EARLY ALMA RESULTS ON MASSIVE STAR FORMATION

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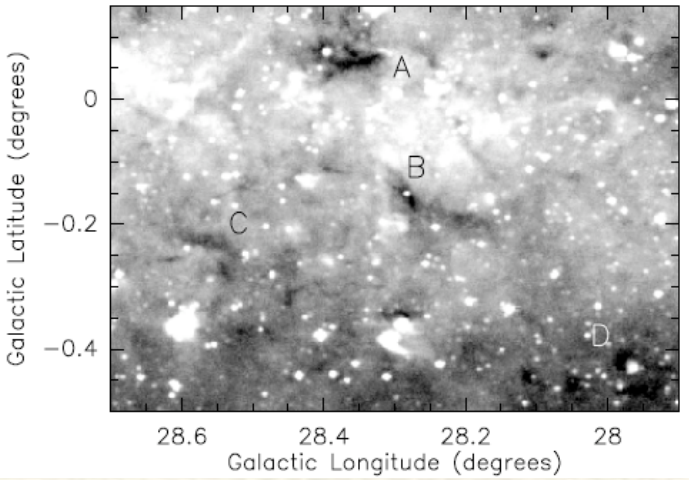
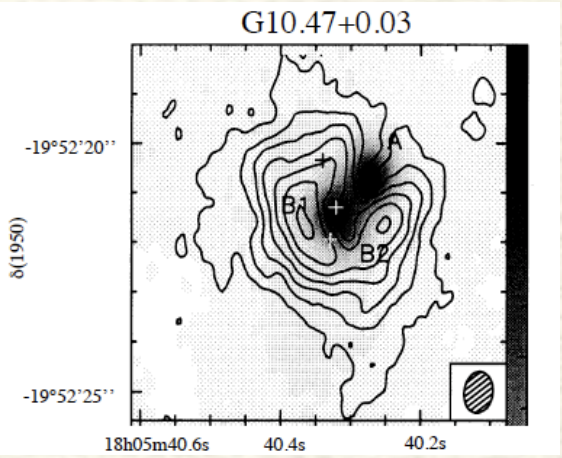
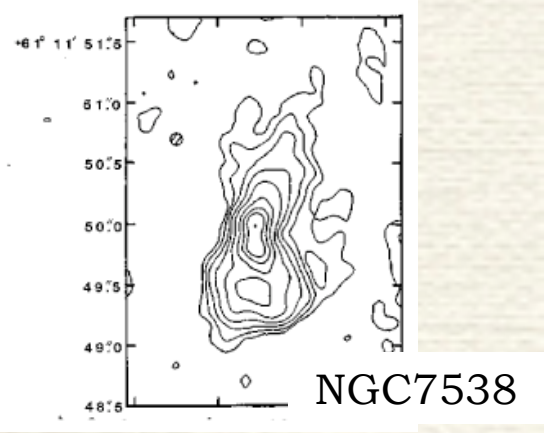
Introduction

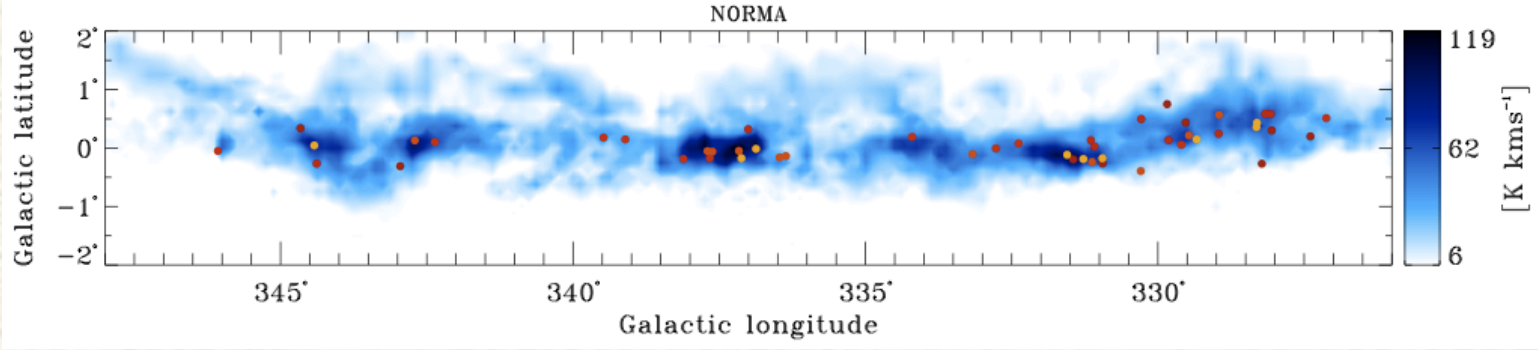
- Massive stars:
  - Principal source of heavy elements and UV radiation.
  - Source of turbulence and mixing in the ISM of galaxies: winds, massive outflows, expanding HII regions and supernova explosions
  - Still no complete picture:
    - Some observational problems:
    - Short timescale of early stages (<10^4 yrs)
    - Large distances
- Early stages of massive SF:
  - Embedded phase observations:
    - IRDC
    - Hot molecular cores
    - HCHII and UCHII regions





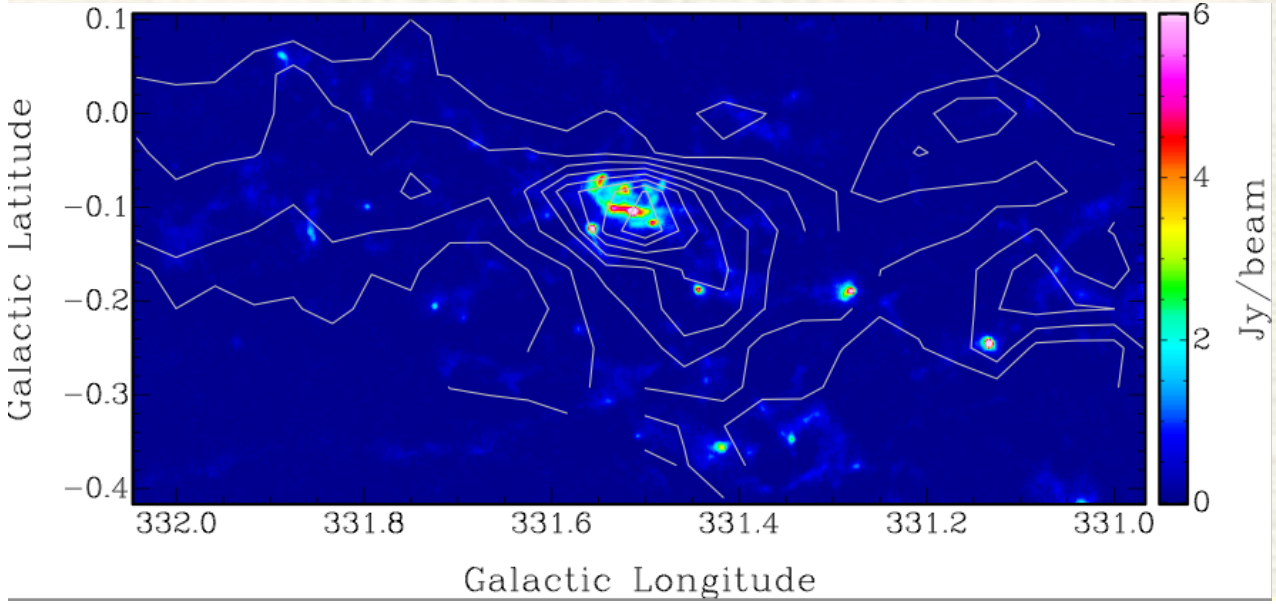


The G331.5-0.1 region



CO(2-1) map with IRAS point sources

Dust emission: ATLASGAL survey

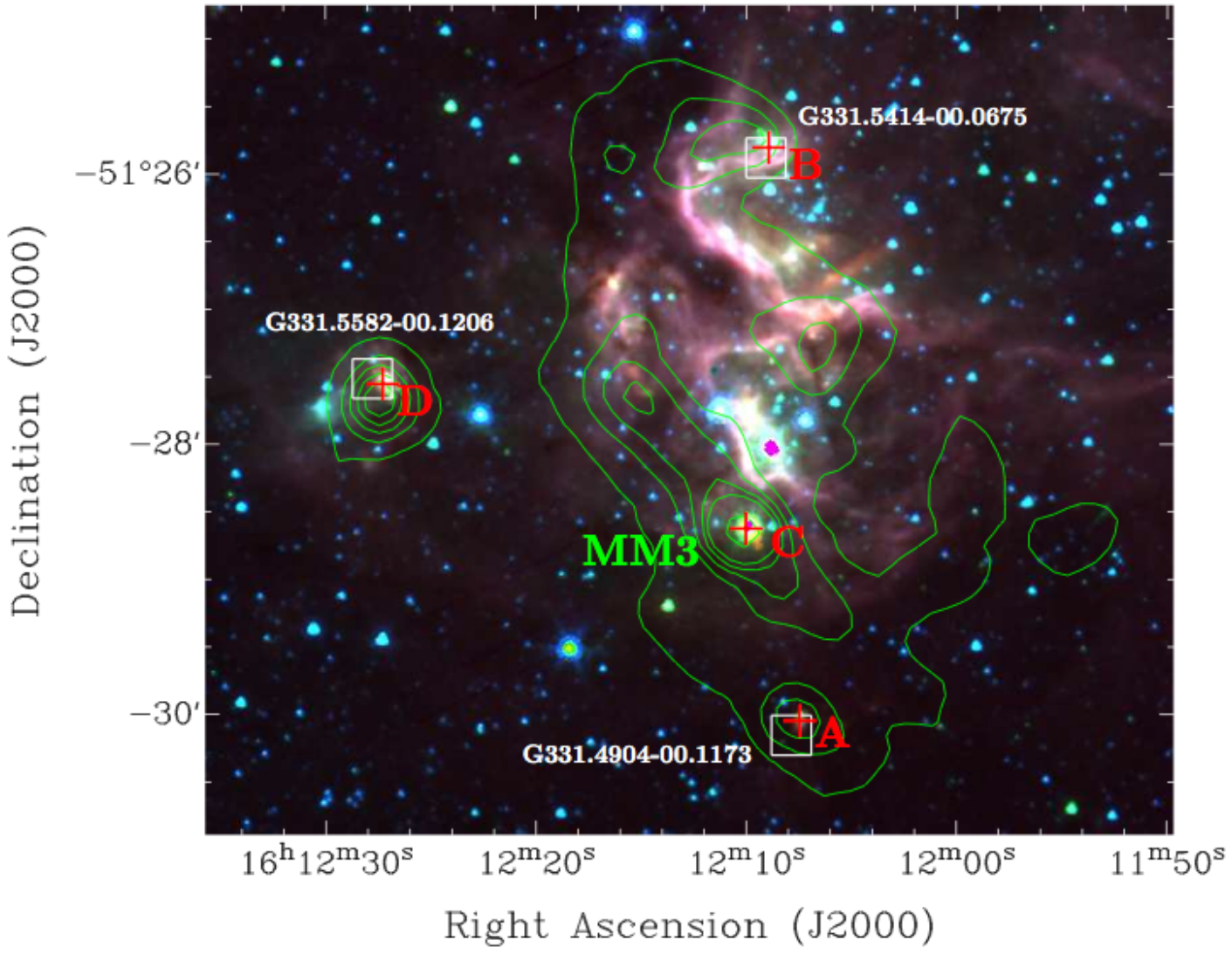


- Distance: 7.5 kpc
- Mass ($C^{18}O$): 3.5×10^6 Msun

18.2" Resolution, 870 um

Contours:
$C^{18}O$(1-0) by 10% of peak emission

Mid-infrared image toward the G331.5-0.1 complex



Spitzer IRAC
3.6 μm (blue),
4.5 μm (green) and
8.0 μm (red).
Contours: dust emission at 0.87 mm.

Red: ATCA 3.6 cm
White: RMS sources

FIR luminosity:
3.6×10^6 $L_\odot$

Clump MM3:
M = 6000 Msun
r_{clump} = 1.2 pc

Spectral index are consistent with ionized stellar winds (Reynolds 1986)

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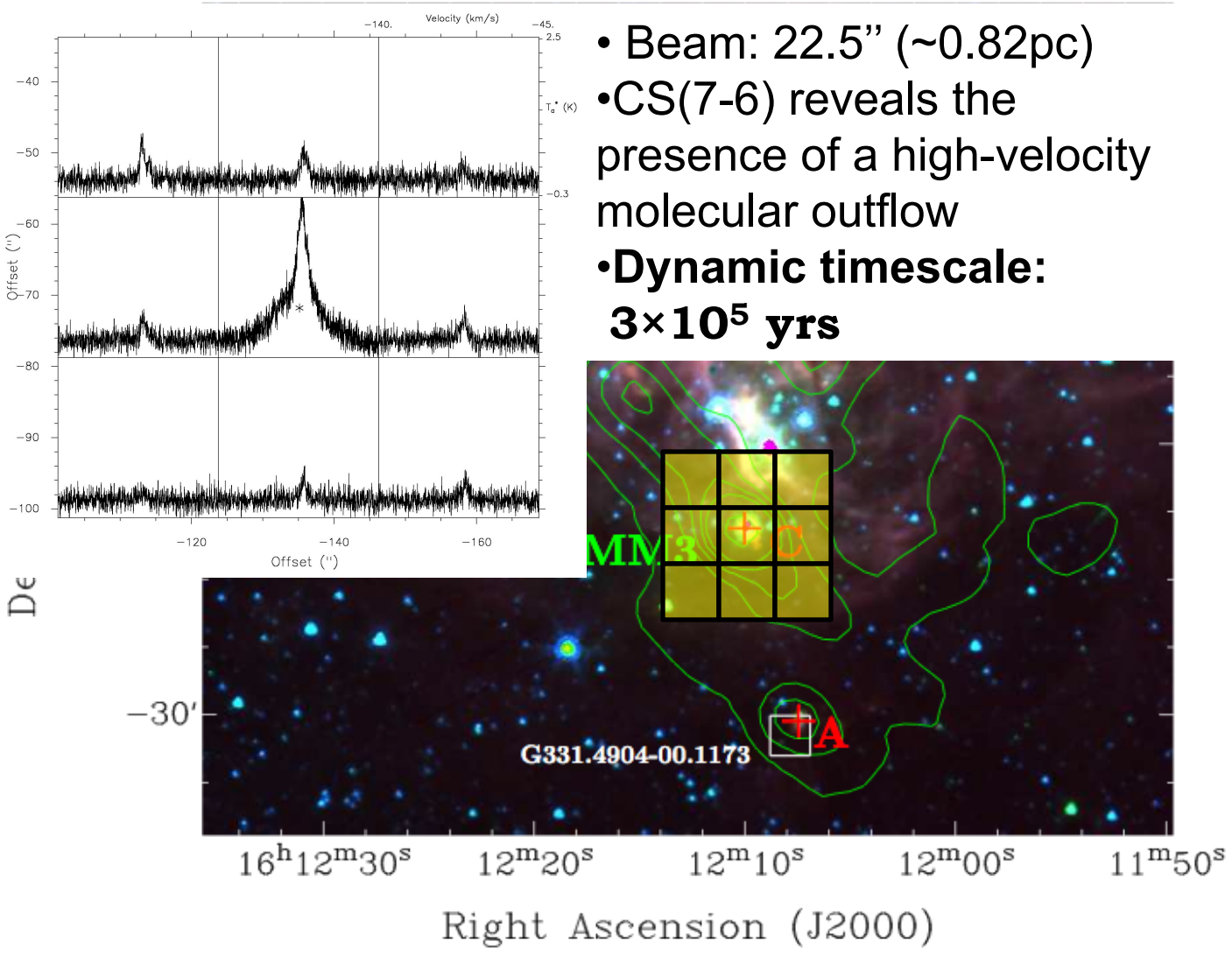

- Beam: 22.5" (~0.82pc)
- CS(7-6) reveals the presence of a high-velocity molecular outflow
- **Dynamic timescale: 3×10^5 yrs**

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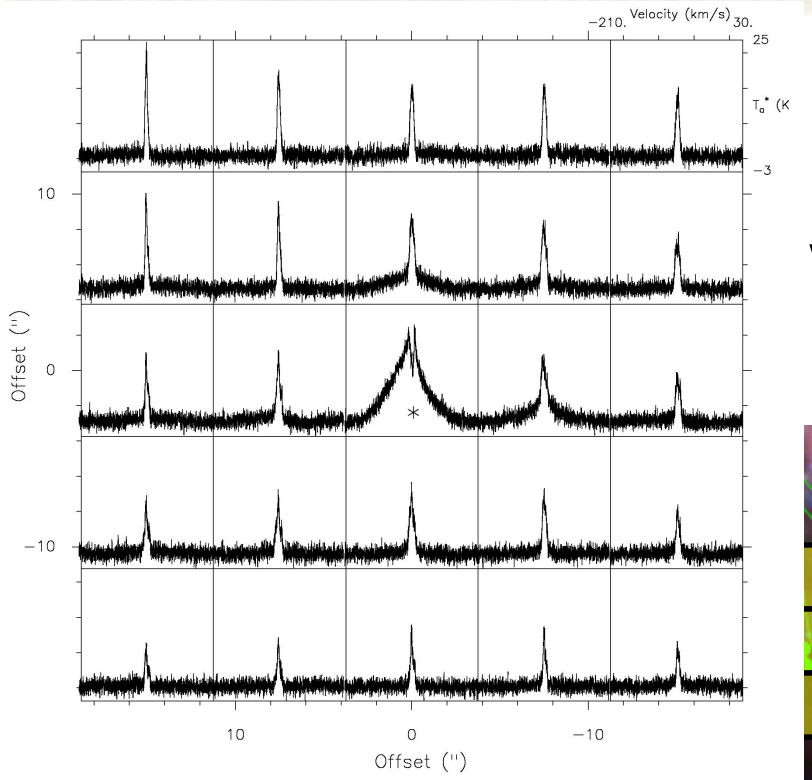
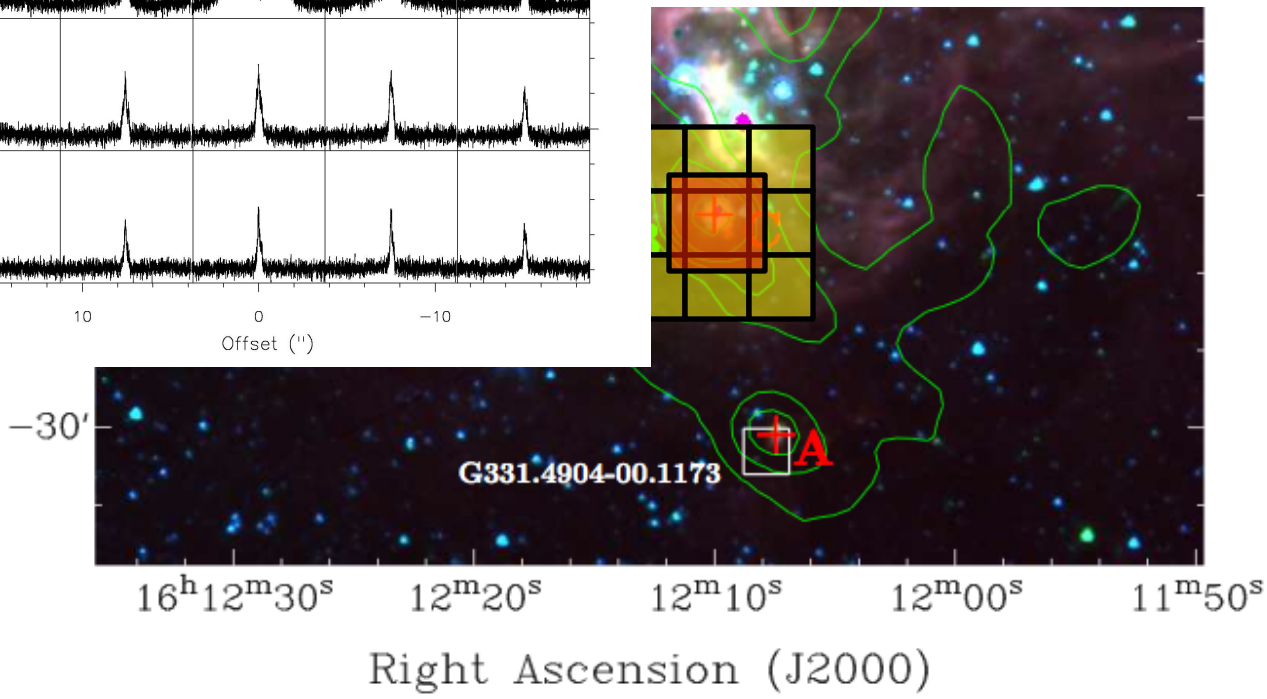


- Beam: 7.7" (~0.28pc)
- CO(7-6): full velocity range (FWZP) of the wing emission 160 km/s
- **Dynamic timescale: 3×10^3 yrs**



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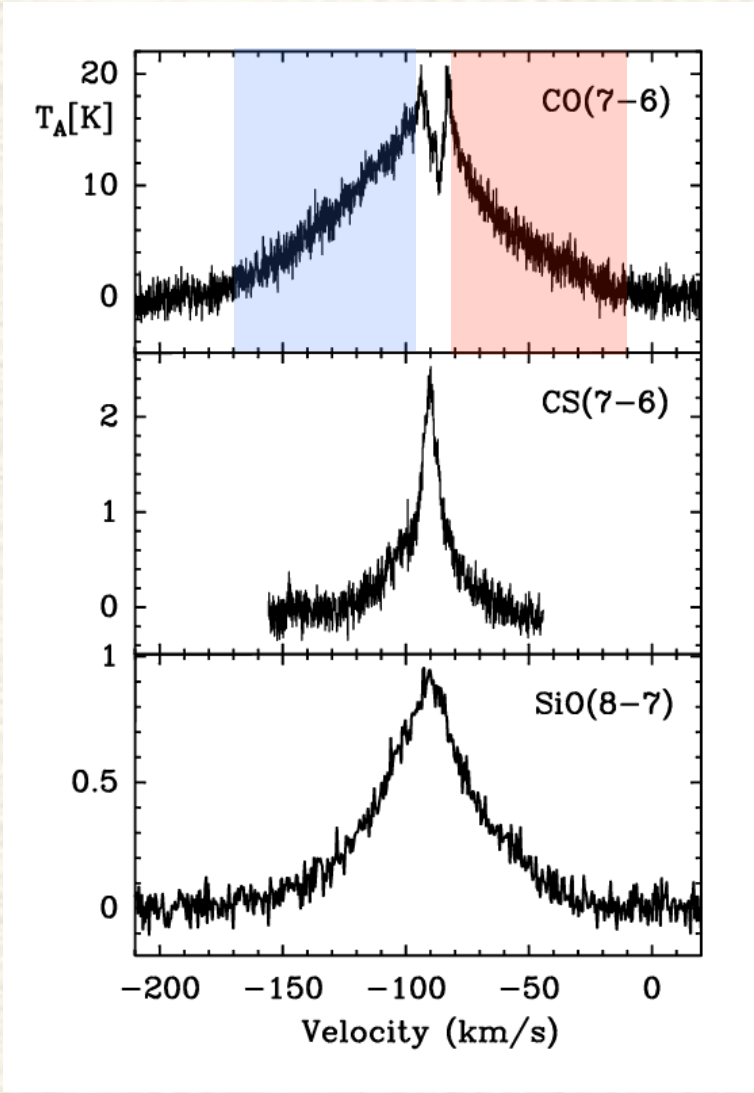
Molecular outflow



- Assuming LTE and optically thin emission, the total mass M(CO) in each lobe are:

  25.9 M⊙ at blueshifted velocities

  16.8 M⊙ at redshifted velocities

One of the most luminous and energetic outflows found toward massive star forming regions

(compare with e.g. Wu et al. 2004, Beuther et al. 2002b)

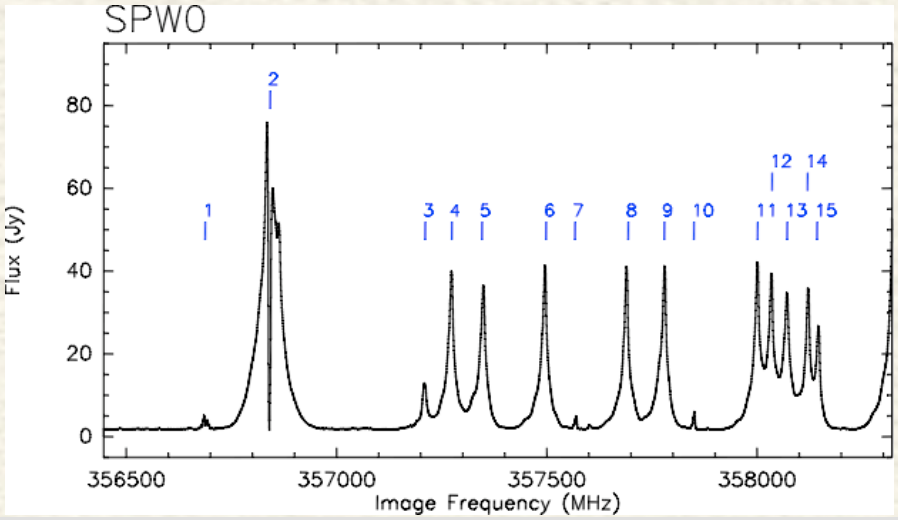
- momentum* ~2.4×10^{3} $M_\odot$ km s^{-1}
- kinetic energy* ~1.4×10^{48} ergs
- mass outflow rate ~1.8×10^{-2} $M_\odot$ yr^{-1}
- momentum outflow rate ~0.77 $M_\odot$ km s^{-1} yr^{-1}
- luminosity ~2×10^{5} $L_\odot$
- Rotational Temp. ~100K

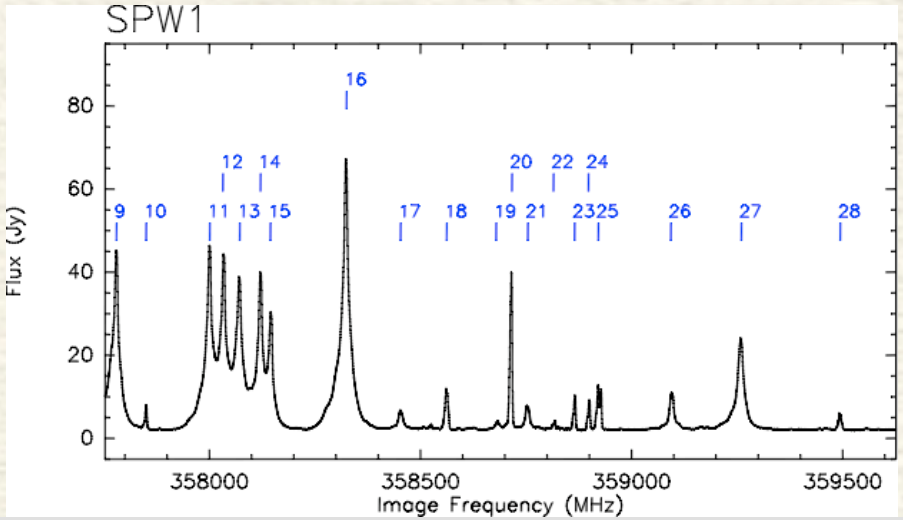
*Assuming a velocity characteristic of the entire flow, V_{char} = 80 km/s

ALMA observations in High-mass SF Regions

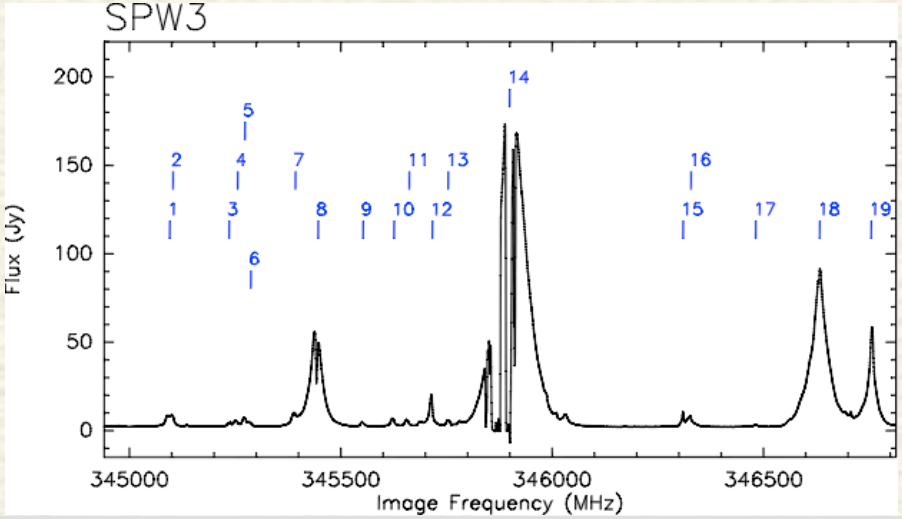
- Massive clusters: case of G025.+0.02 (Rathborne et al.)
- Dynamics of IRDCs, using N_2D+ (Tan et al.)
- Observations of filaments collapsing massive cores (Peretto et al.)
- **Our project: Observations in band 7 of G331.5-0.1 outflow**
  - Aims: Resolve molecular outflow at 1.4", study the physical parameters of the G331.5-01 outflow with different tracers
  - Five lines chosen:

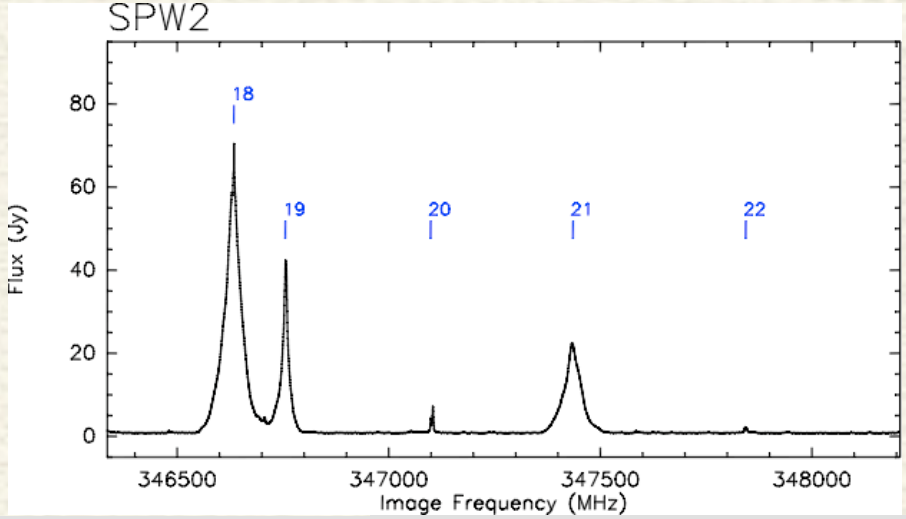
    SiO (8-7) **CO (3-2)** **CH_3OH** **HCO+ (4-3)** **$H^{13}CO+$ (4-3)**
  - 1.7 hrs on source
  - Synthesized beam: 1.38'' x 0.7 ''
  - 17 antennas, 136 baselines (between 18.5 and 269 m)





1 CH3OCH3 8(4,5)-7(3.4)
2 HCO+ v=0 4-3
3 34SO2 v=0 20(0,20)-19(1,19)
4 SO2 v=0 13(4,10)-13(3,11)
5 SO2 v=0 15(4,12)-15(3,13)
6 SO2 v=0 11(4,8)-11(3,9)
7 CH3OCH3 18(2,17)-17(1,16)
8 SO2 V=0 8(4,4)-8(3,5)
9 SO2 v=0 9(4,6)-9(3,7)
10 Unidentified
11 SO2 v=0 7(4,4)-7(3,5)
12 SO2 v=0 6(4,2)-6(3,3)
13 SO2 v=0 17(4,14)-17(3,15)
14 SO2 v=0 5(4,2)-5(3,3)
15 SO2 v=0 4(4,0)-4(3,1)
16 SO2 v=0 20(0,20)-19(1,19)
17 34SO2 v=0 23(4,20)-23(3,21)
18 Unidentified
19 CH3OCHO v=0 29(12,18)-28(12,17)A
20 CH3OHv t=0 4(1,3)-3(0,3)
21 S18O 9(9)-8(8)
22 Unidentified
23 CH3CCH v=0 21(3)-20(3)
24 CH3CCH v=0 21(2)-20(2)
25 CH3CCH v=0 21(1)-20(1) / CH3CCH v=0 21(0)-20(0)
26 Unidentified (possible 34SO2 v=0 15(2,14)-14(1,13))
27 SO2 v=0 25(3,23)-25(2,24)
28 CH3OCH3 12(3,10)-11(2,9)





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3 CH3OCH3 35(2,33)-35(1,34)
4 Possible SO2 v=0 5(5,1)-6(4,2)
5 34SO2 v=0 8(4,4)-8(3,5)
6 NH2CHO 17(0,17)-16(0,16)
7 Unidentified (possible 34SO2 v=0 9(4,6)-9(3,7))
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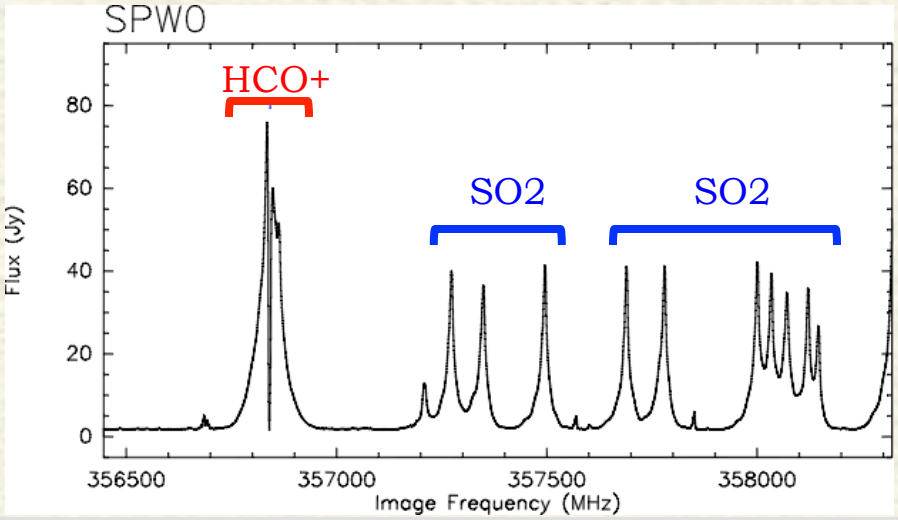
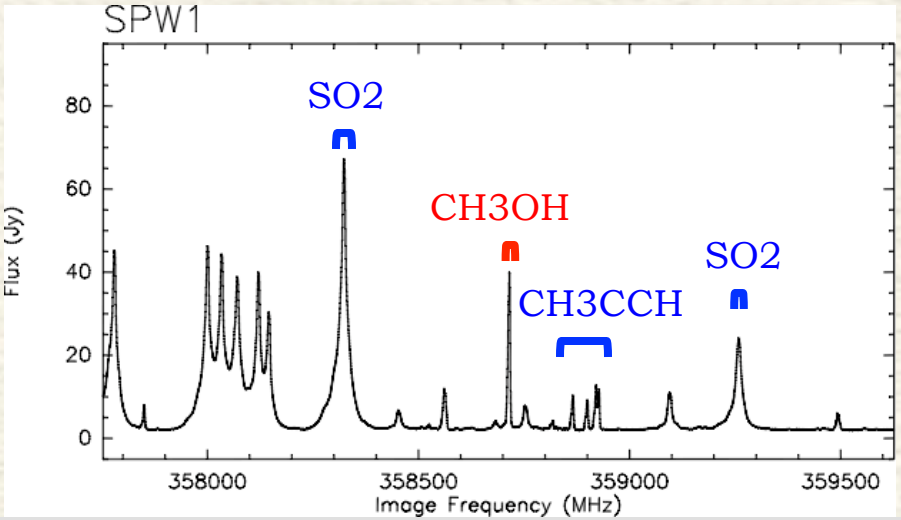
9 SO2 v=0 26(9,17)-27(8,20)
10 34SO2 v=0 7(4,4)-7(3,5)
11 34SO2 v=0 6(4,2)-6(3,3)
12 HC3N v=0 J=38-37
13 34SO2 v=0 6(4,2)-6(3,3)
14 CO v=0 3-2
15 CH3OHv t=0 5(4,2)-6(3,3)-- / CH3OHv t=0 5(4,1)-6(3,4)++
16 NS J=15/2-13/2,Omega=1/2,F=17/2-15/2,I=f
17 SO2v2=1 19(1,19)-18(0,18)
18 SO2 v=0 16(4,12)-16(3,13)
19 SO2 v=0 19(1,19)-18(0,18)
20 H13CO+ 4-3
21 SiO v=0 8-7
22 SO+ J=15/2-13/2,Omega=1/2,I=e





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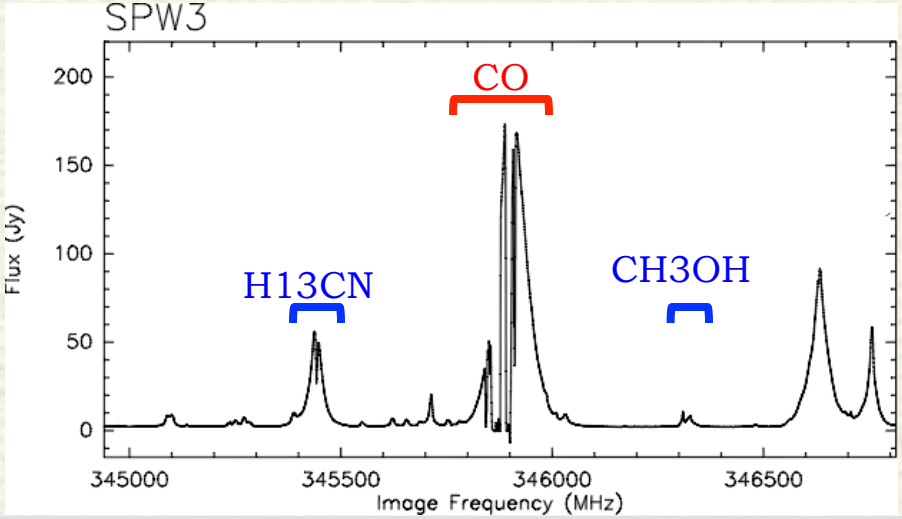

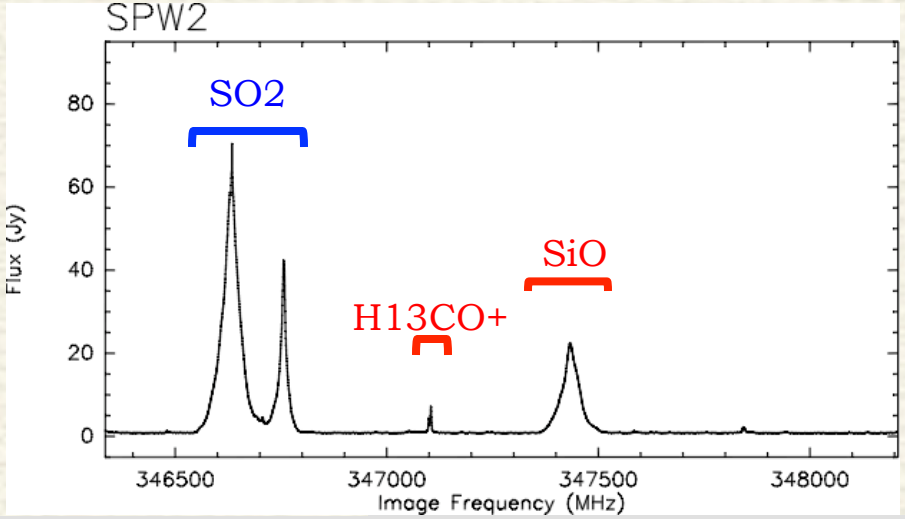

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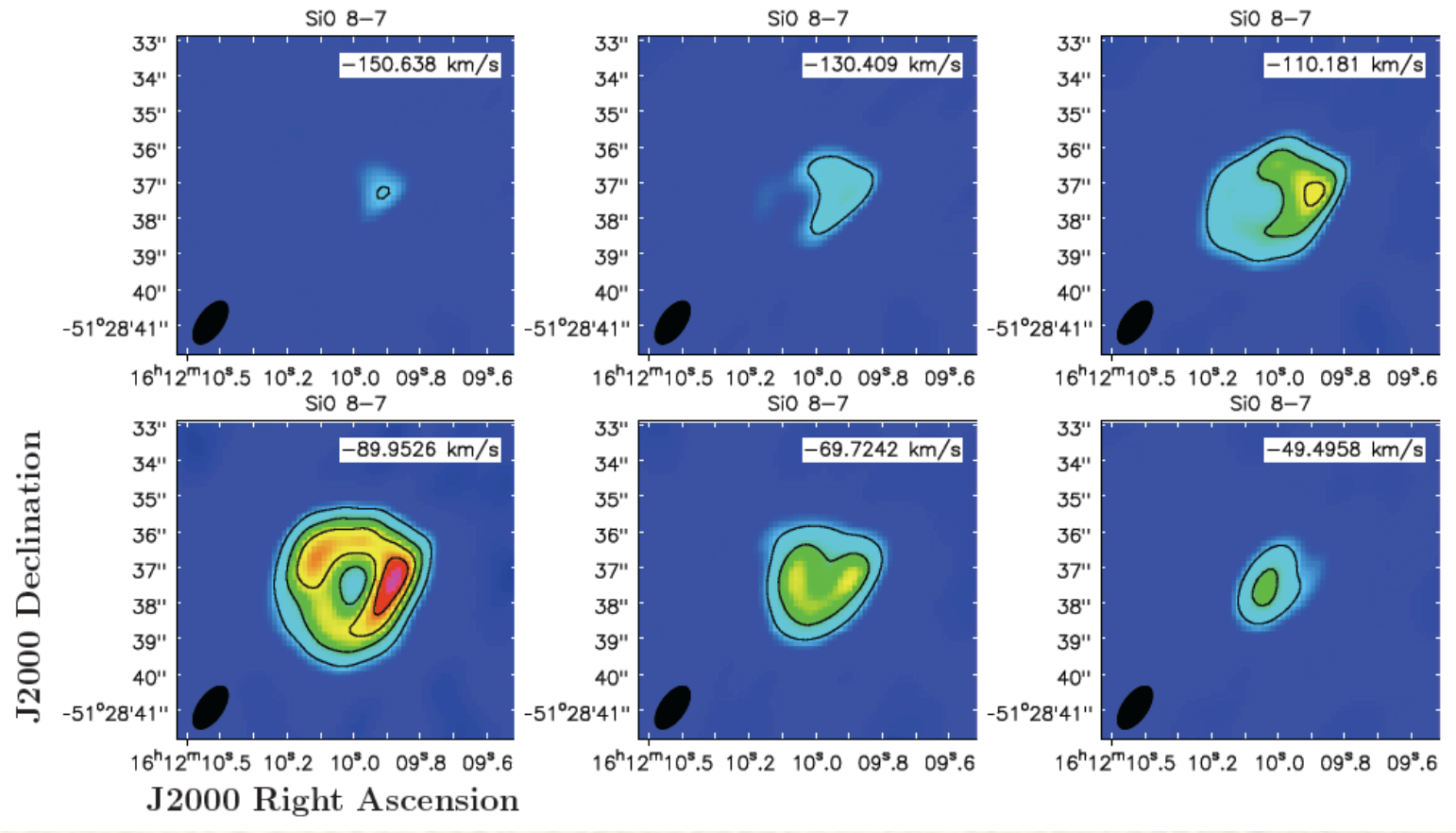
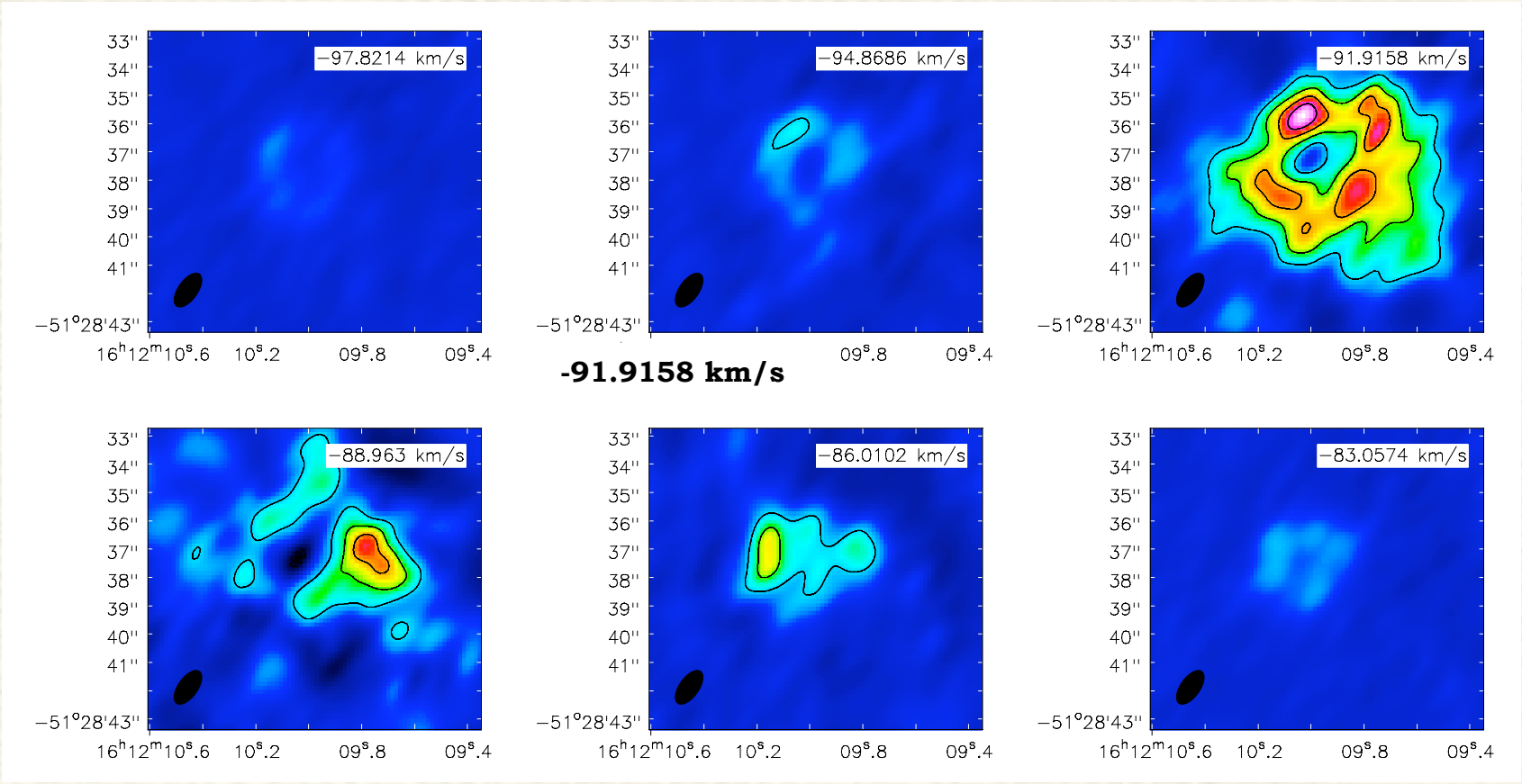
21 SiO v=0 8-7
22 SO+ J=15/2-13/2,Omega=1/2,I=e

Shocked gas



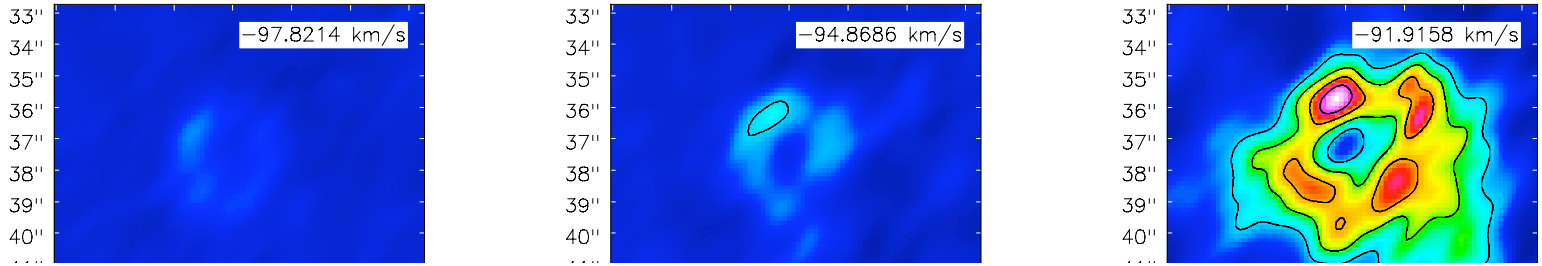
- Emission confined within region of size ~4” (0.14 pc at D=7.5 kpc)
- Ring type or projected shell structure at ambient velocity (-89 km s^{-1}). Inner ring radius ~0.7” (0.03 pc) (beam size)
- **Dynamical time t_{dyn}< 1000 yrs for SiO ring.**

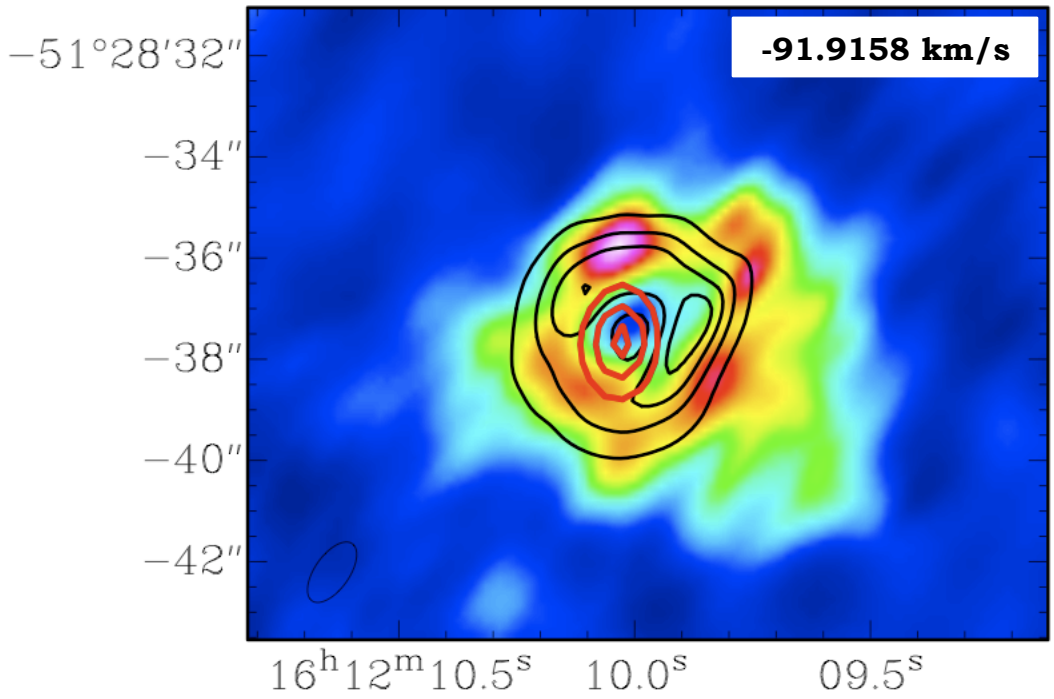
Results: $H^{13}CO+$ (4-3) emission



-91.9158 km/s

Results: $H^{13}CO^+$ (4-3) emission





Colour: H13CO+(4-3)
Black contours: SiO(8-7)
Red contours: 8.64 GHz

- H13CO+ emission: size of 5.8” × 3.64”
- SiO emission centered at the cavity (black contours by 20% of peak emission)
- 3.6 cm continuum emission at the center of the SiO cavity (red contours by 30% peak emission).

IONIZED GAS

↓

SHOCK SHELL

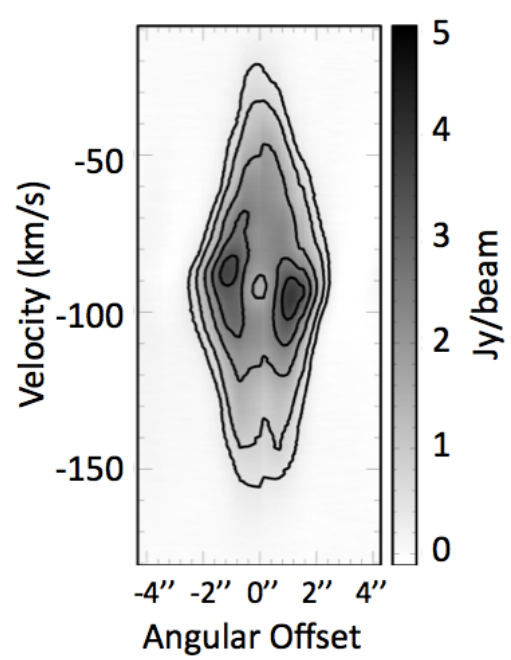
↓

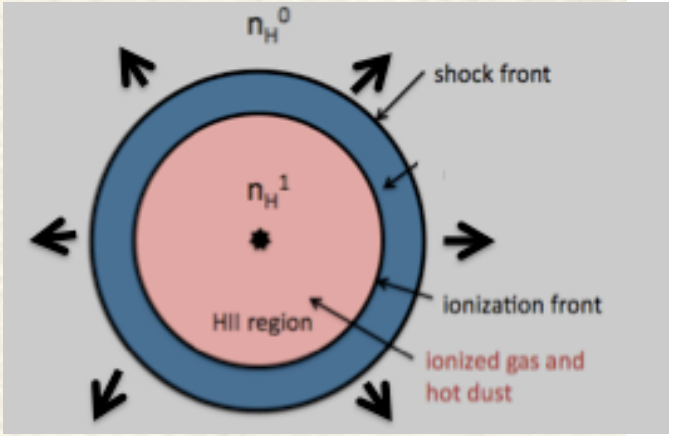
DENSE MOLECULAR GAS

Velocity structure

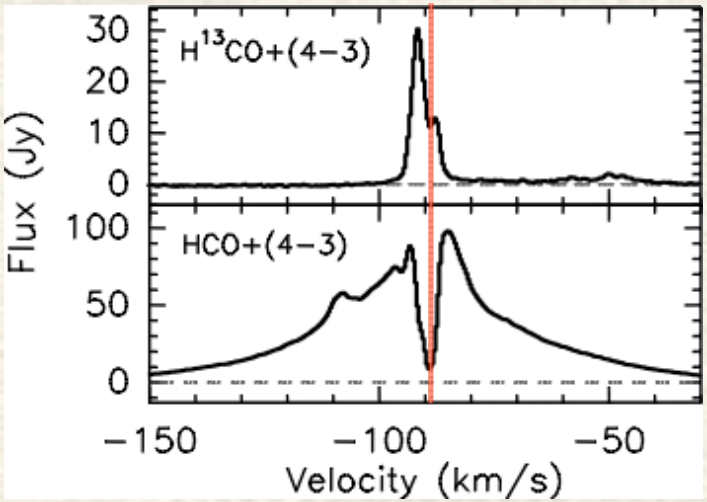
- **Expanding shell with high velocity outflow**

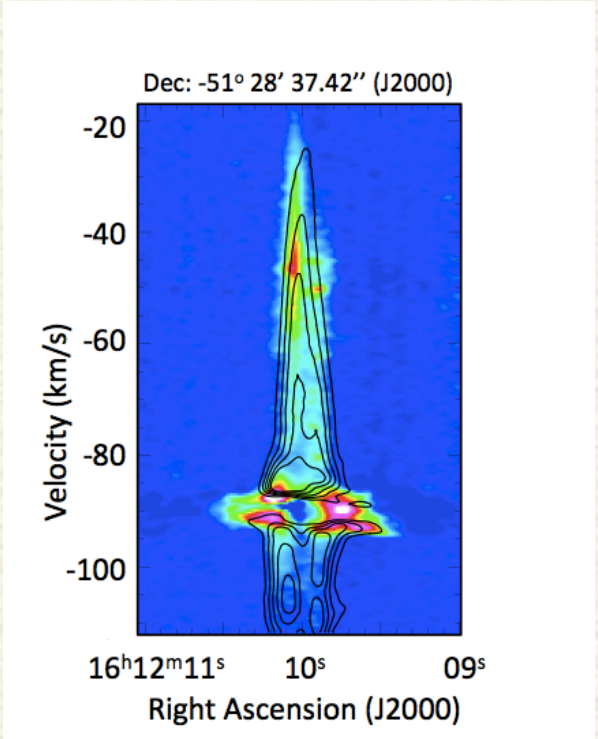
Perpendicular to the jet symmetry axis





•Emission from H13CO+ arises from region of self-absorption in the spectrum profile.
•Dip at ambient velocity of the source.
•Profile could also suggest infalling material.

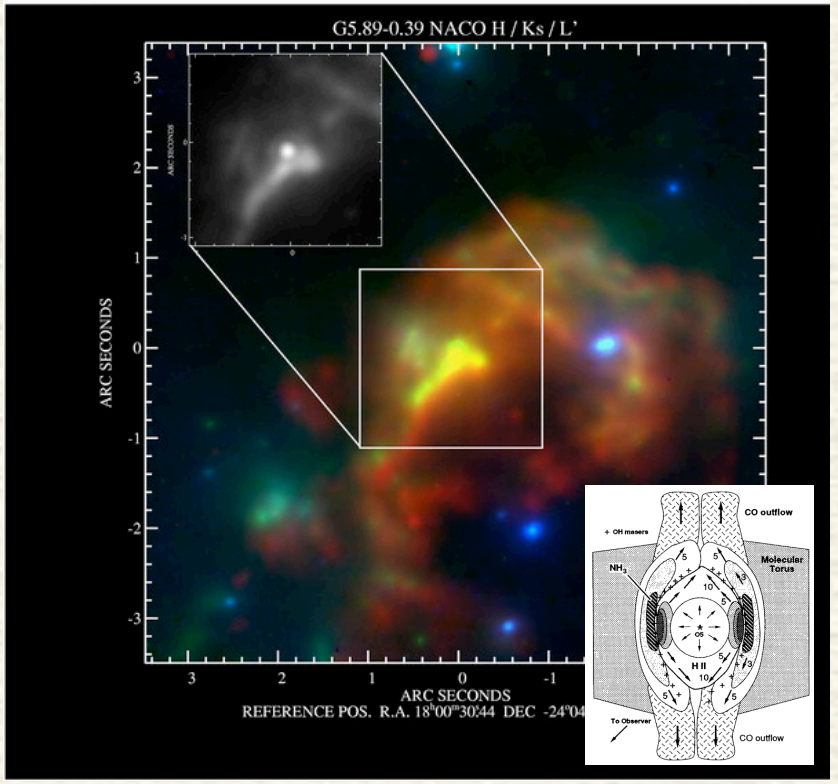




Hot core?

- Compact, infrared-bright regions
- Densities ~ 10^7 cm^-3
- Temperatures 100 K or higher
- Diameters ~ 0.1 pc
- Total mass: several hundred Msun
- Chemical signatures:
  - complex organic molecules and fully hydrogenated molecules as NH3 (first generation: surface chemistry on grains)
  - second generation (gas-phase chemistry between evaporated species): CH3OH, CH3OCH3, CH3OCHO, CH3CCH, NH2CHO.

G5.89-0.39



- No H2O,H2S and NH3 lines fall in the observed spectral windows
- Several molecules from "second generation": SO2, CH3OCH3, CH3CCH

Summary

- G331.5-0.1 region, one of the most extended, massive and luminous complex of massive star formation in the Galactic disk.
- Four compact radio sources. Component C with spectral index consistent with ionized stellar winds.
- Discovery of one of the most powerful molecular outflow known so far. Luminous and massive protostellar object.
- ALMA observations revealed a ring type structure or shell in projection around the peak position of radio continuum.
- The dynamic timescale <1000 yrs
- Model of expanding shell toward the ambient velocity suggested, in addition to the outflow emission
- Chemistry and physical properties suggest that this source could correspond to a hot core.