

# Moving Cluster Method

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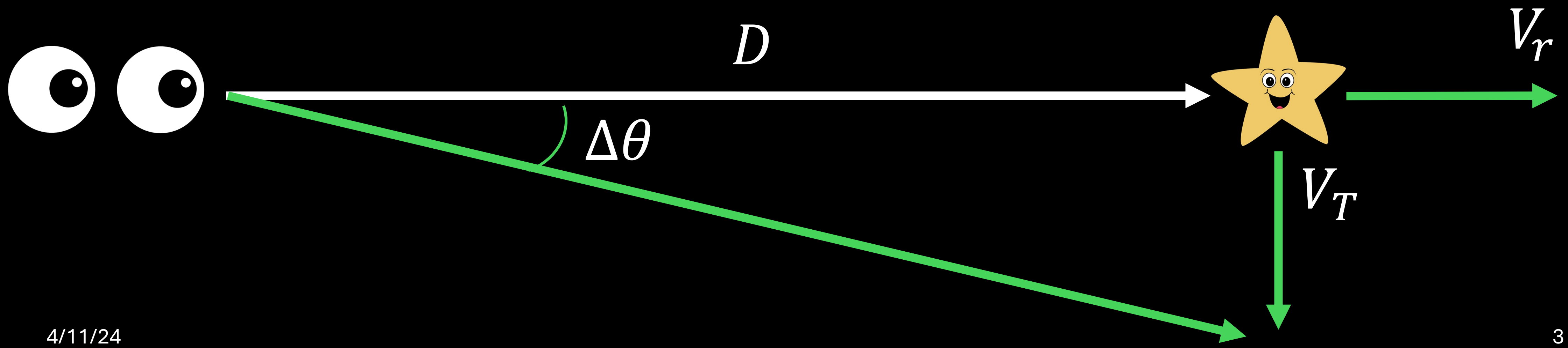
# Outline

1) Background
2) Some Geometry
3) Significance in Context
4) Sources of Error
5) In Research Past and Present

# Background

- Proper Motion: $\mu \ (mas \cdot yr^{-1}) = \frac{\Delta\theta}{t}$
- Radial Velocity: $V_r \ (km \cdot s^{-1})$
- Transverse Velocity: $V_T \ (km \cdot s^{-1}) = 4.74 \cdot \mu D$
- Space Velocity: $V \ (km \cdot s^{-1}) = \sqrt{V_r^2 + V_T^2}$



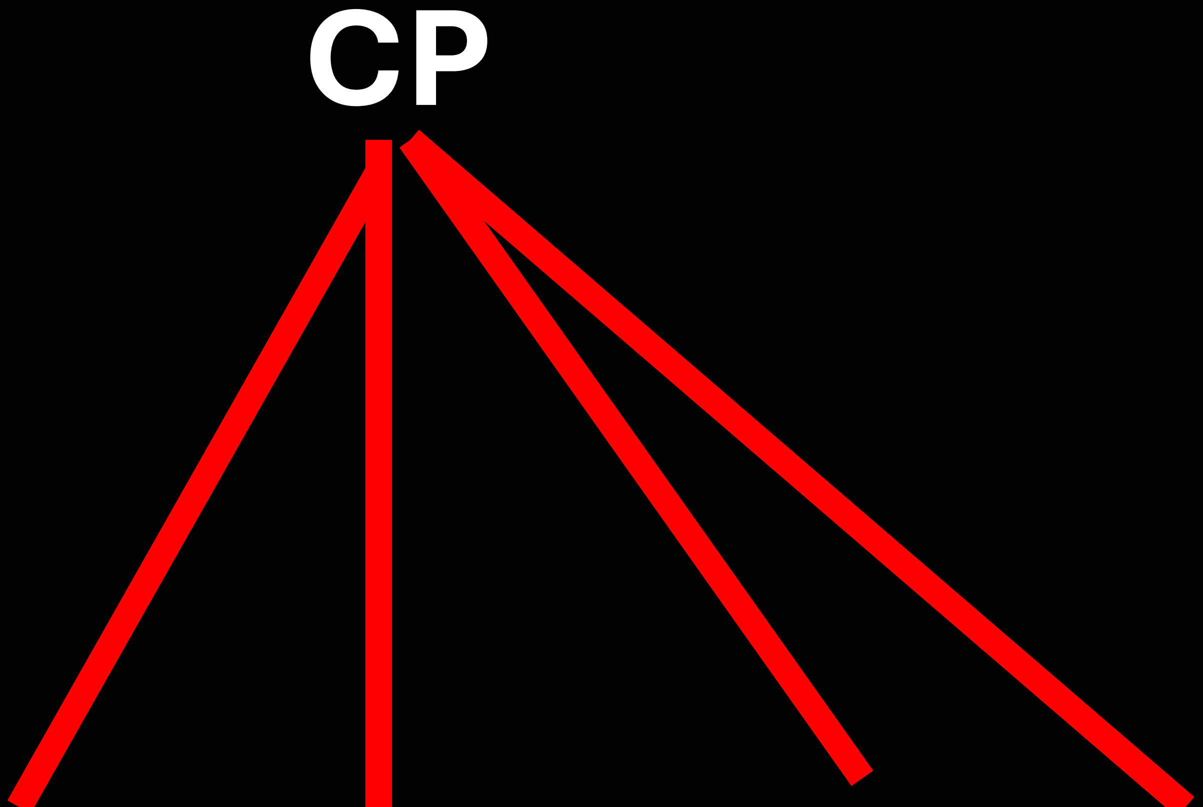


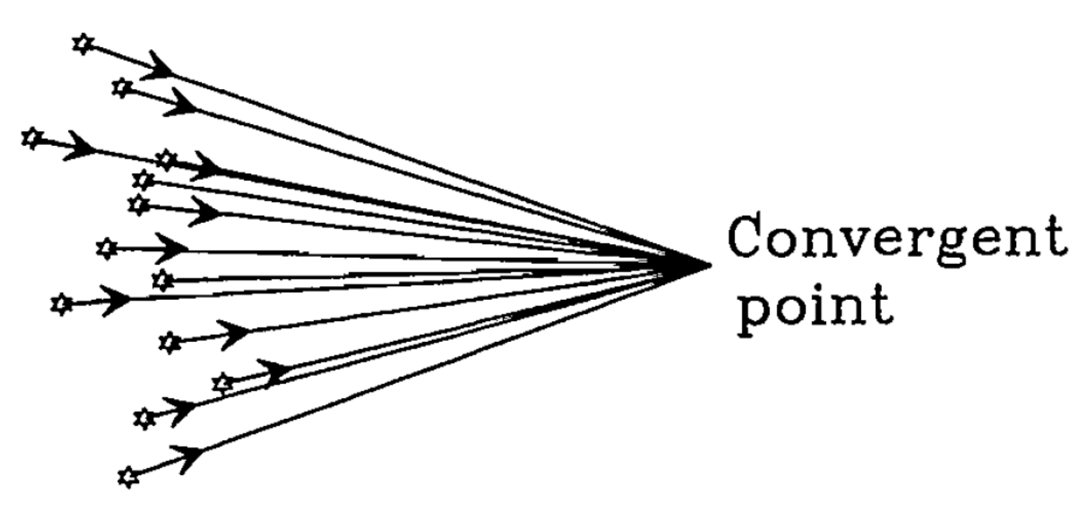
# Some Geometry



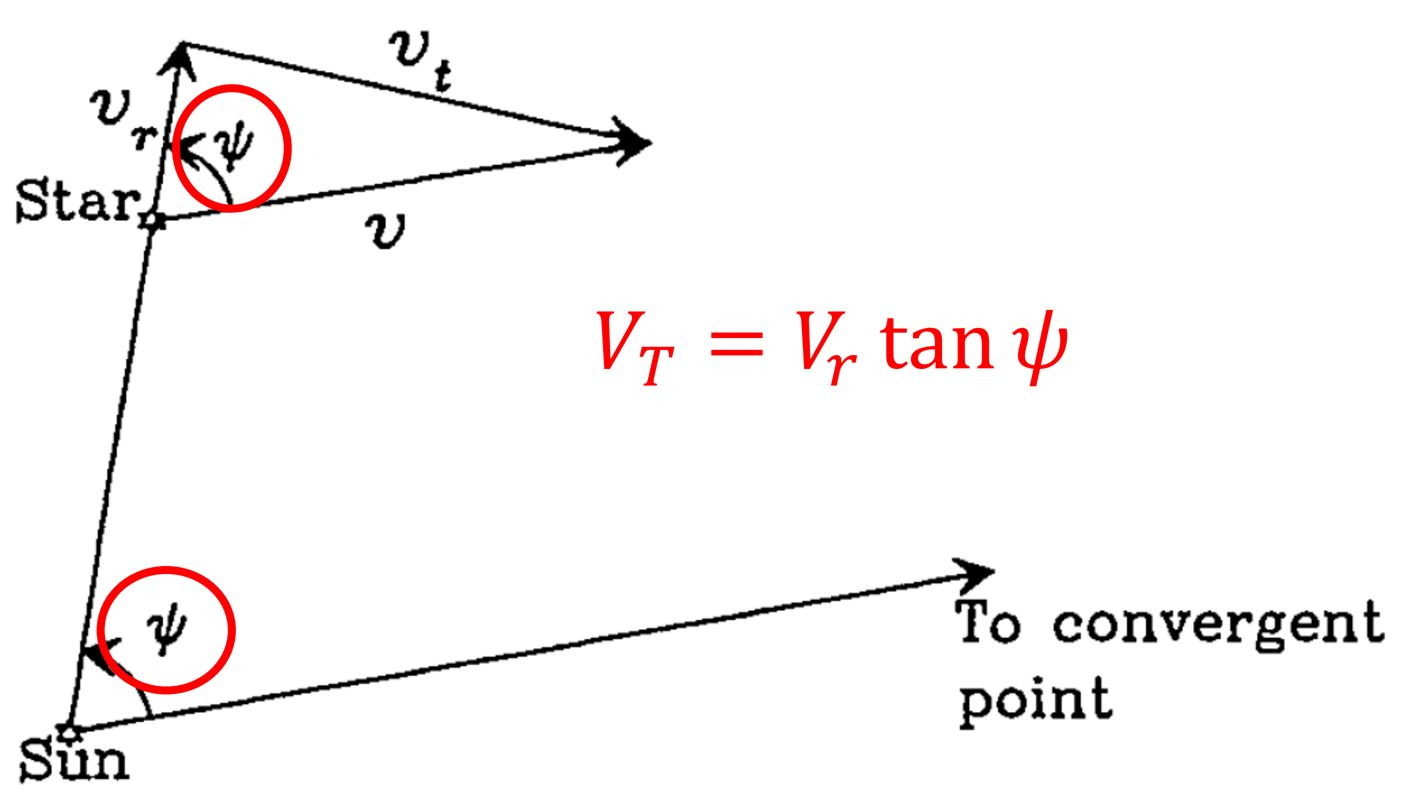

CP

**KEY INSIGHT:** Parallel lines in 3D space will appear to meet at a convergence point when projected onto a 2D plane






Cluster stars have identical velocity vectors




$$V_T = V_r \tan\psi$$

The direction from us to CP tells us the direction of the space velocity $V$ !

Binney & Merrifield (1998)

$$V_T = V_r \tan\psi$$

$$V_T = \mu \cdot D$$

$$D = \frac{V_r \tan\psi}{\mu}$$

$$\frac{\varpi}{mas} = \frac{4.74}{\tan\psi}\left[\frac{V_r}{km \cdot s^{-1}}\right]^{-1} \frac{\mu}{mas \cdot yr^{-1}}$$



# Significance in Context



# Significance of Moving Cluster Method

- ”Historically, the distance to the Hyades cluster was of enormous importance because the cluster includes types of stars whose distances, and hence whose absolute magnitudes, could not be measured by the trigonometric parallax method…The Hyades cluster is less important now that trigonometric parallaxes can be obtained at its distance and beyond” (Binney & Merrifield 1998)
- Hyades MS fitting



# Sources of Error



# Sources of Error

- MCM assumes that the cluster does not rotate, contract, or expand
- MCM assumes random internal motions are small
- MCM assumes all cluster members have velocities equal in magnitude and direction
- MCM highly depends on how you define cluster member sample

Hanson (1975)

# In Research Past and Present





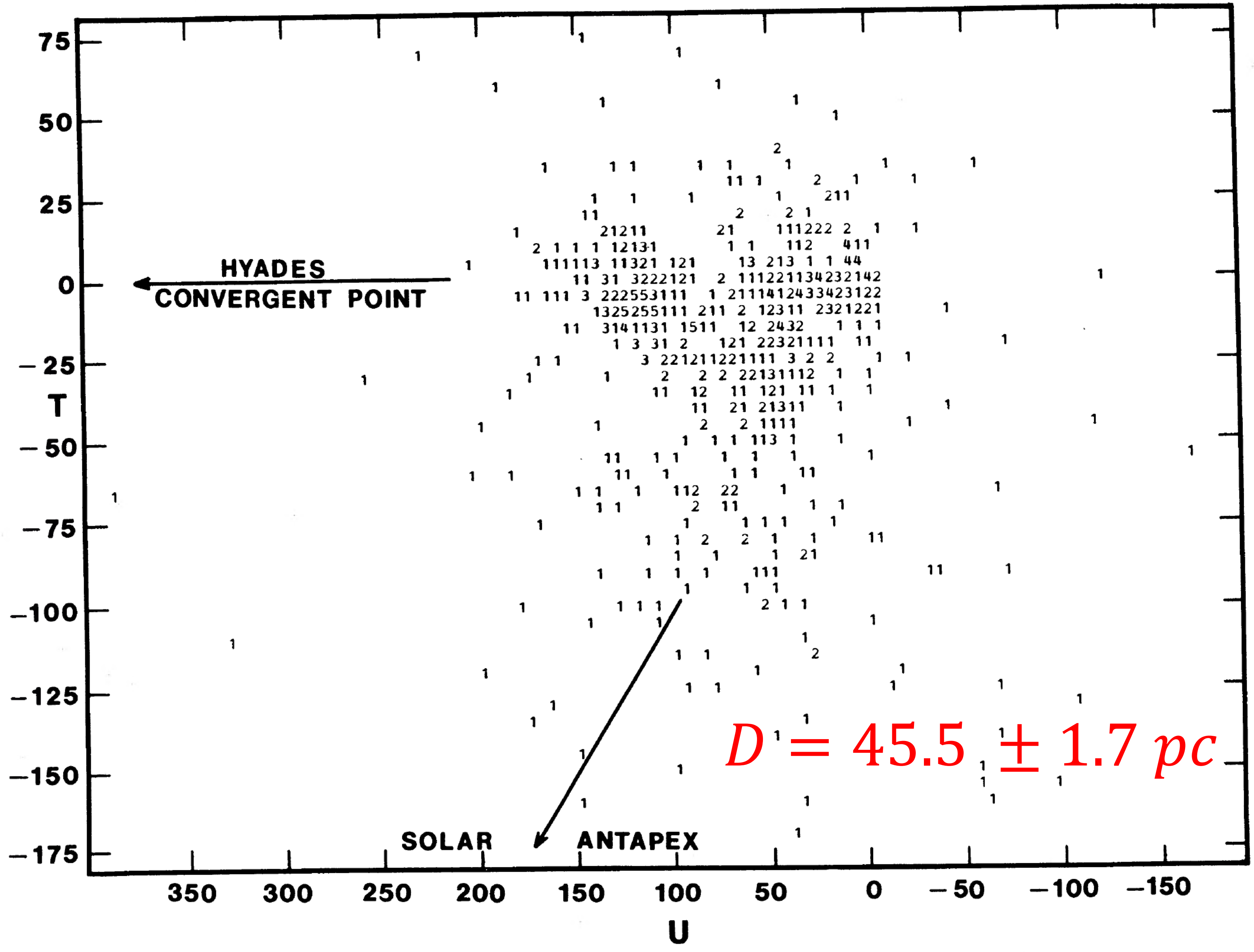




FIG. 1. Proper motion vector point diagram for 617 stars in the Hyades region. $U$, $T$ are in $10^{-3}$ ″/yr. Numbers indicate the number of stars in "bins" 0″.005/yr square in $U$, $T$.

Hanson (1975)

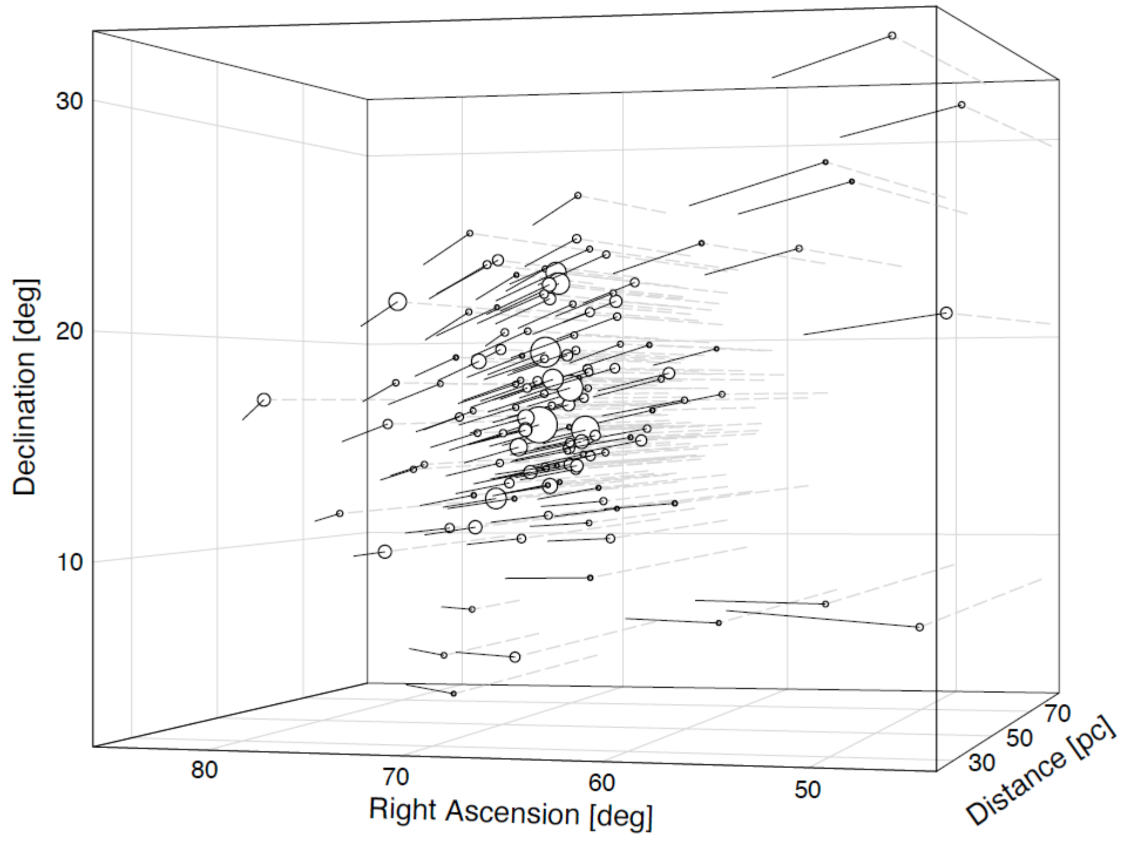



*Figure 1. The principle of determining astrometric radial velocities. Stars in a moving cluster share the same mean velocity vector. Parallaxes give the distance, while proper-motion vectors show the fractional change with time of the cluster's angular size. The latter equals the time derivative of distance, or the radial velocity. This plot shows positions for single stars in the Hyades, together with their measured distances and proper motions (shown over 100 000 years).*

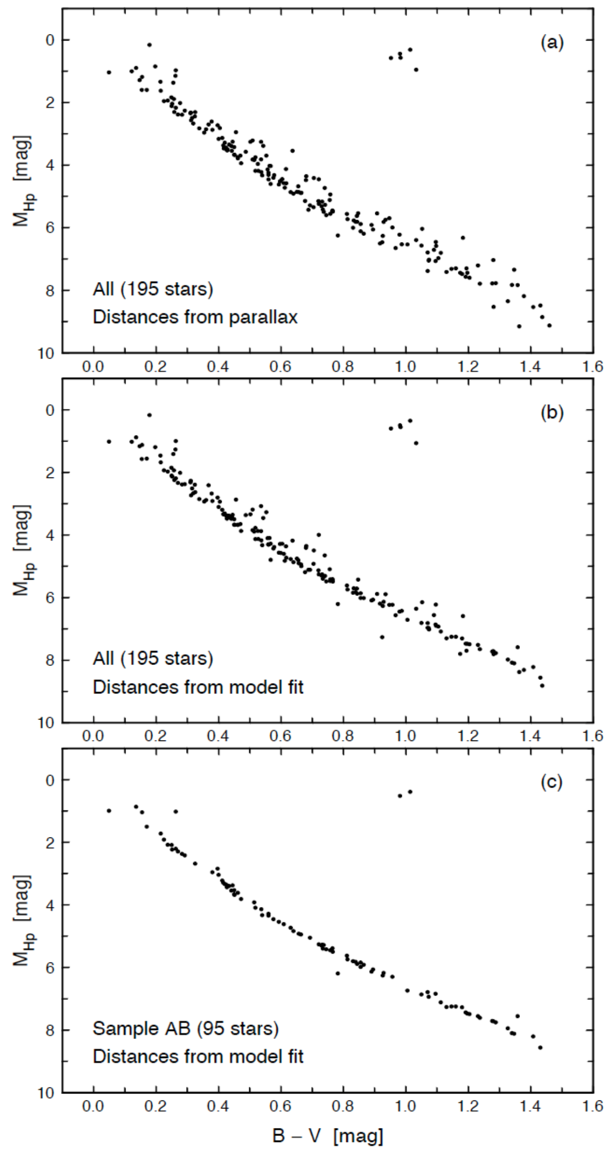



*Figure 2. The HR diagram for the Hyades, using data for all the presumed member stars in our sample (a and b), and for the subset of 98 stars with a good model fit, where known spectroscopic binaries were also excluded (c). In (a) the observed parallaxes were used to compute absolute magnitudes, in (b) and (c) the estimated parallaxes from the model fitting.*

HIPPARCOS Data

$D = 46.75\ pc$ Hyades

$D = 87\ pc$ Coma Berenices

Dravins et al. (1997)

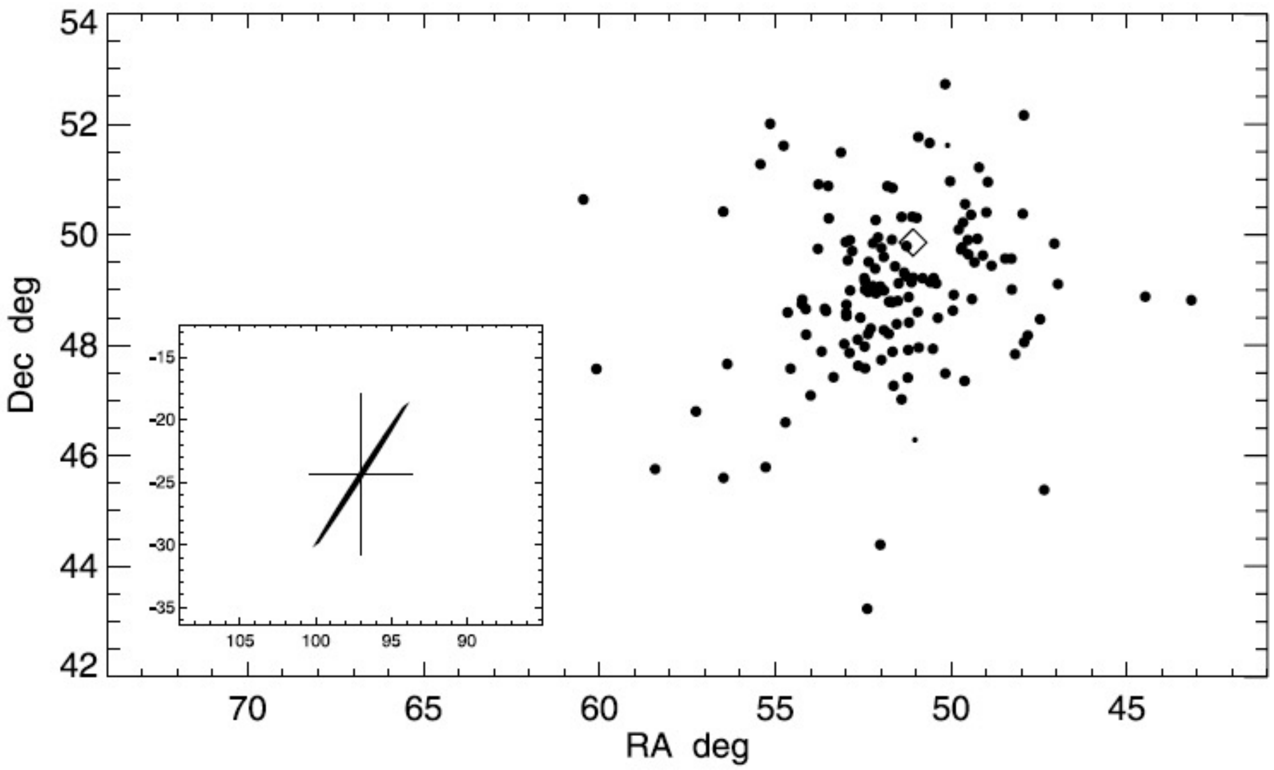
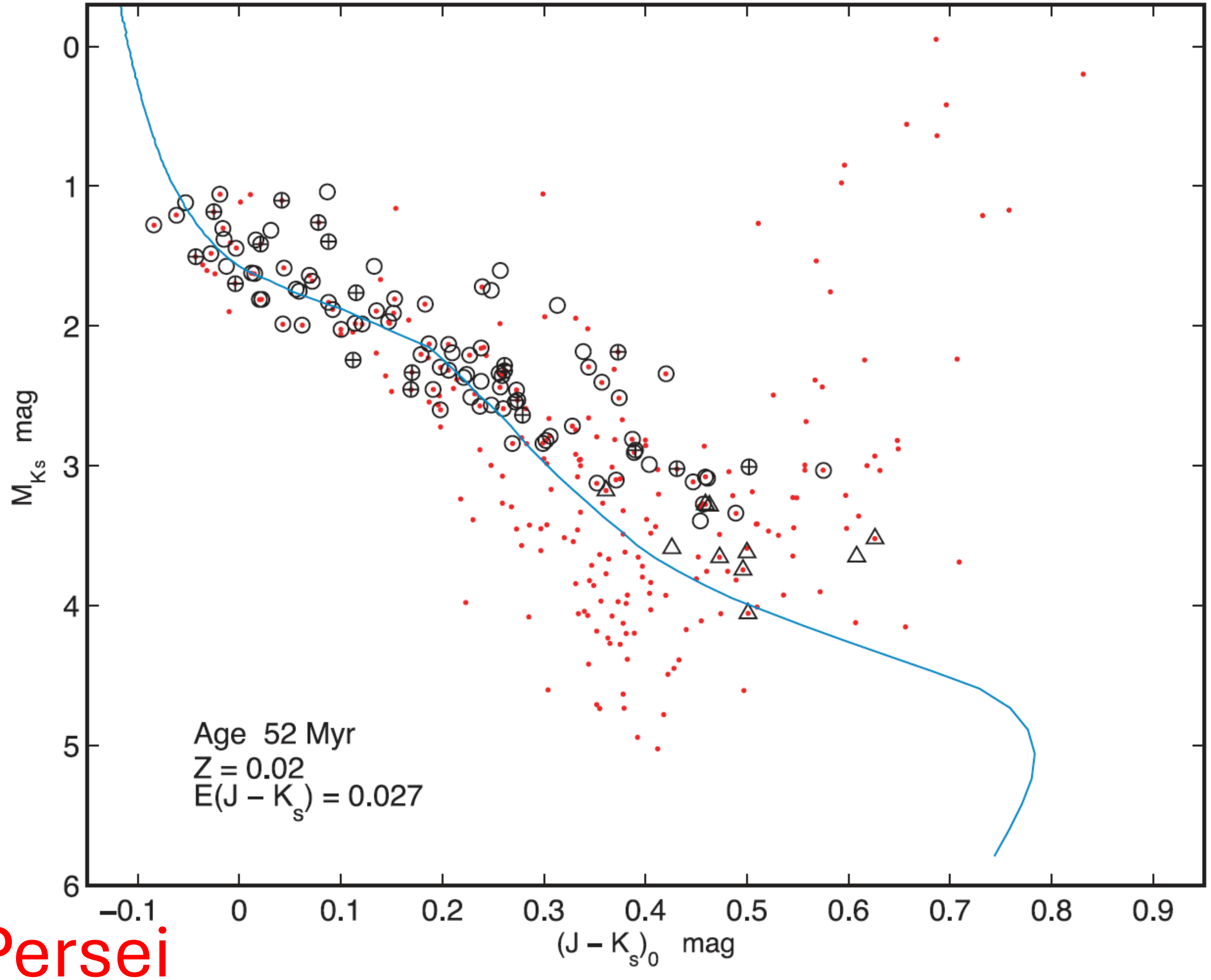



FIG. 2.—Sky positions of $\alpha$ Persei members selected from Tycho-2 in equatorial coordinates (J2000.0). The two stars with $|\Delta/\sigma_\Delta| > 2.5$, possibly non-members, are marked with smaller dots. The star $\alpha$ Per is indicated with an open diamond. The inset shows the position of the convergent point (*in the crosshair of the error bars*) determined by a $\chi^2$ fitting from the proper motions, its formal standard errors, and the highly elongated ellipse of covariance. The convergent point is approximately 83°.8 away from the cluster's center.

$D = 183\ pc\ \alpha$ Persei

Makarov (2006)




$D = 183\ pc\ \alpha$ Persei

FIG. 5.—H-R diagram of the $\alpha$ Persei cluster in the 2MASS near-IR passbands. The isochrone of 52 Myr with overshooting computed from the models by Pietrinferni et al. (2004) is shown for comparison. Known binaries of all kinds (spectroscopic, astrometric, and visual) are marked with crosses. Red dots represent all stars within 10° of $\alpha$ Per on the sky, with proper motions from UCAC2 converging near the cluster's convergent point and proper-motion components within 10 mas yr$^{-1}$ of the mean cluster's proper motion. Additional possible members (not in the Tycho-2 catalog) identified in the literature are marked with open triangles.

Makarov (2006)

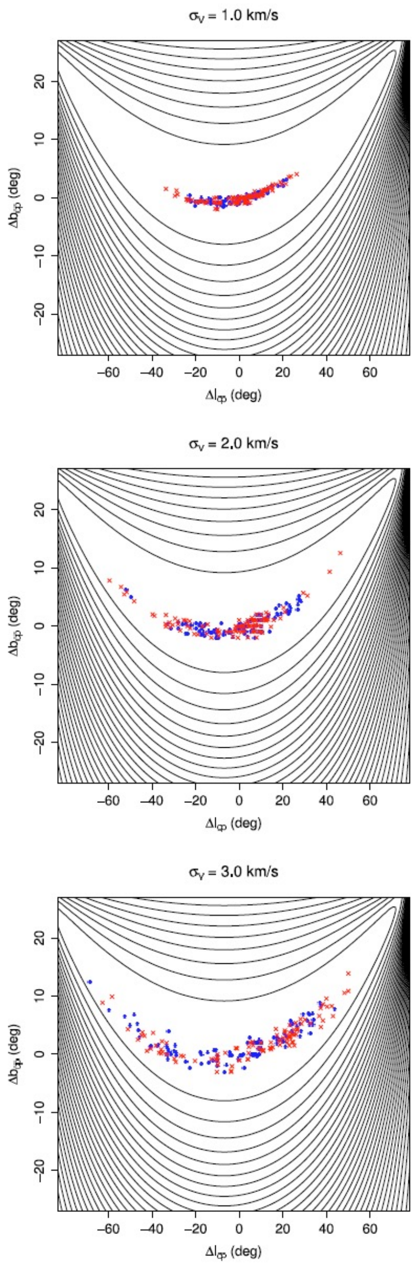
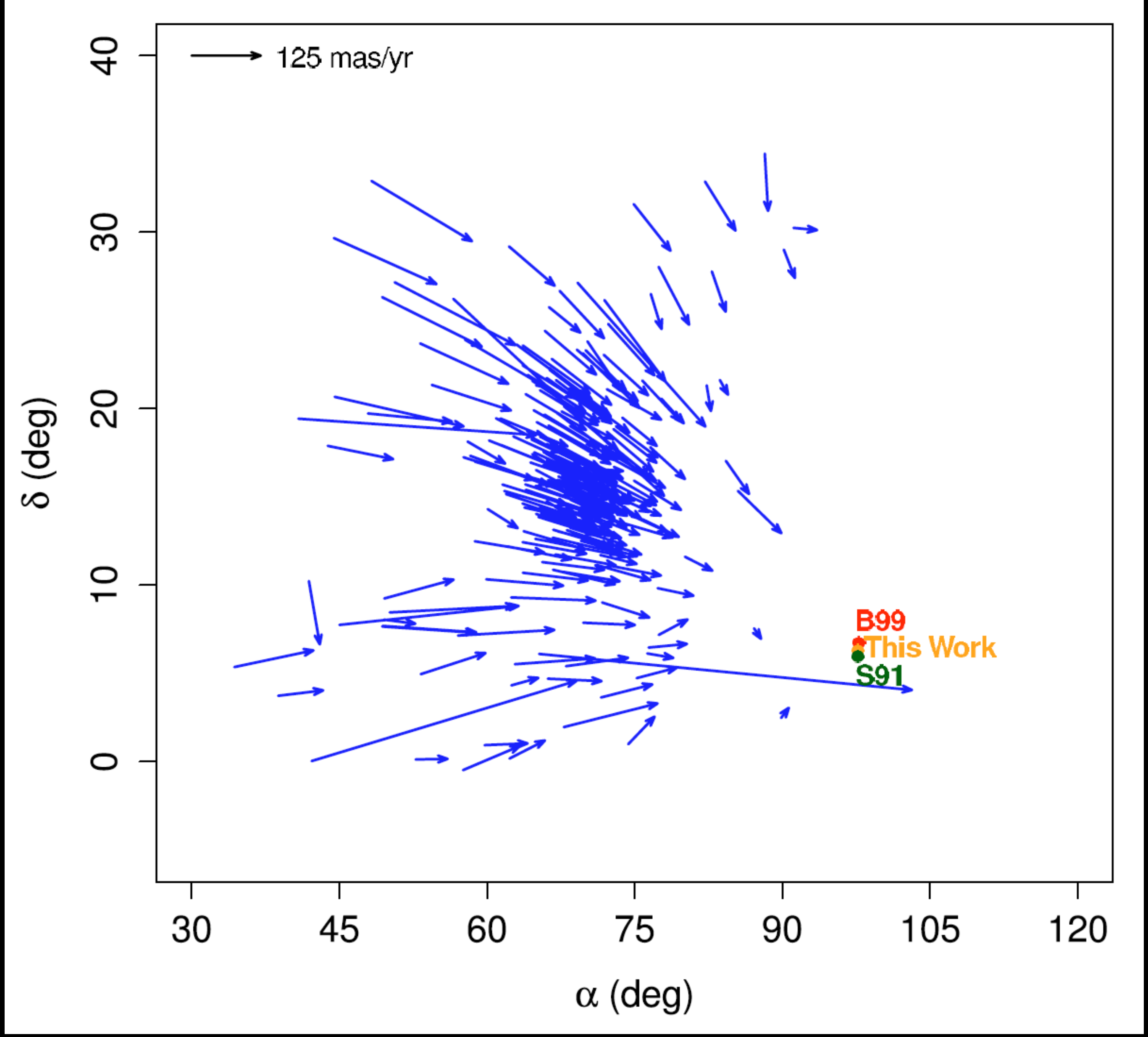



**Fig. 5.** Relative position ($\Delta l_{cp}, \Delta b_{cp}$) of the CP for 100 simulations and three different velocity dispersions. Blue dots and red crosses denote, respectively, the results of the classic and new CPSMs. The contours indicate $X^2$ levels linearly spaced by $\Delta X^2 = 2000$ for a cluster with the properties given in the text. The relative position of the computed CP ($l_{cp}^{sim}, b_{cp}^{sim}$) for each simulation is given by $\Delta l_{cp} = l_{cp}^{sim} - l_{cp}$ and $\Delta b_{cp} = b_{cp}^{sim} - b_{cp}$.




HIPPARCOS with MC statistics

Galli et al. (2012)

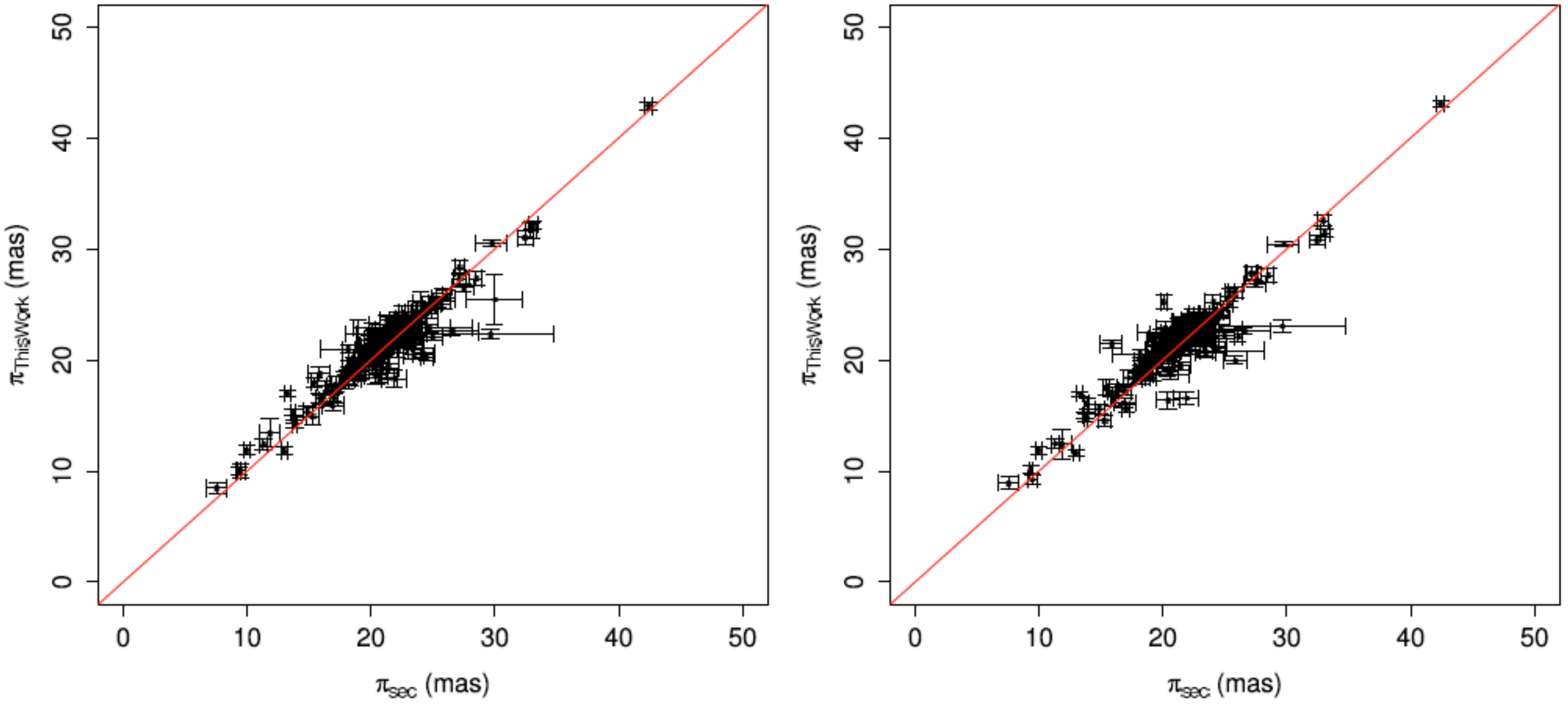



**Fig. 12.** Individual parallaxes of Hyades members derived in this work compared to the secular parallaxes of de Bruijne et al. (2001) derived using proper motion data from the HIPPARCOS (*left panel*) and TYCHO2 (*right panel*) catalogs. The red line represents the expected distribution for equal results. The rms with respect to the HIPPARCOS secular parallaxes is 1.55 mas and 1.68 mas for TYCHO2 secular parallaxes, and the mean difference between the parallaxes is 0.23 mas and –0.27 mas.

HIPPARCOS with MC statistics

Galli et al. (2012)

$D = 134.41 \pm 0.18\, pc$

Pleiades

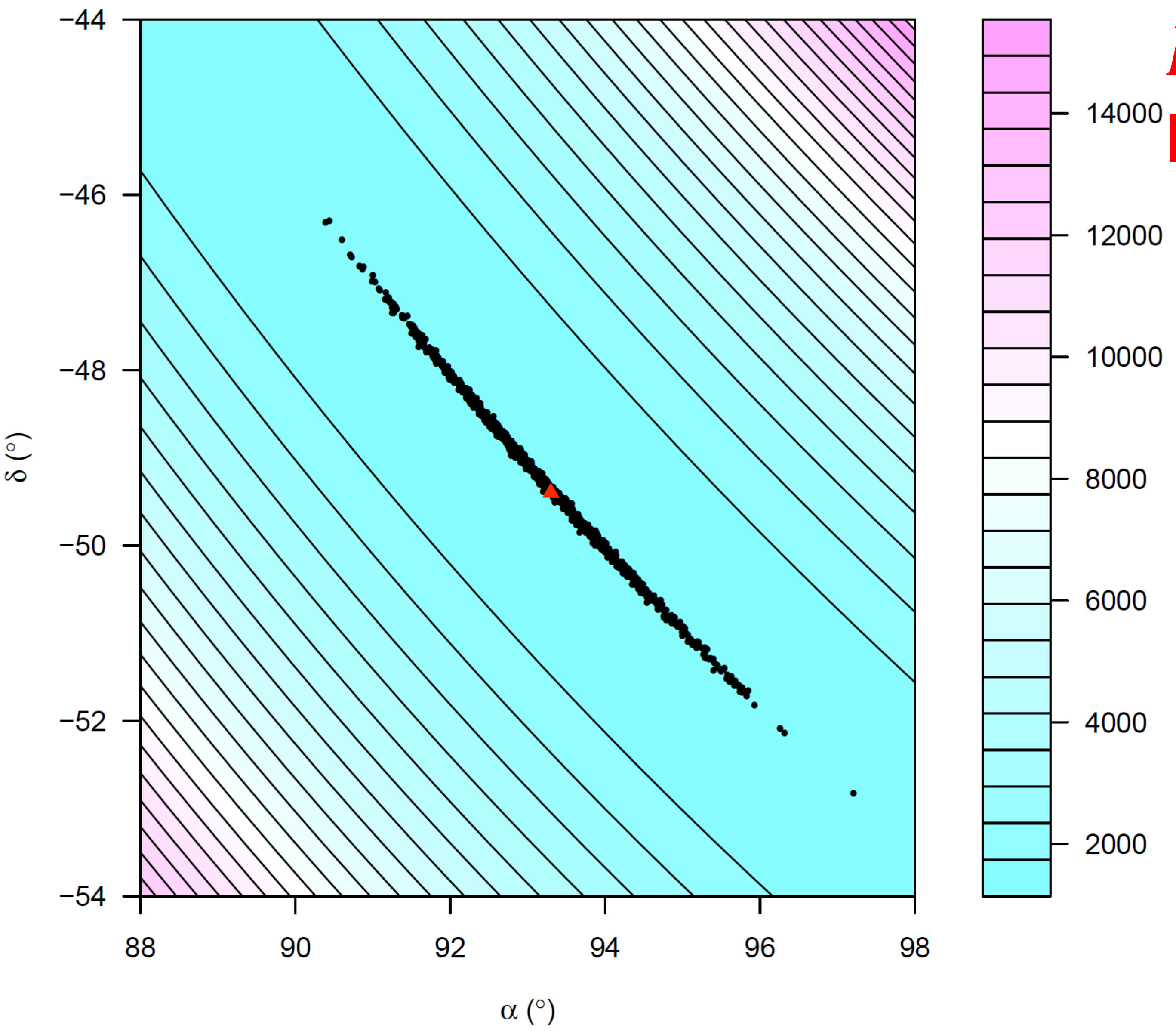



**Fig. 9.** CP solutions (black dots) for 1000 Monte Carlo realizations of the Pleiades open cluster overlaid on the $X^2$ contour levels (solid lines) indicated by the color code. The red triangle indicates the final CP solution given in Sect. 4.4.

APOGEE Radial Velocities
Astrometry from Tycho-2 and DANCe

Galli et al. (2017)

**Table 2.** Spatial velocity of the Pleiades cluster derived in this work from the sample of 64 stars with known radial velocities.

| | Mean ± SEM ($km\,s^{-1}$) | Median ($km\,s^{-1}$) | Mode ($km\,s^{-1}$) | SD ($km\,s^{-1}$) |
|---|---|---|---|---|
| $U$ | −6.2 ± 0.1 | −6.2 | −6.1 | 0.7 |
| $V$ | −28.7 ± 0.3 | −28.5 | −28.2 | 2.5 |
| $W$ | −14.7 ± 0.2 | −14.6 | −14.6 | 1.3 |
| $V_{space}$ | 32.9 ± 0.3 | 32.8 | 31.3 | 2.8 |

**Notes.** We provide for each velocity component the mean, standard error of the mean (SEM), median, mode and standard deviation (SD) values.

$$D = 134.41 \pm 0.18\,pc$$

Pleiades

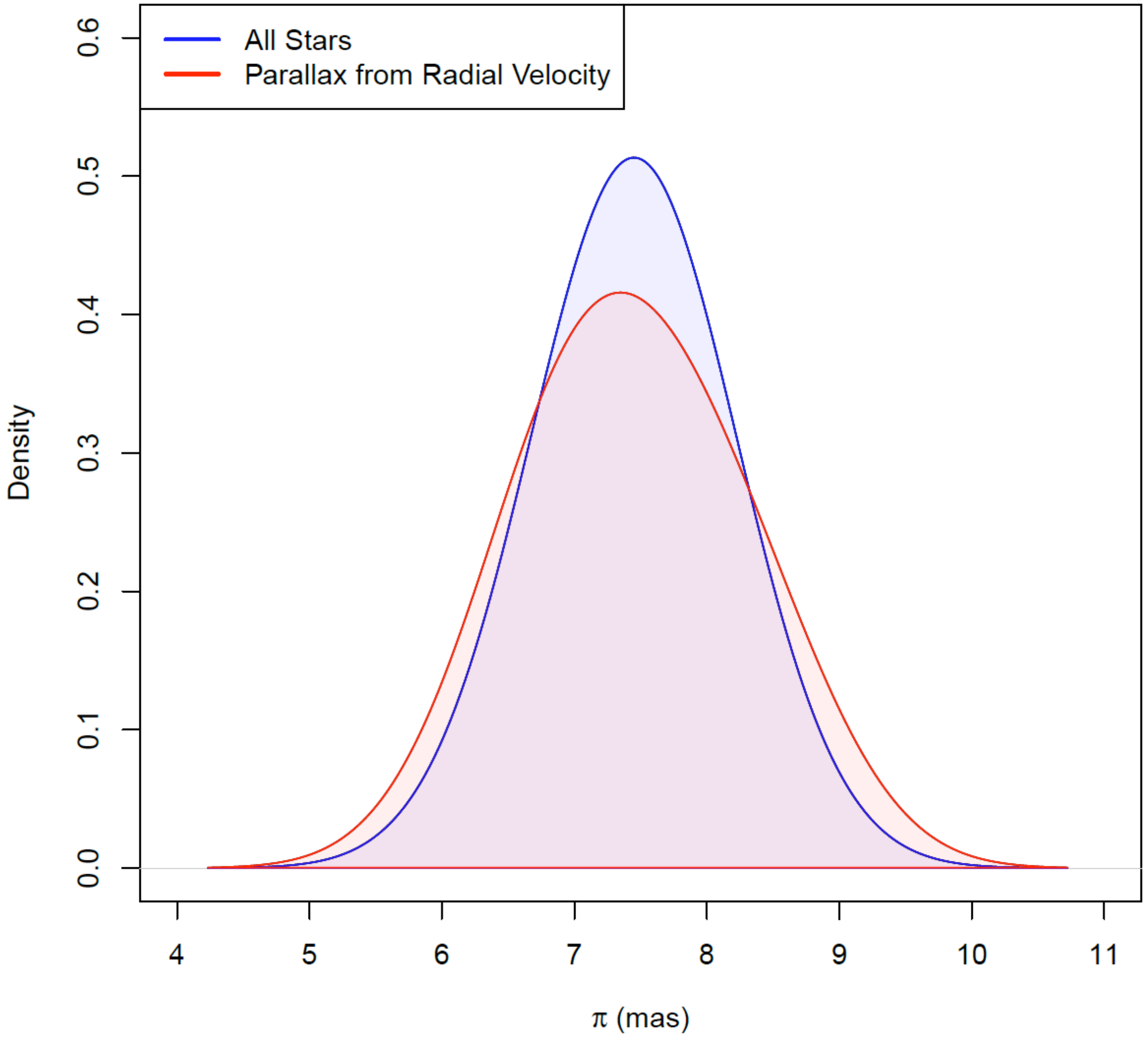



**Fig. 13.** Probability density function for the parallaxes obtained from the sample of members with known radial velocities (64 stars) and all cluster members (1210 stars).

APOGEE Radial Velocities
Astrometry from Tycho-2 and DANCe

Galli et al. (2017)

# Summary

1) MCM can be applied to nearby open clusters
2) From $V_R$ and $\mu$, can use trigonometry to find $D$
3) MCM assumes velocity vector is identical for all stars in cluster
4) With fancy statistics and precise astrometry, can get very accurate distances to nearby clusters and account for internal motions/rotation

# References

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