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

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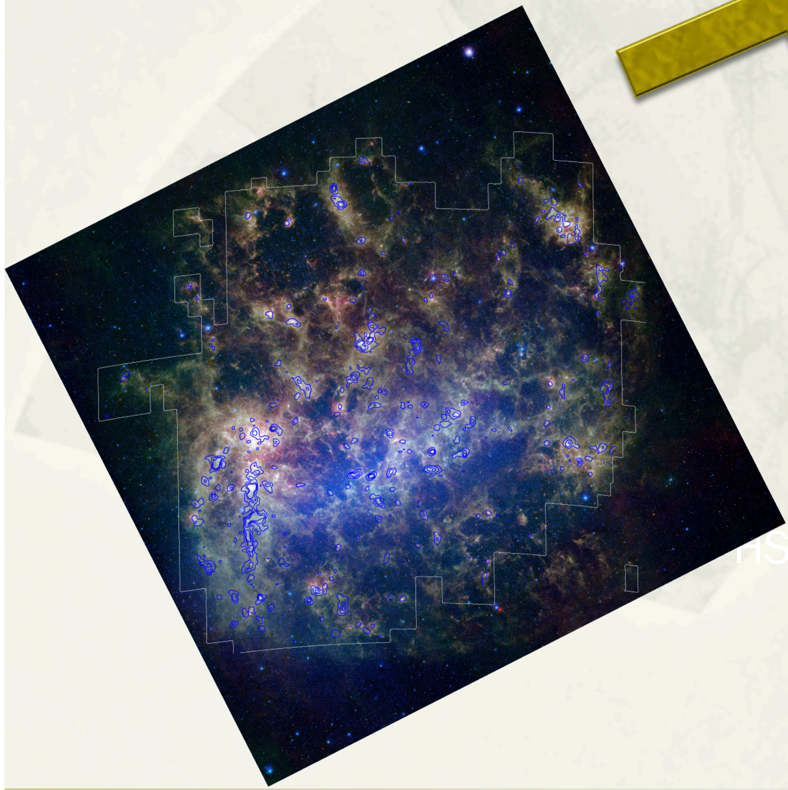
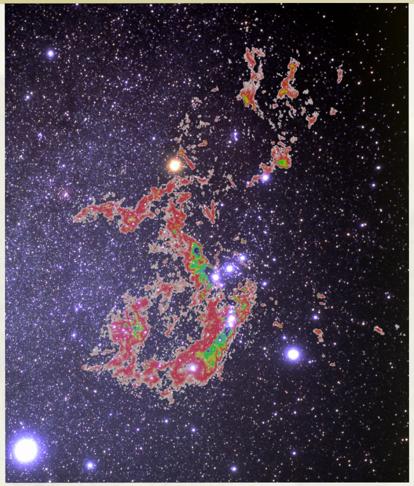
NANTEN2, Spitzer-Mega-SAGE, Herschel-HERITAGE teams

and many others

Galaxy evolution→ Individual star formation

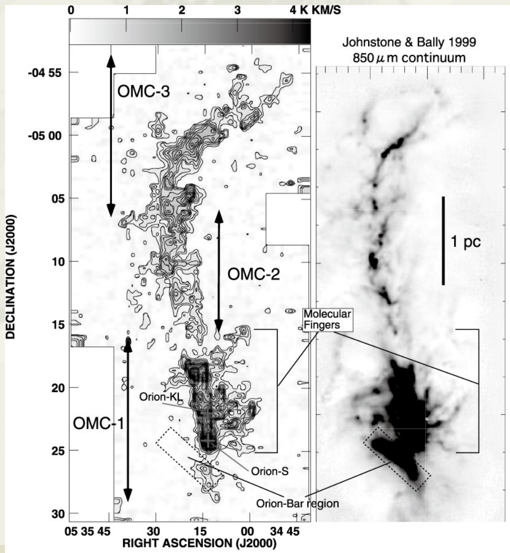
The galaxy scale SF : kpc





1-100pc

<1pc



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

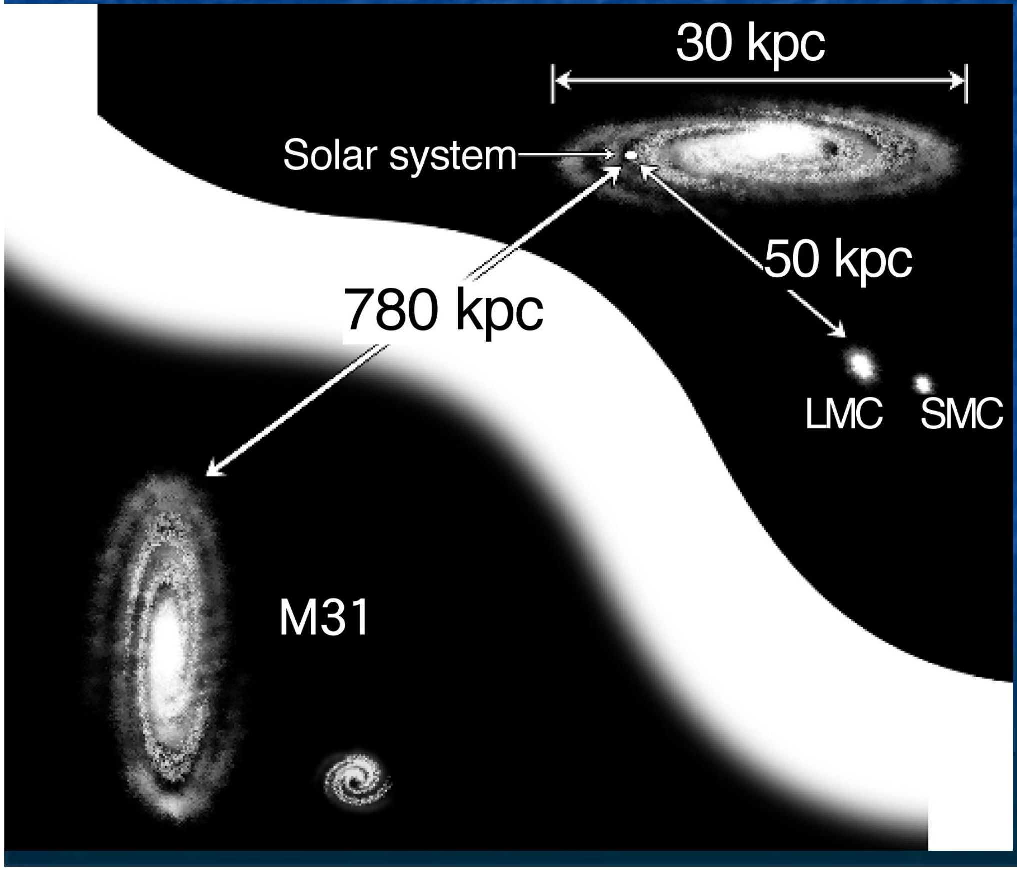
Star formation in GMCs

- 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

Extending surveys of the molecular clouds to the nearby galaxies

- Survey of molecular clouds over a large-scale in a galaxy with uniform sampling
- Comparisons with Star formation activities

  Molecular clouds evolution -> Star formation



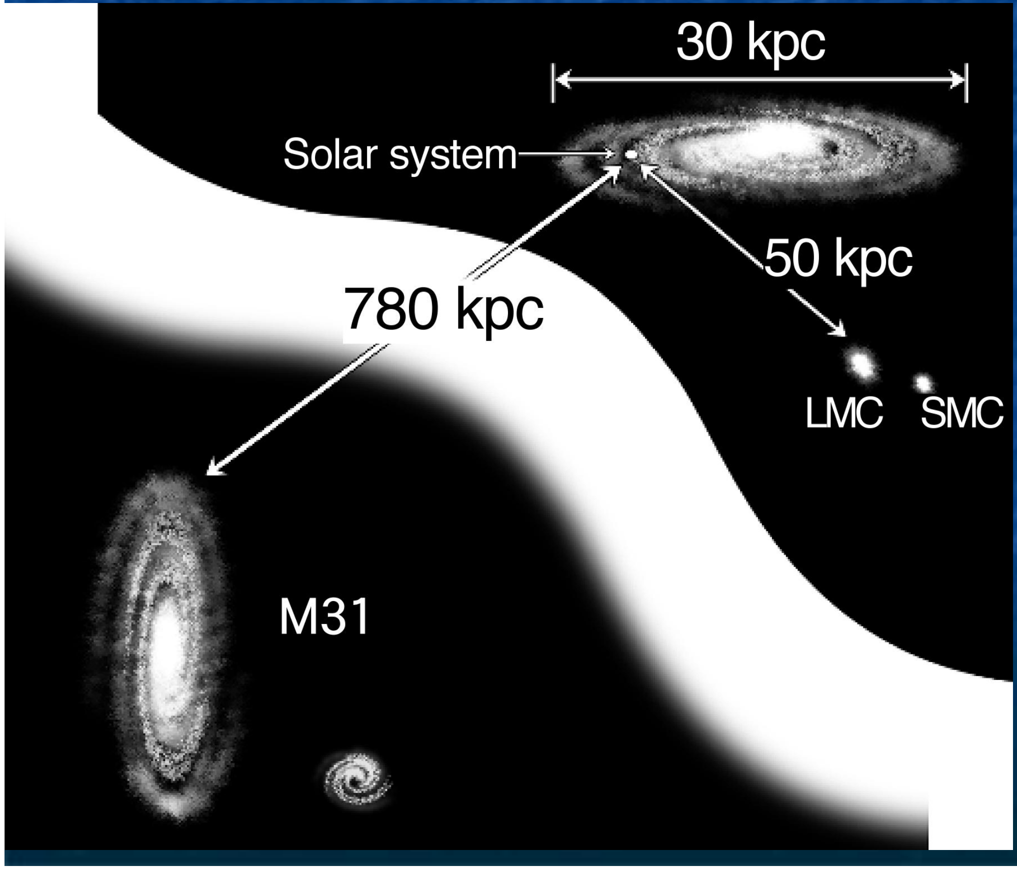
Bridge between the Milky way and the nearby galaxies

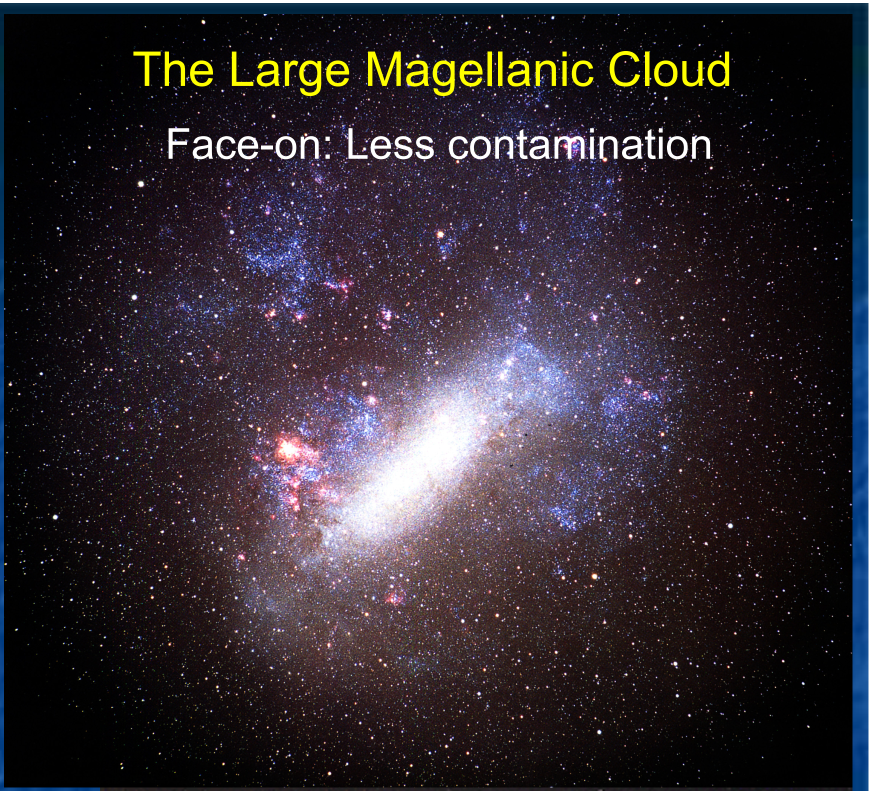
→Magellanic system

(1”=>0.24pc, 0.1”=>0.024pc)

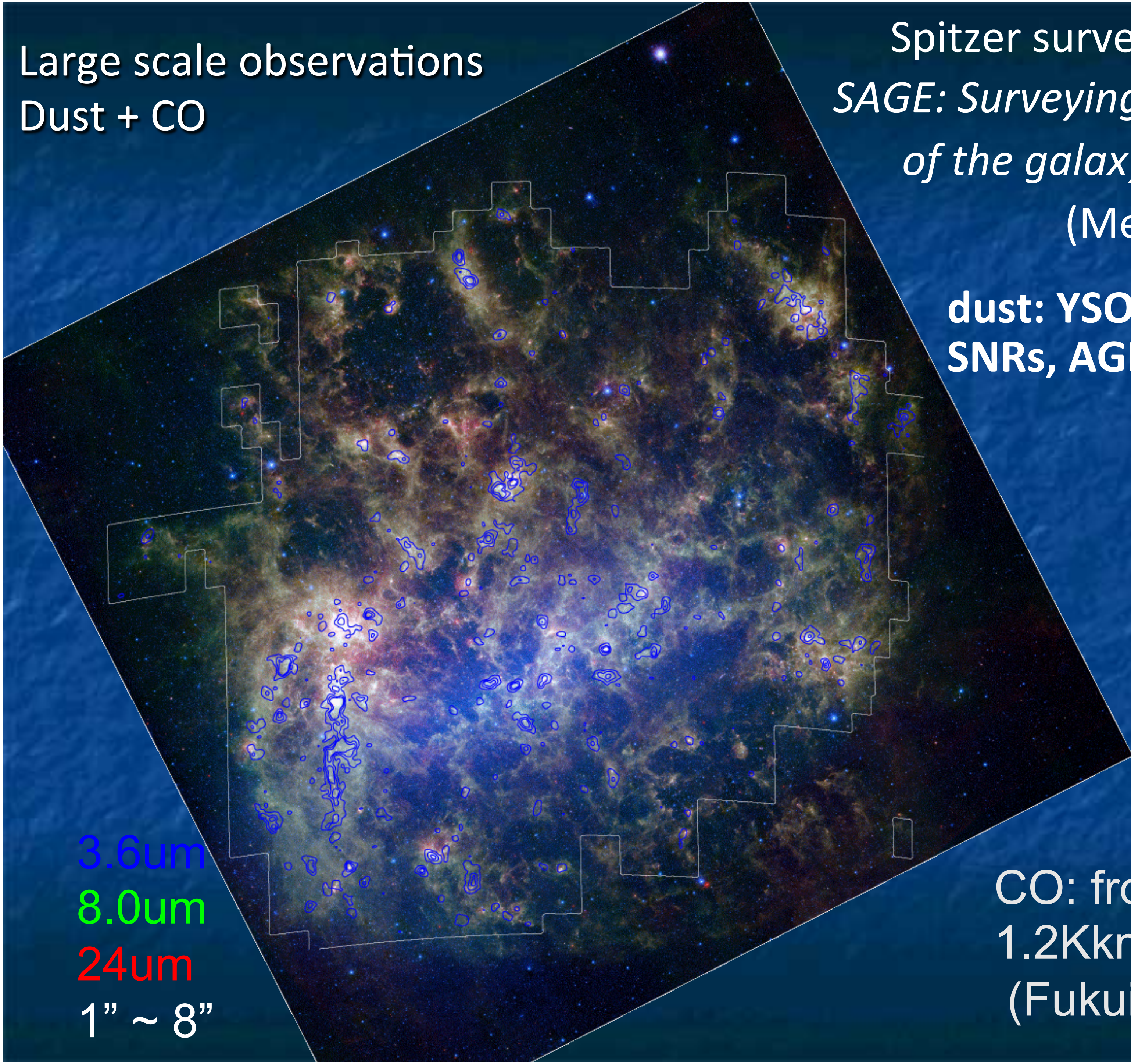
Magellanic Clouds

- 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

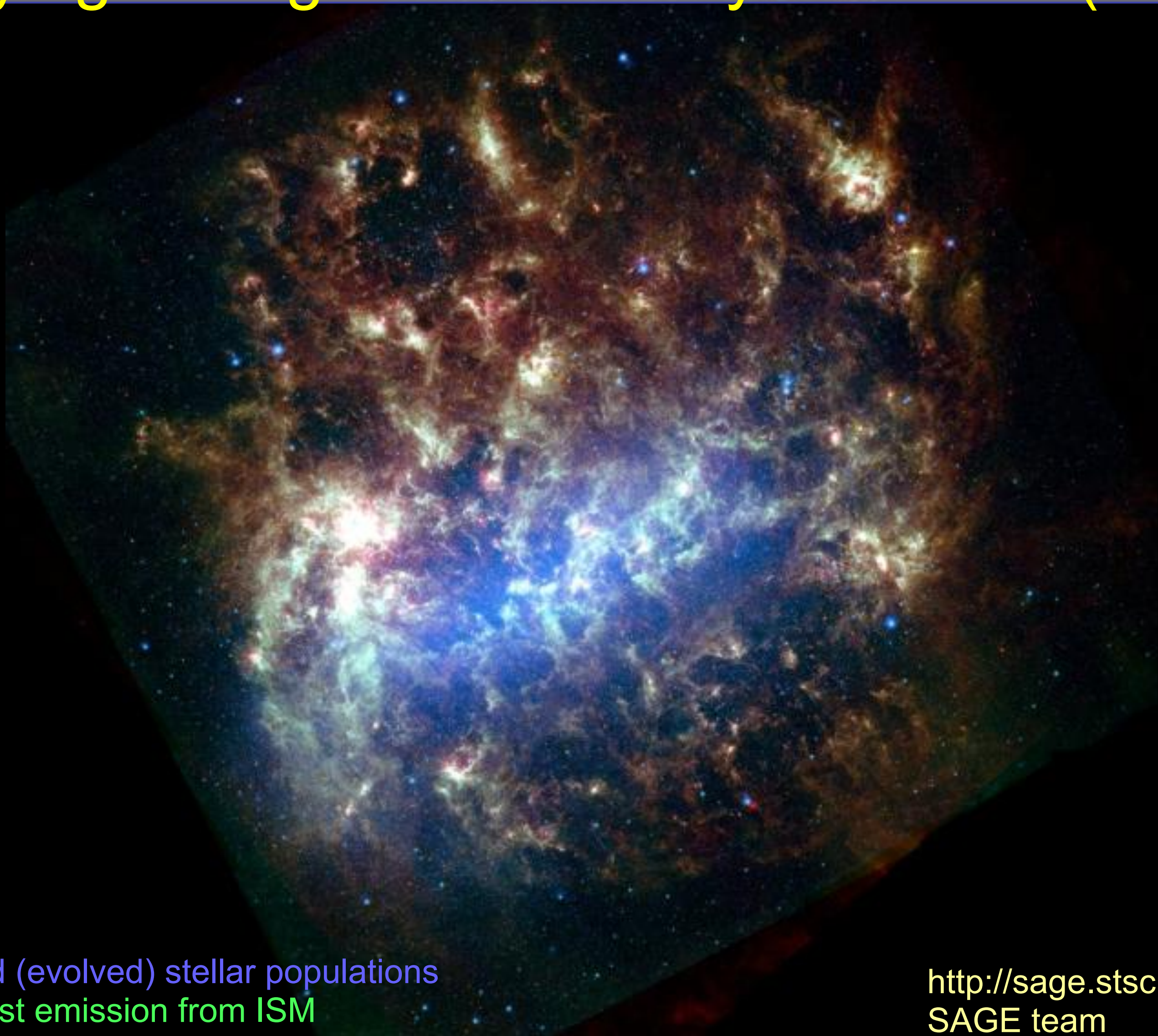


Spitzer survey of the LMC
SAGE: Surveying the Agency of the galaxy’s evolution
(Meixner et al.)

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

CO: from 1.2 Kkm/s
1.2Kkm/s intervals
(Fukui et al. 2008)

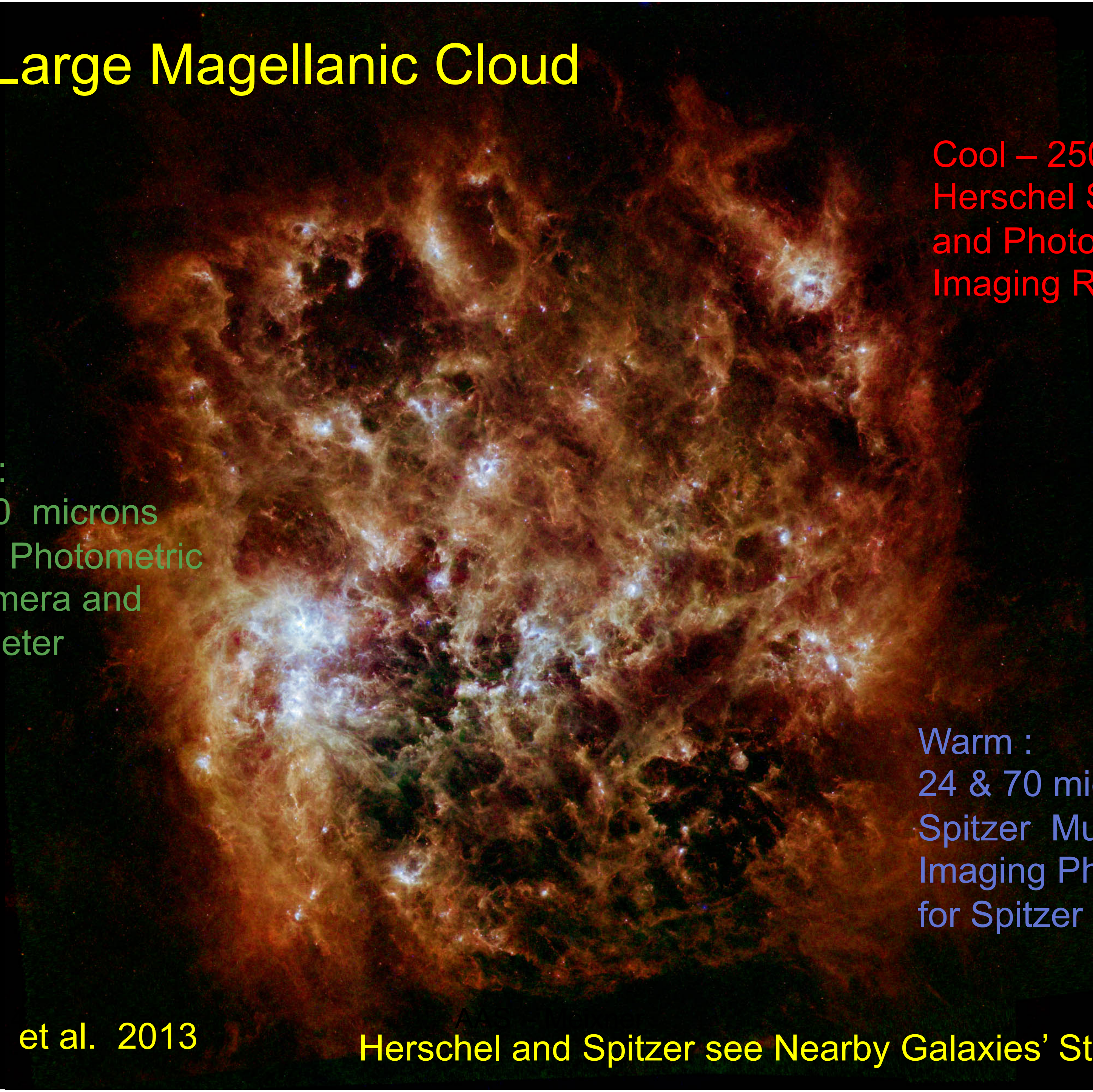
Spitzer Survey of the Large Magellanic Cloud (LMC): Surveying the Agents of Galaxy Evolution (SAGE)



IRAC 3.6 μm: old (evolved) stellar populations
IRAC 8.0 μm: dust emission from ISM
MIPS 24 μm: new massive star formation

http://sage.stsci.edu/
SAGE team
Meixner et al. 2006

The Large Magellanic Cloud



Cool – 250 microns
Herschel Spectral and Photometric Imaging Receiver

Mid-temp:
100 & 160 microns
Herschel Photometric Array Camera and Spectrometer

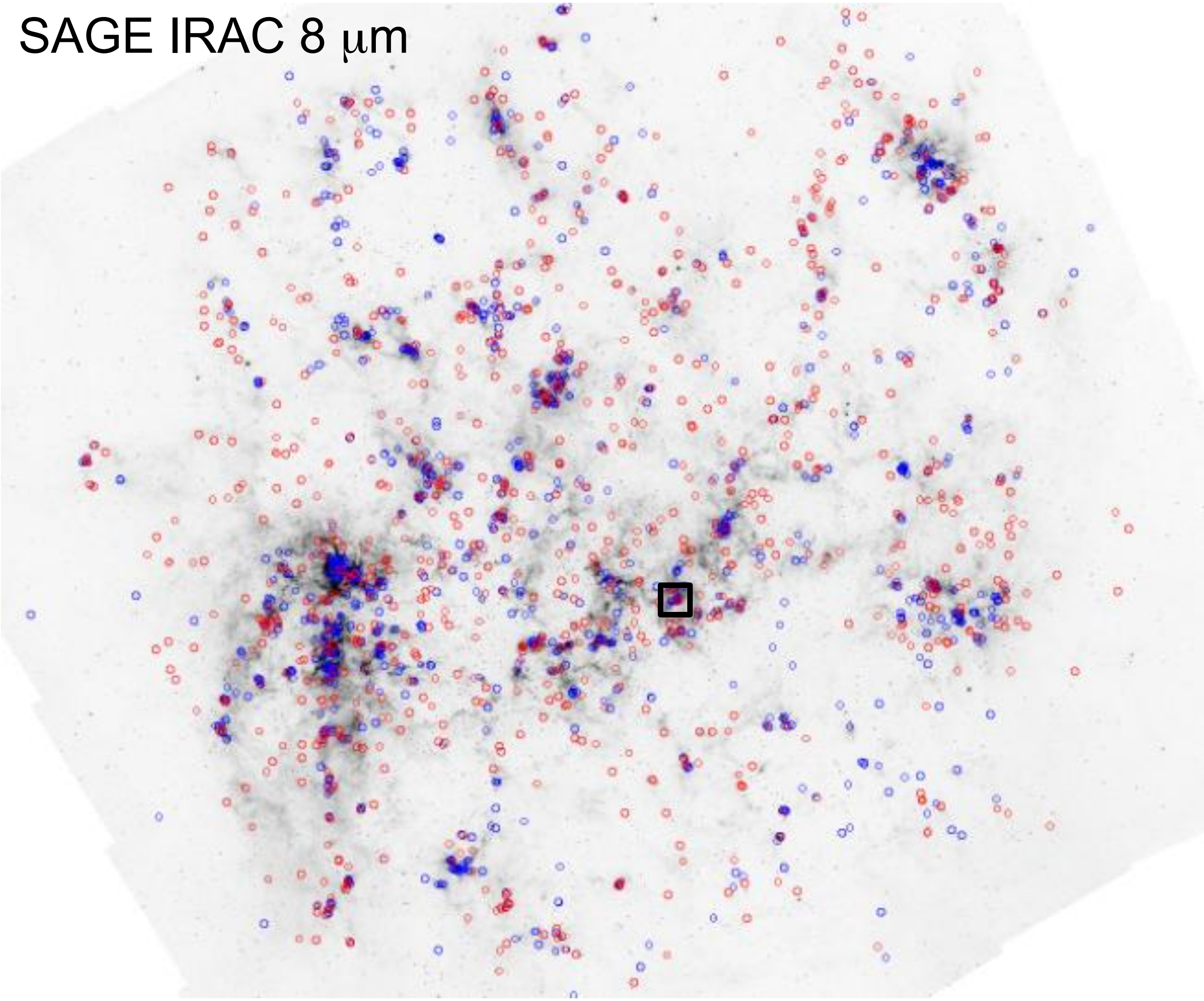
Warm :
24 & 70 microns
Spitzer Multi band Imaging Photometer for Spitzer

Meixner et al. 2013

Herschel and Spitzer see Nearby Galaxies’ Stardust

Spitzer Discovers More than Thousand Young Stellar Objects in the LMC

SAGE IRAC 8 μm



Pre-*Spitzer*:

~20 protostars known

Spitzer:

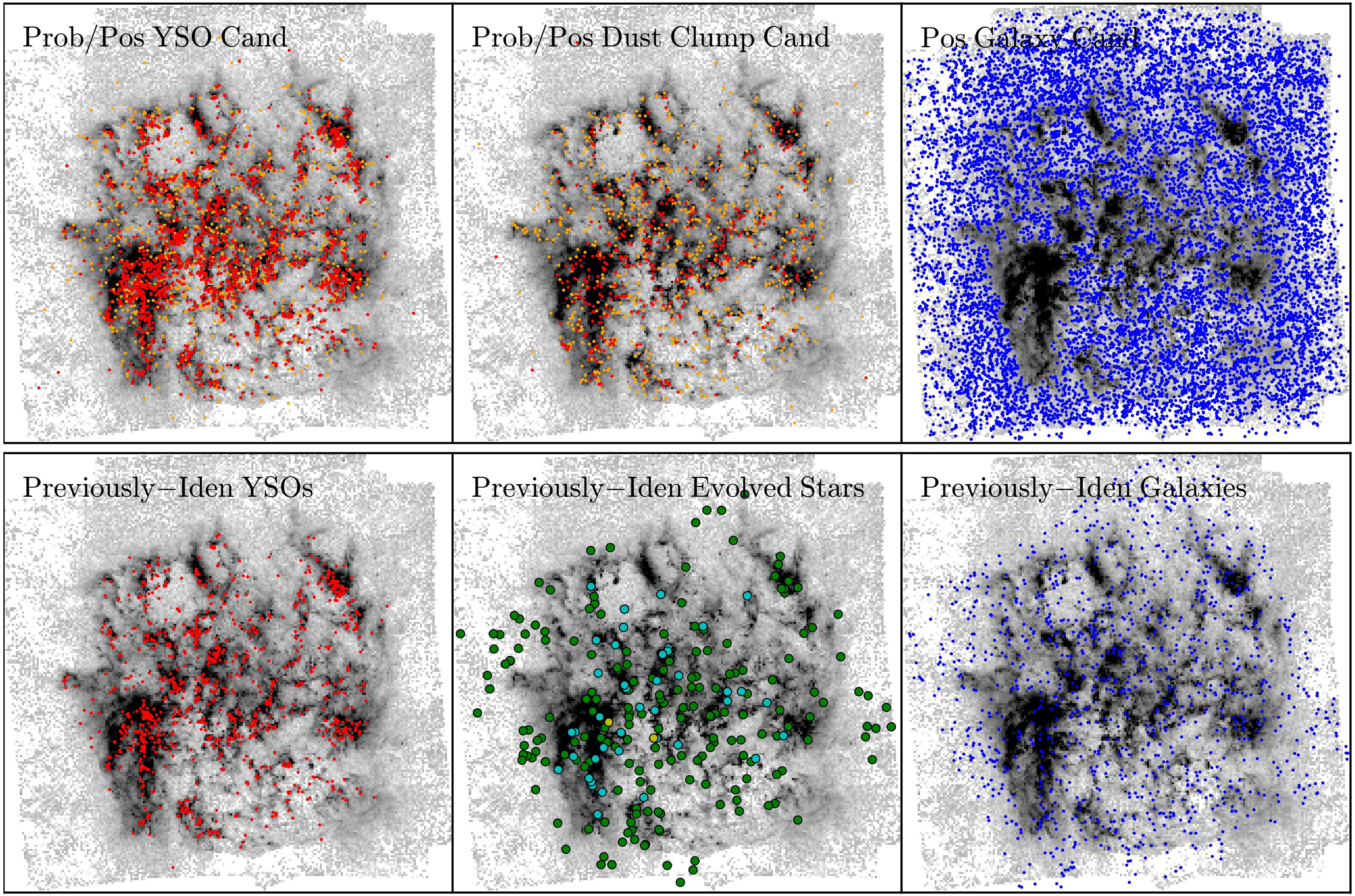
~1000 YSO candidates
Whitney, Sewilo et al. (2008)

~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

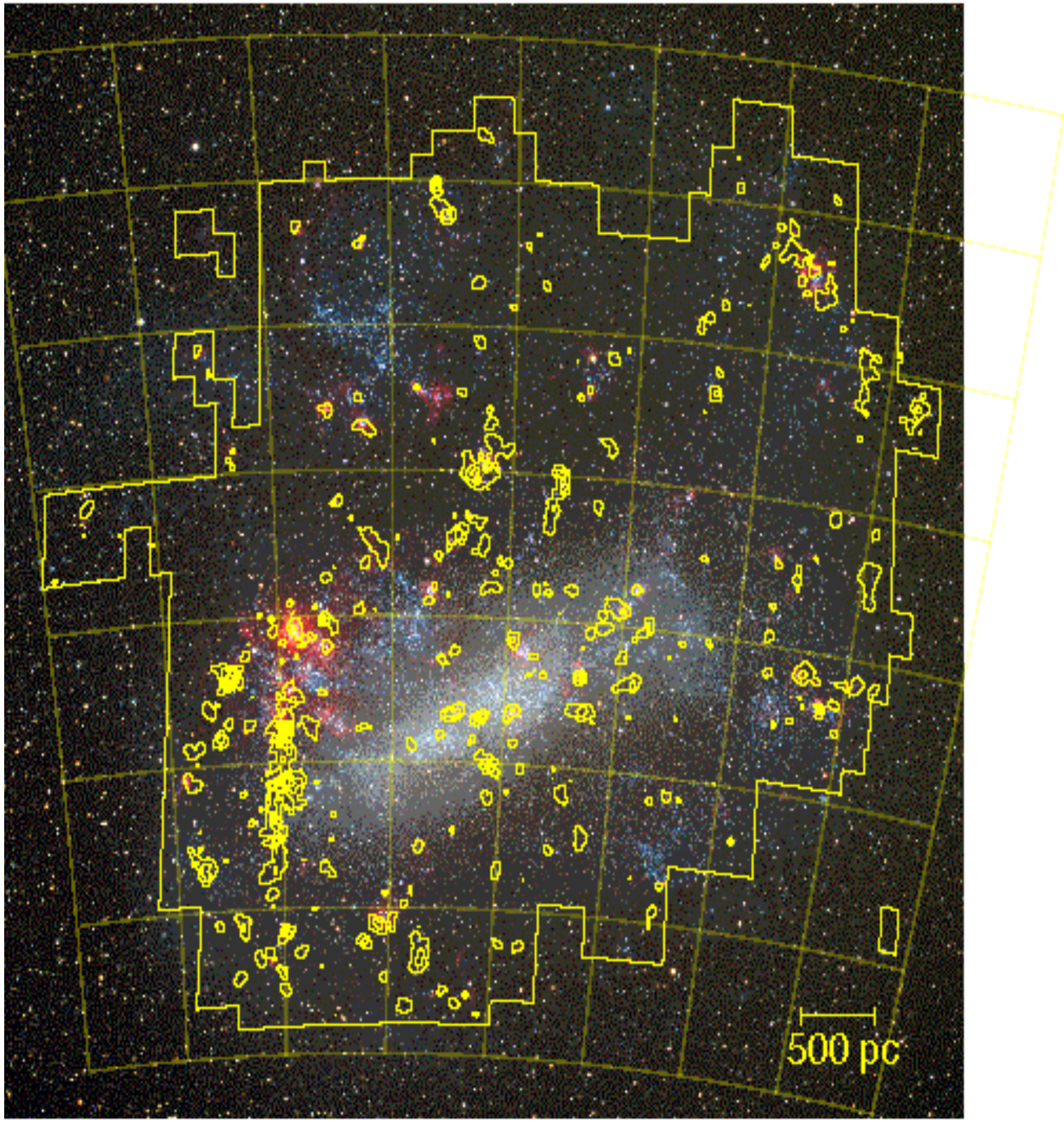
	LMC	SMC
Galaxy Candidates	9,745	5,111
Probable YSO	2,493	425
Possible YSO	1,025	238
Probable Dust Clumps	1,175	36
Possible Dust Clumps	1,569	74

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



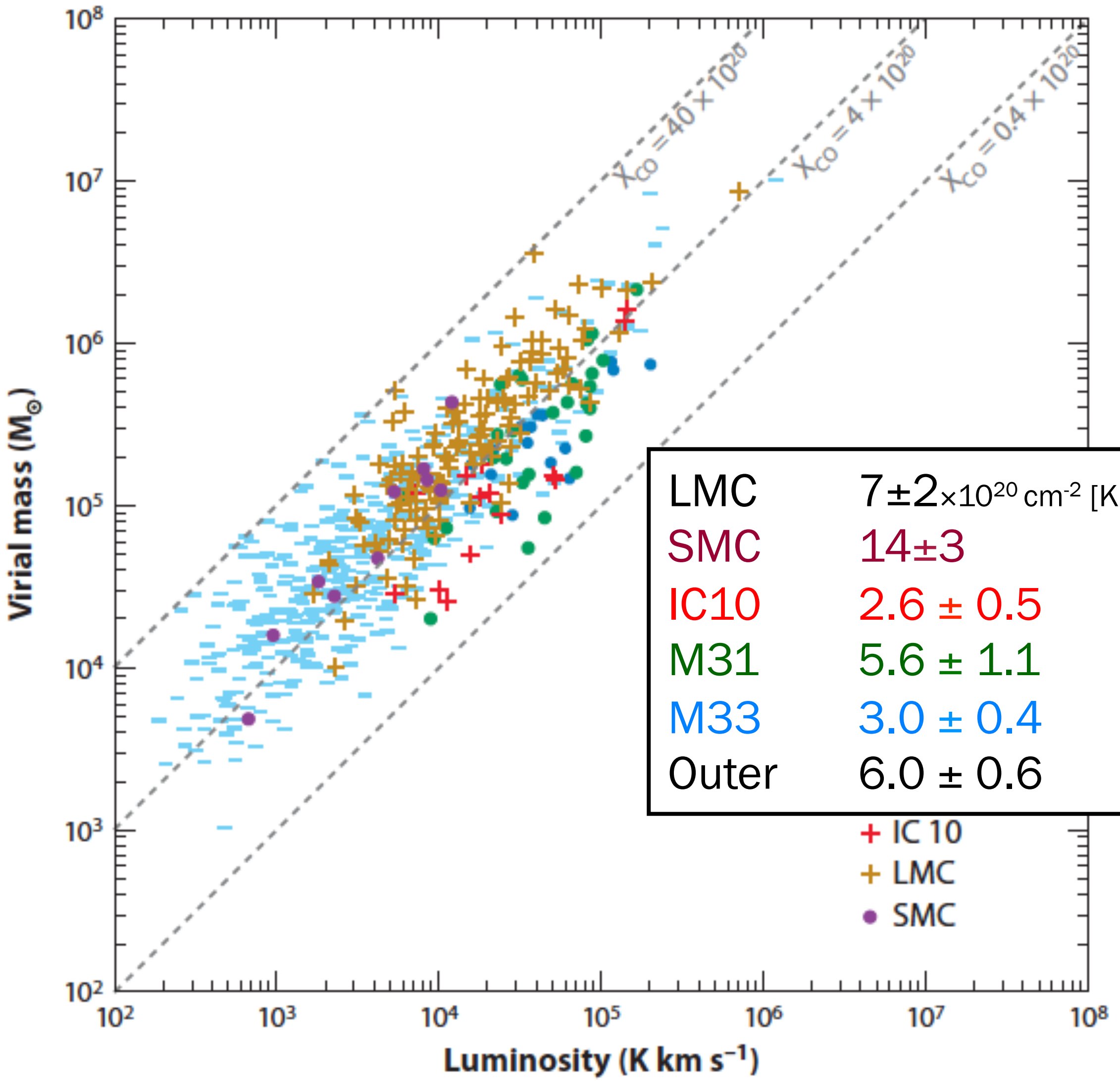
- **Contours: CO J=1-0**
- **270 GMCs**
- **X_{LMC} ~ 9×10^{20} cm^{-2} / [K km s^{-1}] ~ 3 X_G is used (Mizuno et al. 2001))**

  ($X = N(H_2) / I_{CO} = M/L_{CO}$)

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

Scaling relations

Viral mass vs. luminosity X factor



LMC	$7\pm2 \times 10^{20}$ cm^{-2} [K km s^{-1}]$^{-1}$
SMC	14±3
IC10	2.6 ± 0.5
M31	5.6 ± 1.1
M33	3.0 ± 0.4
Outer	6.0 ± 0.6

Large dispersion but fit into one-order of mag.
Except for SMC
Average value X = 4×10^{20} cm^{-2} [K km s^{-1}]$^{-1}$
c.f. γ-ray value X = 2×10^{20}

No linear trend with metallicity:
c.f. SMC ~ 1/6-1/10 Z_O,
IC10 ~1/6 Z_O

Properties of the GMCs
in several nearby Galaxies(LMC, SMC, M33, M31, IC10)

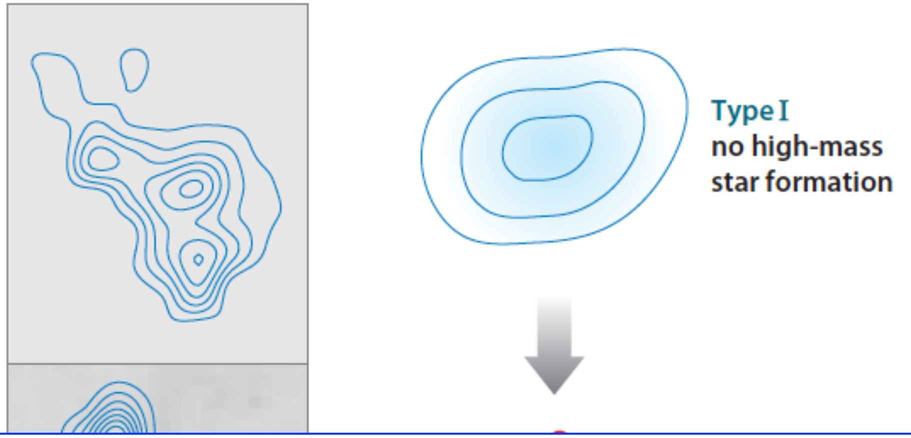
- Remarkable similarities in the properties of the CO-bright regions:
  - ✓ Follows Galactic Larson's relations
  - ✓ Mass-Luminosity relation is similar too: Xco is approximately Galactic inner GMCs
  - ✓ Mass spectra share similar shape
- There are also dispersions among GMCs and galaxies

Due to host galaxy? metallicity, gas-to-dust ratio, morphology, … ?

Due to environment? Star forming activity, gravitational potential, external pressure like shells?

Blitz et al. 2007, Fukui & Kawamura 2010

GMCs & high mass star formation activities in the LMC

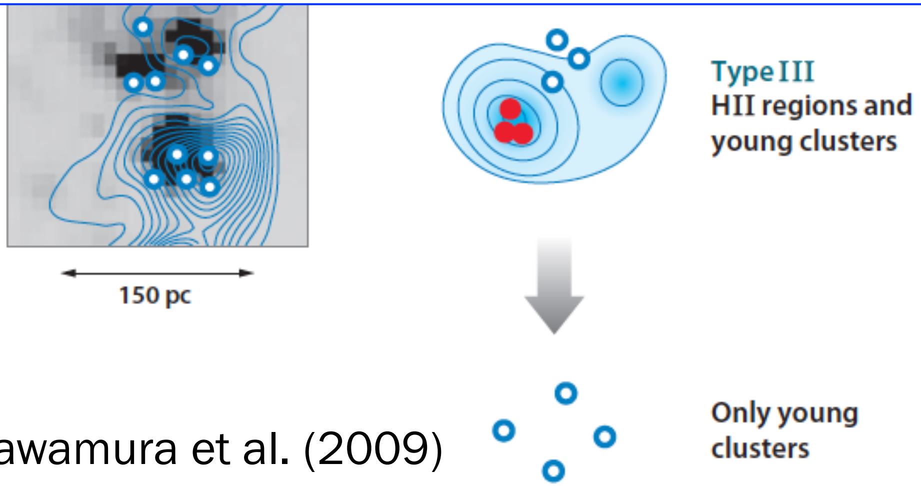


Time scale

44 clouds (26%) — 7Myr

GMCs
With > 5×10^4 Mo

- Individual GMC and its high mass star forming activities in 40 pc scale.
- How about detailed structure and properties in smaller scales, related to individual star formation activities?



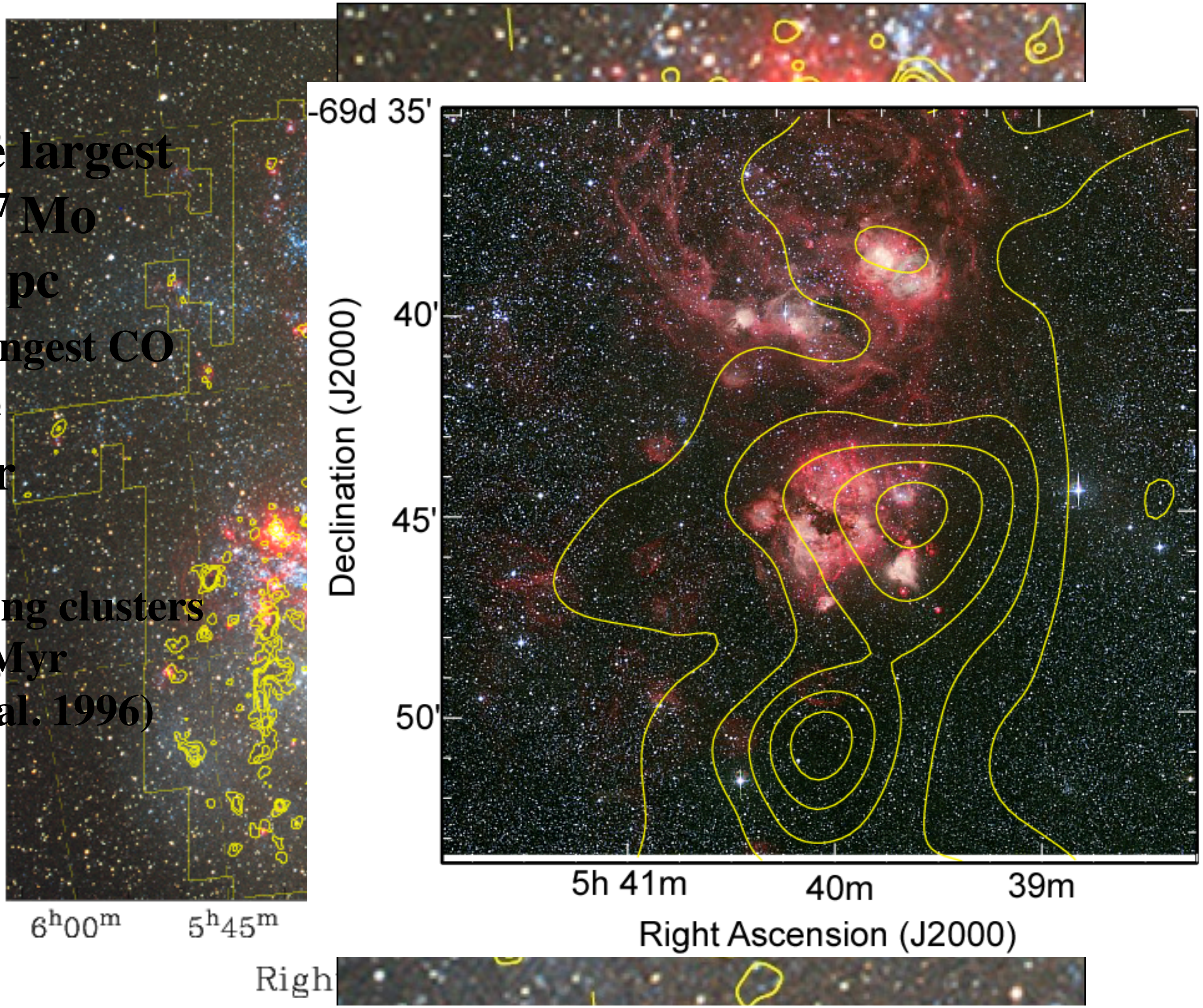
39 clouds (23%) Associated with 82 clusters — 6Myr

55 clusters — 4Myr

Kawamura et al. (2009)

N159

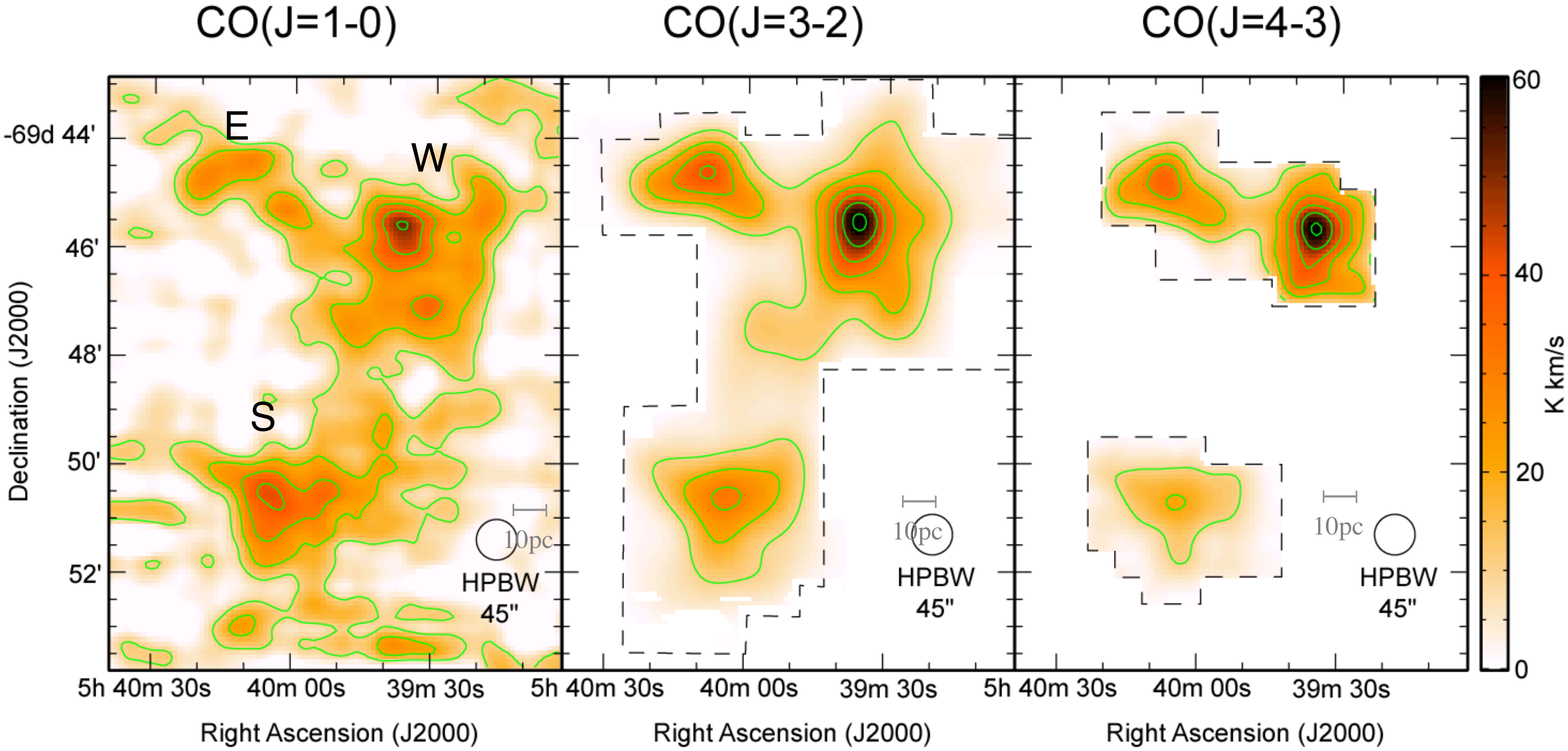
- **N159**
  - **One of the largest**
    Mass：10^7 Mo
    Size：220 pc
    - **Has strongest CO emission**
  - **Active star formation**
    - **Five young clusters age<10Myr (Bica et al. 1996)**



CO distribution in N159

T_{kin} = 15-200 [K]
$n(H_2)$ = 0.8-7×10^3 [cm^{-3}]

~10 pc resolution



Mopra

Ott et al. 2008,
Wong et al. 2011

ASTE

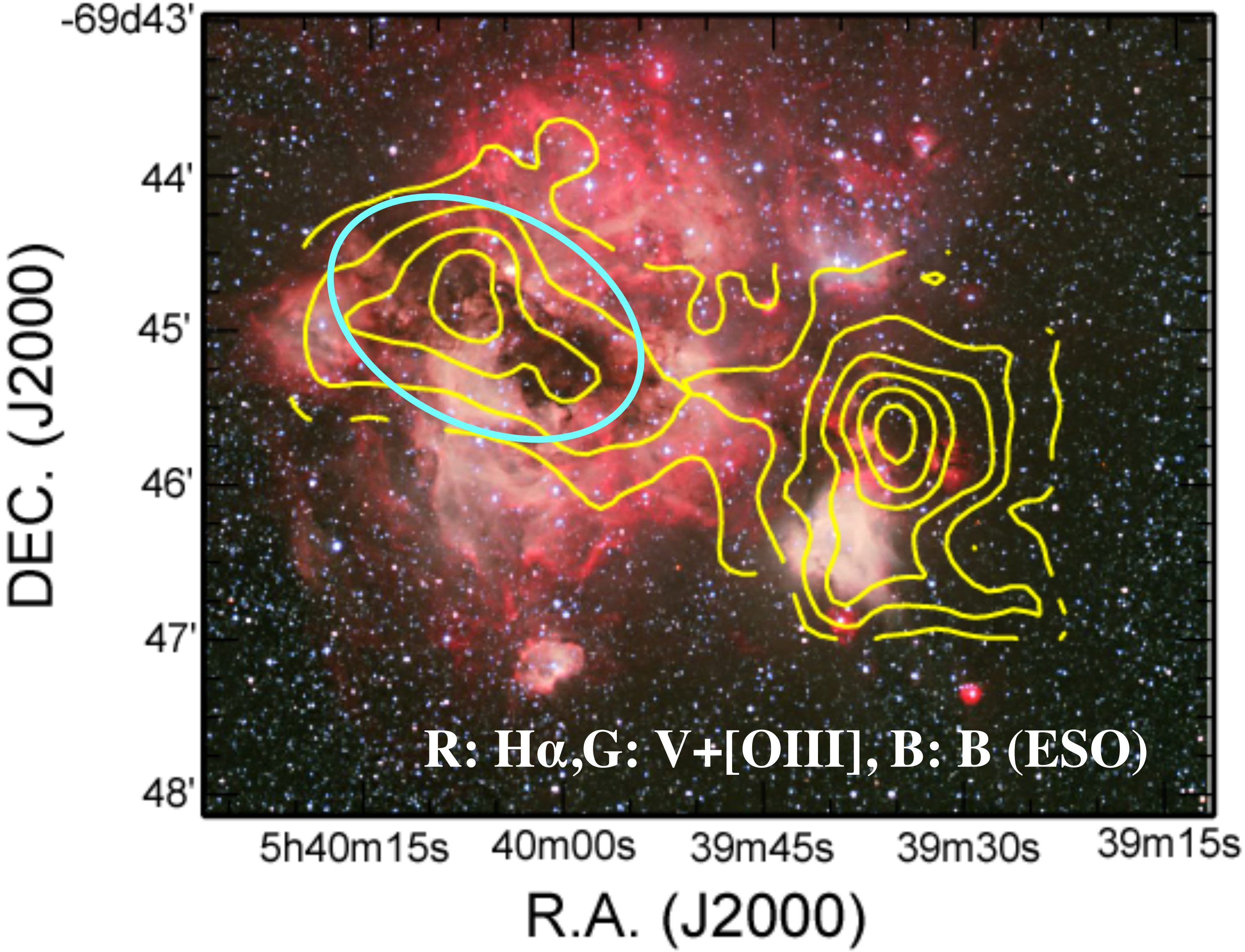
Minamidani et al. 2008

NANTEN2

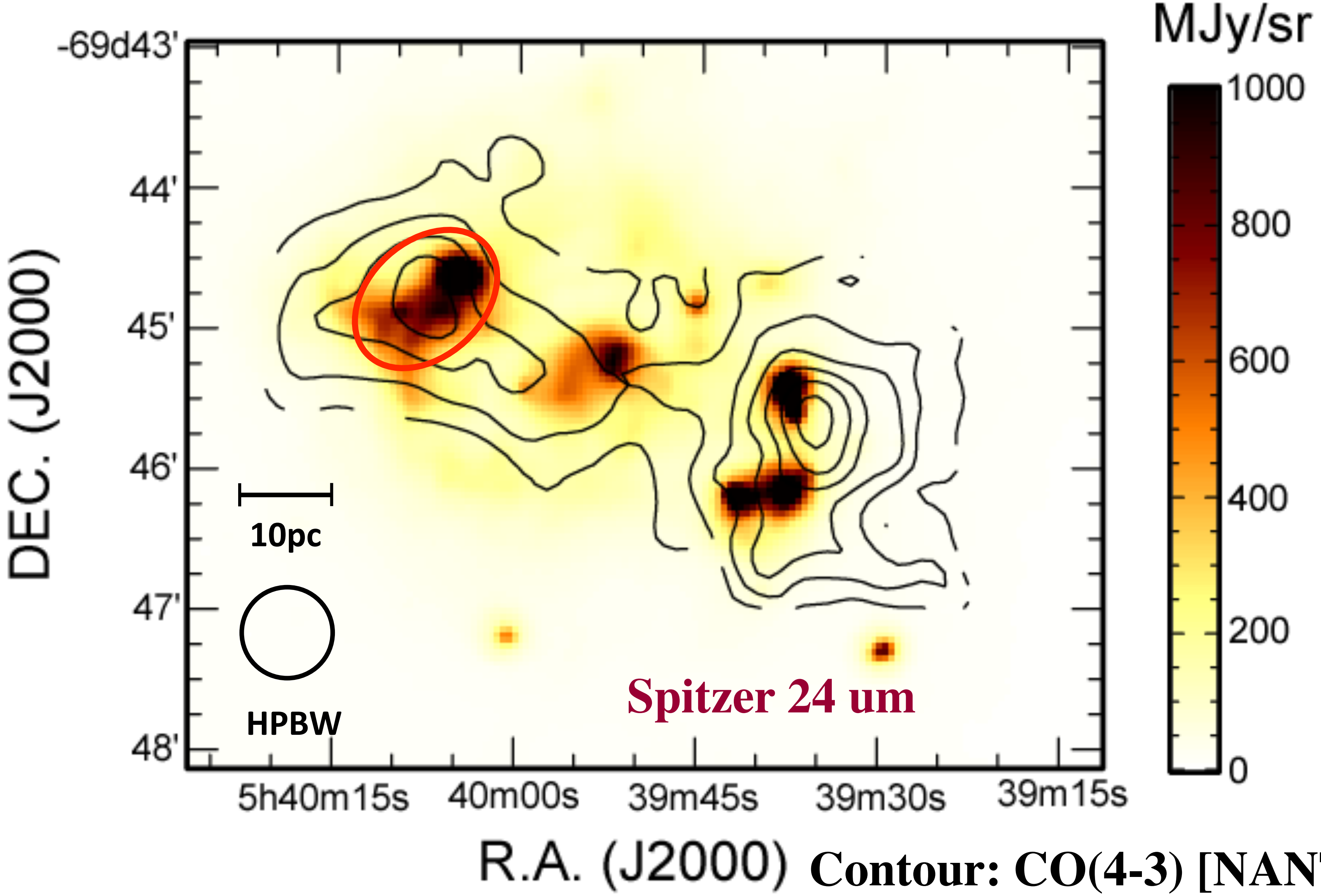
Mizuno et al. (2009)

Star forming activity in the North region of N159

Contour: CO(4-3) [NANTEN2]



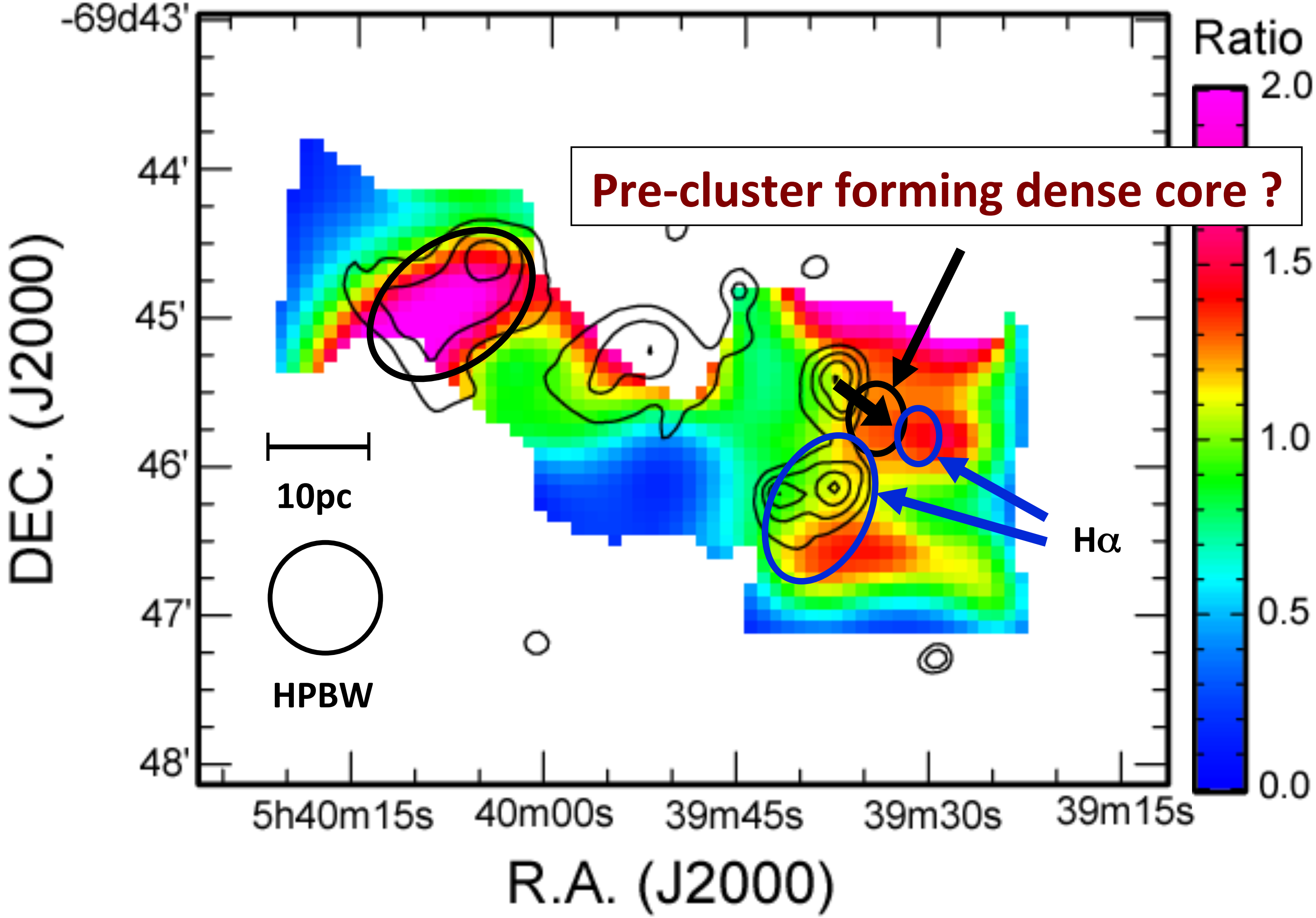
Star forming activity in the North region of N159



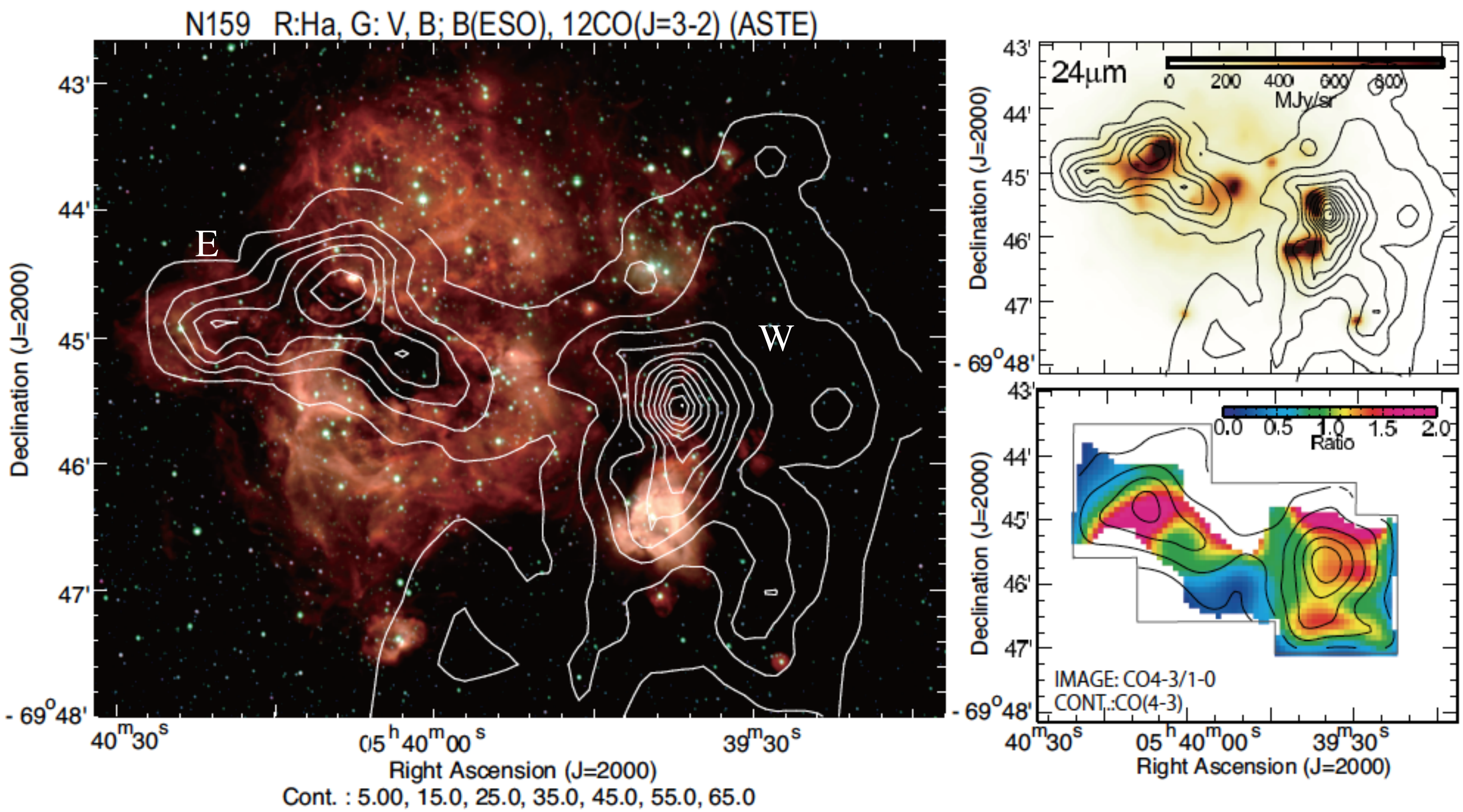
Contour: CO(4-3) [NANT

Line ratio and star formation activities

Color : ^{12}R 4-3/1-0, Contour: 24um



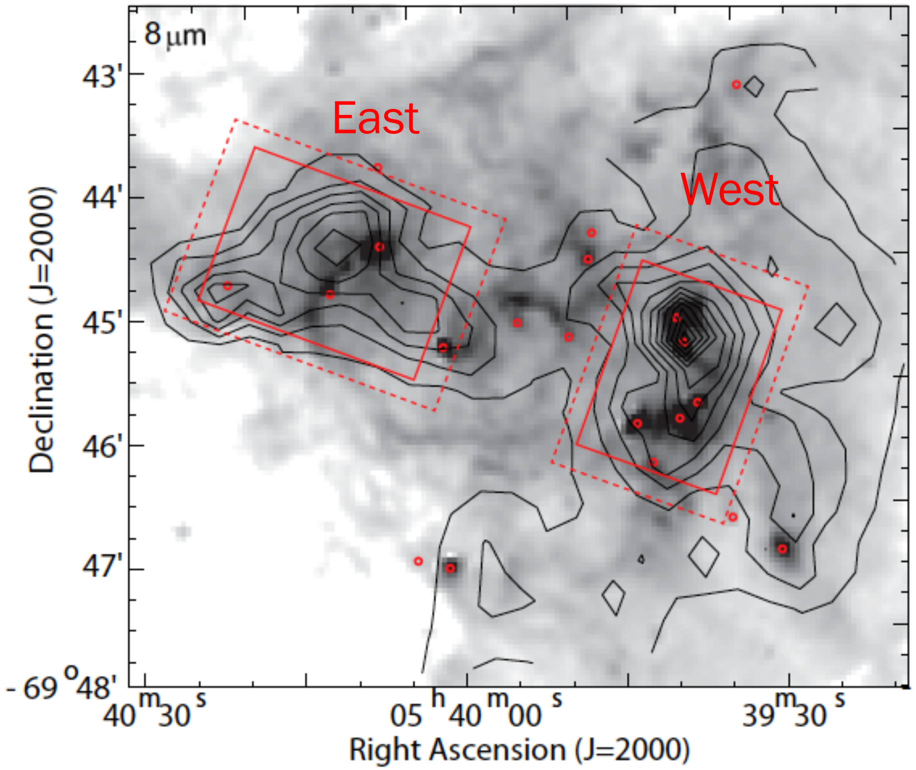
N159 Molecular Clouds in ~5pc resolution

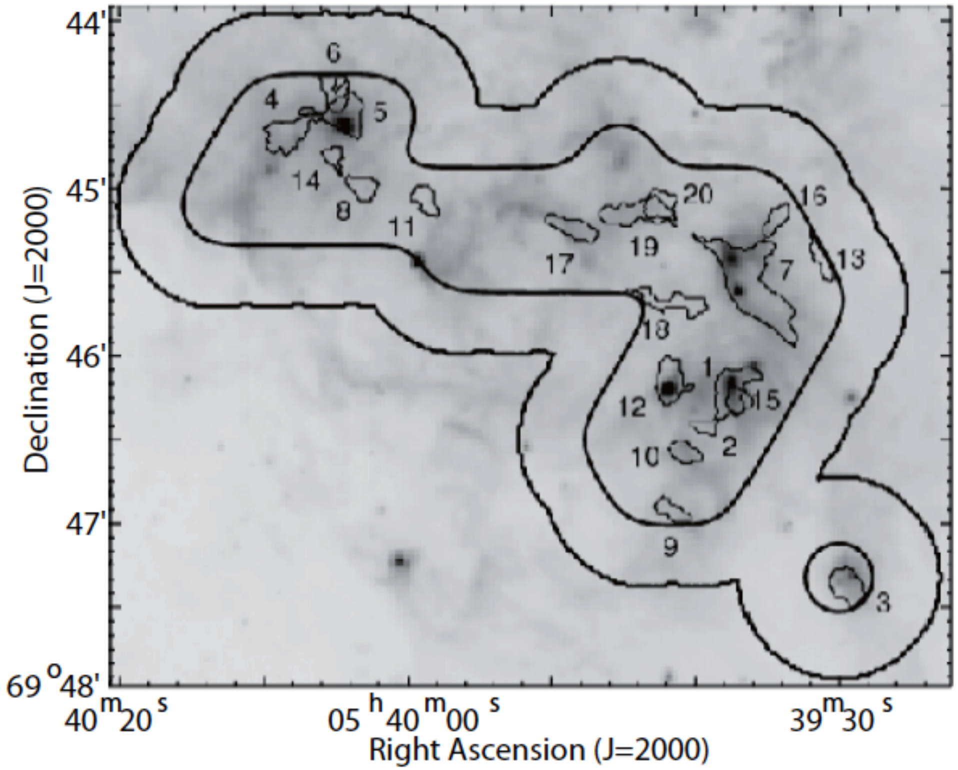


ALMA

- 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
    - Just delivered to us on Monday!!!
- 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

N159





Band 3: 13CO, C18O(J=1-0), CS (J=2-1), Dust continuum
Band 6: 12CO, 13CO, C18O (J=2-1), Dust continuum

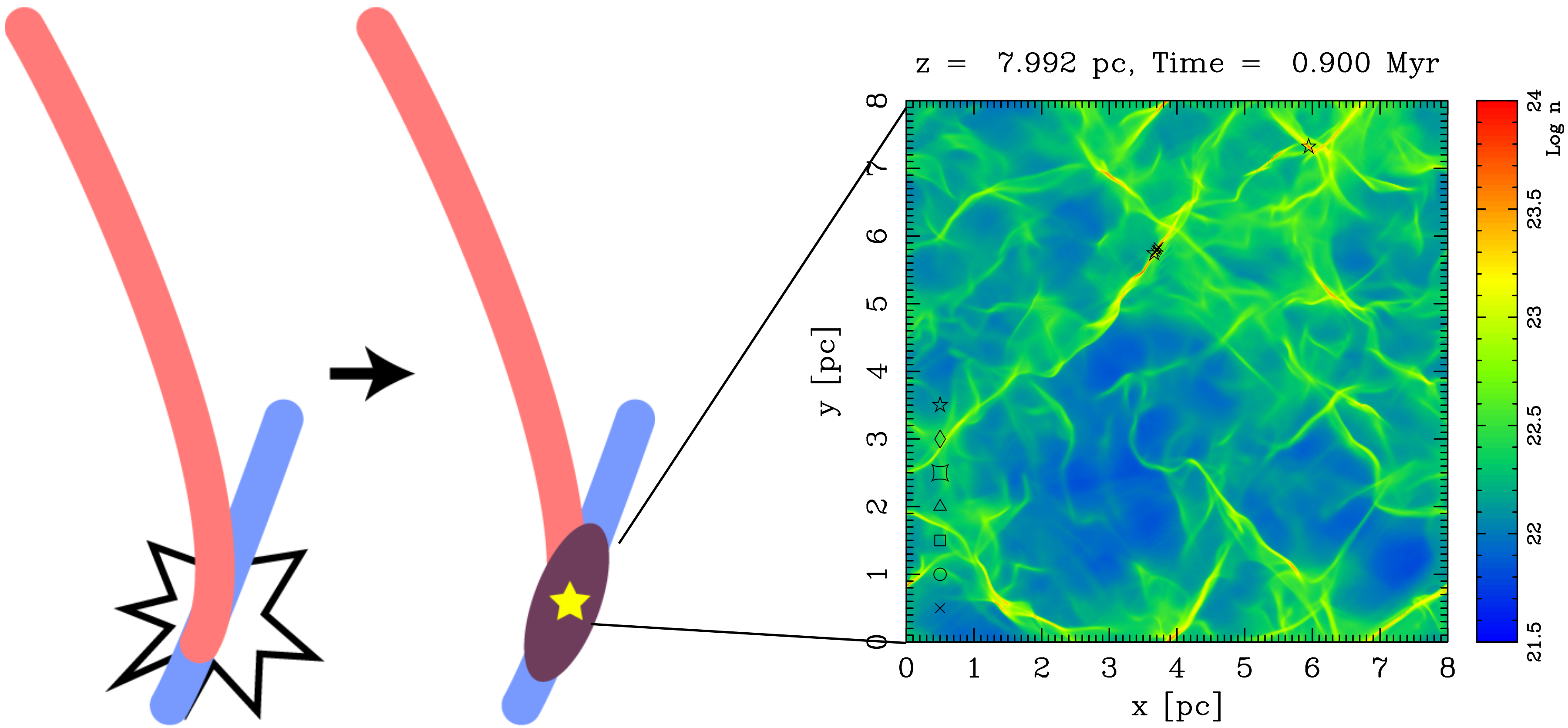
+ACA

Angular resolutions: Band 3: 3.0" (0.72pc), Band 6: 1.5" (0.36pc)

Star formation in N159W [ALMA cycle1]

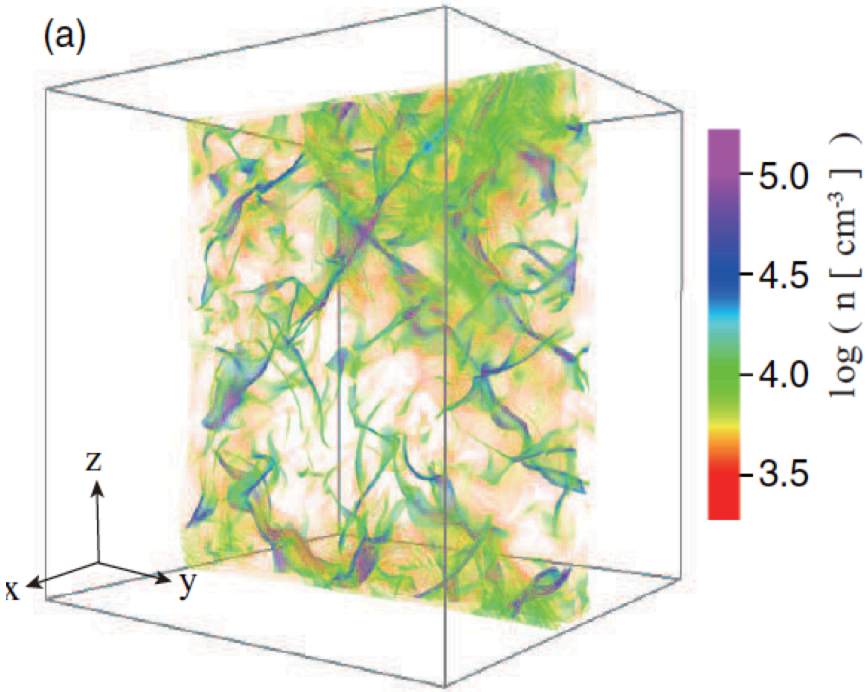
- Filaments dominate the CO distribution
- High mass stars are forming in regions where two or more clouds with different velocities intersect.

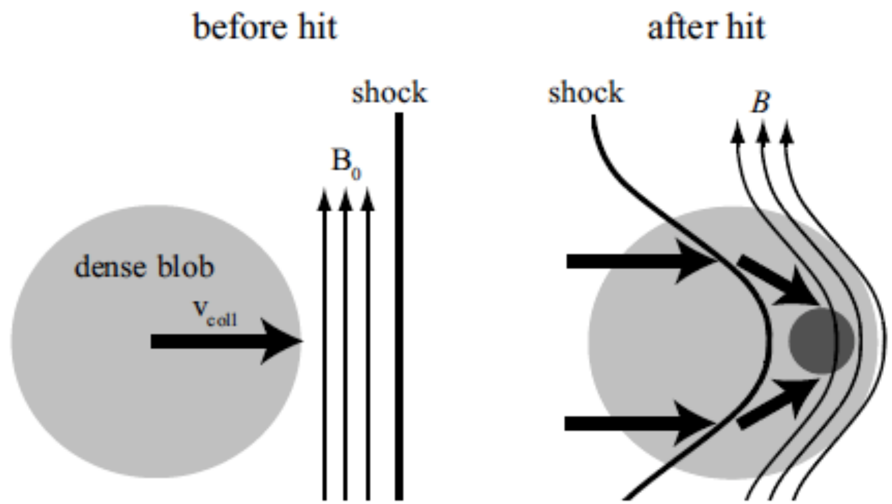
Filament-filament collision



Inoue & Fukui 2013

Cloud-cloud collision rapidly triggers formation of massive dense cores: MHD simulations





Inoue and Fukui 2013

FIG. 1.— Schematics of the gas stream before (*left*) and after (*right*) the interaction between a shock and a dense blob. Because the deformed shock wave leads to a kink of stream lines across the shock, stream lines are headed toward convex point of the deformed shock wave.

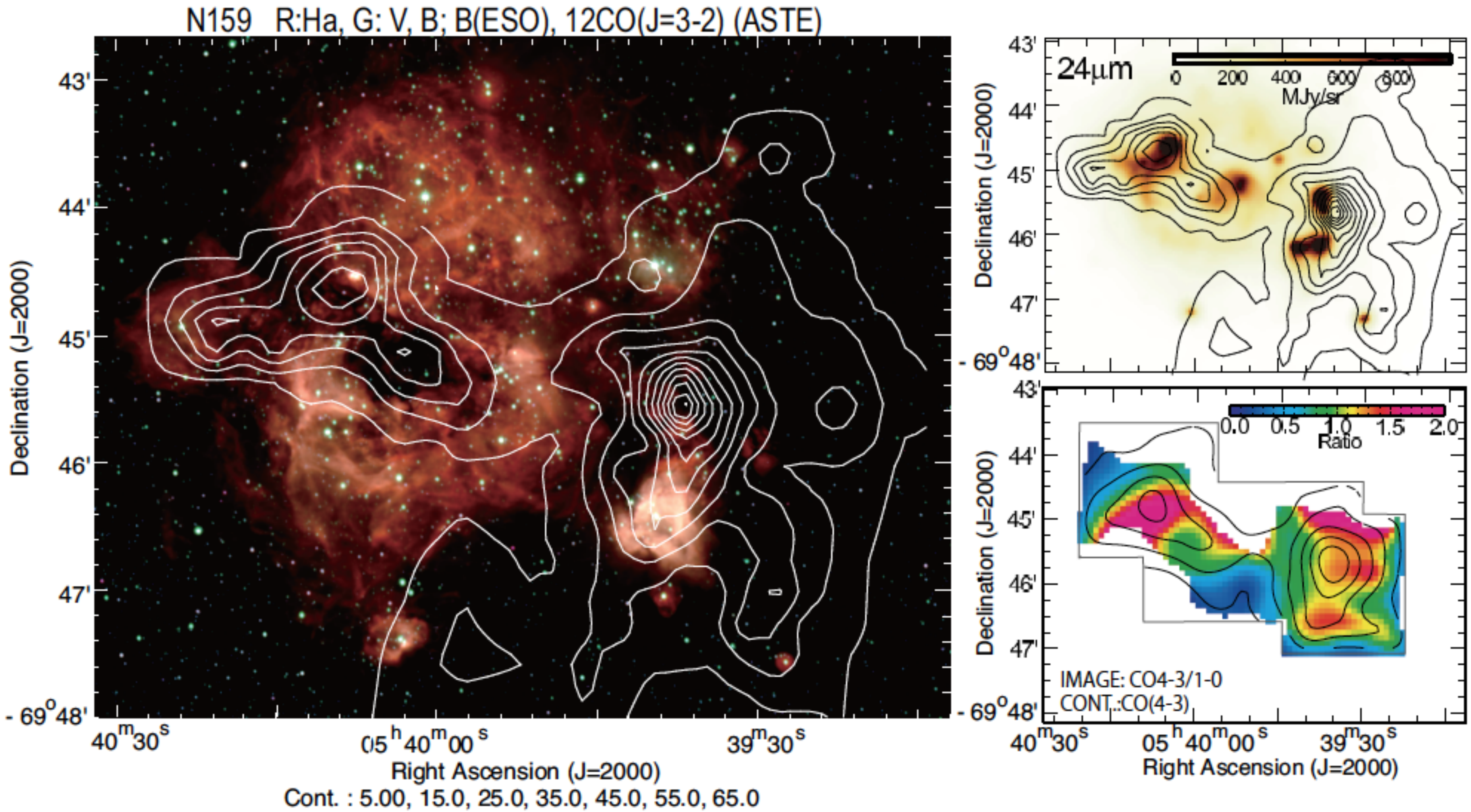
Star formation in N159W [ALMA cycle1]

- Colliding (Merging?) filaments
  - Width: 1pc
  - Velocity difference: 2-5 km/s
  - Time scale: 10^5yrs
- Massive YSOs at the intersection
  - Outflow: Mass is infalling (~10^4yrs)
  - Radio recombination lines: ionized

Massive stars are formed rapidly after the collision

Large scale v.s. small scale

- Arrays
  - 12m
  - 7m (ACA: Morita Array)
  - TP (Single Dish) : Not yet


N159 R:Ha, G: V, B; B(ESO), 12CO(J=3-2) (ASTE)
43'
44'
45'
46'
47'
- 69°48'
Declination (J=2000)
40m30s
05h40m00s
39m30s
Right Ascension (J=2000)
Cont. : 5.00, 15.0, 25.0, 35.0, 45.0, 55.0, 65.0
24μm
0 200 400 600 800
MJy/sr
0.0 0.5 1.0 1.5 2.0
Ratio
IMAGE: CO4-3/1-0
CONT.:CO(4-3)

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
  - Signature of individual star formation: Outflow, H40α
  - Need compact array: Large-scale -> Small-scale