FORCAST's View of the Serpens South Protostellar Core

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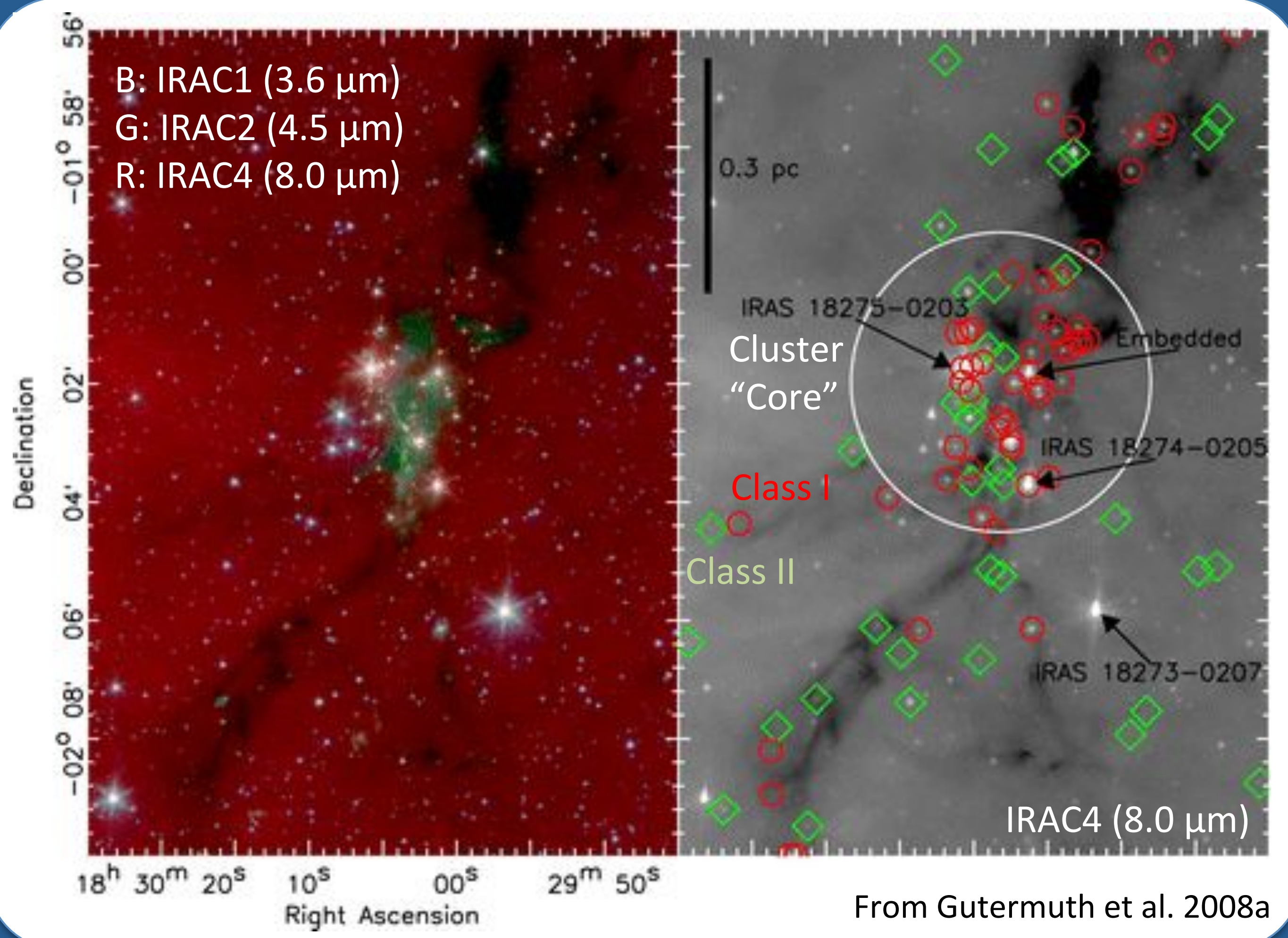
Slide 02

Serpens South Protocluster

Discovered by Gould's Belt Spitzer Legacy Team (Gutermuth et al. 2008a, ApJL, 673)

Embedded cluster associated with filamentary cloud

Adopted distance of 415± 25 pc (Dzib et al. 2010)



From Gutermuth et al. 2008a

In this field…

54 Class I

37 Class II

In the cluster core…

37 Class I

11 Class II

Unusually high

$$\frac{\text{Class I}}{\text{Class I+II}} = 77\%$$

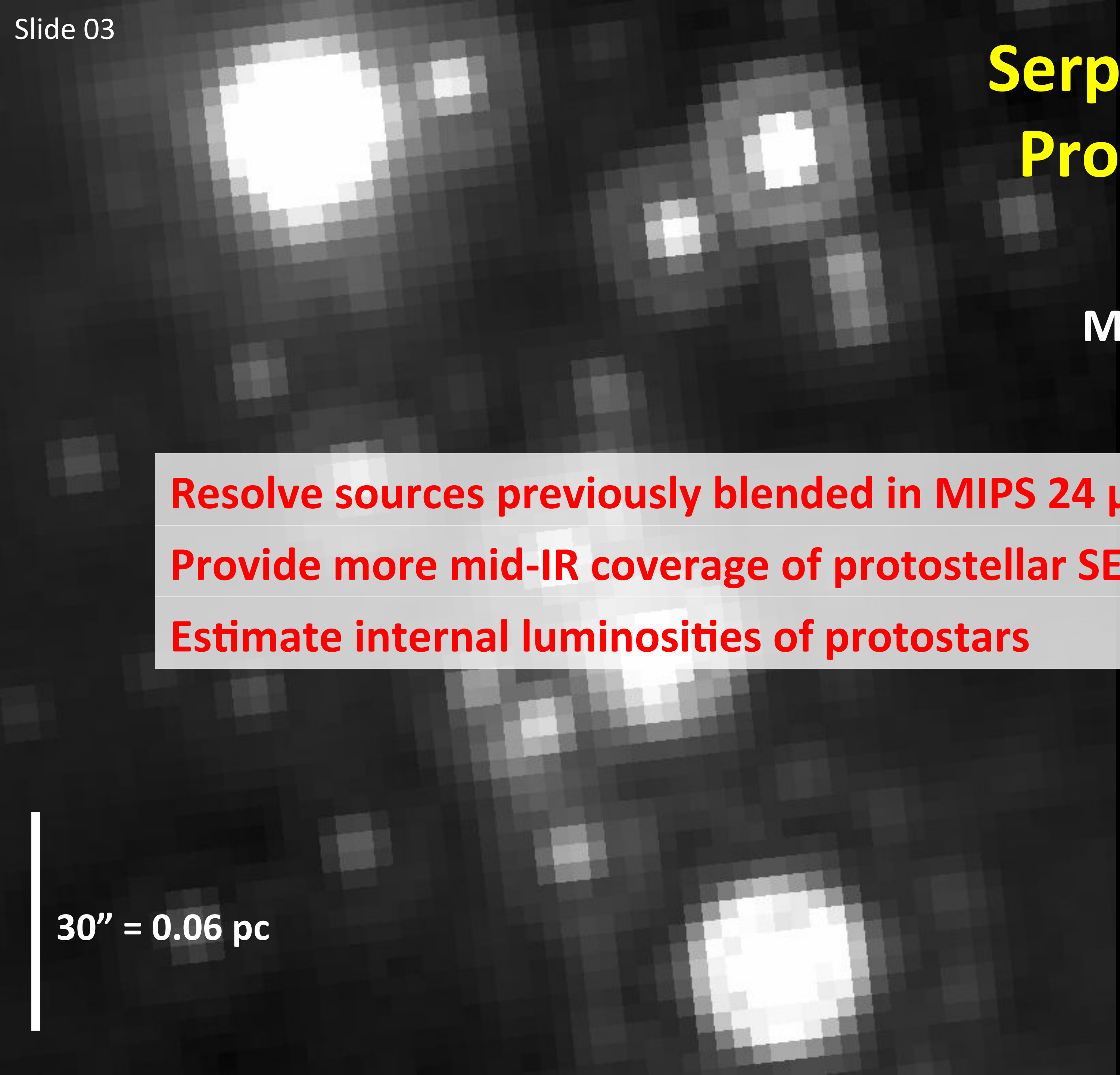
Serpens Main: 57%

NGC 1333: 29%

(Gutermuth et al. 2008b, ApJ, 674)

Serpens South Protocluster

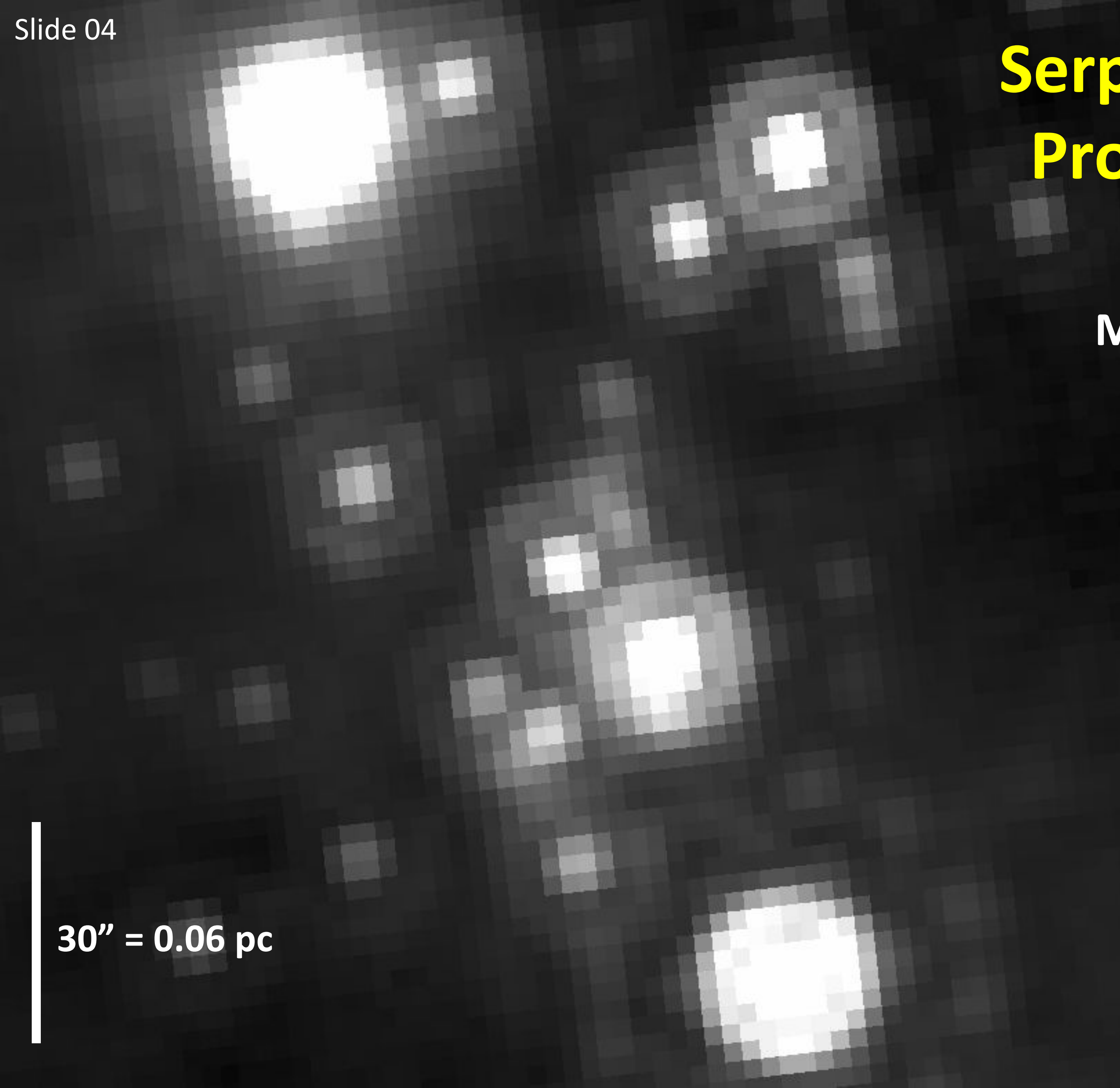
MIPS 24 µm



- Resolve sources previously blended in MIPS 24 µm
- Provide more mid-IR coverage of protostellar SEDs
- Estimate internal luminosities of protostars

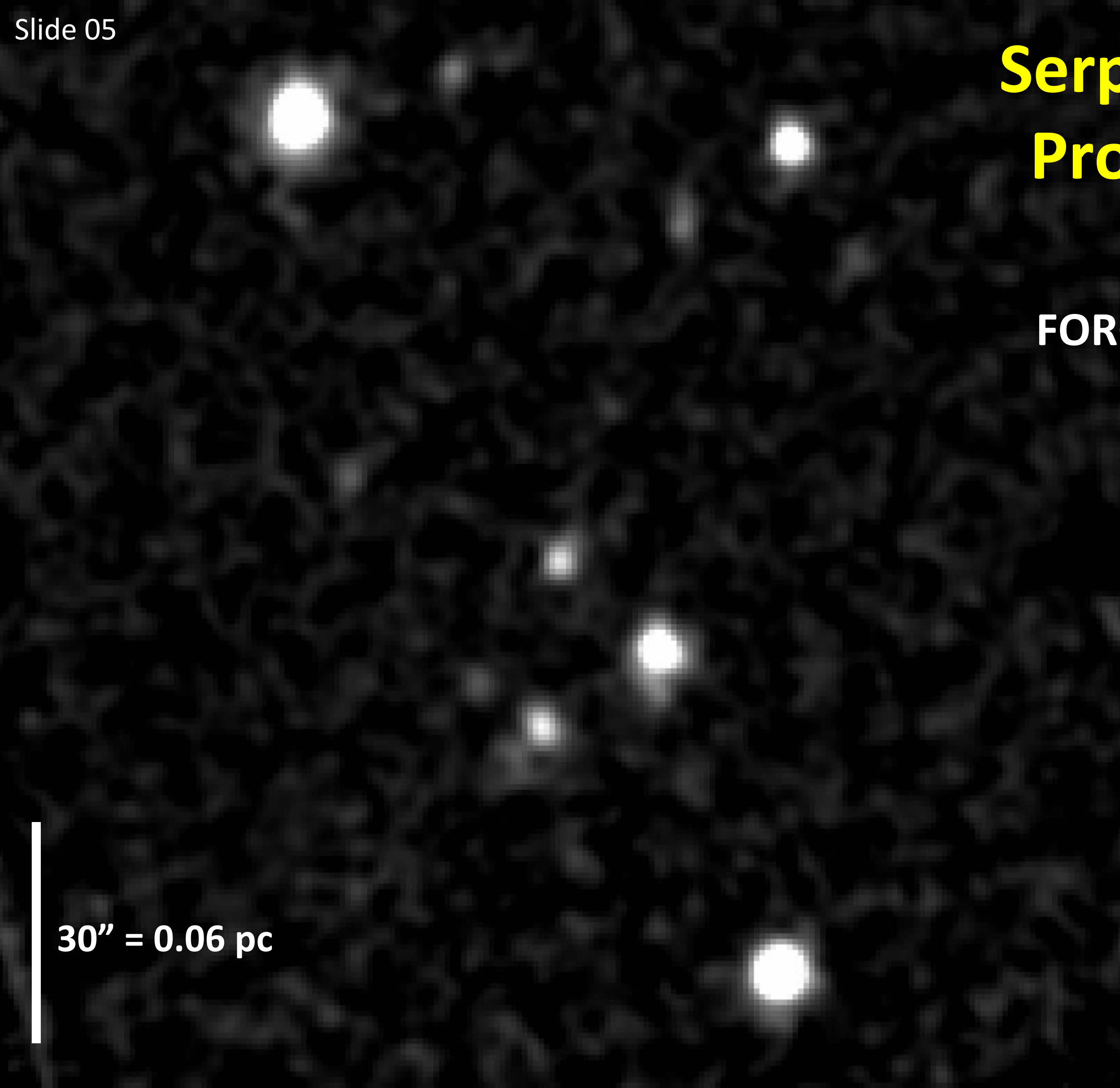
Serpens South Protocluster

MIPS 24 μm

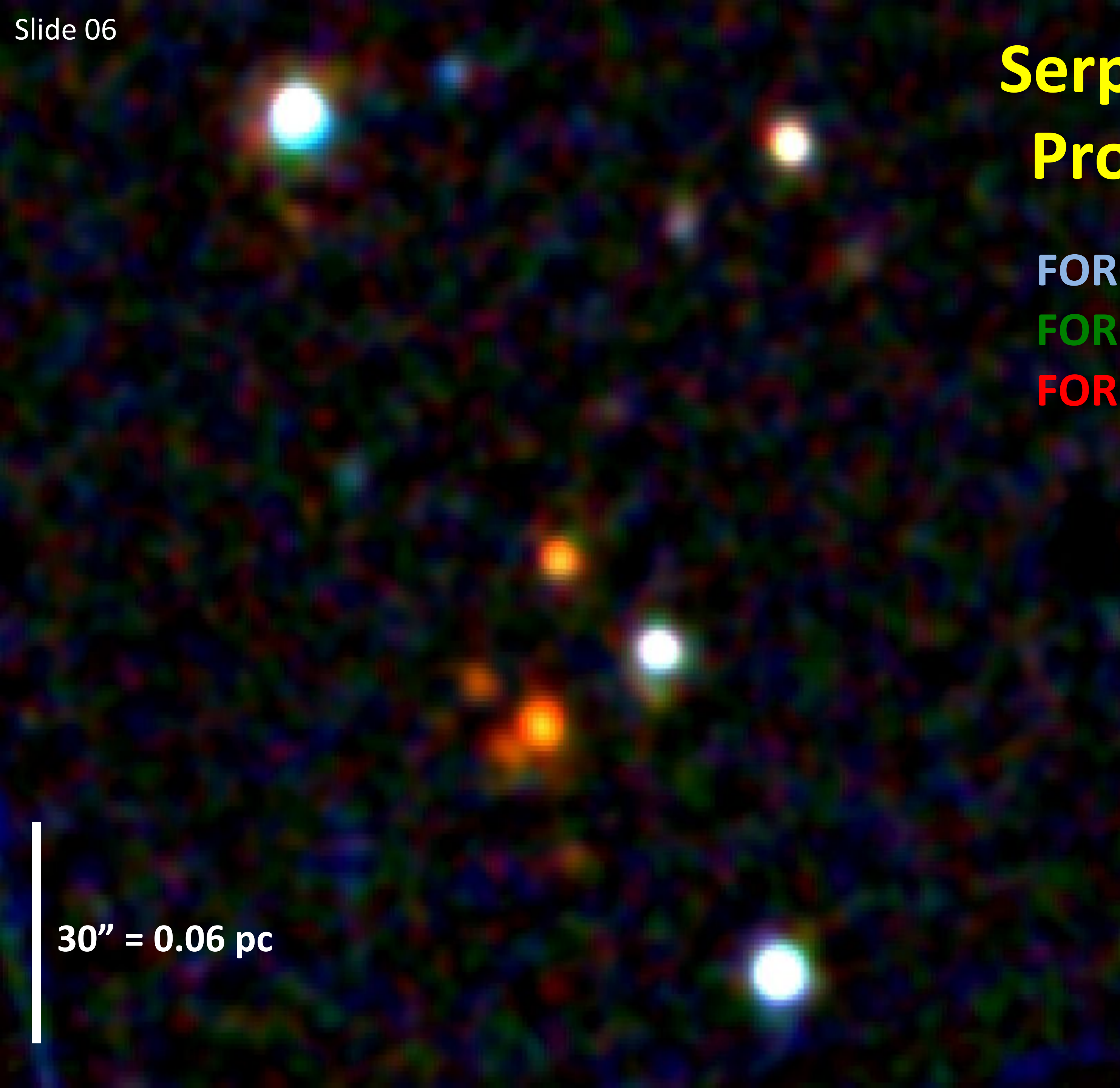


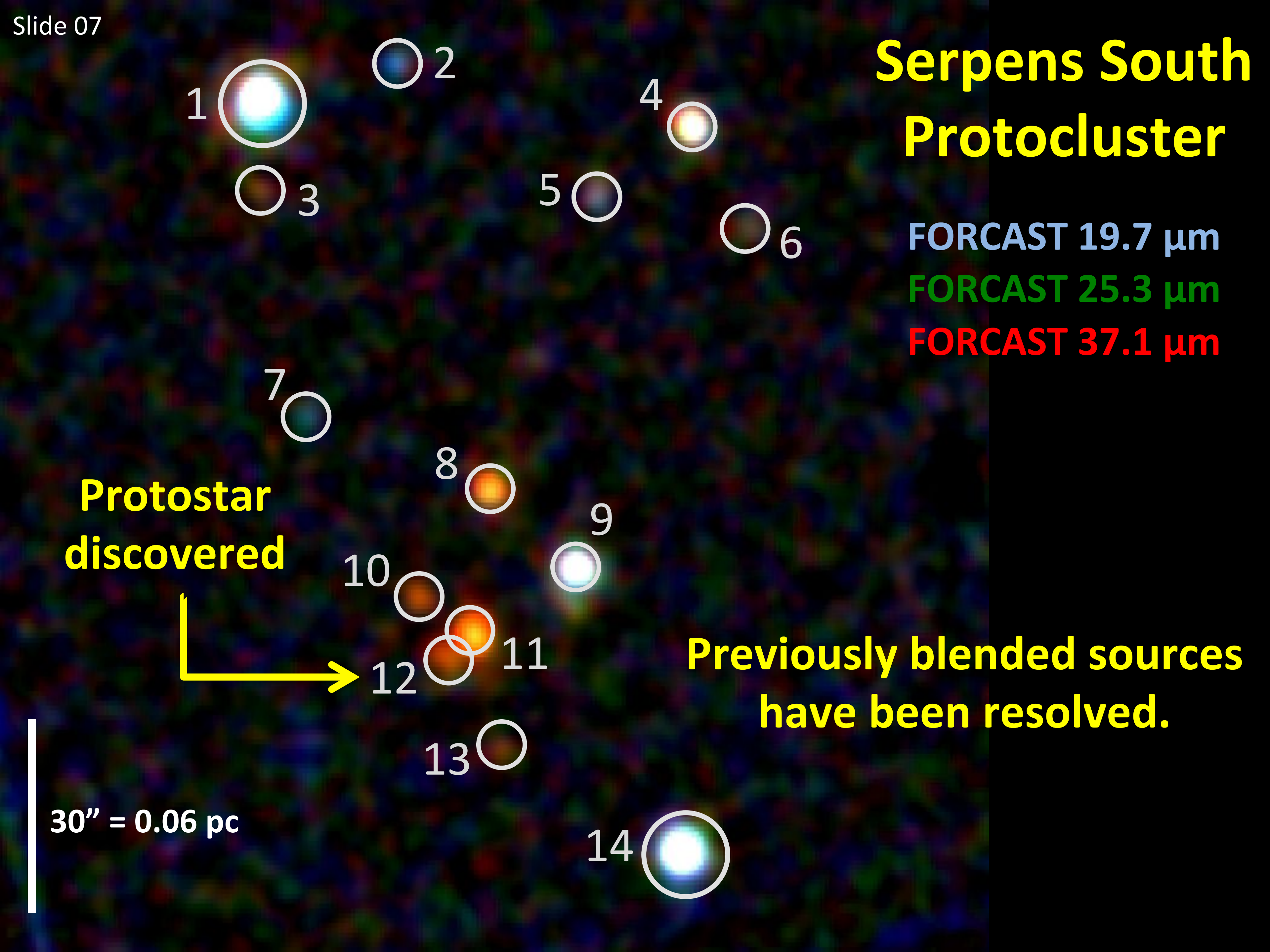
Serpens South Protocluster

FORCAST 25.3 µm



Serpens South Protocluster



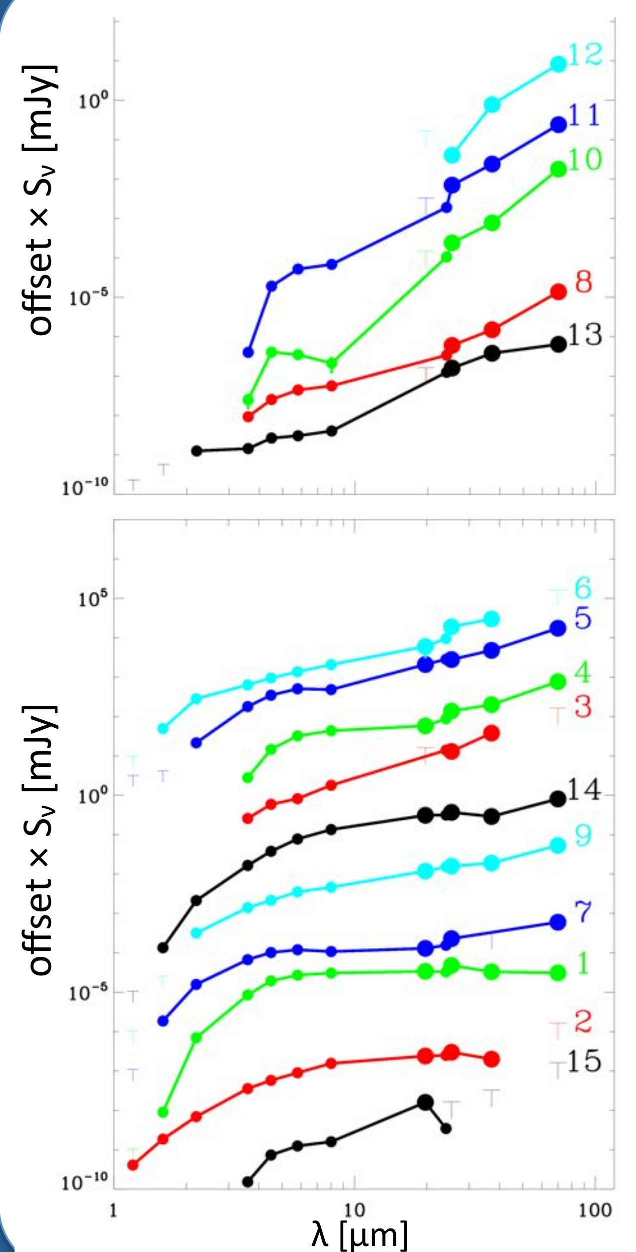

Slide 07
Serpens South Protocluster
FORCAST 19.7 µm
FORCAST 25.3 µm
FORCAST 37.1 µm
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Protostar discovered
Previously blended sources have been resolved.
30” = 0.06 pc

Slide 08

Serpens South: Flux Densities, SEDs

ID	Flux Densities, S_ν [mJy][a]				
	19.7 μm	24 μm	25.3 μm	37.1 μm	70 μm[b]
1	3390 ± 90	3300 ± 300	4800 ± 100	3300 ± 100	3100 ± 400
2	240 ± 30	250 ± 20	300 ± 50	*200 ± 70*	< 1000
3	< 100	140 ± 20	*130 ± 50*	380 ± 80	< 1000
4	580 ± 30	880 ± 80	1380 ± 50	2000 ± 100	7680 ± 30
5	210 ± 30	280 ± 30	280 ± 40	480 ± 80	1750 ± 30
6	*60 ± 30*	90 ± 10	190 ± 40	300 ± 70	< 1000
7	130 ± 30	160 ± 10	230 ± 50	< 200	600 ± 30
8	< 100	340 ± 30	600 ± 50	1500 ± 100	13730 ± 30
9	1190 ± 50	1500 ± 100	1590 ± 60	1900 ± 100	5340 ± 30
10	< 90	100 ± 10	240 ± 40	770 ± 80	17800 ± 900[c]
11	< 200	190 ± 20	700 ± 50	2400 ± 100	24000 ± 900[c]
12	< 100	...	190 ± 40	770 ± 90	8200 ± 900[c]
13	< 100	120 ± 10	160 ± 50	380 ± 80	640 ± 30
14	3110 ± 80	3200 ± 300	3700 ± 100	2900 ± 100	8100 ± 90

[a] Flux uncertainties cited are 1-σ statistical uncertainties; non-detected fluxes are cited as 3-σ upper limits.
[b] Systematic and calibration uncertainty is 7% (Balog et al. 2013).



Derived FORCAST fluxes densities appear consistent with Spitzer MIPS flux densities and SEDs

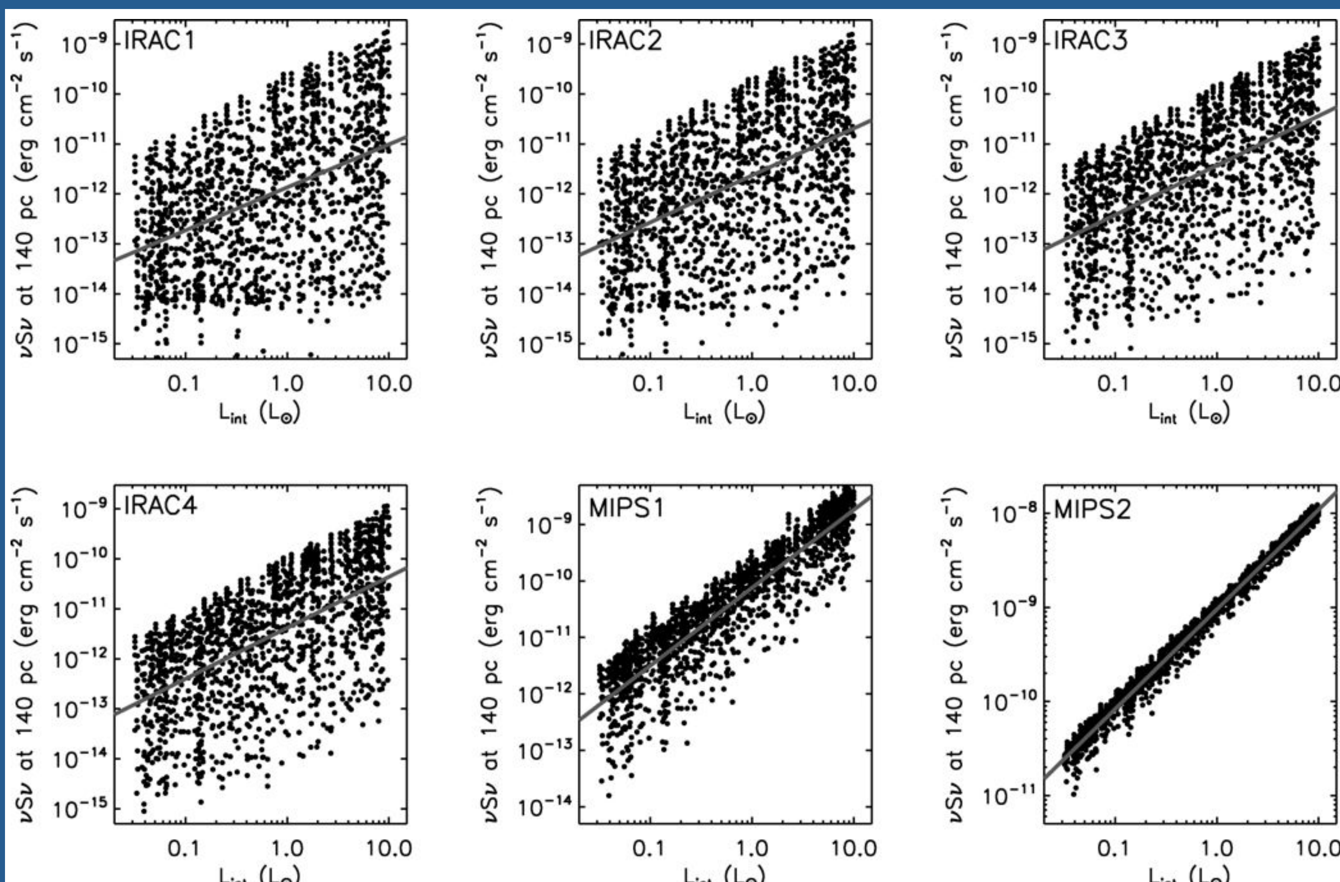
Spitzer Study of Protostars

Dunham et al. (2008) found:

- Good correlation between MIPS 70 µm flux and L_{int} following:

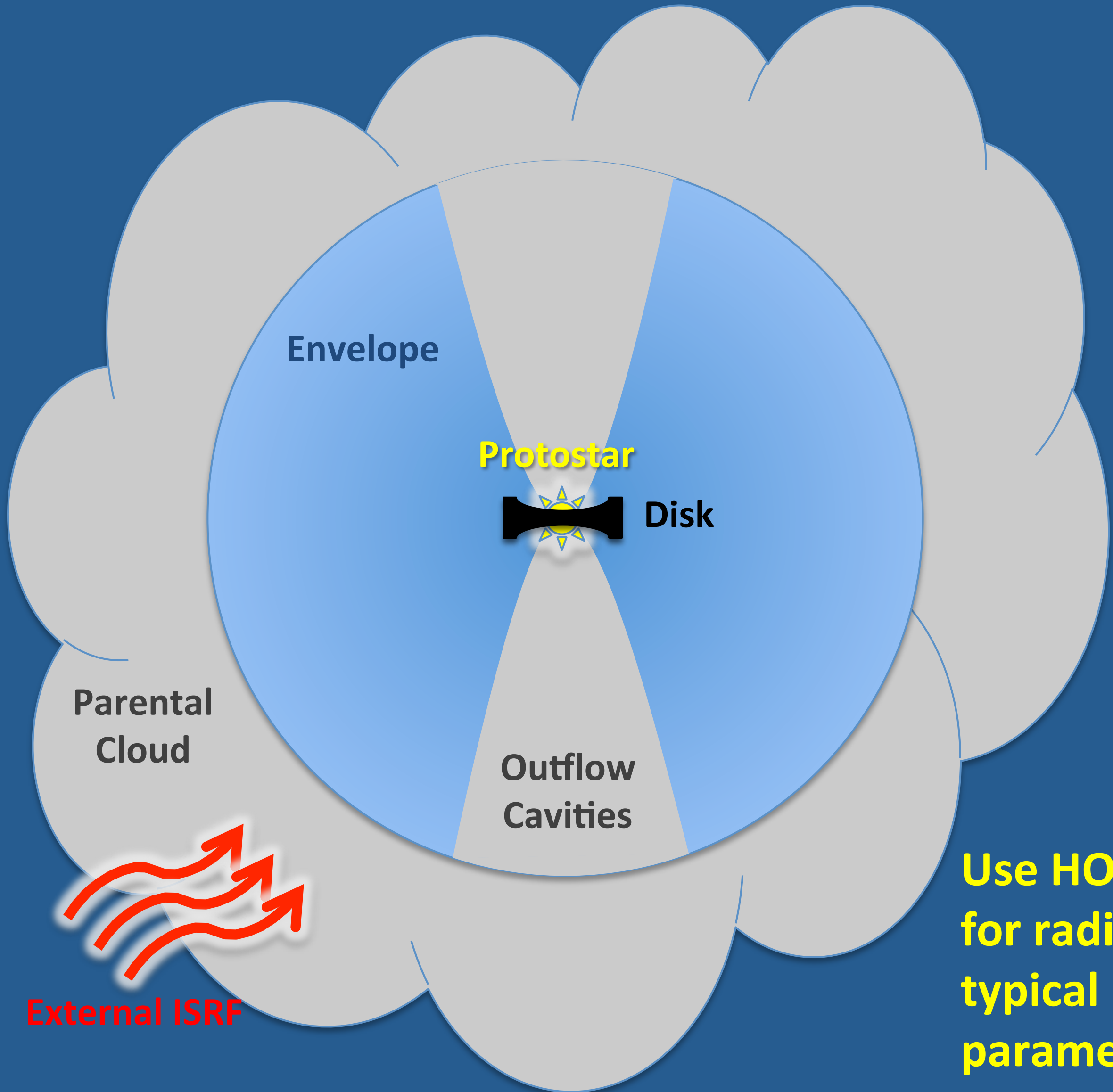
$$\log L_{int}\,[L_\odot] = (1.06 \pm 0.01)\,\log F_\nu\,[\text{cgs}] - (9.02 \pm 0.01) \quad [\text{at } 140\text{ pc}]$$

- Increasingly unreliable relationship for shorter λ (≤ 24 µm)



Can FORCAST be used in a similar manner to estimate protostellar luminosities?

FORCAST Study of Protostars: Typical Protostellar Environment



Protostar
- Blackbody with T = 3000 K
- L_{int} = [0.03, 30] $L_\odot$

Flared Disk
- Outer radius = 100 AU
- Mass = [10^{-5}, 10^{-3}] $M_\odot$

Rotationally Flattened Envelope
- Outer radius = 14,000 AU
- Rc = [100, 900]
- Mass = [1, 10] $M_\odot$

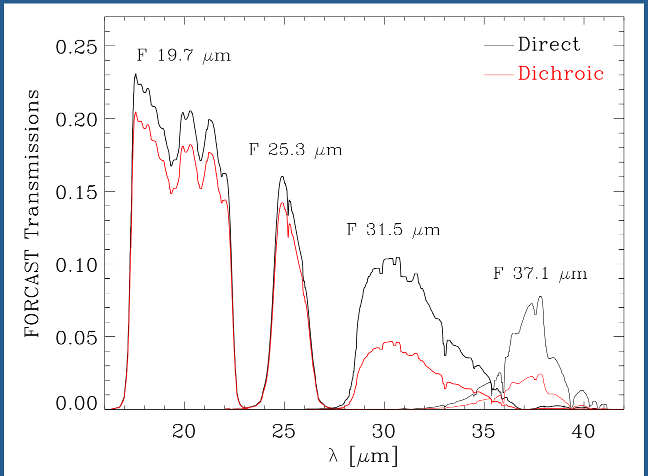
Outflow Cavities
- Opening angle = 30°

Parental Cloud
- Av = [1, 5] mag

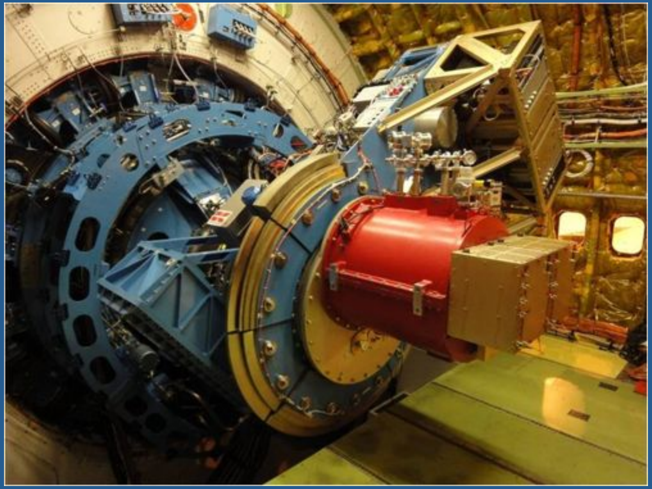
External ISRF
- Black-Draine ISRF scaled by [1/3, 3]

Use HOCHUNK3D (Whitney et al. 2013) for radiative transfer modeling of 350 typical protostellar environments, with parameter values randomly chosen

FORCAST Study of Protostars: Fiducial Sensitivities



Transmission Functions
(Thank you, Joe Adams!)



FORCAST

Consider the 7 FORCAST filters spanning 19.7 – 37.1 μm

Include transmission functions for typical conditions:
- Altitude of 41,000 feet
- Precipitable water vapor of 7.1 μm
- Telescope pointings at 50° from zenith

Define fiducial sensitivity limits:
- Point source flux densities associated with SNR=3 after 1 hour exposure

Estimate limits using SOFIA Instrument Time Estimator

Fiducial Sensitivities Limits

FORCAST Filter[a]	Dichroic [mJy]	Direct [mJy]
F 19.7 μm (SWC)	25	23
F 24.2 μm (LWC)	52	50
F 25.3 μm (SWC)	63	59
F 31.5 μm (LWC)	84	60
F 33.6 μm (LWC)	182	116
F 34.8 μm (LWC)	114	78
F 37.1 μm (LWC)	168	97

FORCAST Study of Protostars: 1-Filter Fits

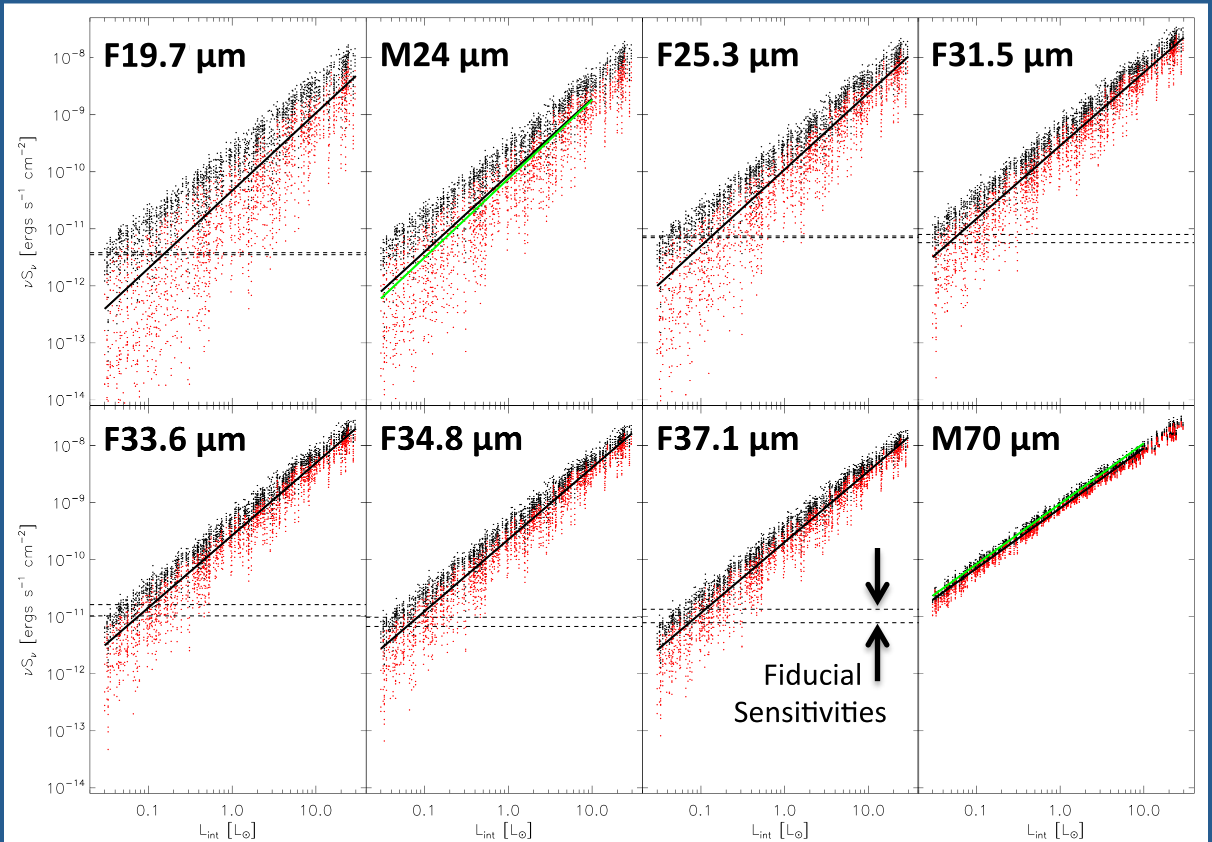
Include FORCAST filters and Black-Draine ISRF in HOCHUNK3D

Consider 350 environments, each with 10 inclinations
cos i = [0.05, 0.15, 0.25, …, 0.95]

Total of 3500 models, each with 10M photons

$$\log F_\nu\,[\mathrm{cgs}] = m \log L_{int}\,[L_\odot] + b$$

Filter[a]	m	b	χ^2_{red}	$\sigma(\log L_{int})$
MIPS 24 μm	1.34 ± 0.01	−10.06 ± 0.01	153	0.40
MIPS 70 μm	1.054 ± 0.002	−9.099 ± 0.002	4	0.080
F 19.7 μm	1.36 ± 0.01	−10.33 ± 0.01	280	0.39
F 24.2 μm	1.34 ± 0.01	−9.960 ± 0.008	116	0.29
F 25.3 μm	1.327 ± 0.009	−9.704 ± 0.008	134	0.28
F 31.5 μm	1.283 ± 0.007	−9.543 ± 0.006	59	0.22
F 33.6 μm	1.267 ± 0.006	−9.573 ± 0.005	48	0.20
F 34.8 μm	1.259 ± 0.006	−9.645 ± 0.005	44	0.19
F 37.1 μm	1.243 ± 0.005	−9.691 ± 0.004	37	0.18



MIPS results consistent with Dunham et al. (2008)

Given flux density Sv [Jy] at FORCAST 37.1 μm at 140 pc:

$$L_{int} = 0.476\, S_{\nu,37}^{\;0.805}\, L_\odot$$

to within ~50% (1σ).

Source #14 (415 pc):

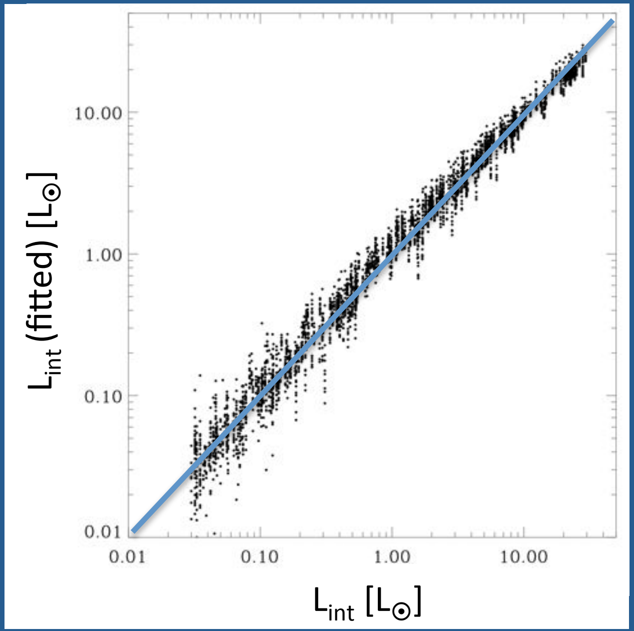
$$L_{int} = \begin{cases} 6.5\, L_\odot \text{ (FORCAST)} \\ 3.3\, L_\odot \text{ (PACS)} \end{cases}$$

FORCAST Study of Protostars: 2-Filter Fits

$\log L_{int}\,[L_{\odot}] = C_1 \log F_{\nu 1}\,[\mathrm{cgs}] + C_2 \log F_{\nu 2}\,[\mathrm{cgs}] + C_3$

Filter 1	Filter 2	C_1	C_2	C_3	$\sigma(\log L_{int})$
F 37.1 μm	F 19.7 μm	1.175 ± 0.006	-0.352 ± 0.005	7.749	0.09
F 37.1 μm	F 24.2 μm	1.75 ± 0.01	-0.899 ± 0.009	8.247	0.09
F 37.1 μm	F 25.3 μm	1.52 ± 0.01	-0.682 ± 0.009	7.958	0.10
F 34.8 μm	F 19.7 μm	1.205 ± 0.006	-0.395 ± 0.005	7.538	0.09
F 34.8 μm	F 24.2 μm	1.93 ± 0.01	-1.09 ± 0.01	8.03	0.09
F 34.8 μm	F 25.3 μm	1.61 ± 0.01	-0.79 ± 0.01	7.71	0.10
F 33.6 μm	F 19.7 μm	1.222 ± 0.007	-0.419 ± 0.005	7.358	0.09
F 33.6 μm	F 24.2 μm	2.05 ± 0.01	-1.22 ± 0.01	7.79	0.09
F 33.6 μm	F 25.3 μm	1.67 ± 0.01	-0.86 ± 0.01	7.47	0.11
F 31.5 μm	F 19.7 μm	1.266 ± 0.008	-0.480 ± 0.006	7.121	0.10
F 31.5 μm	F 24.2 μm	2.43 ± 0.02	-1.62 ± 0.02	7.52	0.10
F 31.5 μm	F 25.3 μm	1.80 ± 0.02	-1.01 ± 0.02	7.15	0.12

Suggests two FORCAST filters may be used to provide estimate of L_{int} to within ~25% (1σ).



For example, given flux densities Sv [Jy] at FORCAST 37.1 µm and 25.3 µm (at 140 pc):

$$L_{int} = 0.24\,[S_{\nu,37}]^{1.52}\,[S_{\nu,25}]^{-0.682}\,L_{\odot}$$

Source #14 (415 pc): $L_{int} = \begin{cases} 3.1\,L_{\odot} \text{ (FORCAST)} \\ 3.3\,L_{\odot} \text{ (PACS)} \end{cases}$

FORCAST Study of Protostars: 2-Filter Fits

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L_{int} [$L_\odot$] FORCAST	L_{int} [$L_\odot$] PACS
3.1 (5%)	1.3 (10%)
0.29 (50%)	< 0.46
1.4 (40%)	< 0.46
3.4 (8%)	3.1 (7%)
1.2 (30%)	0.77 (7%)
0.74 (40%)	< 0.46
< 0.35	0.28 (8%)
3.9 (10%)	5.4 (7%)
2.9 (8%)	2.2 (7%)
2.6 (20%)	6.8 (8%)
7.2 (8%)	9.1 (8%)
3.1 (20%)	3.3 (10%)
1.2 (40%)	0.30 (8%)
3.1 (6%)	3.3 (7%)

Results are TENTATIVE!
1) Check photometry; 2) Check more sources.

Currently, 9 protostars with FORCAST-PACS consistent (1σ) luminosities; 5 are inconsistent

Summary

Our FORCAST observations of Serpens South were successful.

Previously blended MIPS sources were resolved.

FORCAST (19.7 – 37.1 µm) and PACS (70 µm) flux densities were derived to provide better SED coverage for protostars.

We discovered 1 additional protostar.

Radiative transfer modeling suggests that combinations of two FORCAST filters (19.7 – 37.1 µm) may be used to estimate protostellar luminosities to within ~20-25%, comparable to that achieved with MIPS or PACS 70 µm. (Tentative!)