Distance to VY Canis Majoris with VERA

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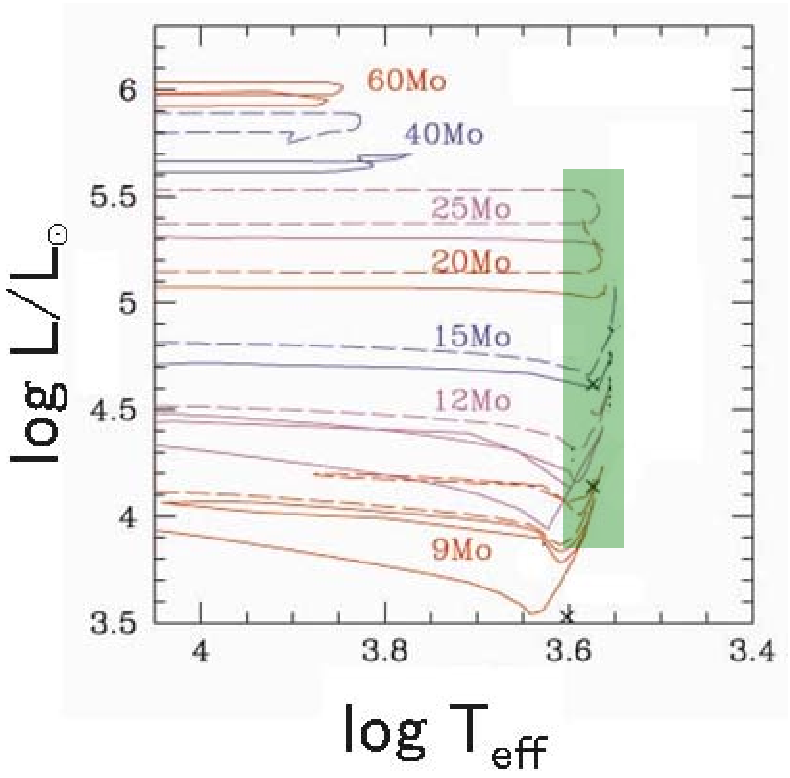
Outline

- Red Supergiants on HR diagram
- VY Canis Majoris
- Phase-referencing VLBI Observations with VERA
- Results & Discussion

 - Distance to VY CMa
 - Estimation of Stellar Position using SiO masers
 - Kinematics of the H_2O masers in the Circumstellar Envelopes

- Summary

Red Supergiants ①



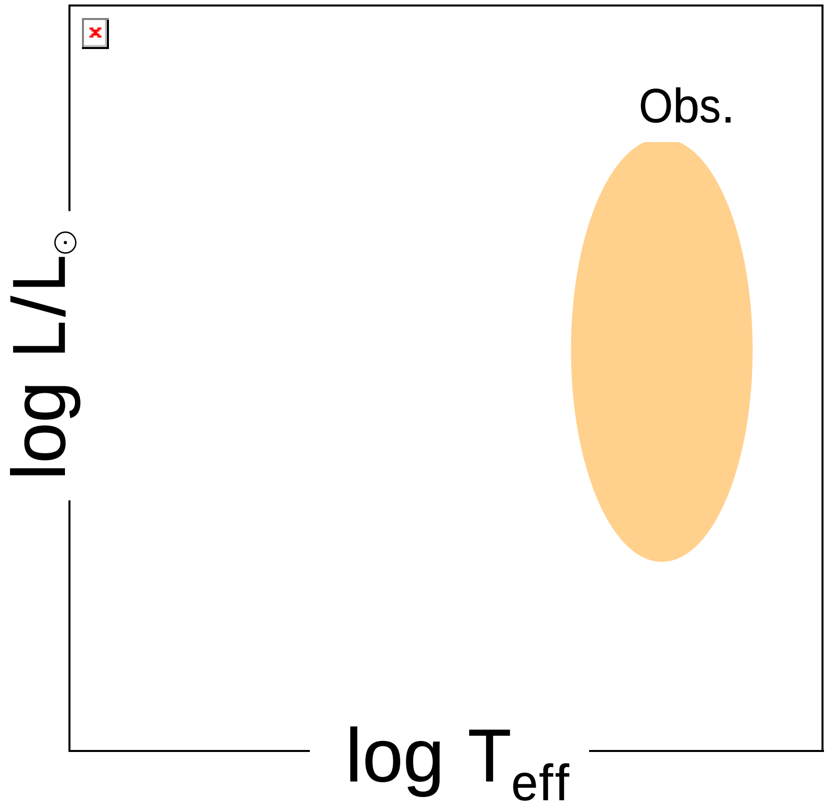
Theoretical evolutionary model

(Massey et al. 2005)

Red Supergiants

- Evolved phase of 9 $M_\odot$< M < 40 $M_\odot$ stars on main sequence
- mass-loss rate 10^{-4}-10^{-5} $M_\odot$ yr^{-1}
- lifetime 10^{5-6} yr on RSG
- luminosity 10^{4-5} $L_\odot$
- effective temperature 3000 K

Red Supergiants ②



(Massey et al. 2005)

Problem

- There is a discrepancy between theoretically predicted and observed locations of RSGs on the HR diagram

luminosity depends on the $(\text{distance})^2$

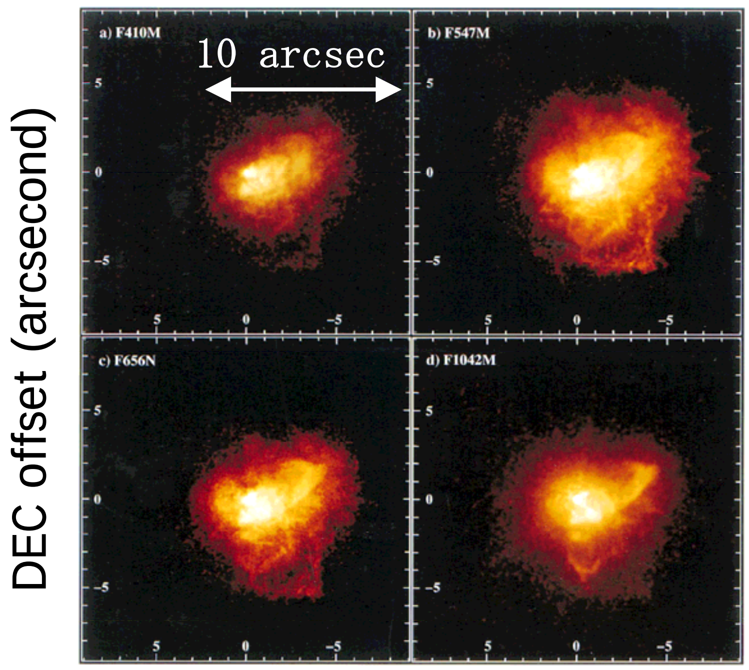
→ accurate distance measurements are essential

- The distance to RSGs

→ too far to obtain reliable distance with trigonometric parallax measurements

The distance measurements of red supergiants are important to study properties of evolved massive stars.

VY Canis Majoris ①

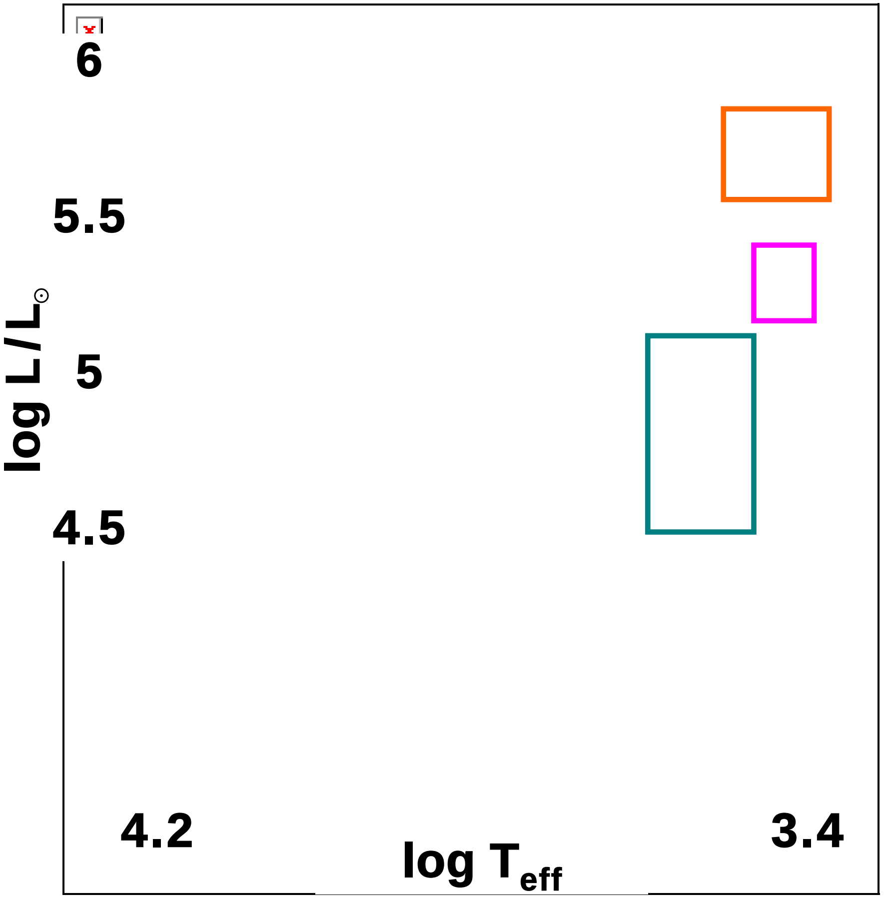


HST images (Smith et al. 2001)

Properties

- distance 1.5 kpc (Lada & Reid 1978)
  with 30% accuracy !
- luminosity 5 × 10^5 $L_\odot$
  (Humphreys & Davidson 1994)
- mass-loss rate 3 × 10^{-4} $M_\odot$ yr^{-1}
  (Danchi et al. 1994)
- effective temperature 2800 K
  (Monnier et al. 1999)

VY Canis Majoris ②



(Massey et al. 2006)

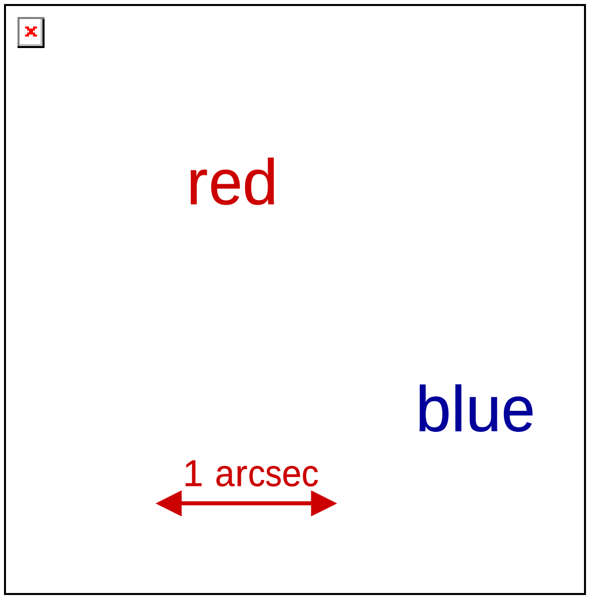
distance 1.5 kpc
Luminosity from the SED: 2-5 × 10^5 $L_{\odot}$
Temperature based on the spectral type: 2800 K

Aperture masking interferometry R_*~8.3 AU
Temperature based on the spectral type: 2800 K

distance 1.5 kpc
V=8.5 (AAVSO)
A_V & T_{eff} (MARCS Model)
(4) TiO (red/NIR bands) : 3650 ± 25 K
(5) TiO (blue/yellow bands) : 3450 ± 25 K
(6) V-K: > 3475 ± 35 K
(7) V-J: 3705 ± 90 K
A_V=3.20

We need to measure a trigonometric parallax to obtain accurate luminosity.

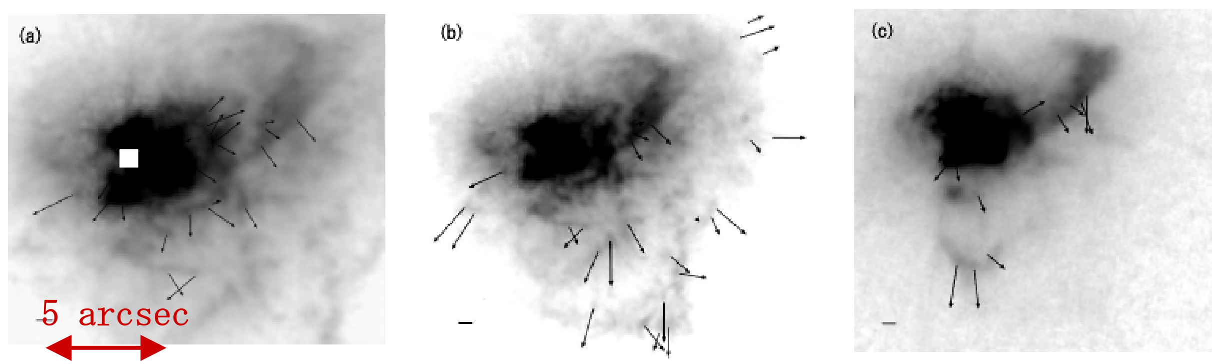
VY Canis Majoris ③



Bipolar outflow
SiO (v=0 J=1–0) emission
VLA
(Shinnaga et al. 2004)

Mass-loss

- bipolar outflow (Shinnaga et al. 2004)
- asymmetric mass loss
  (Humphreys et al. 2007)



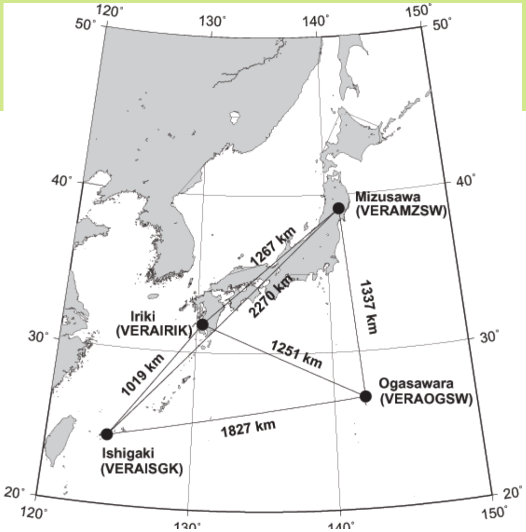
Asymmetric mass loss by HST observations
(Humphreys et al. 2007)

Aim of this study

- Measure the distance to VY CMa with a trigonometric parallax method.

- Reveal the structure and the 3-dimensional kinematics of the circumstellar envelopes around VY CMa using H_2O and SiO masers.

Observations



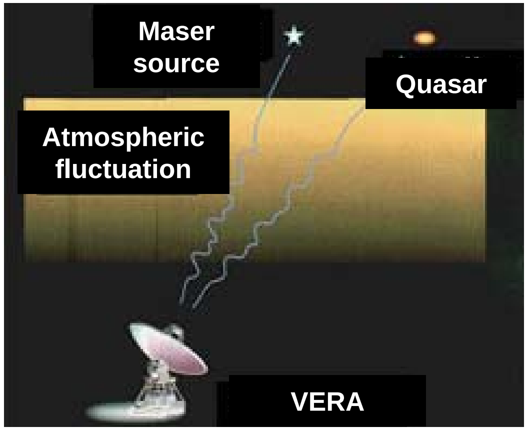
- Phase-referencing VLBI observations with VERA
- 10 epochs for 13 months since April 2006
- H_2O masers (22 GHz) & SiO masers (43 GHz)
- Simultaneous dual-beam observations

  Target source: VY CMa

  Reference source:

  J0725-2640

  (S.A. 1.059 degrees)

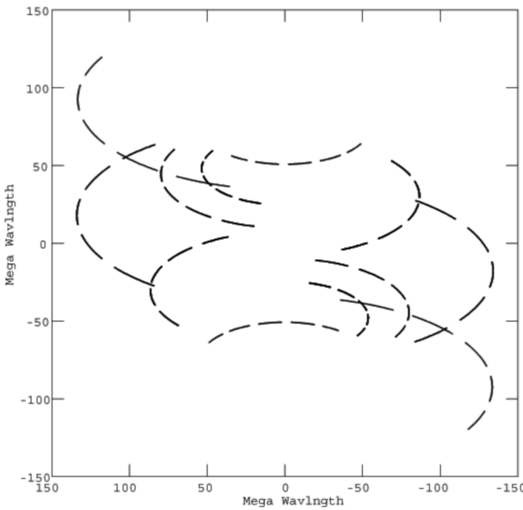


Two receivers in each antenna

- Angular resolution (2270 km baseline)

  1.2 mas at 22 GHz

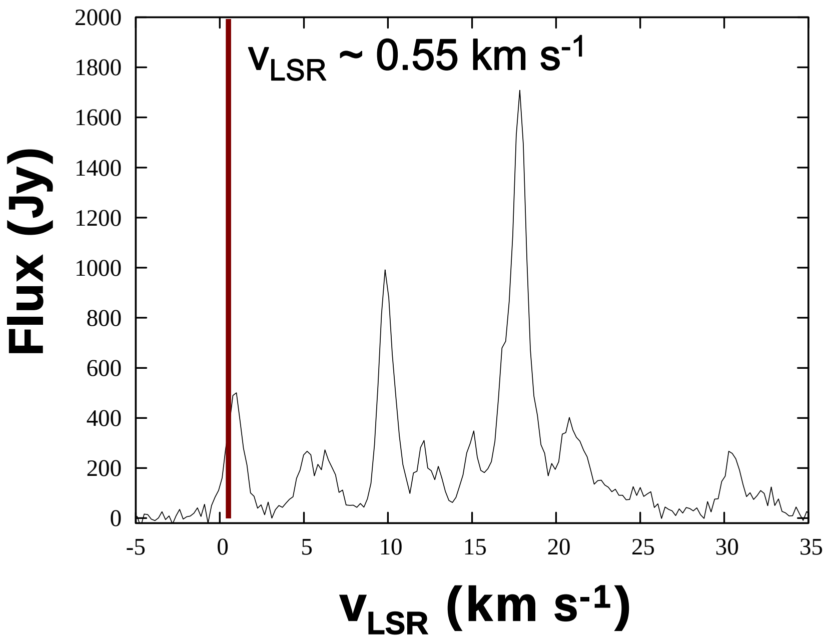
  0.6 mas at 43 GHz
- Velocity resolution ~ 0.21 km s^{-1}

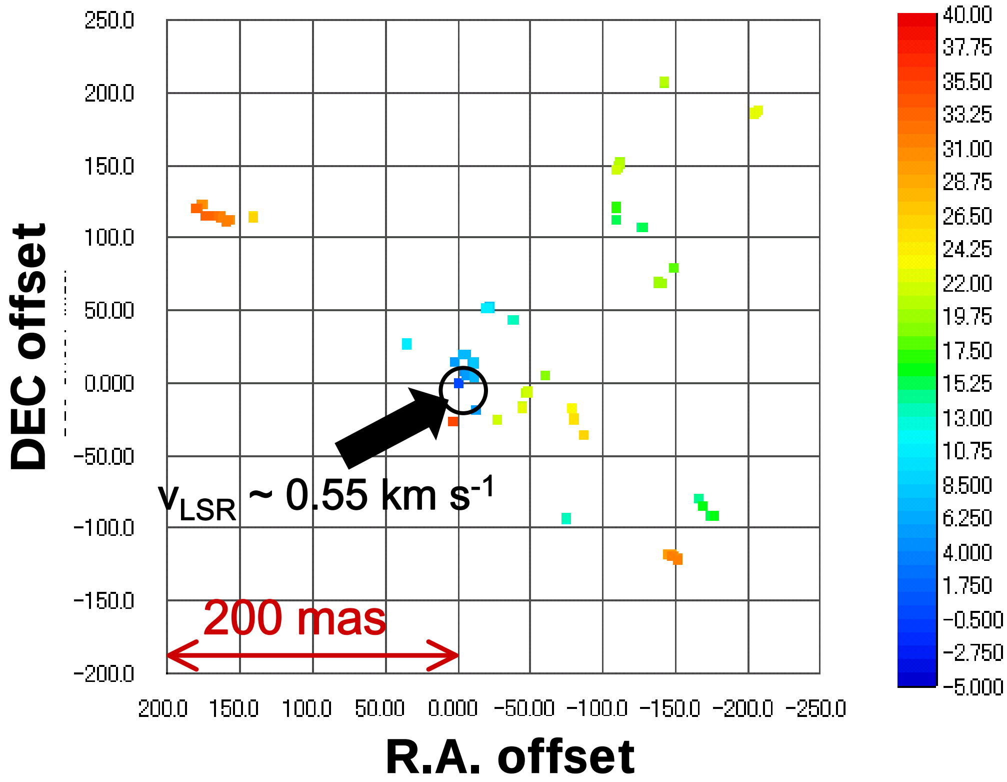


uv coverage

H_2O masers of VY CMa

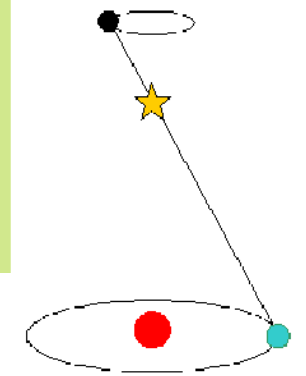
April, 2006





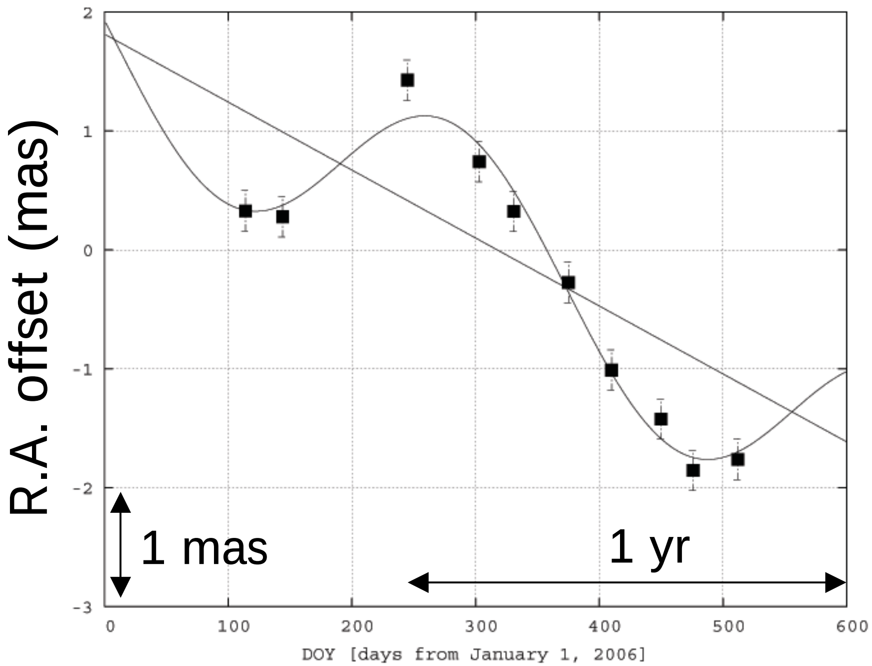
(Choi et al. 2008, PASJ in press)
astro-ph arXiv:0808.0641

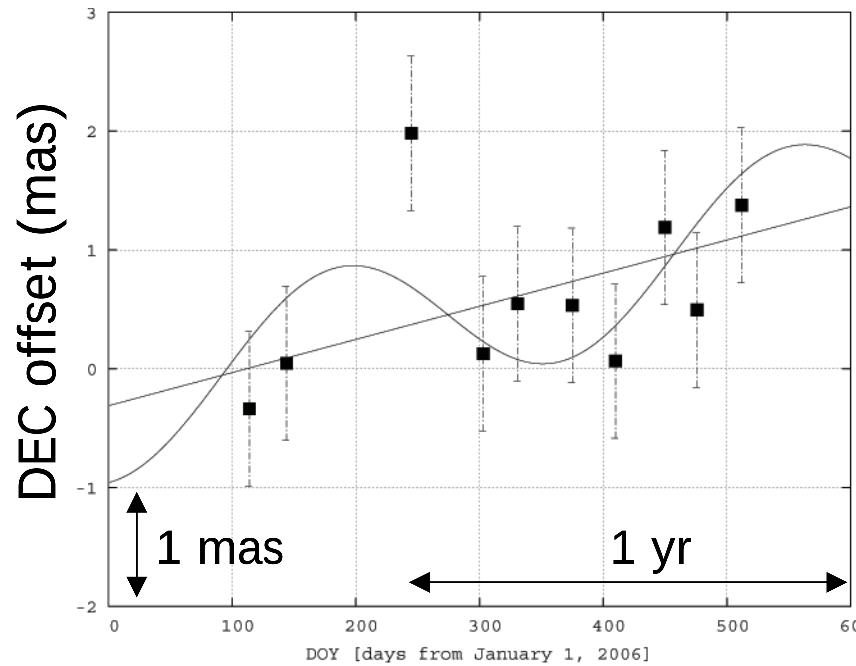
Parallax Measurements



Measured positions = parallax + proper motion

H_2O maser component at V_{LSR} ~ 0.55 km s^{-1}





Best fit for R.A. :

π = 0.88 $\pm$ 0.08 mas $\rightarrow$ d = 1.14 $^{+0.11}_{-0.09}$ kpc

Proper motion : -2.09 $\pm$ 0.16 mas yr^{-1} in R.A.

1.02 $\pm$ 0.61 mas yr-1 in DEC

(Choi et al. 2008, PASJ in press)
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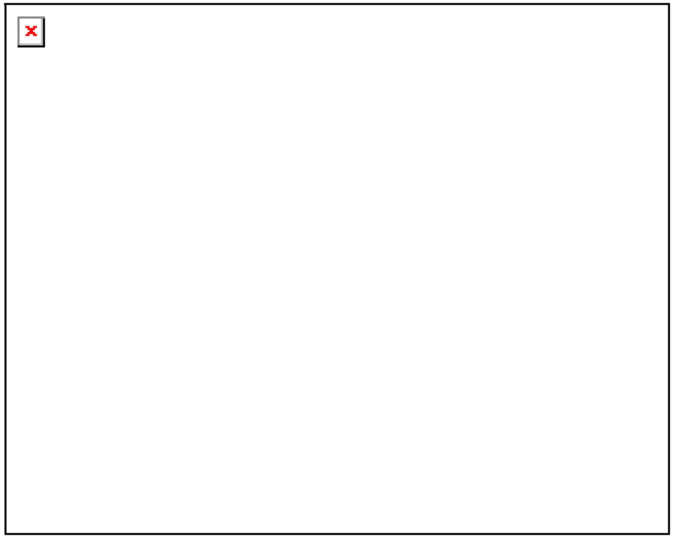
Luminosity of VY CMa



The SED of VY CMa
(Humphreys 2006)

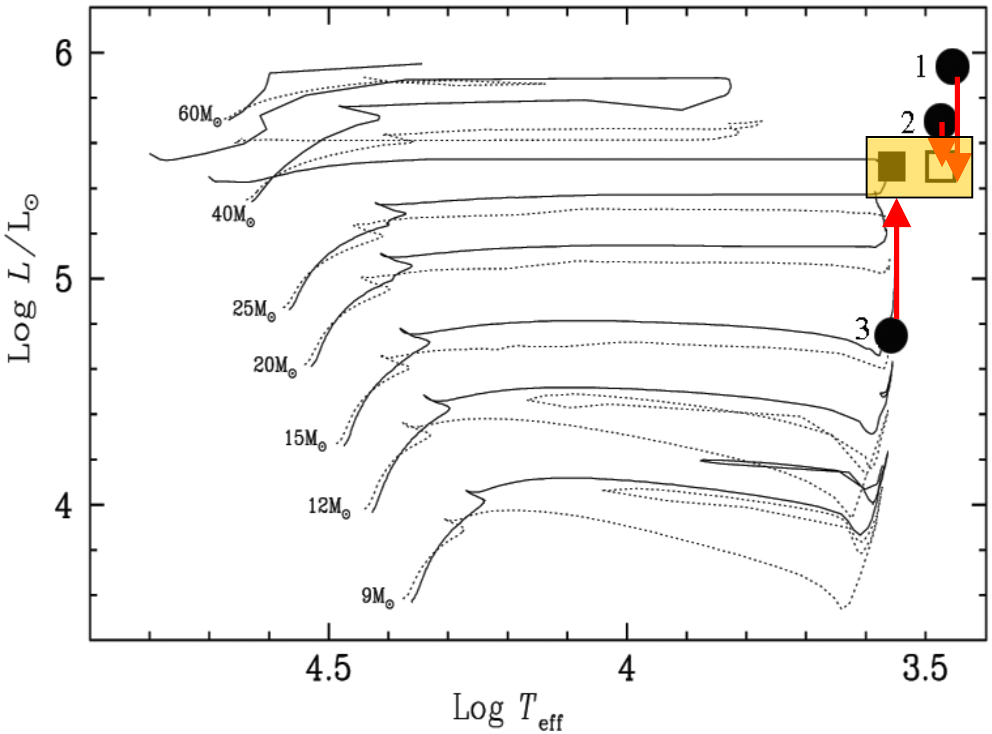
- With our distance, we re-estimate the luminosity

$$L = 4\pi d^2 F_{bol}$$

$$d = 1.14^{+0.11}_{-0.09}\ \mathrm{kpc}$$

$$\mathbf{L = (3.0 \pm 0.5) \times 10^5\ L_\odot}$$

The location of VY CMa on the HR diagram

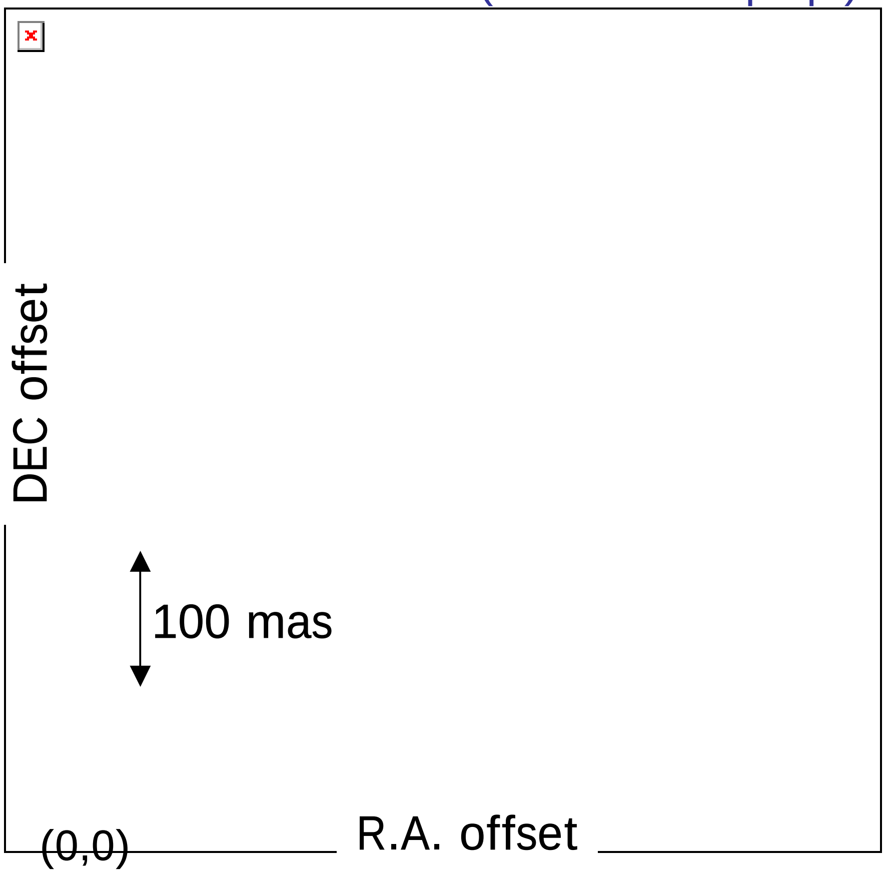


(Choi et al. 2008, PASJ in press)
astro-ph arXiv:0808.0641

- Re-estimated luminosity with our distance of 1.14 kpc
  $L \sim (3 \pm 0.5) \times 10^5 L_\odot$
- When we adopt the effective temperature of 3650 K (Massey et al. 2006), our result is consistent with the theoretical evolutionary track of initial mass of 25 $M_\odot$.
- There is still uncertainty in the estimation of temperature.

Inner motions of H_2O masers

(Choi et al. in prep.)

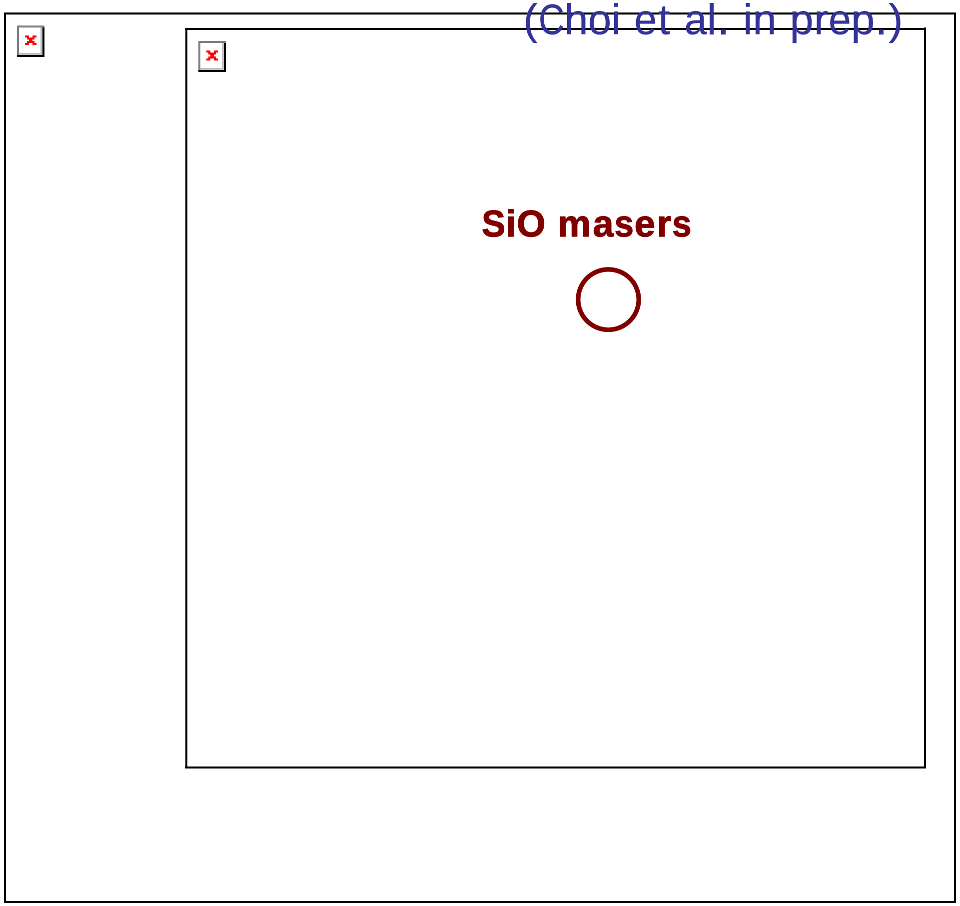


α (J2000) 07h22m58.3315s
δ (J2000) -25d46'03.174"

- Subtract averaged absolute proper motions
- Average motion
  -3.24 ± 0.16 mas yr^{-1}
  in right ascension
  2.06 ± 0.60 mas yr^{-1}
  in declination

Superposition of masers

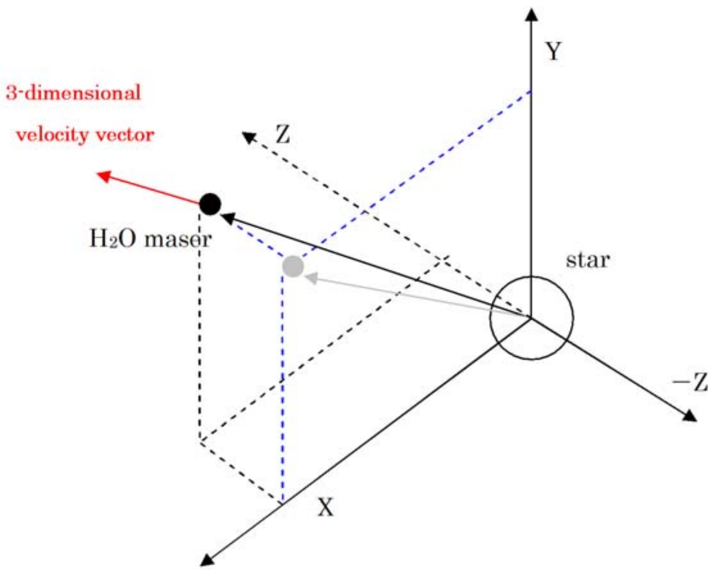
(Choi et al. in prep.)



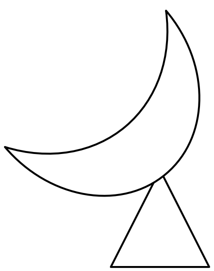
- The circumstellar structure is revealed by phase-referencing VLBI observations with different frequencies of masers in detail.
- The SiO masers are tools to estimate the stellar position in the obscured dusty region by mass-loss with the highest resolution.

(0,0) α (J2000) 07h22m58.3315s
δ (J2000) -25d46'03.174"

Coordinate System

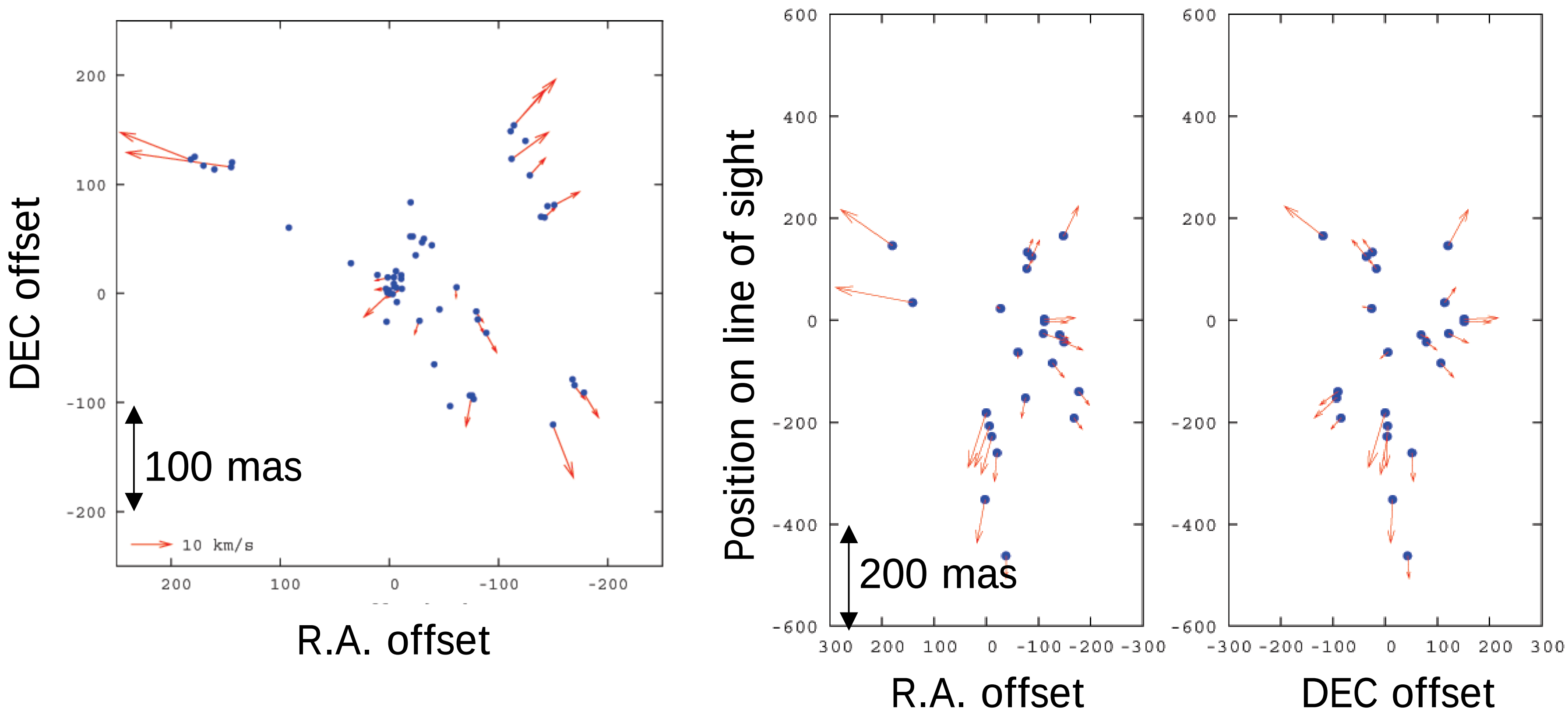


For H_2O masers, we know
① positions on 2-dimension, and
② velocities on 3-dimension.



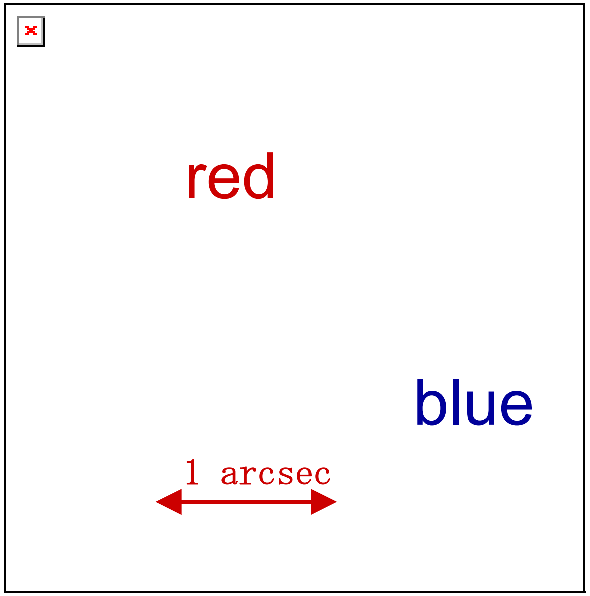
X-axis : right ascension
Y-axis : declination
Z-axis : radial direction

3-dim. Kinematics of the H_2O Masers

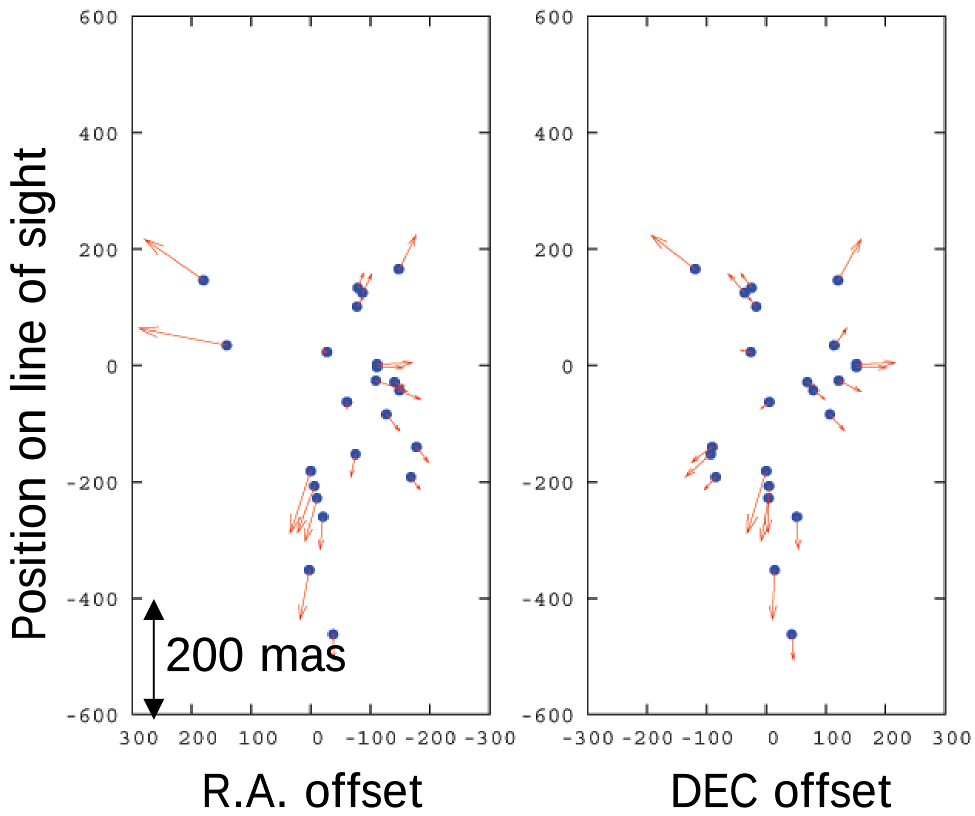


- Our results show the bipolar outflow along to the line of sight.

3-dim Kinematics of the H_2O Masers



Bipolar outflow
SiO (v=0 J=1–0) emission with VLA
(Shinnaga et al. 2004)



- Our results show the bipolar outflow along to the line of sight.
- This is consistent with the result from Shinnaga et al. (2004).

Summary

- We measured a distance to VY CMa with a trigonometric parallax.

  π = 0.866 $\pm$ 0.075 mas $\rightarrow$ d = 1.14 $^{+0.11}_{-0.09}$ kpc

- We re-estimated the luminosity of VY CMa

  $\rightarrow$ L = (3.0 $\pm$ 0.5) $\times$ 10^5 $L_\odot$

- When we adopt the temperature of 3650 K, the location of VY CMa on HR diagram is consistent with the evolutionary track of initial mass of 25 $M_\odot$ star.
- The maps of the H_2O and SiO masers are superposed, and we estimated a stellar position.
- 3-dimensional kinematics of the circumstellar envelopes of the H_2O masers suggest a bipolar outflow along the line of sight.