ALMA observations of high-mass star-forming filamentary cradles in the Large Magellanic Cloud

Kazuki Tokuda (Osaka Pref. Univ./NAOJ)

Contents

- Introduction: Why do we investigate filamentary clouds?
- The N159 GMC in the LMC
- ALMA high-resolution studies of the N159E/W regions
- On-going works

Collabolators:
Fukui, Yasuo; Harada, Ryohei; Saigo, Kazuya; Tachihara, Kengo; Tsuge, Kisetsu; Inoue, Tsuyoshi; Torii, Kazufumi; Nishimura, Atsushi; Zahorecz, Sarolta; Nayak, Omnarayani; Meixner, Margaret; Minamidani, Tetsuhiro; Kawamura, Akiko; Mizuno, Norikazu; Indebetouw, Remy; Sewiło, Marta; Madden, Suzanne; Galametz, Maud; Lebouteiller, Vianney Chen, C. -H. Rosie; Onishi, Toshikazu

Self-Introduction

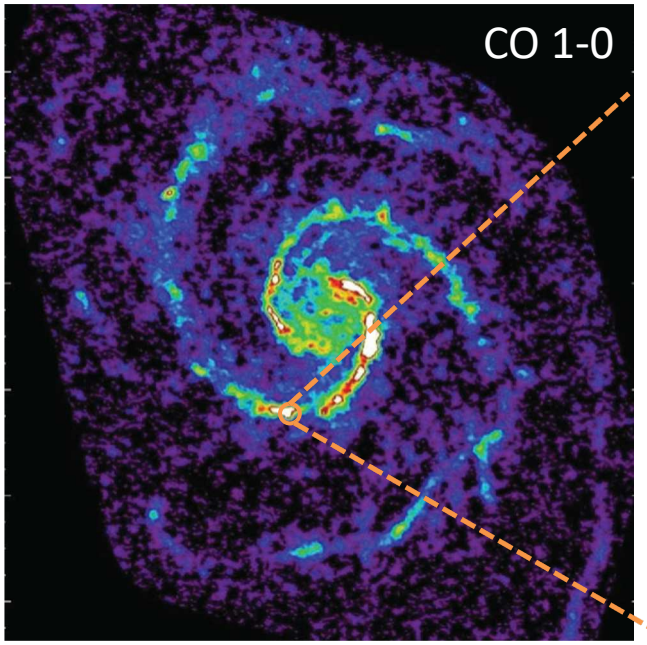


Telescope experience
- Osaka 1.85m telescope
- NRO45m, IRAM30m, ASTE10m
- ALMA (This work)

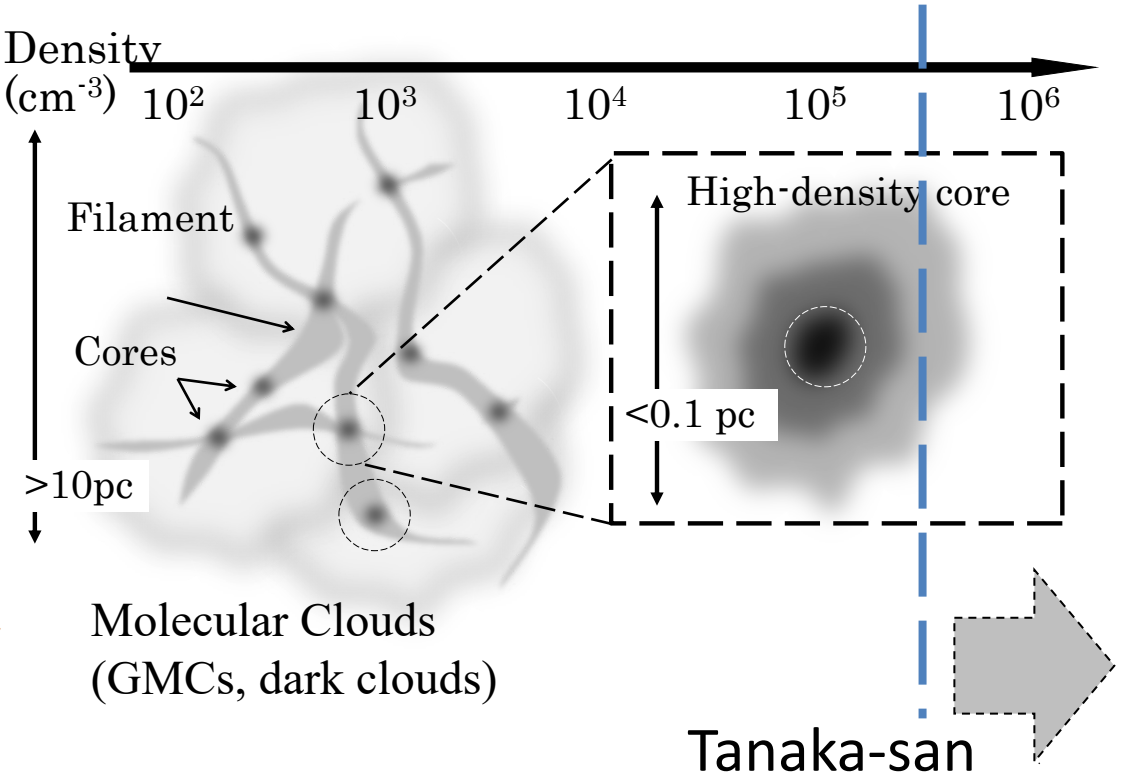
and so on

My research interests:
- Molecular clouds
- Low-mass/high-mass star formation
- Development of receivers for radio telescopes

Star formation in molecular clouds



Koda et al. 2011



Tanaka-san
and Yichen's talks

Spatial resolution

>10 pc: Giant molecular clouds

~1 pc: Identify molecular clumps / filaments

<0.1 pc: Resolving the filaments/cores

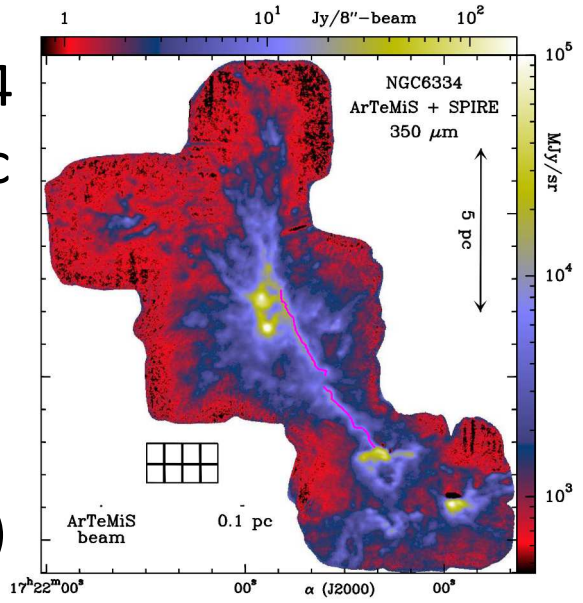
Why filamentary clouds?

Filaments are ubiquitous in galactic MCs and fragments into cores.

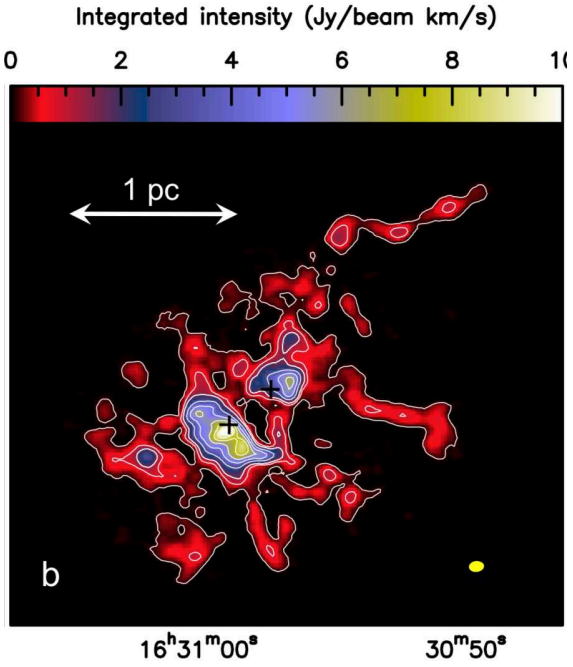
(e.g., Mizuno+95; Nagahama+98; Inutsuka & Miyama 97; Arzoumanian+11, André+14)

<0.1 pc obs. of filaments in (galactic) massive star-forming regions

NGC6334
@1.7 kpc



(André+16)



SDC335
@3.25 kpc

(Peretto+13)

Resolution = 8"(~0.07 pc), Width ~ 0.15 pc,
Massive filaments (or "Ridges")
M_{line} ~ 500 –2000 $M_\odot$ /pc (Unstable!!)

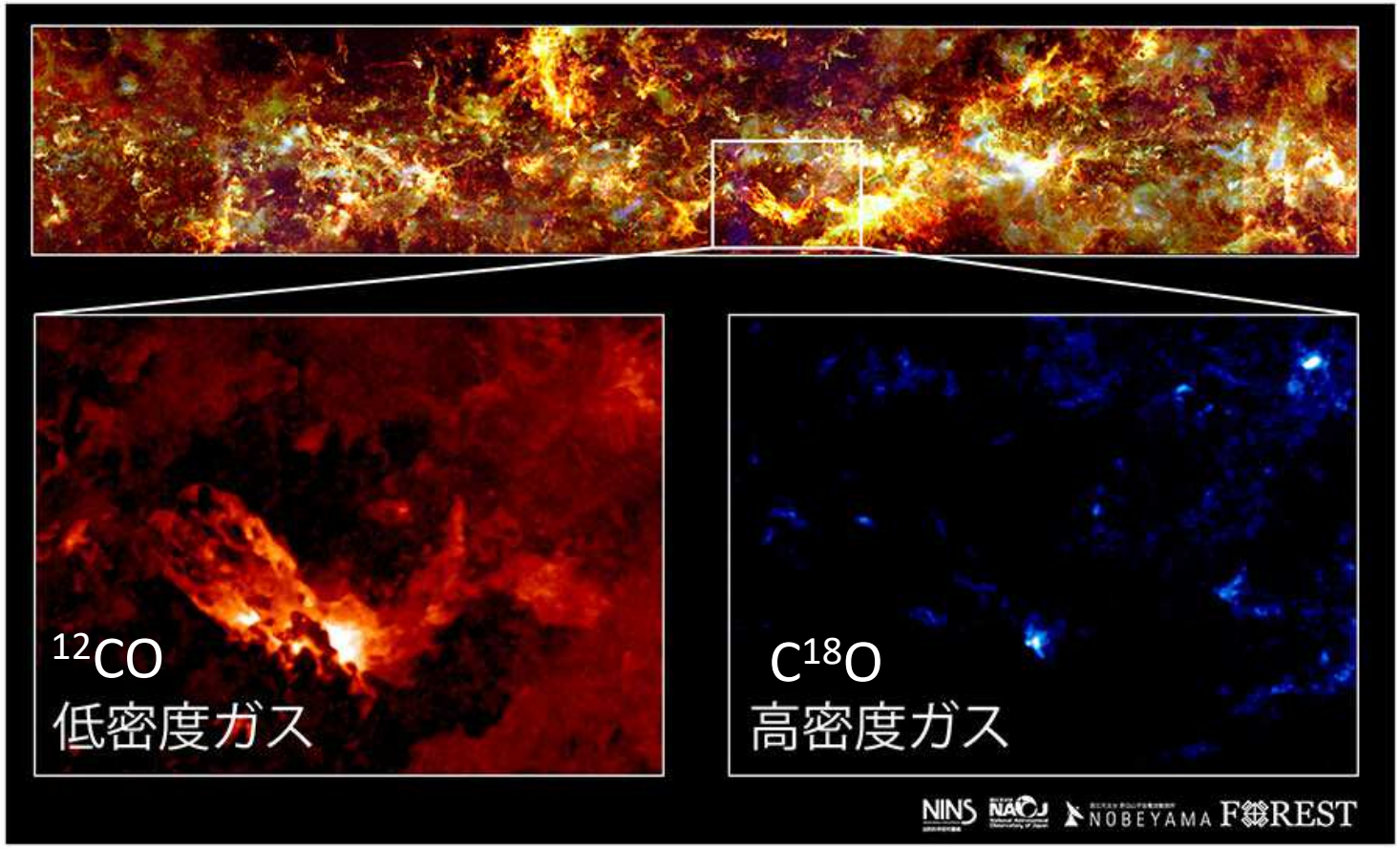
Resolution = 5"(~0.07 pc)
Massive cores /protostars inside
hub(web) filaments

Possible formation trigger: Large-scale colliding flow (André+14;16)

Why filamentary clouds?

Filaments are ubiquitous in galactic MCs and fragments into cores.

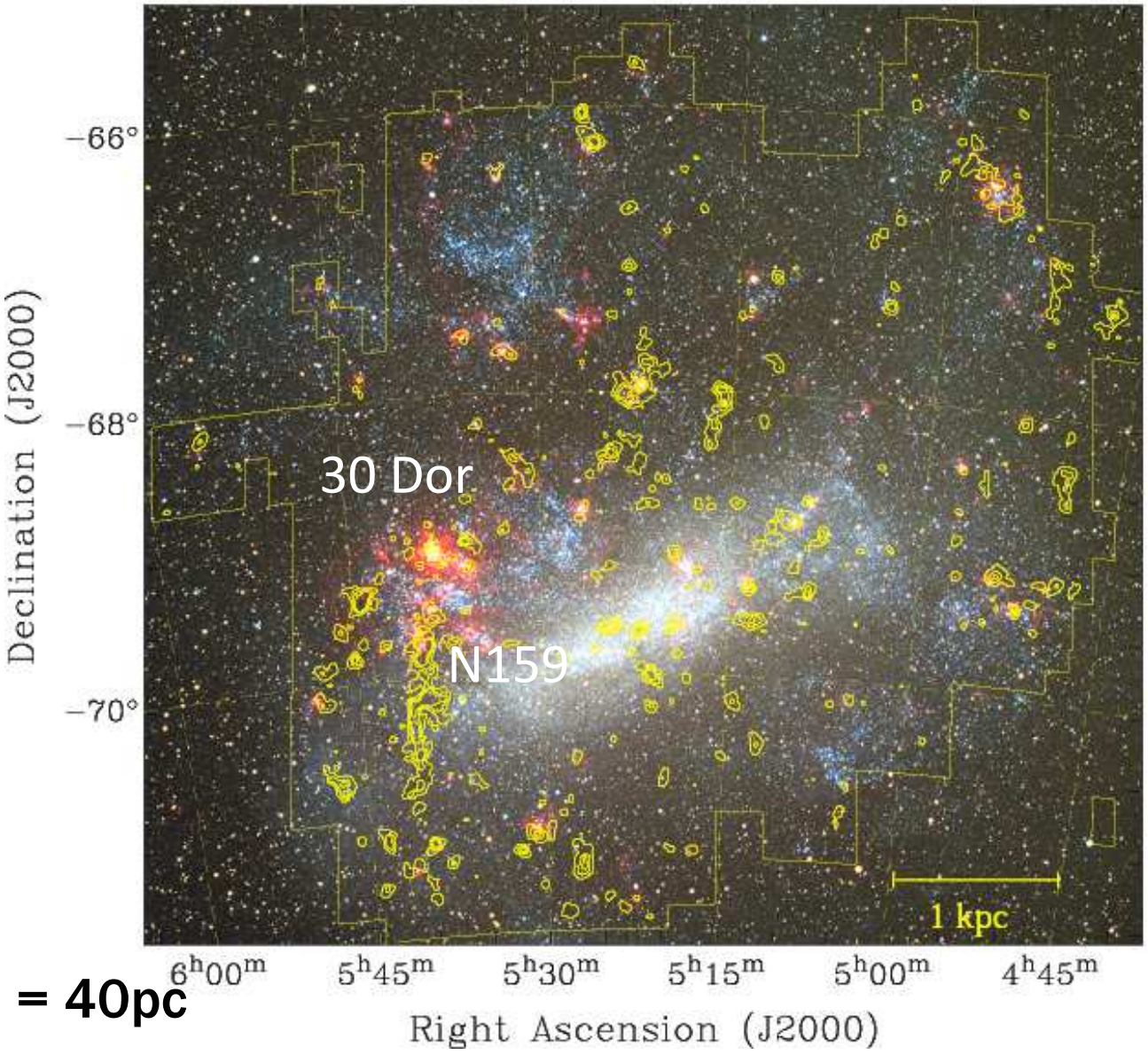
(e.g., Mizuno+95; Nagahama+98; Inutsuka & Miyama 97; Arzoumanian+11, André+14)



FUGIN(e.g., Umemoto+17, Torii+19)

Observational difficulty: heavy contaminations on the Galactic Plane

N159 in the LMC

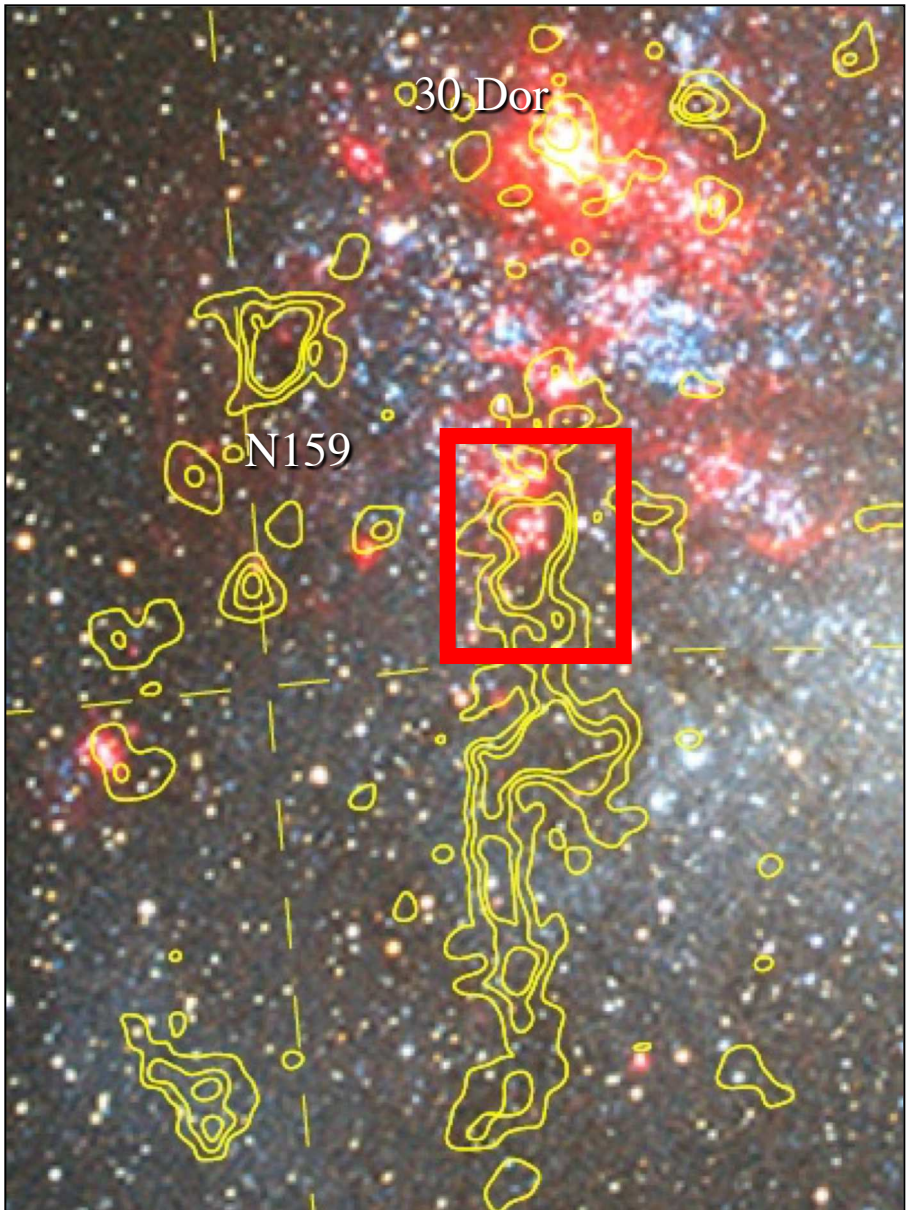


2.7arcmin = 40pc

Giant molecular clouds traced by CO (1-0) with the NANTEN 4m telescope (Fukui+08; Kawamura+09)

N159 in the LMC

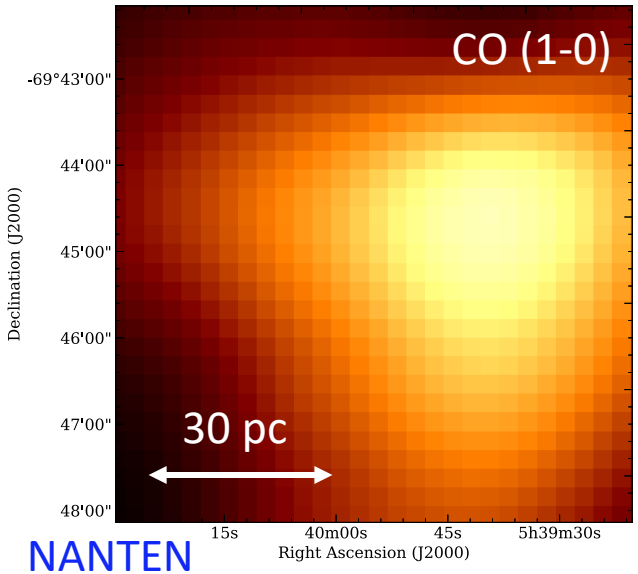
- **N159**
  - **One of the largest**
    Mass : ~10^6 Mo
    Size : ~200 pc
    - **Has strongest CO emission**
  - **Active star formation**



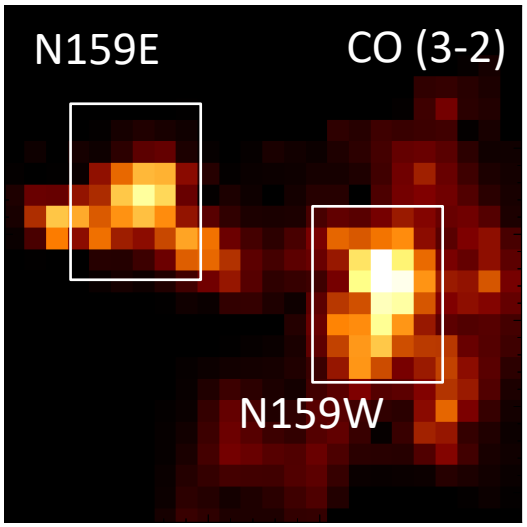
The N159 GMC in the LMC

One of the most active star-forming sites in the LMC
The total gas mass: ~10^6 Mo

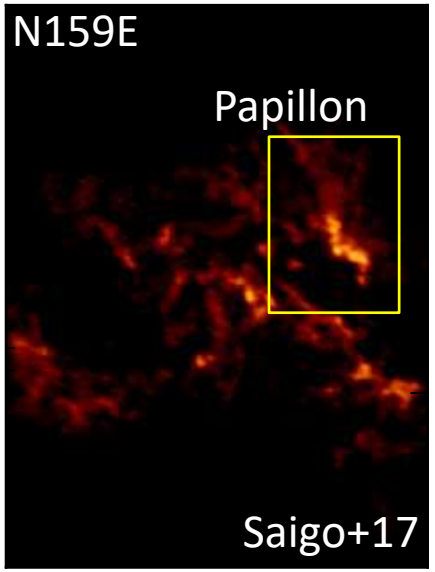
at ~50 kpc

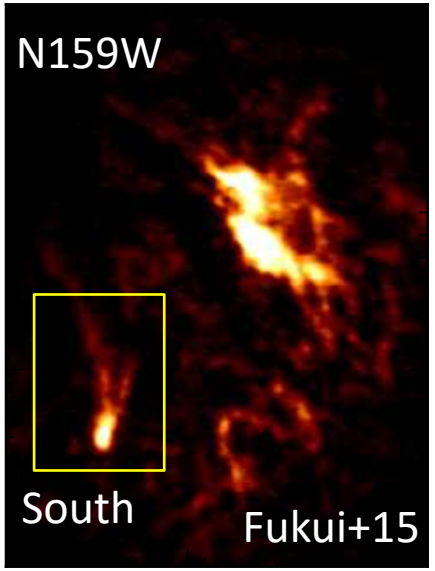


NANTEN
(4m telescope)

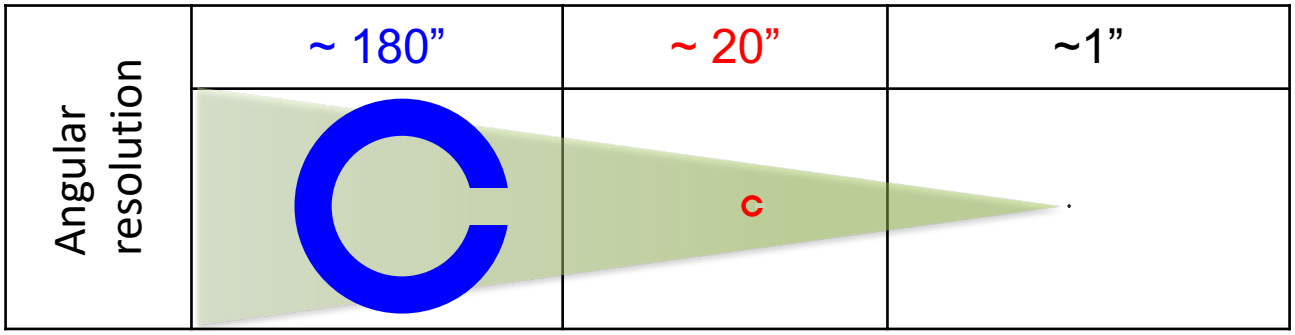


ASTE
(10m telescope)



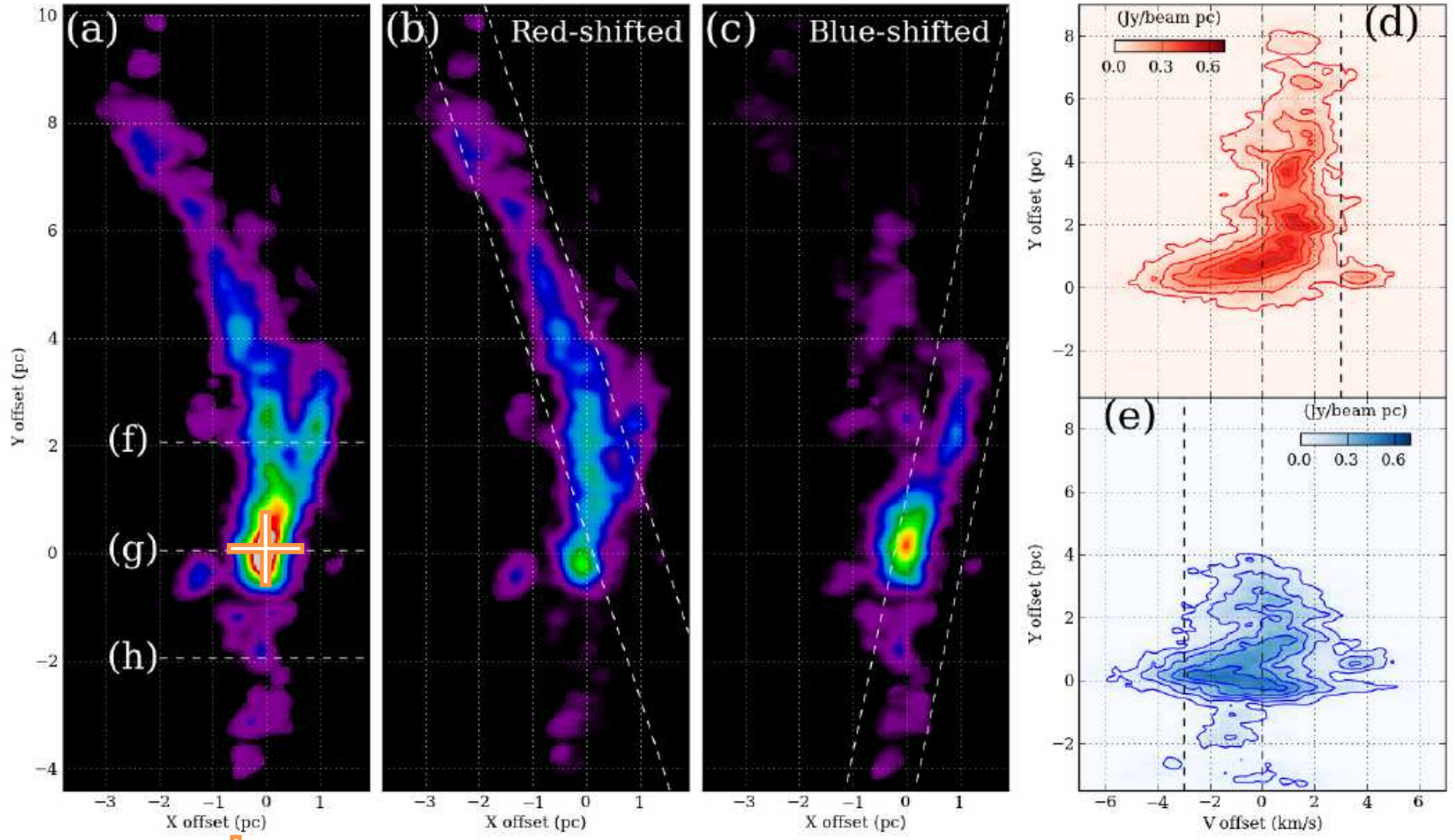


^{13}CO (2-1) ALMA Cycle 1



The ALMA observations found high-mass star forming filamentary clouds

Filament-Filament Collision ?? Fukui+15, Saigo+17



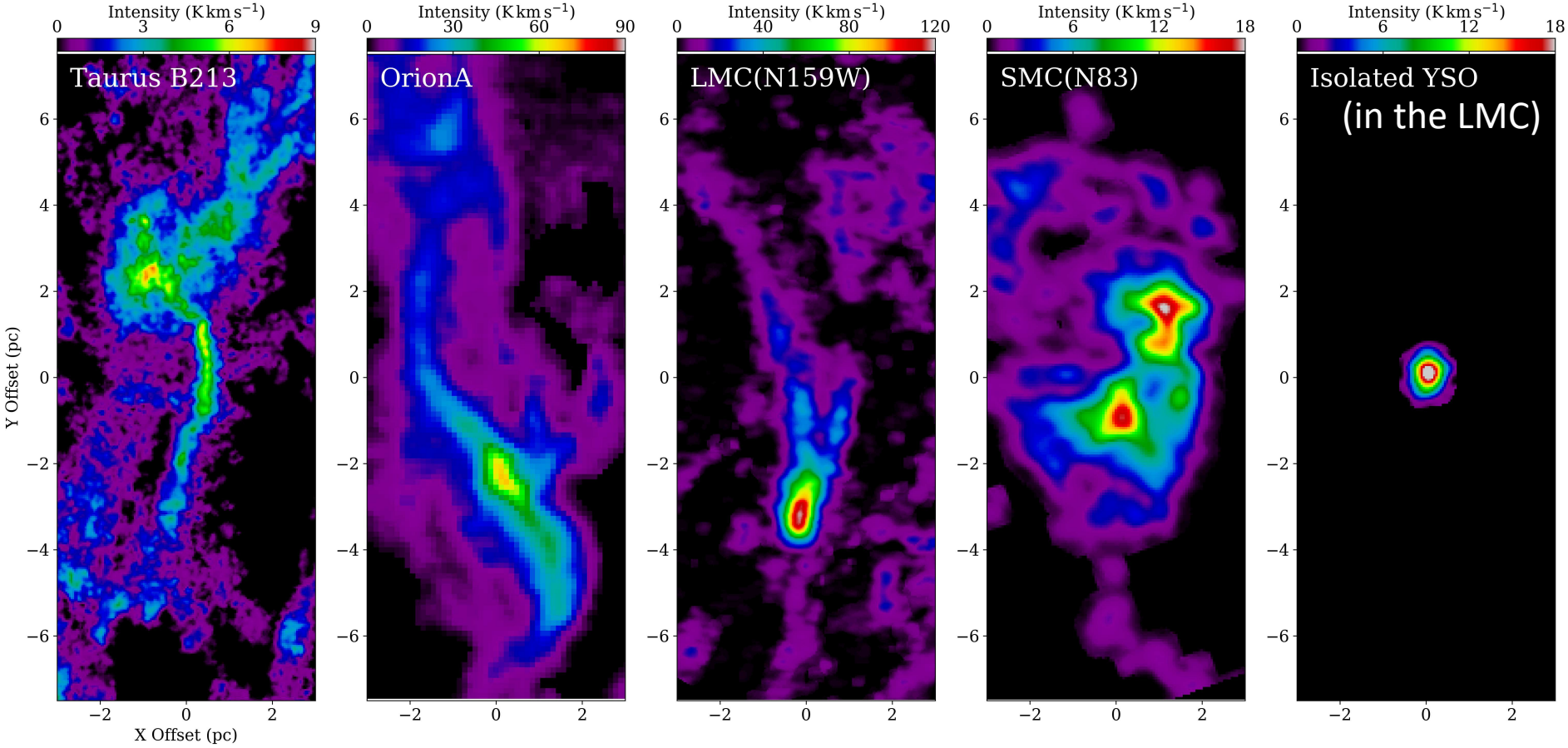
High-mass (~30 *Mo*) protostar

Line mass ~ 9 x 10^2 *Mo*/pc
Width ~ 0.5 –1 pc
Obs. resolution ~0.24 pc

^{13}CO (2-1) views of Galactic/Magellanic molecular clouds

The Osaka 1.85m telescope

ALMA

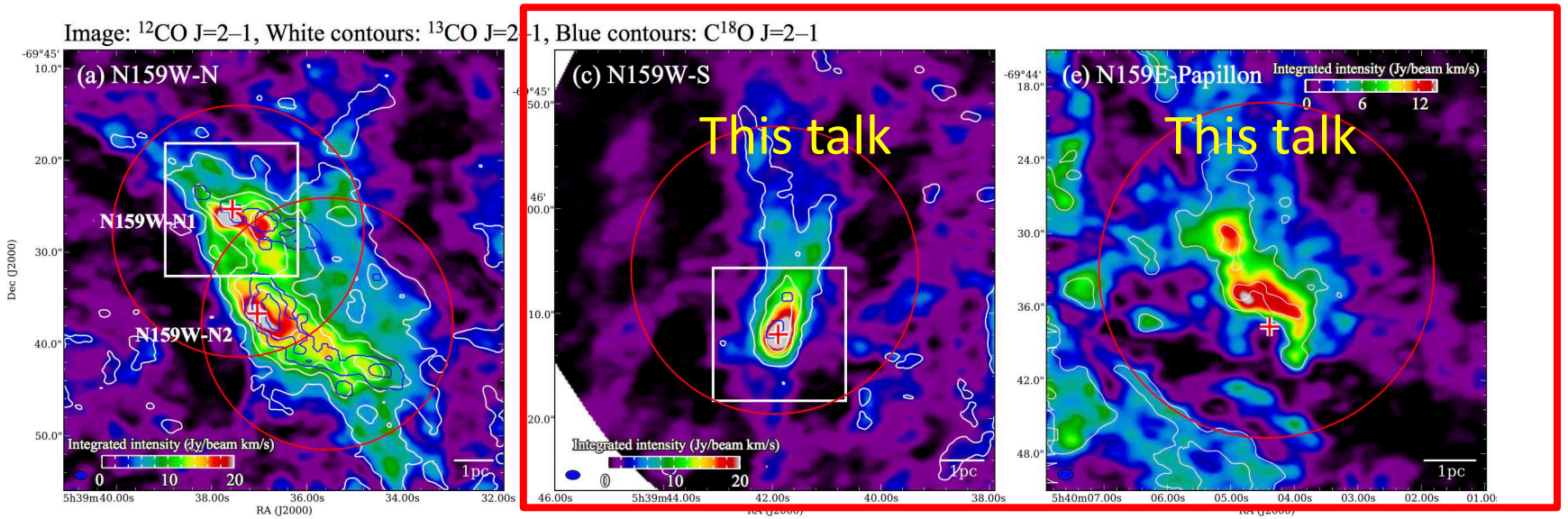


Tokuda+in prep. Nishimura+15 Fukui+15 Muraoka+17 Harada+19

Follow-up high-resolution observations of N159

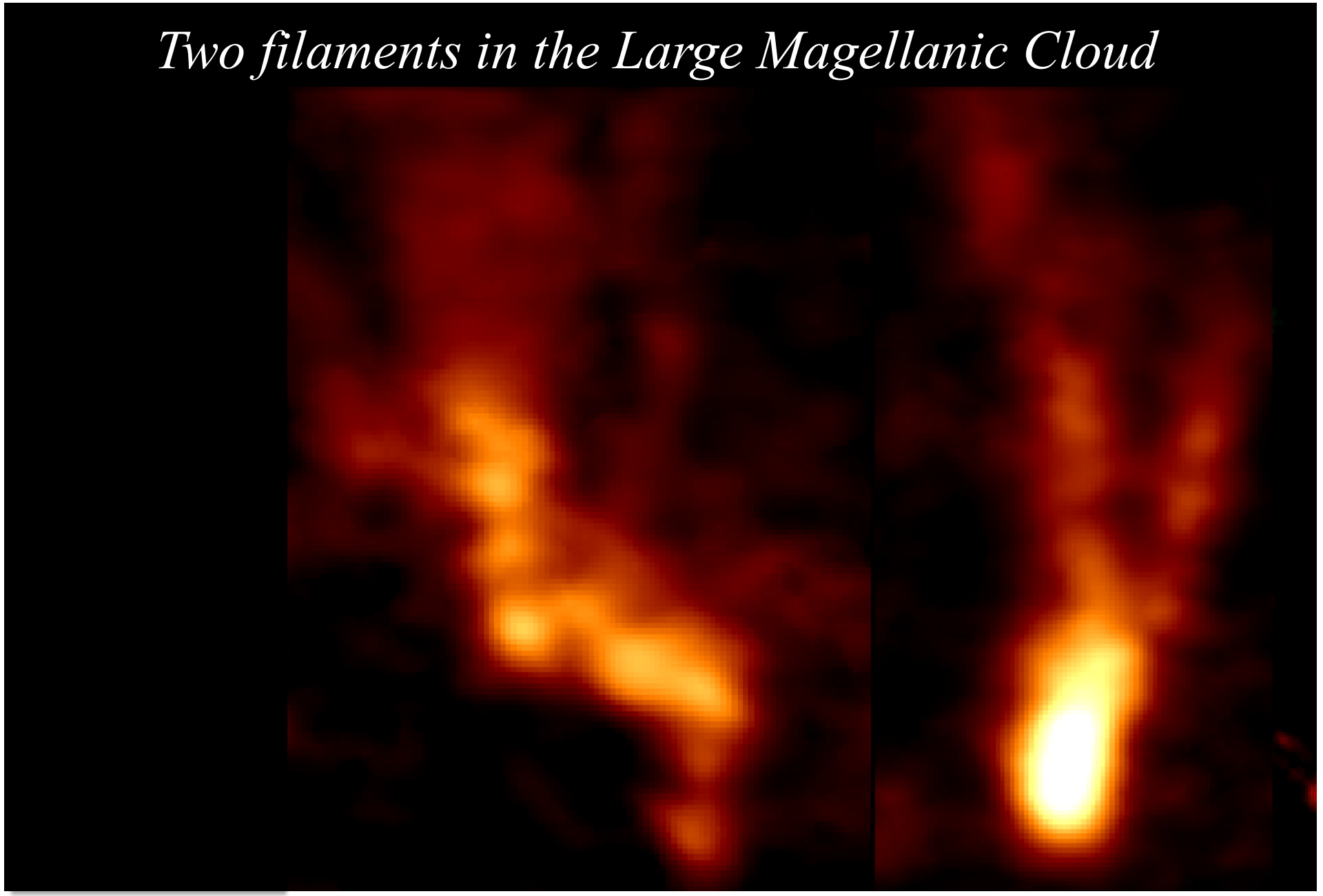
Table: ALMA observations

Target	N159E-Papillon, N159W-South, N159W-North
Frequency	^{12}CO, ^{13}CO, C^{18}O (2–1), SiO, H30α, 1.3 mm cont.
Sensitivity (Line)	~1.5 K (@dv=0.2 km/s)
Spatial Resolution	0.”28 x 0.”25 (= 0.067 pc x 0.06 pc)



Figs. form ALMA Cycle 1 observations (Fukui et al. 2015, Saigo et al. 2017)

Two filaments in the Large Magellanic Cloud

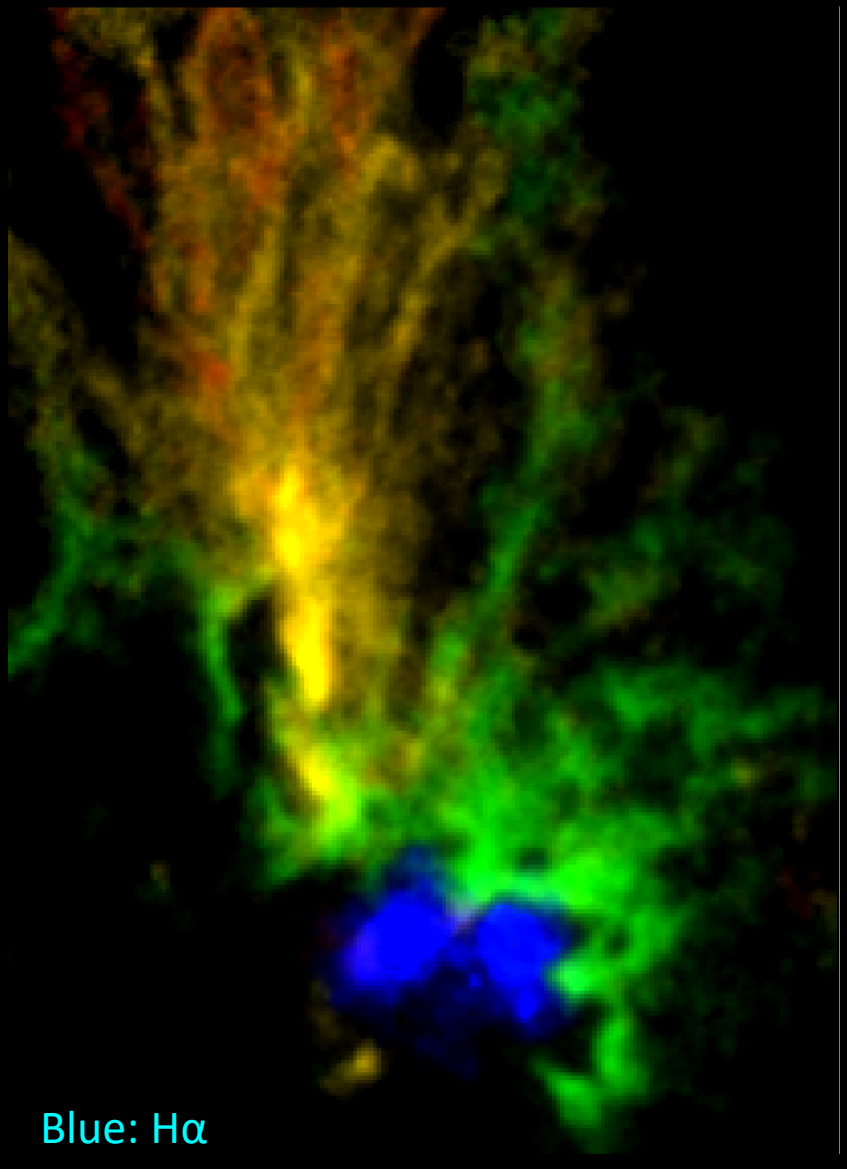


13CO (2-1), ALMA Cycle 1 (Fukui+15, Saigo+17)

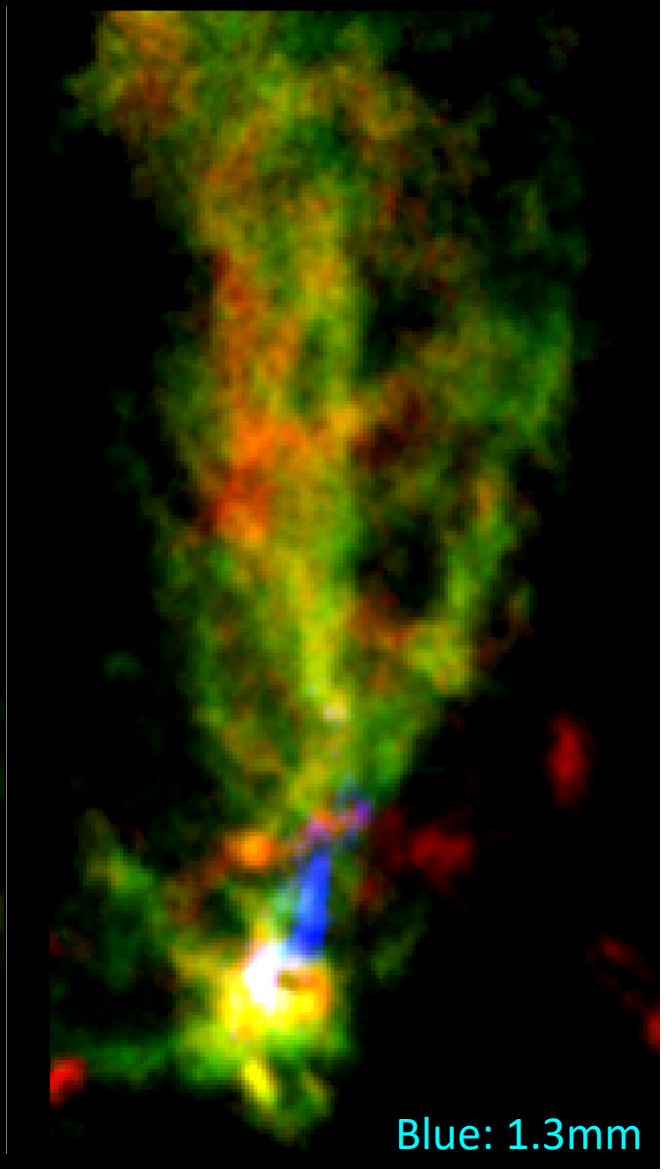
Two Cosmic Peacocks in the Large Magellanic Cloud



Credit: TANAKA Juuyoh



Blue: Hα

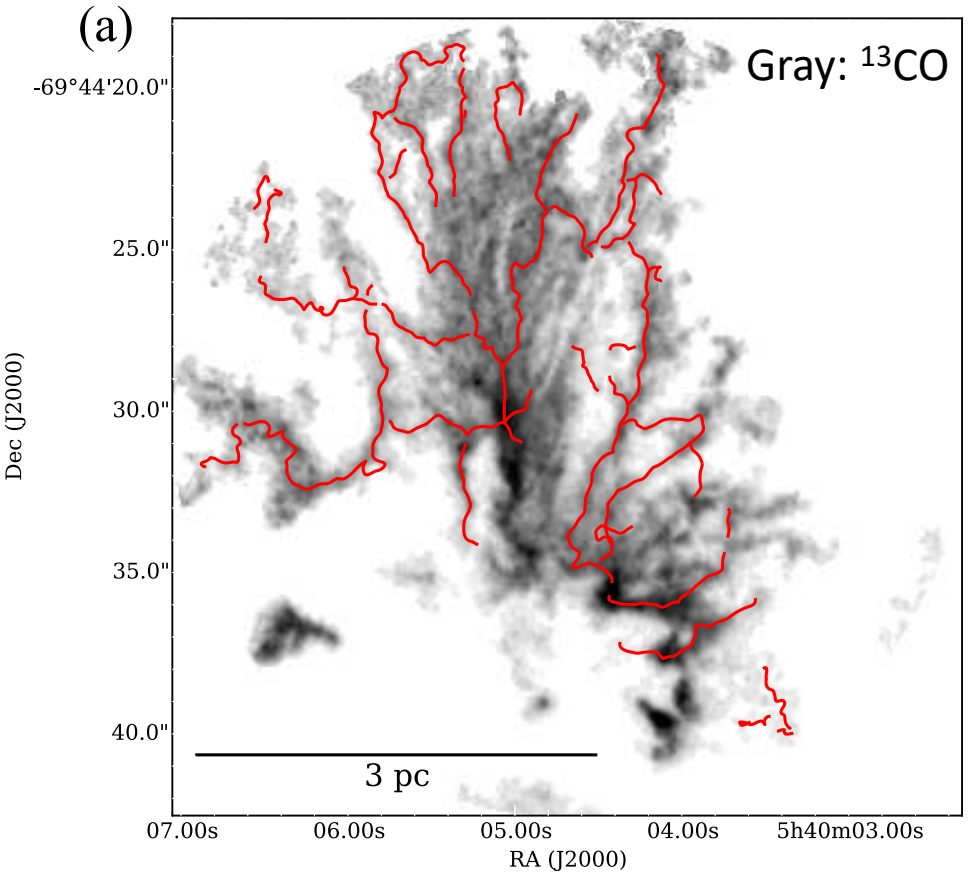


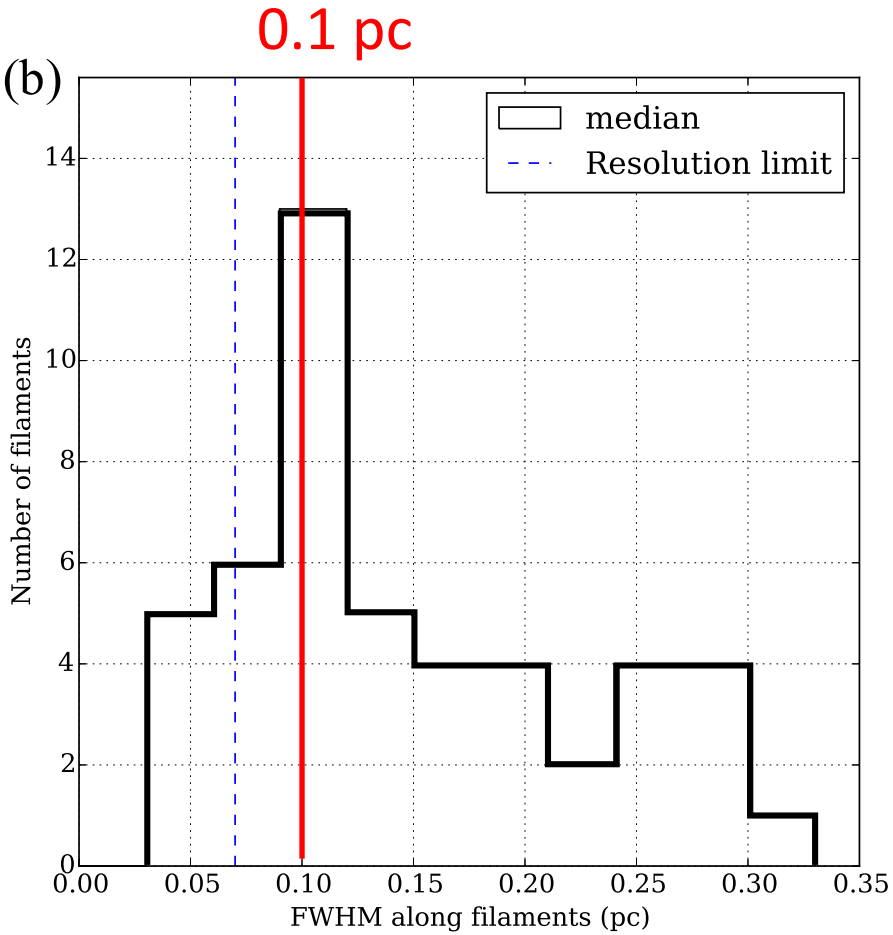
Blue: 1.3mm

13CO (2-1), ALMA Cycle 4 (Fukui+19, Tokuda+19)

Filamentary clouds in N159E-Papillon

Identified by the DisPerSE algorism





Typical filament width ~0.1 pc (but marginally resolved)

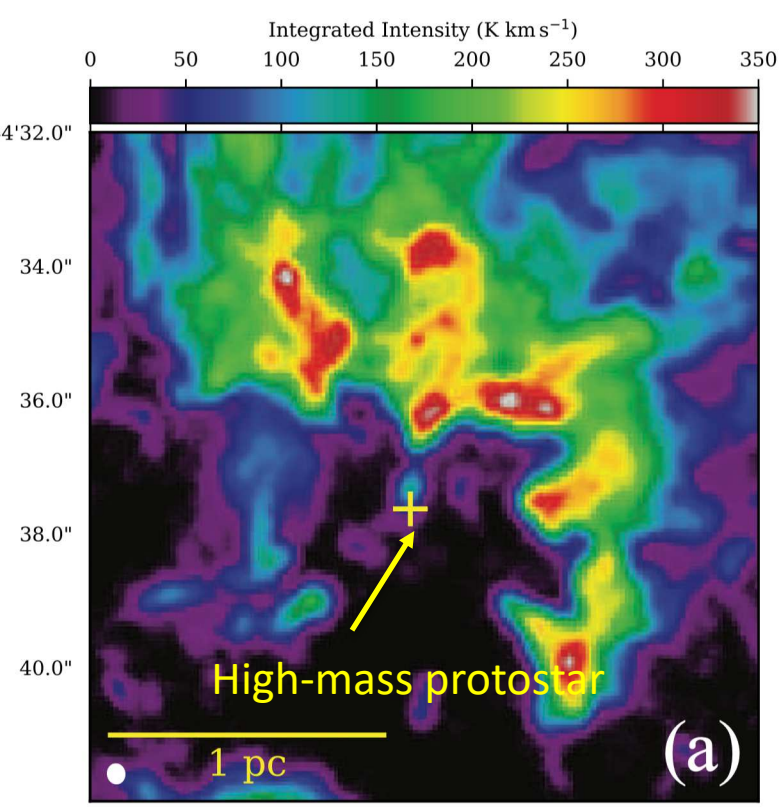
Typical length from ~ a few pc (to ≥10 pc); σ_V ~ 0.7 km/s

M_{line} = 300 – 700 M_o/pc,

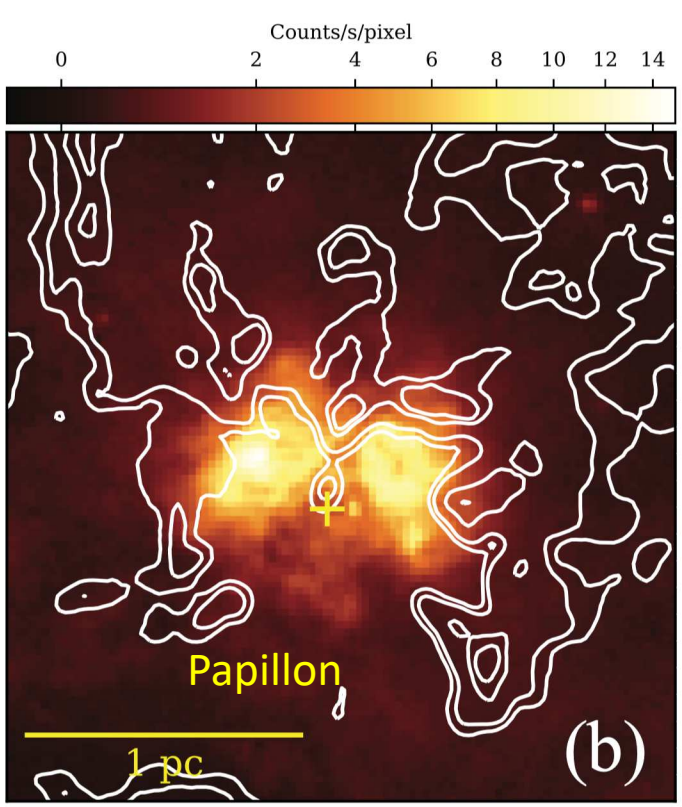
larger than $M_{line,crit}$, but about the same as Galactic massive filaments

An extragalactic view of pillars of creation

N159E



^{12}CO (2-1)



Color:Hα

Contour: ^{12}CO (2-1)



Pillars in M16

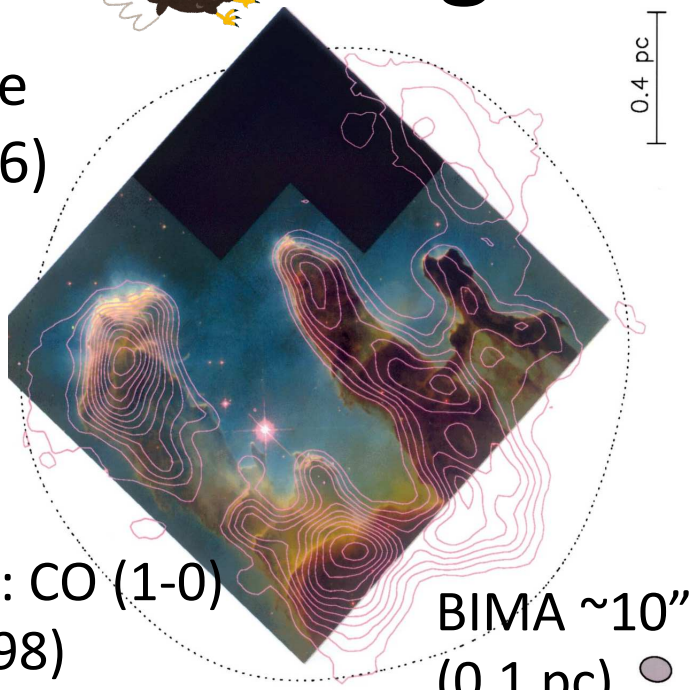
Fukui+19

Eagle v.s. Papillon



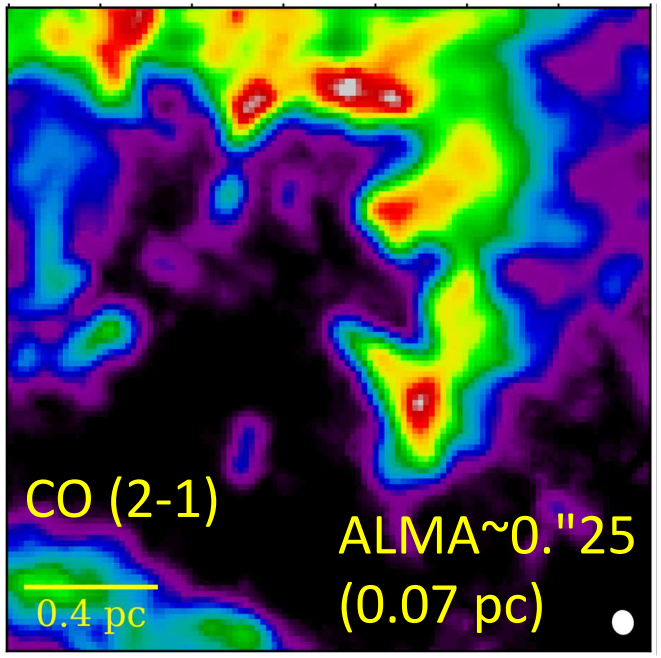


Eagle
(M16)



Contour: CO (1-0)
(Pound 98)

BIMA ~10”
(0.1 pc)



*same linear scale

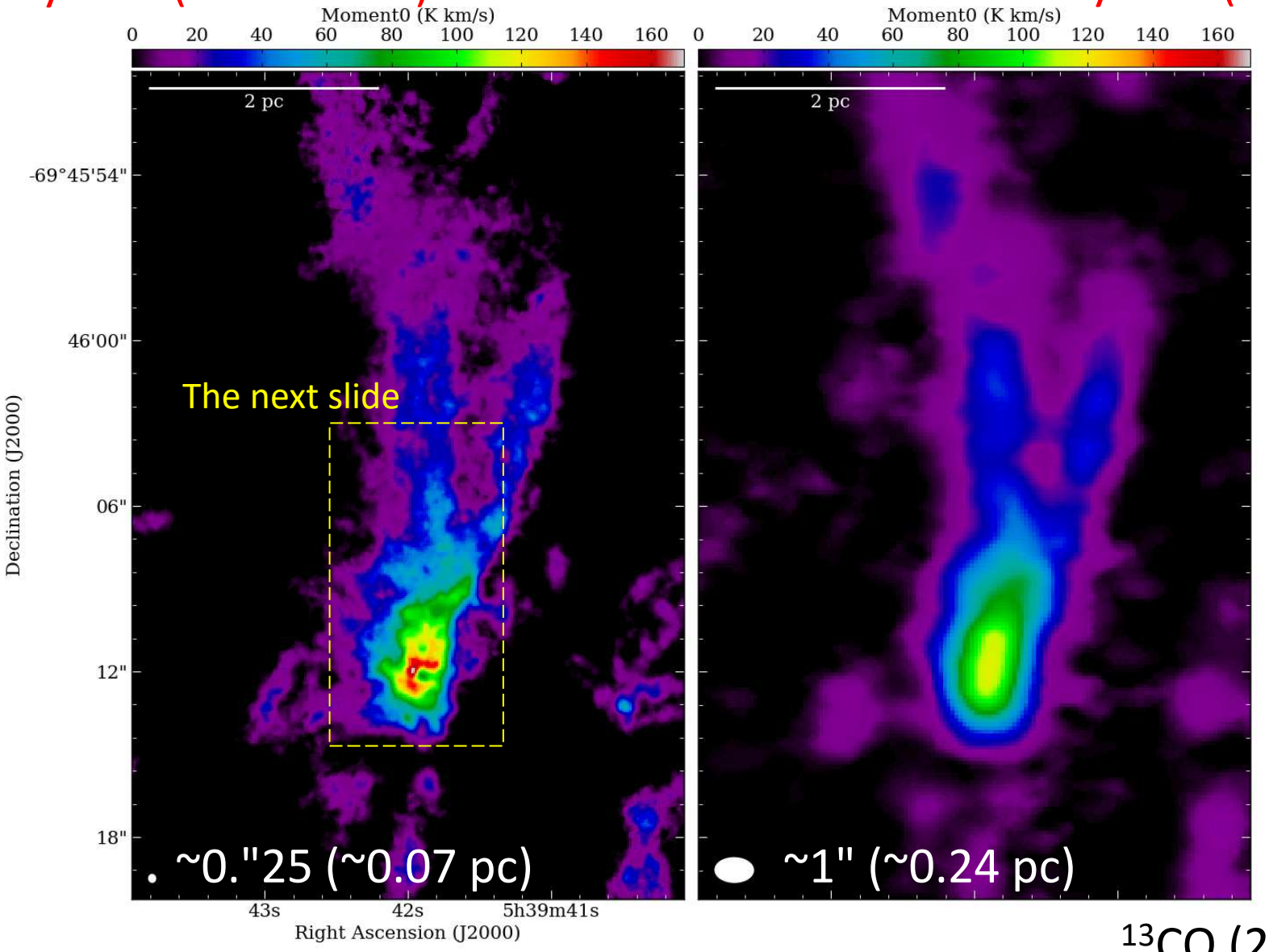
	Eagle	Papillon
Column density, $N(H_2)$	~ 2 x 10^{22} cm^{-3}	~2 x 10^{23} cm^{-3}
$n(H_2)$	~3 x 10^{3} cm^{-3}	~6 x 10^{5} cm^{-3}
σ_v (km/s)	1.2 km/s	~1.3 km/s
Temperature (K)	~40 K	~ 70–80K

CO pillars around the Papillon Nebula => Early phase of their creations

N159W-South region

Cycle 4 (Tokuda+19)

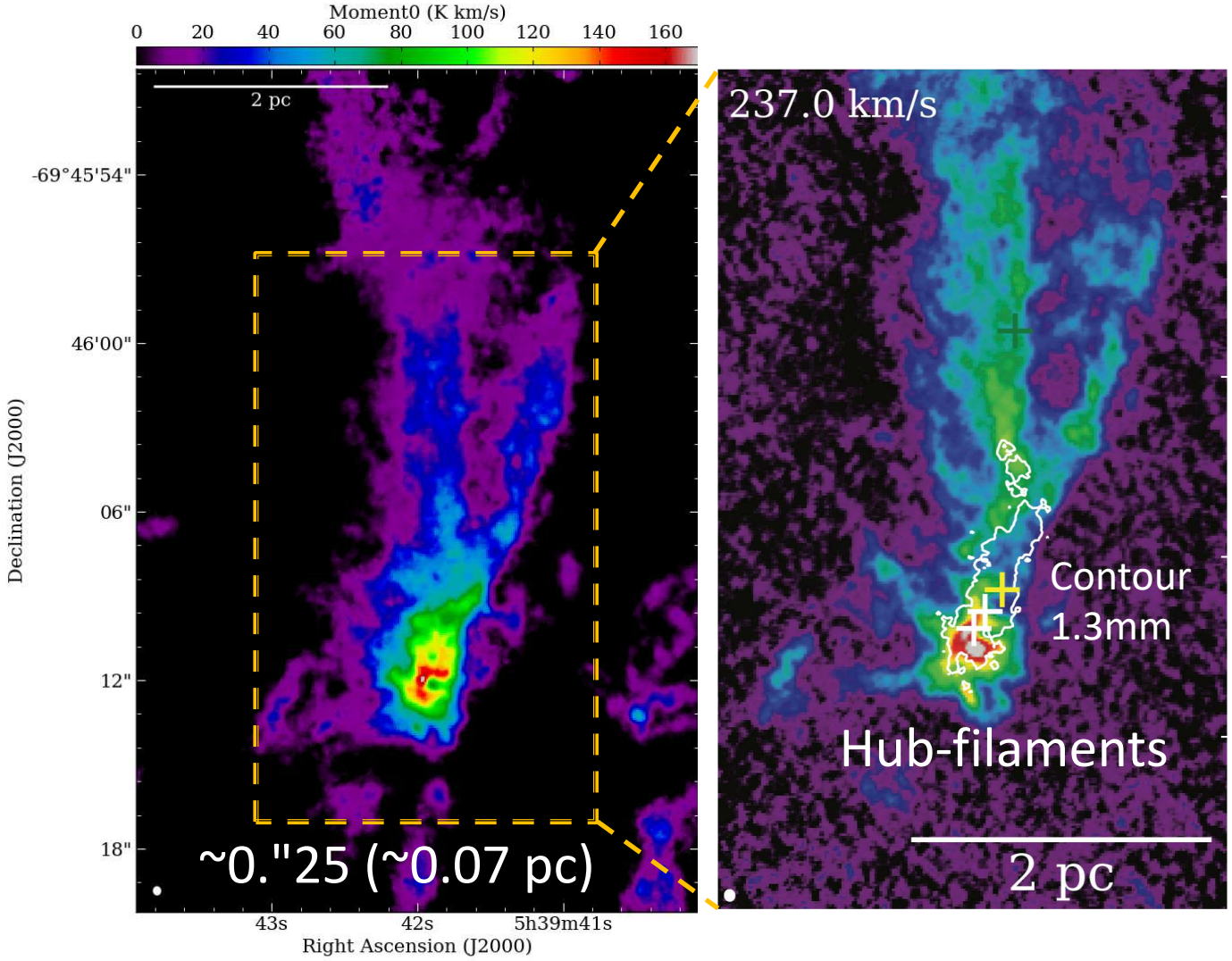
Cycle 1 (Fukui+15)



^{13}CO (2-1)

N159W-South region

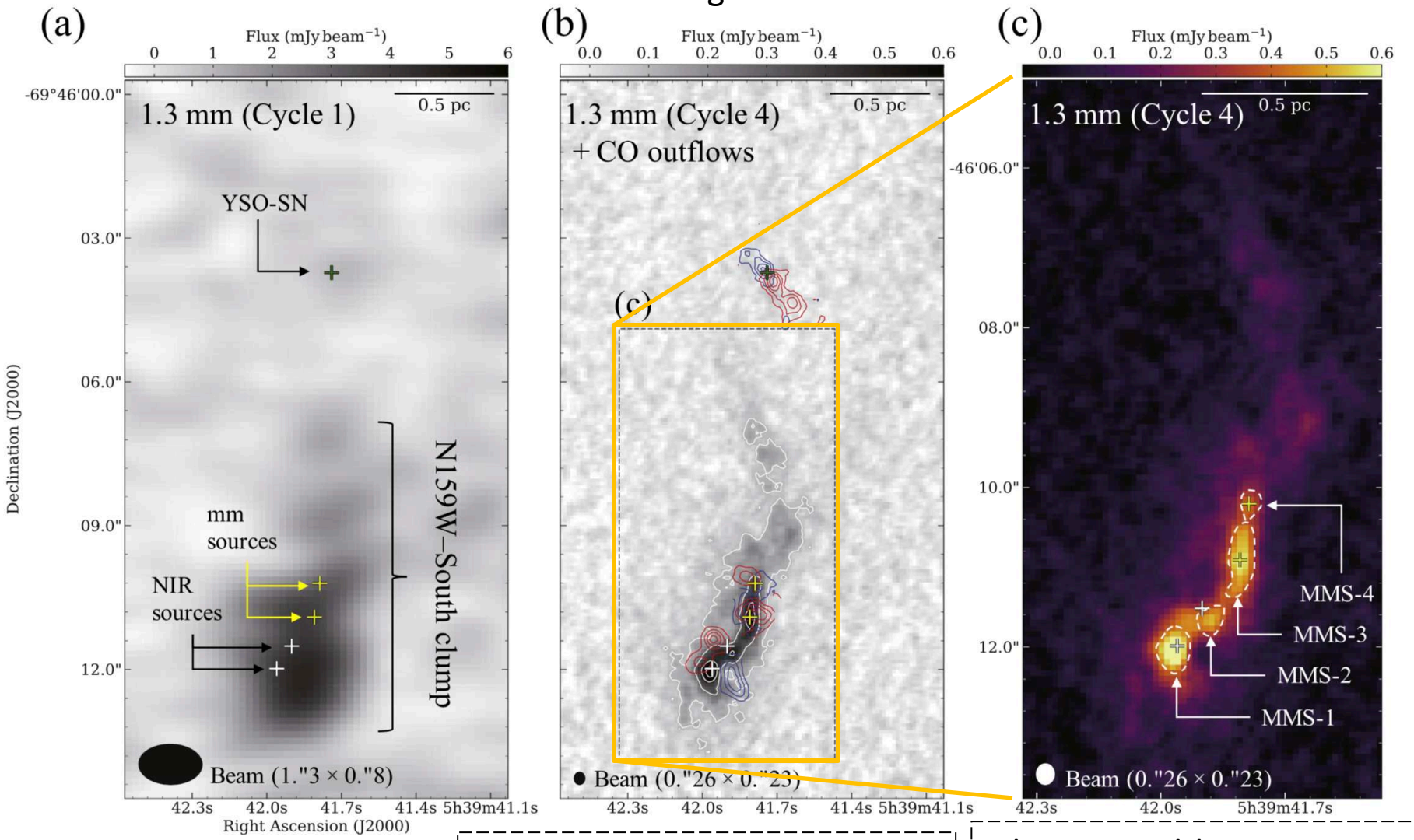
ALMA Cycle 4



Molecular outflow along high-mass filament

N159W

CO outflows along the 1.3 mm filament



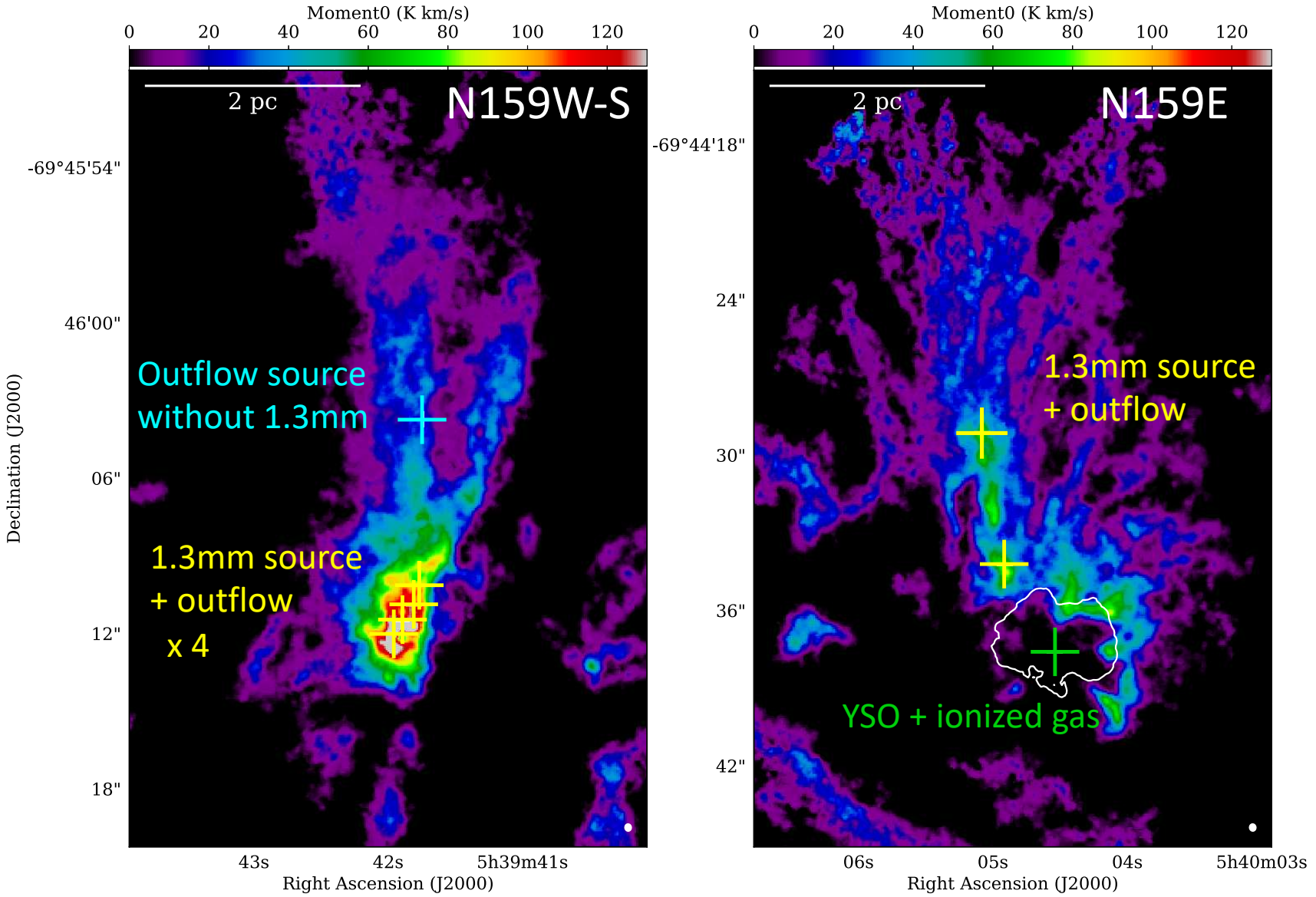
Five outflows along the filament (t_d ~ 10^3-10^4 yr)

Filament width ~ 0.14 pc

M_{line} ~ 2 x 10^3 *Mo*/pc

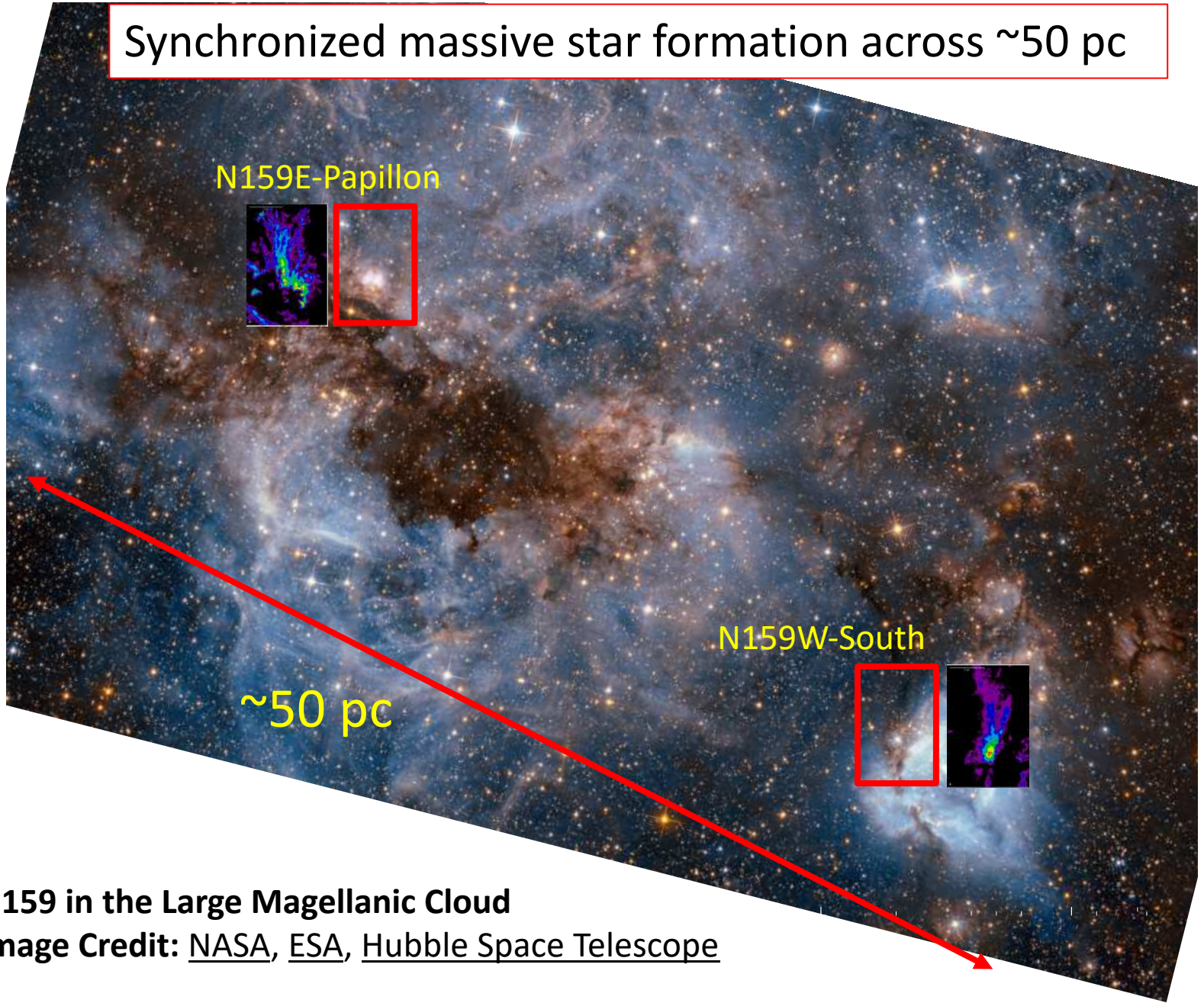
Core mass ~ a few x 100 *Mo*

Discussions: Origin of the twin filaments?



ALMA ^{13}CO (2–1)

Discussion: What is the Origin of the massive filaments?

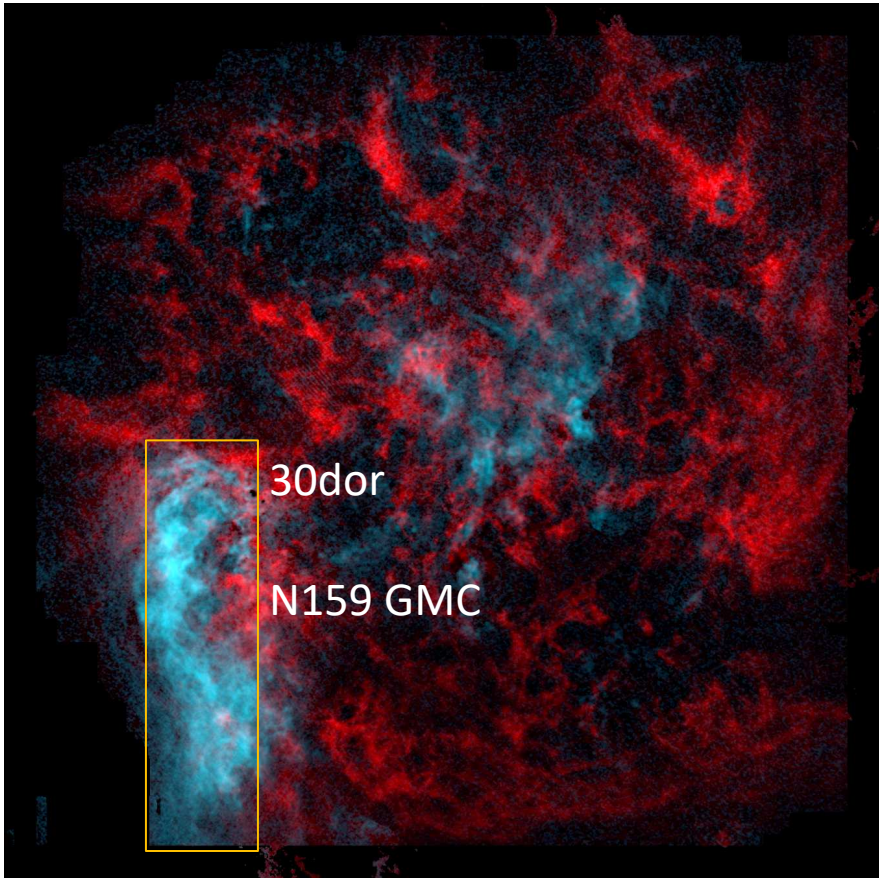


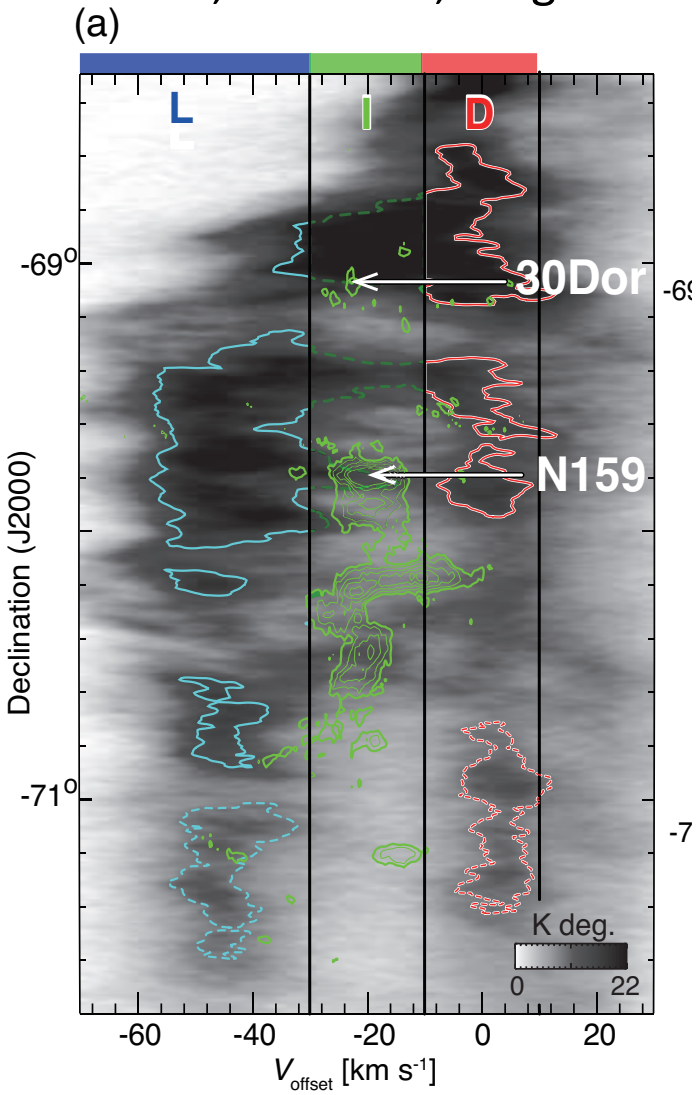
N159 in the Large Magellanic Cloud
Image Credit: NASA, ESA, Hubble Space Telescope

Large-scale colliding flow driven by the last tidal interaction

c.f., Fukui+17, Tsuge+19

HI obs. in the LMC





Blue: L-(low-velocity) HI component

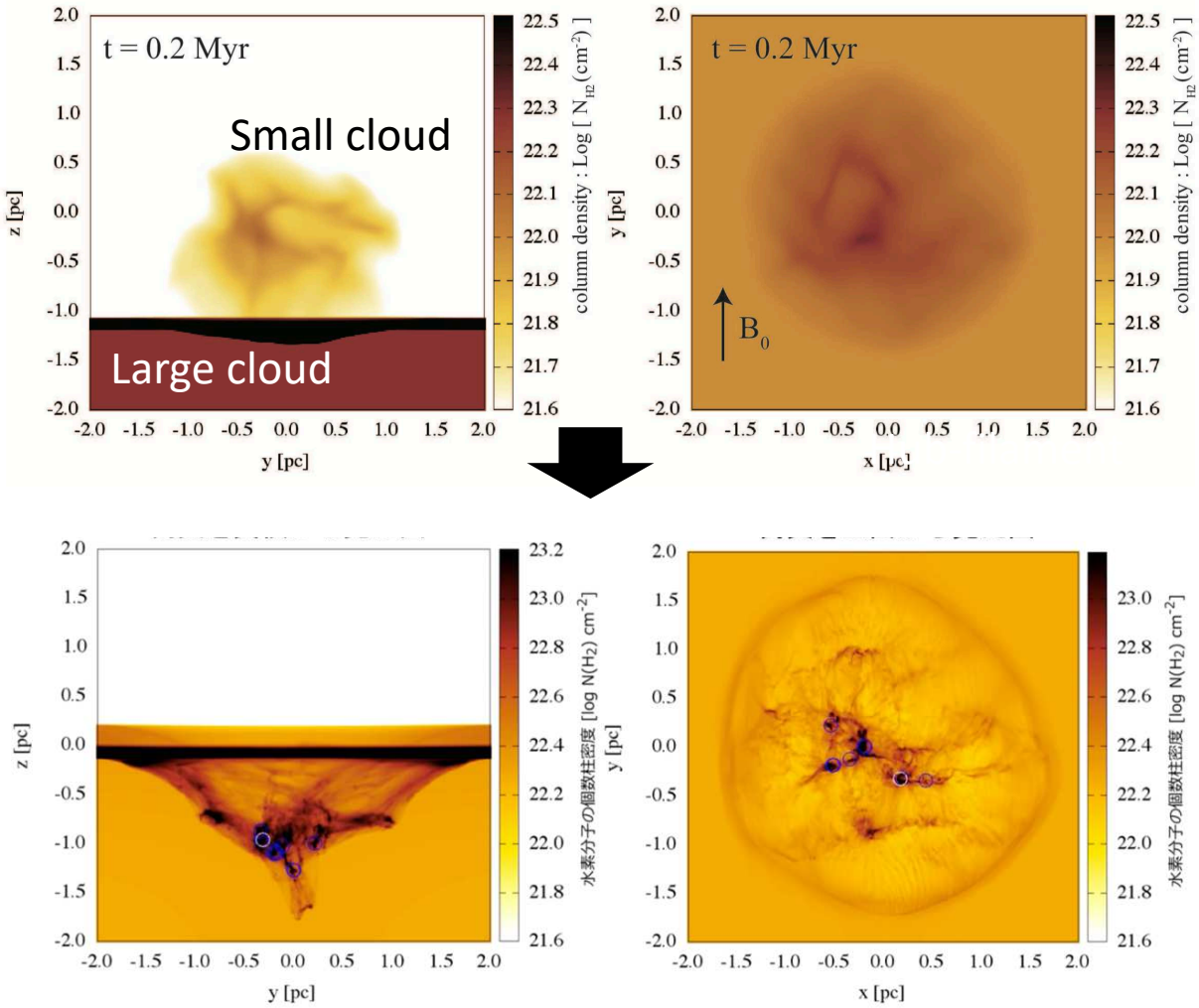
Red: D-(disk) HI component

Fukui+17; Tsuge+19

Green: CO (1-0)

Gray: HI

MHD Simulations of colliding clouds (Inoue et al. 2018)



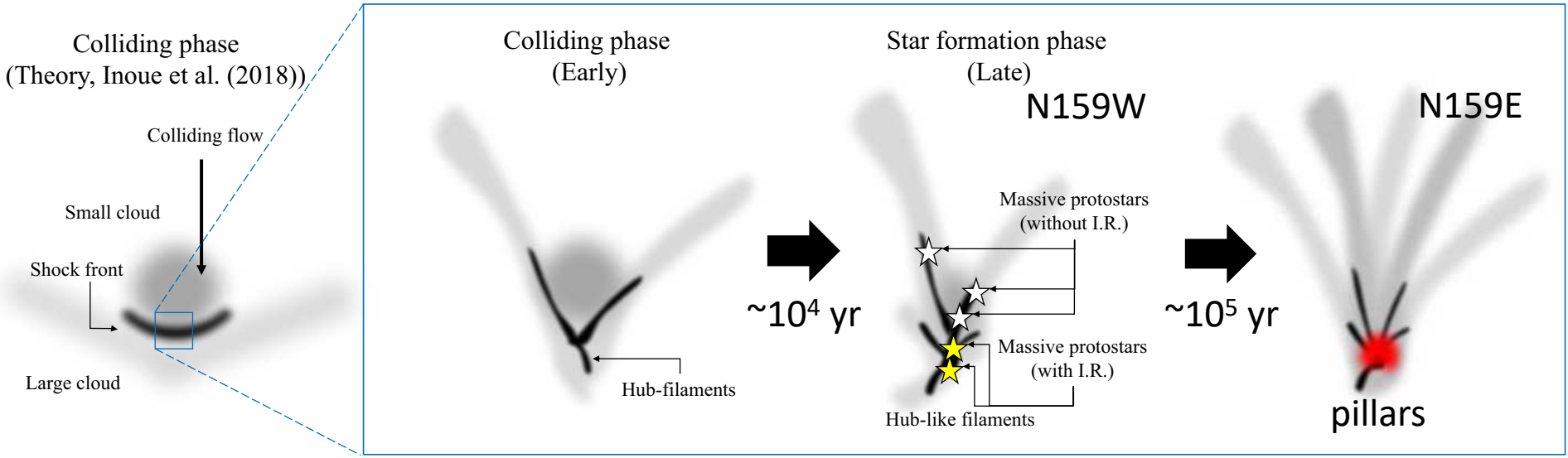
Consequences of Cloud-Cloud Collision

- Formation of hub filaments (fan shaped structure)
- The massive filaments collapse into protostars

Two Cosmic Peacocks show Violent History of the Magellanic Clouds

1. Colliding flow driven by the last tidal interaction btw the LMC/SMC

2. Hub filaments at the shock compressed layers



3. High-mass SF along the filaments

4. Ionization and pillars of creation

Summary of the N159E/W obs.

ALMA obs. toward the N159 regions with a ~0.07 pc resolution

- Resolving (hub) filamentary structures with ongoing massive SF
- Pillars of creation / multiple protostellar outflows
- Large-scale colliding flow promoted the filament/massive star formation

N159E: Fukui, Tokuda, et al., 2019, ApJ,886, 14
N159W: Tokuda, Fukui, et al.,2019, ApJ,886, 15

On-going works

- N159W-North as the largest peacock in the Local Group
- Statistical study toward ~40 YSOs in the LMC
  =>Pick up some of the objects and perform high-resolution obs.