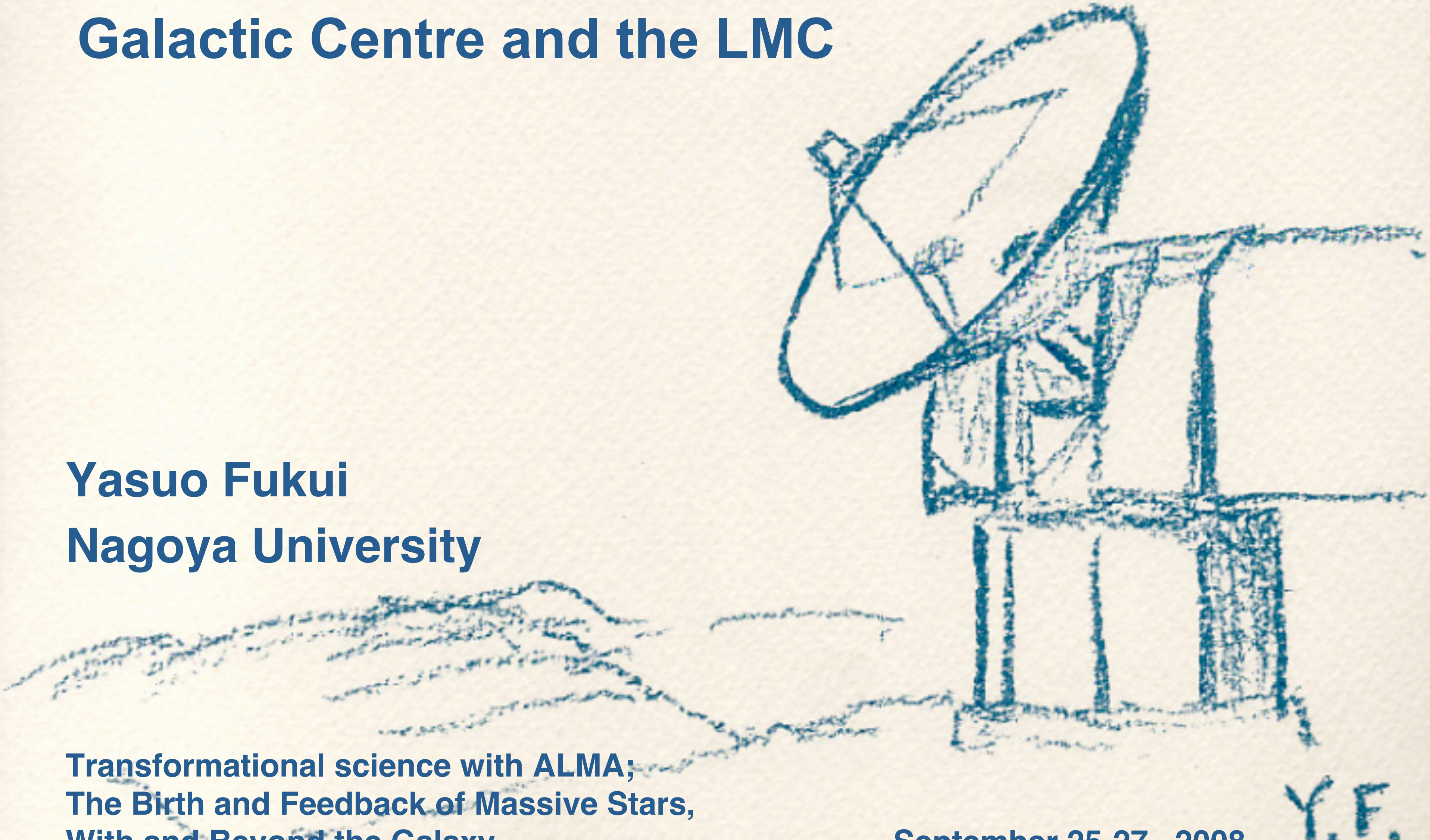
NANTEN
Submillimeter Observatory

What are the conditions for making massive star clusters; lessons in the Galactic Centre and the LMC

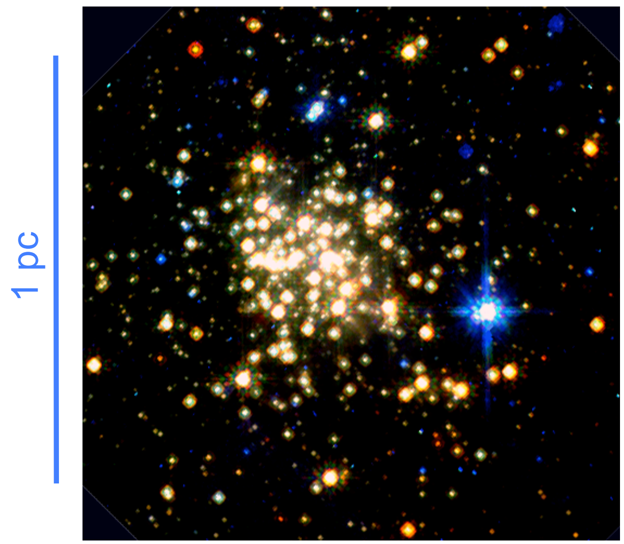


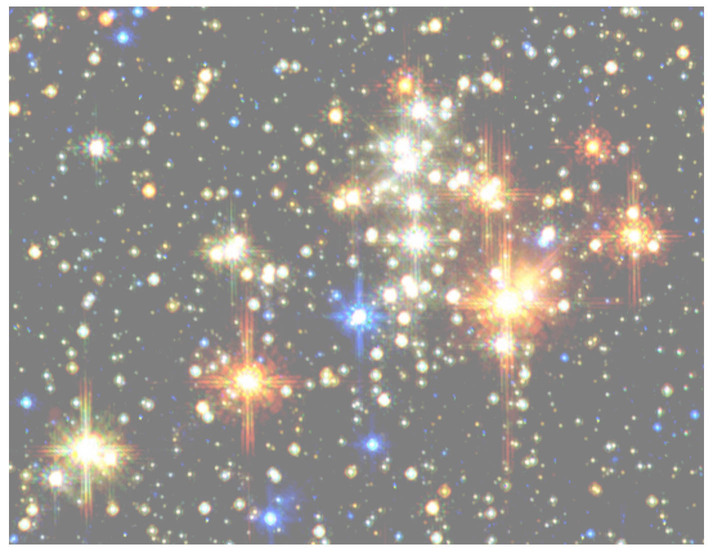
Yasuo Fukui
Nagoya University

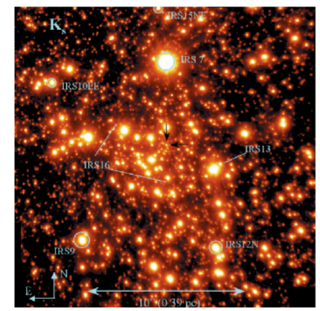
Transformational science with ALMA;
The Birth and Feedback of Massive Stars,
With and Beyond the Galaxy

September 25-27, 2008

Galactic Centre Clusters







Arches Cluster, Quintuplet Cluster, Central Cluster
HST•NICMOS, VLT•NOAS•CONICA

Figer et al. 1999; Genzel et al. 2003

Key Issue

- **Massive stars form in clusters**
- **Super clusters of 10^4 stars are the most extreme sites of numerous massive stars, WR's**
- **<u>How to form a super cluster</u>**

The Galaxy:

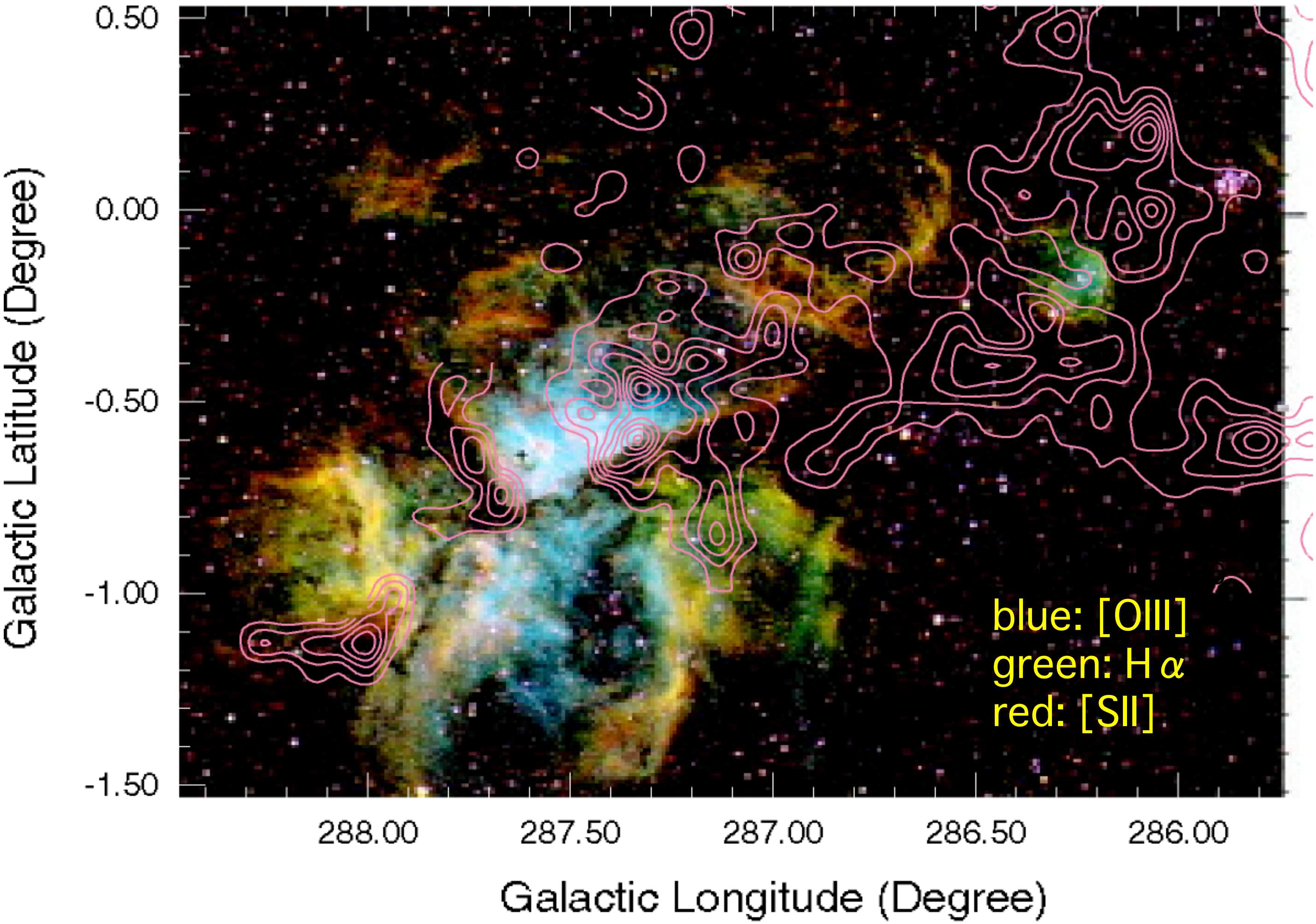
Disk - Westerlund 1 and Westerlund 2

Centre - Arches, Quintuplet, central cluster

The LMC:

Populous clusters, R136

Car GMC (Yonekura et al. 2005)

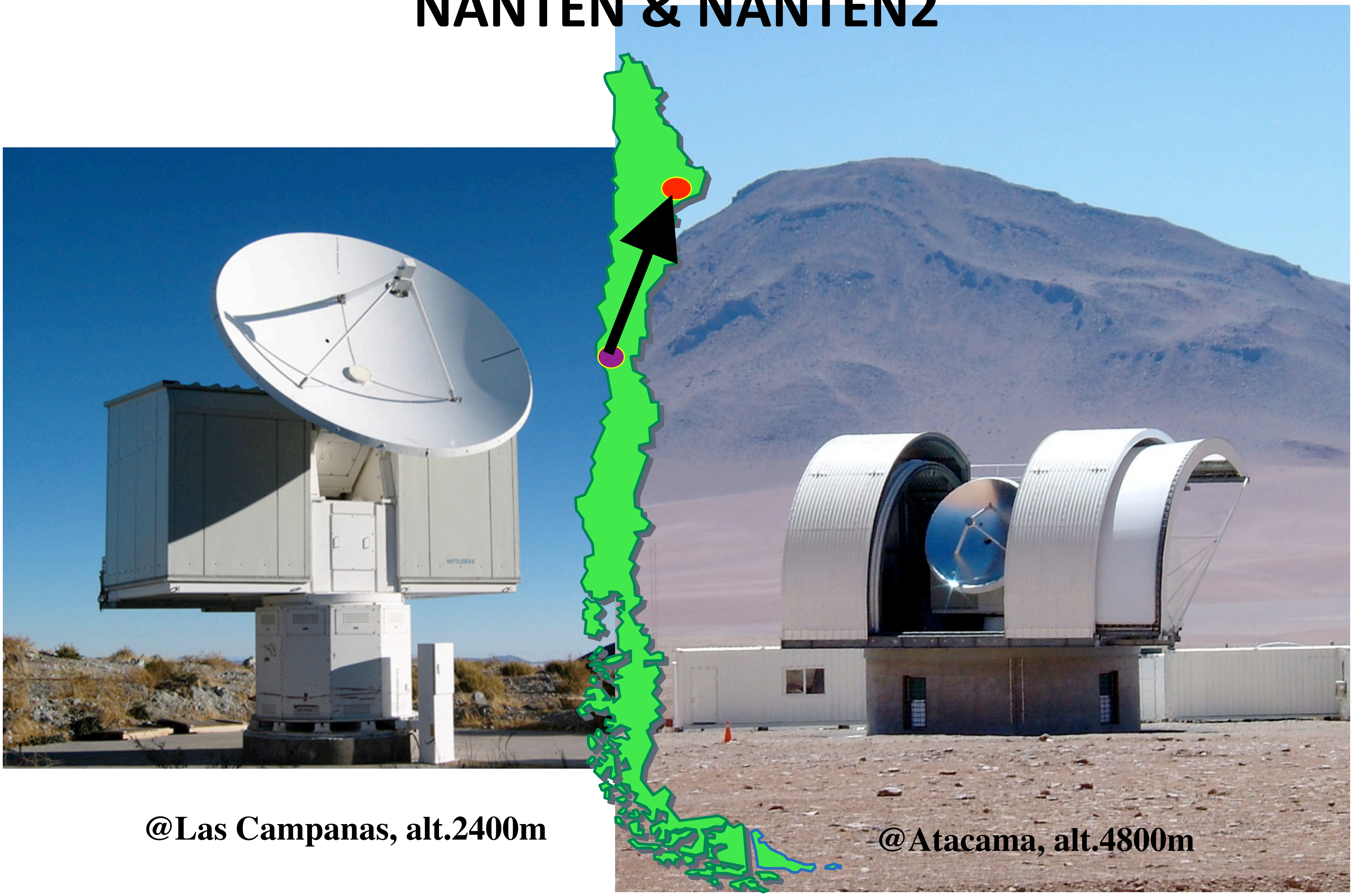


Pre-cluster cloud core; requirements

- **Compact, dense, massive cores;**
  mass $10^4 M_o$ – $10^5 M_o$, radius 1pc
- **These are rare in the solar vicinity, because a dense core of $10^3 M_o$ quickly forms a cluster and is dissipated e.g., η Carnae**
- **We need non-star forming dense gas [magnetic field, strong turbulence, etc.]**

- **Case 1: quick formation of cores by shocks at 10-100km/s and/or**
- **Case 2: slow formation (3km s-1) but with gas of low-star formation efficiency**

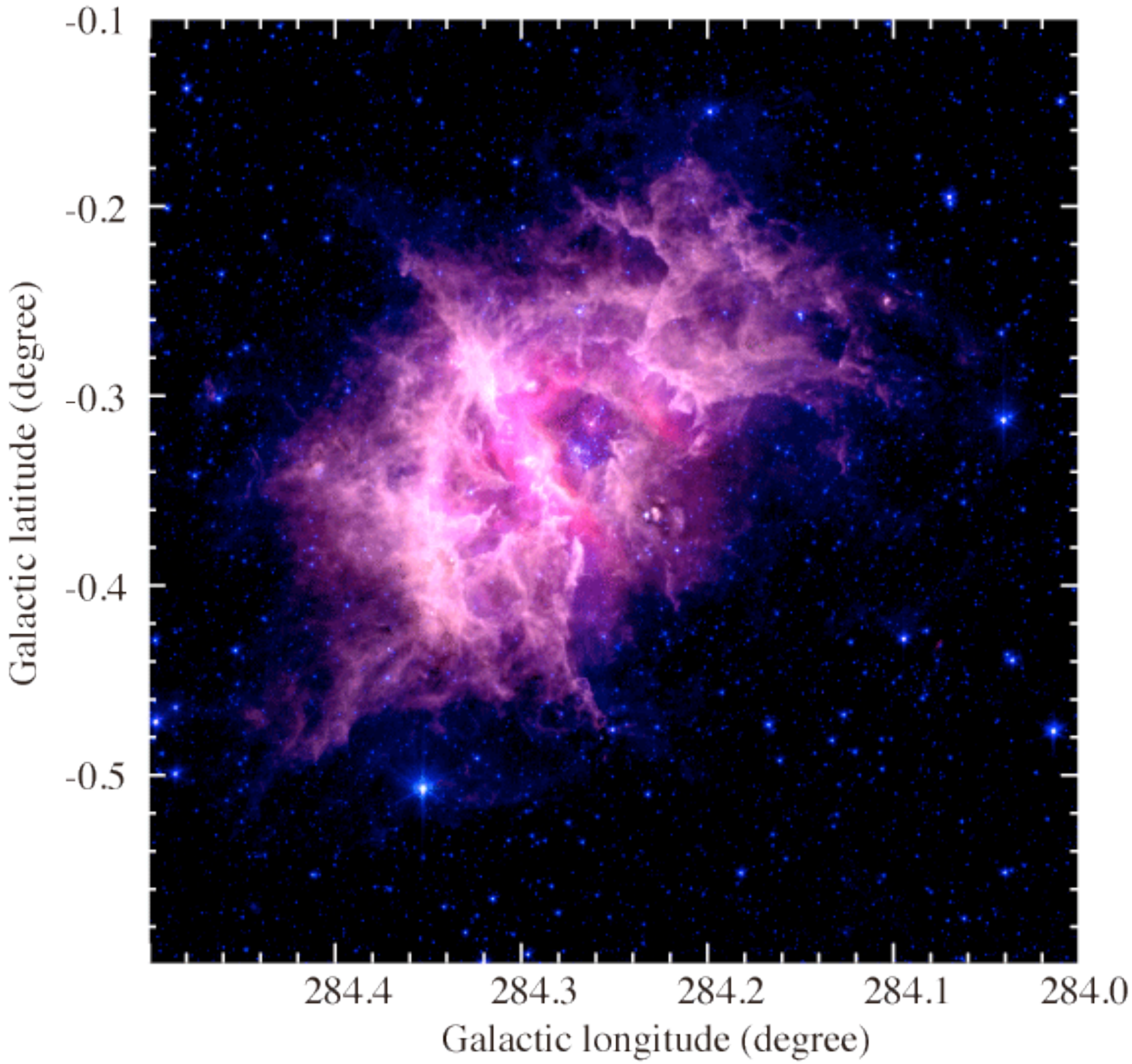
NANTEN & NANTEN2



@Las Campanas, alt.2400m

@Atacama, alt.4800m

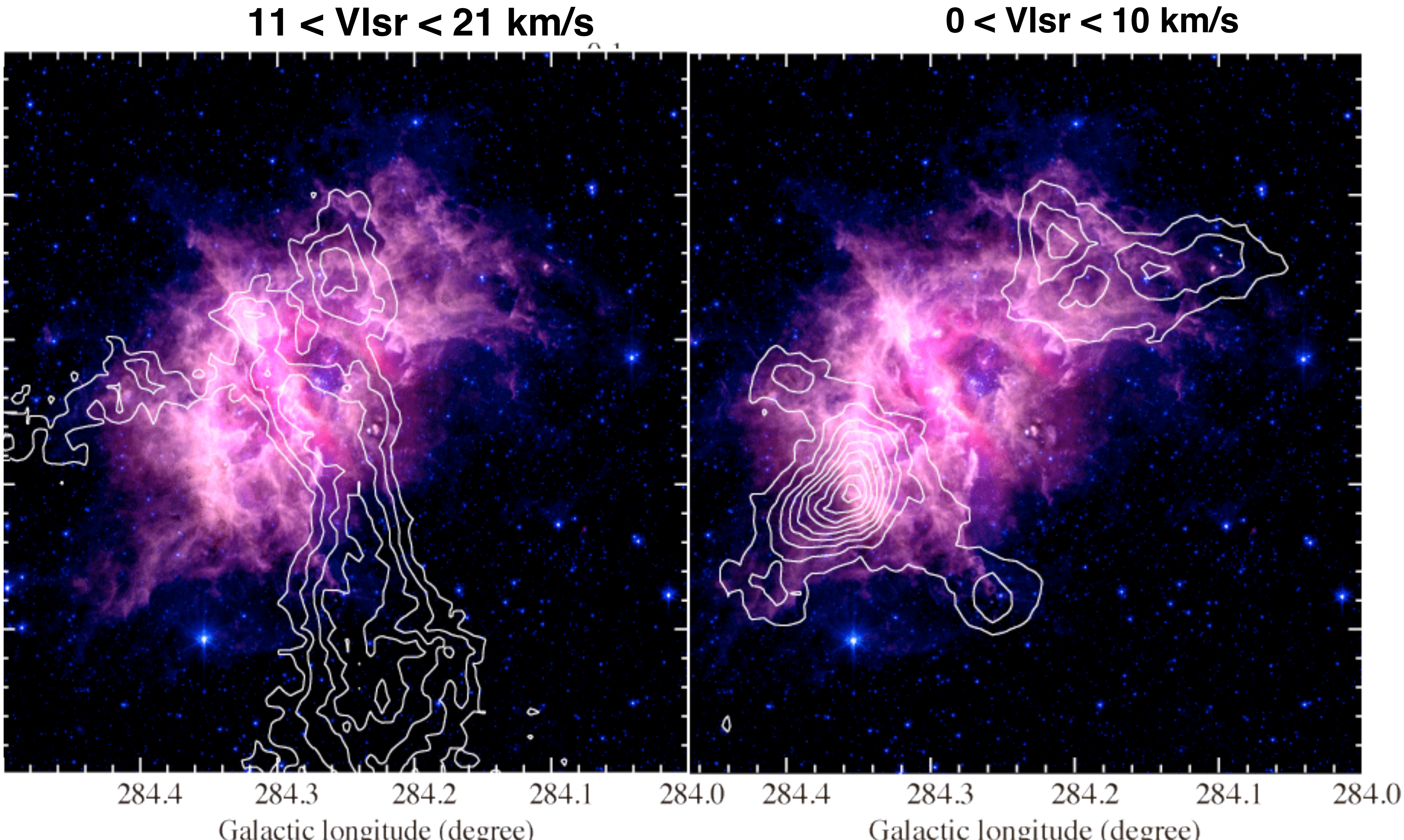
Westerlund 2 super cluster



Spitzer 3.6um, 5.8um, 8.0um (Churchwell et al. 2004)

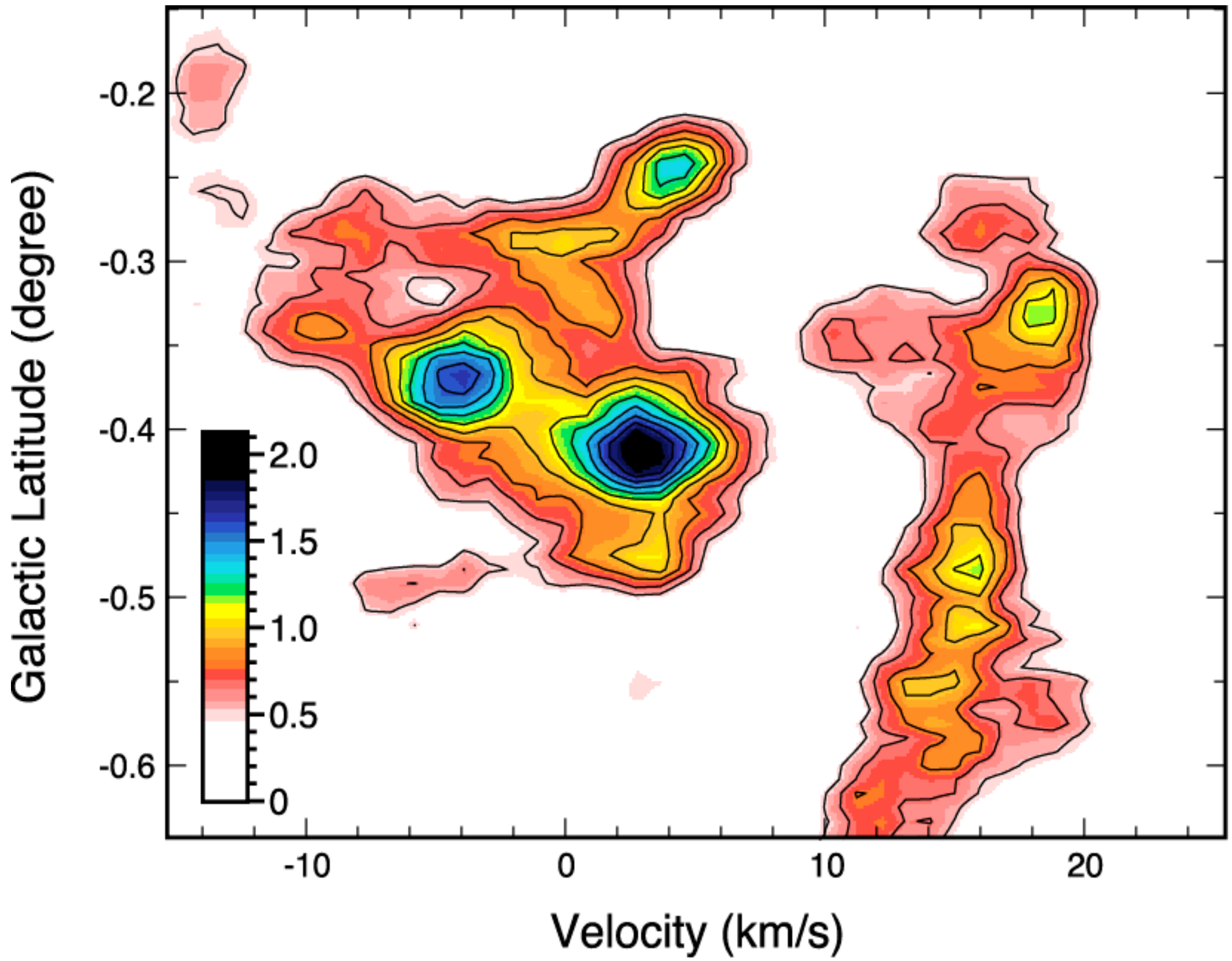
4500 stars (2WR)
Distance :
5kpc +-1kpc
Age : 2x10^6yrs

Wd2 NANTEN2 CO J=2-1 Furukawa et al. 2008



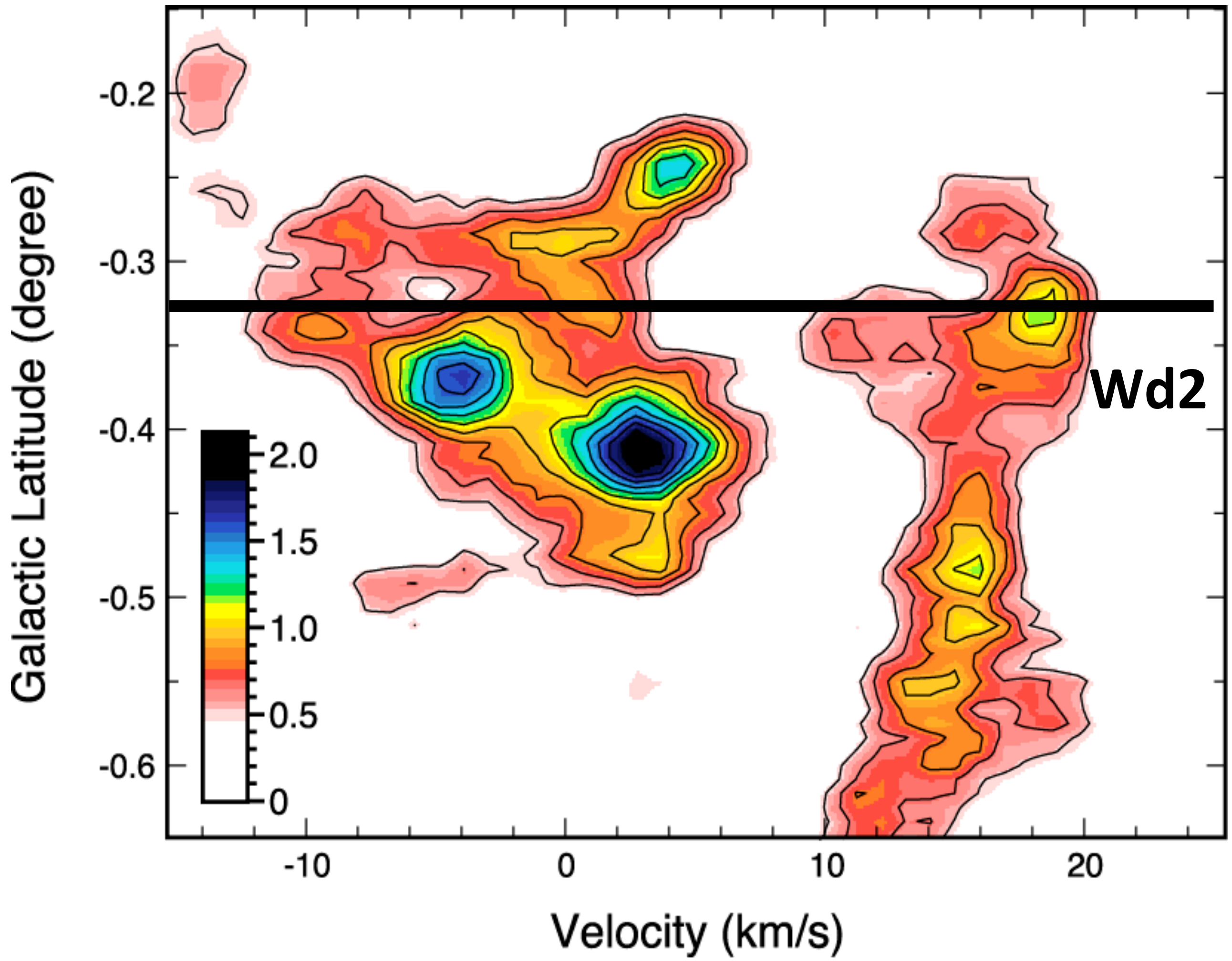
Spitzer 3.6um, 5.8um, 8.0um (Churchwell et al. 2004)

Velocity – latitude diagram of Molecular Clouds toward RCW49/Wd2



Integrated longitude
284.1 to 284.5 degree
Contour level
min. 0.5 K degrees
interval 0.15 K degrees

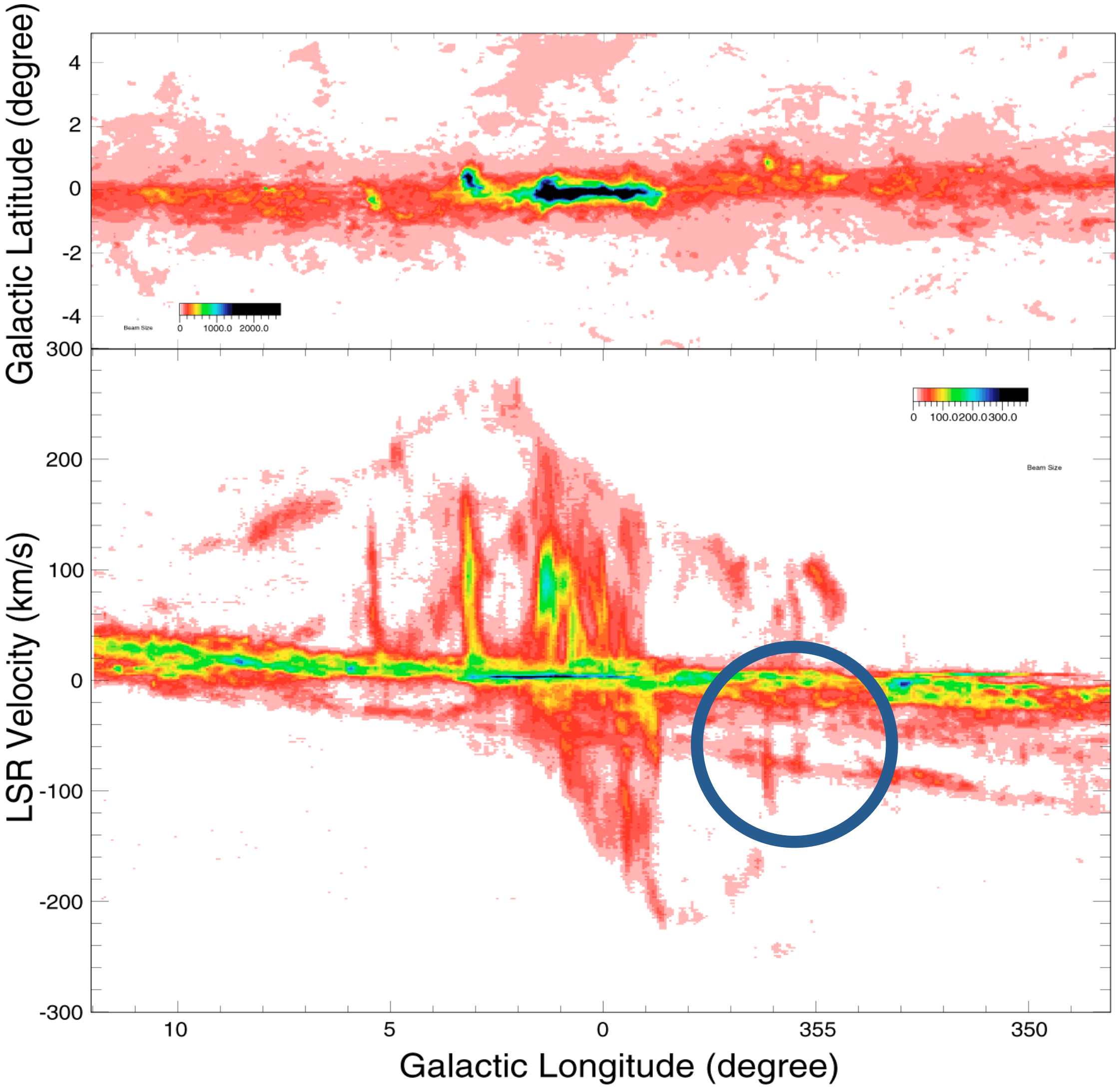
Velocity – latitude diagram of Molecular Clouds toward RCW49/Wd2



Two clouds collided and triggered super cluster formation

Integrated longitude
284.1 to 284.5 degree
Contour level
min. 0.5 K degrees
interval 0.15 K degrees

The Galactic Centre NANTEN CO J=1-0

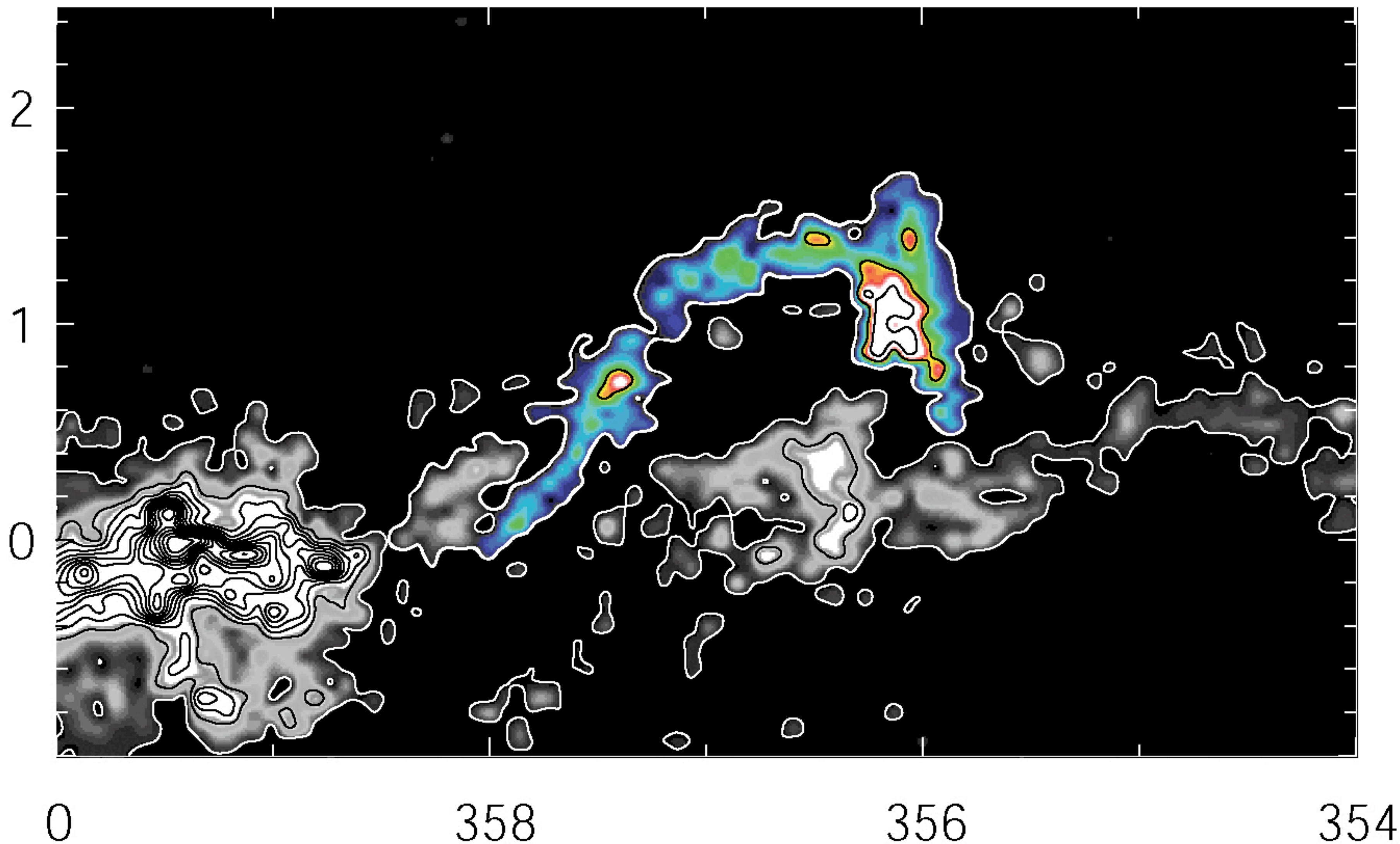


Violent gas motion of 50-150 km/s

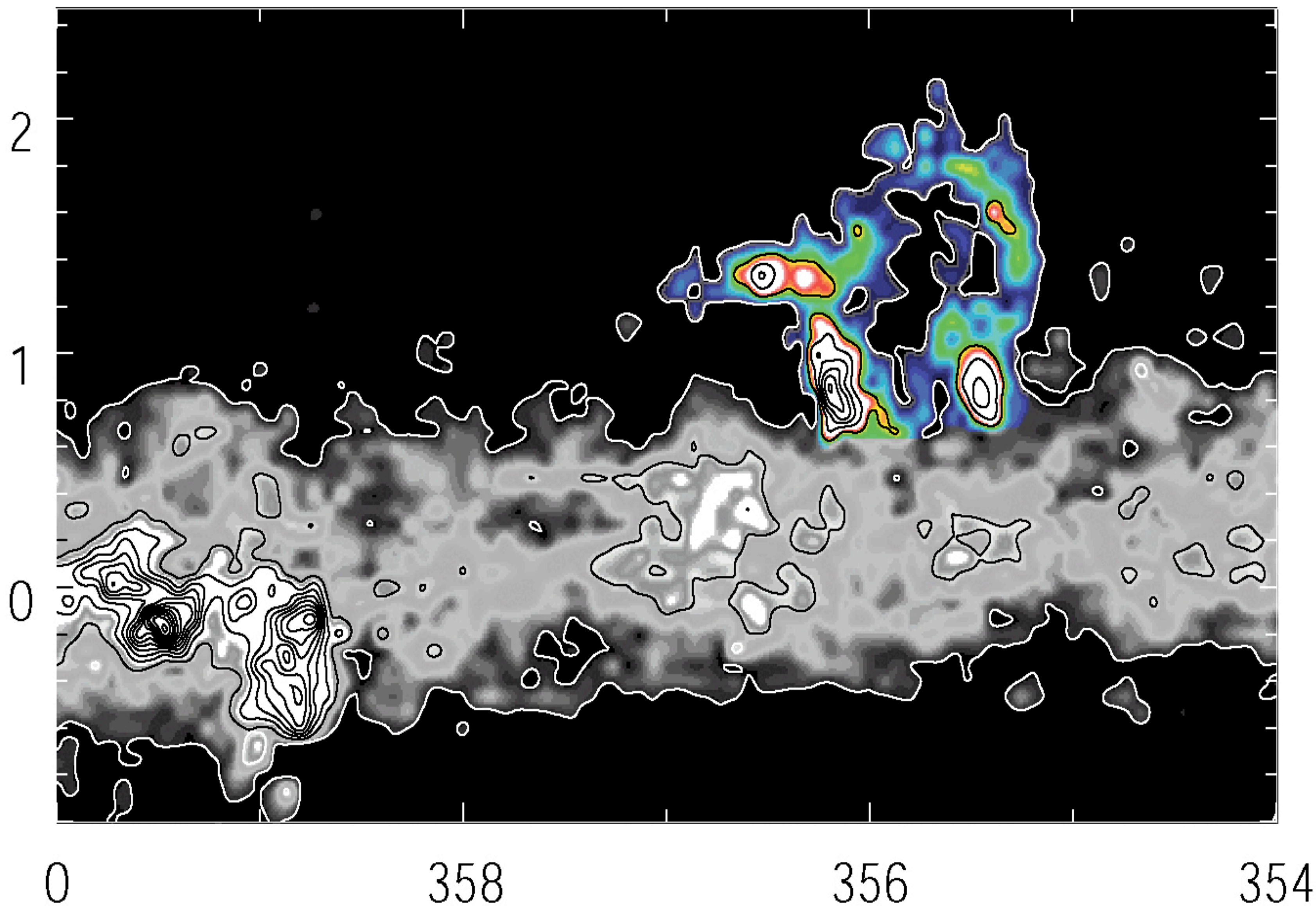
Sock compression leads to super cluster formation

Loop 1 discovered by NANTEN

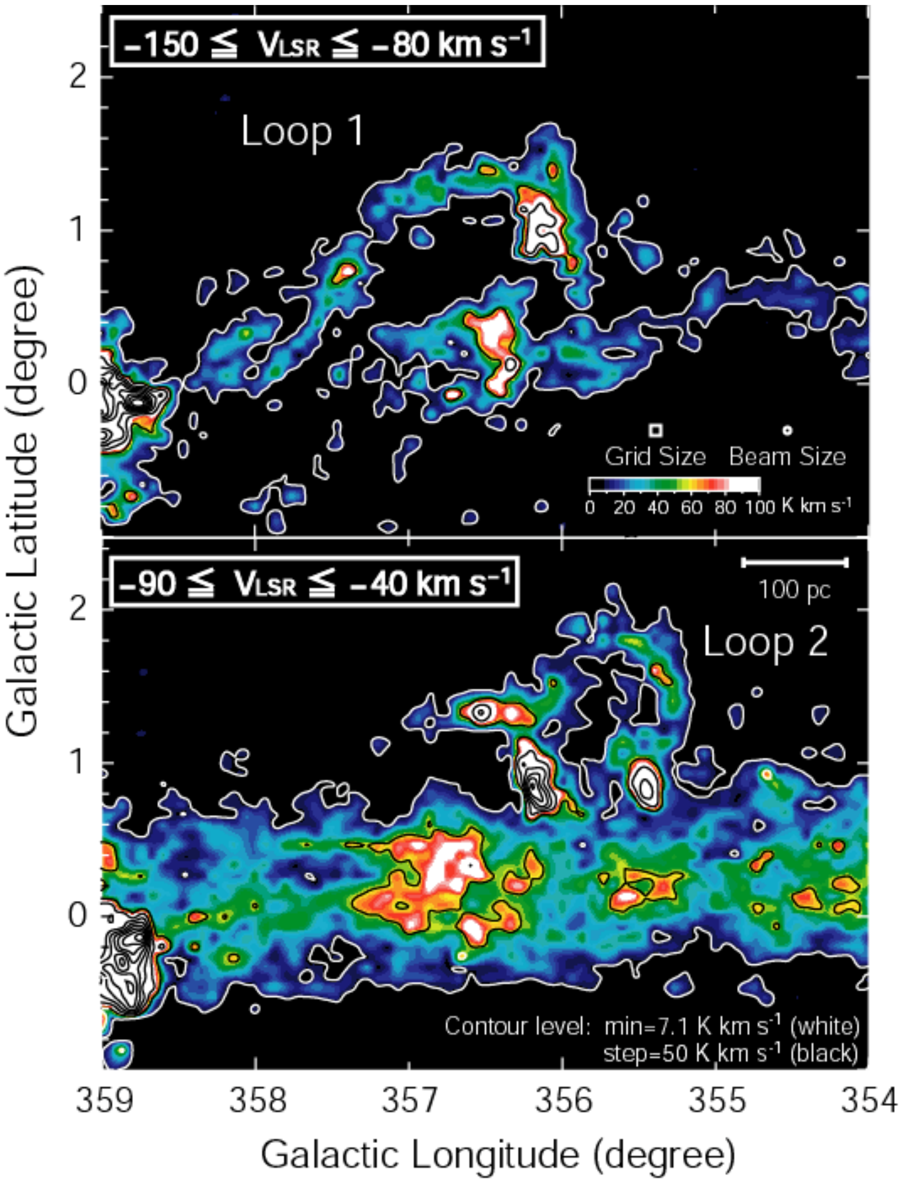
Y. Fukui et al. 2006, in Science 314, 106

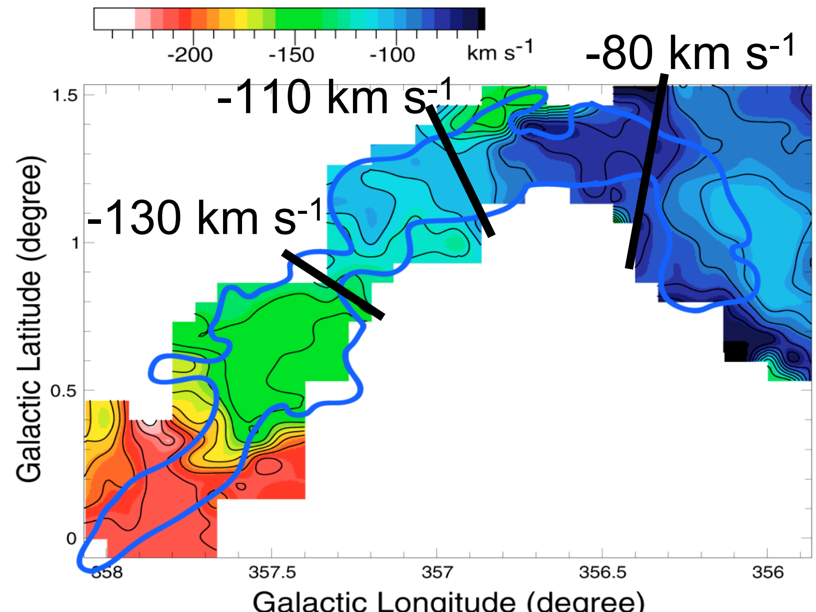


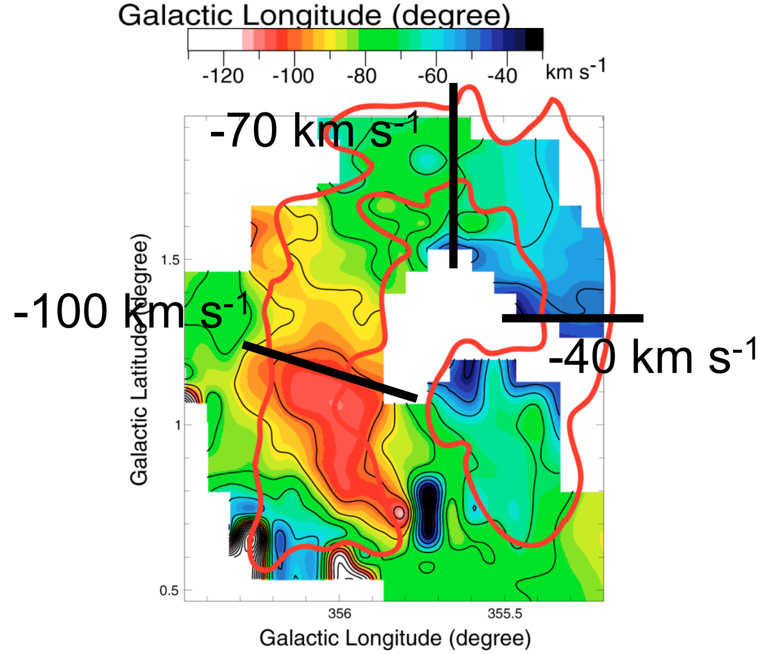
Loop 2 discovered by NANTEN



Molecular loops and velocity gradients

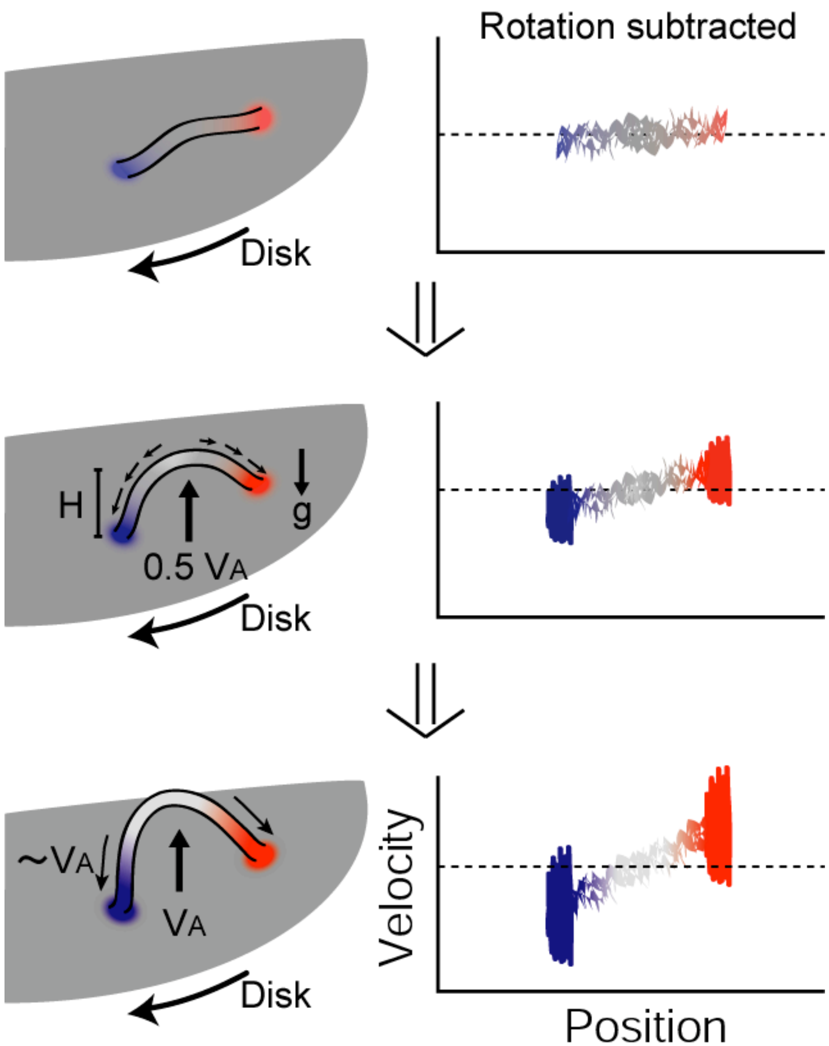




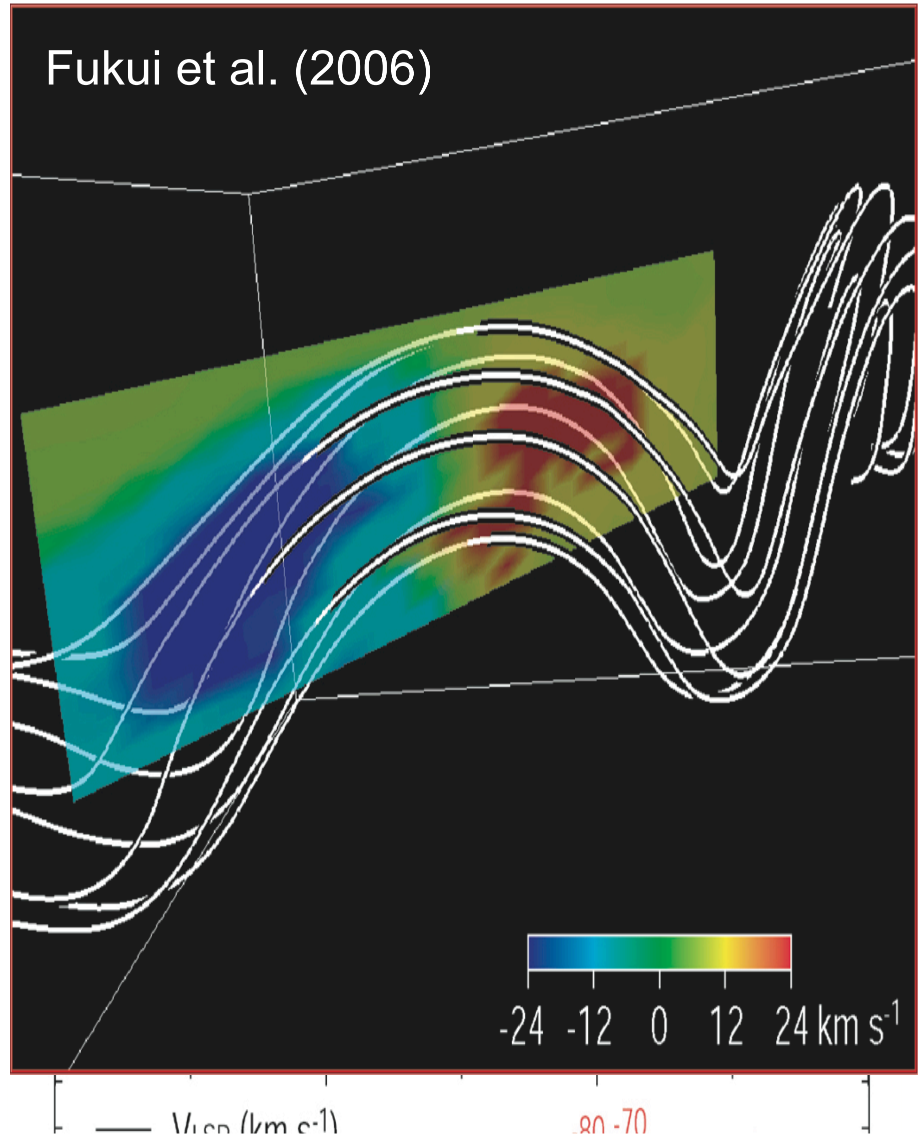


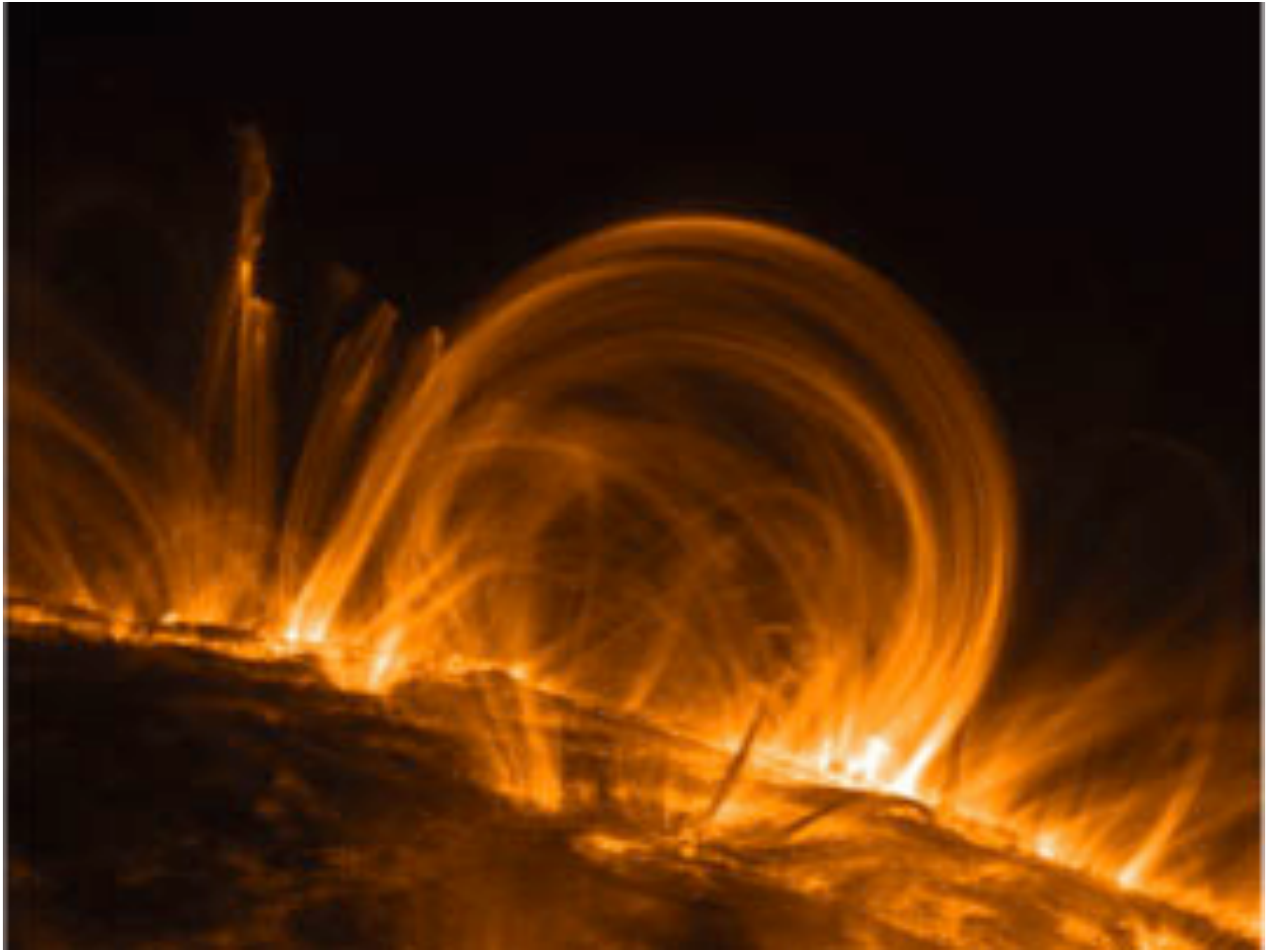
Formation of loop by magnetic flotation

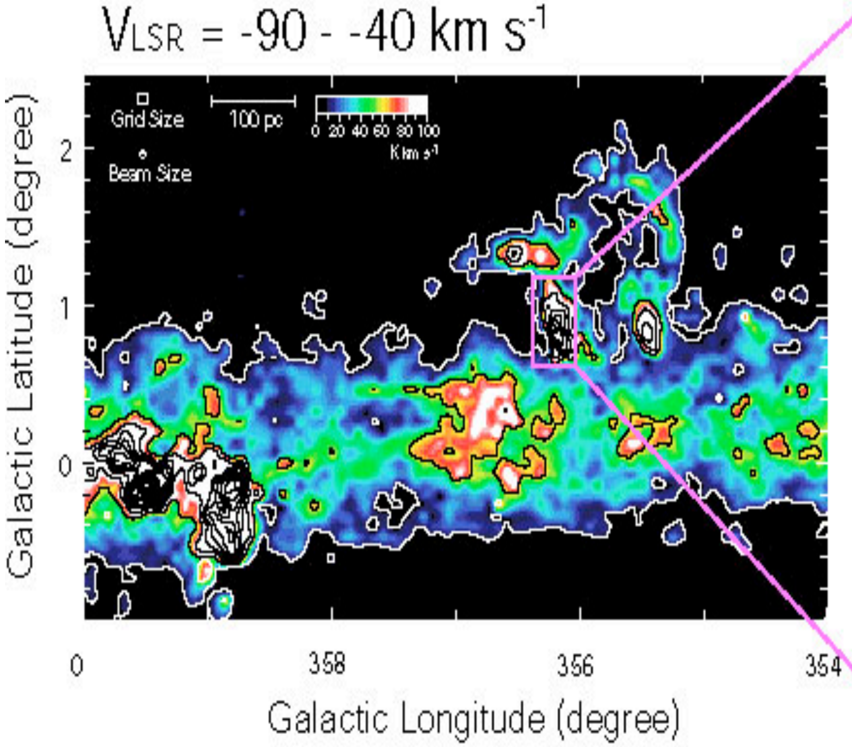
Schematic view of the scenario

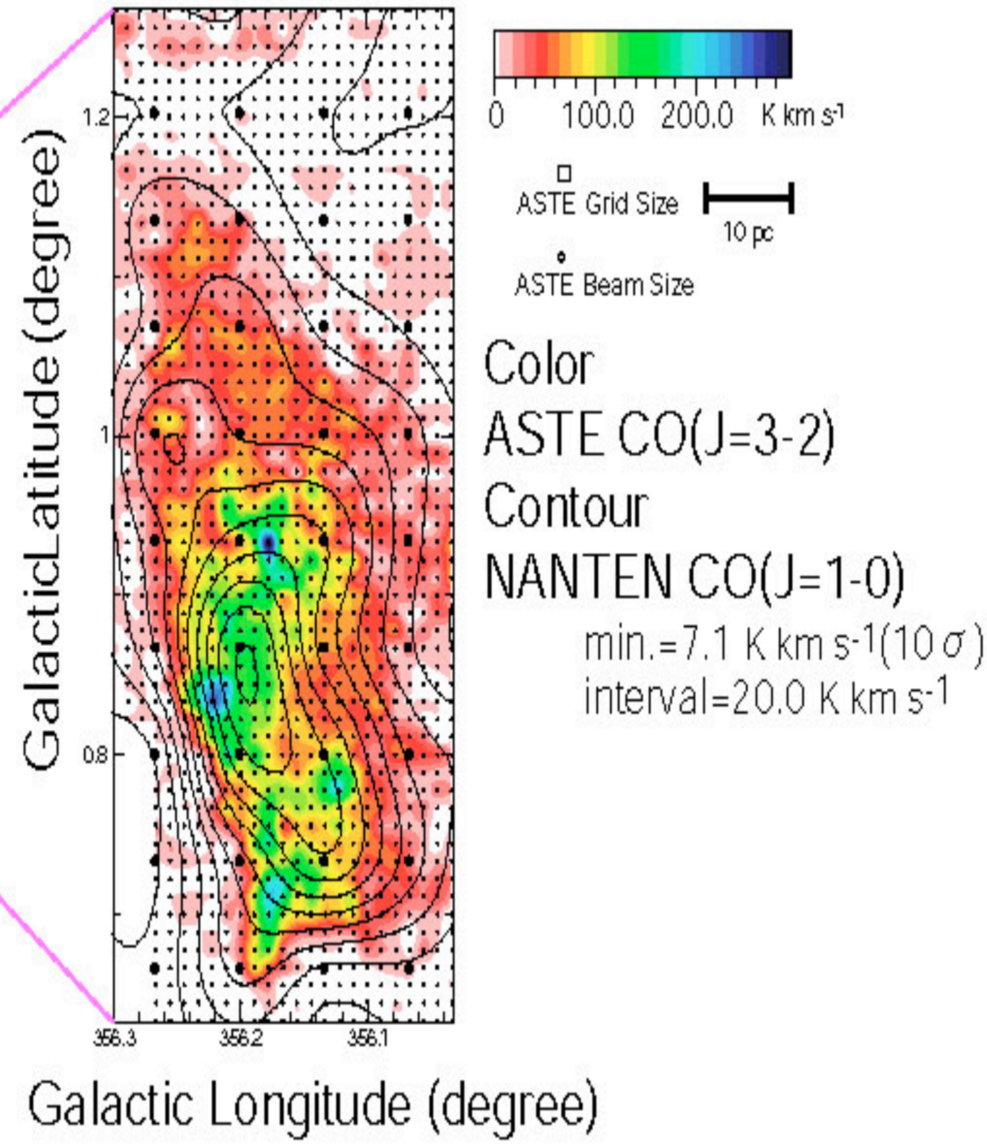


2D MHD simulations of Parker instability



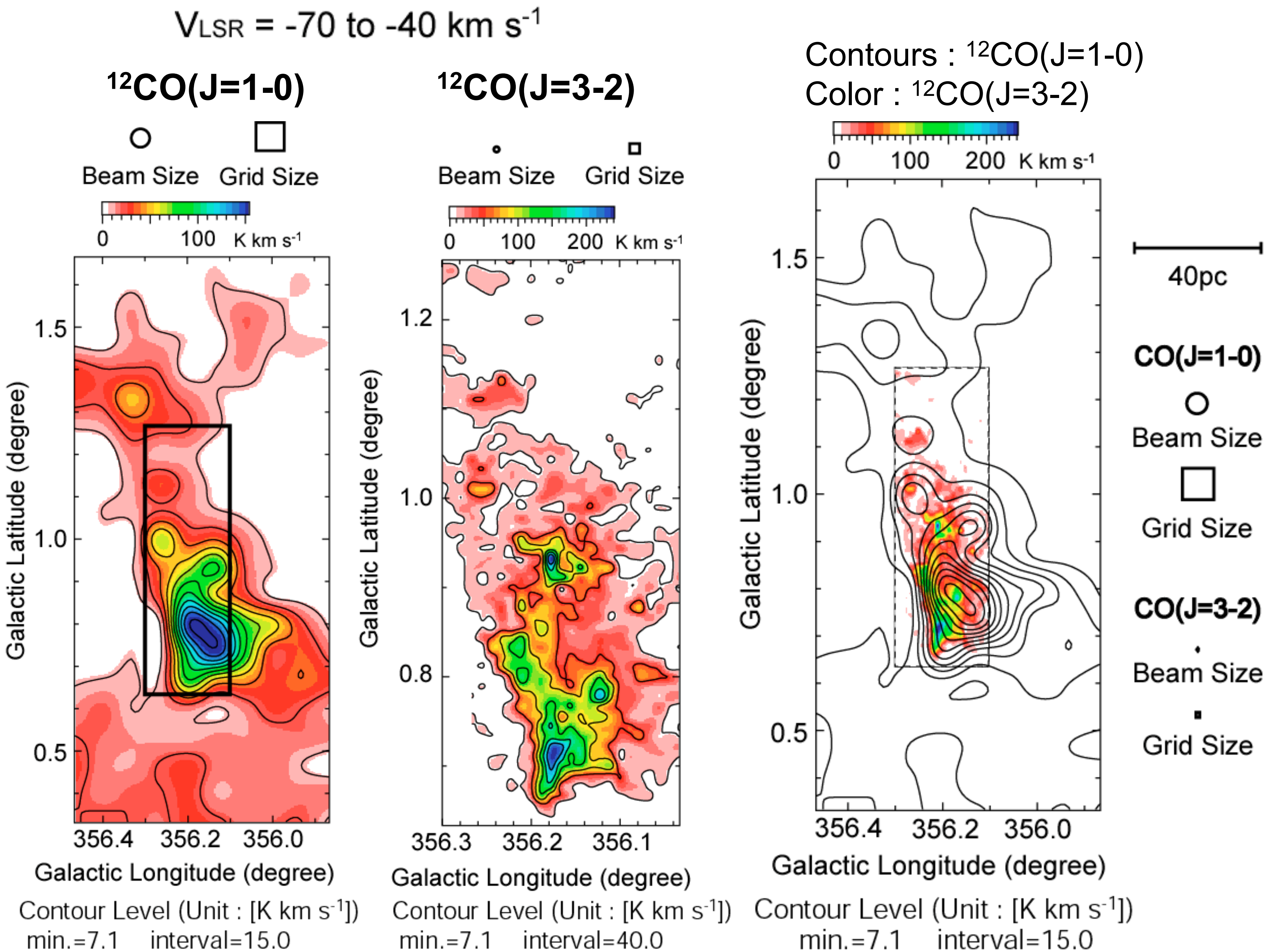






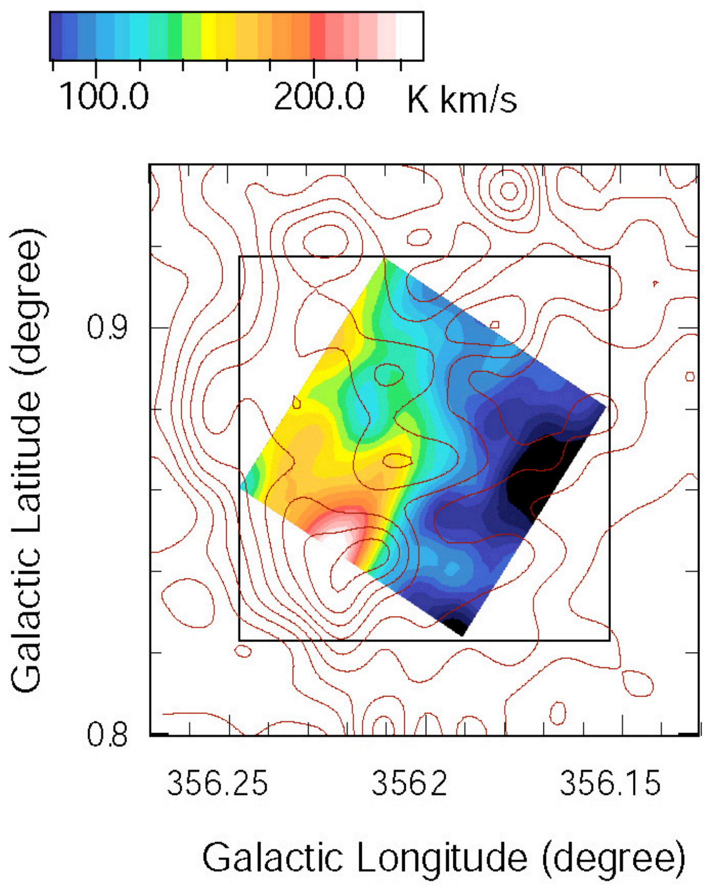
Sub-mm ASTE

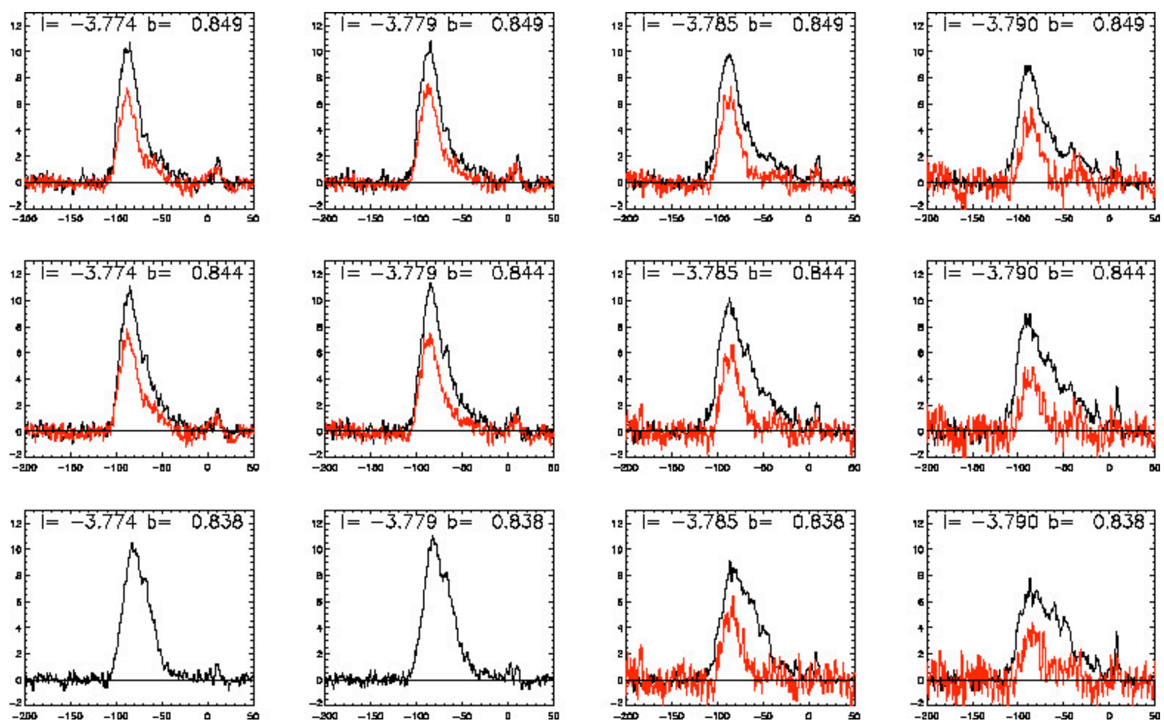
Probe shock heating etc.


VLSR = -70 to -40 km s-1
12CO(J=1-0)
Beam Size
Grid Size
0
100
K km s-1
1.5
1.0
0.5
Galactic Latitude (degree)
356.4
356.2
356.0
Galactic Longitude (degree)
Contour Level (Unit : [K km s-1])
min.=7.1 interval=15.0
12CO(J=3-2)
Beam Size
Grid Size
0
100
200
K km s-1
1.2
1.0
0.8
Galactic Latitude (degree)
356.3
356.2
356.1
Galactic Longitude (degree)
Contour Level (Unit : [K km s-1])
min.=7.1 interval=40.0
Contours : 12CO(J=1-0)
Color : 12CO(J=3-2)
0
100
200
K km s-1
1.5
1.0
0.5
Galactic Latitude (degree)
356.4
356.2
356.0
Galactic Longitude (degree)
Contour Level (Unit : [K km s-1])
min.=7.1 interval=15.0
40pc
CO(J=1-0)
Beam Size
Grid Size
CO(J=3-2)
Beam Size
Grid Size

NANTEN2 CO(J=4-3) Observations toward the Foot Point

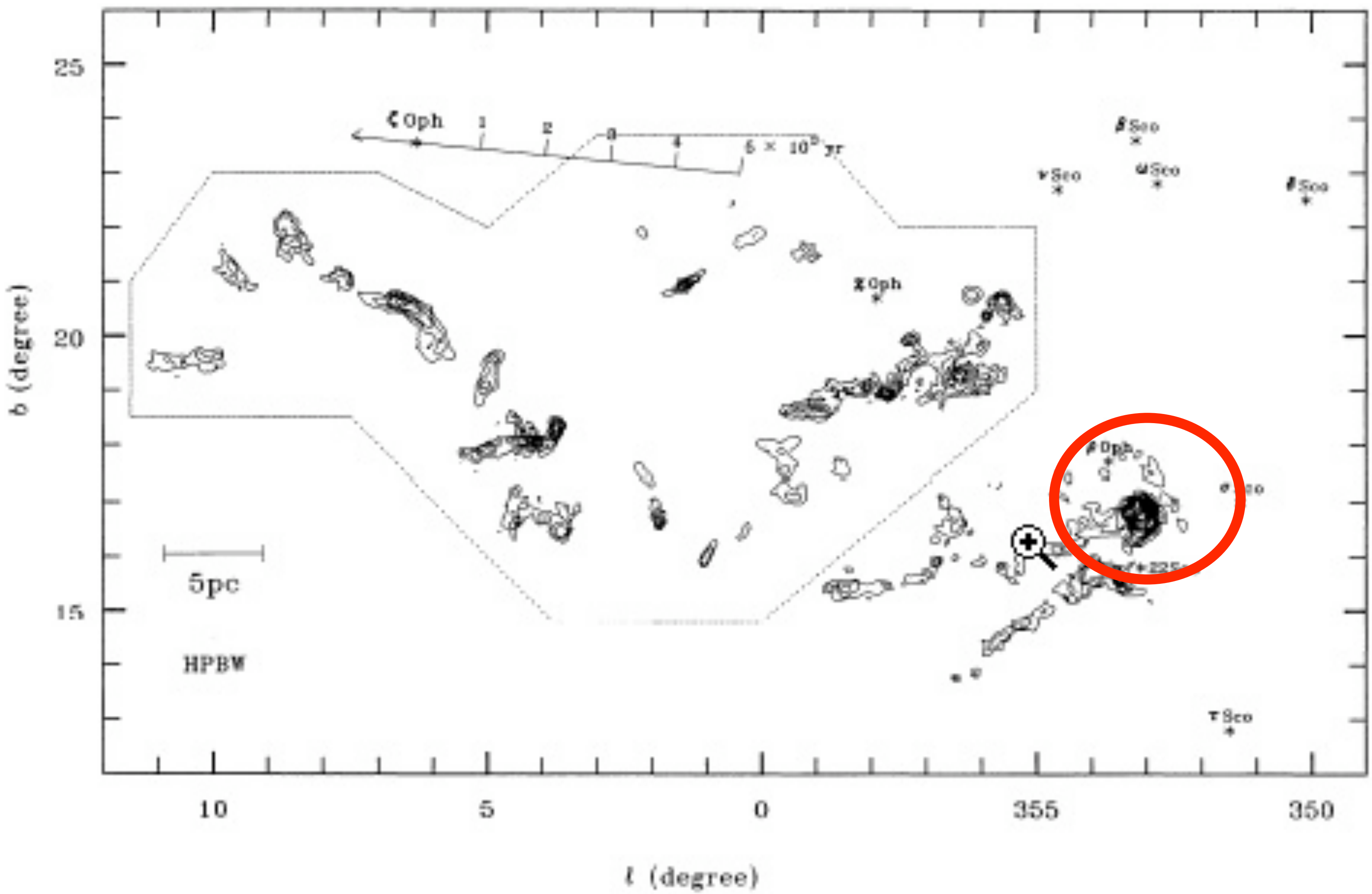
NANTEN2(color)+ASTE(contour)



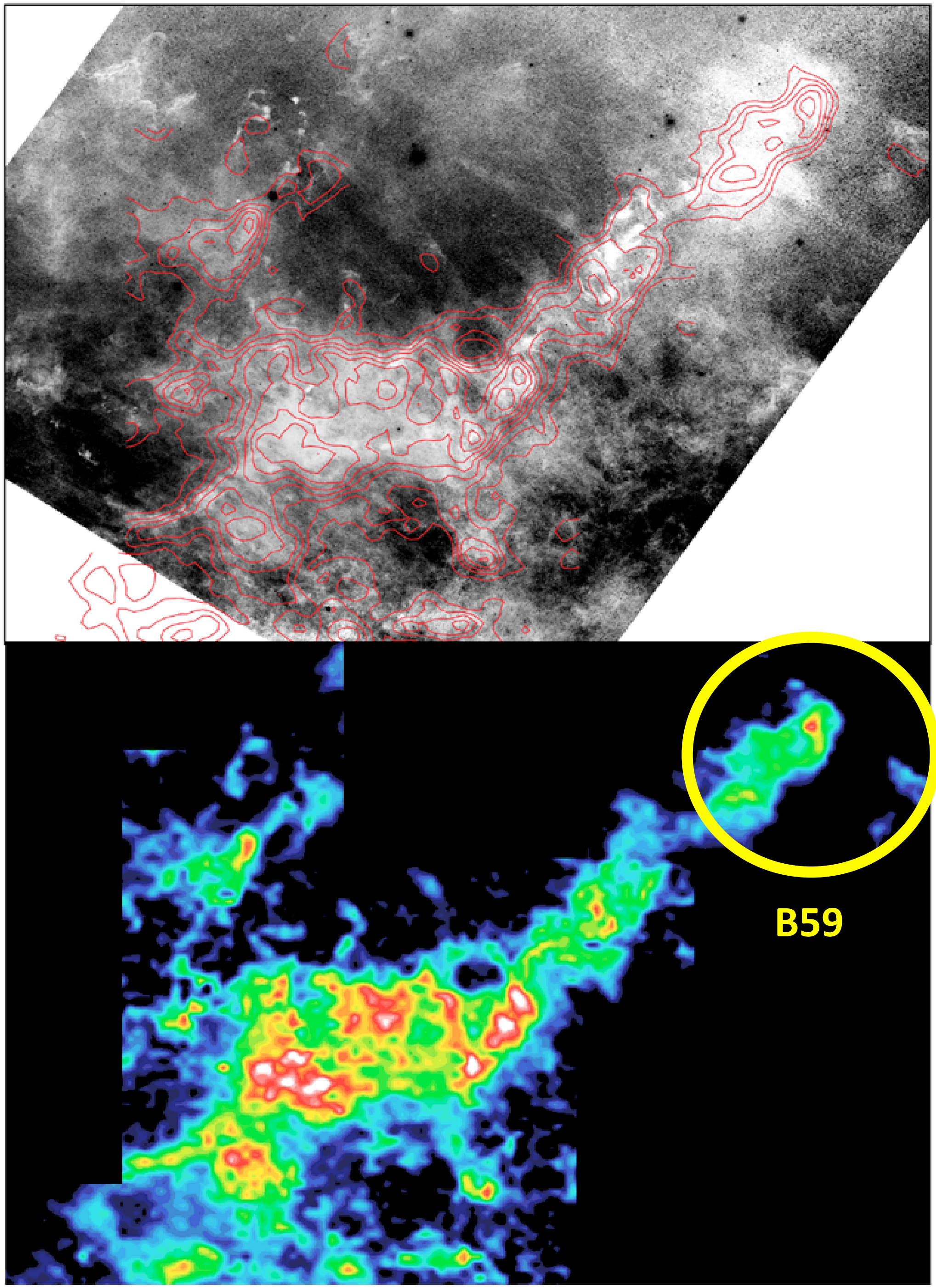


Black：CO(3-2)　Red：CO(4-3)

Northern Ophiuchus --- non-star forming gas



S.Nozawa et.al 1991 ApJS, 77, 647 FIG. 3



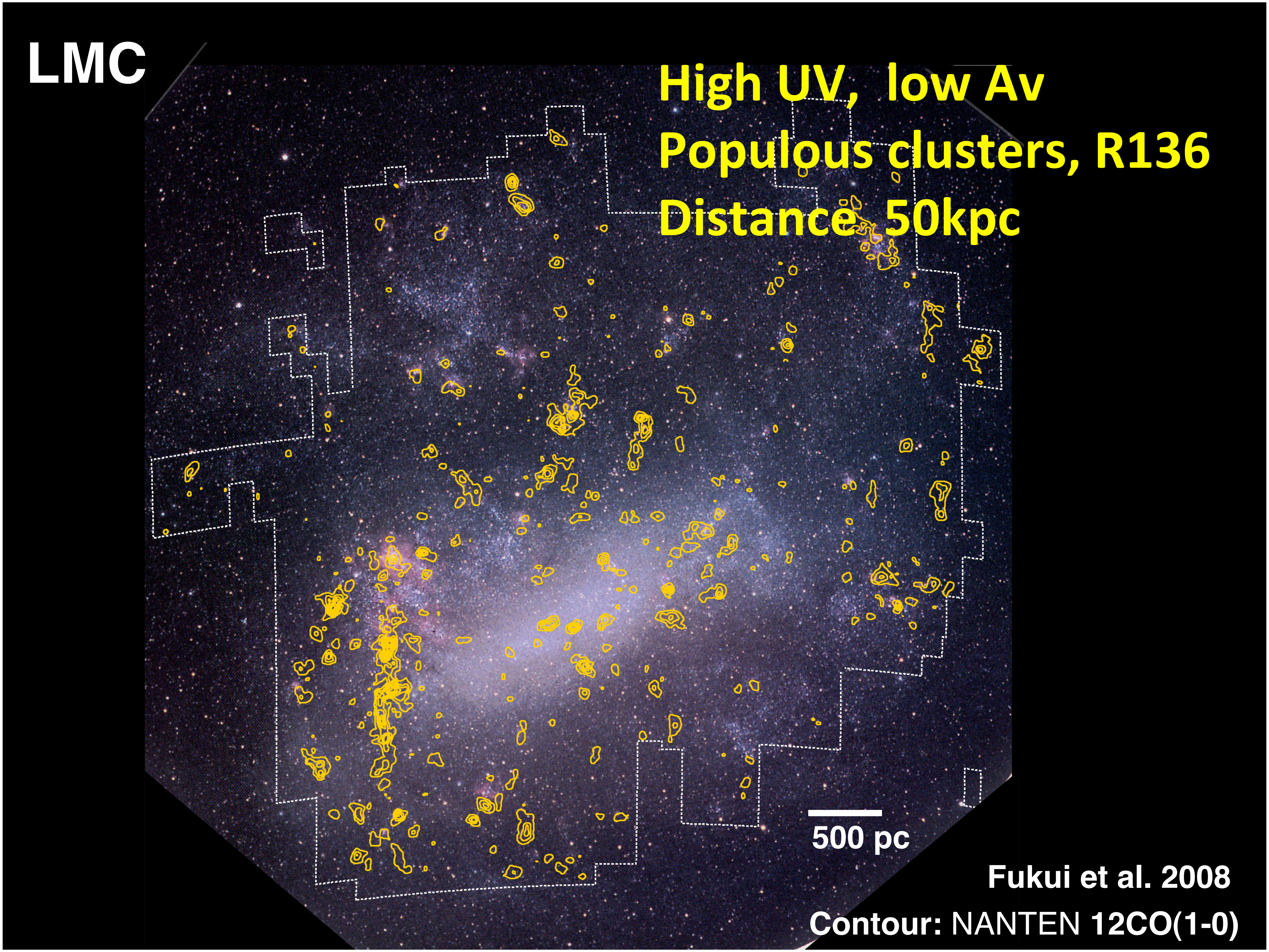
<u>High UV. by Sco OB1</u>

Higher ionization
stronger coupling with
magnetic field

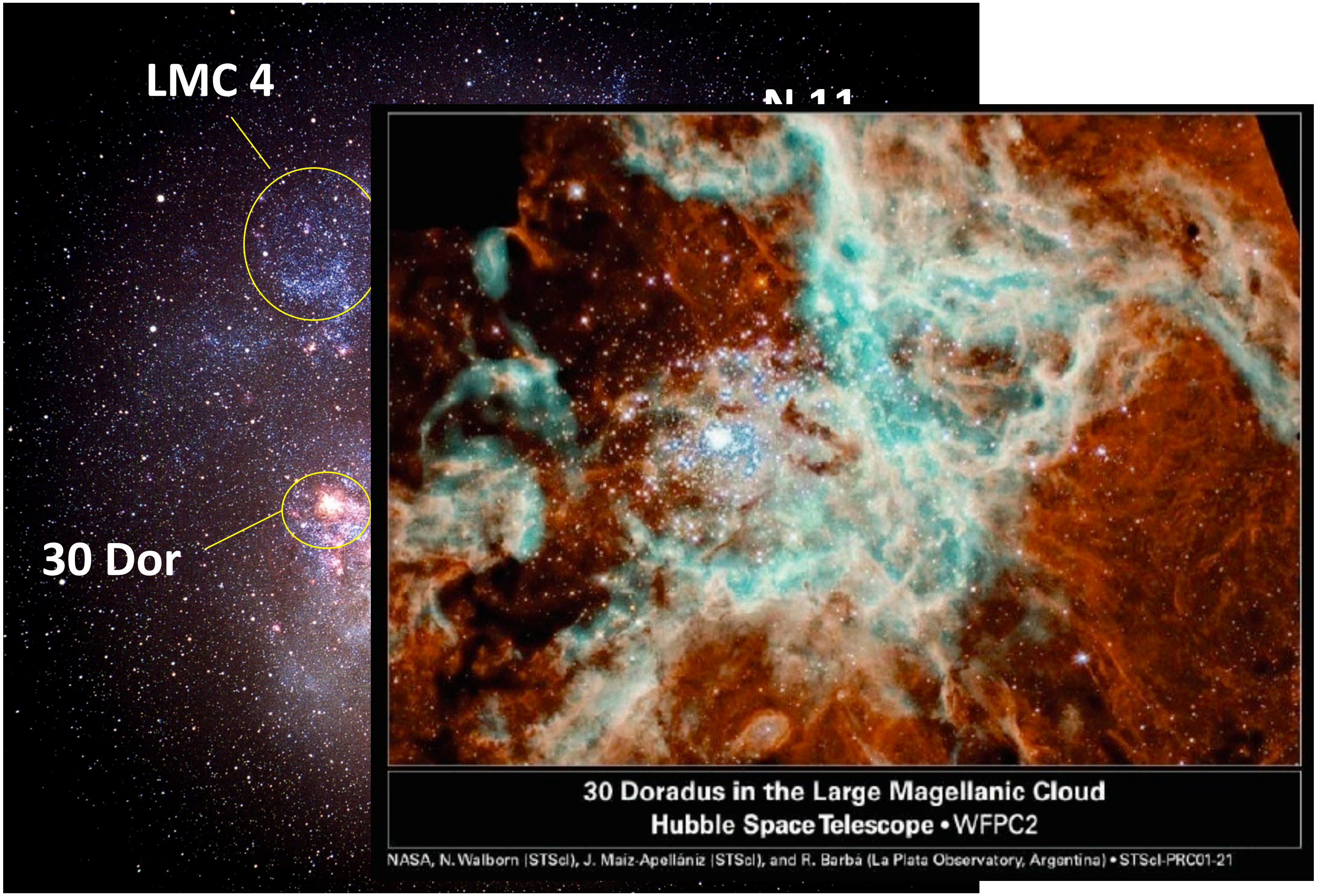
No star formation
in North Oph and Pipe
Except for ρOph and
B59

SFE less than 0.1 of
Taurus

N Oph: Nozawa et al. 1990
Pipe: Onishi et al. 1999
in PASJ


LMC
High UV, low Av
Populous clusters, R136
Distance 50kpc
500 pc
Fukui et al. 2008
Contour: NANTEN 12CO(1-0)

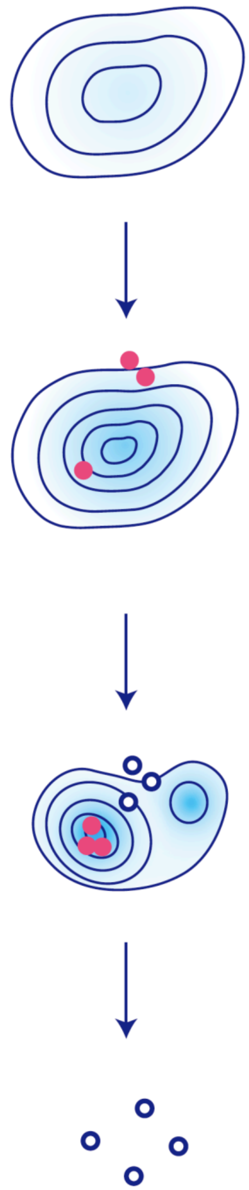
Active star formation indicators: giant HII regions in the LMC



Types of GMCs

(poster by Kawamura et al.)

GMC evolution



time scale

Type I
no massive
star formation
46 clouds

~ 6 Myr

Type II
only HII regions
98 clouds

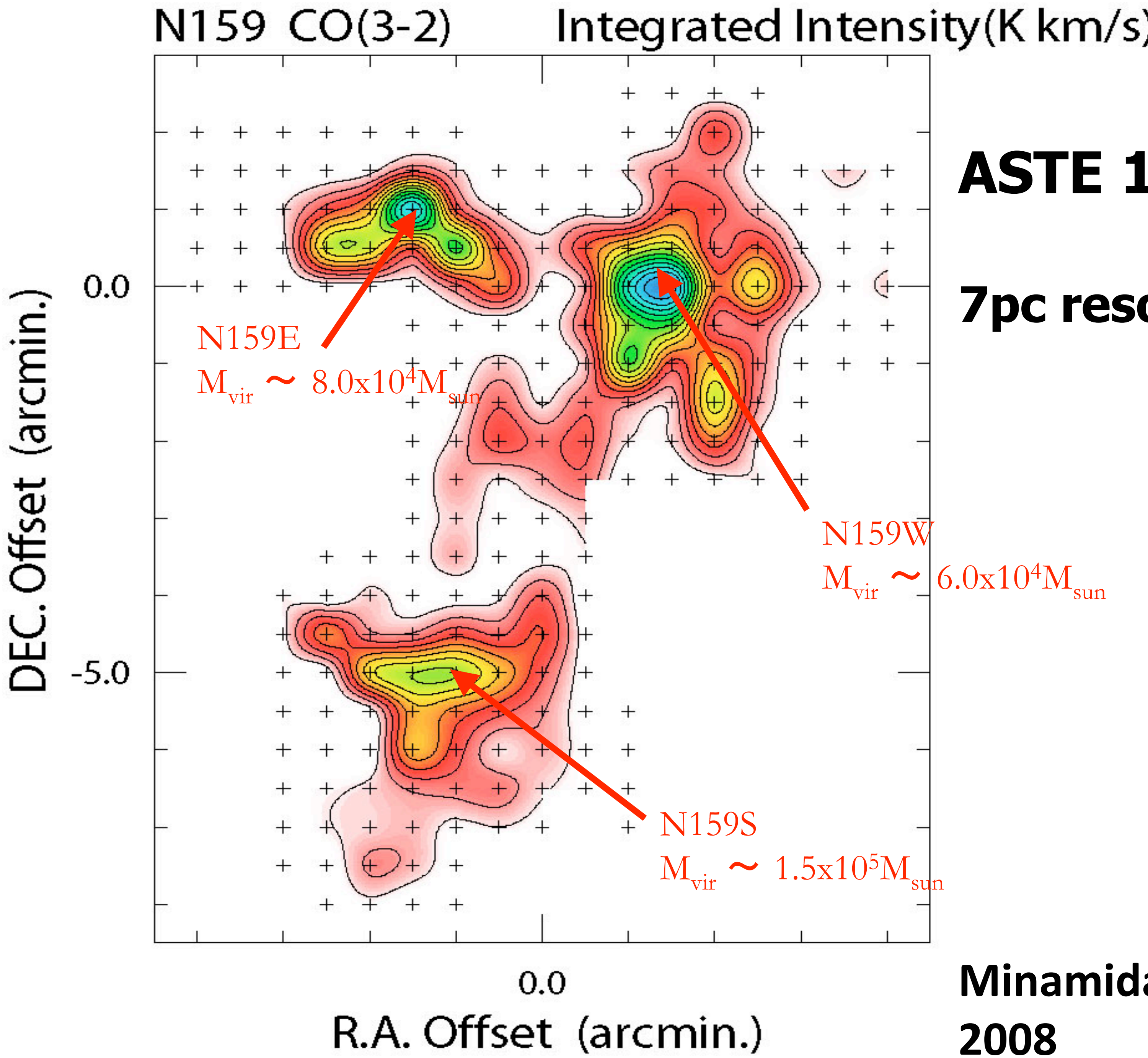
~ 13 Myr

Type III
HII regions and
young clusters
47 clouds

~ 6 Myr

only young clusters

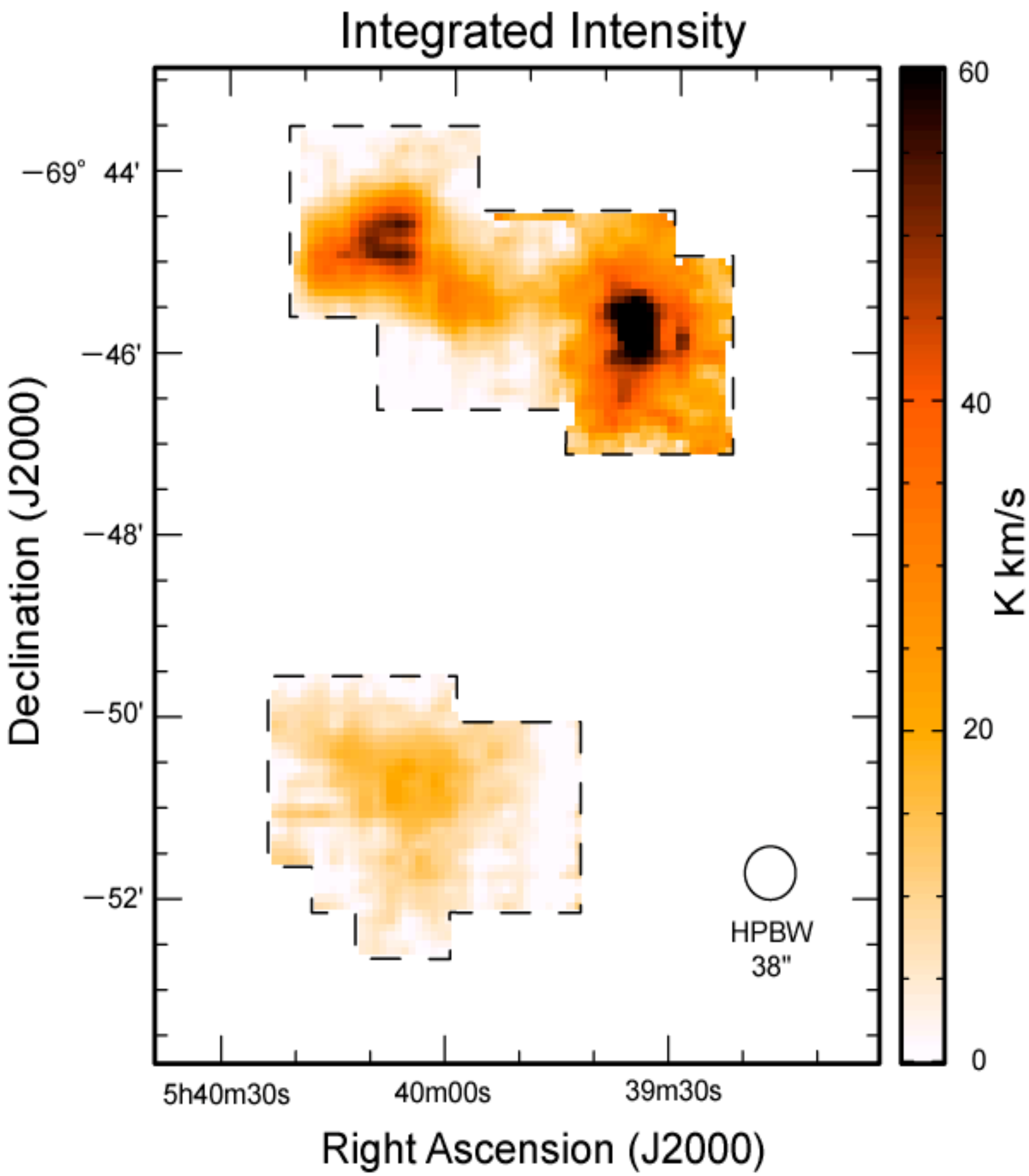
~ 4 Myr



ASTE 10m

7pc resolution

Minamidani et al. 2008

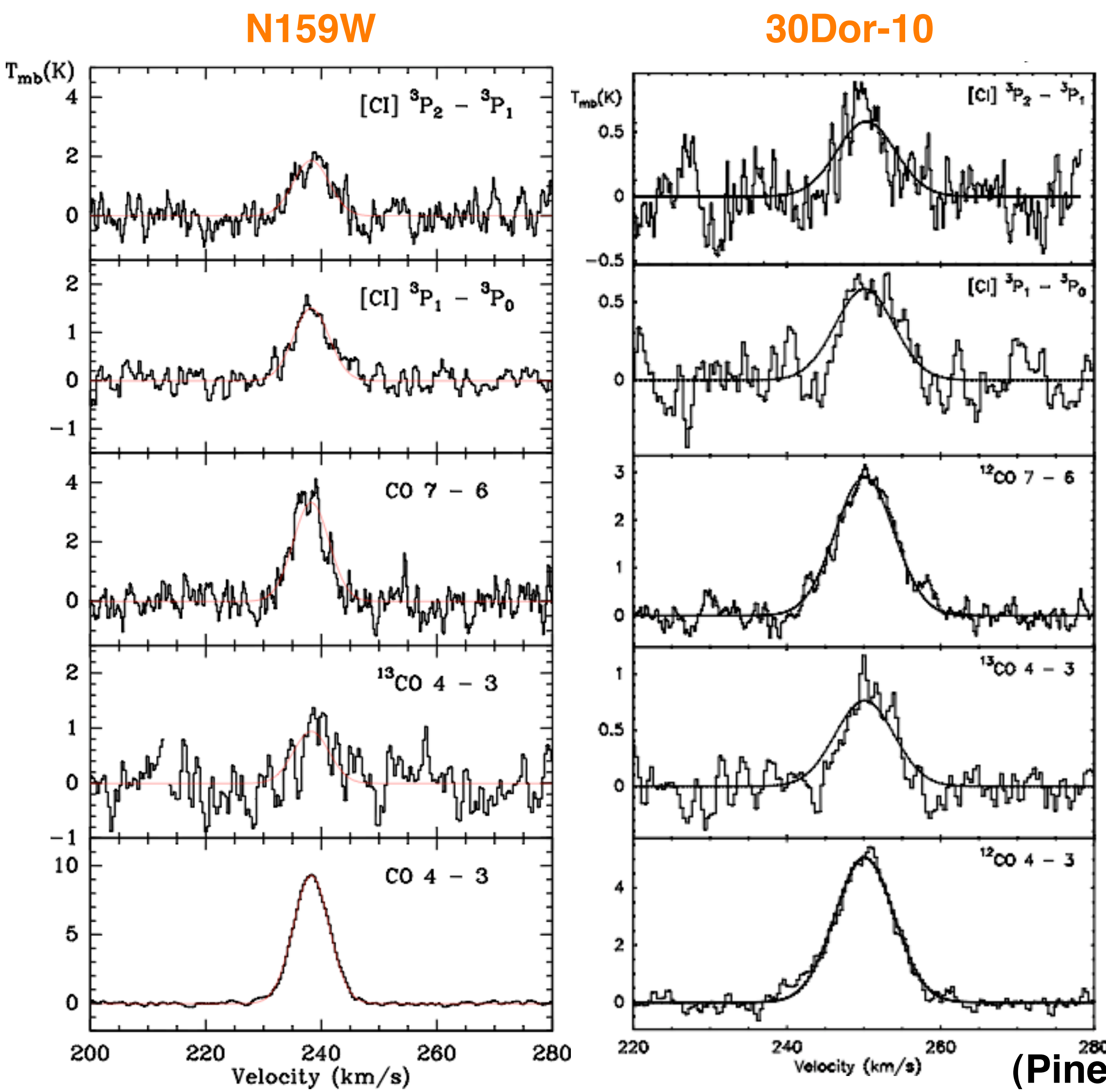


N159

CO J=4-3
NANTEN2

10pc resolution

Sub-mm spectra with NANTEN2

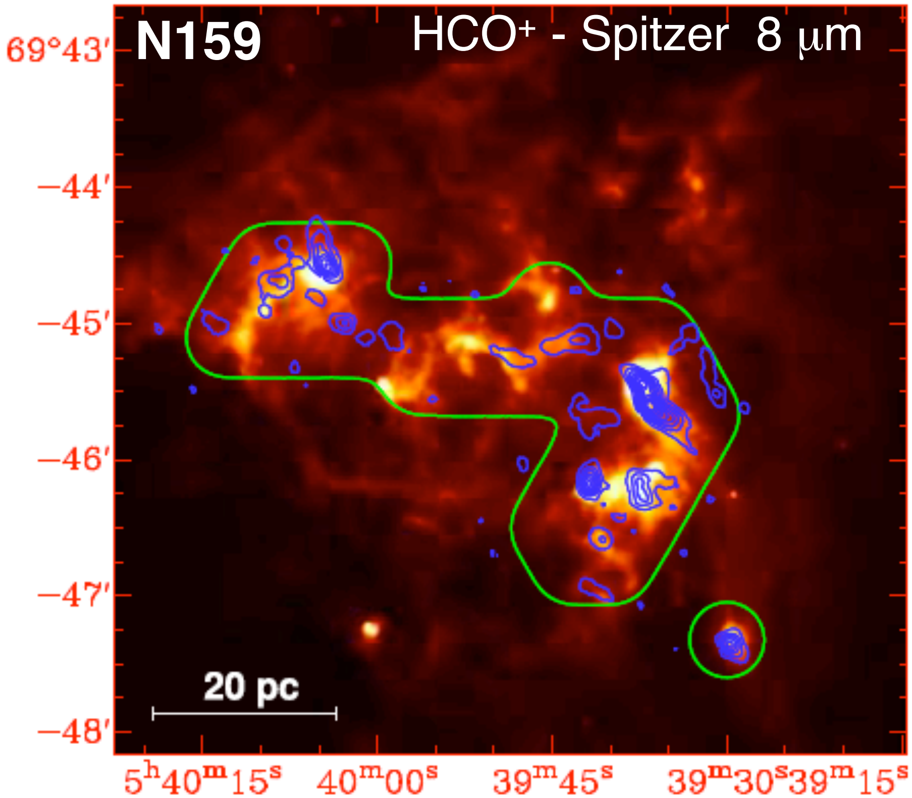


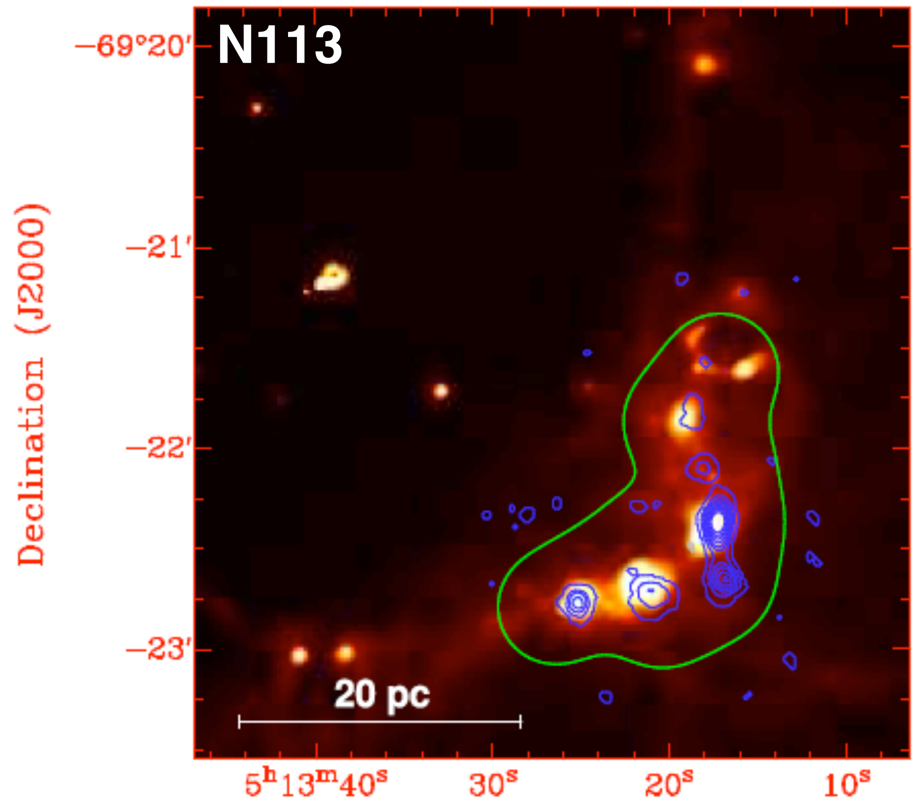
Hot and Dense
T ~ 80-100 K,
n ~ 10^{4-5} cm^{-3}

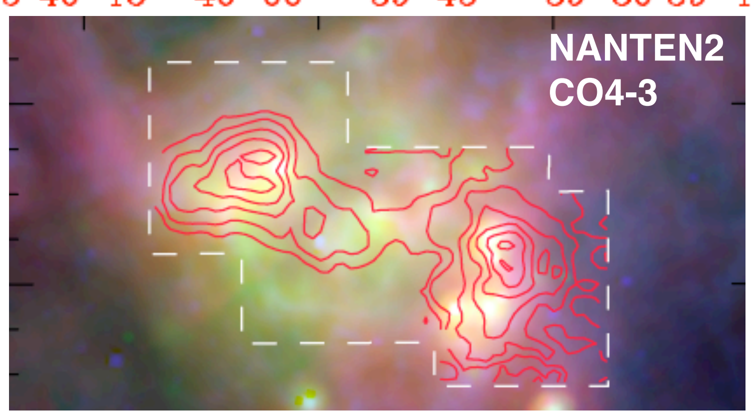
(Pineda, Mizuno et al. 2008)

ATCA interferometric HCO^+ image (Ott. et al. 2008)

7”=1.7 pc resolution







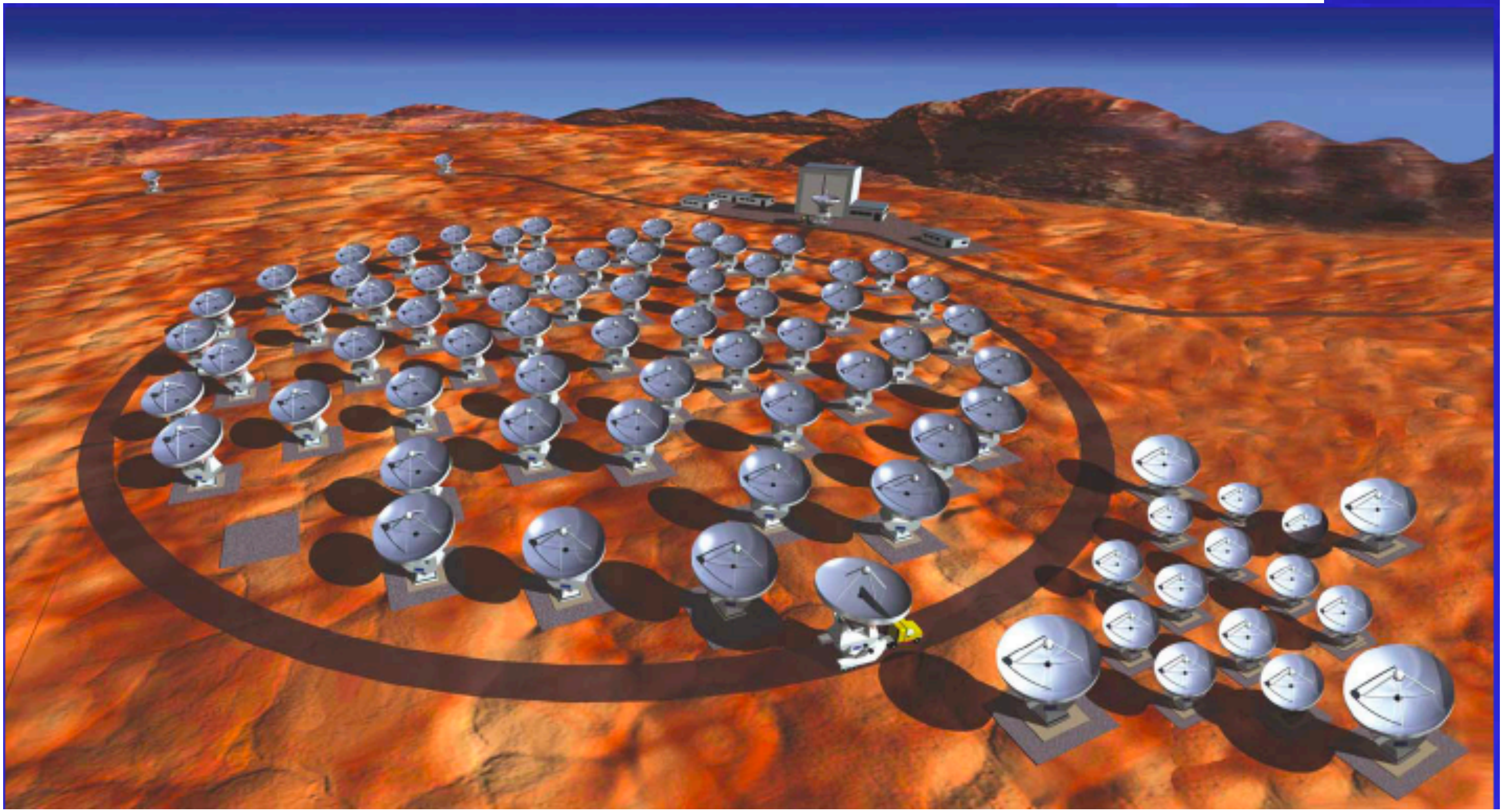
Slow collapse by high ionization, strong coupling with B field

High mass cores of 10^4Mo

ALMA (2012-)

Atacama Large Millimeter/submillimeter Array

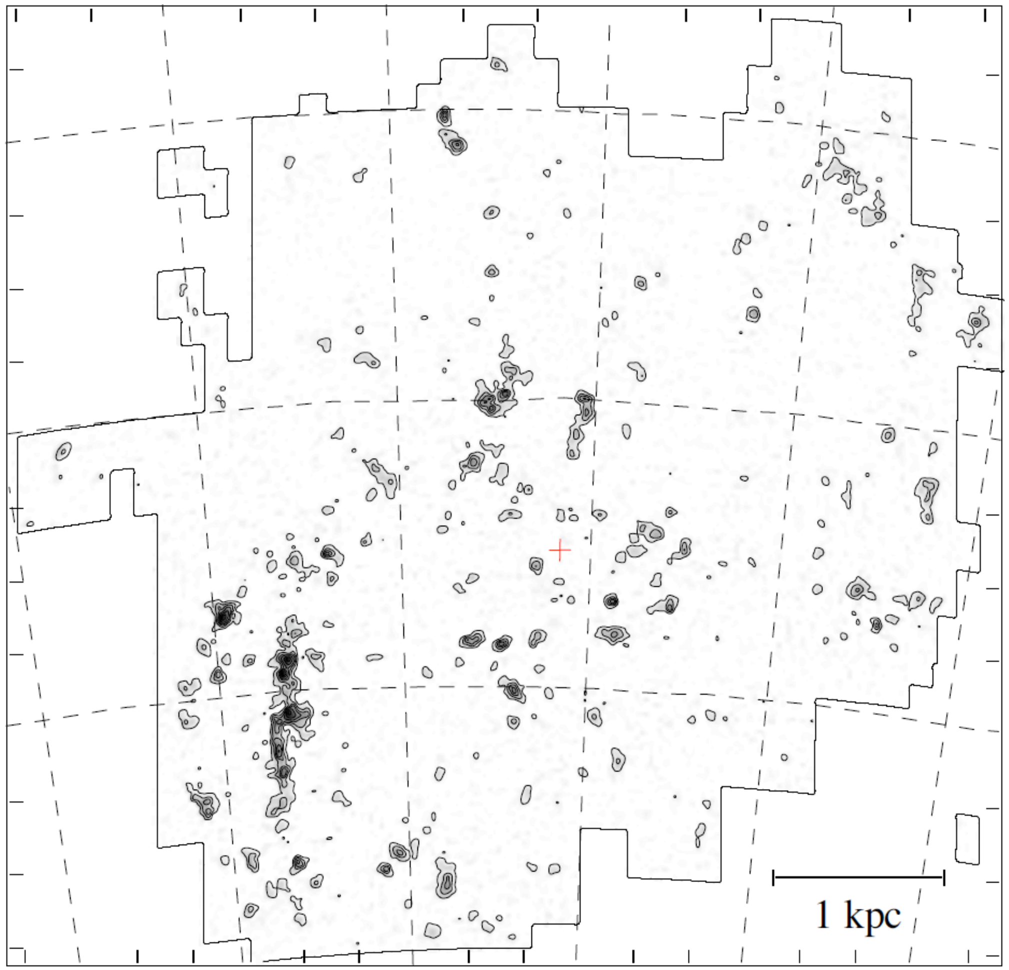
0.1″-1″(~ 0.1 pc@50kpc)



2^{nd} survey of GMCs in the LMC

(Fukui et al. 2008, in ApJS)

- 272 GMCs indentified by finding algorithm, “fitstoprops” (Rosolowsky & Leroy 2006)
- All data (Galactic, SMC) are re-analyzed using the same methods to minimize systematics.
- Cloud properties of GMCs (size, line width, CO luminosity, virial mass) were derived.



Summary

1) Super clusters can be formed by rapid shock compression and/or in non-star forming gas
2) Shocks can be by cloud collisions or violent motions driven by magnetic instability in the Galactic centre
3) Non-star forming gas may happen due to strong magnetic field, higher ionization degrees, violent motions
4) ALMA will resolve the pre-cluster cores into 0.1pc scales in the LMC

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