2017 Nov 28, EA ALMA Science WS in Korea

# Microscopic World of the Galactic Center Opened by ALMA

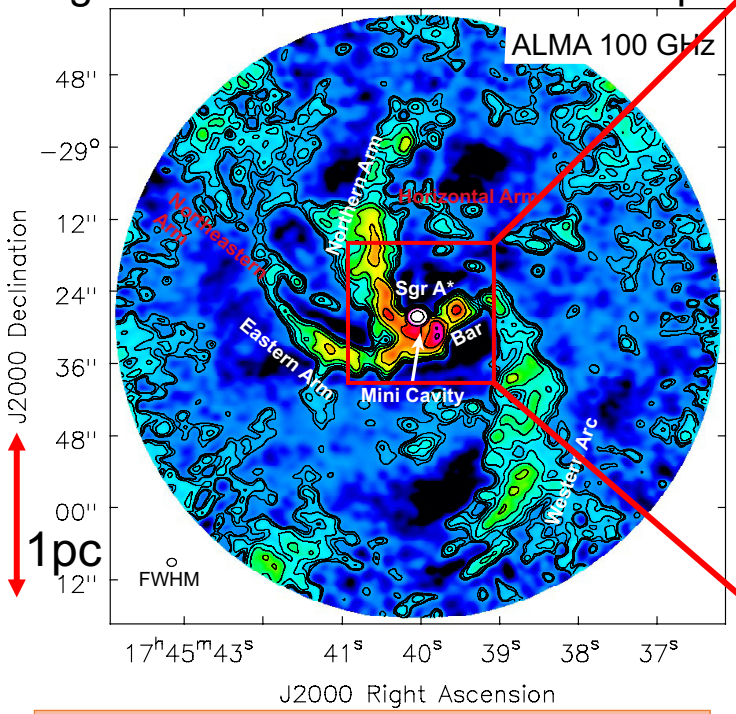
Masato Tsuboi (ISAS/JAXA)

# CONTENTS

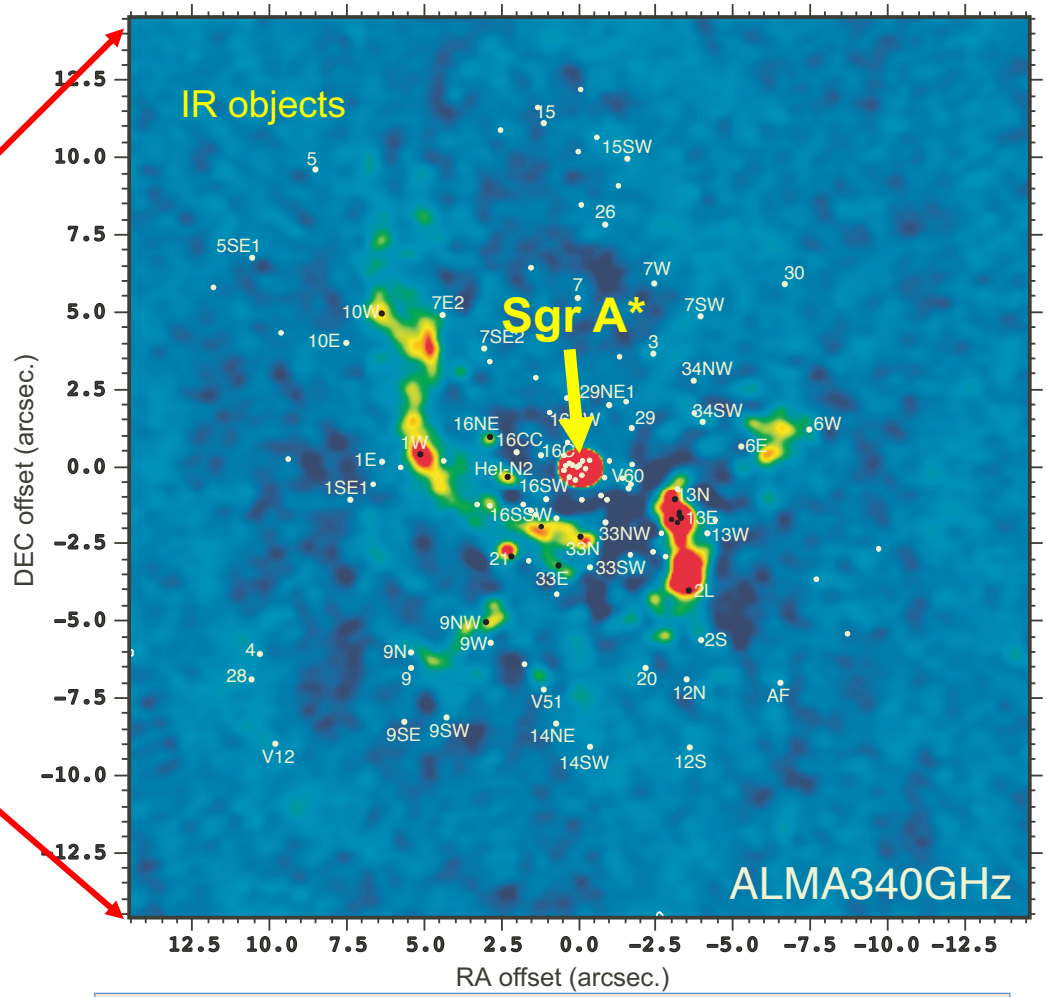
- Introduction
- ALMA View of the CND
- ALMA View of the Minispiral
- Miscellaneous

# Introduction

## Sgr A* and Galactic Center Mini-spiral




100 GHz map shows 100”x100” area centered at Sgr A*. The angular resolution is 1.57"x1.33”. (Tsuboi+ PASJ 2016, ALMA#2011.0.00887.S)



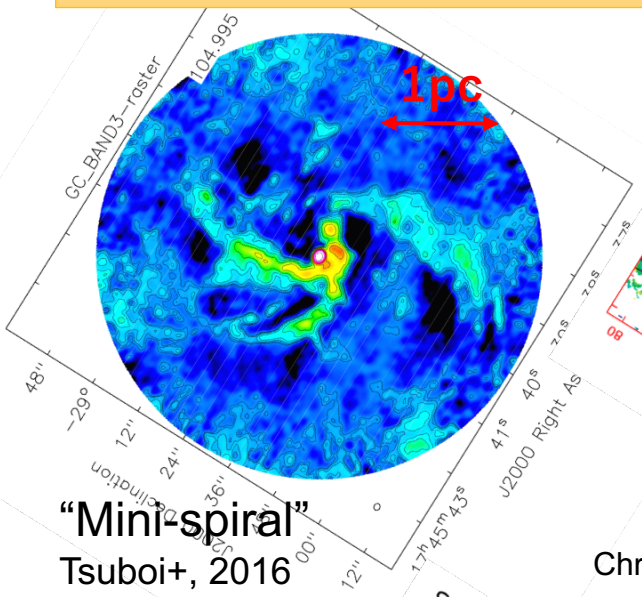

340 GHz continuum(FOV=17”). The angular resolution is 0.44"x0.38". The rms noise level is Sn =0.150 mJy/beam. (Tsuboi+ PASJ 2016, ALMA#2011.0.00887.S)

## Sgr A* and Galactic Center Mini-spiral

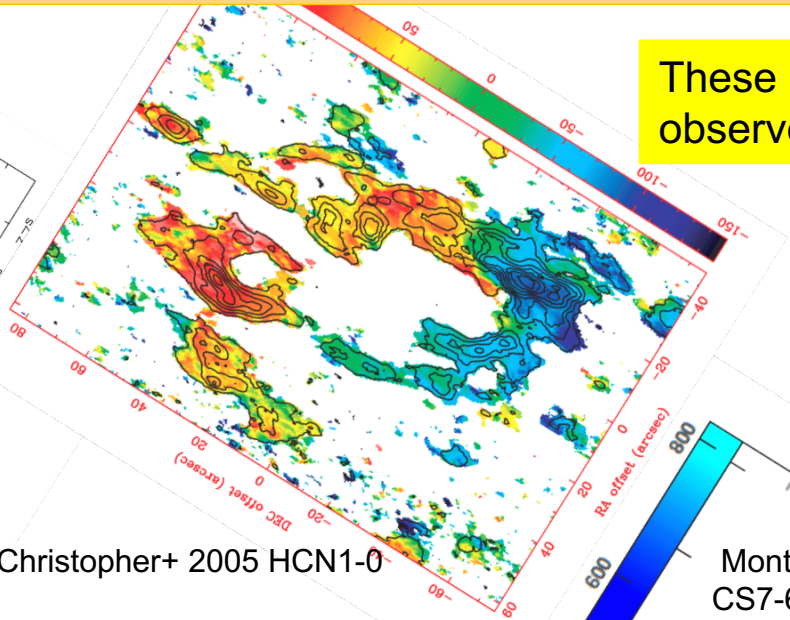
The Galactic Center Mini-spiral (GCMS)” was found using Very Large Array (VLA) and IR telescopes (e.g. Ekers et al. (1983), Lo & Claussen (1983). ). The GCMS is located within 2pc of Sgr A* in projection. The stretched appearance and kinematics of the GCMS suggest that the bundle of the ionized gas streams are tentative structures with Keplerian orbits around Sgr A* (e.g. Zhao et al. (2009), Zhao et al. (2010)).

# Previous Observation of the Circum-Nuclear Disk around Sgr A*(mm and sub-mm regions)

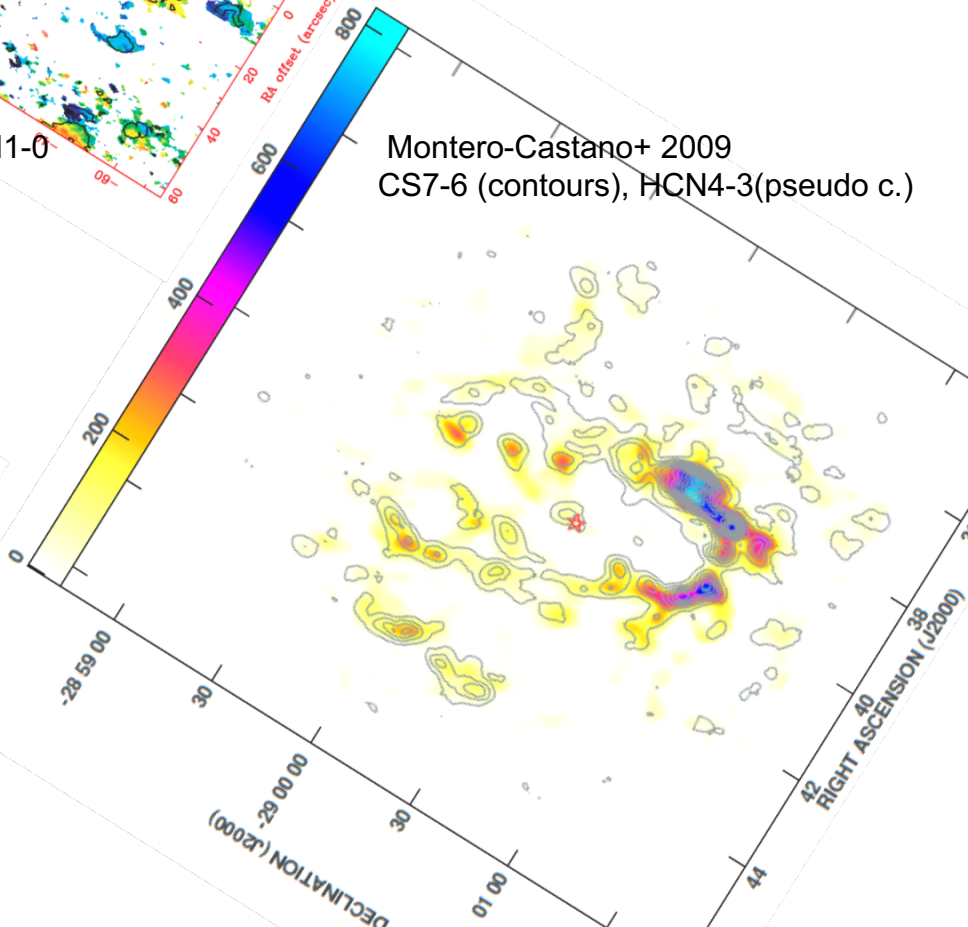
These are the maps of the CND observed before the ALMA era.




"Mini-spiral"
Tsuboi+, 2016

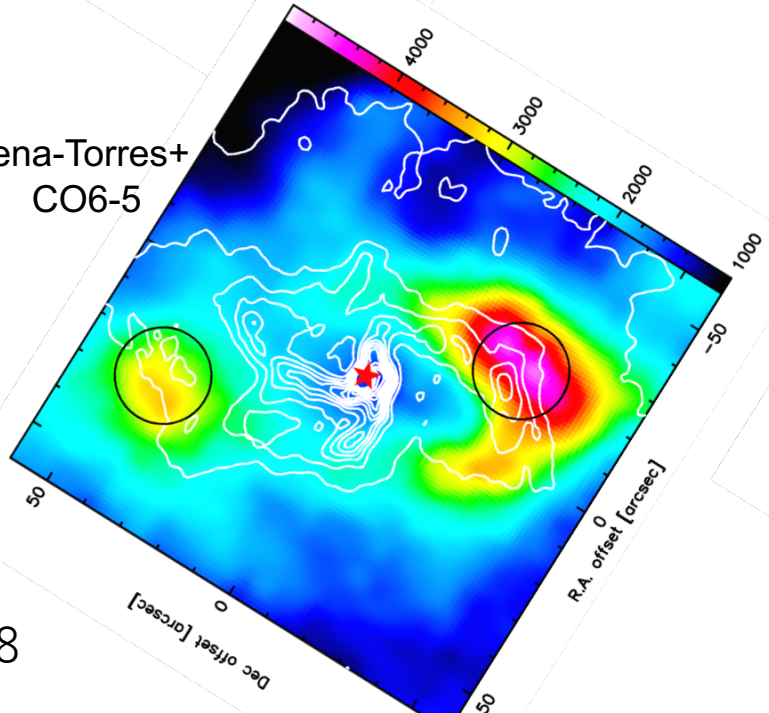



Christopher+ 2005 HCN1-0

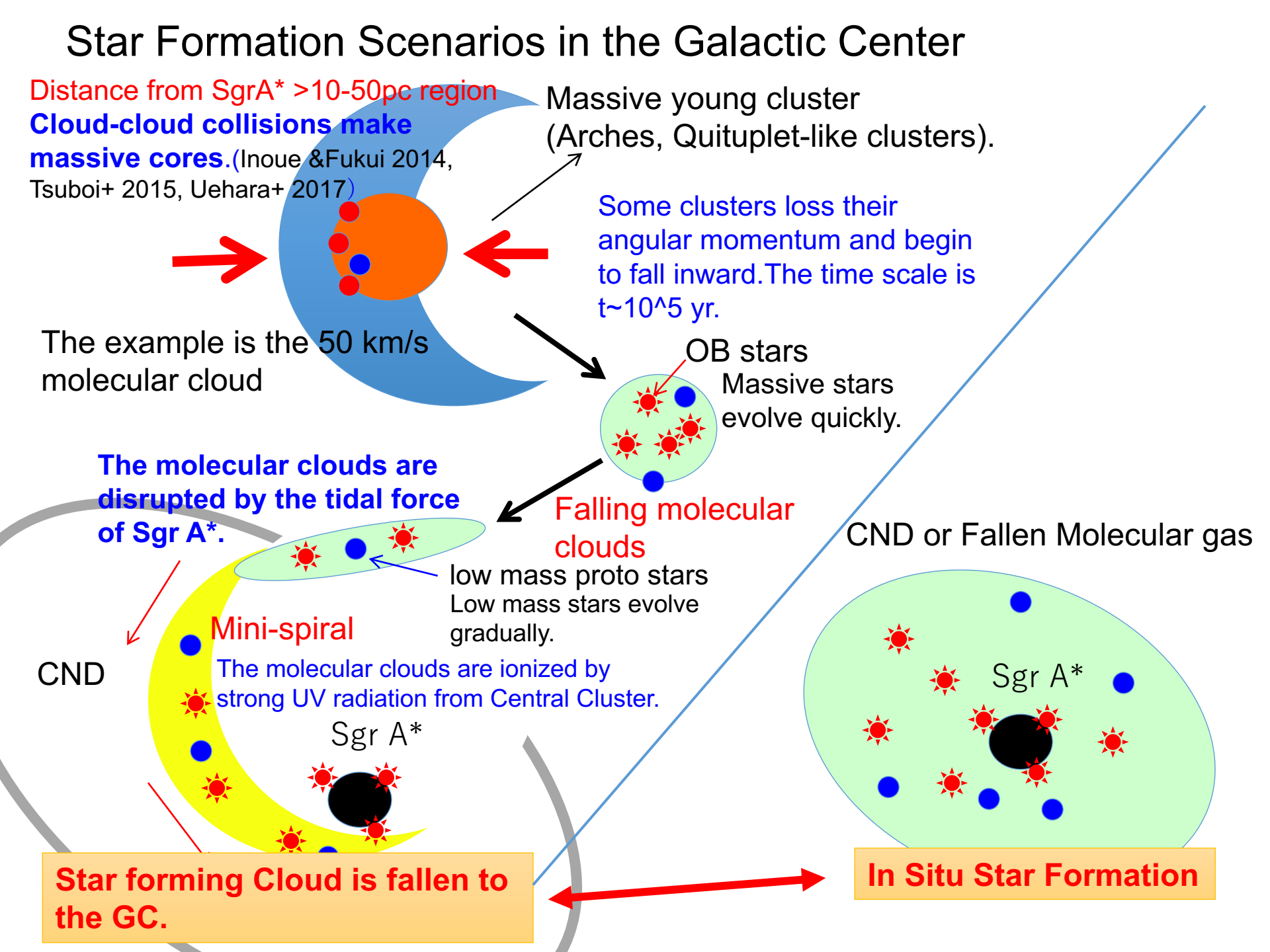



Montero-Castano+ 2009
CS7-6 (contours), HCN4-3(pseudo c.)

Requena-Torres+
2012 CO6-5



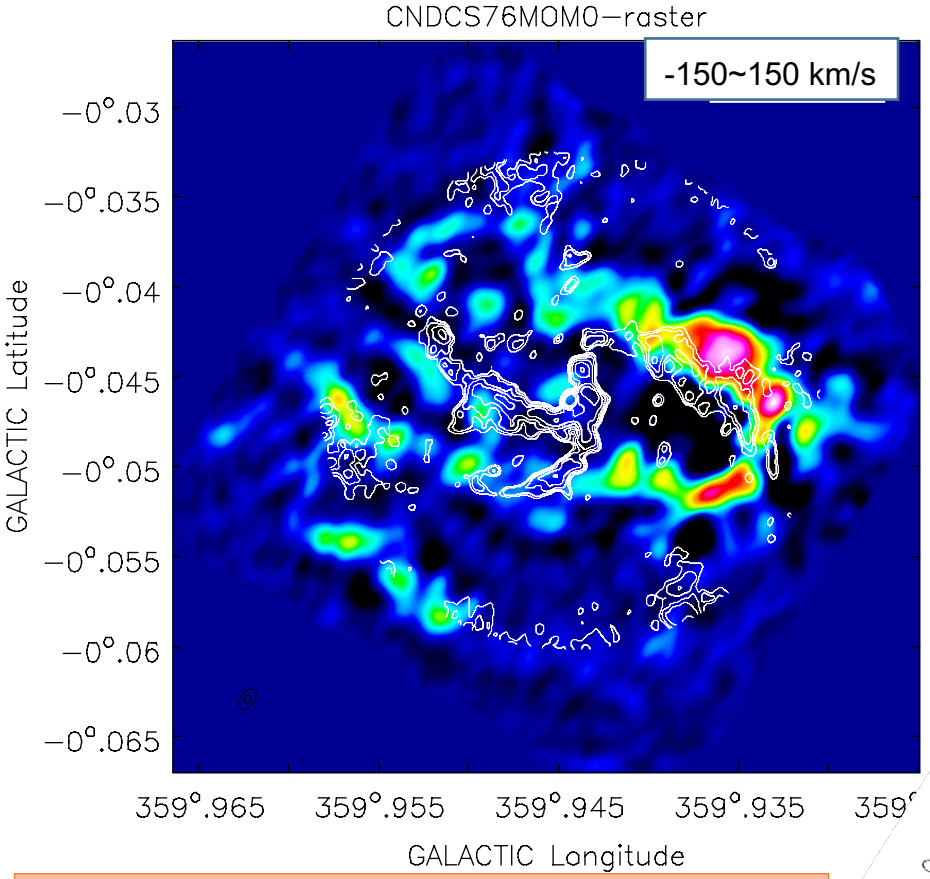
# Star Formation Scenarios in the Galactic Center



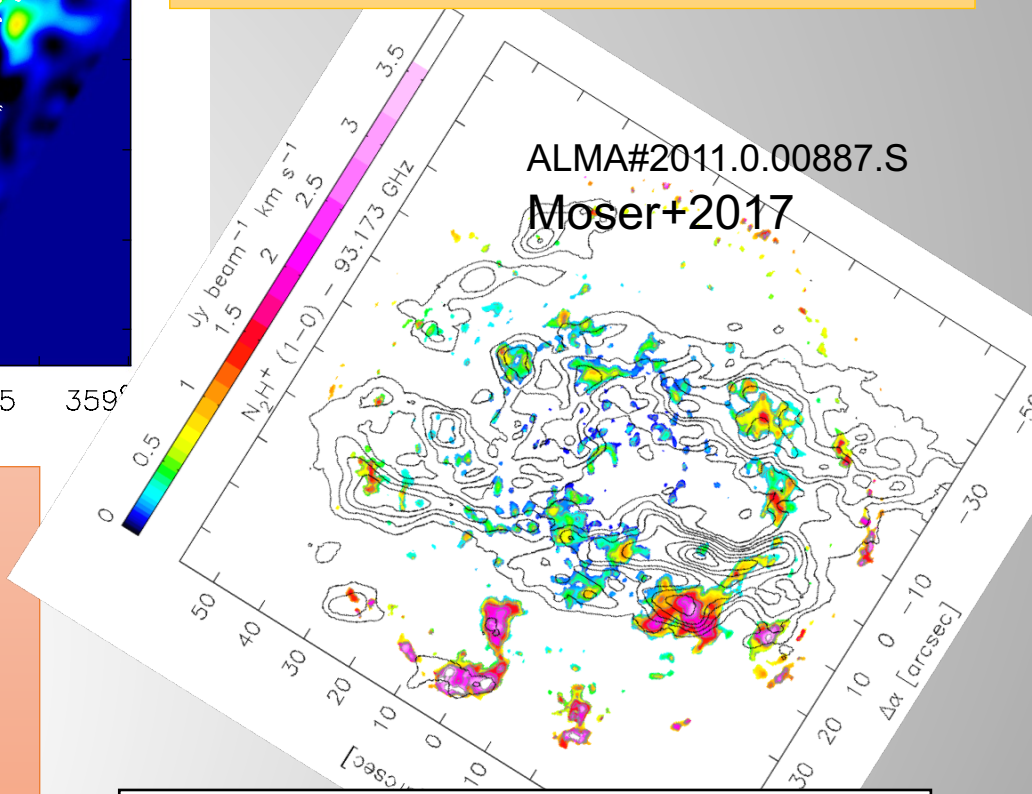
# CONTENTS

- Introduction
- ALMA View of the CND
- ALMA View of the Minispiral
- Miscellaneous

# ALMA Views of the CND




Low –J molecular emission line
$N_2H^+$1-0(pseudocolor)
low-J molecular emission line observations does not always represent the CND itself well.

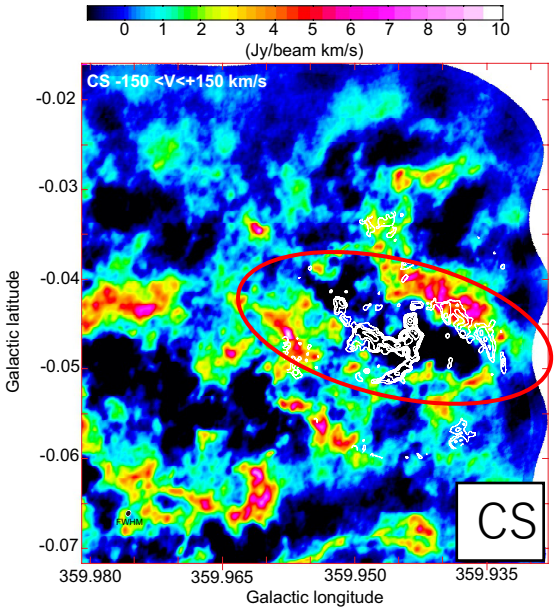


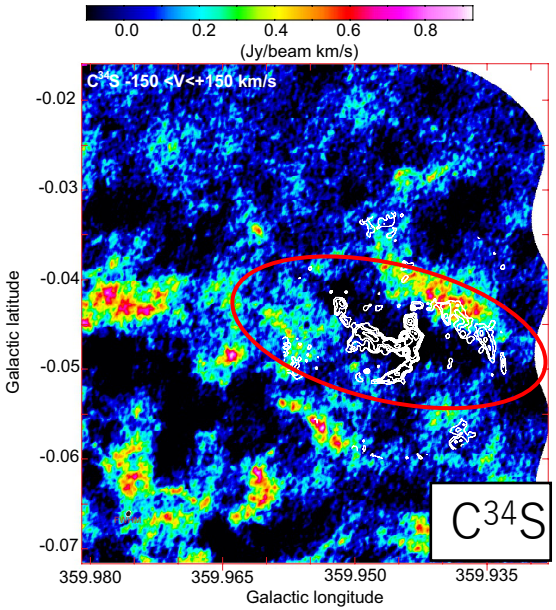

High-J molecular emission line
CS 7-6 ALMA#2012.1.00543.S
Not yet published??

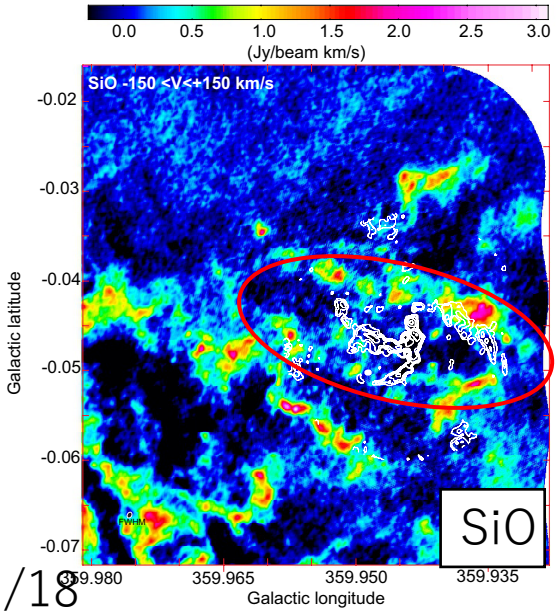
High-J molecular emission line observations represent the CND itself well.

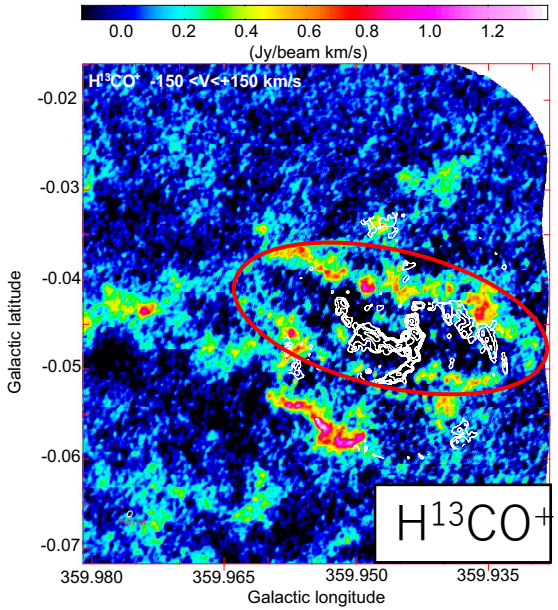
ALMA archive is full of good data to be analyzed.

# ALMA View of the CND(Integrated Intensity Maps)



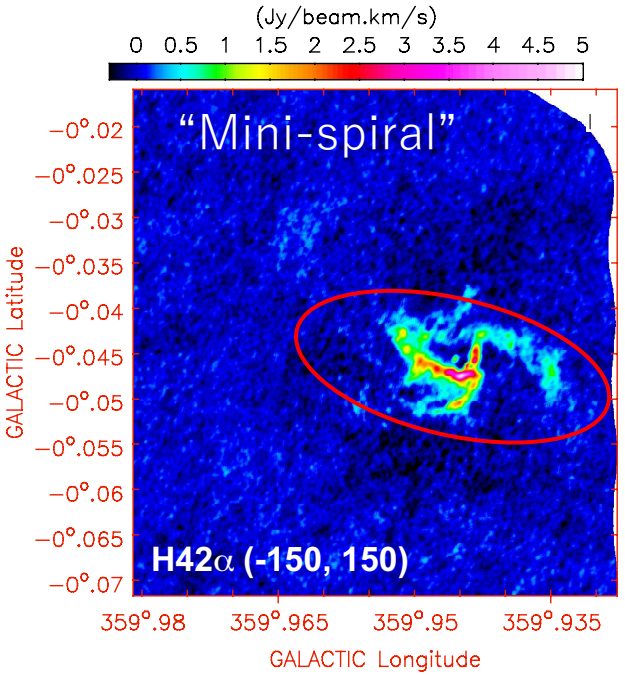



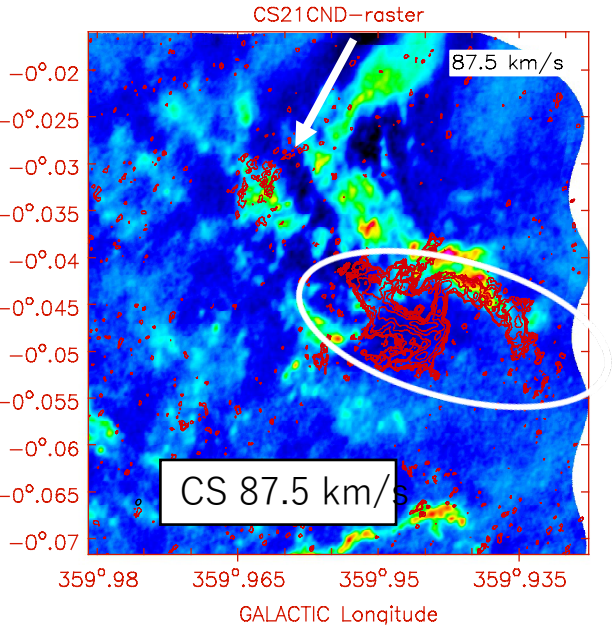

Low-J molecular emission lines
(2.3-2.5)"x(1.6-1.8)"
=(0.09-0.10)pc x (0.06-0.07)pc

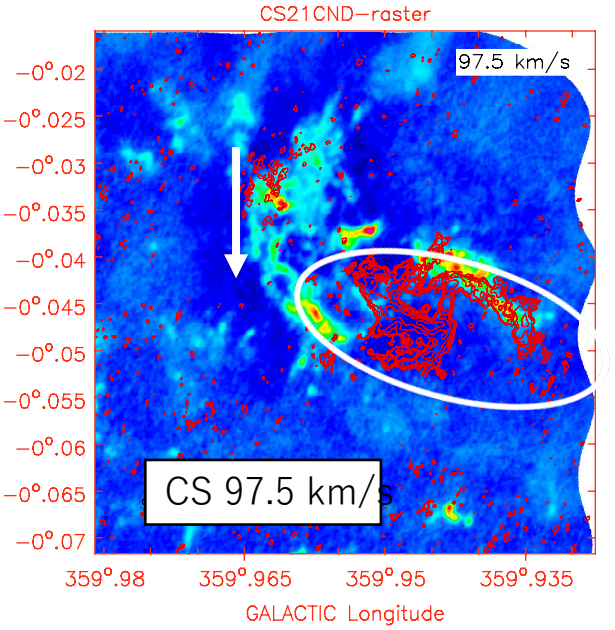
Tsuboi+ 2017
ALMA#2012.1.00080.S
In preperation.

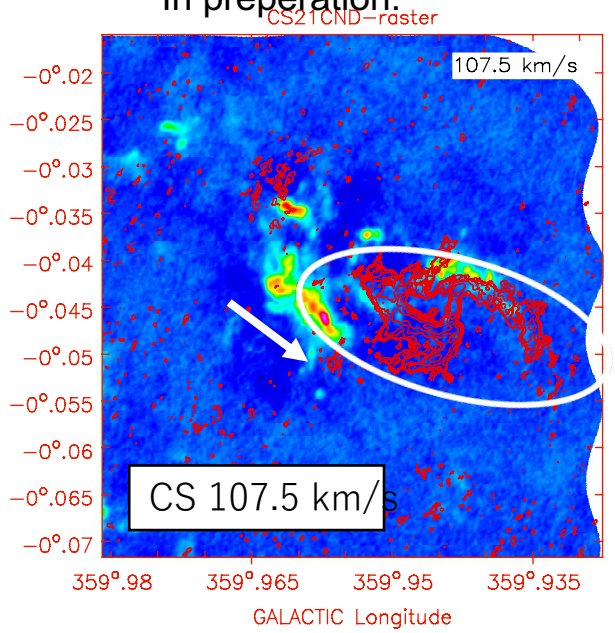


# Tidally disrupted molecular cloud falling to the minispiral

Tsuboi+ 2017 IAU322 Proc.
ALMA#2012.1.00080.S
In preperation.

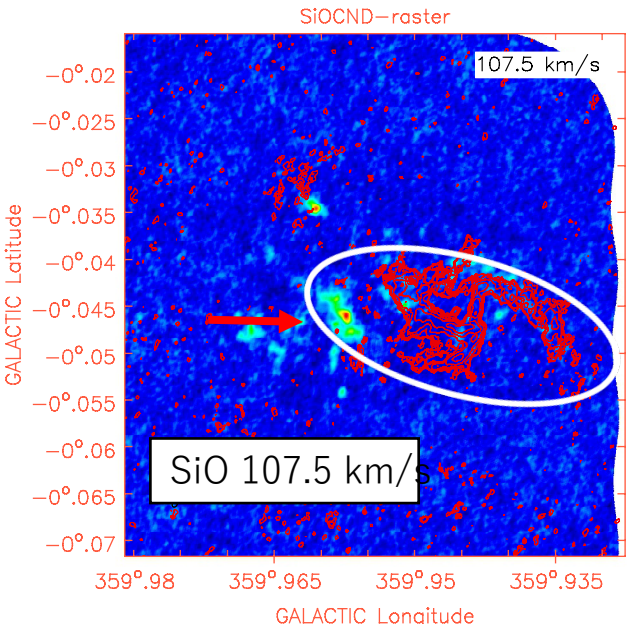


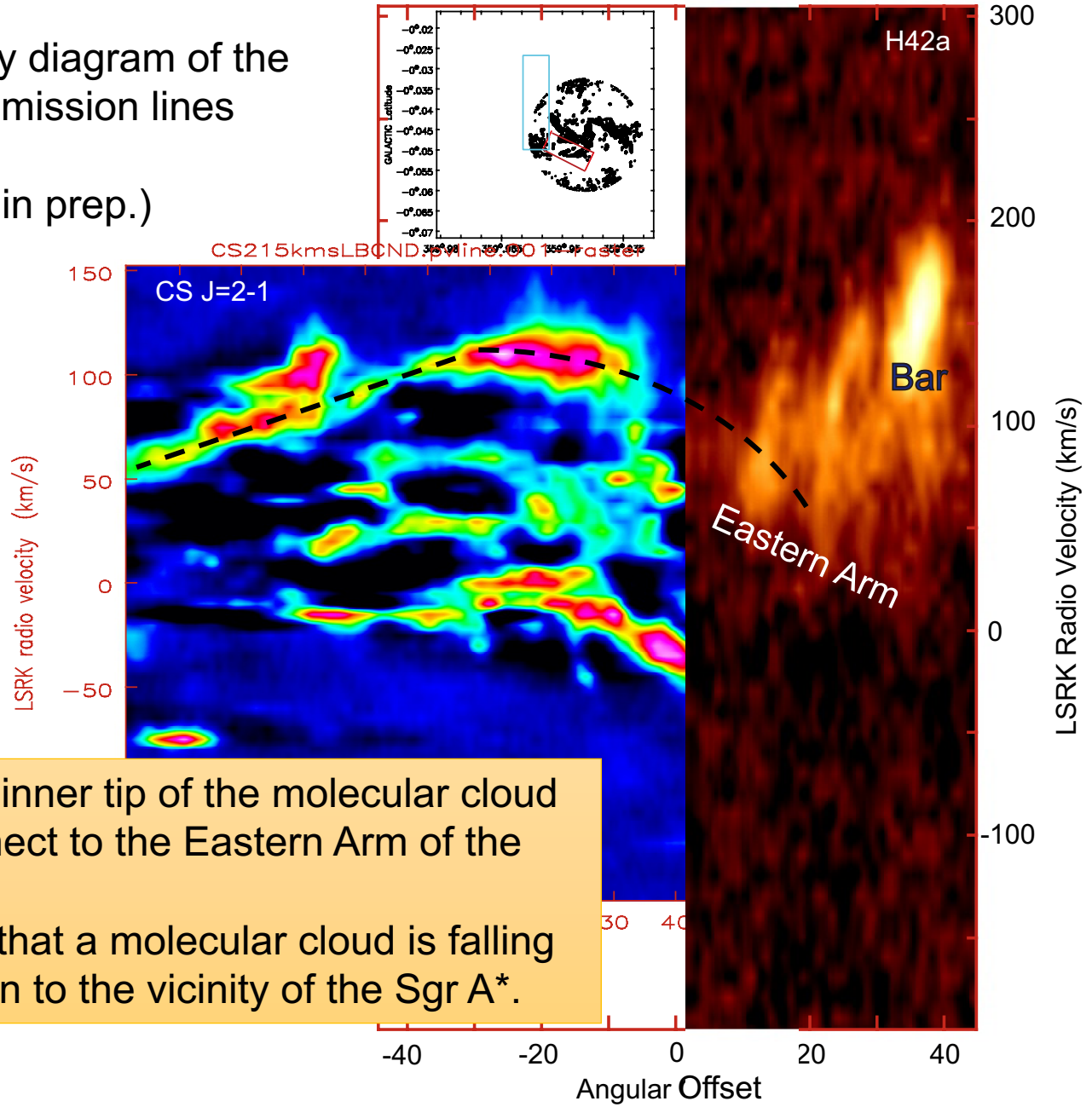

## Tidally disrupted molecular cloud falling to the minispiral

1) There is a molecular cloud with filamentary structure located north of the CND (White arrows).
2) The elongated appearance of the cloud suggests that the cloud is tidally disrupted by Sgr A*.
3) The inner tip of the cloud is seen to connect to the Eastern Arm of the Mini-spiral.
4) There is a SiO compact emission around the contact area (Red arrow). This indicates that shocked molecular gas is here because the SiO emission line is a famous shock tracer.



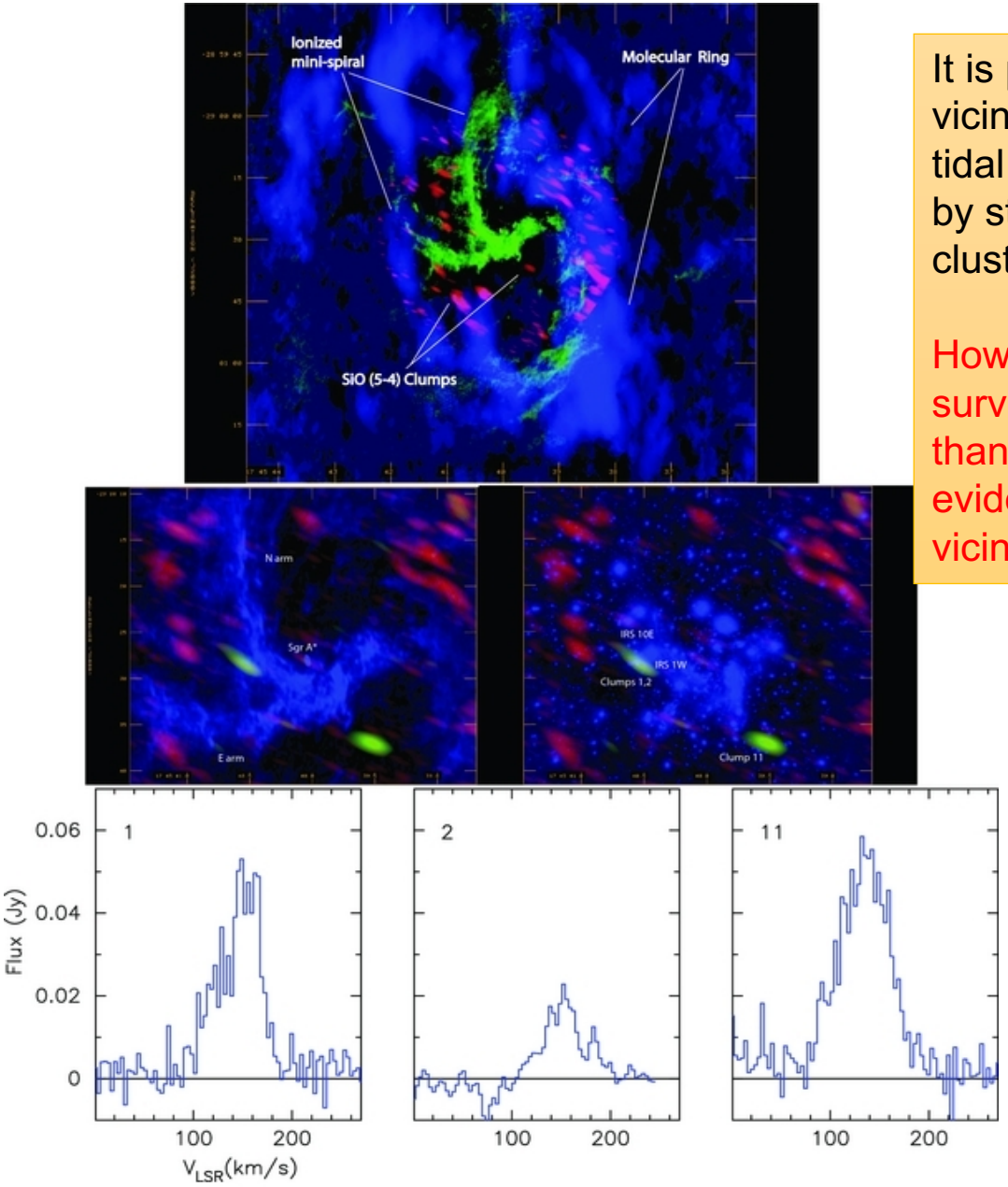
Position-velocity diagram of the CS and H42a emission lines

(Tsuboi+ 2017, in prep.)




In this diagram, the inner tip of the molecular cloud is also seen to connect to the Eastern Arm of the Mini-spiral.
We probably found that a molecular cloud is falling from the outer region to the vicinity of the Sgr A*.

F. Yusef-Zadeh et al. 2013 ApJL 767 L32 doi:10.1088/2041-8205/767/2/L32



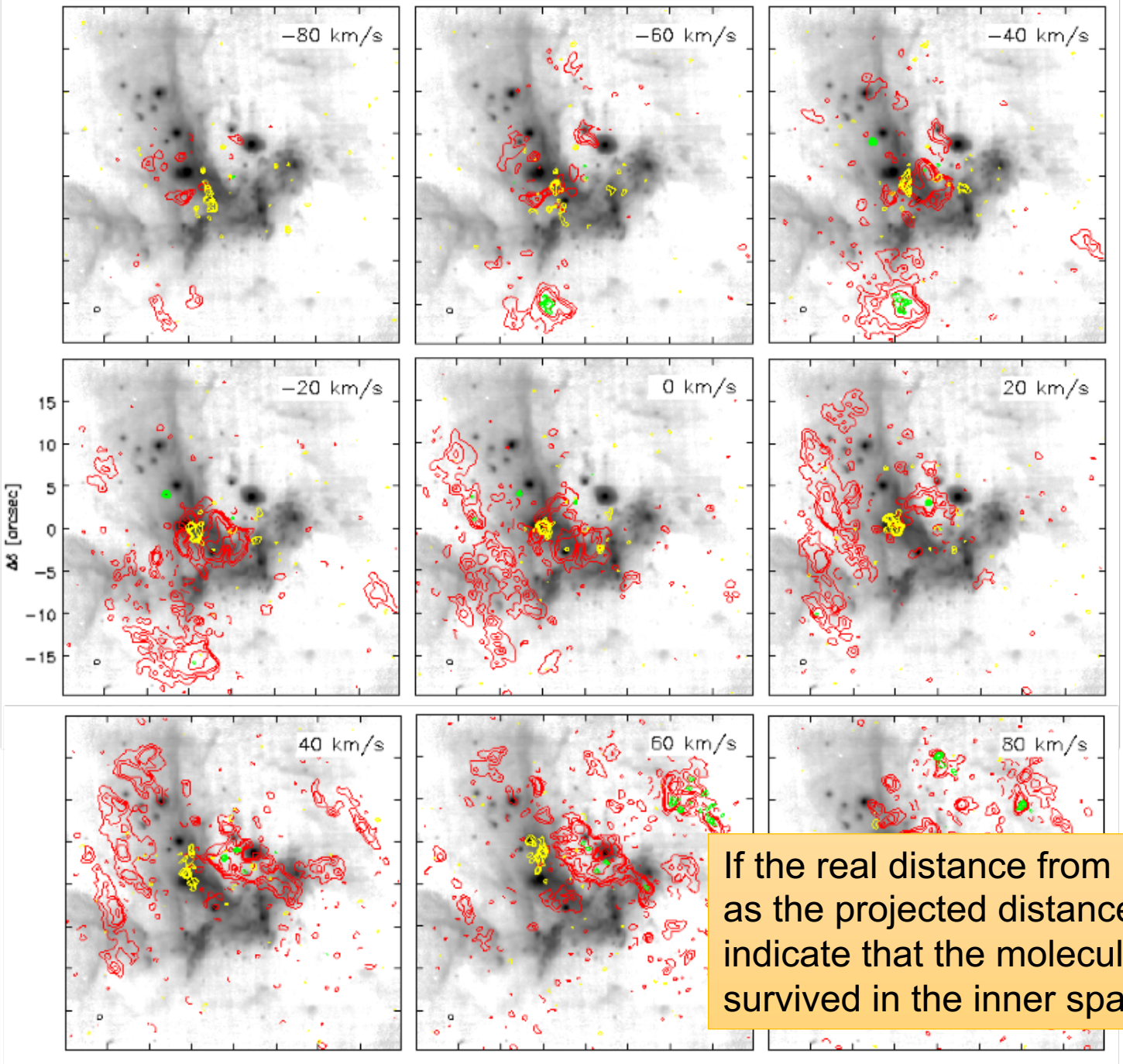

It is plausible that molecular clouds in the vicinity of Sgr A* are disrupted by the strong tidal force of Sgr A* itself and ionized quickly by strong UV radiation from the nuclear star cluster.

However, if the molecular gas can be survived survived for long duration in the inner space than the CND, it may be a circumstantial evidence that star formation could occur in the vicinity of Sgr A*.

Y-Z+ 2013

ALMA found compact objects in the vicinity of Sgr A* in the SiO emission line.

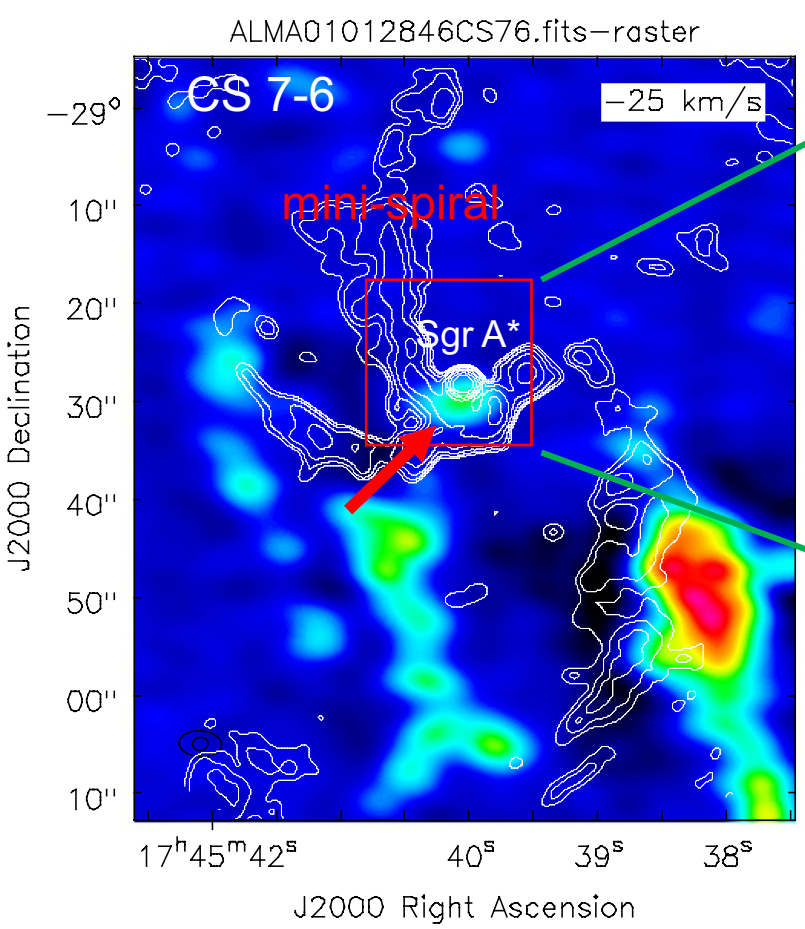
It is advocated that these objects are star forming molecular cores and massive star formation could occur in the vicinity of Sgr A*.

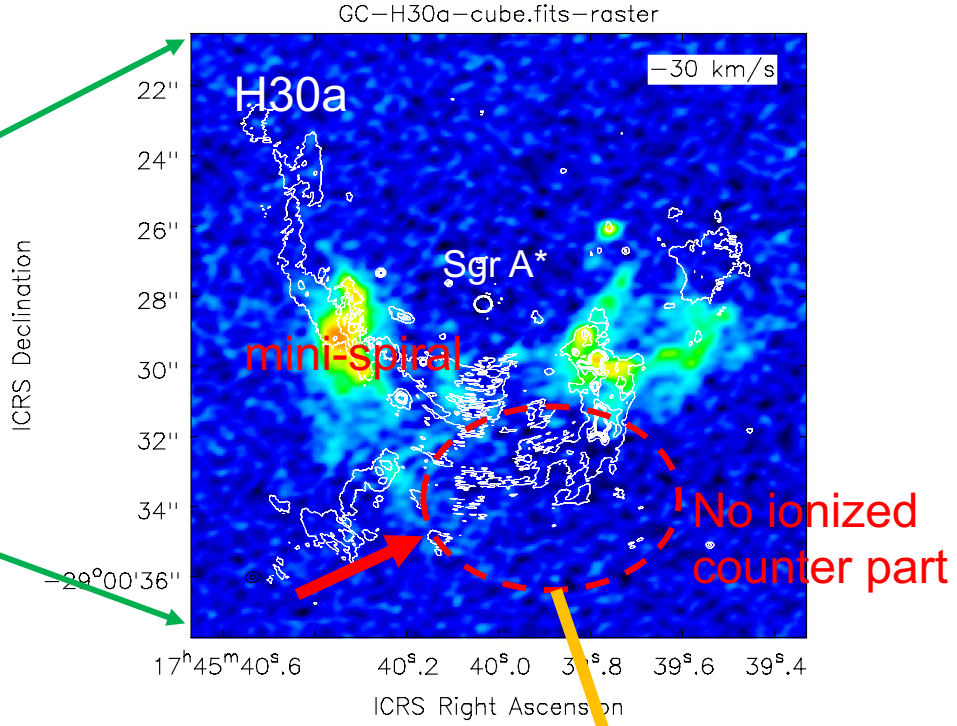


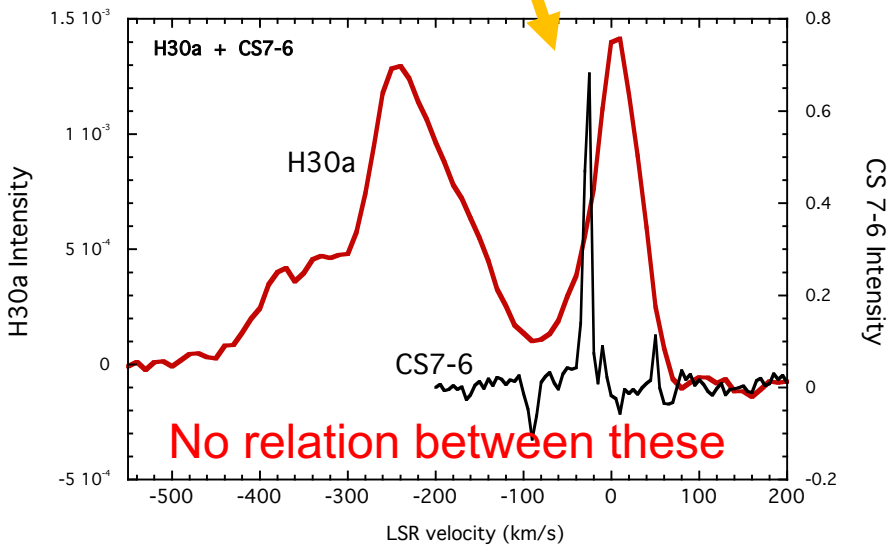

Red contour:
CS 5-4
Green contour:
SiO 6-5

If the real distance from Sgr A* is as near as the projected distance, this figure should indicate that the molecular gas can be survived in the inner space than the CND.

Moser+ 2017



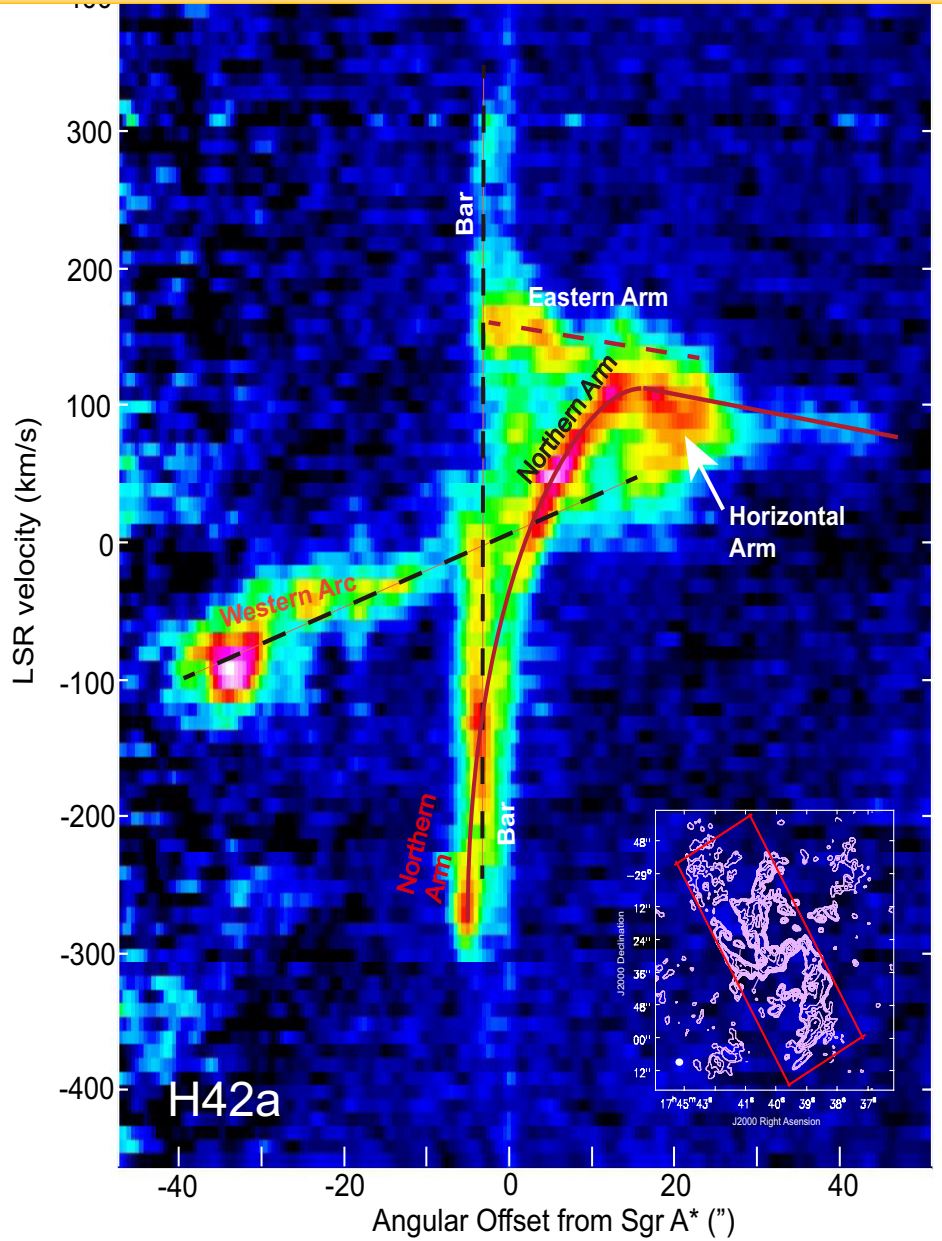

We would check the surviving cloud by other observation data.

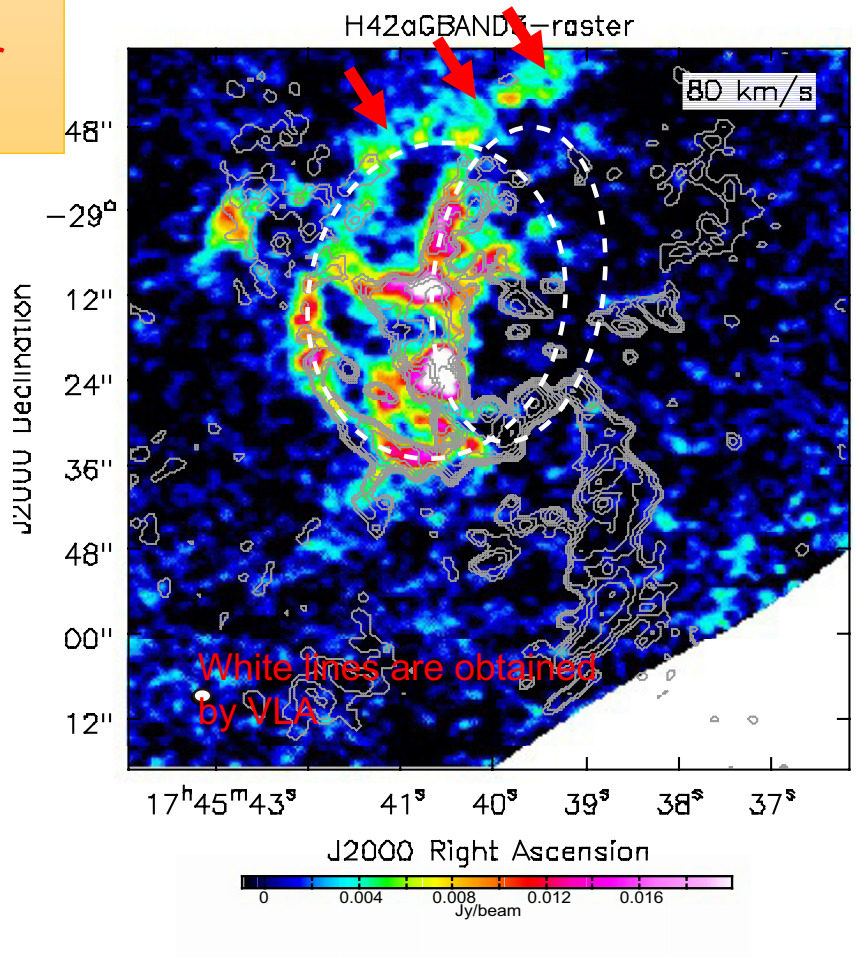
We don't yet find the circumstantial evidence for the surviving cloud in the vicinity of Sgr A*.

# CONTENTS

- Introduction
- ALMA View of the CND
- ALMA View of the Minispiral
- Miscellaneous

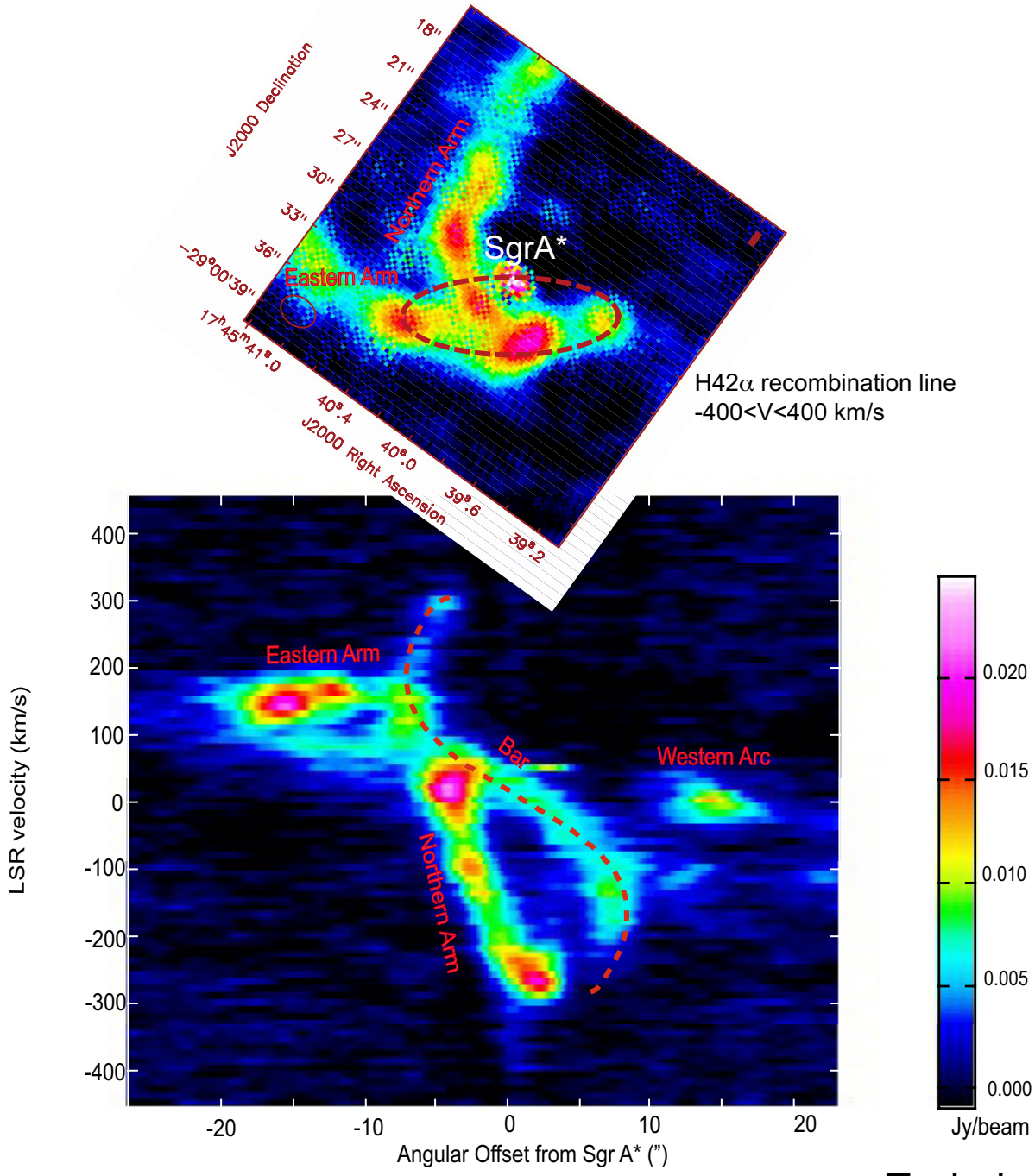
The orbits are consistent with the classical image obtained by VLA observation except for orbit parameters of the Keplerian orbits.



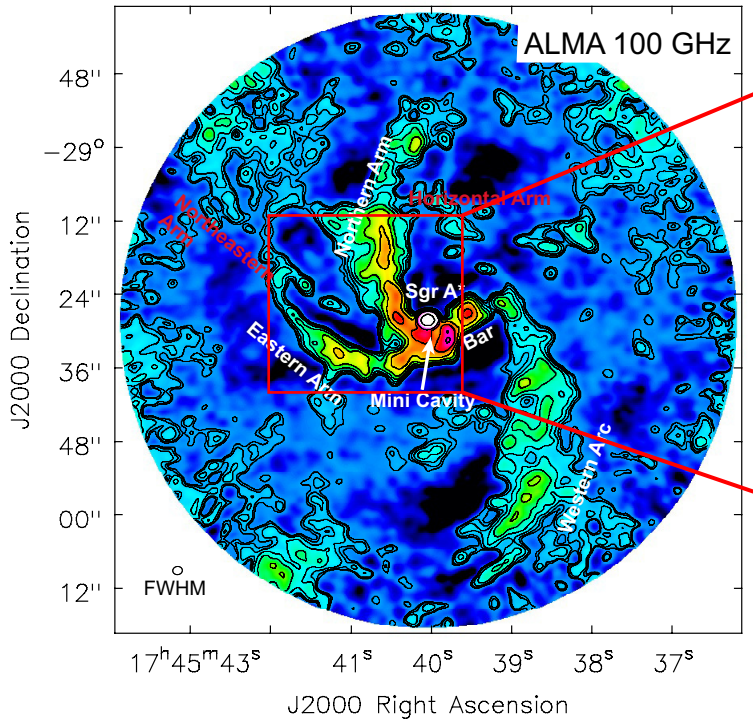



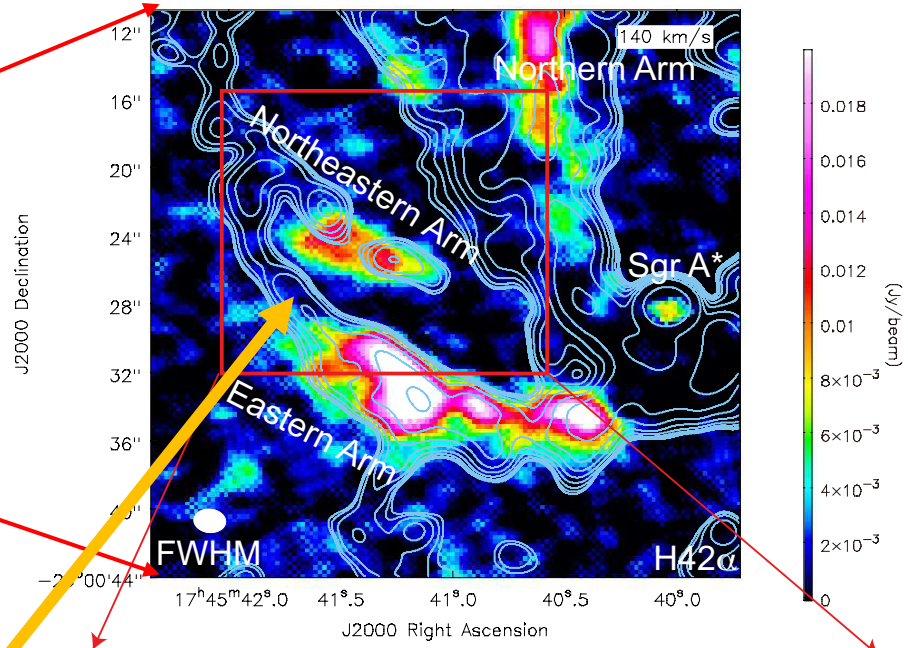

The semi measure axis is larger than the VLA derived value.

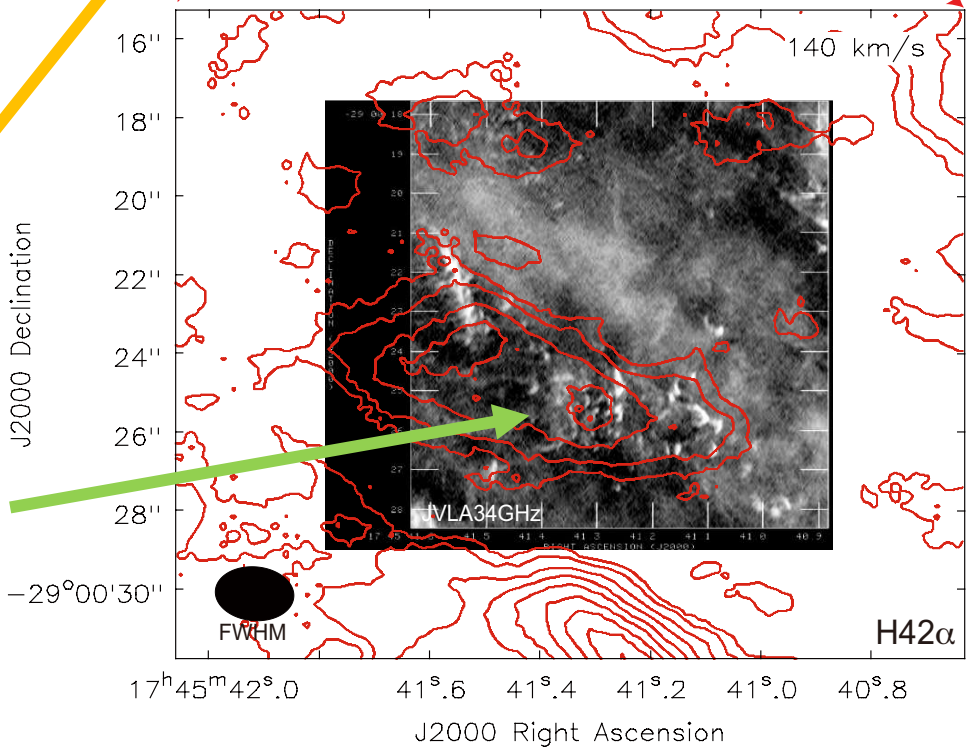
Tsuboi+ 2017a




Tsuboi+ 2017a

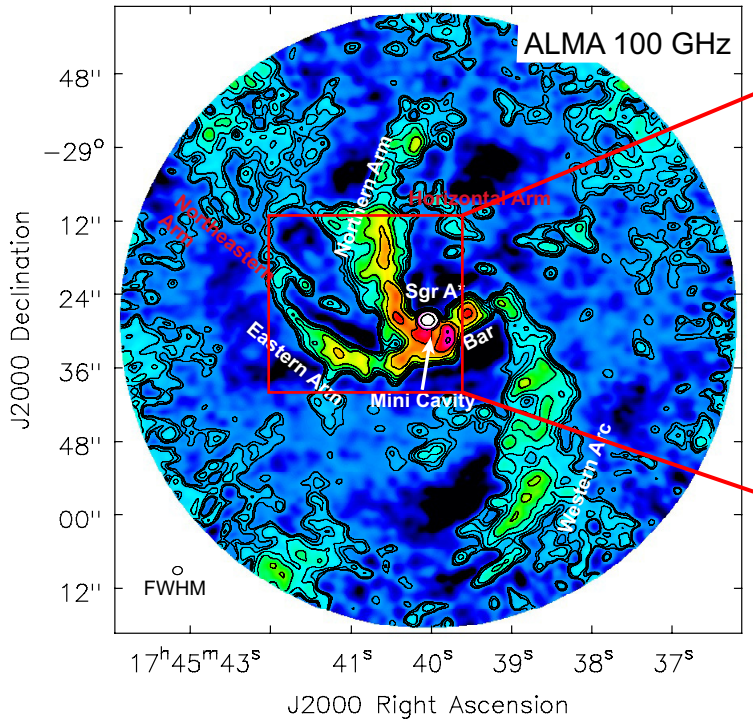


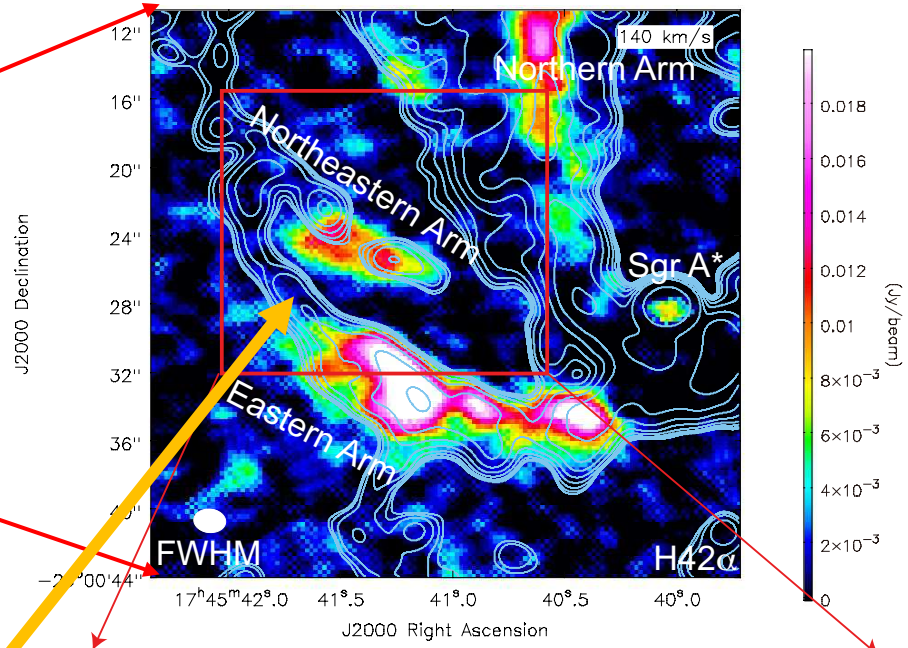



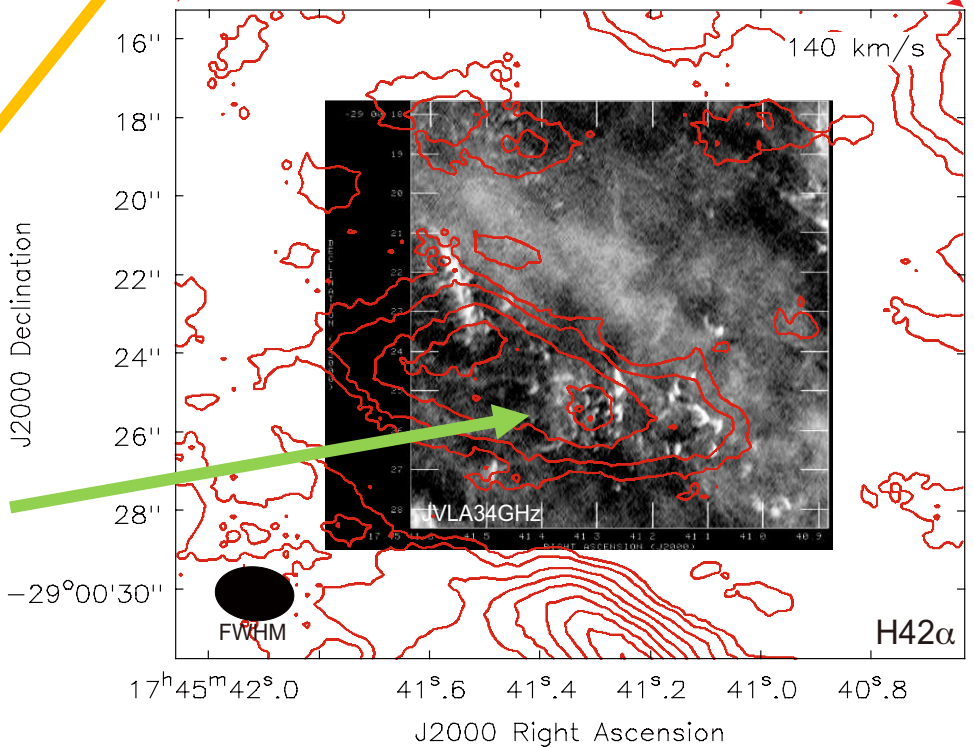




The low-mass proto stars are located in the Northeastern Arm which is ionized gas streamer apprachin to Sgr A*. Tsuboi+2017a

Many compact half shell-like ionized objects around Sgr A* using VLA. These are low-mass proto stars with dust disk. The dust disks are ionizing by strong UV radiation from Central Cluster. Y-Z+ 2015



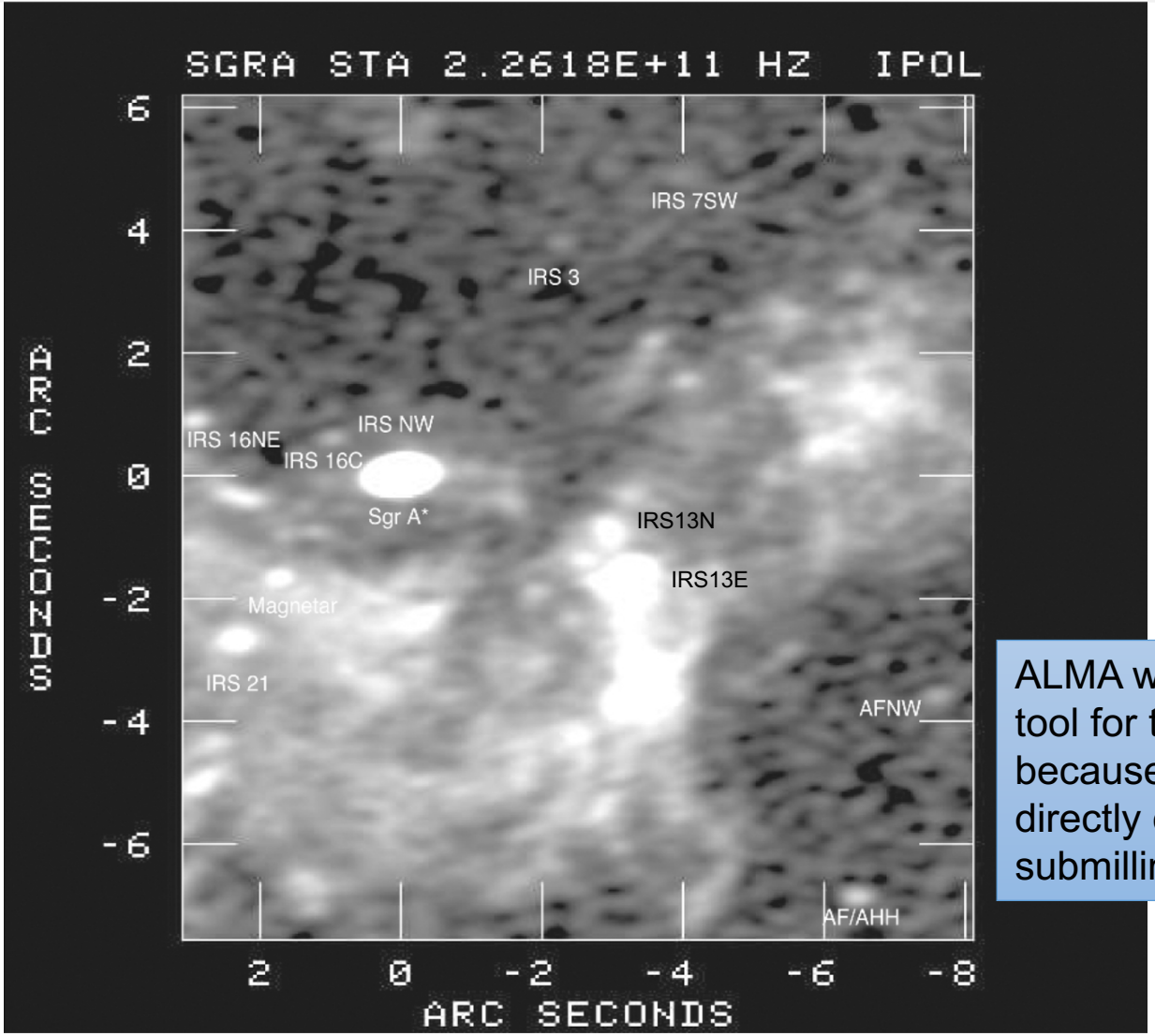




The low-mass proto stars are located in the Northeastern Arm which is ionized gas streamer apprachin to Sgr A*. Tsuboi+2017a

Many compact half shell-like ionized objects around Sgr A* using VLA. These are low-mass proto stars with dust disk. The dust disks are ionizing by strong UV radiation from Central Cluster. Y-Z+ 2015

# CONTENTS

- Introduction
- ALMA View of the CND
- ALMA View of the Minispiral
  Higher Angular Resolution!
- Miscellaneous



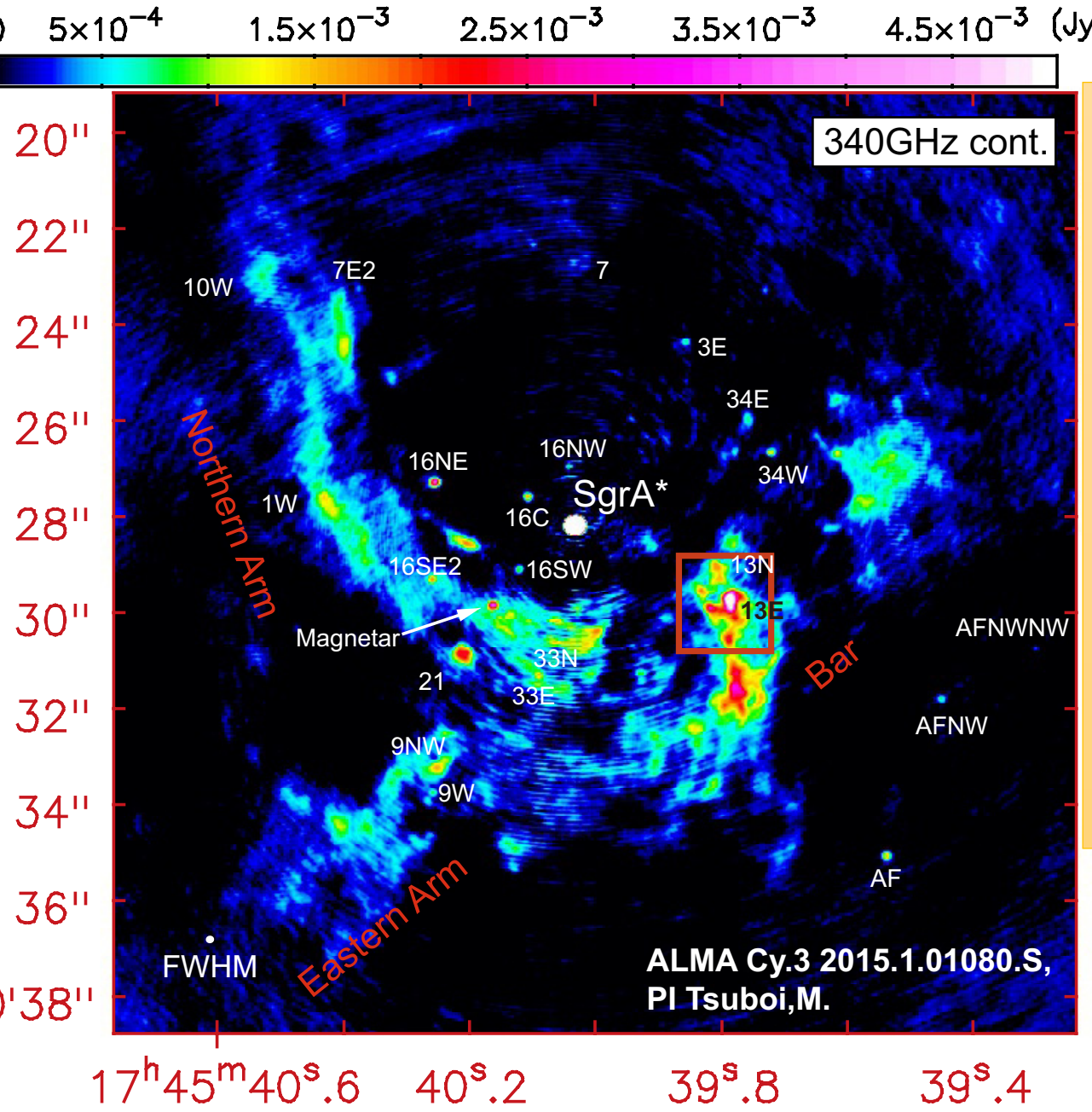

high angular resolution and high dynamic range image of the vicinity of Sgr A* using ALMA.

a 226 GHz image of the mini-spiral 0.38”x0.27”
Yusef-Zadeh+ 2017
ALMA#2015.A.00021.S.

ALMA will become better astrometry tool for these stars than IR telescopes because the position of Sgr A* can be directly observed in millimeter and submillimeter.

From: ALMA and VLA observations of emission from the environment of Sgr A*
Mon Not R Astron Soc. 2017;470(4):4209-4221. doi:10.1093/mnras/stx1439

# 340-GHz Continuum Observation

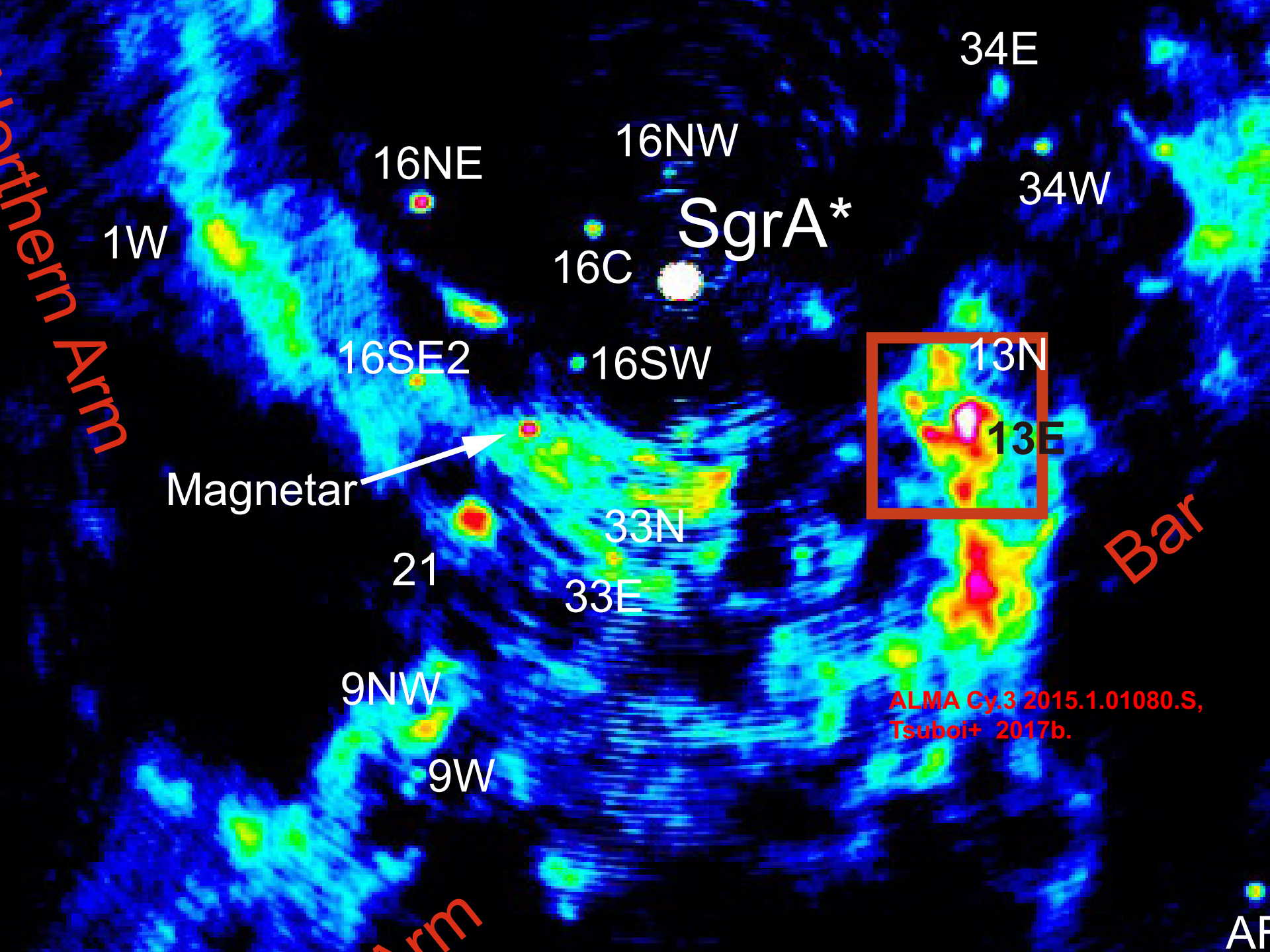


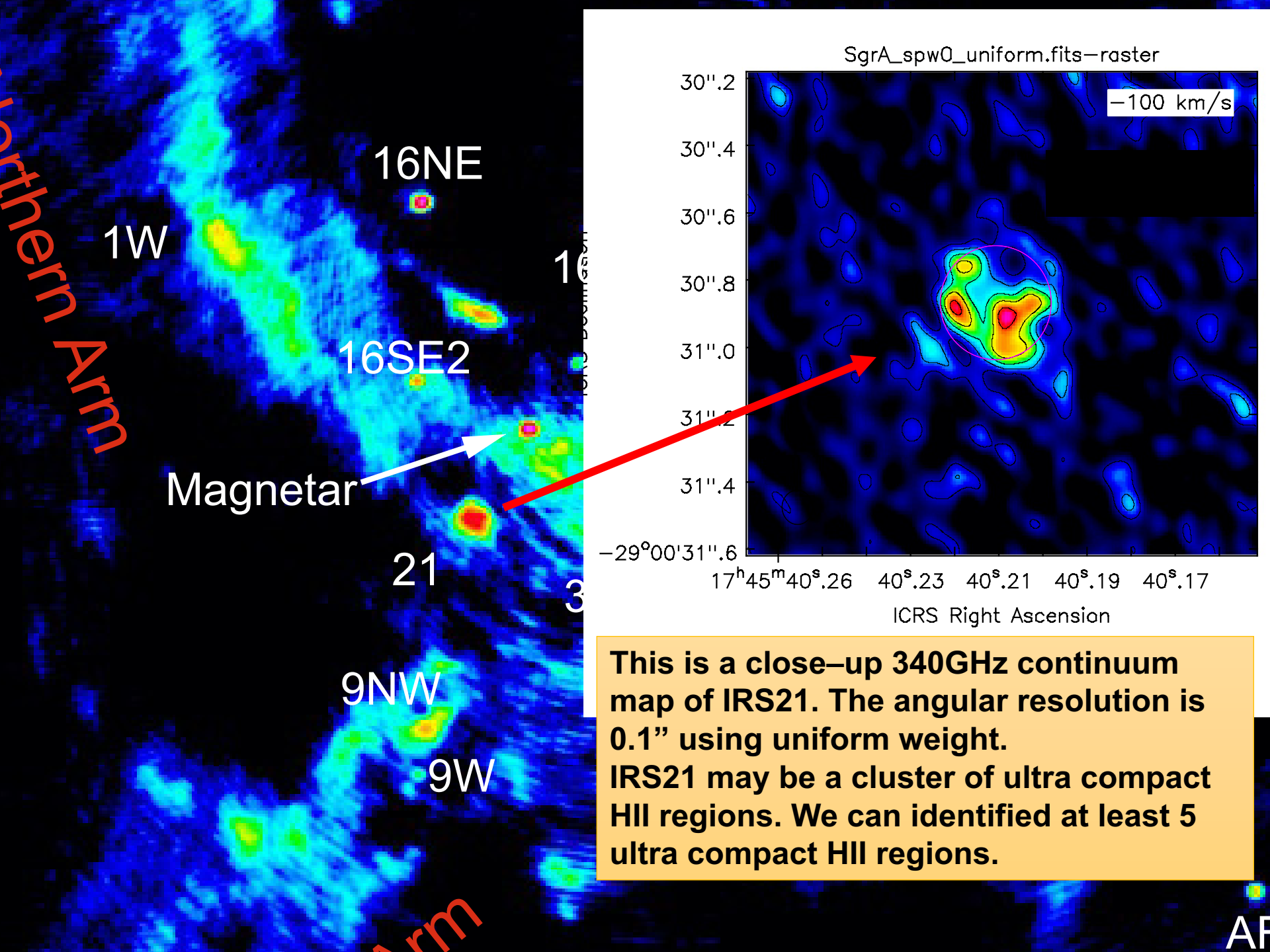

**Angular resolution of the figure is 0.14”x0.12” using natural weight, but 0.10”x0.09” using uniform weight.**

**Sgr A*, Galactic Center mini-spiral, and IRS13E objects are clearly detected in the figure.**

**The Galactic Center Magnetar, J1745-2900 is also detected (2016. Sep.).**

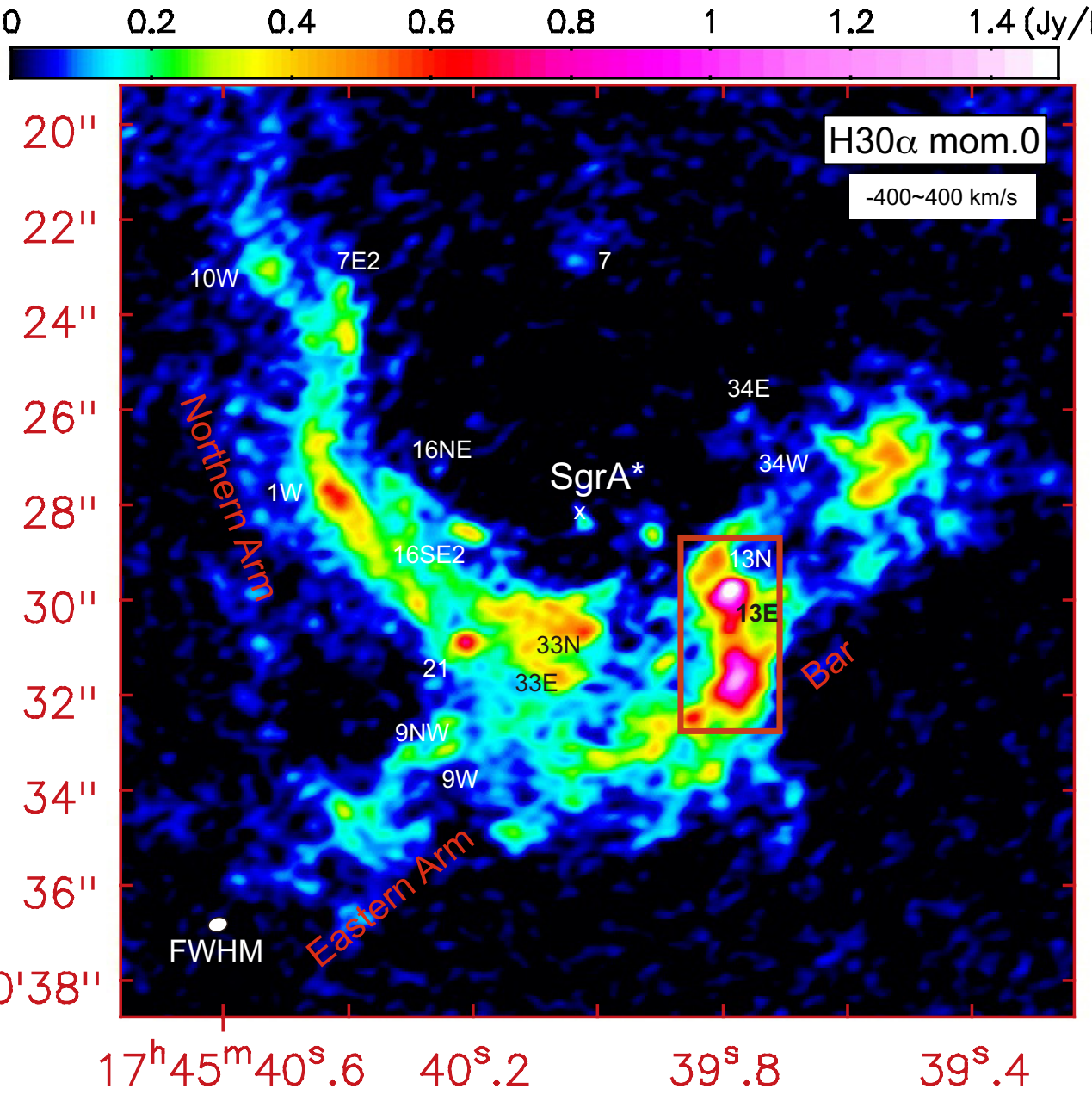
Tsuboi+2017b
APJL


34E
16NW
16NE
34W
SgrA*
1W
16C
16SE2
16SW
13N
13E
Magnetar
33N
21
33E
Bar
9NW
9W
ALMA Cy.3 2015.1.01080.S,
Tsuboi+ 2017b.




**This is a close–up 340GHz continuum map of IRS21. The angular resolution is 0.1” using uniform weight.**
**IRS21 may be a cluster of ultra compact HII regions. We can identified at least 5 ultra compact HII regions.**

# Integrated intensity map of Hydrogen H30a recombination line




H30a recombination integrated intensity (230GHz)
This is DDT data released in Sep. 2016.

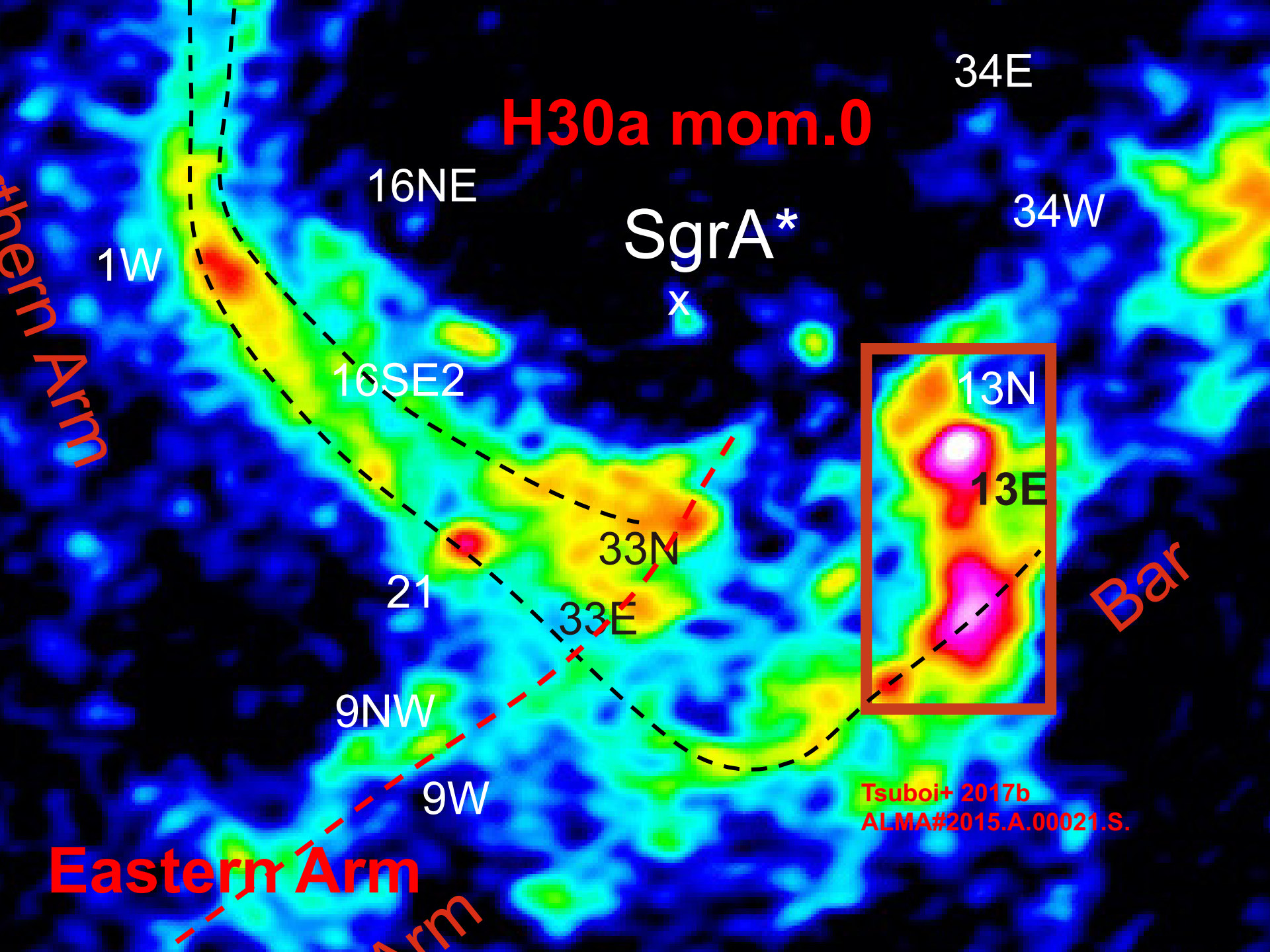
Beam size: 0.4”x0.3”
=0.016pcx0.012pc

Mini-spiral and IRS13E are clearly detected.

Several IR stars (WR stars) are detected. The ionized gas of IRS21 is also clearly detected.

Sgr A* itself is not detected.

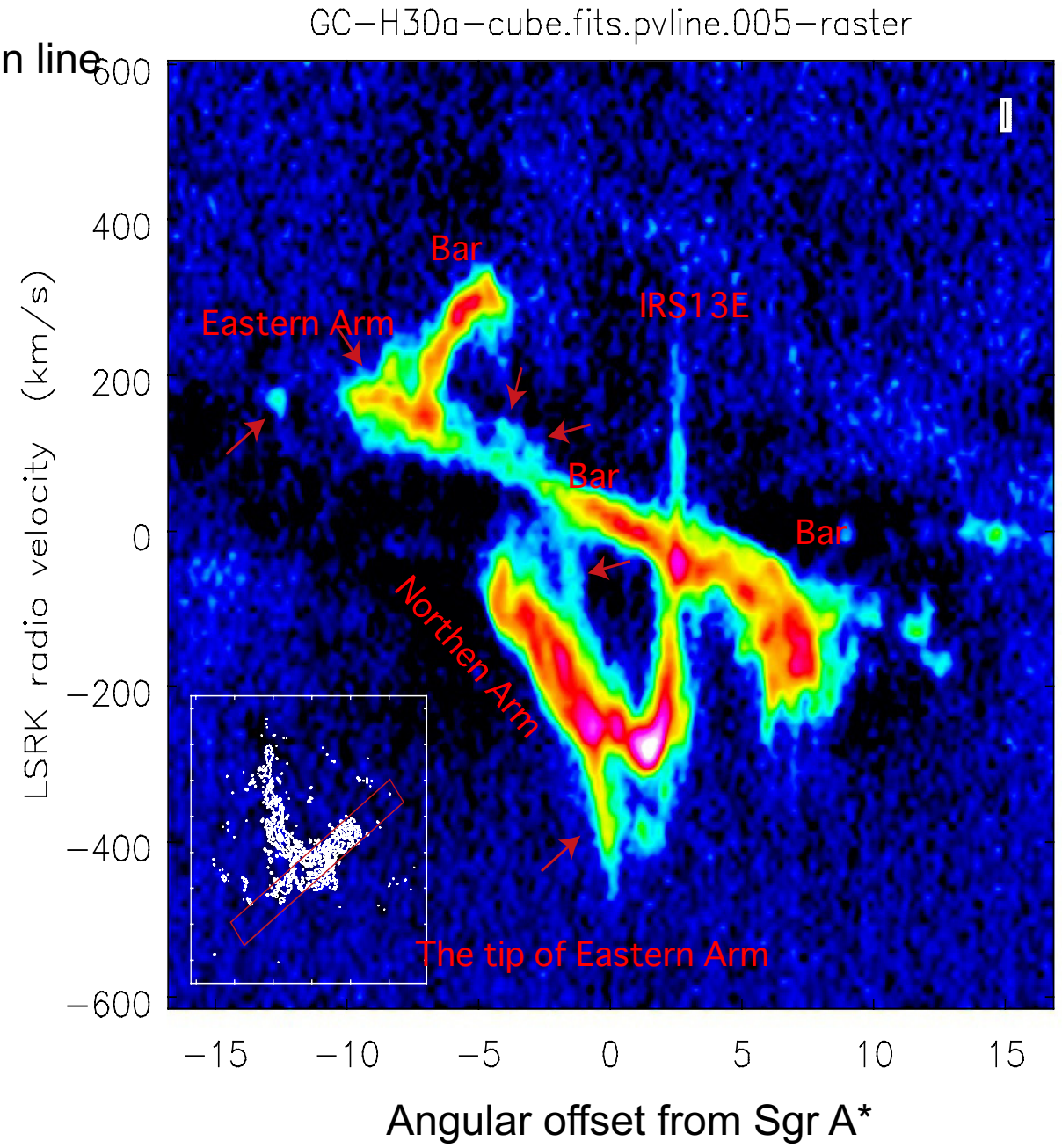
Tsuboi+2017b
APJL


H30a mom.0
34E
16NE
SgrA*
34W
1W
x
16SE2
13N
13E
33N
21
33E
Bar
9NW
9W
Tsuboi+ 2017b
ALMA#2015.A.00021.S.
Eastern Arm

H30a recombination line

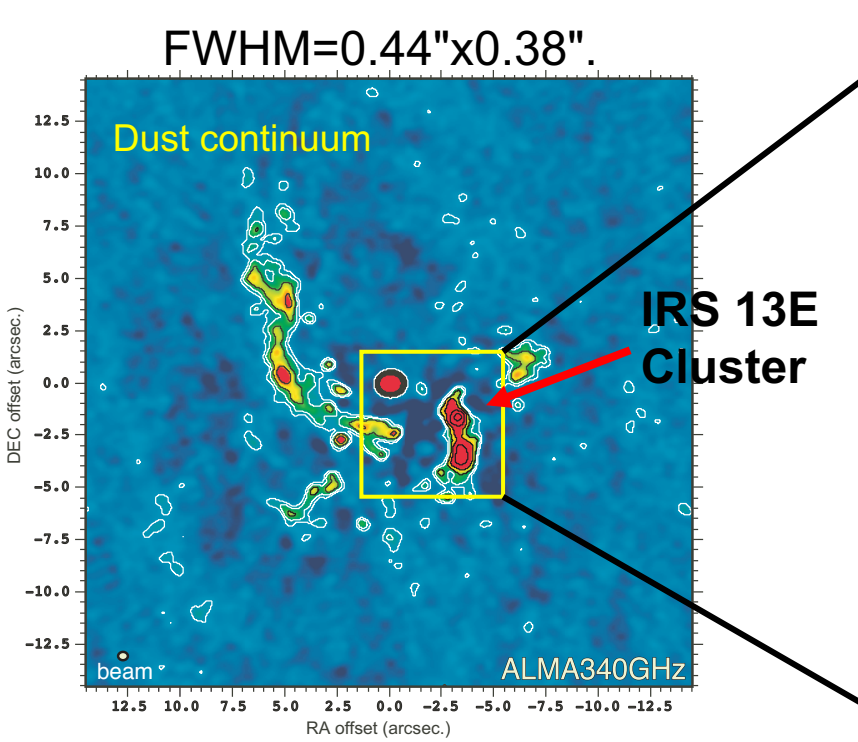
Angular res.~0.4”

Tsuboi + in prep.

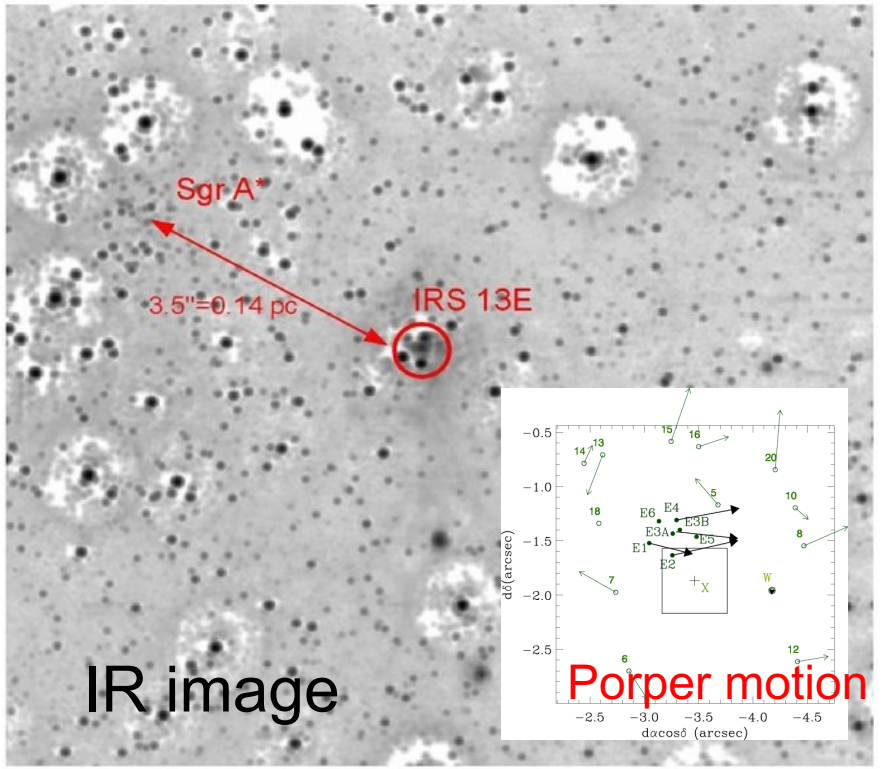


CONTENTS

- Introduction
- ALMA View of the CND
- ALMA View of the Minispiral
- Miscellaneous




**IRS 13E Cluster**




(Tsuboi+ PASJ 2016)

## IRS 13E Cluster

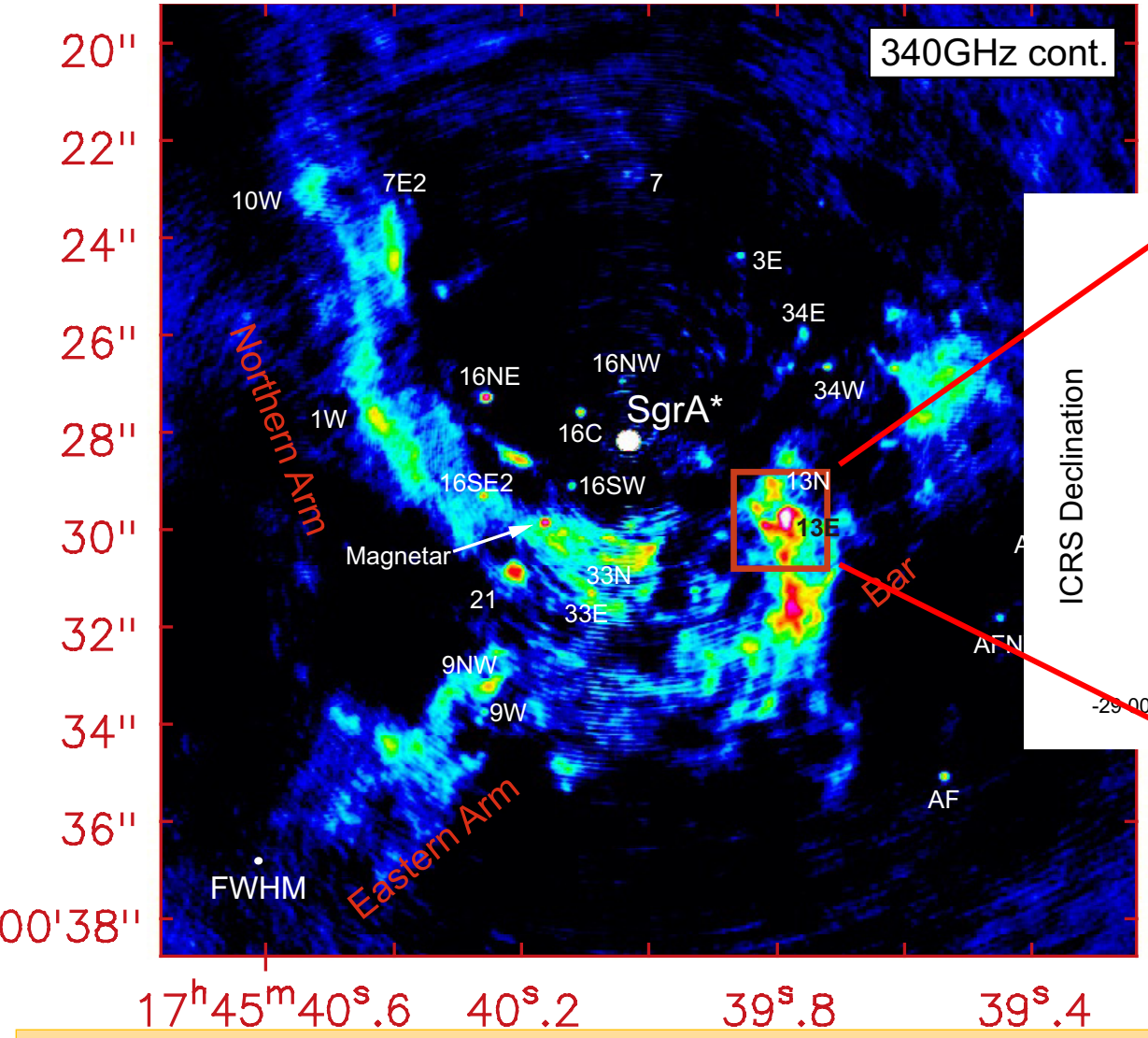
The IRS 13E cluster is a very intriguing IR object identified within 0.2 pc from the Sgr A*, which was found in the early days of the Galactic Center observation.

The complex contains several (at least three) massive stars in a diameter of about 0.5”.

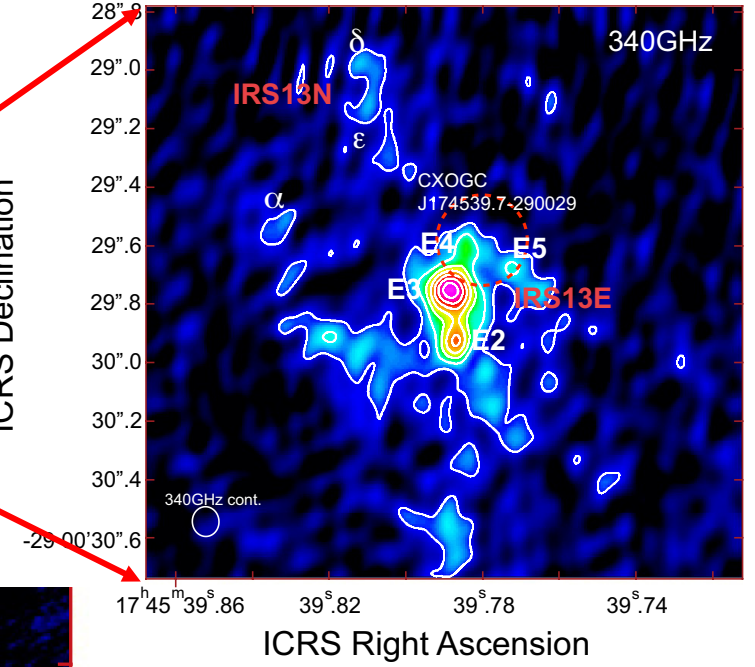
The common direction and similar amplitude of these proper motions suggest that the main members of the cluster are physically bound although the strong tidal force of Sgr A* should disrupt the cluster.

One of the possible speculation is that a dark mass like IMBH in the cluster may prevent the cluster disruption.

# 340-GHz Continuum Observation

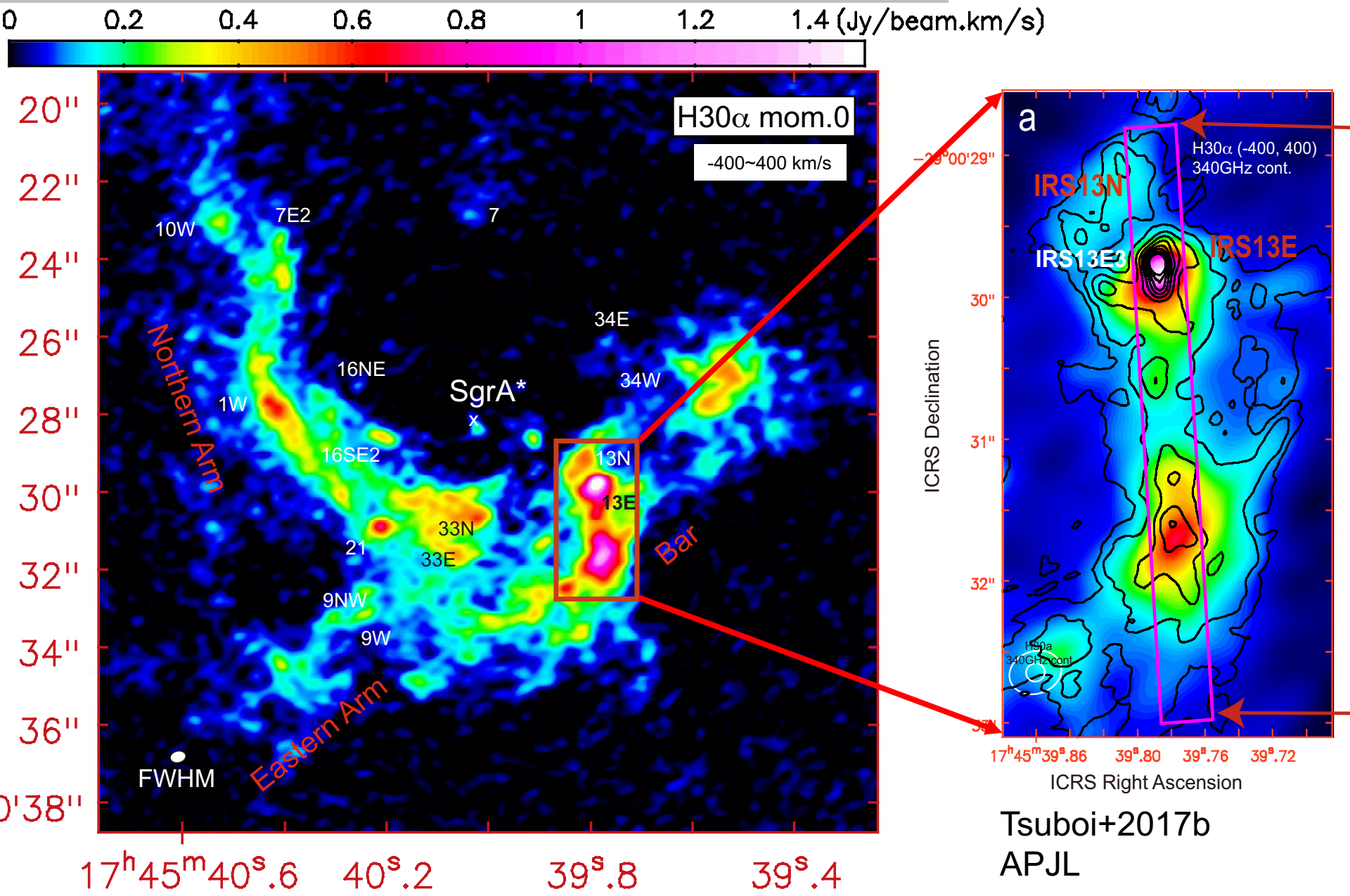



Tsuboi+2017b
APJL



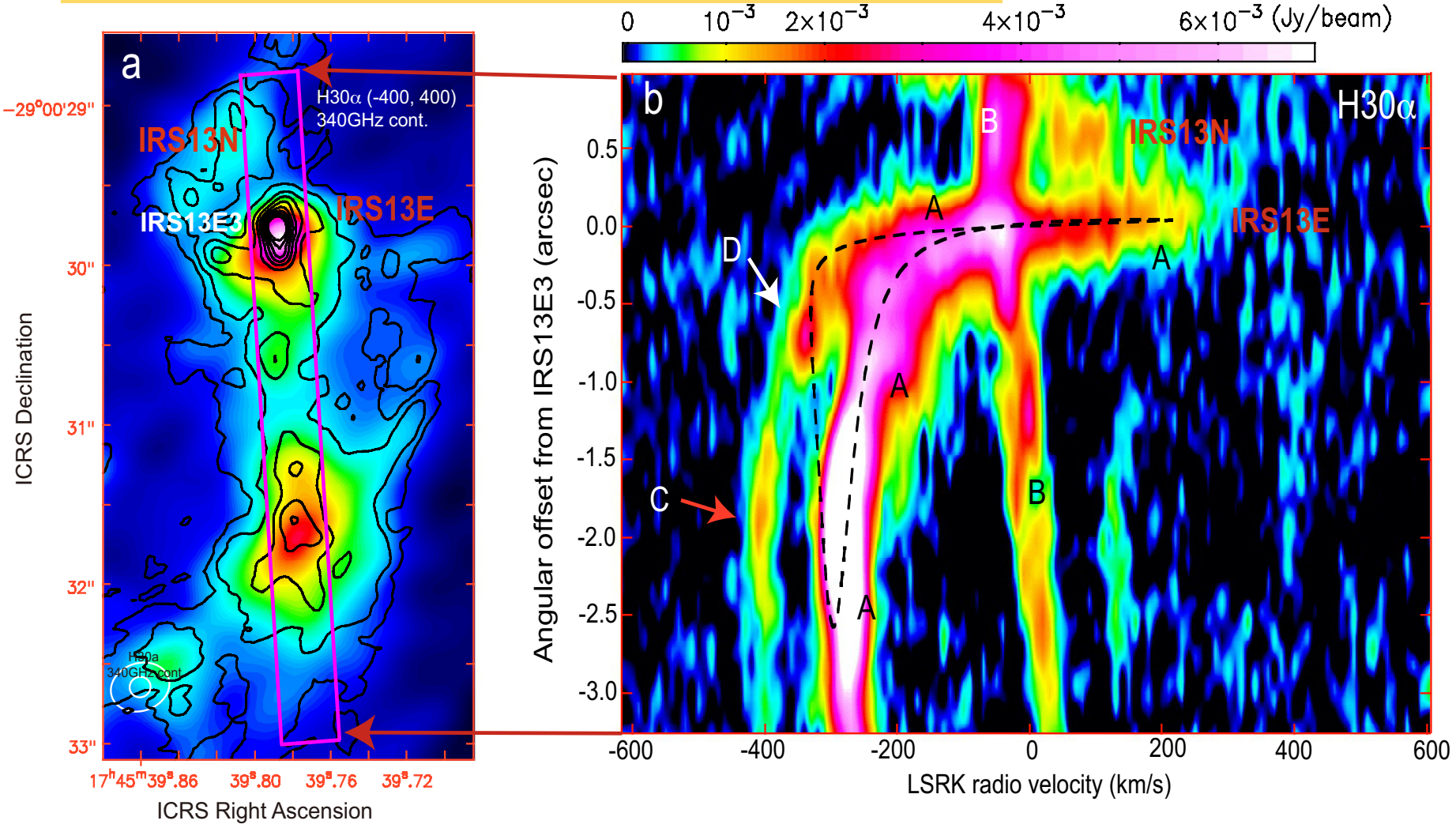

IRS13E3: deconvolved size
major axis FWHM: 101.7 +/- 7.6 marcsec (=0.0040pc=800AU)
minor axis FWHM: 90.4 +/- 7.6 marcsec (=0.0036pc=720AU)
Flux ---Integrated: 10.81 +/- 0.45 mJy, Peak: 5.42 +/- 0.16 mJy/beam

# Integrated intensity map of Hydrogen H30a recombination line




Tsuboi+2017b
APJL

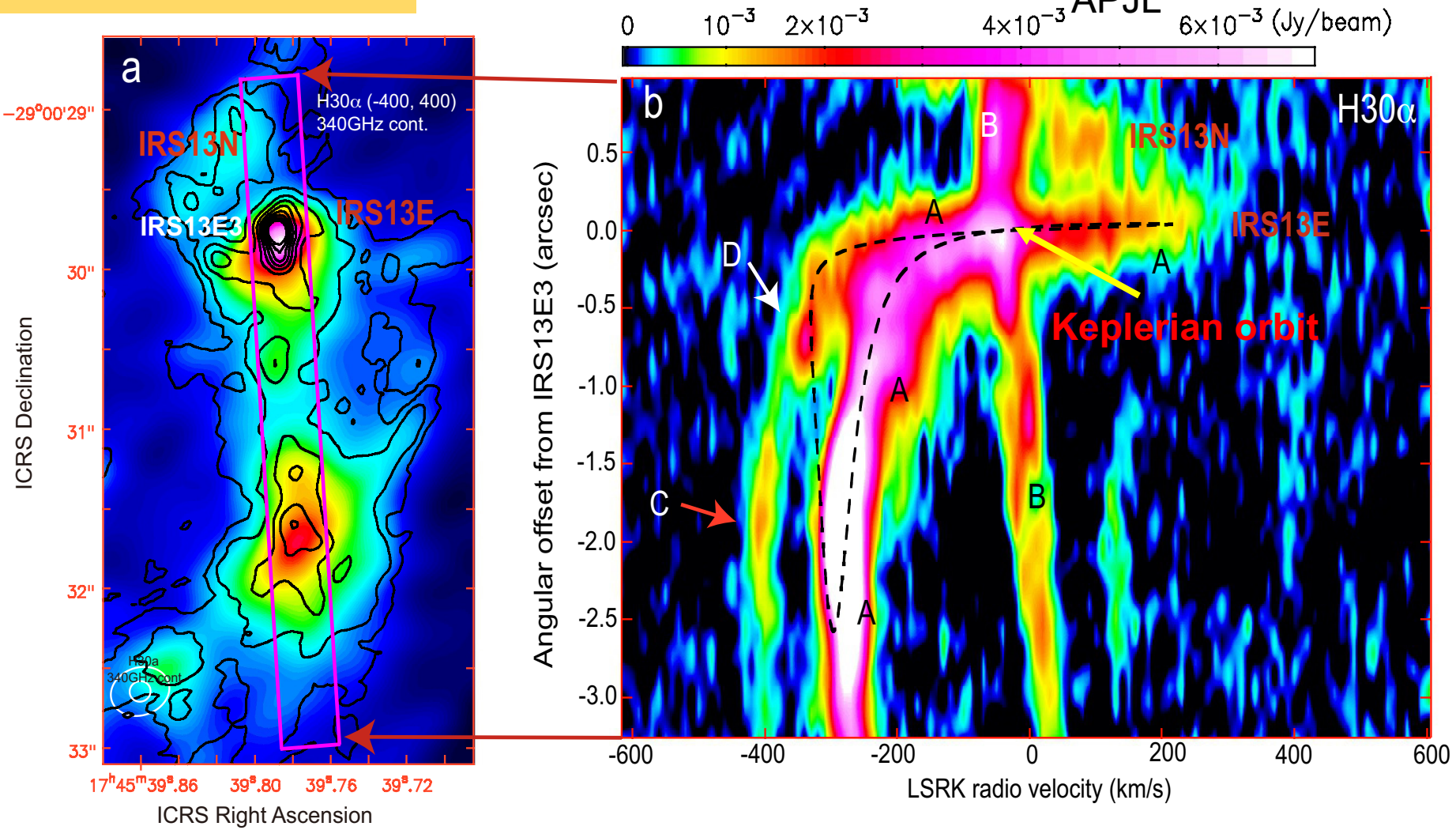
# Position–velocity diagram of H30a recombination line




**The velocity width toward IRS13E3 is very large, up to 500 km/s. IRS 13E3 is connected to the southern extended component by a curved ridge. What is this?**

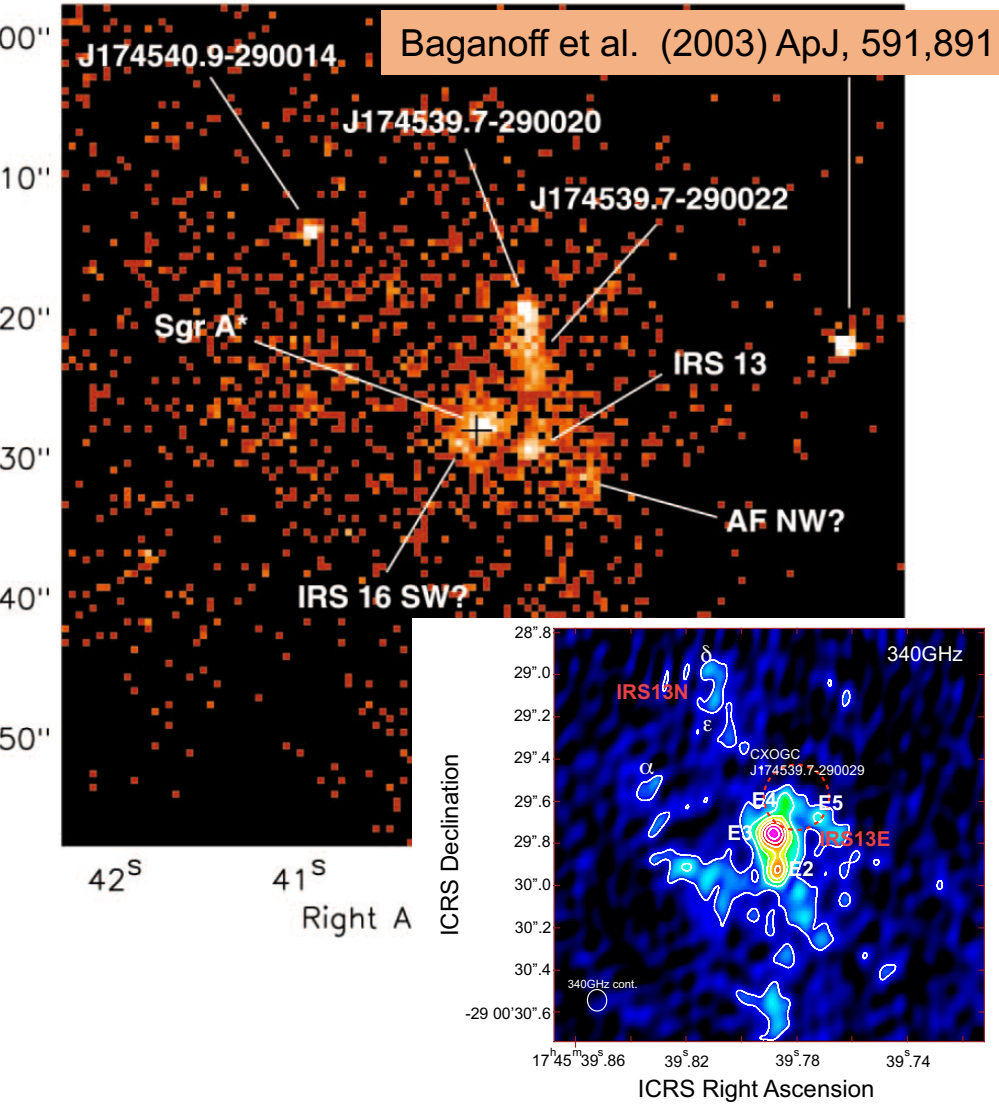
# What is this?

Tsuboi+2017b
APJL




The ionized gas can be described by a Keplerian Orbit (broken curve). Semi-major axis; a~1.5x$10^{17}$ cm, eccentricity; e~0.97, viewing angle; PA~60d and $M_{IRS13E}$~6x$10^4$ Mo. Tsuboi+ APJL 2017

# X-ray Counterpart?




**This object is probably an IMBH with $10^4$Mo.**

(1)The peak position of the integrated H30α emission line:

α=17h45m39.786s, δ=-29d00'29.883"
(position error :0.02")

(2)The peak position of the X-ray continuum emission (CXOJ174539.7-290029; 0.5-7 keV):

α=17h45m39.759s, δ=-29d00'29.85"
(position error :0.10")
(absolute accuracy: 0.76")
This corresponds to IRS13E3.

(3) The positional difference:
Δα =0.35", Δδ =0.03"

**However, this difference is as small as the positional accuracy of these. These positions are identical.**

**Probably Yes.**

(4) X-ray count rate
S=2.76+-0.30 x 10^-3 s^-1
This is about half of the X-ray count rate of Sgr A*.

IRS13E(~6x10^4Mo): Lum. ~10^35 erg/s

# Summary

As shown here, the Galactic Center has already observed by many observers with ALMA.

ALMA archive is full of good data to be analyzed. Some are essentially important for understanding the Galactic Center.

If you start the research on the Galactic Center by the archive, it is now!

Thank you for your attention.