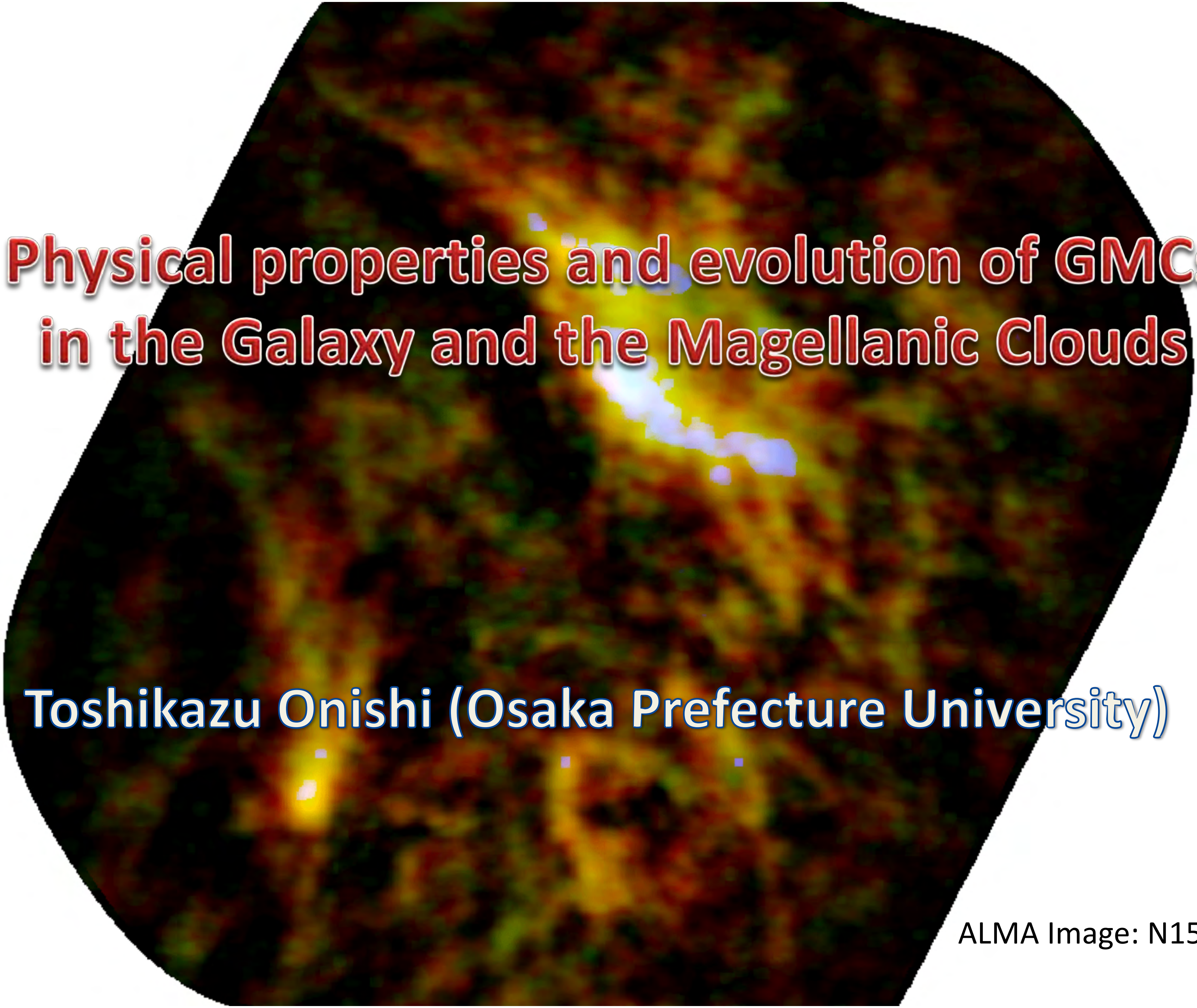
Physical properties and evolution of GMCs in the Galaxy and the Magellanic Clouds

Toshikazu Onishi (Osaka Prefecture University)



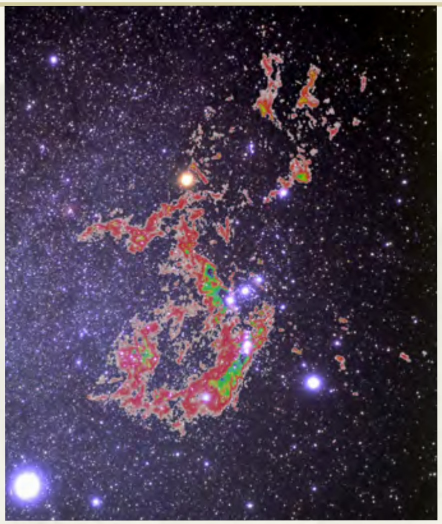
ALMA Image: N159W

GMC as a site of high-mass star formation

From galaxy evolution to individual star formation

kpc

GMAs: 10^7Mo



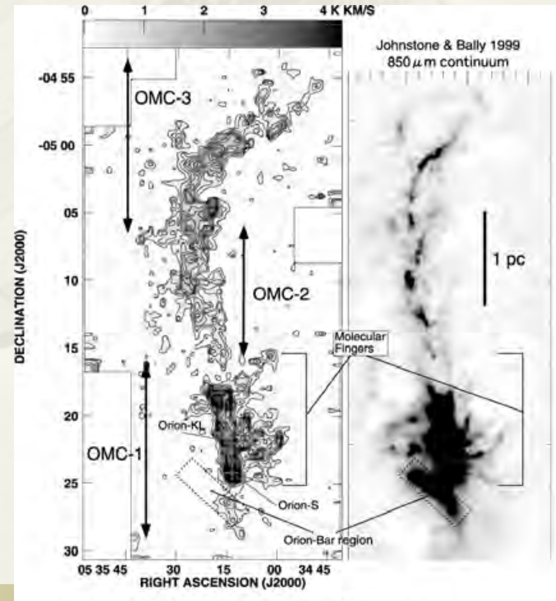
1-100pc

GMCs: 10^4 - 10^6Mo
$n(H_2)$ ~ 1000cm^{-3}

Clumps, Cores
10^2 - 10^3Mo
$n(H_2)$ ~ >$10^4 cm^{-3}$

<0.1 pc

Wide range of scales
Various distances
Use of various telescopes



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

High mass SF

- Initial condition
  - Need high Jeans mass (effective a~10km/s)
    - Monolithic collapse? (McKee and Tan 2002)
    - Competitive mass accretion? (Bonnel et al. 2010)
  - Origin of IMF
  - Effect of the total mass of the cloud?
  - Origin of isolated high mass star: 20%?(Gies 1987)
- Rapid destructive process
  - Information on natal clouds dissipates very fast.

Galactic plane surveys

- Sites of high-mass star formation in the Galaxy.
- CO, ^{13}CO, C^{18}O, J=1-0: Mass tracers
- J=2-1, 3-2 lines: Density, temperature dependent

- Angular resolution: 3 arcmin
  - NANTEN2 4m: ^{12}CO(1-0), ^{13}CO(1-0), Entire Southern Sky
  - Osaka 1.85m at NRO: ^{12}CO(2-1), ^{13}CO(2-1), C^{18}O(2-1), Northern sky
- Angular resolution: better than ~1'
  - FCRAO 14m: ^{13}CO(1-0), 55.7°>L>18°, |b|<1°
  - Mopra 22m: ^{12}CO(1-0), ^{13}CO(1-0), C^{18}O(1-0), 358°>L>300°, |b|<0.5°
  - JCMT 15m: ^{12}CO(3-2), ^{13}CO(3-2), C^{18}O(3-2), 43°>L>28°, |b|<0.5°
  - NRO 45m: ^{12}CO(1-0), ^{13}CO(1-0), C^{18}O(1-0), 50°>L>10°, 236°>L>198°, |b|<1°

NRO Galactic Plane Survey

- Using multi-beam receiver **FOREST**, OTF mapping of the Galactic plane in $^{12}CO(1\text{-}0)$, $^{13}CO,(1\text{-}0)$, $C^{18}O(1\text{-}0)$, **simultaneously**

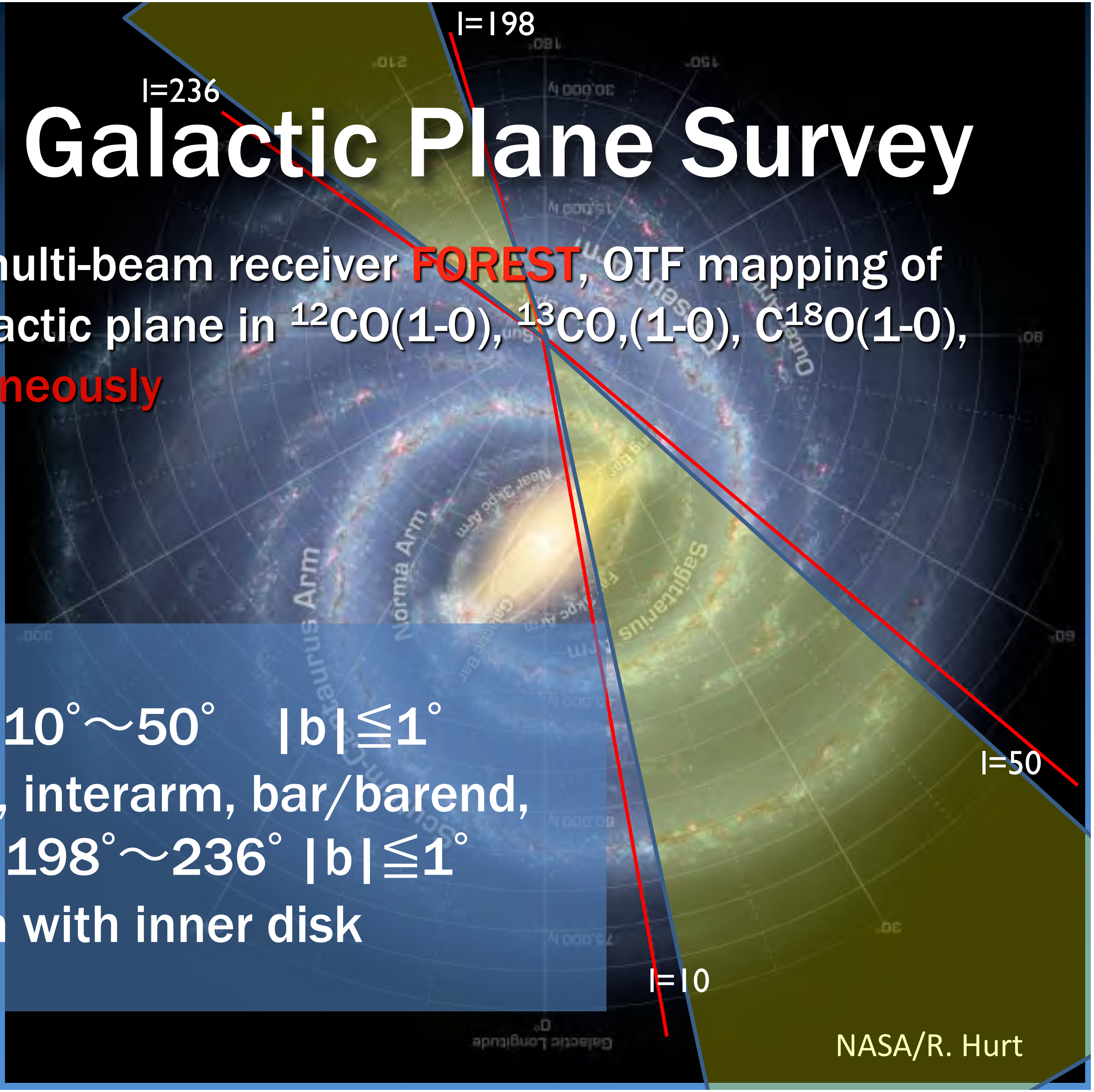
Mapping area:

inner disk: l = 10°～50°　|b|≦1°

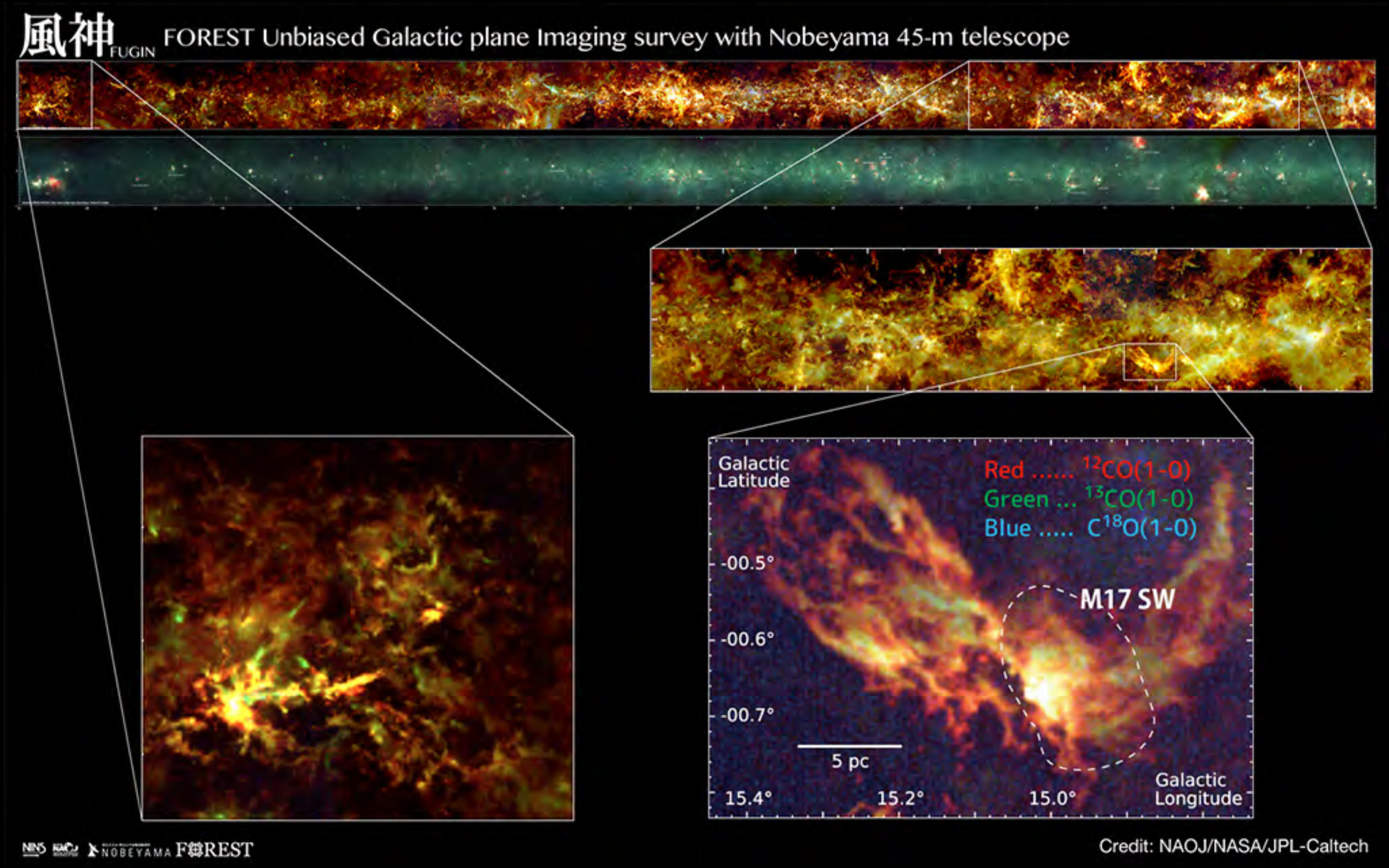
Spiral arms, interarm, bar/barend,

outer disk: l = 198°～236° |b|≦1°

Comparison with inner disk



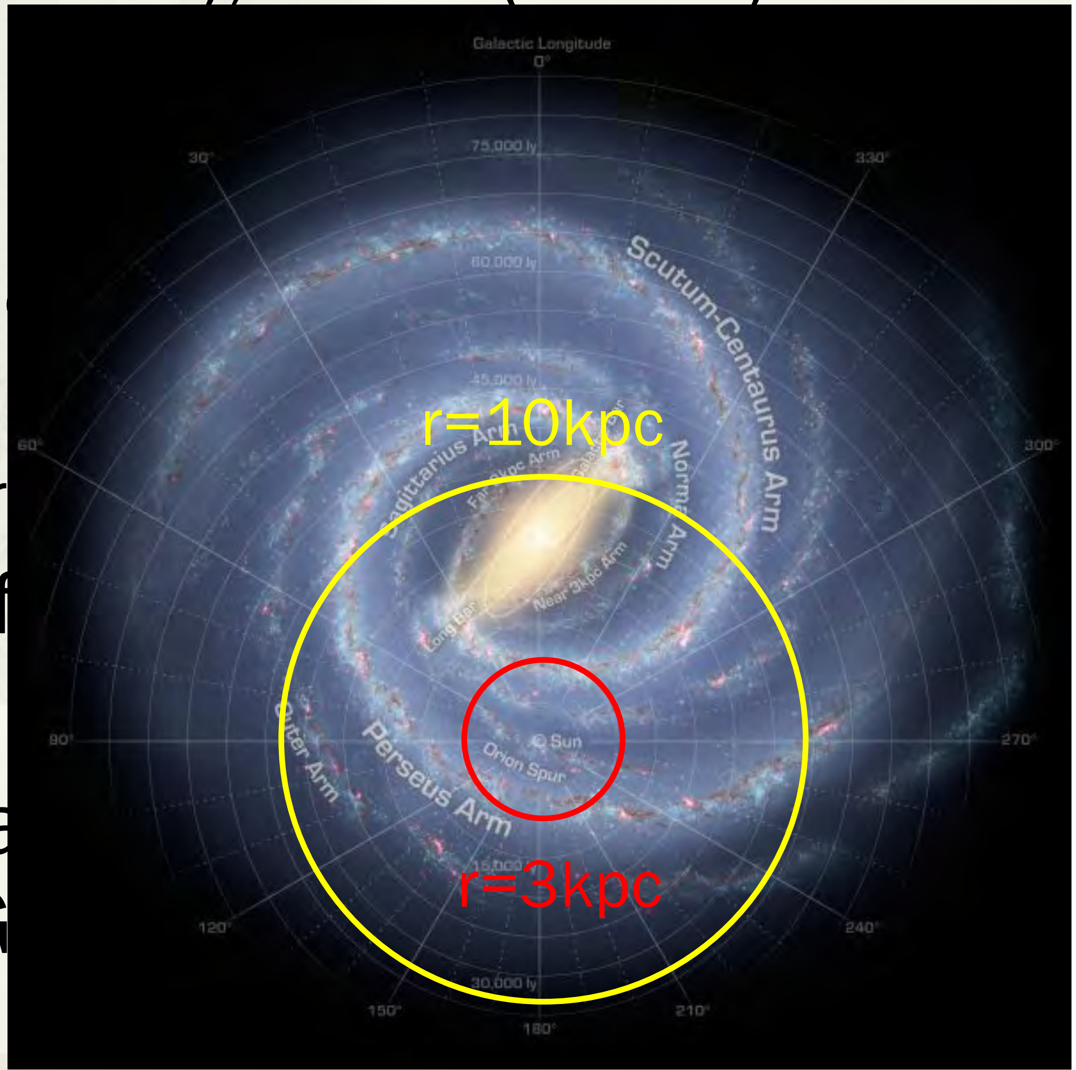
CO three lines



~JCMT CO(3-2) resolutions R $^{12}CO(1\text{-}0)$, G $^{13}CO(1\text{-}0)$, B $C^{18}O(1\text{-}0)$

Survey with <20” resolutions

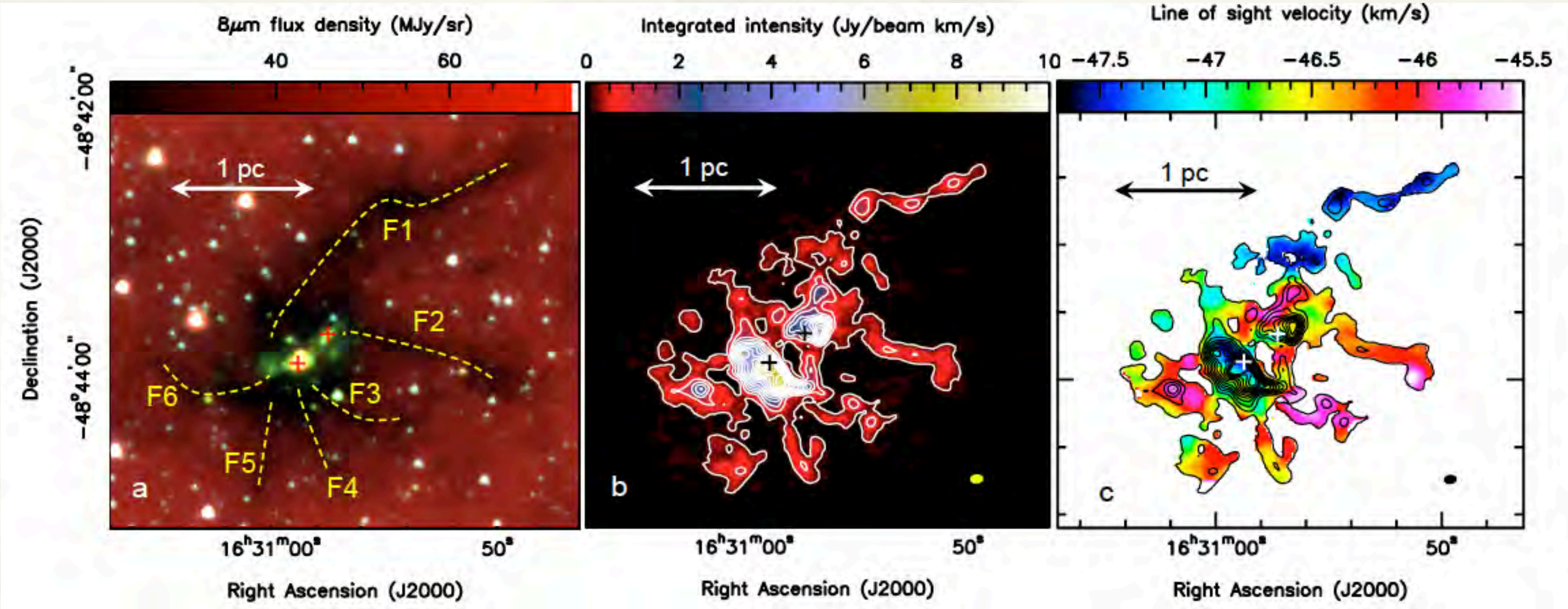
- NRO (J=1-0), IRAM (J=2-1), JCMT (J=3-2)
- Spatial resolution
  - 0.3pc at 3kpc
    - Can spatially resolve
  - 1pc at 10kpc
    - Can detect dense cor
- Velocity structures of
  distribution
- Essential to investiga
  GMCs in the entire G



Interaction of clouds: Cloud-Cloud collision

- Multiple velocity components are frequently seen toward high-mass star forming regions
  - Dynamics of gas is a key for high-mass star formation
- Increase Jeans mass, compression of gas
- Frequency?
  - can be large
    - No. of GMCs ~ 10^5(Kwan 1979)
    - Mean free time ~10Myr: one collision within its lifetime
- Small scale (dense clumps) collision

Collision or total collapse?



Peretto et al. (2013)

Need supersonic flow to form high mass stars

Massive star cluster formation by CCC

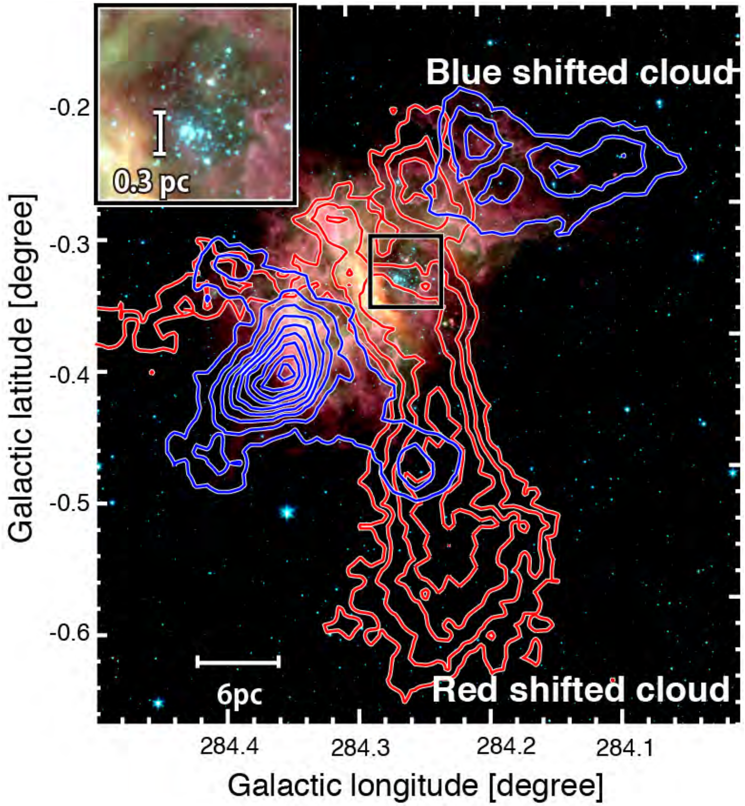
Westerlund2

NGC3603

RCW38

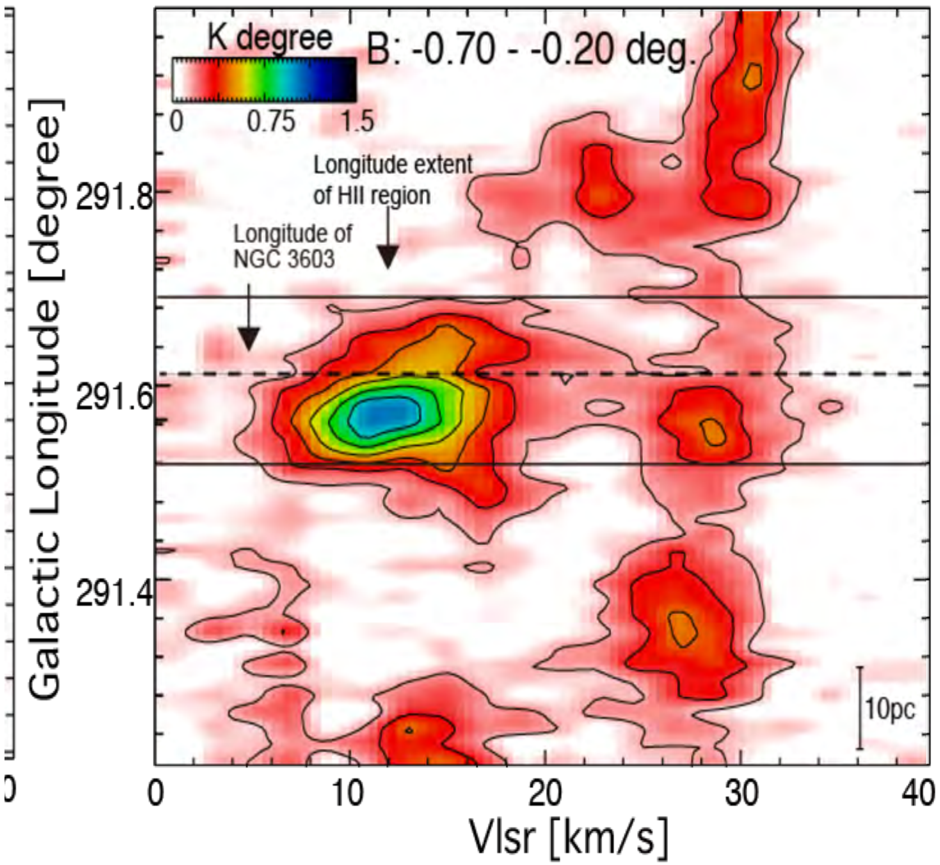
[DBS2003]179

- **All of the known four young massive star clusters (MSC) having nebulosity are each associated with two clouds.**
- **The velocity separations between two clouds are typically 10–20 km/s.**
- **MSC formation by CCC.**
- **Time scale of CCC and MSC formation can be estimated as < ~0.5 Myrs.**



NGC3603 star formation is quick, in 10^5yrs

Fukui et al. 2014



Kudryavtseva et al. 2012

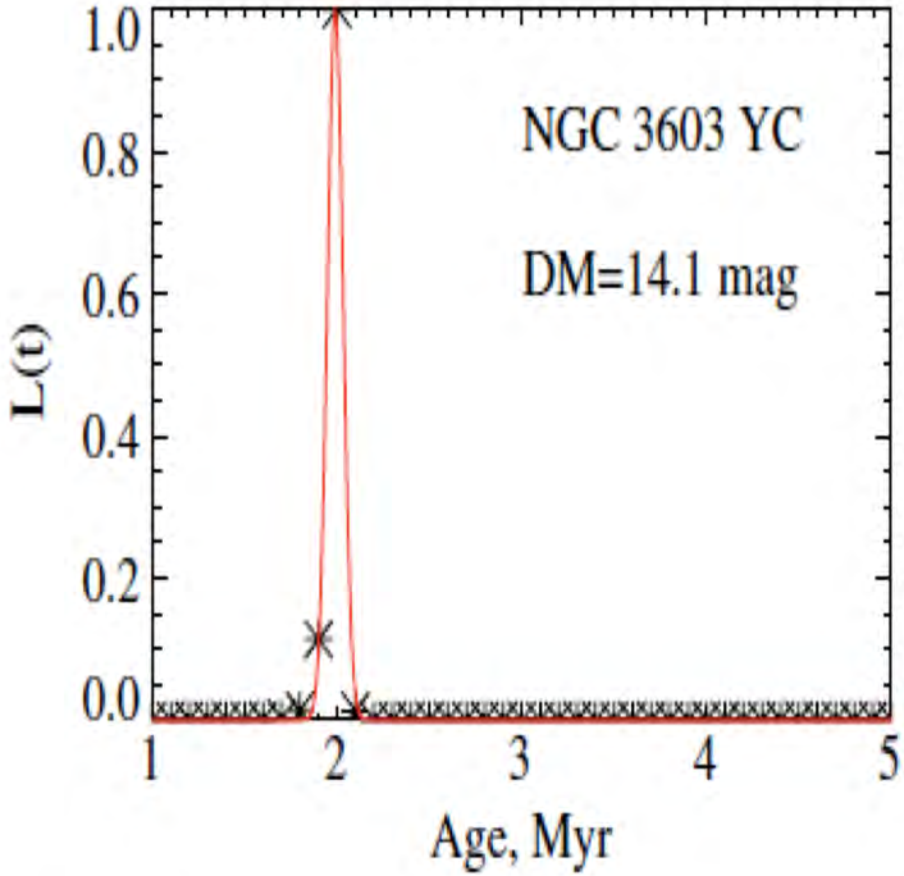
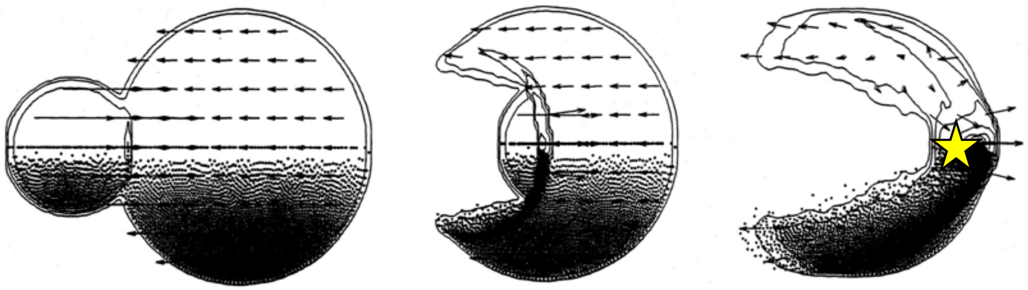


Figure 4. Normalized $L(t)$ for NGC 3603 YC at DM = 14.1 mag. The most probable age is 2.0 Myr. The red curve is a fitted Gaussian function.

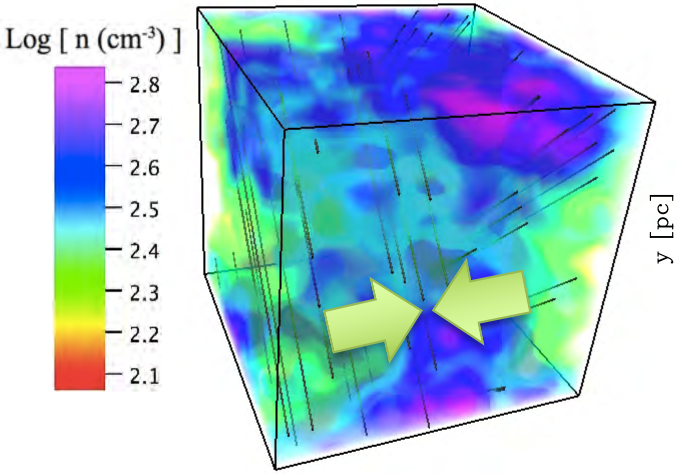
Massive star formation by cloud-cloud collision

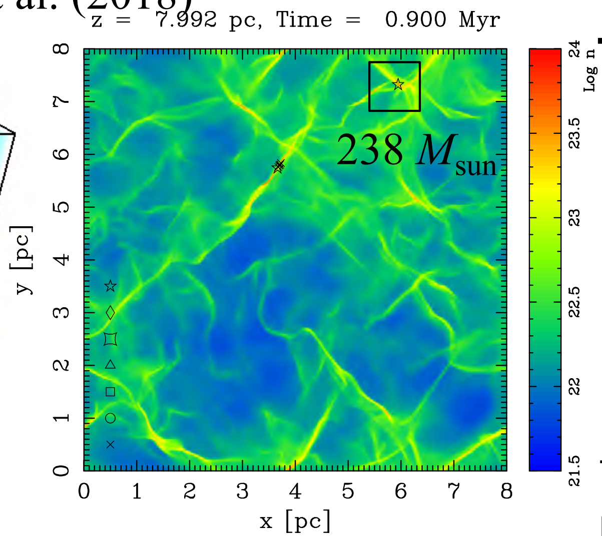
Habe & Ohta (1992)



Cloud-cloud collision (CCC) can induce strong compression of the gas, leading high-mass star formation.

Inoue & Fukui (2013), Inoue et al. (2018)





Theoretical work：

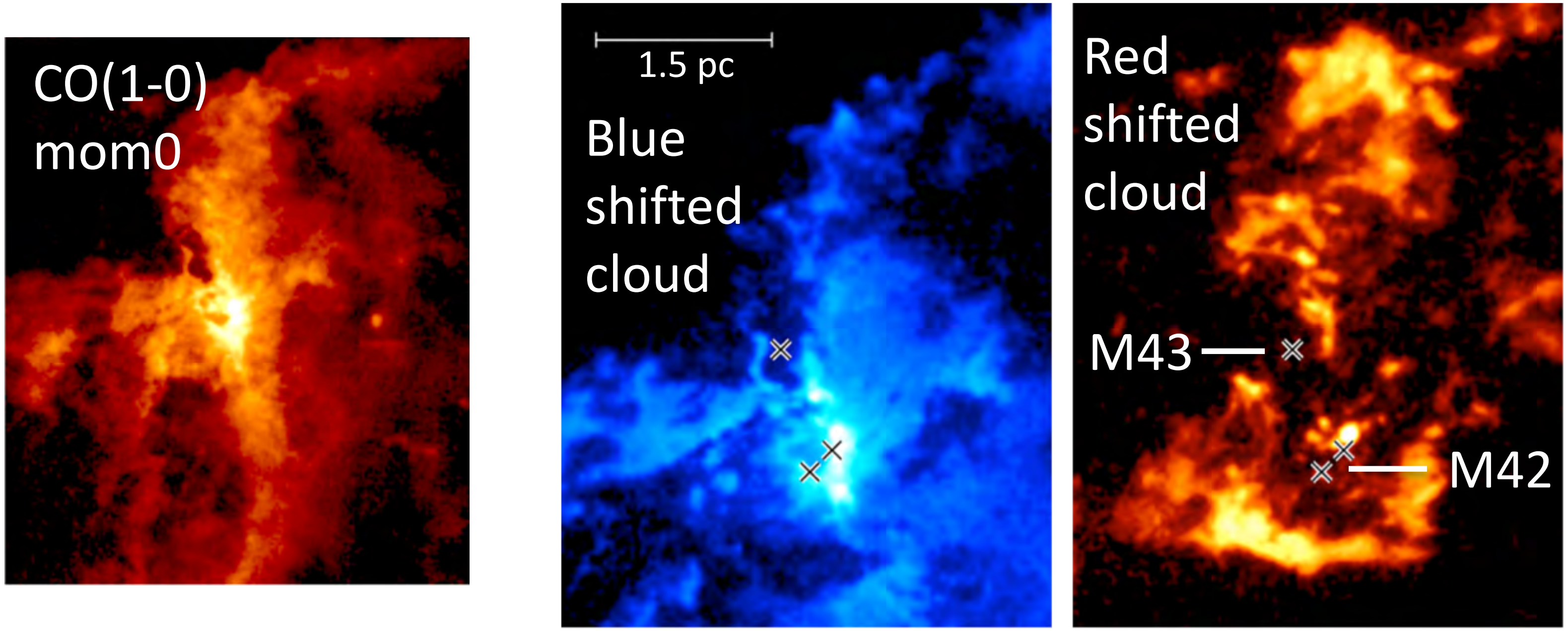
- CCC can increase mass accretion rate by more than 100 times than that in the low-mass star formation

→ leading formation of massive filament/clump/core.

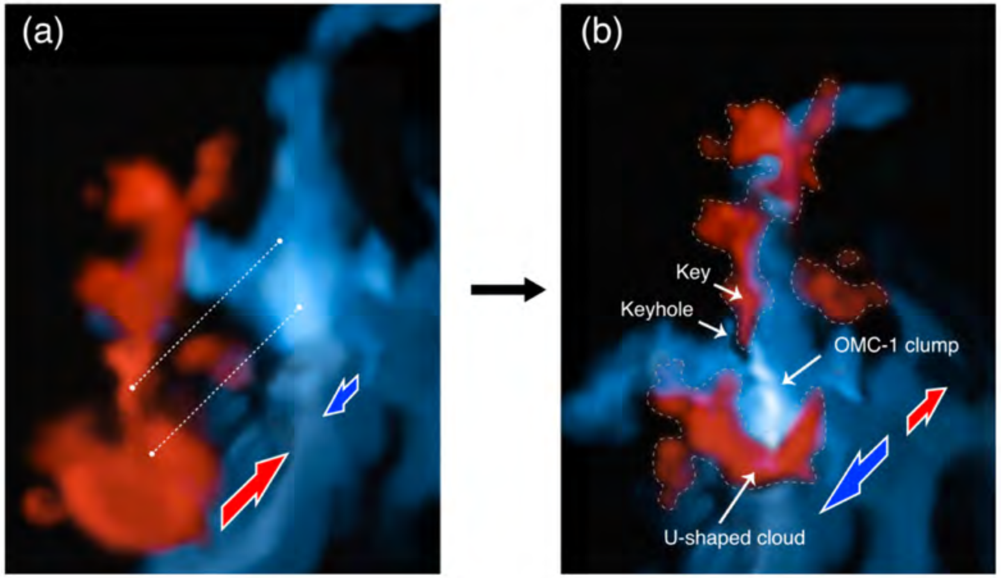
$$\dot{M} \sim \frac{M_{\rm J,eff}}{t_{ff}} \sim (c_s^3 + c_A^3 + \Delta v^3)/G \quad (c_s^3 : c_A^3 : \Delta v^3 = 1 : \underline{125 : 90})$$

$$\dot{M} = 5\times10^{-4} - 4\times10^{-3} \quad M_{\rm Sun}/{\rm yr}$$

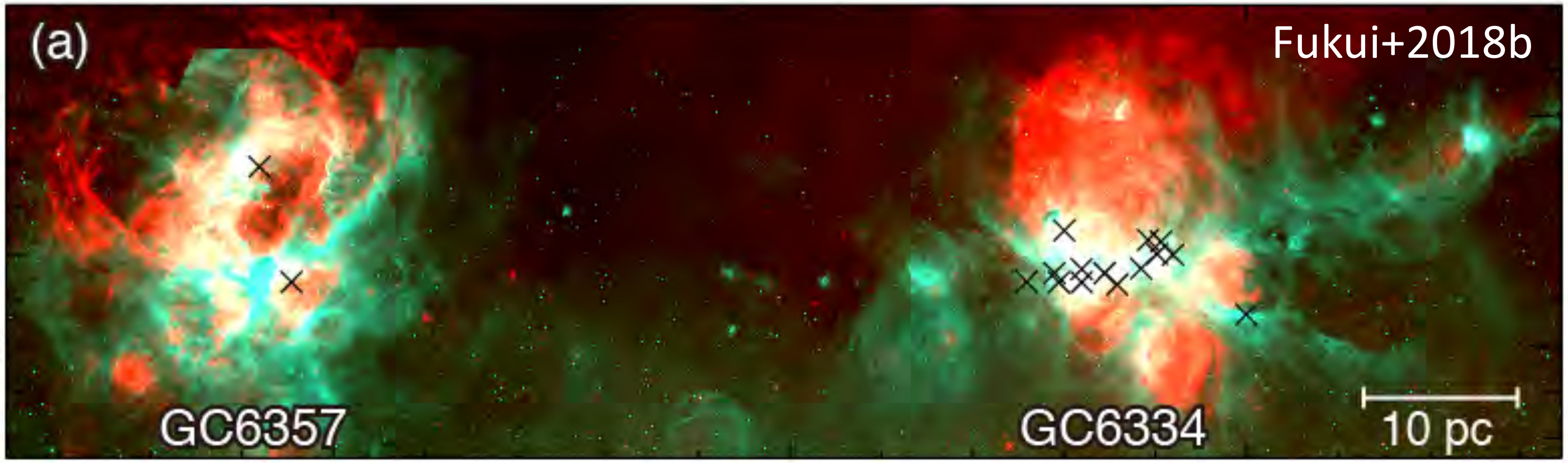
Sites of the massive star formation by CCC



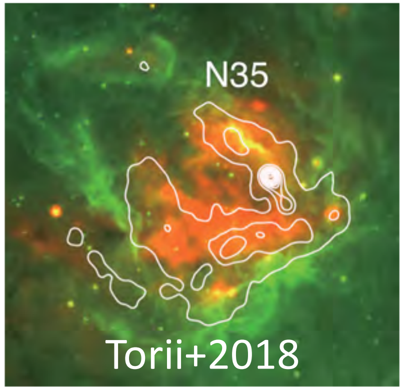
- **Orion Nebula (Fukui+2018a)**
  - **The GMC can be separated into two velocity components.**
  - **Colliding higher-density cloud makes a hole in lower-density cloud.**
  - **M42 and M43 could be formed by CCC.**



Sites of the massive star formation by CCC



- PASJ Special Issue : CCC (May 2018)
- Single O star formation
  - Spitzer bubbles (RCW79, N35, etc.)
  - UCHII region (RCW166 : Ohama+18b)
- Galactic mini-starbursts
  - NGC6334+NGC6357 (Fukui+18b)
- High-mass star cluster formation
  - M17 (Nishimura+18), W33 (Kohno+18)
  - Vela region (Sano+18, Hayashi+18, Enokiya+18)



Spitzer bubbles

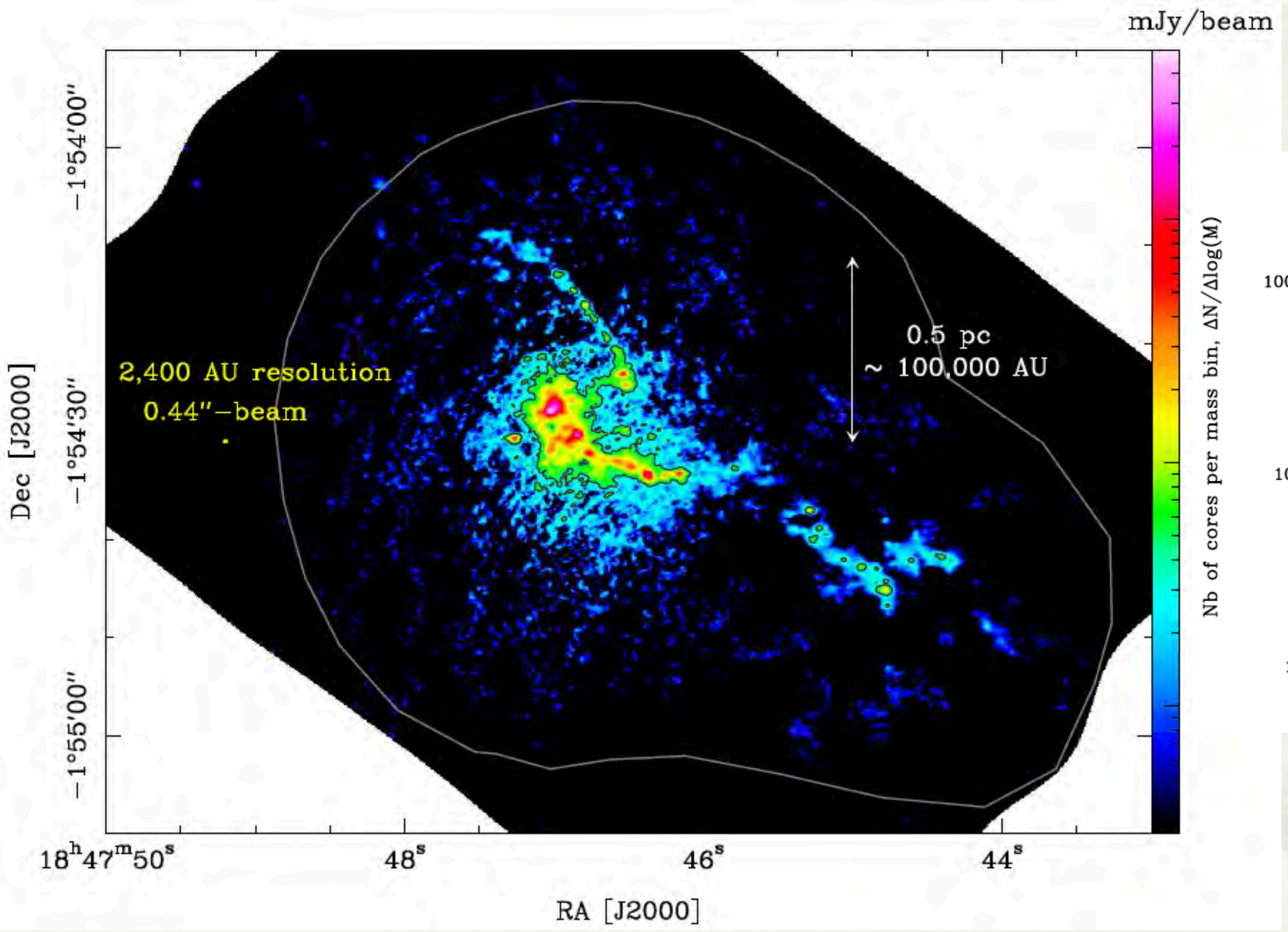
Initial condition for Massive SF

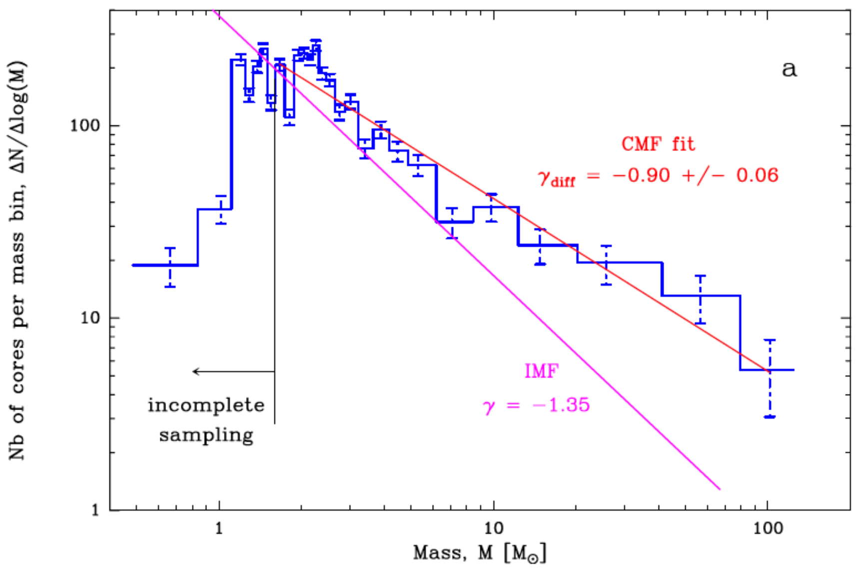
- Collision/Interaction process can be one of the main cause of massive stars
  - Line observations are important
- Severe contamination in the Galactic plane
  - Large errors in distance determination

- Extragalactic observations
  - Less contamination, same distances in a galaxy
- Distribution of extended emission
  - ALMA + ACA (Morita array)

ALMA

W43@5.5kpc

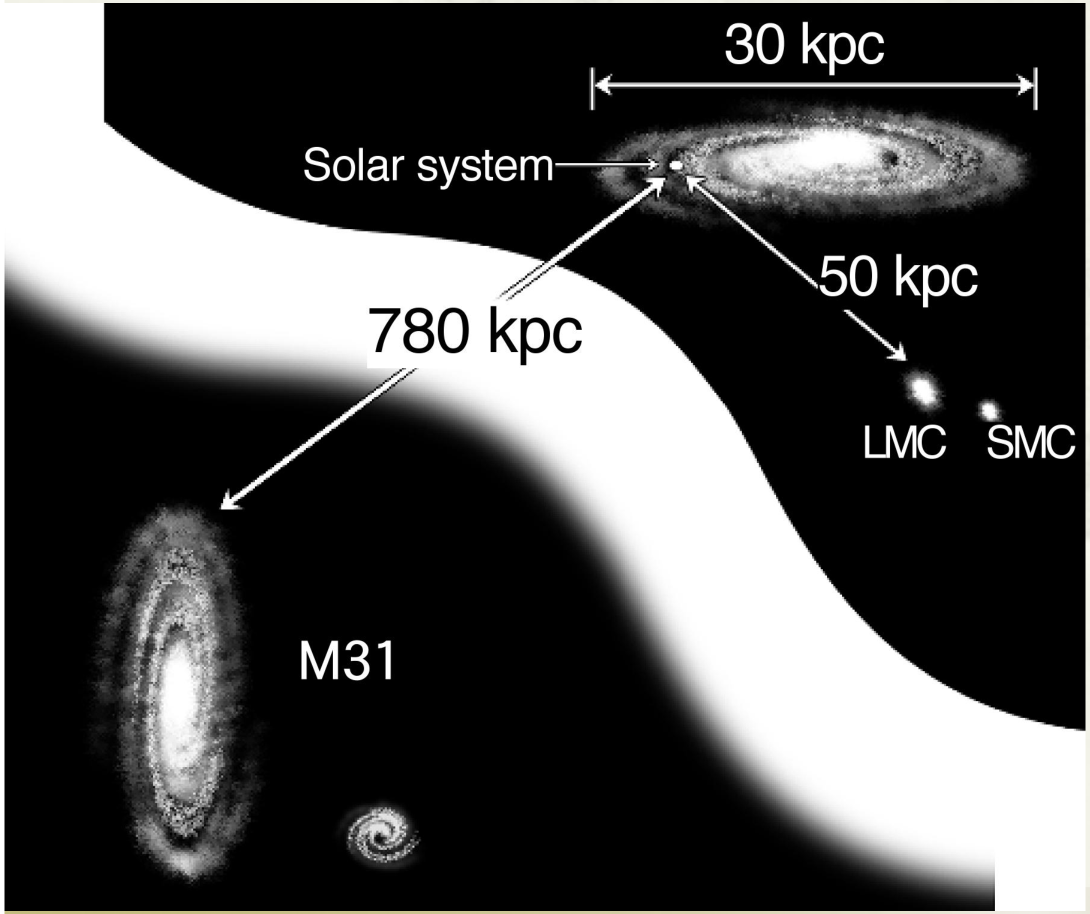


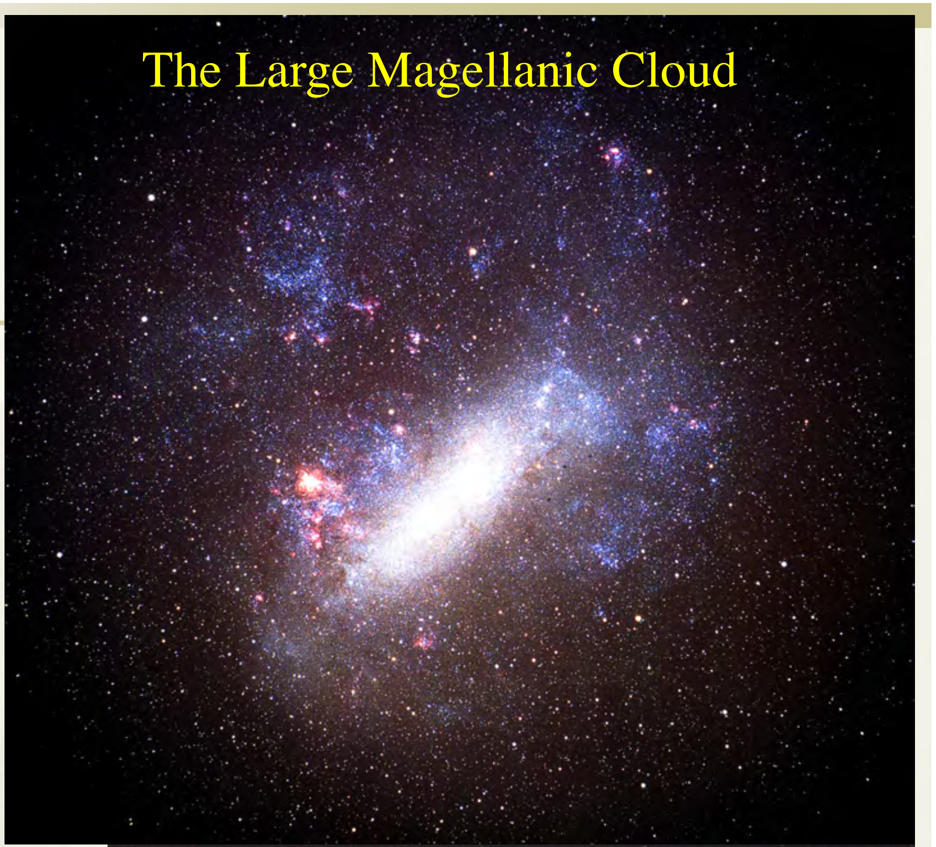


Motte et al. (2018)

Magellanic Clouds

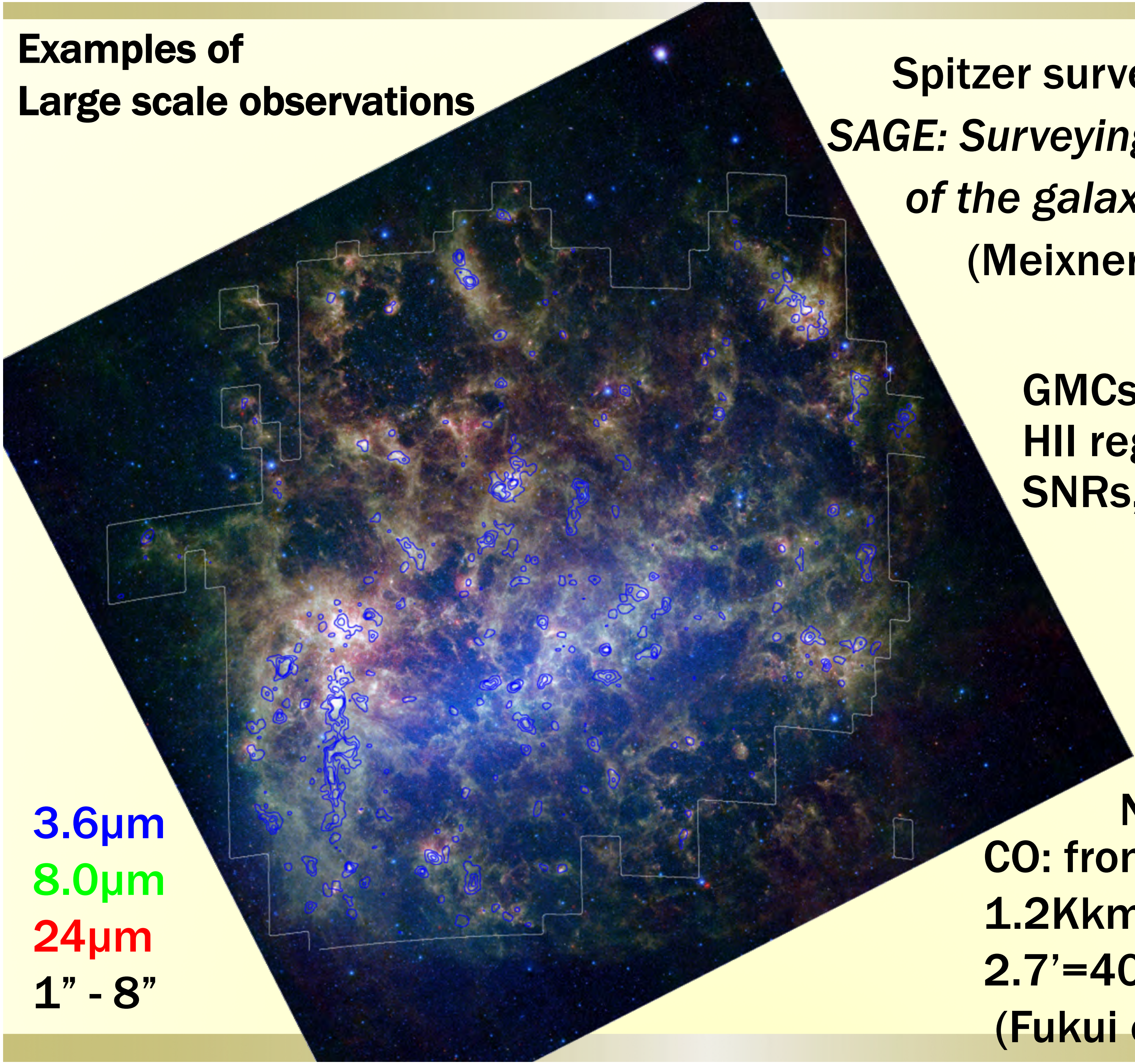
- D~ 50 kpc (one of the nearest)
- Different environment from the MW.
  - High gas-dust ratio
  - Low metallicity
- Active star formation
  - Massive star formation
  - Young populous clusters





Examples of Large scale observations

Spitzer survey of the LMC
SAGE: Surveying the Agency of the galaxy's evolution
(Meixner et al. 2006)



GMCs, dust, YSOs,
HII regions,
SNRs, AGBs,,...

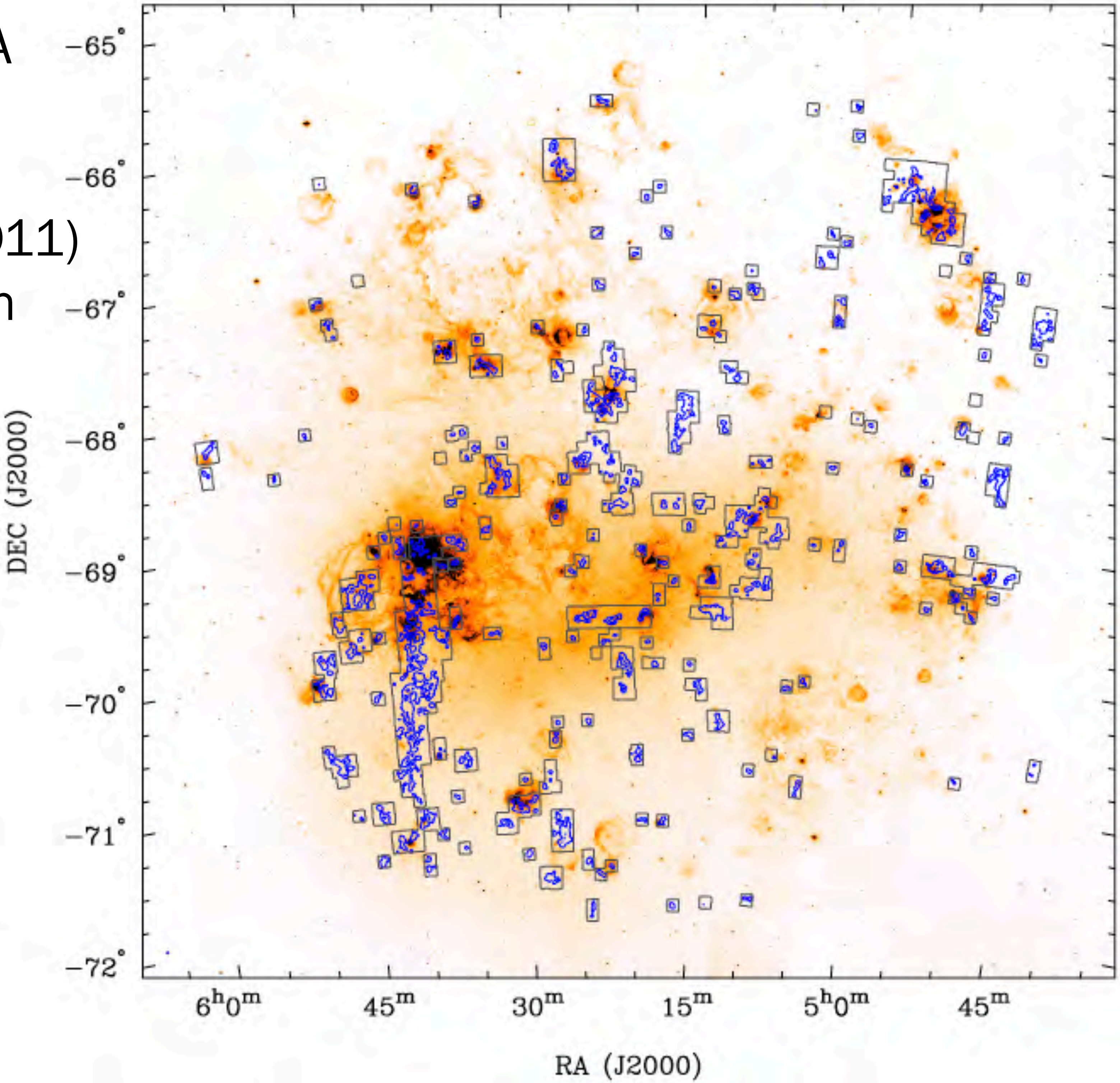
+AKARI
Herschel
Hα, HI,

NANTEN
CO: from 1.2 Kkm/s
1.2Kkm/s intervals
2.7'=40pc resolution
(Fukui et al. 2008)

3.6μm
8.0μm
24μm
1" - 8"

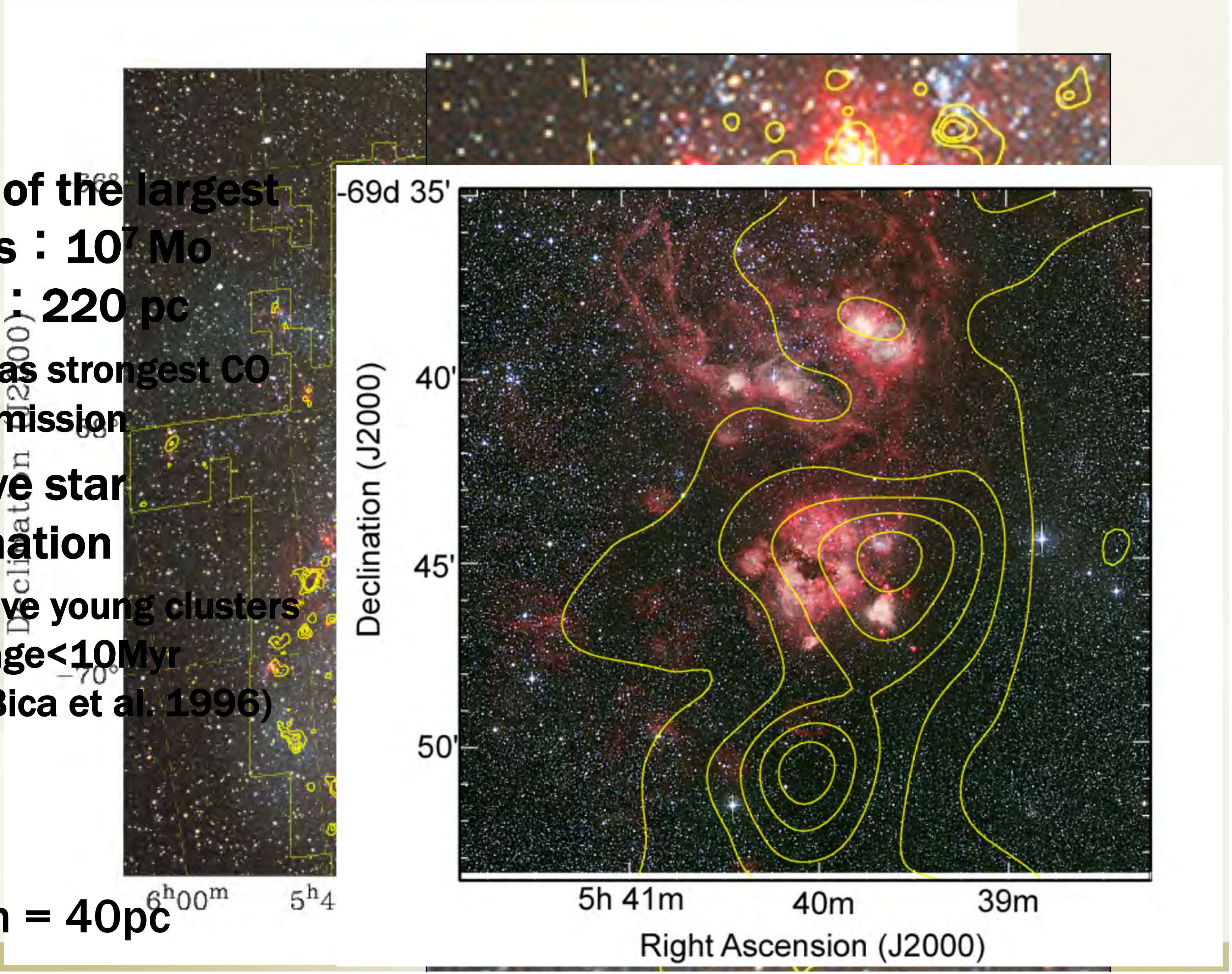
Mopra: MAGMA

(Wong et al. 2011)
11pc resolution



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)

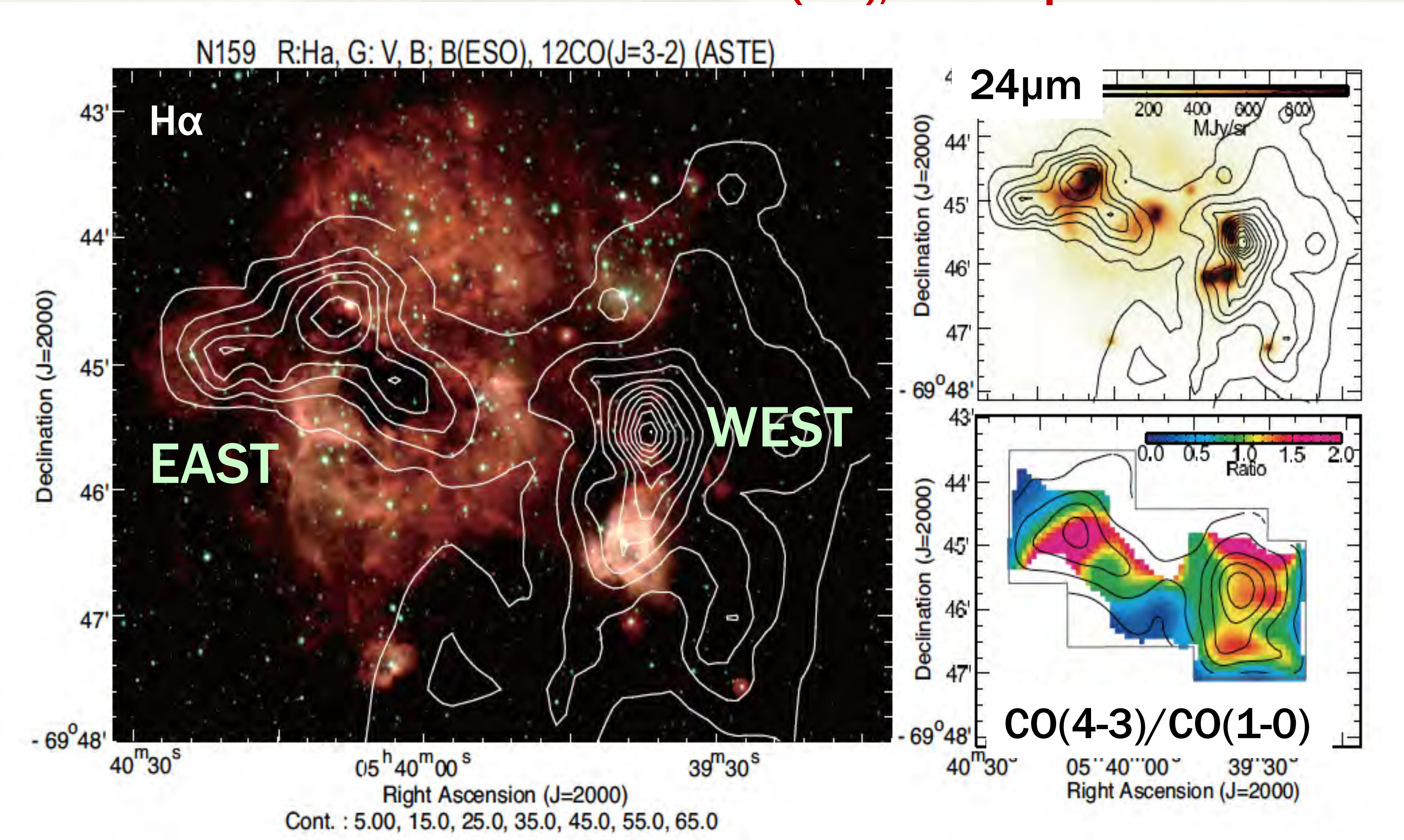


2.7arcmin = 40pc

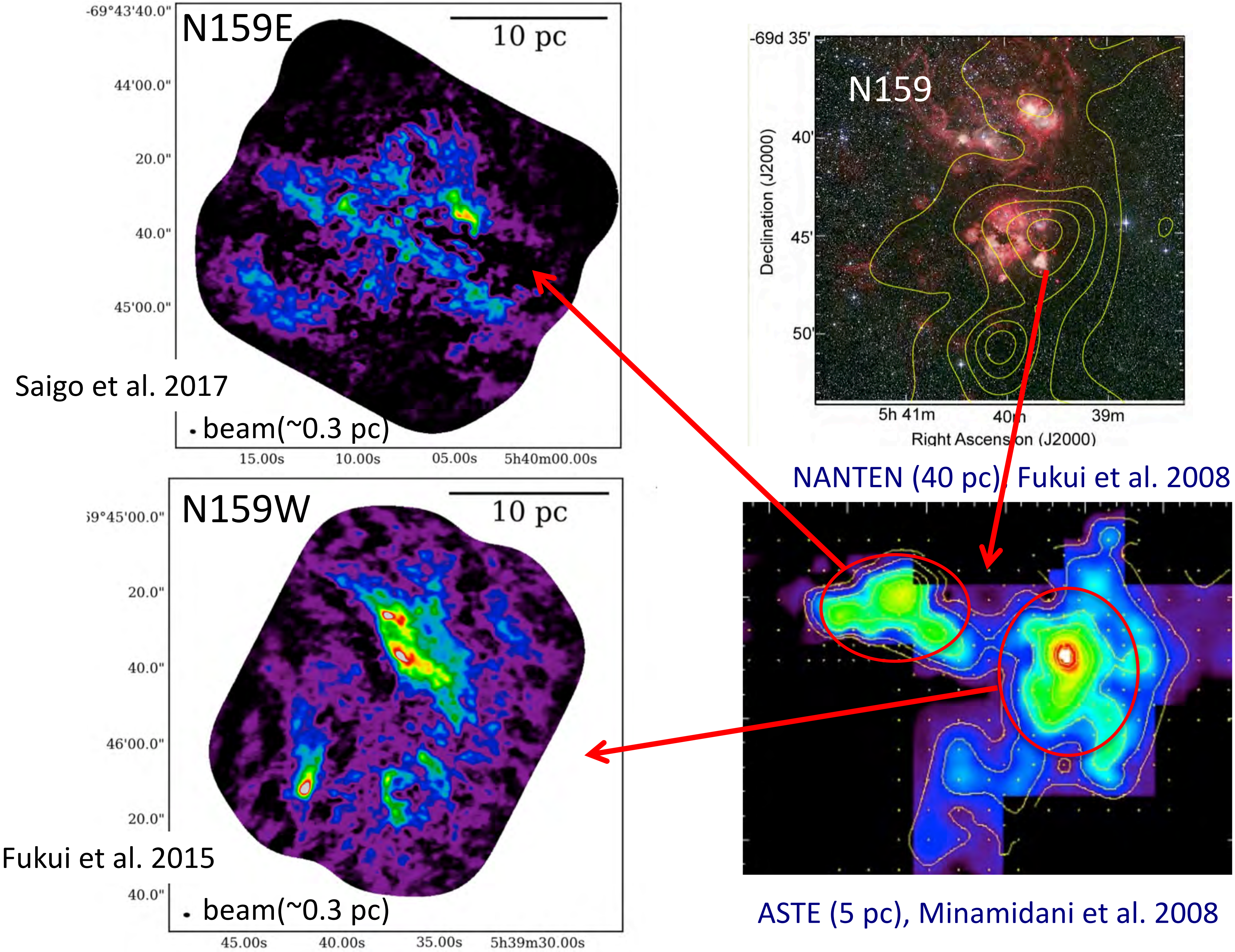
N159: Most active on-going star formation in the Local Group: Resolving filaments and cloud cores in the LMC

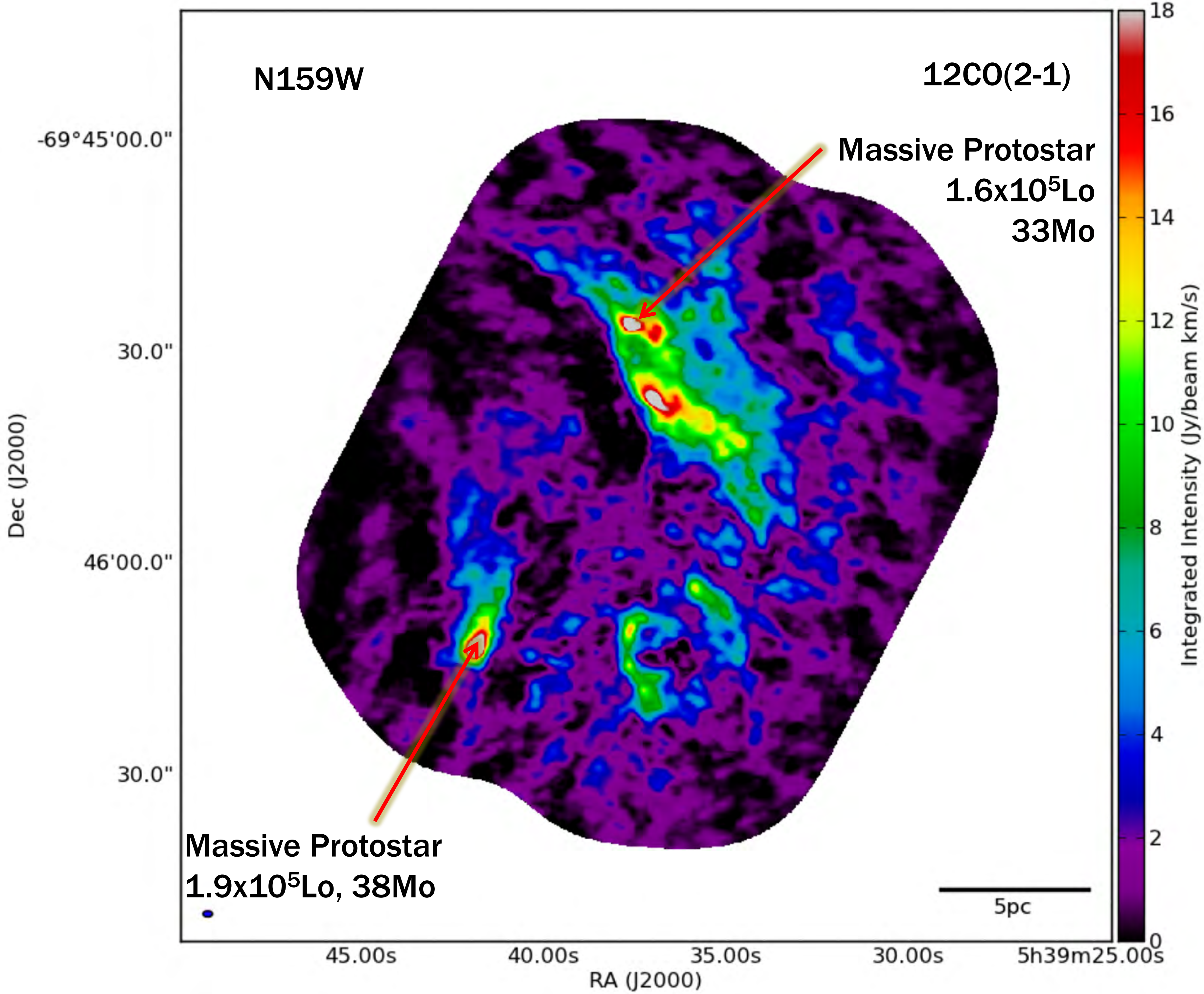
Fukui [PI]
Yamamoto
Ohama
Onishi
Kawamura
Minamidani
Inbedetouw
Madden
Galametz
Lebouteiller
N.Mizuno
R.Chen
Seale
Sewio
Meixner

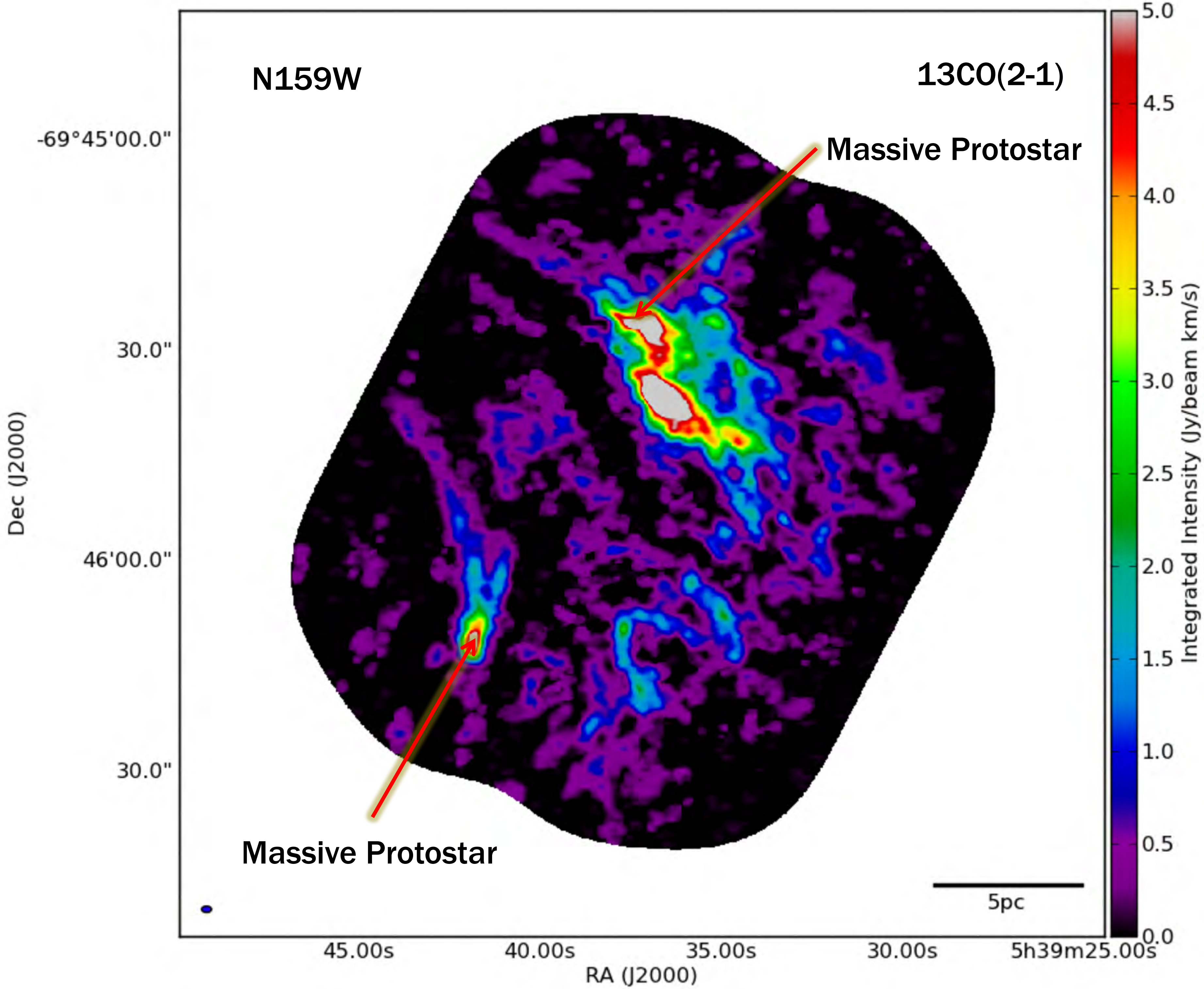
Contour: ASTE 12CO(3-2), 22” = 5pc

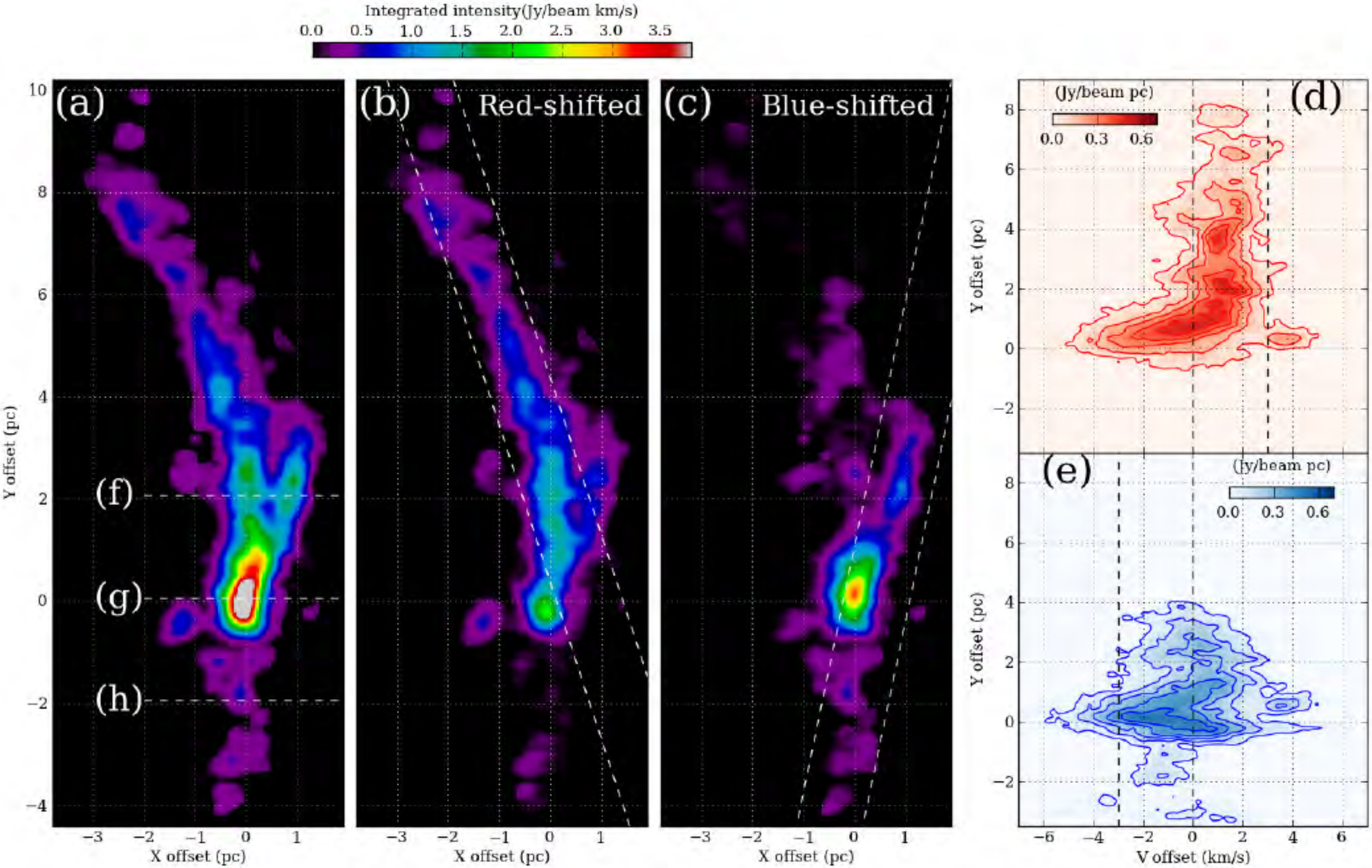


Y. Mizuno et al. 2010


N159E
10 pc
-69°43'40.0"
44'00.0"
20.0"
40.0"
45'00.0"
Saigo et al. 2017
beam(~0.3 pc)
15.00s
10.00s
05.00s
5h40m00.00s
N159W
10 pc
69°45'00.0"
20.0"
40.0"
46'00.0"
20.0"
40.0"
Fukui et al. 2015
beam(~0.3 pc)
45.00s
40.00s
35.00s
5h39m30.00s
N159
-69d 35'
40'
45'
50'
Declination (J2000)
5h 41m
40m
39m
Right Ascension (J2000)
NANTEN (40 pc), Fukui et al. 2008
ASTE (5 pc), Minamidani et al. 2008


N159W
12CO(2-1)
Massive Protostar
1.6x10⁵Lo
33Mo
Massive Protostar
1.9x10⁵Lo, 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

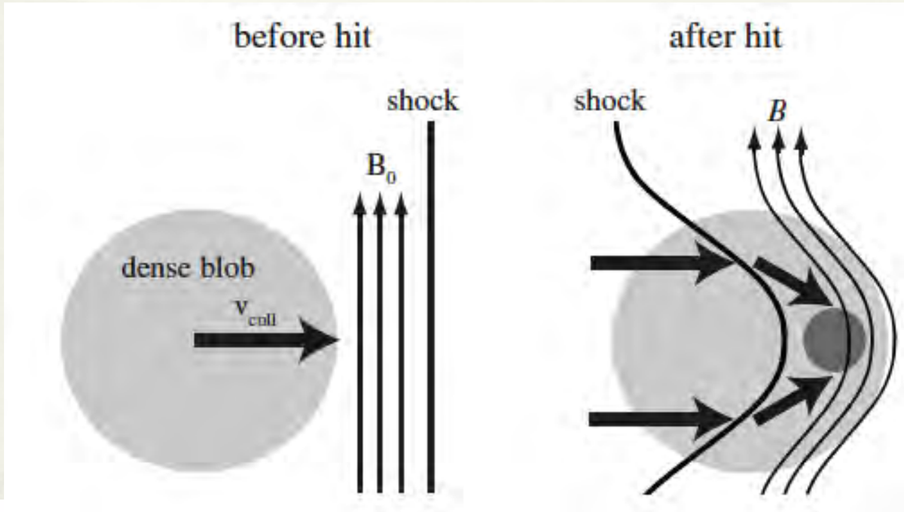

N159W
13CO(2-1)
Massive Protostar
Massive Protostar
-69°45'00.0"
30.0"
46'00.0"
30.0"
Dec (J2000)
45.00s
40.00s
35.00s
30.00s
5h39m25.00s
RA (J2000)
5pc
Integrated Intensity (Jy/beam km/s)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0

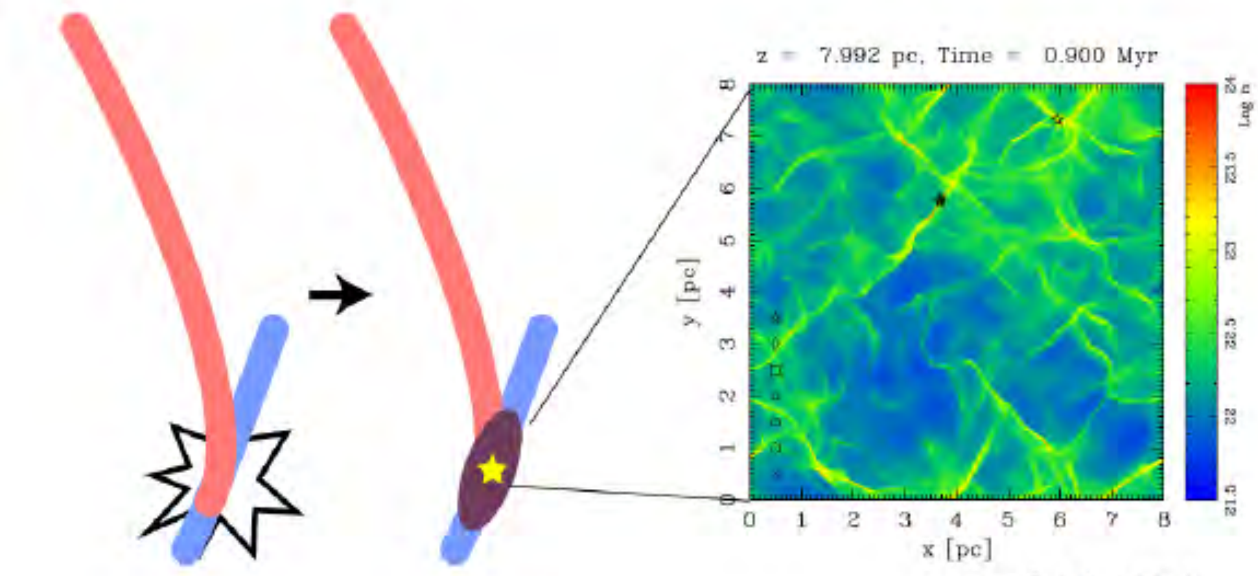


Integrated intensity(Jy/beam km/s)
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5
(a)
(b) Red-shifted
(c) Blue-shifted
(d)
(e)
(f)
(g)
(h)
(Jy/beam pc)
0.0 0.3 0.6
Y offset (pc)
X offset (pc)
V offset (km/s)

Massive star formation by cloud-cloud collisions

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

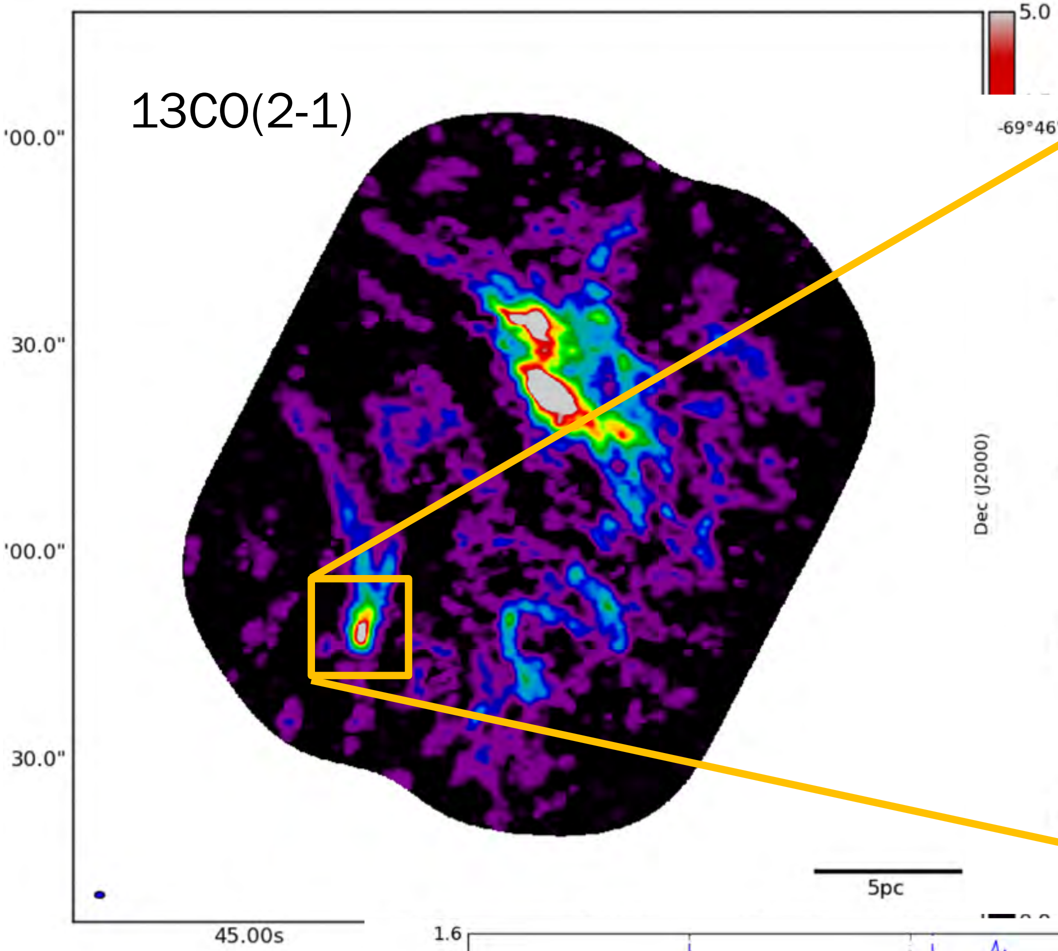


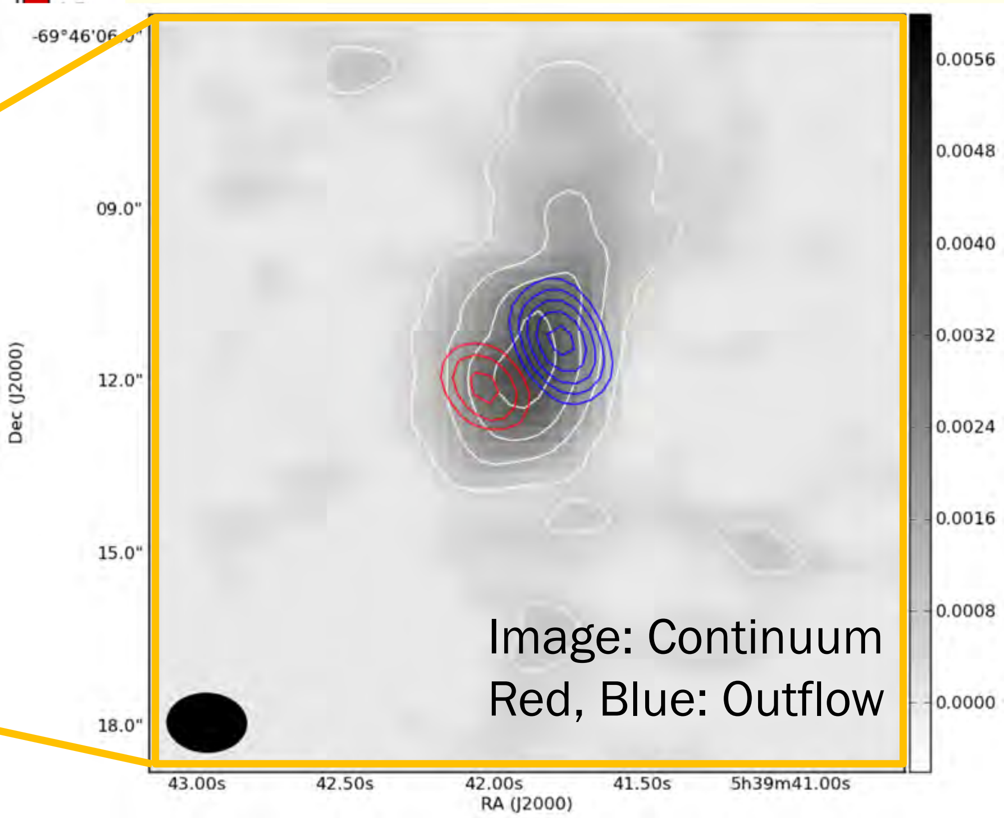


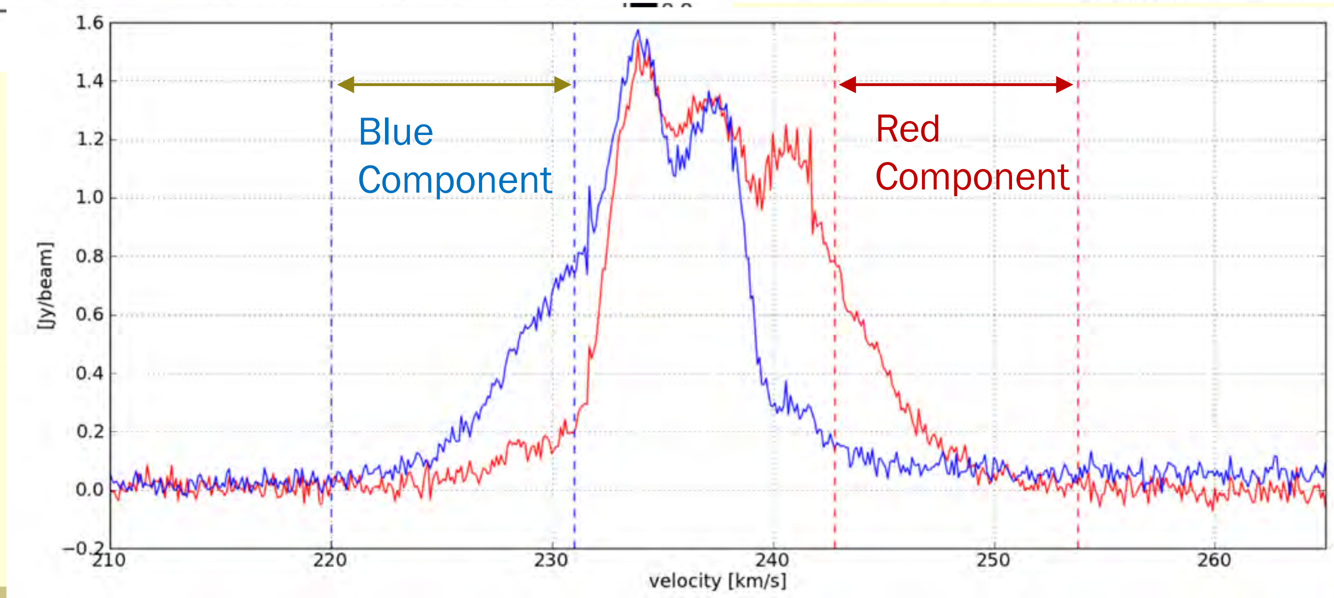
Inoue & Fukui 2013

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

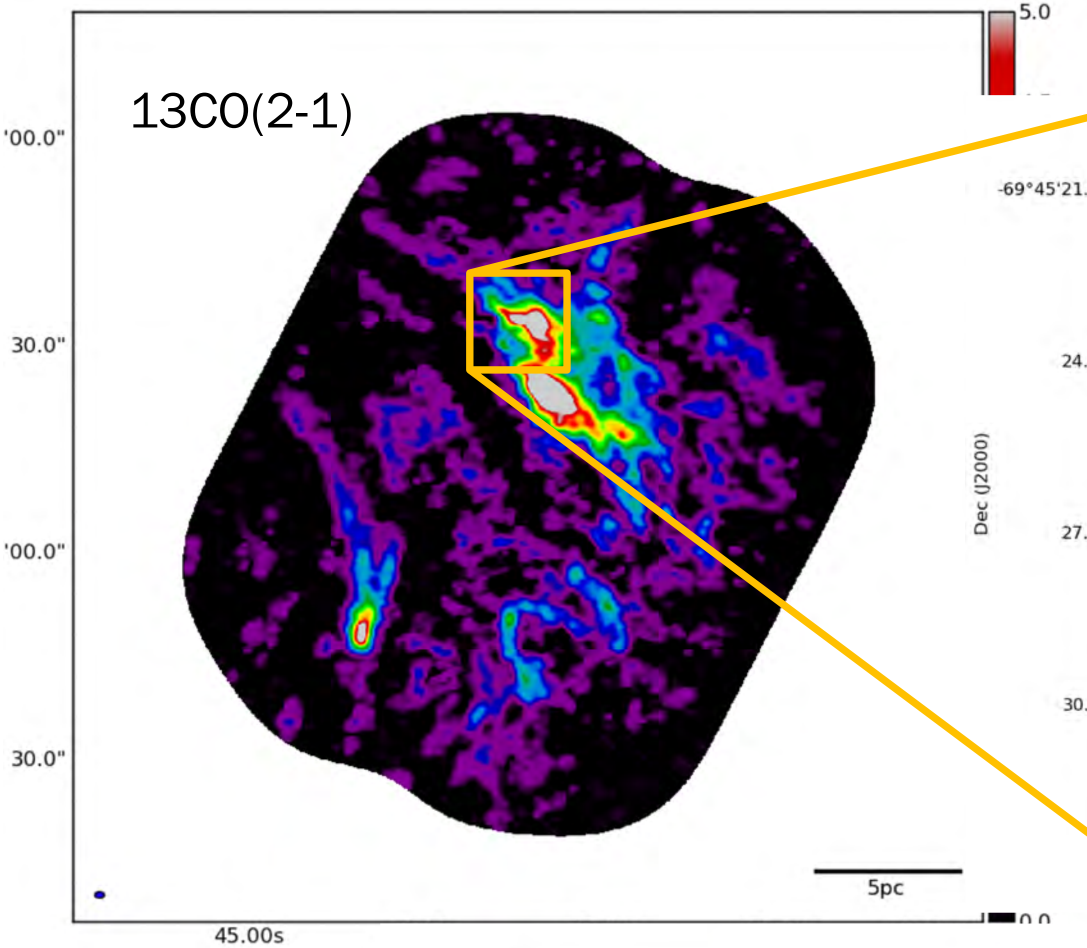
Outflow from massive YSO

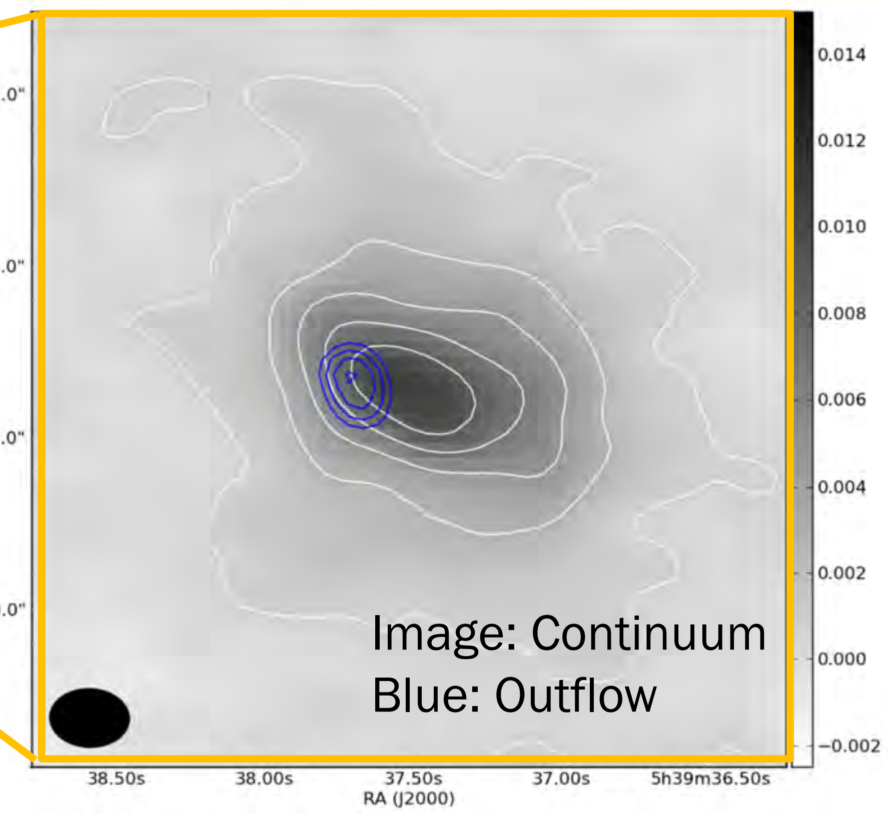


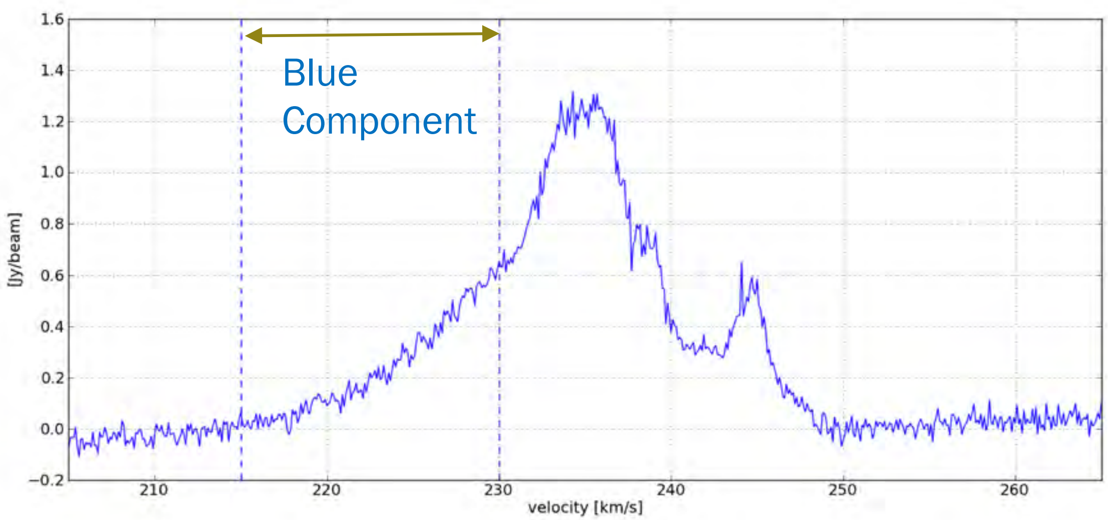


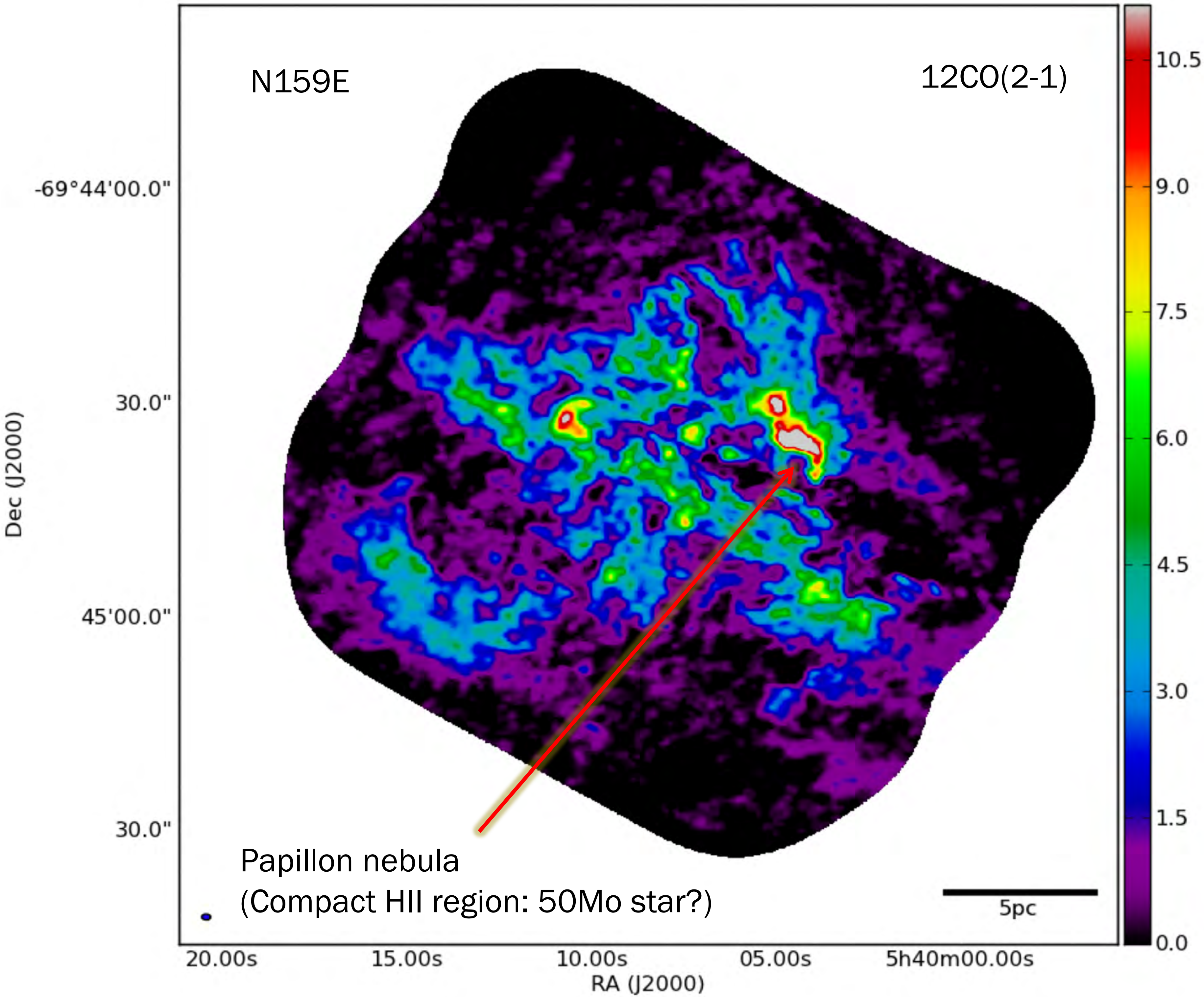


Outflow from massive YSO

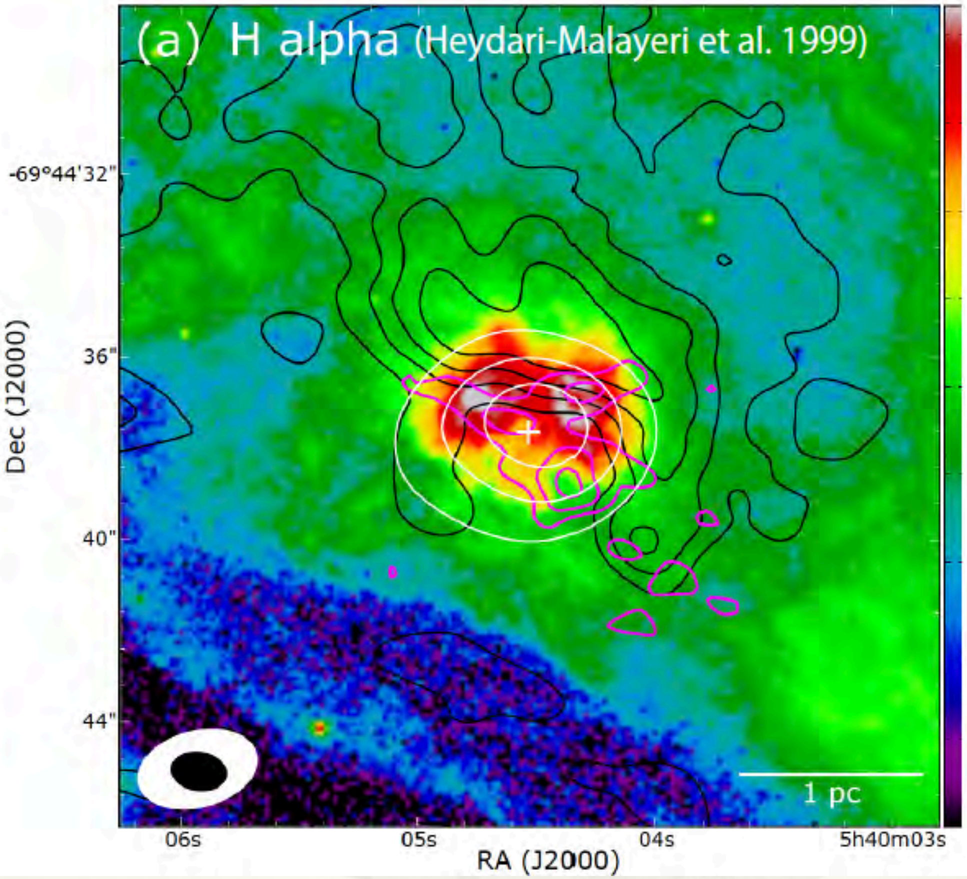


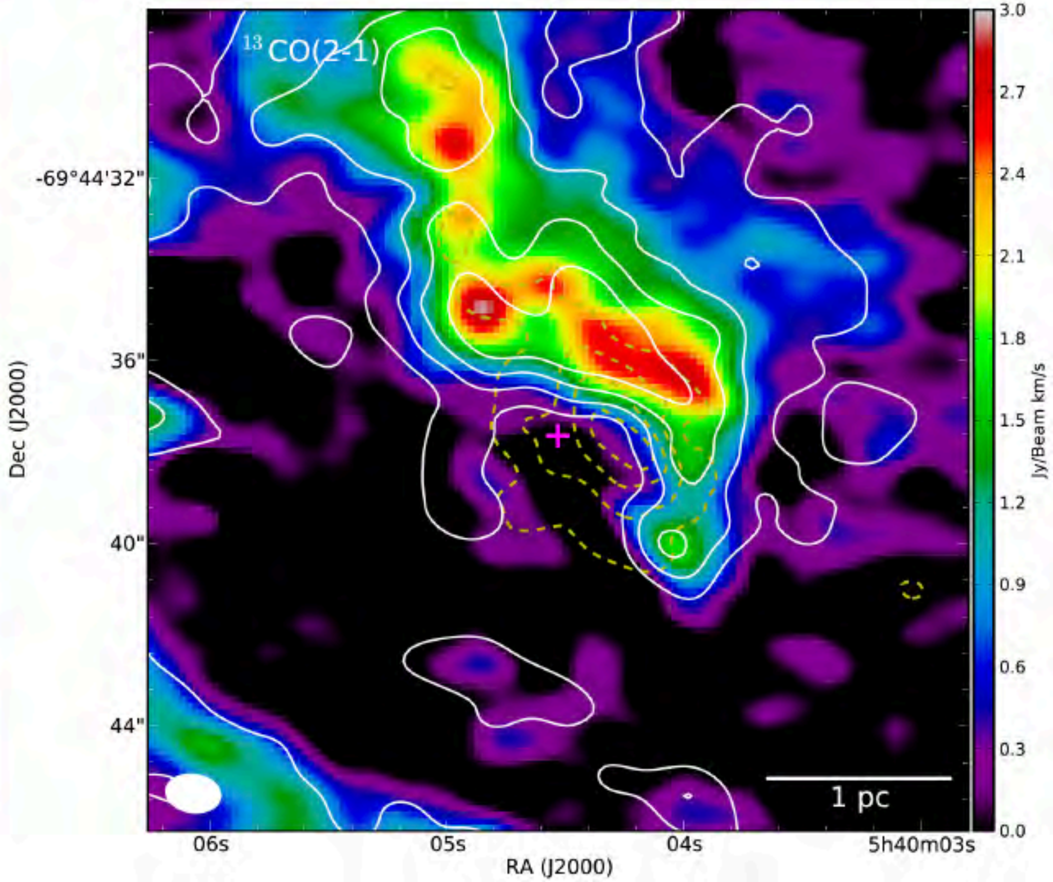





N159E
12CO(2-1)
-69°44'00.0"
30.0"
45'00.0"
30.0"
Dec (J2000)
20.00s
15.00s
10.00s
05.00s
5h40m00.00s
RA (J2000)
10.5
9.0
7.5
6.0
4.5
3.0
1.5
0.0
5pc
Papillon nebula
(Compact HII region: 50Mo star?)

N159 East Papillon



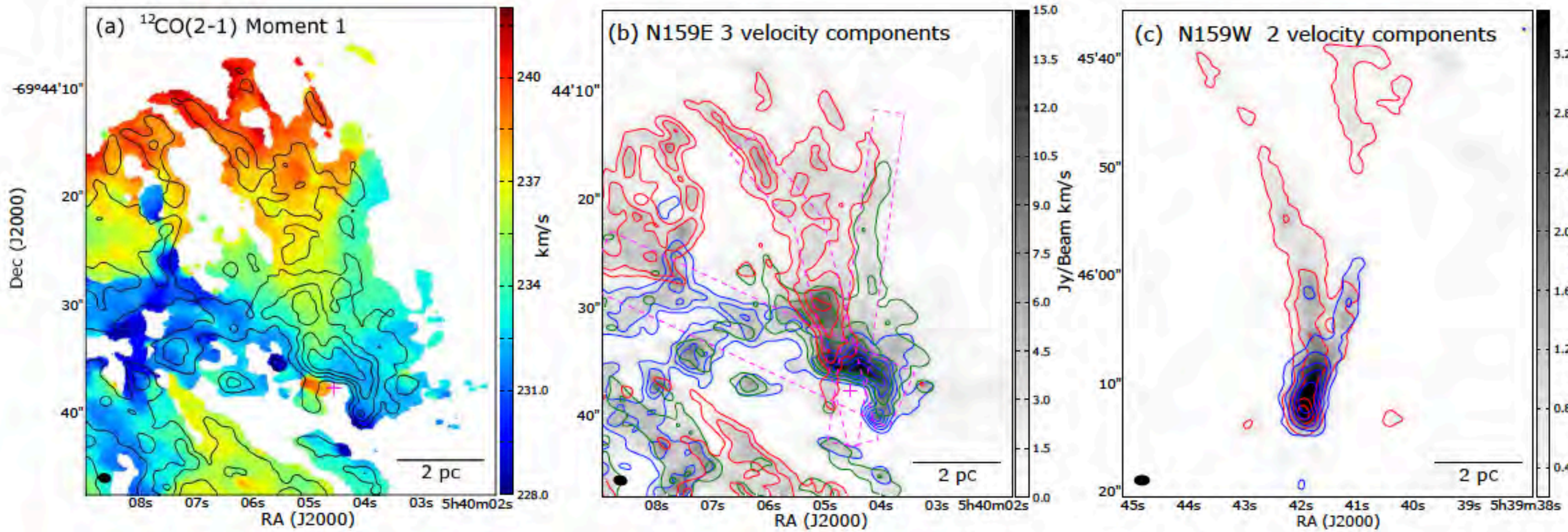


Black Contour: 12CO(2-1)
White Contour: 98GHz Continuum (free-free)
Magenta Contour: H30α

White Contour: 12CO(2-1)
Yellow dashed Contour: 231GHz Continuum (thermal)

Three velocity components?

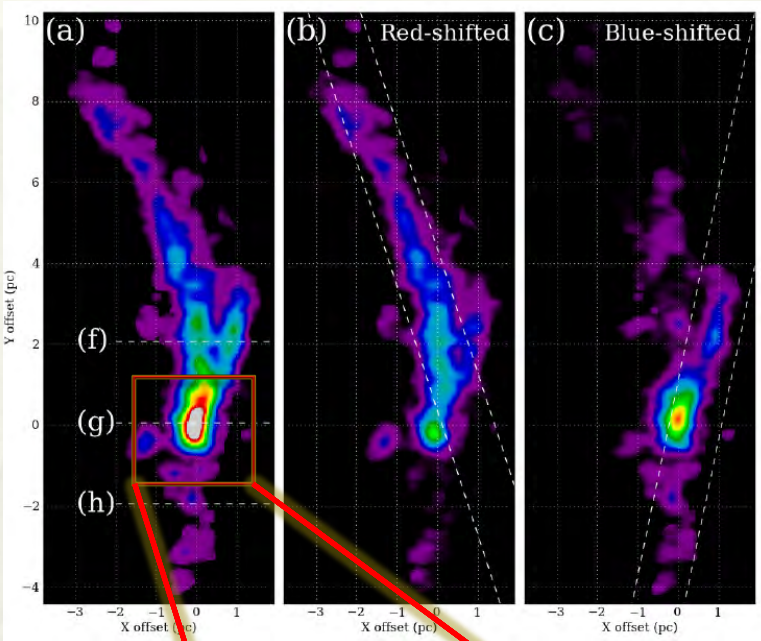
Blue: 228km/s – 232km/s
Green: 232km/s – 334km/s
Red: 235km/s – 240km/s

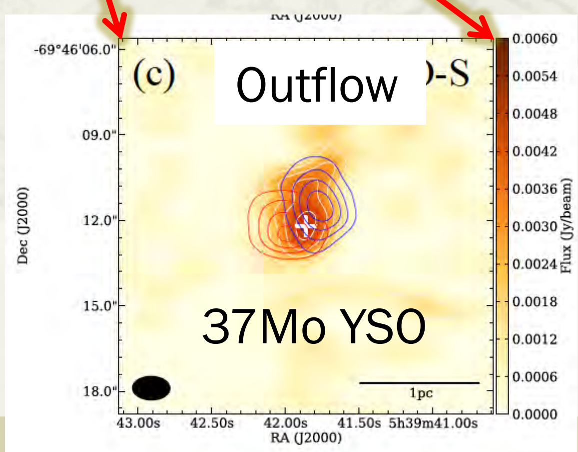


Filaments are merging at Papillon
CO gas is rapidly dissociated by the high-mass star
Similar, but more complex velocity structure compared with the N159W filaments

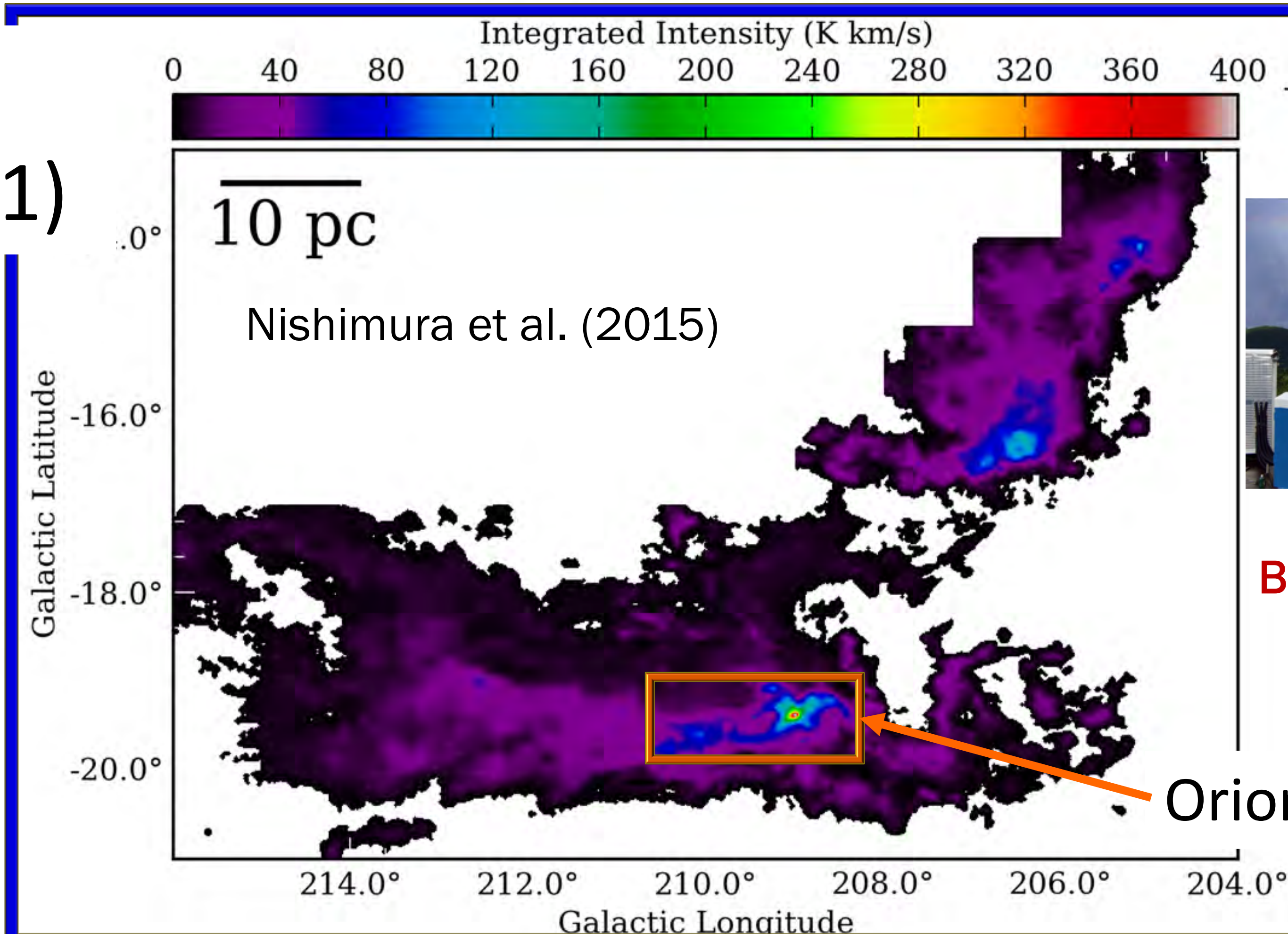
ALMA observations N159W/E in the LMC

- 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

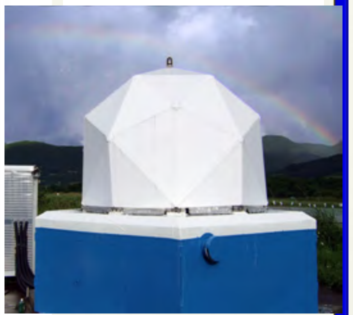




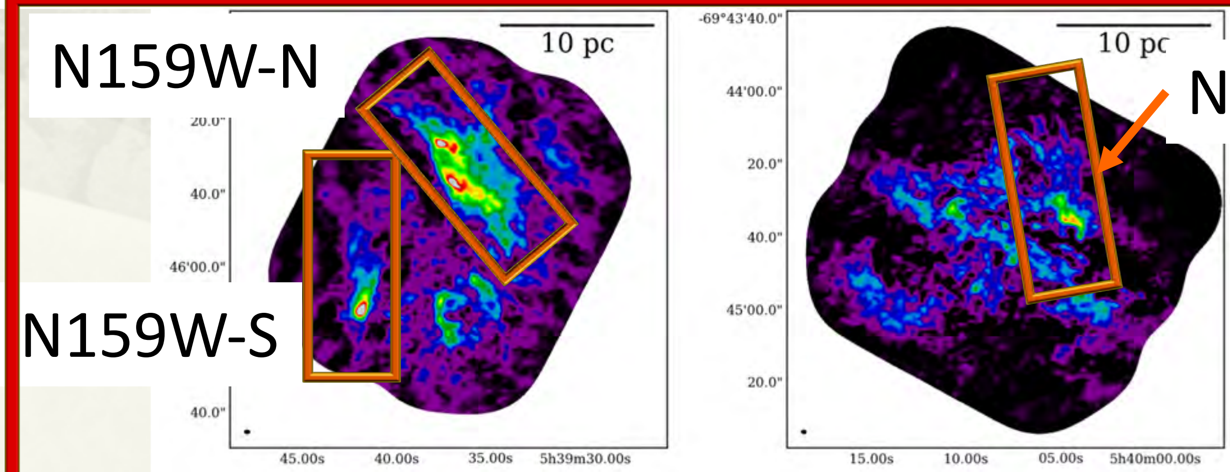
^{12}CO (J = 2–1)



Osaka 1.85-m



Beam: 0.35 pc

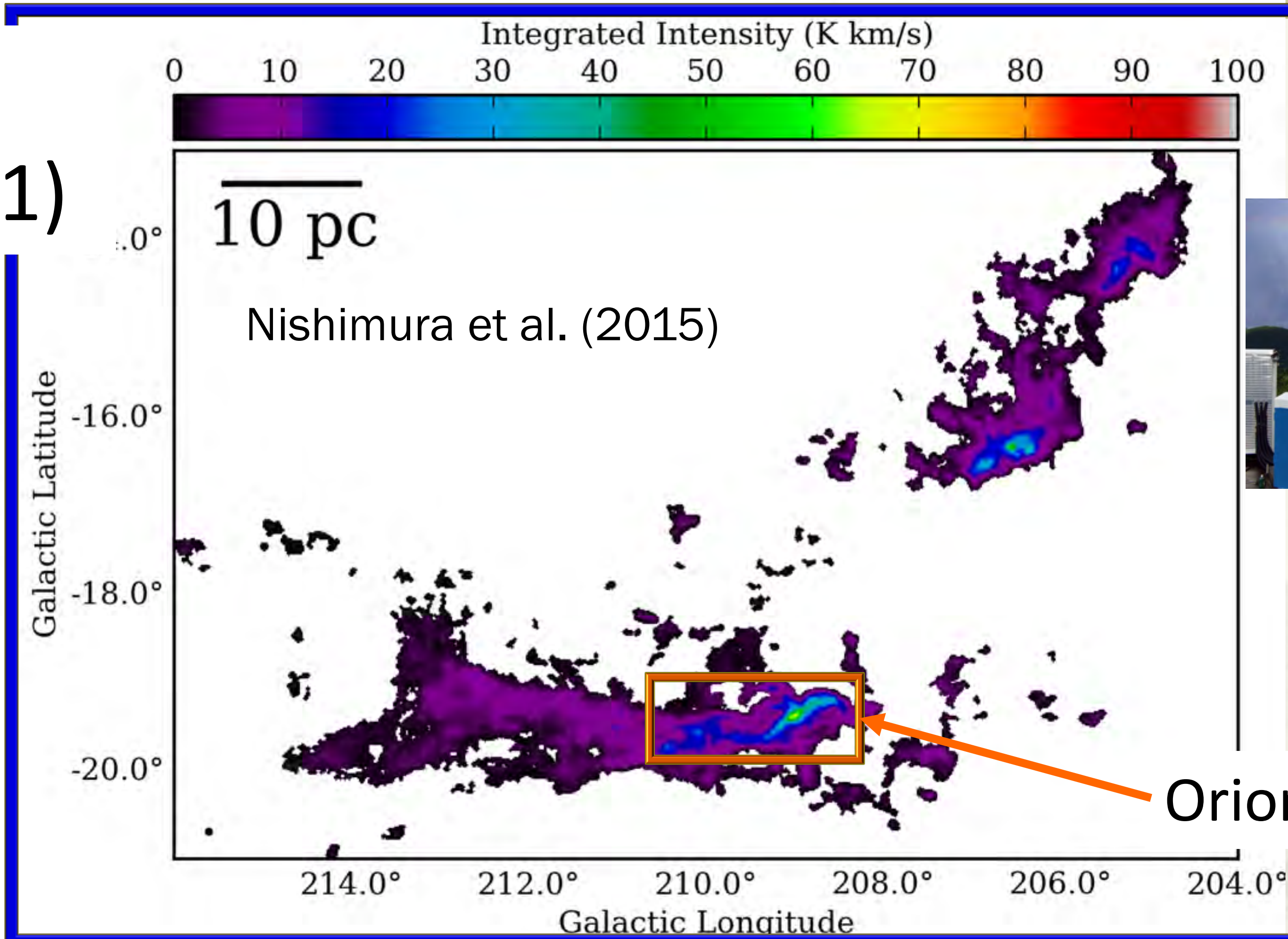


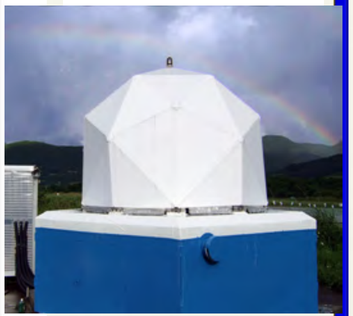
Beam: 0.24 pc

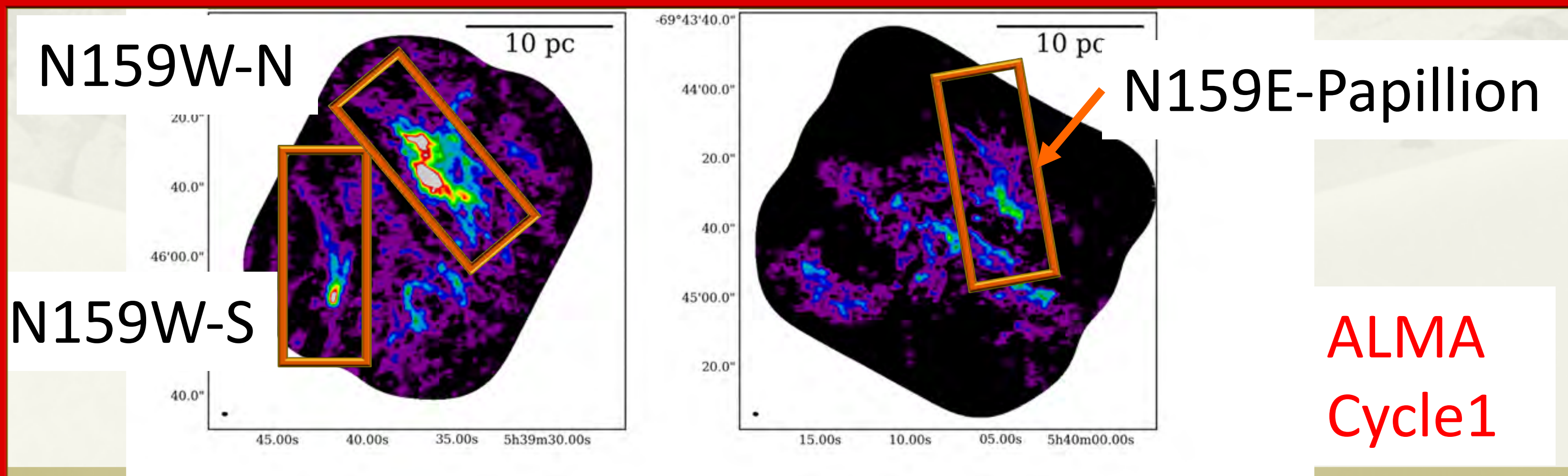
ALMA Cycle1

^{13}CO (J = 2–1)

Osaka 1.85-m

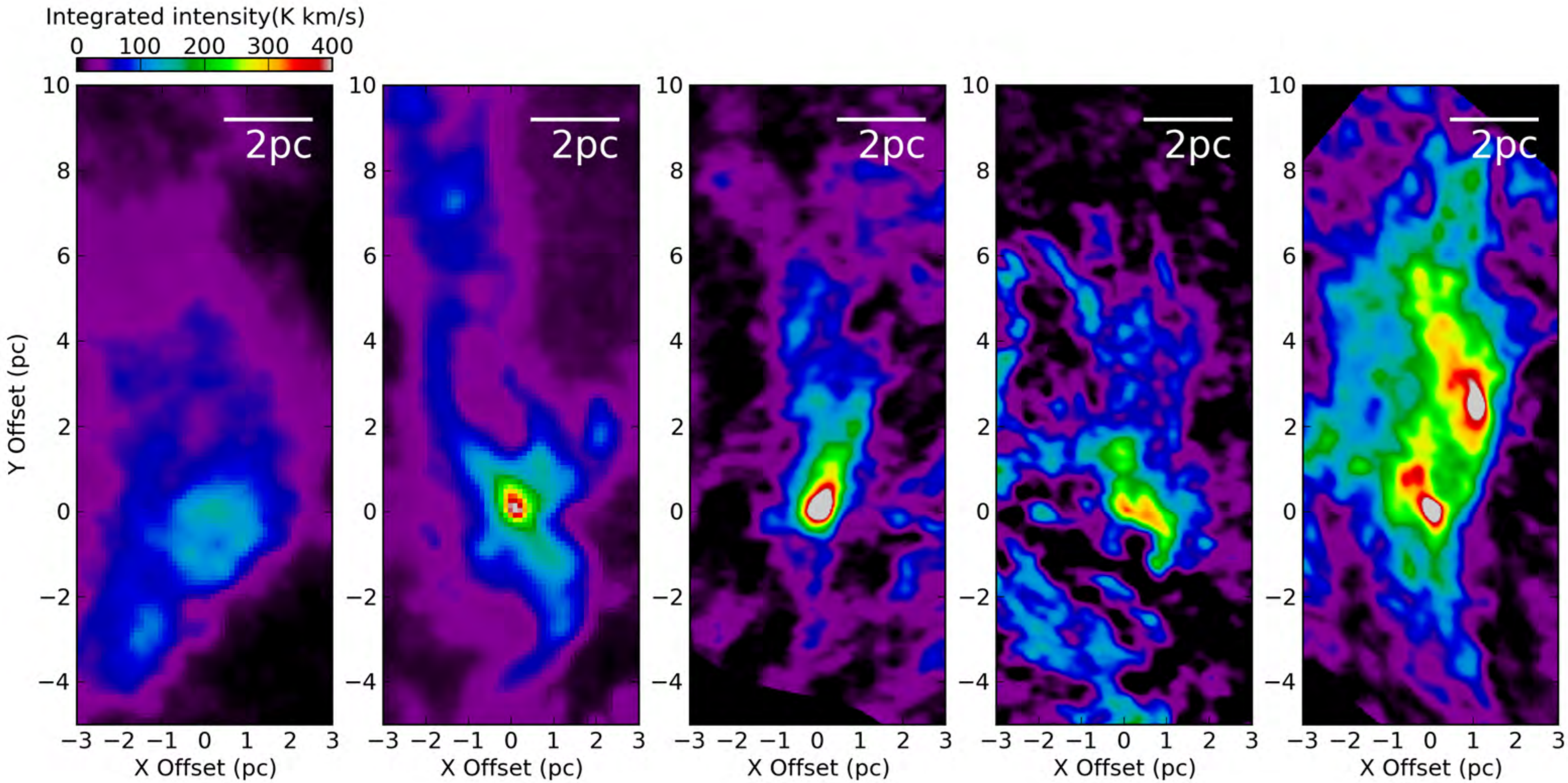






ALMA Cycle1

Moment 0 map (^{12}CO (J = 2–1))

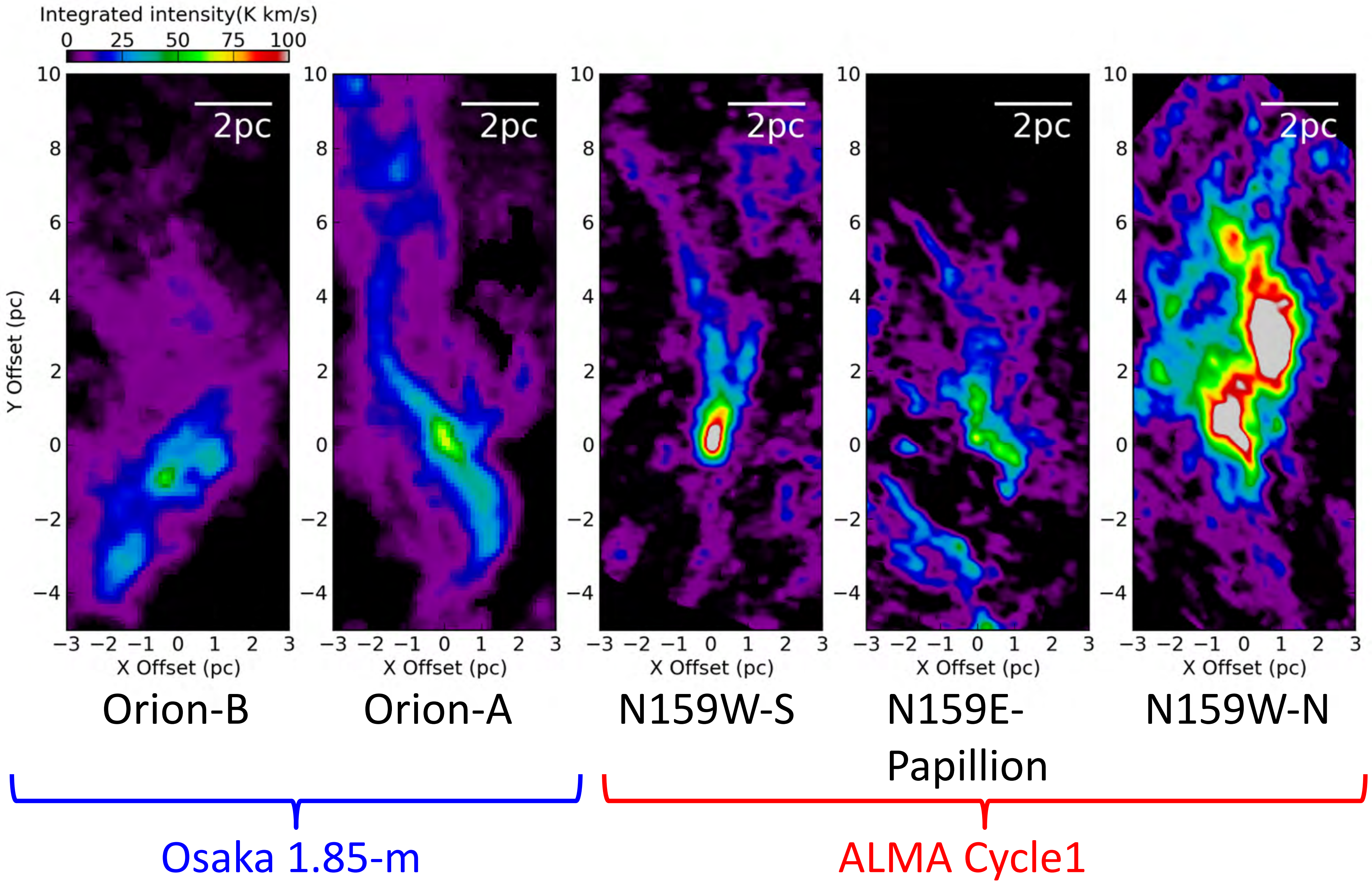


Orion-B | Orion-A | N159W-S | N159E-Papillion | N159W-N

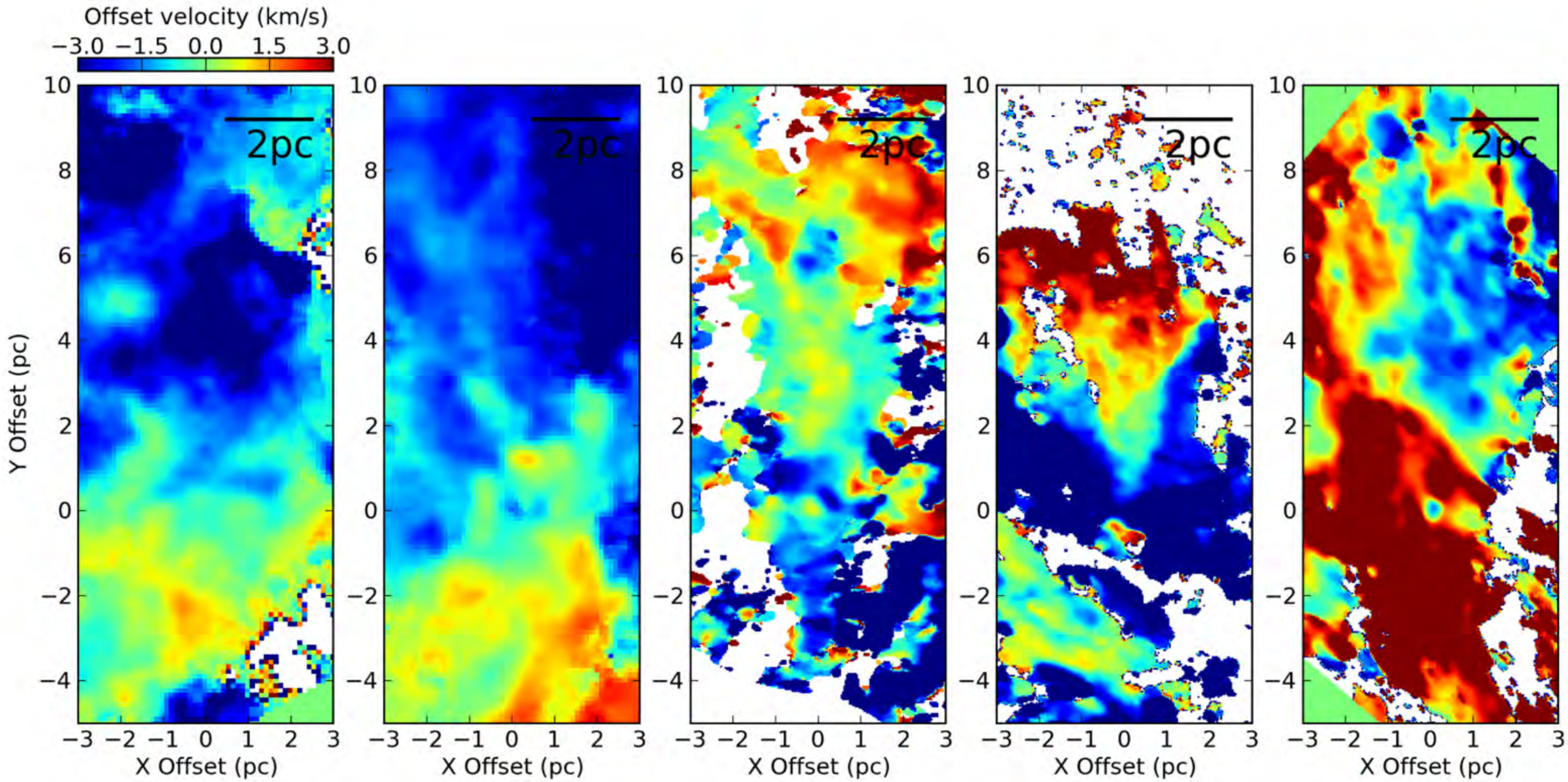
Osaka 1.85-m

ALMA Cycle1

Moment 0 map (^{13}CO (J = 2−1))



Moment 1 map (^{12}CO (J = 2−1))



Ori ... W-N

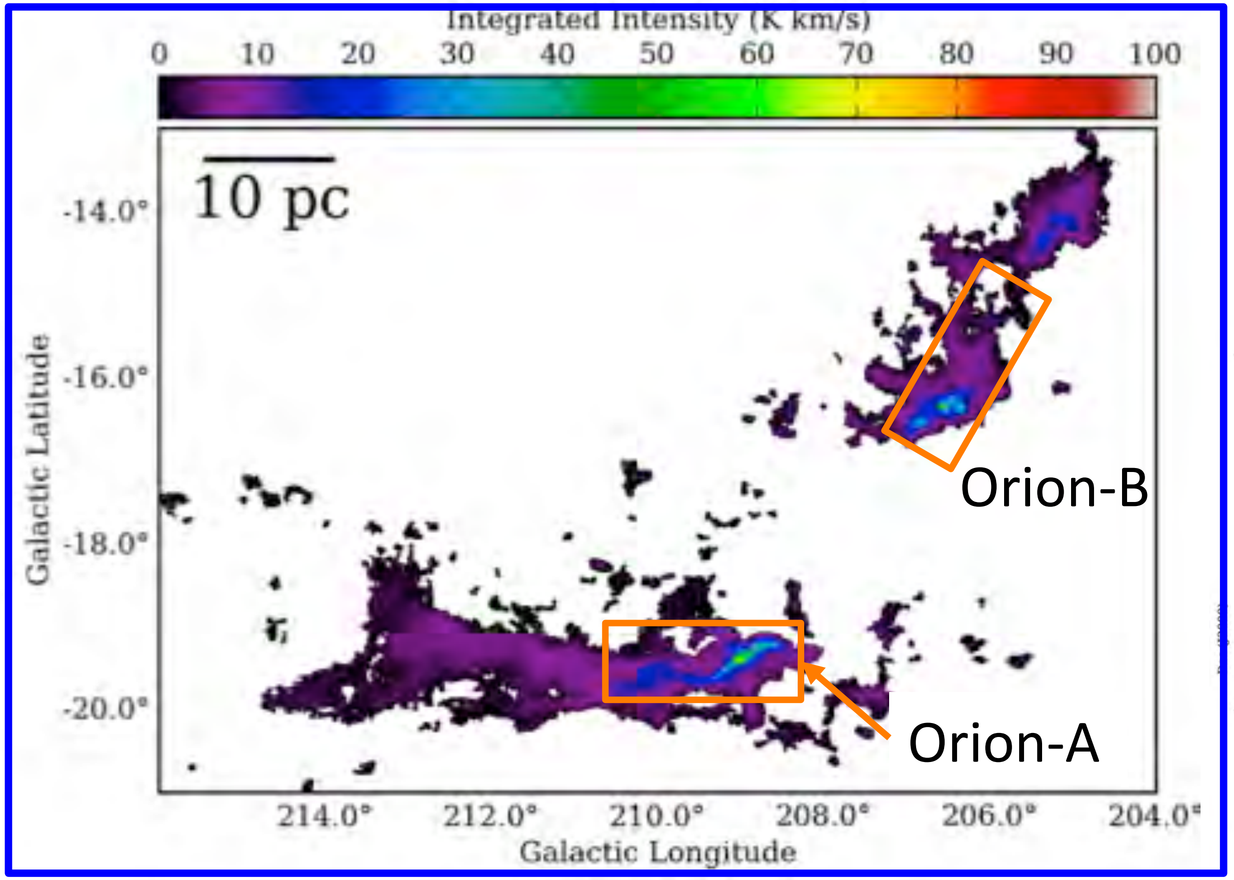
Complex velocity field
=>Components having different velocities

Osaka 1.85-m

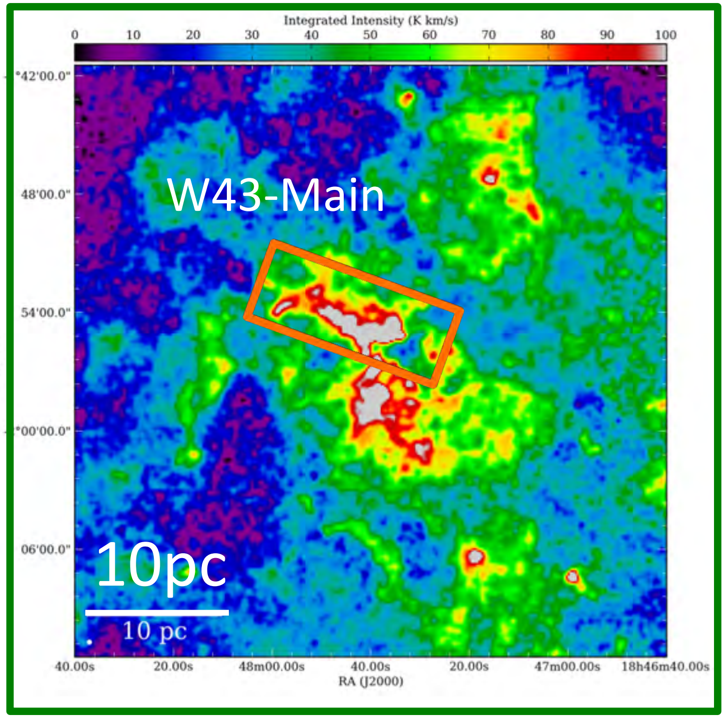
ALMA Cycle1

^{13}CO (J = 2–1)

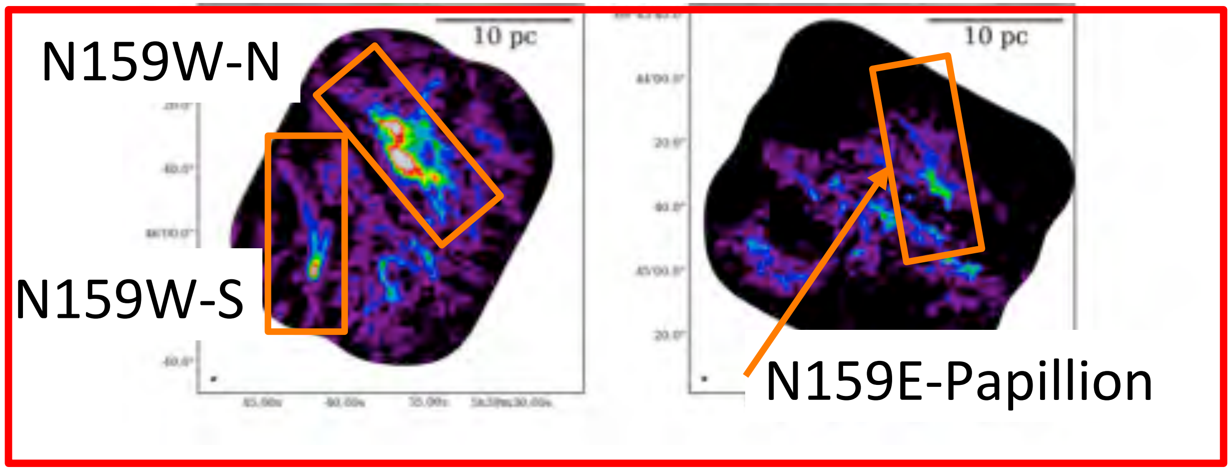
Osaka 1.85-m (~3')



W43 (Carlhoff+2013)

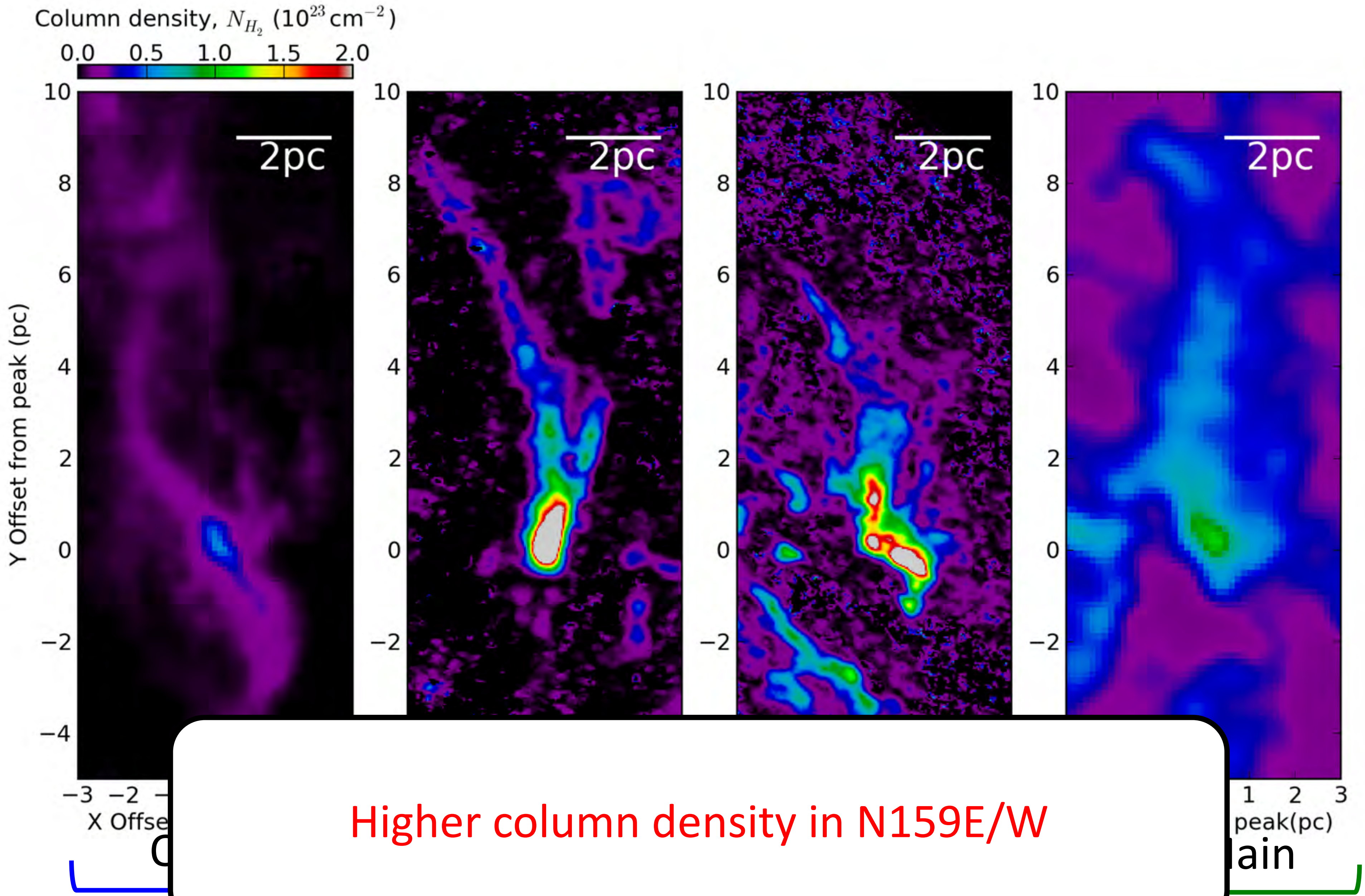


IRAM 30-m (~11")



ALMA Cycle1(~1")

Column Density ※ Derived from 13CO(2-1)



Higher column density in N159E/W

Osaka 1.85-m

ALMA

IRAM 30-m

GMCs in the Galaxy and LMC

- Massive star forming regions: >30Mo, 10^5Lo
- Similar shapes
  - Filaments + Multiple velocity components
  - Filament-filament interaction?
- Different column density
  - GMCs in the LMC have higher $N(H_2)$
  - More active star formation in the LMC??

GMCs in the LMC

- Clouds in super star cluster: 30Dor
  - R. Indebetouw et al. (2013), O. Nayak et al. (2016)
- N159
  - Fukui et al. (2015), Saigo et al. (2017), Nayak et al. (2018)
- GMCs with different evolutionary stages
  - PI: A. Kawamura, R. Chen, T. Wong, S. Zahorecz
- Developed HII regions: N55
  - N. Naslim et al. (2018)
- Cold GMC at the edge of the LMC
  - T. Wong et al. (2017)
- High mass star formation in an isolated environment
  - PI: R. Harada
- Complex Organic Molecules
  - M. Sewiło et al. (2018)

GMCs in the LMC

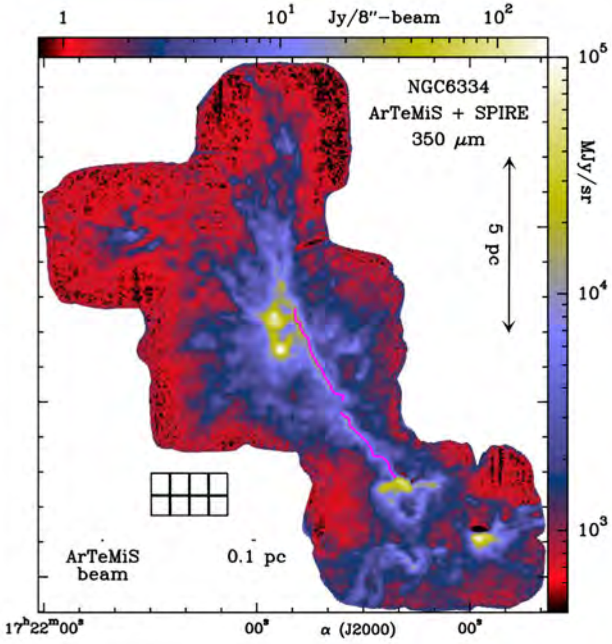
- “Starless” GMCs
  - Clumpy + filamentary
- GMCs with high-mass star formation
  - Compact clump + highly filamentary clouds
    - Similar to the Galaxy
- Higher Column density?
- Scaling relations, Mass spectra
  - Similar to those in the Galaxy except for 30Dor???

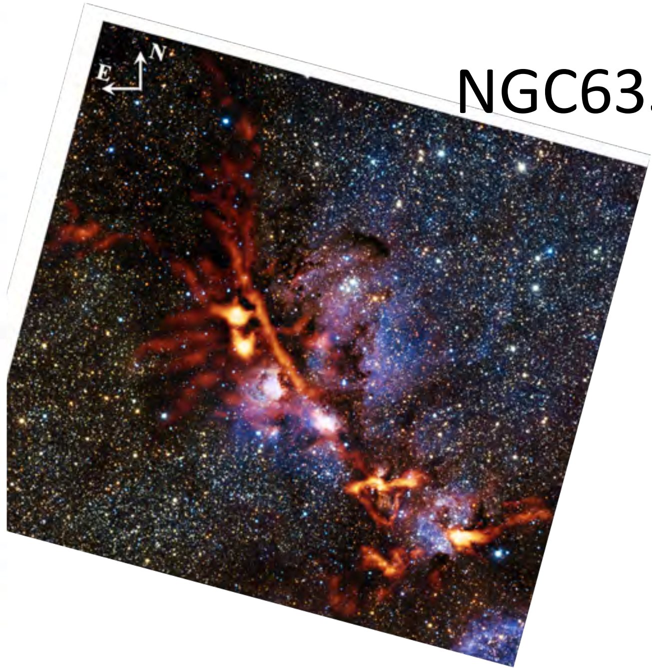
Why filamentary clouds?

To understand roles of filaments in SF are quite important!

(e.g., Inutsuka & Miyama 1997, Arzoumanian et al. 2010, André et al. 2014)

Spatially resolved observations (<0.1 pc) of filaments in (galactic) massive star-forming regions are rare so far...





NGC6334 @1.7 kpc

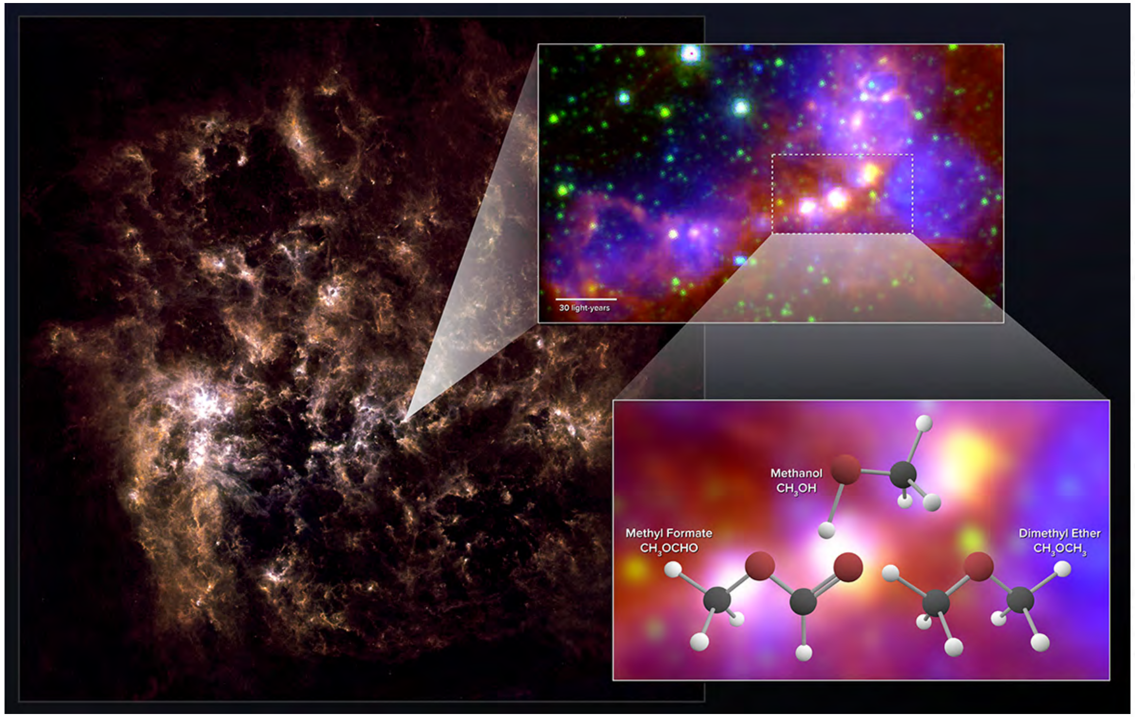
Resolution = 8”(~0.07 pc), Width ~ 0.15 pc, Line mass $\sim$ 500 –2000 $M_\odot$ /pc

Possible formation mechanisms of massive filaments :

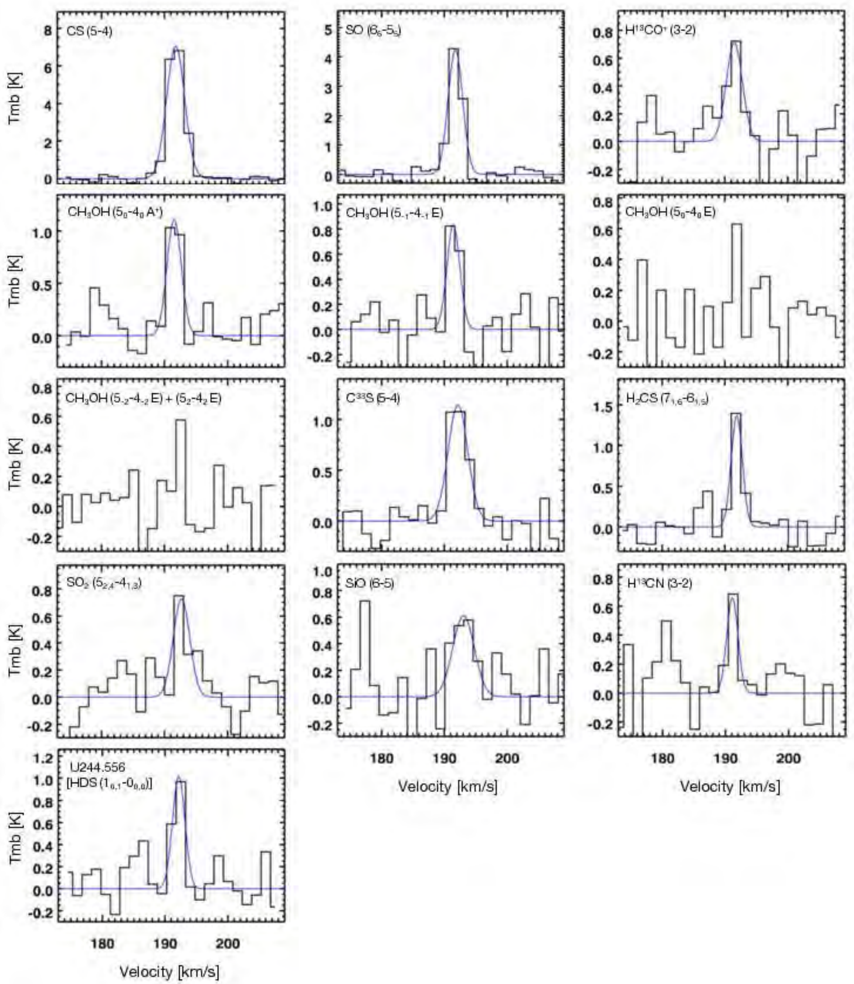
- Recent large-scale compression
- Dynamically supported by accretion driven MHD waves

(André et al. 2016)

Chemistry in Magellanic Clouds



N113 in the LMC
methanol, dimethyl ether, and methyl formate
Sewilo et al. (2018)



IRAS 01042-7215 in the SMC
Detection of Methanol
Shimonishi et al. (2018)

N83 in the SMC

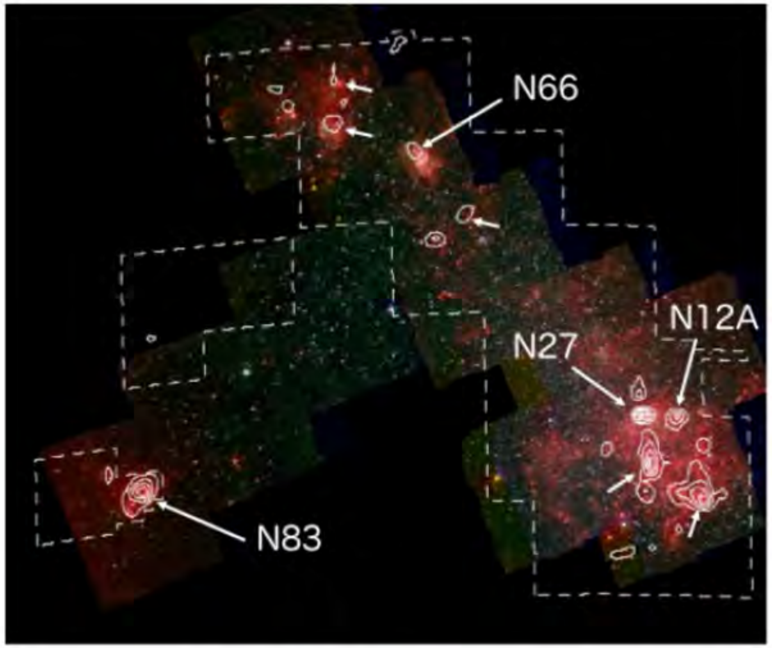
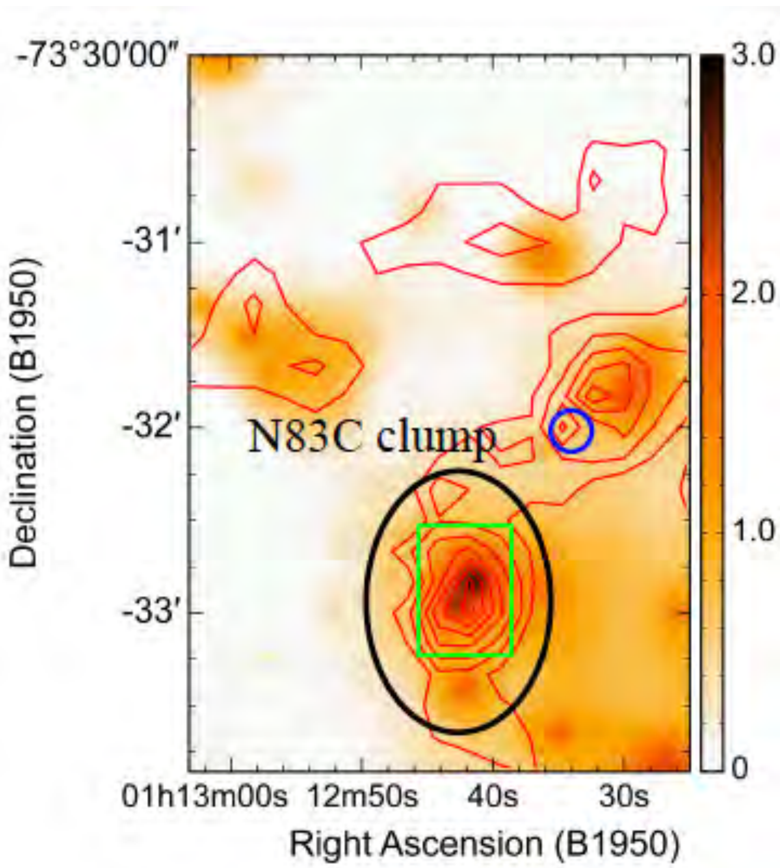
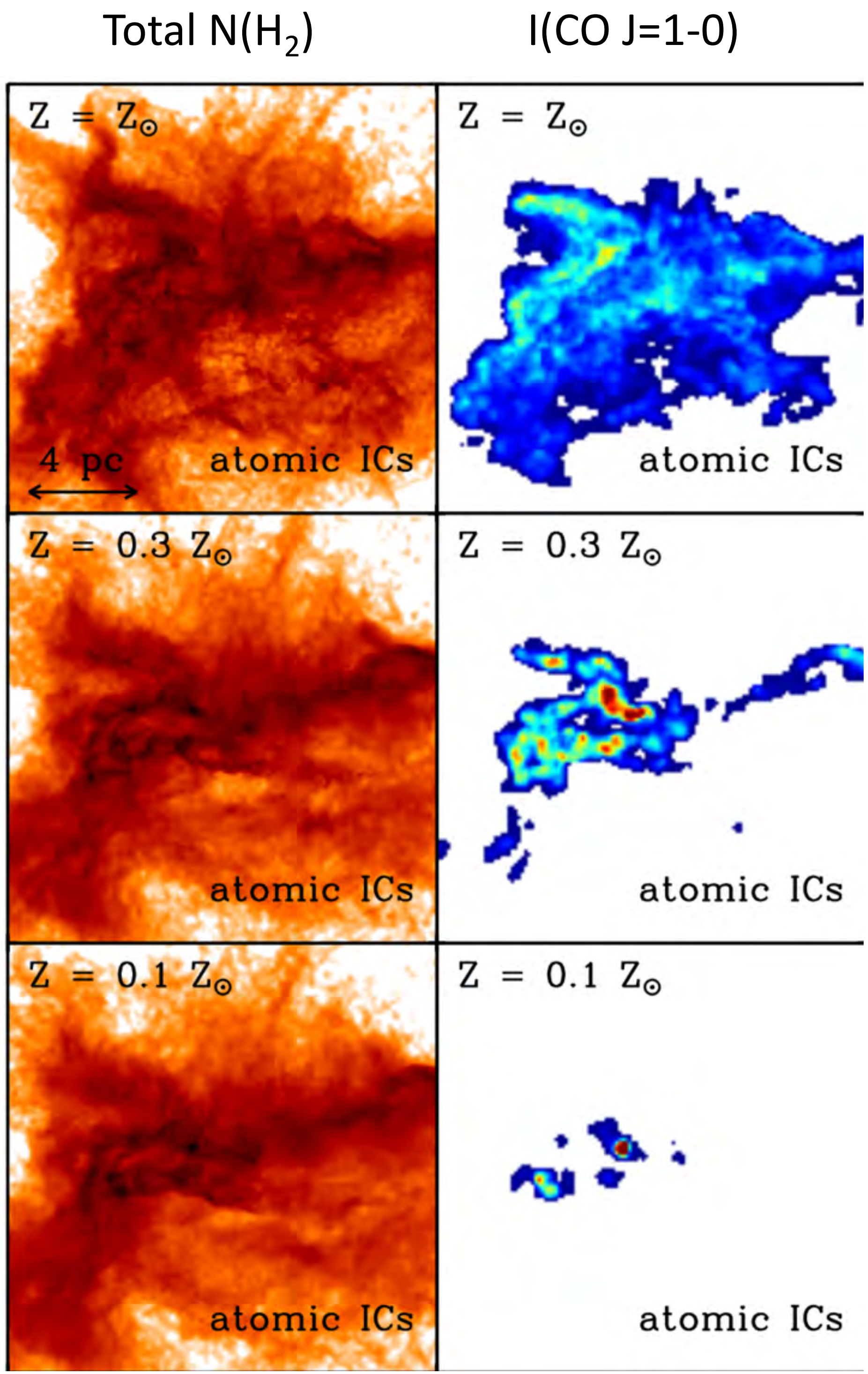


Figure 1: Contour: CO(1-0) intensity distribution toward the SMC (Mizuno et al. 2001). Color: Spitzer S3MC (Bolatto et al. 2007). The white arrows indicate the clouds observed by ASTE in the lines of CO(3-2).



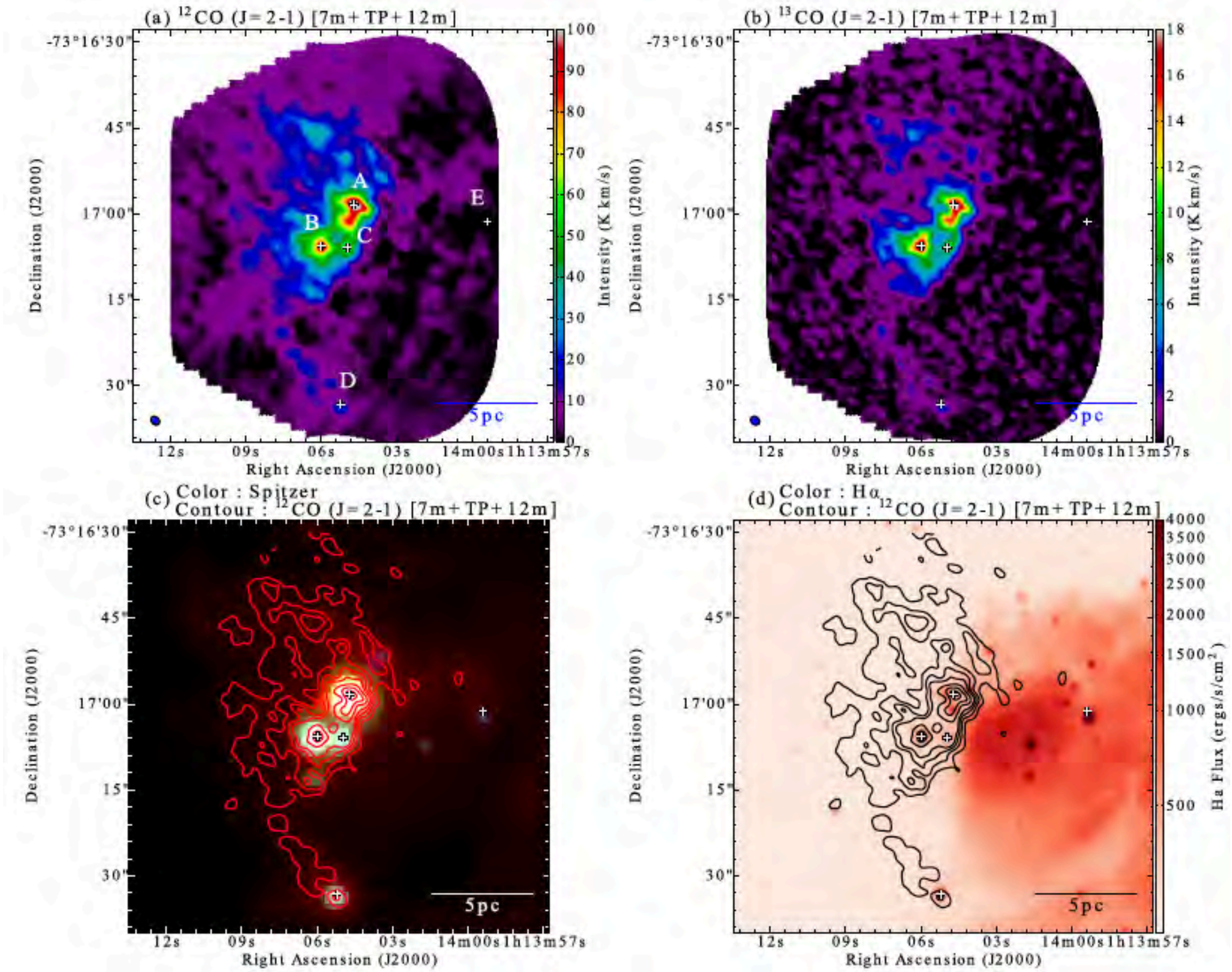
NANTEN CO

Red contour : ASTE 12CO(J=3-2)



Glover & Clark 2012

N83C in the SMC
Muraoka et al. (2017)



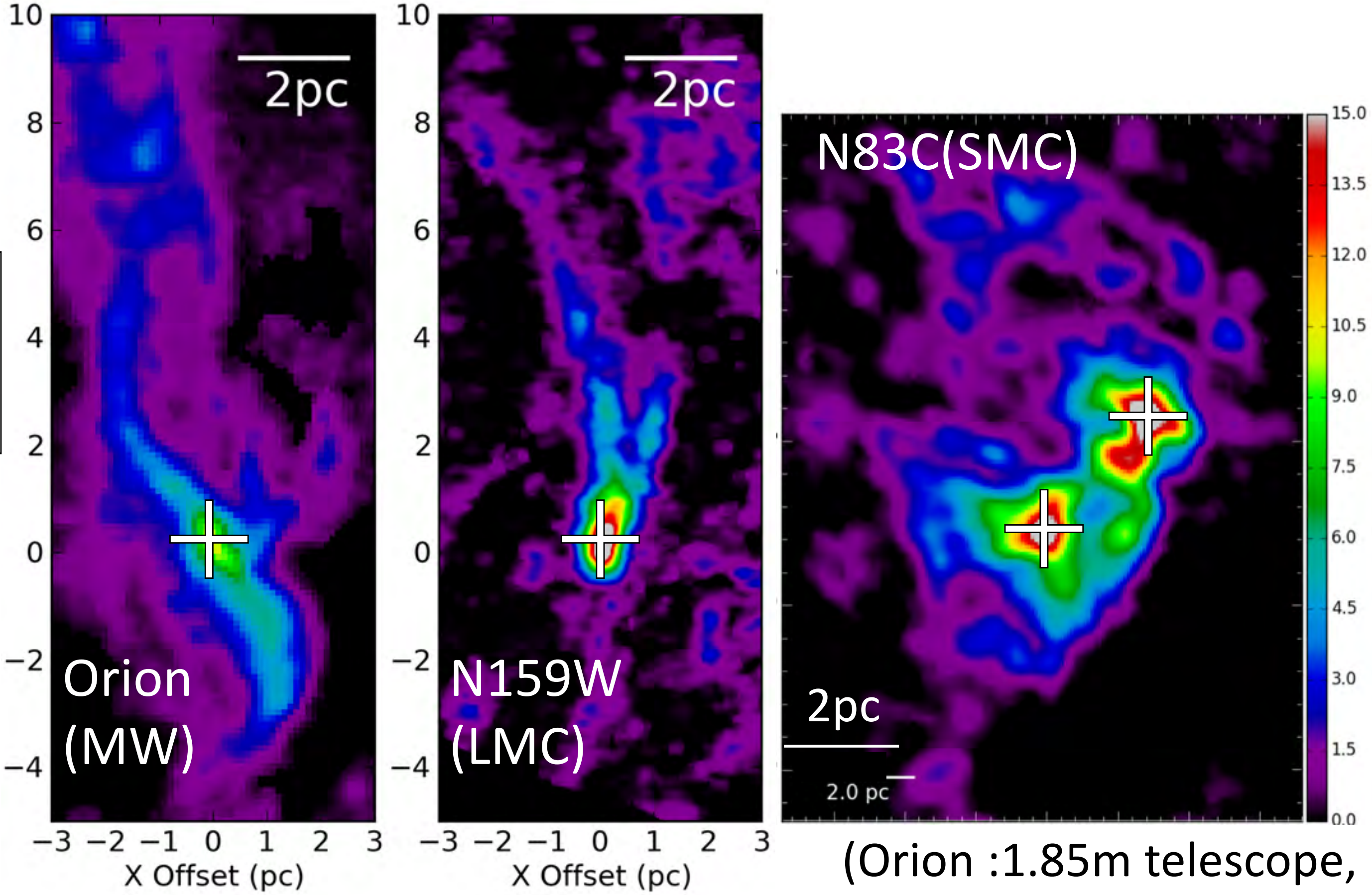
Density: $10^4 cm^{-3}$

T_k: 30-50K

Less filamentary structure

Line : 13CO (J=2-1)

Massive YSOs



(Orion :1.85m telescope, LMC/SMC : ALMA)

Metalicity MW (1) LMC (1/2) SMC(1/5)

High low

Less filamentary structure in the SMC?

SMC: ALMA observations

- Clumps are starting to be spatially resolved
  - R ~ 1pc, M ~ 1000Mo
- X Factor from Virial analysis
  - Consistent with the metallicity
- Density of 12CO clump
  - a few x $10^4 cm^{-3}$
    - a few x $10^3 cm^{-3}$: MW and LMC
  - $T_{kin} \gtrsim 40K$
  - CO heavily dissociated?
  - [CI] observations: Honma et al.

Summary

- LMC
  - Filaments + Multiple velocity components
  - Filament-filament interaction
    - Formation of high-mass stars (>30Mo)
  - Higher column density than MW clouds?
    - More active star formation in the LMC
    - Populous cluster forming clump?
- SMC
  - Clumps are starting to be spatially resolved
  - X Factor ~ 4 x Galactic value
  - 12CO clump: high-density, high-temperature
  - No significant filaments?

High mass SF in GMC

- Resolved CO observations toward GMCs
  - from nearby GMCs to GMCs in the LMC
    - from small telescopes to ALMA
  - a lot of samples with resolutions of <~ 0.1pc
    - along the galactic plane and in the Magellanic Clouds
  - Dynamical interaction of the gas is a key to understand the high mass star formation.