Radio Astrometry of Red Supergiant VY CMa using VLBA and VLA

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in collaboration with
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BESSEL

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

Friedrich Wilhem Bessel
1784 -1846

*On the parallax of 61 Cygni (**1838MNRAS...4..152B**)*

Structure and kinematics of the Milky Way?

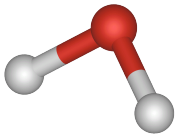
We are inside the Milky Way.....

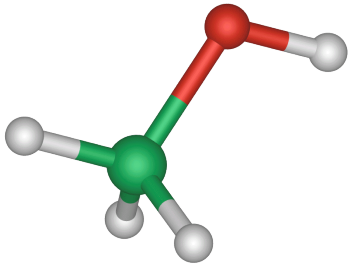
Find tracers of the arm structure and measure their distances to map the Milky Way.

Young stars
HI, HII, CO

Luminosity distance: *Extinction at optical wavelength*
Kinematic distance: *Uncertain Galactic parameters, peculiar motion*

Strong Astronomical Masers:





		First found	# known YSOs	# known AGB*
OH	Hydroxyl (1.7 GHz)	1965	many	many
H_2O	Water vapor (22.2 GHz)	1969	very many	many
SiO	Silicon monoxide (43 GHz)	1974	3	very many
CH_3OH	Methanol (12.2/6.7 GHz)	1971/ 1986	very many	0

The Very Long Baseline Array (VLBA)

- Radio waves “see” through galaxy
- Can “synthesize” telescope the size of the Earth

Angular resolution:

$\theta_f \sim \lambda/D$ ~ 1 cm / 8000 km = 250 μas

Centroid Precision:

0.5 θ_f / SNR ~ 10 μas

Systematics:

path length errors ~ 2 cm (~2 λ)

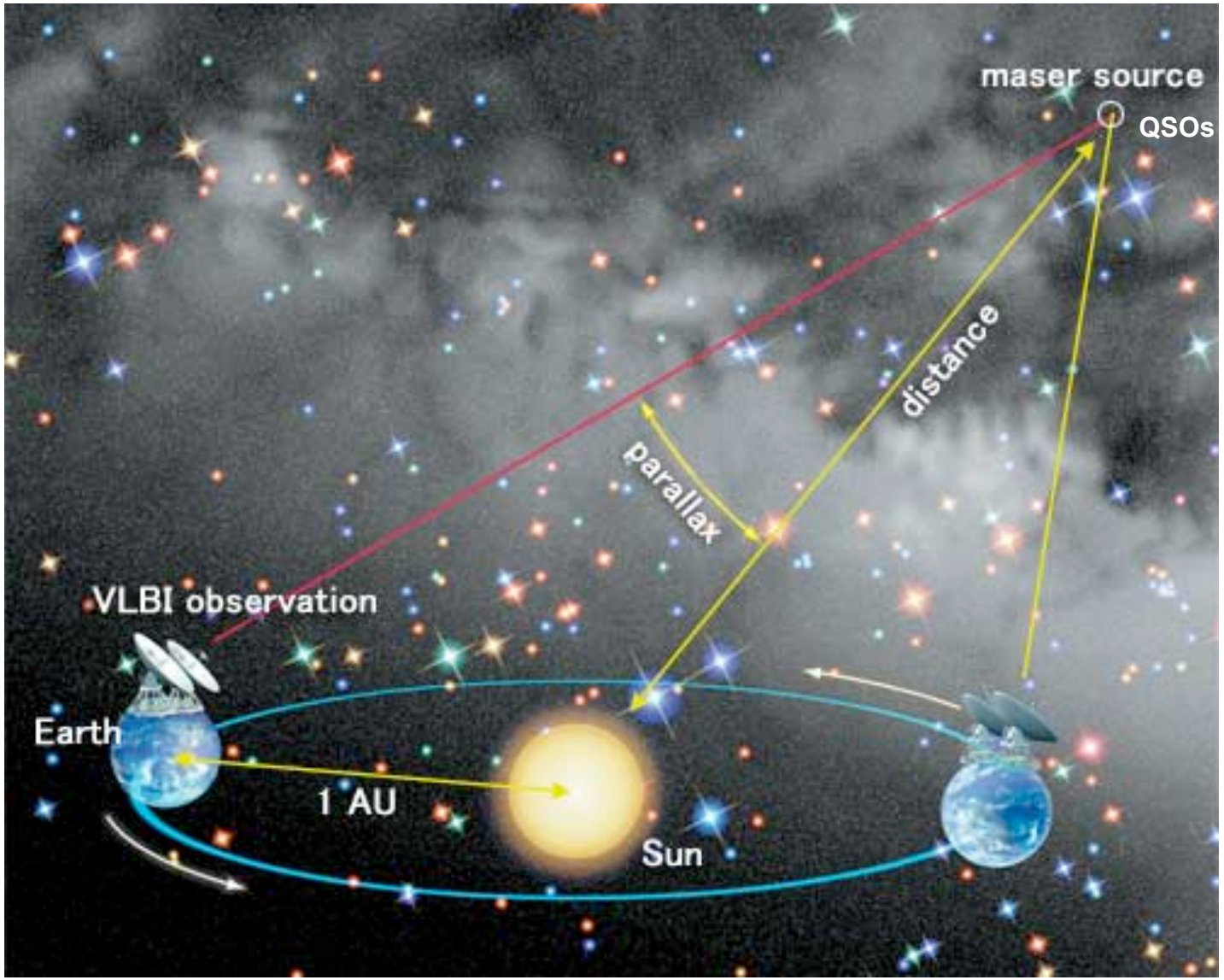
shift position by ~ $2\theta_f$ ~ 500 μas

Relative positions (to QSOs):

$\Delta\Theta$ ~ 1 deg (0.02 rad)

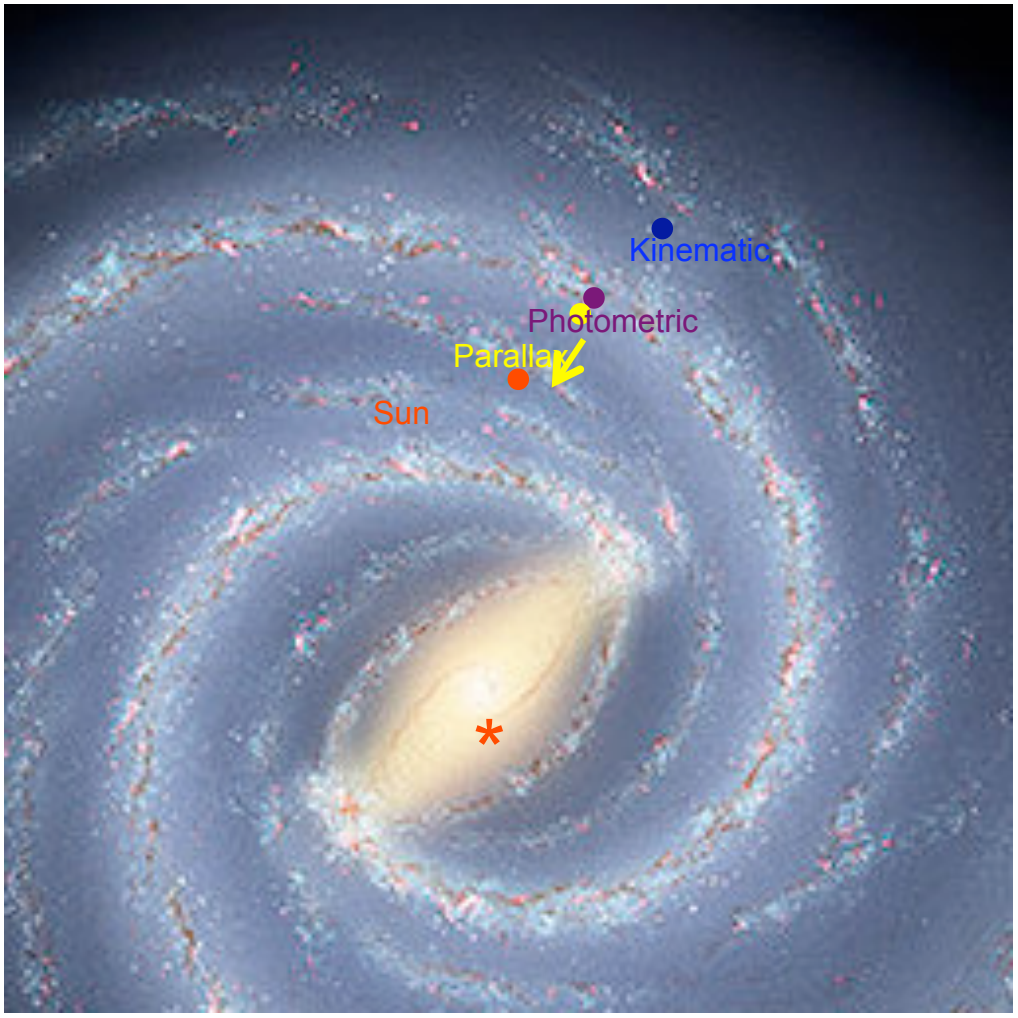
cancel systematics: $\Delta\Theta * 2\theta_f$ ~ 10 μas

VLBI (phase referencing) Trigonometric Parallaxes



http://veraserver.mtk.nao.ac.jp/outline/vera2-e.html

The Distance to the Perseus Arm: W3OH



Artist conception: Robert Hurt (NASA:SSC)

Distance estimates:

Kinematic = 4.3 kpc

Photometric = 2.2 kpc

(R. Humphreys 1970's)

Maser parallaxes: (2%)

CH_3OH 1.95±0.04 kpc

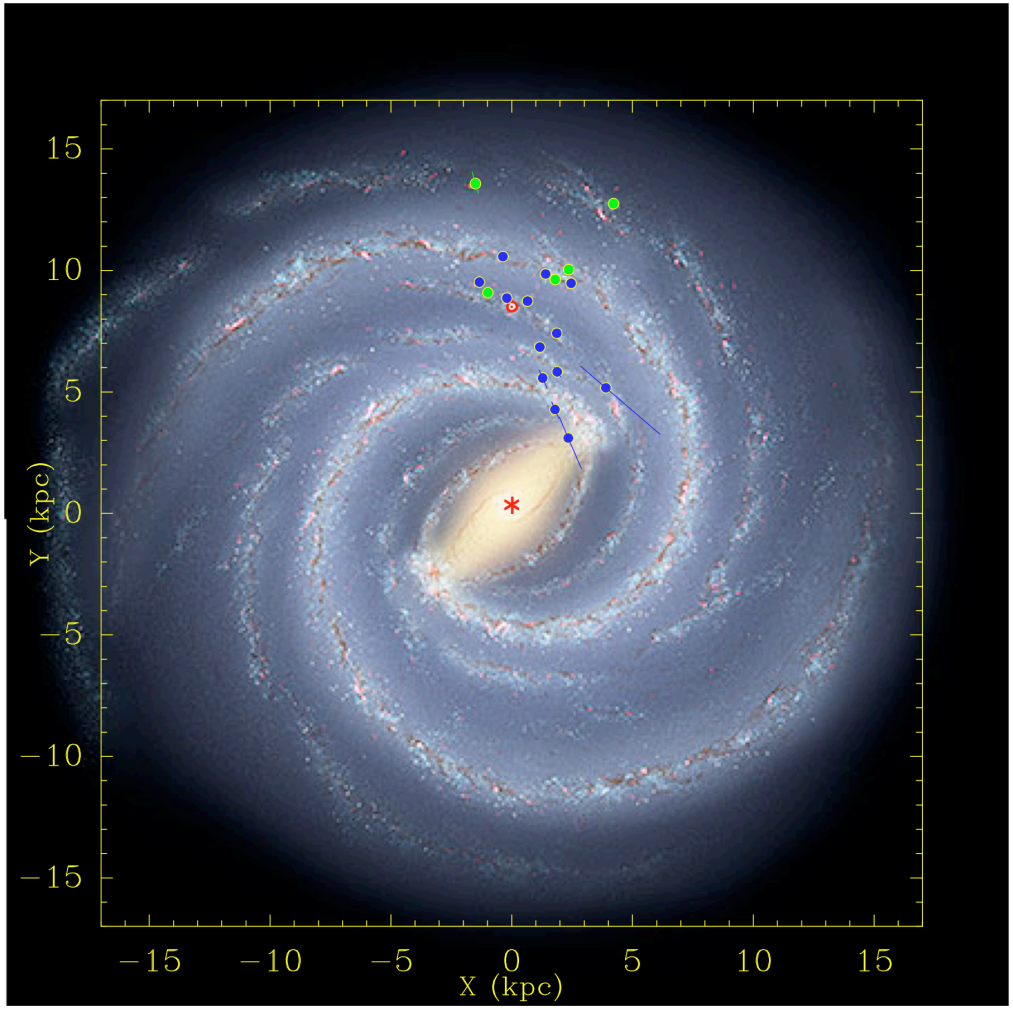
Xu et al. 2006

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

Mapping the Milky Way (18 MSFRs)



Artist conception: Robert Hurt (NASA:SSC)

Our proposed revision:

- Distance to Galactic Center
  $R_0 = 8.4 \pm 0.6$ kpc
- LSR rotation speed:
  $\Theta_0 = 254 \pm 16$ km/s

  15% faster than IAU value

Reid et al. 2009

BeSSeL Survey

http://bessel.vlbi-astrometry.org/index.shtml

BeSSeL Survey

BeSSeL

Bar and Spiral Structure Legacy Survey

(Background image: Tony Hallas) Impressum

Project Team

Mark Reid (PI) & Tom Dame	: Harvard-Smithsonian Center for Astrophysics, USA
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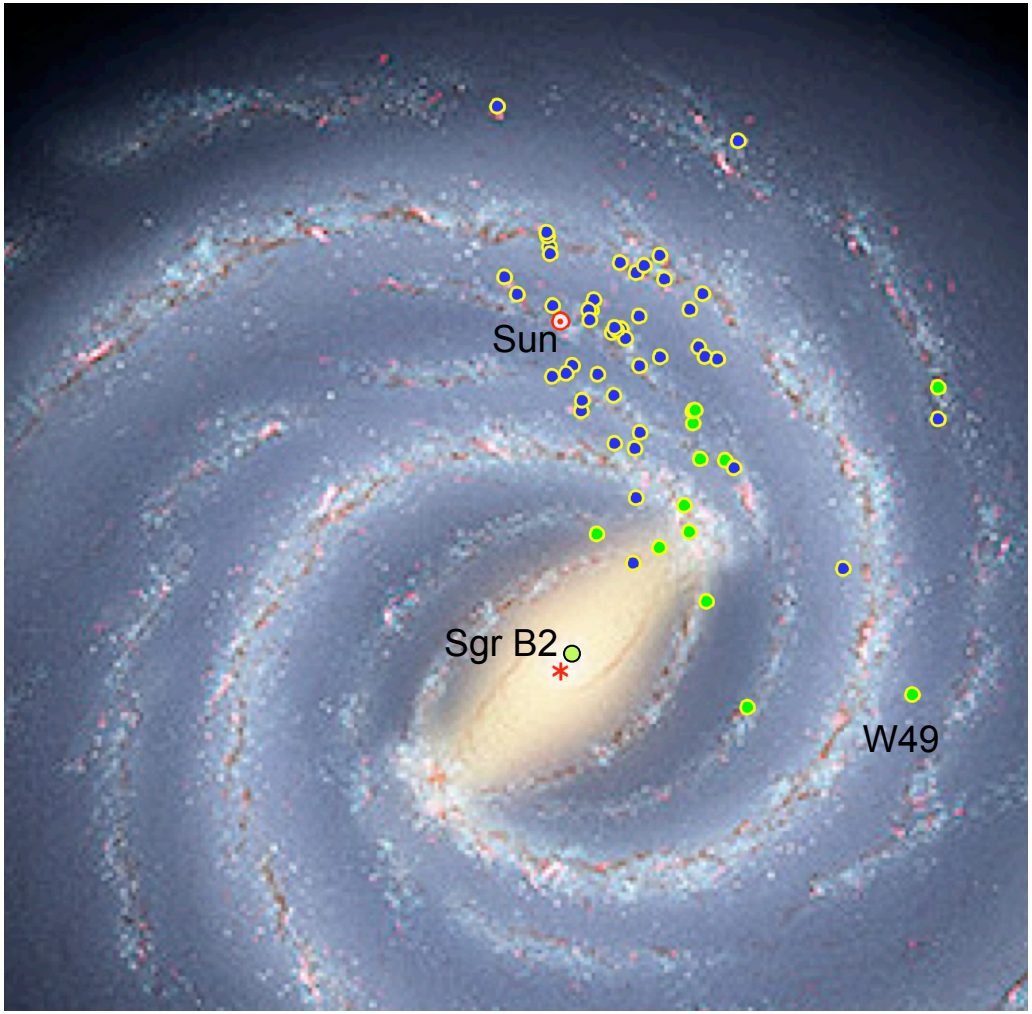
Xu Ye & Yuanwei Wu	: Purple Mountain Observatory, China
Luca Moscadelli	: Arcetri Observatory, Italy
George Moellenbrock	: NRAO, USA
Mayumi Sato	: Tokyo University, Japan
Anna Bartkiewicz	: Torun Centre for Astronomy, Poland
Kazuya Hachisuka	: Shanghai Observatory, China

~400 sources
~5280 hour VLBA
5 years

Participating institutions:

Mapping the Milky Way (the latest)

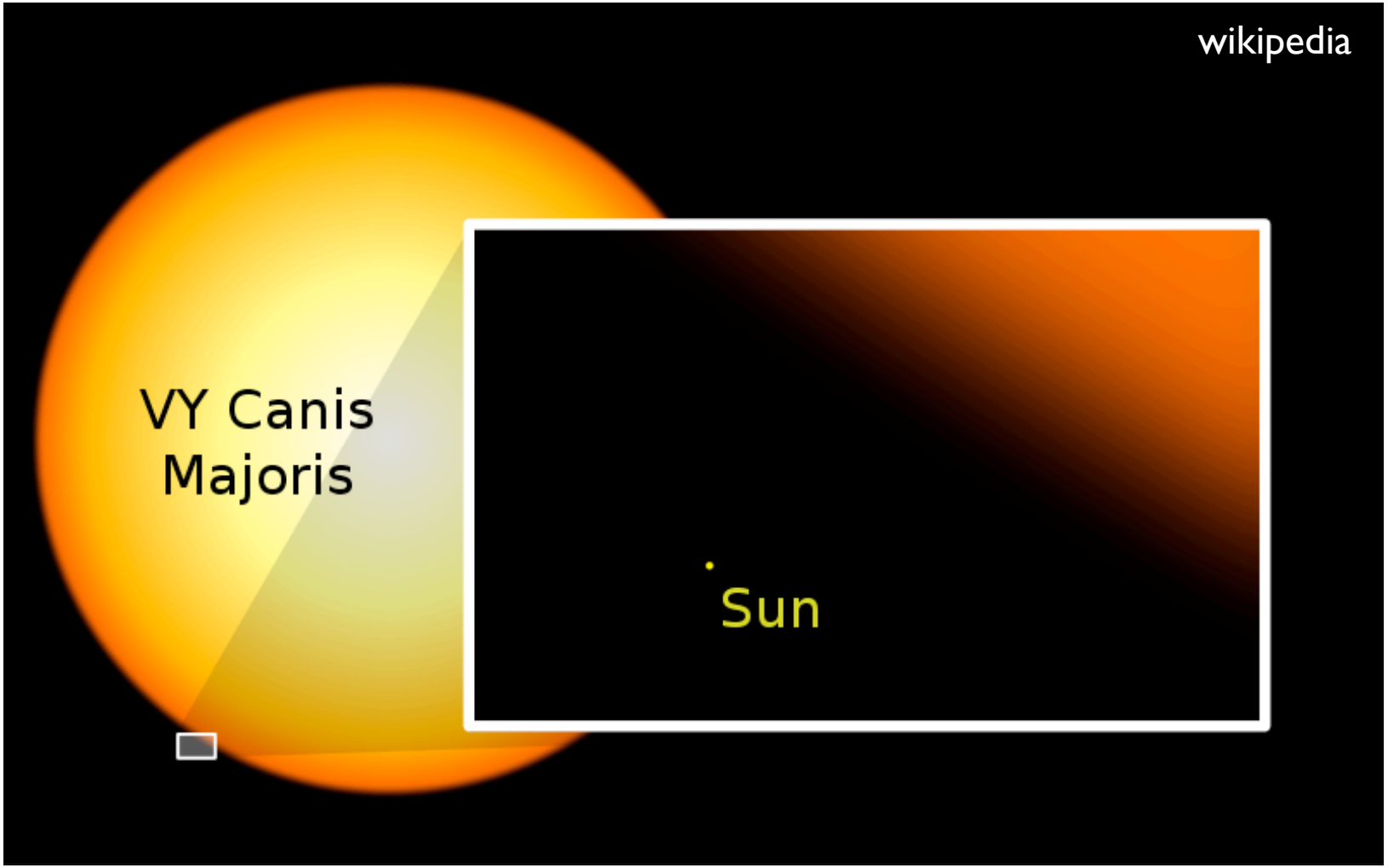


Artist conception: Robert Hurt (NASA:SSC)

- Preliminary results for 62 parallaxes from VERA, EVN & VLBA:
  - blue ($\sigma_d < 0.5$ kpc)
  - green ($\sigma_d > 0.5$ kpc)
- Tracing outer spiral arms, W49 suggests Outer arm bends in more than in artist's model.
- Inner, bar-region is messy

Reid et al. 2012

Radio Astrometry of VY CMa

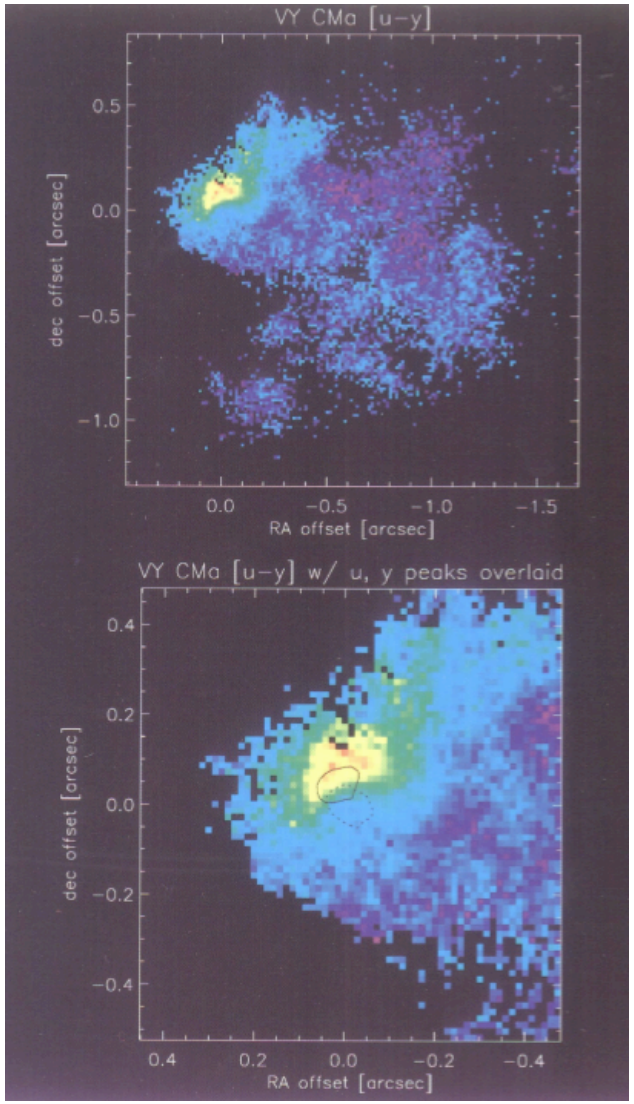


the largest known star, one of the most luminous

Fundamental parameters of a star

- Distance
- Absolute position and proper motion
- Size
- Temperature
- Luminosity
- Mass

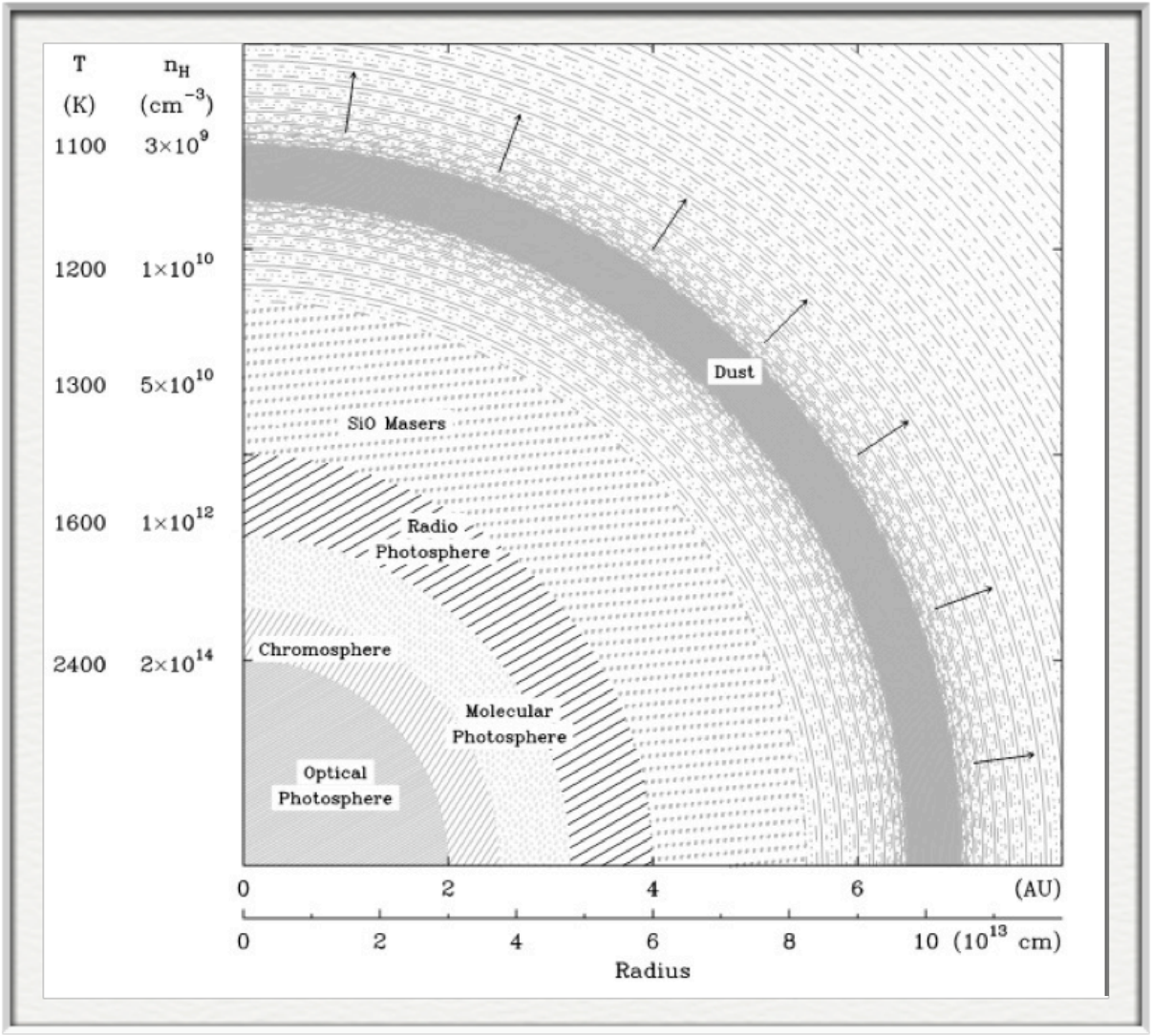
Optical observations



Hubble Faint Object Camera (FOC), removed in early 2002.
Kastner & Weintraub 1998

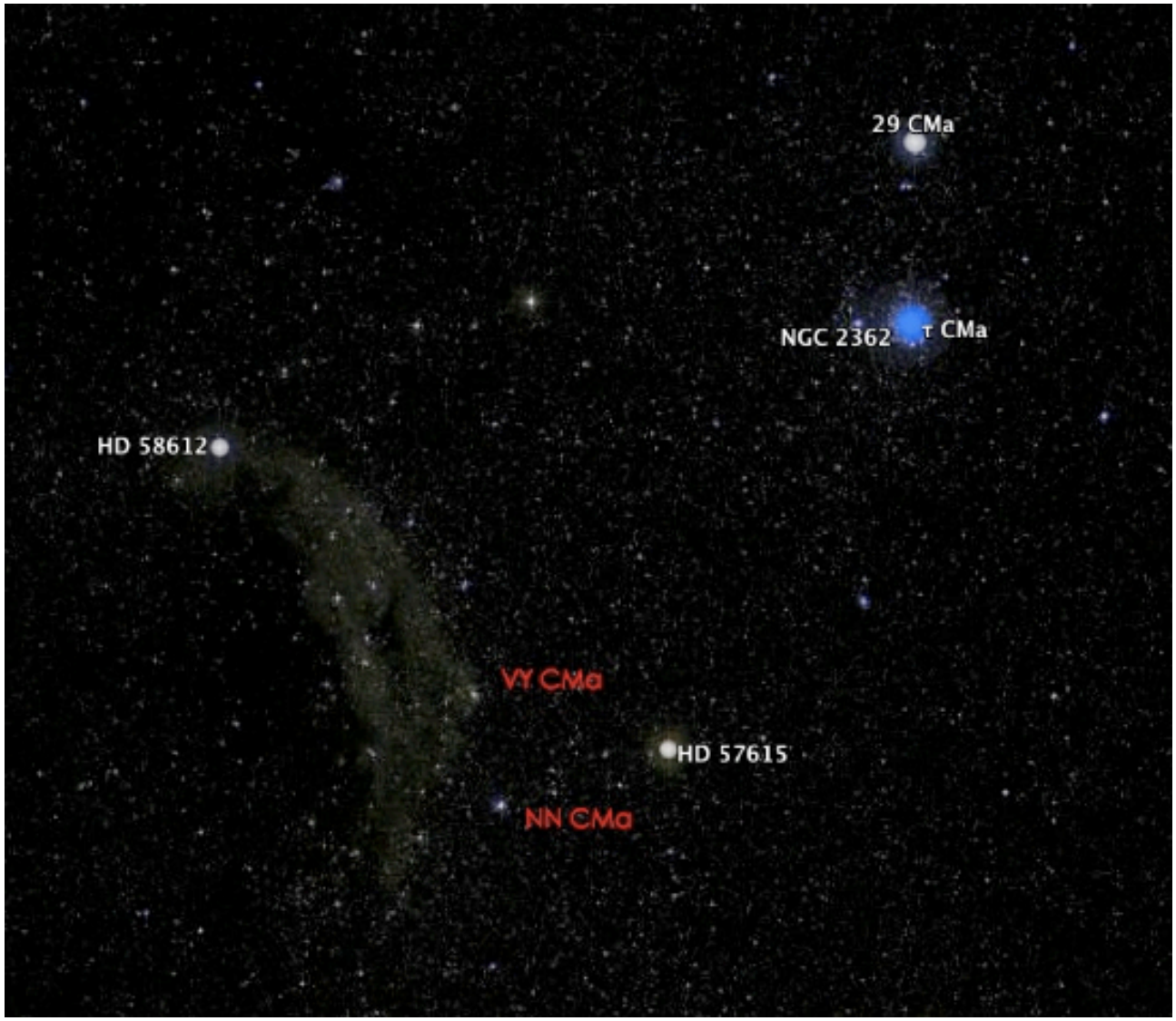
Hubble WFPC2, Wide Field and Planetary Camera 2
Smith et al. 2001

From photosphere to circumstellar envelope



(M. J. Reid & K. M. Menten1997)

Sky position of VY CMa



NGC2362: 1.5 kpc (30%)

Credit: google sky

Hipparcos astrometic result

Proper motion:

Telescope	Epoch	R.A. (J2000) (h m s)	Dec. (J2000) (° ′ ″)	μ_x (mas yr^{-1})	μ_y (mas yr^{-1})
Hipparcos[a]	1991.25	07 22 58.3251 ± 0.0001	−25 46 03.180 ± 0.003	+8.86 ± 1.34	+0.75 ± 3.25
Hipparcos[b]	1991.25	07 22 58.3251 ± 0.0002	−25 46 03.176 ± 0.003	+5.72 ± 2.01	−6.75 ± 4.47

(a) Perryman et al. (1997).
(b) van Leeuwen (2007).

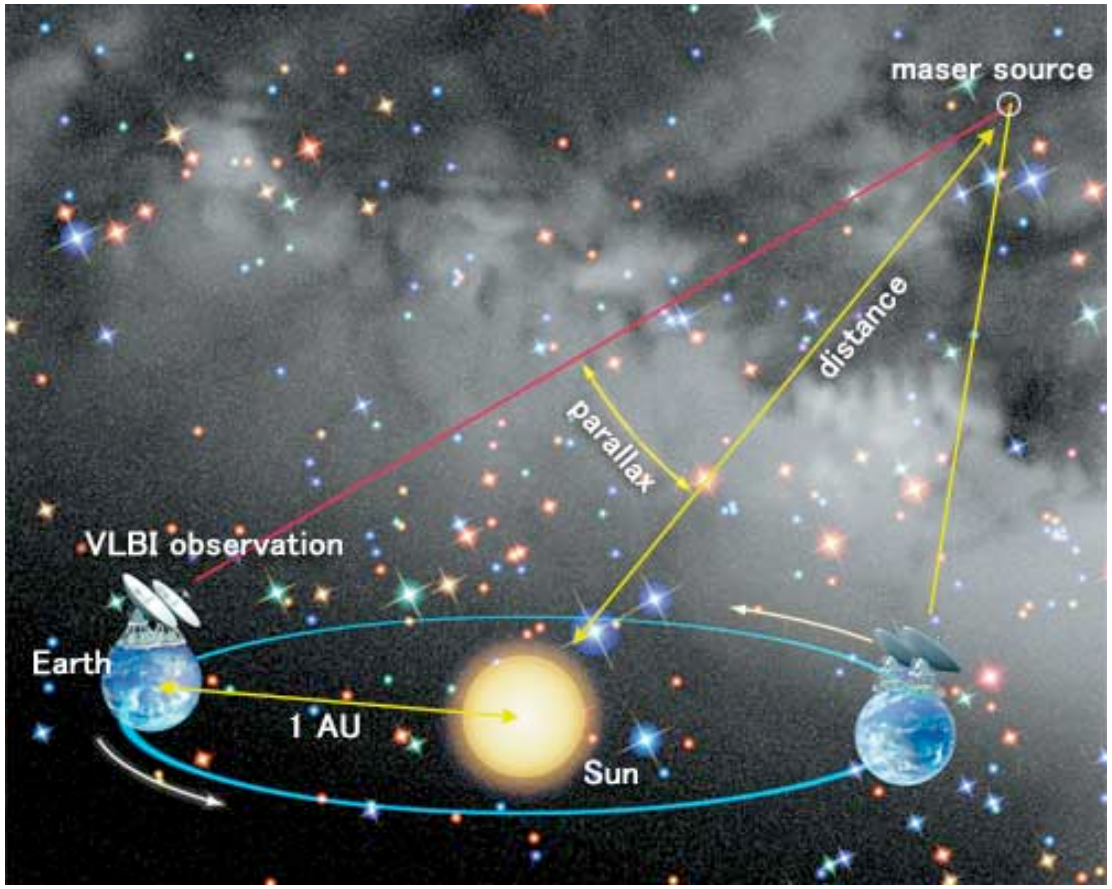
Parallax:

(a) 1.78 +/- 9.84 mas
(b) -4.35 +/- 4.99 mas

Observation I

Parallax and proper motion measurement:
VLBI phase-referencing observation (43 GHz SiO maser)

Very Long Baseline Array (VLBA)
/NRAO

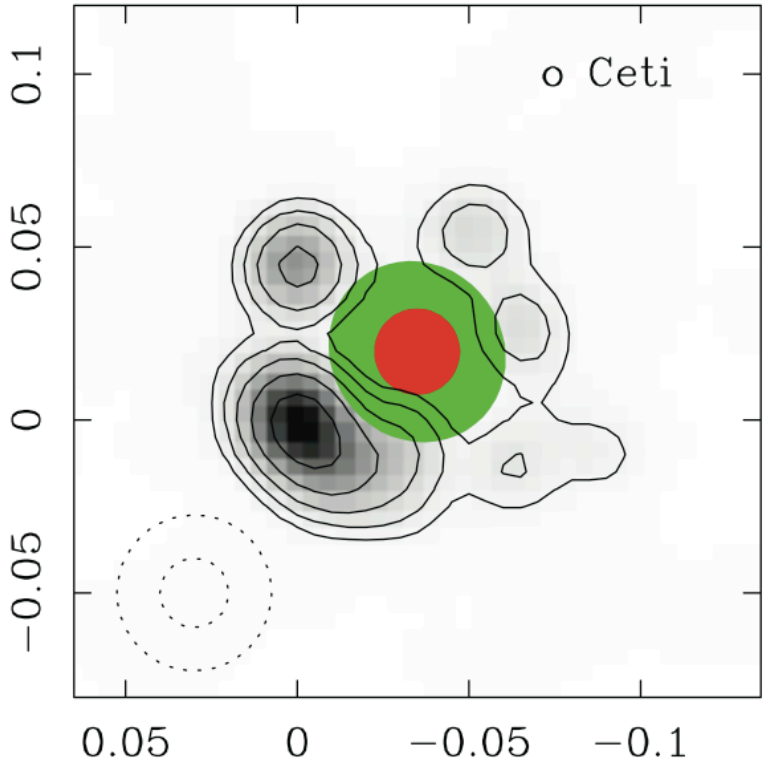


Credit: VERA website/NAOJ

Observation II

Register SiO masers to radio photosphre:
VLA 43 GHz continuum and line observation

Very Large Array (VLA)/NRAO



(M. J. Reid & K. M. Menten 2007)

Observation epochs

Array	Code	Obs. date	Antennae used
VLBA	BR106A	2005OCT20	10
VLBA	BR106B	2006APR16	9
VLA	AR595	2006APR17	27
VLBA	BR106C	2006NOV29	10
VLBA	BR106D	2007APR27	10

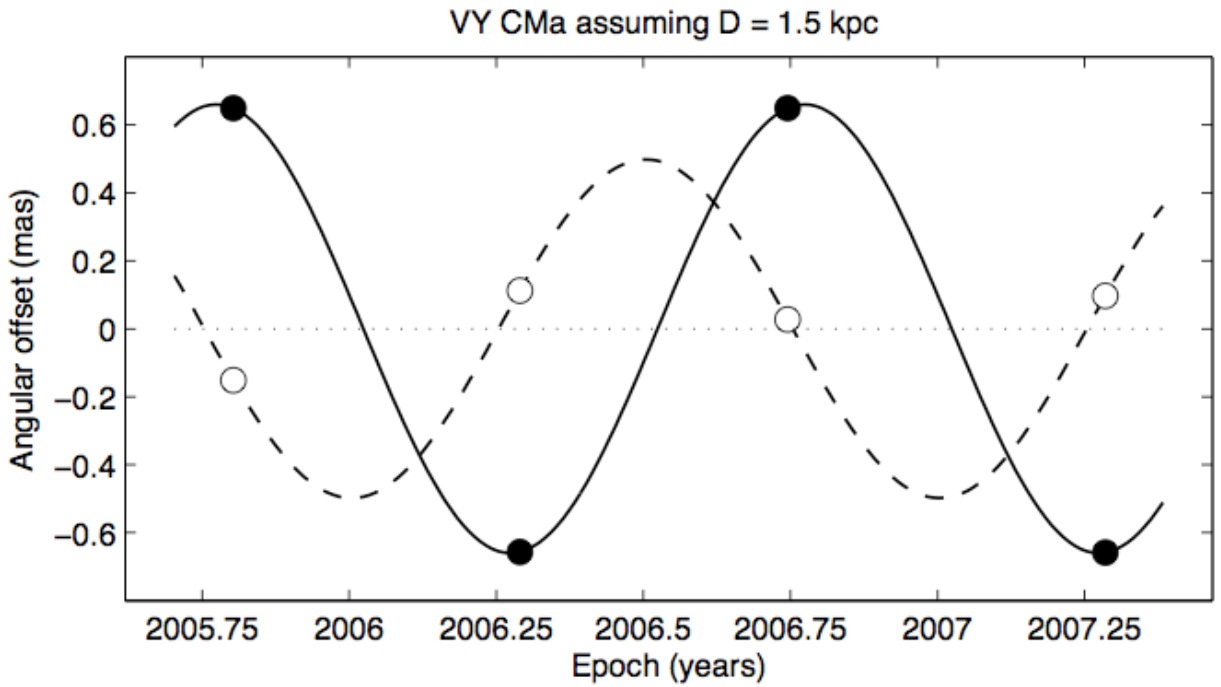
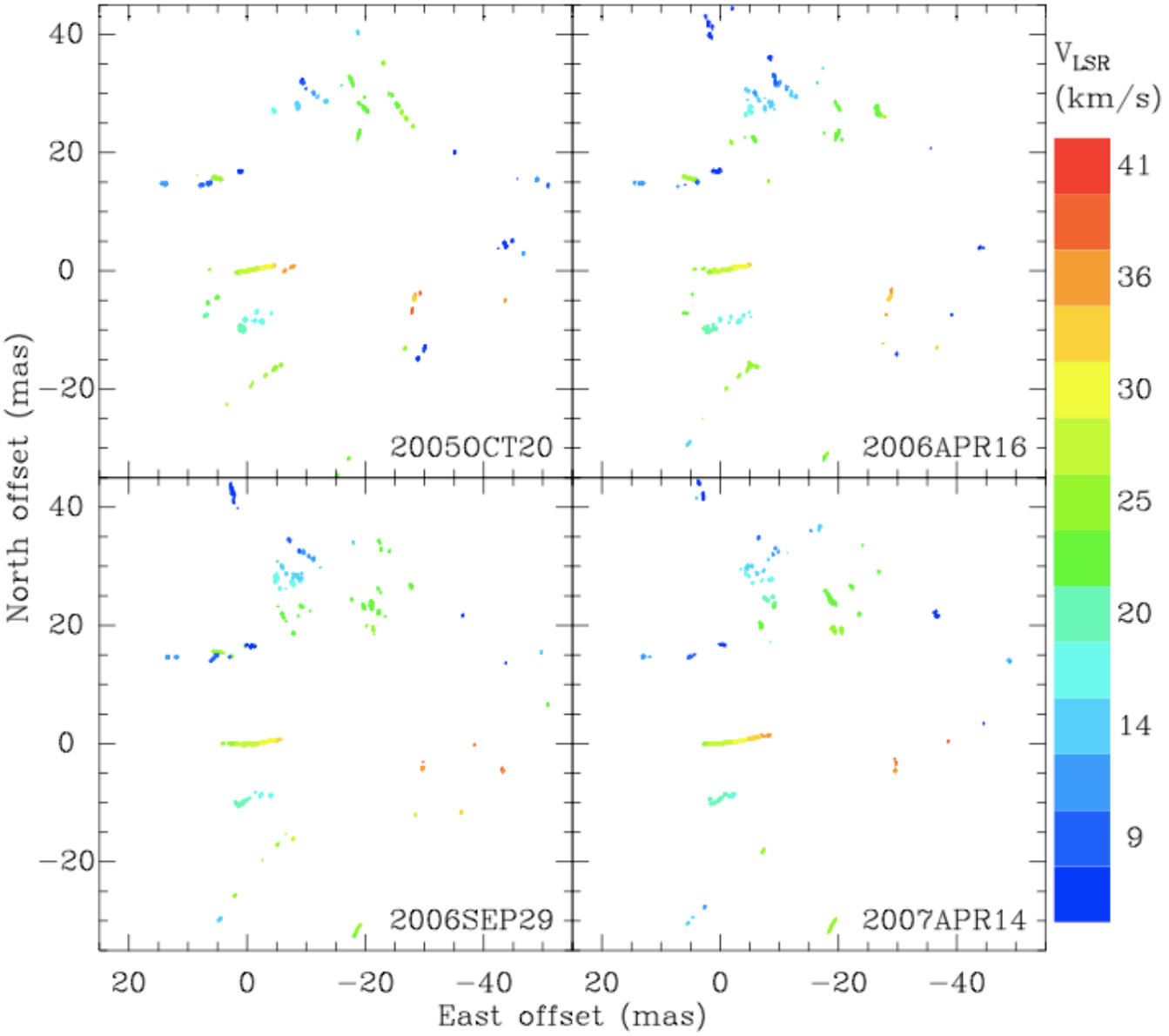


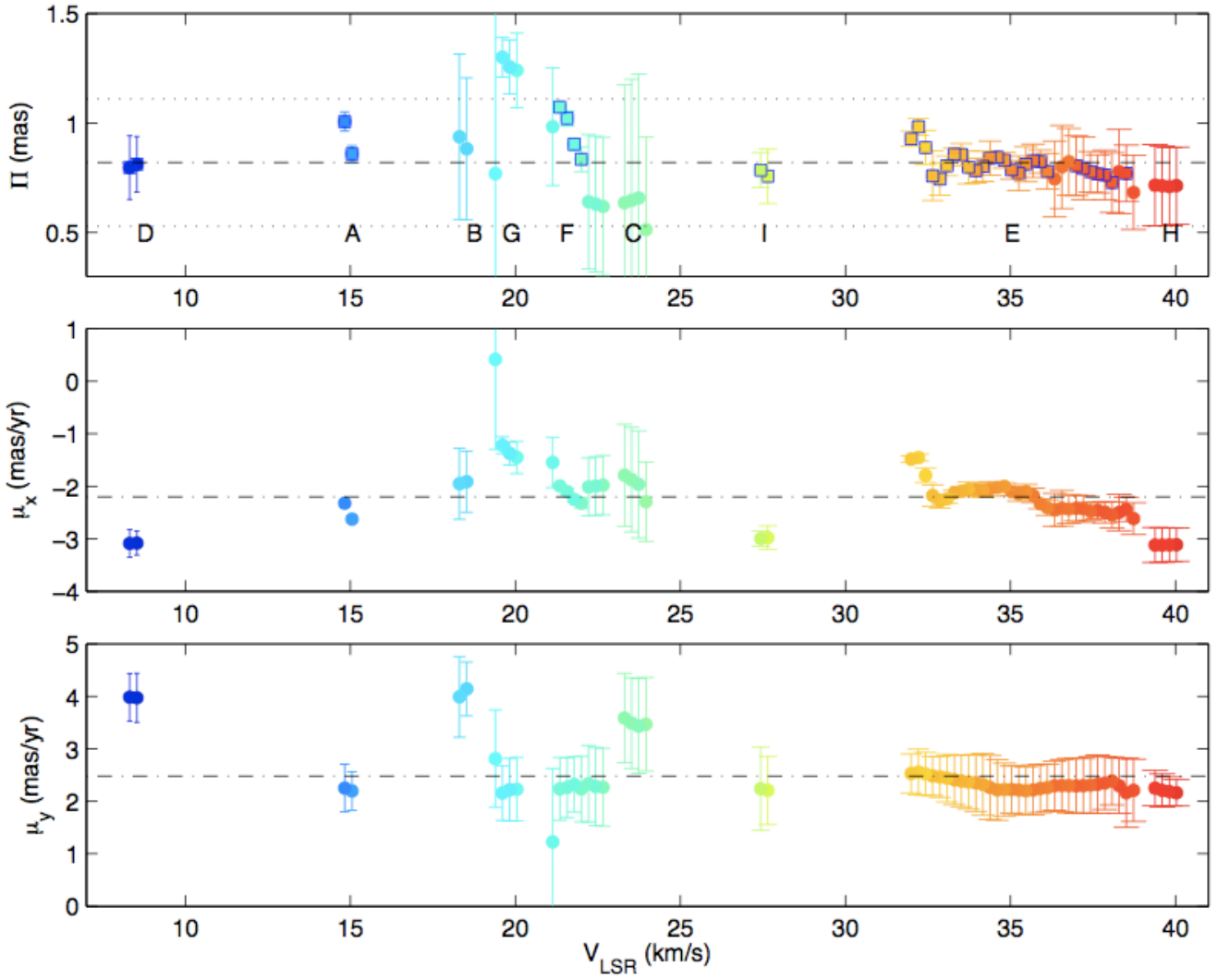
Table: Positions and Brightnesses

Source	R.A. (J2000) (h m s)	Dec. (J2000) (° ′ ″)	T_b (Jy/b)	θ_{sep} (°)	P.A. (°)	$V_{\rm LSR}$ (km s^{-1})	Beam (mas mas °)
VY CMa.....	07 22 58.3283	−25 46 03.075	18 − 27	...	...	22	0.5 × 0.2 @ −12
J0725−2640...	07 25 24.4130	−26 40 32.680	0.03	1.1	+ 34	...	2.8 × 0.6 @ −11
J0731−2341...	07 31 06.6680	−23 41 47.869	0.06	2.8	+136	...	0.8 × 0.3 @ +6

Spatial distribution of maser spots at all epochs (VLBA)



Parallax and proper motion



Parallax:

$\Pi = 0.83 \pm 0.08$ mas $(1.20^{+0.13}_{-0.10}$ kpc) 43 GHz SiO maser, 4 epochs

Proper motion:

$\mu_x = -2.21 \pm 0.06$ mas y^{-1}

$\mu_y = +2.29 \pm 0.30$ mas y^{-1}

Compared with VERA results based on H_2O maser (Choi et al. 2008)

Parallax:

$\Pi = 0.88 \pm 0.08$ mas $(1.14^{+0.11}_{-0.09}$ kpc) 22 GHz H2O maser, 10 epochs

Proper motion:

$\mu_x = -2.09 \pm 0.16$ mas y^{-1}

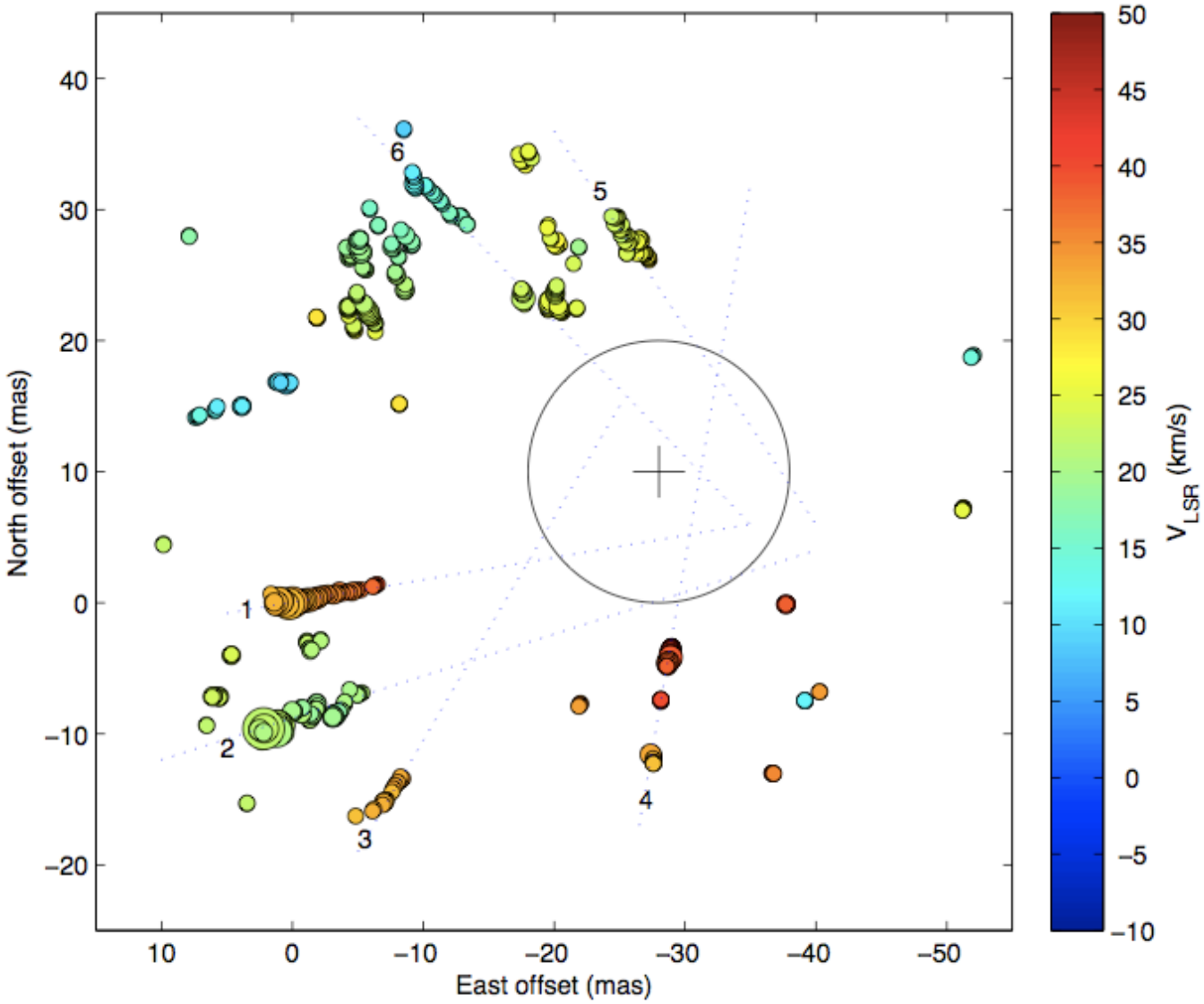
$\mu_y = +1.02 \pm 0.61$ mas y^{-1}

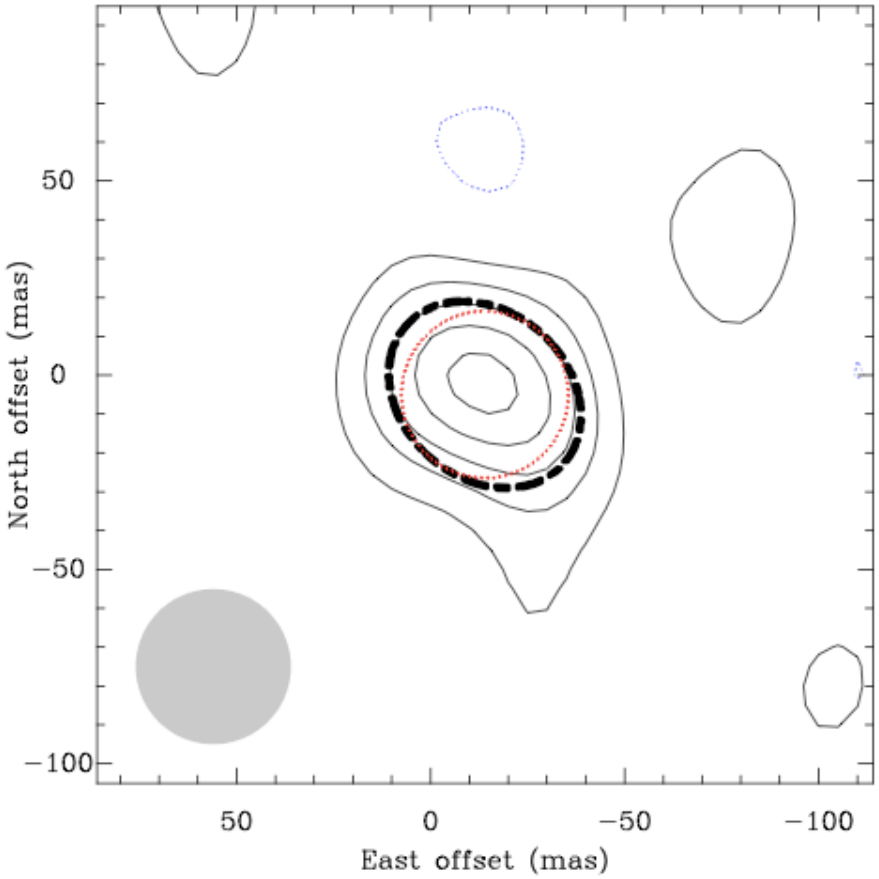
Distance determined from color-magnitude diagram of NGC2362

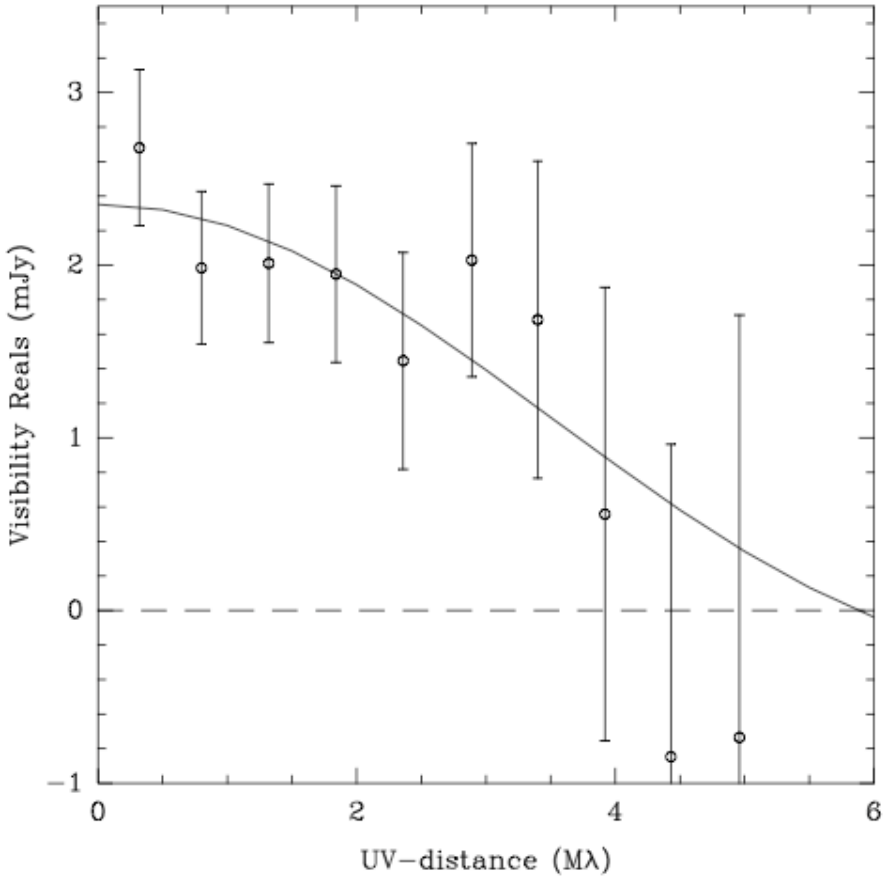
1.5 +/- 0.5 kpc

(Lada & Reid 1978)

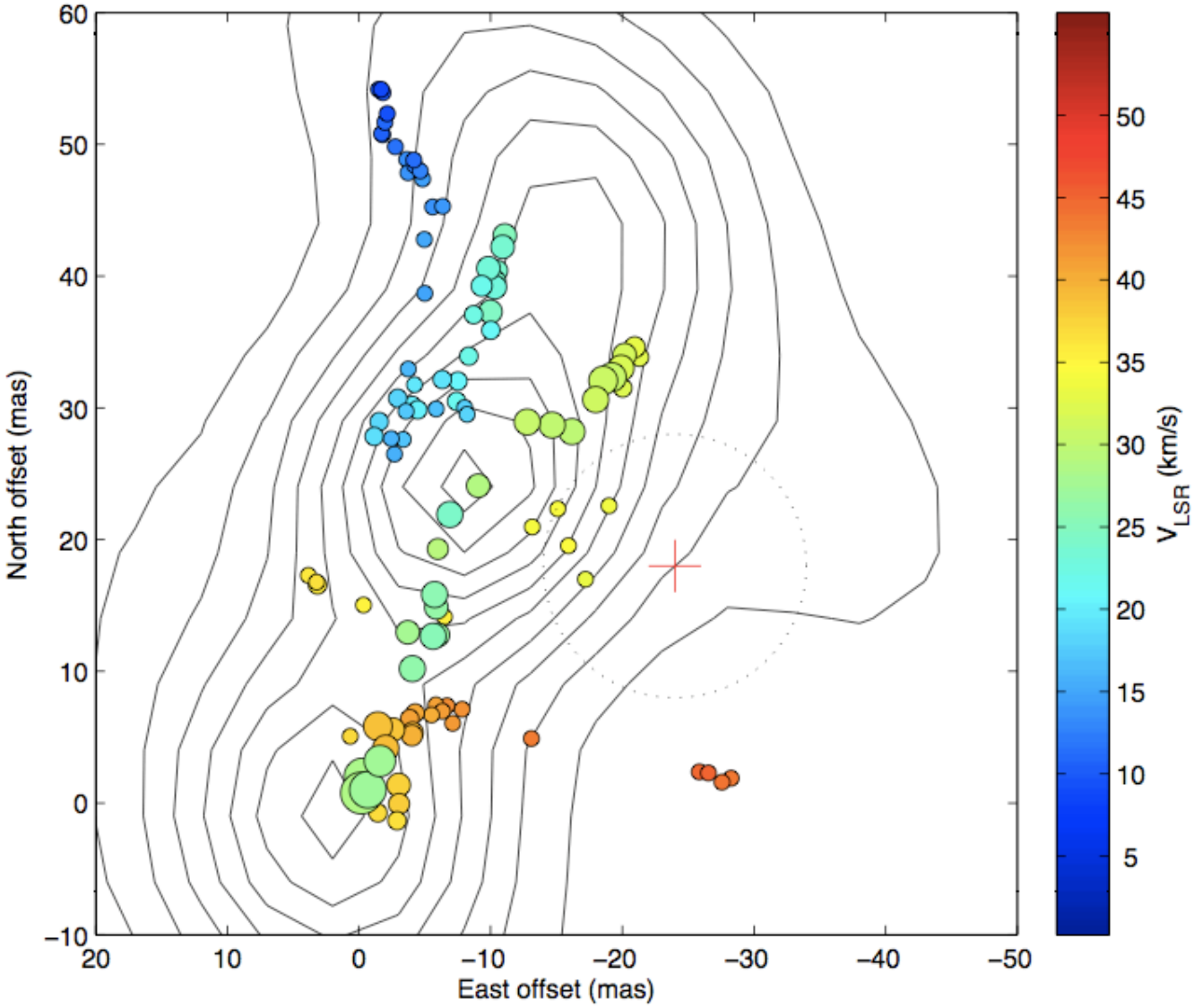
Spatial distribution of maser spots at the second epoch




50
0
−50
−100
North offset (mas)
50
0
−50
−100
East offset (mas)


3
2
1
0
−1
Visibility Reals (mJy)
0
2
4
6
UV−distance (Mλ)

SiO maser spots and radio photosphere (VLA)



SiO maser distributions and derived star postions

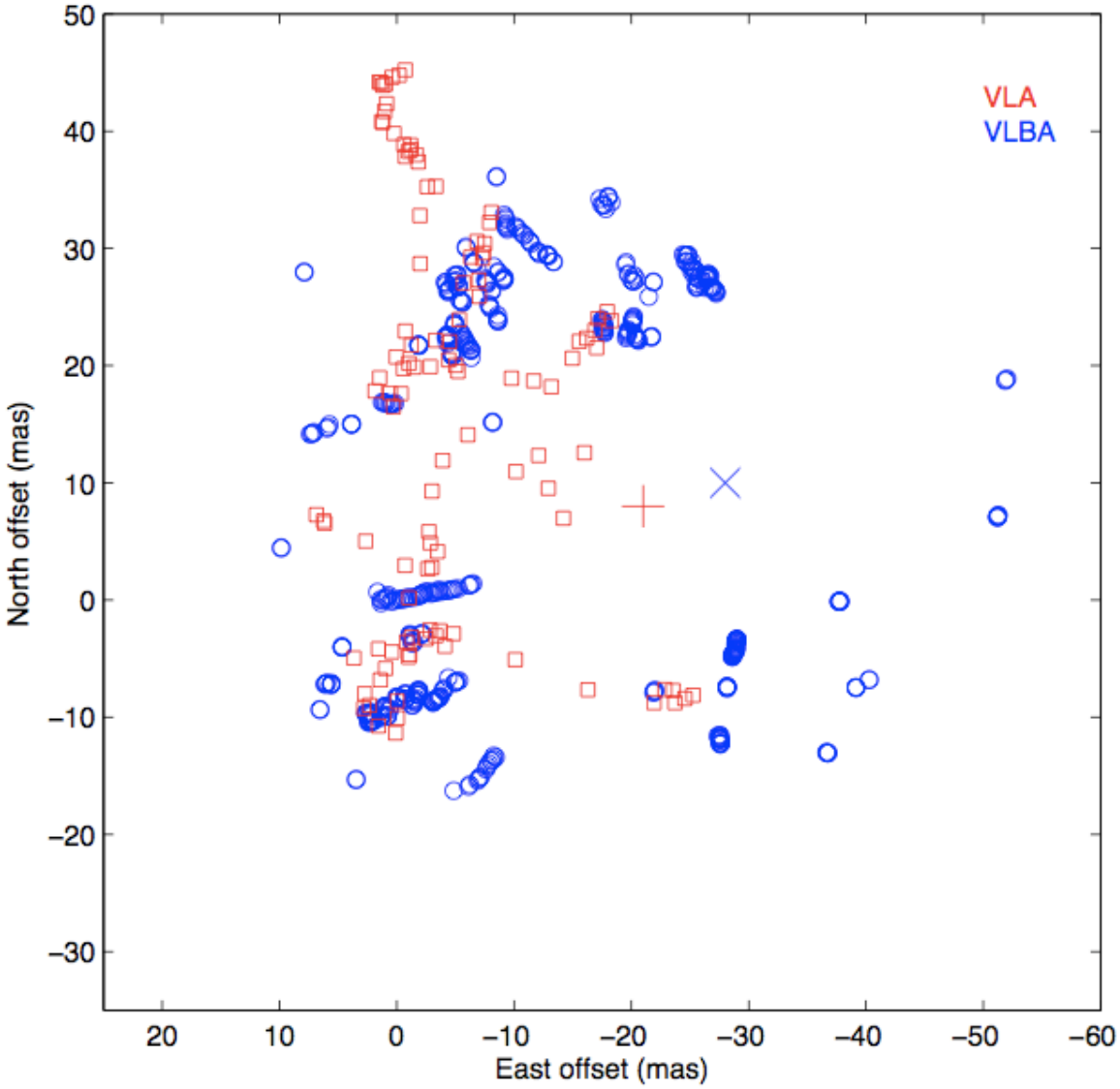
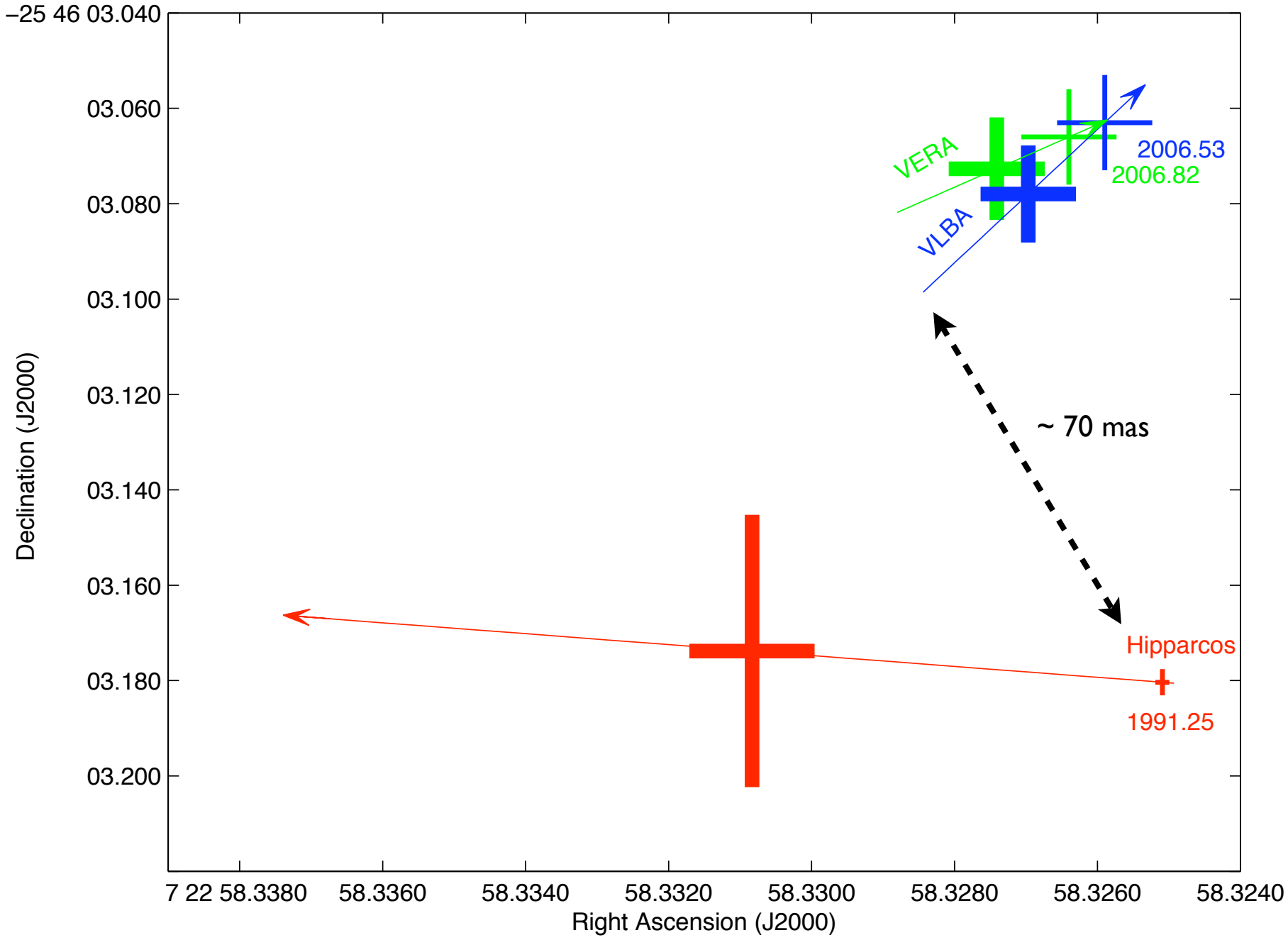
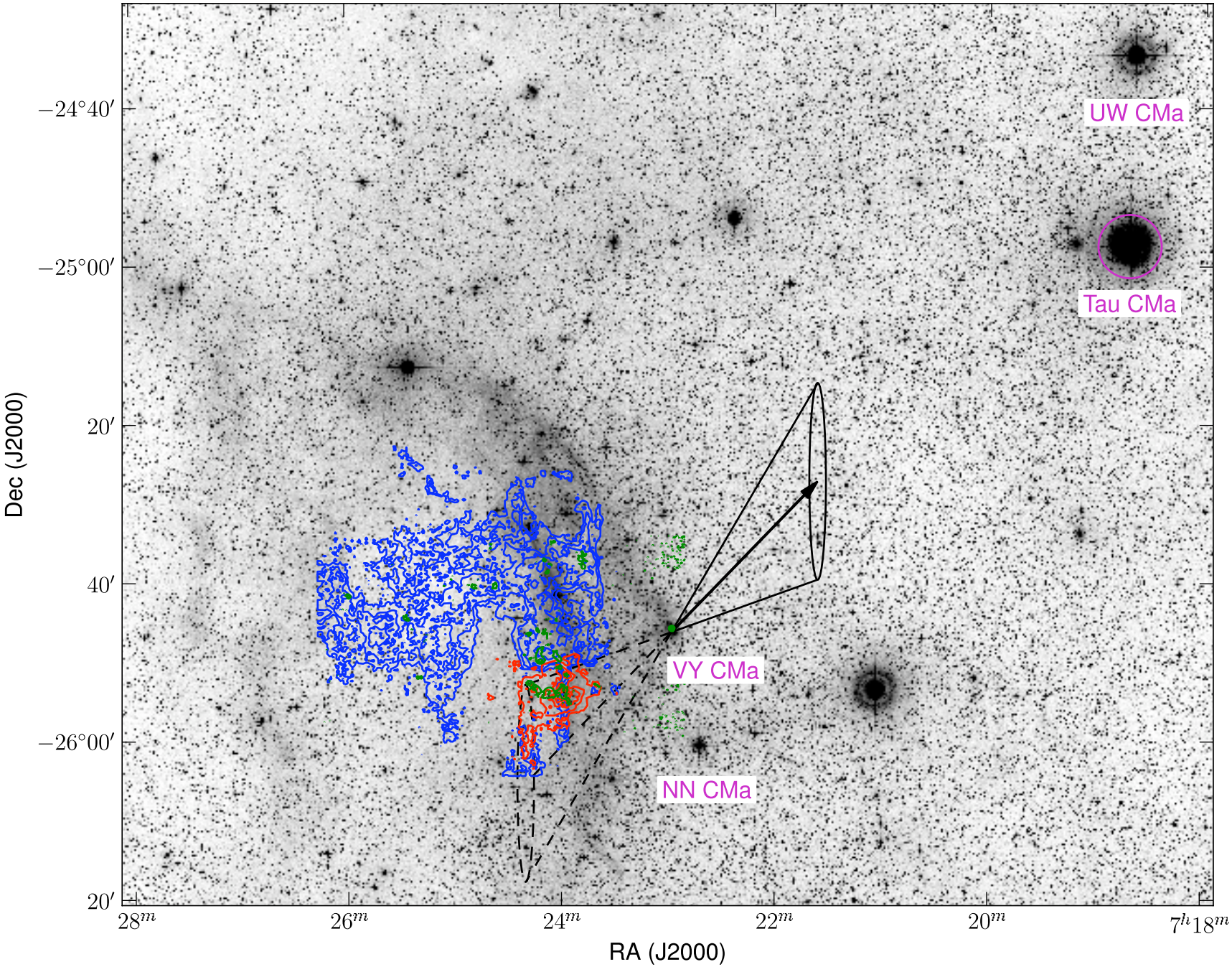


Table 5
Absolute Position and Proper Motion of VY CMa from Different Telescopes

Telescope	Epoch	R.A. (J2000) (h m s)	Decl. (J2000) (° ′ ″)	μ_x (mas yr^{-1})	μ_y (mas yr^{-1})
Hipparcos[a]	1991.25	07 22 58.3251 ± 0.0001	−25 46 03.180 ± 0.003	+8.86 ± 1.34	+0.75 ± 3.25
Hipparcos[b]	1991.25	07 22 58.3251 ± 0.0002	−25 46 03.176 ± 0.003	+5.72 ± 2.01	−6.75 ± 4.47
VERA[c]	2006.82	07 22 58.3264 ± 0.000?	−25 46 03.066 ± 0.00?	−2.09 ± 0.16	+1.02 ± 0.61
VLBA[d]	2006.53	07 22 58.3259 ± 0.0007	−25 46 03.070 ± 0.010	−2.21 ± 0.06	+2.29 ± 0.30

Notes.
[a] Perryman et al. (1997).
[b] van Leeuwen (2007).
[c] Choi et al. (2008a, 2008b), where the position uncertainty is unknown.
[d] This paper.


−25 46 03.040
03.060
03.080
03.100
03.120
03.140
03.160
03.180
03.200
Declination (J2000)
7 22 58.3380
58.3360
58.3340
58.3320
58.3300
58.3280
58.3260
58.3240
Right Ascension (J2000)
VERA
VLBA
2006.53
2006.82
~ 70 mas
Hipparcos
1991.25


UW CMa
Tau CMa
VY CMa
NN CMa
−24°40′
−25°00′
20′
40′
−26°00′
20′
28m
26m
24m
22m
20m
7h18m
Dec (J2000)
RA (J2000)

Summary

We have measured accurate absolute position, parallax and proper motion of VY CMa at radio wavelength, and found that the optical astrometric measurement of this star was problematic.

For details: Zhang et al. 2012, ApJ, 744, 23

Thank you for your attention!