# Masers as probes of star forming regions with ALMA and mm VLBI

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# Talk outline

- Masers as diagnostic tools in SF
- A few highlights from VLBI of cm masers in massive protostars
- Interferometric observations of submm masers:
  - SMA: Orion-KL and Cepheus-A
  - ALMA (test) data: W49N, W51-Main, and W51-North
- Science case for mm VLBI of masers

# Molecular masers as diagnostic tools

- Maser lines occur at radio and mm λ

  => They are unaffected by extinction

- Maser radiation originates from compact and bright maser spots

  => ideal targets of radio (very long baseline) interferometry (VLBI)

- They are excellent probes of *local* conditions and kinematics *very close to the YSO* (<100 AU)

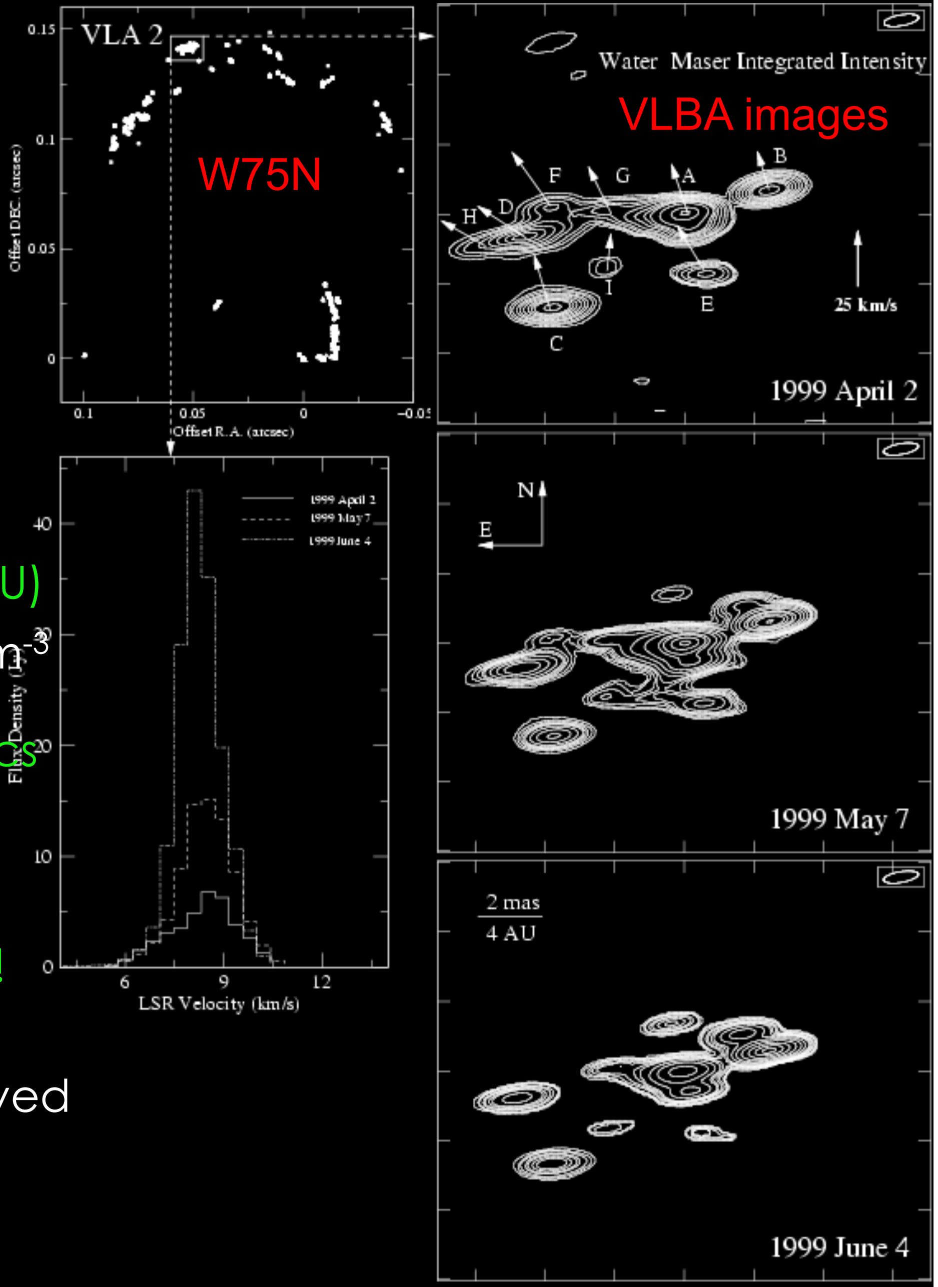
  =>excitation at $T \geq 200\text{-}2000$ K and $n > 10^{7\text{-}10}$ cm$^{-3}$

- Multi-epoch studies provide gas 3-D kinematics

  => proper motions + l.o.s velocities *at the highest angular resolution* [O(mas)]

- Real gas kinematics, not illumination patterns!

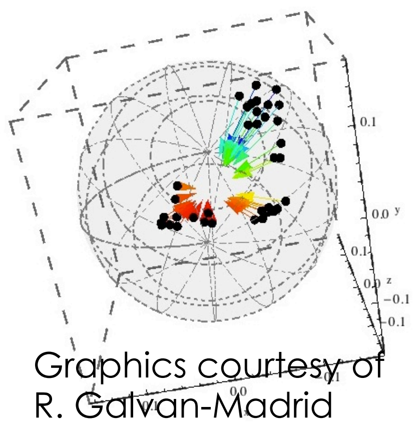
  => morphology of individual spots as well as overall structure of the maser source is preserved over time



*Goddi, Moscadelli, Torrelles, et al., 2006*

# Case I: AFGL 5142 MM-1

## *Gas infall to an intermediate-mass protostar: $V_{3D}$ from $CH_3OH$ masers*



Graphics courtesy of
R. Galvan-Madrid

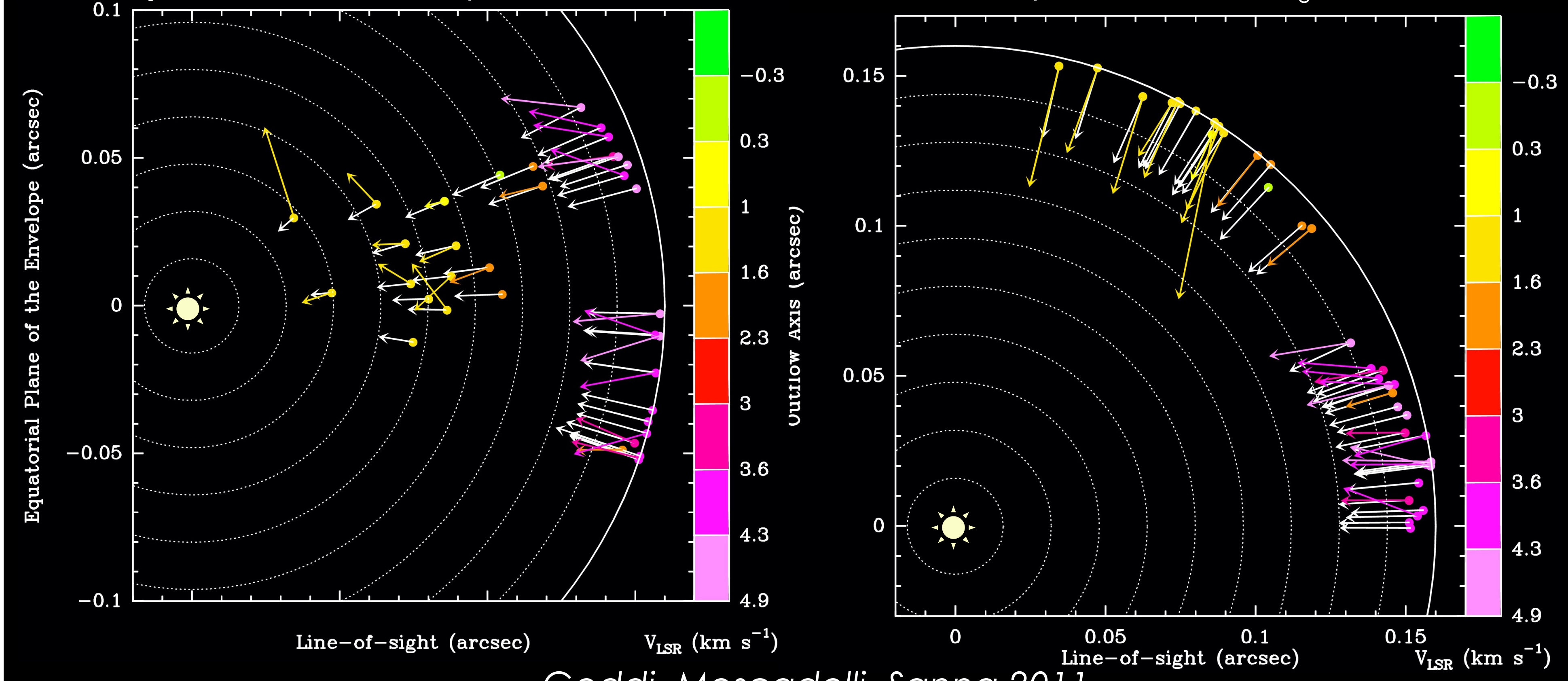
Simple spherical model of infall

$$\vec{V}(\vec{R}) = \sqrt{(2GM/R^3)}\vec{R}$$

With 4 free parameters:
$\alpha_s, \delta_s, R_s, M_*$

| | |
|---|---|
| $L_{bol}$ | $\sim 10^4\ L_\odot$ |
| $M_{*\ dyn}$ | $> 4\ M_\odot$ |
| $R_{inf}$ | 300 AU |
| $V_{inf}$ | 5 km $s^{-1}$ |
| Infall rate | $\sim 6\times10^{-4}\ M_\odot\ yr^{-1}$ |

Projections of model-predicted and observed velocity vectors of $CH_3OH$ masers



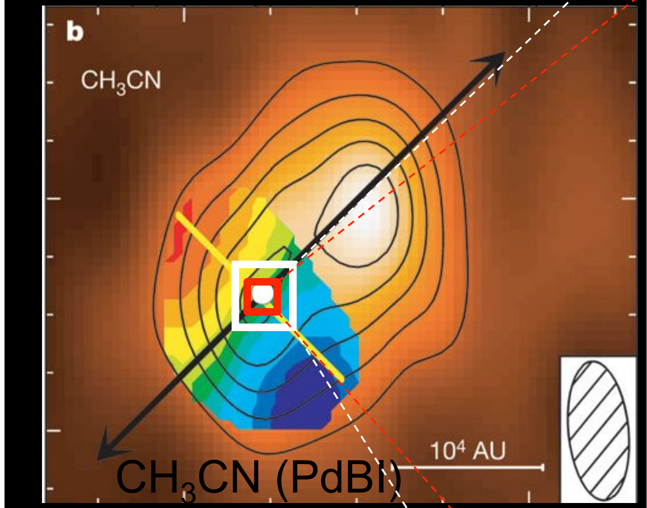
*Goddi, Moscadelli, Sanna 2011*

# Case II: G24.78+0.08 A1

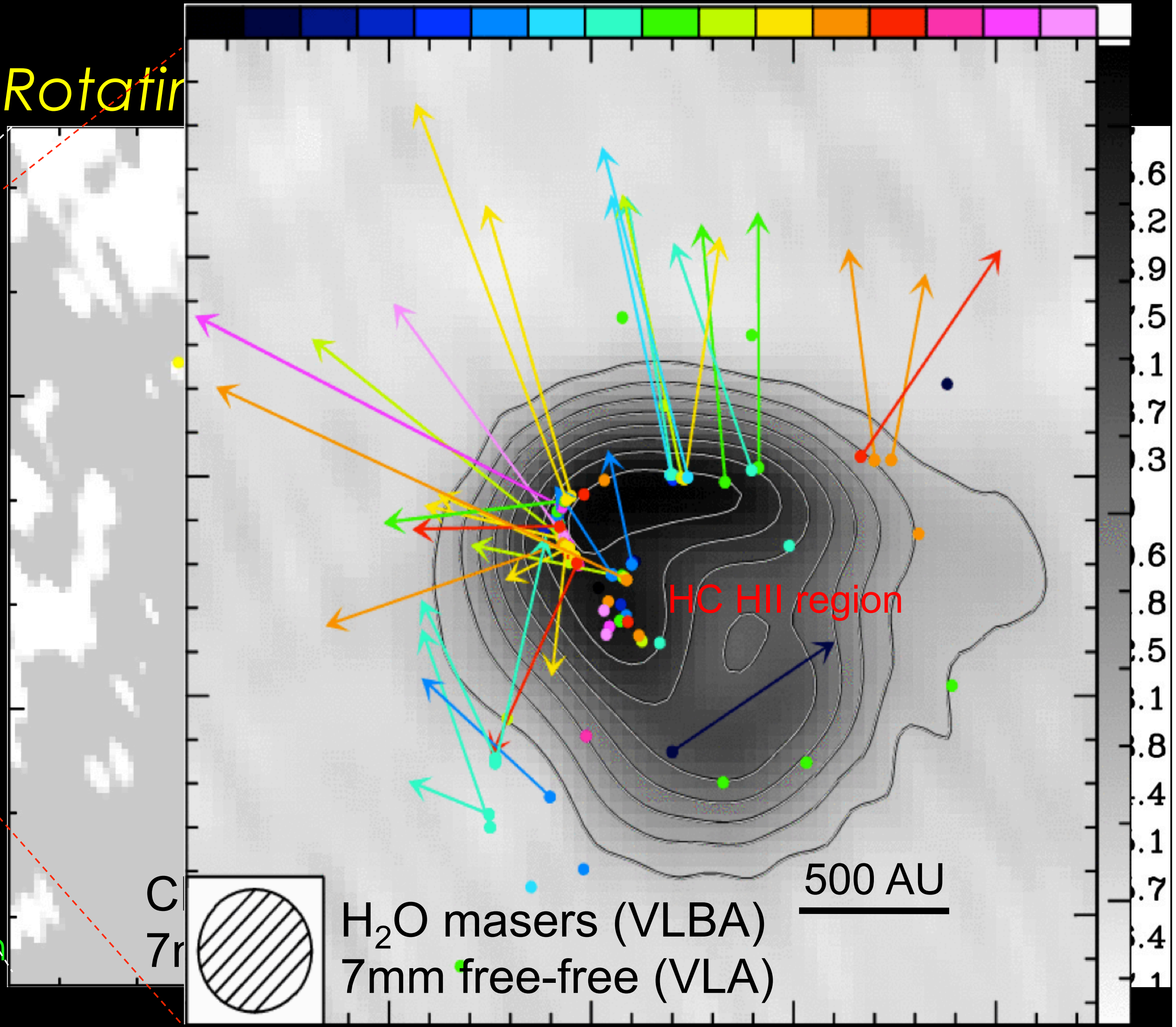
*Wide-angle outflow from $H_2O$ masers*

D~7.7kpc, L~7×$10^4$ $L_\odot$
O9.5 star, 20 $M_\odot$

Rotating toroid from
a dense molecular core



*Rotatir*



Large scales:

HC-HII reg. is confined by a molec. (rotating/infalling) toroid

Small scales:

The HC HII may be expanding based on $H_2O$ masers

Open Q: Has accretion onto the central star(s) ended?

*Moscadelli, Goddi, et al. (2007)*

# Case III: VLBA Movie of the Disk Wind from Source I

## LOS Velocity field

- Time-series over 2 yrs
- SiO v=1,2
  - $T = 21$ months, $\Delta T \sim 1$ month
  - $R < 100$ AU, $\Delta \theta = 0.2$ AU

## Physical flow

- Radial flow (four arms)
- Transverse flow (bridge)

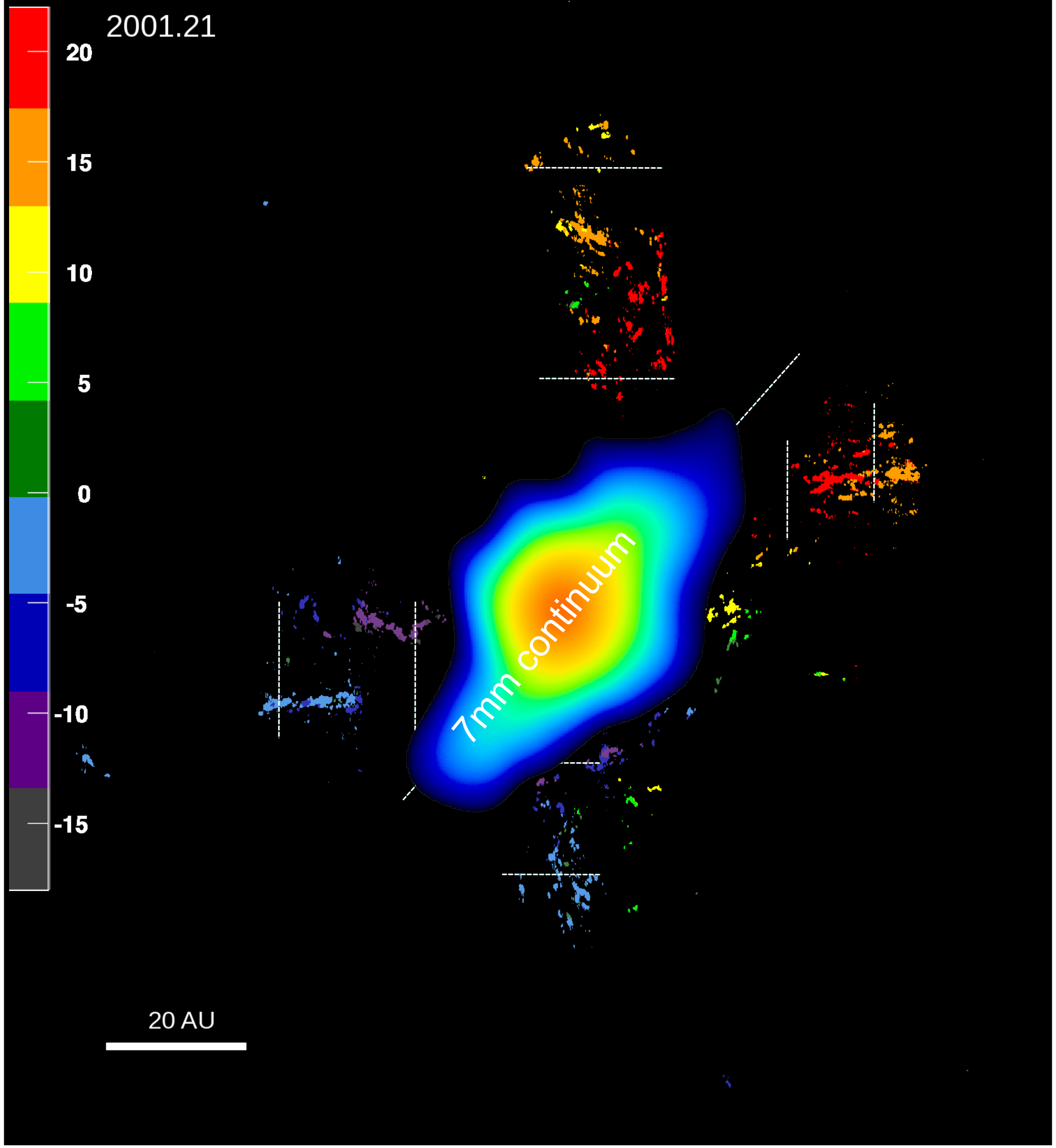
## $V_{LOS}$ rotation

- NE / SW axis
- red/blue arms
  - declining rotation curve
- $\nabla V_{LOS}$ in bridge

## Model

- wide-angle flow (limbs)
- disk rotation

*Matthews, Greenhill, Goddi, et al. 2010*



# What do we know about submm masers in SFRs?

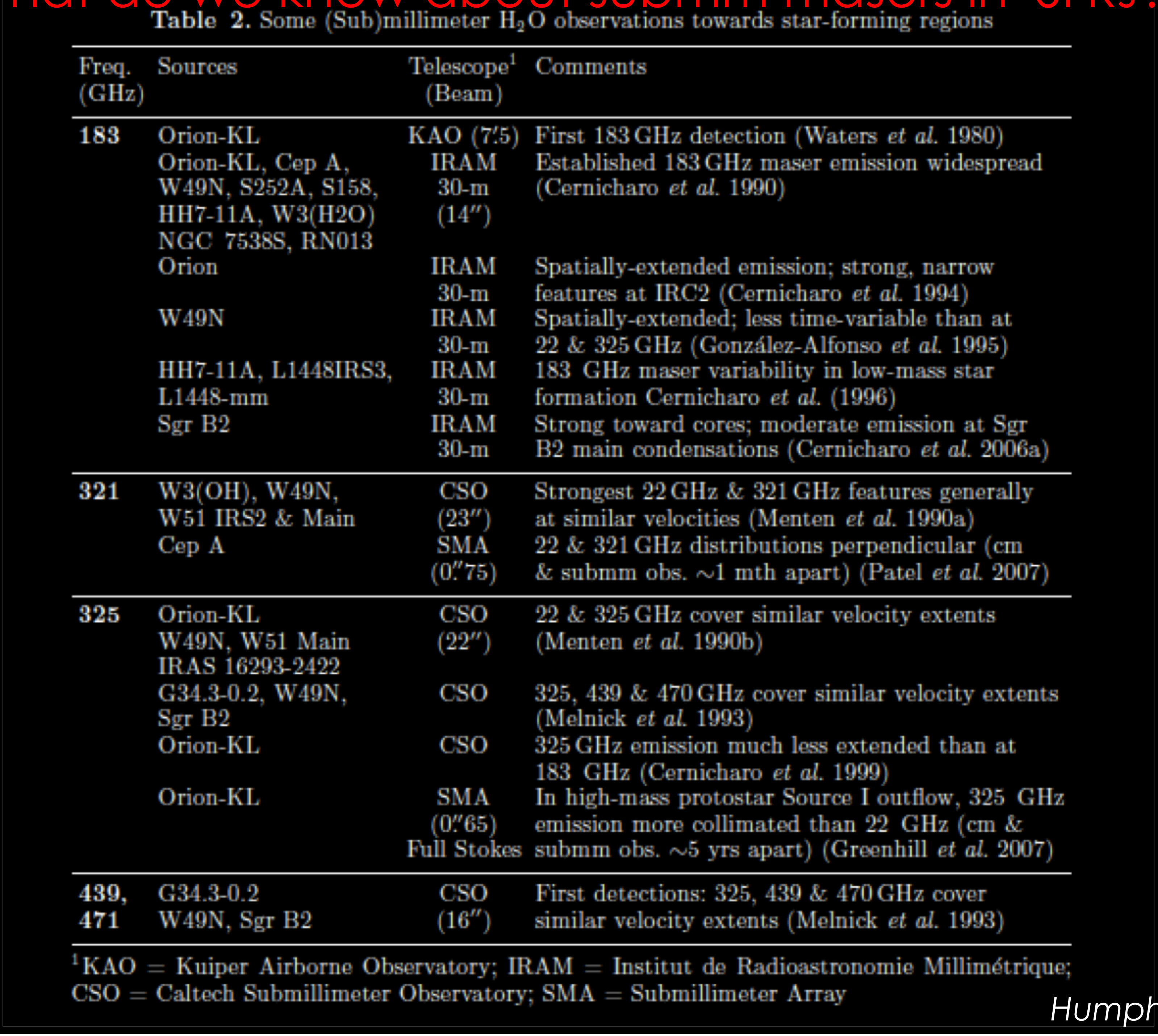


**Table 2.** Some (Sub)millimeter $H_2O$ observations towards star-forming regions

| Freq. (GHz) | Sources | Telescope[1] (Beam) | Comments |
|---|---|---|---|
| **183** | Orion-KL | KAO (7′.5) | First 183 GHz detection (Waters *et al.* 1980) |
| | Orion-KL, Cep A, W49N, S252A, S158, HH7-11A, W3(H2O) NGC 7538S, RN013 | IRAM 30-m (14″) | Established 183 GHz maser emission widespread (Cernicharo *et al.* 1990) |
| | Orion | IRAM 30-m | Spatially-extended emission; strong, narrow features at IRC2 (Cernicharo *et al.* 1994) |
| | W49N | IRAM 30-m | Spatially-extended; less time-variable than at 22 & 325 GHz (González-Alfonso *et al.* 1995) |
| | HH7-11A, L1448IRS3, L1448-mm | IRAM 30-m | 183 GHz maser variability in low-mass star formation Cernicharo *et al.* (1996) |
| | Sgr B2 | IRAM 30-m | Strong toward cores; moderate emission at Sgr B2 main condensations (Cernicharo *et al.* 2006a) |
| **321** | W3(OH), W49N, W51 IRS2 & Main | CSO (23″) | Strongest 22 GHz & 321 GHz features generally at similar velocities (Menten *et al.* 1990a) |
| | Cep A | SMA (0″.75) | 22 & 321 GHz distributions perpendicular (cm & submm obs. ∼1 mth apart) (Patel *et al.* 2007) |
| **325** | Orion-KL W49N, W51 Main IRAS 16293-2422 | CSO (22″) | 22 & 325 GHz cover similar velocity extents (Menten *et al.* 1990b) |
| | G34.3-0.2, W49N, Sgr B2 | CSO | 325, 439 & 470 GHz cover similar velocity extents (Melnick *et al.* 1993) |
| | Orion-KL | CSO | 325 GHz emission much less extended than at 183 GHz (Cernicharo *et al.* 1999) |
| | Orion-KL | SMA (0″.65) Full Stokes | In high-mass protostar Source I outflow, 325 GHz emission more collimated than 22 GHz (cm & submm obs. ∼5 yrs apart) (Greenhill *et al.* 2007) |
| **439, 471** | G34.3-0.2 W49N, Sgr B2 | CSO (16″) | First detections: 325, 439 & 470 GHz cover similar velocity extents (Melnick *et al.* 1993) |

[1] KAO = Kuiper Airborne Observatory; IRAM = Institut de Radioastronomie Millimétrique; CSO = Caltech Submillimeter Observatory; SMA = Submillimeter Array

*Humphreys 2007*

# Why studying submm molecular masers in SFRs?

- Where different maser transitions trace the same gas, we can place new constraints on radiative transfer models to determine temperature and density maps of the circumstellar gas with high spatial resolution

  => e.g. the cm/mm $H_2O$ line ratios can be valuable diagnostics for shocked material in protostellar outflows.

- Where maser lines probe different portions of circumstellar gas and/or different scales, we can map out more of source structures, dynamics, and physical conditions than just with cm lines.

- Submm masers could be particularly important probes of regions in which longer λ maser emission is subject to obscuration (e.g., free-free or synchrotron opacity).

- To understand the physics of the excitation of submm water maser transitions.

- For calibration and commissioning purposes of new submm arrays, as the maser sources with bright narrowband point emission provide excellent targets for assessment of the delays, pointing, baselines as well as strong phase calibrators

*However the lack of angular resolution at submm wavelengths has, until recently*

# 321 GHz $H_2O$ masers in Cepheus-A HW2

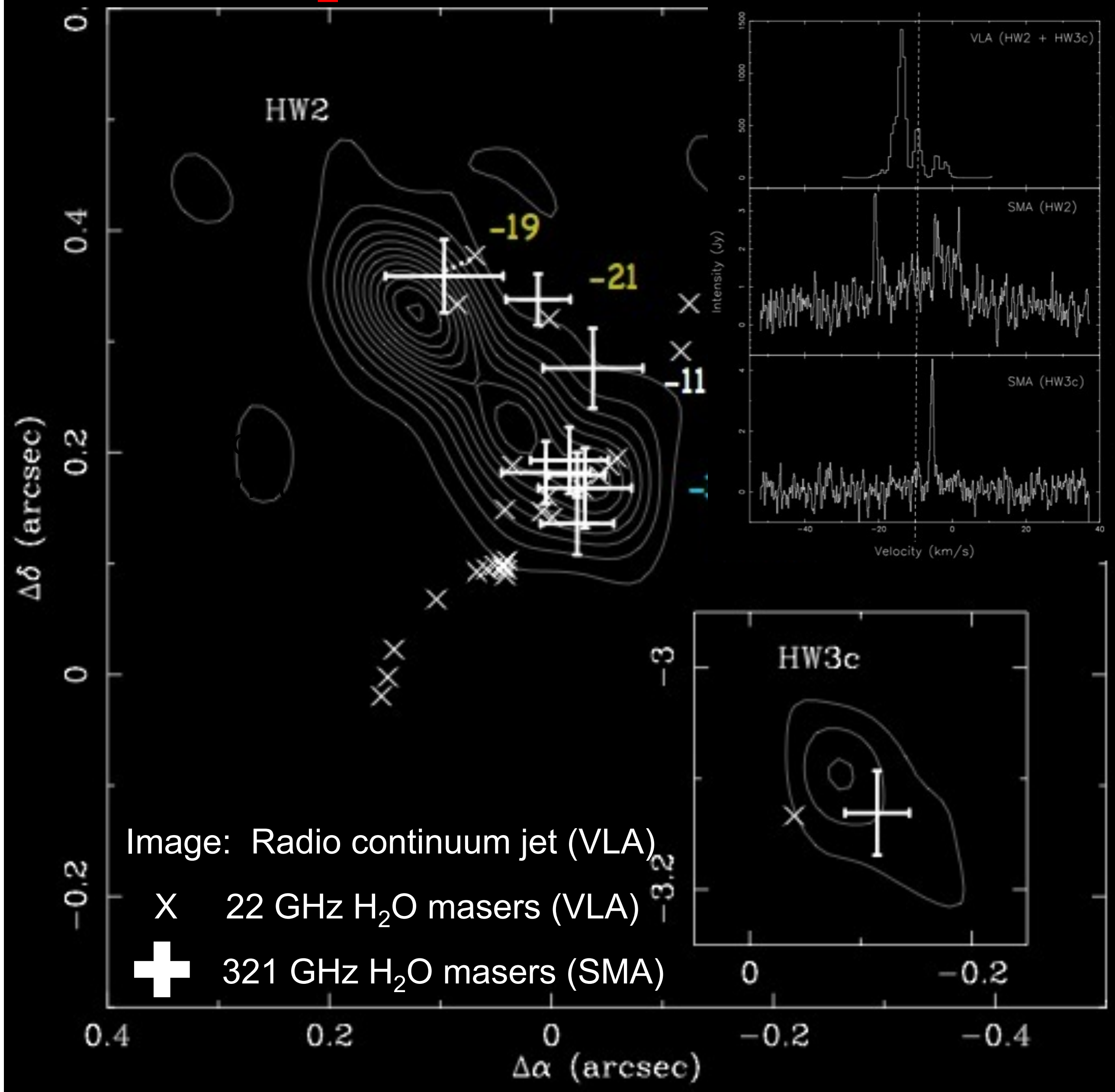


Image: Radio continuum jet (VLA)

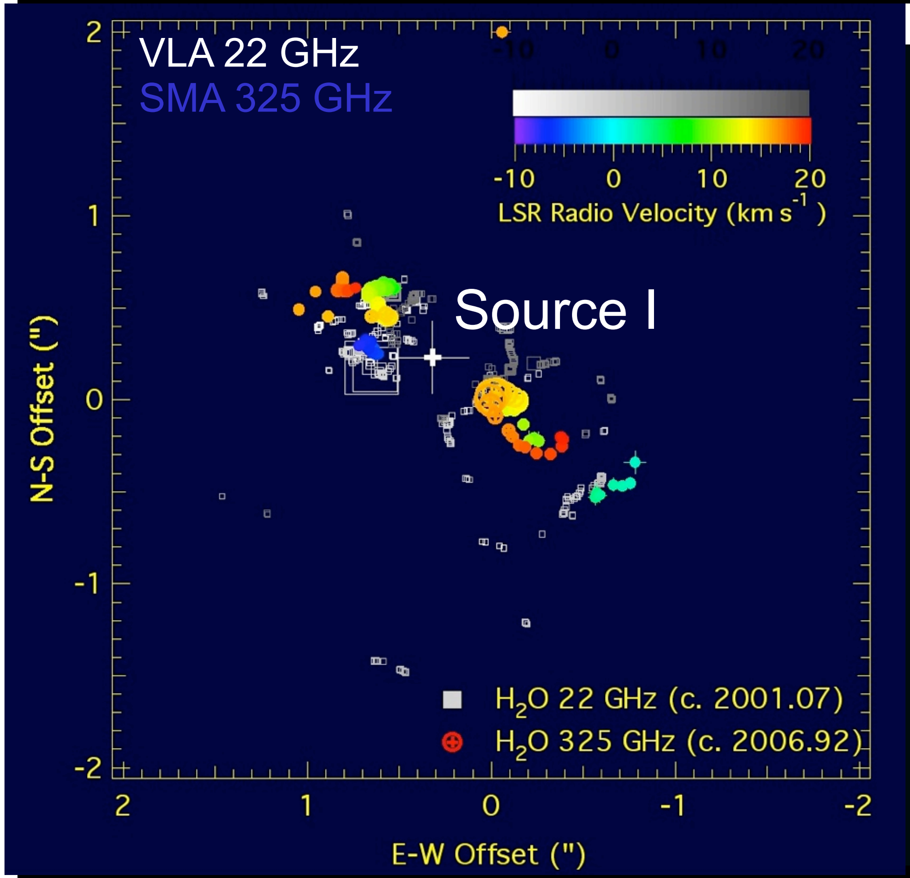
X 22 GHz $H_2O$ masers (VLA)

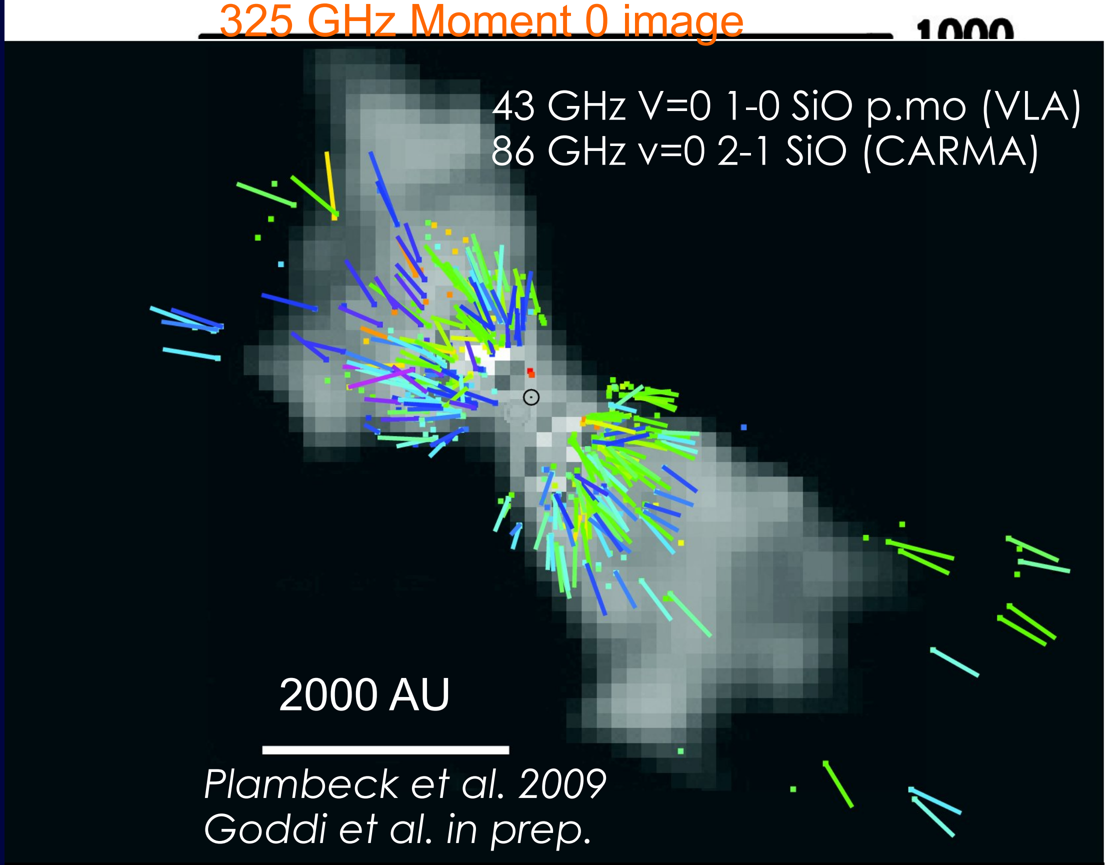
✚ 321 GHz $H_2O$ masers (SMA)

- Only 3 out of 9 submillimeter masers are associated with 22 GHz masers
- The two transitions trace two linear structures roughly perpendicular to each other
- Submm masers trace the outflow jet, presumably arising in hotter gas (1000~2000 K) than the 22 GHz (~400 K)

*Patel et al. 2007*

# 325 GHz $H_2O$ masers in Orion Source I





*Plambeck et al. 2009*
*Goddi et al. in prep.*

- The 325 GHz $H_2O$ masers trace a bipolar collimated outflow originating from Source I
- A V-gradient perpendicular to the outflow axis may indicate rotation: magnetic collimation?
- $H_2O$ masers strongly polarized: Ordered B-field @ $10^2$-$10^3$AU in the protostellar outflow?
- Strong correspondence of 22 and 325 GHz emission over 24 yrs along the outflow
    - 325 GHz emission appears to trace a more collimated region than the 22 GHz emission
    - Favored similar excitation conditions of 22 GHz ortho and 325 GHz para maser emission

*Niederhofer, Humphreys, Goddi, et al. 2012*
*Greenhill, Goddi, et al. in prep.*

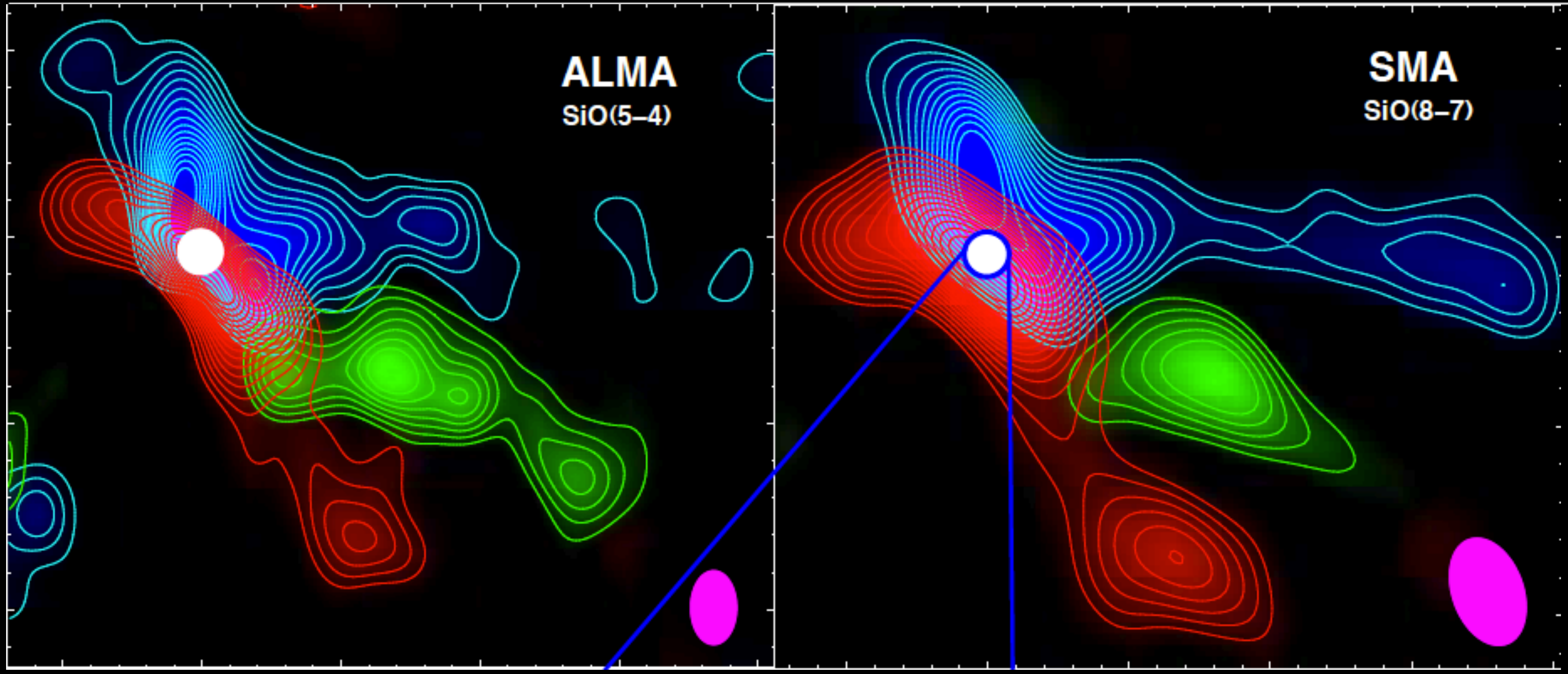
# How about ALMA?

# ALMA Band 6 Survey of Orion-KL

ALMA Observational Parameters

| | |
|---|---|
| Number of Antennas | 16 in compact ES Cycle 0 configuration |
| Frequency Range | 214 -246 GHz (lower 2/3 of total frequency range in ALMA Band 6) |
| Weather Conditions | PWV∼2.3-2.8 (Obs. Setup 1), ∼1.8-2.6 (Obs. Setup 2), ∼1.8-2.5 (Obs. Setup 3) |
| Array Resolution | ∼1.7" |
| Number of Spectral Windows | 20 (3,840 channels each) |
| Spectral Resolution | ∼1MHz |
| Time on Science Target | 75 min in total |
| Theoretical Sensitivity | 0.009 Jy |

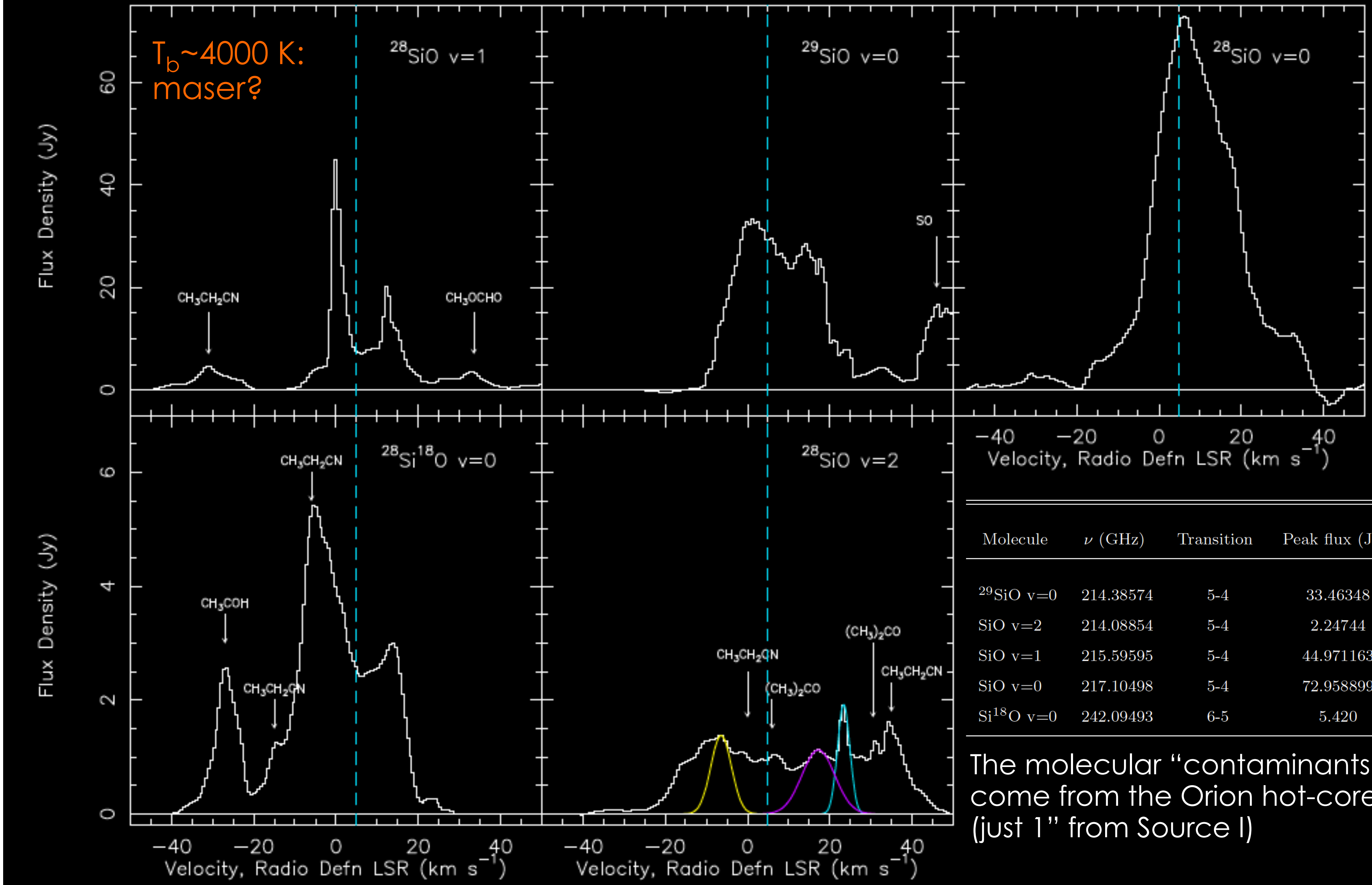
Thermal (v=0) SiO emission



Zapata et al., arXiv:1206.3600

*Based on science verification data: ADS/JAO.ALMA#2011.0.00009.SV*

# ALMA Band 6 J=5-4 SiO lines in Orion Source I



| Molecule | $\nu$ (GHz) | Transition | Peak flux (Jy) |
|---|---|---|---|
| $^{29}$SiO v=0 | 214.38574 | 5-4 | 33.46348 |
| SiO v=2 | 214.08854 | 5-4 | 2.24744 |
| SiO v=1 | 215.59595 | 5-4 | 44.971163 |
| SiO v=0 | 217.10498 | 5-4 | 72.958899 |
| Si$^{18}$O v=0 | 242.09493 | 6-5 | 5.420 |

The molecular “contaminants” come from the Orion hot-core (just 1” from Source I)

*Based on science verification data: ADS/JAO.ALMA#2011.0.00009.SV*

*Niederhofer, Humphreys, Goddi, et al. in prep.*

# ALMA observations of submm $H_2O$ masers with 2km BL

- Transitions: 321 GHz, 325 GHz (Band 7), 658 GHz (Band 9) $H_2O$ masers

- Targets: known bright $H_2O$ maser sources (peak>~100 Jy)
  - SFRs: W49-North, W51-Main, W51-North (only 321/325 GHz)
  - AGB stars: (only 658 GHz)

- Baselines: <400 m (~20 antennas) and ~2 km (only one antenna!)

- 3 datasets taken with different LST on different days ($T_{int}$~20min per source)
  - ➢ earth rotation synthesis enabled to obtain a sufficiently complete uv-coverage to produce images

*N.B.: science demonstration with 2 km BL, test data, not released yet!*

*Other Contact ALMA persons: Violette Impellizzeri, Eric Villard*

# mm VLBI of molecular masers in SFRs

Case I: (sub)mm VLBI to study masers : phasing ALMA with other (sub)mm telescopes

**Resolution**: We still need VLBI to measure p.m., 3D gas dynamics, and maybe even produce movies as in the case of Orion Source I

Example: Maser features with $F_{peak}$=O(1 Jy) moving with $V_{outflow}$ = 20 km/s (as in Source I)
*p.m.* **<** 1 mas/yr for d > 5 kpc

- ALMA only :
  pwv =0.5 mm, $V_{chan}$=0.5 km/s chan, rms=0.01 Jy, $T_{on}$=4.5 hrs => SNR = 100
  BL=14.5 km => resolution=15 mas (at 300 GHz)
  => Relative position accuracy = 0.1 mas

=> Only Proper motions >10 mas/yr could be measured over 1 month with SNR=10

- mm VLBI (e.g., EHT) :

  resolution~20-40 µas at frequencies of 230 GHz and 345 GHz

*=> Proper motions >0.02 mas/yr could be measured over 1 month with SNR=100*

**Sensitivity**: the inclusion of ALMA is essential to any (sub)mm VLBI array

# mm VLBI of molecular masers in SFRs

## Case II: Phasing ALMA at 7mm and 3mm with the VLBA: HSA

- 7mm (43 GHz) and 3mm (86 GHz ) routinely observed at the VLBA
  => provides 120 uas, the highest angular resolution imaging in astronomy

- Phasing ALMA will:
  I. more than double angular resolution of the VLBA at 7mm and 3mm
  II. add very sensitive new North-South baselines (the total collecting area of ALMA exceeds the collecting area of the VLBA)

- Examples of experiments that could benefit:
  1. Absolute astrometry with phase-reference technique:
     => To date limited to cases where strong calibrators (F>100 mJy) are present within O(1°) from the maser source
  2. high dynamic range imaging by including short spacings: essential maser emission where strong maser features may occur at similar velocities as weak maser features

- Also phasing a JVLA (sub)array at 7mm enables to improve the sensitivity and dynamic range of maser images at 7mm