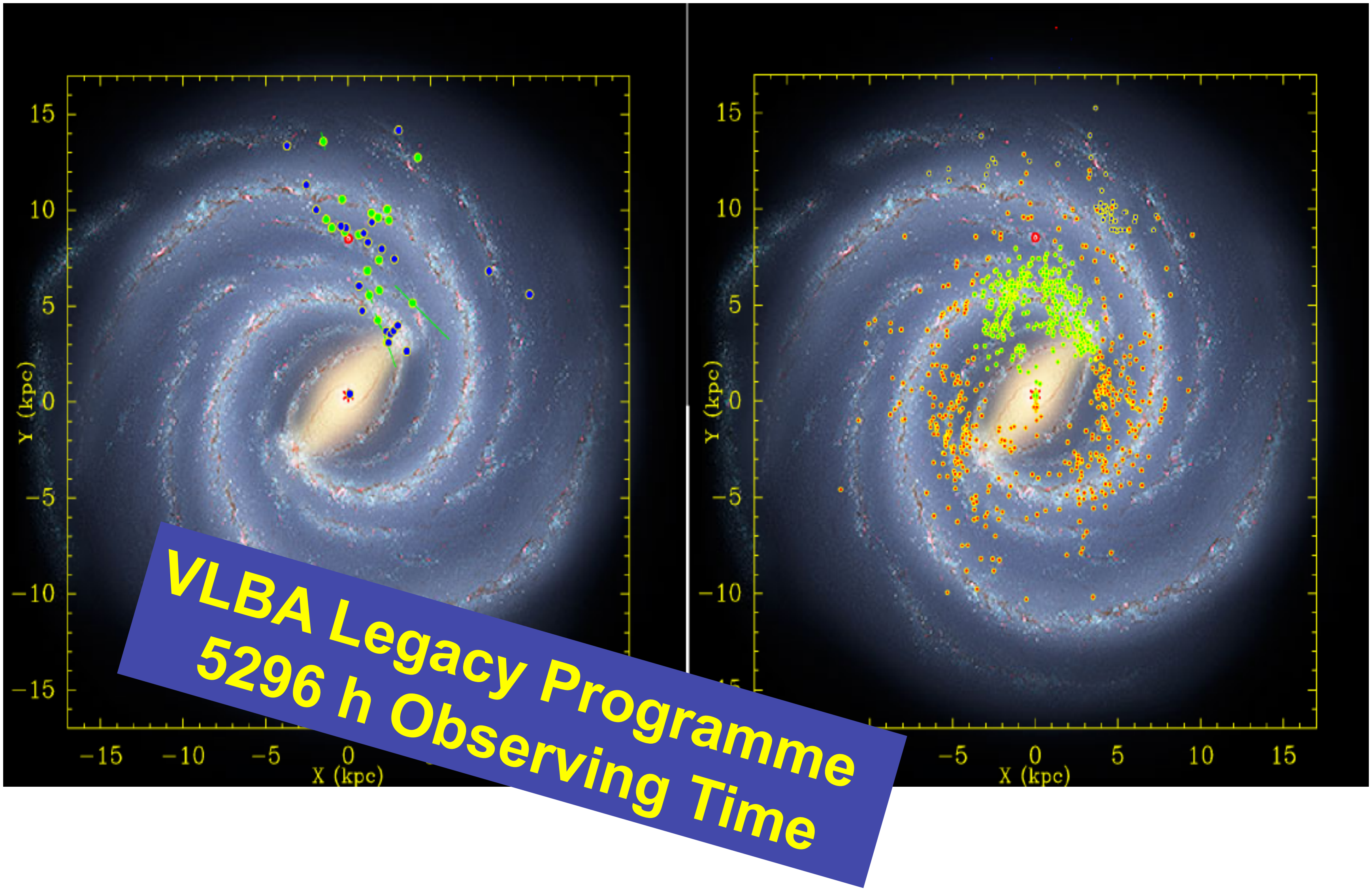
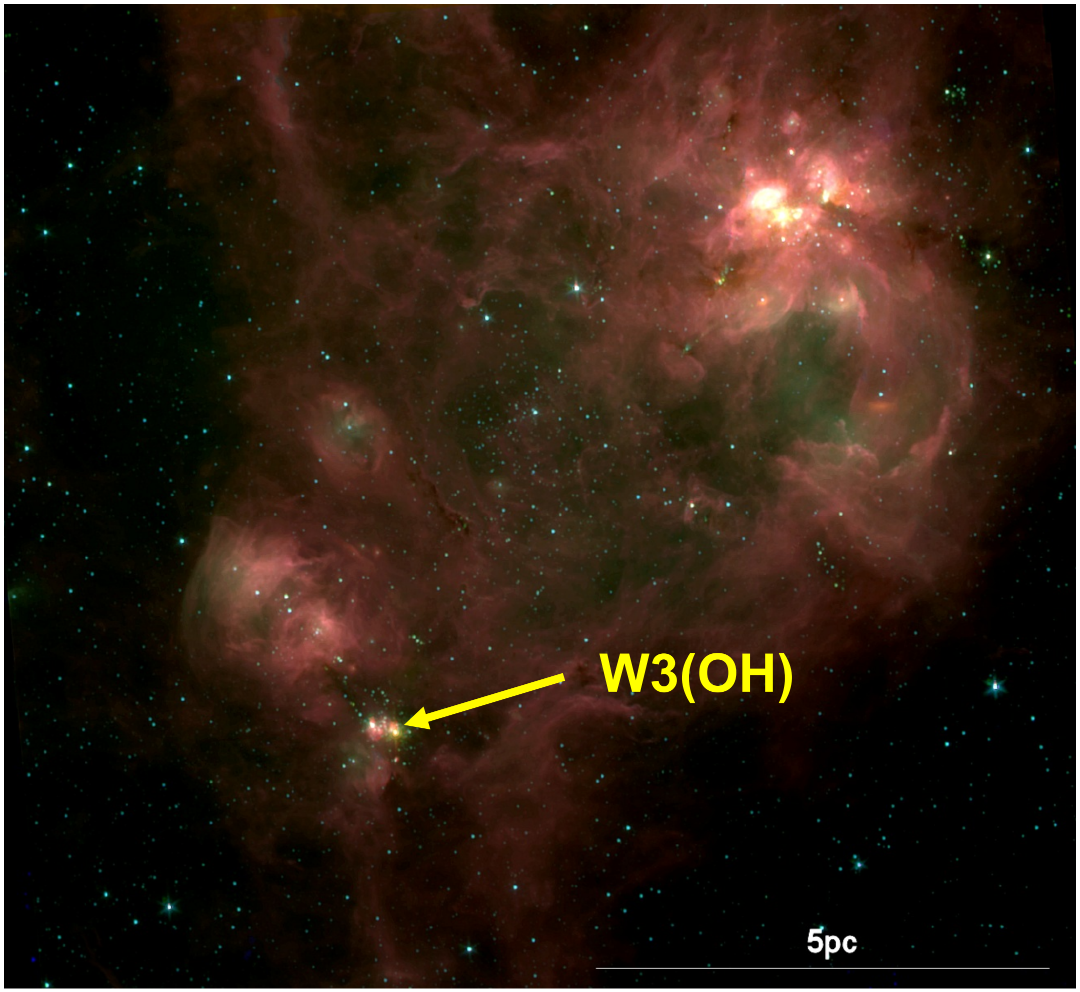
# Spiral Structure and Kinematics of the Milky Way Using $H_2O$ and Methanol Masers: Plans for the Future

**Karl M. Menten**

**Max-Planck-Institut für Radioastronomie, Bonn**


VLBA Legacy Programme
5296 h Observing Time
Y (kpc)
X (kpc)
15
10
5
0
−5
−10
−15

# Milky Way Parallaxes




T. Megeath (Spitzer Space Telescope)

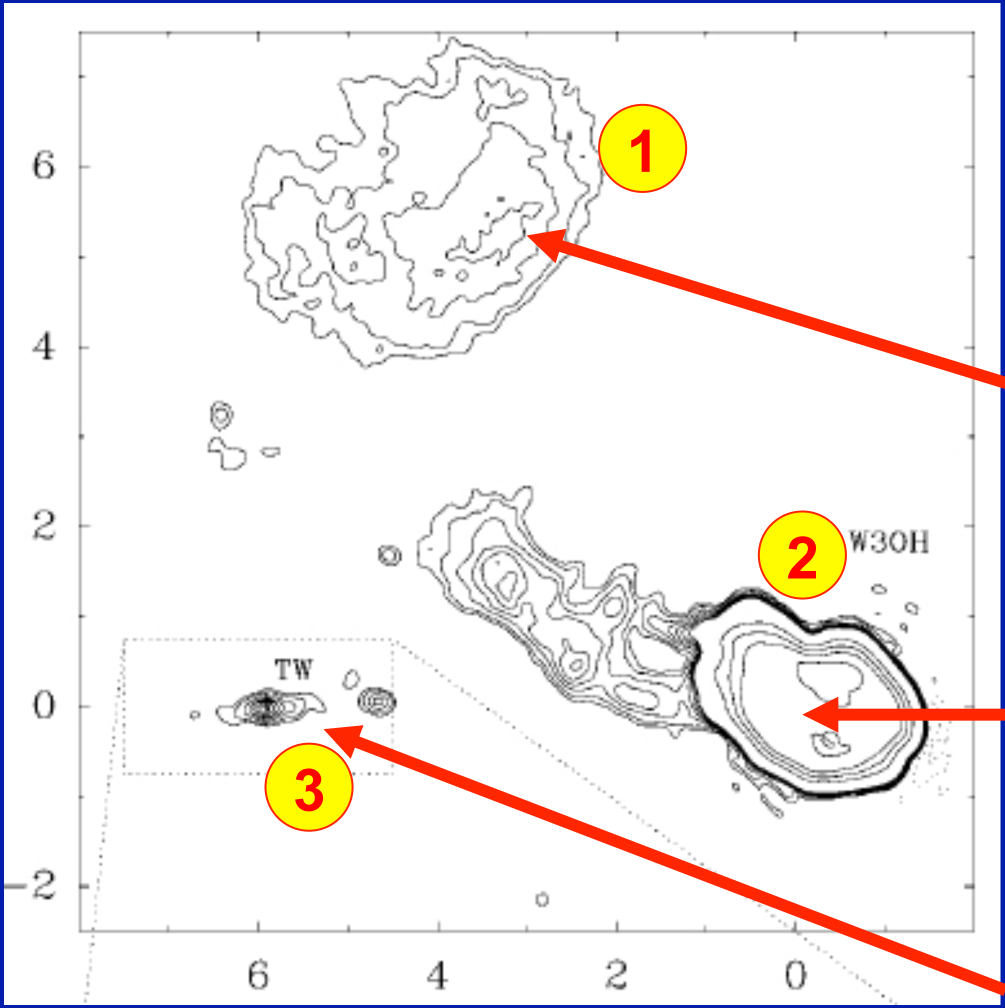
Distance estimates:

Kinematic = 4.3 kpc

Photometric = 2.2 kpc

(R. Humphreys 1970’s)

# The W3OH region – different stages of high-mass star formation



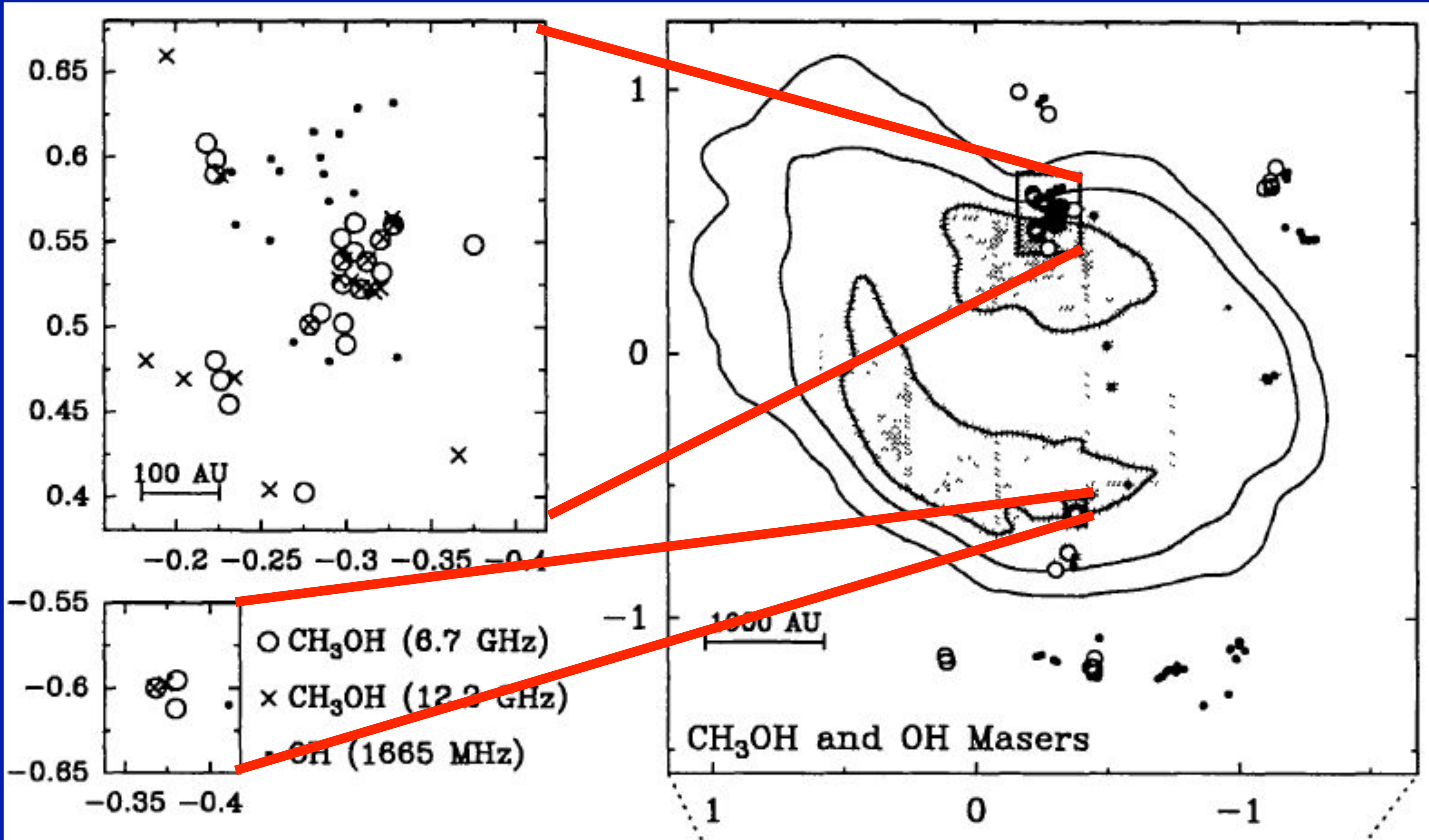

Wilner, Reid, & Menten 1995

1) CHII region: dynamical age ~ 5000 yr

2) UCHII region: dynamical age 2300 yr

⇐ Kawamura & Masson (1998) use VLA to determine expansion between 1986 and 1995

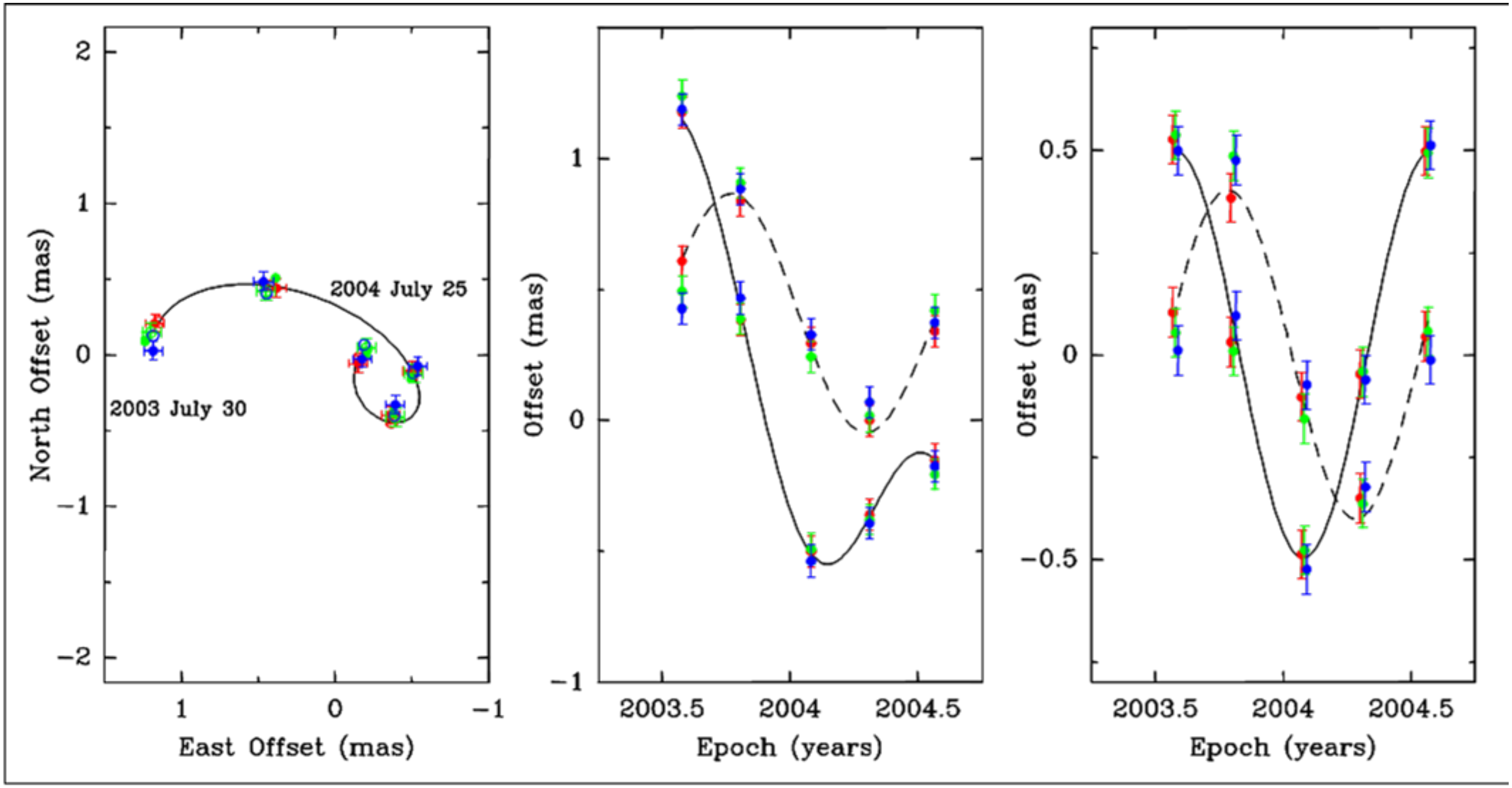
3) Even younger: Turner-Welch (1984) object




**W3OH**

Menten et al. 1988,1992

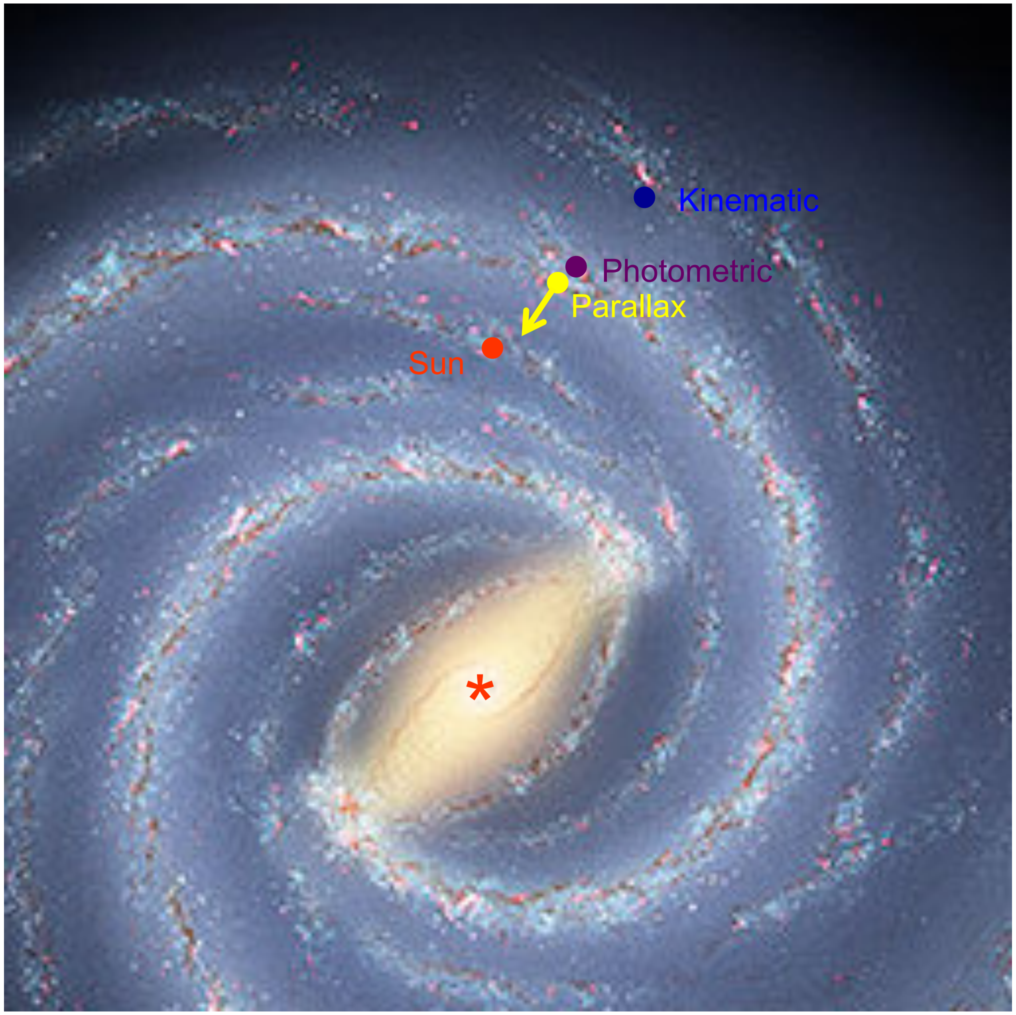
# W3OH Parallax




Xu, Reid, Zheng & Menten
(Science, 2006)

$\pi$ = 0.512 +/- 0.010 mas

# The Distance to the Perseus Arm: W3OH Parallaxes




**Distance estimates:**

Kinematic = 4.3 kpc

Photometric = 2.2 kpc

R. Humphreys 1970's

**Maser parallaxes:**

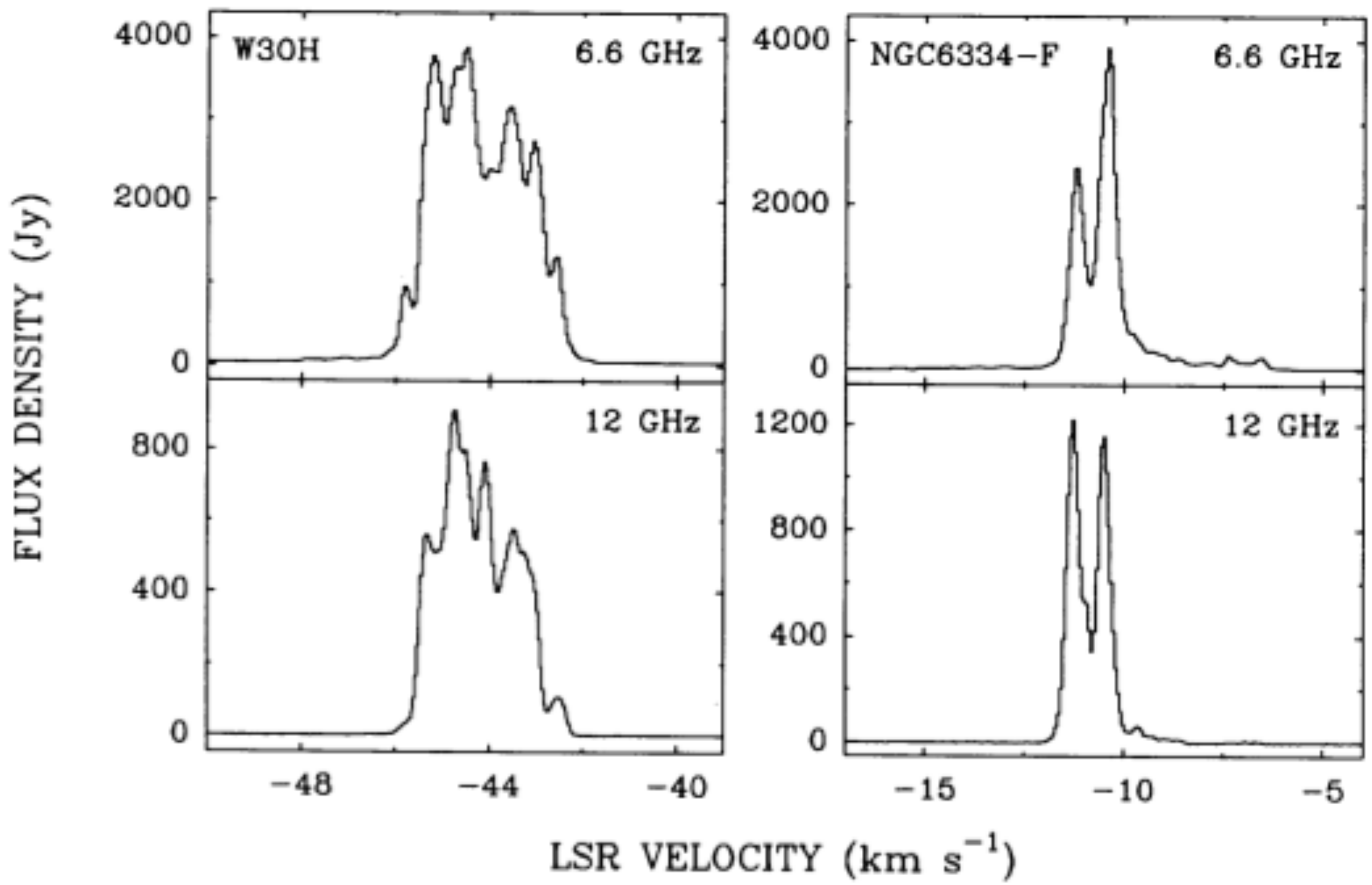
$CH_3OH$ 1.95±0.04 kpc

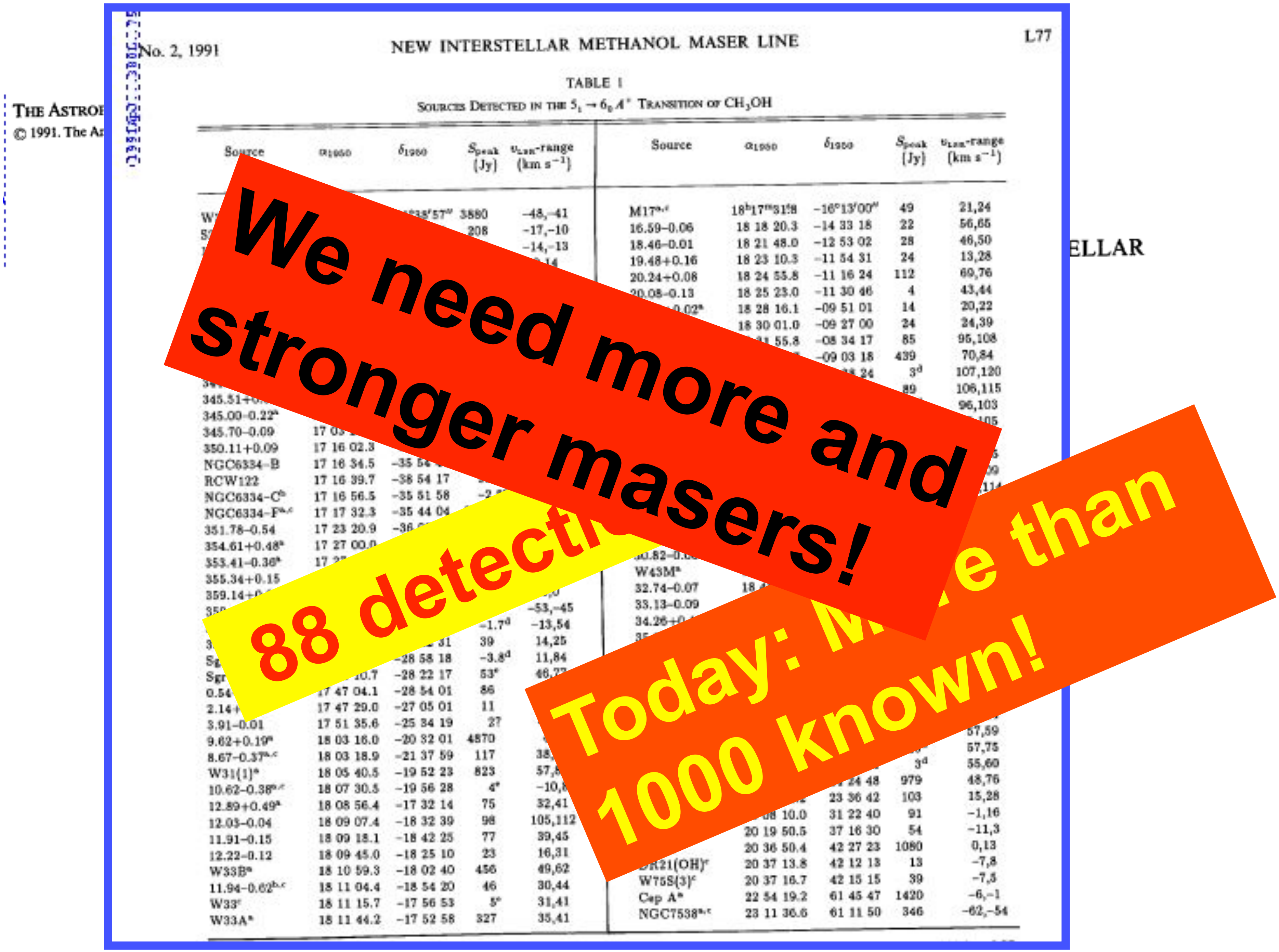
$H_2O$ 2.04±0.07 kpc

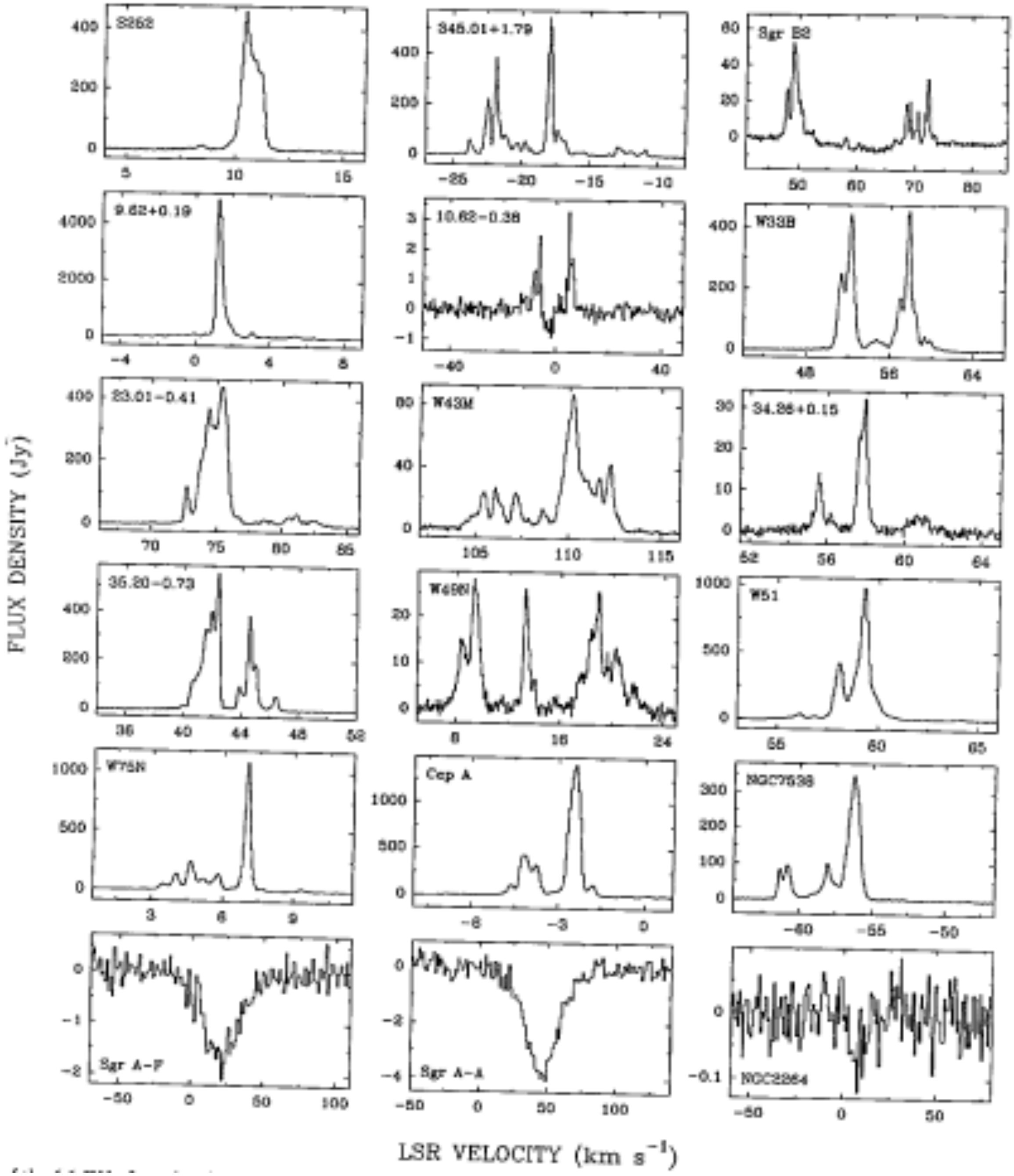
Hachisuka et al. 2006

- $D_{photo} \sim D_{parallax}$
- $D_k$ way off
- In Perseus Arm, not in Outer Arm
- Large peculiar V

MENTEN (1991)

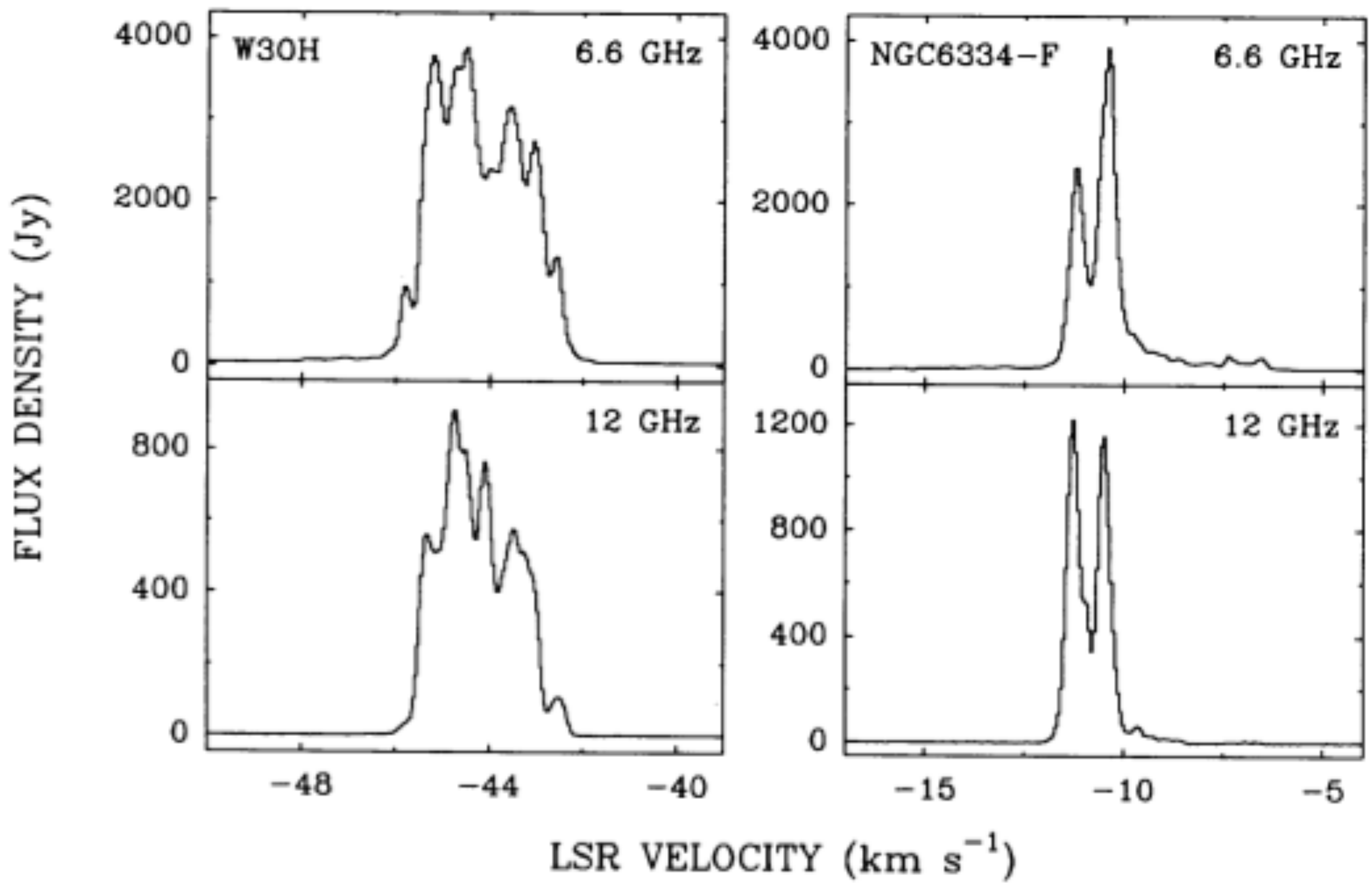

W3OH
6.6 GHz
12 GHz
NGC6334-F
6.6 GHz
12 GHz
FLUX DENSITY (Jy)
4000
2000
0
800
400
0
4000
2000
0
1200
800
400
0
−48
−44
−40
−15
−10
−5
LSR VELOCITY (km s⁻¹)


No. 2, 1991
NEW INTERSTELLAR METHANOL MASER LINE
L77
TABLE 1
Sources Detected in the $5_1 \rightarrow 6_0 A^+$ Transition of $CH_3OH$
We need more and stronger masers!
88 detections
Today: More than 1000 known!


S252
345.01+1.79
Sgr B2
9.62+0.19
10.62-0.38
W33B
23.01-0.41
W43M
34.26+0.15
35.20-0.73
W48N
W51
W75N
Cep A
NGC7538
Sgr A-F
Sgr A-A
NGC2264
FLUX DENSITY (Jy)
LSR VELOCITY (km s$^{-1}$)

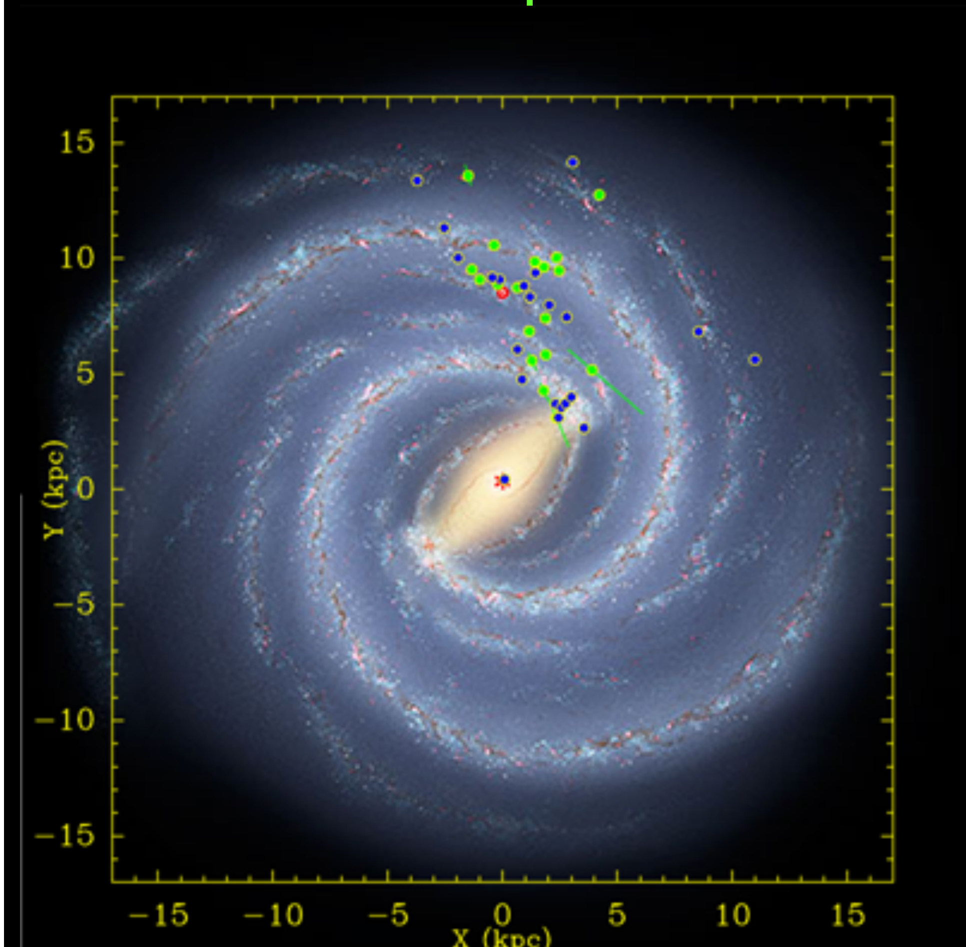
Menten 1991

## MENTEN (1991)

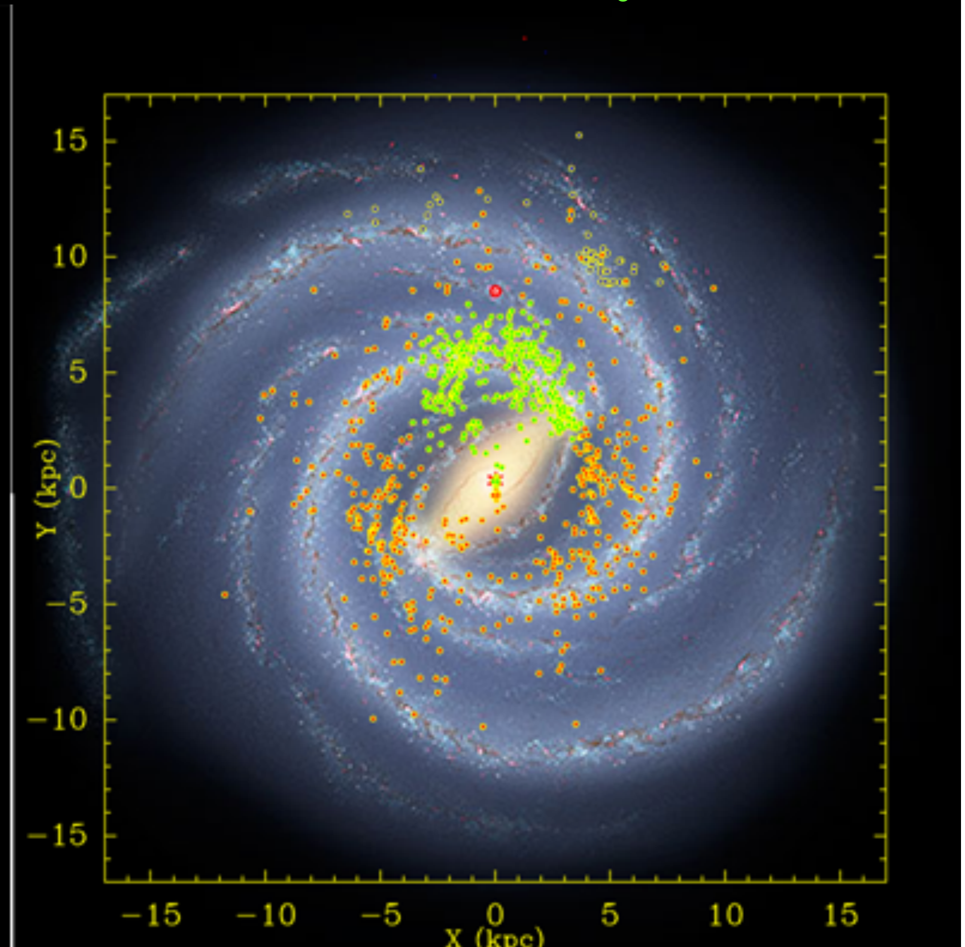


W3OH
6.6 GHz
12 GHz
NGC6334-F
6.6 GHz
12 GHz
FLUX DENSITY (Jy)
LSR VELOCITY (km s$^{-1}$)
4000
2000
0
800
400
0
4000
2000
0
1200
800
400
0
−48
−44
−40
−15
−10
−5

**Masers with parallaxes**




**Catalogued 6.7 GHz $CH_3OH$ Masers**

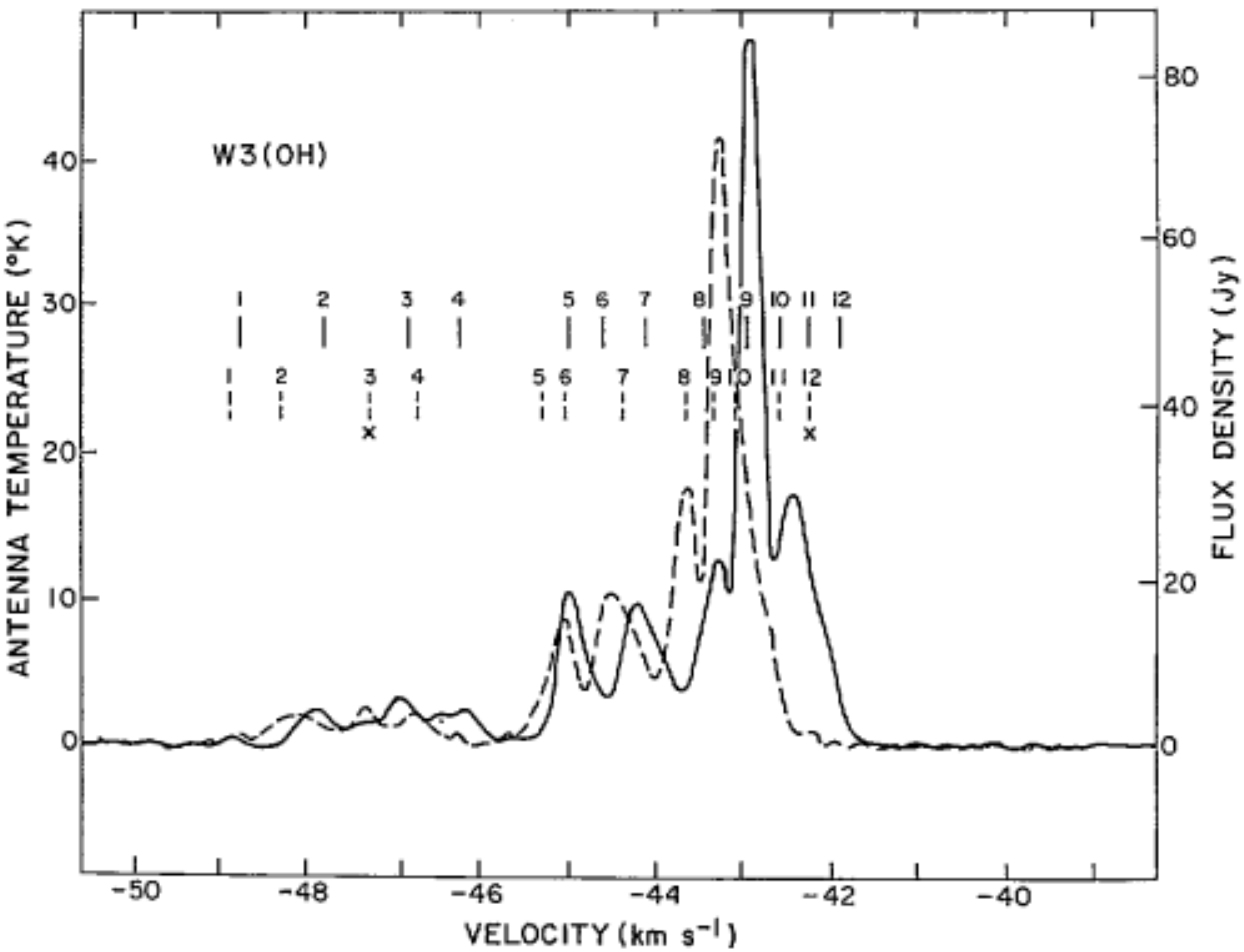



- near kinematic distance
- far kinematic distance

# VLBA C-band upgrade: More Masers

| Species | Transition | Frequency (MHz) | Number/Type |
|---|---|---|---|
| OH $^2\Pi_{3/2}$ | $J=\frac{3}{2}, F=1\rightarrow 2$ | 1612.2310(2) | $T$ SFR/$H$ O-CSE |
| | $F=1\rightarrow 1$ | 1665.4018(1) | $H$ SFR/$T$ O-CSE |
| | $F=2\rightarrow 2$ | 1667.3590(1) | $H$ SFR/$T$ O-CSE |
| | $F=2\rightarrow 1$ | 1720.5300(1) | $H$ SFR |
| | $J=\frac{5}{2}, F=2\rightarrow 2$ | 6030.747(5) | $T$ SFR |
| | $F=3\rightarrow 3$ | 6035.092(5) | $T$ SFR |
| | $J=\frac{7}{2}, F=4\rightarrow 4$ | 13441.4173(2) | $S$ SFR/$T$ SNR |
| OH $^2\Pi_{1/2}$ | $J=\frac{1}{2}, F=0\rightarrow 1$ | 4660.242(3) | $T$ SFR |
| | $F=1\rightarrow 1$ | 4750.656(3) | $T$ SFR |
| | $F=1\rightarrow 0$ | 4765.562(3) | $T$ SFR |
| $H_2O$ | $J_{K_a,K_c}=6_{16}\rightarrow 5_{23}$ | 22235.08(2) | $H$ SFR/$H$ O-CSE |
| $CH_3OH$[a] | $J_k=5_1\rightarrow 6_0 A^+$ | 6668.5192(8) | $H$ SFR/Cl II |
| | $9_{-1}\rightarrow 8_{-2} E$ | 9936.202(4) | $1$ SFR/Cl I (W33-Met) |
| | $2_0\rightarrow 3_{-1} E$ | 12178.597(4) | $H$ SFR/Cl II |

MORAN *ET AL.* 1978




**OH 6035 GHz**

## VLBA C-band upgrade:

**3 times higher continuum sensitivity**

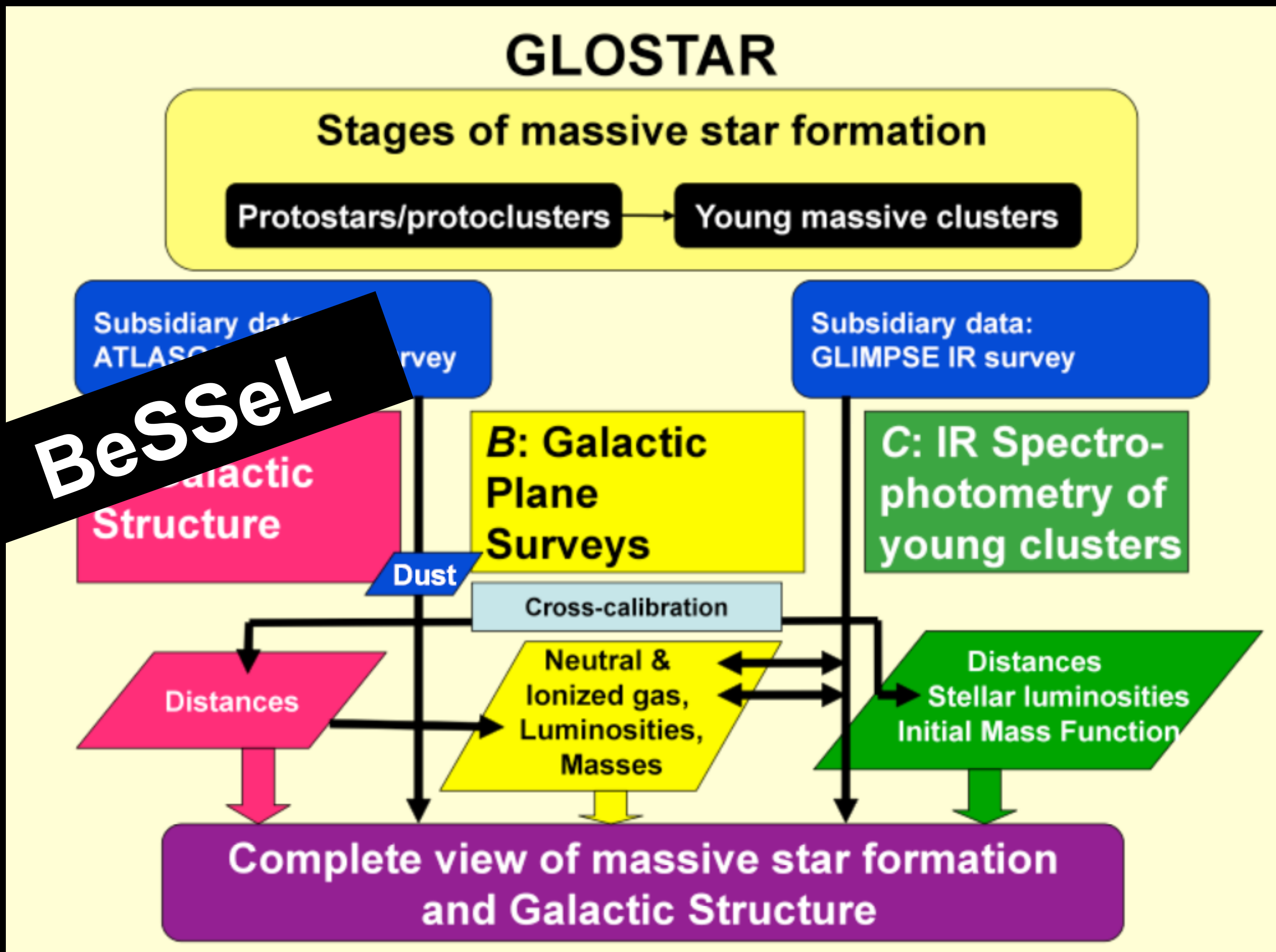
- **weaker (closer-by) phase referencing sources**


Bar and Spiral Structure Legacy Survey,
a VLBA Key Science Project

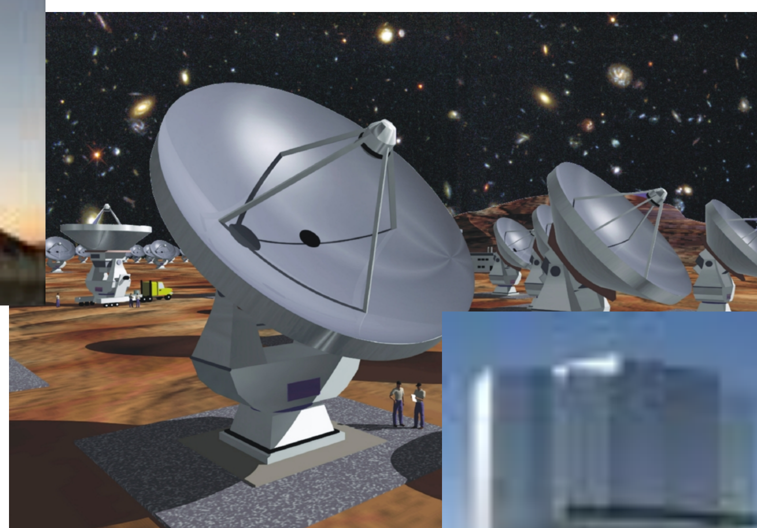
# The BeSSeL Team:

| | |
|---|---|
| **Mark Reid (PI),** Tom Dame, Mayumi Sato | Harvard-Smithsonian Center for Astrophysics, USA |
| **Karl Menten**, Andreas Brunthaler, Yoon Kyung Choi, Bo Zhang, Kazi Rygl, Katharina Immer, & Alberto Sanna | Max-Planck-Institut für Radioastronomie, Germany |
| **Xing-Wu Zheng** | Nanjing University, China |
| Ye Xu | Purple Mountain Observatory, Nanjing, China |
| Kazuya Hachisuka | Shanghai Astronomical Observatory, China |
| Luca Moscadelli | Osservatorio di Arcetri Observatory, Florence, Italy |
| George Moellenbrock | National Radio Observatory, USA |
| Anna Bartkiewicz | Torun Centre for Astronomy, Poland |

**GLOSTAR: A Global View of Star Formation in the Milky Way**
**European Research Council Advanced Investigator Grant**





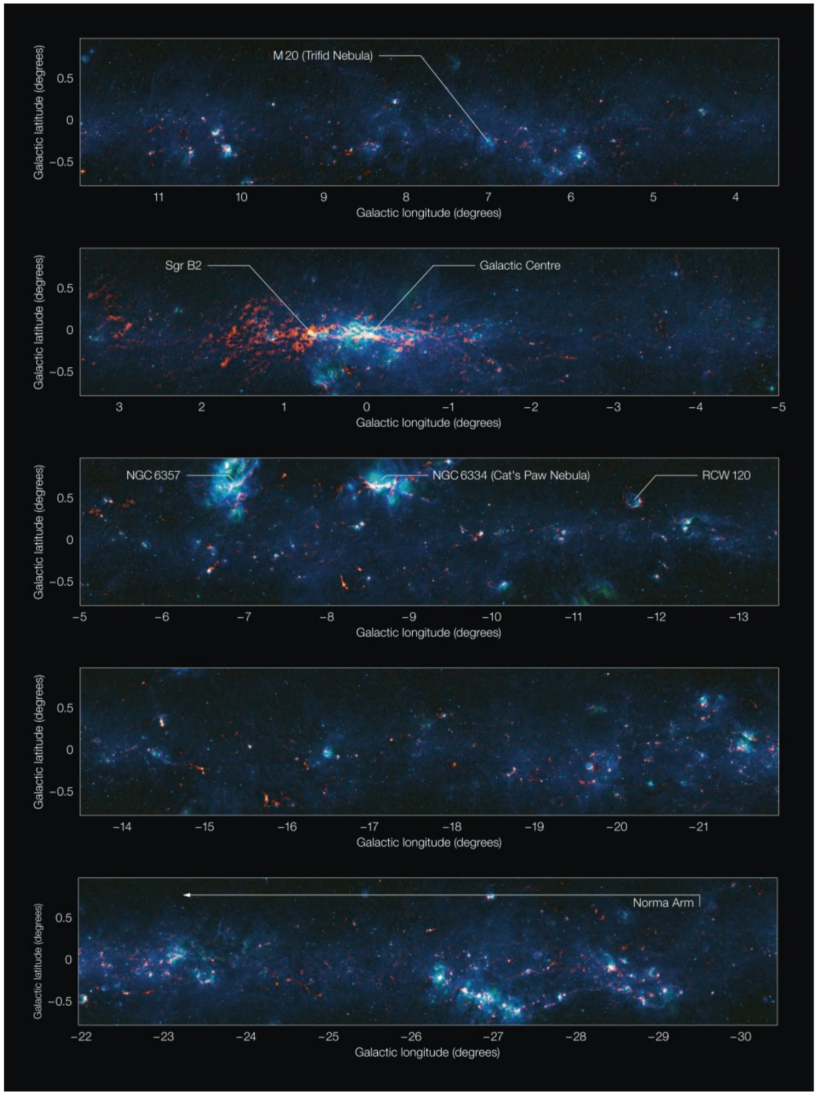




# GLOSTAR B: A comprehensive galactic plane radio and submillimeter star formation survey

**APEX Telescope LArge Survey: The GALaxy**

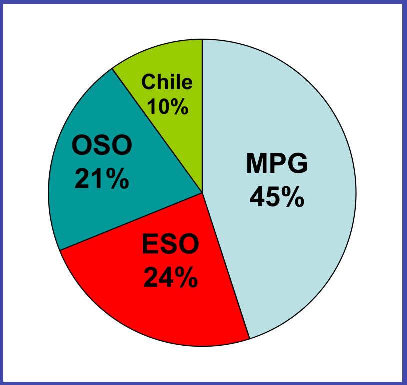
**ATLASGAL**

Expanded Very Large Array



# The Atacama Pathfinder Experiment (APEX)

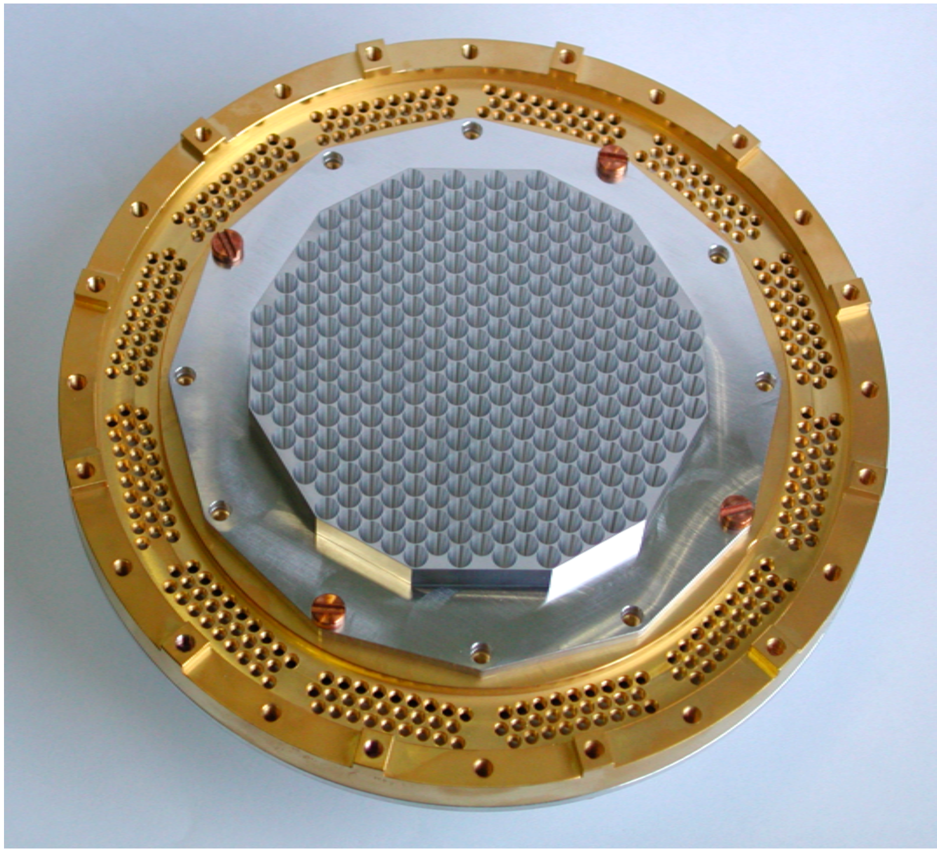
Built and operated by
• Max-Planck-Institut fur Radioastronomie
• Onsala Space Observatory
• European Southern Observatory
on
Llano de Chajnantor (Chile)
Longitude: 67° 45' 33.2" W
Latitude: 23° 00' 20.7" S
Altitude: 5098.0 m



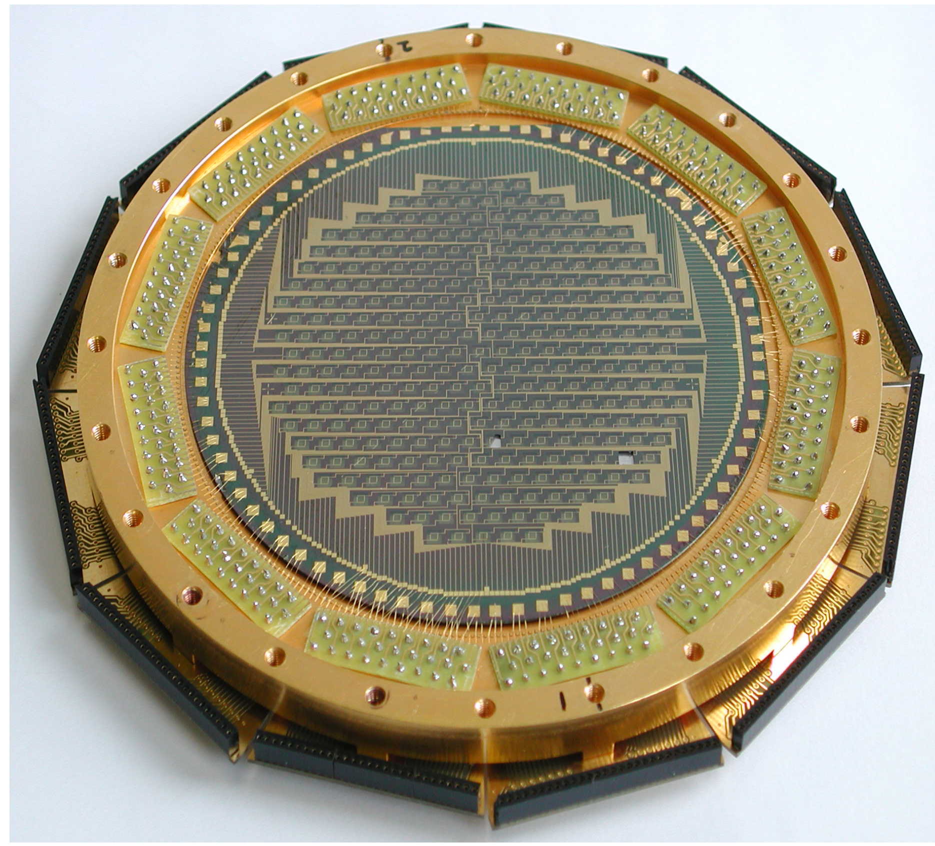

• ∅ 12 m
• $\lambda$ = 200 μm – 2 mm
• 15 μm rms surface accuracy
• In operation since September 2010
• PI and facility instruments:
    • 200 –1400 GHz GHz heterodyne RX
    • 295 element 870 μm Large Apex Bolo meter Camera (LABOCA)

http://www.mpifr-bonn.mpg.de/div/mm/apex/

# The Large APEX Bolometer Camera – LABOCA



Horn array



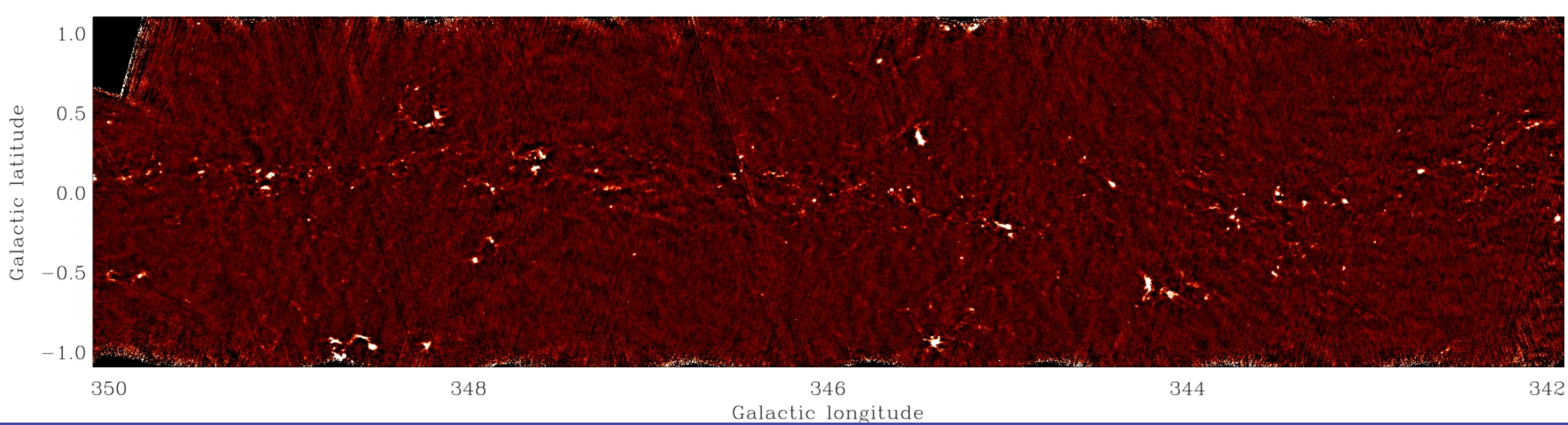
Bolometer array

# ATLASGAL – APEX Telescope Large Survey: The Galaxy

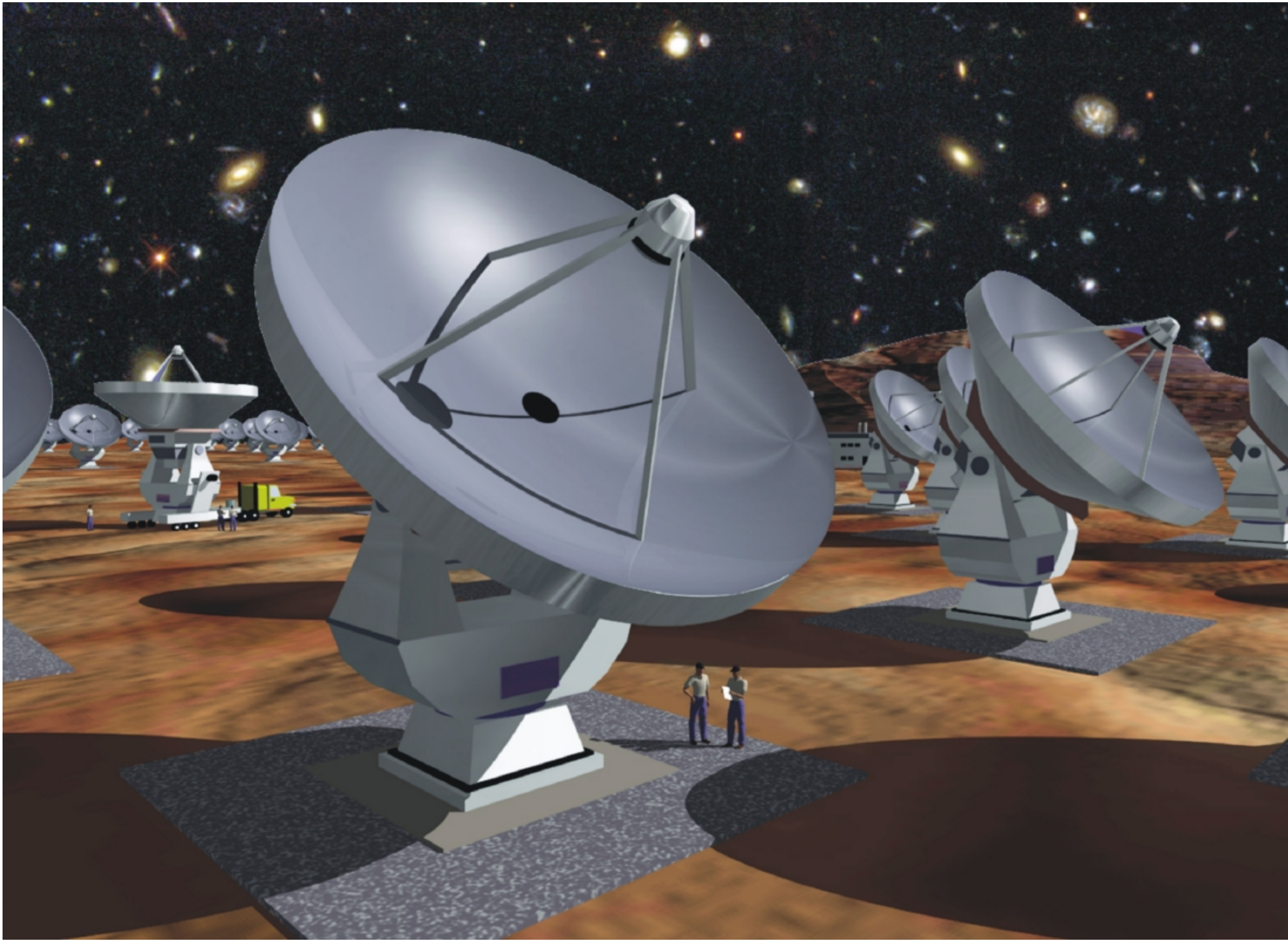
**Main goals:**

- To have a complete 350 GHz census of high mass star formation in the Galaxy (= whole part of Galactic plane visible with APEX)
- To detect protostellar condensations down tens of $M_\odot$ throughout the Milky Way

***Total observing time: ~1000 hours***




Schuller et al. 2009



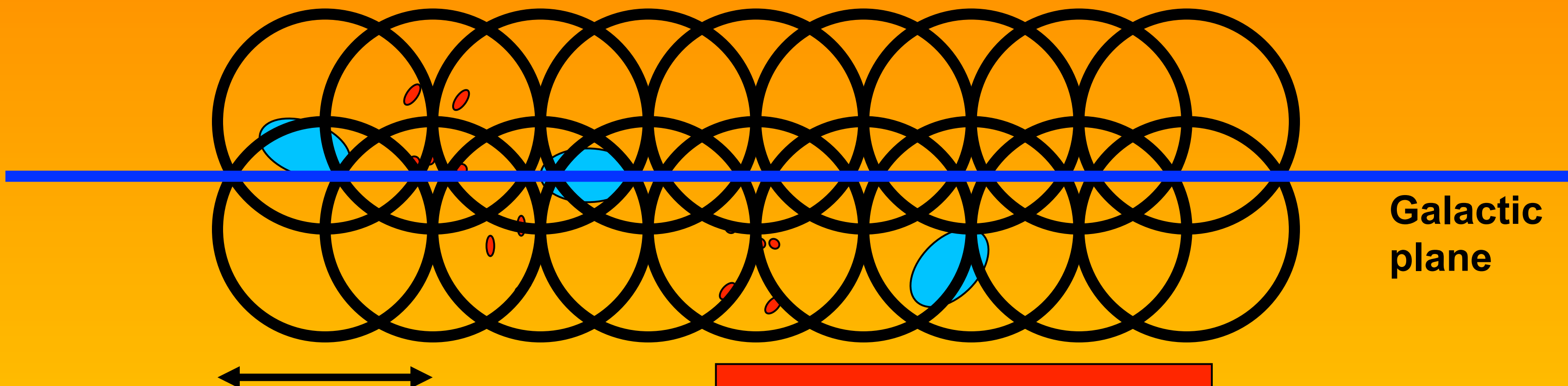
# The Expanded Very Large Array (VLA)

VLA in D-configuration
(1 km maximum baseline)

# Blind surveys with the EVLA

**Blind interferometer surveys means "mosaicing"**

**Example:** The $CH_3OH$ maser/UCHIIR survey to end all $CH_3OH$ maser/ UCHIIR surveys




= 6.7 arcmin/6

**RCP+LCP**

rms ($\Delta v$ = 0.1 km/s in 10 sec) = … nd survey)

rms (BW= 1 GHz in 10 sec) = …

Band 4 … 8 GHz → determine S…

B array: $\theta_B$= ca. 1 arcsec

Need 290 pointings to cover 1 square degree (= 0.8 h + dead time + … calibration)

F… DO 6030/6035 MHz OH lines, RRLs, $H_2CO$ absorption + …

SIMULTANEOUSLY!

# 1 deg$^2$ in 22.2 GHz $H_2O$ line

rms ($\Delta$v = 0.1 km/s in 10 sec) = 65 mJy

rms (BW= 2 GHz in 10 sec) = 125 $\mu$Jy

Band 18 … 26 GHz → determine S.I. of continuum emission

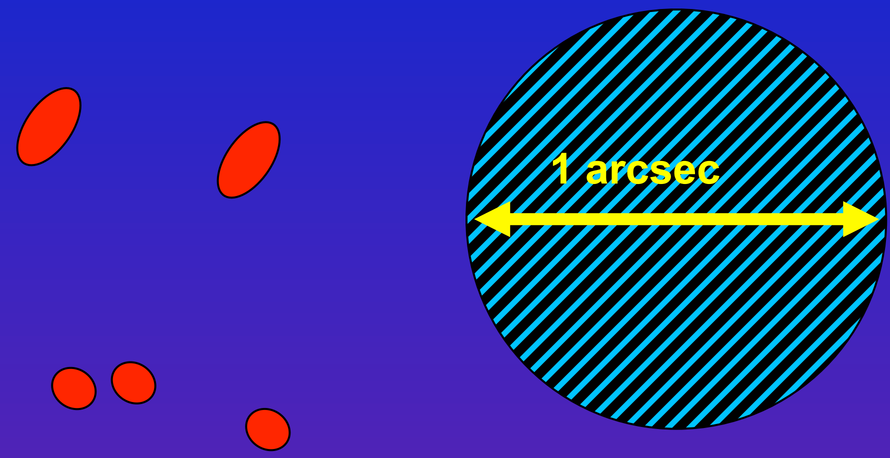
C array: $\theta_B$= ca. 1 arcsec (same as 6.67 GHz survey)

Need ca. 3300 pointings to cover 1 square degree (= 9.2 h + dead time + time for calibration)

6GHz + 22 GHz → Identify many HCHIIRs

PLUS: Do 19.9, 23.1, 25, other $CH_3OH$ lines, many $NH_3$ lines, RRLs, + … SIMULTANEOUSLY!

**VLA range: -15° < *l* < 260°**

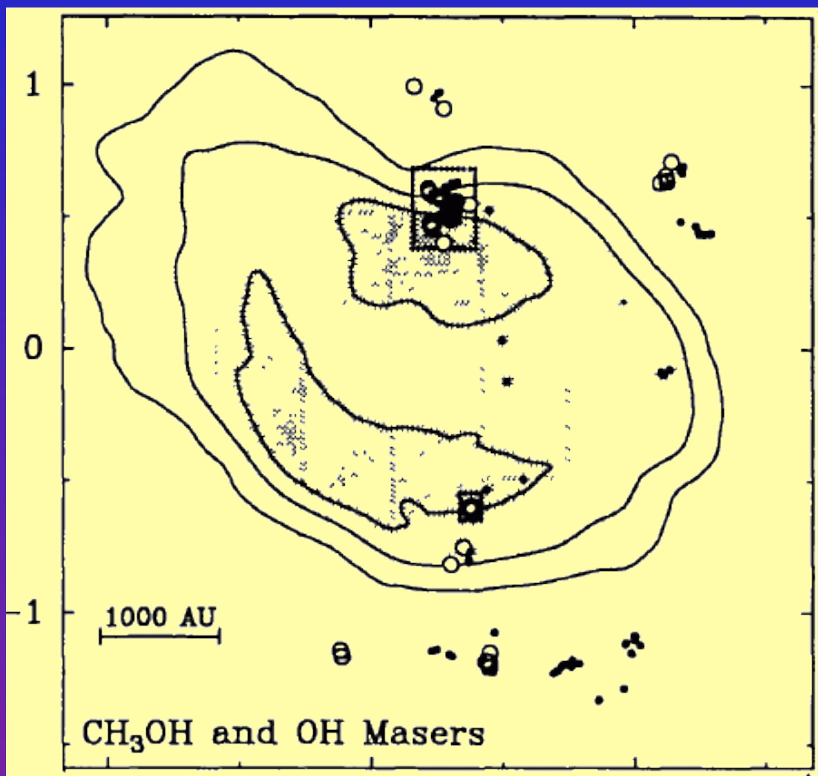



$$\Delta\theta_{x \text{ or } y} \approx 0.5 \frac{\theta_{\text{beam}}}{\text{SNR}}$$

**→ Survey will deliver maser spot positions, sizes of masing regions**

**(For radiativeley pumped masers) this size estimate yields a lower limit to the luminosity of the exciting source**

# Example: $CH_3OH$ masers in W3(OH)



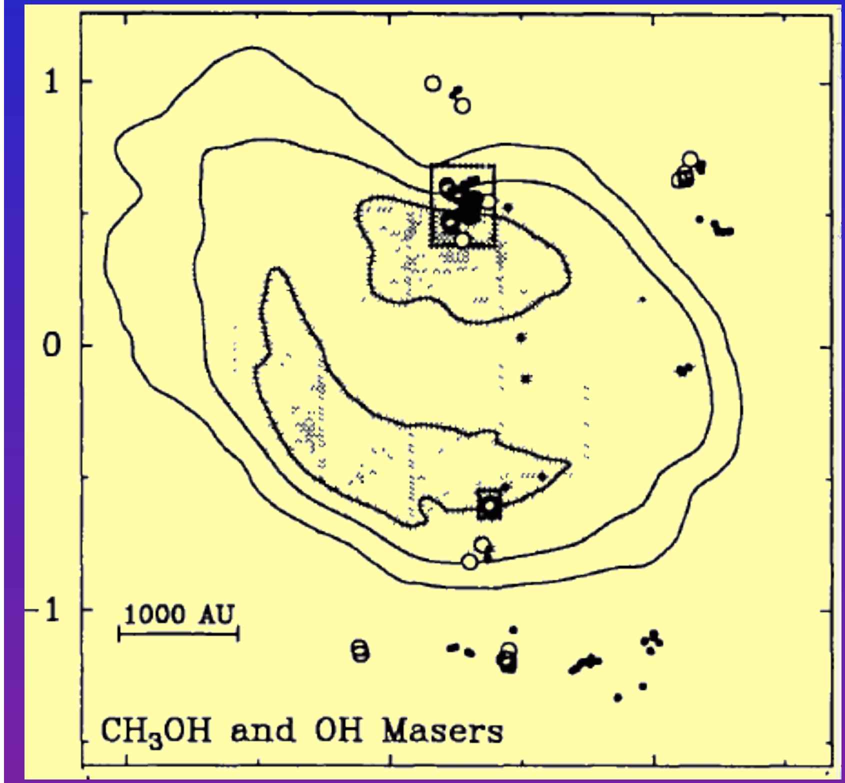

$$L = 4\pi\left(\frac{d}{2}\right)^2 \sigma T^4$$

$d \approx$ 4000 AU

$T \approx$ 80 K (required to produce high $CH_3OH$ abundance and pump maser)

$$\Rightarrow L_{\min} = 1.7 \times 10^4 L_{\mathrm{Sun}}$$

# $CH_3OH$ masers in W3(OH) cont'd




$$\Rightarrow L_{\min} = 1.7 \times 10^4 L_{\mathrm{Sun}}$$

$T \approx$ 150 K from VLA observations of thermal $NH_3$ and OH absorption

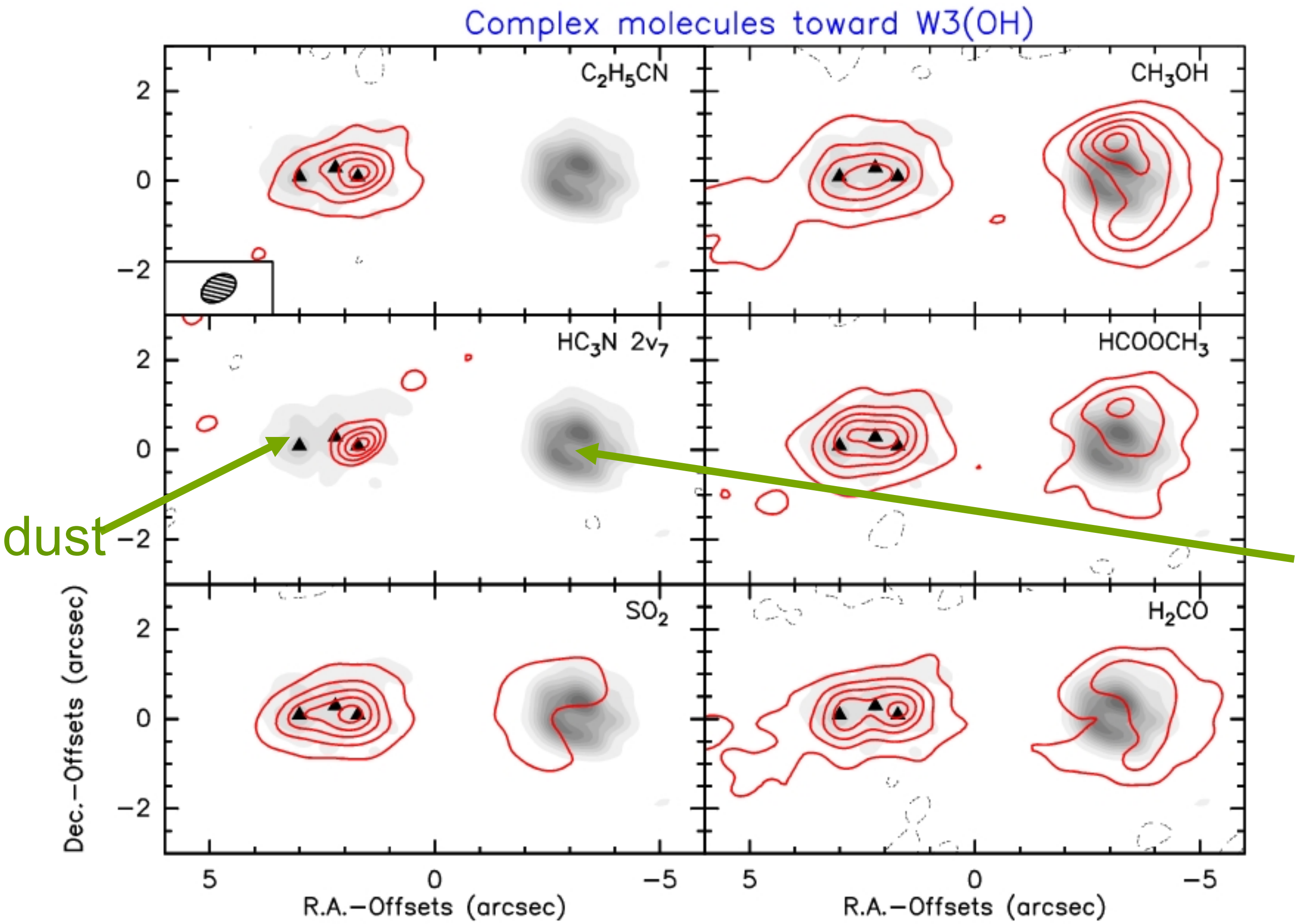
$$\Rightarrow L = 8.5 \times 10^4 L_{\mathrm{Sun}}$$

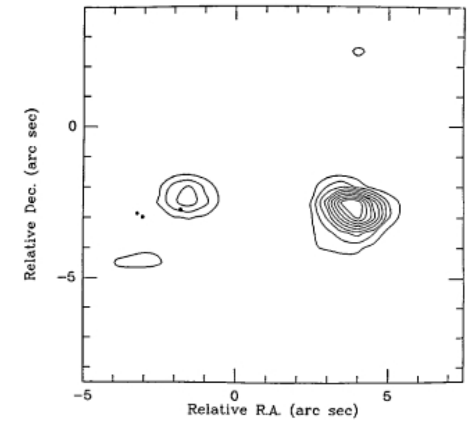
Total luminosity from IR observations:

$$L = 8 - 10 \times 10^4 L_{\mathrm{Sun}}$$

# Hot cores around dusty HMPO(s) and UCHIIRs

## Chemical Diversity: The W3(OH) Region

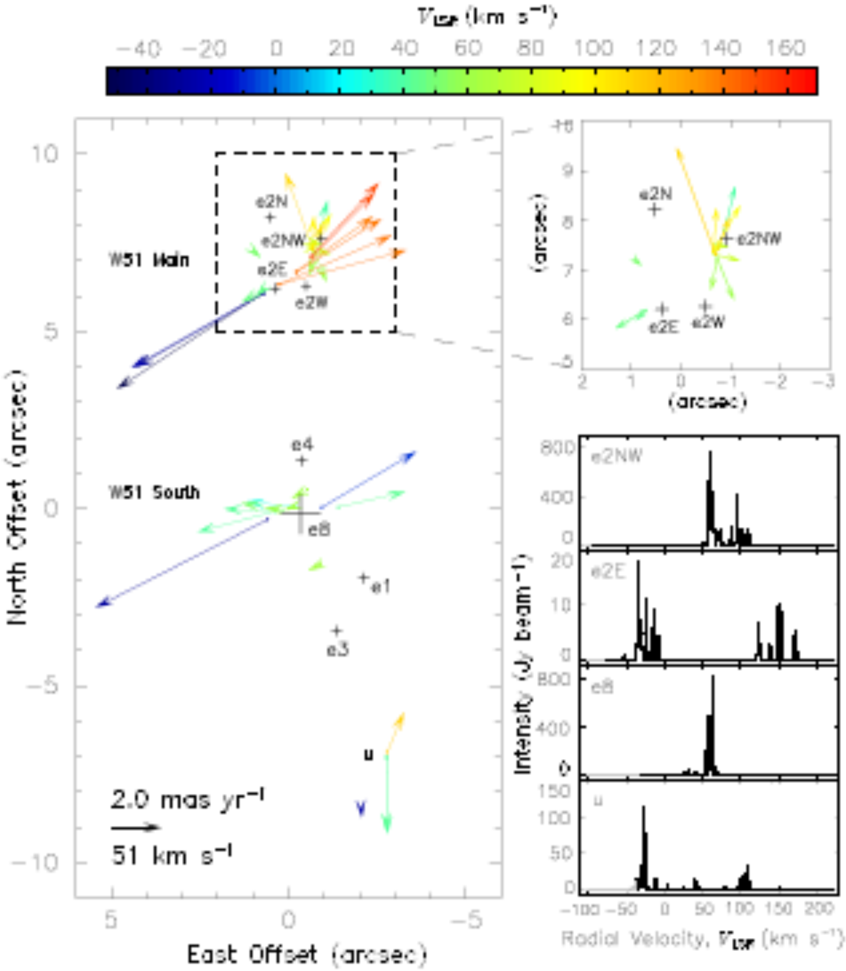


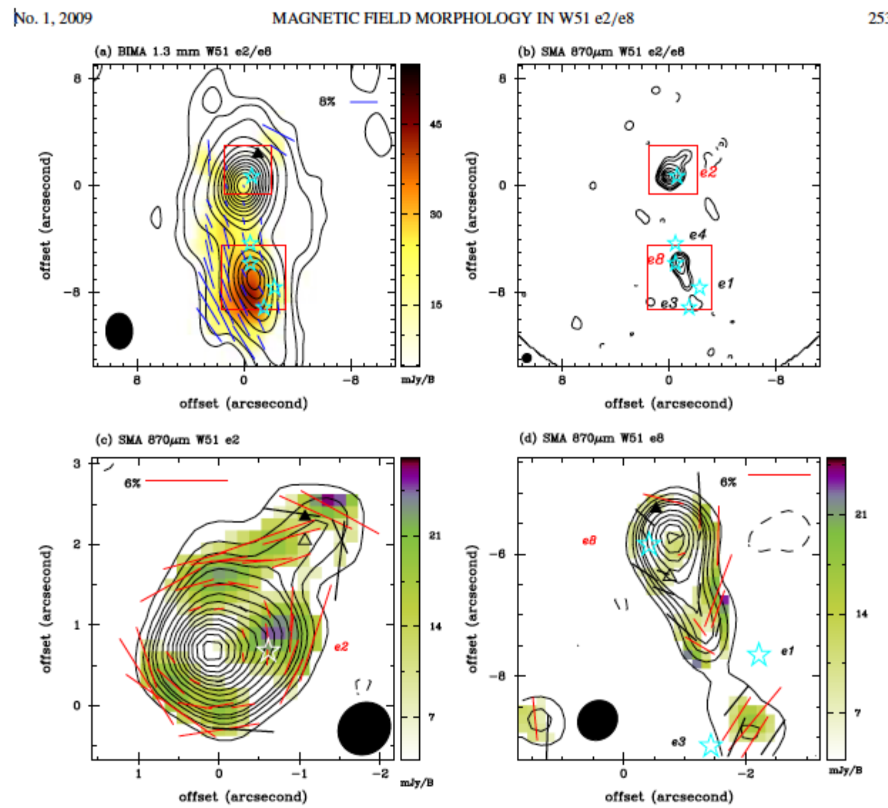

(Turner & Welch 1984)

(Wyrowski et al. 1999)

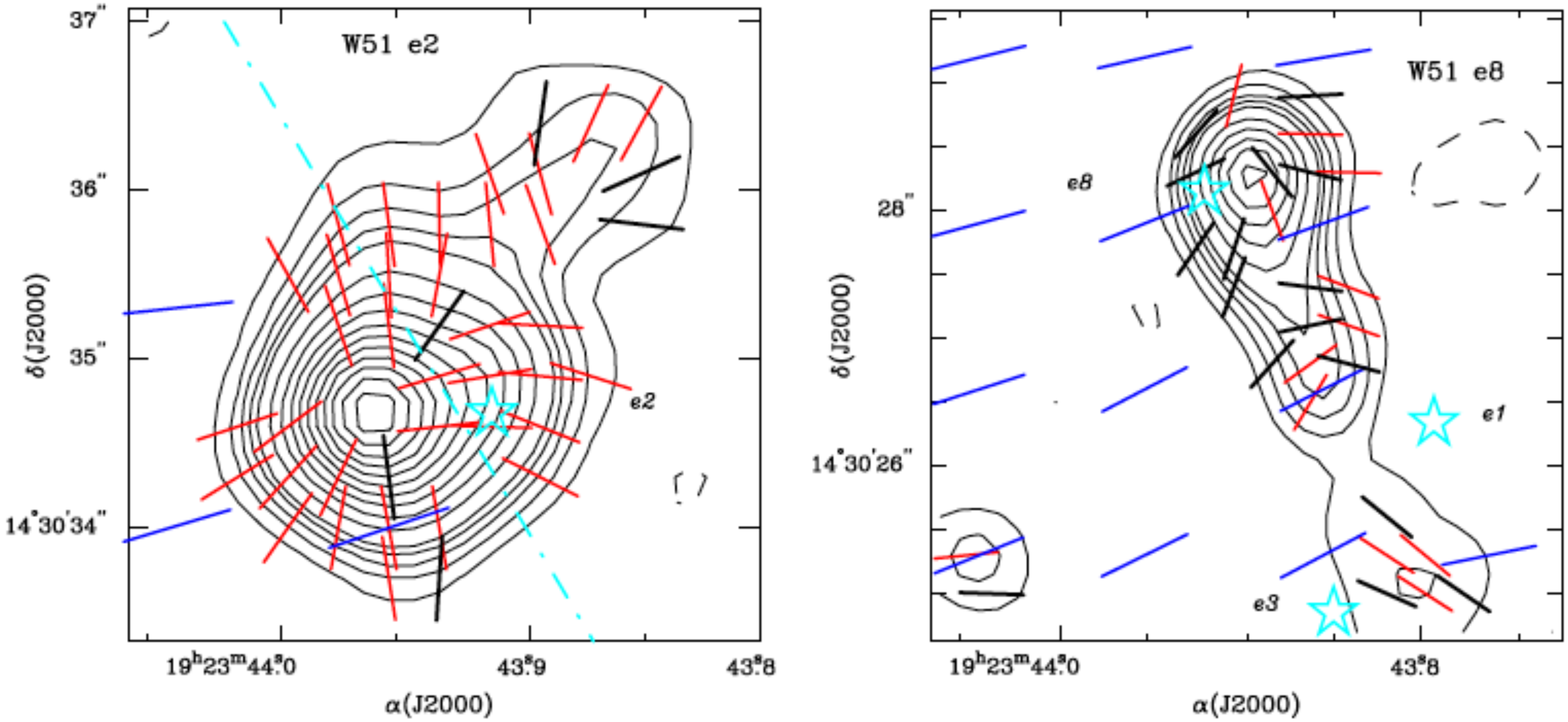
# Intrinsic proper motions from 6.7 GHz methanol VLBI will allow 5 D modeling of hot cores



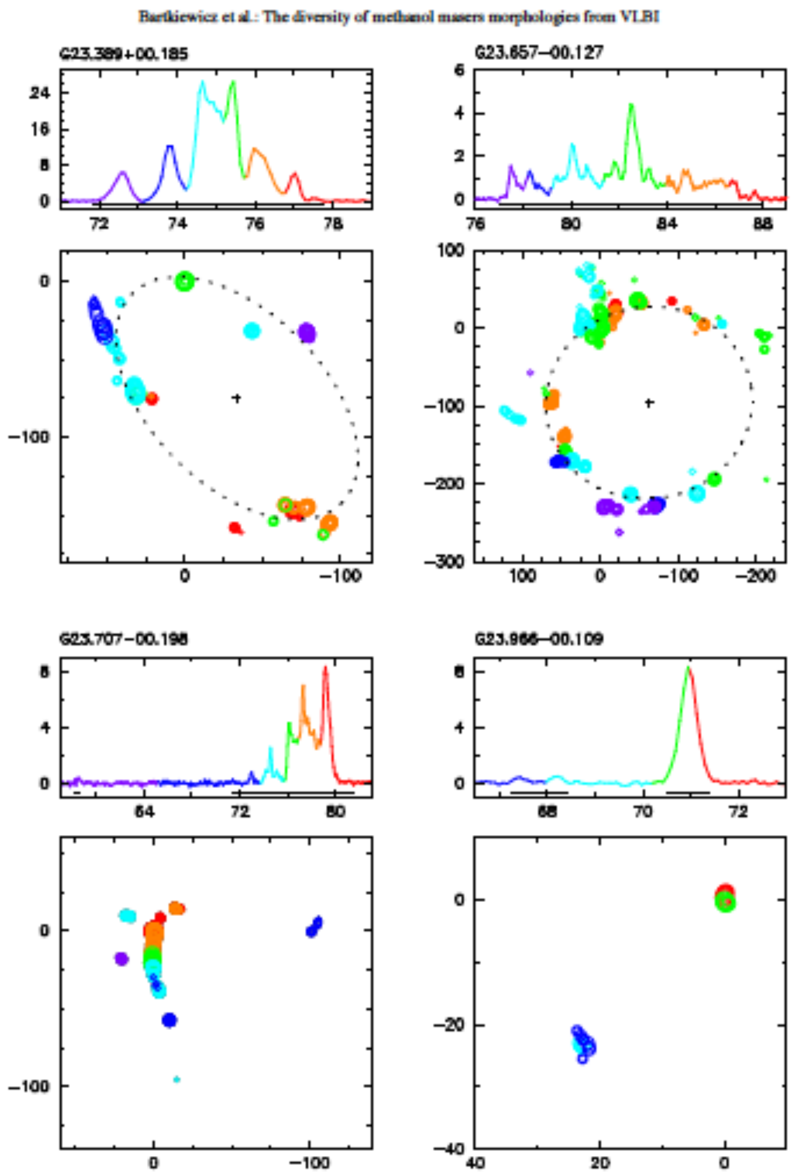

**VLBA**/Sato et al. 2009

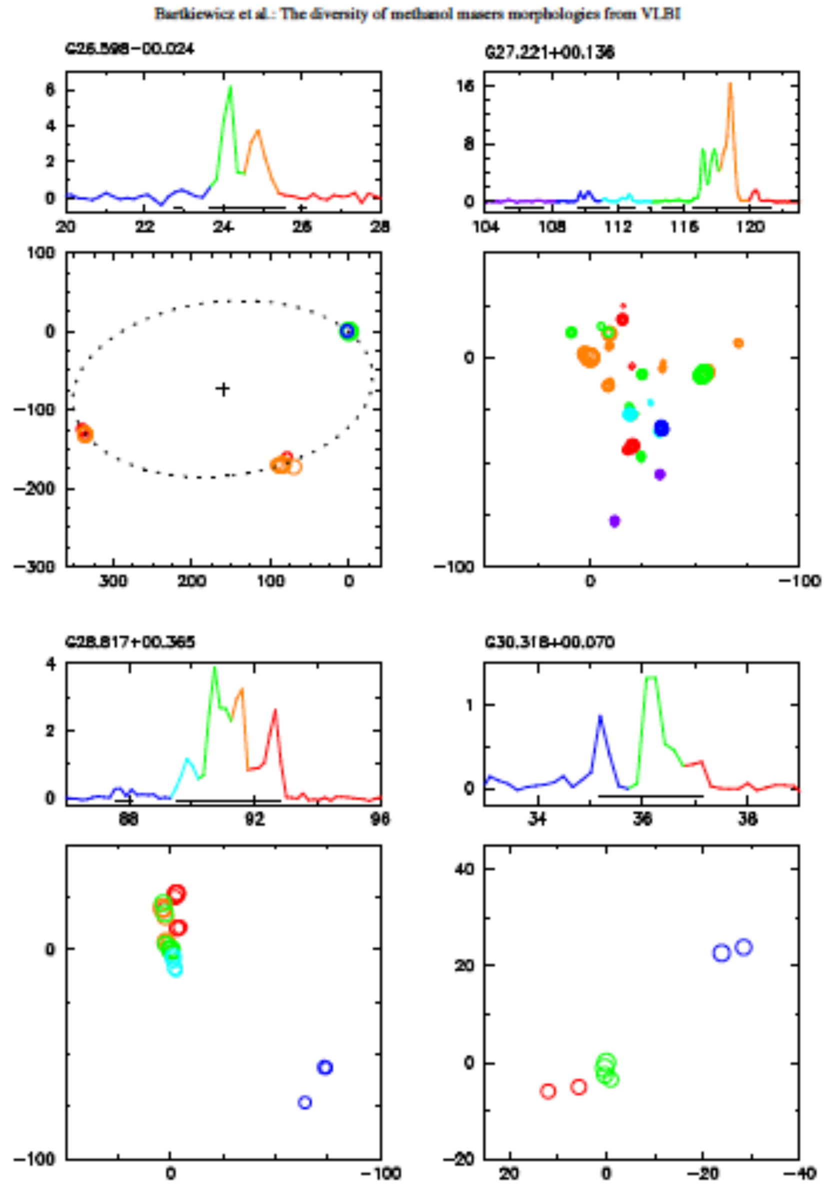



**SMA**/Tang et al. 2009




SMA/Tang et al. 2009




**EVN**/Bartkiewicz et al. 2009

The coming C-band upgrade of the VLBA will greatly expand the scope of maser parallax, imaging and magnetic field studies

Great synergy with ALMA and EVLA in studies of high-mass star formation!

Thanks for your attention!