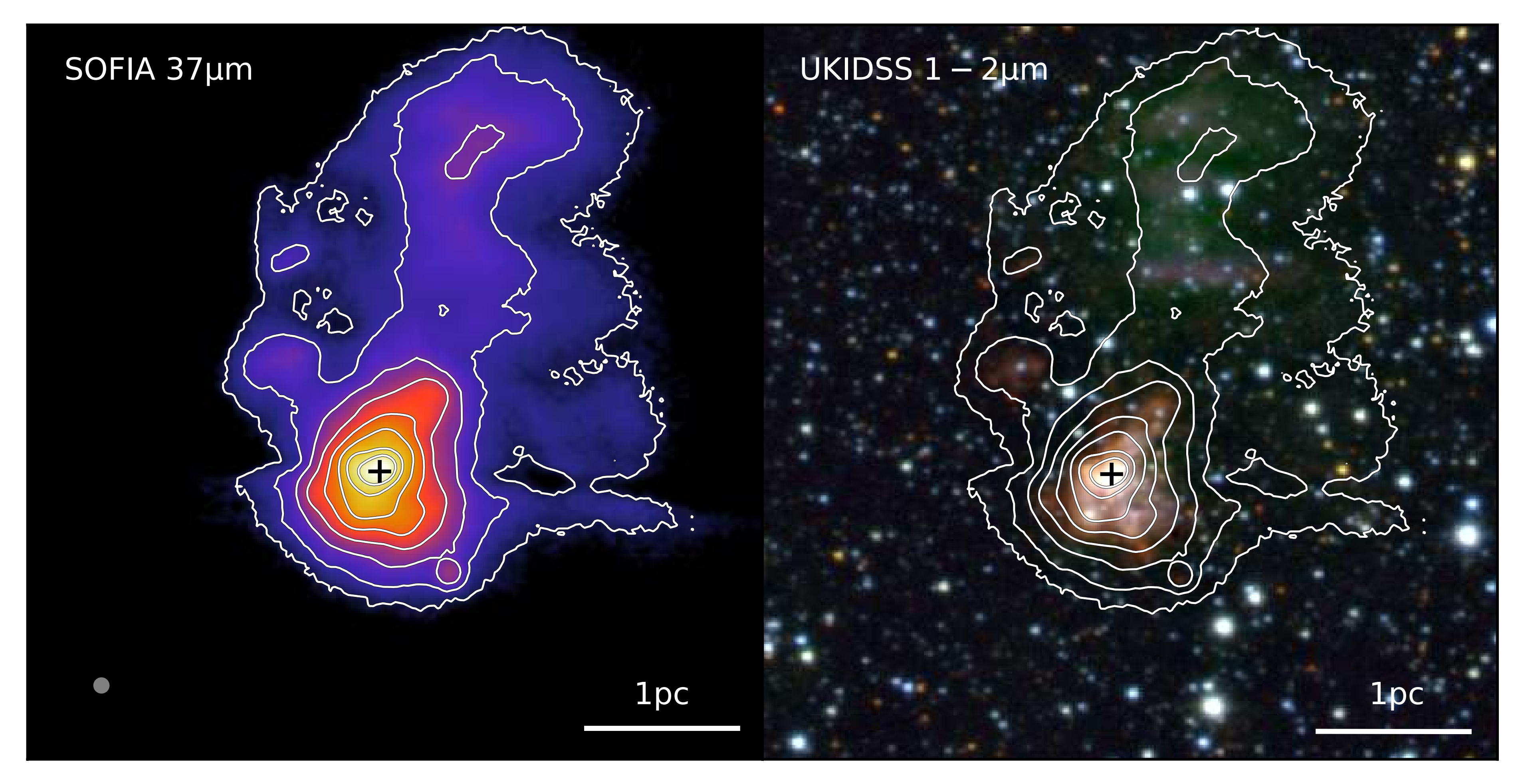

G45.12+0.13
G309.92+0.48
G35.58−0.03
IRAS16562
G305.20+0.21
G49.27−0.34
G339.88−1.26
νF_ν (ergs s^{-1} cm^{-2})
λ (μm)
1
10
100
1000
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}

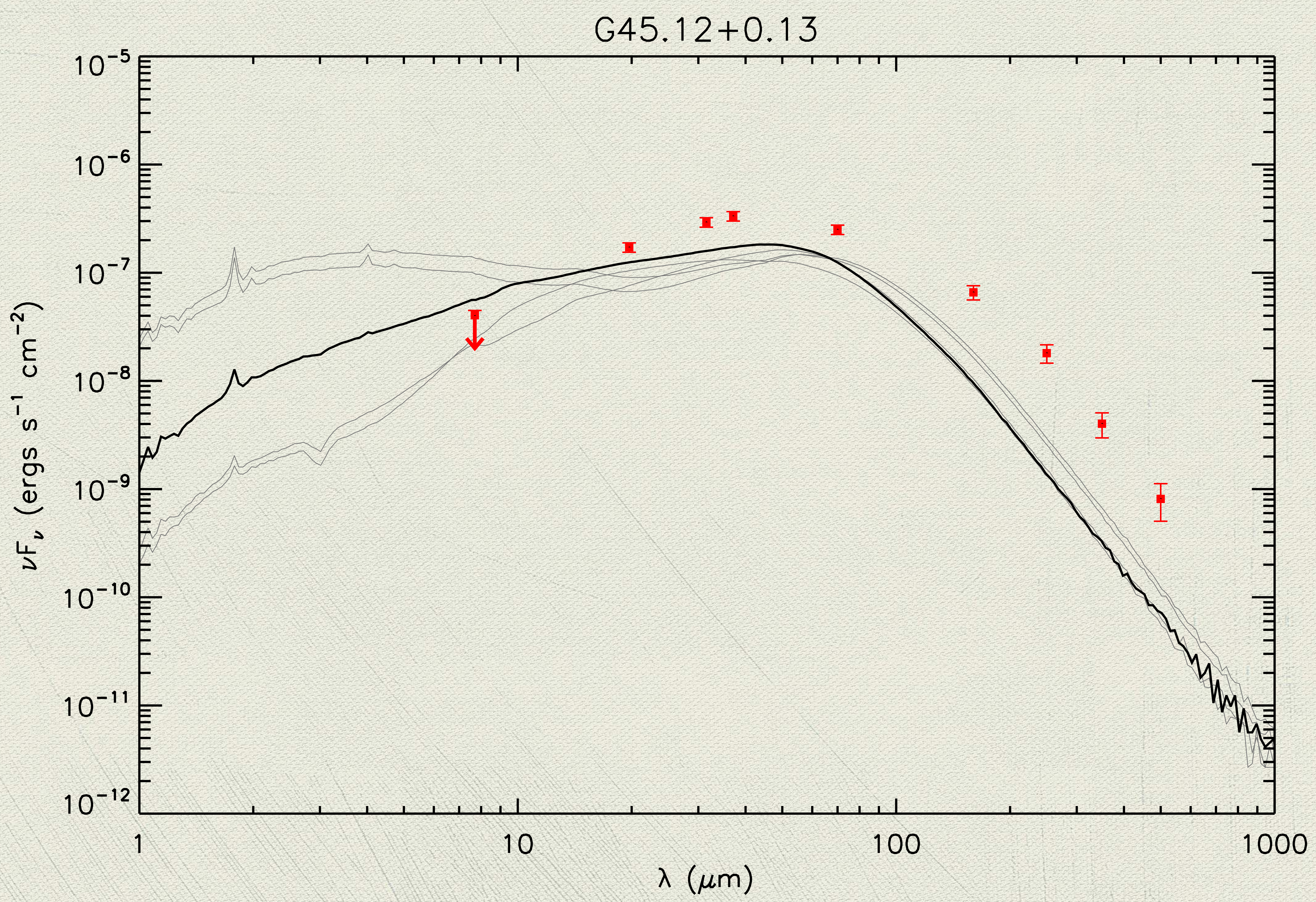
Comparison with Robitaille et al. (2006) models

- Widely used for fitting low-mass protostars
- 14 free parameters
- Lead to disk accretion rates $\dot{m}_*$ about 100x smaller, and consequently higher m_*, much lower Av, or more face-on views.

Limitations of ZT models

- Hit the model limits
- Clustered environment

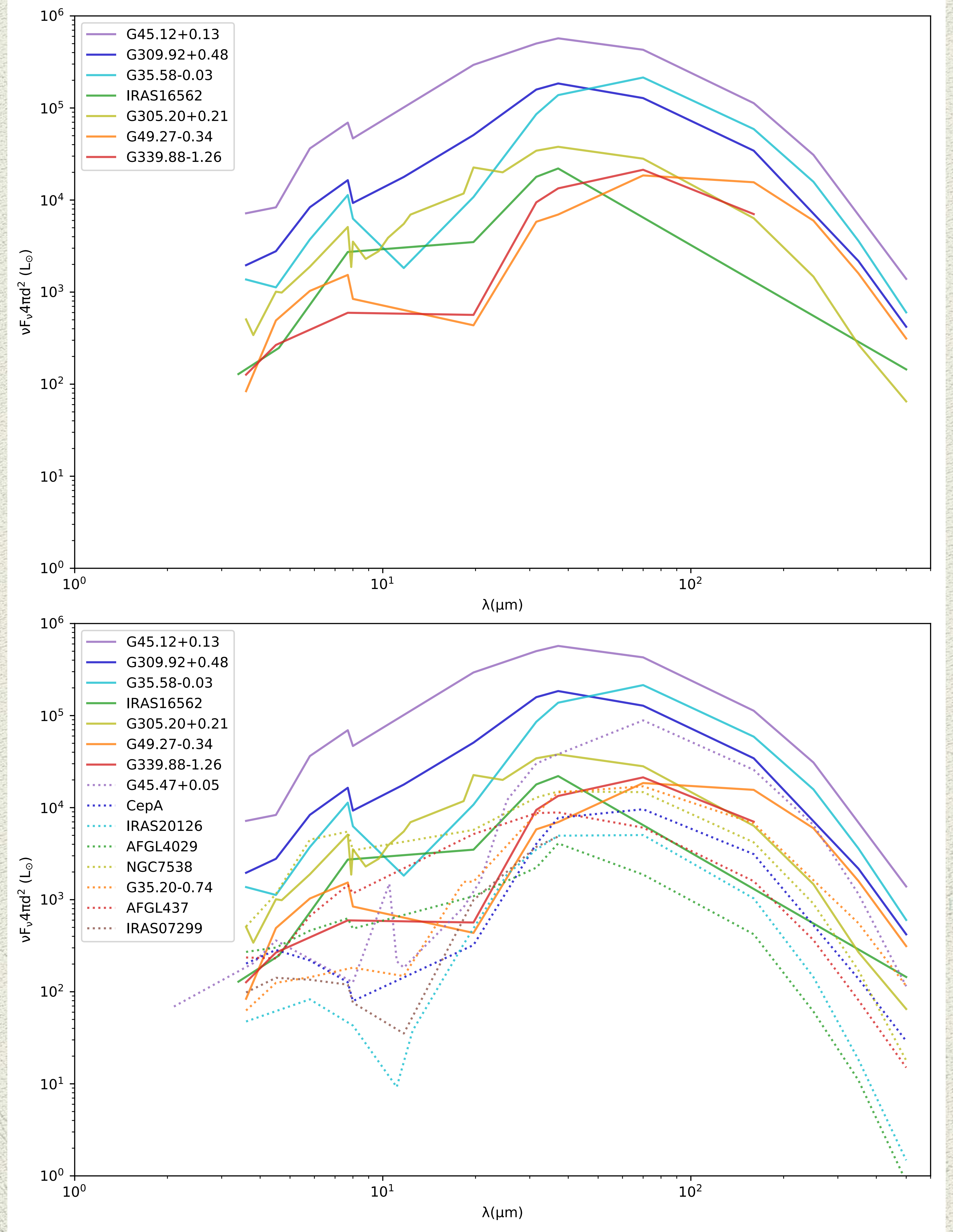




Trend in the SED shape?

SED Shape

- When the viewing angle is close to the outflow opening angle, a relatively flat slope at short wavelengths results.
- More evolved protostars tend to peak at relatively shorter wavelengths.
- No obvious relations between SED shape and bolometric luminosity.

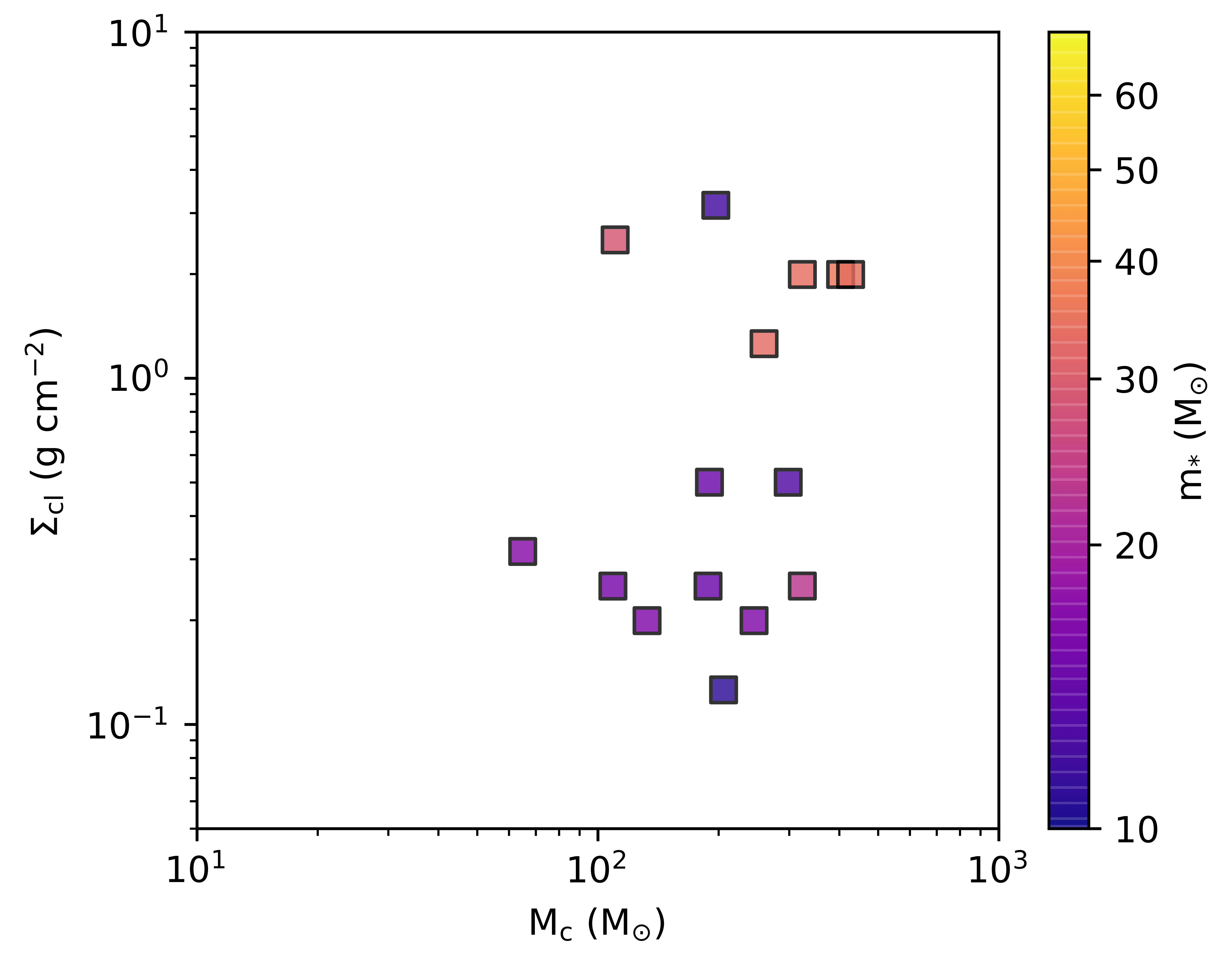


Dependence on Environment?

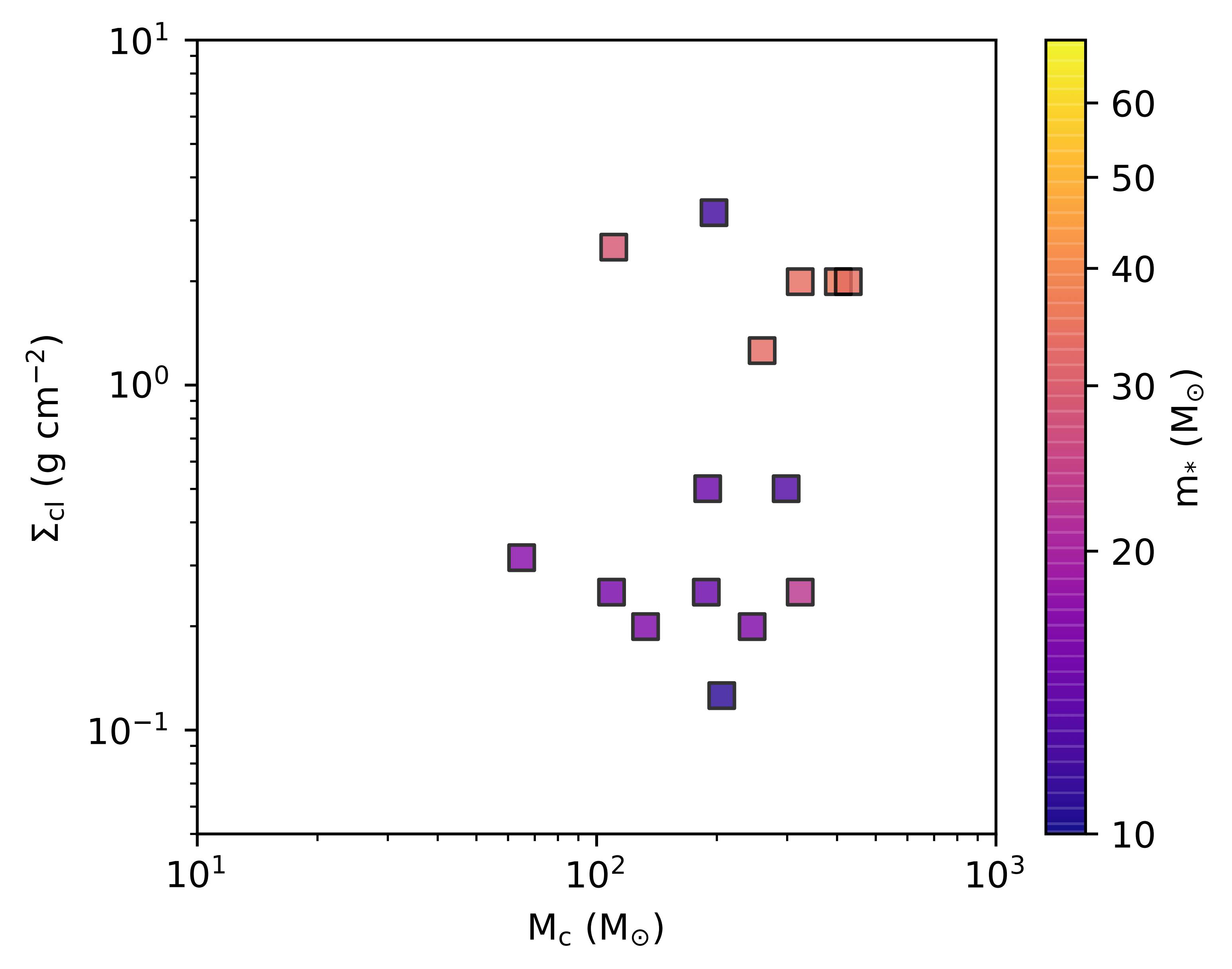
M_c vs. Σ_{cl} vs. m_*

Geometric mean values
of best 5 models

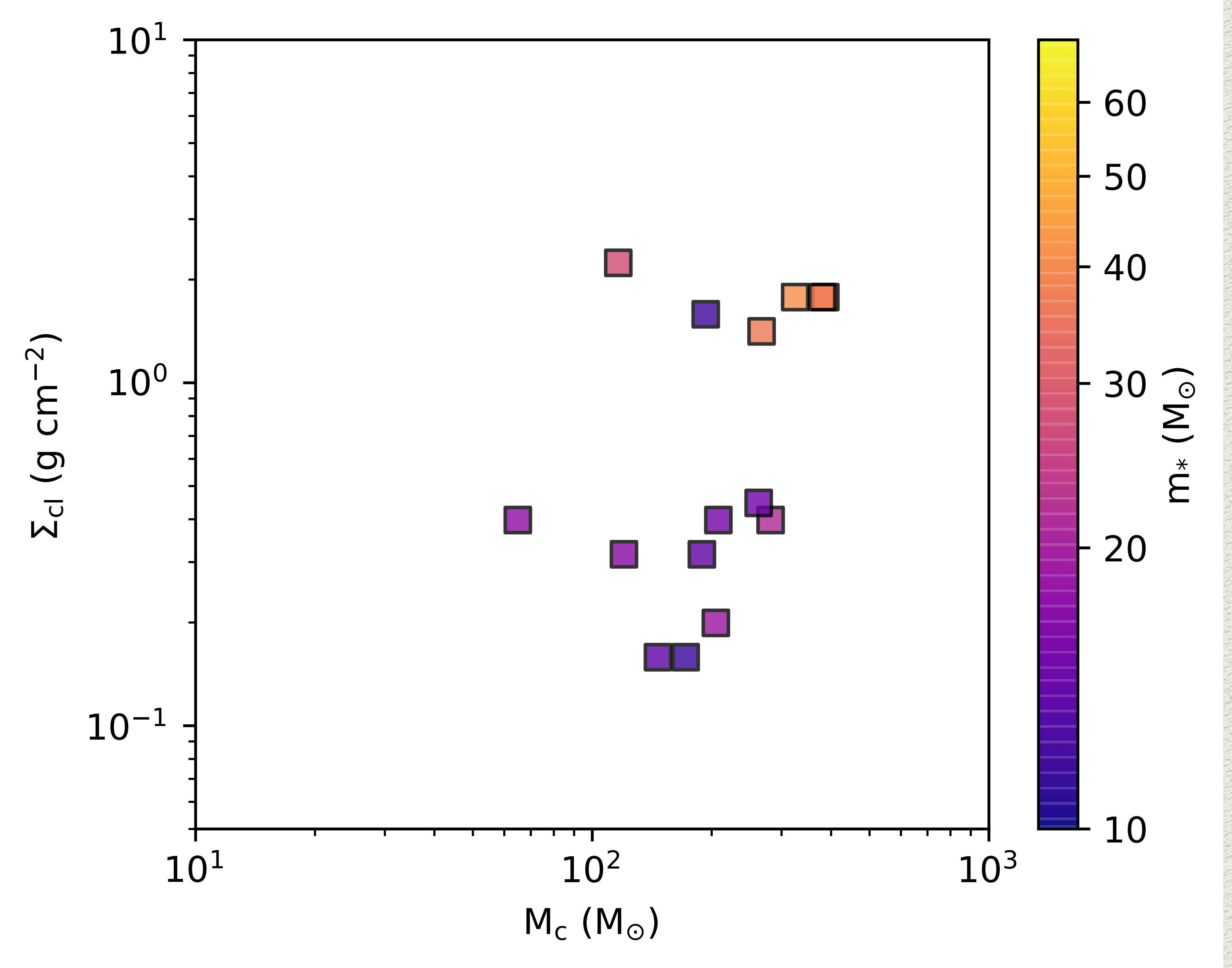
(Liu+ 2019)



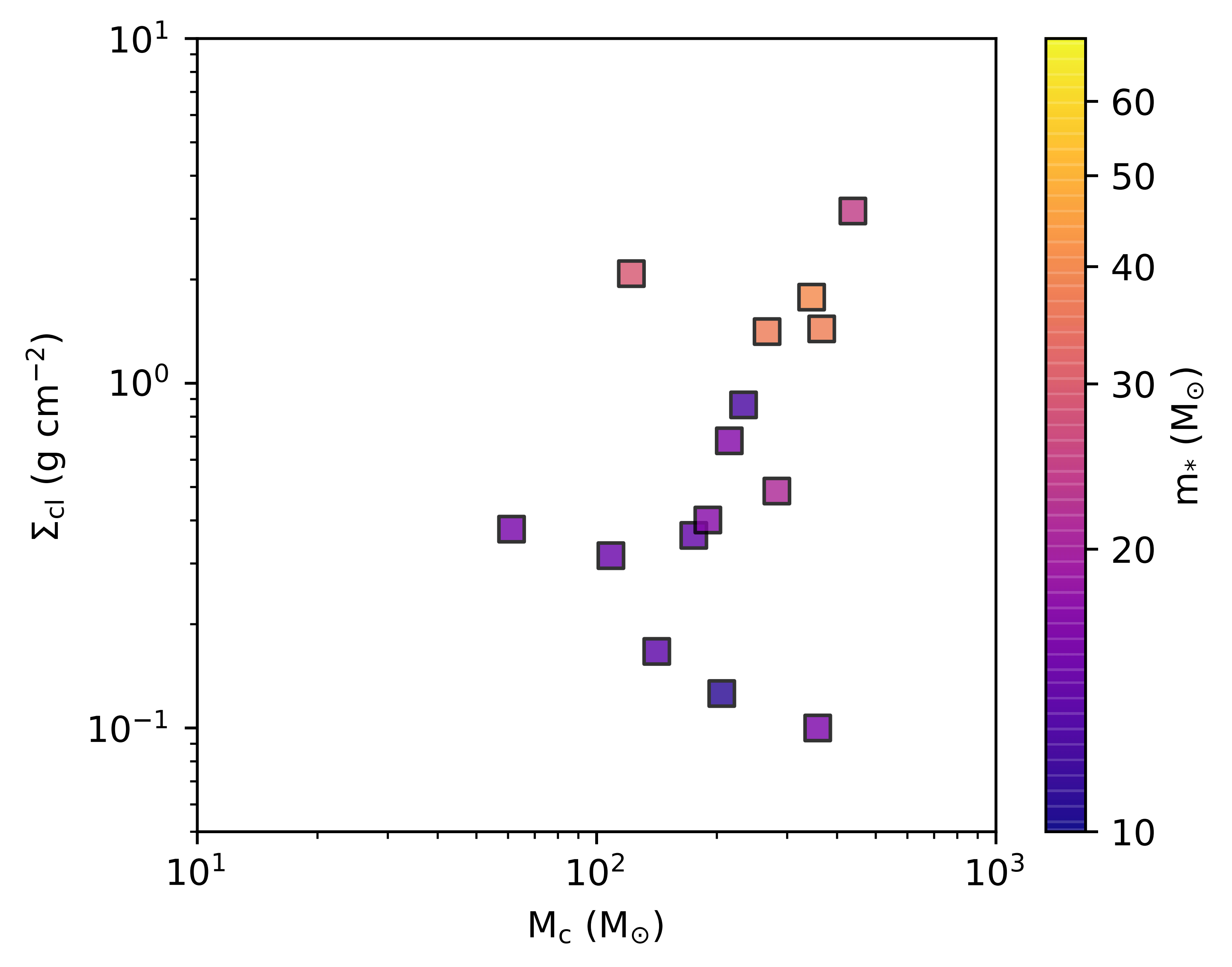
best 5 models



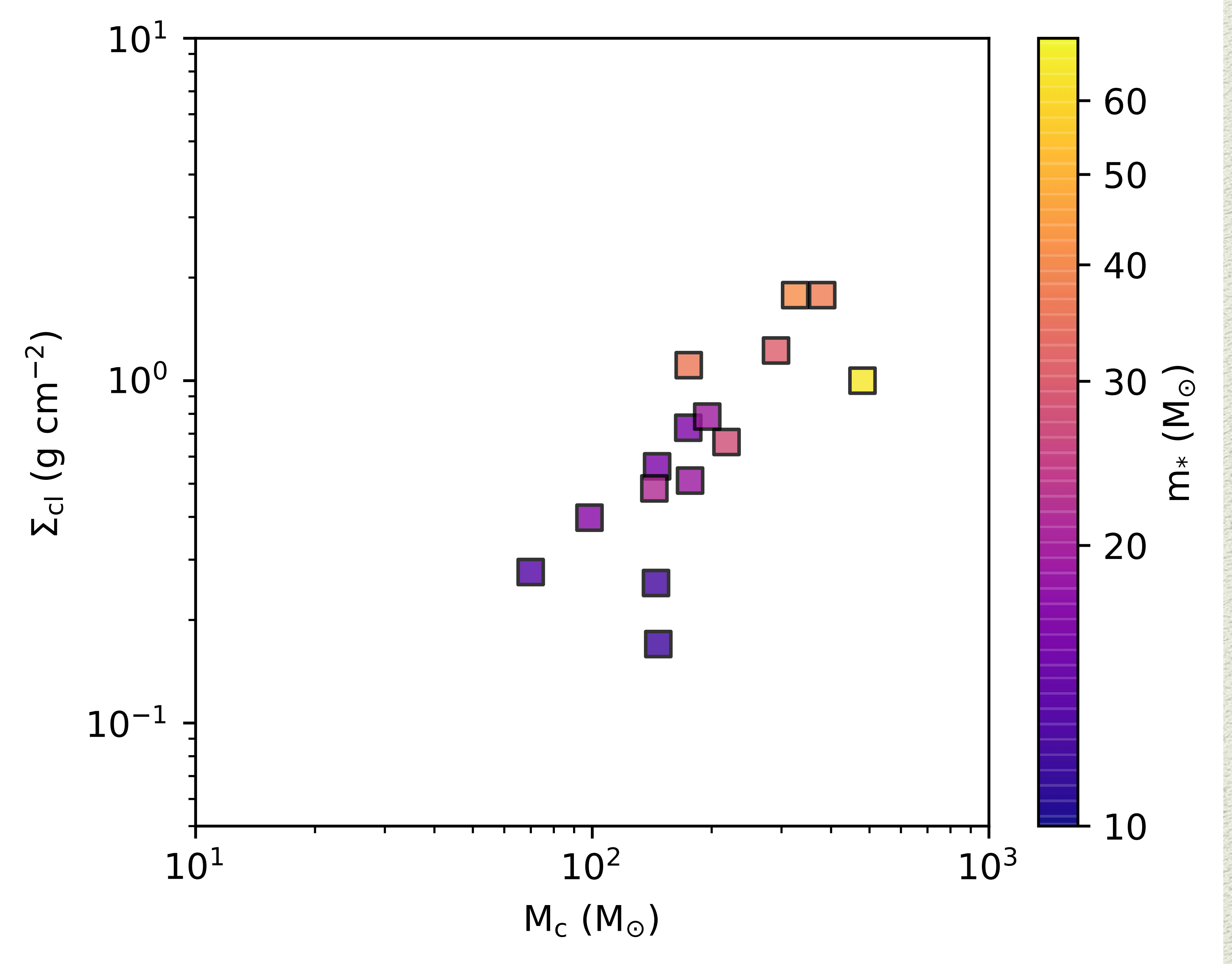
best 10 models



$\chi^2 \leq 2\times\chi^2_{\mathrm{min}}$

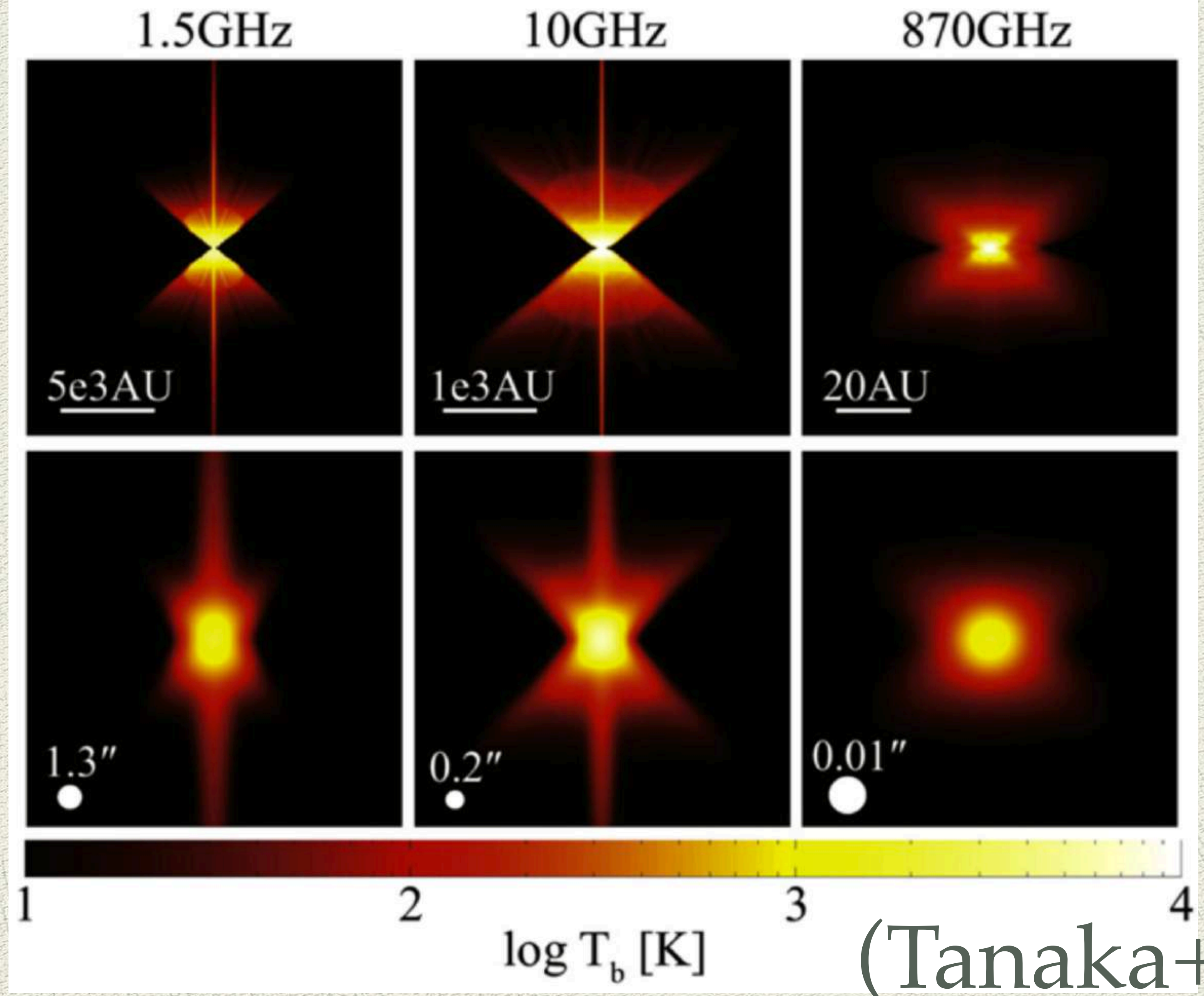


$\chi^2 \leq \chi^2_{\mathrm{min}} + 5$

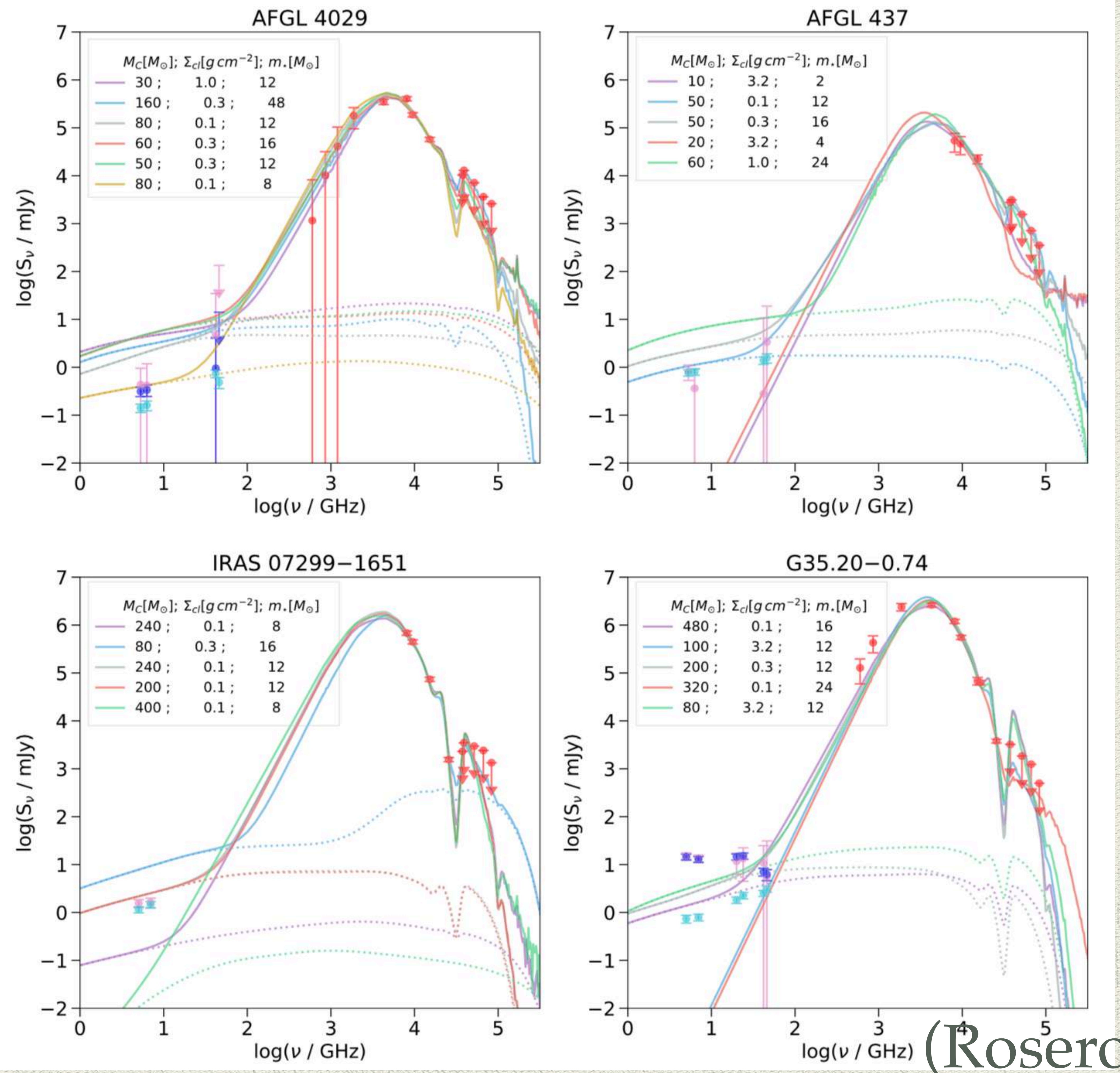


Breaking the Degeneracy

- Include disk-wind feedback
- Free–free radio emission from the ionized outflow



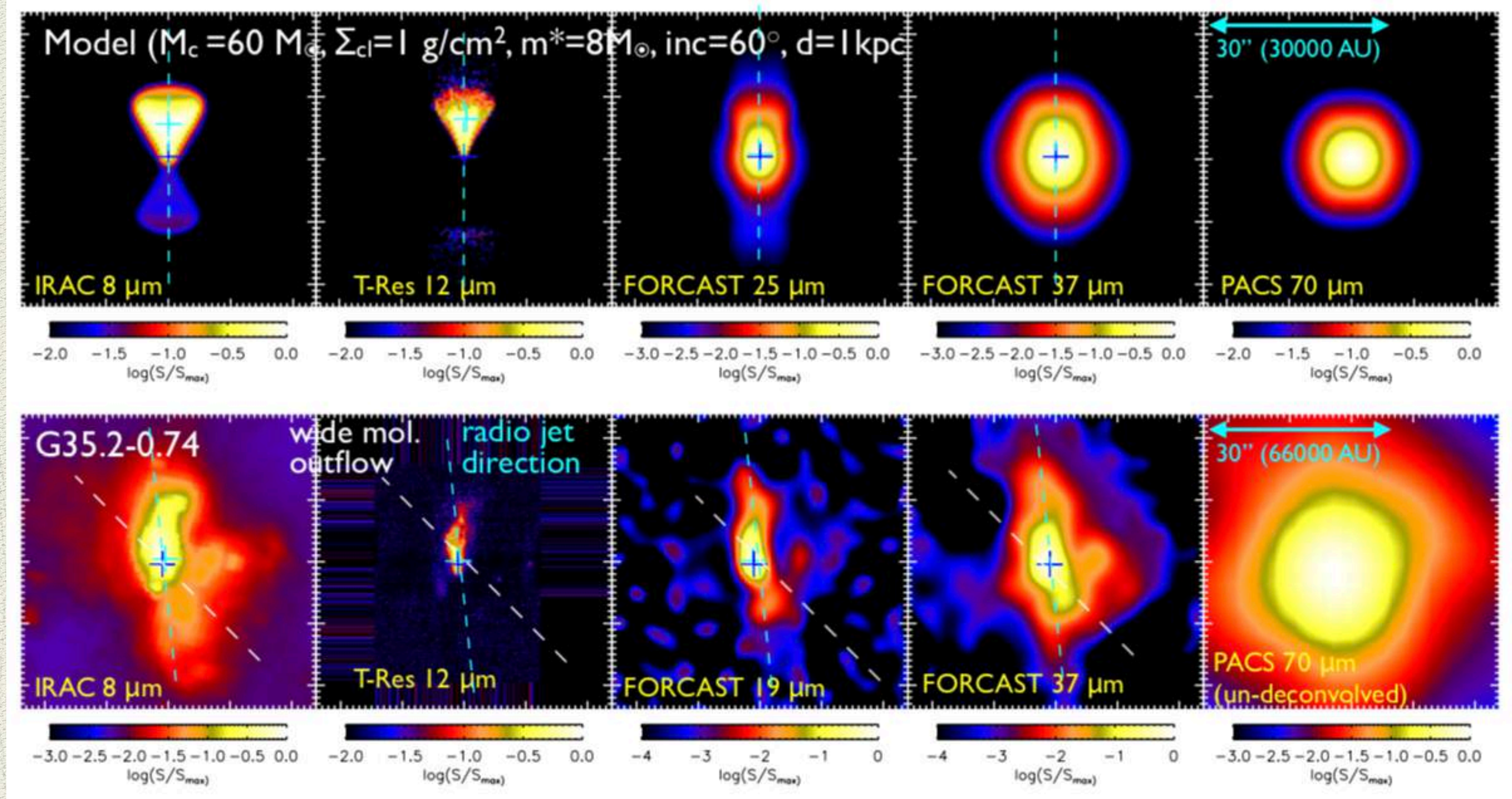
(Tanaka+ 2016)



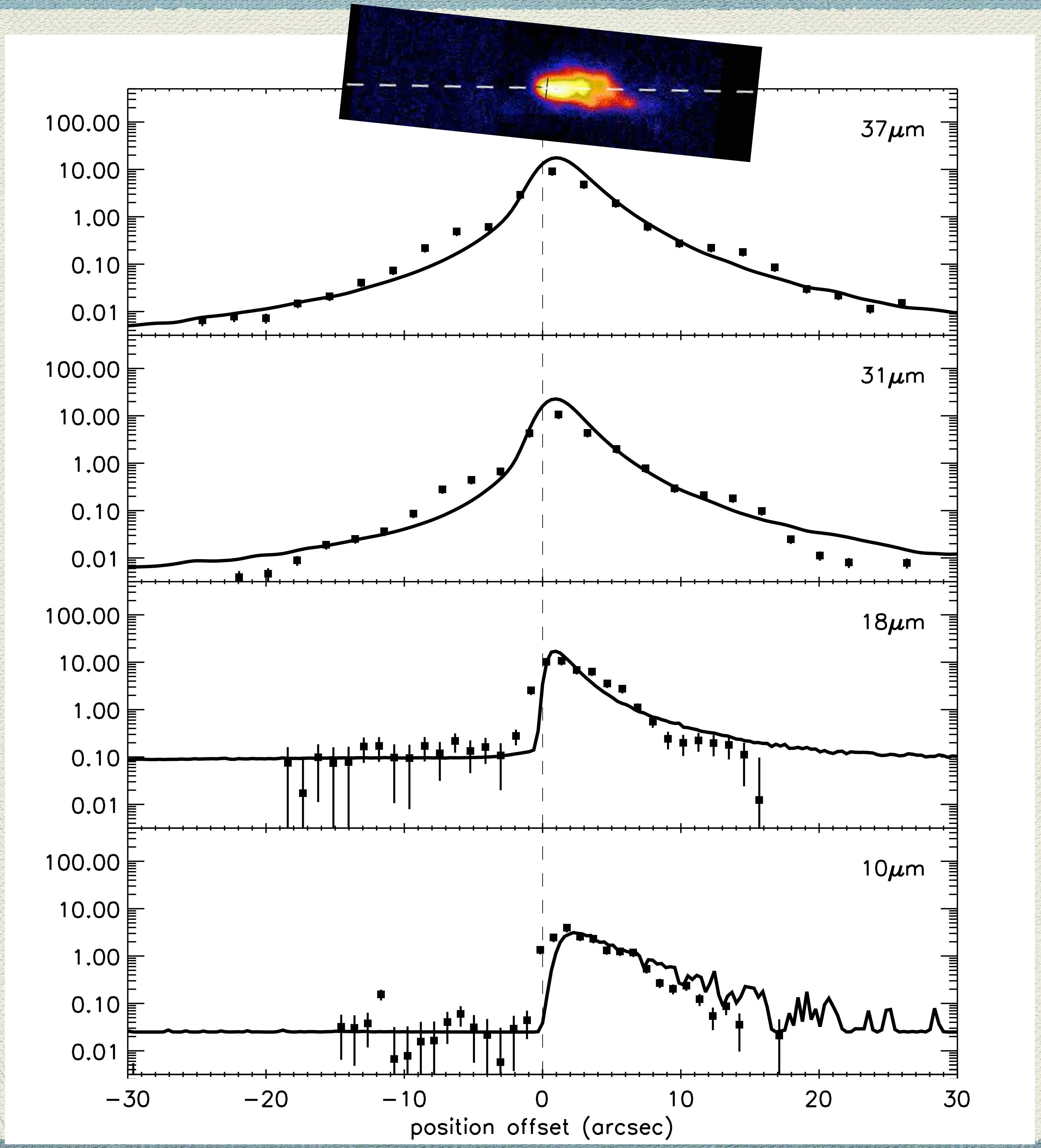
(Rosero+ 2016)

Breaking the Degeneracy

- Image intensity profile fitting

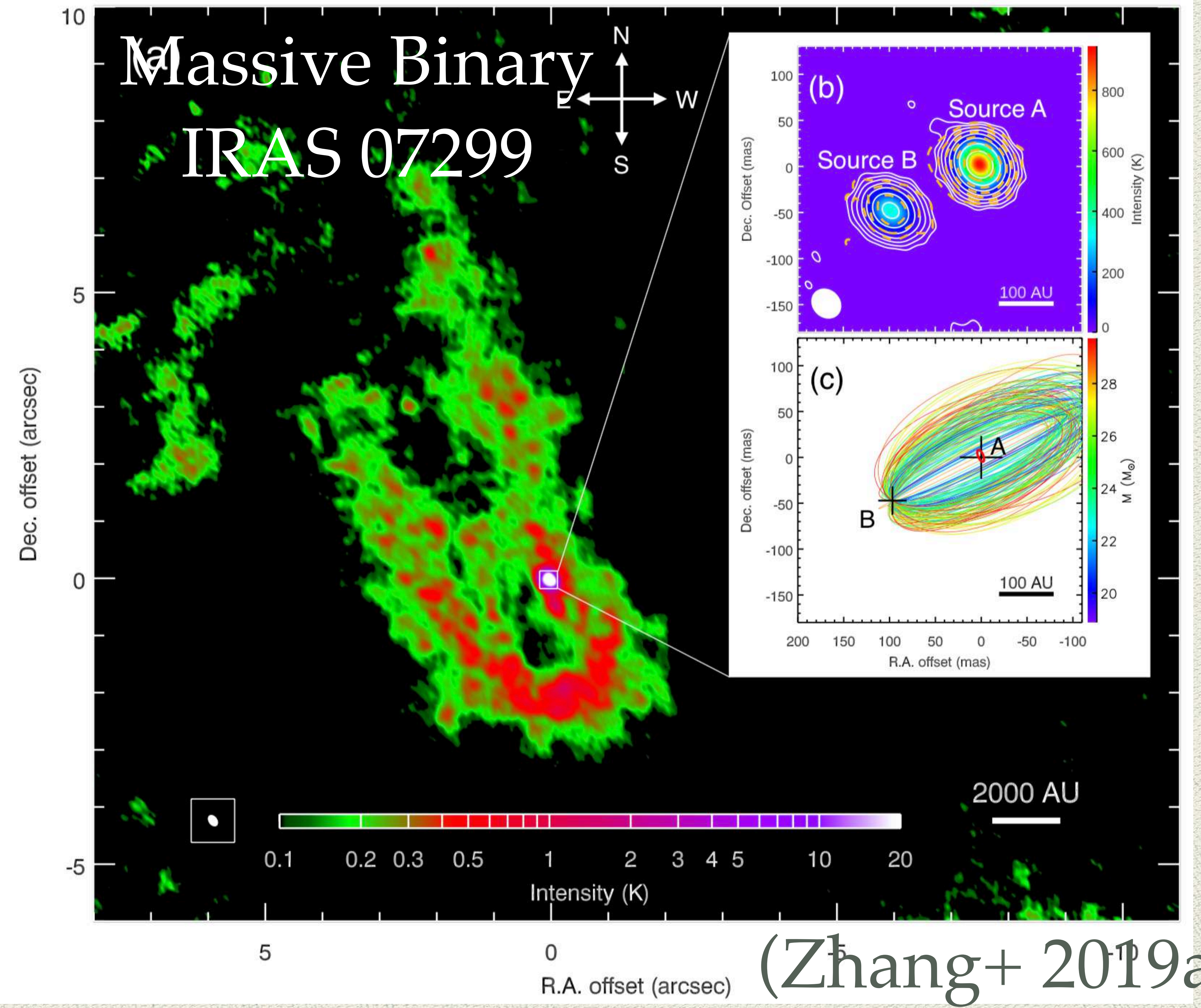


(Zhang et al. 2013)



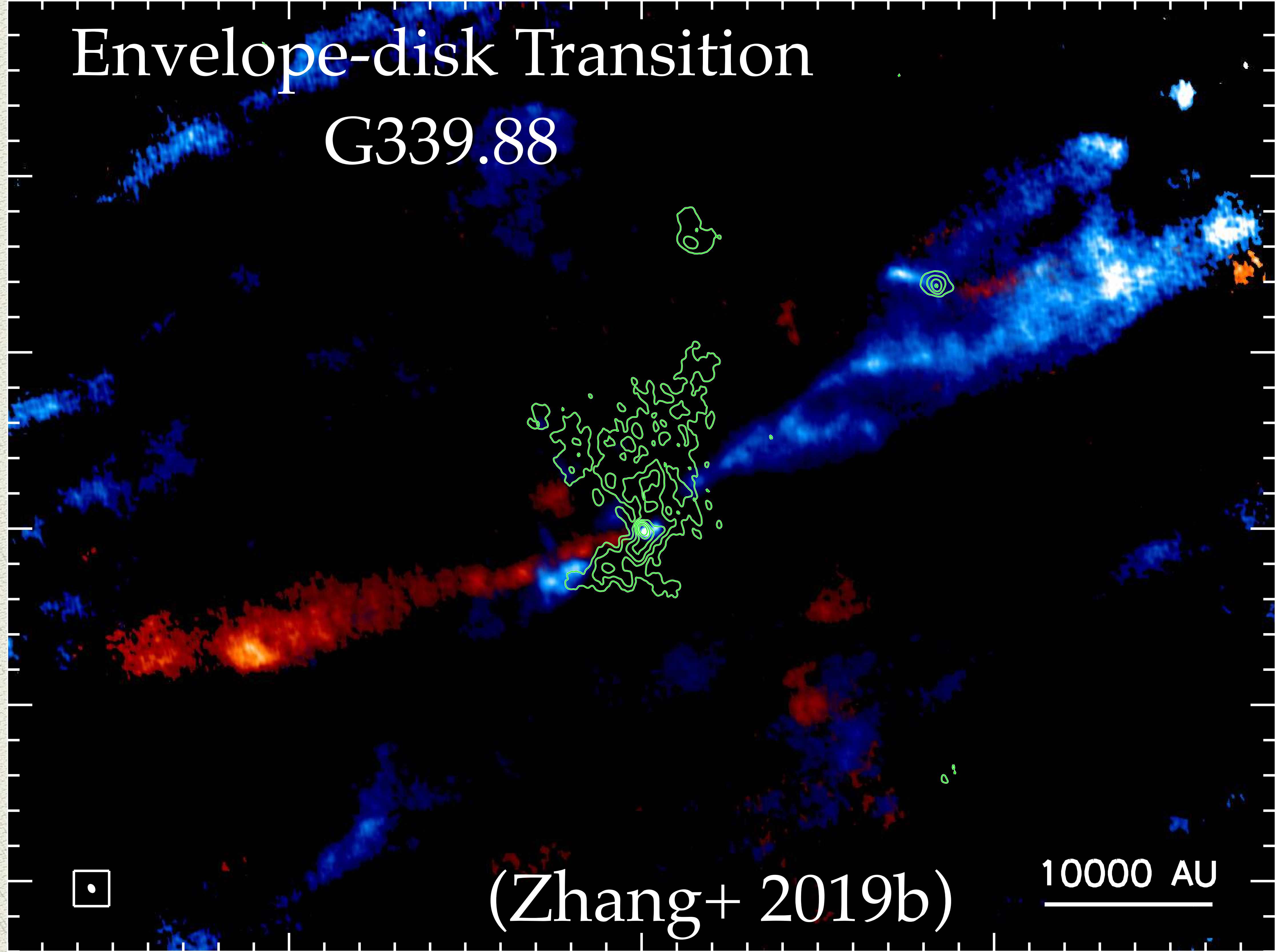
Breaking the Degeneracy

- ALMA follow-up to determine kinematics and multiplicity



Massive Binary
IRAS 07299

(Zhang+ 2019a)

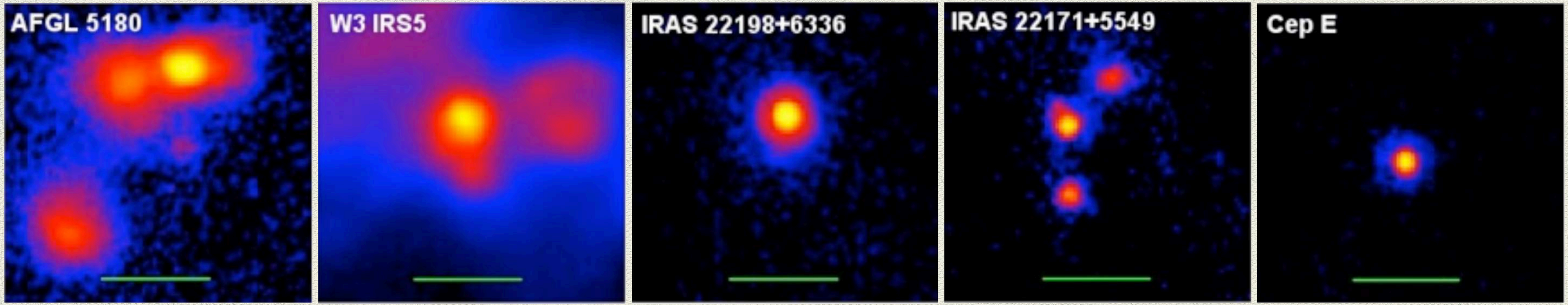


Envelope-disk Transition
G339.88

(Zhang+ 2019b)

Future Work

- Expanding the sample to >40 sources
- Do high-mass protostars and intermediate-mass protostars share similar morphology?
- How do these properties vary with environment?
- Does the outflow cavity opening angle increase with evolutionary stage?



SOFIA 37μm image

Scale bar: 30″

Summary I

- We aim to obtain the 10-40μm images with *SOFIA-FORCAST* of ~50 high- and intermediate-mass protostars to test theoretical models. So far 41 sources have been observed, and 15 sources have been published.
- MIR/FIR morphology is largely influenced by outflow cavities and dust extinction, as expected by the Turbulent Core Accretion model.
- RT models based on the Turbulent Core Accretion scenario can reasonably well fit the SEDs of most sources, but may not be valid for very crowded regions.

Summary II

- Clump mass surface density Σ_{cl} does not need to be very high to form massive stars.
- Millimeter observations, radio extended SED fitting, and image intensity profile fitting will help break the degeneracy of the physical parameters.
- With more sample of protostars toward the intermediate-mass end, together with the high-mass sample, we will soon fully characterize the variation of star formation across environment, evolution, and the mass regime.

Thanks!