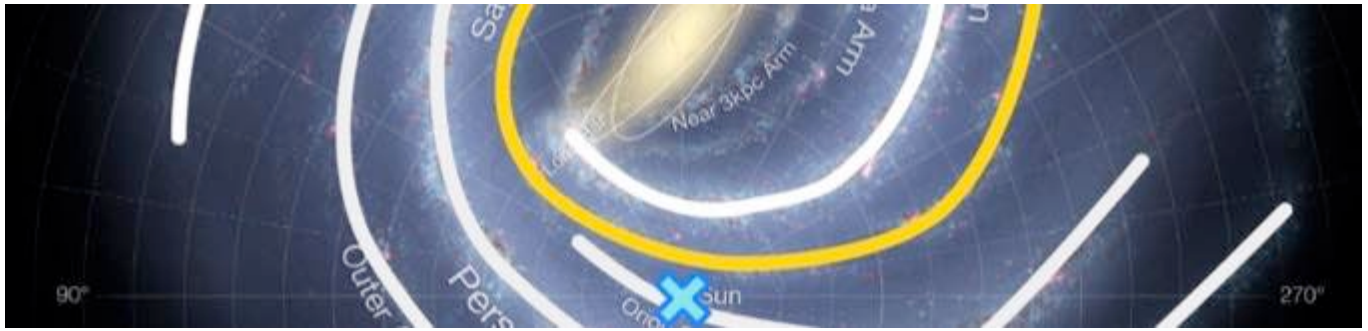
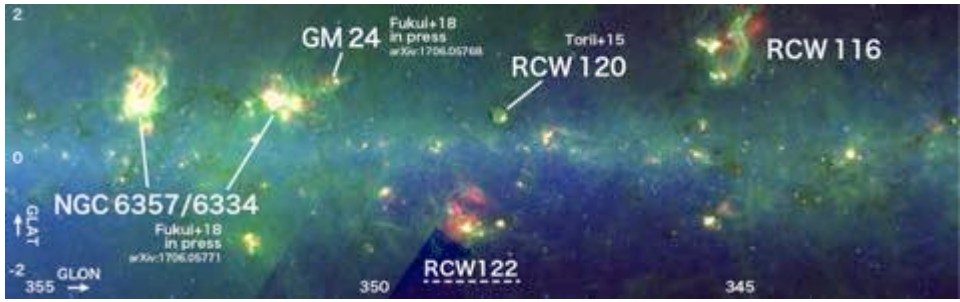


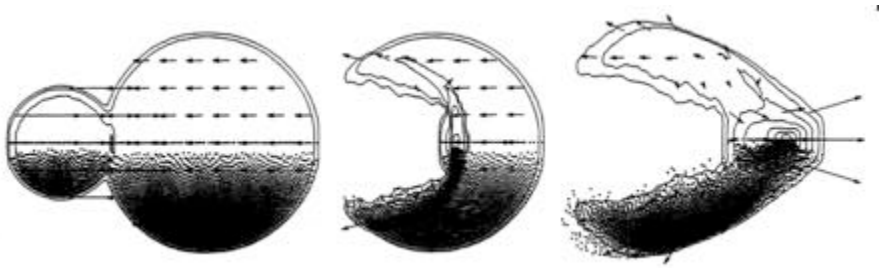
Cloud collision triggering high-mass star formation in the Sagittarius Arm

Atsushi Nishimura (Nagoya U)

Main collaborators:
S. Fujita[1], M. Kohno[1], A. Ohama[1], K. Torii[2], S. Yoshiike[1],
D. Tsutsumi[1], K. Okawa[1], T. Minamidani[2], K. Tachihara[1], Y. Fukui[1]
and NANTEN2/FUGIN members (1: Nagoya U, 2: NRO/NAOJ)



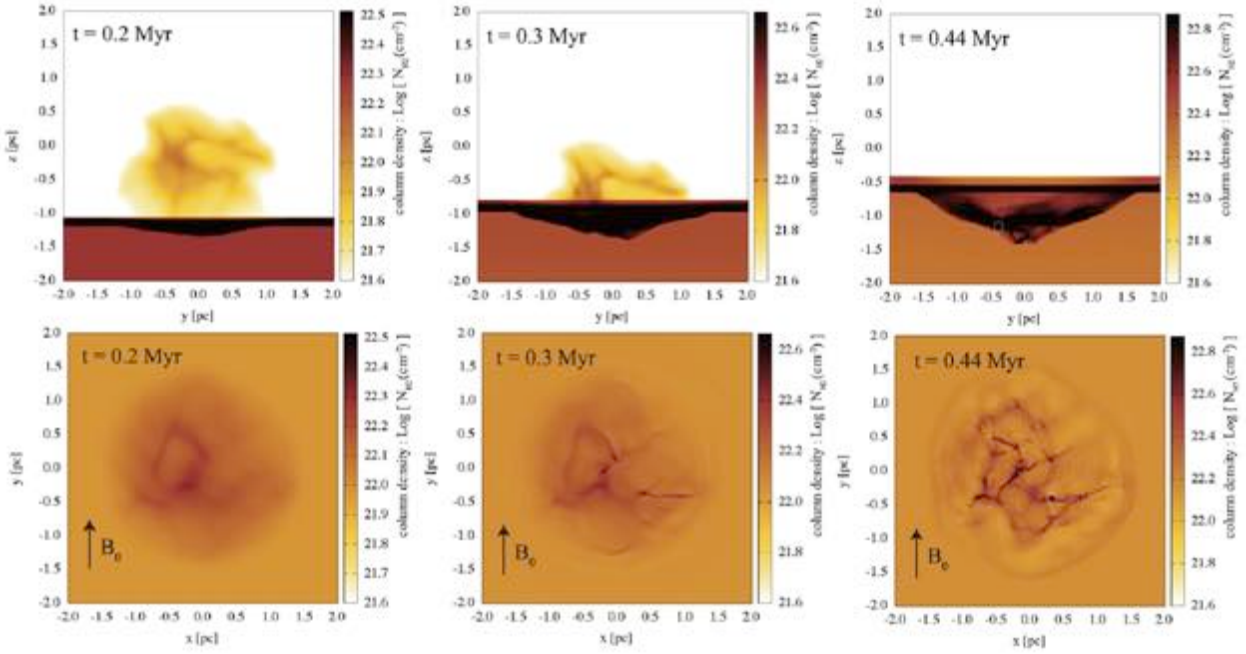
Cloud cloud collision (CCC)



Habe & Ohta (1992)

SF mechanism

① Shock compression



Inoue et al. (2018) in press arXiv:1707.02035

②

Growth of massive filaments
supported by enhanced magnetic field

③

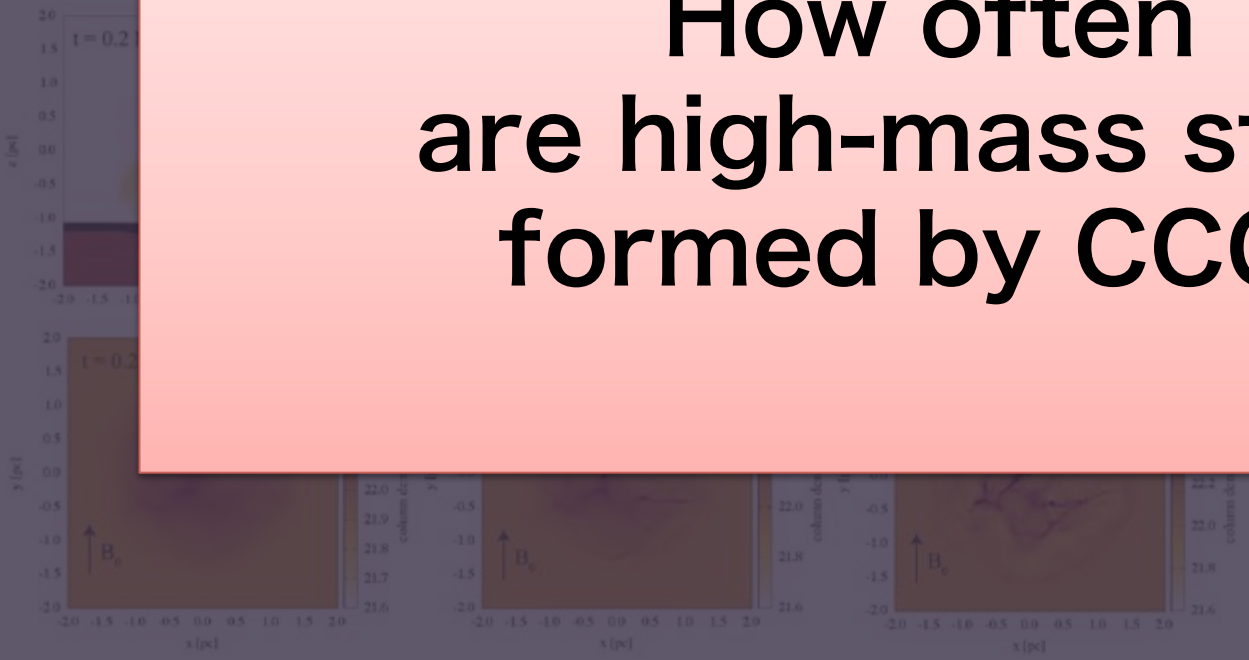
Collapse of massive filament
mass accretion rate will be $>10^{-4}$ M_{sun} yr^{-1}

Cloud cloud collision (CCC)

SF mechanism

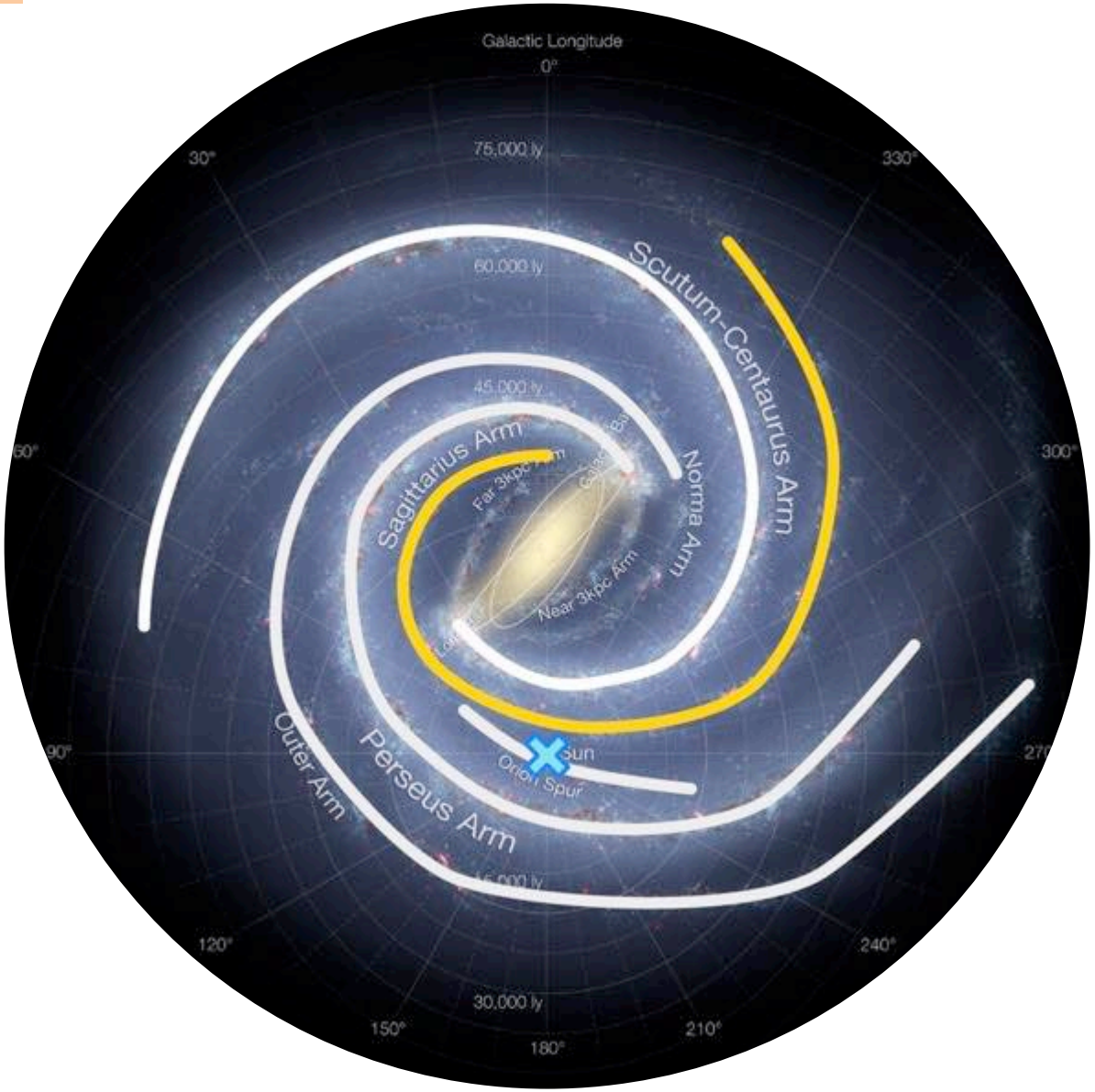
- Shock compressed layer
- ts
- by
- lapse through the filament provide high mass accretion rate $>10^{-4}\ M_{sun}\ yr^{-1}$.

How often are high-mass stars formed by CCC?



Inoue et al. (2018) in press arXiv:1707.02035

Spiral arms in the Galaxy

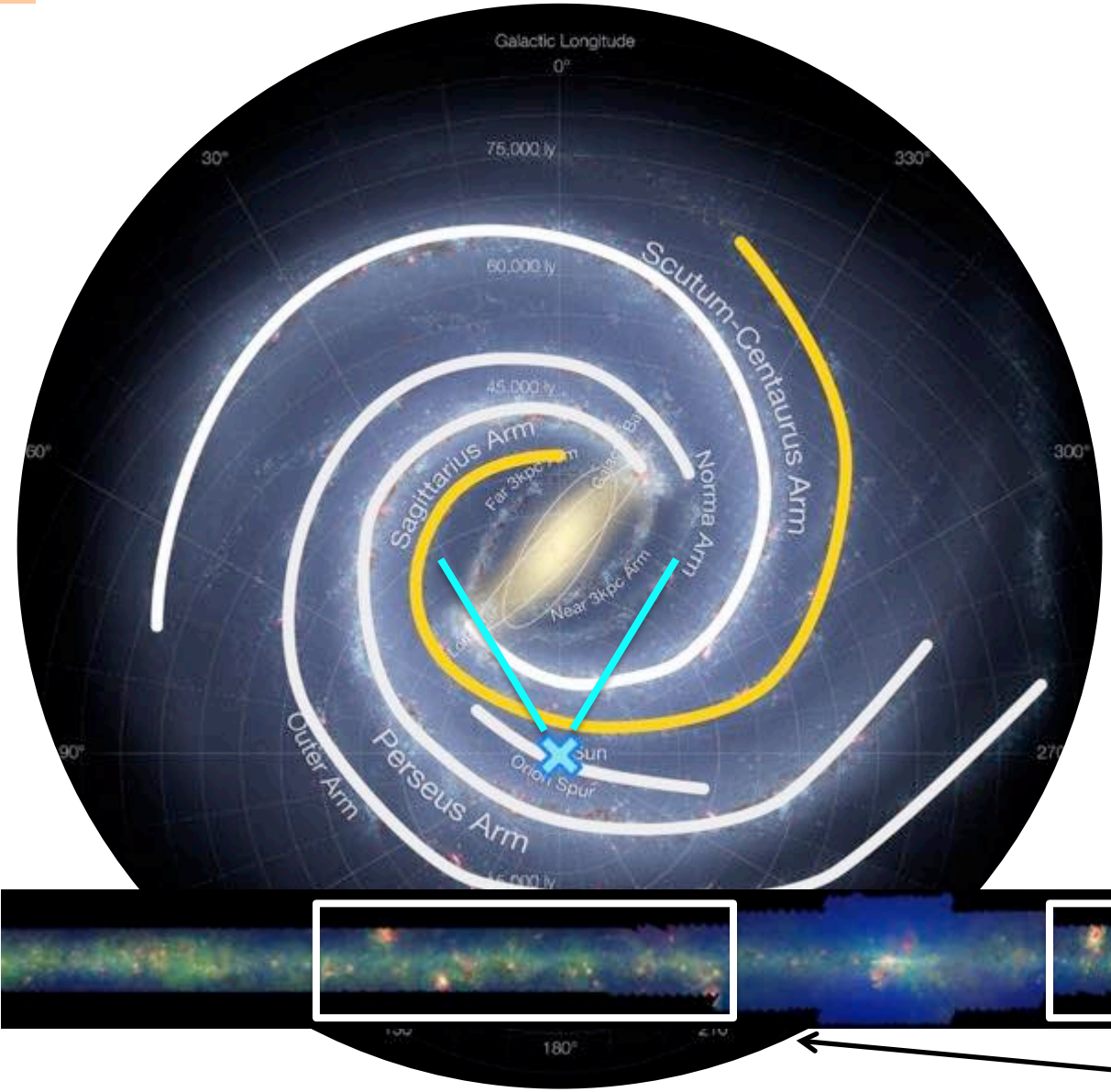


Most stars are formed on arms in spiral galaxies.

Sagittarius Arm is...

- nearest inner arm
- best target to study SF statistics
- except for Galactic Center region

Spiral arms in the Galaxy



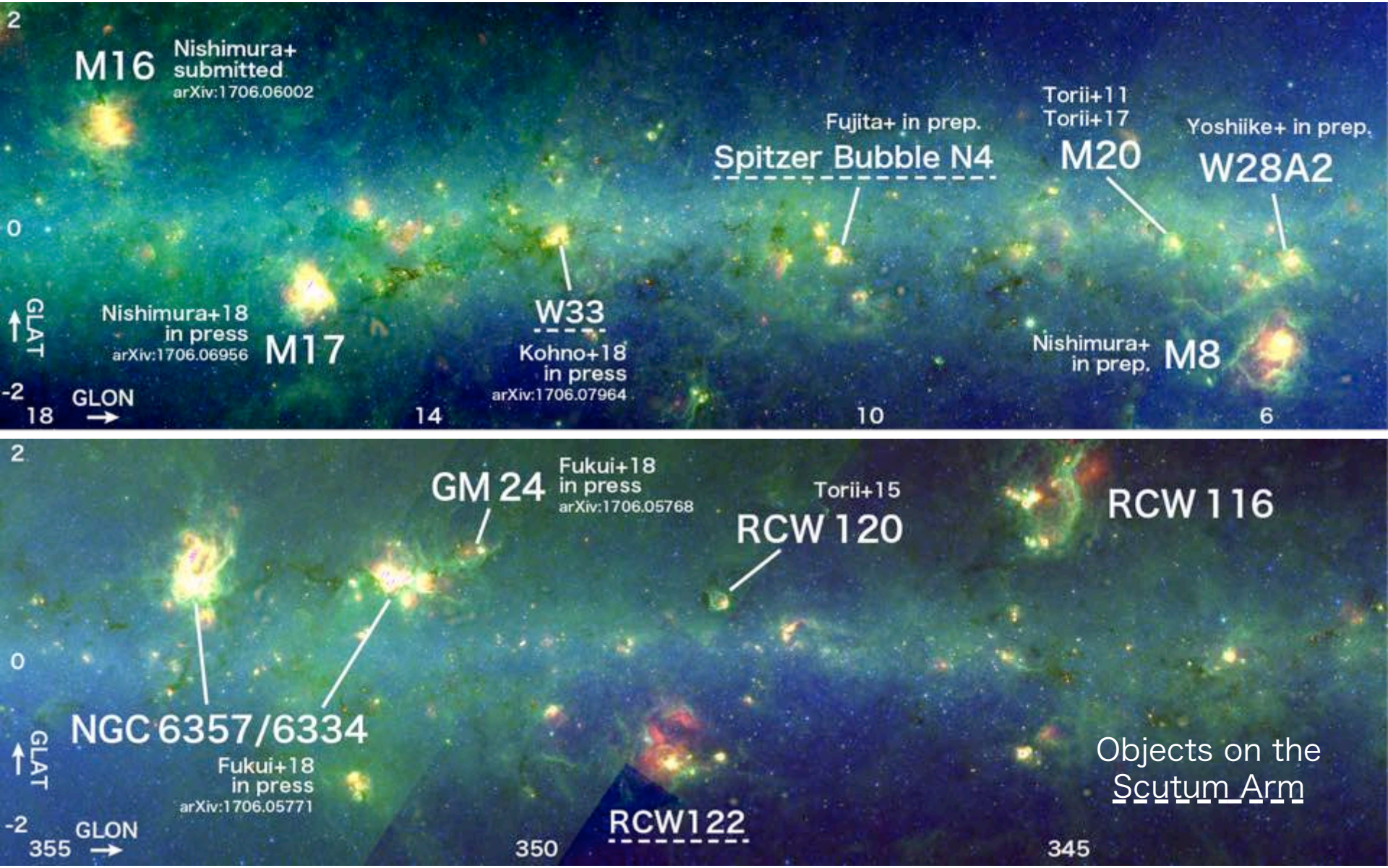
This talk

Most stars are formed on arms in spiral galaxies.

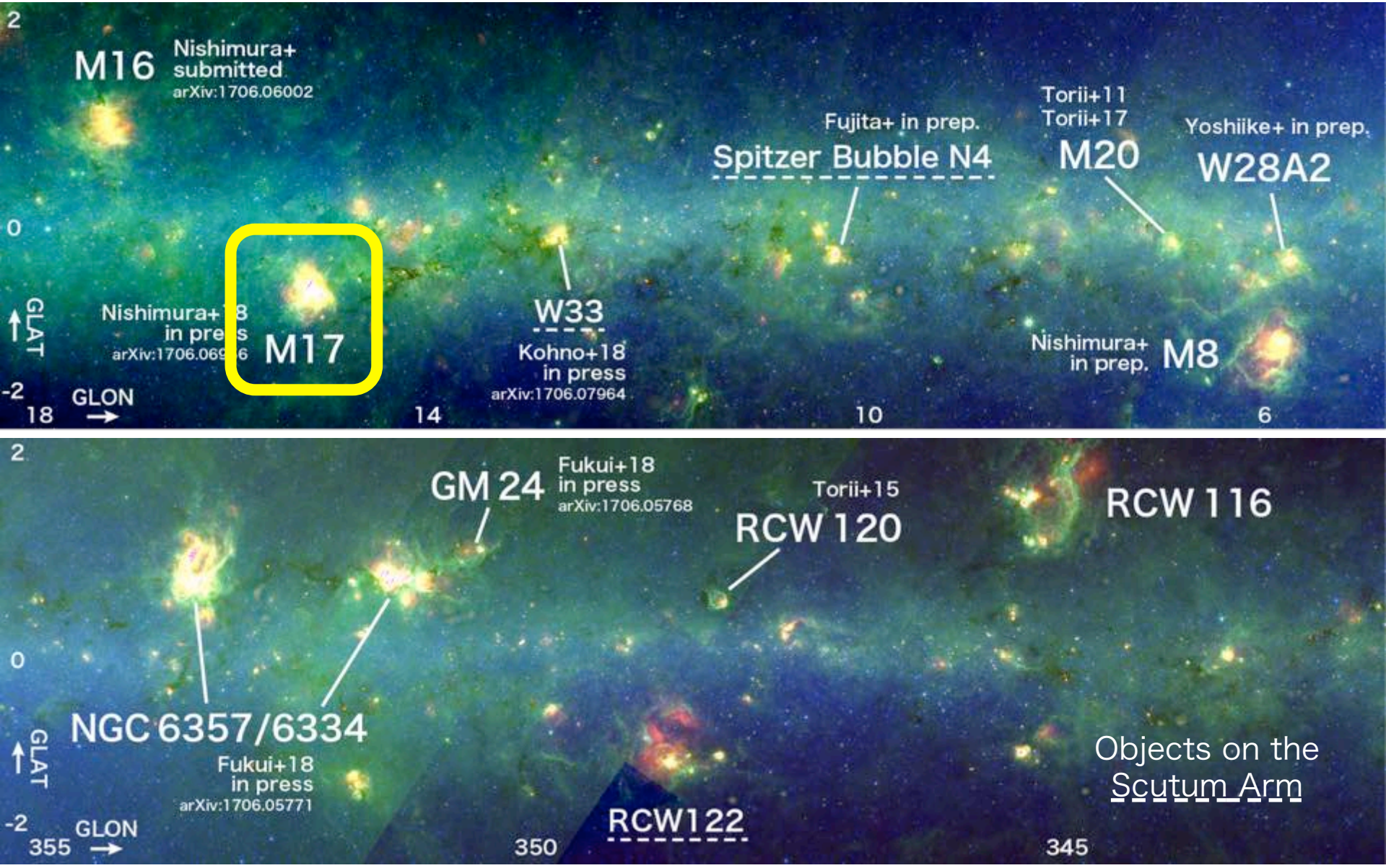
Sagittarius Arm is...

- nearest inner arm
- best target to study SF statistics
- except for Galactic Center region

Sagittarius Arm

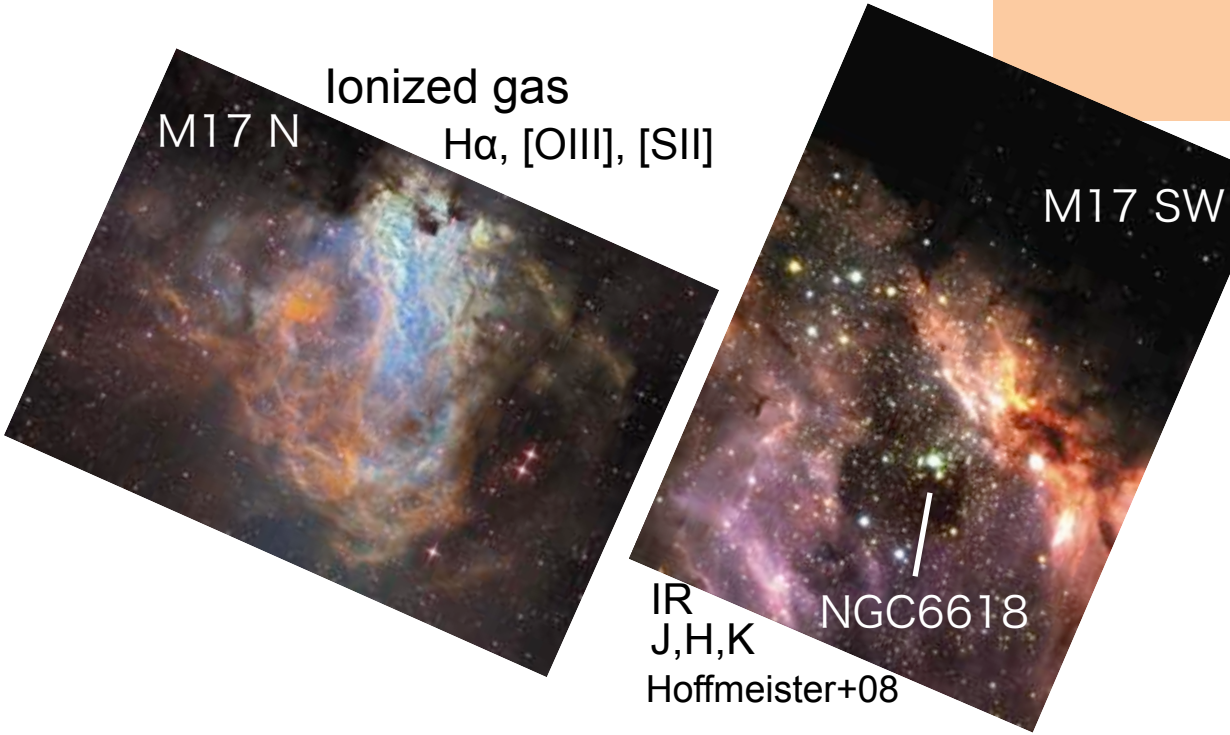


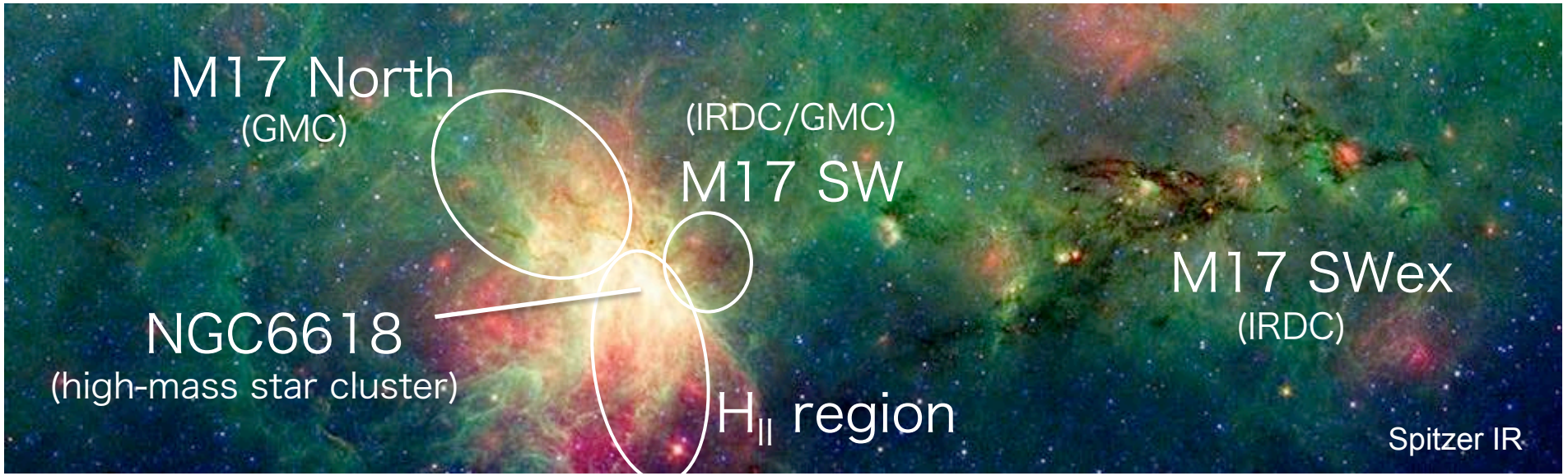
Sagittarius Arm : M17



M17 : Omega

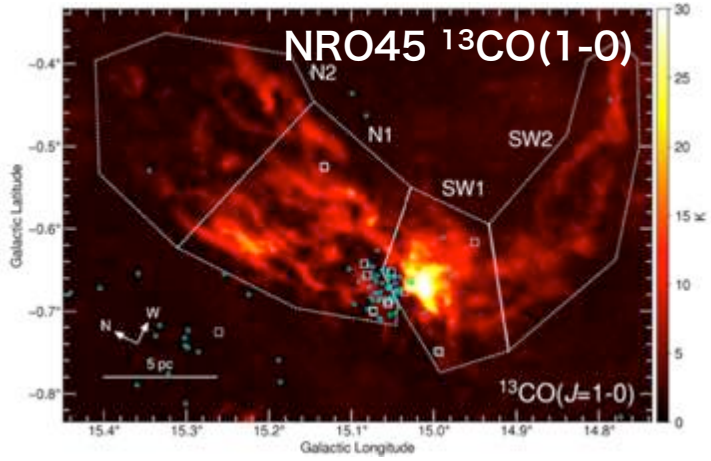
- Distance : ~ 2.1 kpc
- GMC : SW, North
  - M_{mol} ~ 10^5 Mo
- Cluster : NGC6618
  - n_{Ostars} : >16
    - with O4-O4 binary
  - t_{age} <1 Myr

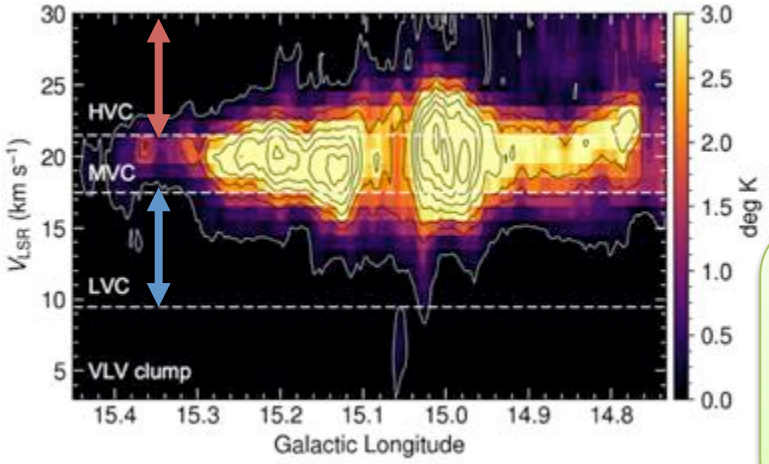


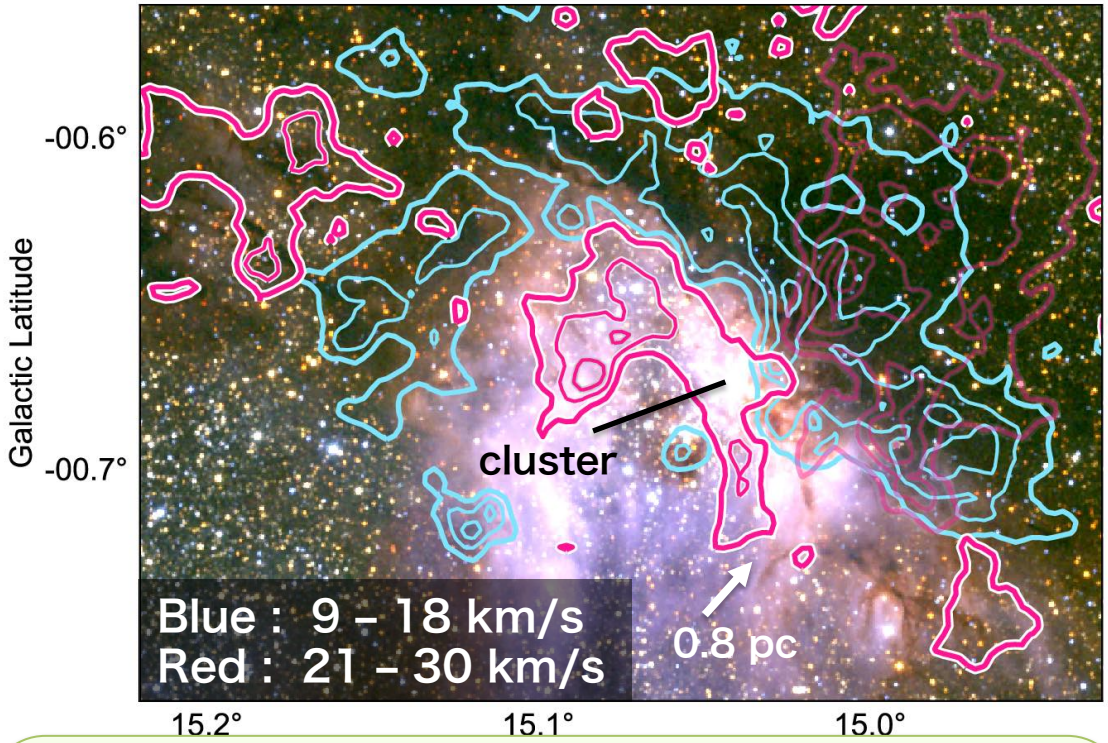


M17 : Gas dynamics

Nishimura et al. (2018), PASJ
arXiv:1706.06956



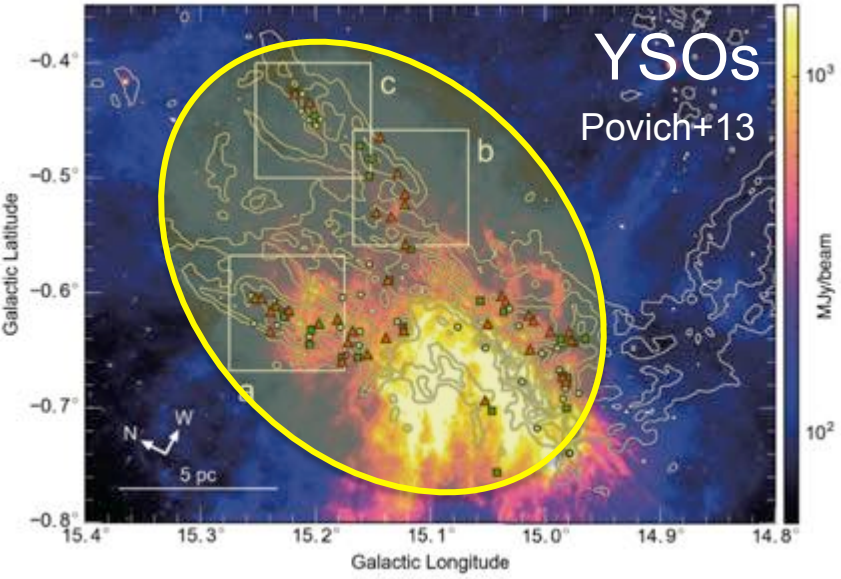


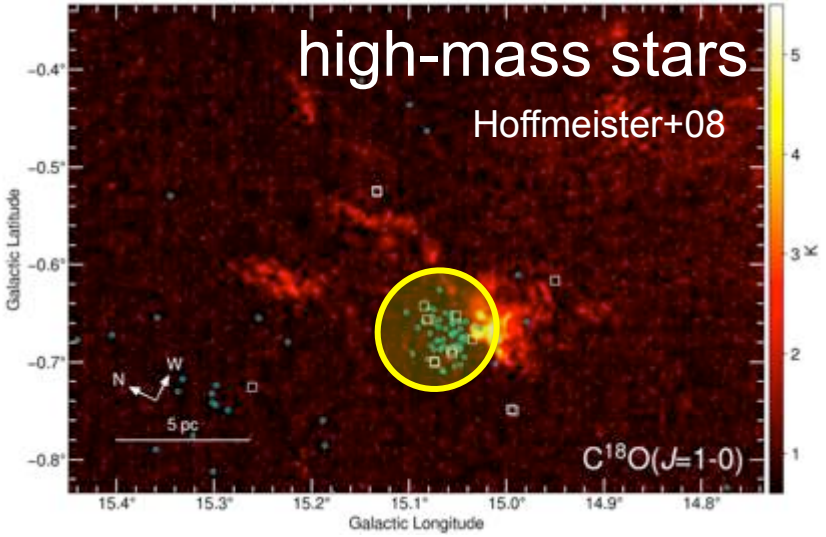


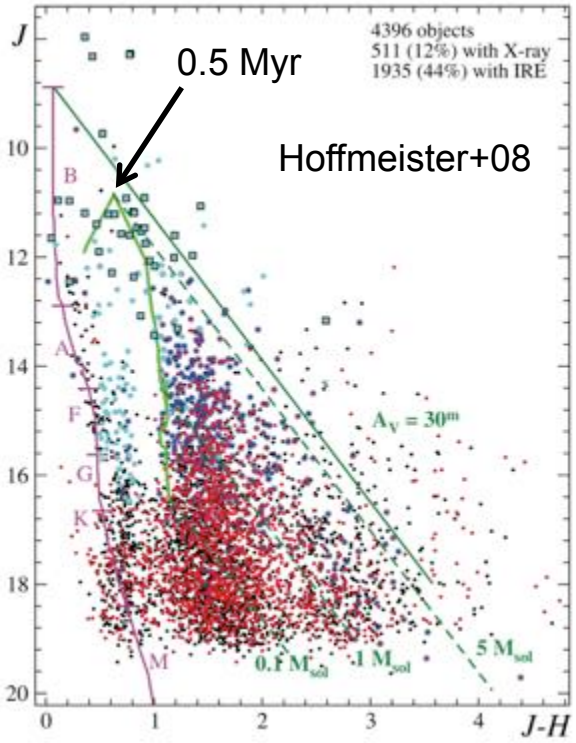
Complementary distribution is found in Red-/Blue- shifted gas clearly.
→ Cloud collision

- collision velocity : 9.9 km/s
- collision timescale : ~0.1 Myr

M17 : Stars



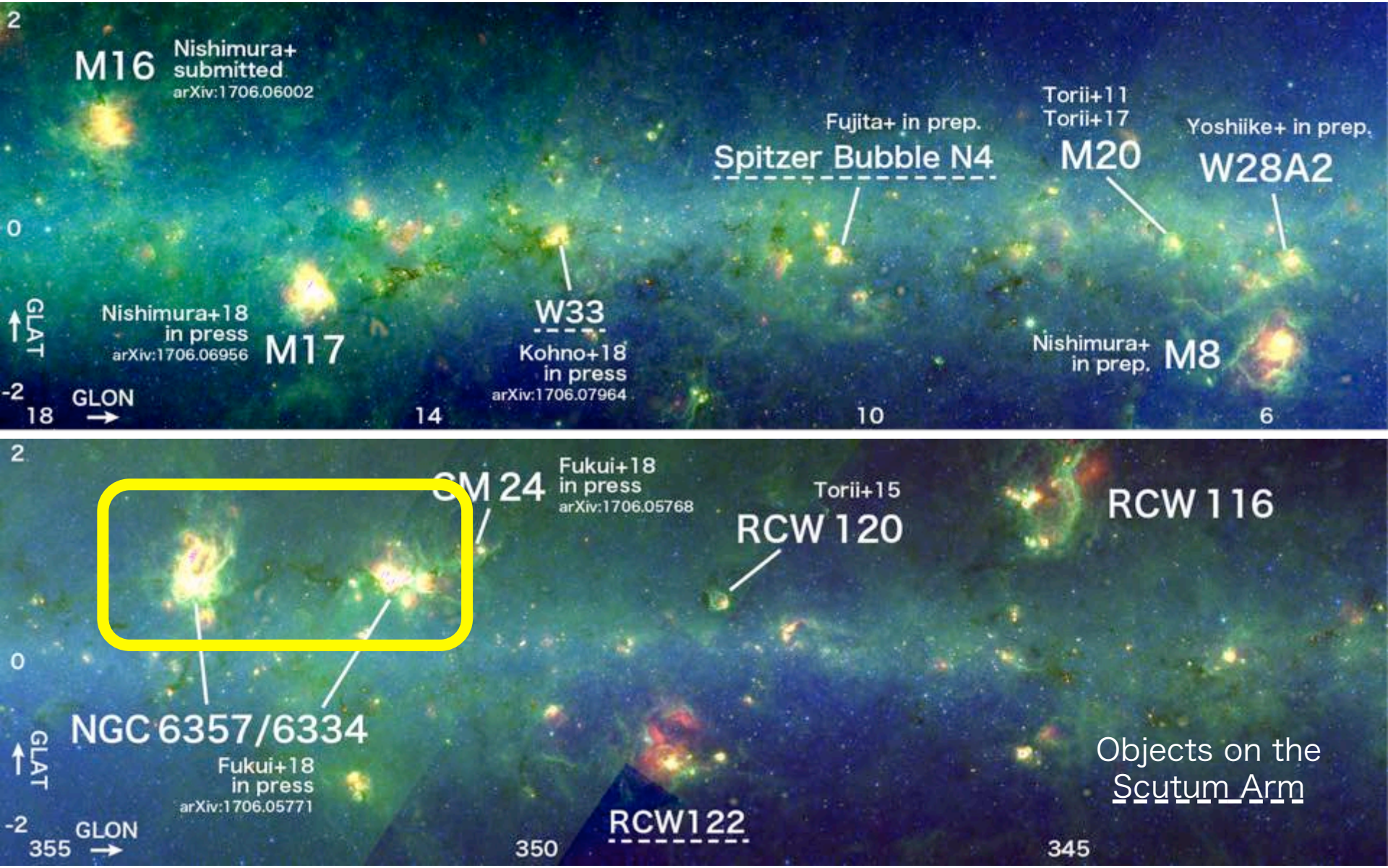




- Low-mass stars
  - global, age gap at ~0.5 Myr ago
- High-mass stars
  - local, age : <1 Myr

Stellar distribution/age are well consistent with collision model.

Sagittarius Arm : NGC6357/6334



NGC 6357, 6334

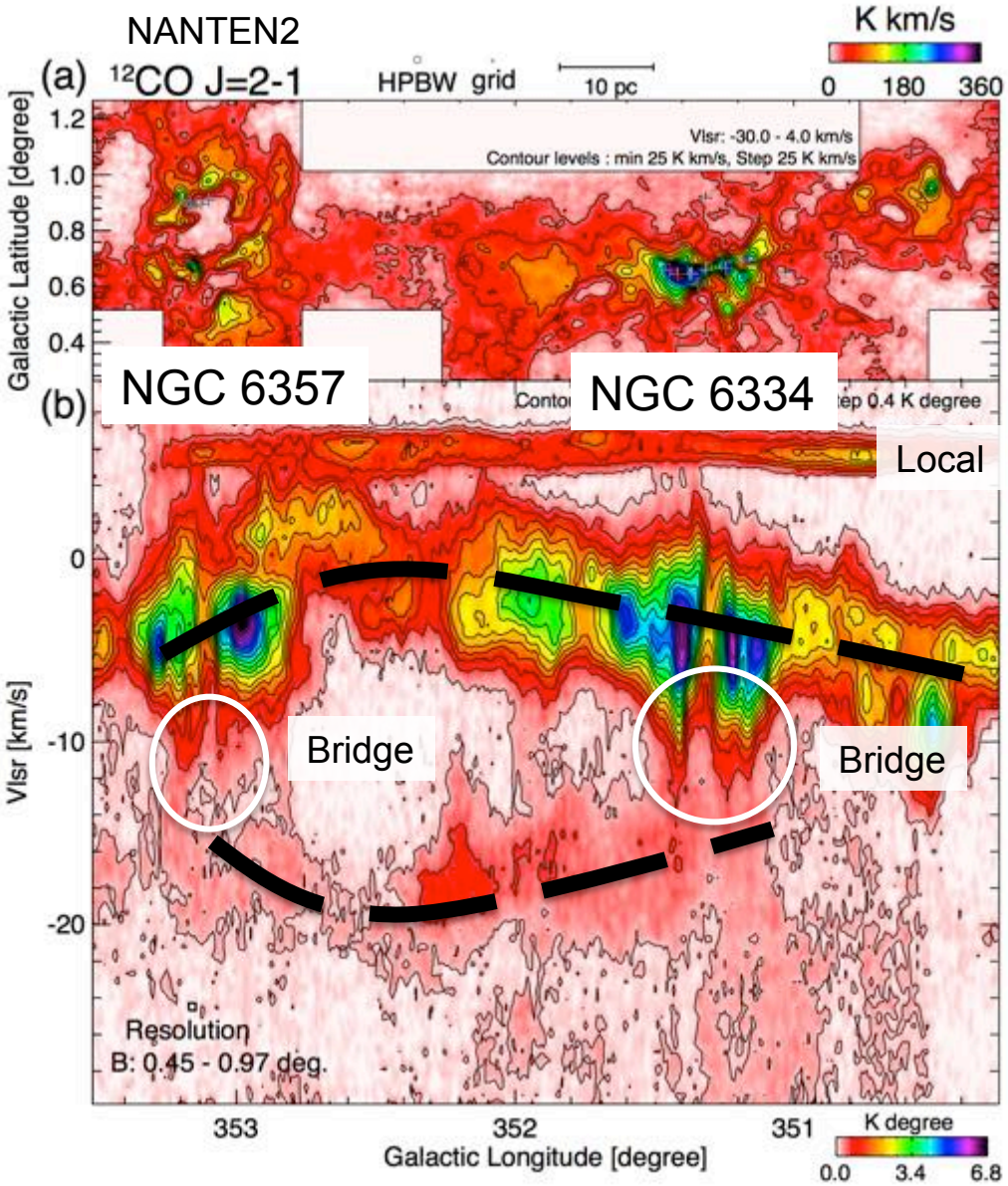
NGC 6357

- Distance : ~1.7 kpc
- GMC : M_{mol} ~ 10^4 Mo
- O/early-B stars
  - >9, age : >1 Myr

NGC 6334

- Distance : 1.61 kpc
- GMC : M_{mol} ~ 10^5 Mo
- O/early-B stars
  - >18, age : 10^4-10^6 yr

NGC 6357, 6334 : Gas dynamics

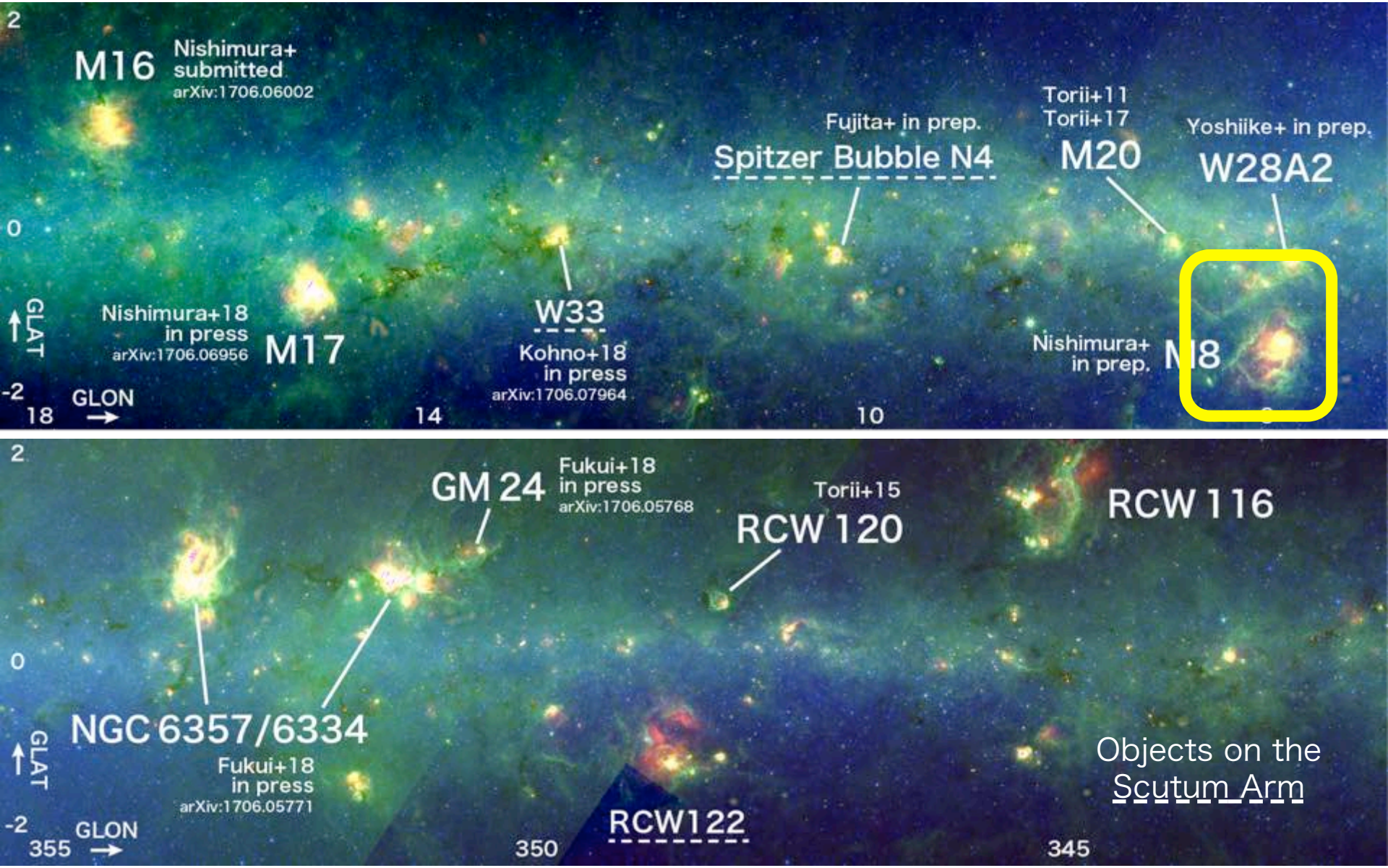


Fukui et al. (2018a), PASJ
arXiv:1706.05771

- 2 velocity components are physically connected
  - bridge feature
  - similar physical property

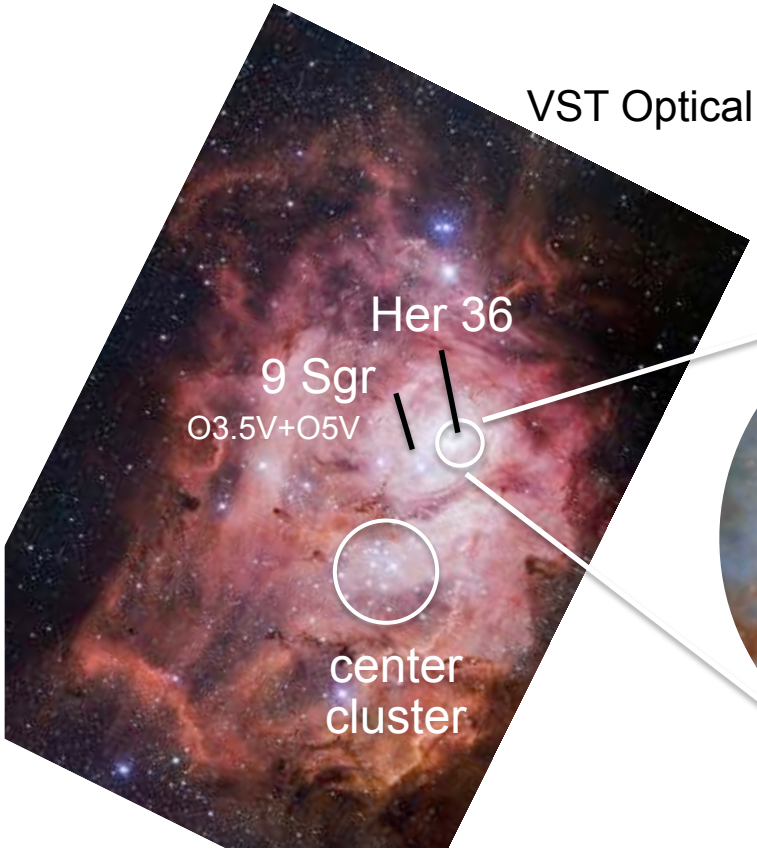
- collision velocity :
  - ~12 km/s
- collision timescale :
  - ~1 Myr

Sagittarius Arm : M8



M8 : Lagoon

Spitzer IR

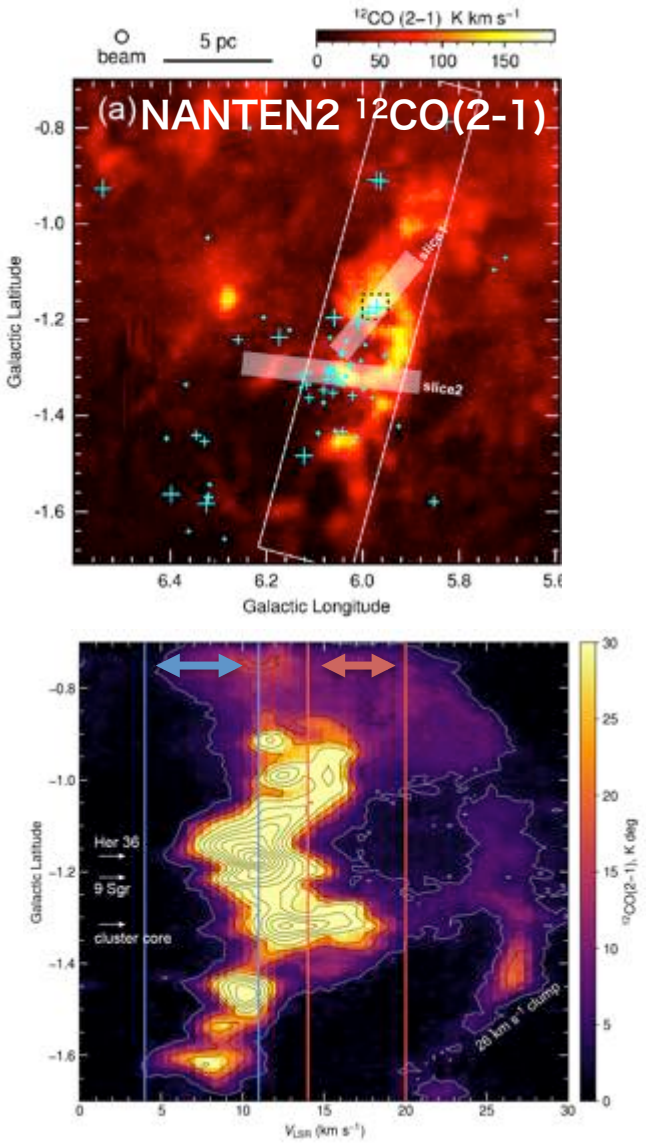


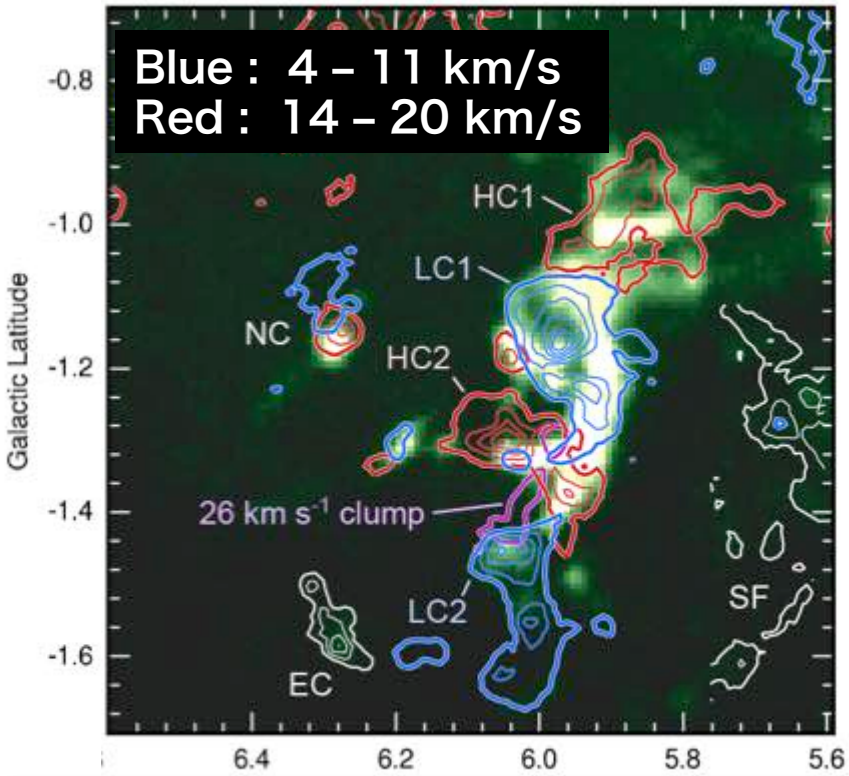
- Distance : ~ 1.3 kpc
- GMC:
  - M_{mol} ~ 4 × 10^4 Mo

- Center cluster
  - >10 B stars, 2-3 Myr
- O stars
  - n_{Ostars} : >10, ~1 Myr

M8 : Gas dynamics

Nishimura et al. in prep.



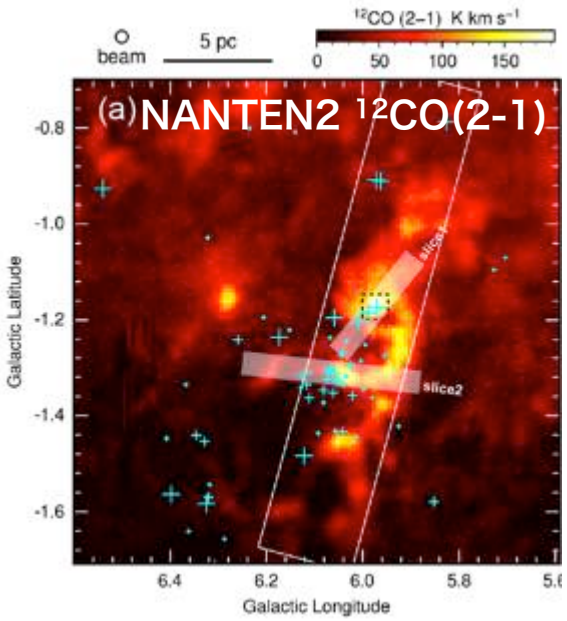


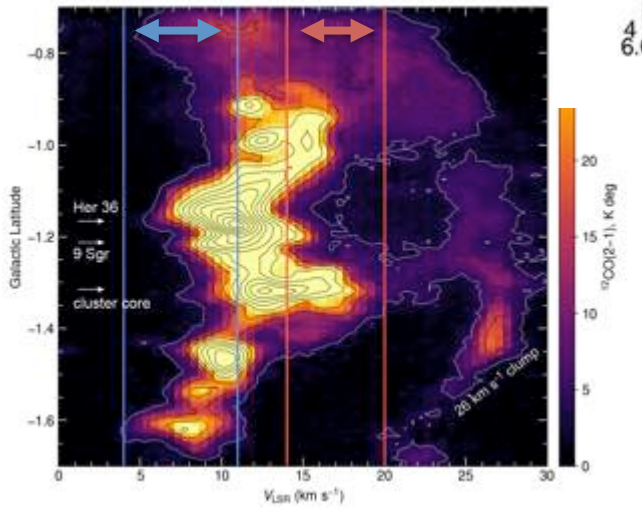
- Complementary distribution
- V-shaped velocity feature

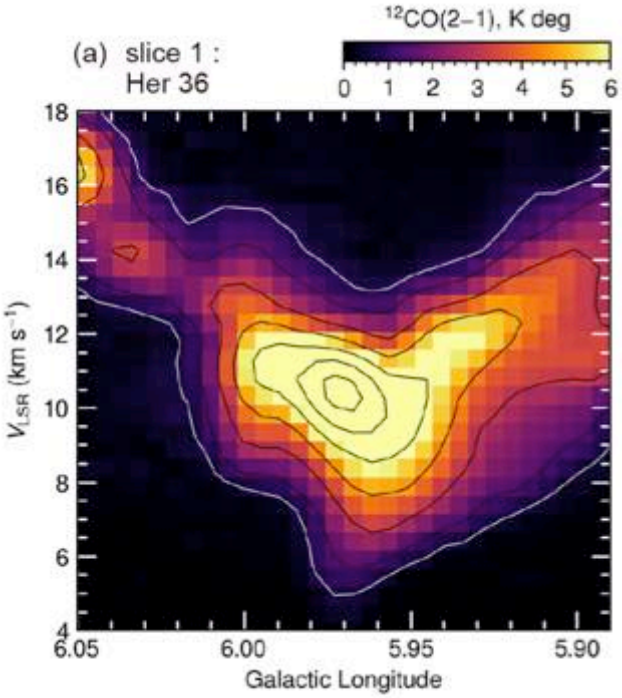
- collision velocity : 10 km/s
- collision timescale : ~0.3 Myr

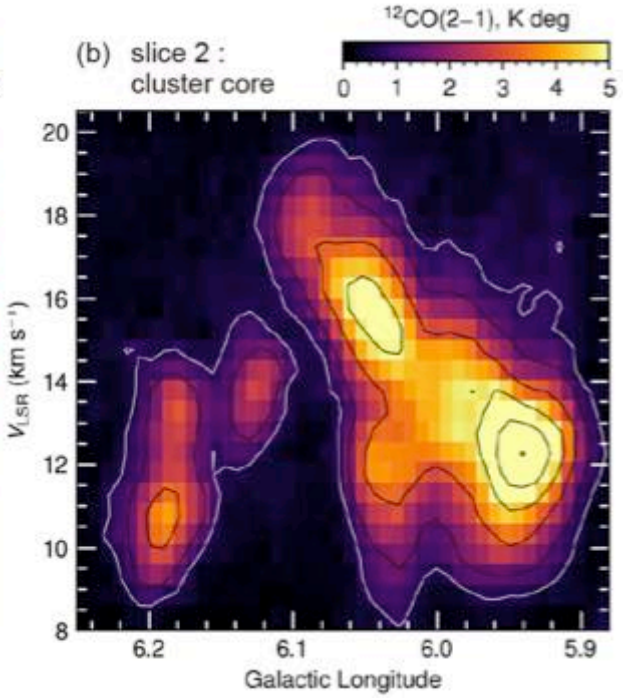
M8 : Gas dynamics

Nishimura et al. in prep.





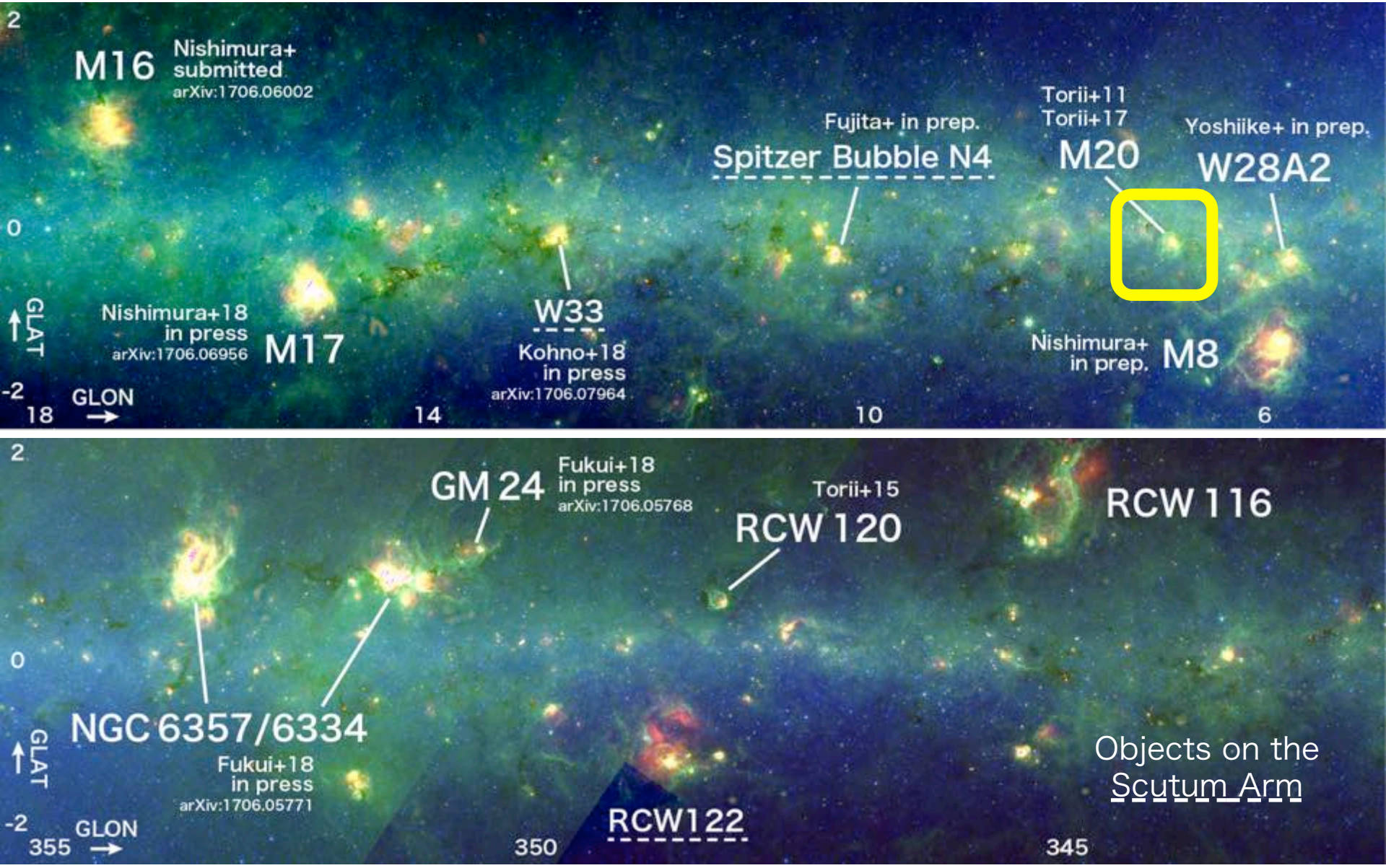




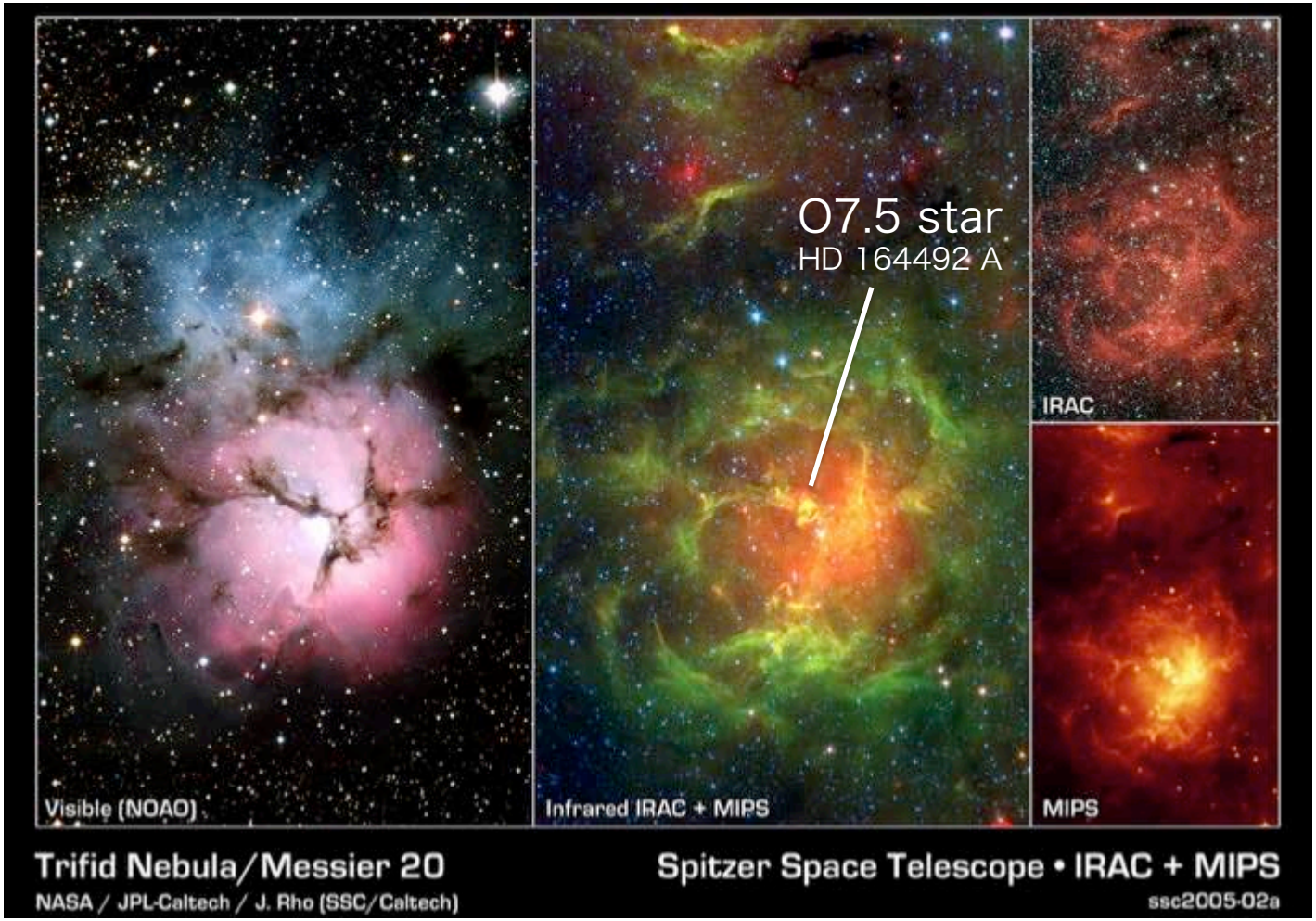
- Complementary distribution
- V-shaped velocity feature

- collision velocity : 10 km/s
- collision timescale : ~0.3 Myr

Sagittarius Arm : M20



M20



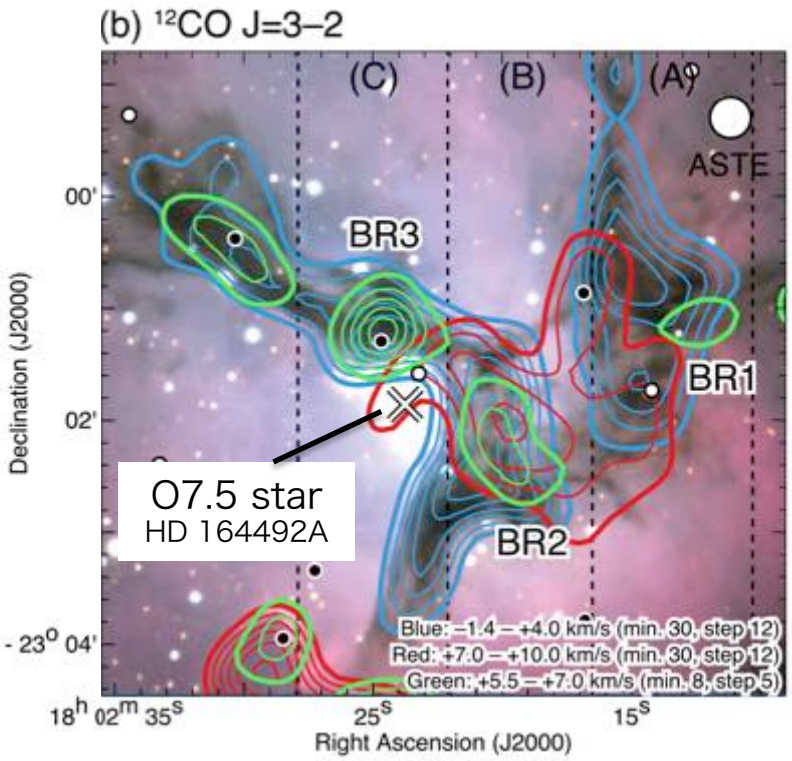
- Distance : ~ 1.7 kpc
- GMC : M_{mol} ~ 3×10^3 Mo

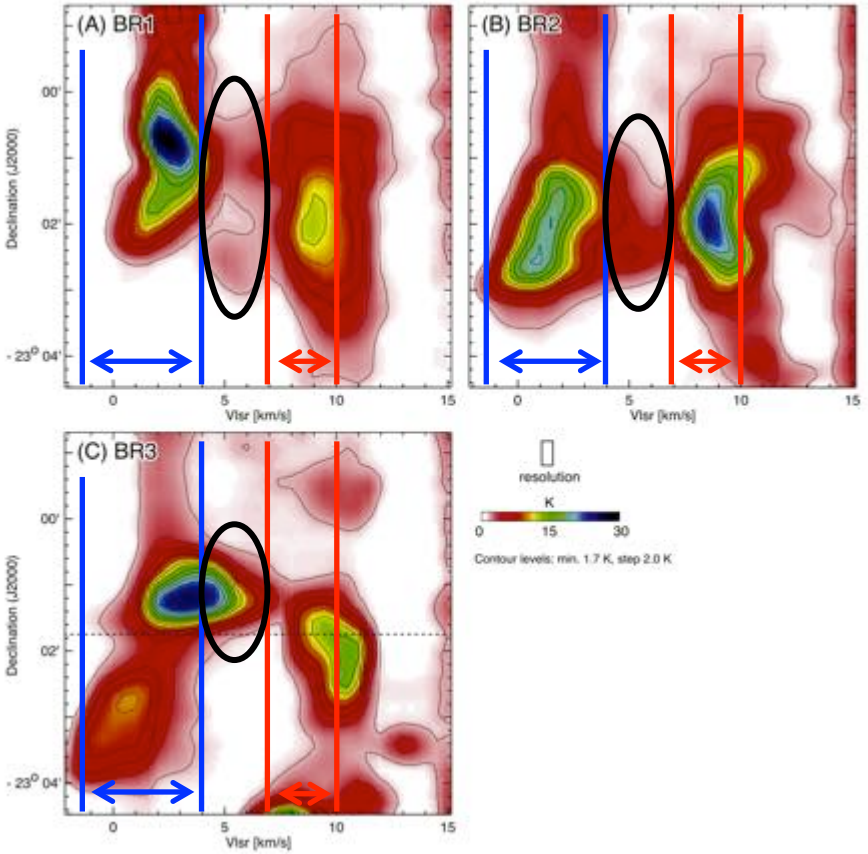
O star

- num: 1 (O7.5), age : ~0.3 Myr

M20

Torii+11,17

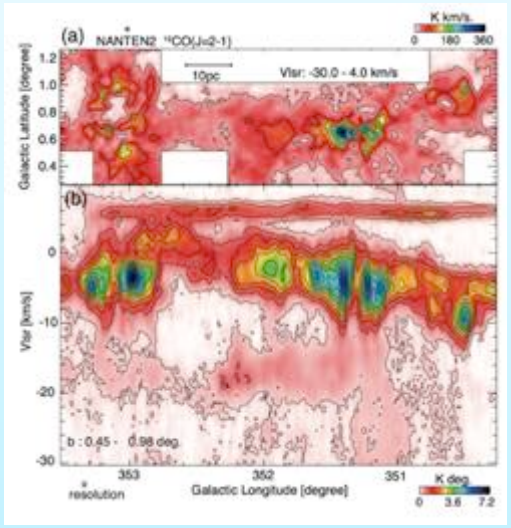




- Complementary distribution
- Bridge velocity feature

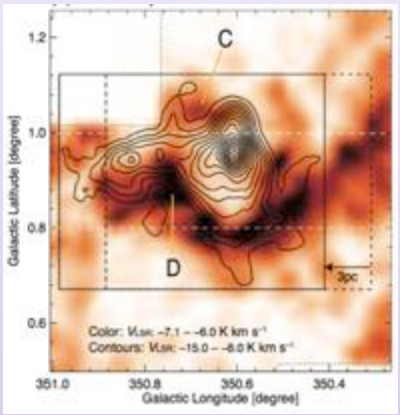
- collision velocity :
  - ~7.5 km/s
- collision timescale :
  - ~0.3 Myr

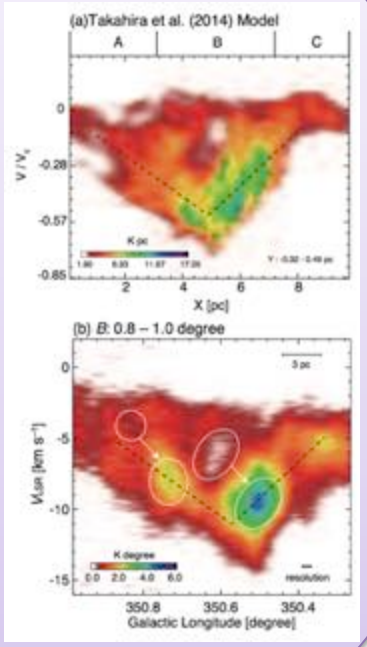
Sagittarius A

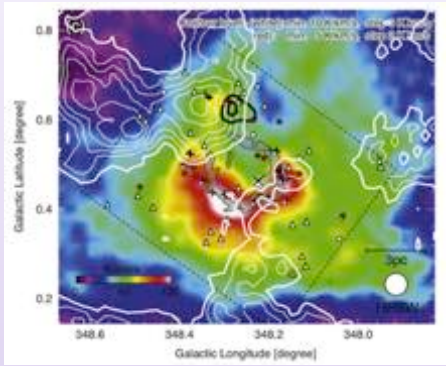


Fukui+18a in press

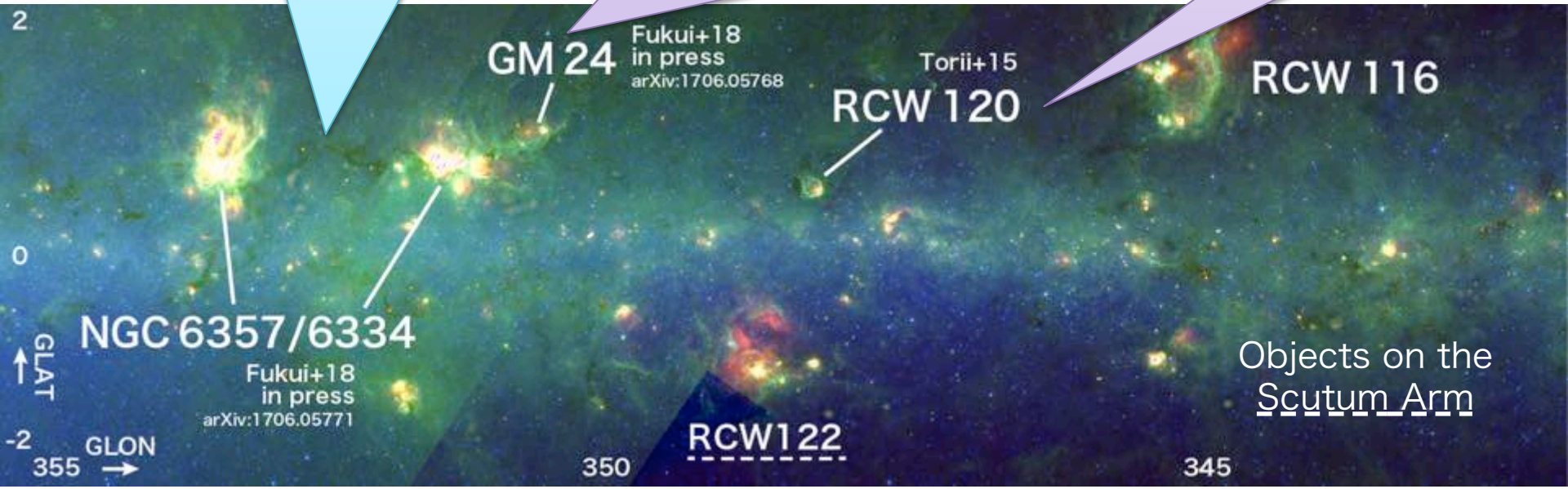
Fukui+18b
in press



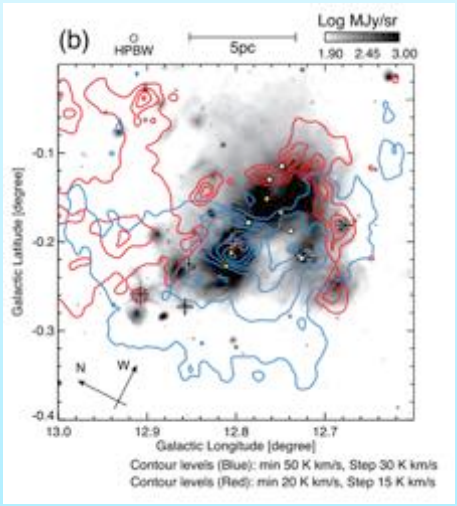




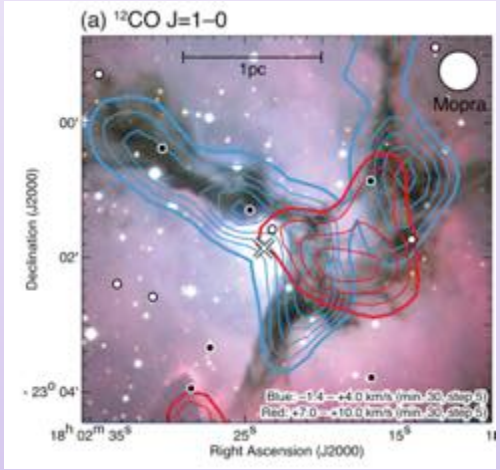
Torii+15



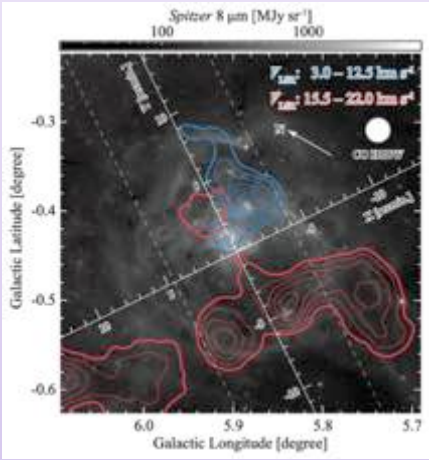
Sagittarius Arm



Kohno+18 in press

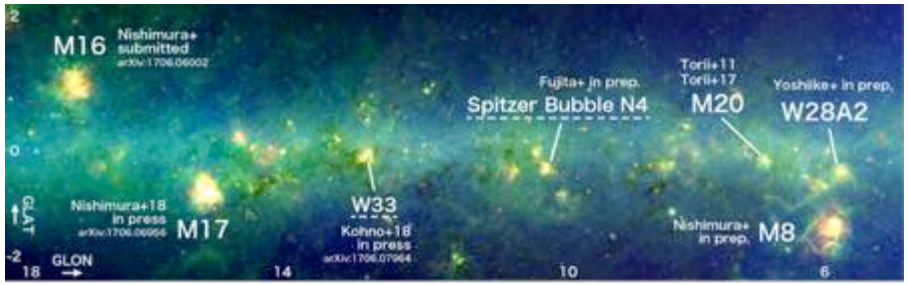


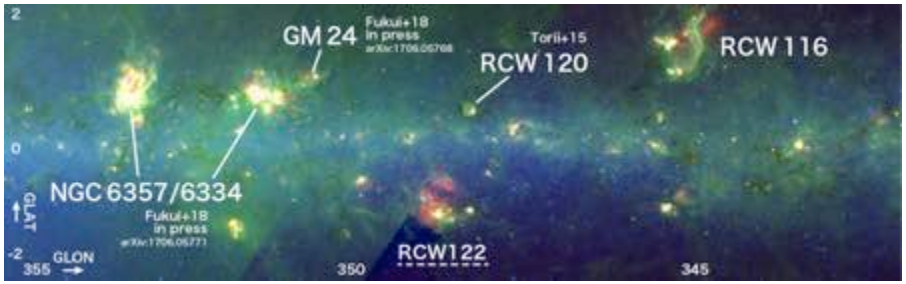
Torii+11, 17



Yoshiike+ in prep.

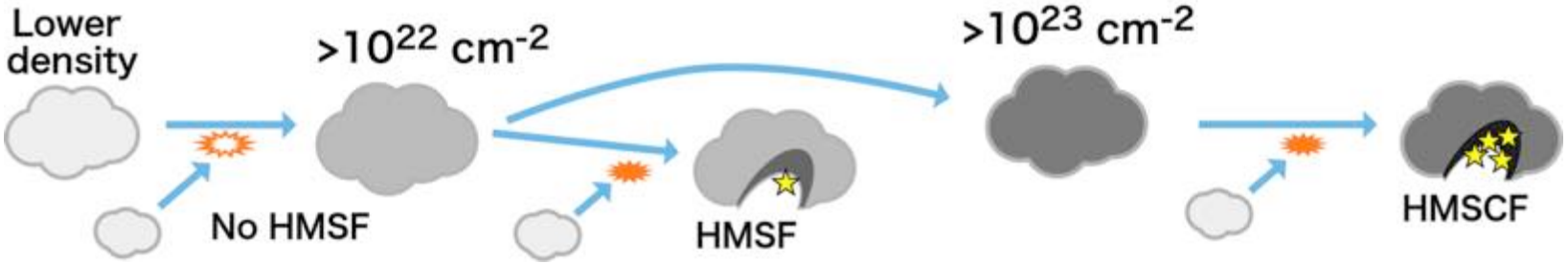
Discussion



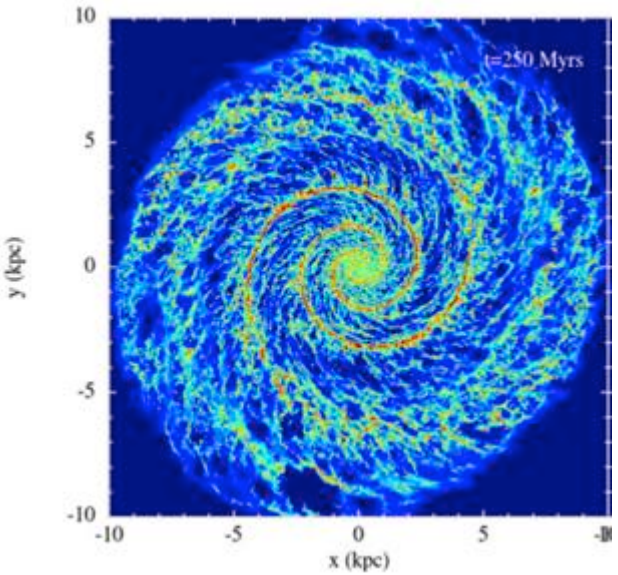


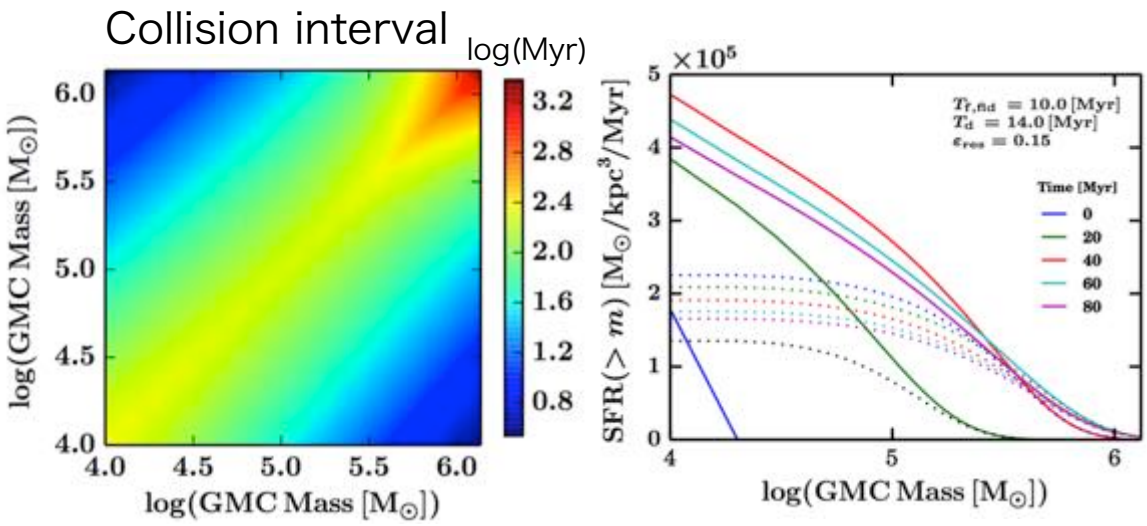
- CCC signatures are found in almost all famous SF regions in the Sagittarius Arm (n=9)
- ~10 km/s collision velocity is required for HMSF
- Collision of >10^{23} cm^{-2} clouds results in massive cluster (n_{Ostars}>10)

Name	M_{gas} (M_{sun})	$N(H_2)$ (cm^{-2})	v_{col} (km/s)	t_{col} (Myr)	#O stars
M16	1E+5	2E+22	10	1-2	10
M17	1E+5	**6E+23**	10	0.1	**24**
M20	3E+3	1E+22	8	0.3	1
W28 A2	1E+4	6E+22	8	0.3	1
M8	1E+5	2E+22	10	1-2	10
NGC6334	1E+5	**1E+23**	12	1	**>18**
NGC6357	1E+4	**1E+23**	12	1	**>9**
GM24	1E+4	2E+22	5	1	1
RCW120	5E+4	3E+22	20	0.3	1



Discussion





Clouds experience collision a few times in their lifetime for spiral galaxies.

(Dobbs et al. 2015)

Larger GMC experiences collision more frequently.

(Kobayashi et al. 2018)

Galactic scale calculations expect that cloud collision is occurred frequently.

Future works 1

Cloud collision seems to be essential for HMSF in the Galactic inner arms.

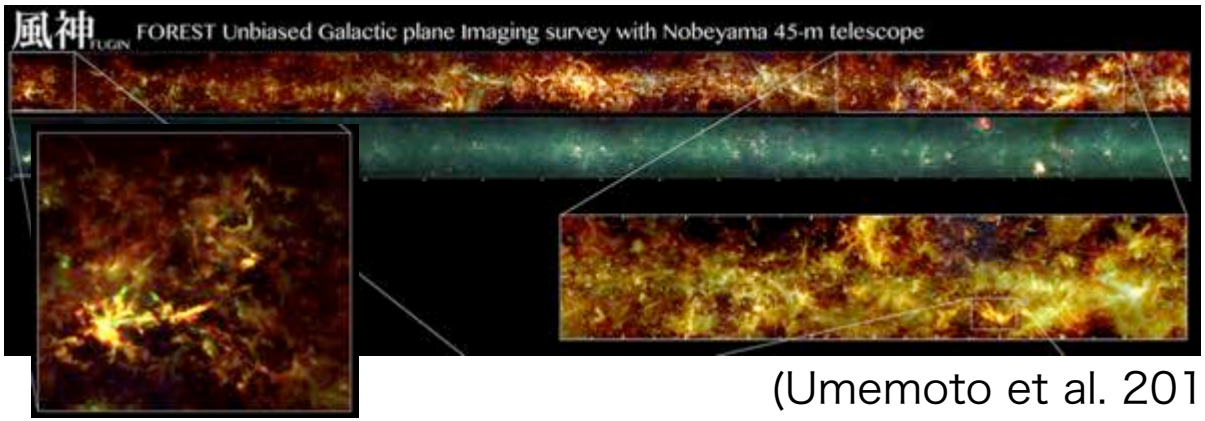
More wider / farther

- any exception?
- statistics
  - e.g., collision rate : GMC_{col}/GMC_{total}
- variation with arm position?

FUGIN

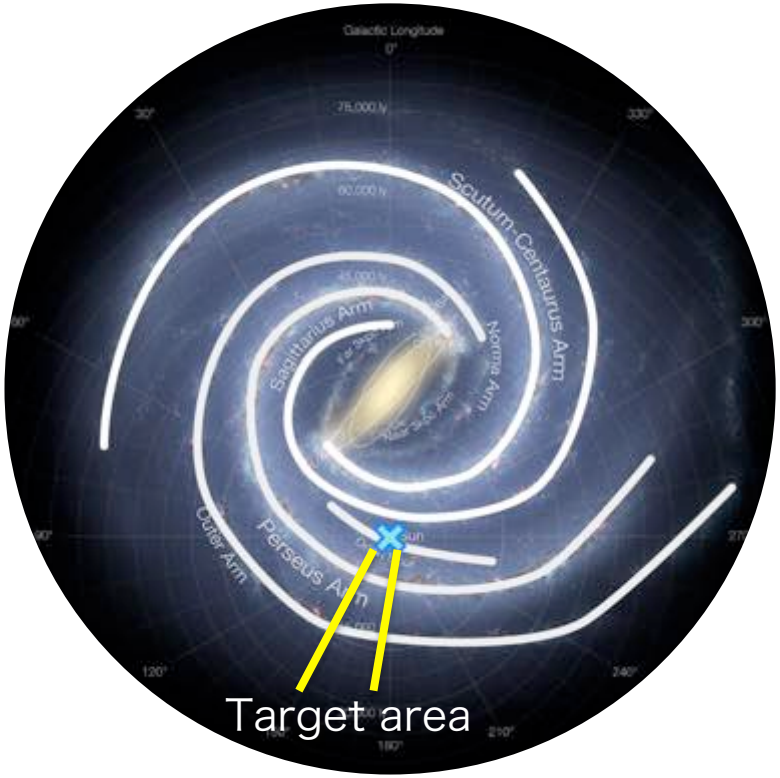
- NRO Legacy project
- L=10°-50°, B=±1°
- ^{12}CO, ^{13}CO, $C^{18}O$(1-0)
- data release date:

May 2018



(Umemoto et al. 2017)

Future works 2

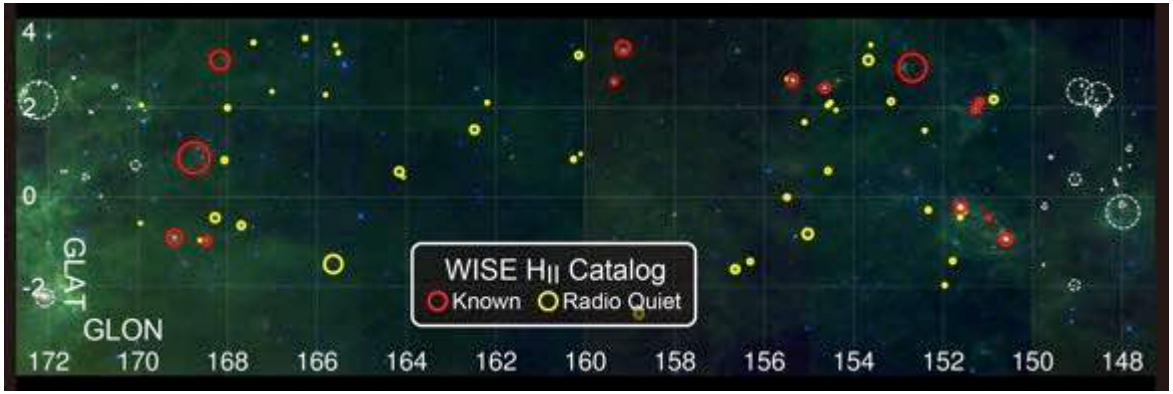


Cloud collision seems to be essential for HMSF in the Galactic inner arms.

How about the outer arms?

- collision frequency is expected to be lower than inner as ~1/3.
  (Tasker 2011; Dobbs et al. 2015)

Perseus/Outer Arm HII region survey



- 65 HII regions
  - Per. 56%, Out. 38%
- NRO45, 70 hours
- Obs. are finished

Summary

- Cloud Cloud Collision
  - Most promising HMSF scenario
  - Accountable for filament formation, filament fragmentation and high mass star formation
  - Observational inspection methodology is established
- Sagittarius Arm
  - Almost all famous HMSF regions in L=±5°-20° have collision signatures which are explainable SF history in the region
  - Collision frequency is in agreement with galactic scale calculations