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

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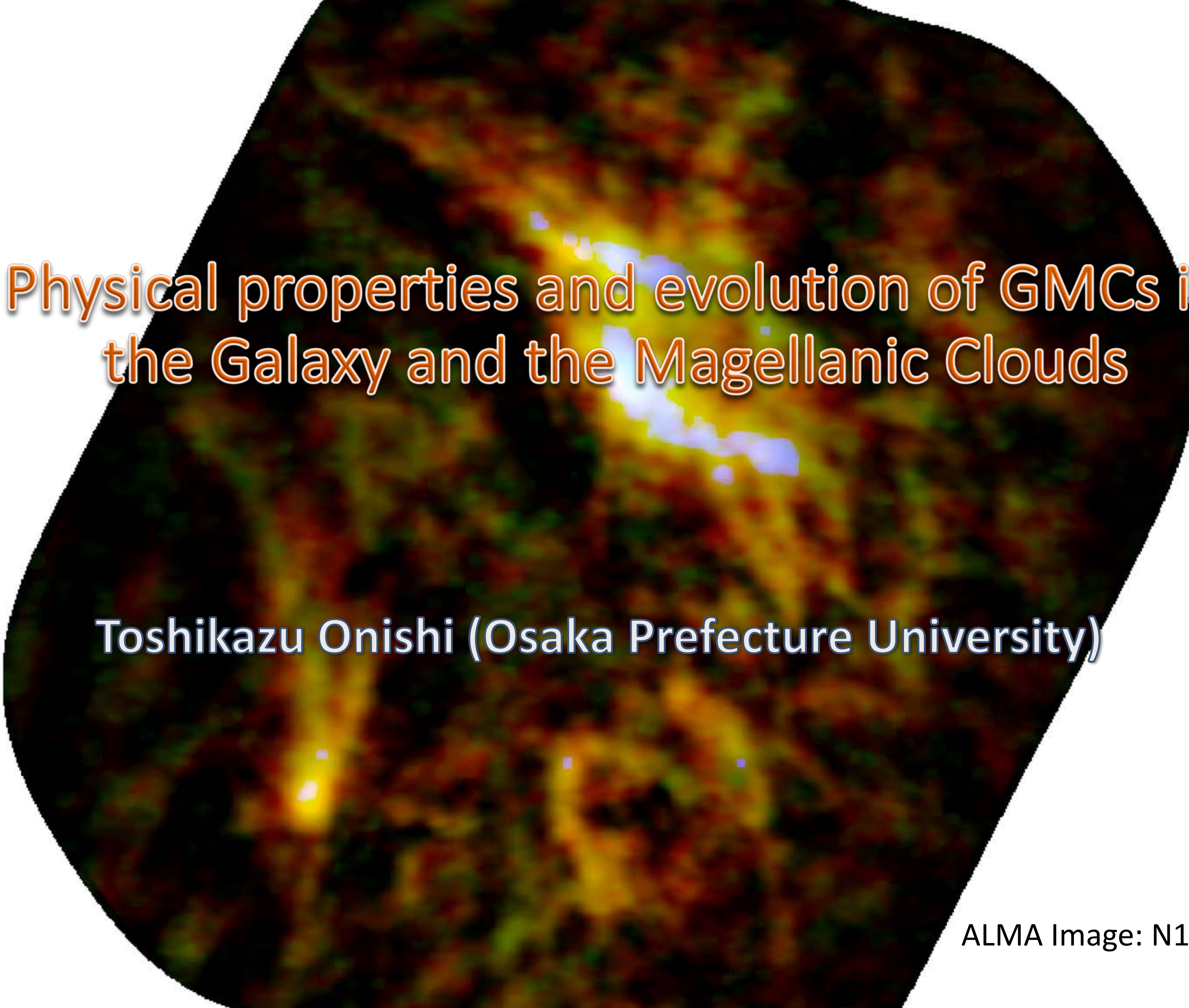


ALMA Image: N159W

GMC as a site of high-mass star formation

From galaxy evolution to individual star formation

kpc

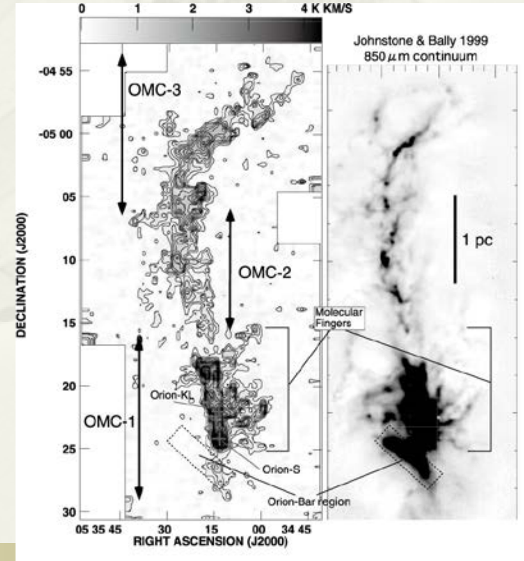
GMAs: 10^7Mo

1-100pc

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

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

<0.1 pc



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

Wide range of scales
Various distances
Use of various telescopes

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 nearby 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.

Progress

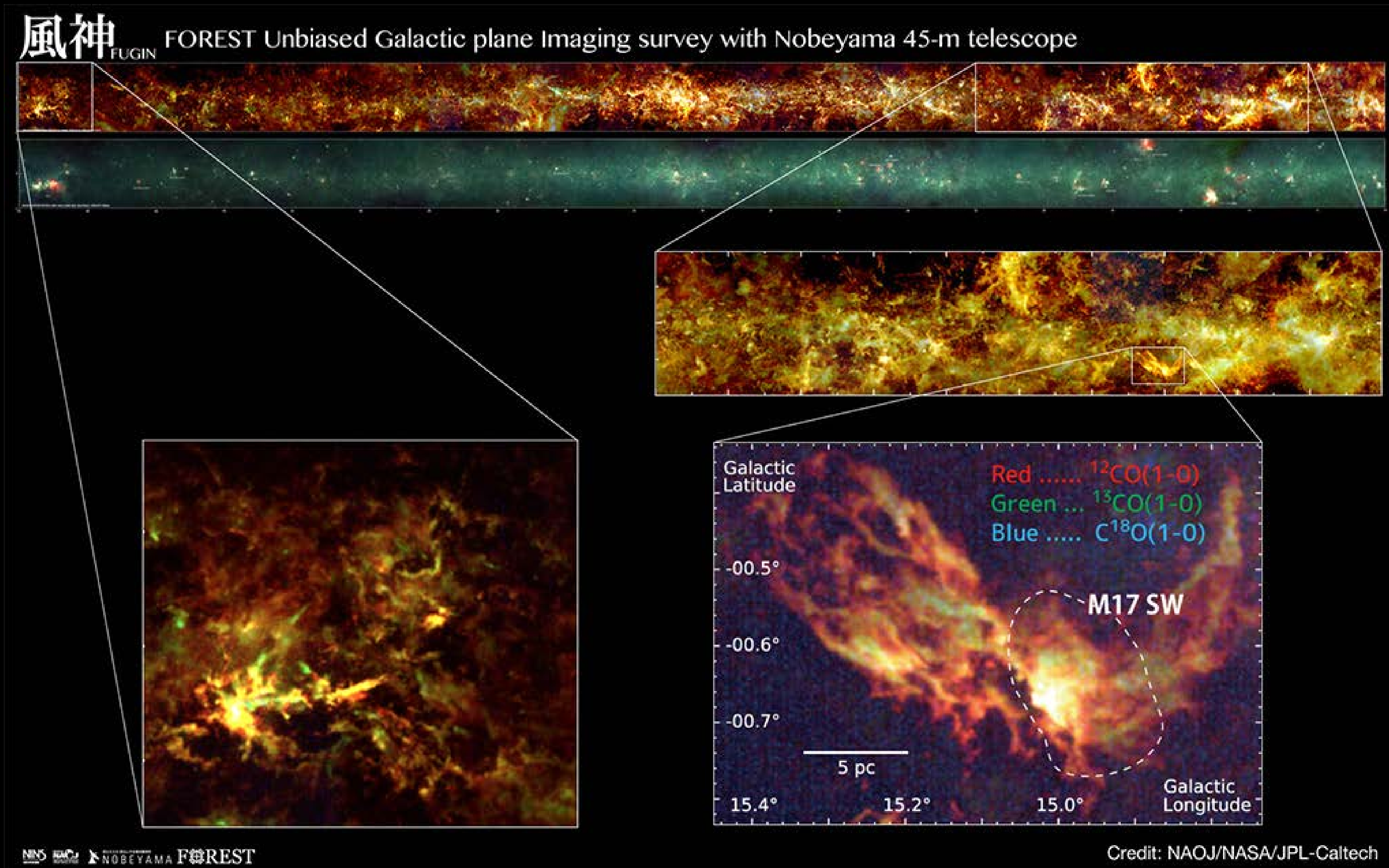
- High precision (large aperture) telescopes with sensitive receivers installed
  - NANTEN2 4m
  - NRO 45m, IRAM 30m
  - ASTE 10m, APEX 12m
- Sensitive receivers at higher freq. and telescopes at high site
  - CO (J=2-1,3-2,4-3,6-5,7-6,…)
- ALMA
  - Spatial scale: 0.01 ~ 100 arcsec
  - Band 6 and Band 7 observations of external galaxies
    - Highly efficient

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°

CO three lines



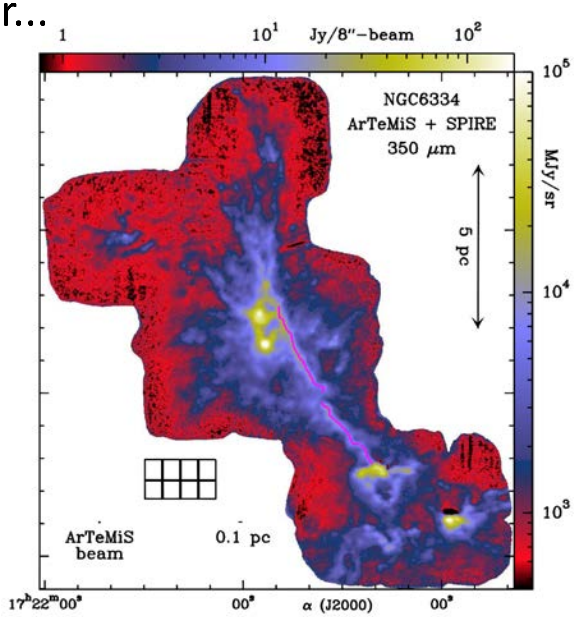
~JCMT CO(3-2) resolutions R ^{12}CO(1-0), G ^{13}CO(1-0), B C^{18}O(1-0)

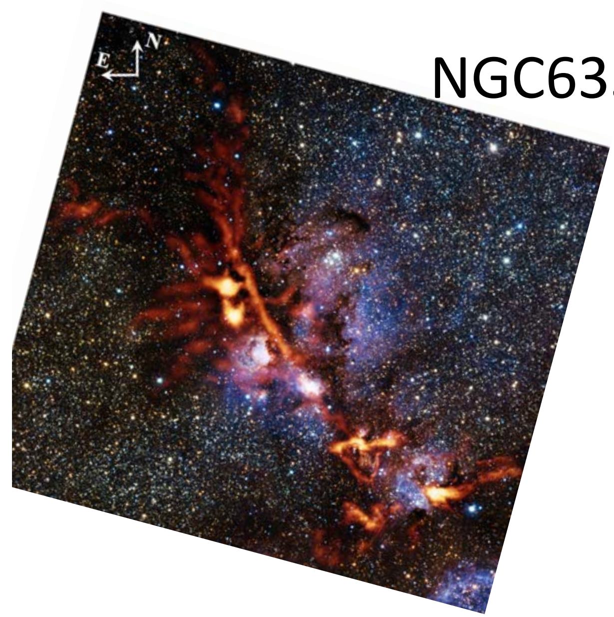
Why filamentary clouds?

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 very rare so far...





NGC6334 @1.7 kpc

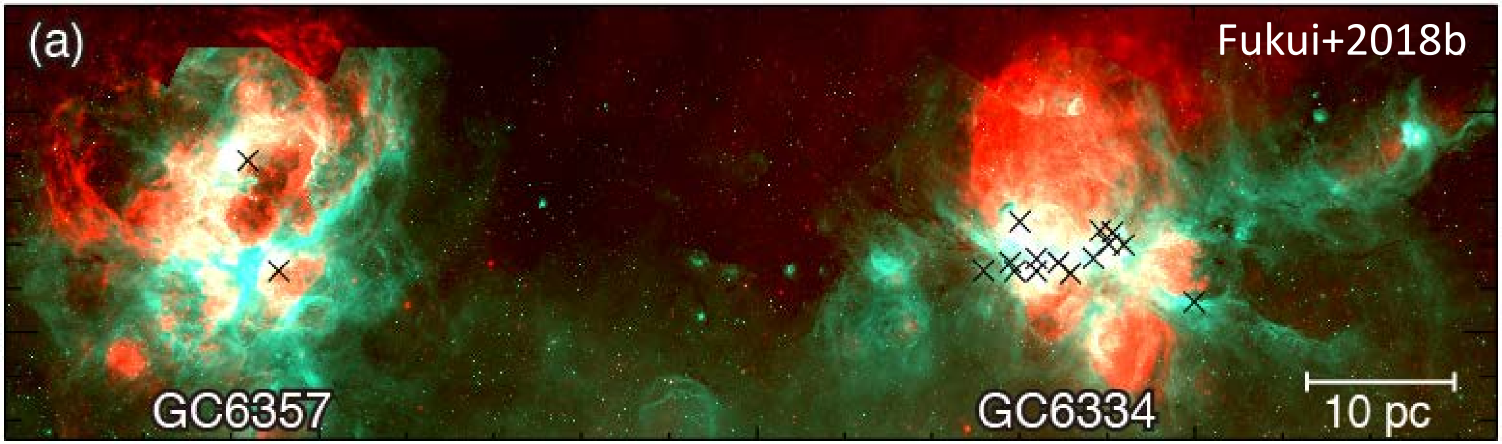
Resolution = 8”(~0.07 pc), Width ~ 0.15 pc, Line mass ~ 500 –2000 $M_{\odot}$ /pc

Possible formation mechanisms of massive filaments :

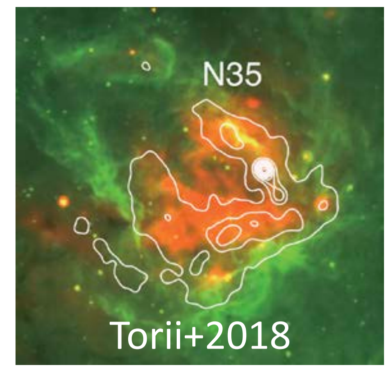
- Recent large-scale compression
- Dynamically supported by accretion driven MHD waves

(André et al. 2016)

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)**

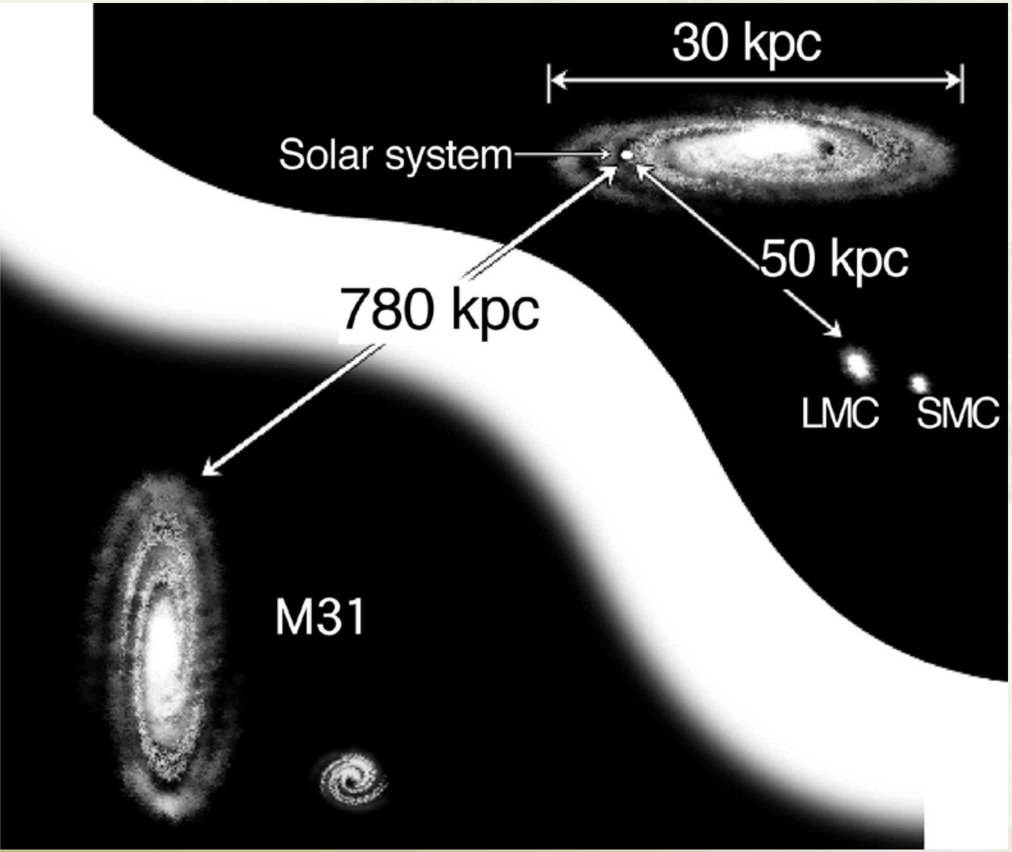


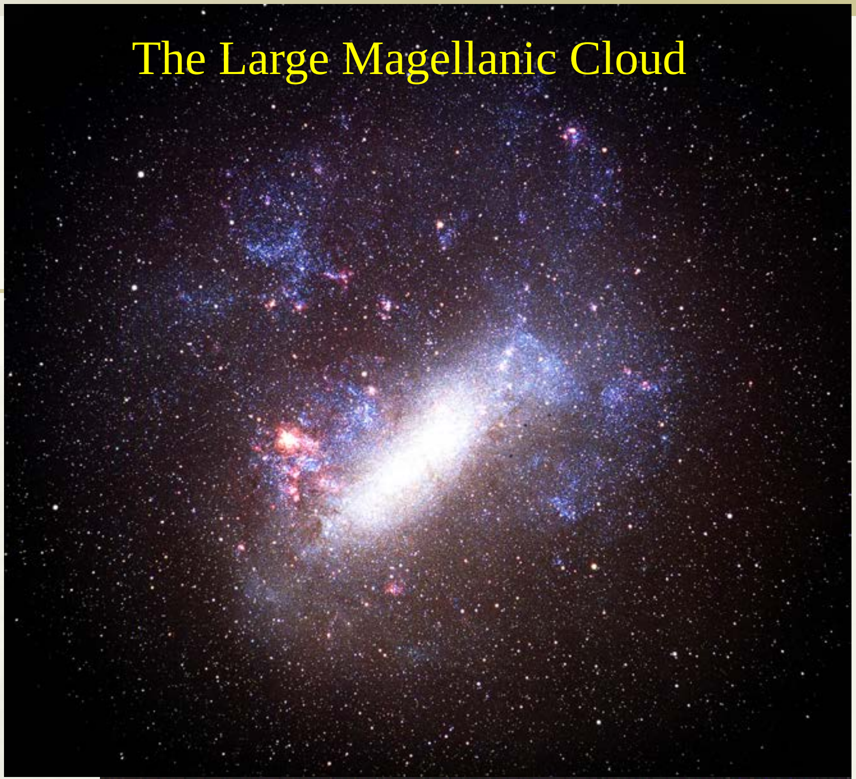
Spitzer bubbles

ALMA

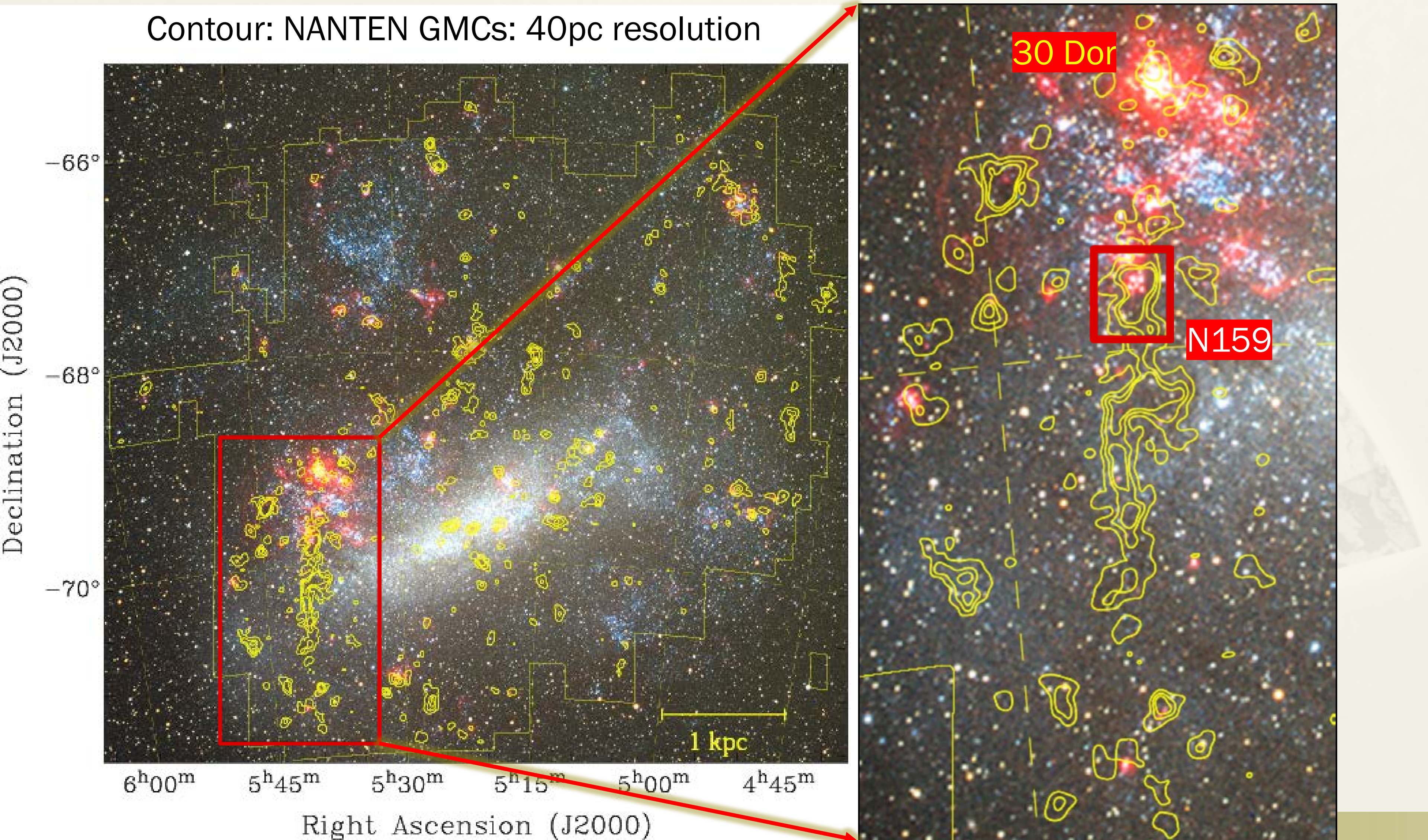
Magellanic Clouds

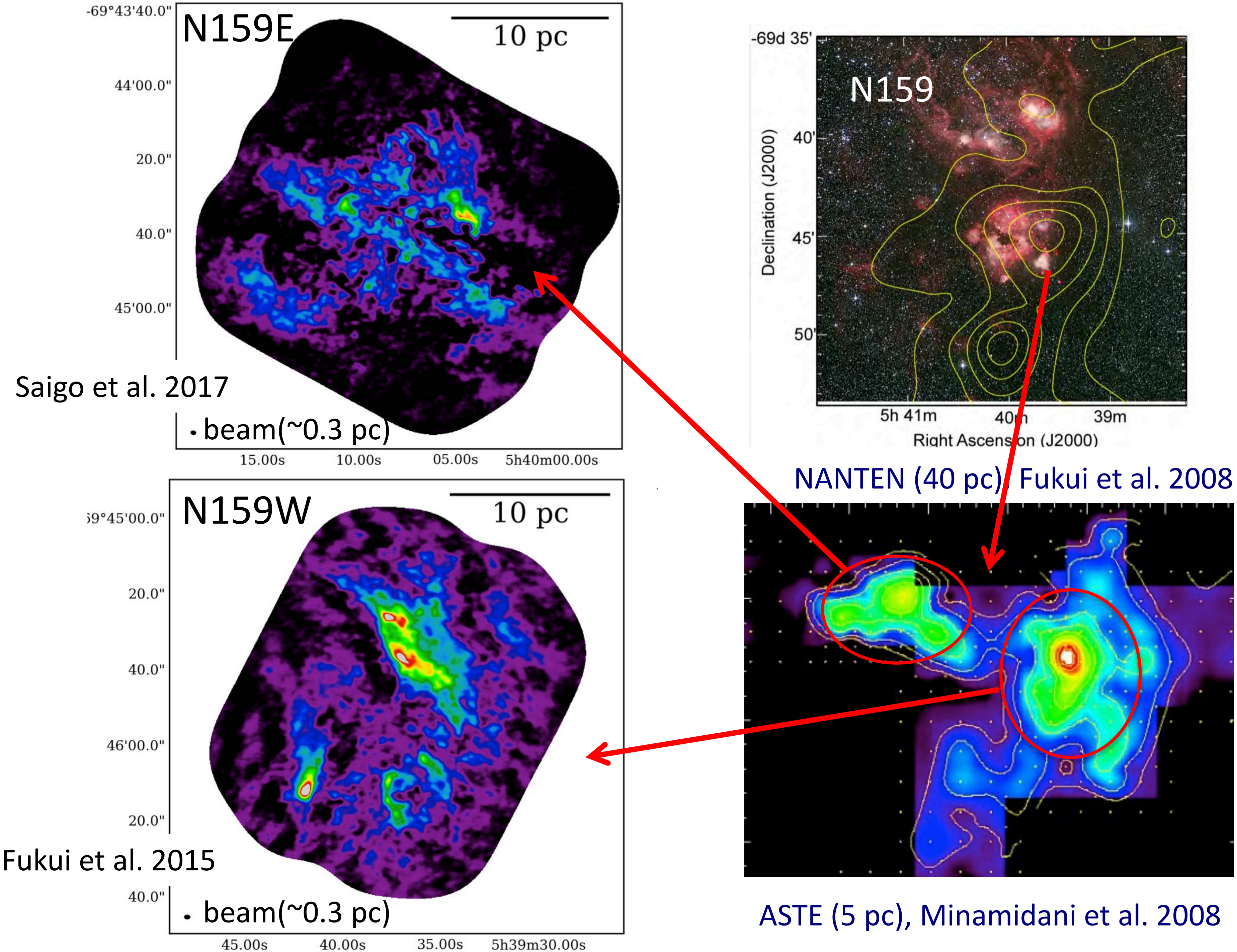
- D~ 50 kpc (one of the nearest)
- Different environment from the MW.
  - High gas-dust ratio
  - Low metallicity
- Active star formation
  - Massive star formation
  - Young populous clusters

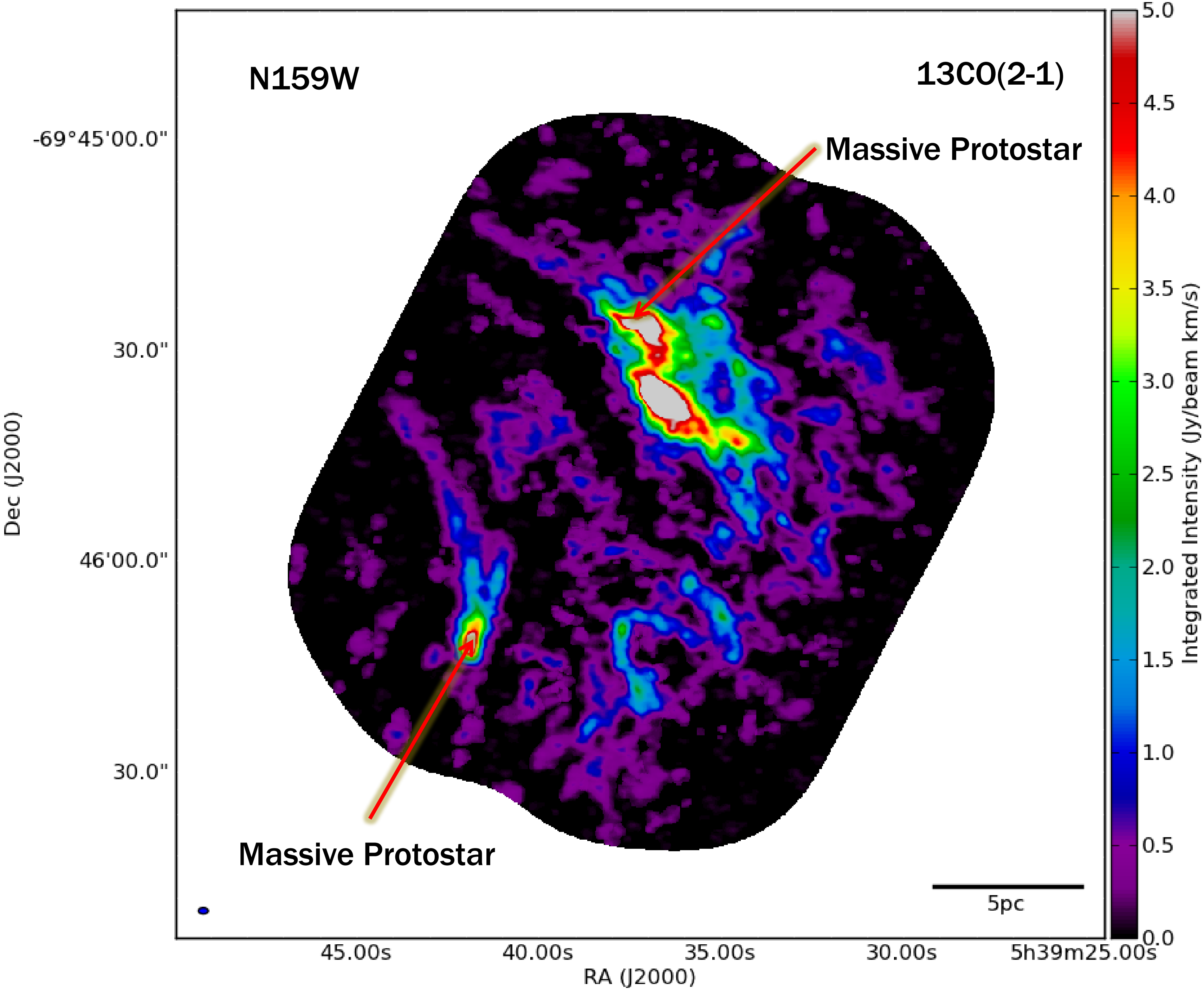


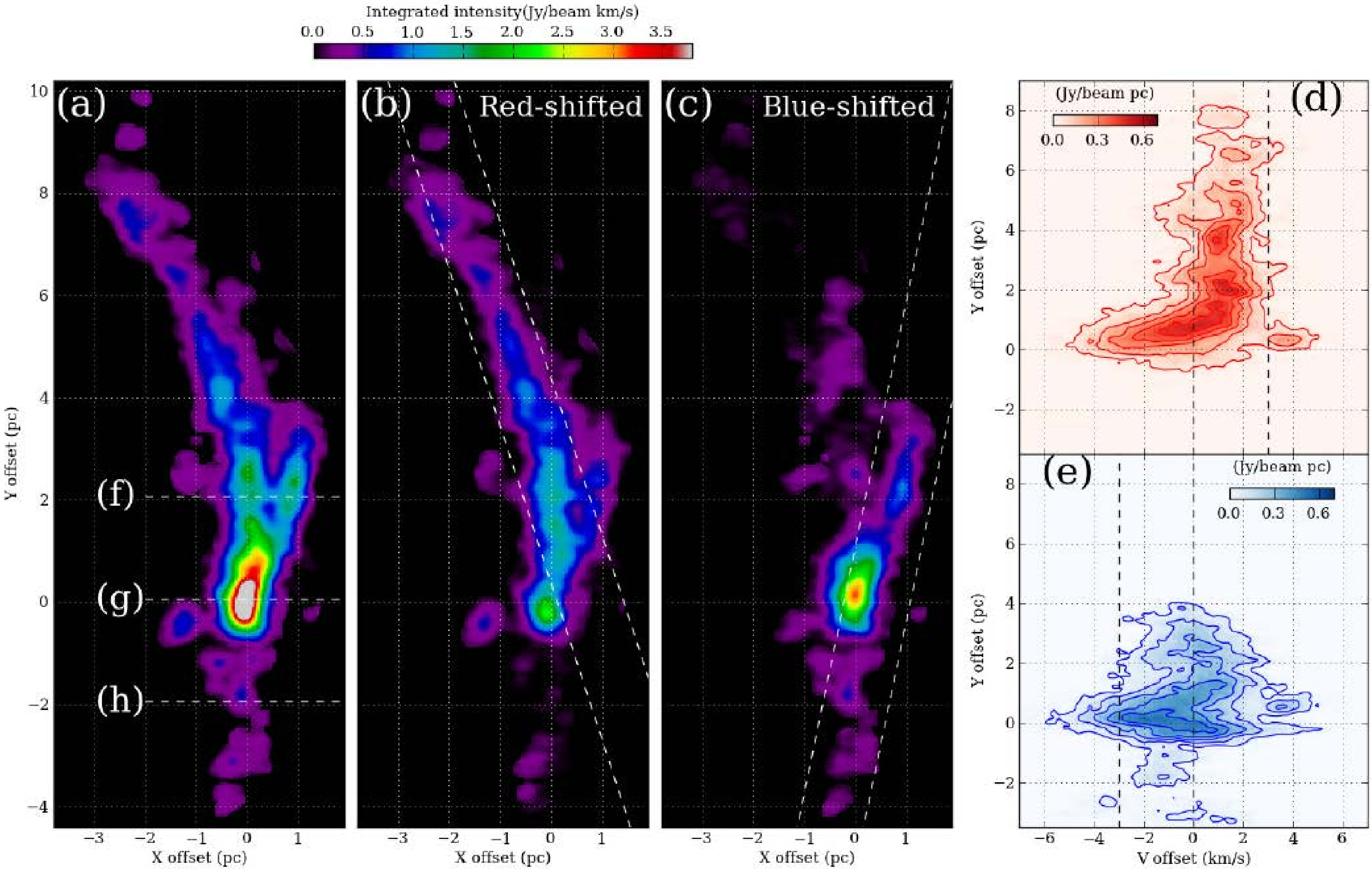


N159: One of the largest GMCs in the LMC
10^7Mo, 220pc, Four young clusters (age <10Myr)
ALMA observations: Cycles 1 and 4




N159E
10 pc
-69°43'40.0"
44'00.0"
20.0"
40.0"
45'00.0"
15.00s
10.00s
05.00s
5h40m00.00s
beam(~0.3 pc)
Saigo et al. 2017
N159W
10 pc
20.0"
40.0"
46'00.0"
20.0"
40.0"
45.00s
40.00s
35.00s
5h39m30.00s
beam(~0.3 pc)
Fukui et al. 2015
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

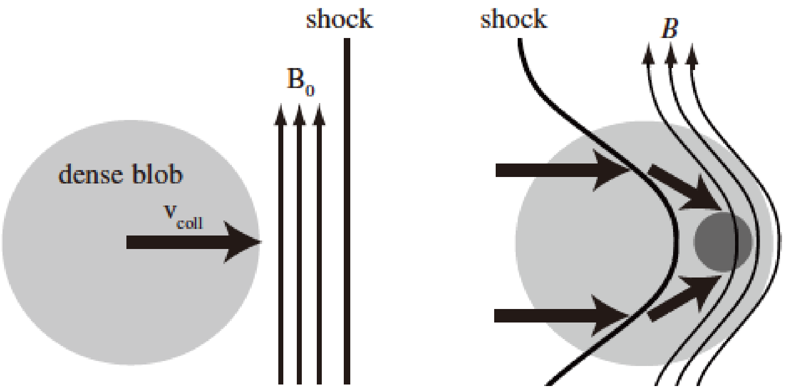

N159W
13CO(2-1)
Massive Protostar
Massive Protostar
-69°45'00.0"
30.0"
46'00.0"
30.0"
Dec (J2000)
45.00s
40.00s
35.00s
30.00s
5h39m25.00s
RA (J2000)
5pc
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Integrated Intensity (Jy/beam km/s)

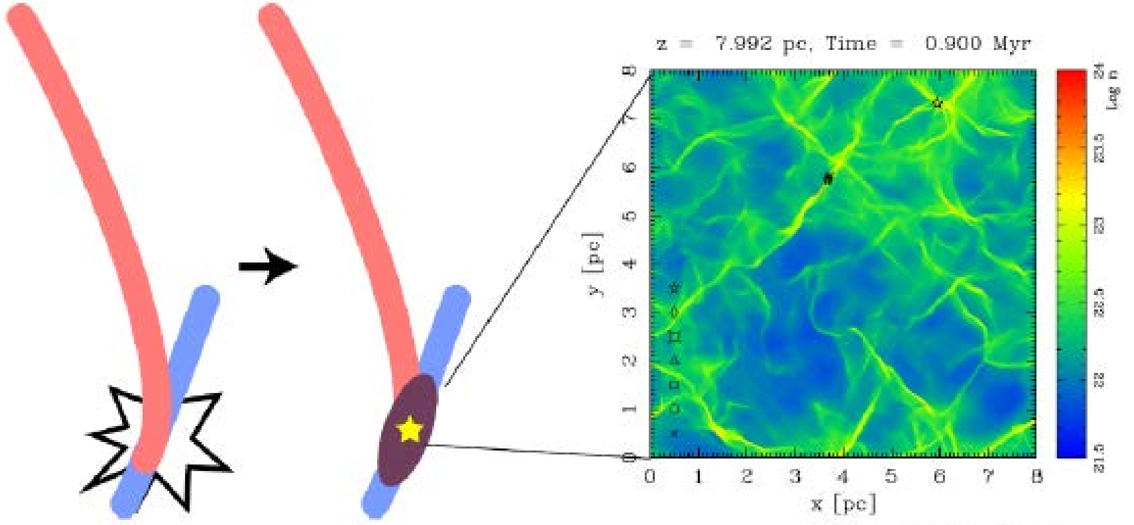


Integrated intensity(Jy/beam km/s)
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5
(a)
(b) Red-shifted
(c) Blue-shifted
(d)
(e)
(f)
(g)
(h)
(Jy/beam pc)
0.0 0.3 0.6
Y offset (pc)
X offset (pc)
V offset (km/s)

Massive star formation by cloud-cloud collisions

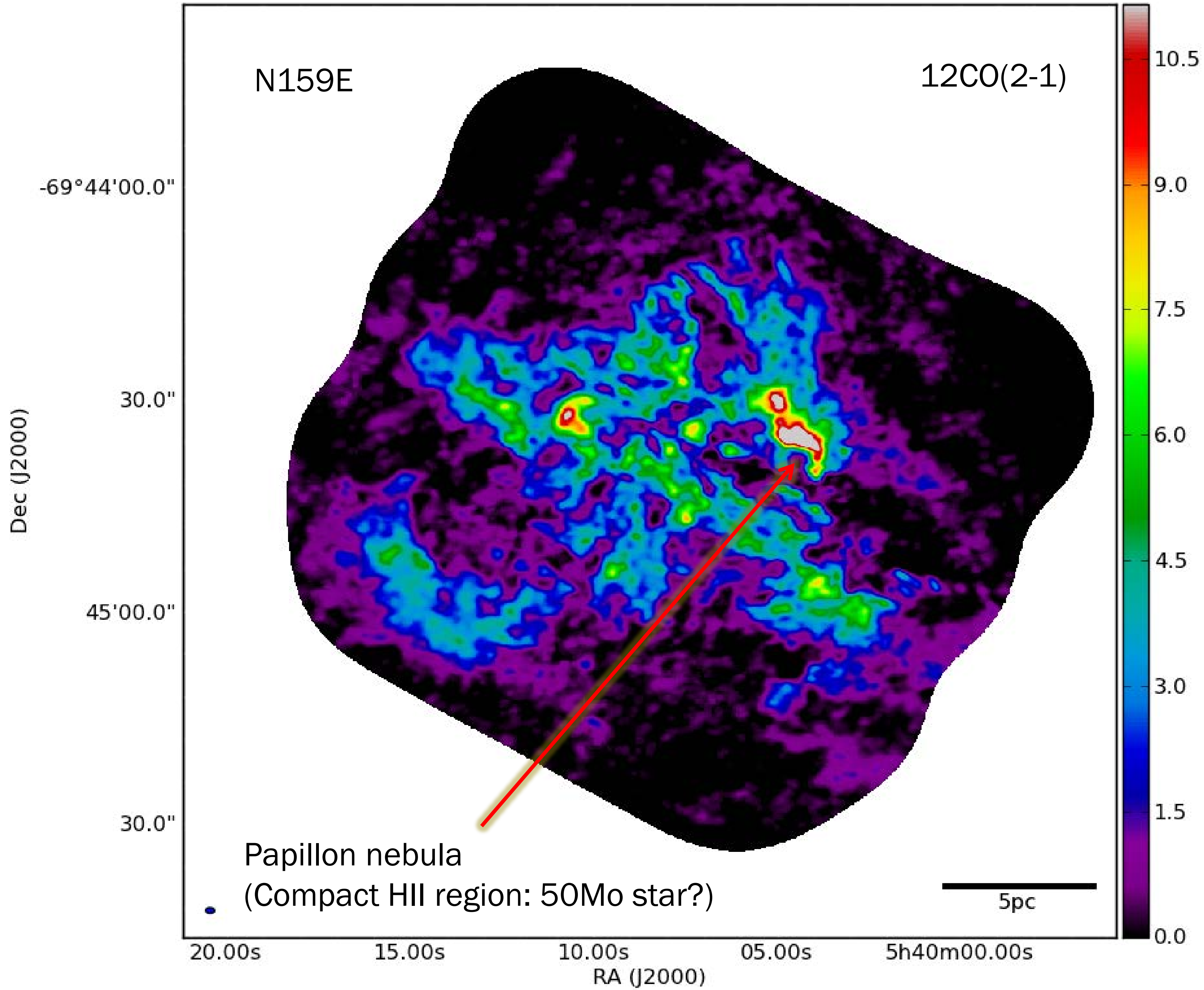
3-D MHD simulation with self-gravity of colliding clouds
Inoue & Fukui 2013



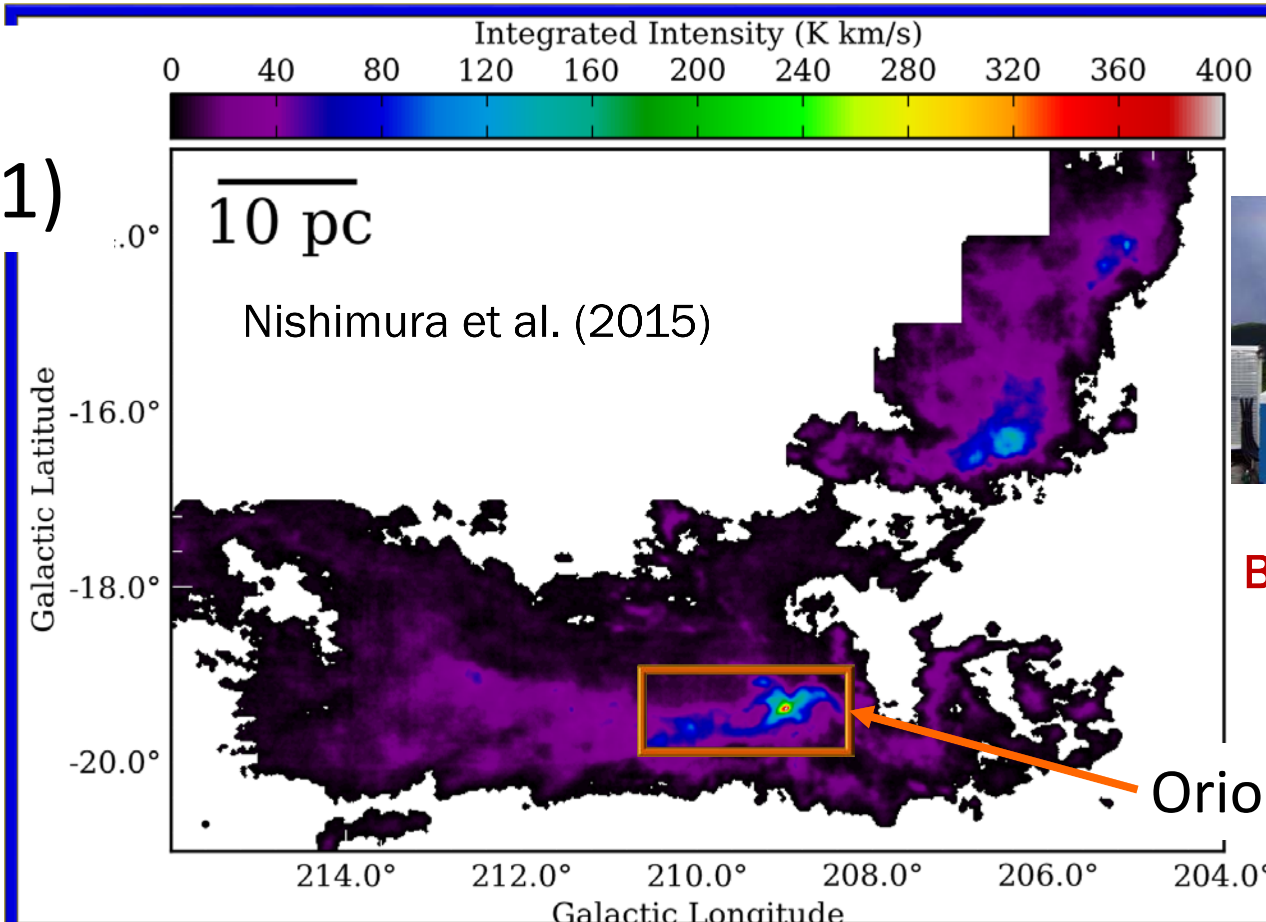


Inoue & Fukui 2013

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

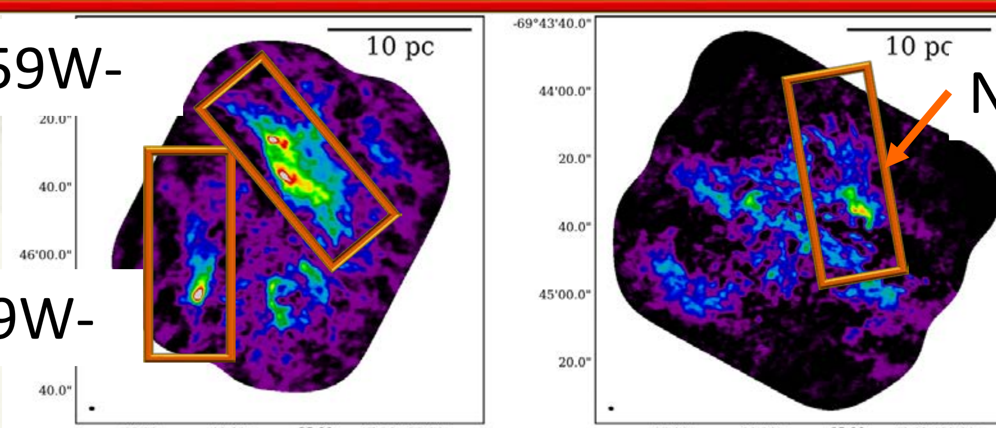

N159E
12CO(2-1)
-69°44'00.0"
30.0"
45'00.0"
30.0"
Dec (J2000)
20.00s
15.00s
10.00s
05.00s
5h40m00.00s
RA (J2000)
10.5
9.0
7.5
6.0
4.5
3.0
1.5
0.0
Papillon nebula
(Compact HII region: 50Mo star?)
5pc

^{12}CO (J = 2–1)



Osaka 1.85-m

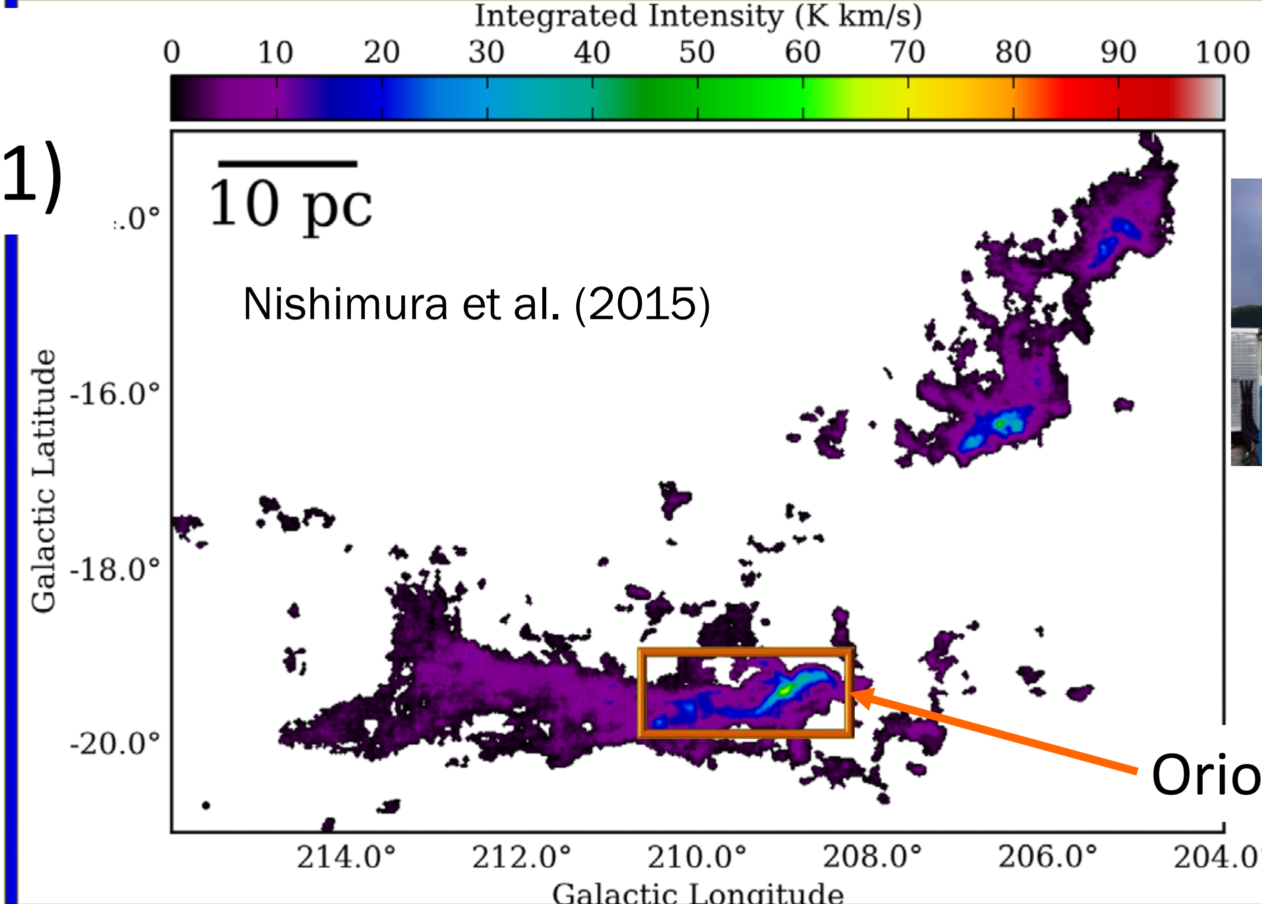
Beam: 0.35 pc



Beam: 0.24 pc

ALMA Cycle1

^{13}CO (J = 2–1)

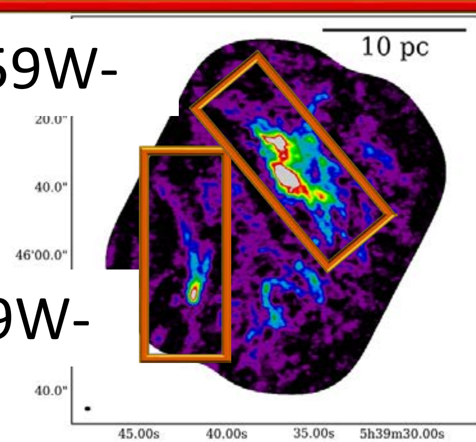


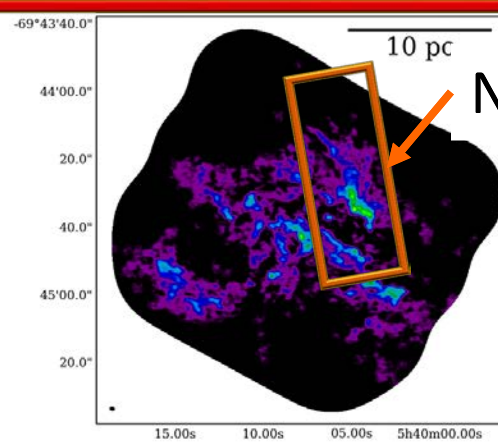
Osaka 1.85-m

Orion-A

N159W-N

N159W-S

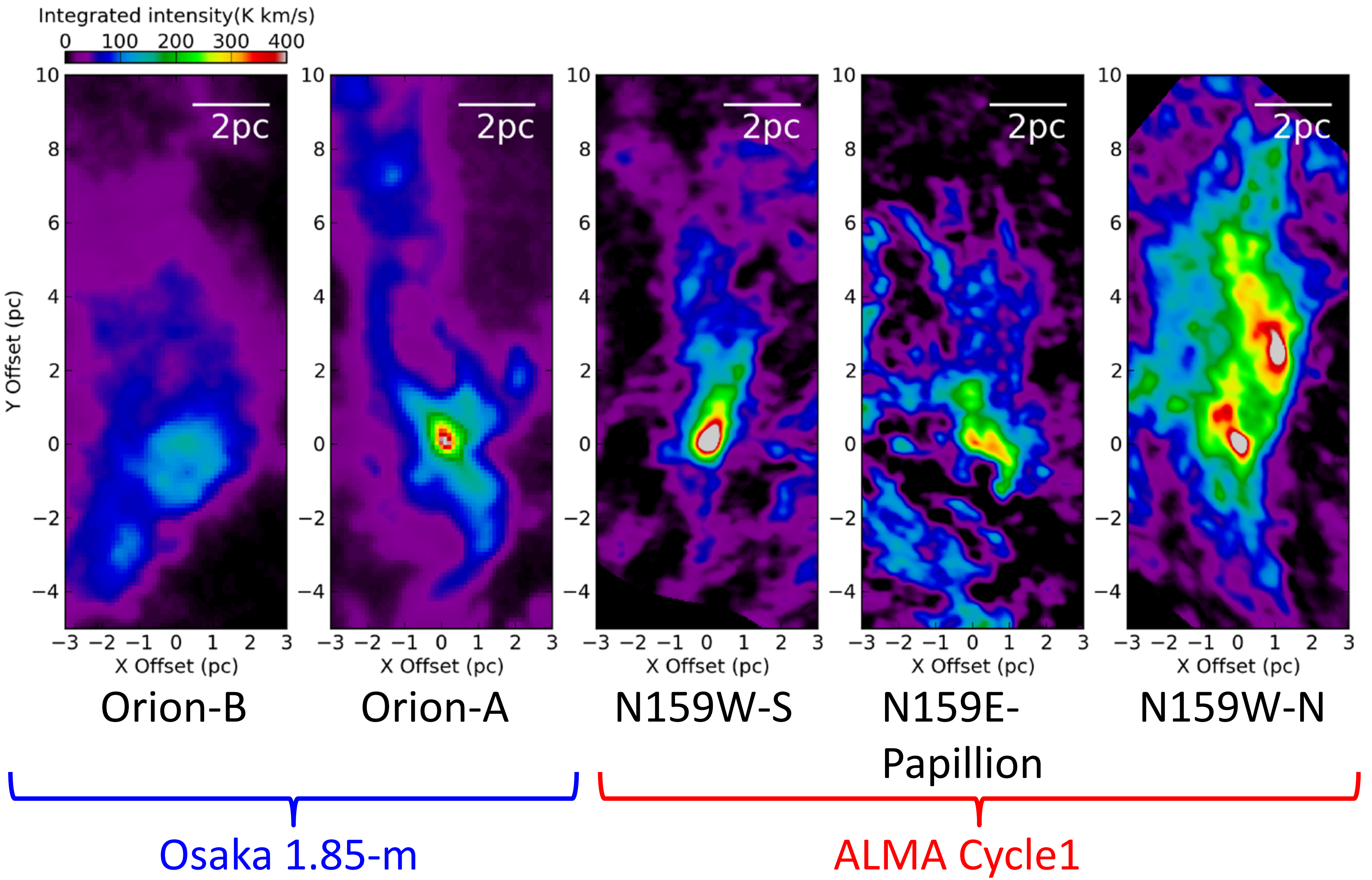




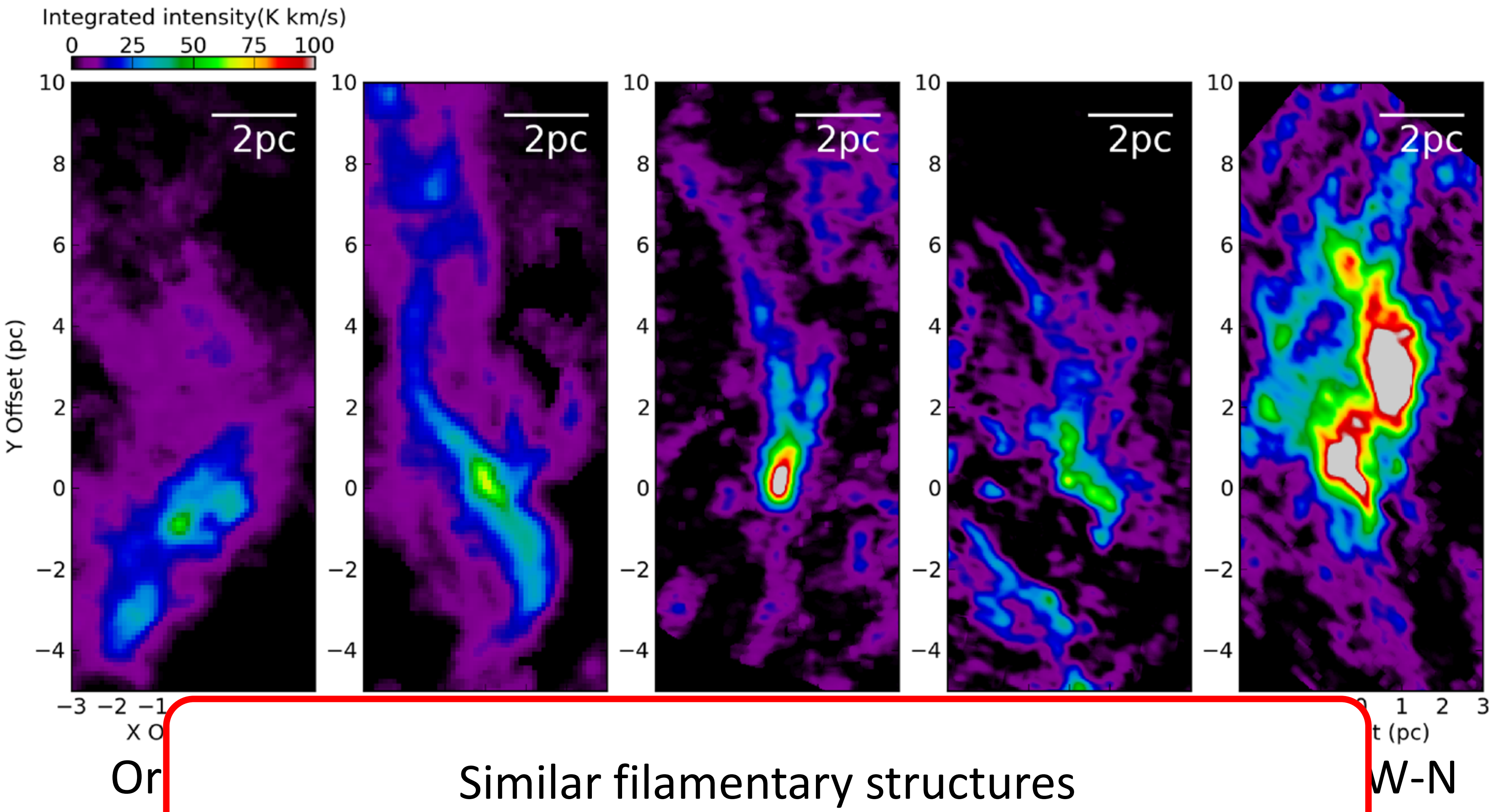
N159E-Papillion

ALMA Cycle1

Moment 0 map (^{12}CO (J = 2–1))



Moment 0 map (^{13}CO (J = 2–1))

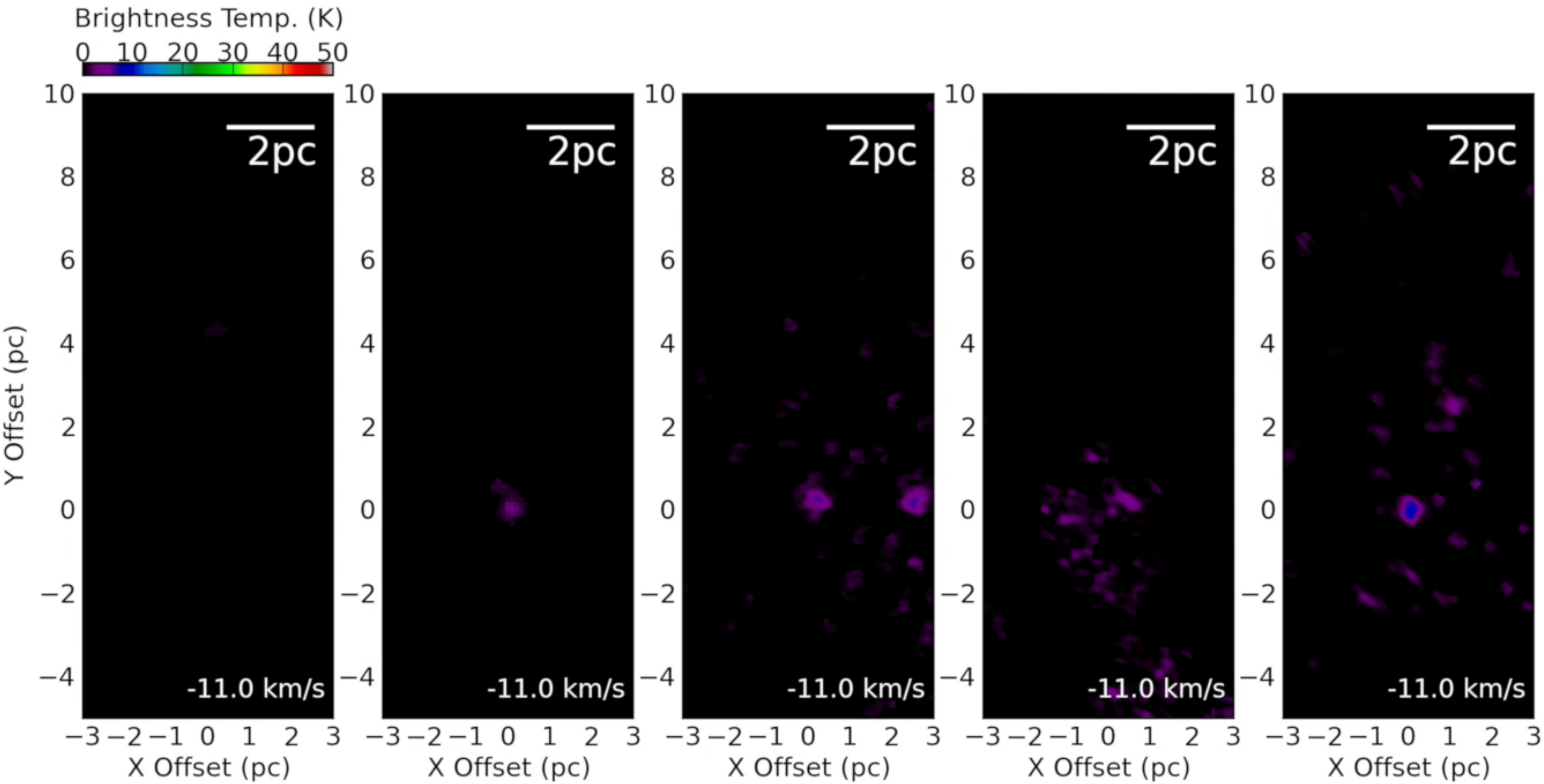


Similar filamentary structures

Osaka 1.85-m

ALMA Cycle1

Channel map (^{12}CO (J = 2–1))

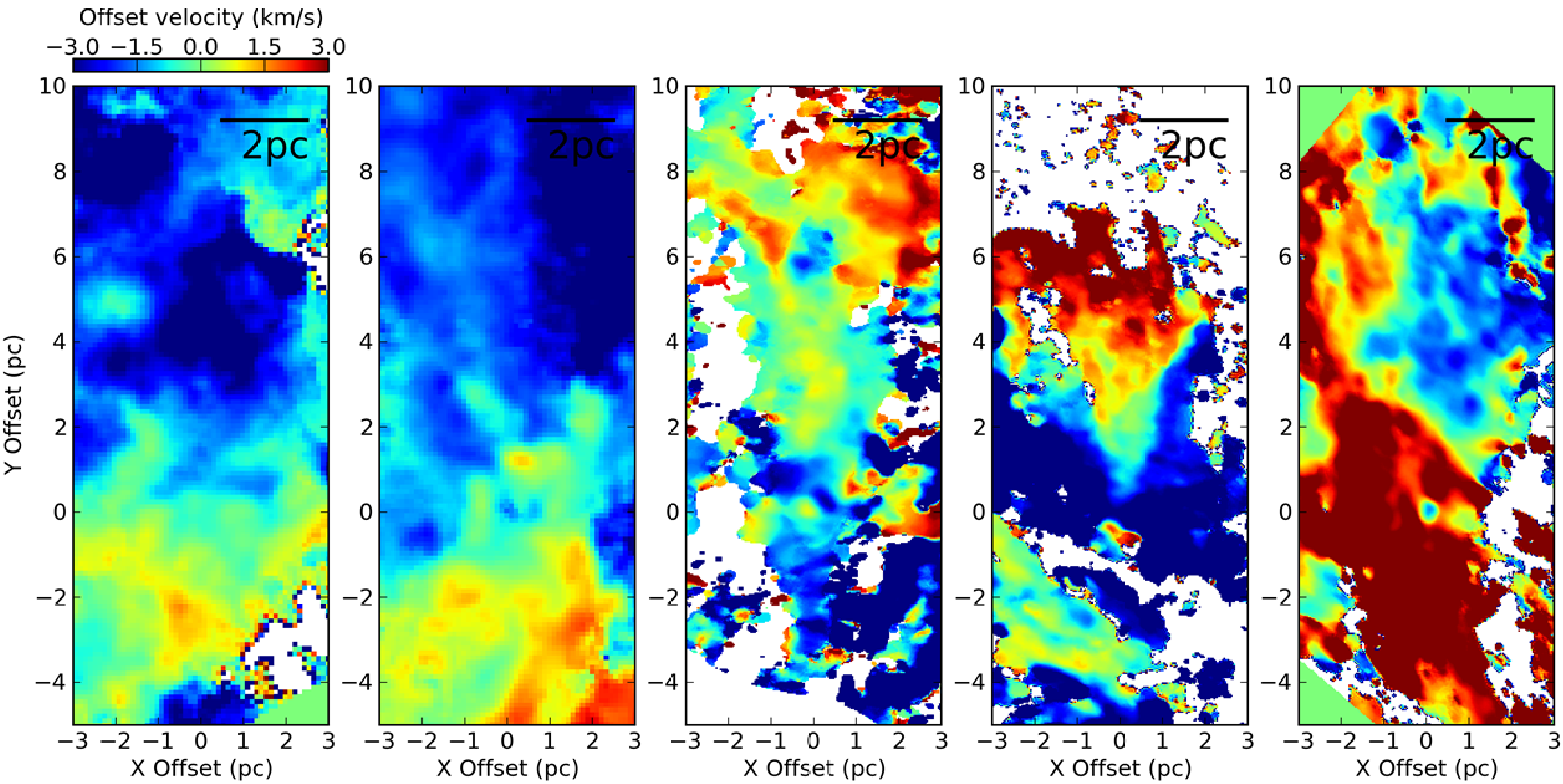


Orion-B Orion-A N159W-S N159E-Papillion N159W-N

Osaka 1.85-m

ALMA Cycle1

Moment 1 map (^{12}CO (J = 2–1))



Ori

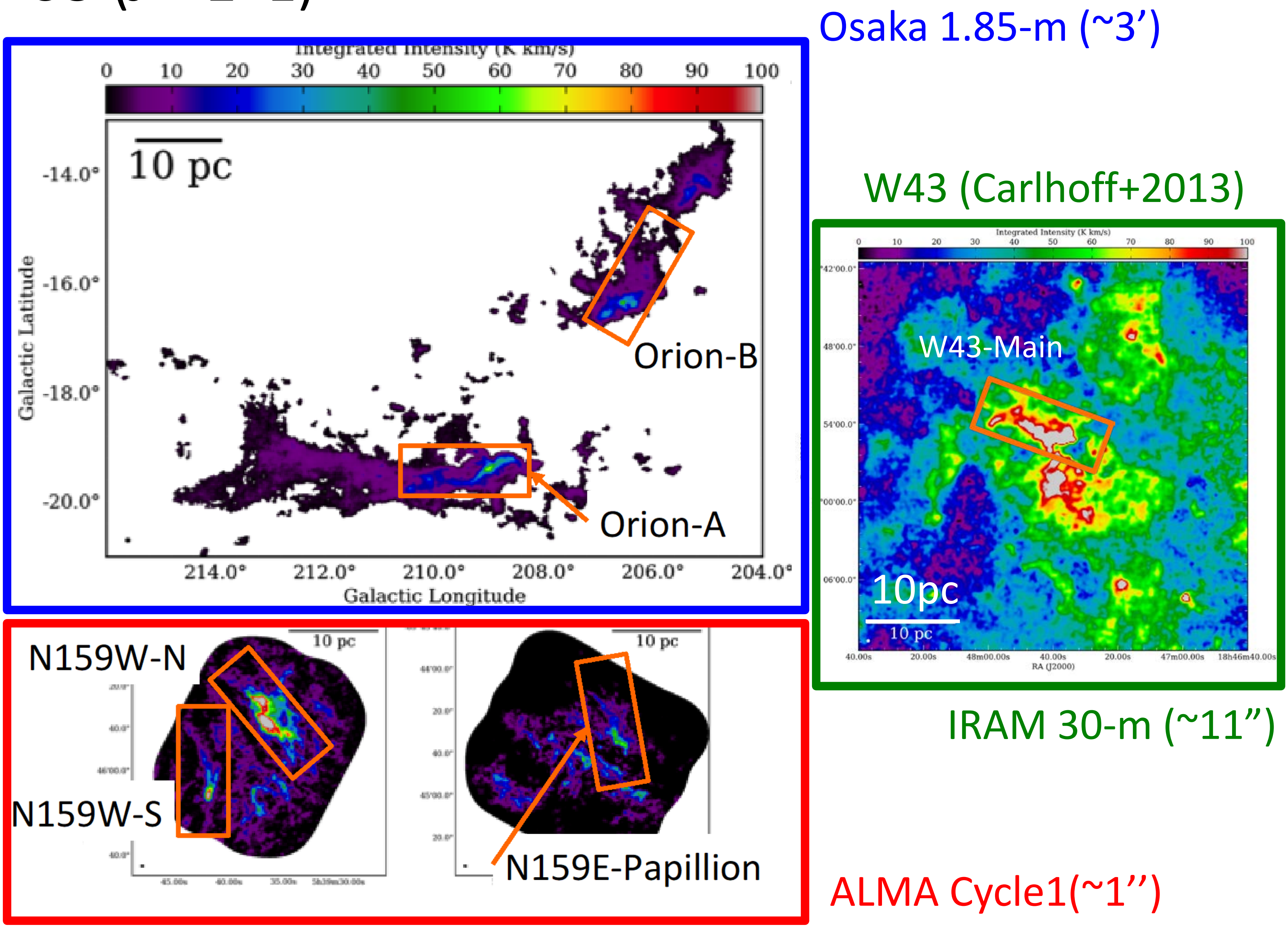
W-N

Complex velocity field
=>Components having different velocities

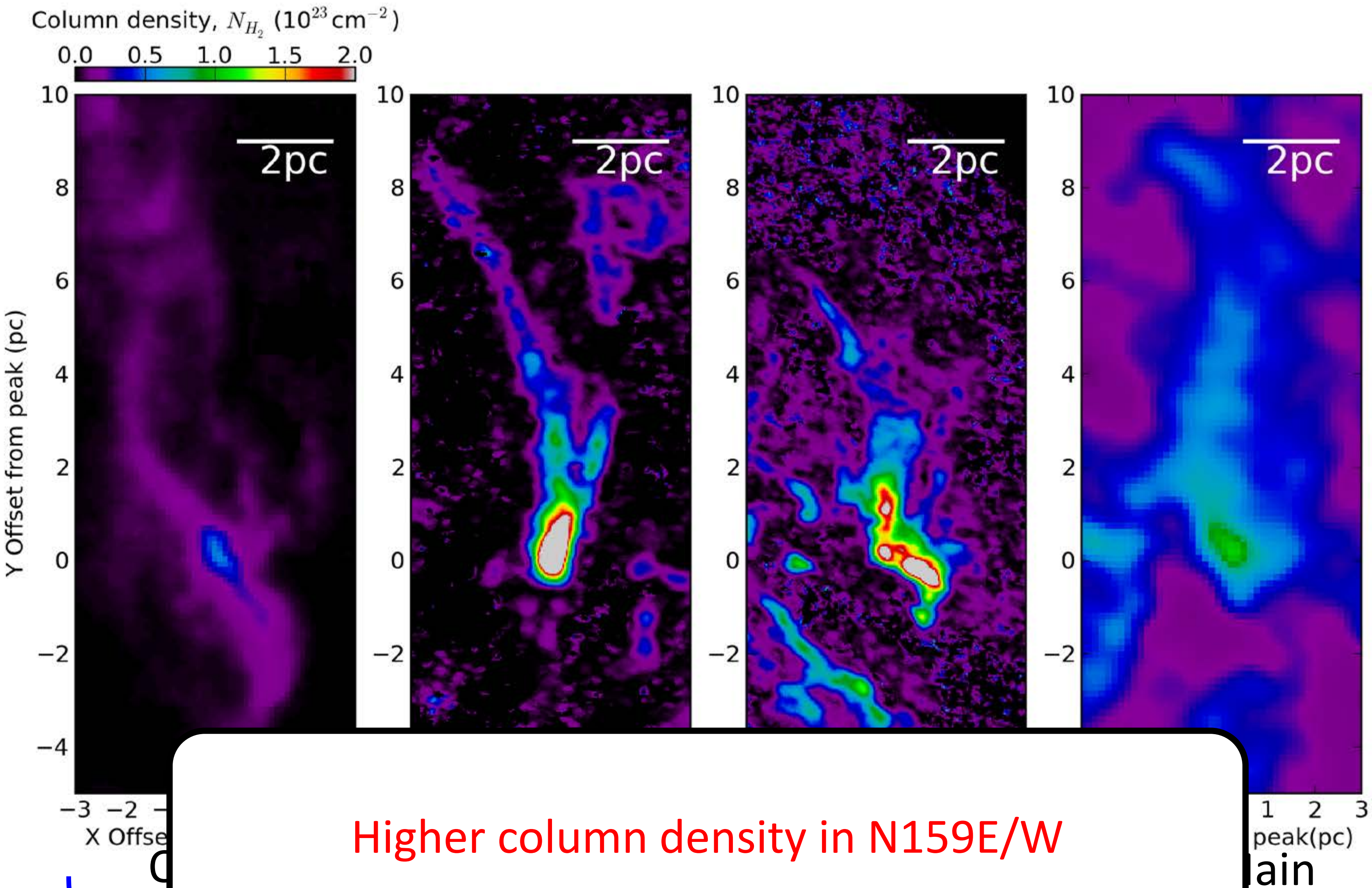
Osaka 1.85-m

ALMA Cycle1

^{13}CO (J = 2–1)


Osaka 1.85-m (~3')
Integrated Intensity (K km/s)
0 10 20 30 40 50 60 70 80 90 100
10 pc
-14.0°
-16.0°
-18.0°
-20.0°
Galactic Latitude
Orion-B
Orion-A
214.0° 212.0° 210.0° 208.0° 206.0° 204.0°
Galactic Longitude
W43 (Carlhoff+2013)
W43-Main
10pc
10 pc
RA (J2000)
IRAM 30-m (~11")
N159W-N
N159W-S
10 pc
10 pc
N159E-Papillion
ALMA Cycle1(~1")

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



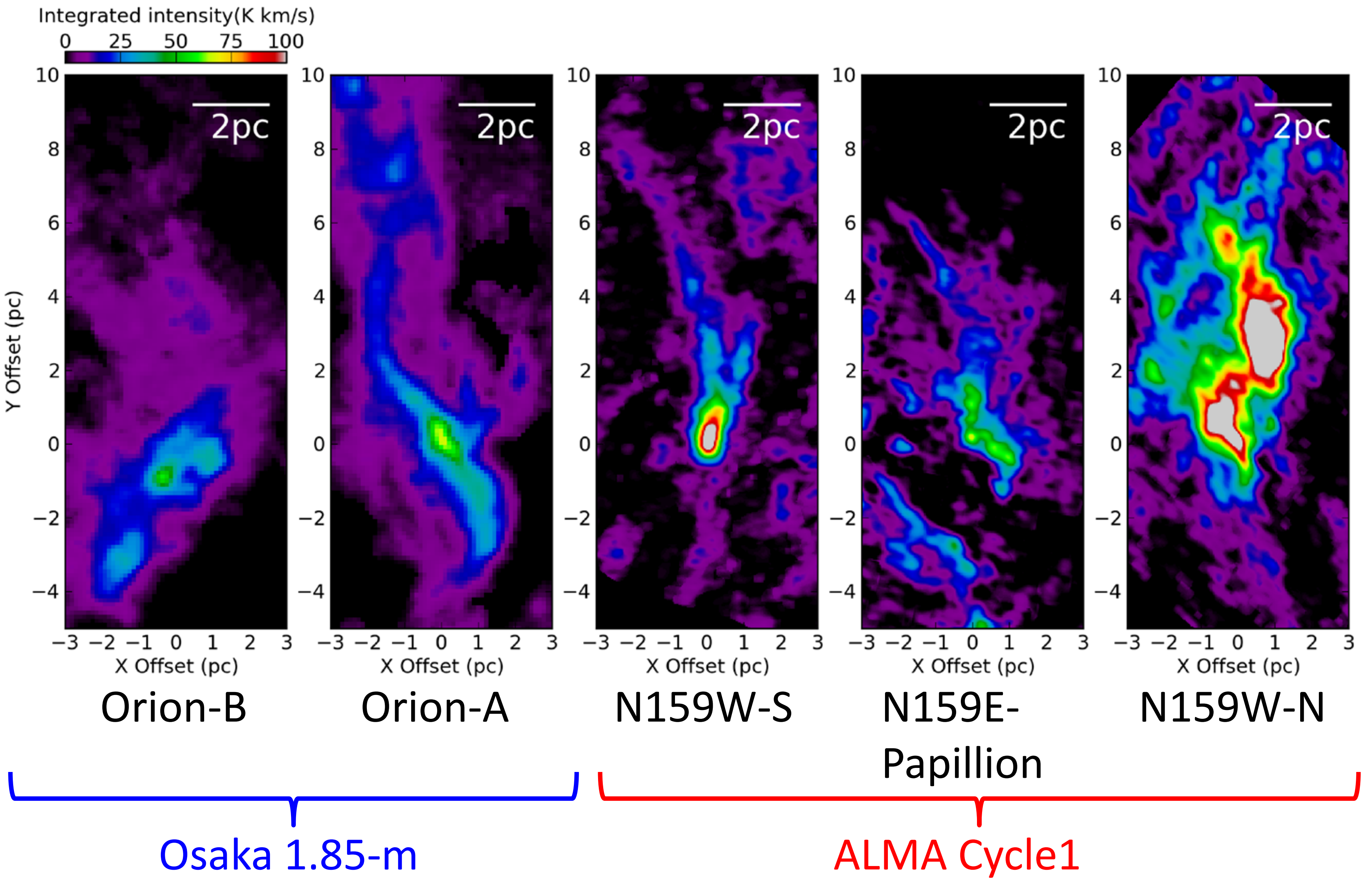
Higher column density in N159E/W

Osaka 1.85-m

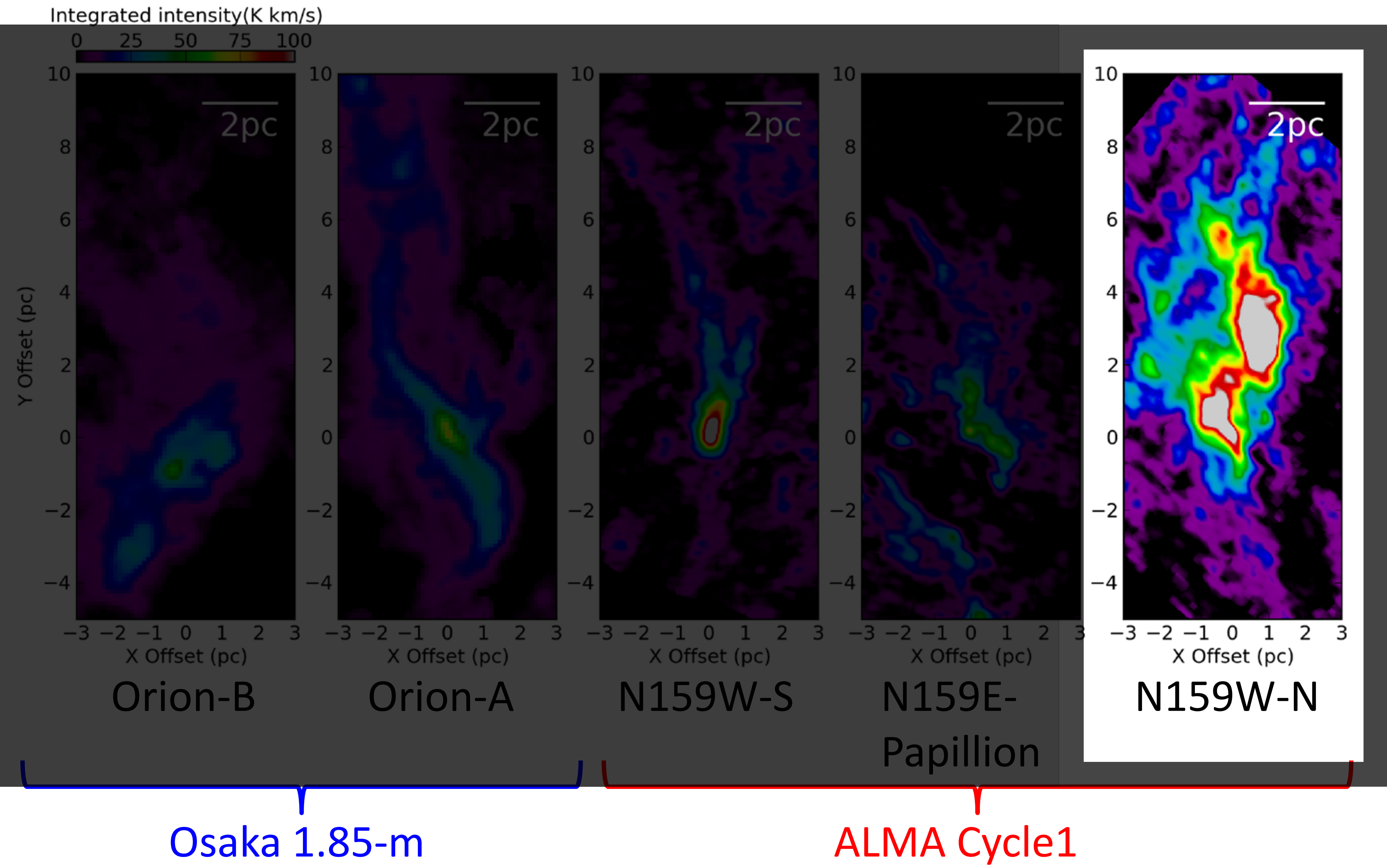
ALMA

IRAM 30-m

High density core in N159W-North



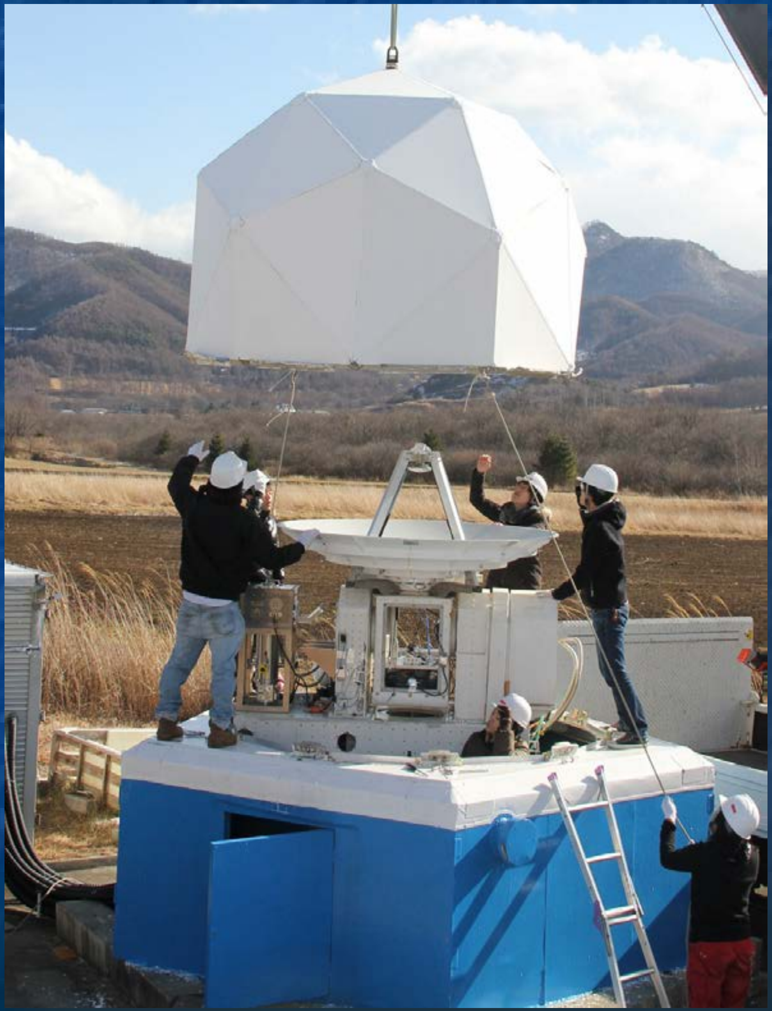
High density core in N159W-North



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??

1.85m telescope

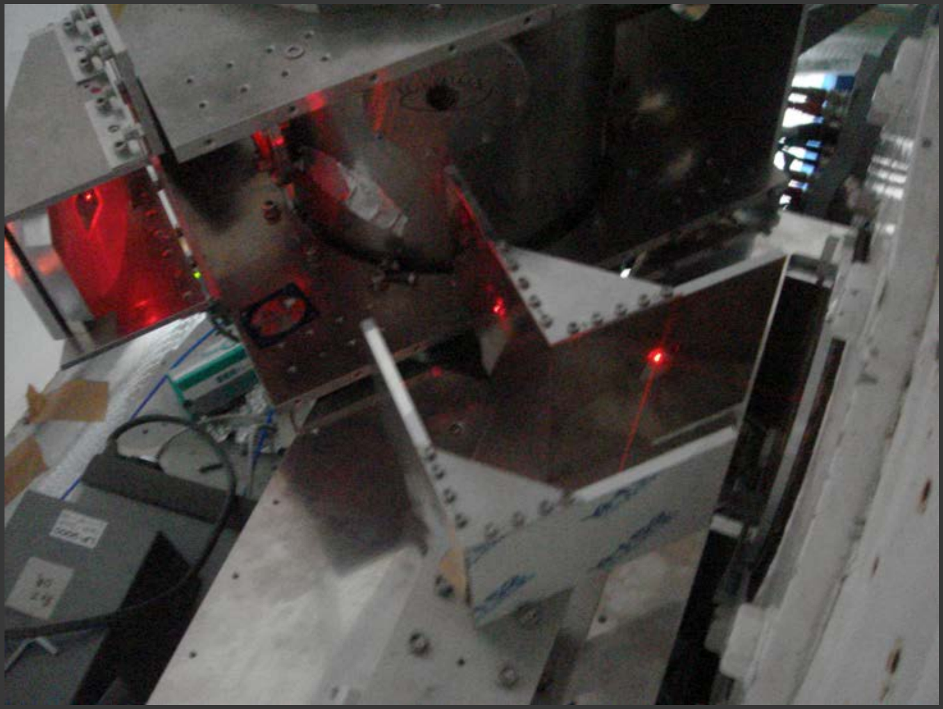


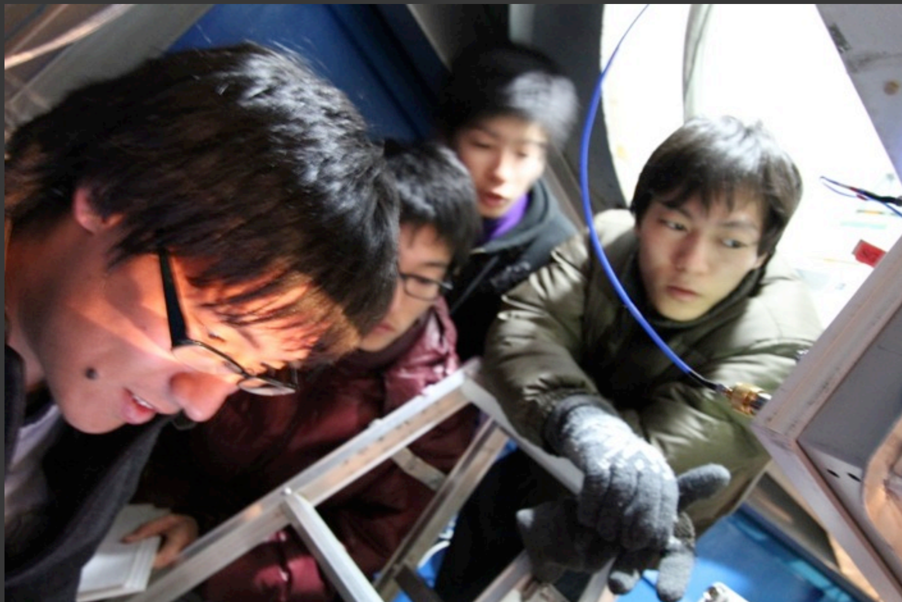
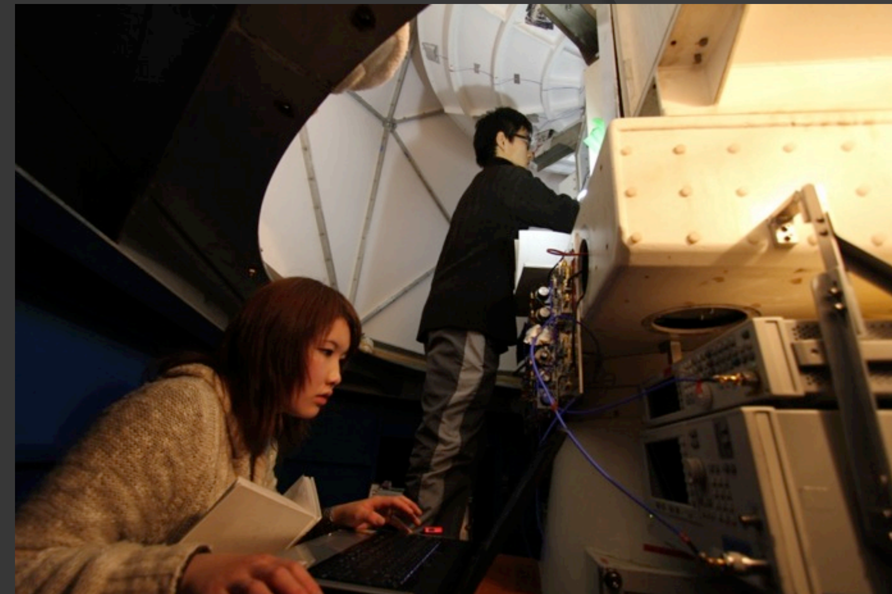
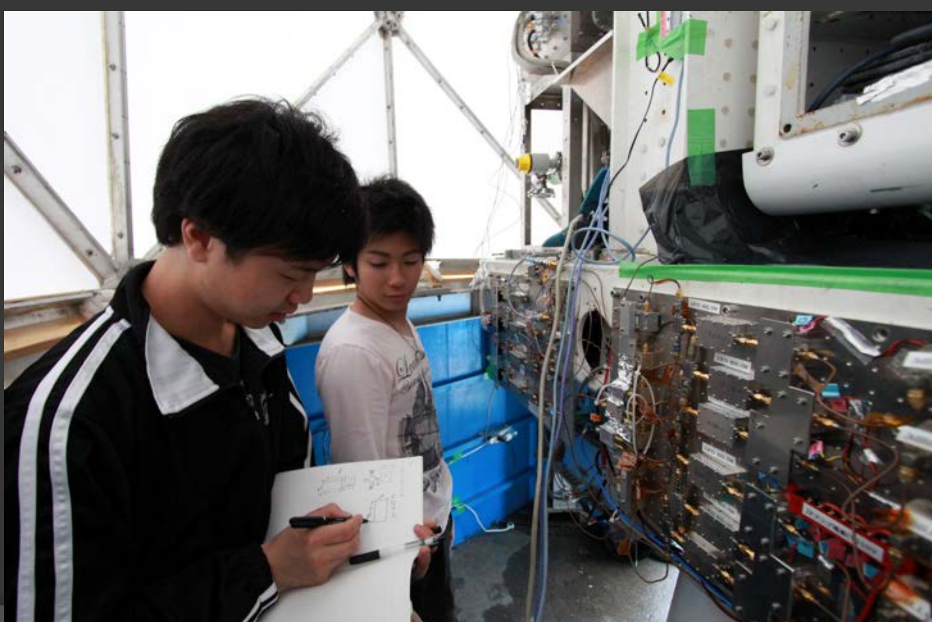
- ^{12}CO, ^{13}CO, $C^{18}O$ (J=2–1) simultaneously
  - 2SB mixer, Dual pol.
- Beam size: 2.7 arcmin
  - 0.1pc@140pc, 1pc@1-2kpc
- Targets
  - GMCs (^{12}CO, ^{13}CO)
  - Dense cores ($C^{18}O$)
  - Comparison with larger radio telescopes, Planck, Fermi, Akari, Herschel

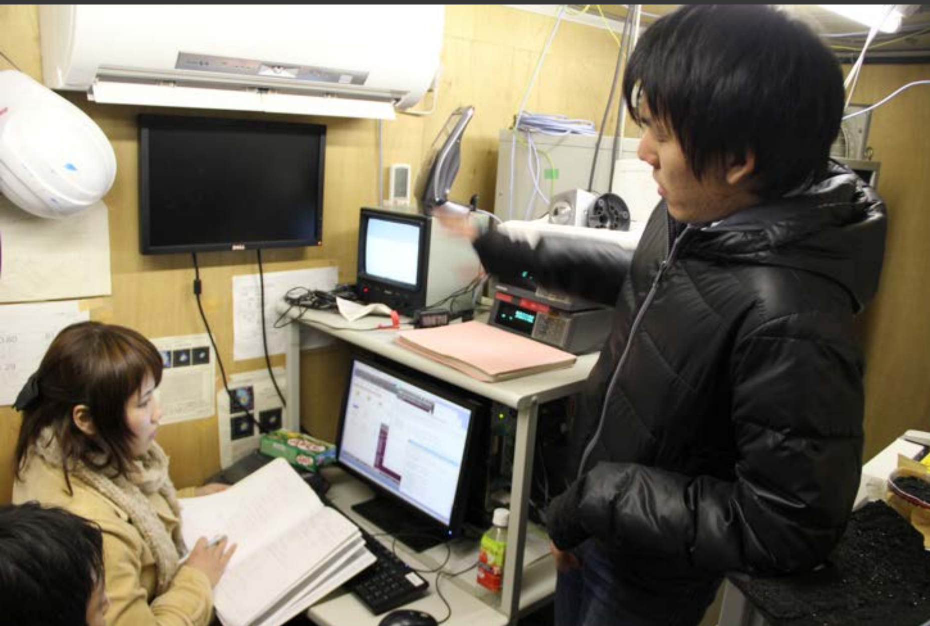


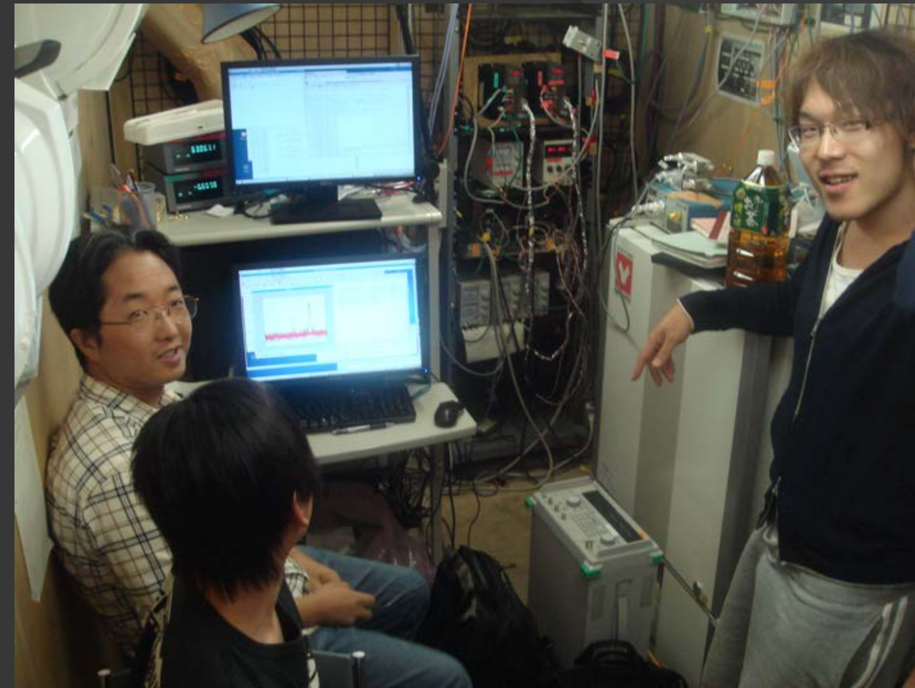
S
180

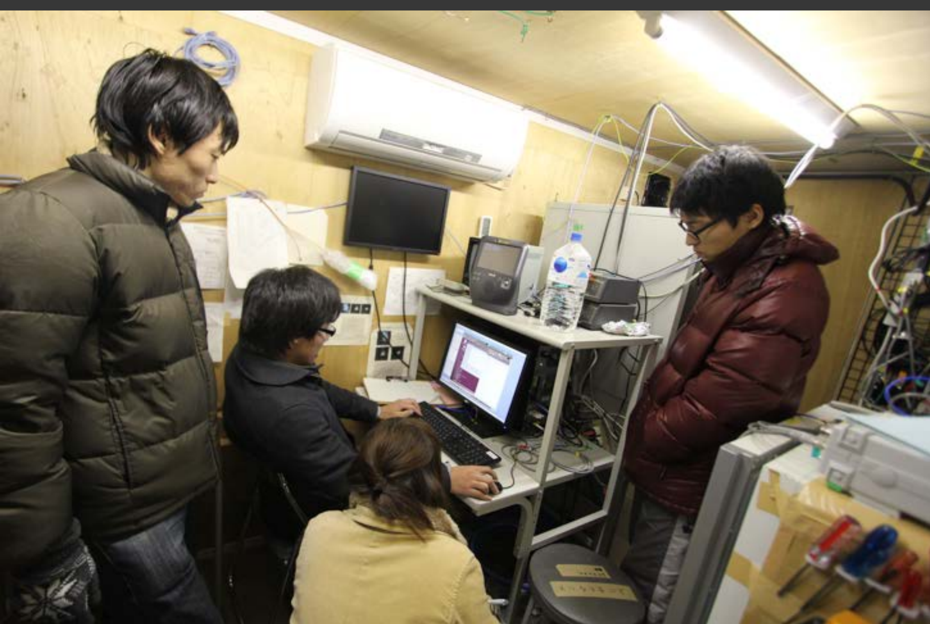

UNIC



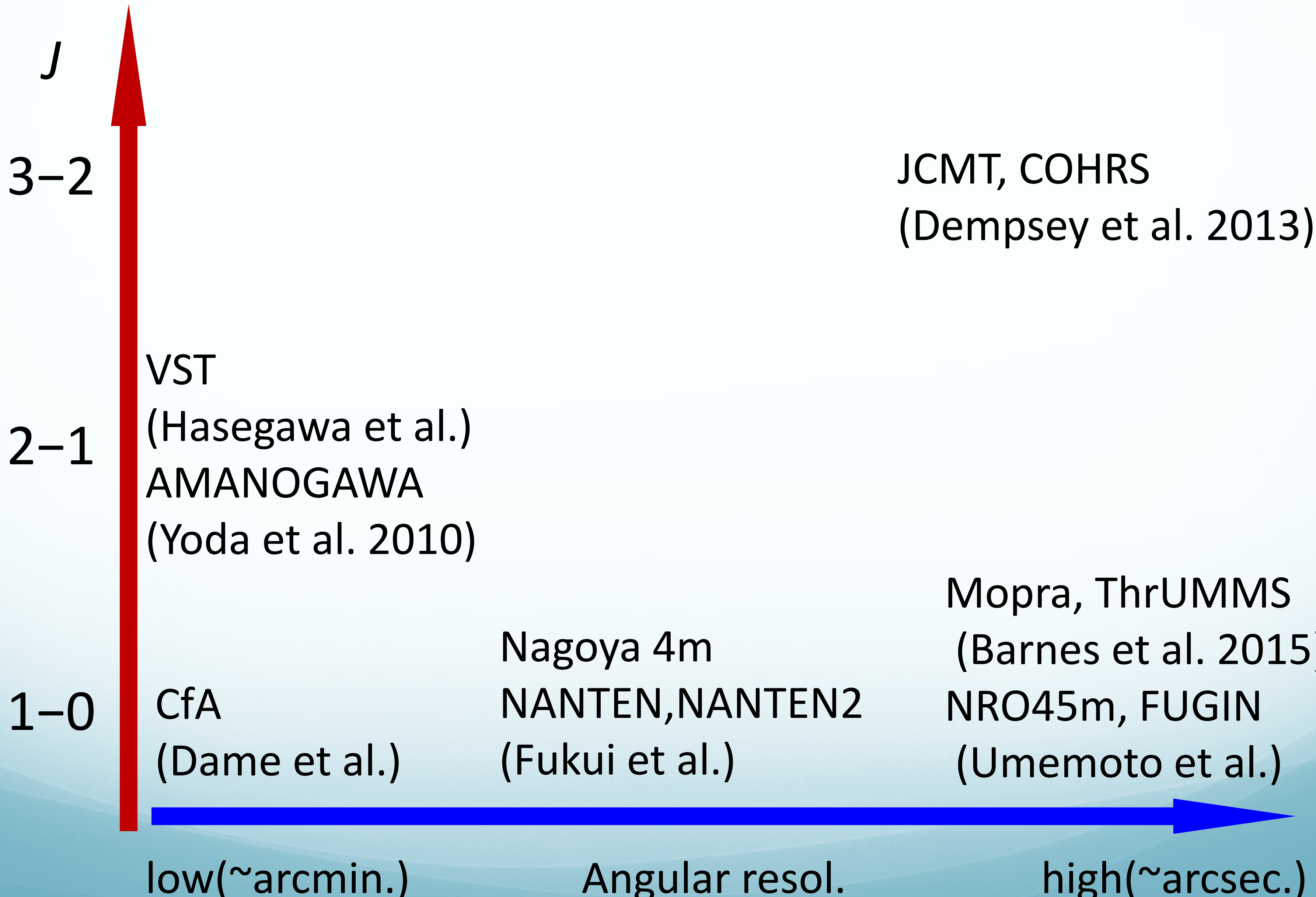





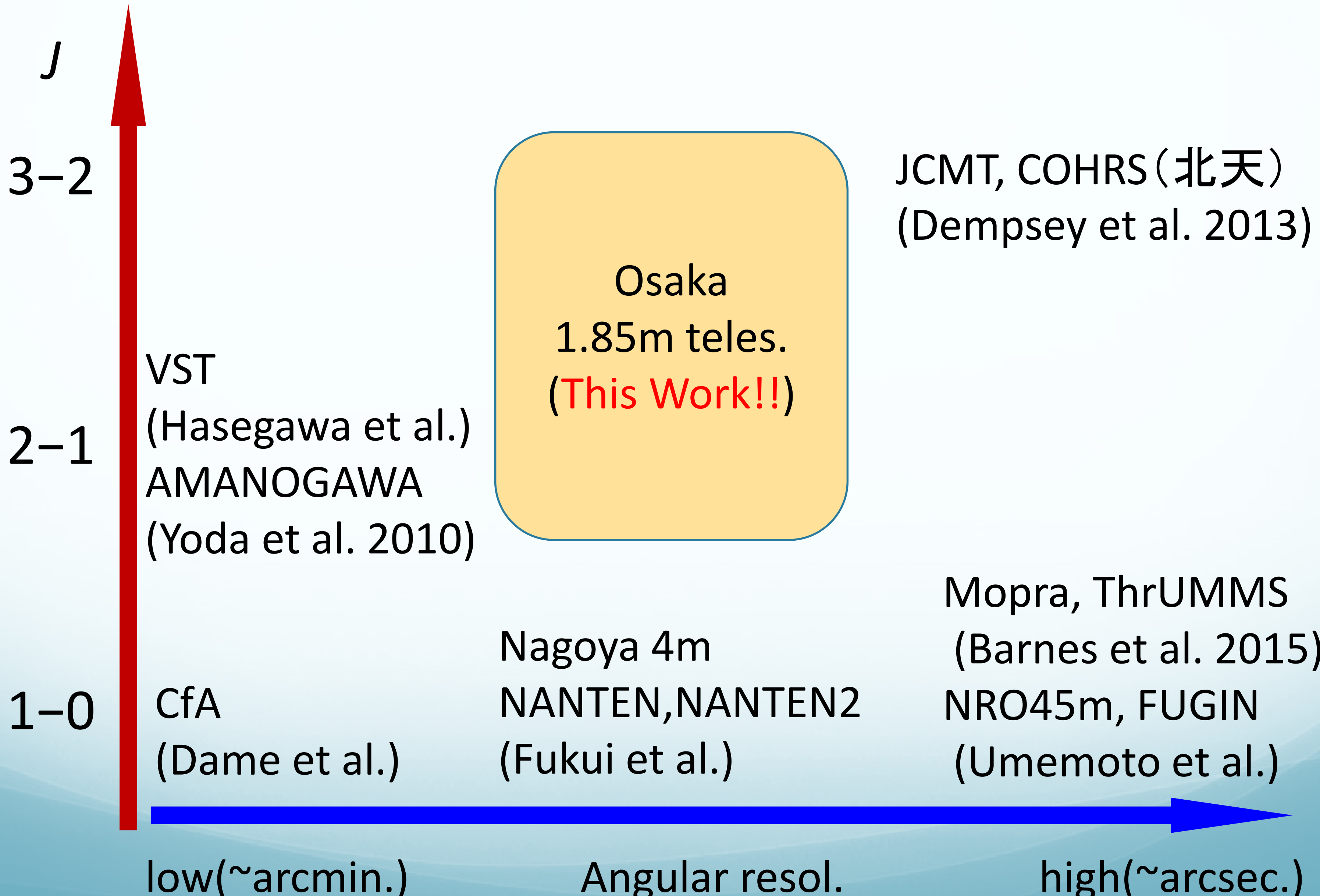



80-80

Galactic Plane Survey

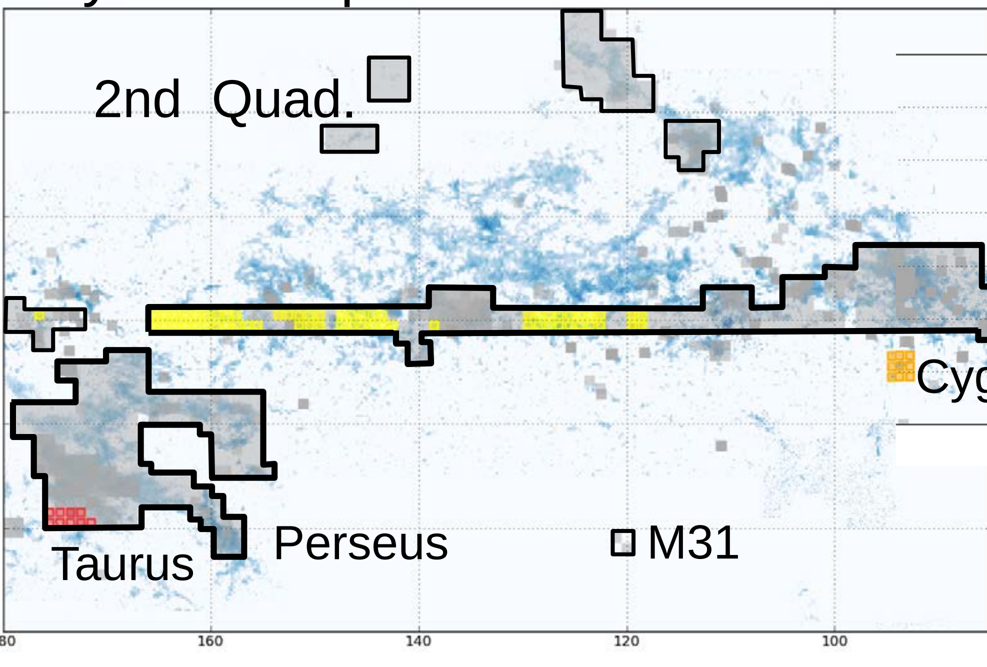


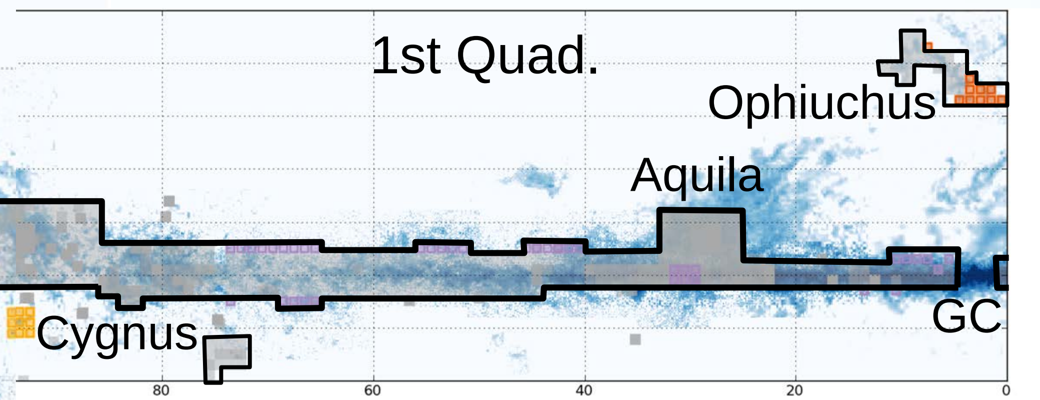
Galactic Plane Survey



Coverage

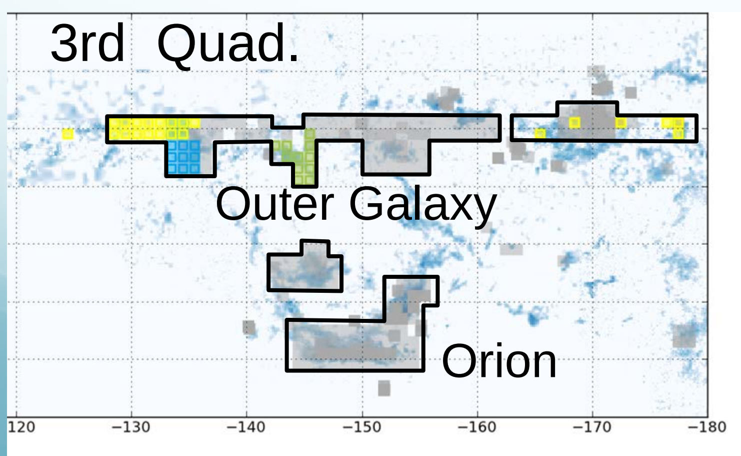
5 years of operations





Back ground : CO (1–0) Dame et al. 2001

Gray : 2010~2013
Color : 2014~

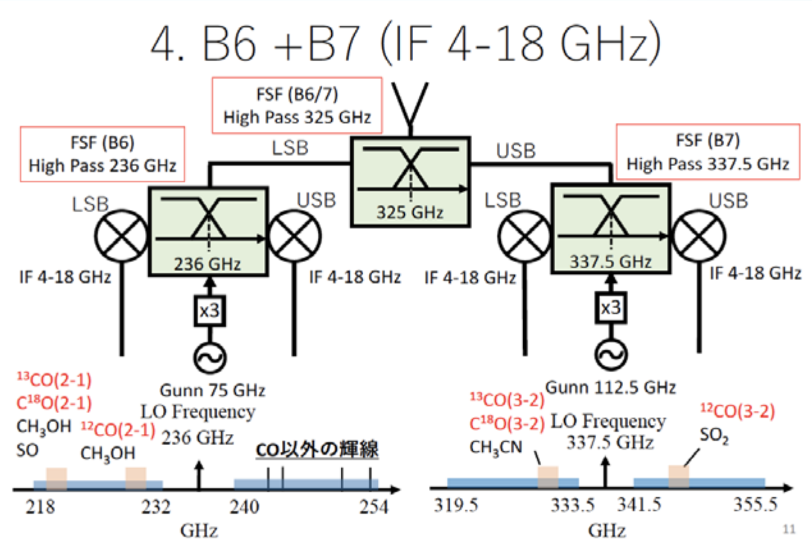


Parameters

Area covered	~1450 square degrees
Ang. reso.	~ 3’
Grid size	1’
RMS noise	~ 0.45 K (@dv ~ 0.3km/s)

1.85m telescope→Chile

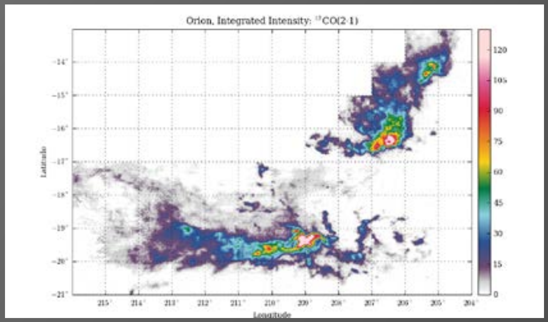
- TAO facility in San Pedro de Atacama（@2500m）
  - ALMA site is expensive!!
- Ultra-wide band receivers（NAOJ + Osaka Pref. Univ.）
  - Band 6 (230GHz)+7 (345GHz) receivers
  - Wide IF: 4-18GHz (→ 4-25GHz)
  - CO(J=2-1, 3-2) simultaneous obs.
- Targets
  - Galactic Plane
  - Magellanic Clouds



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.

1.85m telescope
Orion



SMALL ⟷ LARGE in Chile

ALMA
LMC