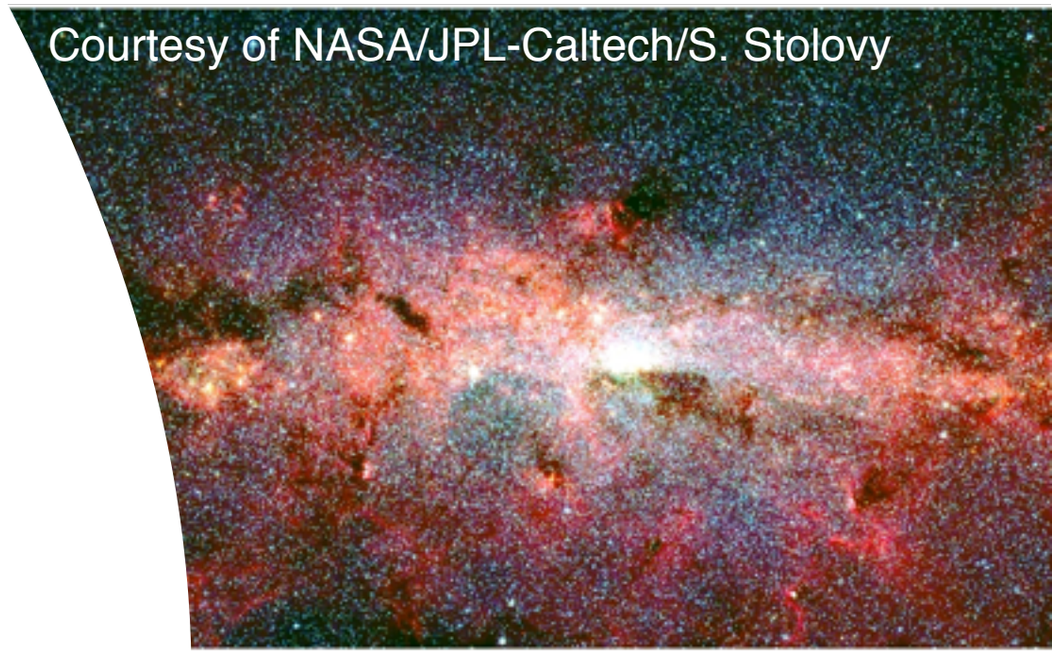
南京大学
NANJING UNIVERSITY

HARVARD-SMITHSONIAN
CENTER FOR ASTROPHYSICS

Deeply Embedded Incipient Star Formation in Massive Clouds in the Central Molecular Zone



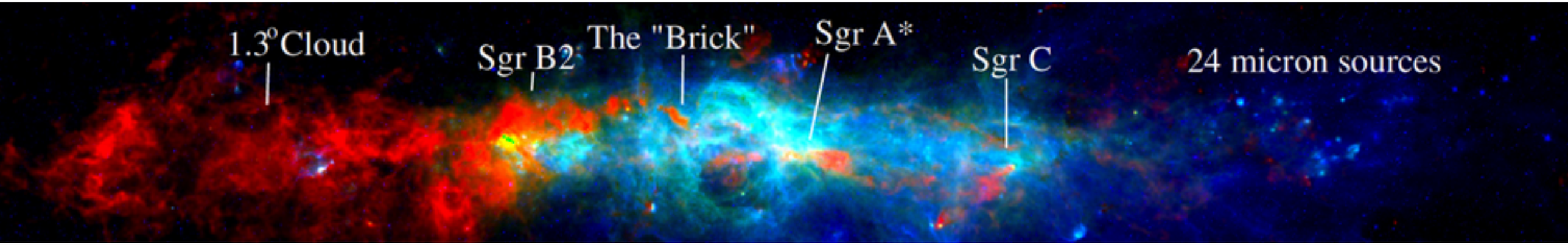
Xing “Walker” Lu (Nanjing Univ., CfA),
Qizhou Zhang (CfA), Jens Kauffmann (MPIfR), Thushara Pillai (MPIfR), Steve Longmore (LJMU), J. M. Diederik Kruijssen (ZAH), & Cara Battersby (CfA).

IAU Symposium 322, Palm Cove
July 19, 2016

Motivation: ‘missing’ star formation in the CMZ

The Central Molecular Zone (CMZ): inner ~500 pc of the Galaxy.

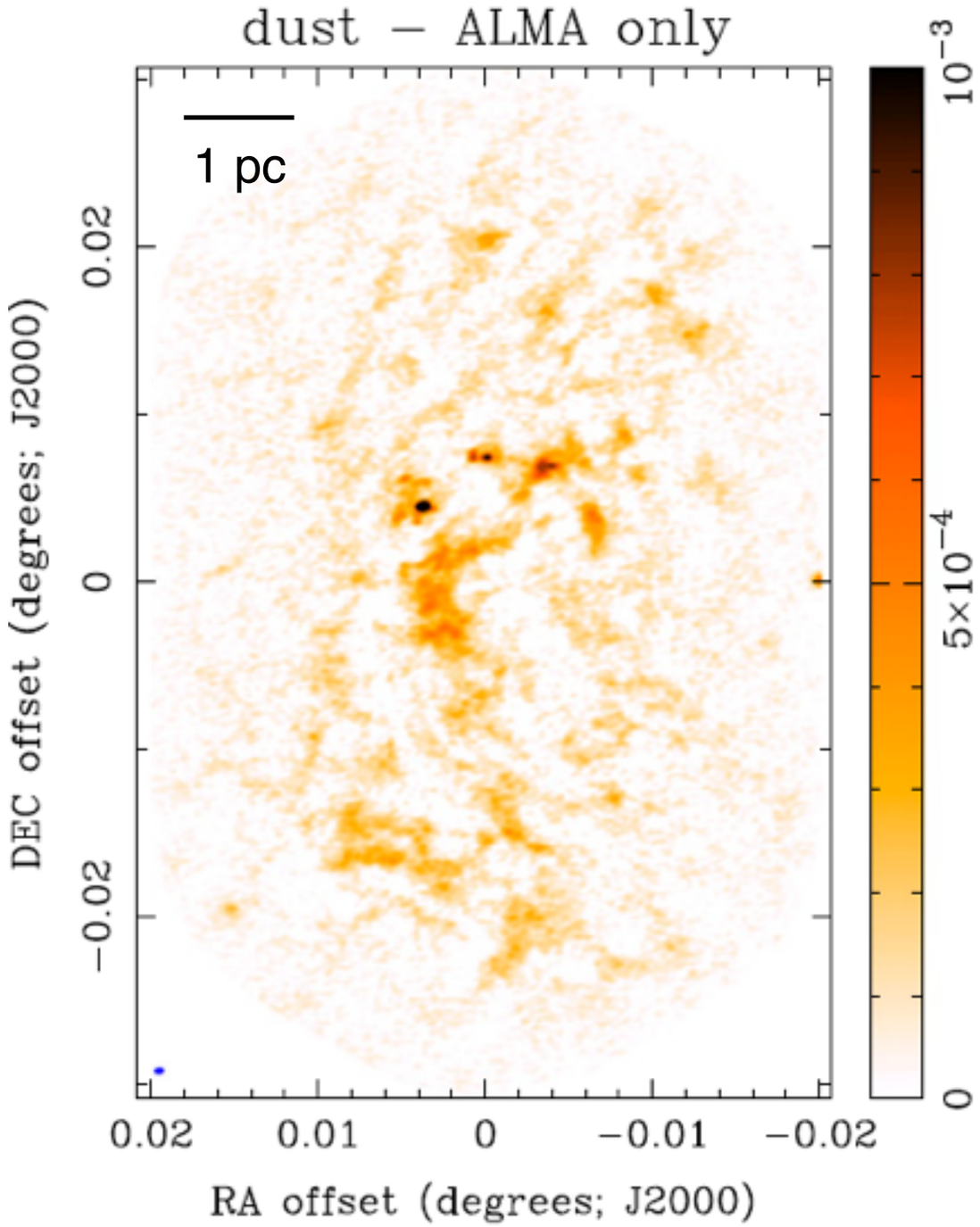
- A series of massive ($\gtrsim 10^5\ M_\odot$) molecular clouds: Sgr B2, G0.253+0.016, Sgr C, …
- Most clouds are quiescent in **current** star formation despite their huge dense gas reservoir. Extreme case is G0.253+0.016 (Longmore et al. 2012; Kauffmann et al. 2013; Johnston et al. 2014; Rathborne et al. 2015; Mills et al, 2015).
- Total SFR in the CMZ is an order of magnitude lower than expected (Longmore et al. 2013).



From the SMA CMZoom website, https://www.cfa.harvard.edu/sma/LargeScale/CMZ/

Motivation: ‘missing’ star formation in the CMZ

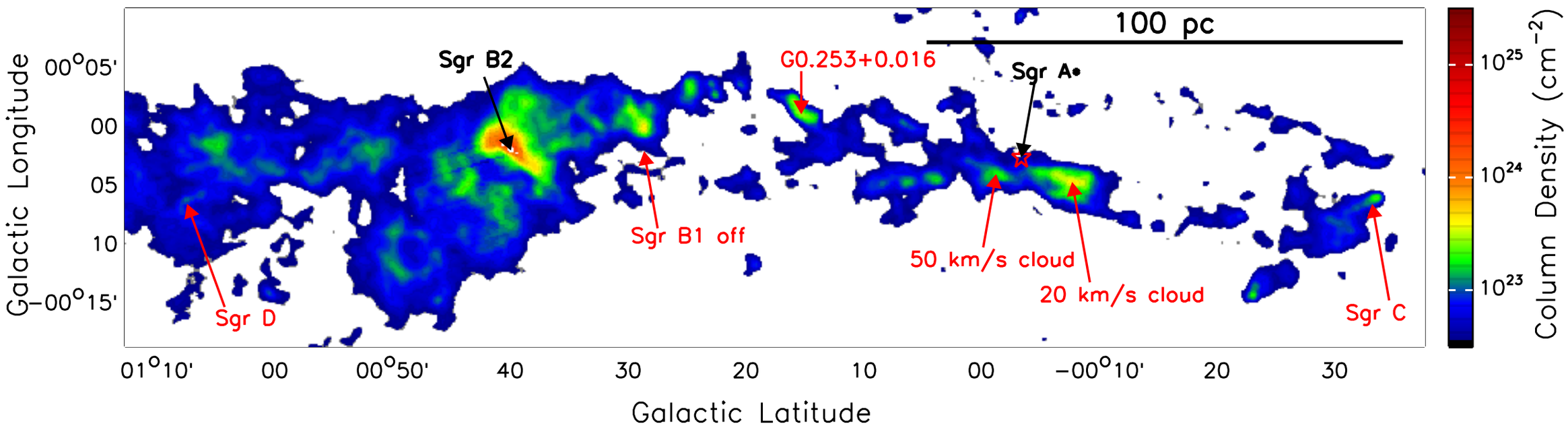
- G0.253+0.016:
  - Sole SF site: One weak H_2O maser in one dense core (Lis et al. 1994; Kauffmann et al. 2013; Johnstone et al. 2014; Rathborne et al. 2015; Mills et al.2015).
  - Low SF due to strong turbulence that inhibits gas collapse? (Kruijssen et al. 2014; Rathborne et al. 2015)
- Questions:
  - Do other massive clouds in the CMZ have similar internal structures (a lack of dense cores)?
  - If they instead present more dense cores, how is their SF?



ALMA dust emission of G0.253+0.016 (Rathborne et al. 2015)

Search for dense cores and masers

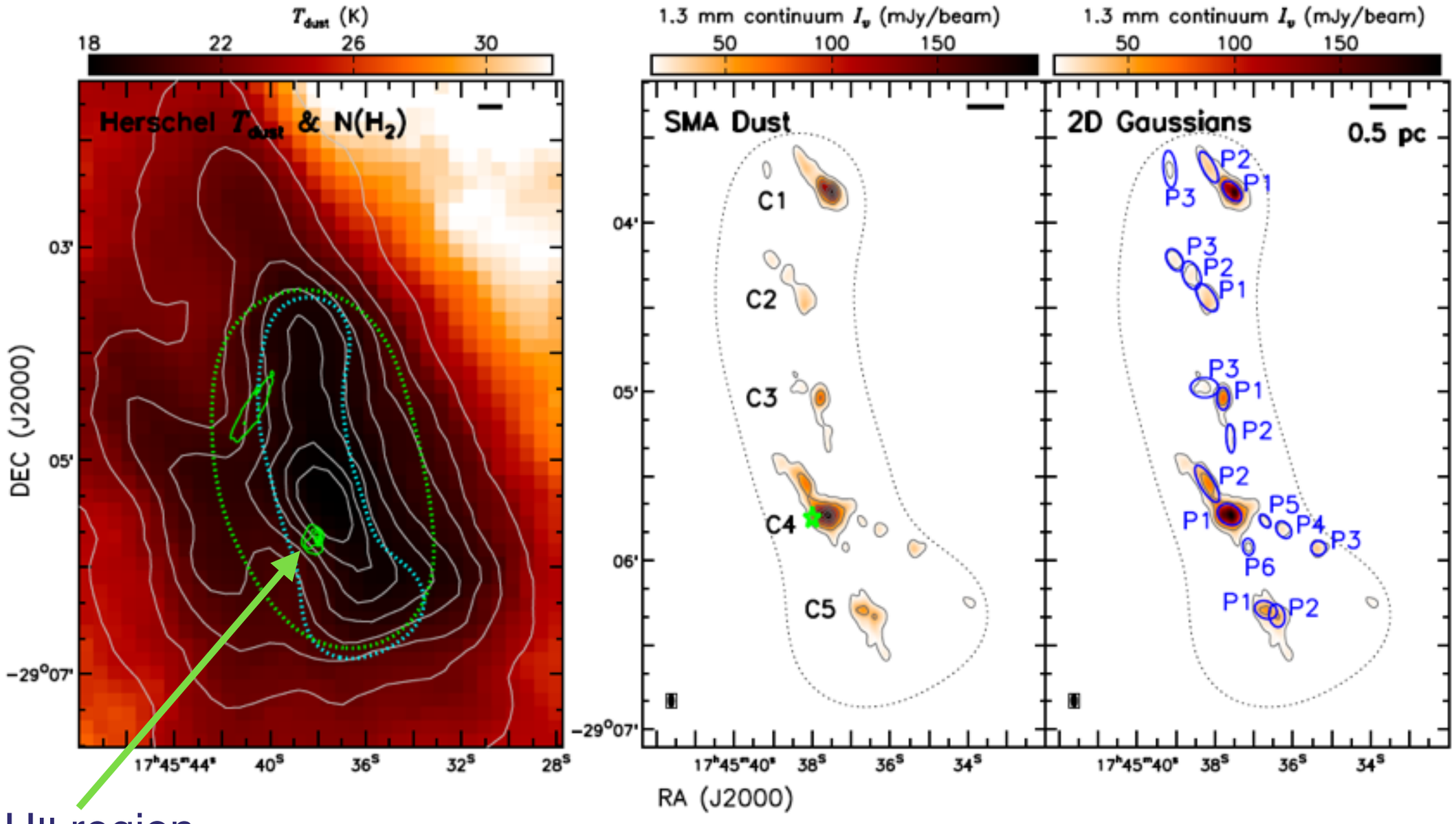
- Targets:
  - 6 massive clouds ($\gtrsim 10^{23}$ cm^{-2}, $\gtrsim 10^5$ $M_\odot$) in the CMZ.
- Observations:
  - SMA compact/subcompact, 1.3 mm continuum (3 mJy@4" beam) and lines (CH_3CN, H_2CO, CH_3OH, SiO, …);
  - JVLA DnC, NH_3 (1,1)-(5,5), H_2O maser (6 mJy@3" beam&0.2 km/s), 1.3 cm continuum (30 μJy@3" beam).
- Objective:
  - Search for dense cores and H_2O masers.



Search for dense cores and masers

Outstanding case — the 20 km s^{-1} cloud (Lu et al. 2015, ApJL, 814, 18)

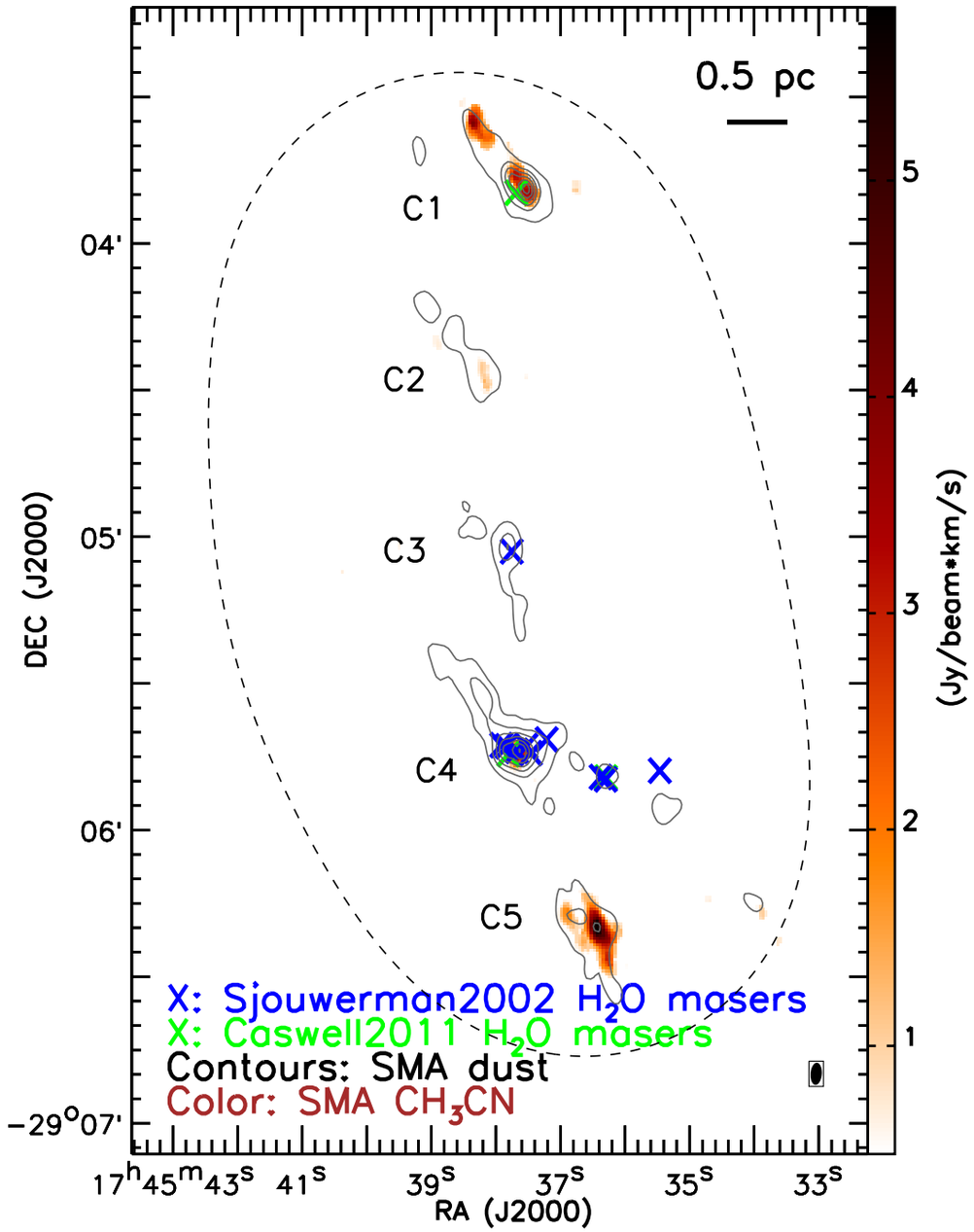
- 12 (gravitationally bound) dense cores.



HII region

Search for dense cores and masers

20 km s^{-1} cloud

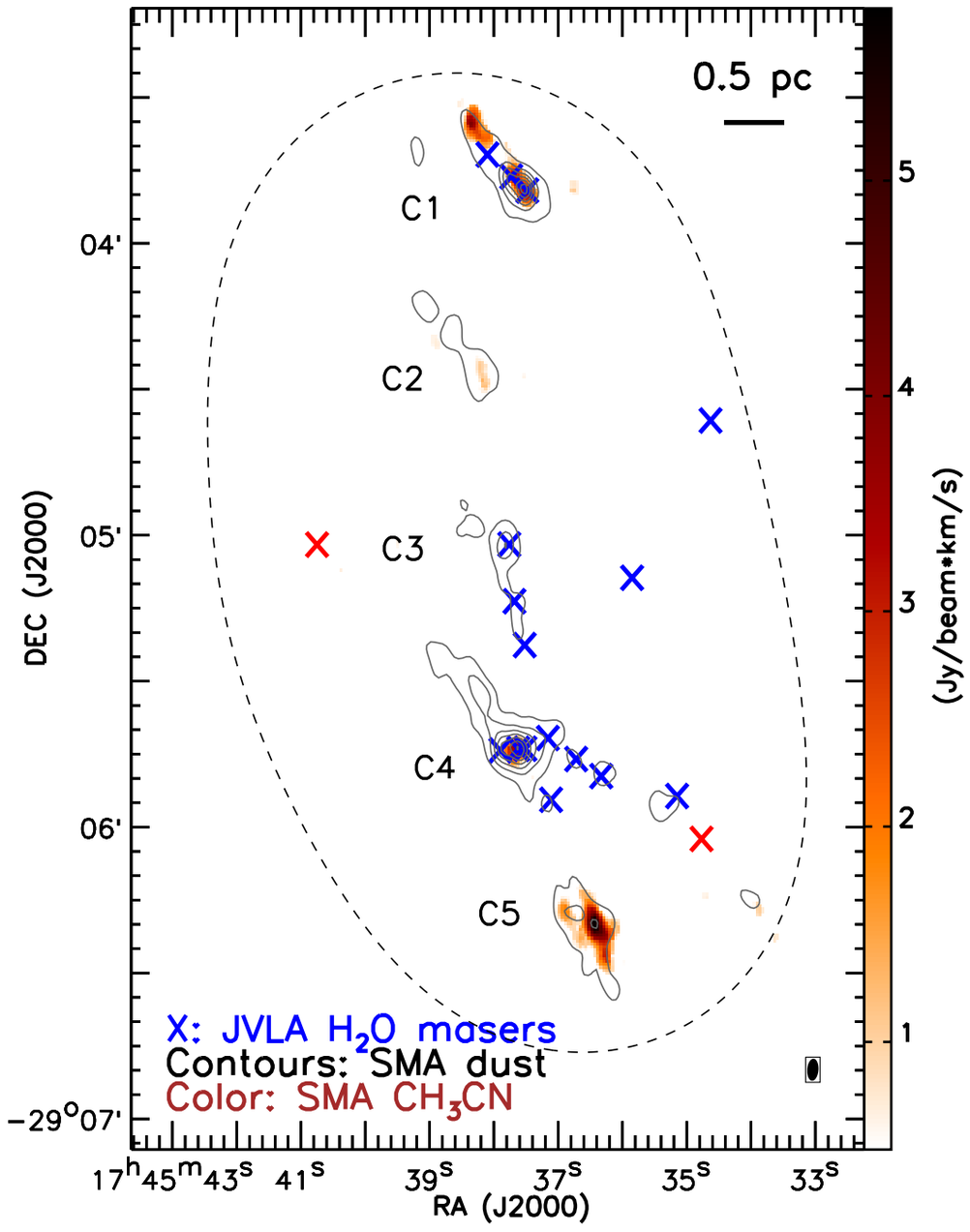


What we knew:

- 11 known H_2O masers, mostly concentrated in C4 (Sjouwerman et al. 2002; Caswell et al. 2011).

Search for dense cores and masers

20 km s^{-1} cloud

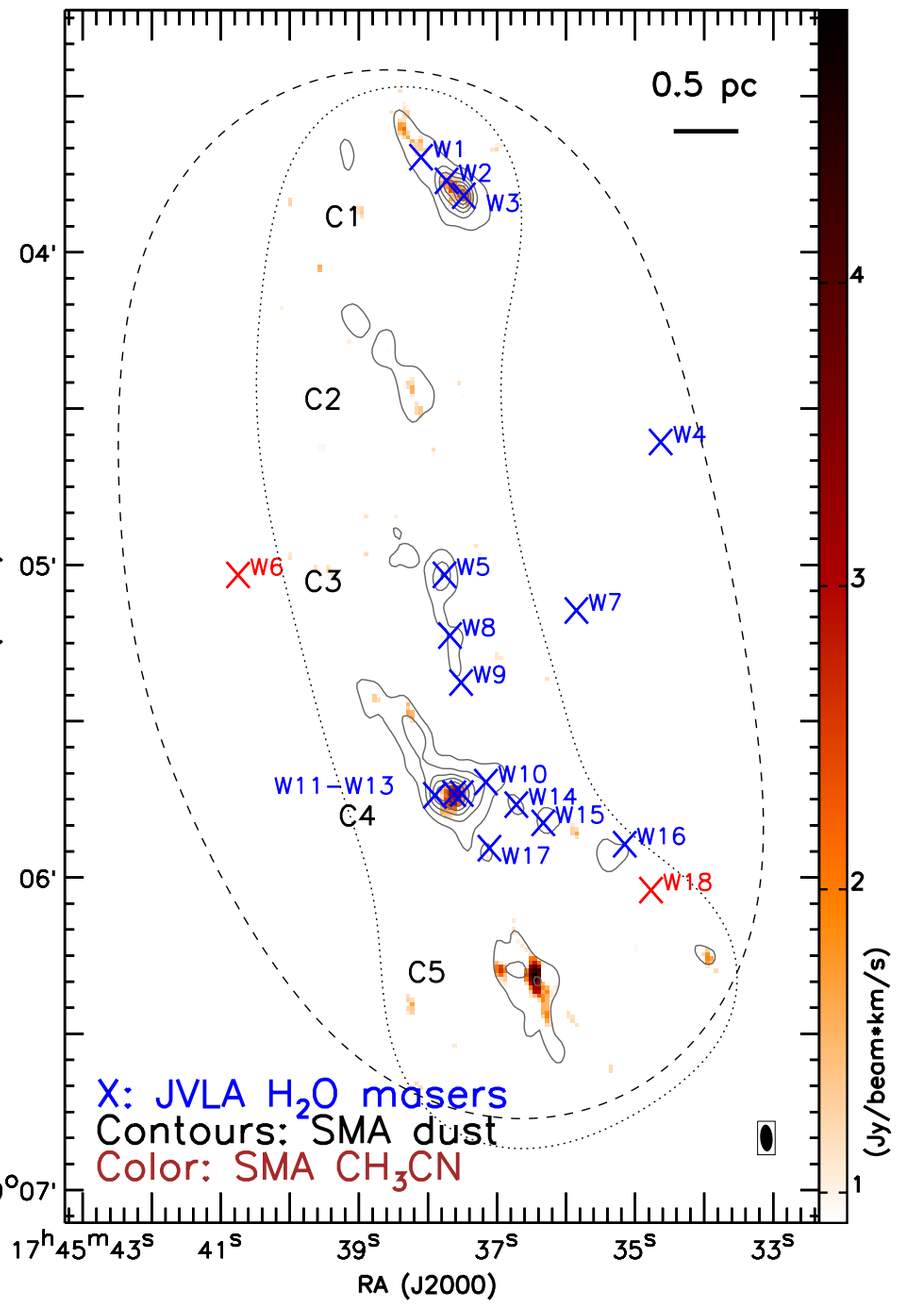


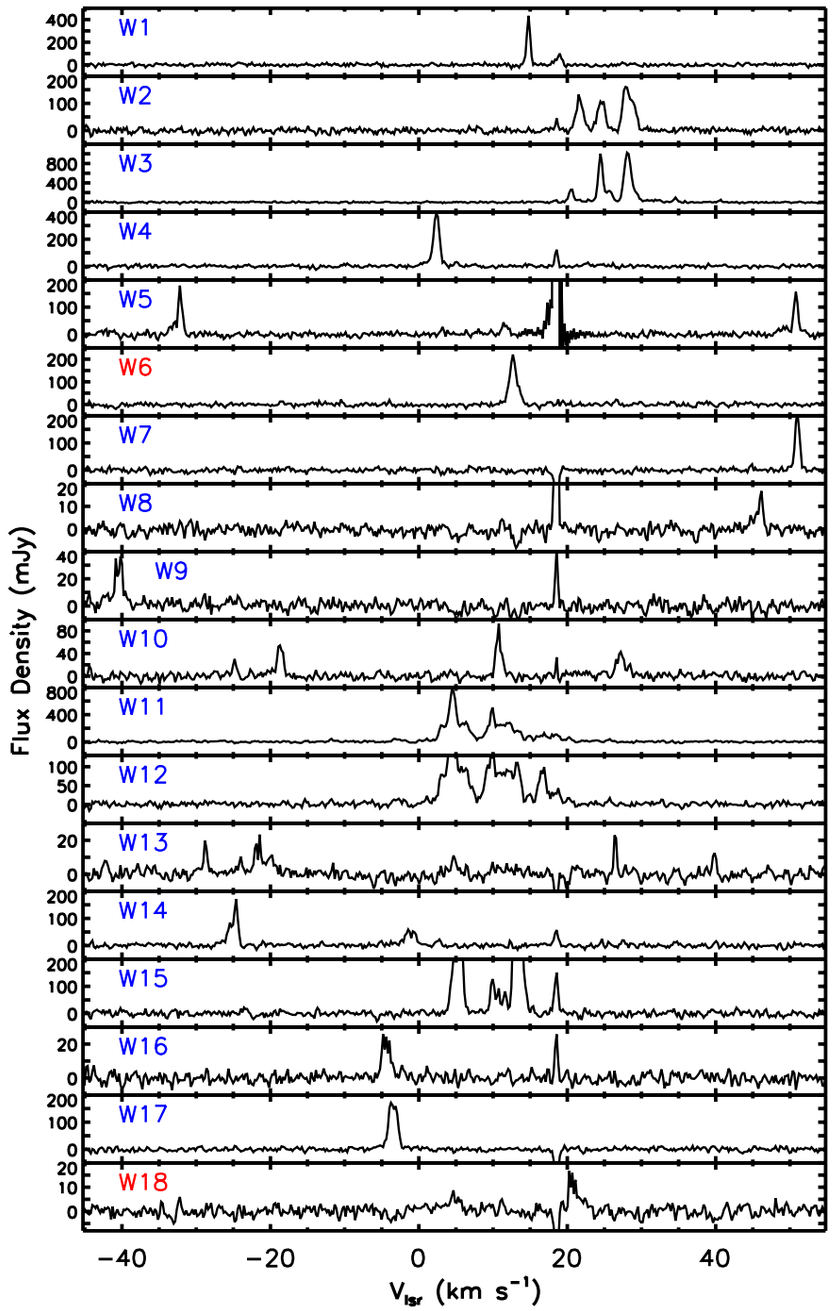
What we find:

- 18 H_2O masers (Lu et al. 2015).
- Tight spatial correlation between dense cores and masers.

Search for dense cores and masers

20 km s^{-1} cloud

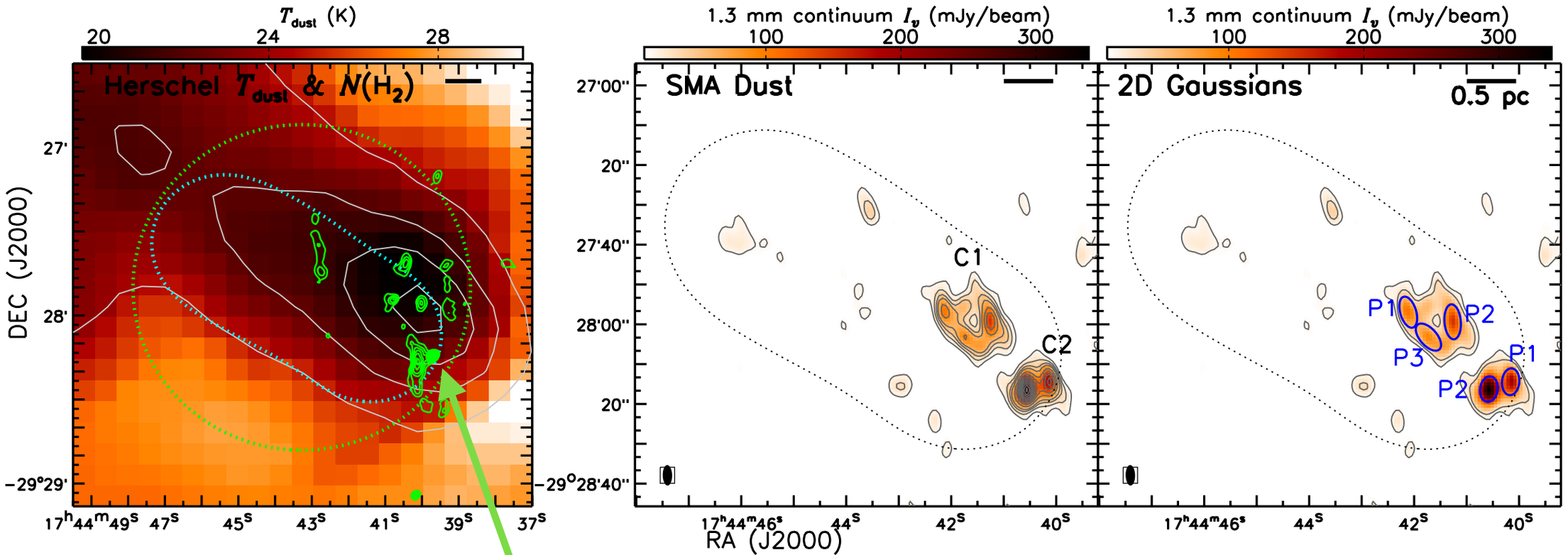




Search for dense cores and masers

Outstanding case — Sgr C (Lu et al. in prep.)

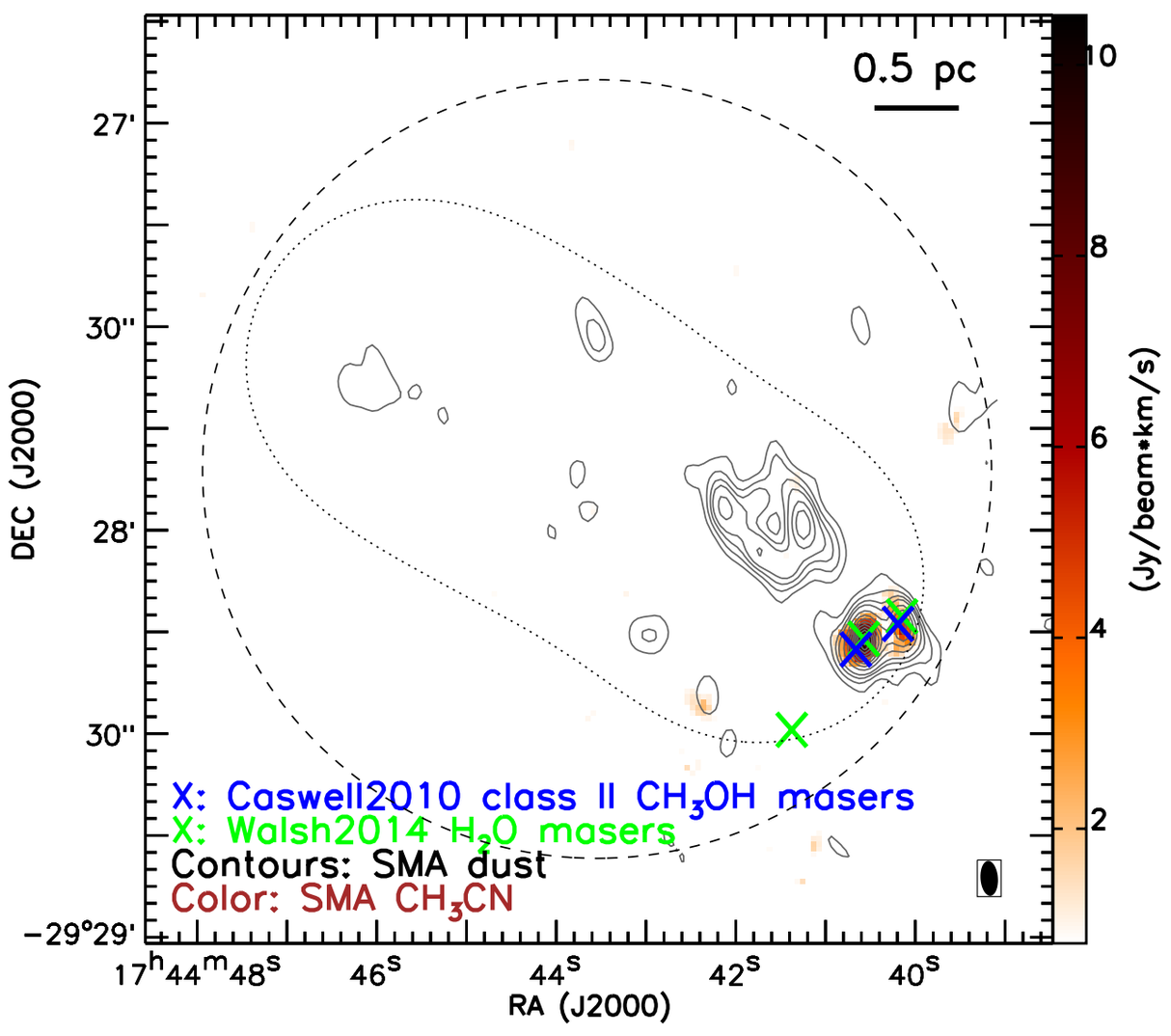
- At least 8 (gravitationally bound) dense cores.



HII regions?

Search for dense cores and masers

Sgr C

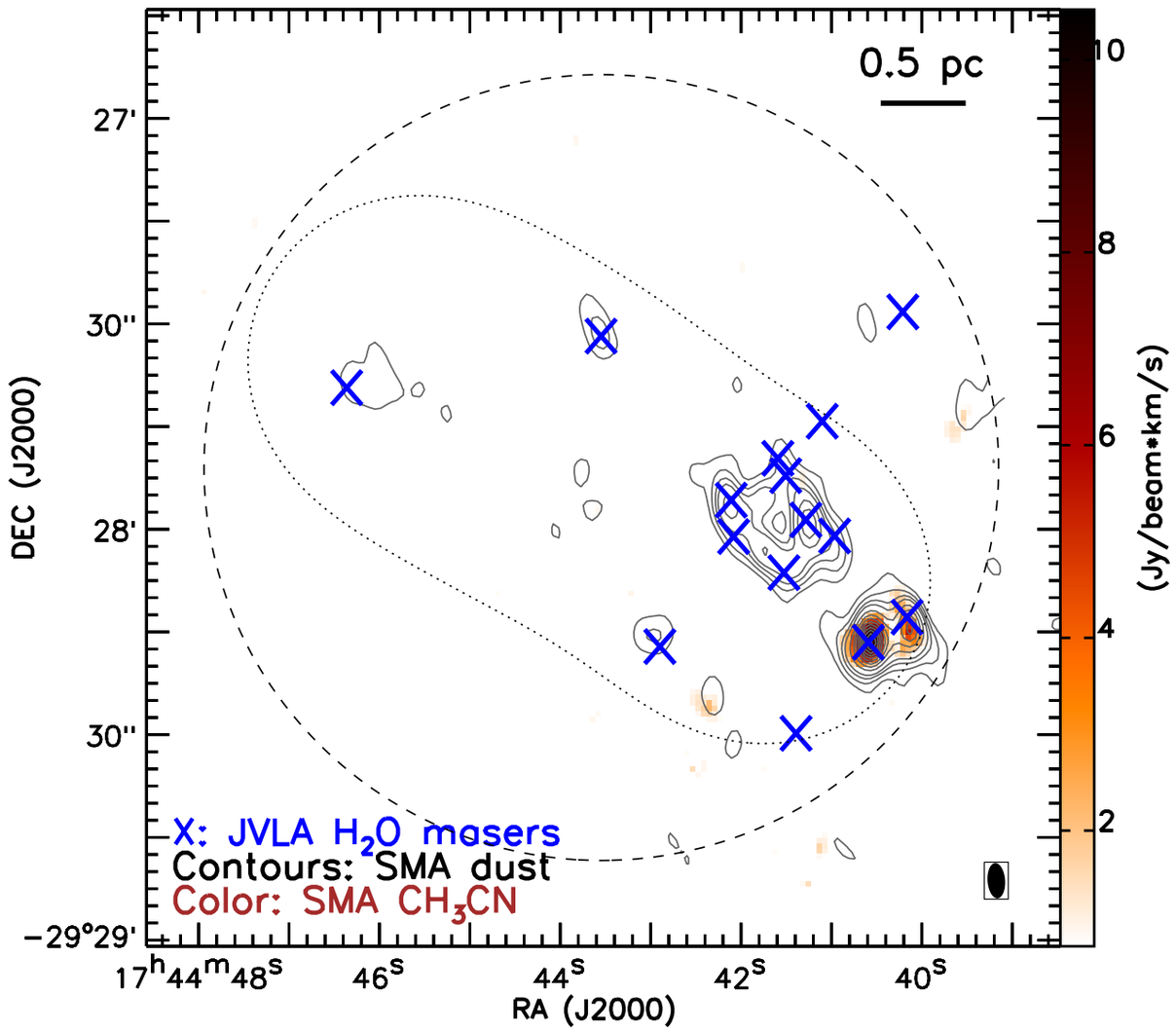


What we knew:

- 2 class II CH_3OH masers and 4 H_2O masers (Caswell et al. 2010; Walsh et al. 2014).
- Two protostellar cores (Kendrew et al. 2013).

Search for dense cores and masers

Sgr C

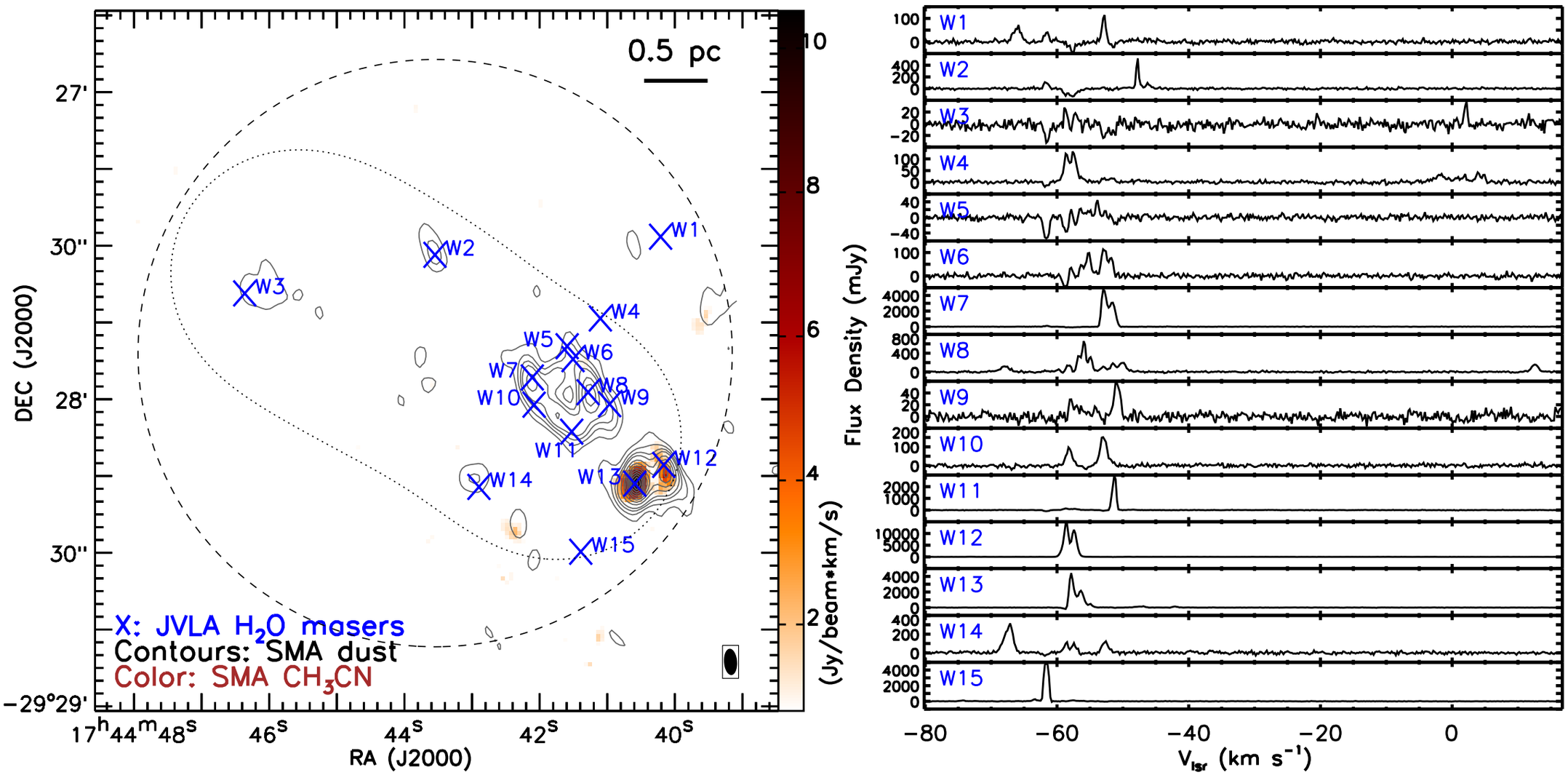


What we find:

- 15 H_2O masers (Lu et al. in prep.).
- Tight spatial correlation between dense cores and masers.

Search for dense cores and masers

Sgr C



Hidden star formation exposed

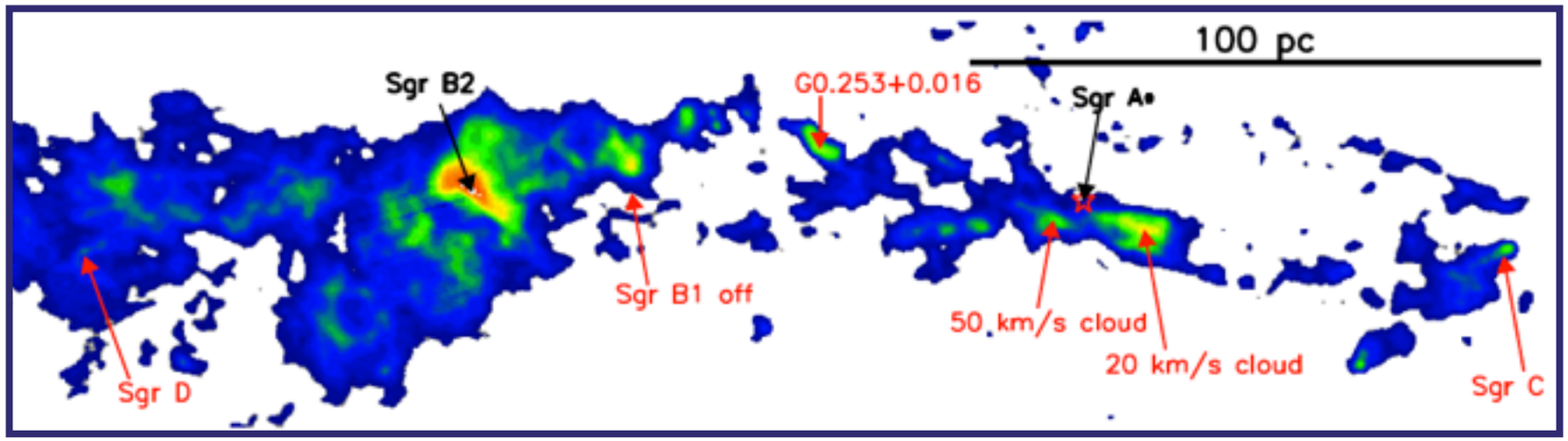
Do they trace star formation
(instead of large-scale shocks, cosmic ray, evolved stars, …)?

Hidden star formation exposed

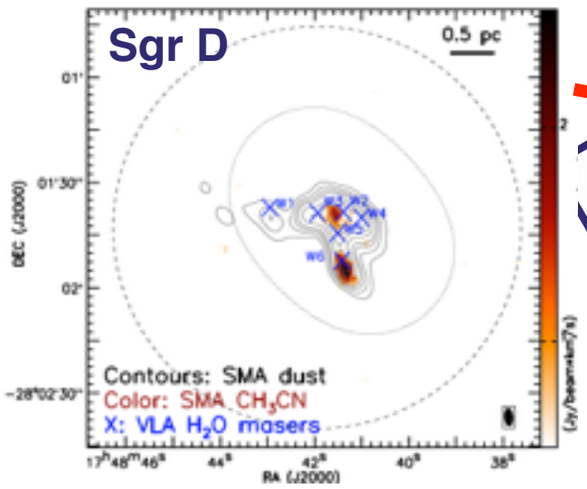
Do they trace star formation
(instead of large-scale shocks, cosmic ray, evolved stars, …)?

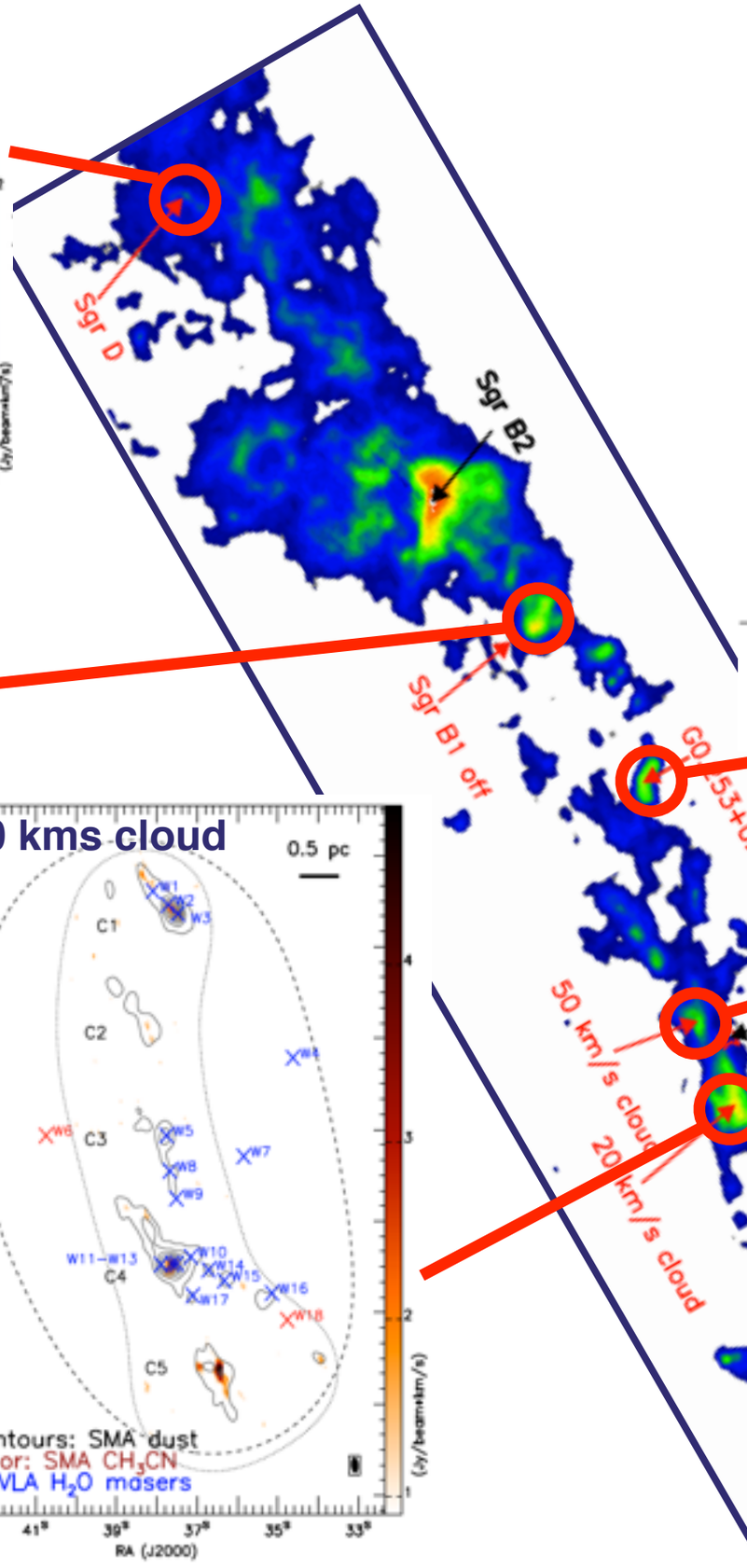
- Tight spatial correlation between dense cores and H_2O masers.
- Velocities of H_2O masers are scattered, rather than concentrated at the ‘shock velocity’.
- Detected H_2O masers do not behave like class I CH_3OH masers that likely trace shocks or cosmic rays (Yusef-Zadeh et al. 2013; Mills et al. 2015).
- Water masers could trace evolved stars (Sjouwerman & van Langevelde 1996). We have ruled out those with known evolved star counterparts.

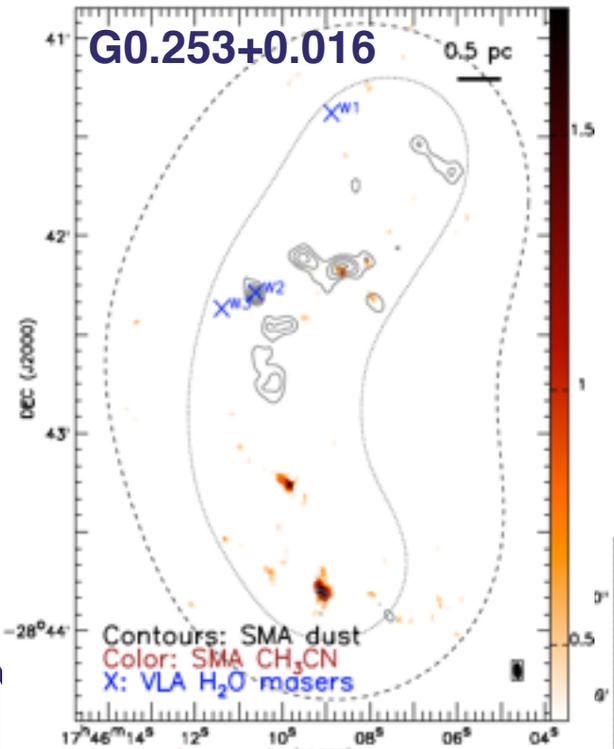
Hidden star formation exposed

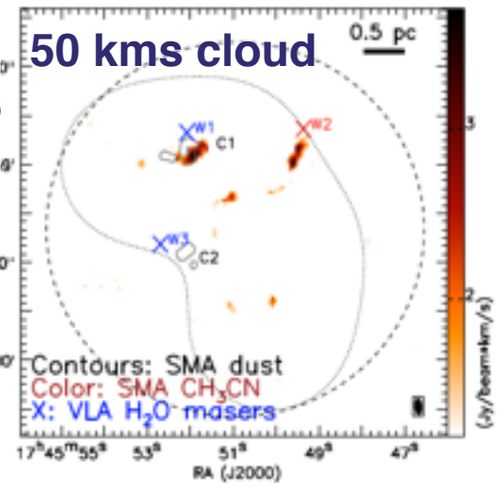


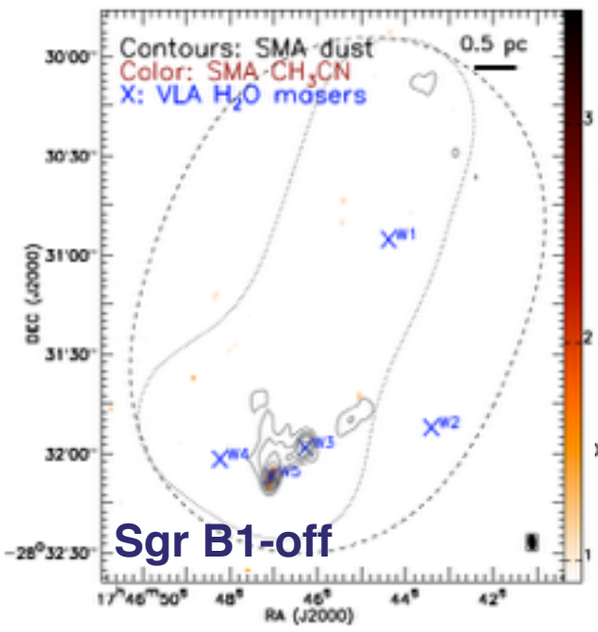
Hidden star formation exposed

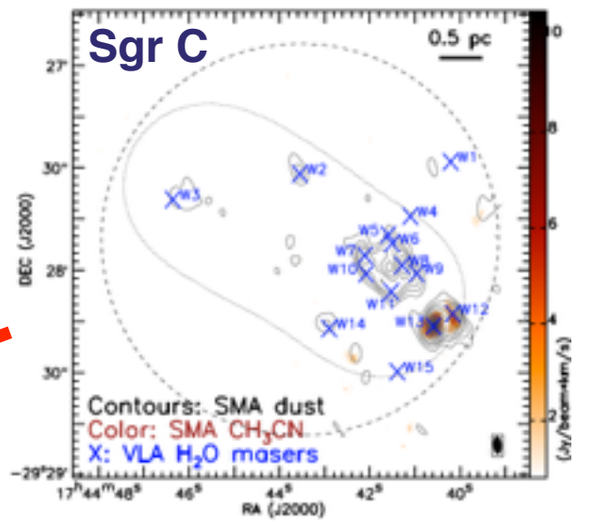






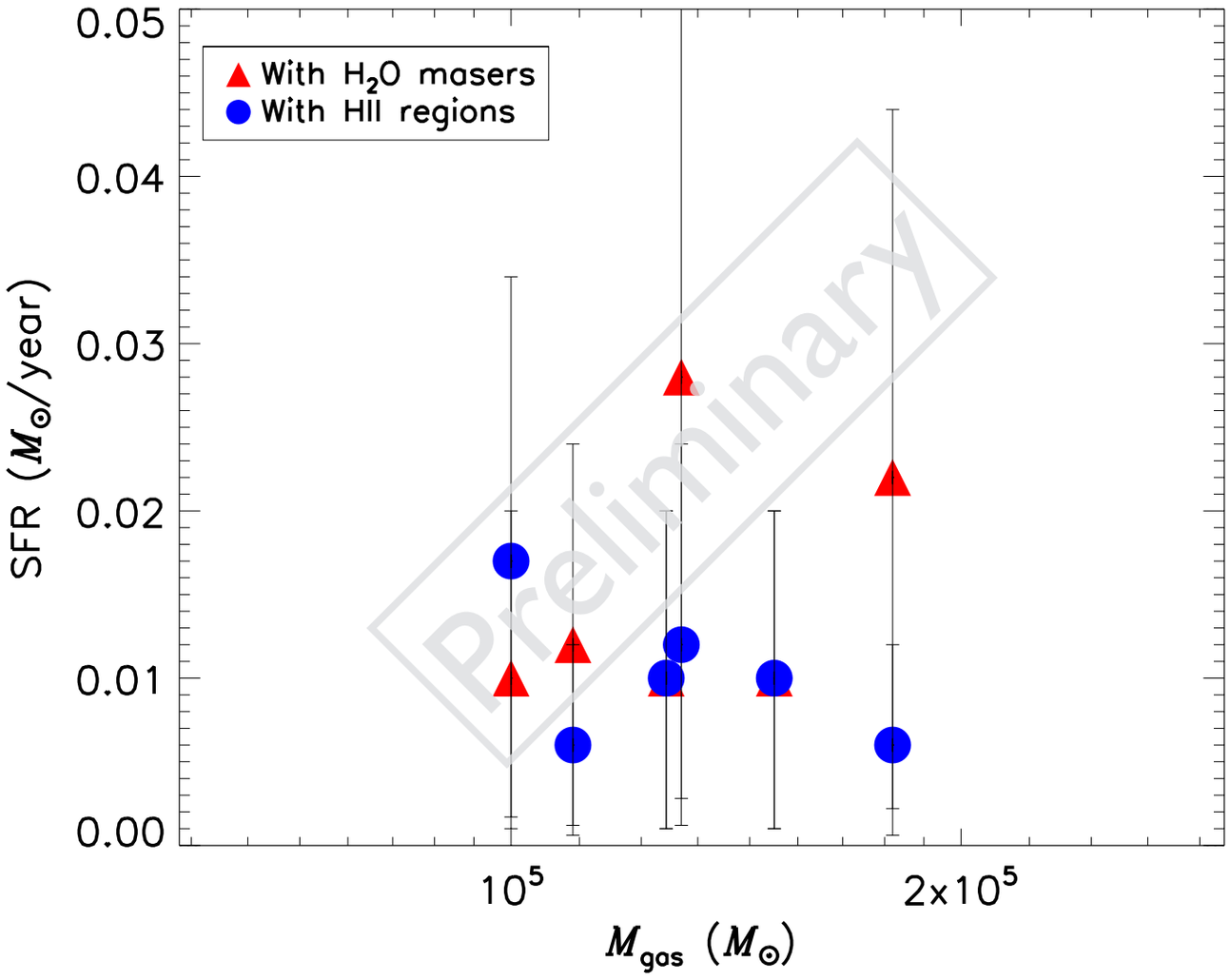






SFRs of the massive clouds

- Estimate of SFRs: count masers and convert to stellar masses; time scales of ~0.1 Myr.
- More active star formation than previous known for the 20 km s^{-1} cloud and Sgr C.
- A new generation of active star formation in these two clouds?



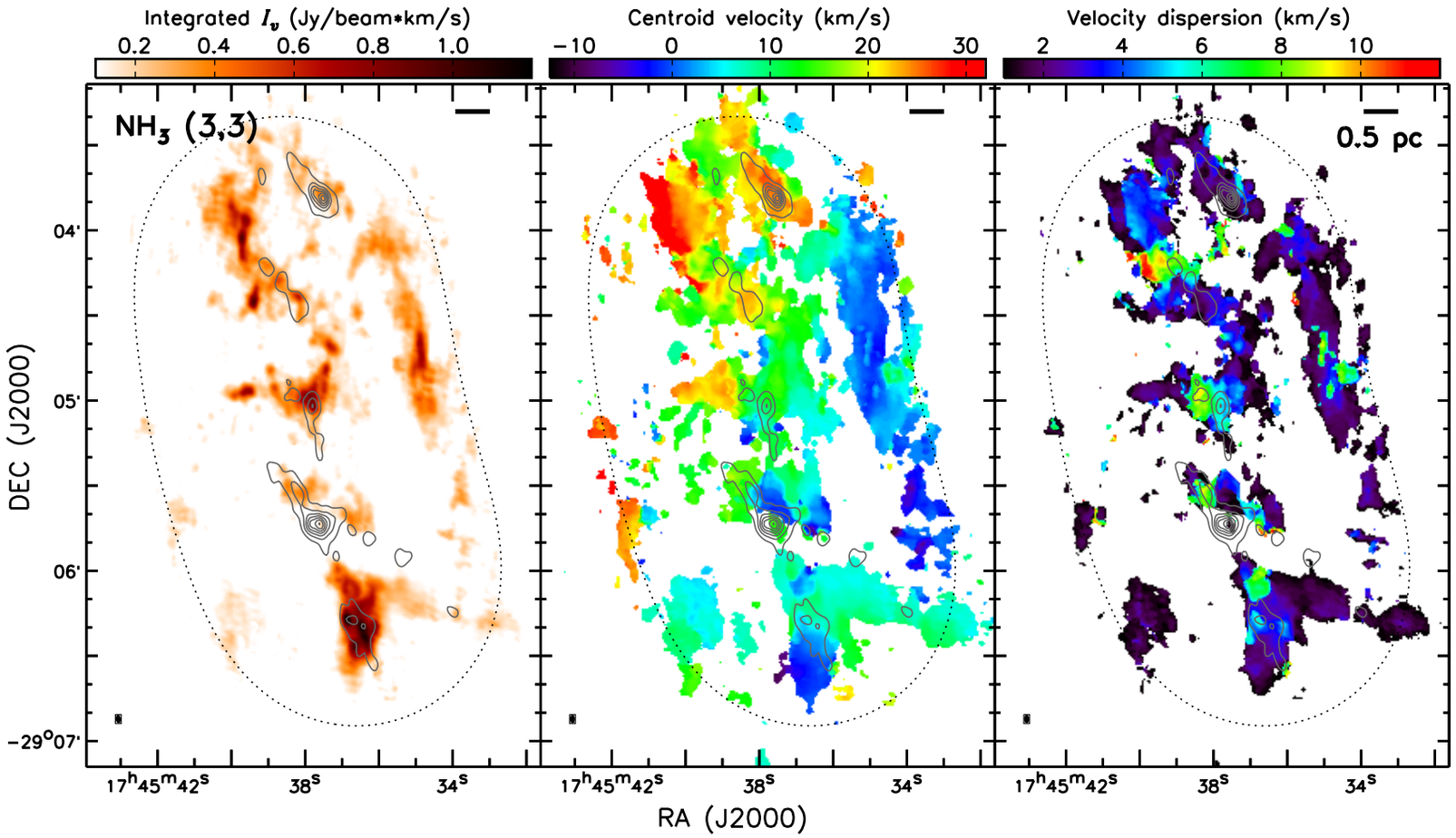
Take-home message

Some clouds in the CMZ
have active (but deeply embedded)
'current' star formation

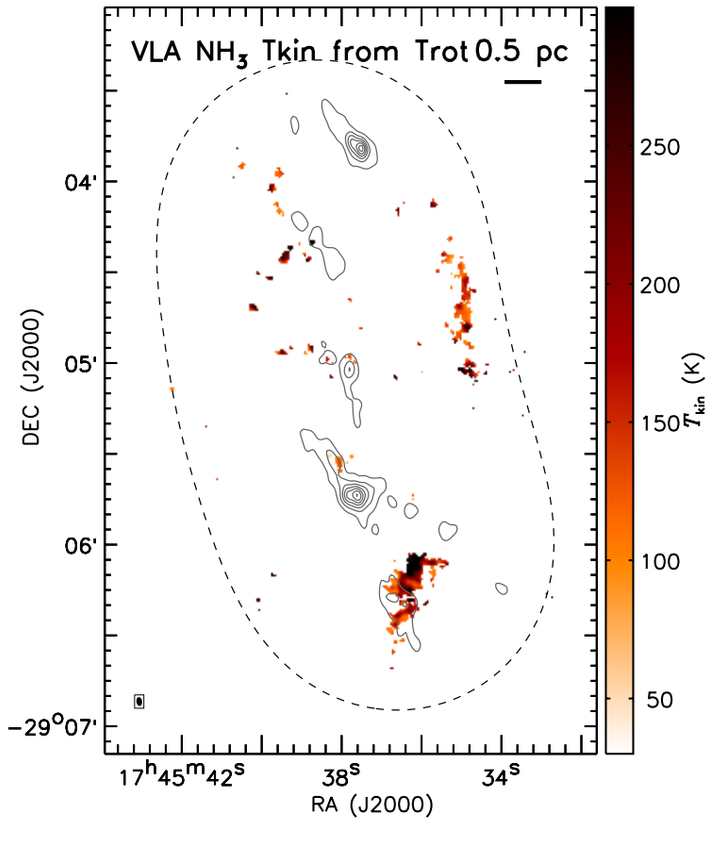
- Numerous dense cores and H_2O masers are detected in the 20 km s^{-1} cloud and Sgr C, which likely trace early phase star formation.
- Their SFRs traced by H_2O masers are much higher than traced by HII regions.
- New star formation signatures are detected in the other clouds too (Sgr B1-off, the 50 km s^{-1}, G0.253+0.016, Sgr D), but they only contain a few dense cores/masers and their SFRs remain to be low in general.

For the next step…

- SMA/JVLA spectral line data, to study kinematics/temperatures. (paper in prep.)
- New ALMA observations, to search for hot molecular cores. (proposal submitted in cycle4)



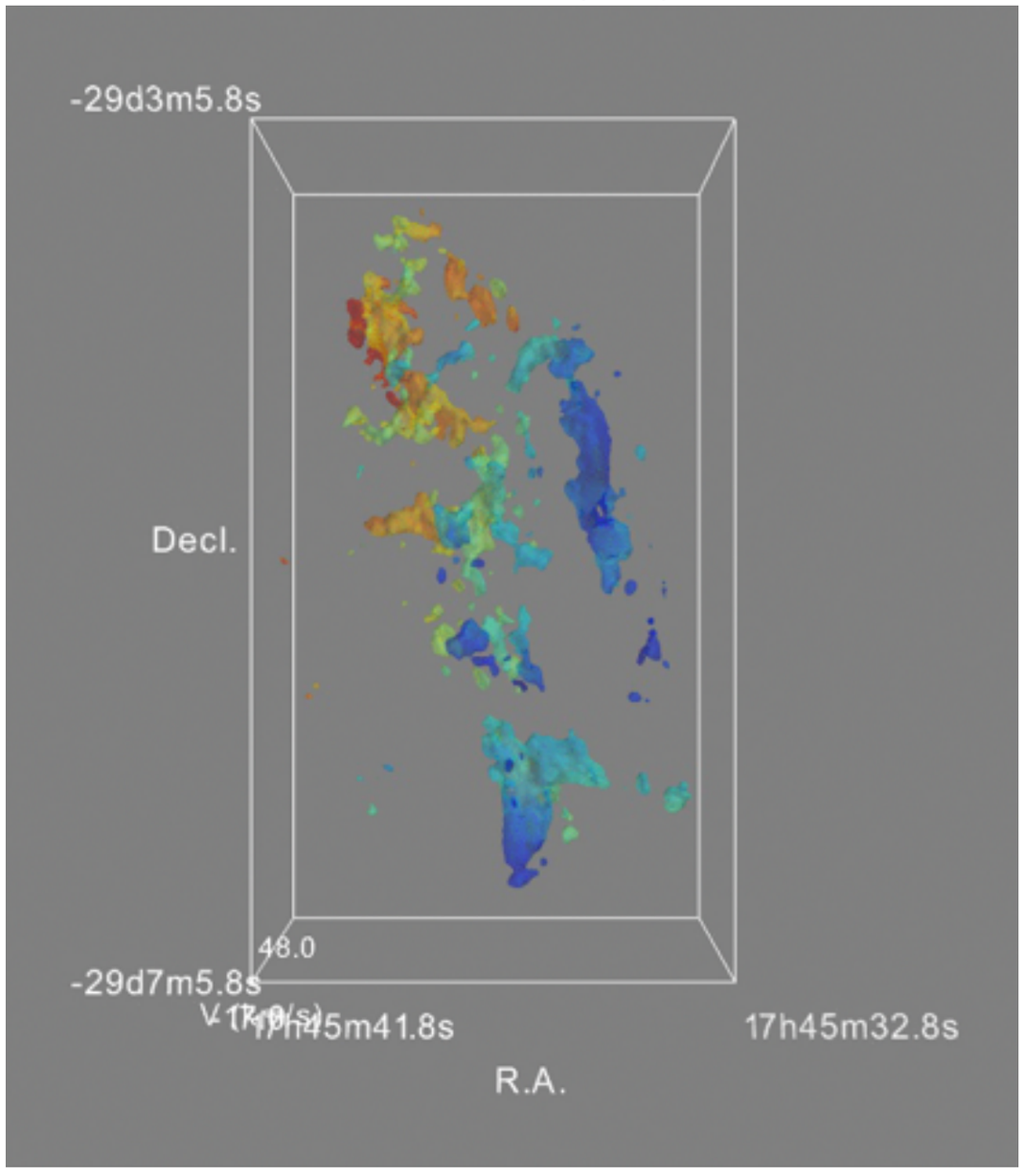
Integrated intensities, velocity field, and velocity dispersion of NH_3 (3,3) in the 20 km s^{-1} cloud



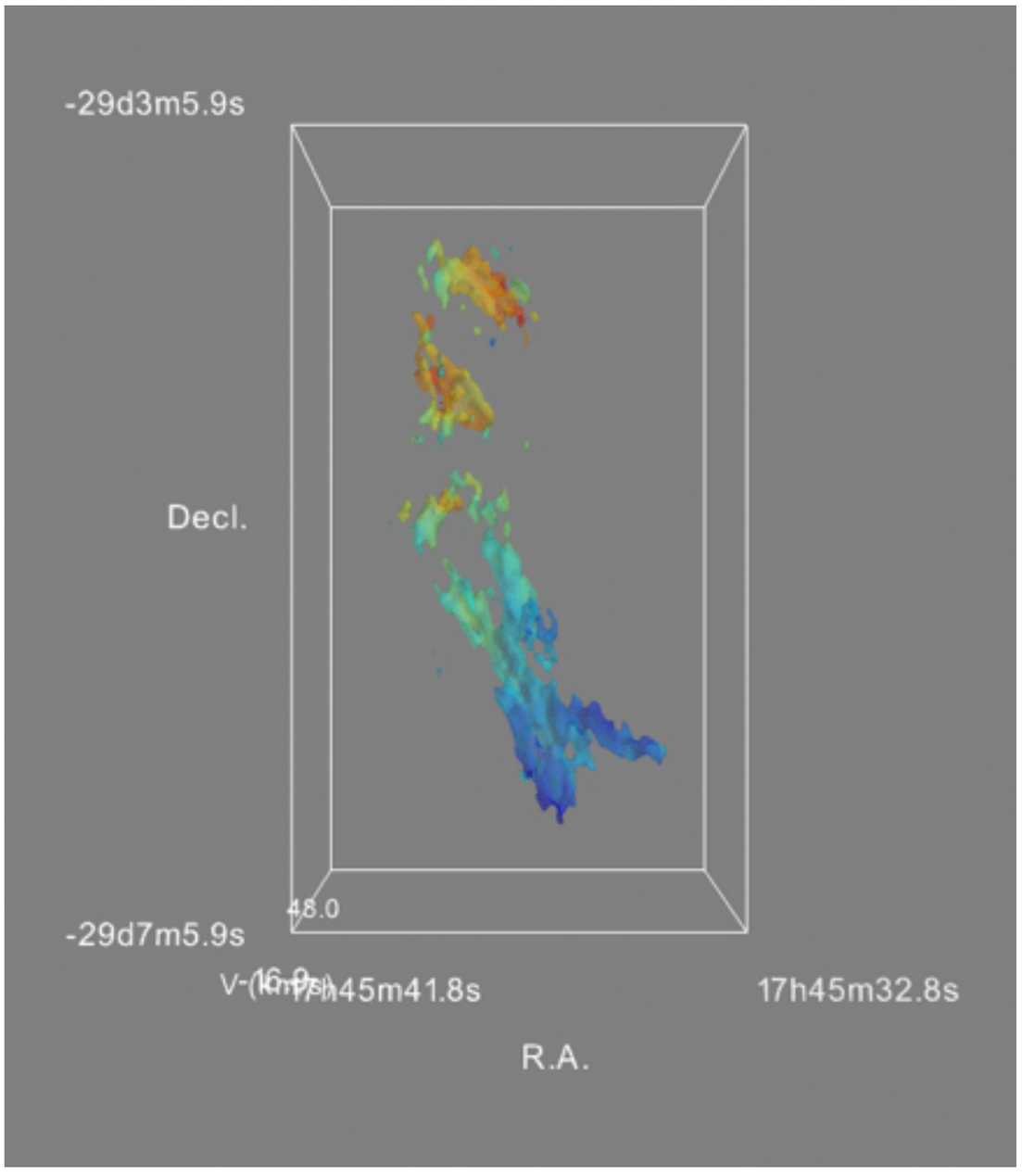
Kinetic Temperatures from NH_3 (4,4)/(2,2)

Position-position-velocity cubes of the 20 km s^{-1} cloud

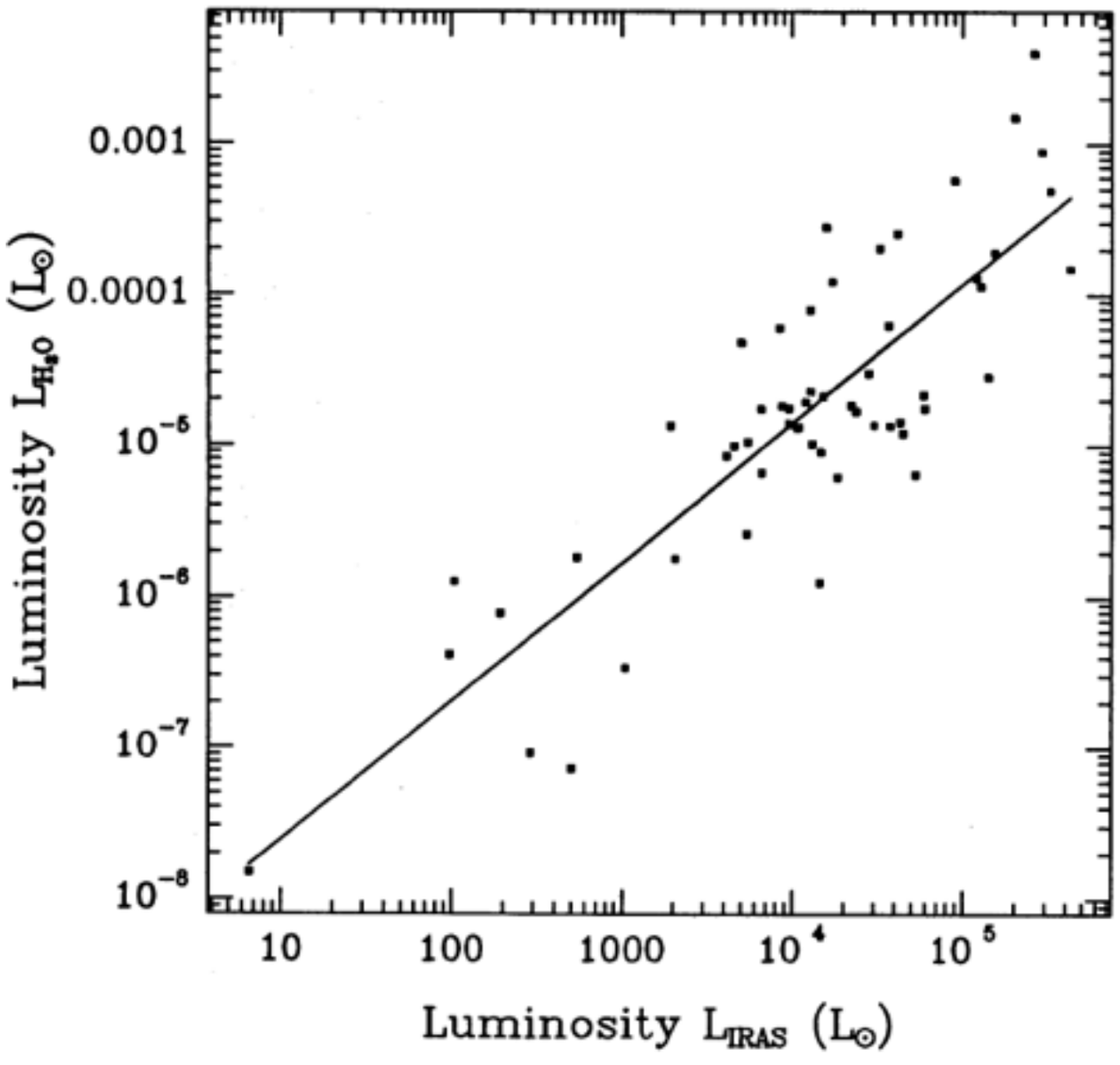
VLA NH_3 (3,3)



SMA+CSO HNCO $10_{0,10}$-$9_{0,9}$



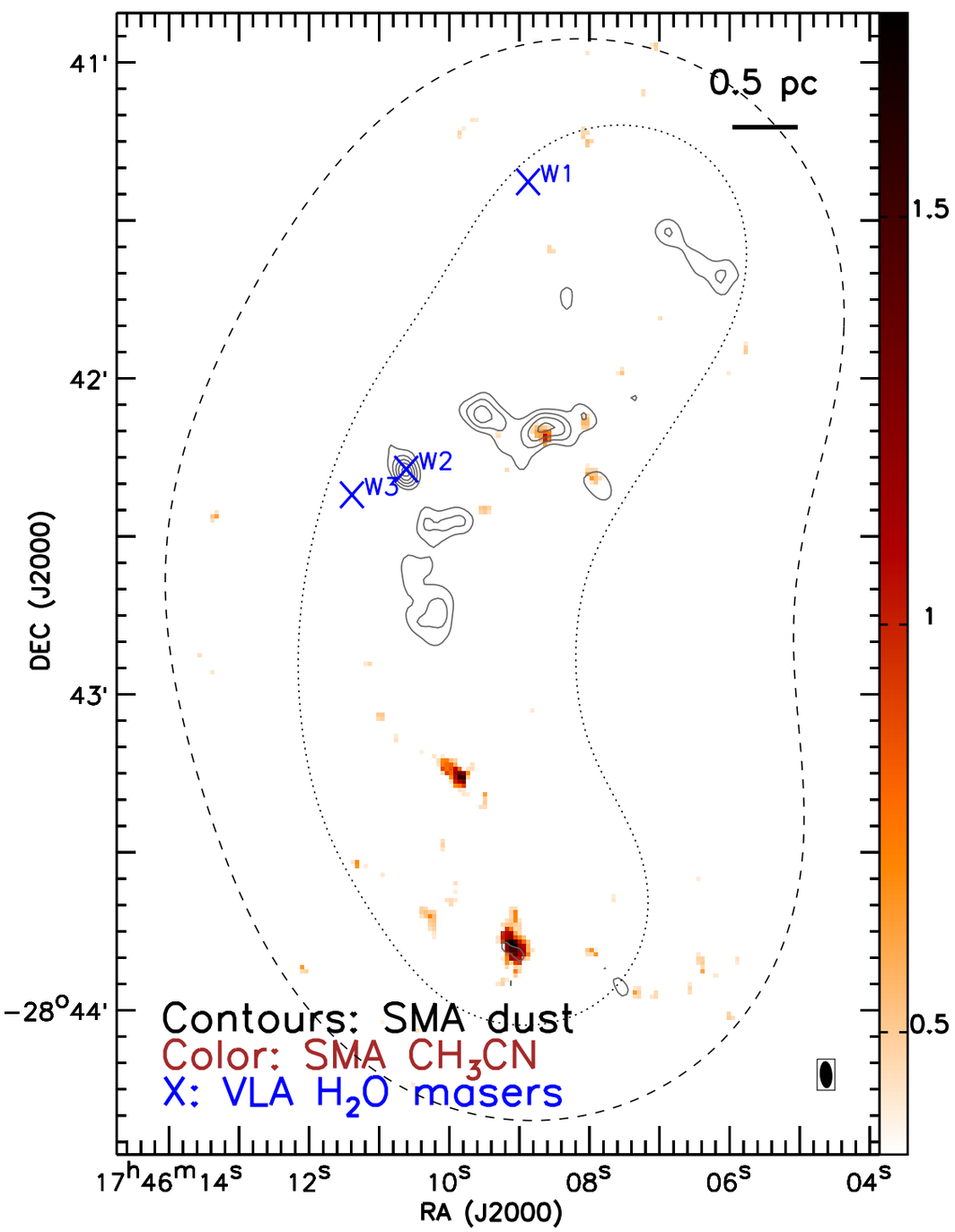
Correlation between luminosities of IRAS sources and H_2O masers (Palla et al. 1993)

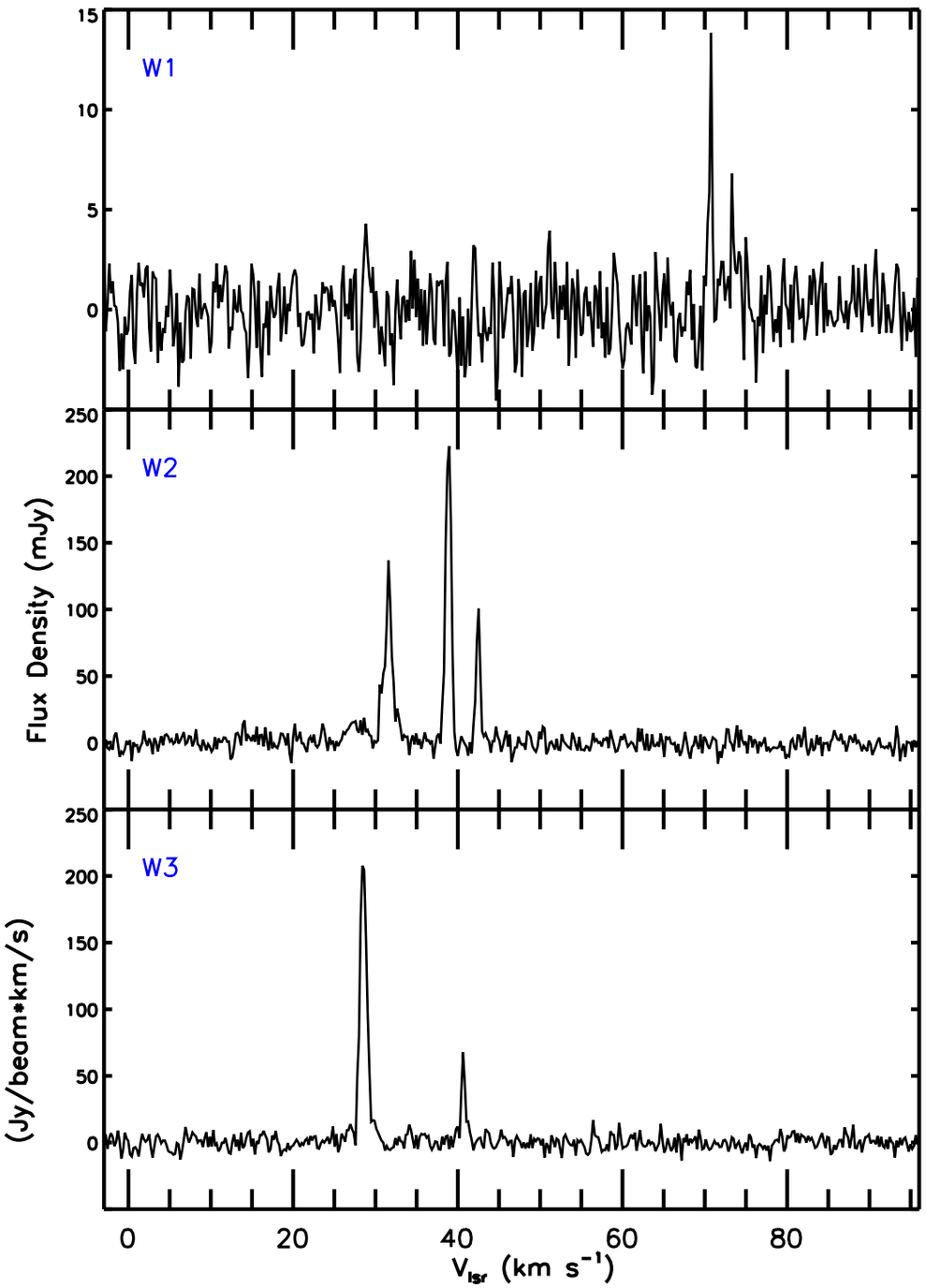


Calculation of SFRs:

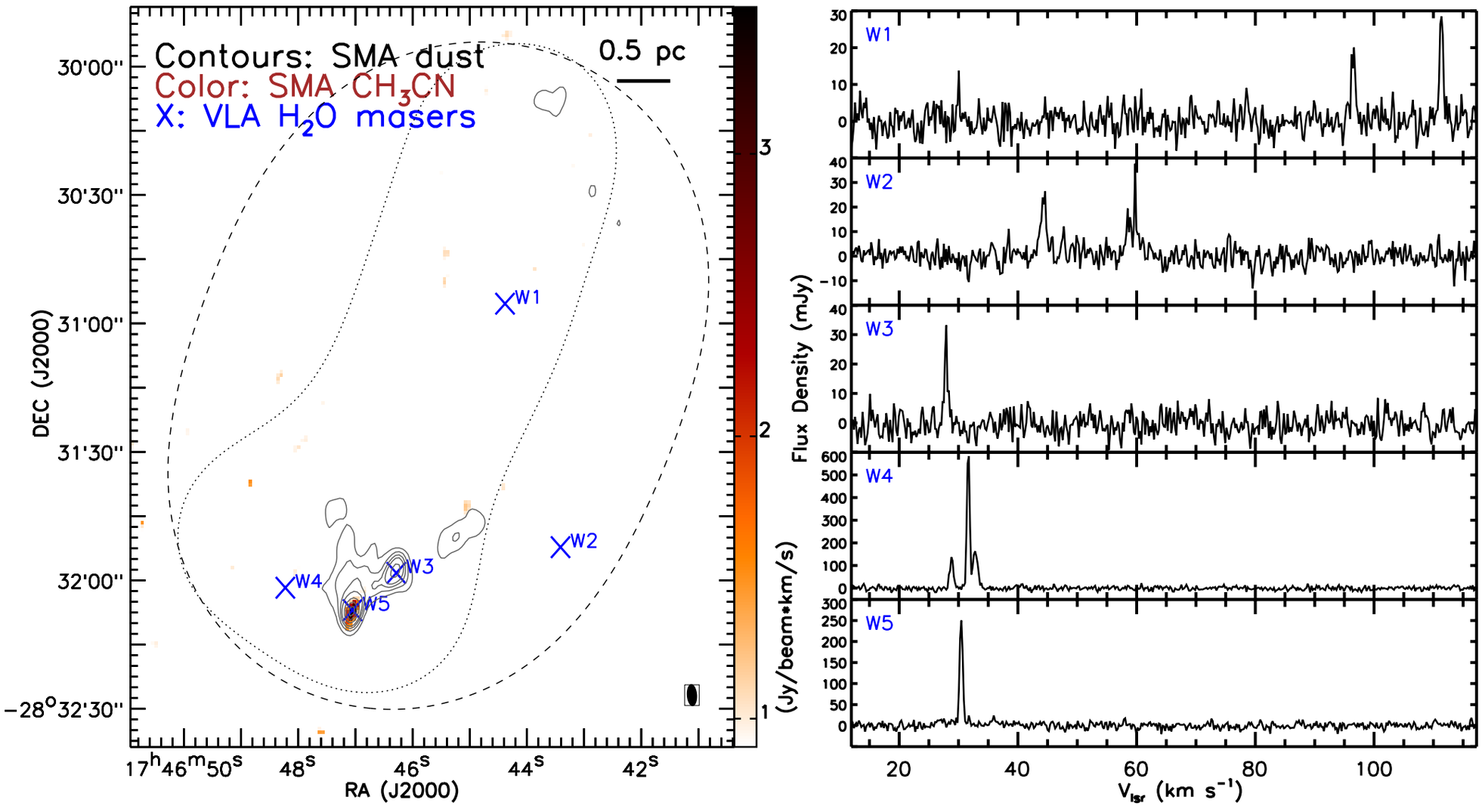
1. Masers with L_{maser}>4x10^{-6} $L_{\odot}$ are supposed to trace high-mass protostars (M>8 $M_{\odot}$) according to the correlation in Palla et al. (1993).
2. Convert high-mass stellar mass to total stellar mass, assuming an IMF with power-law index -2.3 between 0.01 $M_{\odot}$ and max mass from L_{maser}.
3. Star formation time scale is assumed to be 0.1 Myr, which is about the protostellar phase (before HII regions; Gerner et al. 2014) or the class 0 phase.
4. SFRs are obtained from the total stellar masses divided by time scales.
5. Plotted error bars in SFRs come from uncertainties in assumed IMFs.

G0.253+0.016 “The Brick”

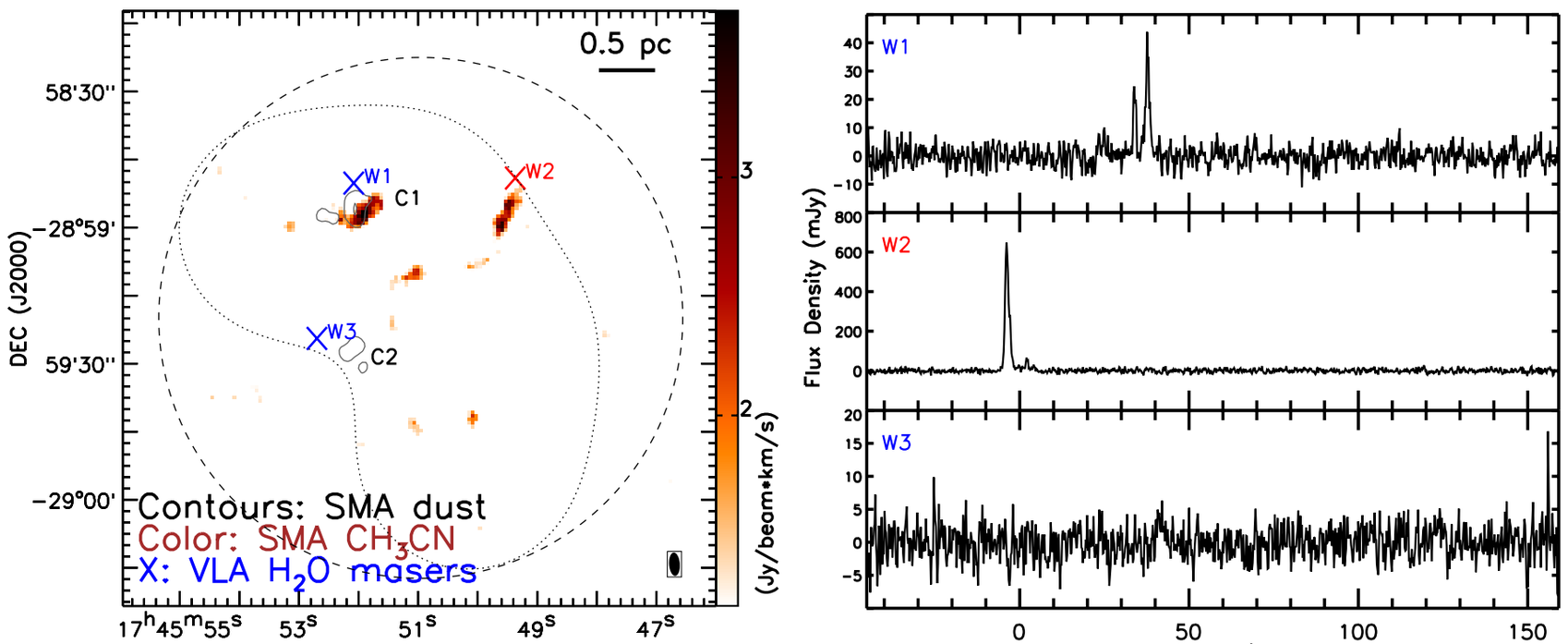




Sgr B1-off (aka dust ridge clouds e/f)



50 km s^{-1} cloud



Sgr D