Young Stellar Objects in the Large Magellanic Cloud

You-Hua Chu
University of Illinois

Robert Gruendl
Leslie Looney
C.-H. Rosie Chen
Jonathan Seale
Adeline Caulet
Kaushar Vaidya
Tony Wong

Chao-Chin Yang
Mordecai Mac Low
Barbara Whitney
Dimitrios Gouliermis
Wolfgang Brandner
Bernhard Brandl
Geoffrey Blake
Yasuo Fukui
Chris Smith
Sean Points

Laura Book
Maxwell Schoenoff
Christine Fleener
James Payne
Karna Desai
Brian O'Neill
Antonio Ortiz
+ many more


AURA
OBSERVATORIO
INTERAMERICANO
CERRO TOLOLO

Tracers of Star Formation

Diffuse Emission:				
Hα	-	ionizing flux of massive stars	-	MS stars
FIR	-	reprocessed stellar radiation	-	MS stars
NUV	-	emission from massive stars	-	MS stars
Radio	-	nonthermal radiation	-	SNe
X-ray	-	hot ISM and X-ray binaries	-	SNe

Point Sources:				
IR	-	stellar core + CS dust	-	PMS, YSO

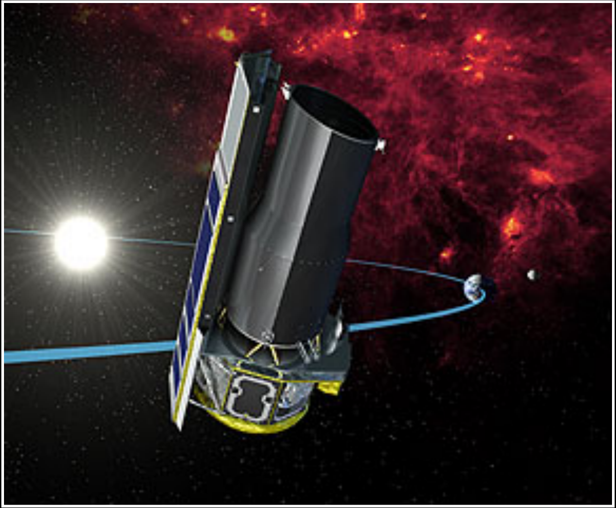
Pre-main sequence stars (PMSs) and young stellar objects (YSOs) can be identified by their IR excesses.

These point sources can be identified easily in the Galaxy, but not in other galaxies.

Ground-based and HST images in *JHK* are used to identify young stars in 30 Dor (Walborn, Rubio, Barbá, etc).

Deeply embedded YSOs need mid-IR obs, large extragalactic surveys with useful resolution are provided by Spitzer.

Spitzer Space Telescope



- 0.85 meter infrared telescope
- Launched in August 2003
- Cooled to ~1.5 K

IRAC

Imaging @
3.6, 4.5, 5.8,
8.0 μm

MIPS

Imaging @
24, 70, 160 μm

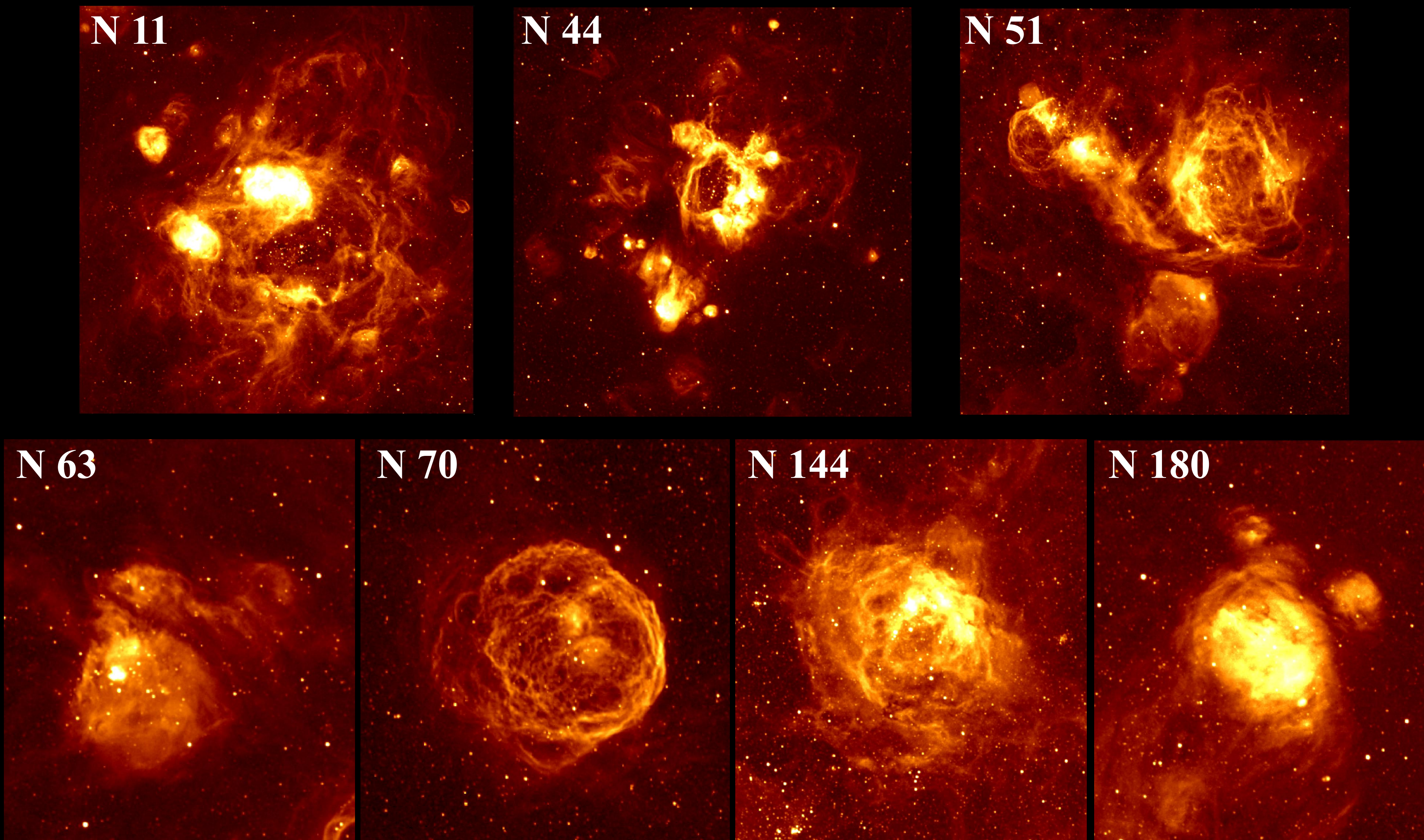
SED 52-100 μm
7% resolution

IRS

Spectrographs (4)
5.3-38 μm

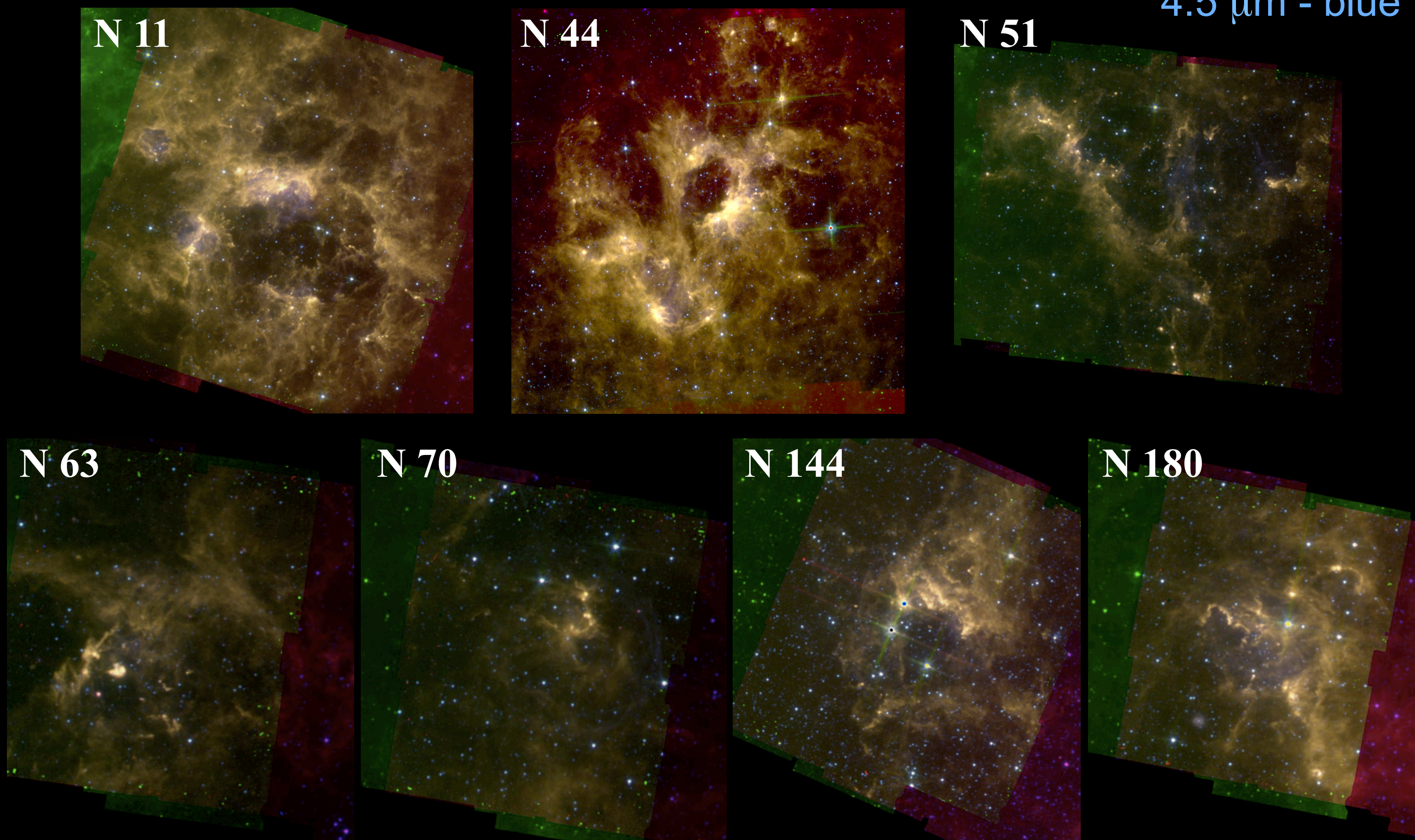
Short-hi, short-lo
Long-hi, long-lo

The Magnificent Seven (Spitzer Cycle 1 program)



The Magnificent Seven
(Spitzer Cycle 1 program)

8.0 μm - red
5.6 μm - green
4.5 μm - blue

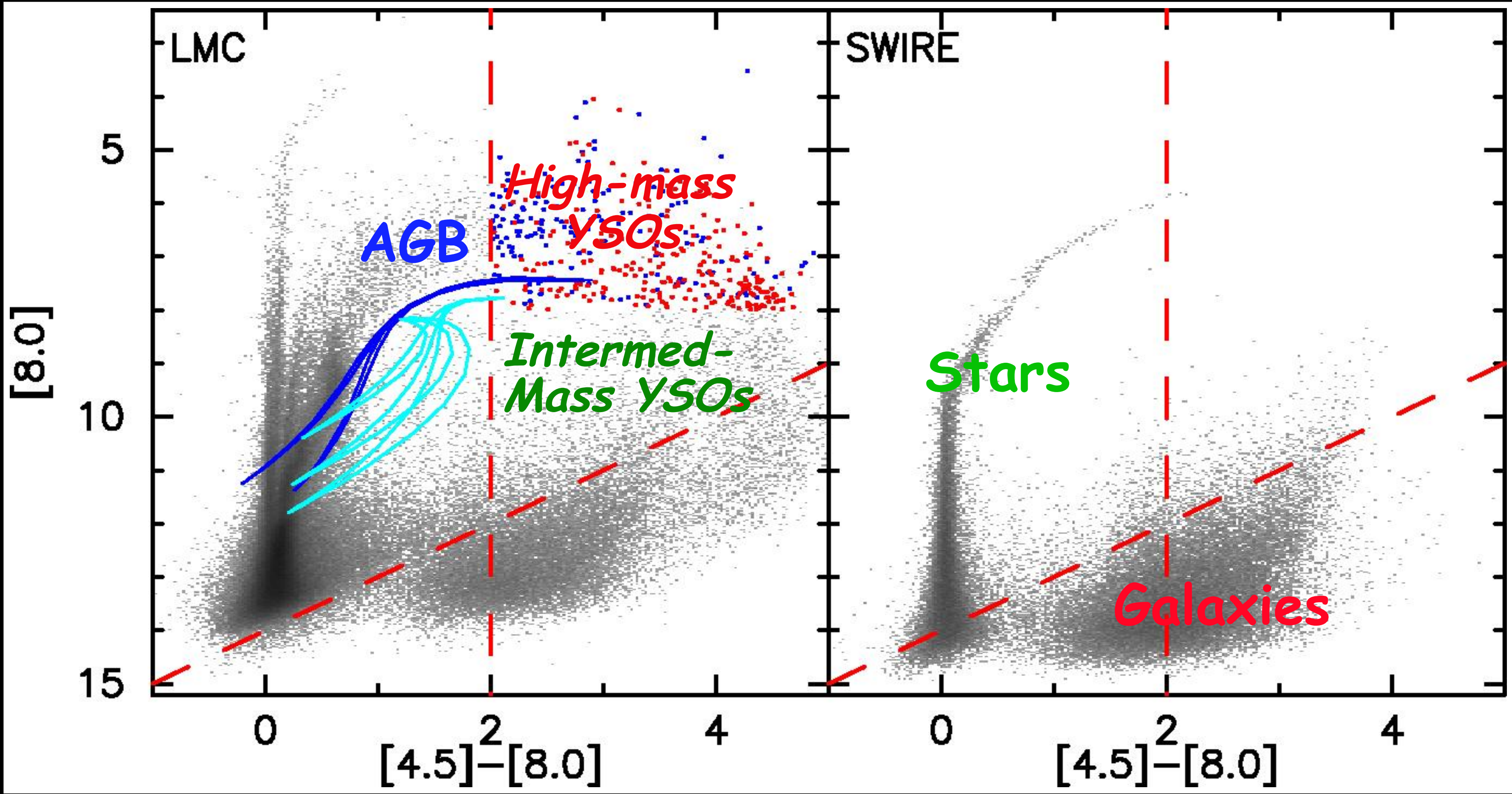


Spitzer mosaic of the LMC - SAGE

Meixner et al. 2006

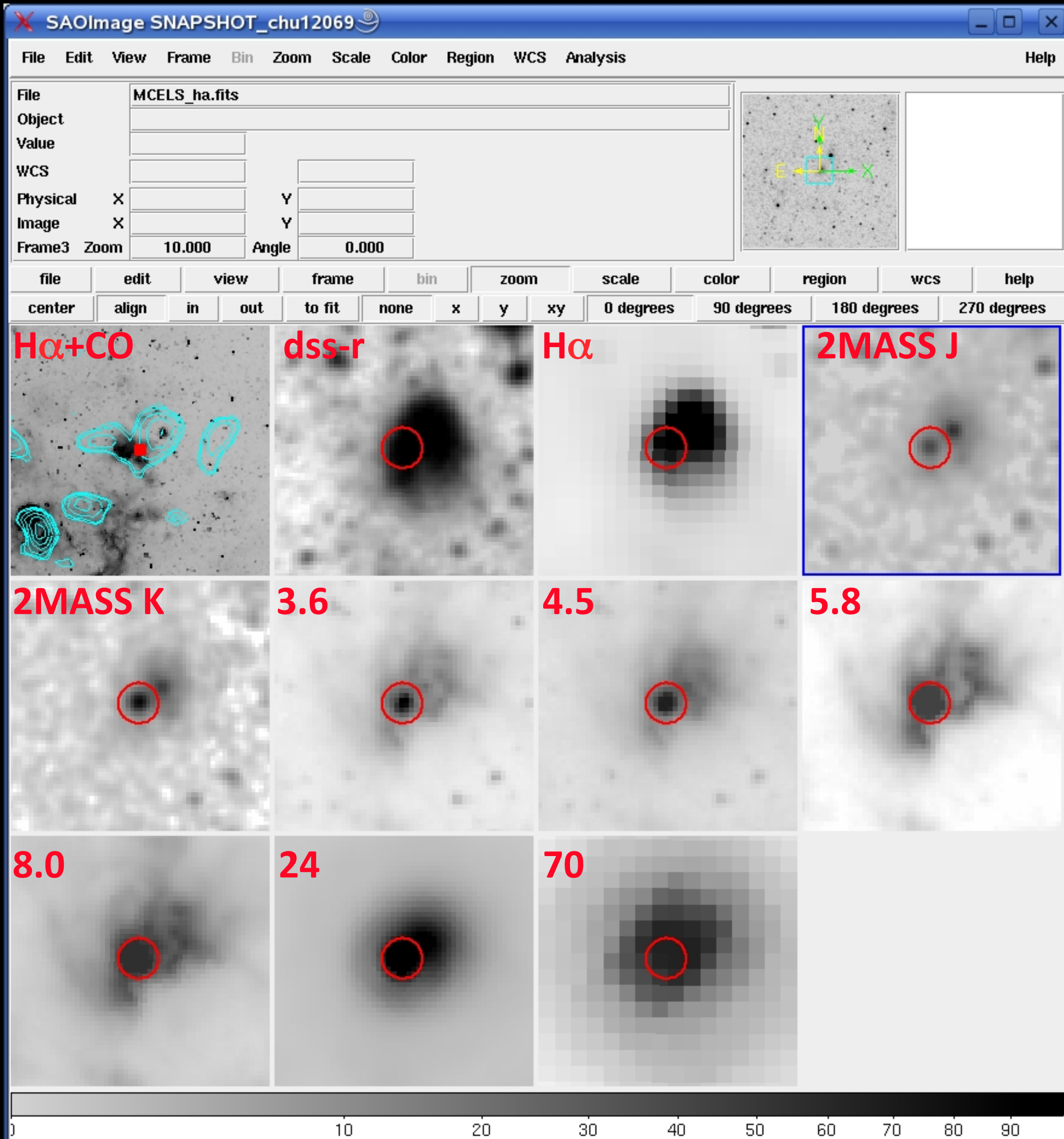
Identification of YSOs in the LMC

Step 1 (DM of the LMC= 18.5)



Gruendl & Chu (2009)

Step 2



SAOImage SNAPSHOT_chu12069
File Edit View Frame Bin Zoom Scale Color Region WCS Analysis Help
File MCELS_ha.fits
Object
Value
WCS
Physical X Y
Image X Y
Frame3 Zoom 10.000 Angle 0.000
file edit view frame bin zoom scale color region wcs help
center align in out to fit none x y xy 0 degrees 90 degrees 180 degrees 270 degrees
Hα+CO
dss-r
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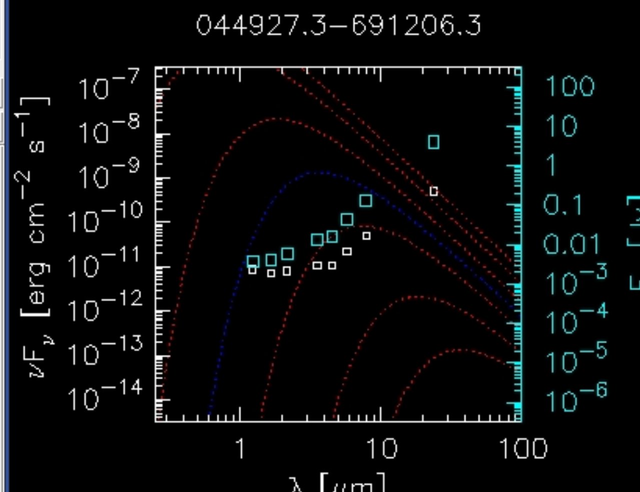
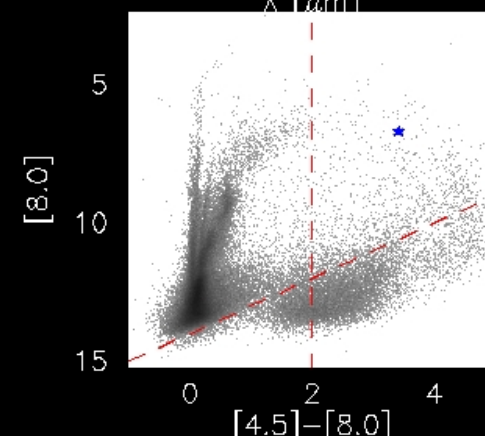
2MASS J
2MASS K
3.6
4.5
5.8
8.0
24
70
10 20 30 40 50 60 70 80 90

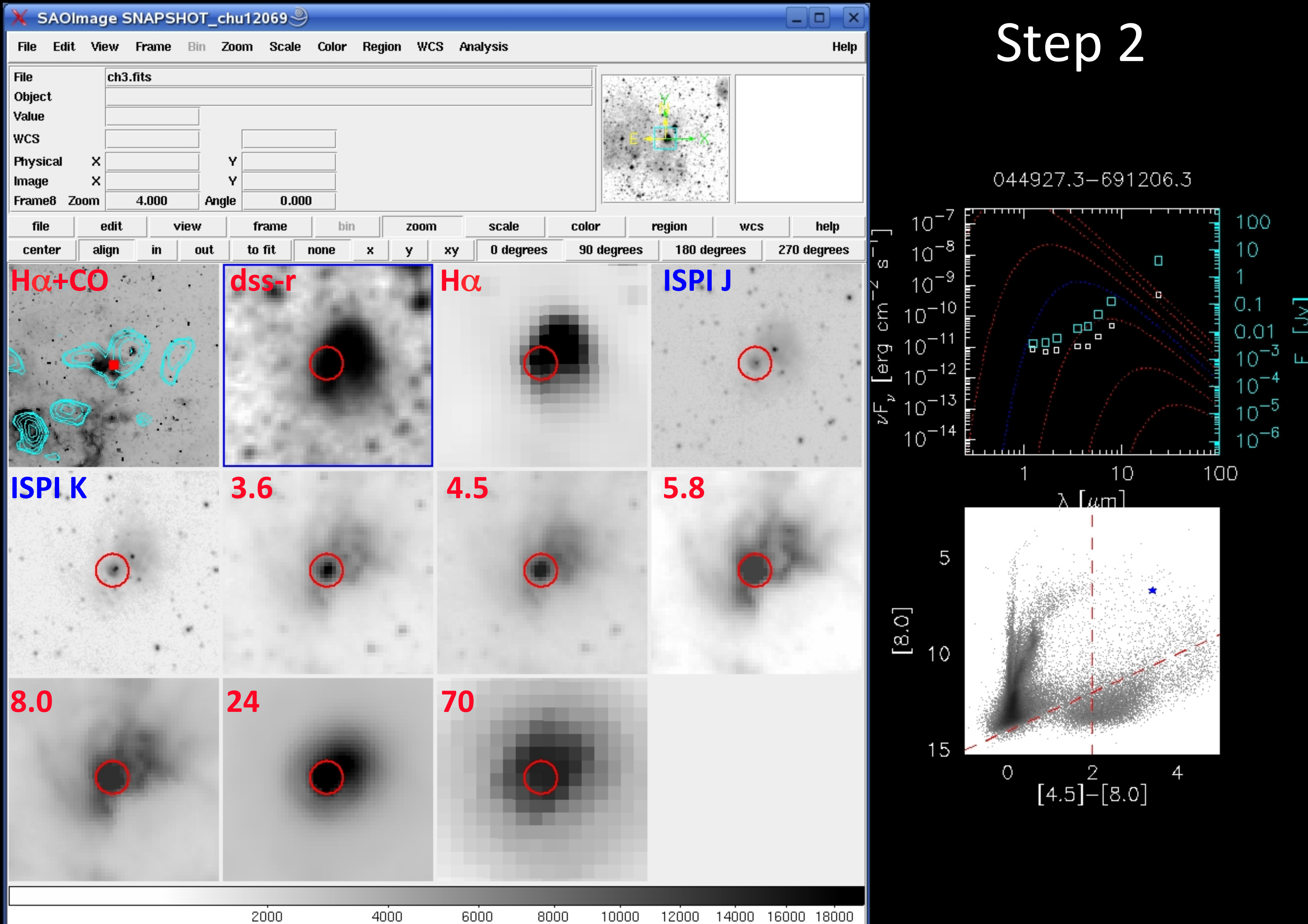


044927.3−691206.3
νF_ν [erg cm^{-2} s^{-1}]
10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12} 10^{-13} 10^{-14}
100 10 1 0.1 0.01 10^{-3} 10^{-4} 10^{-5} 10^{-6}
F_ν [Jy]
1 10 100
λ [μm]



[8.0]
5 10 15
0 2 4
[4.5]−[8.0]

Step 2



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Hα+CO
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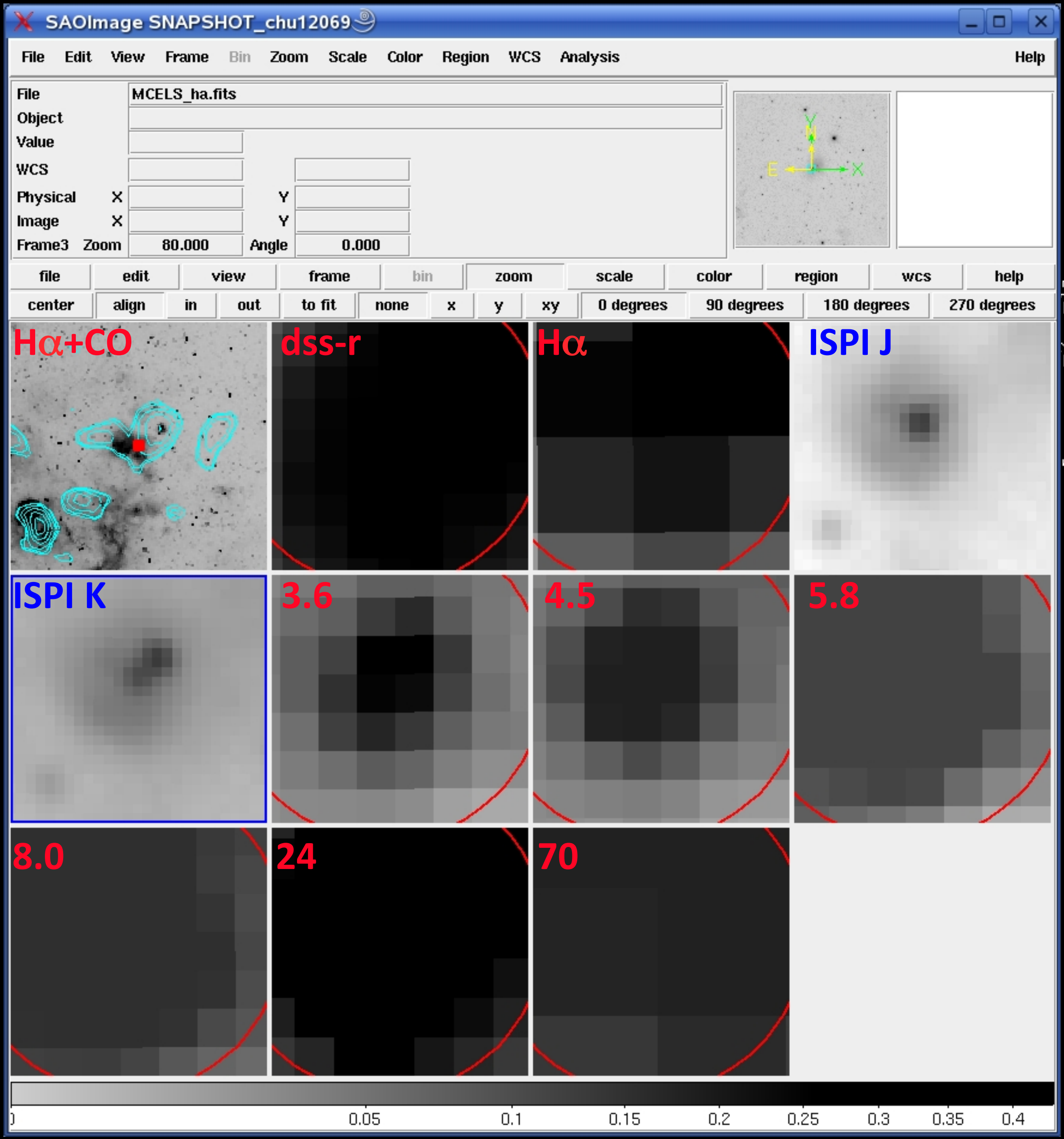
2000 4000 6000 8000 10000 12000 14000 16000 18000
044927.3−691206.3
νF_ν [erg cm^{-2} s^{-1}]
F_ν [Jy]
λ [μm]
[8.0]
[4.5]−[8.0]

Step 2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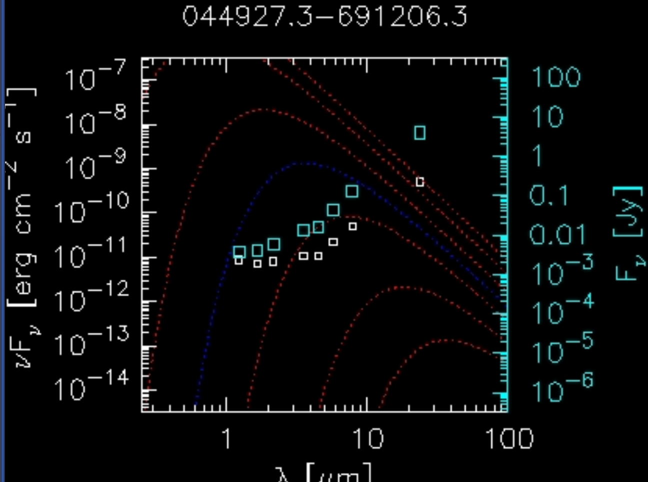
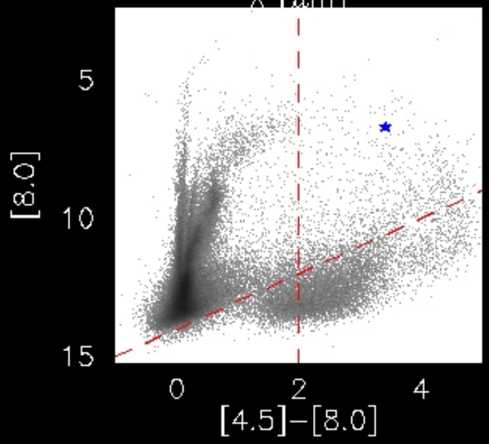
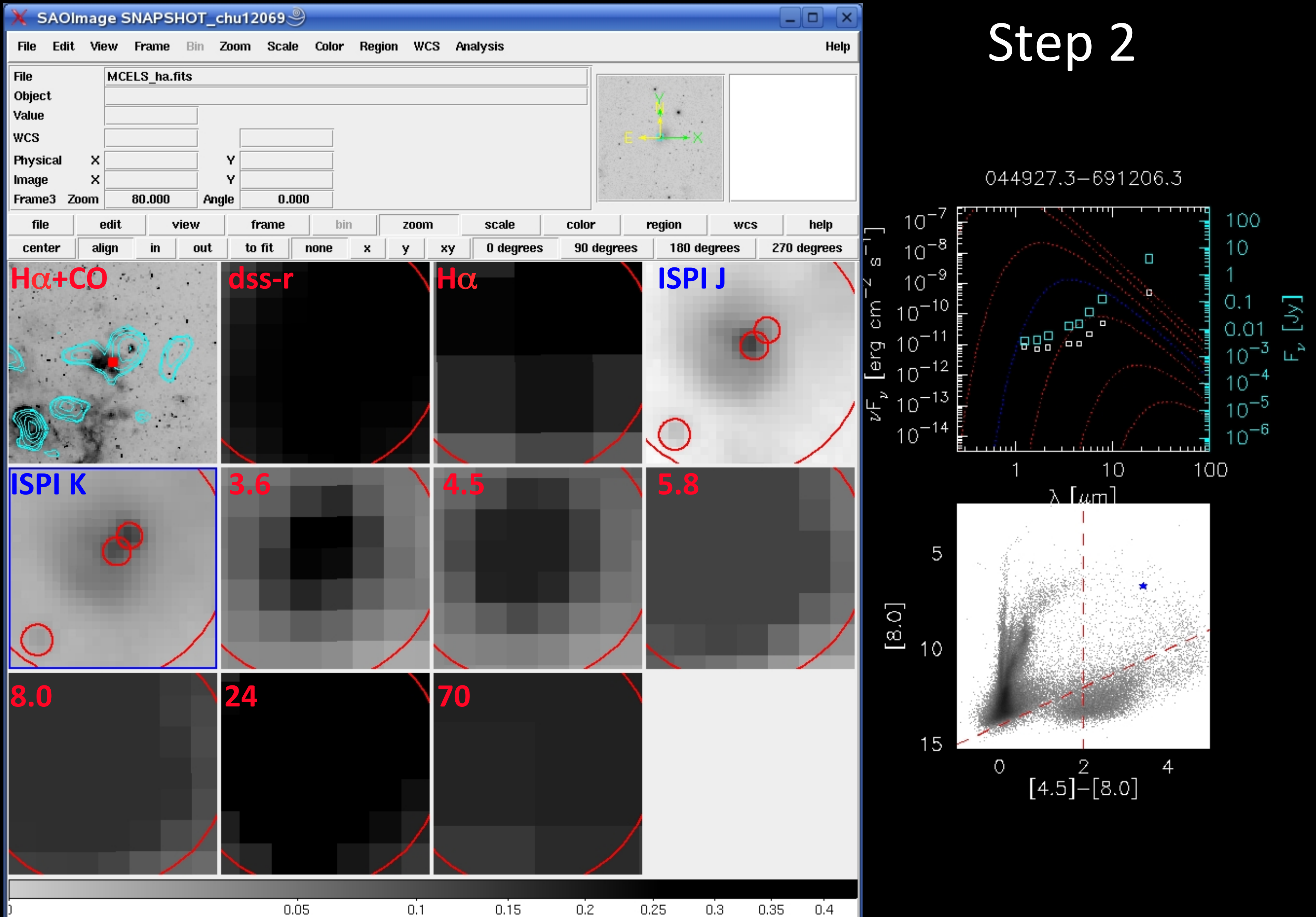
center align in out to fit none x y xy 0 degrees 90 degrees 180 degrees 270 degrees
Hα+CO
dss-r
Hα
ISPI J
ISPI K
3.6
4.5
5.8
8.0
24
70
0.05 0.1 0.15 0.2 0.25 0.3 0.35 0.4


044927.3−691206.3
νF_ν [erg cm^{-2} s^{-1}]
F_ν [Jy]
λ [μm]


[8.0]
[4.5]−[8.0]

Step 2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center align in out to fit none x y xy 0 degrees 90 degrees 180 degrees 270 degrees
Hα+CO
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3.6
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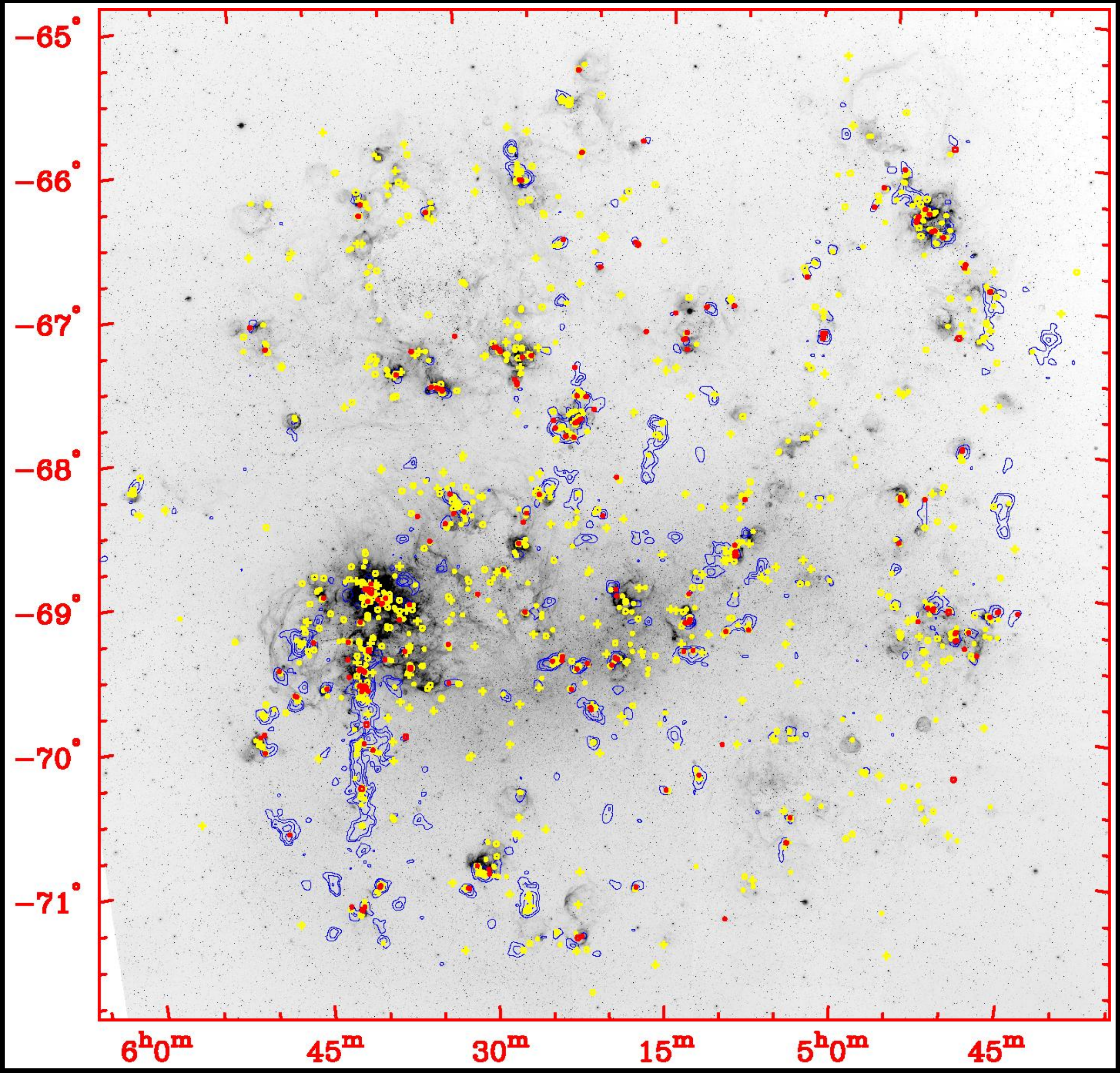
5.8
8.0
24
70
0.05 0.1 0.15 0.2 0.25 0.3 0.35 0.4
044927.3−691206.3
νF_ν [erg cm^{-2} s^{-1}]
F_ν [Jy]
λ [μm]
[8.0]
[4.5]−[8.0]

Massive YSO Candidates in the LMC



Source	[8]>8	[8]<8
YSO ●	858	234
YSO ◉	303	14
YSO ✚	167	
	>4M$_\odot$	>10M$_\odot$
Neb	126	13
AGB	110	105
PNe	52	9
Galaxy	947	6
Galaxy?	126	

Comparisons with SAGE YSO Results

HIGH- AND INTERMEDIATE-MASS YOUNG STELLAR OBJECTS IN THE LARGE MAGELLANIC CLOUD

2

ROBERT A. GRUENDL[1] AND YOU-HUA CHU
Astronomy Department, University of Illinois, 1002 W. Green Street, Urbana, IL 61801, USA; gruendl@astro.illinois.edu, chu@astro.illinois.edu
Received 2008 September 14; accepted 2009 August 5; published 2009 August 31

vs.

SPITZER SAGE SURVEY OF THE LARGE MAGELLANIC CLOUD. III. STAR FORMATION AND ~1000 NEW CANDIDATE YOUNG STELLAR OBJECTS

55

B. A. WHITNEY[1], M. SEWILO[2], R. INDEBETOUW[3], T. P. ROBITAILLE[4], M. MEIXNER[2], K. GORDON[5], M. R. MEADE[6], B. L. BABLER[6], J. HARRIS[5], J. L. HORA[7], S. BRACKER[6], M. S. POVICH[6], E. B. CHURCHWELL[6], C. W. ENGELBRACHT[5], B-Q FOR[5,8], M. BLOCK[5], K. MISSELT[5], U. VIJH[2], C. LEITHERER[2], A. KAWAMURA[9], R. D. BLUM[10], M. COHEN[11], Y. FUKUI[9], A. MIZUNO[9], N. MIZUNO[9], S. SRINIVASAN[12], A. G. G. M. TIELENS[13], K. VOLK[14], J-P. BERNARD[15], F. BOULANGER[16], J. A. FROGEL[17], J. GALLAGHER[6], V. GORJIAN[18], D. KELLY[5], W. B. LATTER[19], S. MADDEN[20], F. KEMPER[21], J. R. MOULD[10], A. NOTA[2], M. S. OEY[22], K. A. OLSEN[23], T. ONISHI[9], R. PALADINI[24], N. PANAGIA[2], P. PEREZ-GONZALEZ[5], W. REACH[24], H. SHIBAI[9], S. SATO[9], L. J. SMITH[2,25], L. STAVELEY-SMITH[26], T. UETA[27], S. VAN DYK[24], M. WERNER[18], M. WOLFF[1], AND D. ZARITSKY[5]
[1] Space Science Institute, 4750 Walnut St. Suite 205, Boulder, CO 80301, USA; bwhitney@spacescience.org, wolff@spacescience.org
[2] Space Telescope Science Institute, 3700 San Martin Way, Baltimore, MD 21218, USA; sewilo@stsci.edu, meixner@stsci.edu, vijh@stsci.edu, leitherer@stsci.edu, nota@stsci.edu, panagia@stsci.edu, and lsmith@stsci.edu

Comparison with SAGE YSO Results

Gruendl & Chu (2009)

- Aperture photometry
- Simple color criteria

$$[4.5]-[8.0] < 2$$

$$[4.5]-[8.0] > 14 - [8.0]$$

- Use Blanco Hα, *J*, *K*
- Examine images and SEDs to assess nature

Whitney + SAGE (2008)

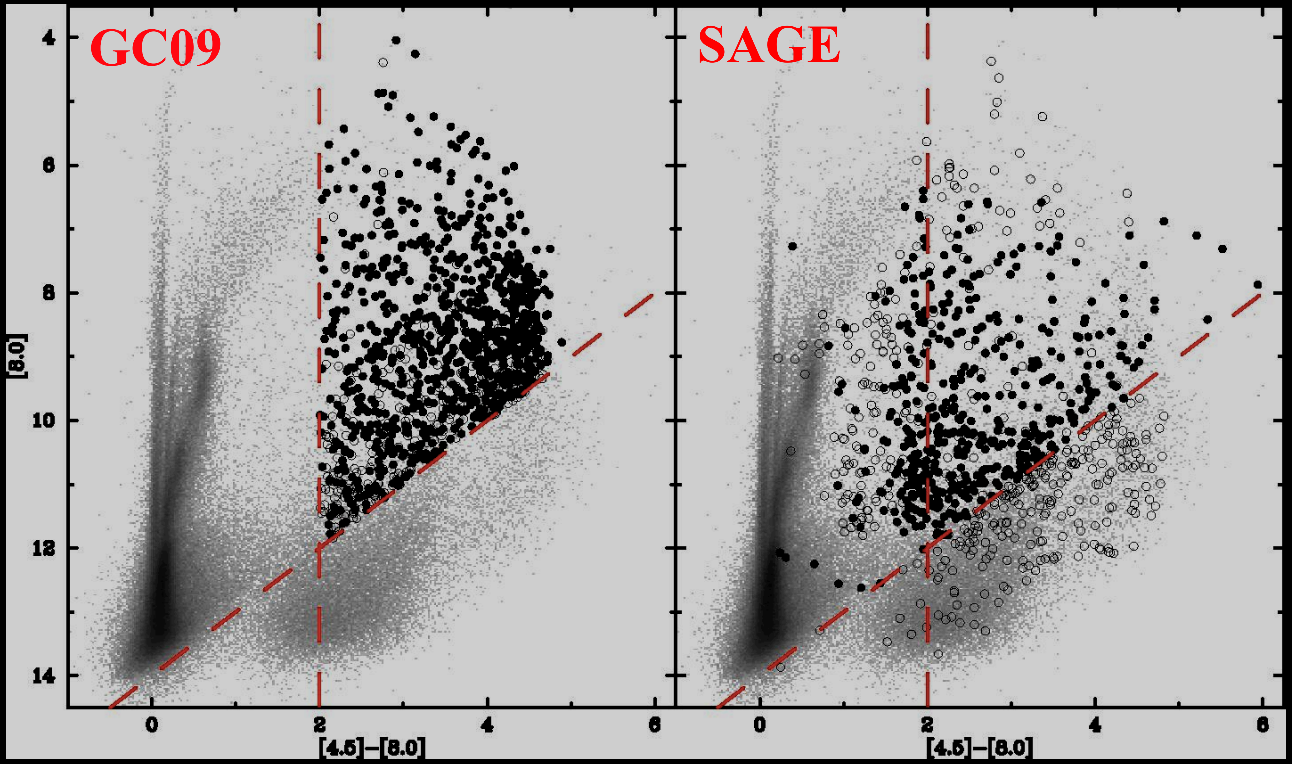
- PSF fitting --> photometry
- Complex color criteria

	$[3.6] < 6.76 + 1.10 \times ([3.6] - [24])$	and	$[3.6] > 13.86 - 0.91 \times ([3.6] - [24])$
or	$[4.5] < 7.26 + 1.02 \times ([4.5] - [24])$	and	$[4.5] > 10.79 - 0.53 \times ([4.5] - [24])$
or	$[3.6] < 10.6 + 3.50 \times ([3.6] - [4.5])$	and	$[3.6] > 13.35 - 2.41 \times ([3.6] - [4.5])$
or	$[3.6] - [4.5] > 1.5$		
or	$[3.6] - [8.0] > 3.5$	and	$[3.6] < 13.5$
or	$[3.6] - [8.0] > 4.5$	and	$[3.6] \geqslant 13.5$
or	$[3.6] - [8.0] > 1.5$	and	$[3.6] - [8.0] \leqslant 3.5$
and	$[3.6] < 13.5$	and	$[3.6] > 10.5)$
or	$[5.8] < 7.83 + 0.89 \times ([5.8] - [24])$	and	$[5.8] > 10.79 - 0.81 \times ([5.8] - [24])$
or	$[8.0] < 7.59 + 1.06 \times ([8.0] - [24])$	and	$[8.0] > 11.0 - 1.33 \times ([8.0] - [24])$
or	$[24] < 3.72 + 0.95 \times ([8.0] - [24])$	and	$[24] > 9.76 - 1.79 \times ([8.0] - [24])$
or	$[4.5] > 11.91 - 2.54 \times ([4.5] - [5.8])$	and	$[4.5] < 9.44 + 3.57 \times ([4.5] - [5.8])$
or	$[8.0] < 12.52 - 0.73 \times ([4.5] - [8.0])$	and	$[8.0] > 28.30 - 18.29 \times ([4.5] - [8.0])$
and	$[8.0] > 10.58 - 1.49 \times ([4.5] - [8.0])$		
or	$[4.5] - [8.0] > 3.7$		
or	$[4.5] - [8.0] > 2.7$	and	$[8.0] < 8.0$
or	$[4.5] < 11.12 + 0.94 \times ([4.5] - [8.0])$	and	$[4.5] > 24.0 - 13.0 \times ([4.5] - [8.0])$
and	$[4.5] > 11.13 - 0.89 \times ([4.5] - [8.0])$		
or	$[5.8] < 10.92 + 0.89 \times ([5.8] - [8.0])$	and	$[5.8] > 16.66 - 6.60 \times ([5.8] - [8.0])$
or	$K > 12.5$	and	$K < 14.0$
and	$K - [4.5] > 1.5$	and	$K - [4.5] < 3.5$
or	$K > 12.5$	and	$K < 13.5$
and	$K - [3.6] > 1.0$	and	$K - [3.6] < 2.5.$

- Compare with radiative transfer models to assess nature

Comparison with SAGE YSO Results

YSOs plotted in [8] vs [4.5]-[8] CMD



577 YSO candidates in common.

In the same region of the CMD we miss 7 SAGE YSOs.

SAGE misses more than half of our YSO candidates.

	GC09	SAGE
Filled Circles: high probability YSOs	1,172	458
Open Circles: lower probability YSOs	213	532

Comparison with SAGE YSO Results

Table 15
Comparison between SAGE and Our Classification

SAGE Class	Sources Among Our Sample[a]	Our Class: Definite YSO	Probable YSO	Possible YSO	GC	Background Galaxy	Evolved Star	ERO	PN
YSO_hp	326	156	51	41	31	65	6	7	0
YSO	161	86	13	13	9	29	19	1	0
Evolved	41	1	3	2	0	0	35	0	0
PN	49	6	5	1	1	0	3	0	34
Galaxy	1	0	0	1	1	0	0	0	0

Note.
[a] Sources in our "sample" refer to all sources from the wedge in the [8.0] vs. [4.5]−[8.0] CMD.

~ 30% of SAGE YSOs were classified by us as background galaxies.

PNe and Evolved Stars had better agreement (~70 & 85%).
(after excluding EROs which SAGE classify as YSOs)

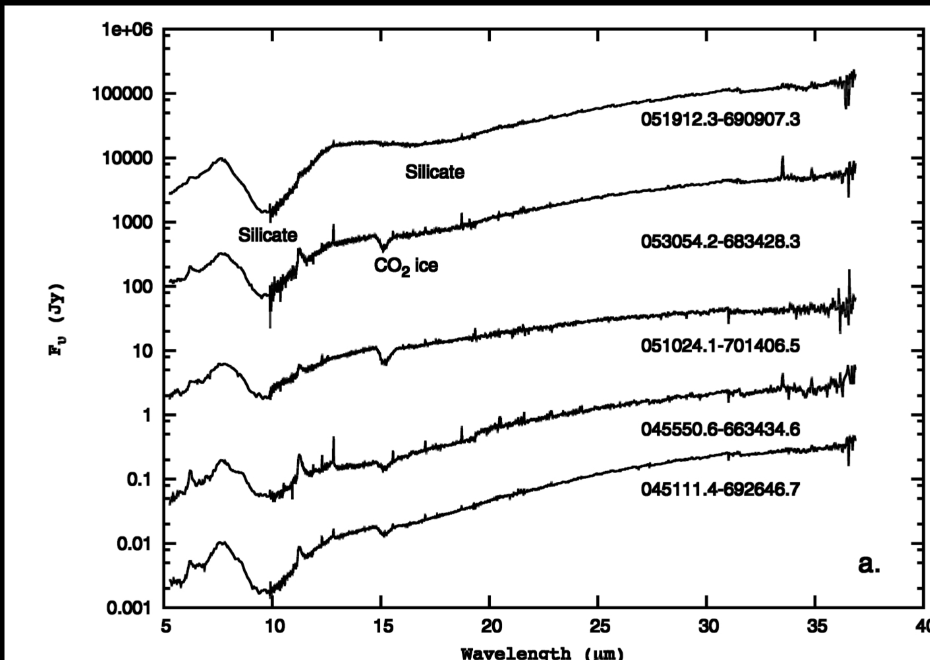
Re-examination of sources with discrepant classifications resulted in no significant change in our conclusion.

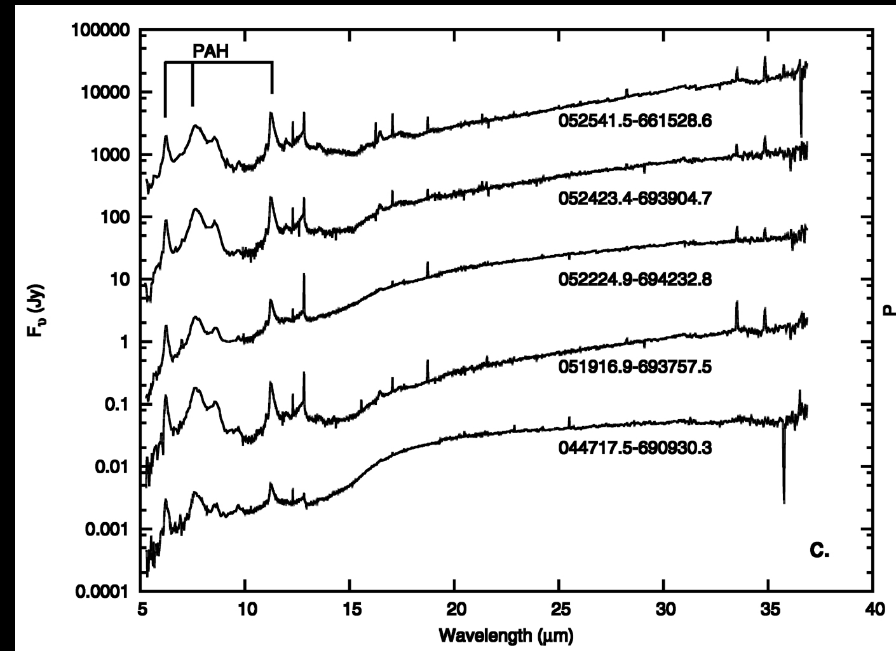
Comparison with SAGE YSO Results

Why such different results?

- Differences do not depend on source brightness.
- PSF fitting too strict. Sources with complex backgrounds will be eliminated.
- Degeneracy in colors. Complementary data and human intervention are necessary.

How Do We Gain Confidence?





- IRS observations of ~270 YSOs confirmed 95% (Seale+2009)
- 13 H_2O maser sources found coincidence in ~10.
- Found ~ expected number of background galaxies.

Chen et al. 2009 ApJ
YSOs in N44 HII region

Chen et al. 2010, ApJ
YSOs in N159 HII region

Sewilo et al. 2010, A&A
Herschel detection of ~200 youngest YSOs

Romita et al. 2010, ApJ
YSOs in N206 HII regon

Carlson et al. 2011, A&A
YSOs in star-forming regions in the LMC

Chen et al. 2009 ApJ
YSOs in N44 HII region

Chen et al. 2010, ApJ
YSOs in N159 HII region

Sewilo et al. 2010, A&A
Herschel detection of ~200 youngest YSOs

Romita et al. 2010, ApJ
YSOs in N206 HII regon

Carlson et al. 2011, A&A

Use these catalogs of YSOs with caution.

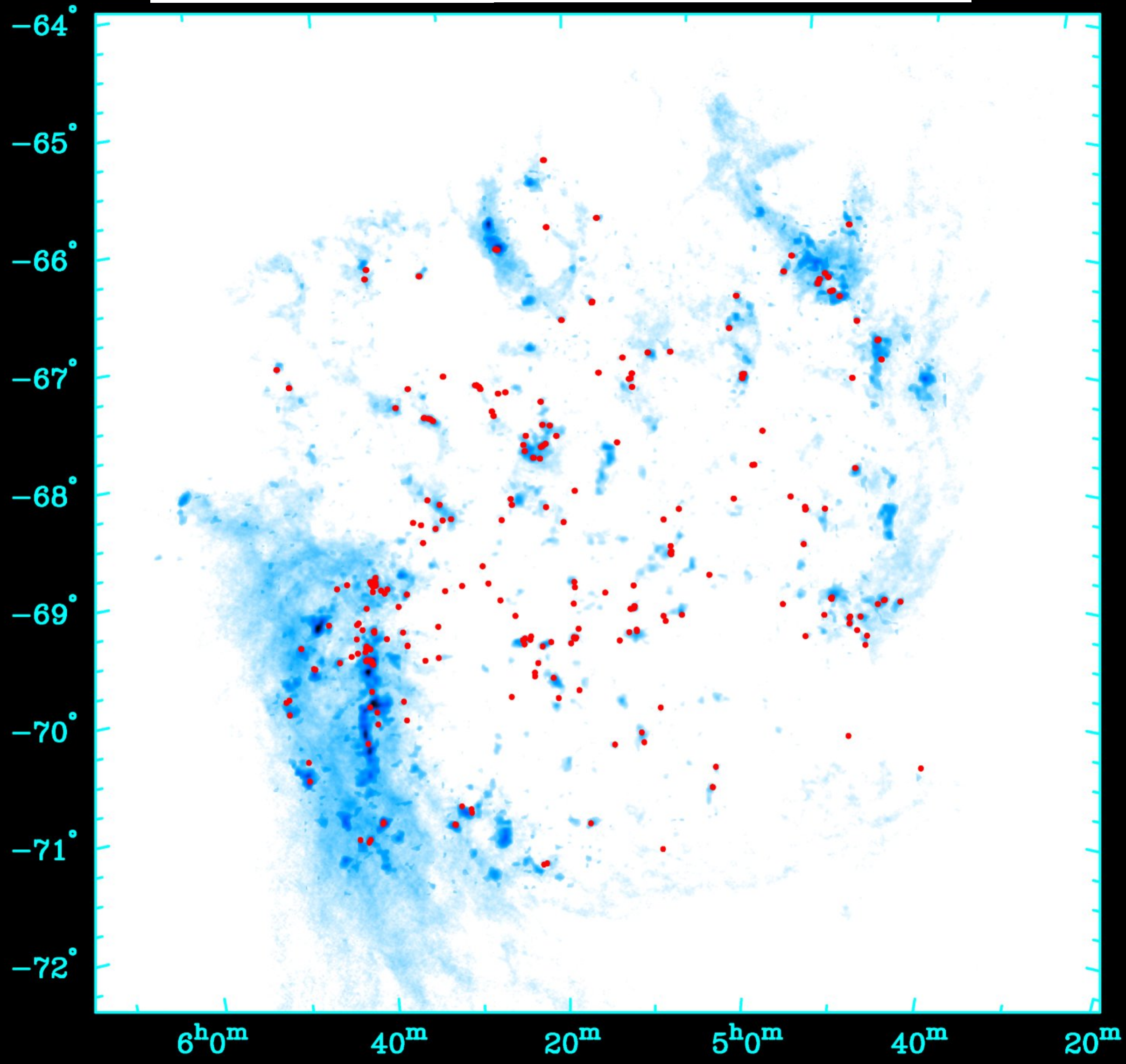
Incomplete and contaminated at faint end.

Global Gravitational Instability & Star Formation

Yang et al. 2007,ApJ, 671,374

Gravitationally Unstable Regions

$$Q_g = \frac{\kappa c_g}{\pi G \Sigma_g} < 1 \quad \textbf{(blue)}$$

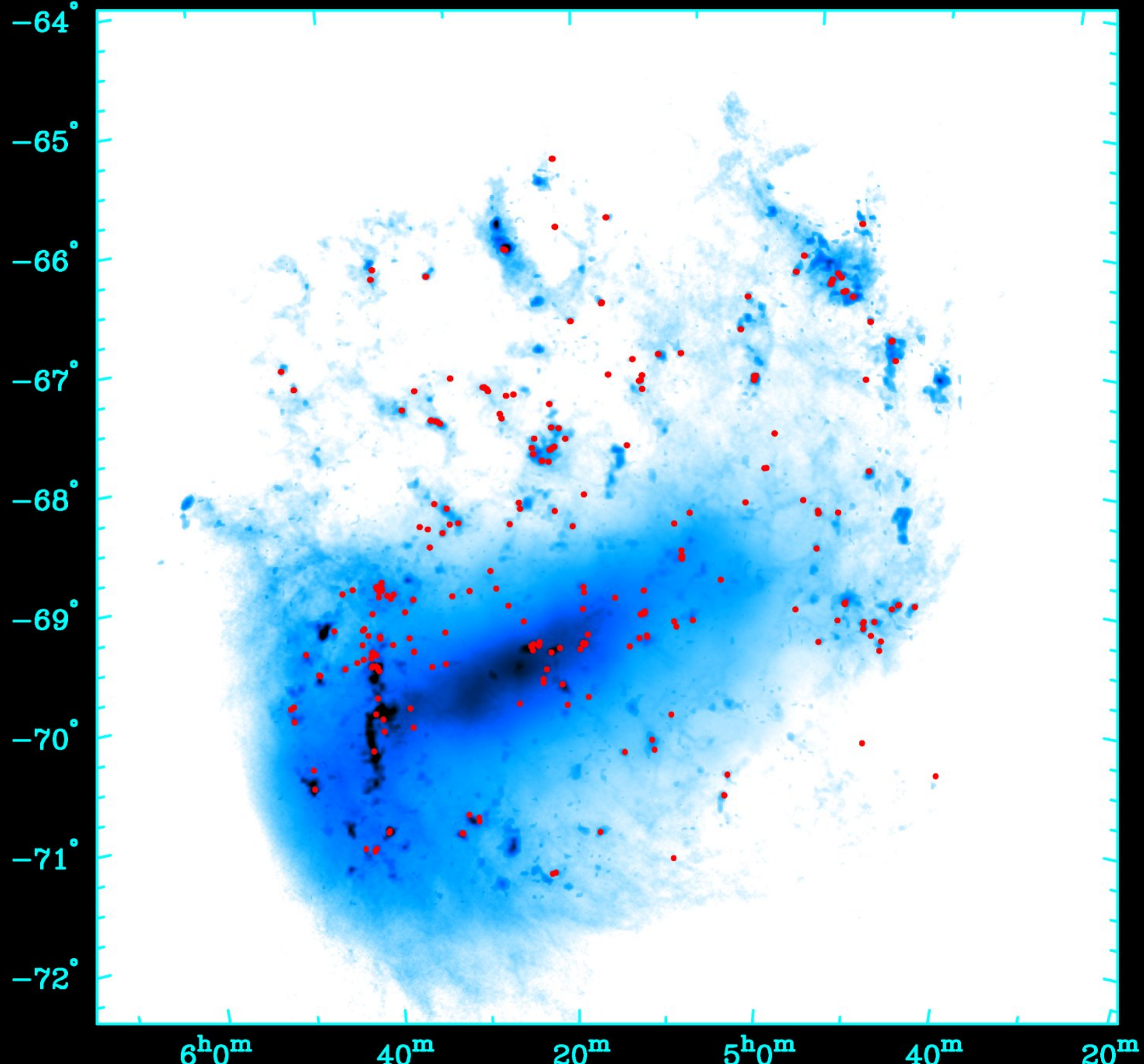


Gravitationally Unstable Regions

$$\frac{2}{Q_s}\frac{1}{q}[1 - e^{-q^2} I_0(q^2)] + \frac{2}{Q_g} R \frac{q}{1 + q^2 R^2} > 1$$

$$q = k\sigma_s/\kappa$$

$$R = c_g/\sigma_s$$

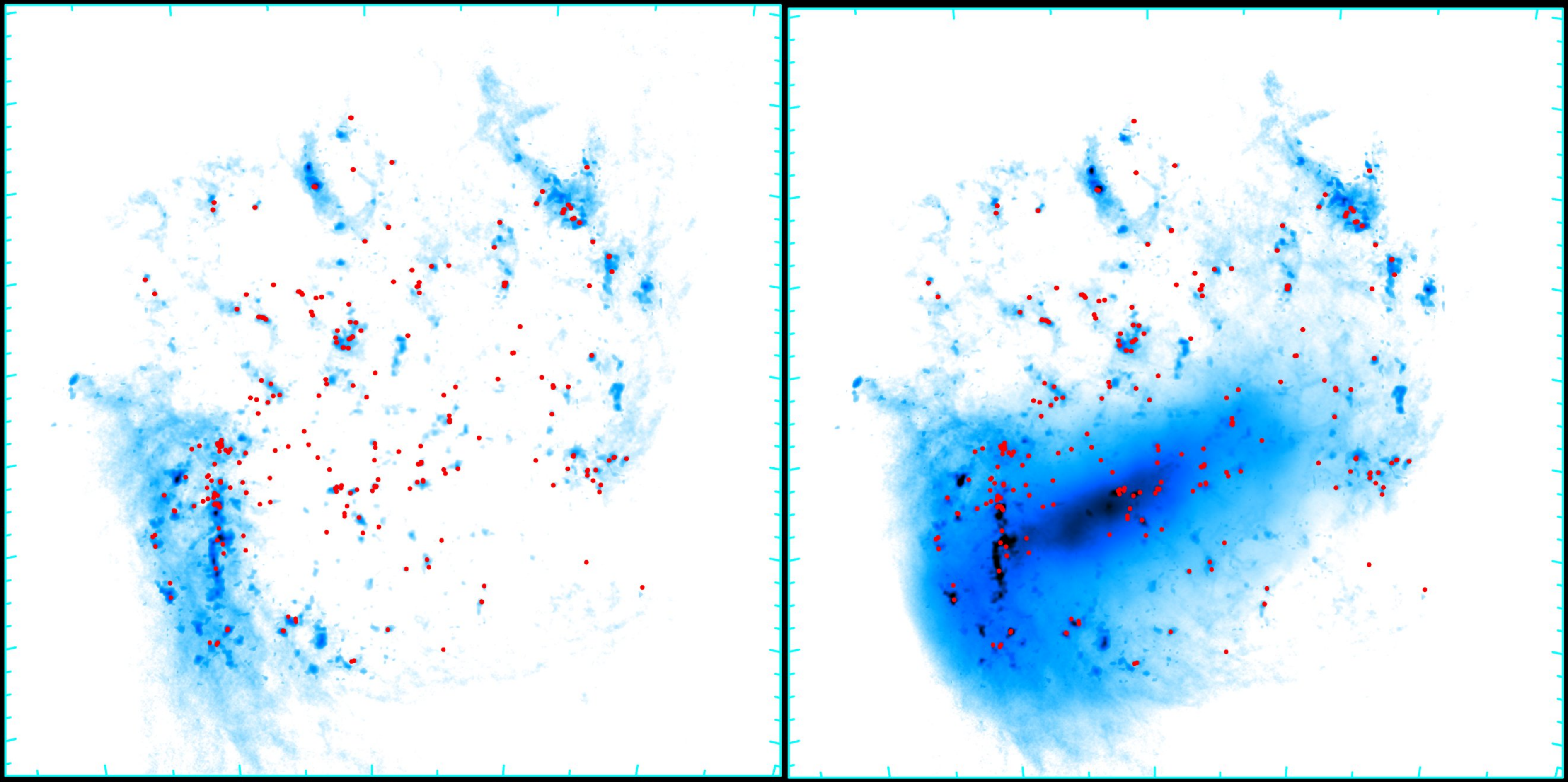


Rafikov
2001

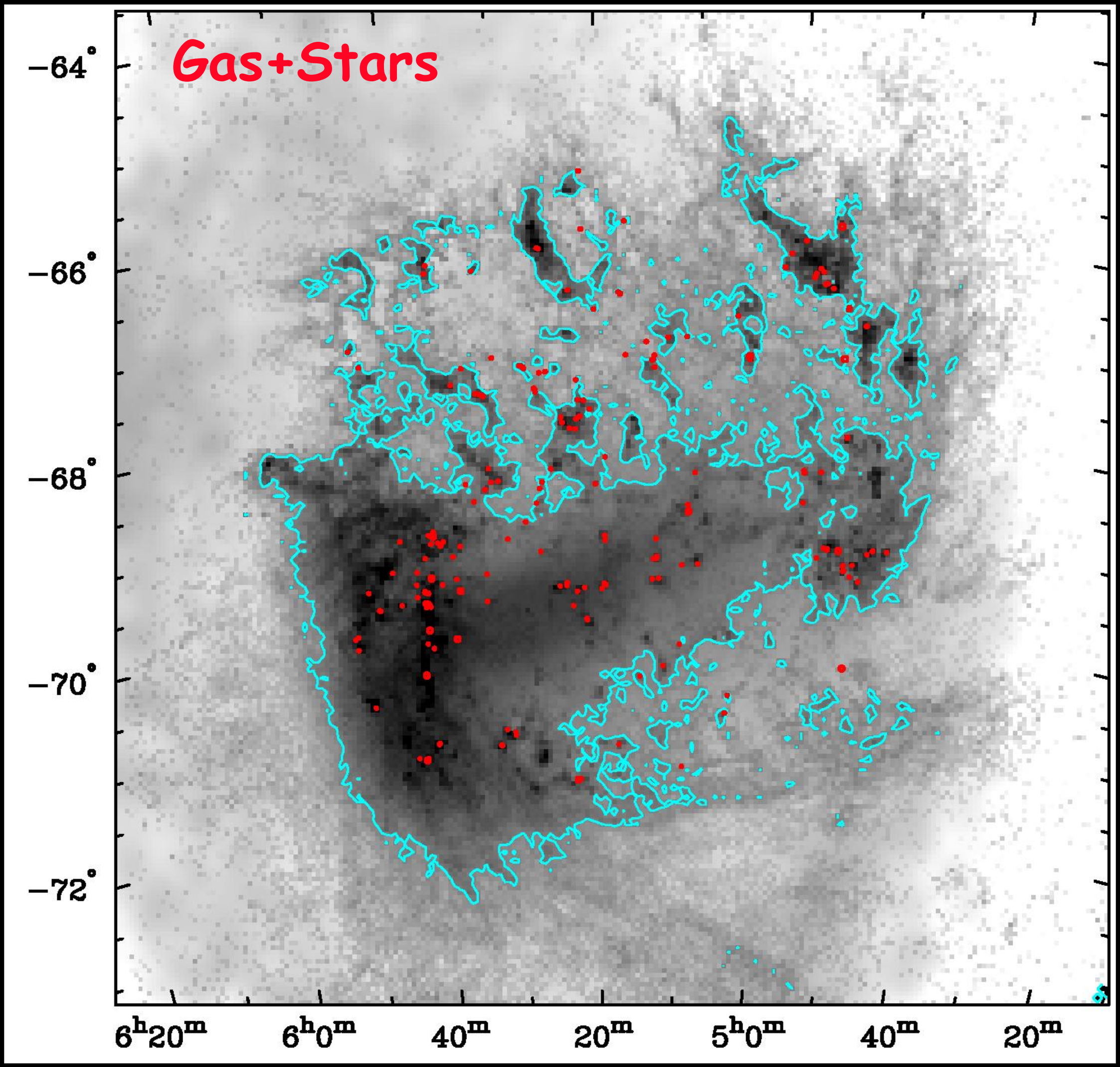
Gravitational Instability & Star Formation

Gas: 6.5×10^8 M⊙

Stars: 2×10^9 M⊙
Gas: 6.5×10^8 M⊙



Large-Scale Gravitational Instability



YSOs in unstable regions:

Gas disk only
62%

Gas + Star disk
85%

Both stars and gas need to be considered.

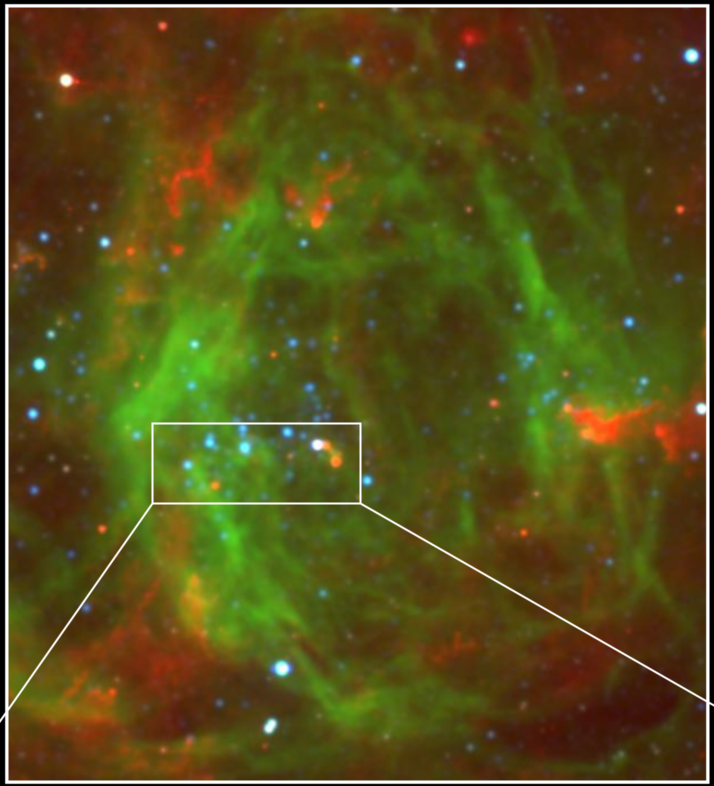
Triggered Star Formation

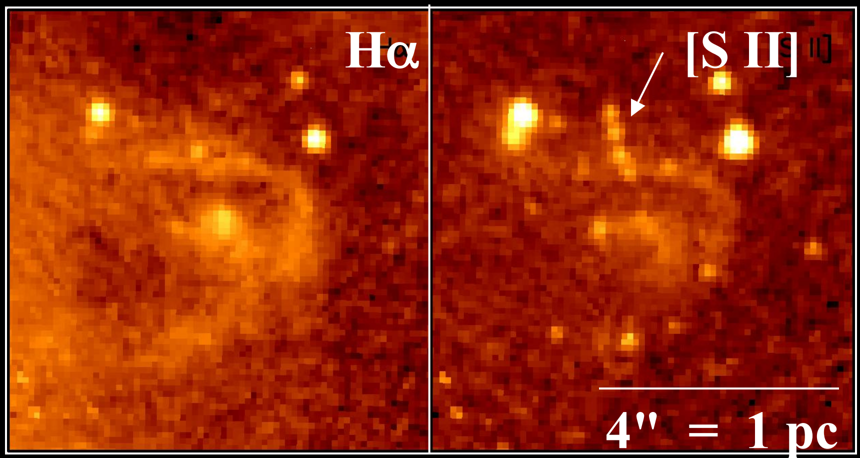
Globule: Chu et al. 2005, ApJ

Superbubble: Chen et al. 2009, ApJ

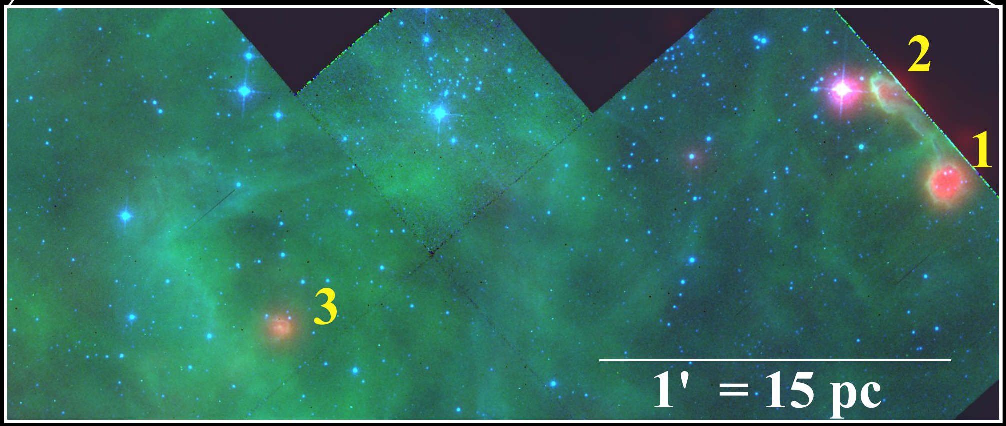
Supergiant Shell: Book et al. 2009, AJ

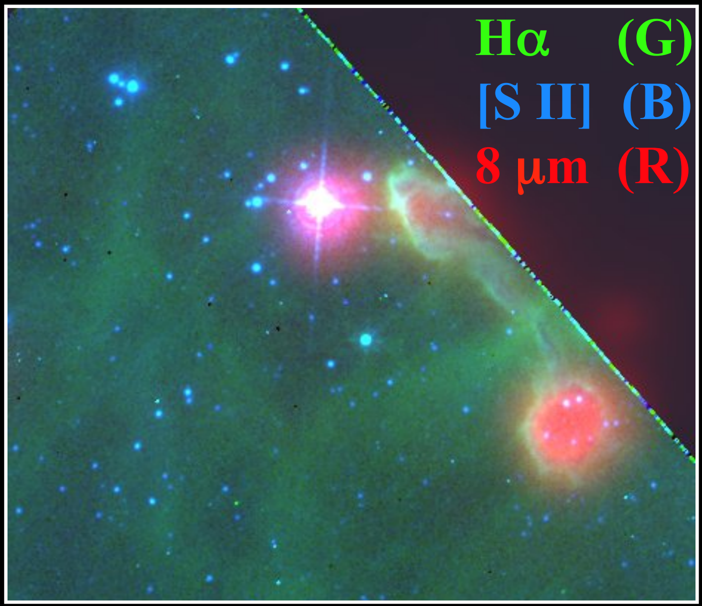
Star Formation in N51





Extragalactic HH object !





YSOs in dust globules

What Caused the Star Formation in N51's Bok Globules?

	n_e (cm^{-3})	T_e (K)	$P/k = n_e T_e$ (cm^{-3} K)
Hot gas	0.03	2.6×10^6	8×10^4
Warm gas	100	10^4	10^6
Cold gas	10^3 H_2	10	10^4

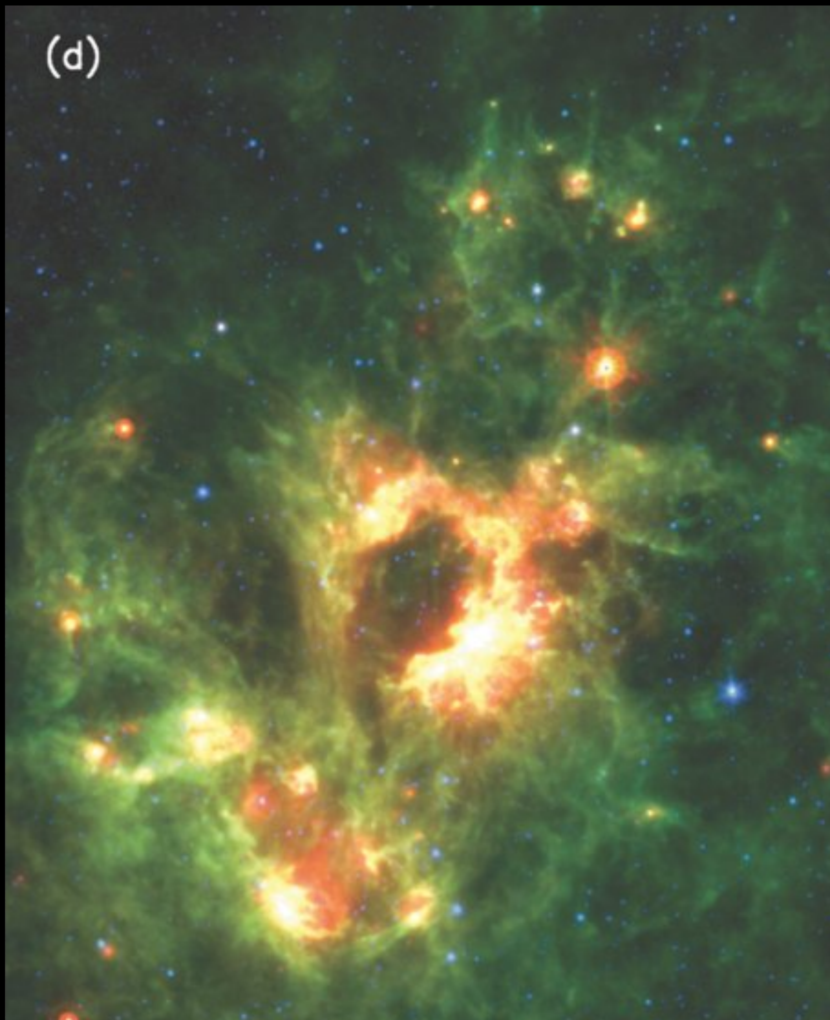
What Caused the Star Formation in N51's Bok Globules?

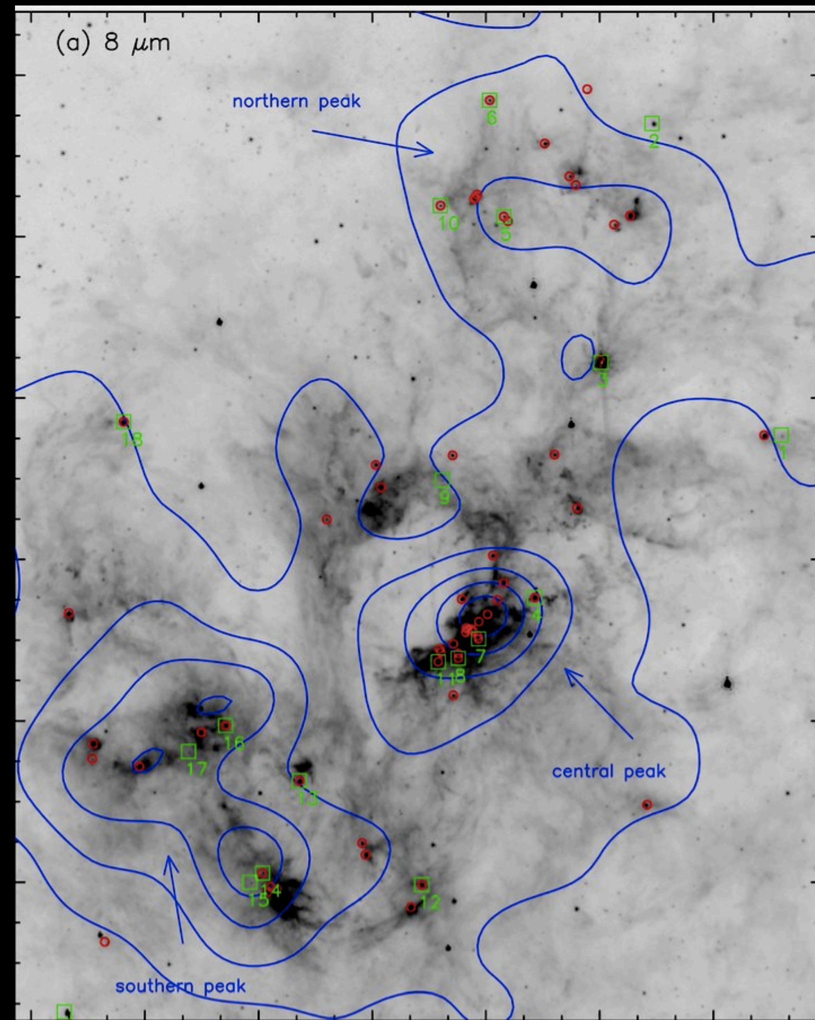
	n_e (cm^{-3})	T_e (K)	$P/k = n_e T_e$ (cm^{-3} K)
Hot gas	0.03	2.6×10^6	8×10^4
Warm gas	100	10^4	10^6

Triggered by photo-implosion

(globule squeezing)

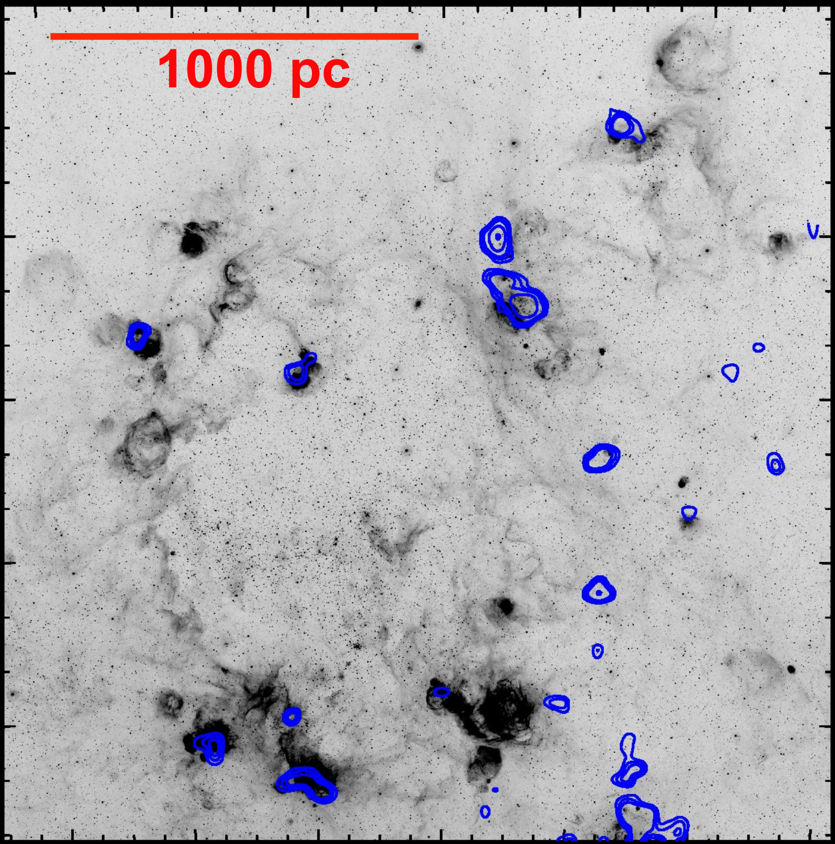
Star Formation in Superbubble N44



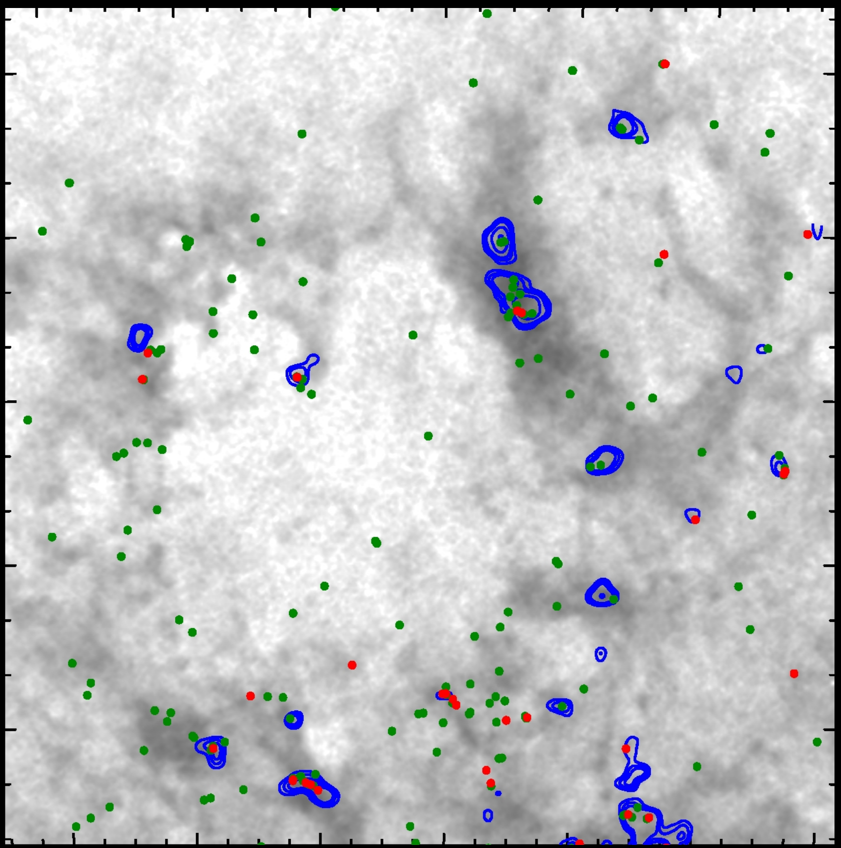


Chen et al. 2009, ApJ, 695, 511

Star Formation Associated with Supergiant Shells



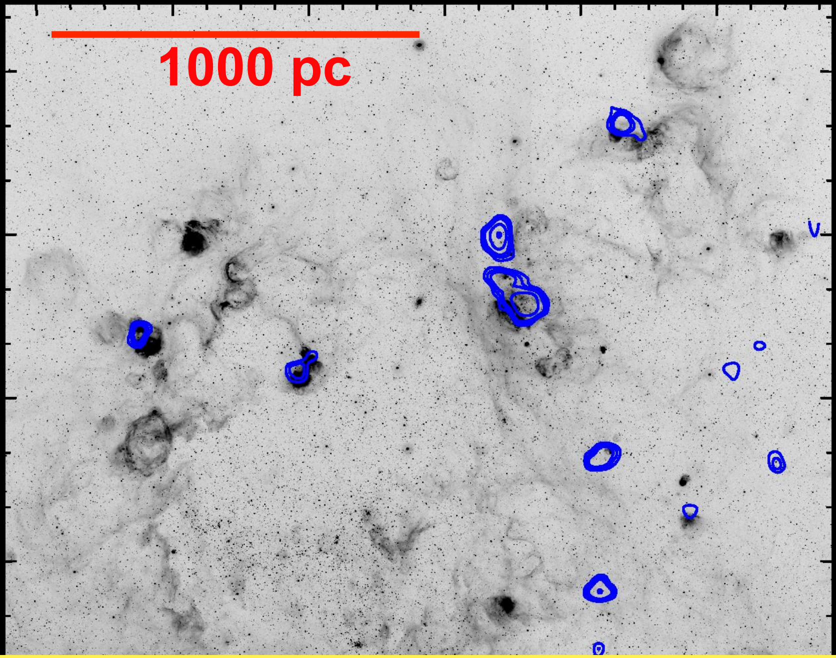
$H\alpha$ + CO contour

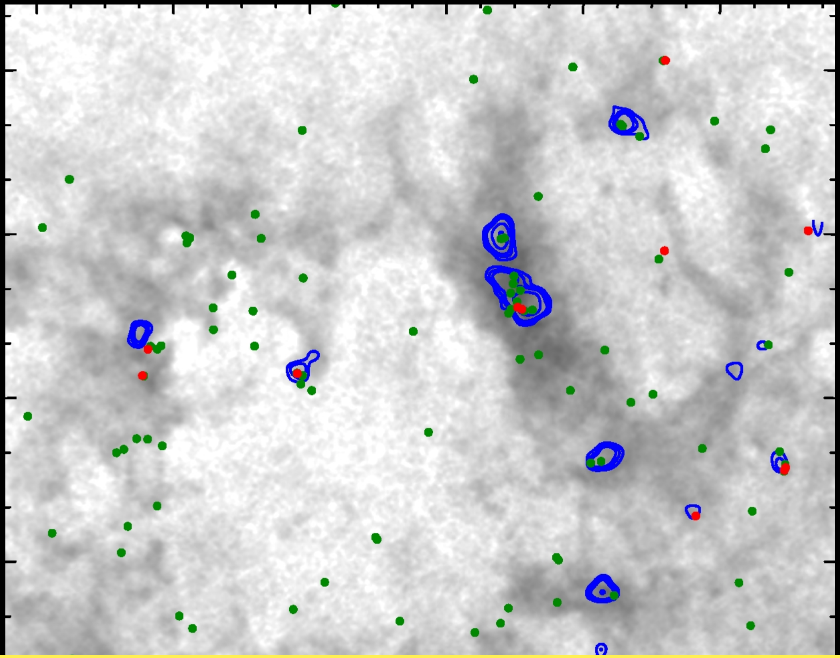


H I + CO contour

Book et al. 2009, AJ, 137, 3599

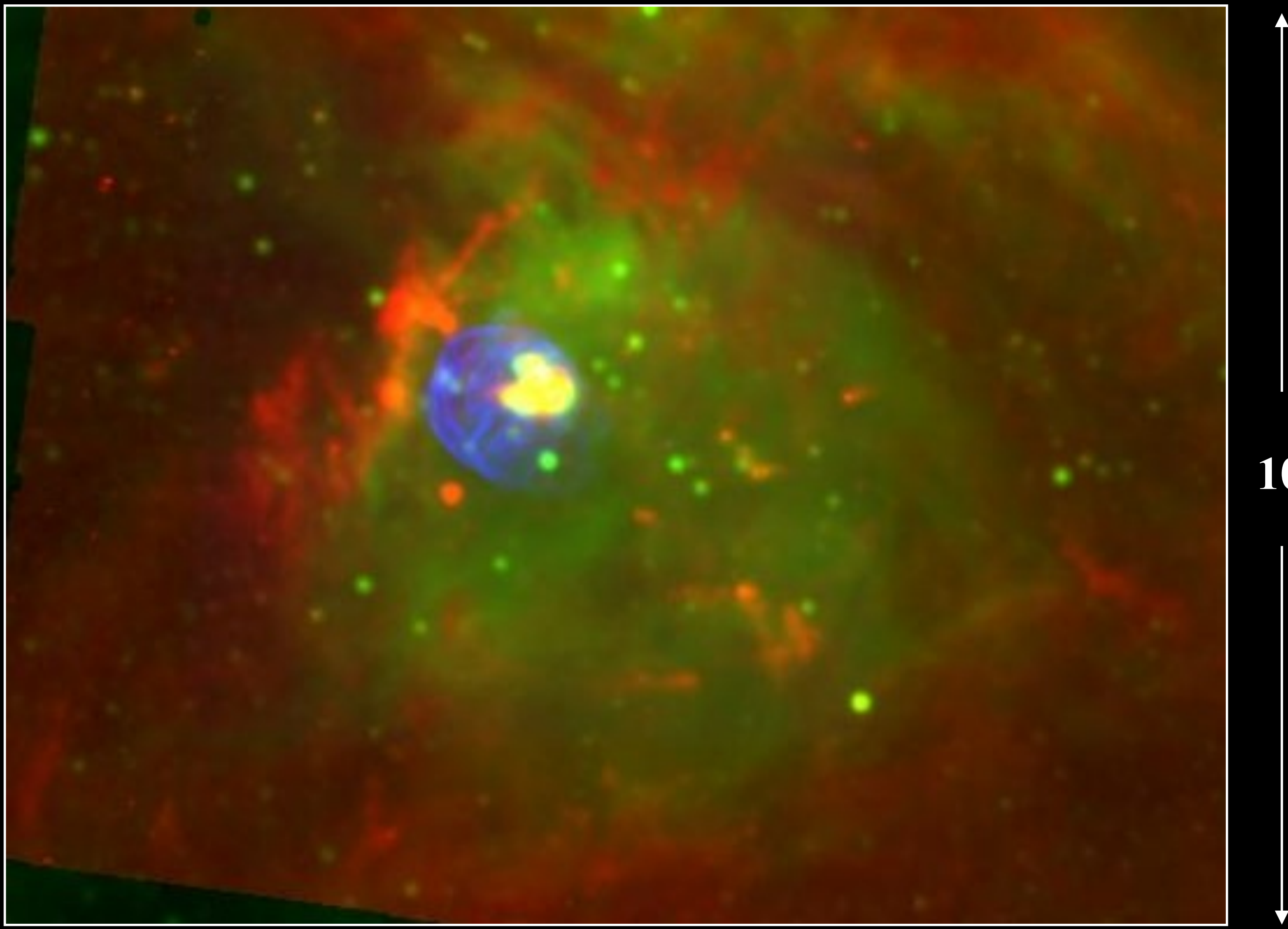
Star Formation Associated with Supergiant Shells





Superbubbles and supergiant shells may trigger star formation

Star Formation in N 63
“ triggered by HII region, enriched by SNR ”



Blue - X-ray   Green - Hα   Red - 8 μm

Star Formation in N 63
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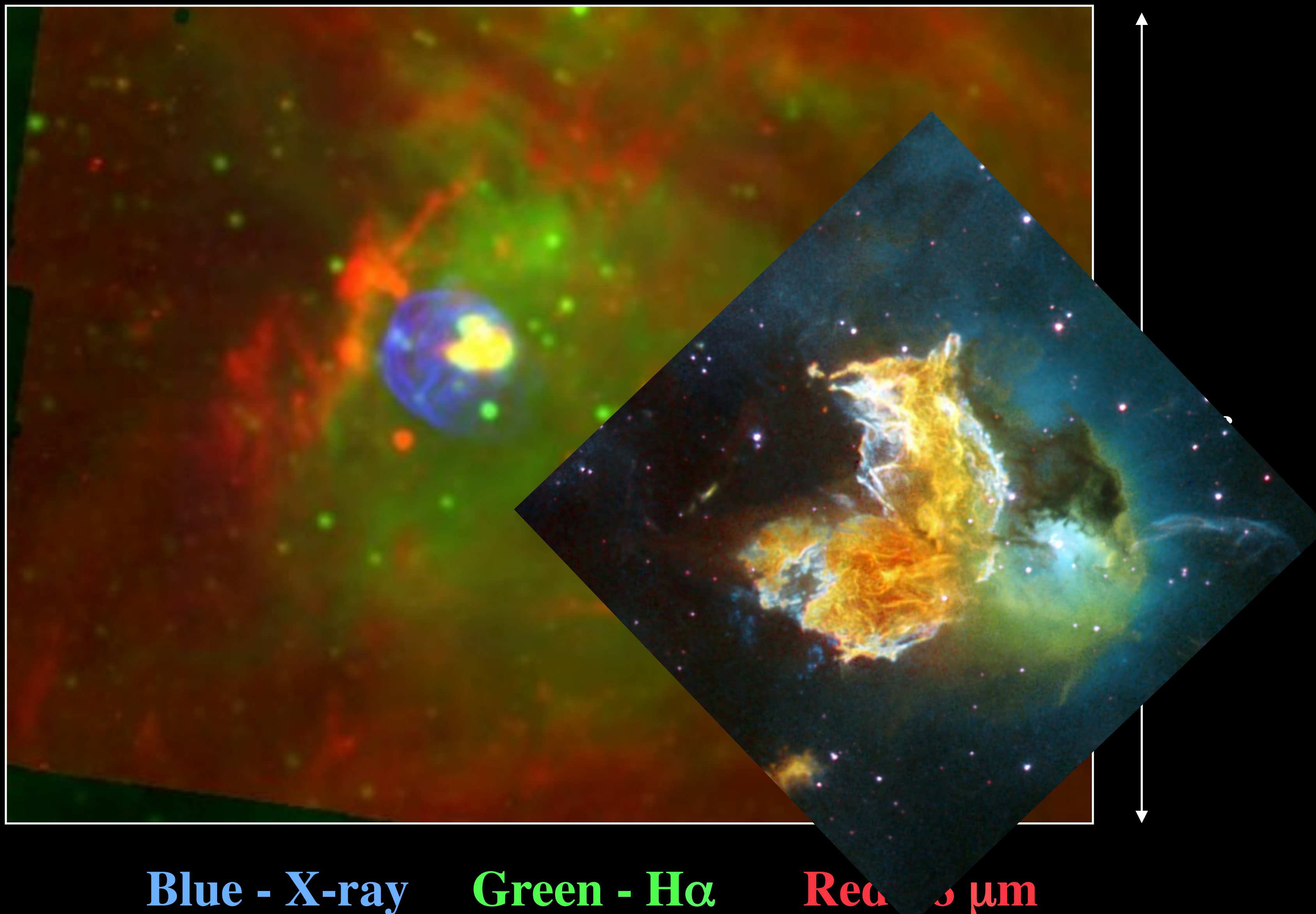
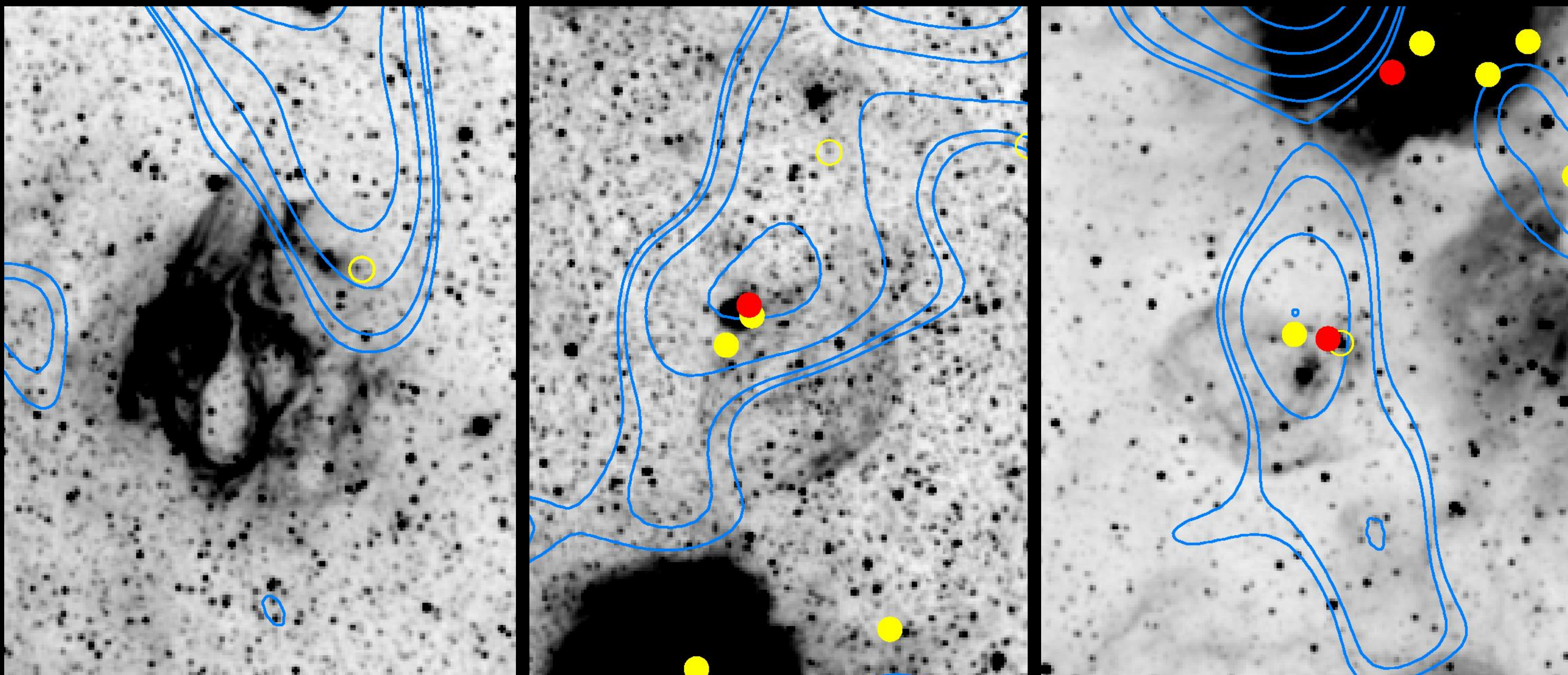


Blue - X-ray **Green - Hα** **Red μm**

Do SNRs Trigger Star Formation?

SNR N86 | SNR 0513-69.2 | DEM L256

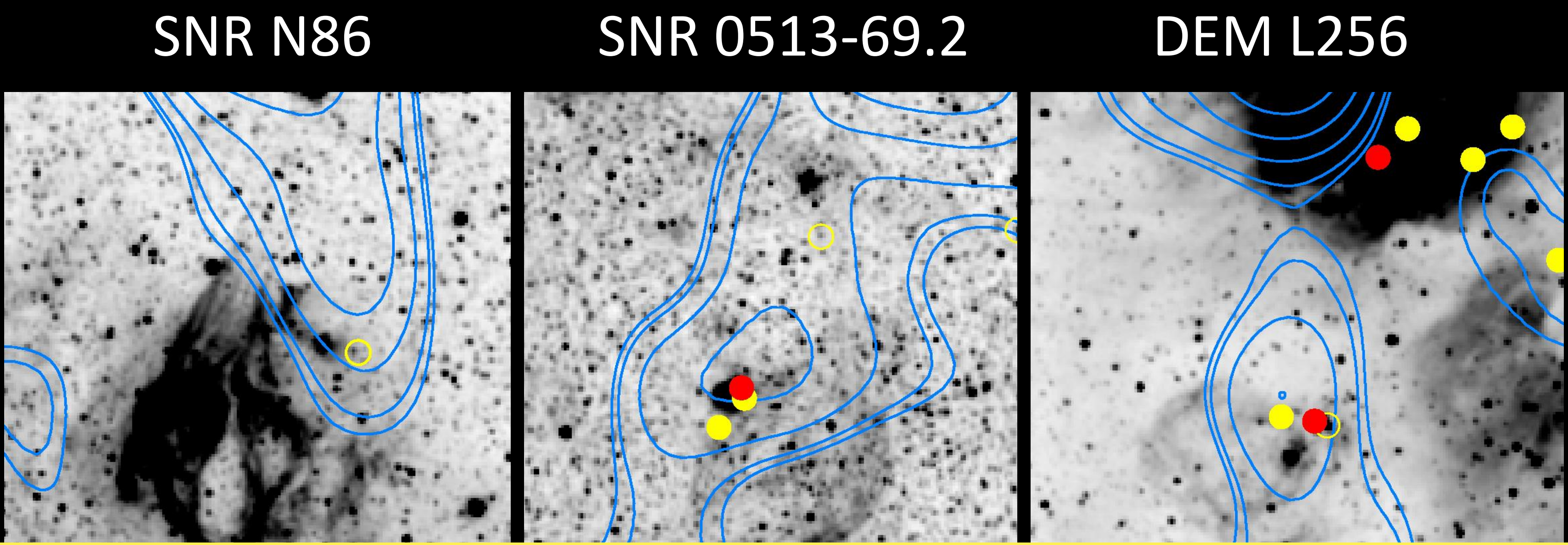


50 pc

CO contours (NANTEN; Fukui et al)
Hα images (MCELS; Smith et al)

Desai et al. 2010

Do SNRs Trigger Star Formation?

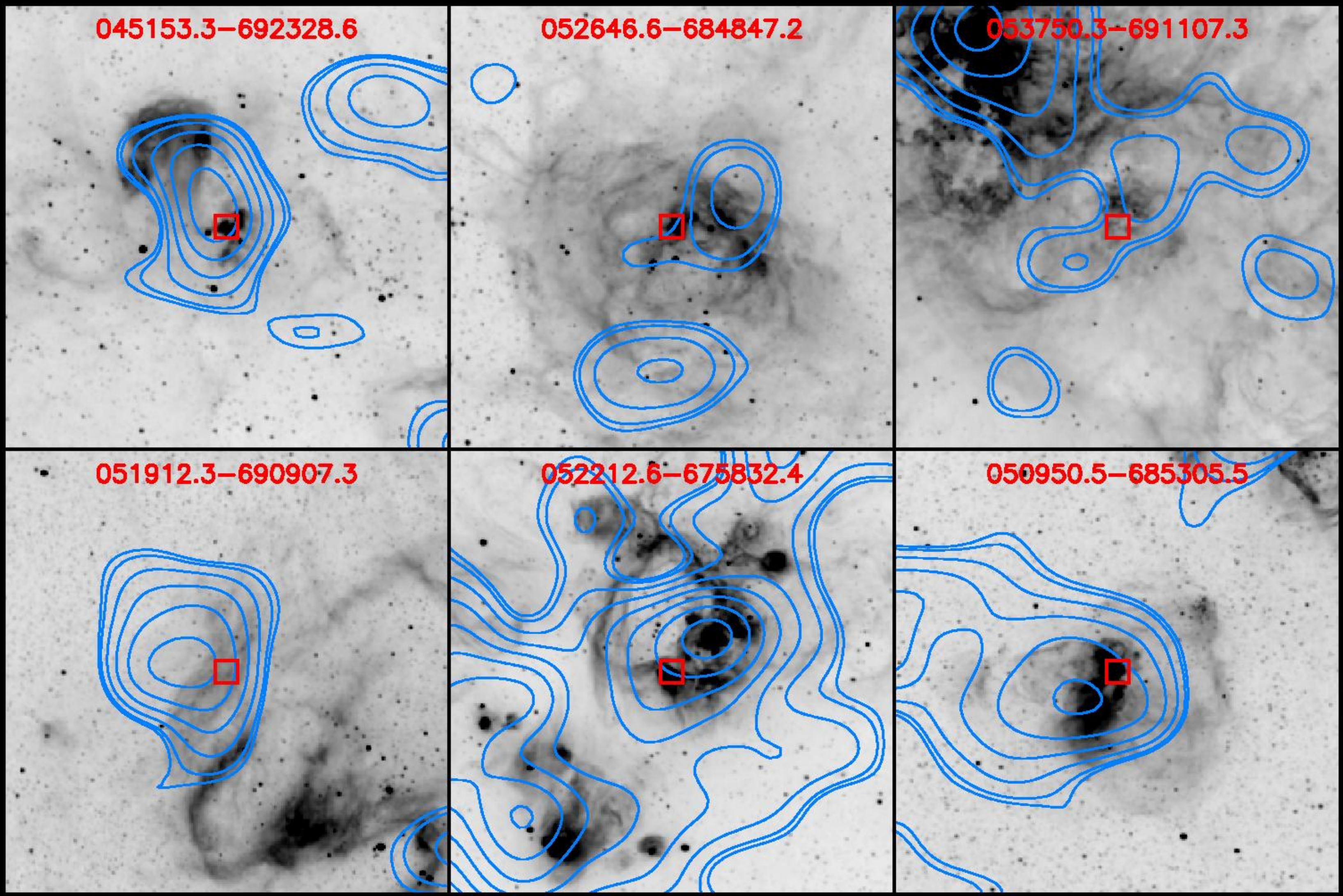


Young SNR's shocks are destructive.

Their progenitors' HII regions or bubbles may have trigger star formation.

What else?

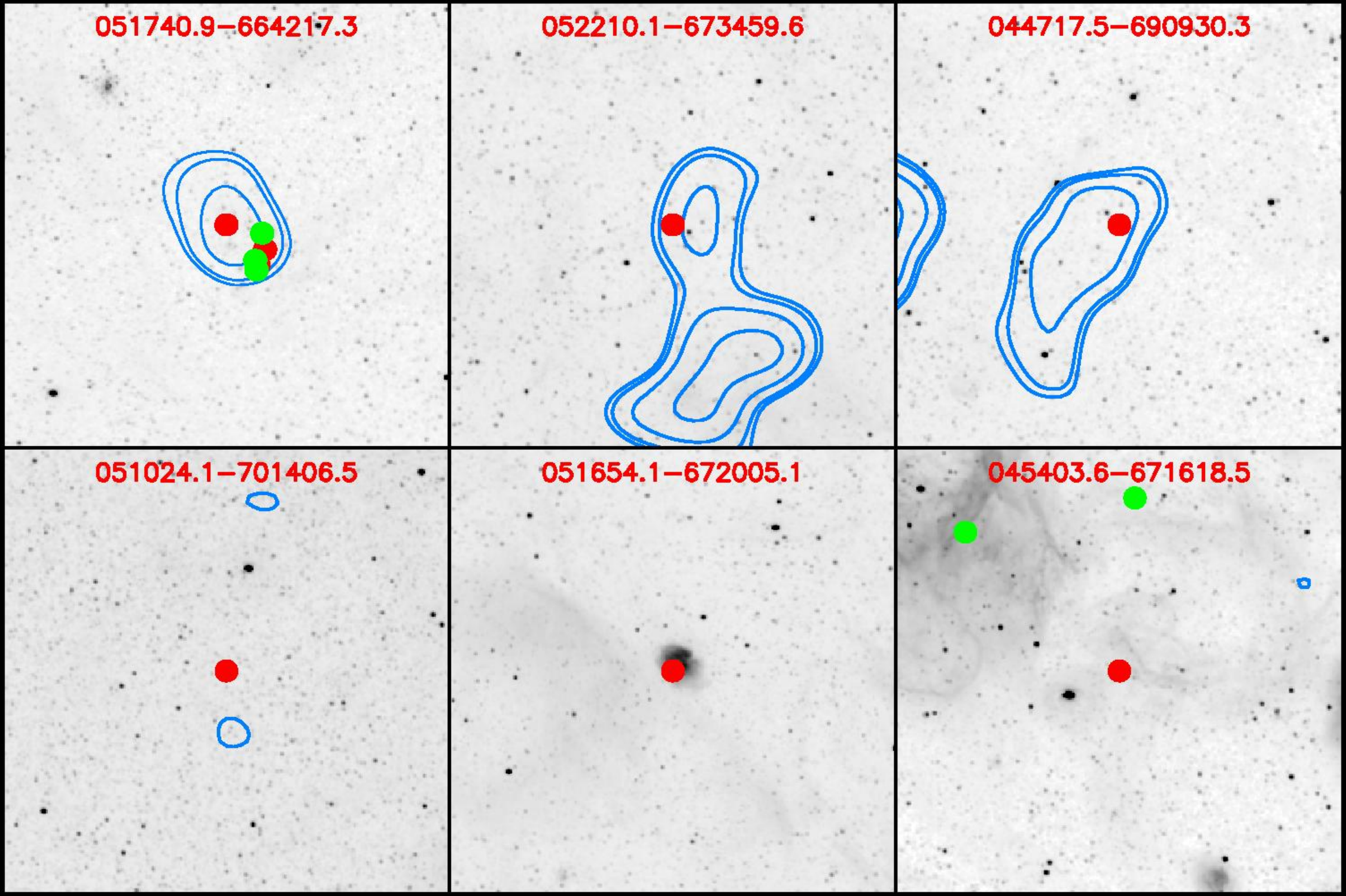
Massive YSOs and Their Environments



15' = 225 pc

CO contours (NANTEN; Fukui et al)
Hα images (MCELS; Smith et al)

Are These Massive YSOs Isolated ?



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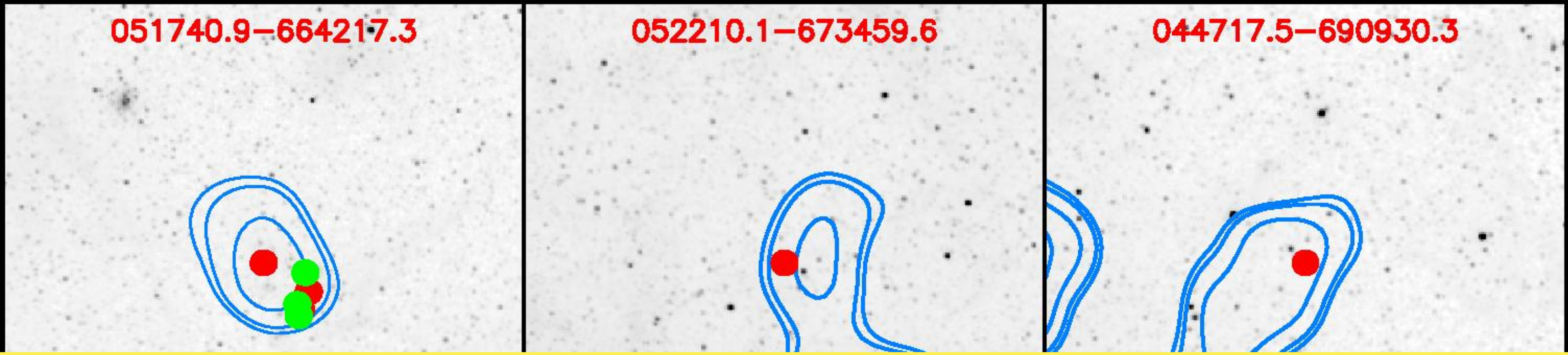


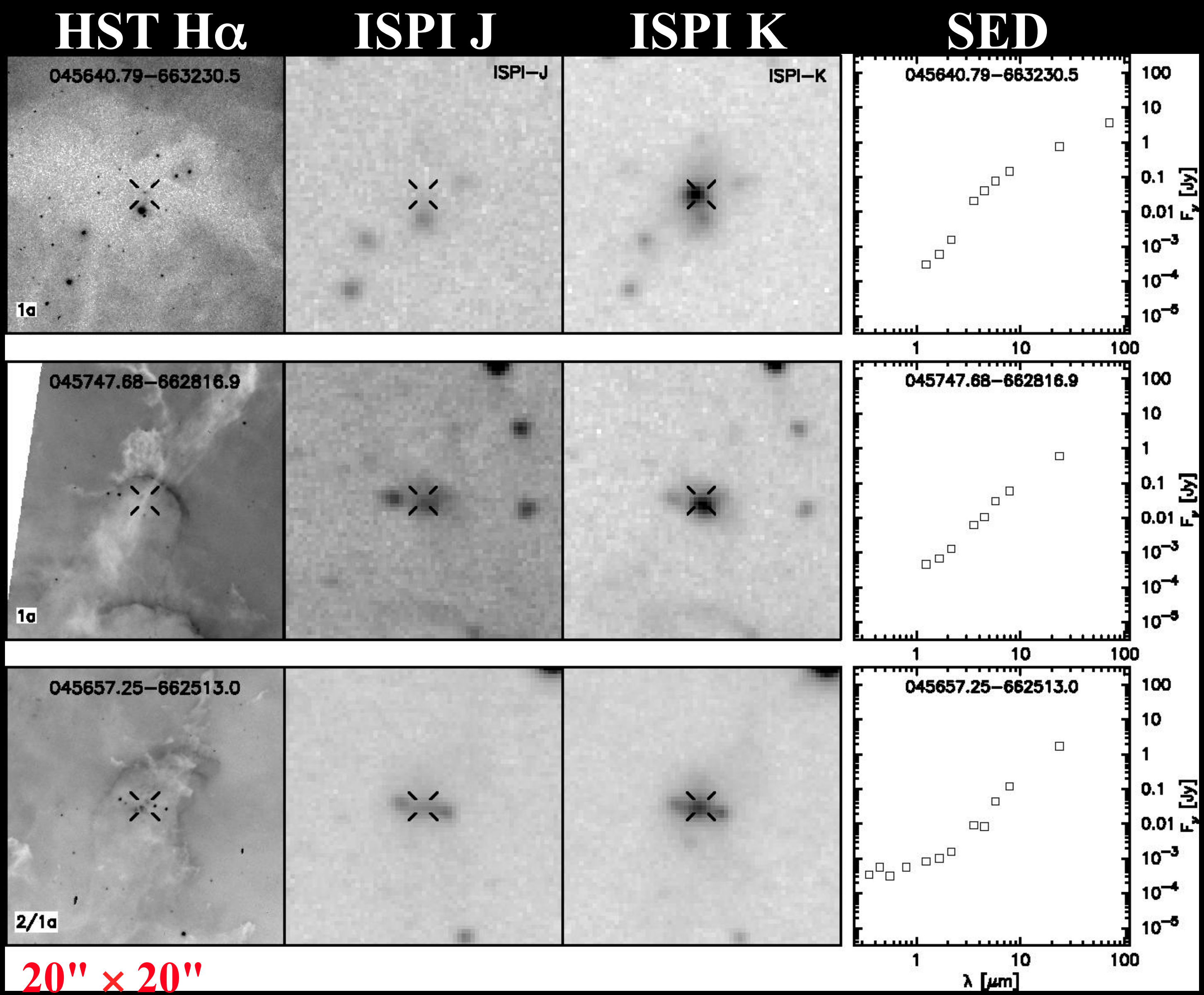
Massive YSOs

~ 85% are in molecular cloud

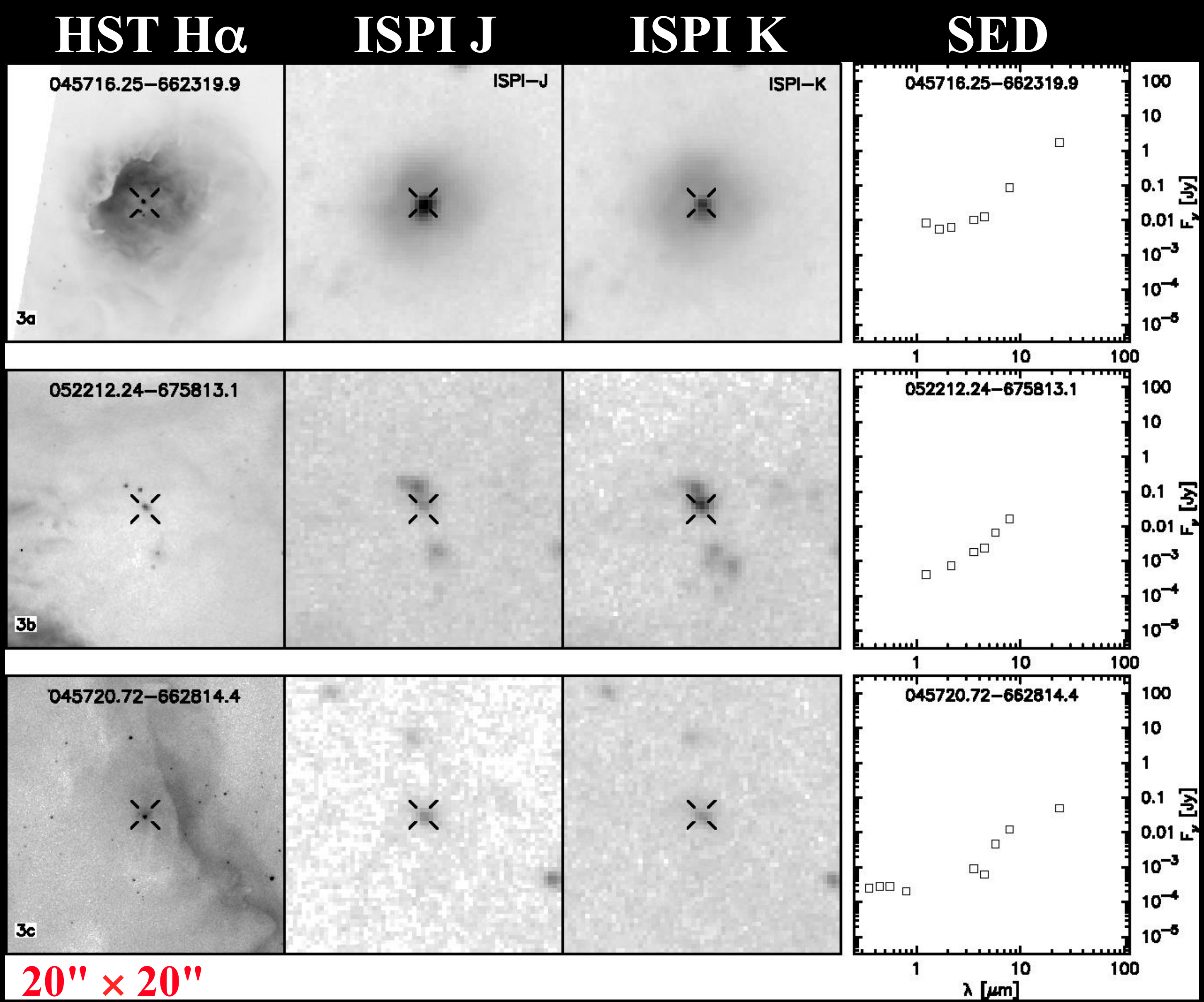
~ 65% are in OB associations

~ 7% are not in OB associations or molecular clouds → HST images show small clusters around some (in prep).

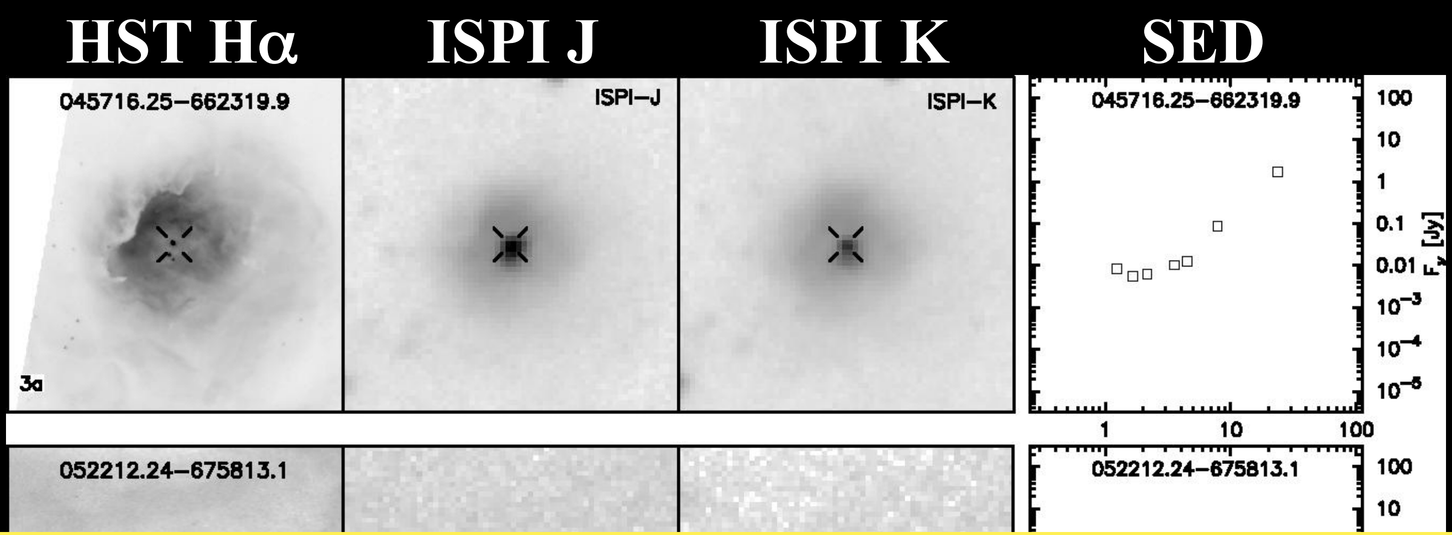
A Closer Look at YSOs' Environments



A Closer Look at YSOs’ Environments



A Closer Look at YSOs' Environments



HST View of YSOs' Environments

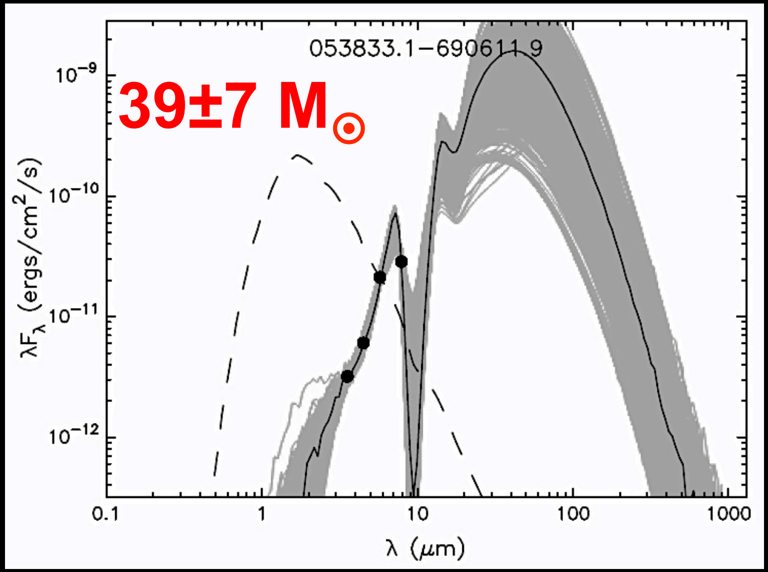
(1) dark clouds, (2) bright-rimmed dust pillars, (3) small compact HII.

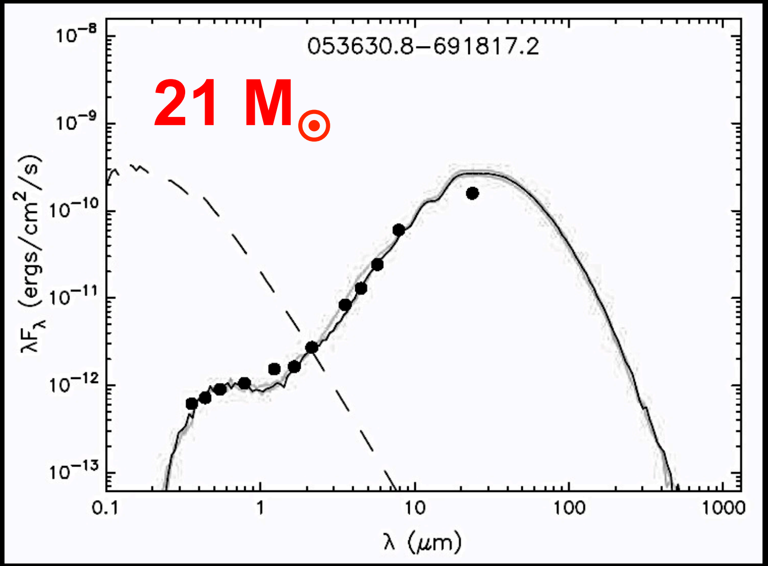
(Vaidya et al. 2009)

YSOs in 30 Doradus - Great Challenge!

Walborn, Barbá, Sewilo 2013
Top10 YSOs in 30 Dor

Online SED Fitter (Robitaille et al . 2007)

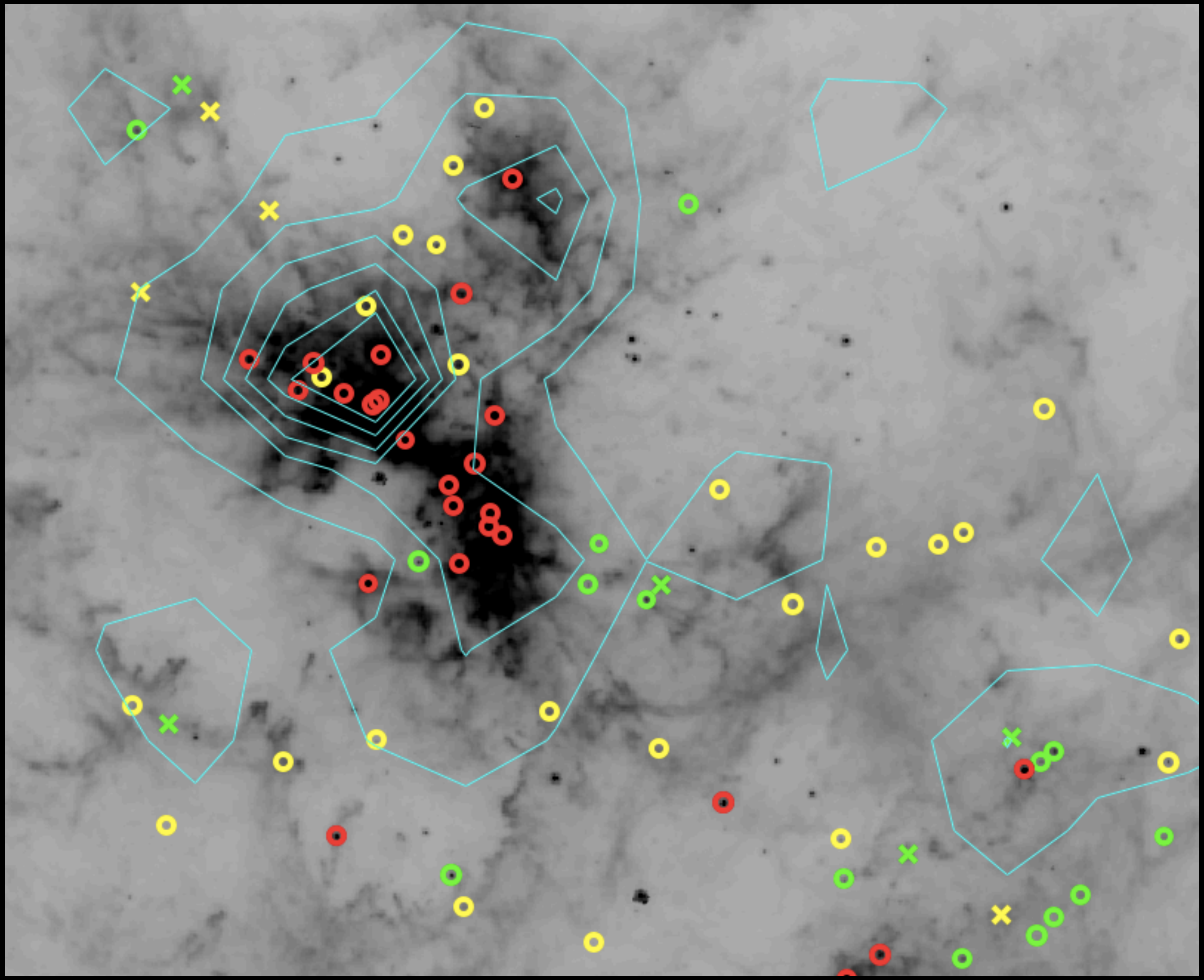




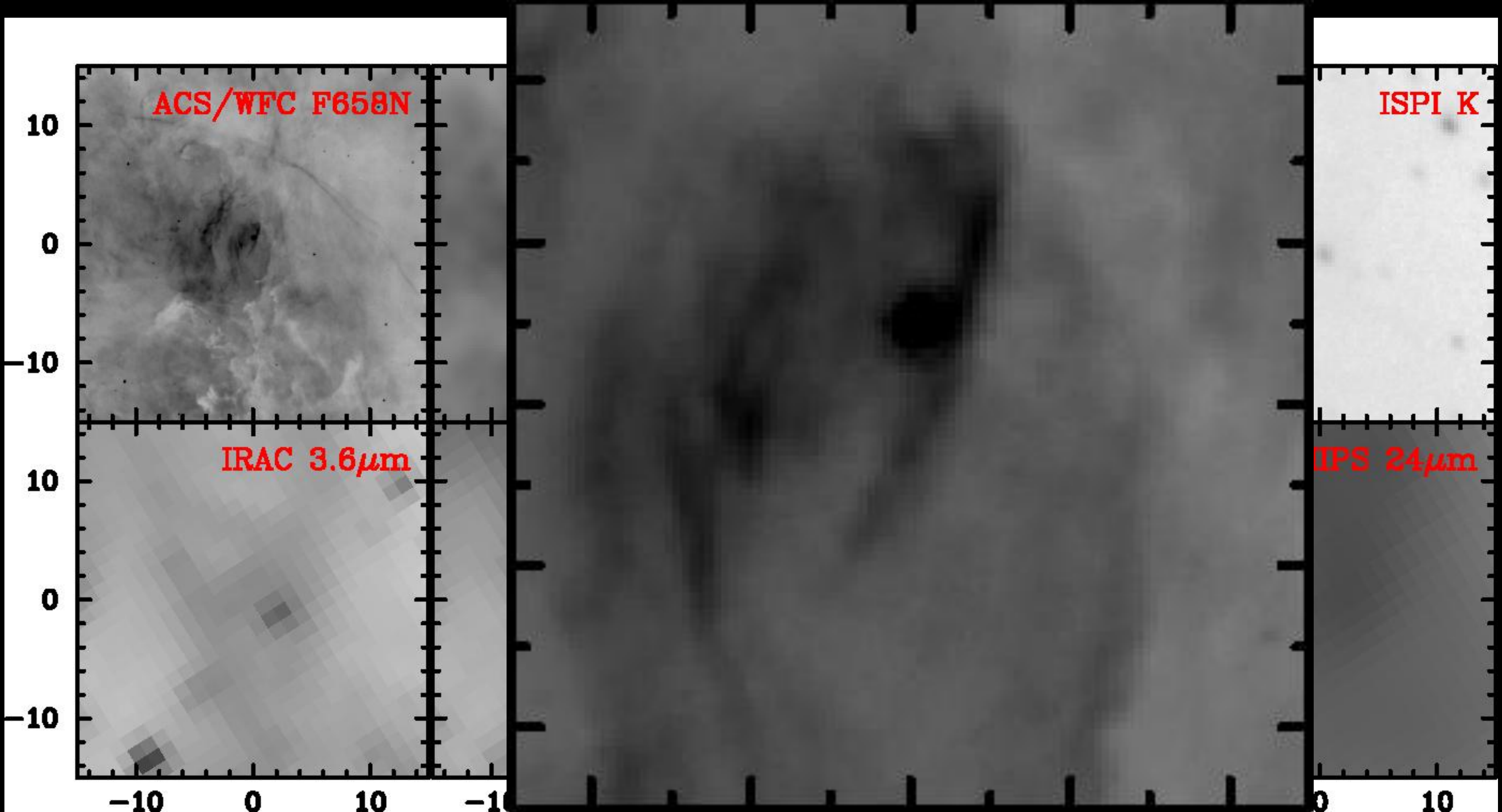
YSOs in 30 Doradus - Great Challenge!

Red: [8.0]< 8 ; Green: [8.0]>8 ; Yellow: [8.0]>8

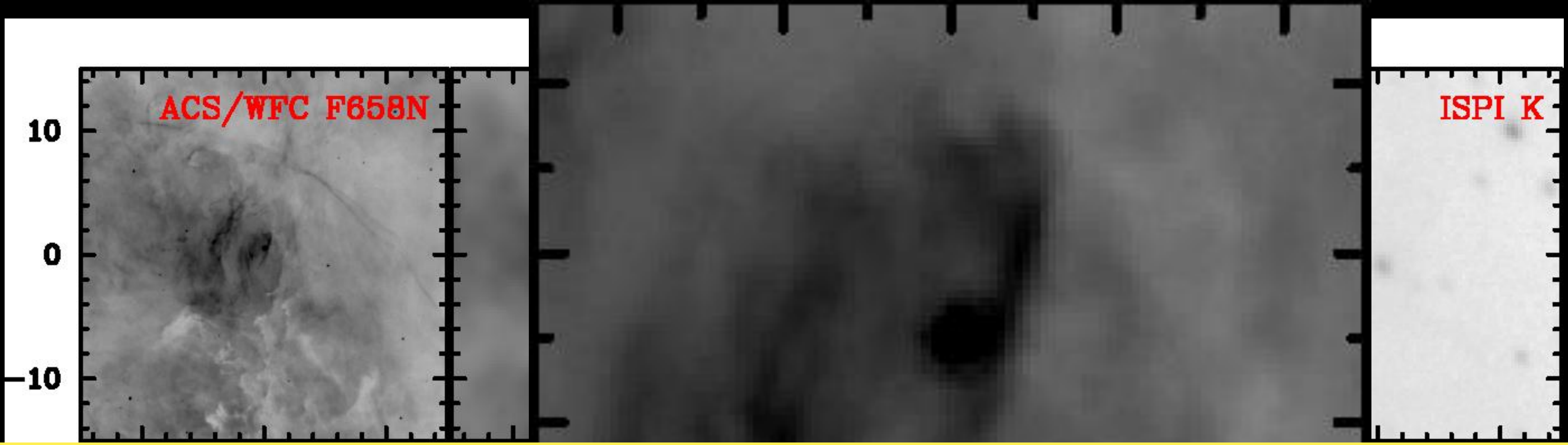
YSO > 10 $M_\odot$ YSO < 10 $M_\odot$ star+IRE



YSOs in 30 Doradus - Great Challenge!



YSOs in 30 Doradus - Great Challenge!



Massive YSOs are in GMCs/HII.

No embedded massive clusters or YSOs > 40 $M_{\odot}$ are found.

HST images will be available soon.

Pre-Main Sequence Stars

Giant molecular clouds with or without massive star formation

- Blanco NEWFIRM data being analyzed

DECam surveys of the MCs would be very useful for identifying PMS stars and optical counterpart of YSOs.

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CTIO continues to make vital contributions to science !!!


Gracias, CTIO!