Star Formation in the Large Magellanic Cloud: Tracing an Evolution of Giant Molecular Clouds

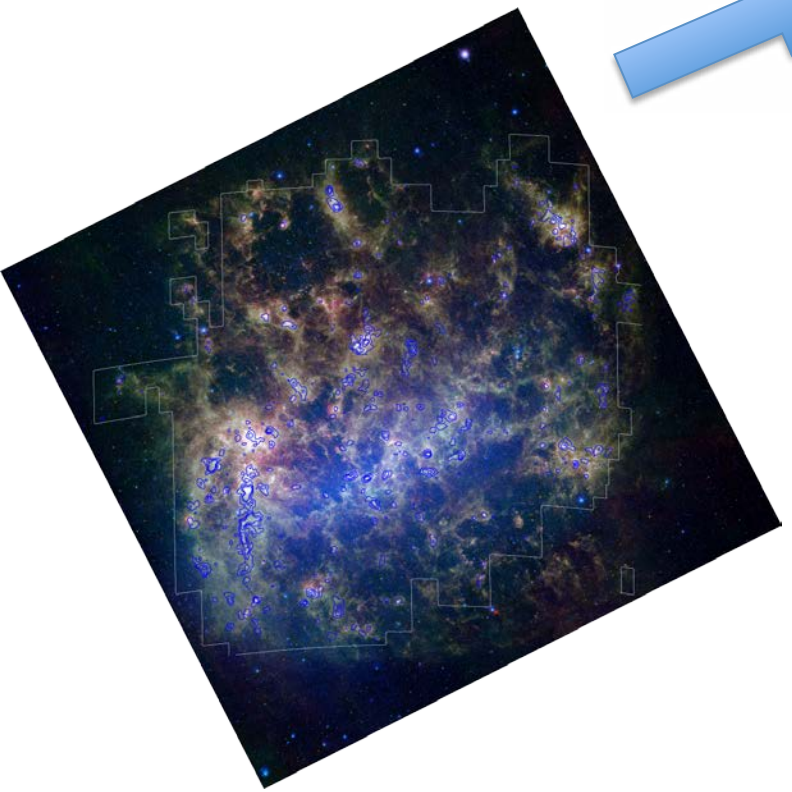
Toshikazu Onishi (Osaka Prefecture University)

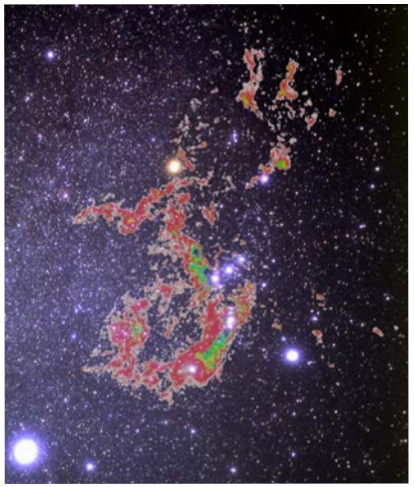
R. Harada, Y. Morioka, K. Tokuda(OPU),Y. Fukui, K. Torii(Nagoya Univ.), A. Kawamuwa, K. Saigo (NAOJ),

M. Meixner (STScI), M. Sewilo, O. Nayak (J. Hopkins Univ.), R. Indebetouw (Univ. of Virginia), and many others

Galaxy evolution→ Individual star formation

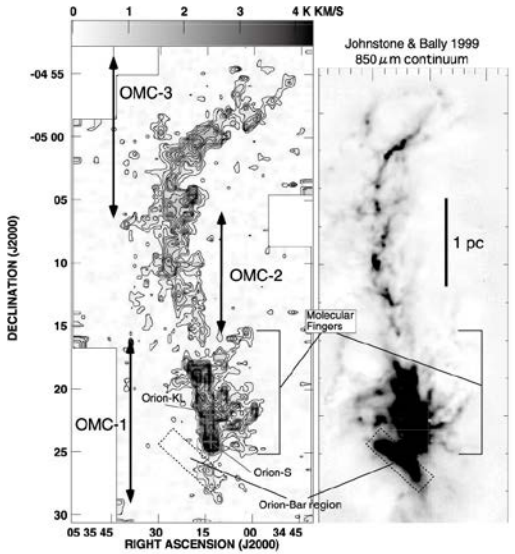
The galaxy scale SF : kpc





1-100pc

<1pc



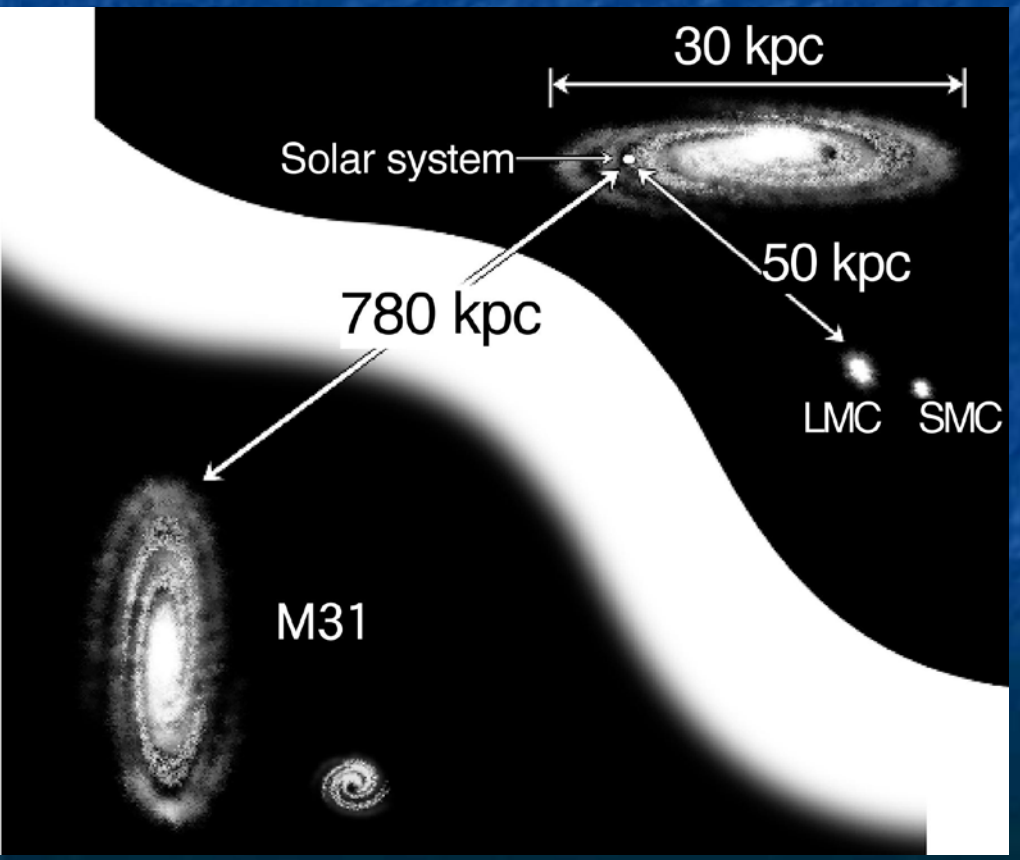
Ikeda et al. 2007 H13CO+ mapping ~0.05pc resolution

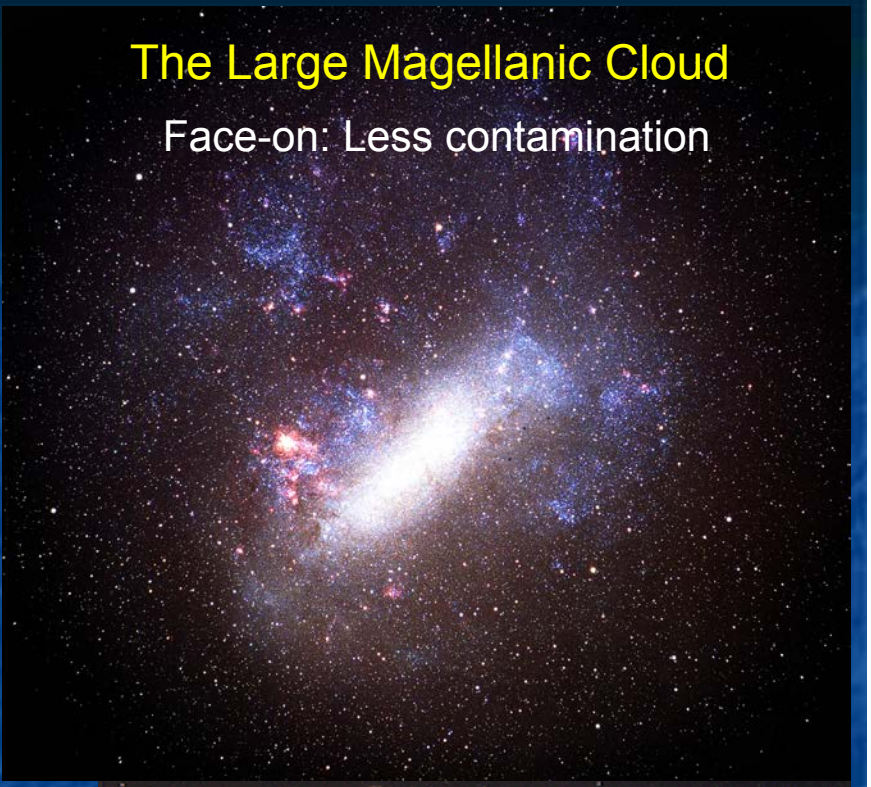
Star formation in GMCs

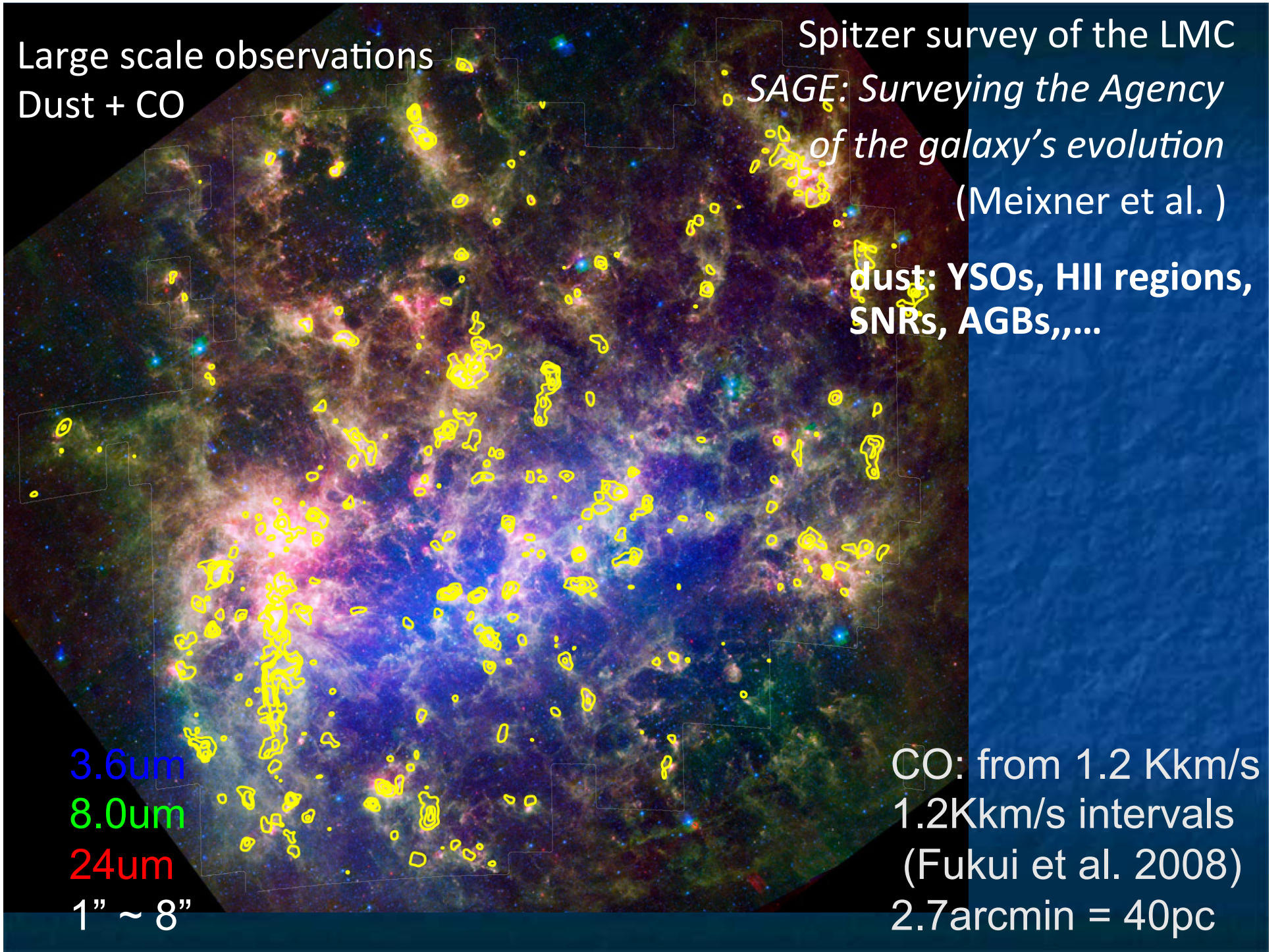
- Most stars form in GMCs
  - K-S law: Gas surface density – SF activities
    - Gas →SF is a "key" to understand the galaxy's evolution
- Key issue for galaxy evolution
  - GMC properties in the MW as templates
    - Some scaling relations (e.g., Solomon et al. 1987)
    - The samples are biased to the neayby GMC?
      - Not a representative for the MW?
  - Magellanic Clouds + some local galaxies
    - Recent high resolution observations + "Uniform" sample
      - Uniform sample of high mass formation from GMC scale down to core scale
    - bridging between MW GMCs and distant galaxies

Magellanic Clouds

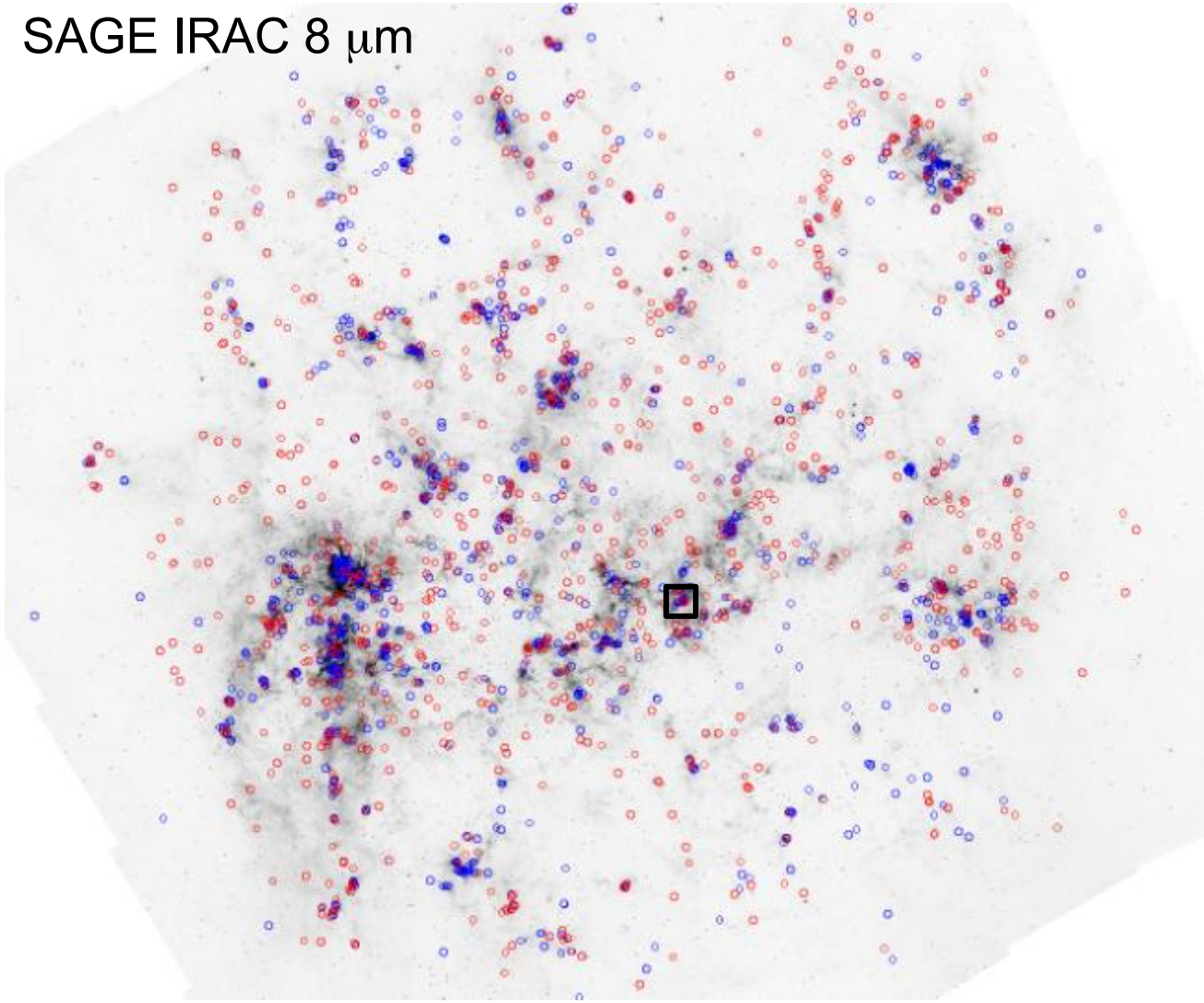
- D~ 50 kpc (one of the nearest)
- Different environment from the MW.
  - High gas-dust ratio
  - Low metallicity
- Active star formation
  - Massive star formation
  - Young populous clusters






Large scale observations
Dust + CO
Spitzer survey of the LMC
SAGE: Surveying the Agency of the galaxy's evolution
(Meixner et al.)
dust: YSOs, HII regions, SNRs, AGBs,,…
3.6um
8.0um
24um
1" ~ 8"
CO: from 1.2 Kkm/s
1.2Kkm/s intervals
(Fukui et al. 2008)
2.7arcmin = 40pc

Spitzer Discovers More than Thousand Young Stellar Objects in the LMC



Pre-*Spitzer*:

~20 protostars known

Spitzer:

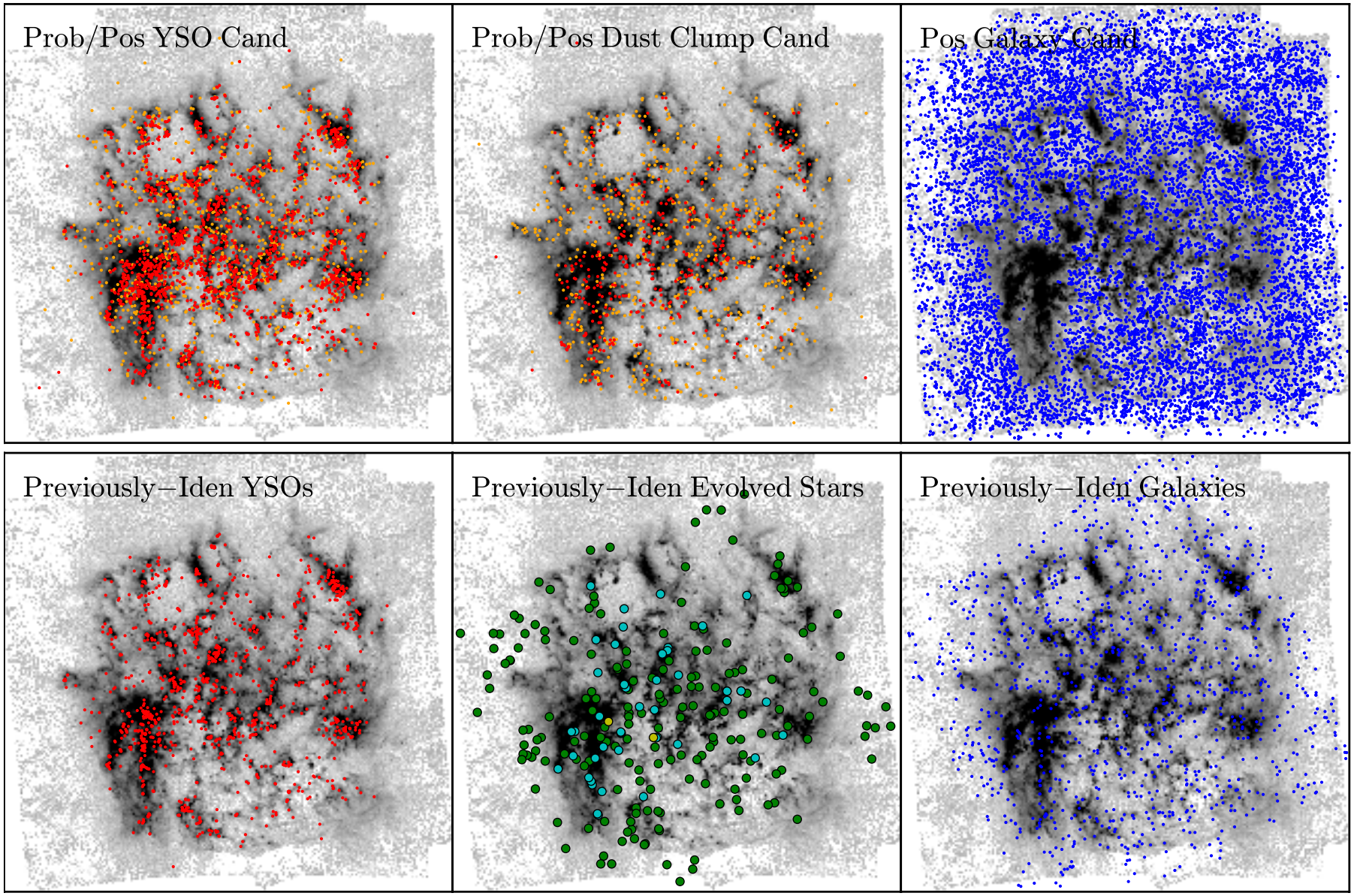
~1000 YSO candidates
Whitney, Sewilo et al. (2008)

~1200 YSO candidates
Gruendl & Chu (2009)

~1800 unique sources

Star Formation Rate:
~0.1 $M_{\odot}$/yr

LMC



Seale et al., 2014

HERITAGE Catalog – Classification stats

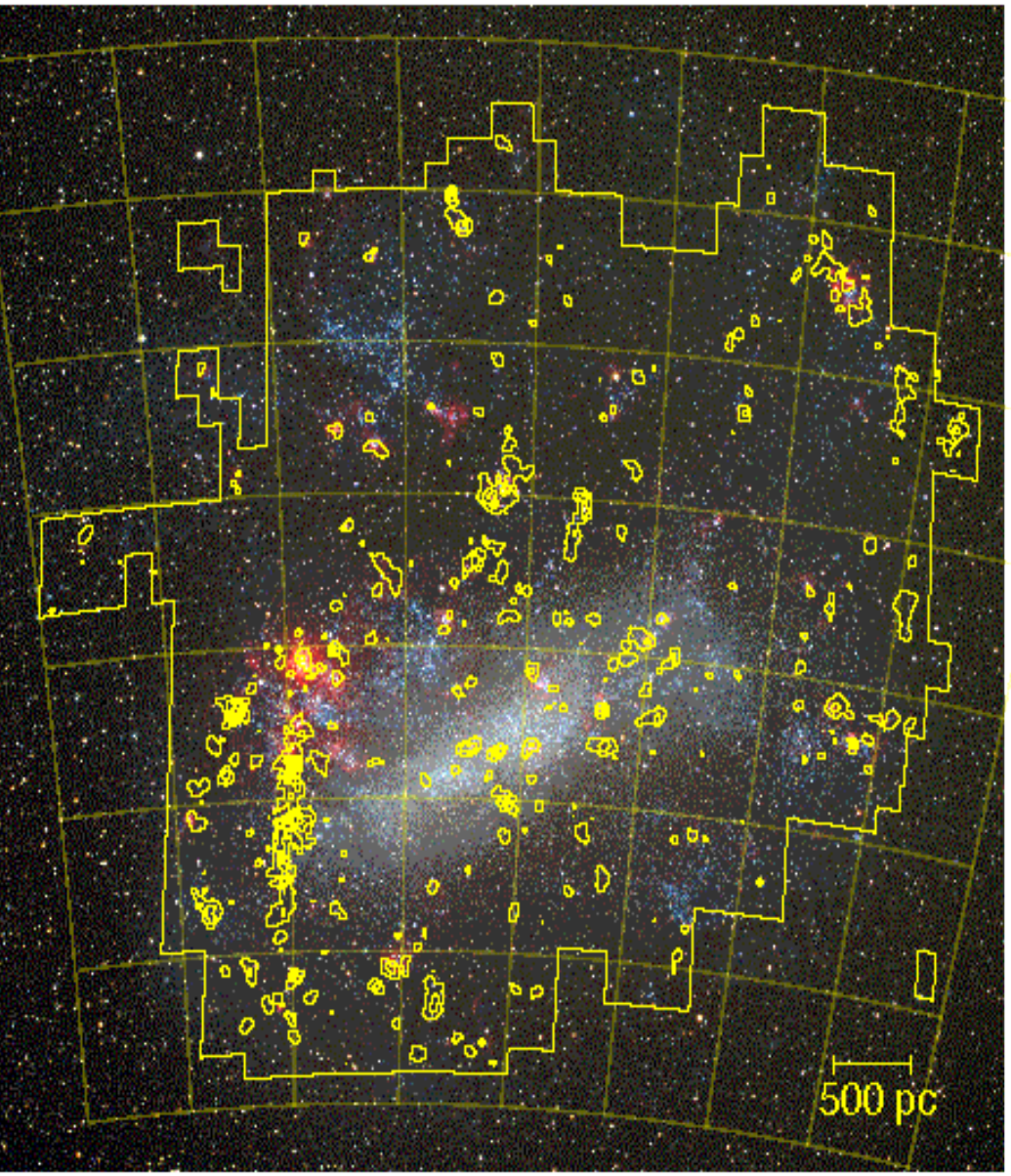
	LMC	SMC
Galaxy Candidates	9,745	5,111
Probable YSO	2,493	425
Possible YSO	1,025	238
Probable Dust Clumps	1,175	36
Possible Dust Clumps	1,569	74

Completeness limit: Young embedded YSOs of 1000Lo (6Mo B4 star)

Seale et al., 2014

These YSO candidate lists enable us to directly investigate the processes of star formation at lower metallicities similar to the metallicity during the epoch of peak star formation in the Universe.

NANTEN 2nd survey of GMCs in the LMC



- **Contours: CO J=1-0**
- **270 GMCs**
- **X_{LMC} ~ 9×10^{20} cm^{-2} / [K km s^{-1}] ~ 3 X_G is used (Mizuno et al. 2001))**
  ($X = N(H_2)/ I_{CO} = M/L_{CO}$)

Mass : 6 ×10^4 – 6 ×10^6 Mo
Size (radius) : 30 - 150 pc
Line width (FWHM) : 3 – 17 km s^{-1}

2.7arcmin = 40pc

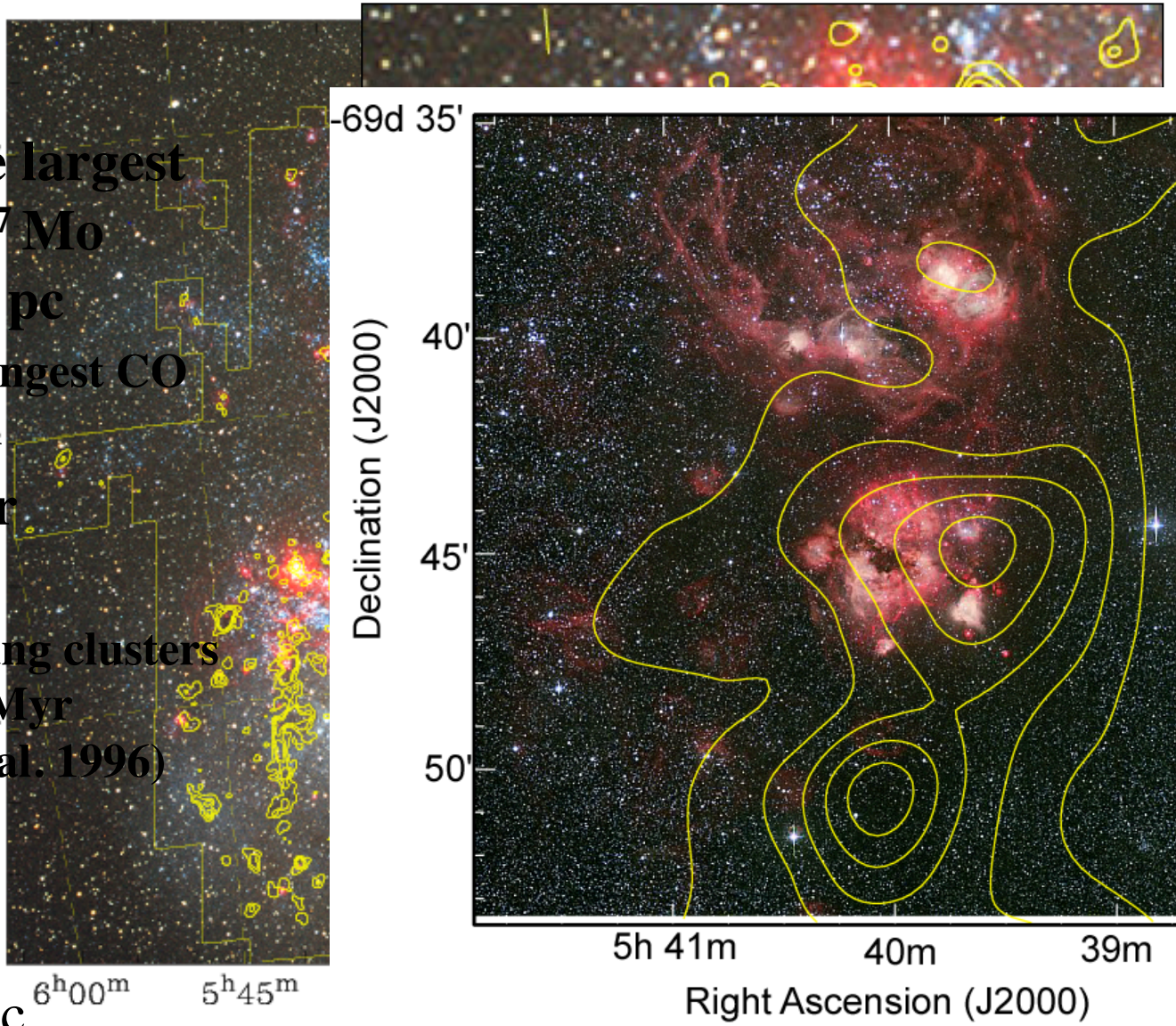
ALMA

- LMC(Cycle 0 & 1)
  - Indebetouw et al.:30 Doradus: Dense Gas in the Nearest Super-Star Cluster Cycle 0 partially published as Indebetouw et al. (2013)
  - Fukui et al.: Observations of N159 +ACA
  - Kawamura et al.: Tracing evolution of giant molecular clouds in the Large Magellanic Cloud +ACA
  - Onishi et al.: Observations of N55 +ACA
- Cycle 2
  - Onishi et al.: Isolated Massive YSOs +ACA
  - Onishi et al.: SMC N83; CO and CI+ACA
  - Jameson, K. et al.: SMC molecular clouds+ACA

ACA = Atacama Compact Array (Morita Array)

N159

- **N159**
  - **One of the largest**
    Mass：10^7 Mo
    Size：220 pc
    - **Has strongest CO emission**
  - **Active star formation**
    - **Five young clusters age<10Myr (Bica et al. 1996)**



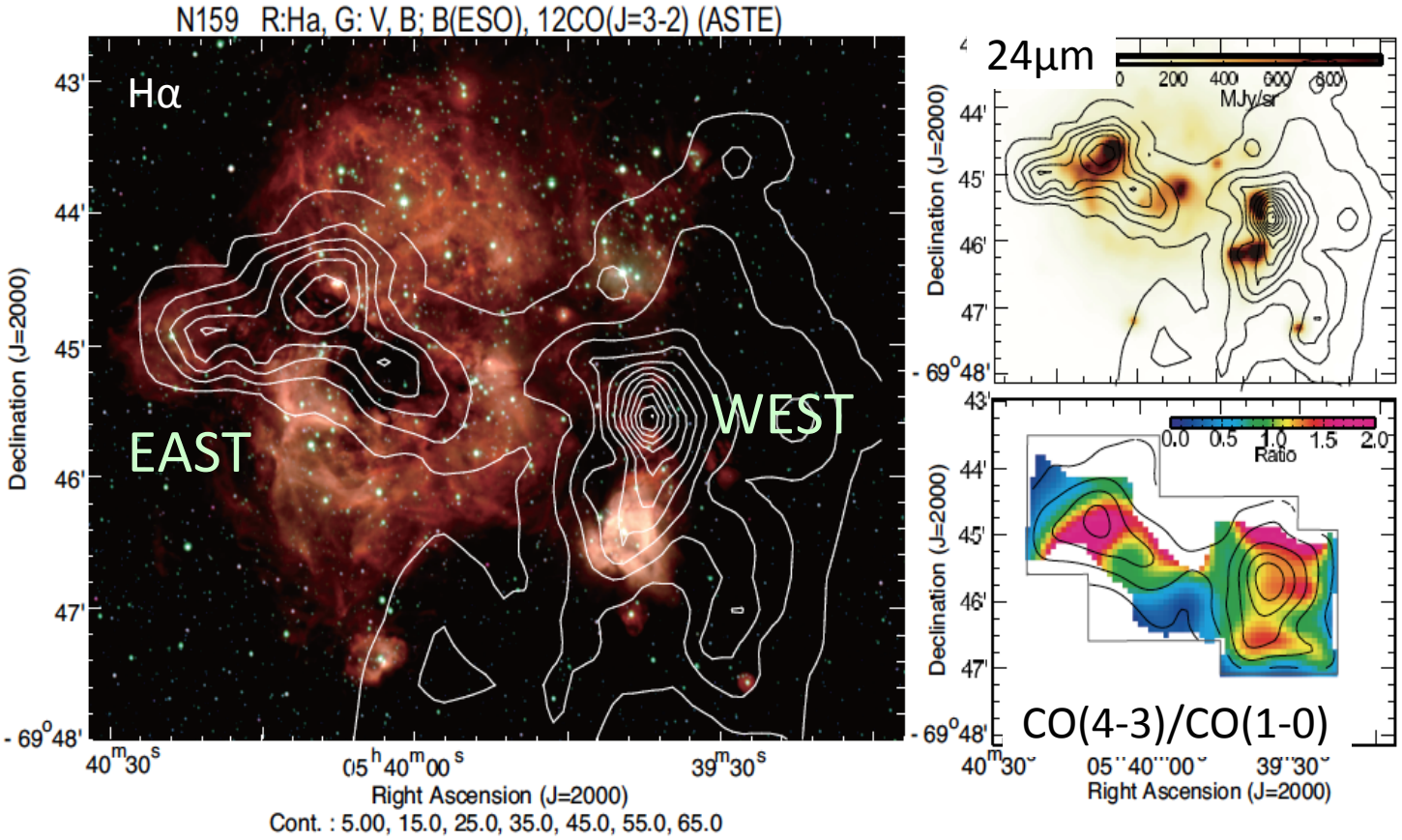
2.7arcmin = 40pc

N159: Most active on-going star formation in the Local Group: Resolving filaments and cloud cores in the LMC

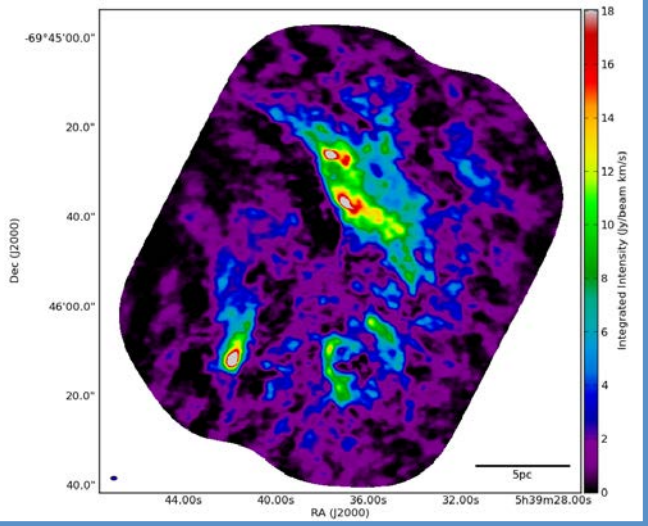
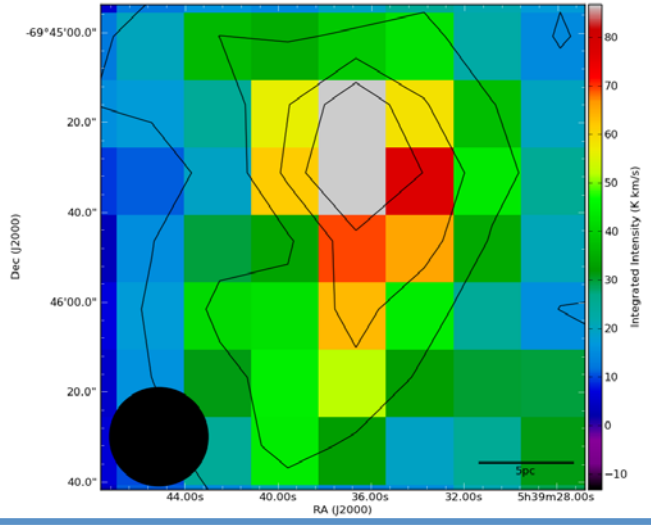
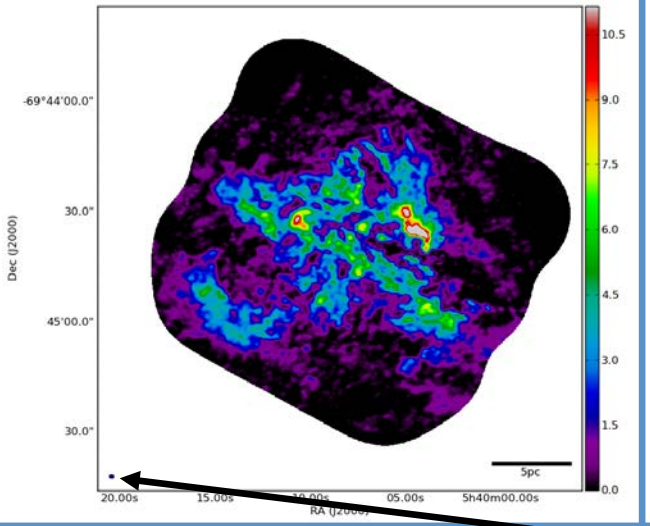
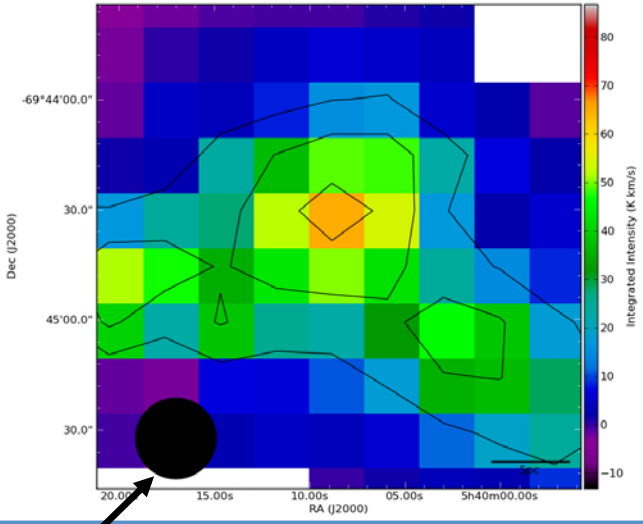
Fukui et al. (2015): arXiv:1503.03540

Fukui [PI]
Yamamoto
Ohama
Onishi
Kawamura
Minamidani
Inbedetouw
Madden
Galametz
Lebouteiller
N.Mizuno
R.Chen
Seale
Sewio
Meixner

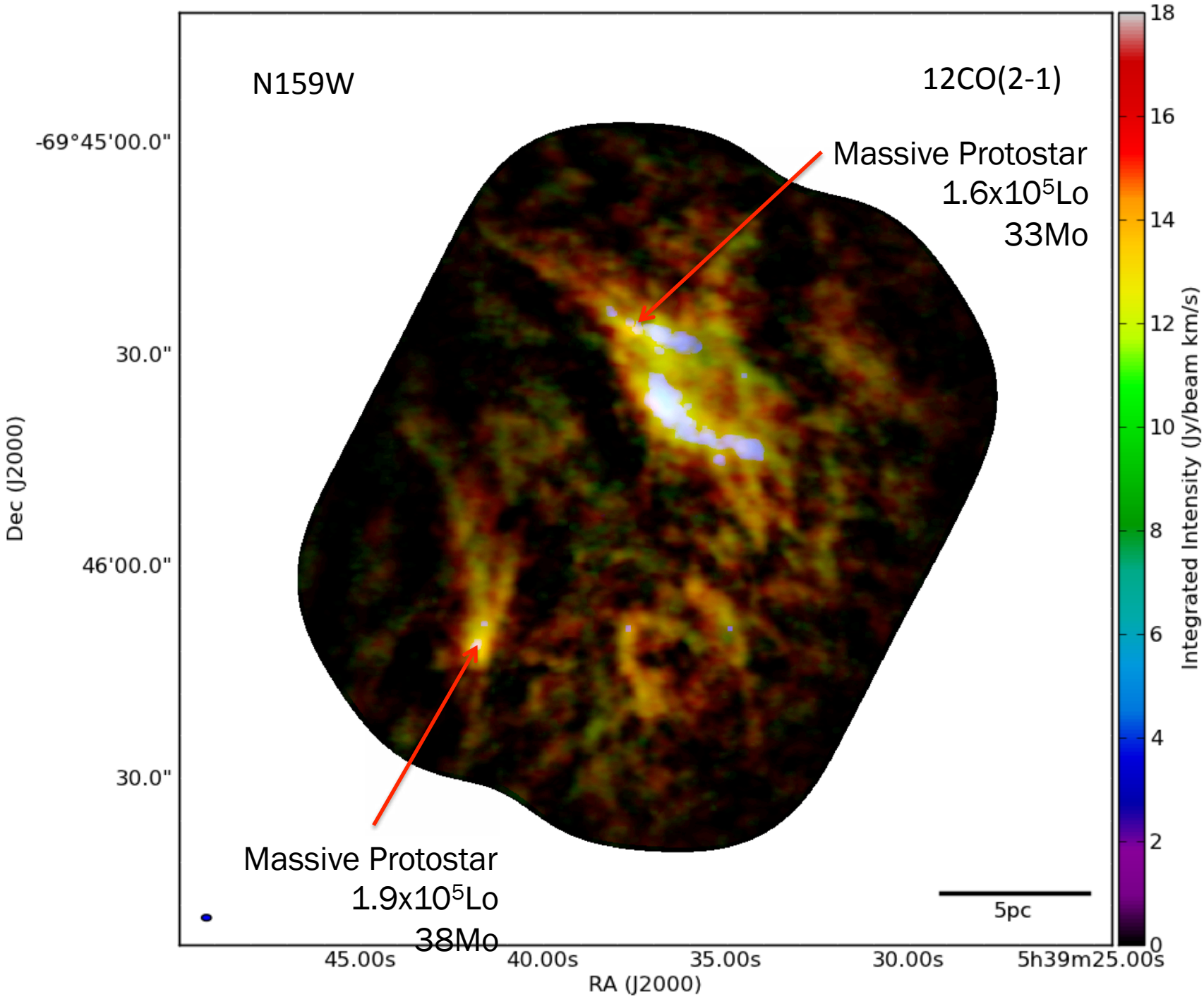
Contour: ASTE 12CO(3-2), 22" = 5pc

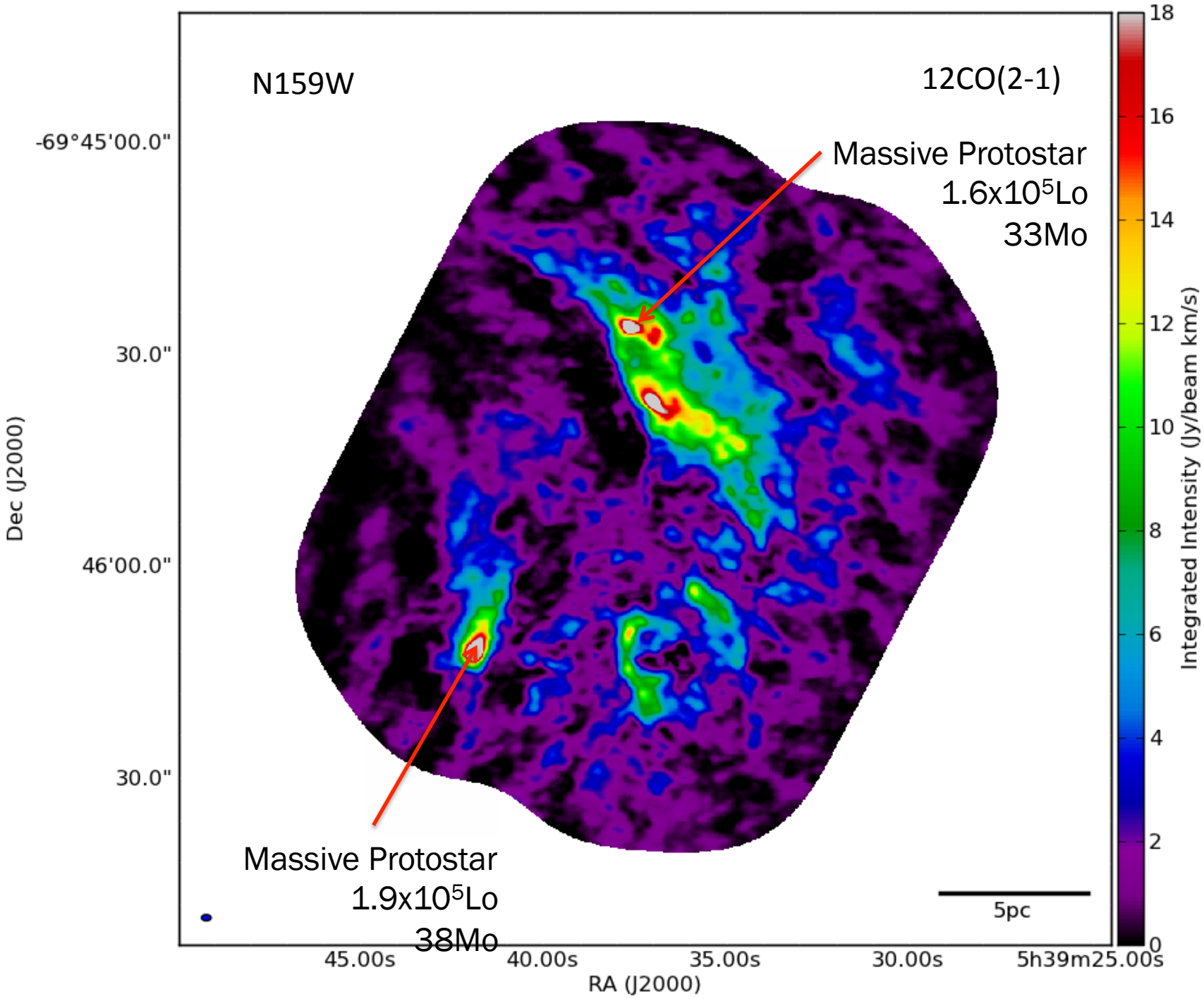


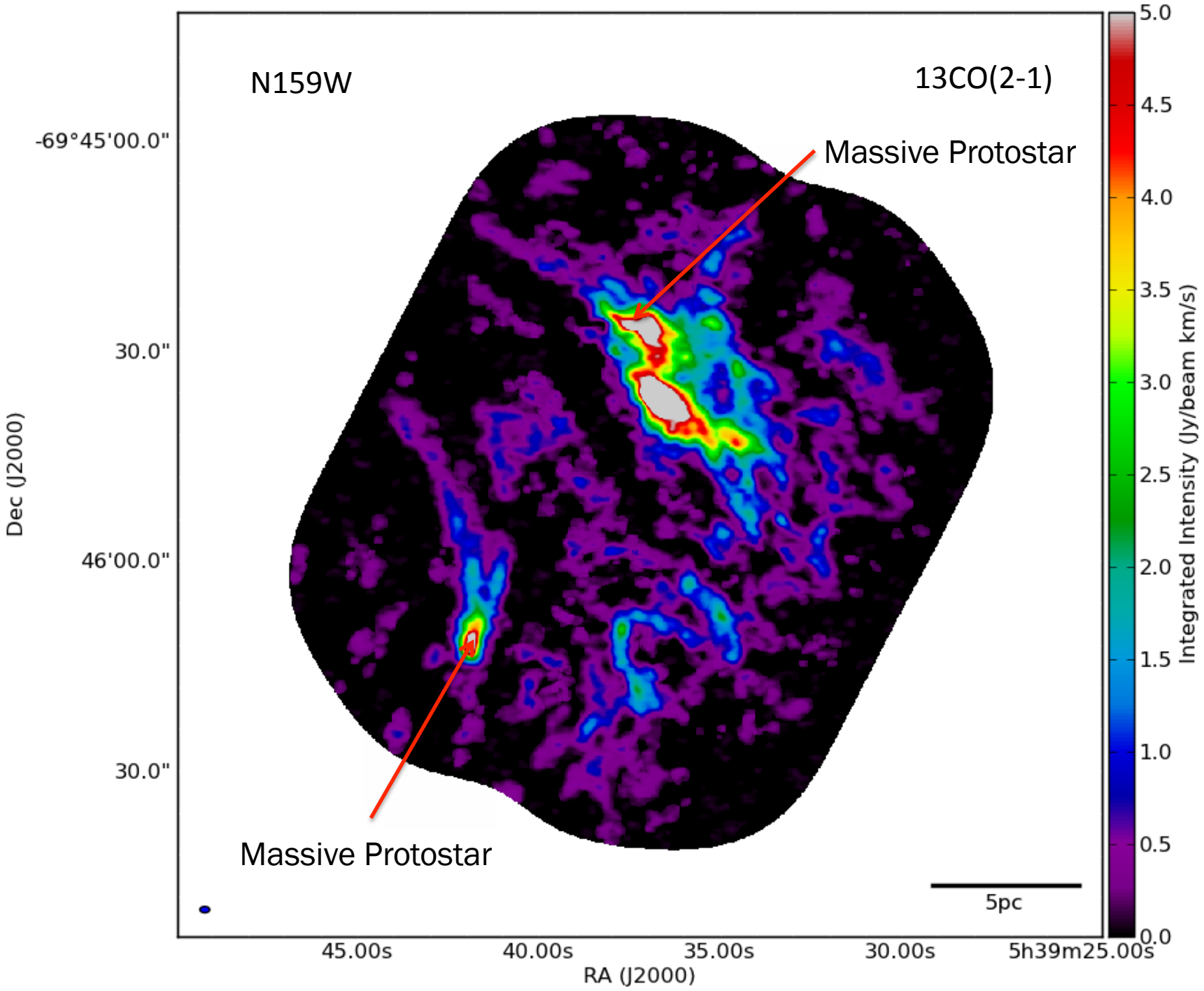
Y. Mizuno et al. 2010

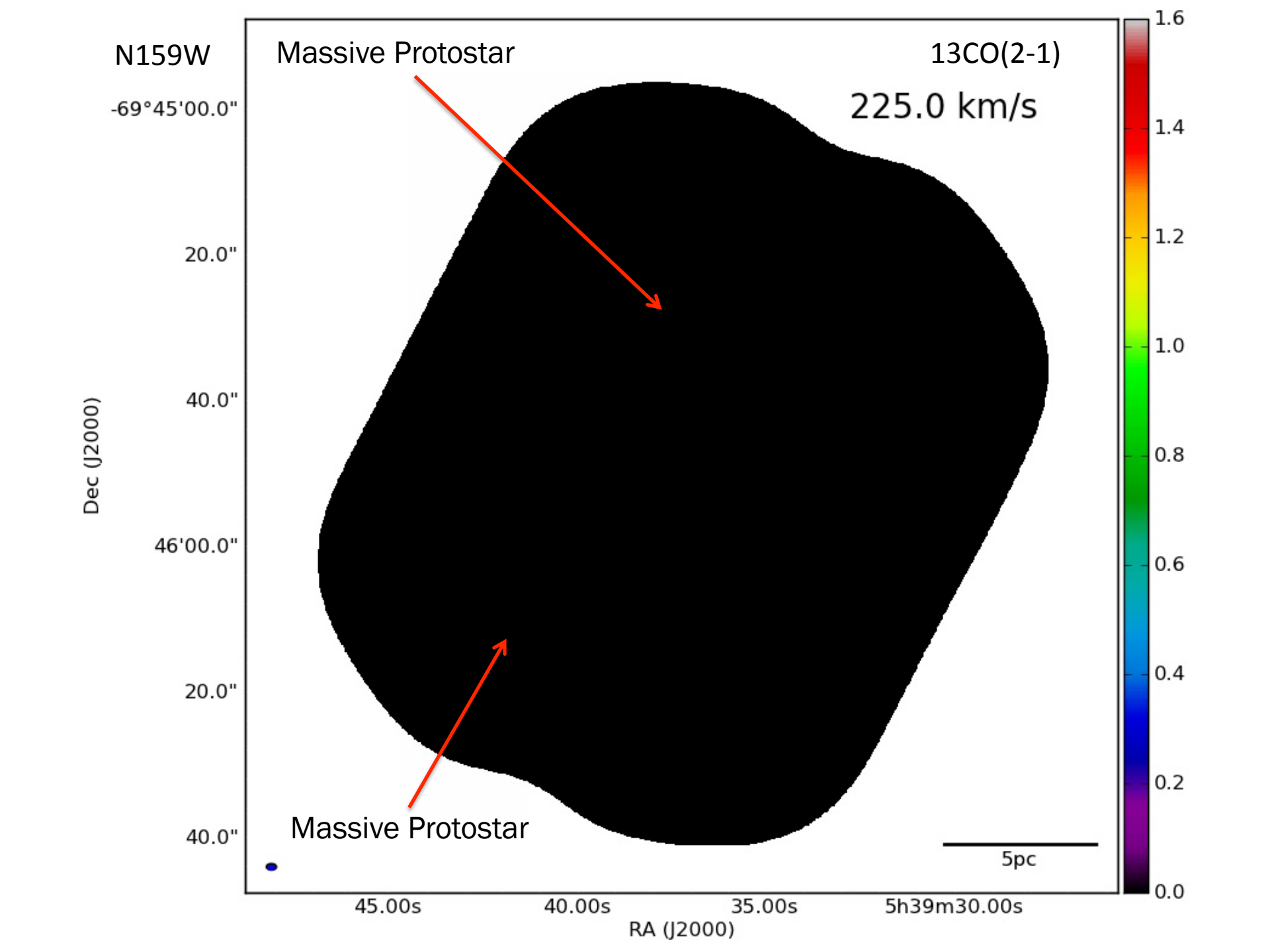
	ALMA ^{12}CO(2-1) Integrated intensity [Jy/beam km/s]	ASTE ^{12}CO(3-2) Integrated intensity [K km/s]
N159 W		
N159 E		

1”.2 × 0”.8 = 0.29 × 0.19pc beam size **22” = 5pc**

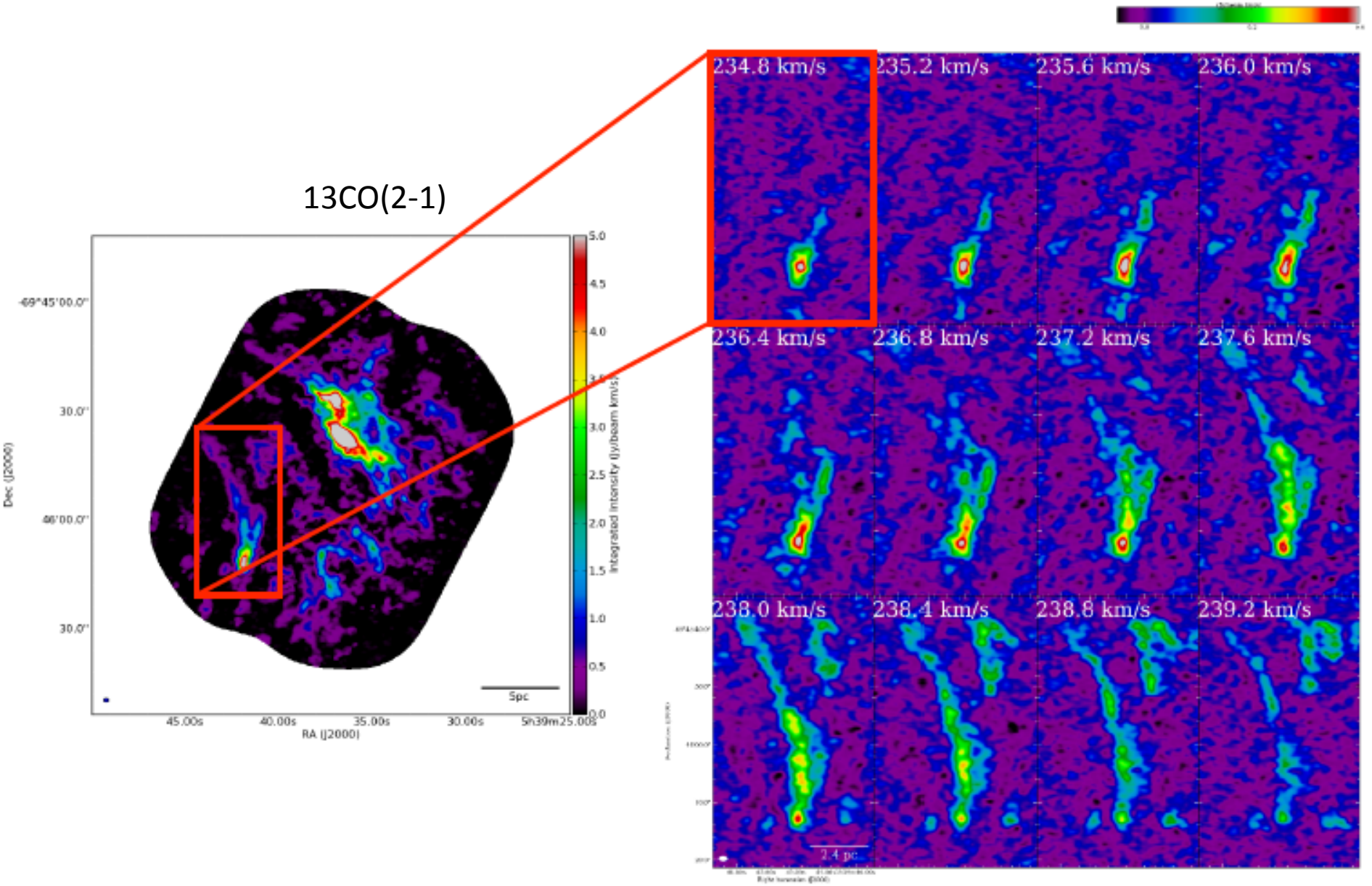

N159W
12CO(2-1)
Massive Protostar
1.6x10^5Lo
33Mo
Massive Protostar
1.9x10^5Lo
38Mo
5pc
-69°45'00.0"
30.0"
46'00.0"
30.0"
Dec (J2000)
45.00s
40.00s
35.00s
30.00s
5h39m25.00s
RA (J2000)
Integrated Intensity (Jy/beam km/s)
0
2
4
6
8
10
12
14
16
18

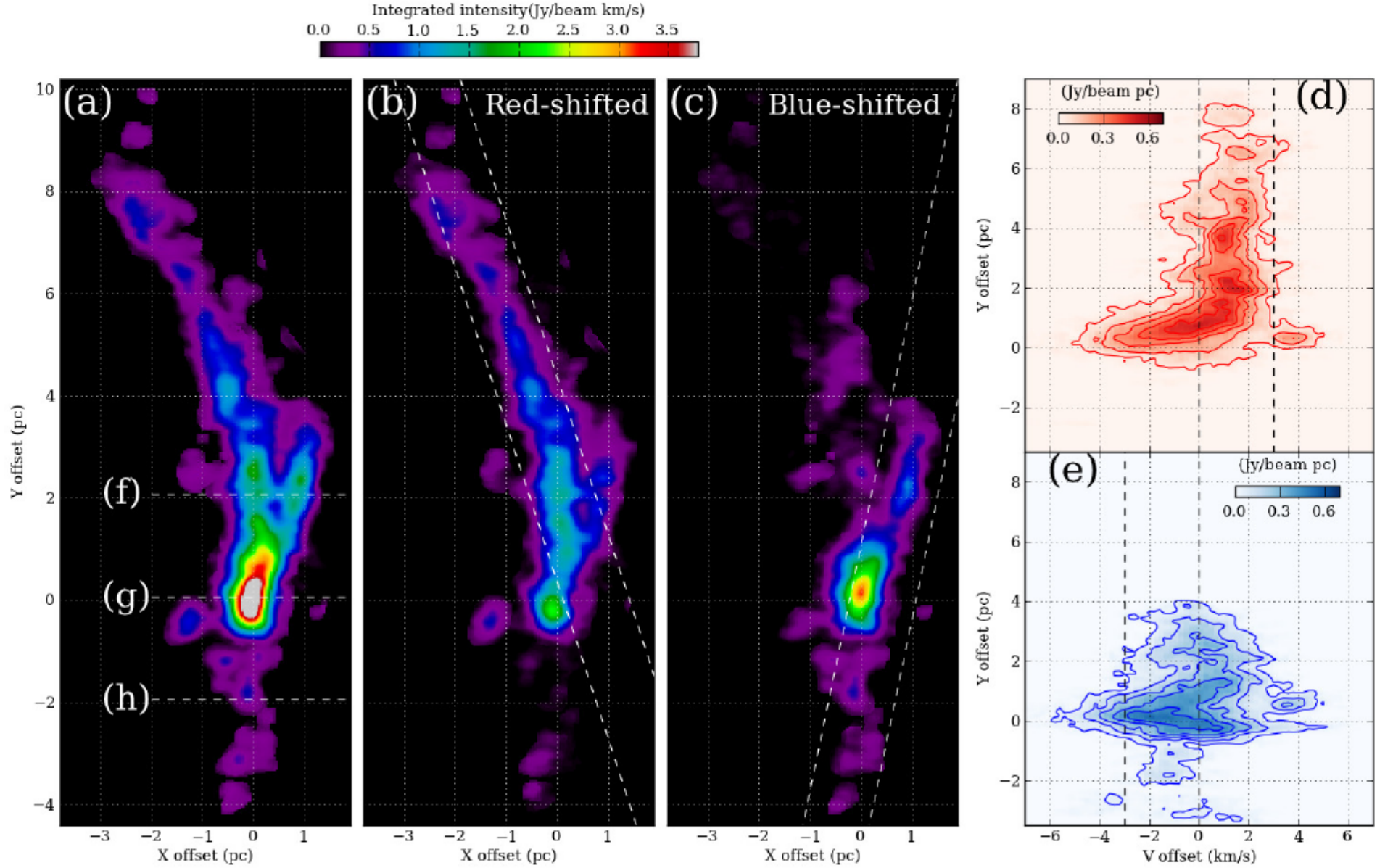

N159W
12CO(2-1)
Massive Protostar
1.6x10^5Lo
33Mo
Massive Protostar
1.9x10^5Lo
38Mo
5pc
-69°45'00.0"
30.0"
46'00.0"
30.0"
Dec (J2000)
45.00s
40.00s
35.00s
30.00s
5h39m25.00s
RA (J2000)
Integrated Intensity (Jy/beam km/s)
0
2
4
6
8
10
12
14
16
18

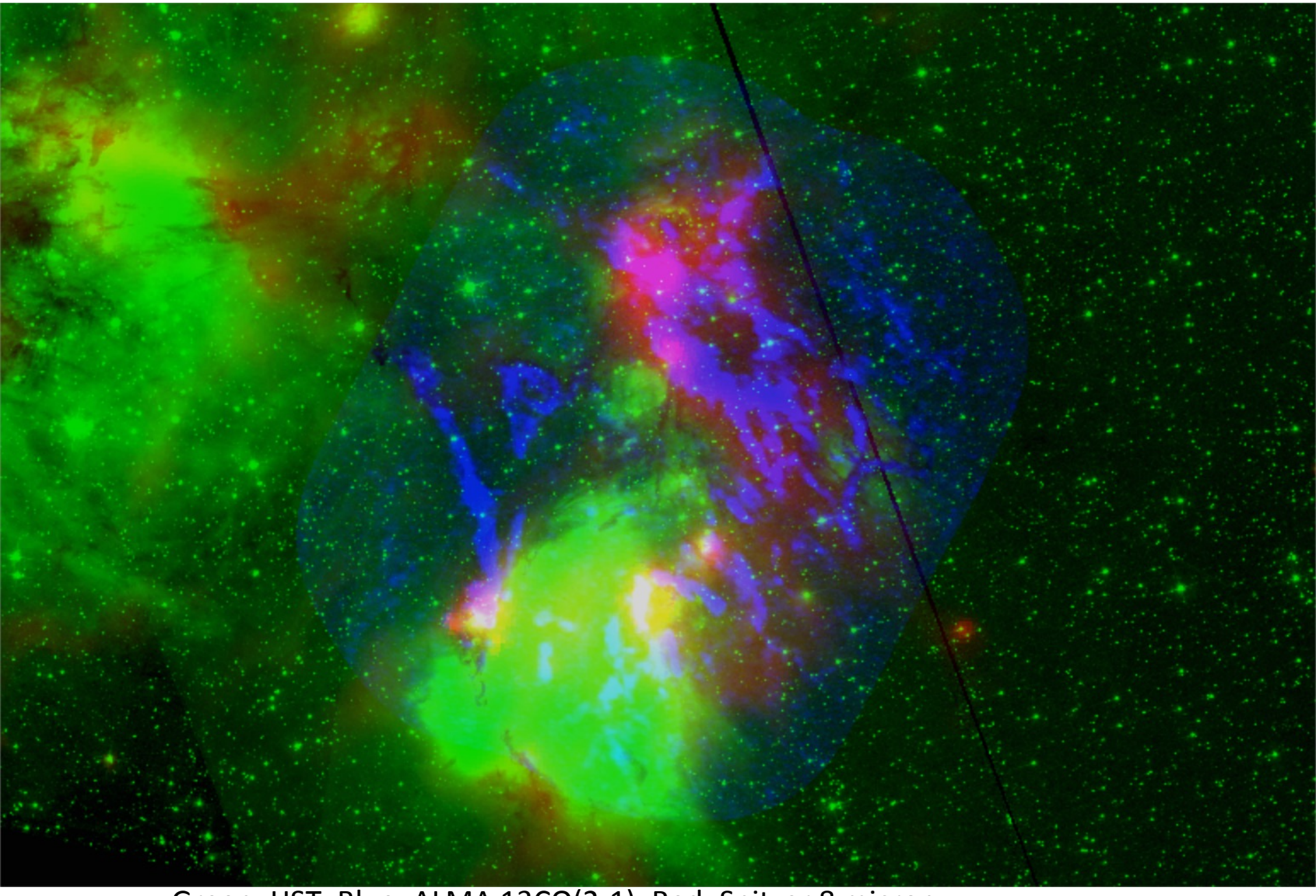

N159W
13CO(2-1)
Massive Protostar
Massive Protostar
5pc
-69°45'00.0"
30.0"
46'00.0"
30.0"
Dec (J2000)
45.00s
40.00s
35.00s
30.00s
5h39m25.00s
RA (J2000)
Integrated Intensity (Jy/beam km/s)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0


N159W
Massive Protostar
13CO(2-1)
225.0 km/s
-69°45'00.0"
20.0"
40.0"
46'00.0"
20.0"
40.0"
Dec (J2000)
Massive Protostar
5pc
45.00s
40.00s
35.00s
5h39m30.00s
RA (J2000)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0

Long filaments in N159W

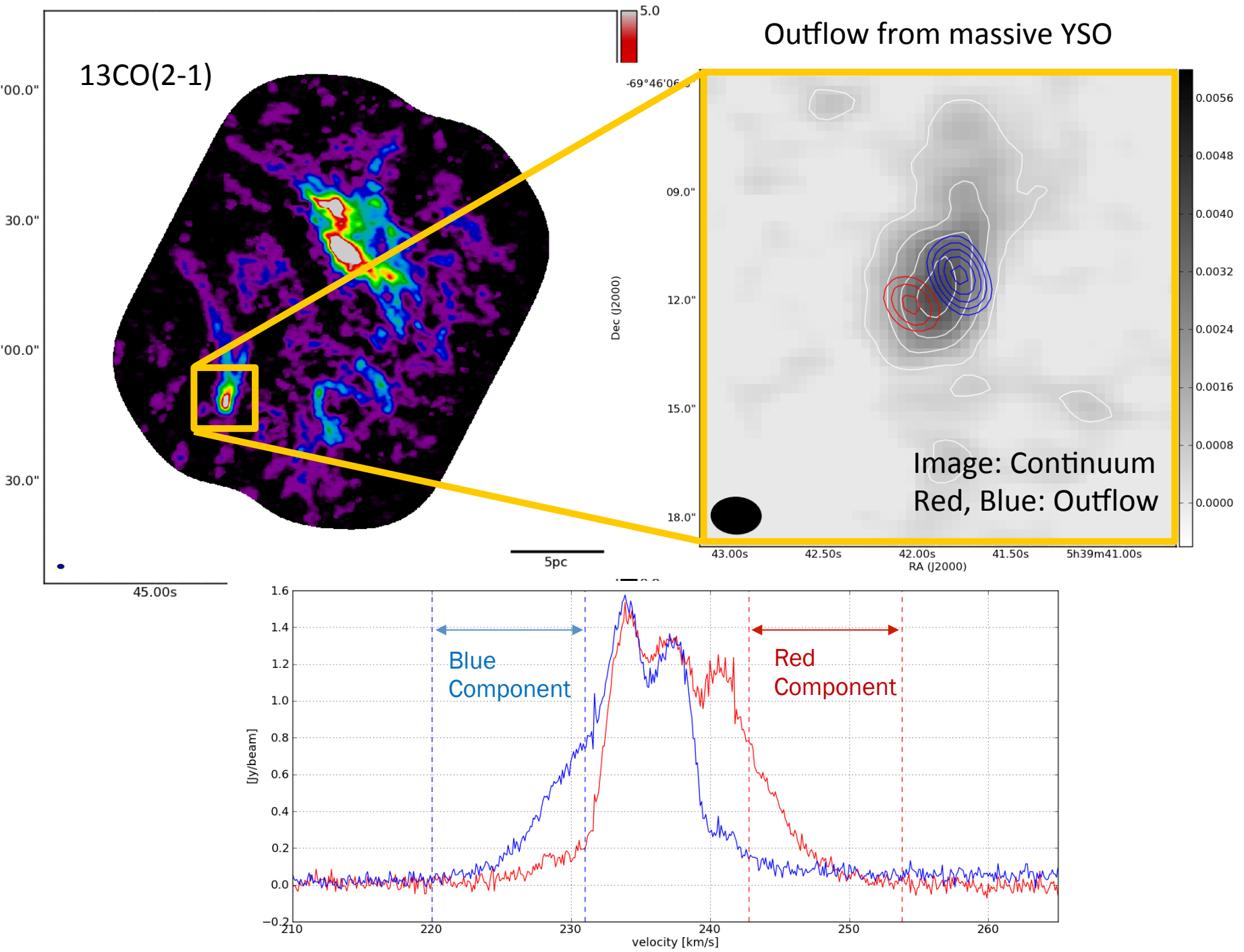


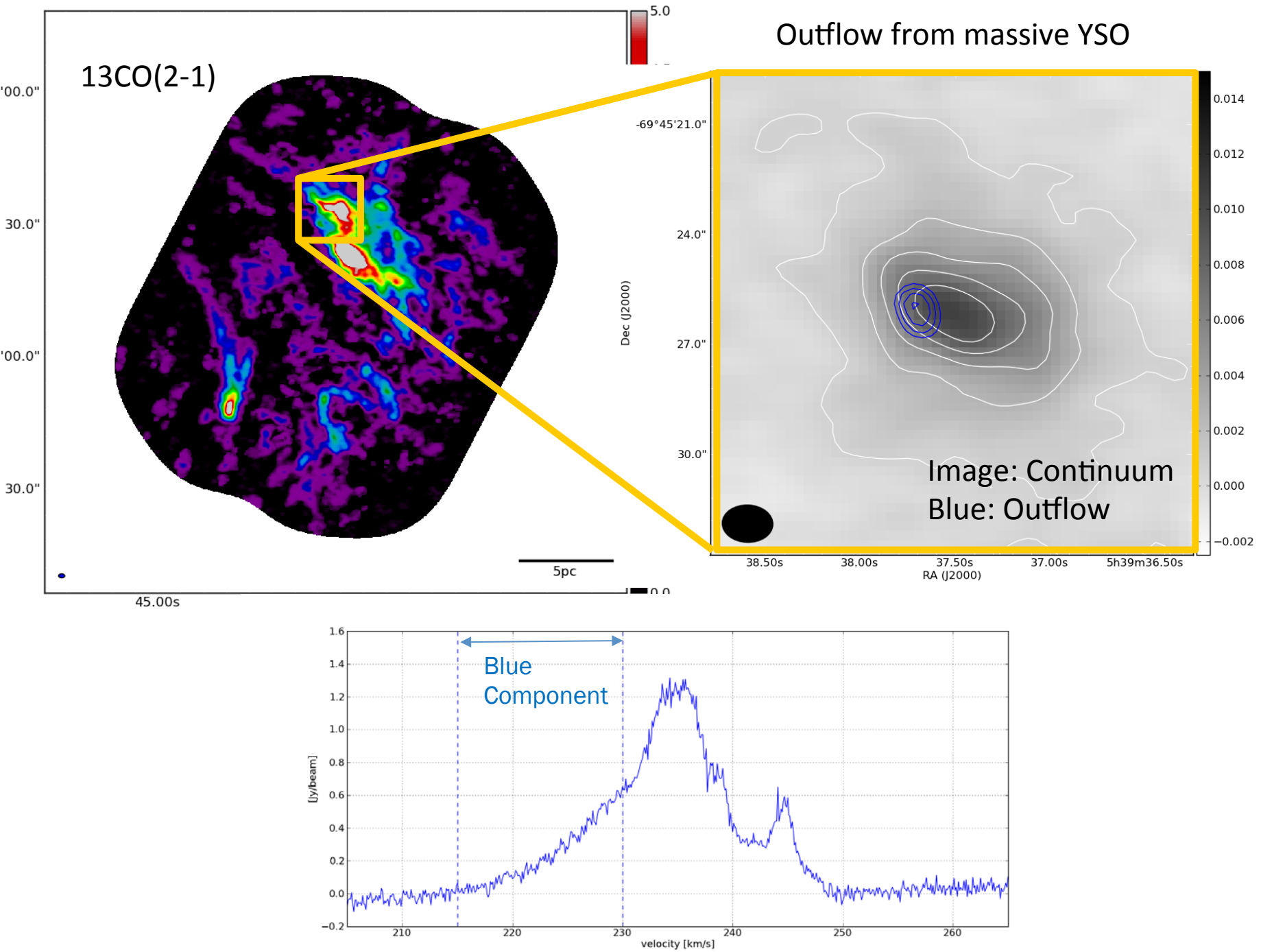

Integrated intensity(Jy/beam km/s)
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5
(a)
(b) Red-shifted
(c) Blue-shifted
(d)
(e)
(f)
(g)
(h)
(Jy/beam pc)
0.0 0.3 0.6
(Jy/beam pc)
0.0 0.3 0.6
Y offset (pc)
X offset (pc)
X offset (pc)
X offset (pc)
Y offset (pc)
Y offset (pc)
V offset (km/s)



Green: HST, Blue: ALMA 13CO(2-1), Red: Spitzer 8 micron

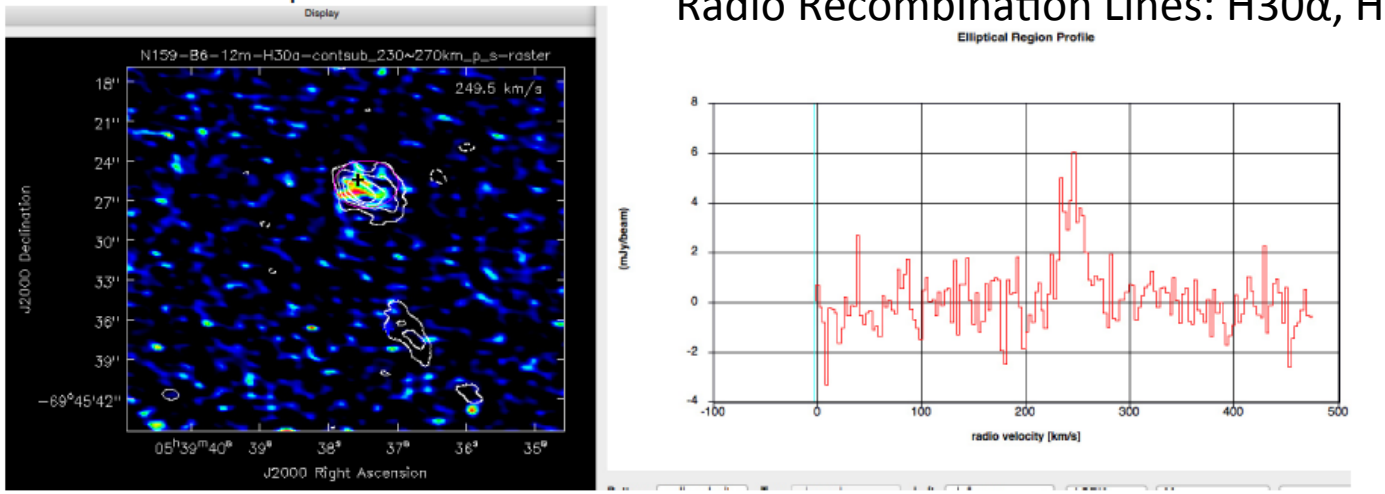
R. Indebetouw


13CO(2-1)
Outflow from massive YSO
5.0
'00.0"
30.0"
'00.0"
30.0"
45.00s
5pc
-69°46'06"
09.0"
12.0"
15.0"
18.0"
Dec (J2000)
0.0056
0.0048
0.0040
0.0032
0.0024
0.0016
0.0008
0.0000
43.00s
42.50s
42.00s
41.50s
5h39m41.00s
RA (J2000)
Image: Continuum
Red, Blue: Outflow
Blue
Component
Red
Component
[Jy/beam]
velocity [km/s]
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
210
220
230
240
250
260


Outflow from massive YSO
13CO(2-1)
5.0
'00.0"
30.0"
'00.0"
30.0"
45.00s
5pc
-69°45'21.0"
24.0"
27.0"
30.0"
Dec (J2000)
38.50s
38.00s
37.50s
5h39m36.50s
RA (J2000)
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
−0.002
Image: Continuum
Blue: Outflow
Blue
Component
[Jy/beam]
velocity [km/s]
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
210
220
230
240
250
260

Radio Recombination Lines: H30α, H40α

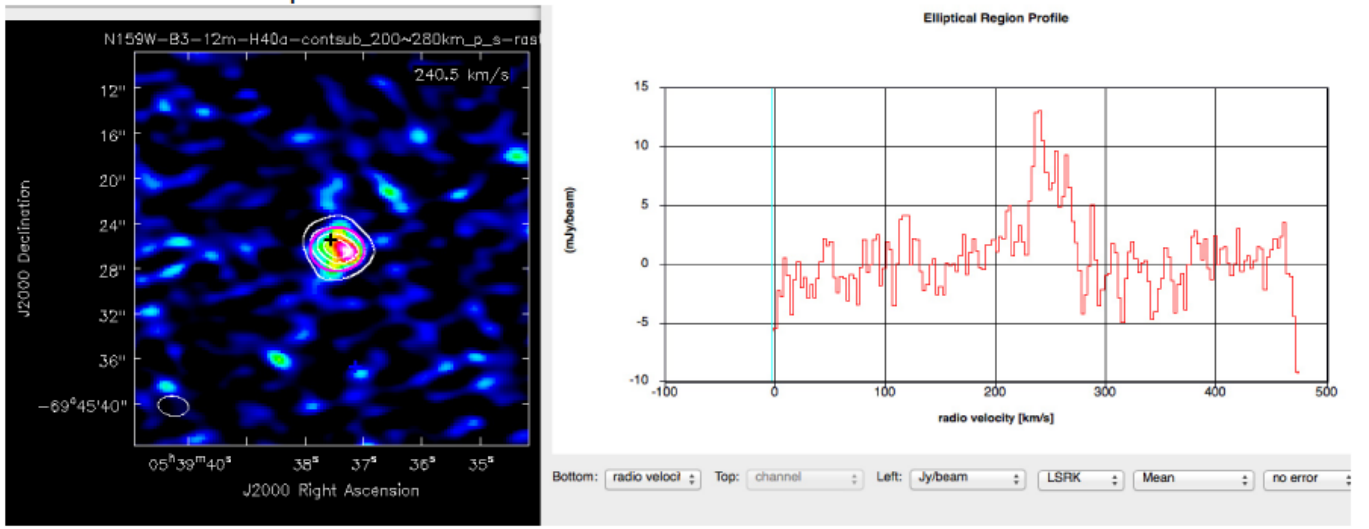
+ N159W Band 6 H30alpha



H30alpha.jpg

White contour is the dust continuum emission in Band 6, and the color is the velocity-integrated intensity of H30alpha with a velocity range from 230 to 270km/s. The cross is a position of a YSO (UCHII, O5.5V) in Chen paper. The red ellipse is the area for the averaged spectrum(right figure).

+ N159W Band 3 H40alpha



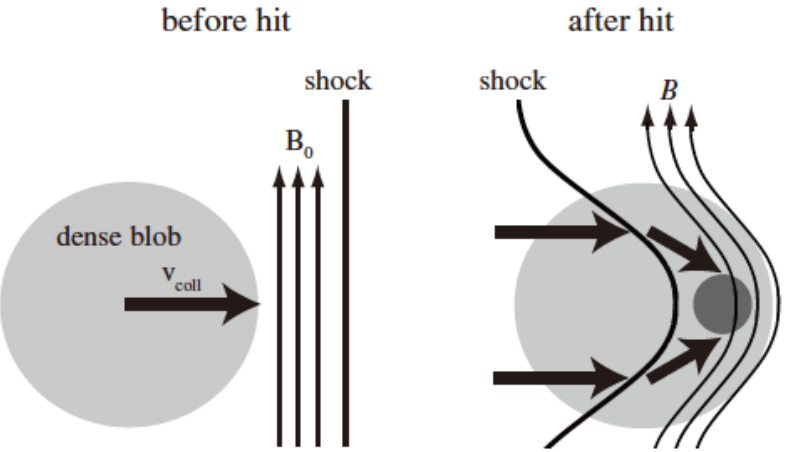
H40alpha.jpg

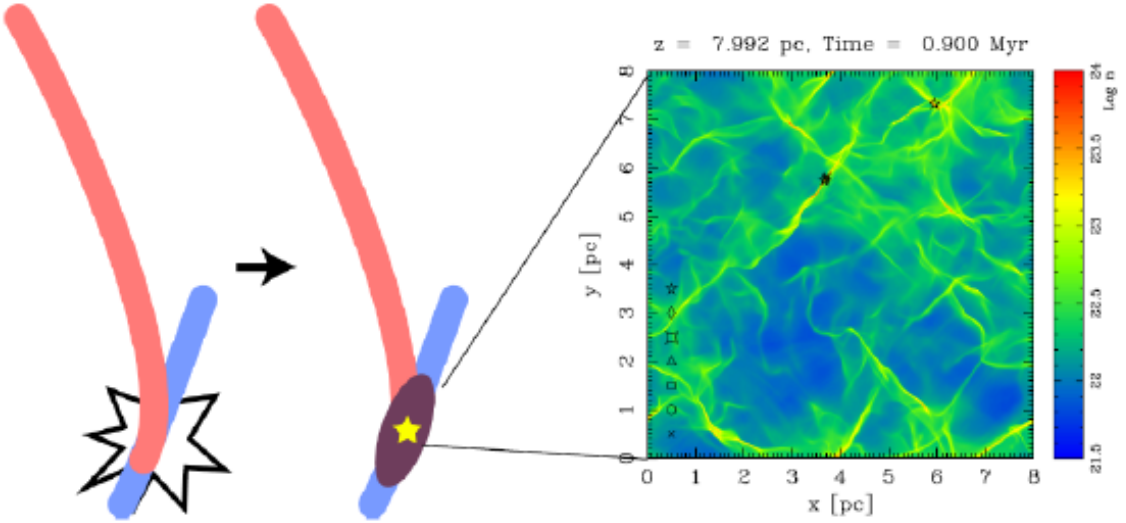
White contour is the dust continuum emission in Band 3, and the color is the velocity-integrated intensity of H40alpha with a velocity range from 200 to 280km/s. The cross is a position of a YSO (UCHII, O5.5V) in Chen paper. The red ellipse is the area for the averaged spectrum(right figure).

- Ne= 2.5 x 10^3 cm^{-3}
- M(ionized)= 350Mo
- EM= 6.3x10^5pc cm^{-6}
- U=170x10^3pc cm^{-2}
- Nc=1.5x$10^{50}$$s^{-1}$
- Spectral Type= O3

Massive star formation by cloud-cloud collisions

3-D MHD simulation with self-gravity
of colliding clouds
Inoue & Fukui 2013





Inoue & Fukui 2013

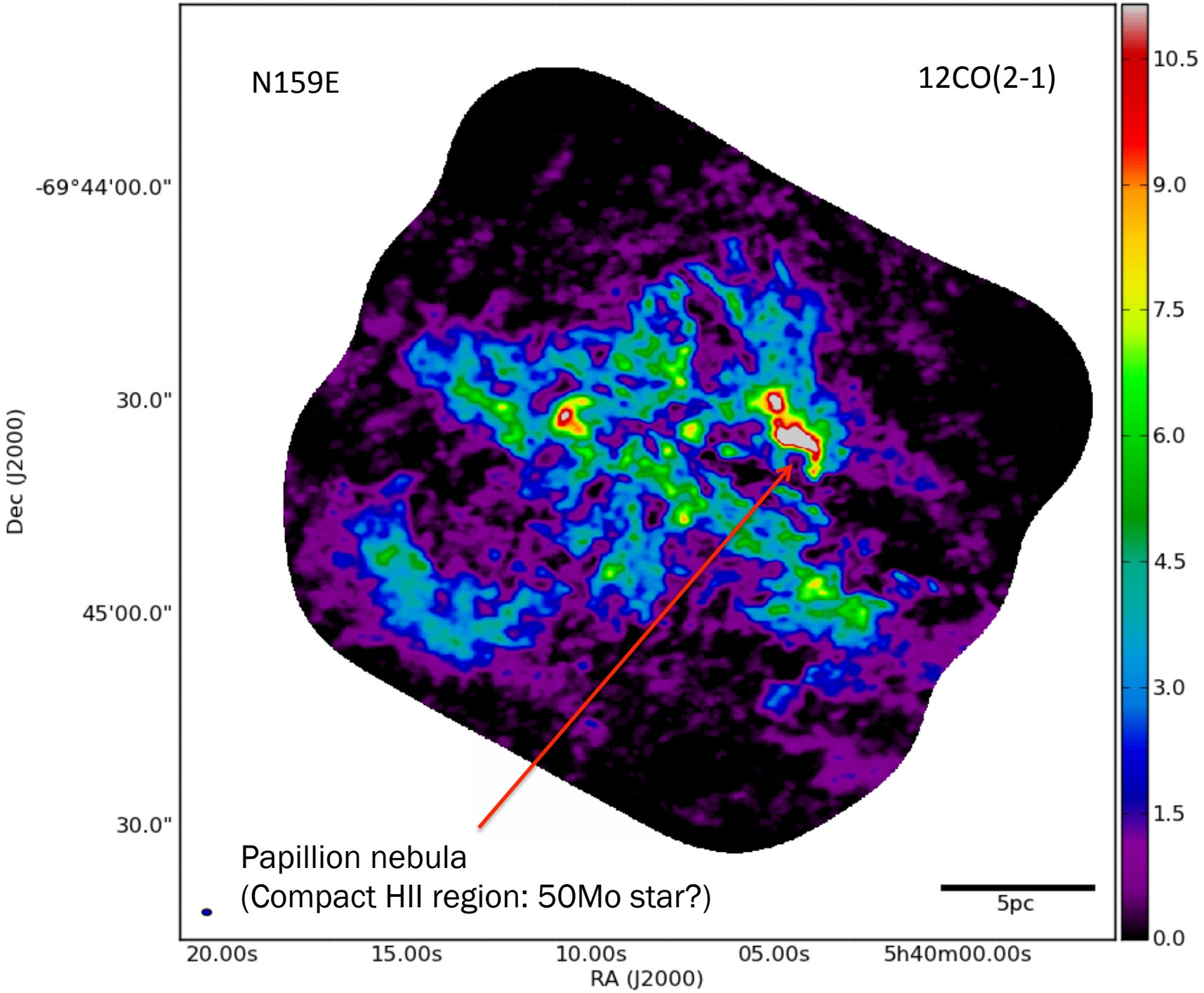
図 4.2　シミュレーションによる分子雲衝突モデル

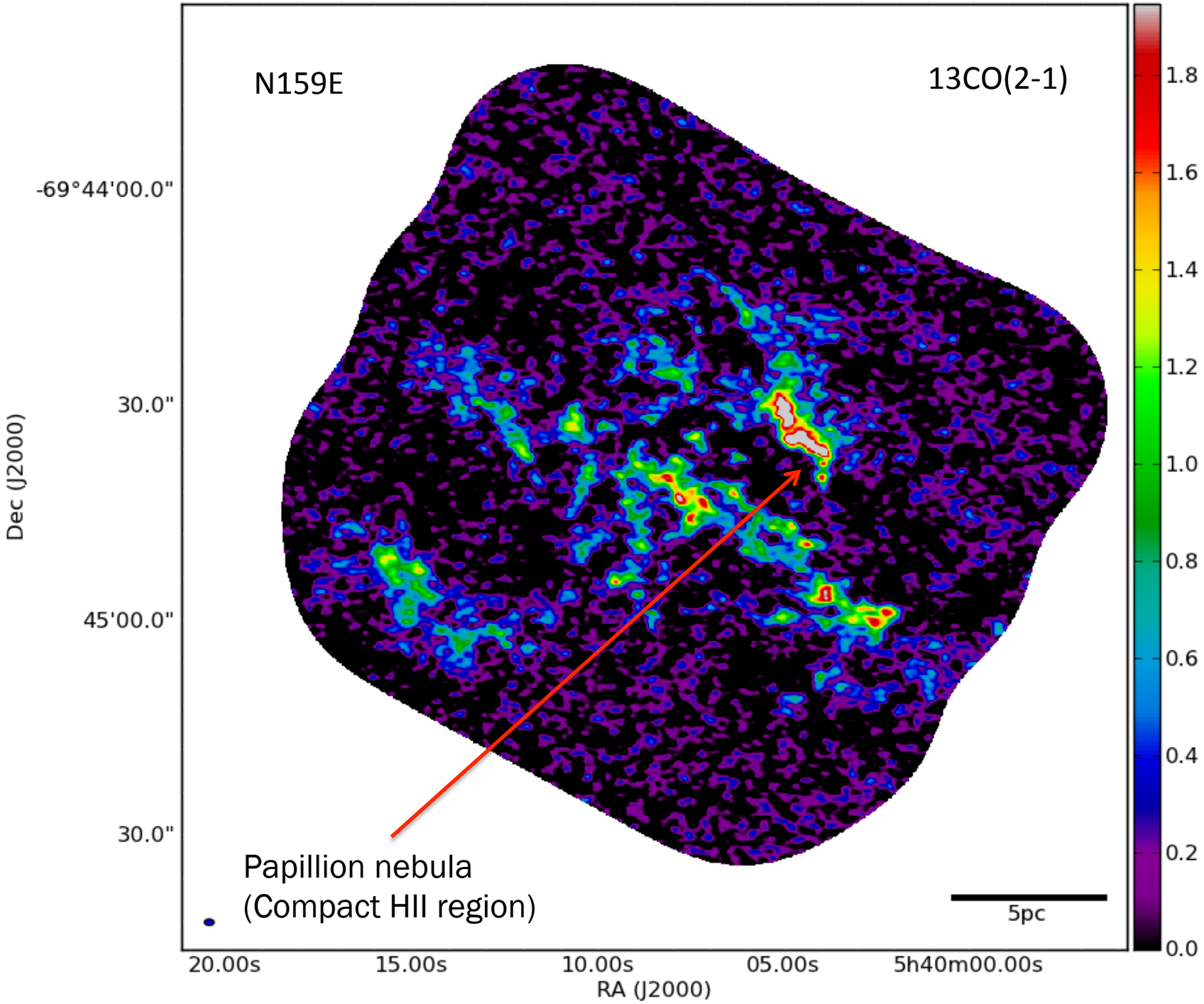
Large effective Jeans mass owing to the enhancement of the magnetic field strength by shock compression and turbulence in the compressed layer

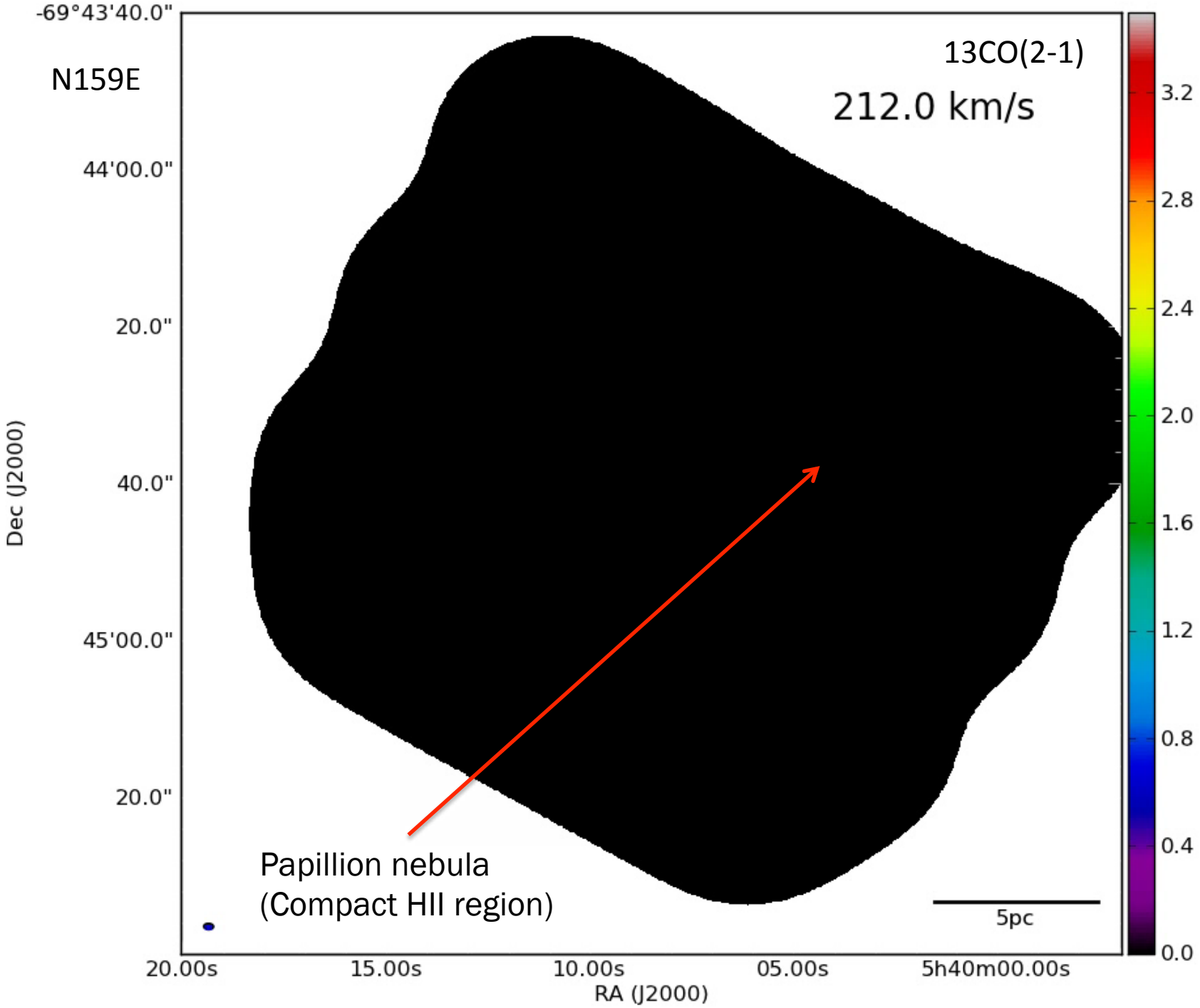
Star formation in N159W [ALMA cycle1]

- Colliding (Merging?) filaments
  - Width: 1pc
  - Velocity difference: 2-5 km/s
  - Time scale: 6 x 10^4yrs
- Massive YSOs at the intersection
  - Outflow: Mass is infalling (~10^4yrs)
  - Mass accretion rate: 37Mo/6 x 10^4yrs=6x10^{-4}Mo/yr
  - Radio recombination lines: No

Massive stars are formed rapidly after the collision

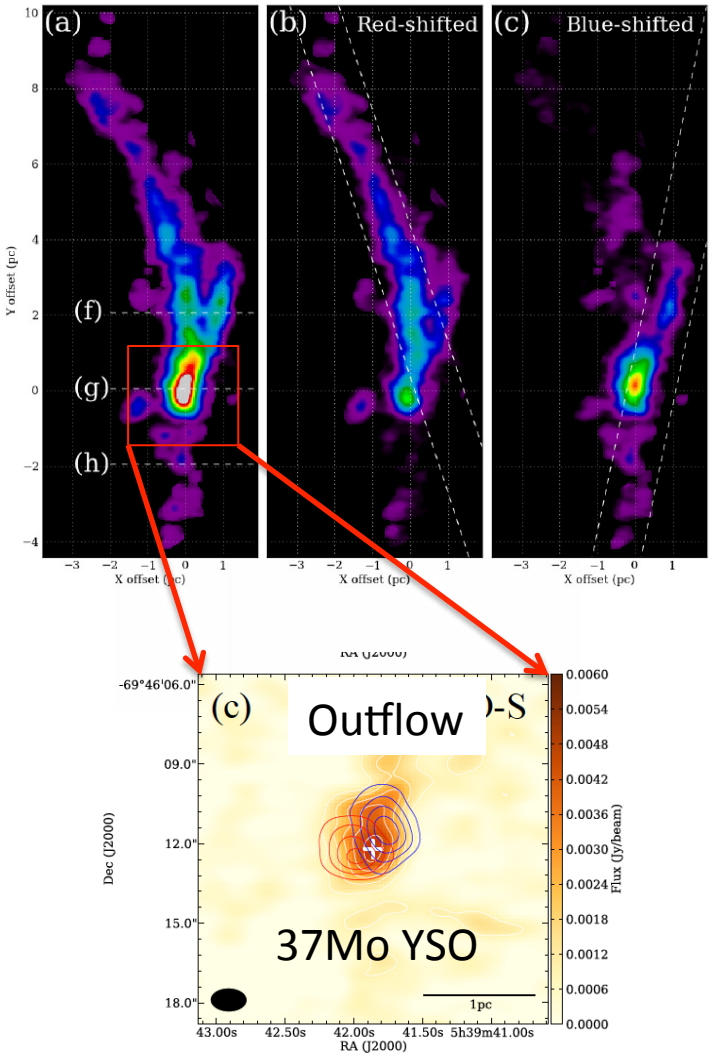

N159E
12CO(2-1)
-69°44'00.0"
30.0"
45'00.0"
30.0"
Dec (J2000)
Papillion nebula
(Compact HII region: 50Mo star?)
5pc
20.00s
15.00s
10.00s
05.00s
5h40m00.00s
RA (J2000)
10.5
9.0
7.5
6.0
4.5
3.0
1.5
0.0


N159E
13CO(2-1)
-69°44'00.0"
30.0"
45'00.0"
30.0"
Dec (J2000)
Papillion nebula
(Compact HII region)
5pc
20.00s
15.00s
10.00s
05.00s
5h40m00.00s
RA (J2000)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0


N159E
13CO(2-1)
212.0 km/s
-69°43'40.0"
44'00.0"
20.0"
40.0"
45'00.0"
20.0"
Dec (J2000)
20.00s
15.00s
10.00s
05.00s
5h40m00.00s
RA (J2000)
Papillion nebula
(Compact HII region)
5pc
3.2
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0.0

ALMA observations N159 in the LMC

- Full of Filaments and Arcs
  - Complex velocity structures
- Molecular outflows
  - Dust continuum/Radio Recombination Lines
- Some filaments are colliding/merging
  - Leading to rapid high-mass star formation



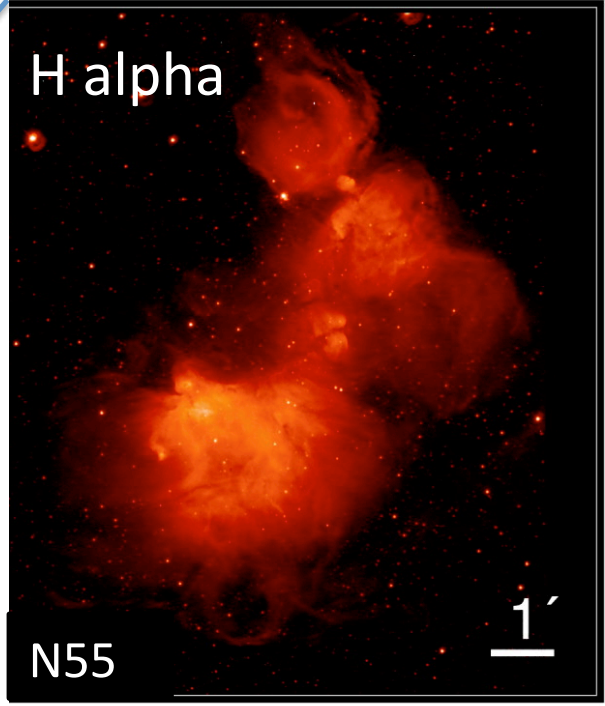
GMC with developed star formation

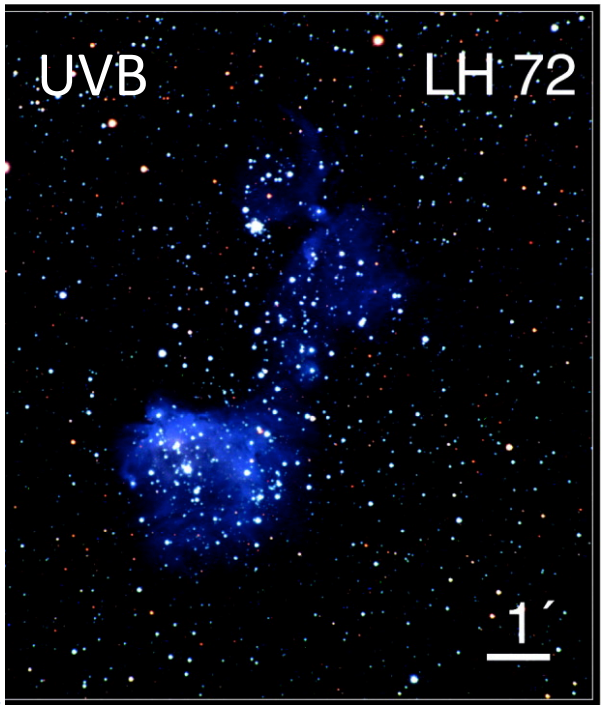
HII region N55

OB association LH72

- 6 O star（O6–O9）
- Age: 10 - 15 Myr

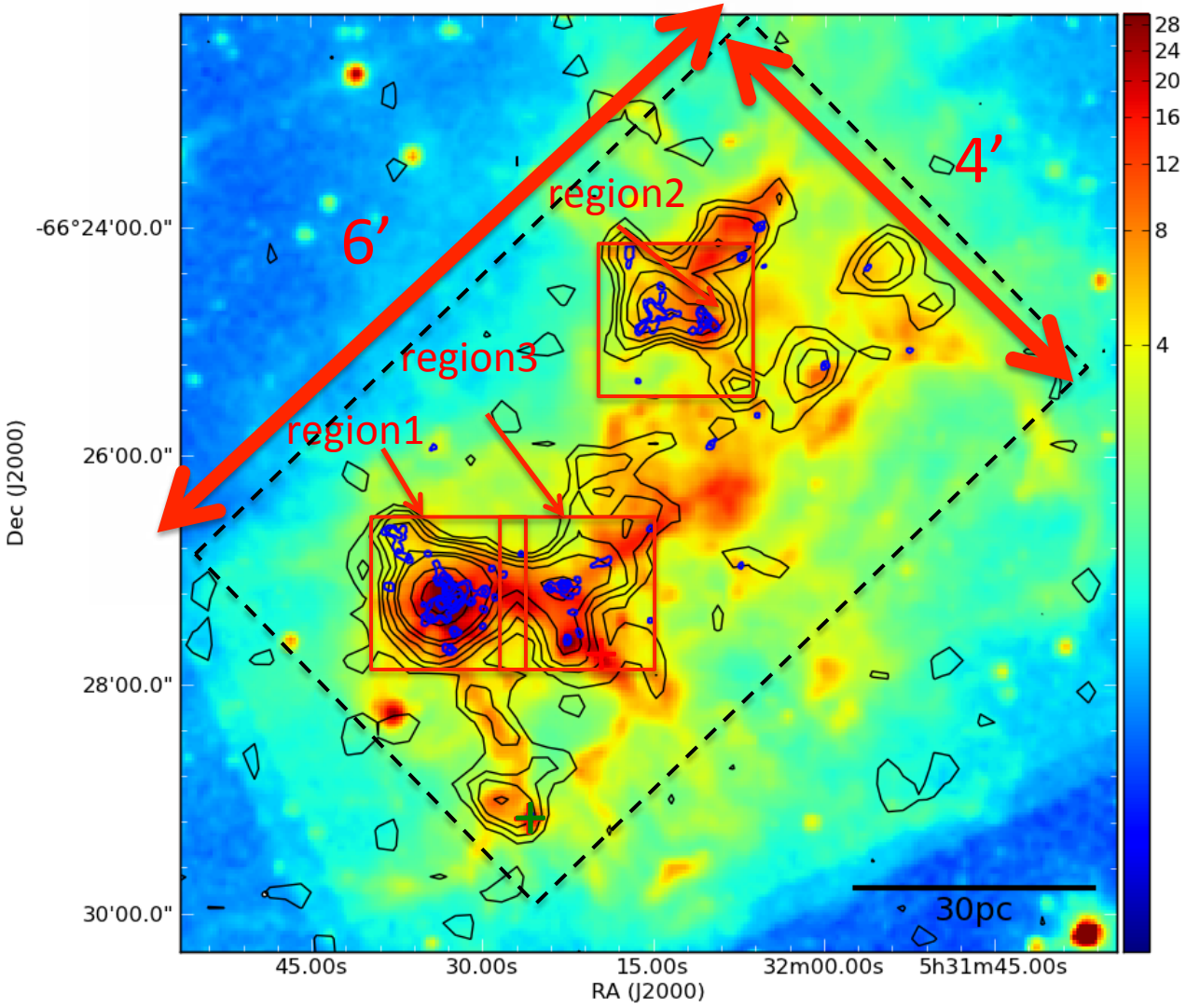
Spitzer (3.6, 8.0, 24μm)





ALMA Observations

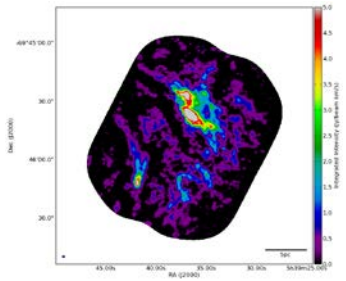
Blue: ALMA ^{13}CO(1-0),Black : ASTE ^{12}CO(3-2),Color: Spitzer 8μm



ALMA Beam Size
3”.1×2”.5 ~ 0.7pc

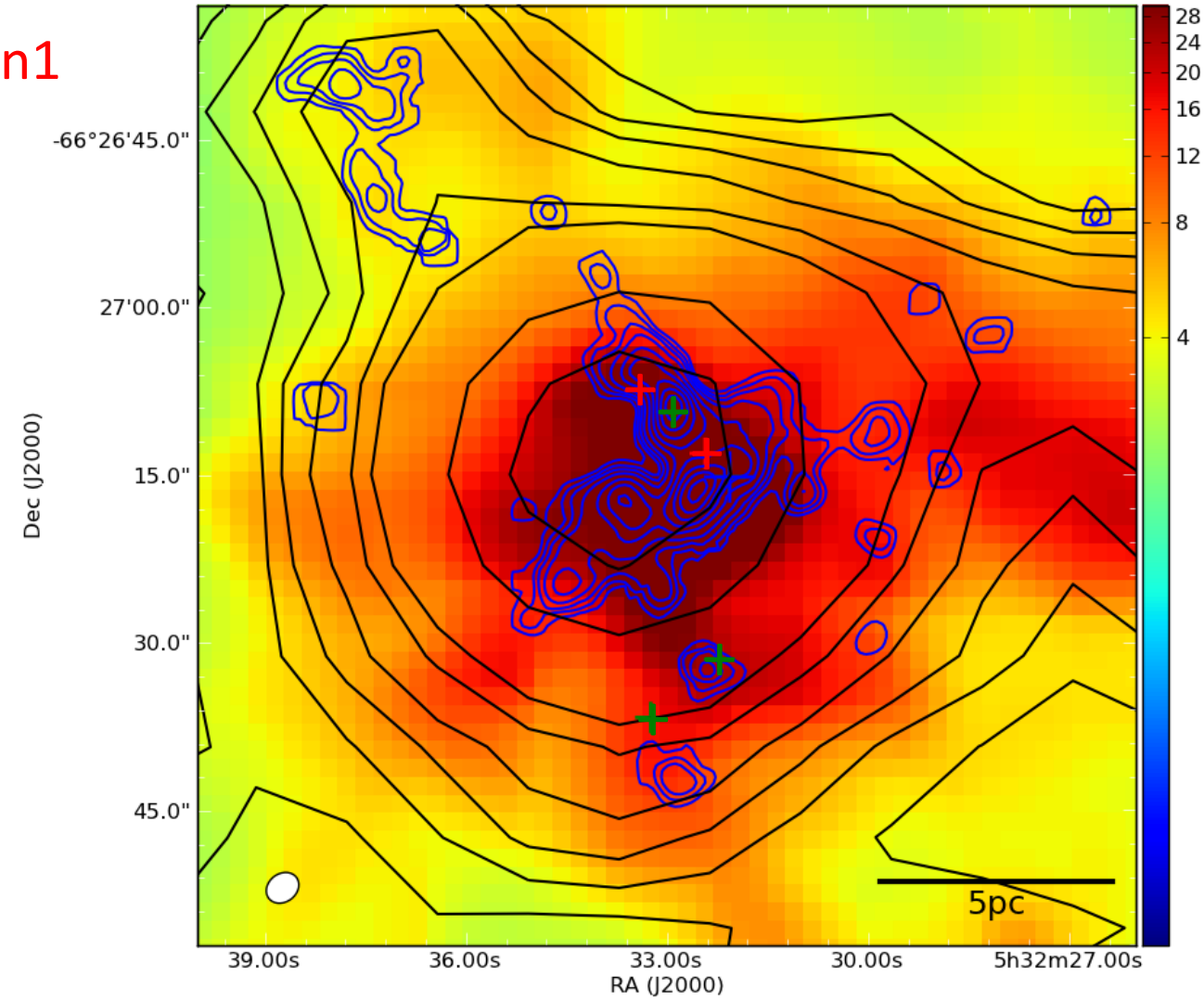
149 pointings

ASTE Beam Size
22” ~ 5pc



N159: Same linear scale

region1



Blue: ALMA ^{13}CO(1-0)

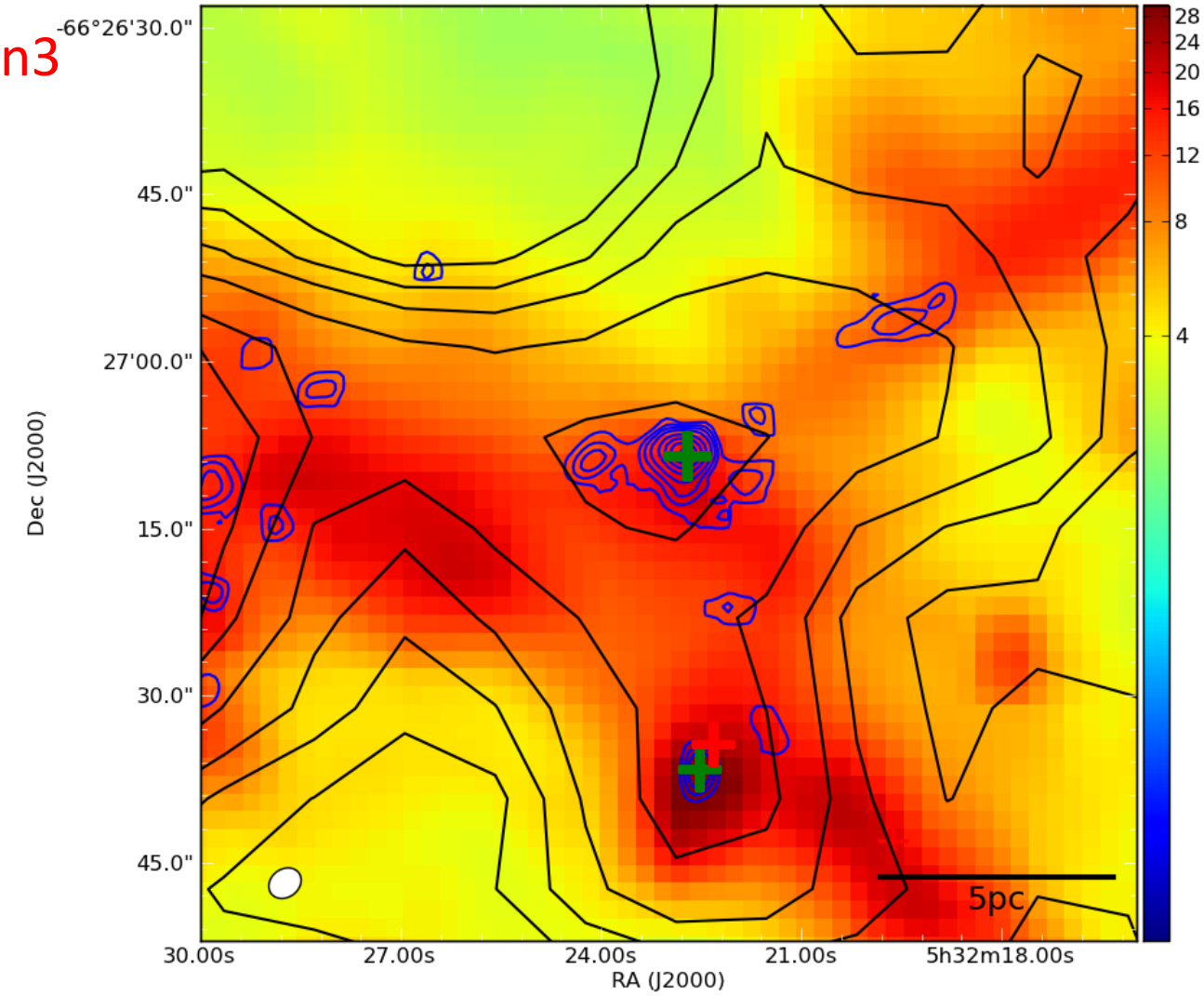
Black: ASTE ^{12}CO(3-2)

Color: Spitzer 8μm

Green Crosses: Spitzer YSO
(Whitney 2008,Gruendl 2009)

Red Crosses: Spectroscopically confiirmed YSO
(Seale 2009)

region3



Blue: ALMA ^{13}CO(1-0)

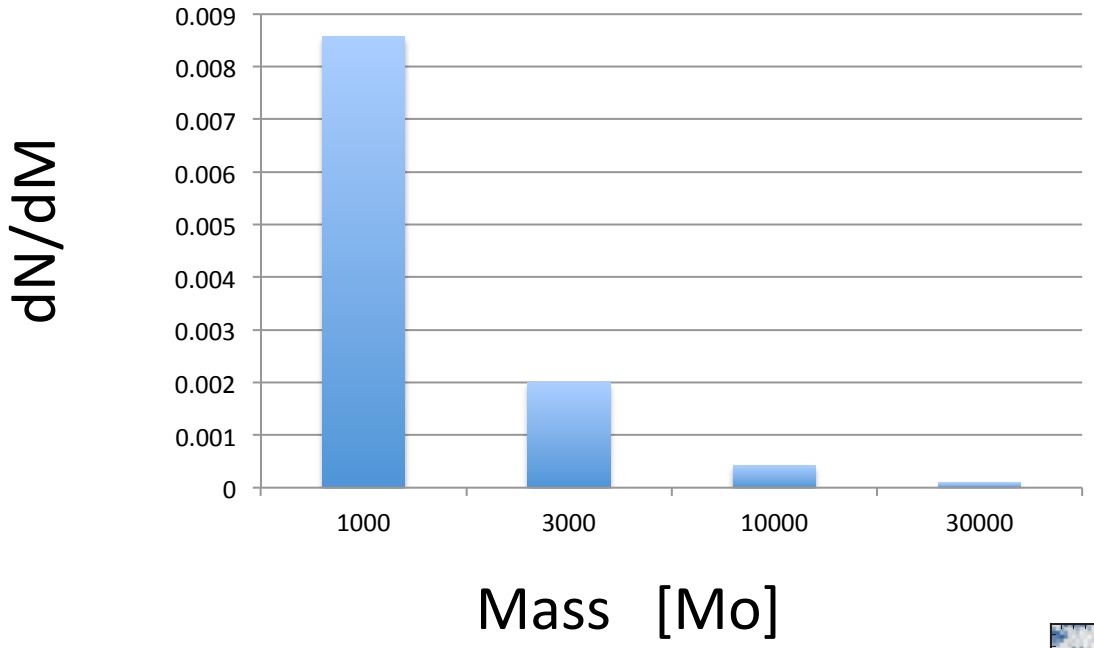
Black: ASTE ^{12}CO(3-2)

Color: Spitzer 8μm

Green Crosses: Spitzer YSO
(Whitney 2008,Gruendl 2009)

Red Crosses: Spectroscopically confiirmed YSO
(Seale 2009)

Mass spectrum of molecular clouds

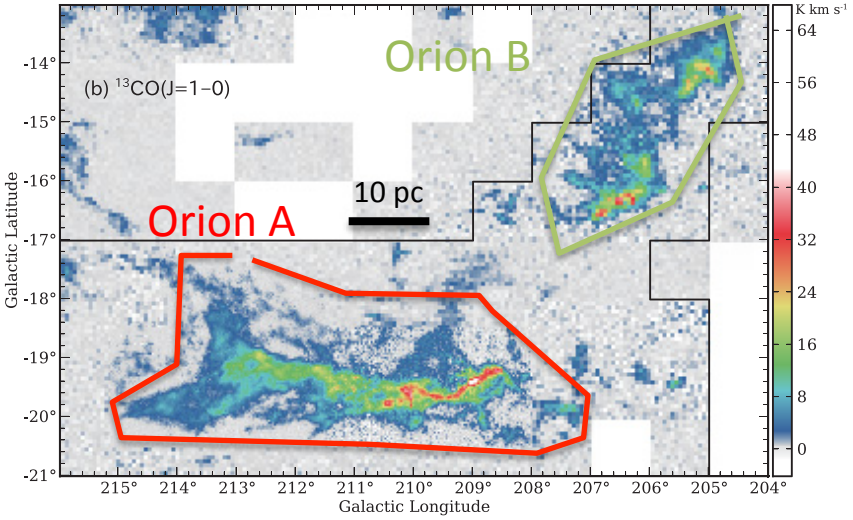


Orion

	Mass [Mo]
Orion A	5.9×10^4
Orion B	3.0×10^4

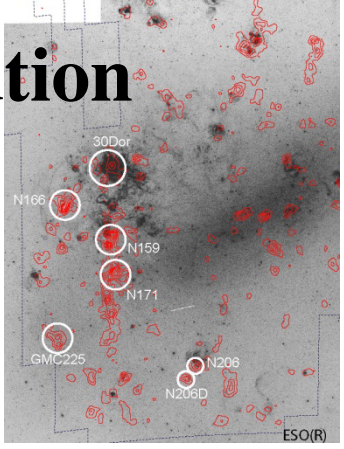
From ^{13}CO(1-0) obs.

Nishimura et al. 2015



- Many clouds with ～1000 Mo
  - Smaller than Orion, Taurus.
- Some compact clouds are associated with high-intermediate star formation

Example of observations with ~5-10 pc resolution



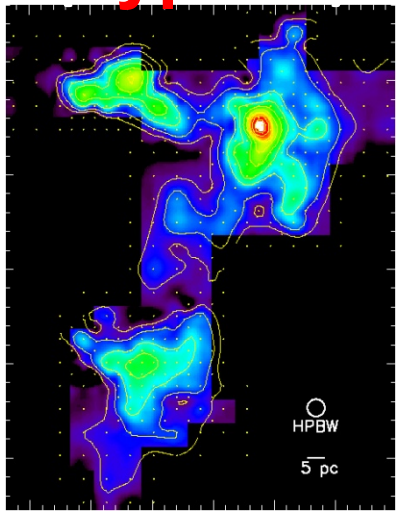
N159
Type III

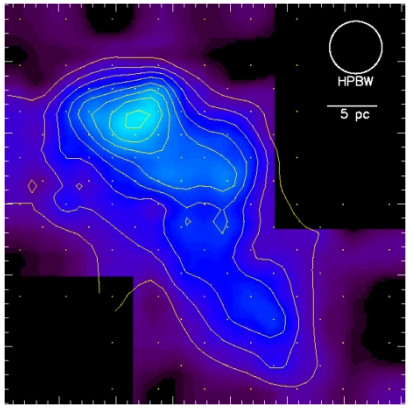
N206D
Type II

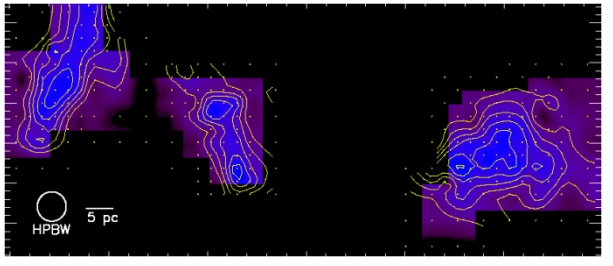
GMC225
Type I

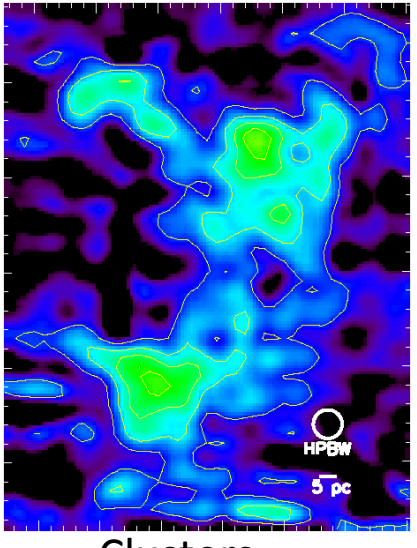
^{12}CO (J=3-2)

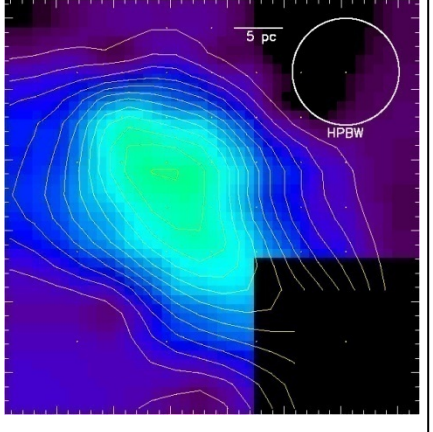
^{12}CO (J=1-0)

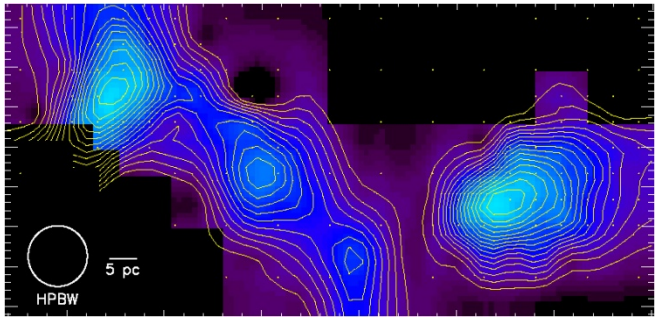










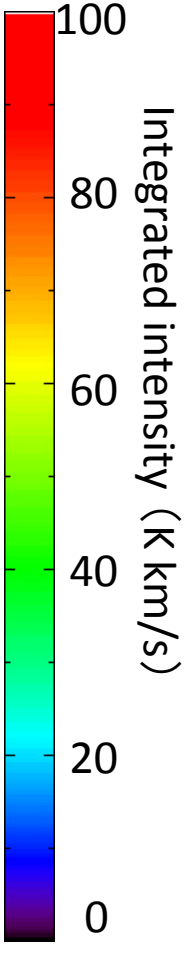


Clusters

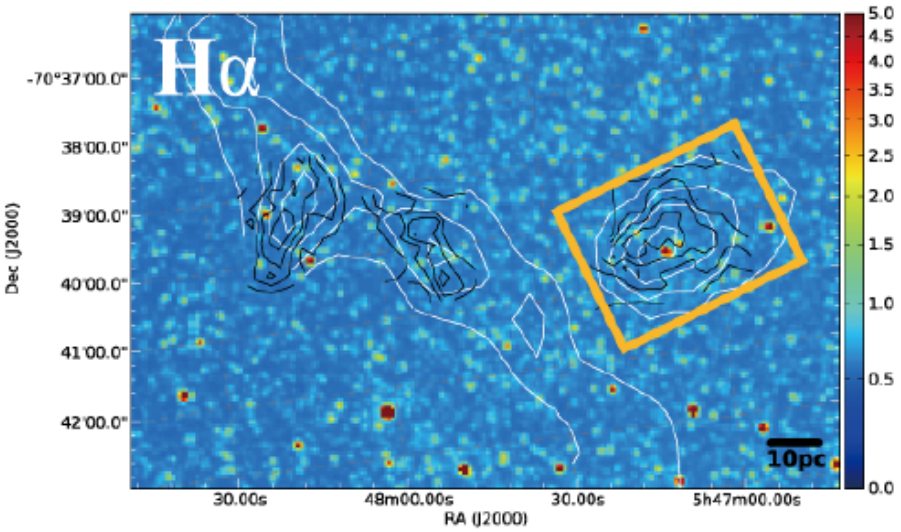
HII regions

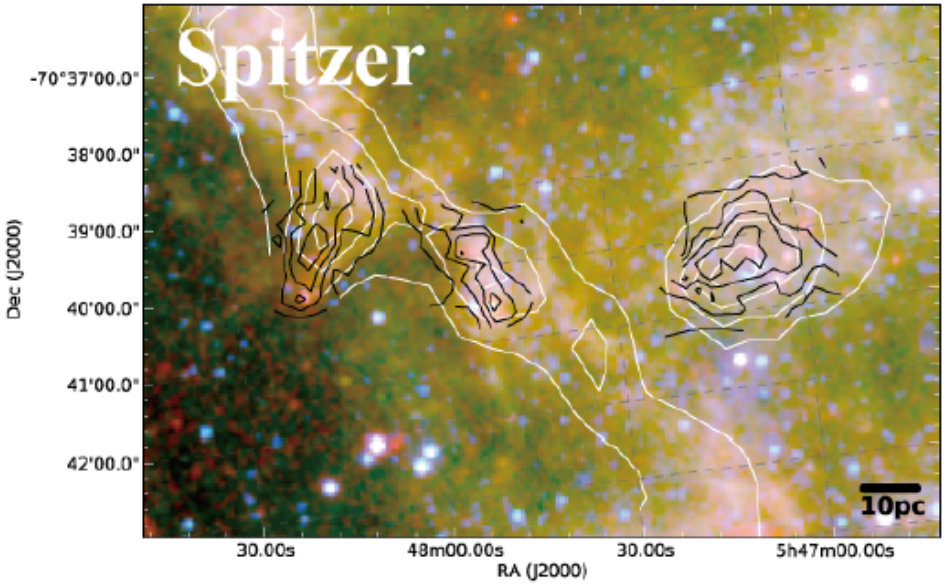
No Massive star formation

Kawamura et al. 2009



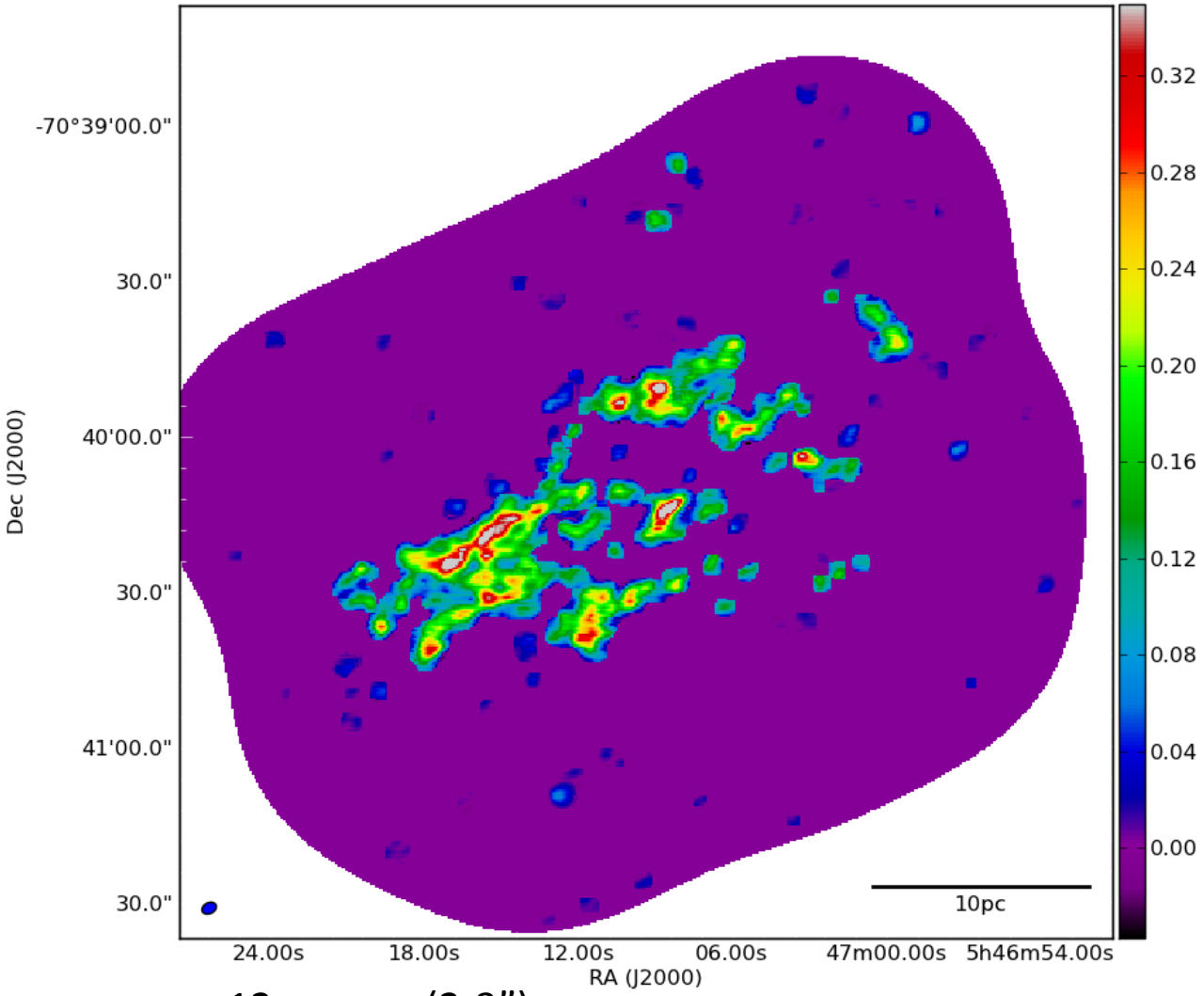
“Starless” GMC



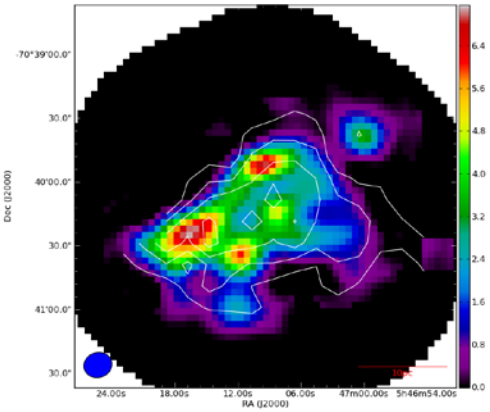


GMC 225

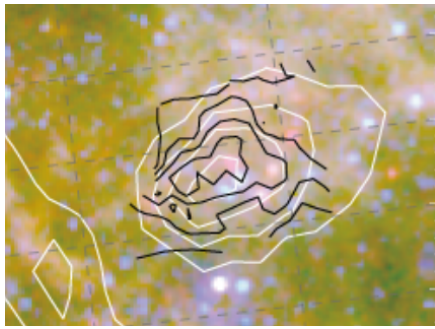
ALMA 13CO(1-0): GMC 225



12m array (2-3”)



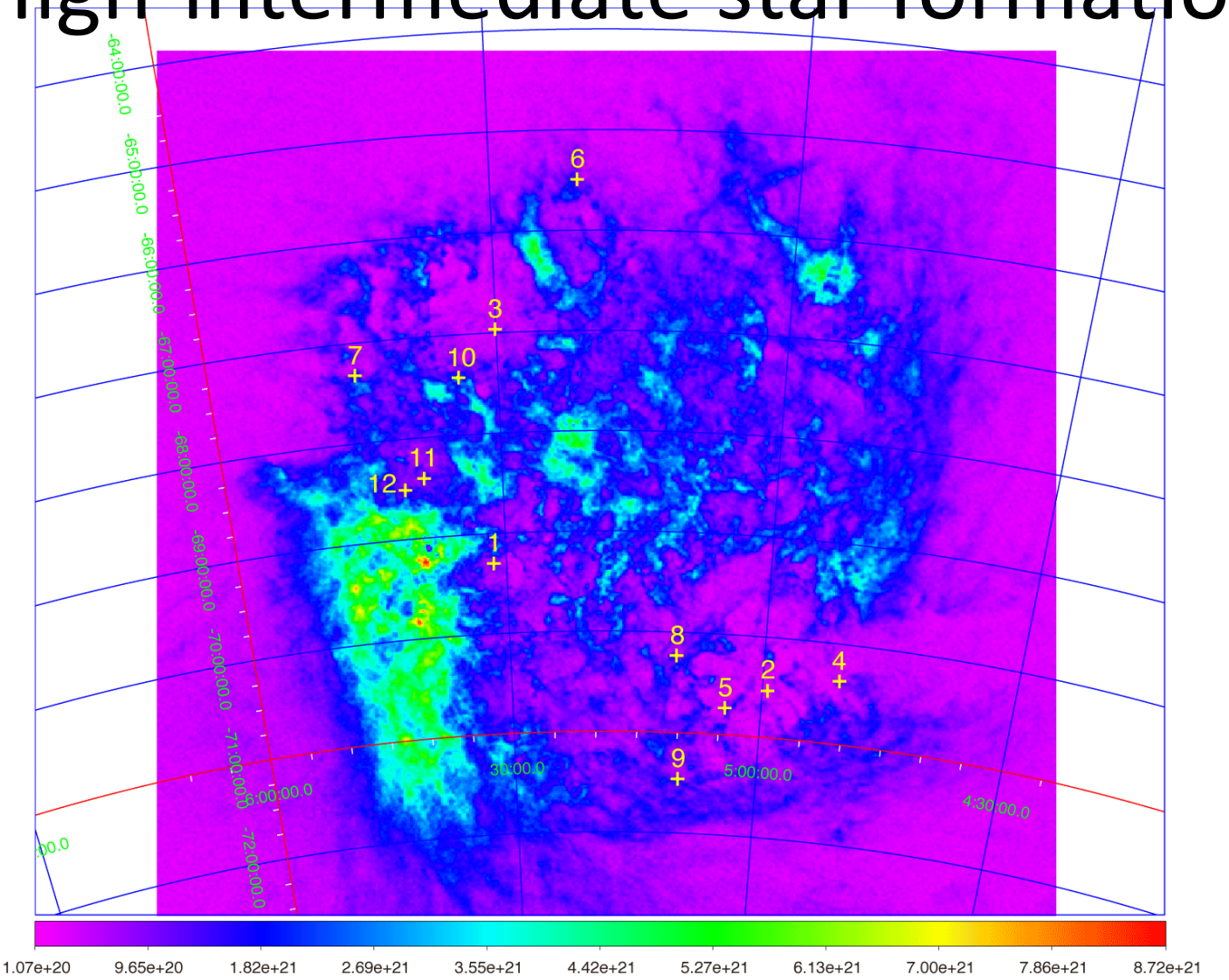
7m array (10”)



Single dish (20”)

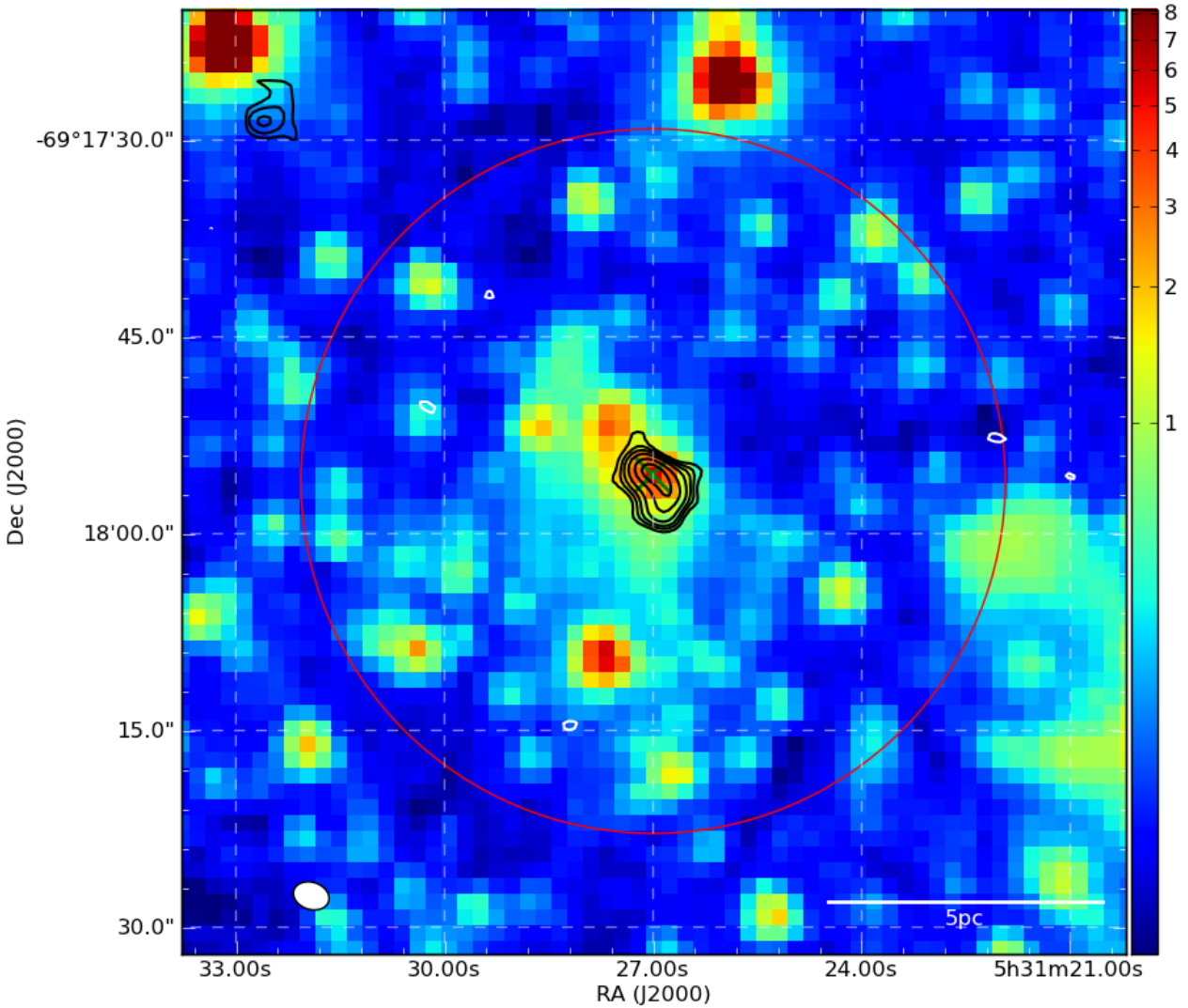
Isolated

High-intermediate star formation



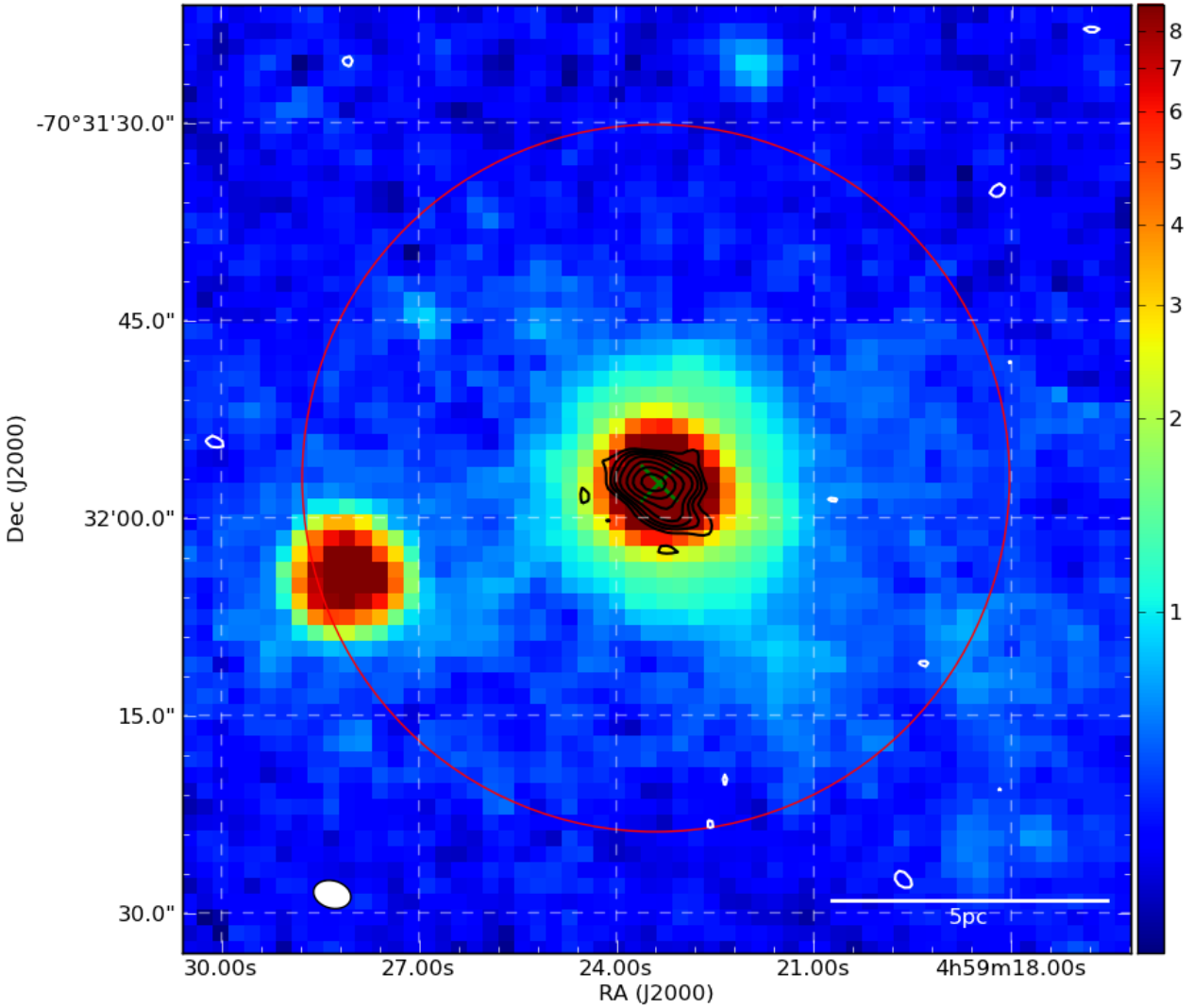
Positions of the isolated intermediate/massive YSOs for the present ALMA observations.

target1



black contour :13CO(1-0) Integrated intensity map
white contour :continuum (band3)
contour level is [3,5,7,10,15]σ
color :Spitzer 8μm
red circle :primary beam
green cross :High- and intermediate-mass YSOs (Gruendle+,2009)

target2



black contour :13CO(1-0) Integrated intensity map

white contour :continuum (band3)

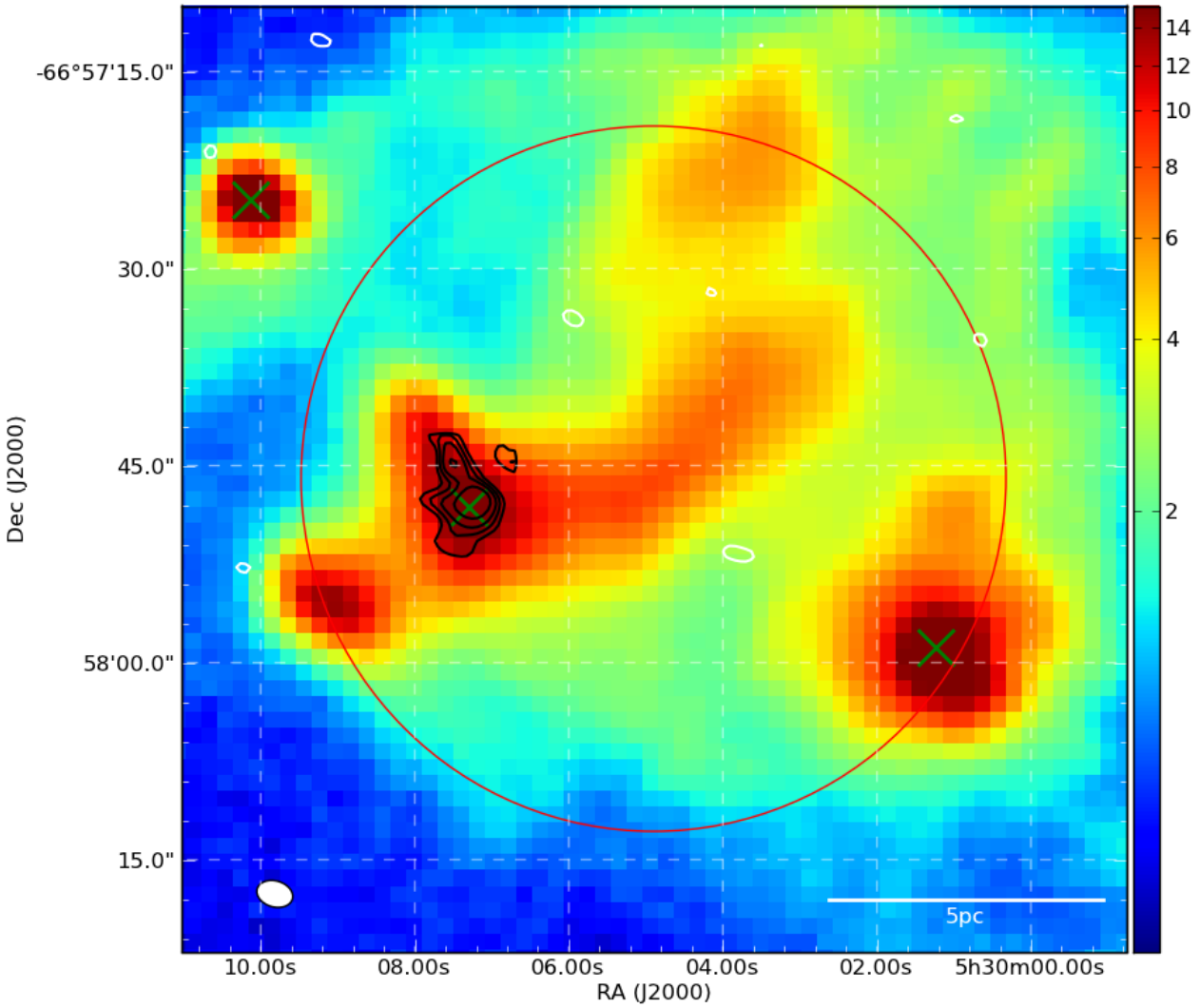
contour level is [3,5,7,10,15]σ

color :Spitzer 8μm

red circle :primary beam

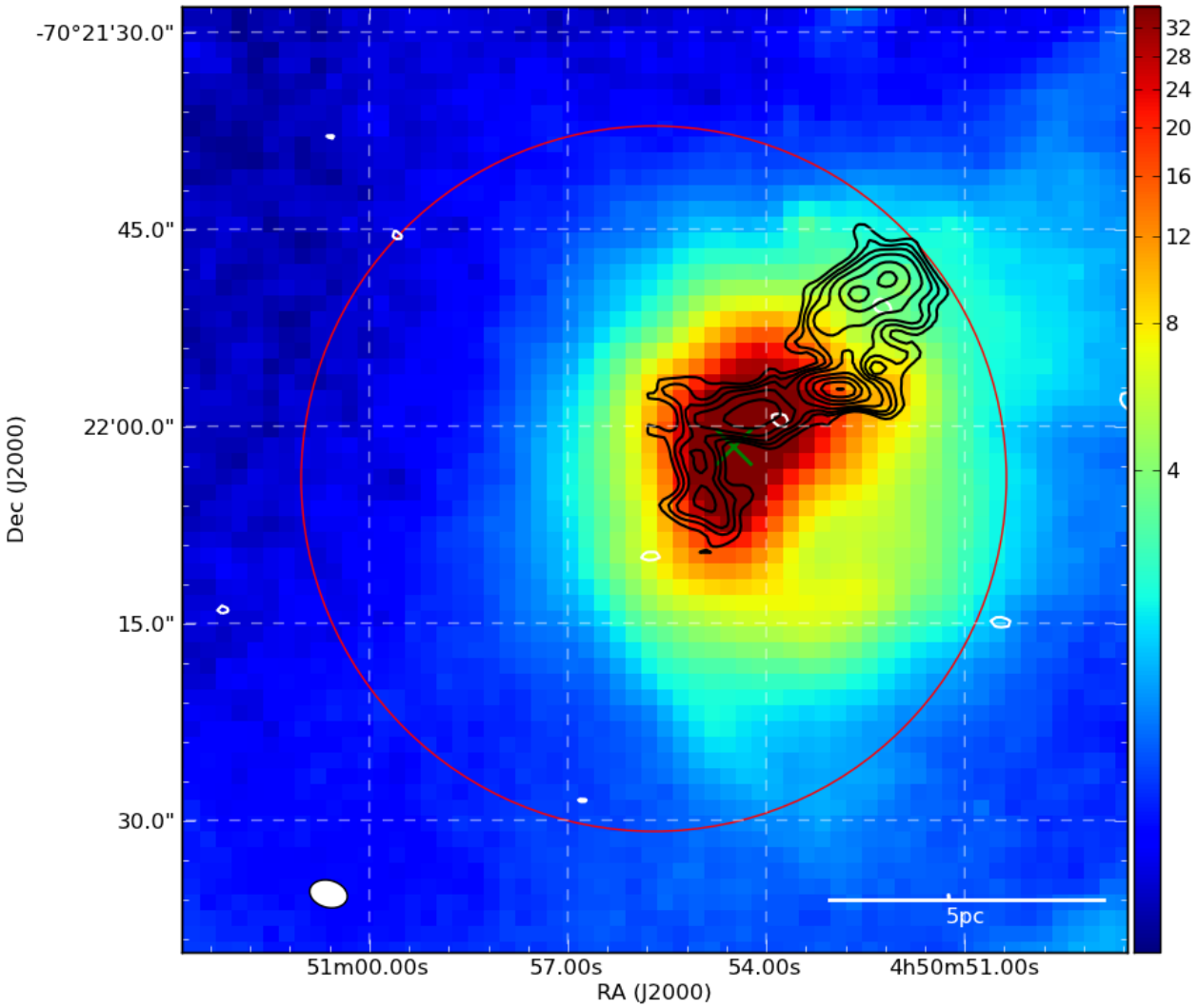
green cross :High- and intermediate-mass YSOs (Gruendle+,2009)

target3



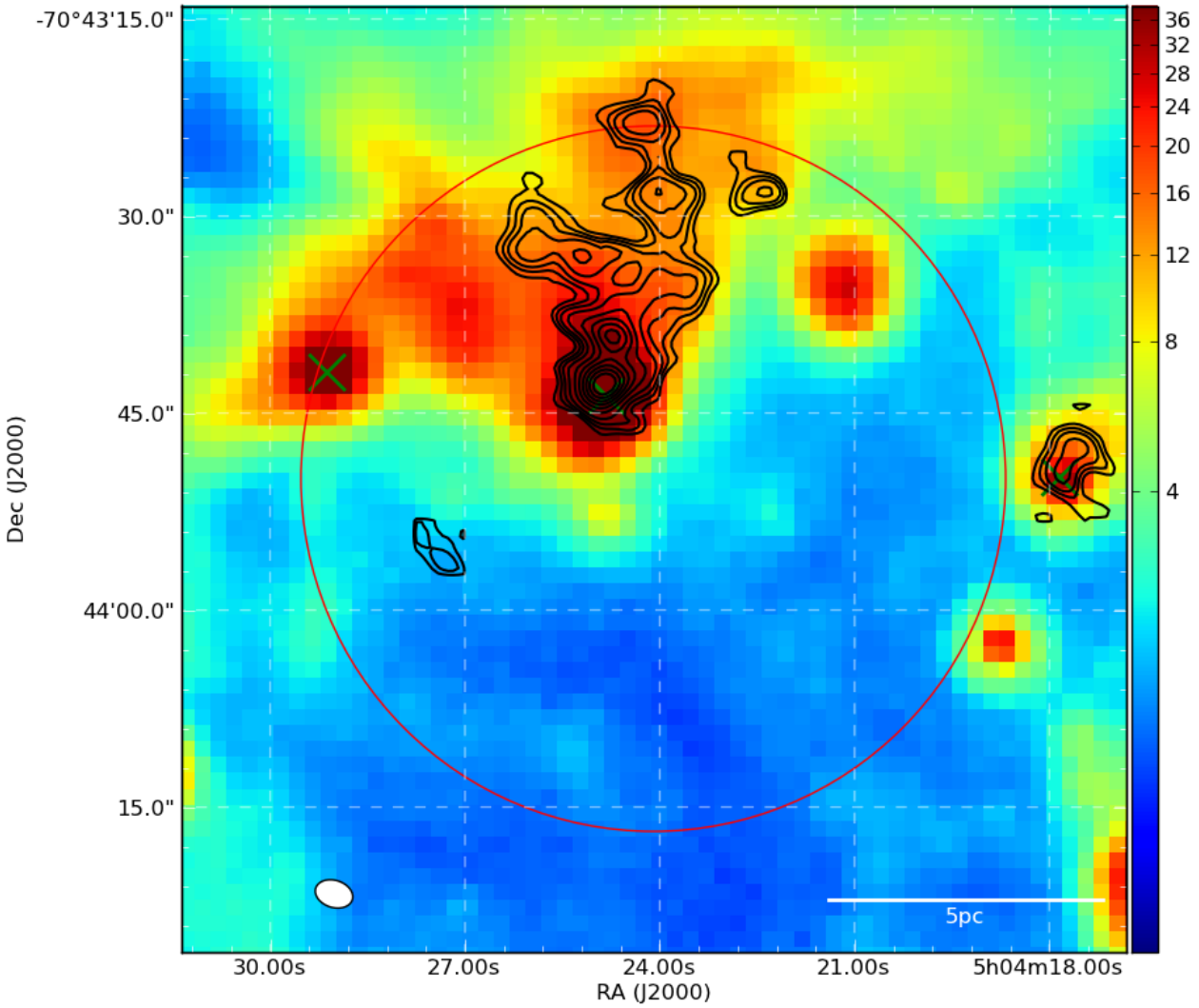
black contour :13CO(1-0) Integrated intensity map
white contour :continuum (band3)
contour level is [3,5,7,10,15]σ
color :Spitzer 8μm
red circle :primary beam
green cross :High- and intermediate-mass YSOs (Gruendle+,2009)

target4



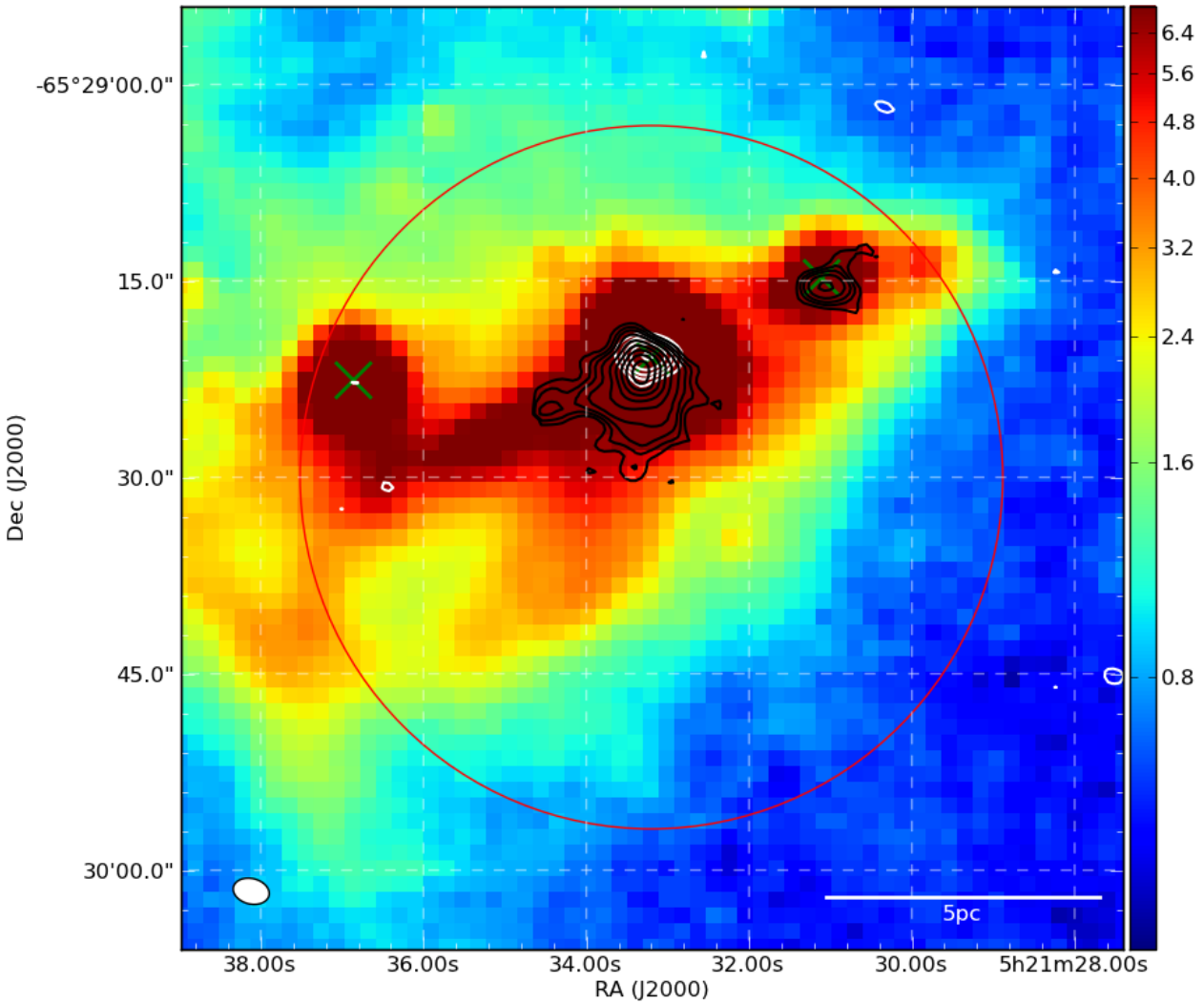
black contour :13CO(1-0) Integrated intensity map
white contour :continuum (band3)
contour level is [3,5,7,10,15]σ
color :Spitzer 8μm
red circle :primary beam
green cross :High- and intermediate-mass YSOs (Gruendle+,2009)

target5



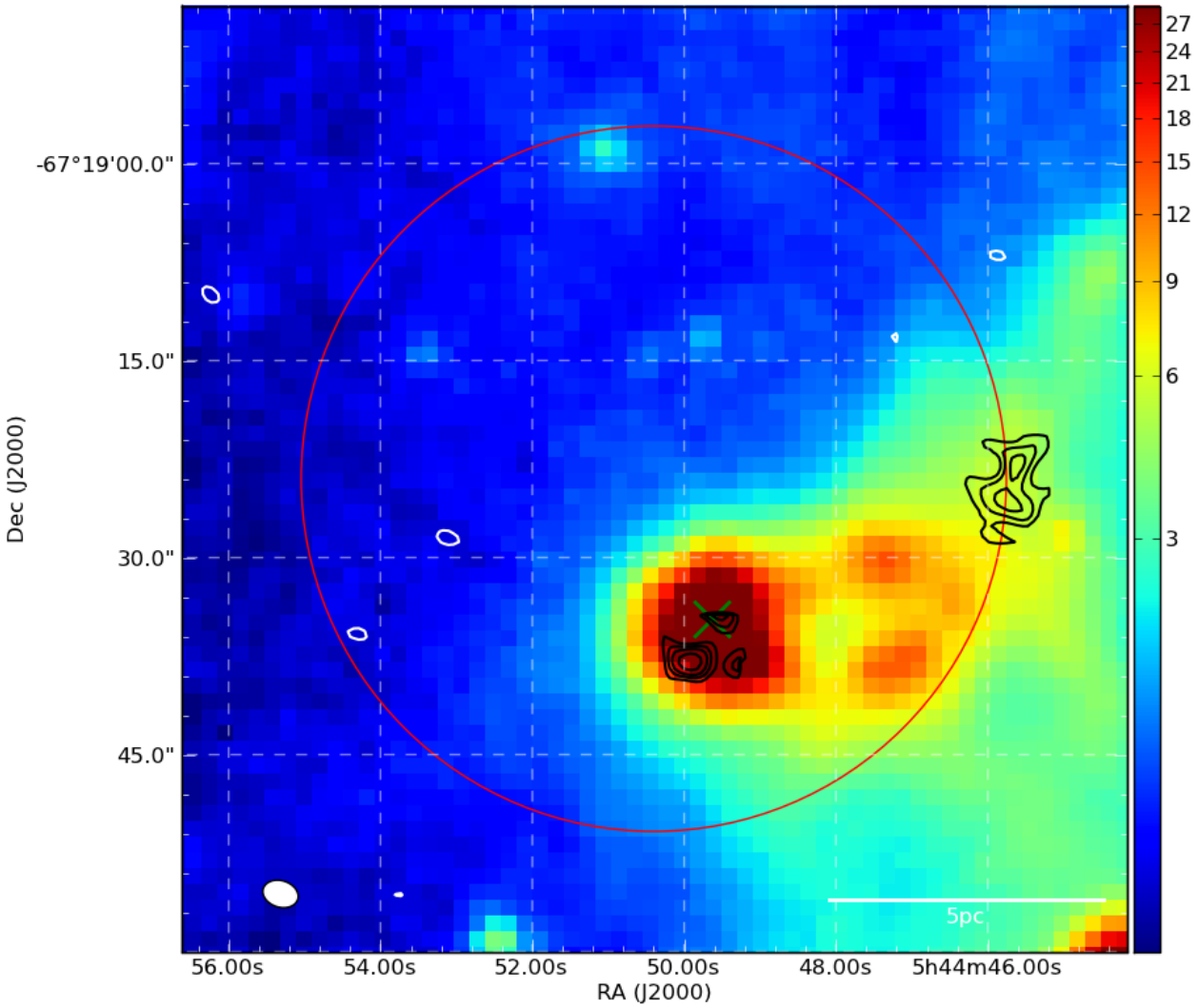
black contour :13CO(1-0) Integrated intensity map
white contour :continuum (band3)
contour level is [3,5,7,10,15]σ
color :Spitzer 8μm
red circle :primary beam
green cross :High- and intermediate-mass YSOs (Gruendle+,2009)

target6



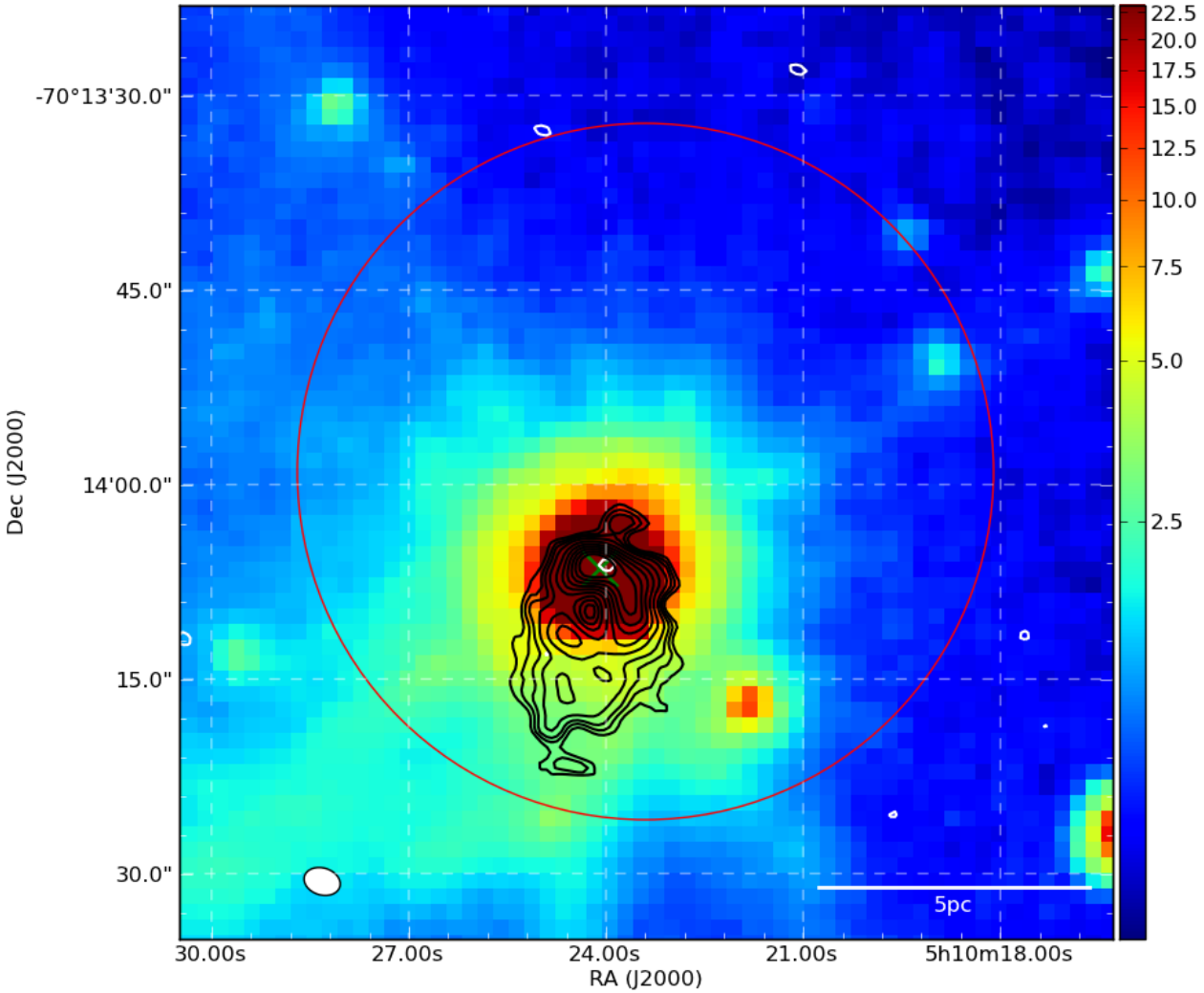
black contour :13CO(1-0) Integrated intensity map
white contour :continuum (band3)
contour level is [3,5,7,10,15]σ
color :Spitzer 8μm
red circle :primary beam
green cross :High- and intermediate-mass YSOs (Gruendle+,2009)

target7



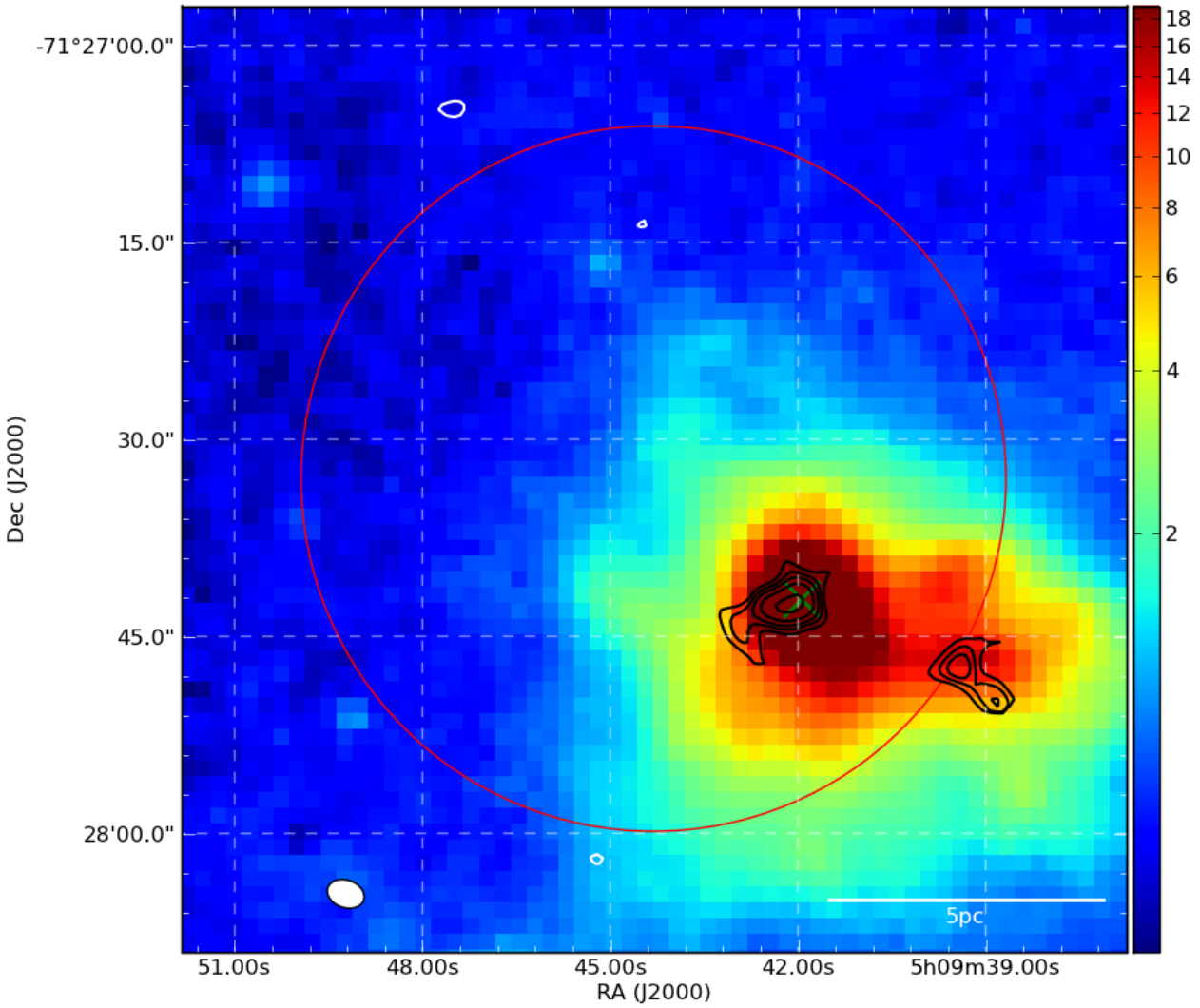
black contour :13CO(1-0) Integrated intensity map
white contour :continuum (band3)
contour level is [3,5,7,10,15]σ
color :Spitzer 8μm
red circle :primary beam
green cross :High- and intermediate-mass YSOs (Gruendle+,2009)

target8



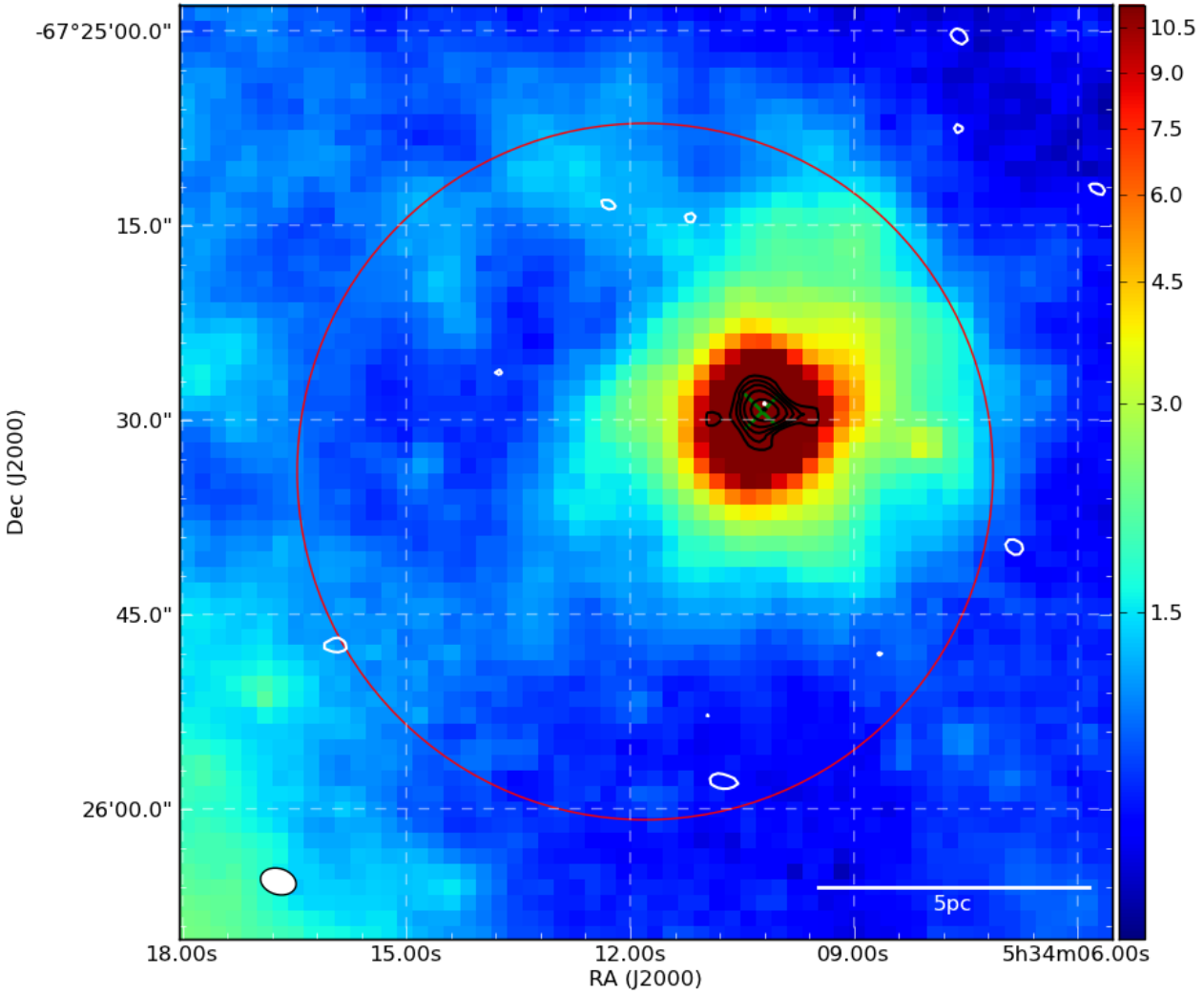
black contour :13CO(1-0) Integrated intensity map
white contour :continuum (band3)
contour level is [3,5,7,10,15]σ
color :Spitzer 8μm
red circle :primary beam
green cross :High- and intermediate-mass YSOs (Gruendle+,2009)

target9



black contour :13CO(1-0) Integrated intensity map
white contour :continuum (band3)
contour level is [3,5,7,10,15]σ
color :Spitzer 8μm
red circle :primary beam
green cross :High- and intermediate-mass YSOs (Gruendle+,2009)

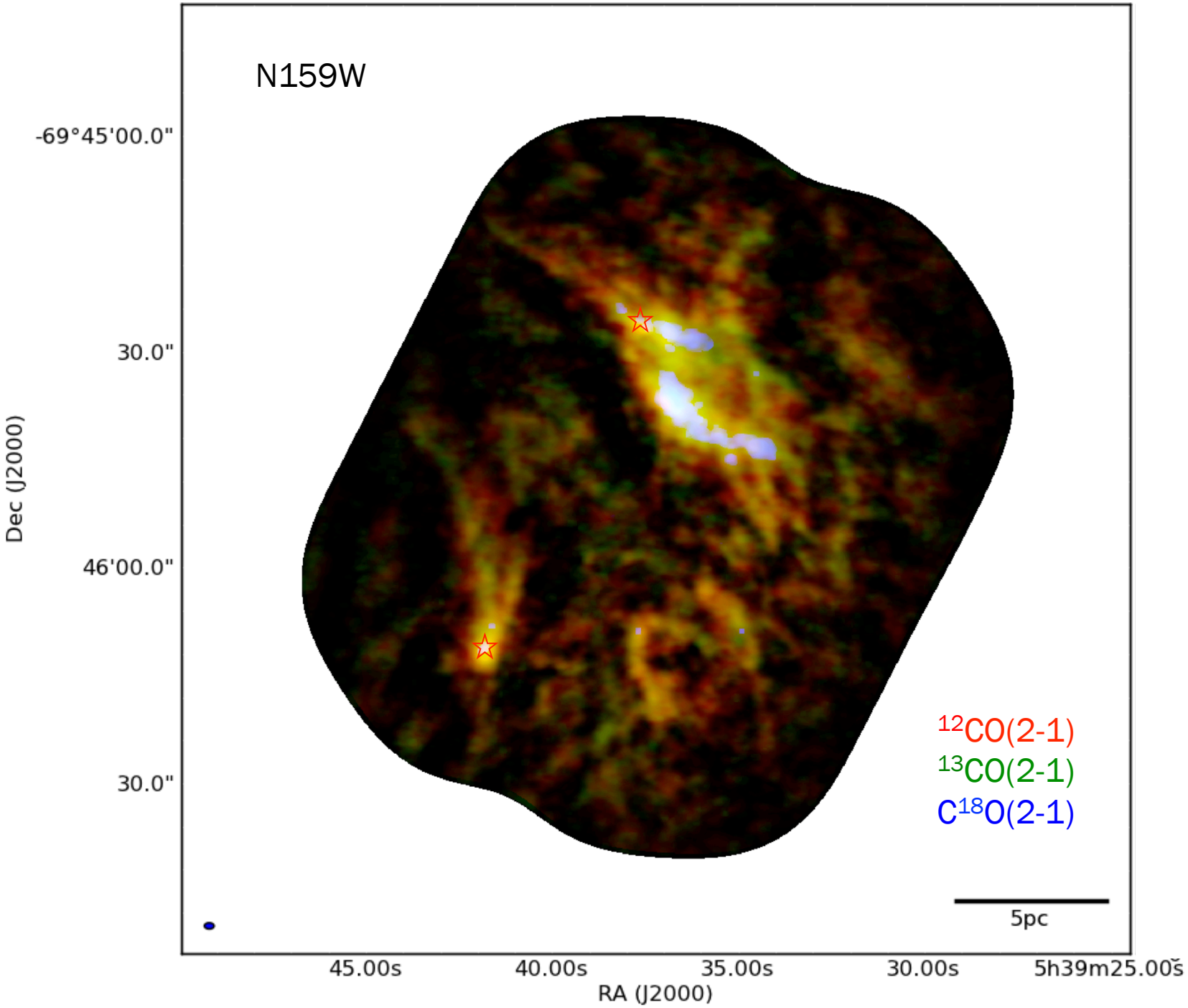
target10



black contour :13CO(1-0) Integrated intensity map
white contour :continuum (band3)
contour level is [3,5,7,10,15]σ
color :Spitzer 8μm
red circle :primary beam
green cross :High- and intermediate-mass YSOs (Gruendle+,2009)

Star Formation in the LMC

- Spitzer, Herschel
  - Dust distribution throughout the Galaxy in sub-pc resolution
  - Uniform sample of YSOs with >1000Lo
- NANTEN
  - MCs in the entire Galaxy in 40 pc res.
- ASTE, Mopra, SEST: 5-10 pc res.
- ALMA: sub-pc res.
  - Detailed structure: Filaments, Compact
  - Signature of individual star formation: Outflow, H{30,40}α


N159W
-69°45'00.0"
30.0"
46'00.0"
30.0"
Dec (J2000)
45.00s
40.00s
35.00s
30.00s
5h39m25.00s
RA (J2000)
12CO(2-1)
13CO(2-1)
C18O(2-1)
5pc