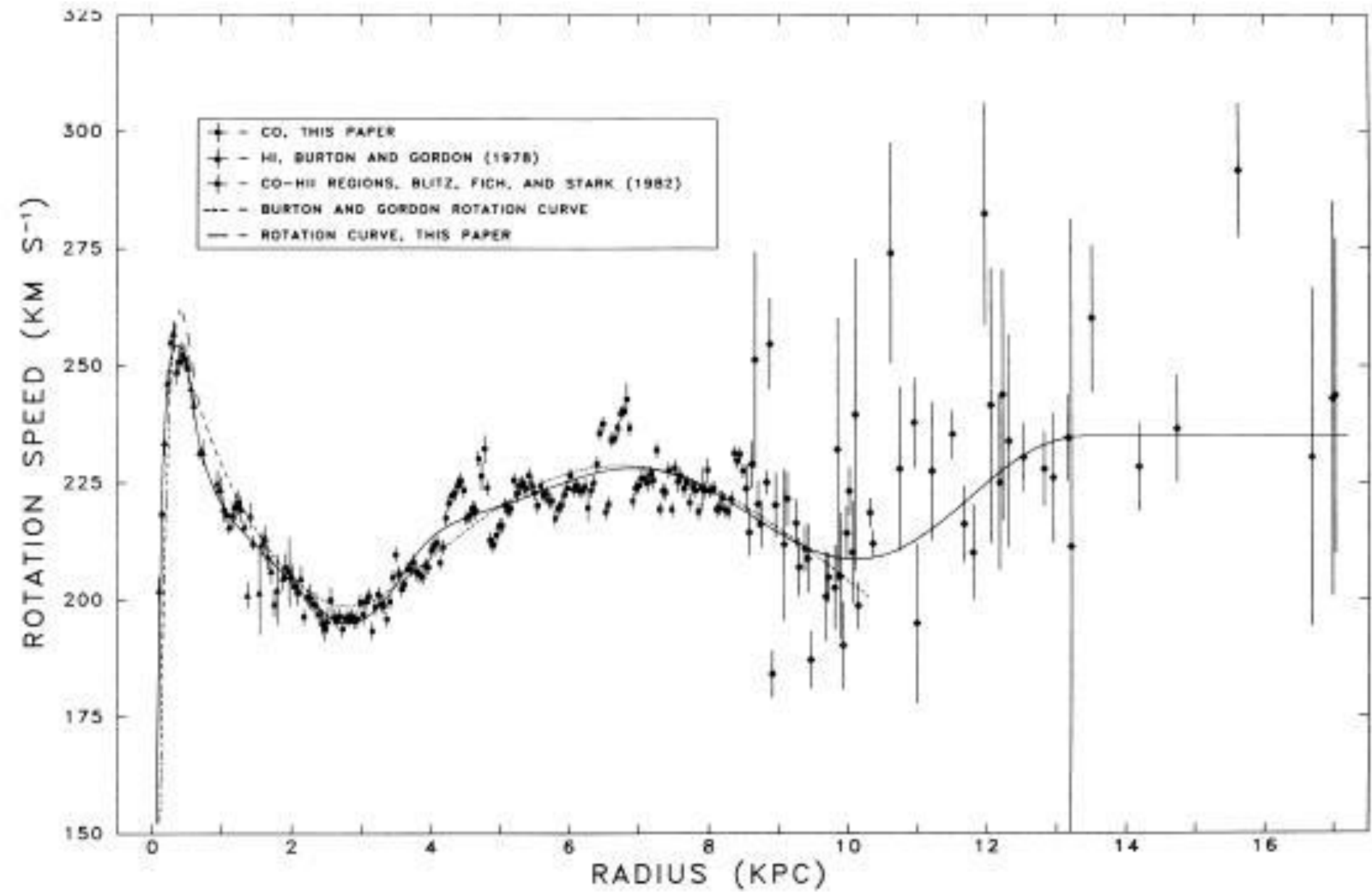
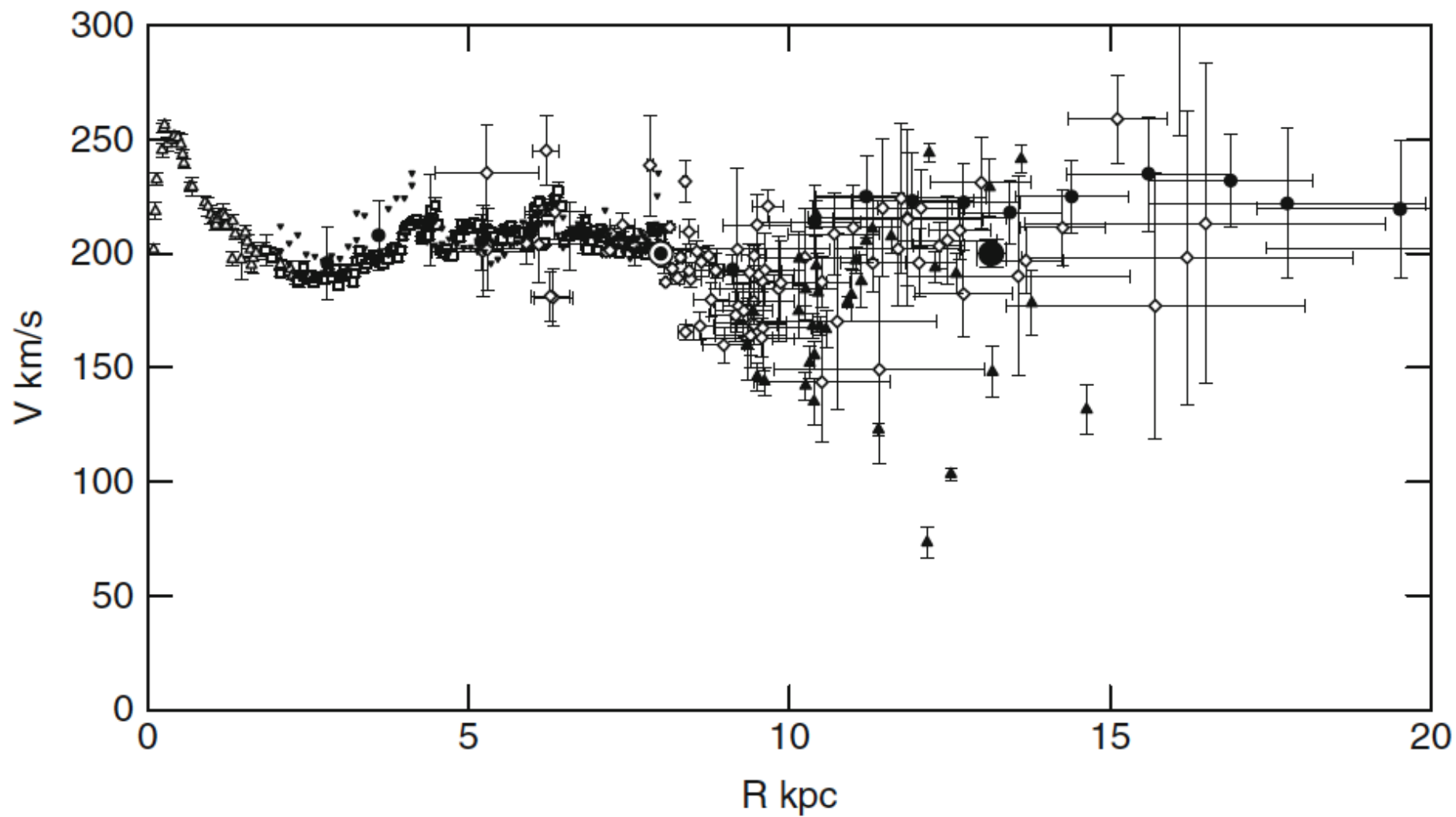


Kinematical membership criteria

- Members follow the motion of the cluster center of gravity
- Internal velocity distribution
- From best to ...
 1. Radial velocity and proper motion
 2. Radial velocity
 3. Proper motion

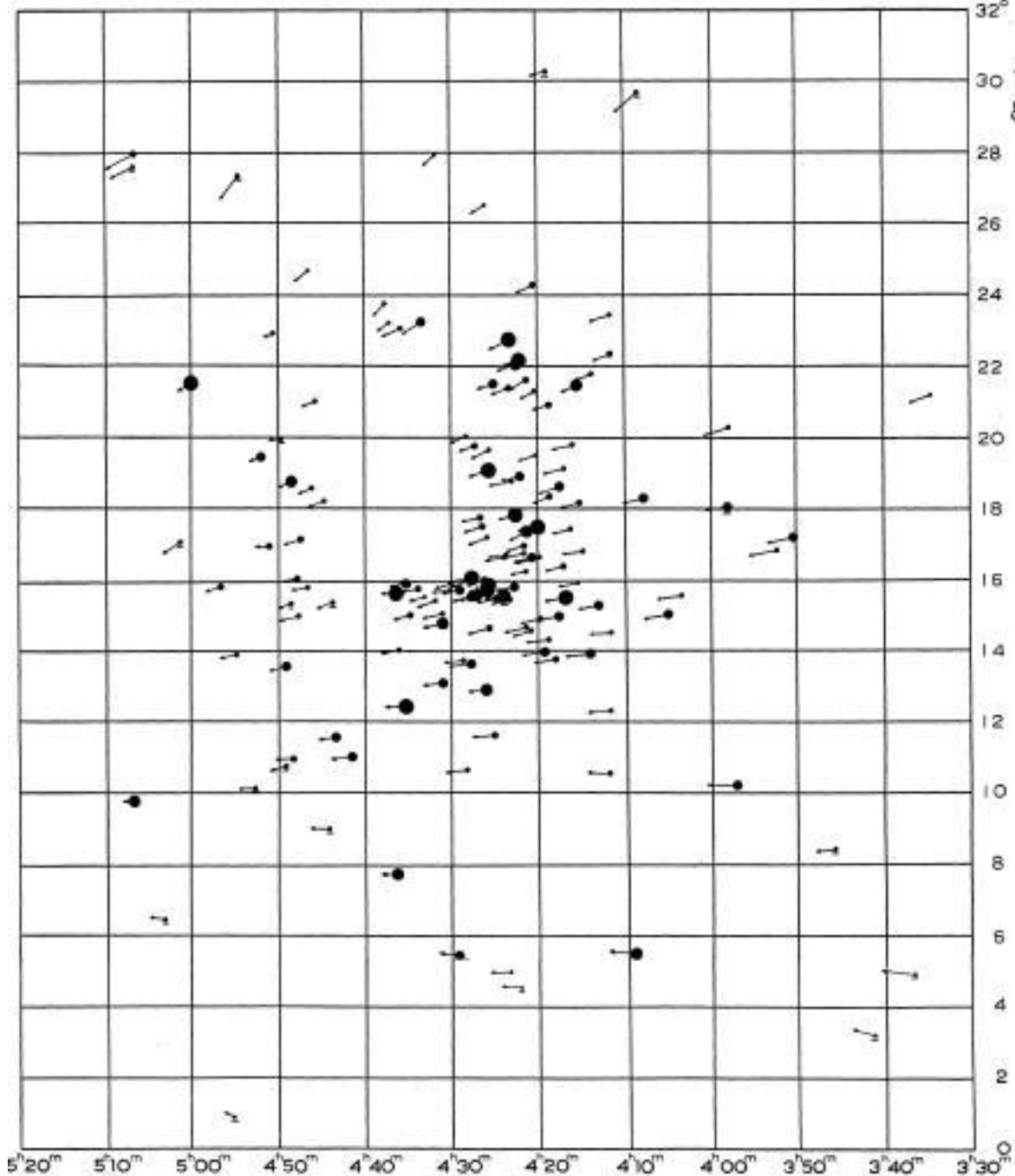




Hyades

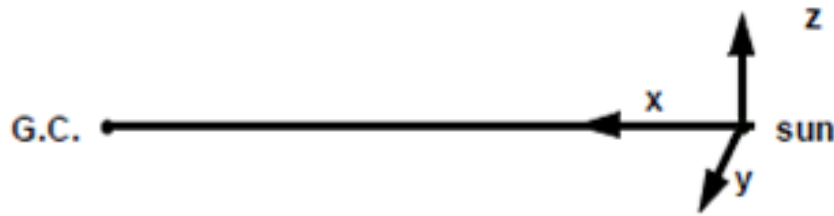
Van Bueren, 1952, BAN,
11, 385

After the
correction of the
solar motion



Map of the Hyades brighter than $9^m.6$ visual. The size of the dots is a measure for the magnitude of the stars; the arrows show the annual proper motion (1 mm $\approx 1^m.030$). Five stars in the very outer regions of the cluster are not shown on the map. Underlined dots indicate stars of which no radial velocity is known.

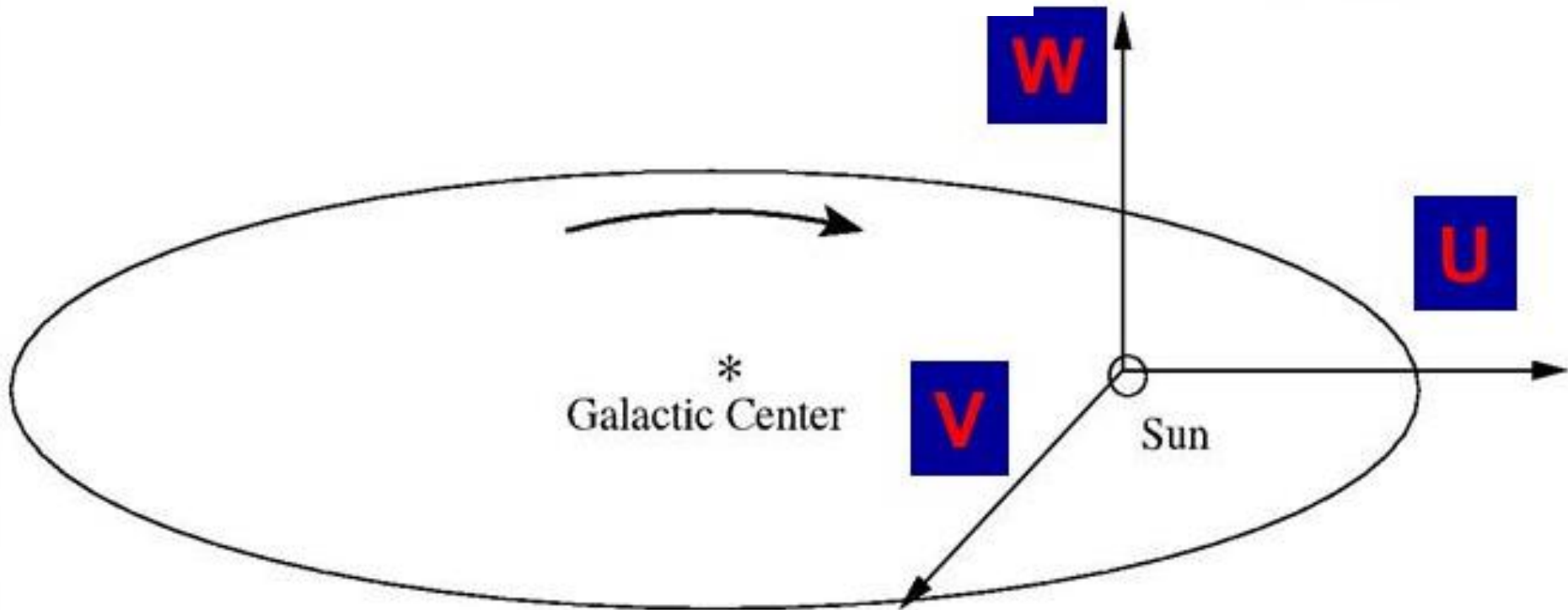
Galactic Components



Be careful about the sign/direction of X and U

- **coordinates:**

- x: $l = 0$ $b = 0$ (Galactic Centre)
- y: $l = 90$ $b = 0$ (Cygnus) direction of disc rotation
- z: $b = 90$ (North Galactic Pole)

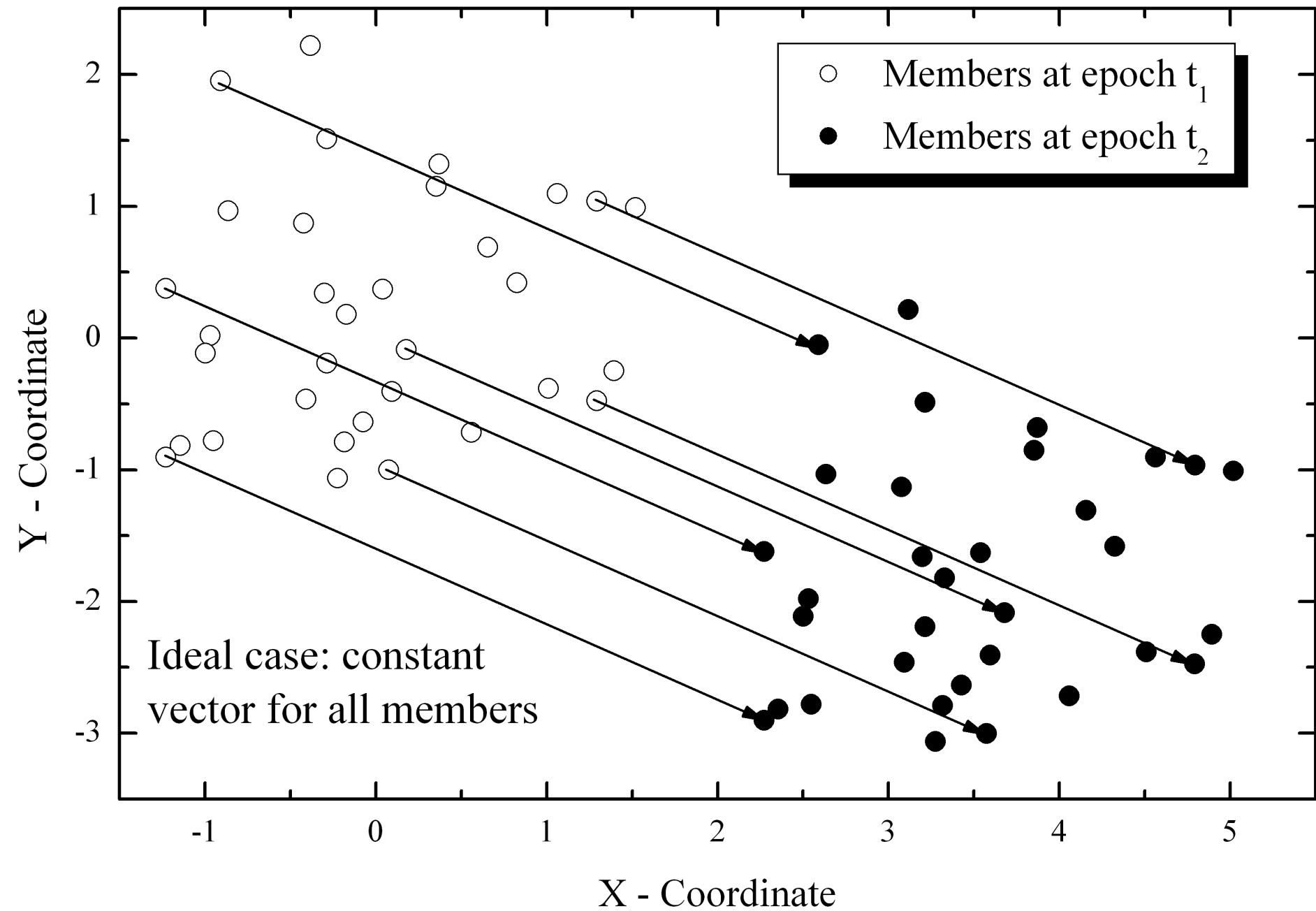


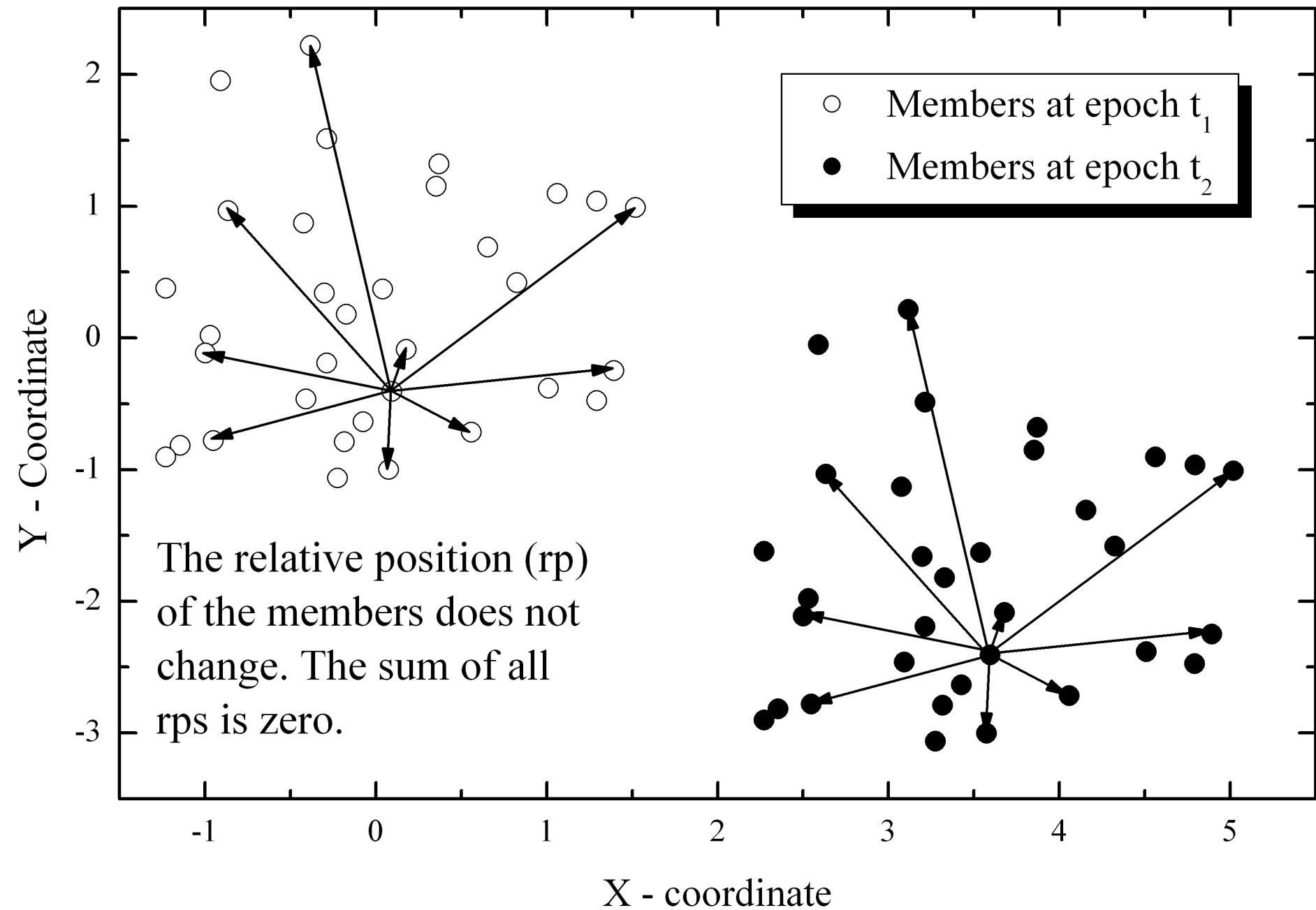
Motion of the Sun

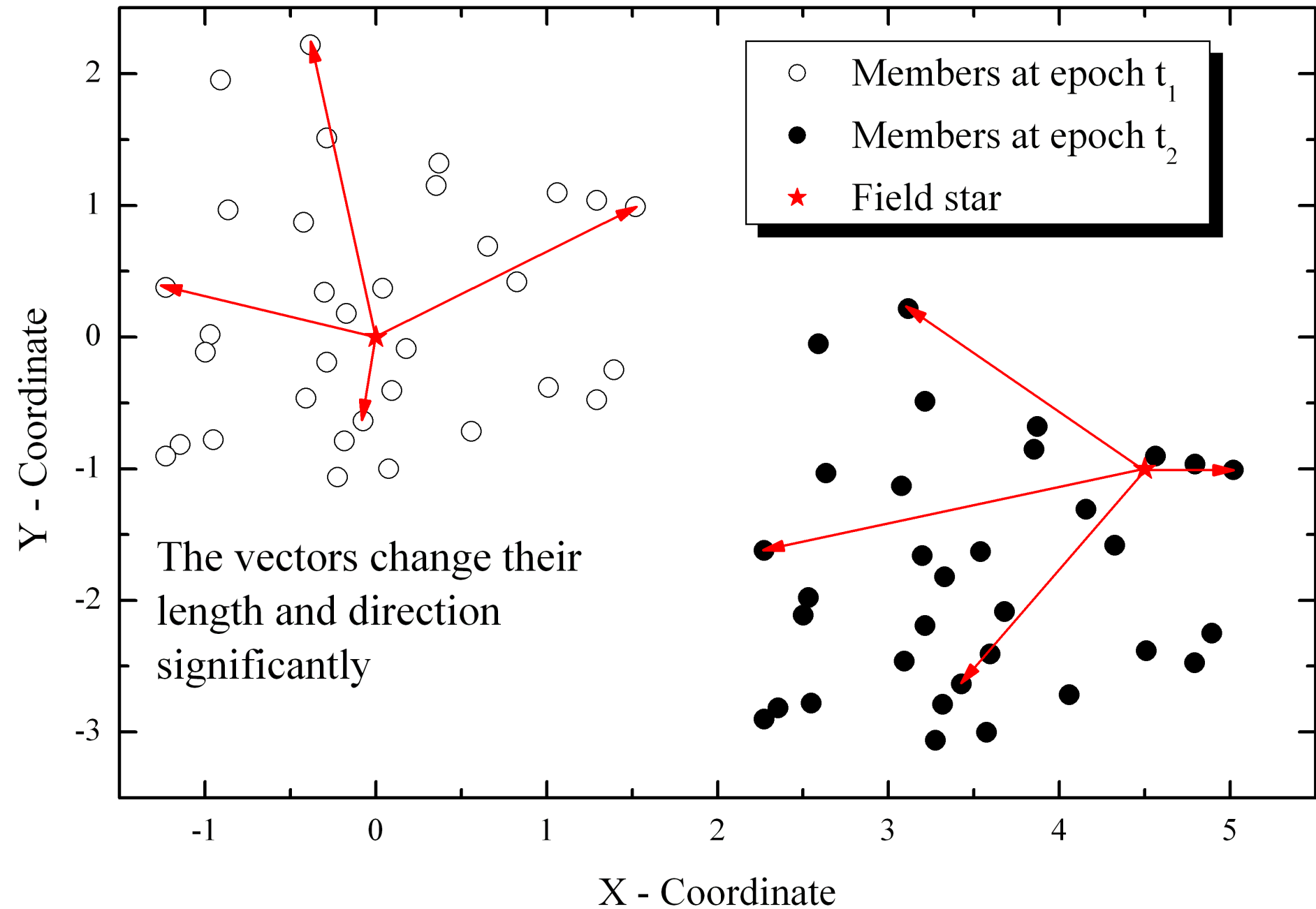
- Peculiar Apex motion: $\alpha = 18^{\text{h}}28^{\text{m}}$,
 $\delta = +30^{\circ}$; $l = 56.24^{\circ}$, $b = +22.54^{\circ}$
- $(U, V, W) = (-10, +5, +7) \text{ km s}^{-1}$
- $v_{\text{orbit}} = 220 \text{ km s}^{-1}$
- Local Standard of Rest (LSR)

Determination of the kinematical membership

- Three possibilities:
 1. Observation of the position at two difference times (= epochs), with a very large time basis. First photographic plates around 1860, largest time scale about 160 years
 2. Proper motions of stars in the direction of the Declination α and Right Ascension δ
 3. Radial velocity measurements







Mathematical method

- Measurement of the position (X, Y) at two different epochs t_1 (') and t_2 ('') for each star
- Calculate the absolute distance in X and Y for both epochs and each star individually

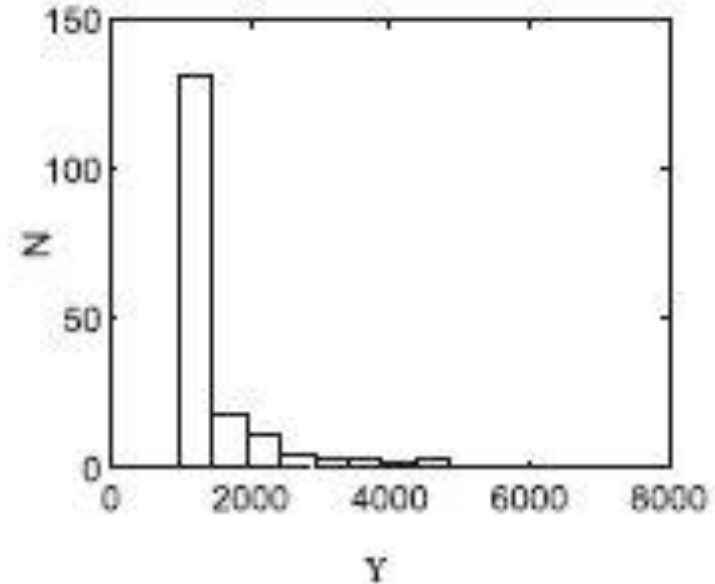
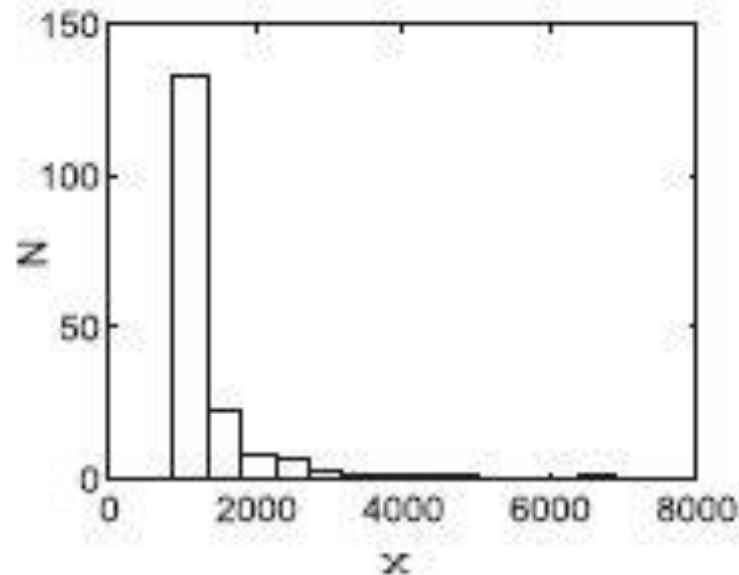
$$S'_{x_i} = \sum_{j=1}^N |x'_i - x'_j|, \quad S'_{y_i} = \sum_{j=1}^N |y'_i - y'_j|, \quad (1)$$

$$S''_{x_i} = \sum_{j=1}^N |x''_i - x''_j|, \quad S''_{y_i} = \sum_{j=1}^N |y''_i - y''_j|, \quad (2)$$

- Determine the differences of the absolute distances

$$\delta S_{x_i} = S'_{x_i} - S''_{x_i}, \quad \delta S_{y_i} = S'_{y_i} - S''_{y_i}, \quad i = 1, \dots, N. \quad (3)$$

- Plot the histograms of the differences of the absolute distances. The members have to group around the minimum of the distributions (ideal case: minimum = zero).



Example from Javakhishvili et al. (2006, A&A, 447, 915) for Collinder 121

Now we need a mathematical formalism to describe the membership probability from the distributions

- Calculate the absolute distance in X and Y for both epochs and each star individually

$$\bar{S}'_{x_i} = \sum_{j=1}^N (x'_i - x'_j), \quad \bar{S}'_{y_i} = \sum_{j=1}^N (y'_i - y'_j), \quad (4)$$

$$\bar{S}''_{x_i} = \sum_{j=1}^N (x''_i - x''_j), \quad \bar{S}''_{y_i} = \sum_{j=1}^N (y''_i - y''_j). \quad (5)$$

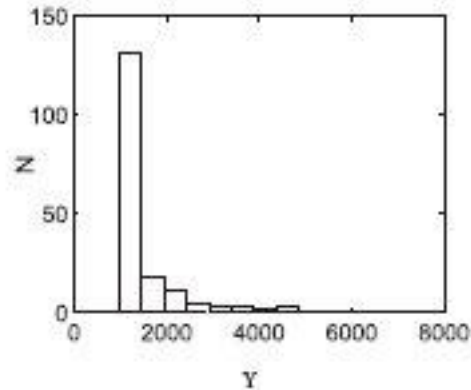
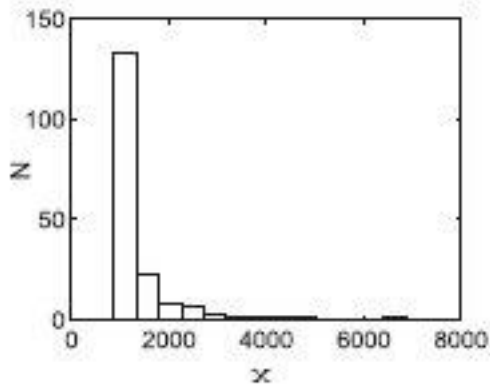
- Plot the histograms of the differences of the absolute distances
- The distributions are fitted with Gaussian functions

$$f(x) = \frac{A_x}{w_x \sqrt{\pi/2}} e^{-2\left(\frac{x-x_0}{\sigma_x}\right)^2}, \quad f(y) = \frac{A_y}{w_y \sqrt{\pi/2}} e^{-2\left(\frac{y-y_0}{\sigma_y}\right)^2}, \quad (6)$$

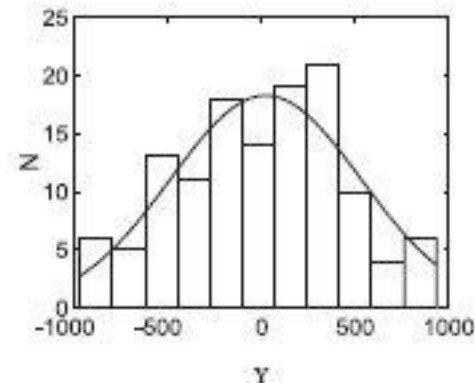
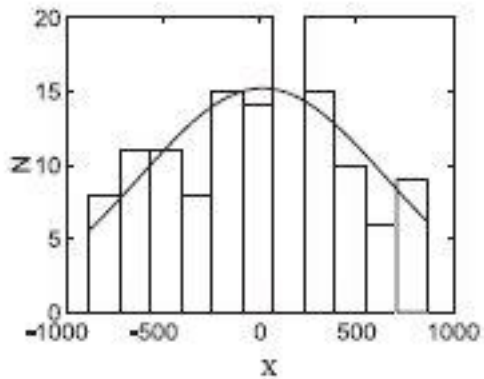
- The probability p , if a star is member of the star cluster is defined as

$$p_x = e^{-2\left(\frac{x-x_0}{\sigma_x}\right)^2}, \quad p_y = e^{-2\left(\frac{y-y_0}{\sigma_y}\right)^2}. \quad (7)$$

$$p = p_x * p_y. \quad (8)$$



Javakhishvili et al.,
2006, A&A, 447, 915 for
Collinder 121



From these diagrams, the
membership probability can
be exactly determined

- In the same way, the proper motions in α and δ can be used, the basic equations and the determination of the membership probability is exactly the same

$$\delta\mu_{\alpha_i} = \sum_{j=1}^N |\mu_{\alpha_i} - \mu_{\alpha_j}|, \quad \delta\mu_{\delta_i} = \sum_{j=1}^N |\mu_{\delta_i} - \mu_{\delta_j}| \quad (9)$$

$$\tilde{\delta}\mu_{\alpha_i} = \sum_{j=1}^N (\mu_{\alpha_i} - \mu_{\alpha_j}), \quad \tilde{\delta}\mu_{\delta_i} = \sum_{j=1}^N (\mu_{\delta_i} - \mu_{\delta_j}). \quad (10)$$

Now, with the new Gaia data we can even investigate very distant star clusters using proper motions

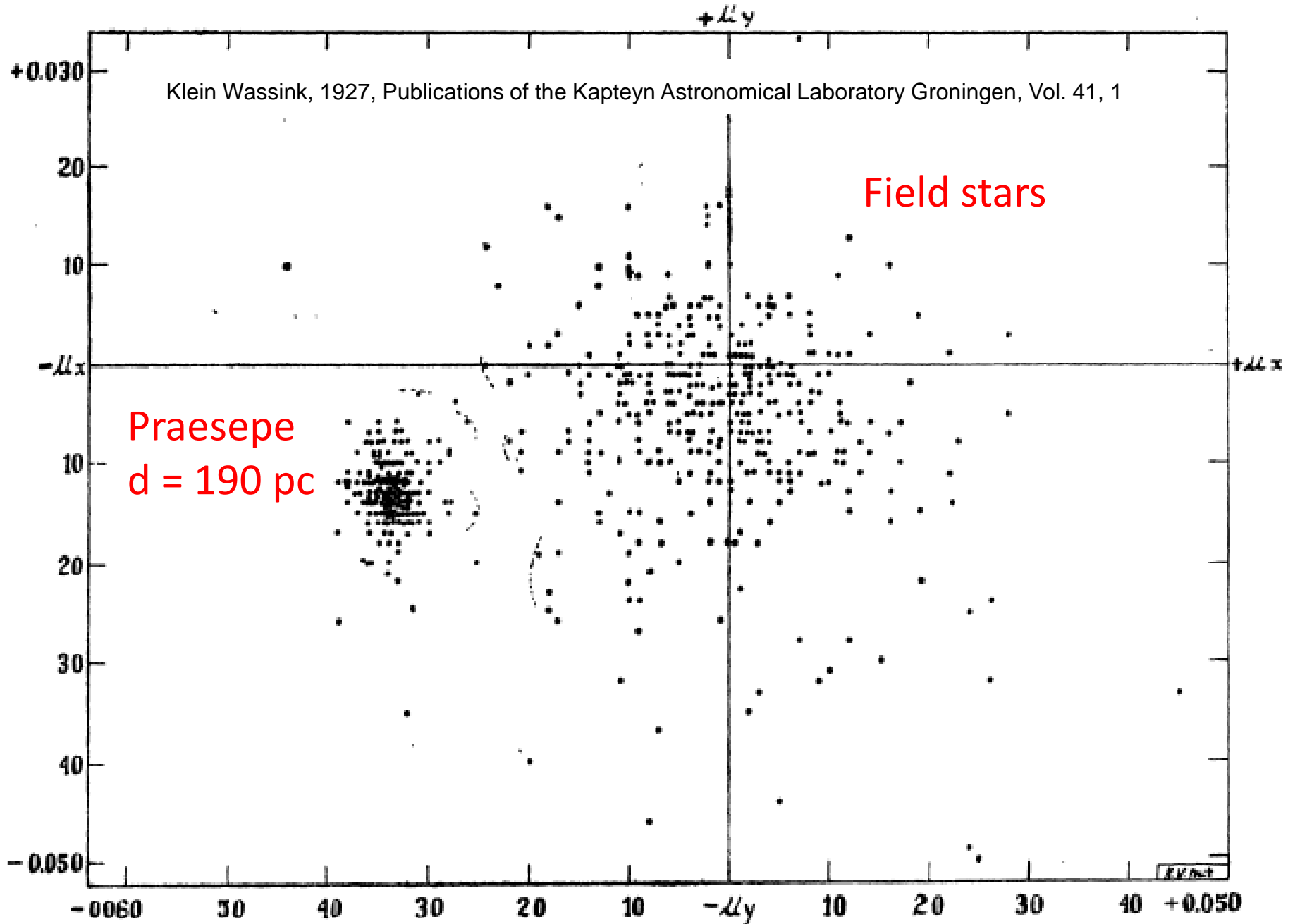
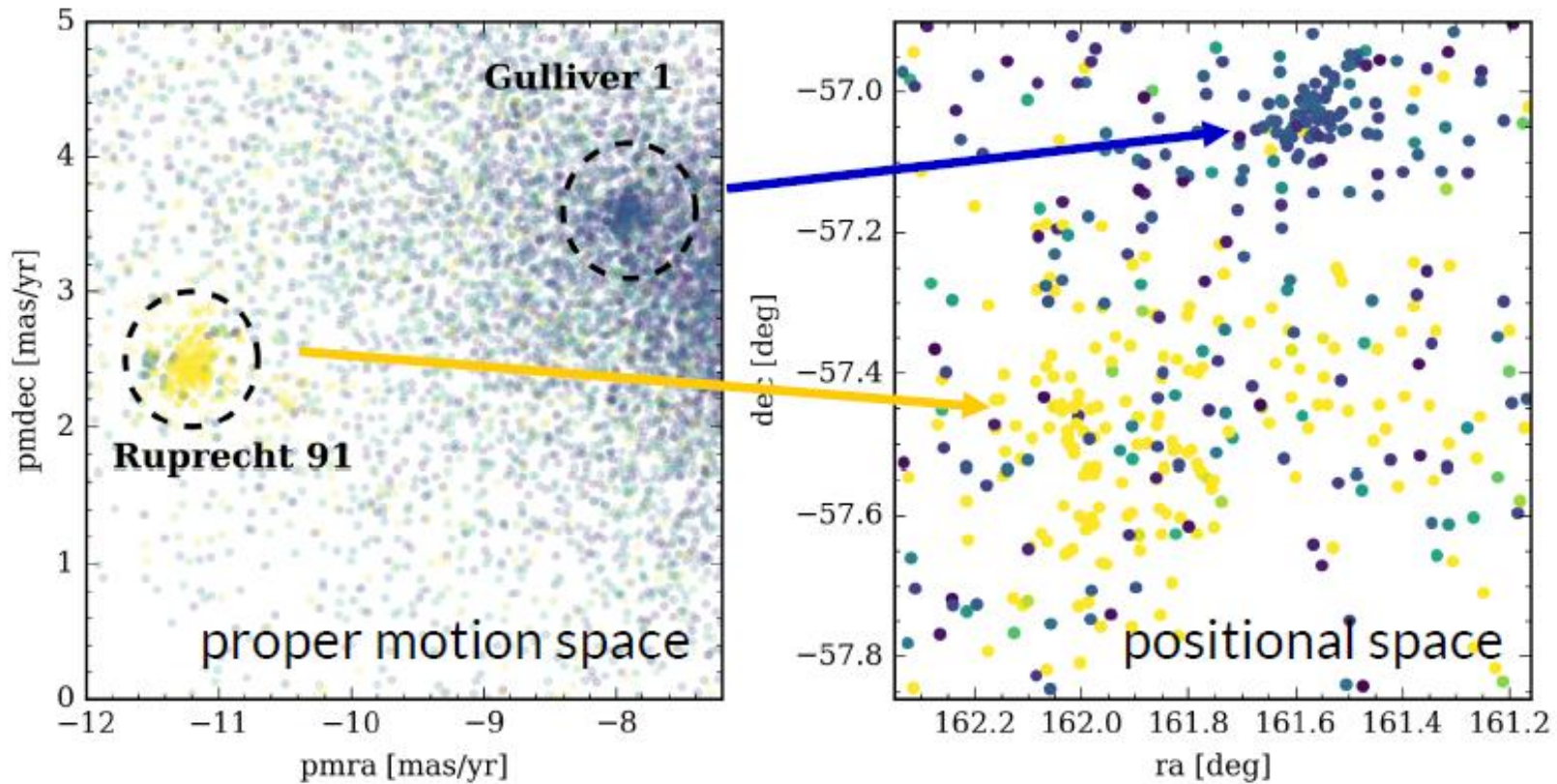


Figure 2. Diagram of the absolute proper motions of the Catalogue; photographic magnitude 6 to 14^o, numbers 1 to 531. The dotted lines separate the Praesepe stars from the backgroundstars.

Common proper motion



Credit: Tristan Cantat-Gaudin

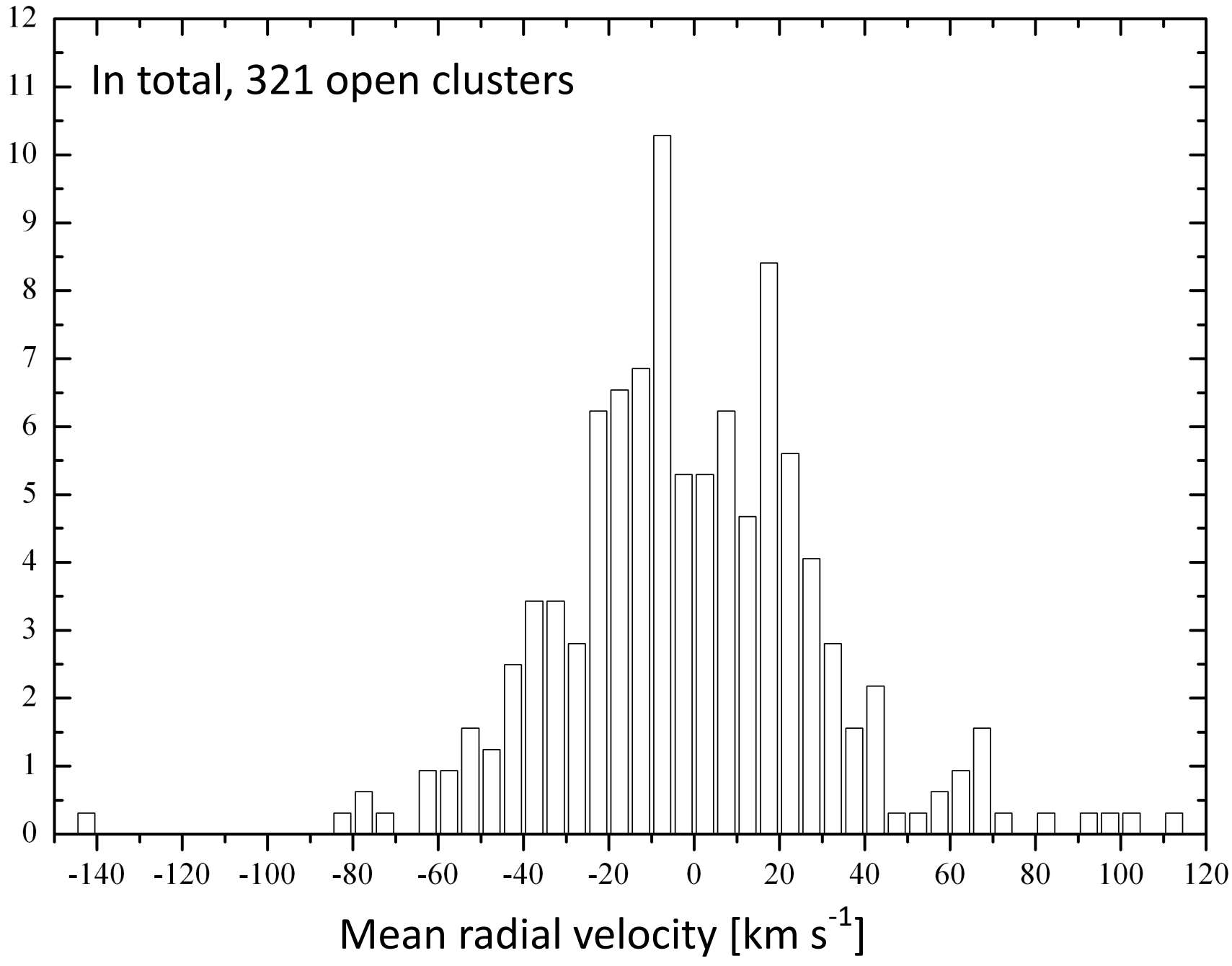
Dramatic improvement by Gaia even for overlapping star clusters

Radial velocities

- Advantages:
 1. Correlated with the galactic rotation only
 2. Possible to measure for most distant cluster members
- Disadvantages:
 1. High-resolution high S/N spectrum needed
 2. Faintness of members for distant clusters

In total, 321 open clusters

Percentage of all open clusters



Determination of the radial velocity

- Doppler shift of spectral lines

$$\Delta\lambda = \frac{v_R \lambda}{c}$$

- Determine the central wavelength of the shifted line
- Better accuracy if
 1. Instrumental resolution ($\lambda/\Delta\lambda$) is higher
 2. Signal-To-Noise ratio (S/N) is higher
 3. $v \sin i$ of star is lower
 4. The number of measured lines is higher

λ [Å]	5	10	30	100	R_V [km s ⁻¹]
3500	0,058	0,117	0,350	1,167	
4000	0,067	0,133	0,400	1,333	
4500	0,075	0,150	0,450	1,500	
5000	0,083	0,167	0,500	1,667	
5500	0,092	0,183	0,550	1,833	
6000	0,100	0,200	0,600	2,000	
6500	0,108	0,217	0,650	2,167	
7000	0,117	0,233	0,700	2,333	
7500	0,125	0,250	0,750	2,500	
8000	0,133	0,267	0,800	2,667	$\Delta\lambda$ [Å]

Instrumental profile defined by the resolution:

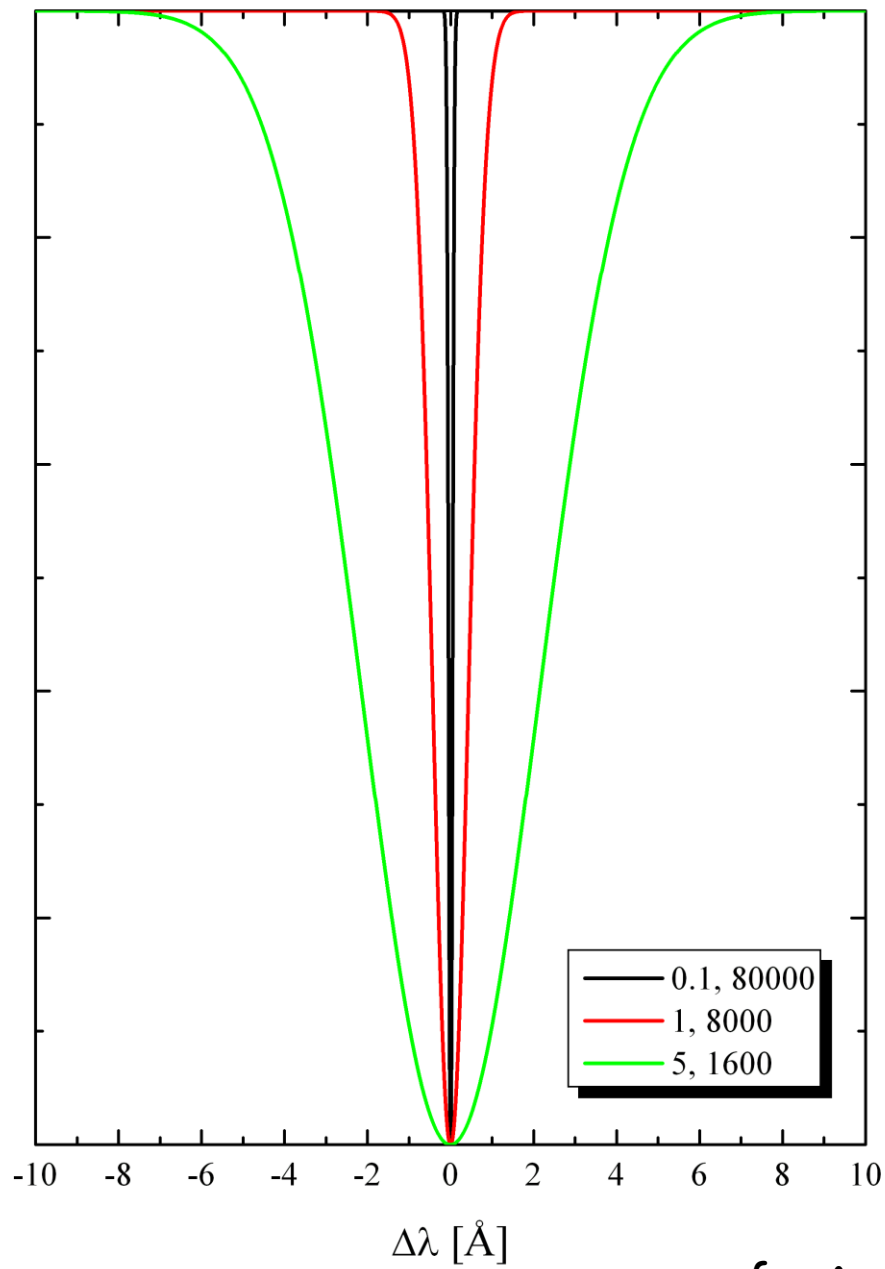
$$IP(\Delta\lambda) = \exp\left[-0.5\left(\frac{(\lambda - \Delta\lambda)}{\sigma}\right)^2\right] \text{ with } \sigma = \frac{FWHM}{2.355}$$

Rotational broadening:

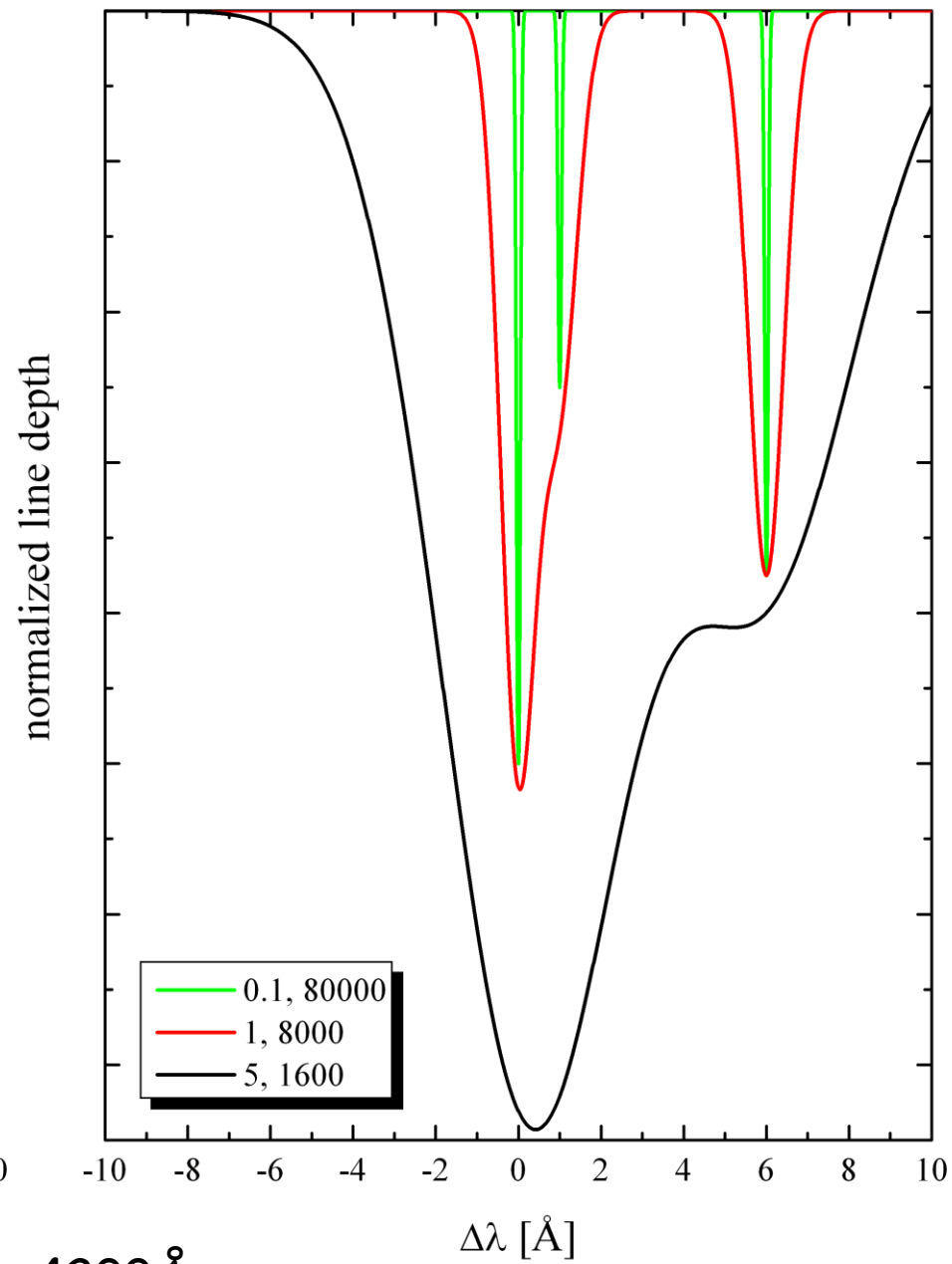
$$RP(\Delta\lambda) = c_1\sqrt{x} + c_2x \text{ with } x = 1 - \left(\frac{\Delta\lambda}{\Delta\lambda_L}\right)^2$$

$$\Delta\lambda_L = \lambda \frac{v \sin i}{c}$$

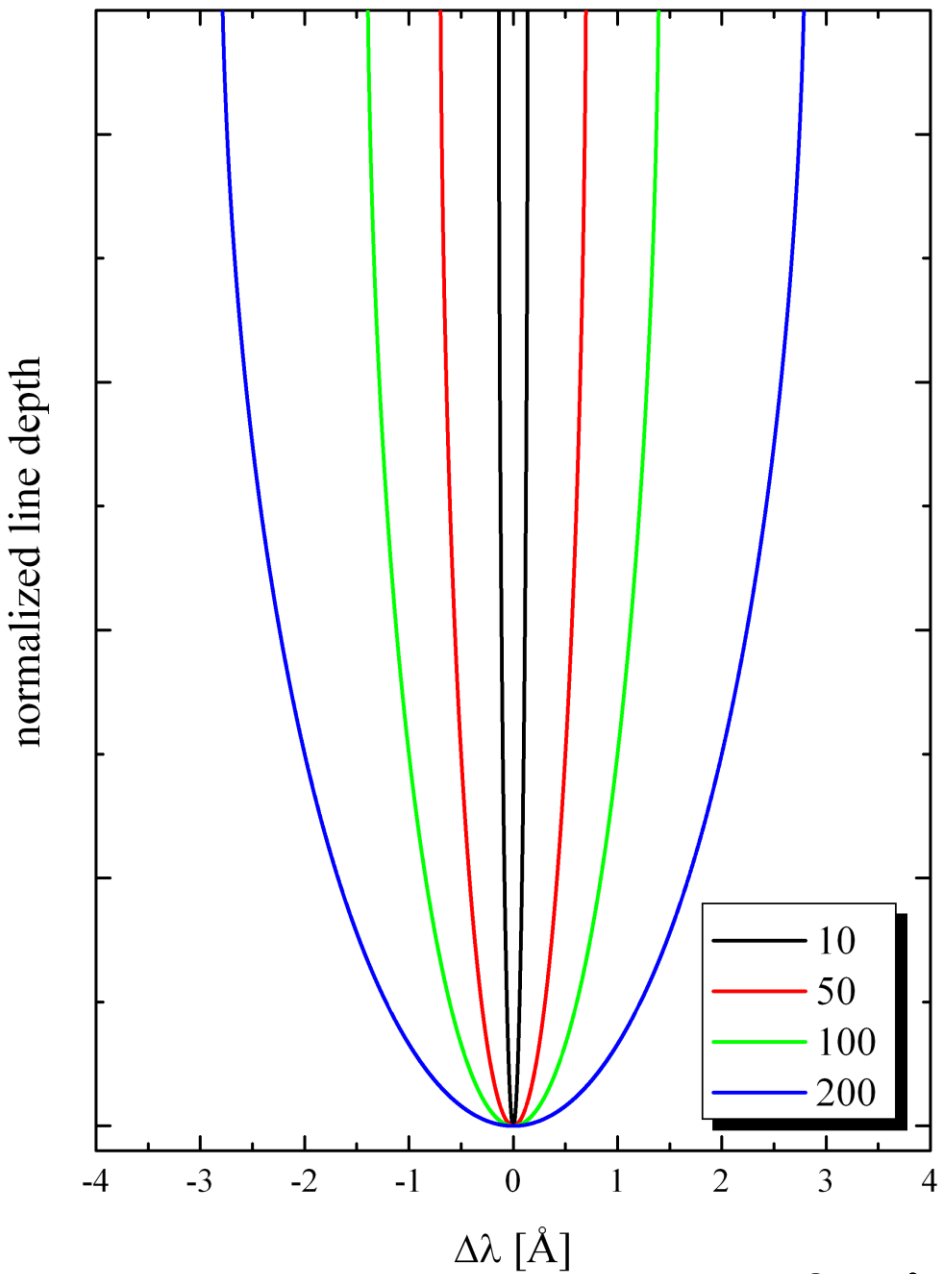
Instrumental profile



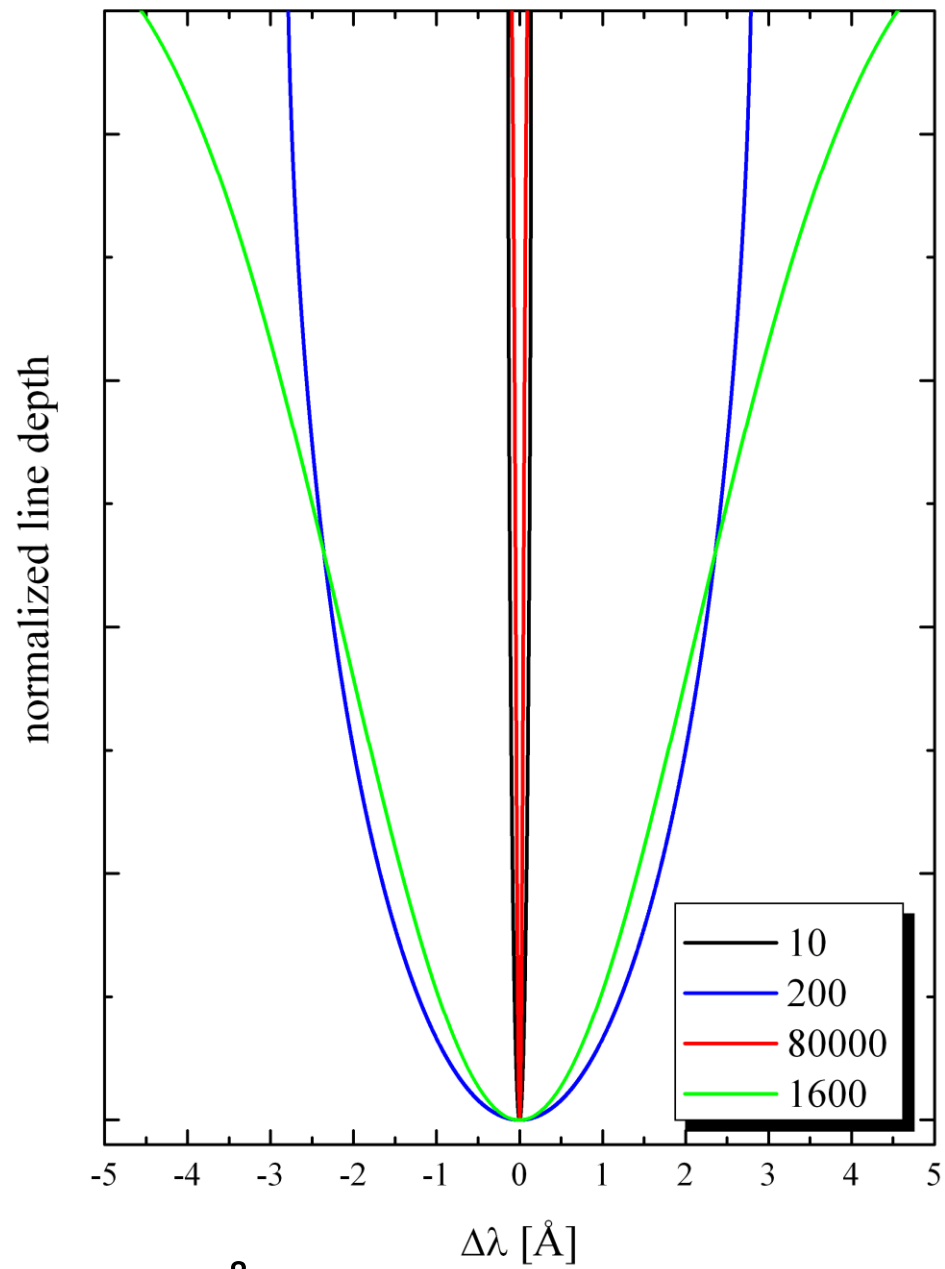
Instrumental profile, resolution of three lines

for $\lambda = 4200 \text{\AA}$

Rotational profile



Rotational- and instrumental profile

for $\lambda = 4200\text{\AA}$

Situation – Gaia DR2

A&A 619, A155 (2018)

<https://doi.org/10.1051/0004-6361/201834020>

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**Astronomy
&
Astrophysics**

Open cluster kinematics with *Gaia* DR2★

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Results. For the high-quality sample of 406 clusters, the median uncertainty of the weighted mean radial velocity is 0.5 km s^{-1} . The accuracy, assessed by comparison to ground-based high-resolution spectroscopy, is better than 1 km s^{-1} .

Can we use this for studying the internal velocity distribution (rms = 4.3 km s^{-1})?

How good can be mean RVs determined?

Situation – Gaia DR2

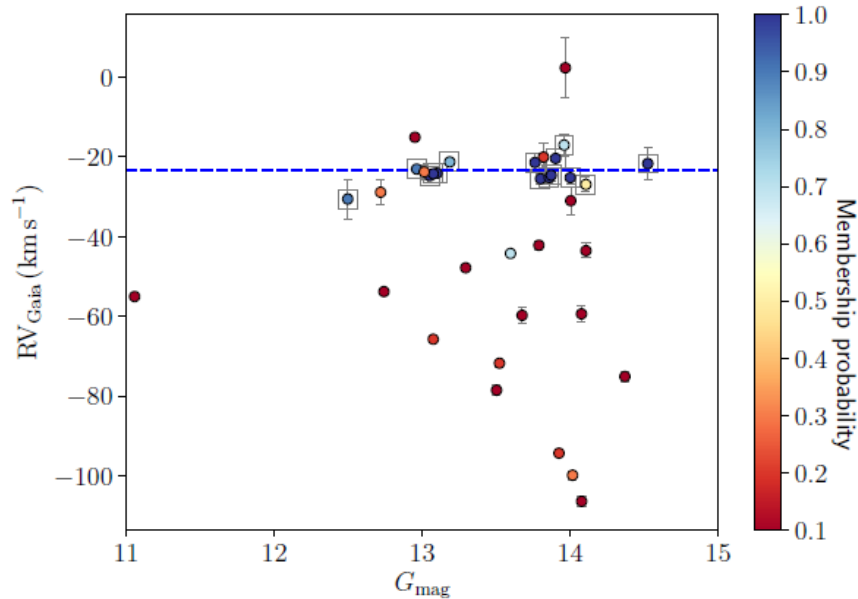


Fig. 2. Distribution of RV as a function of G magnitude for the 36 members of Skiff J0058+68.4

Huge spread and only a few members per cluster

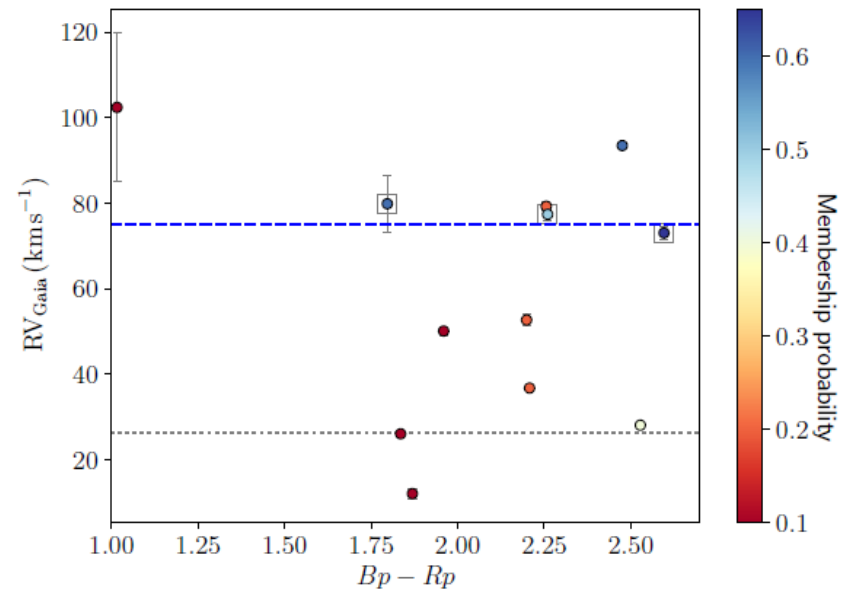
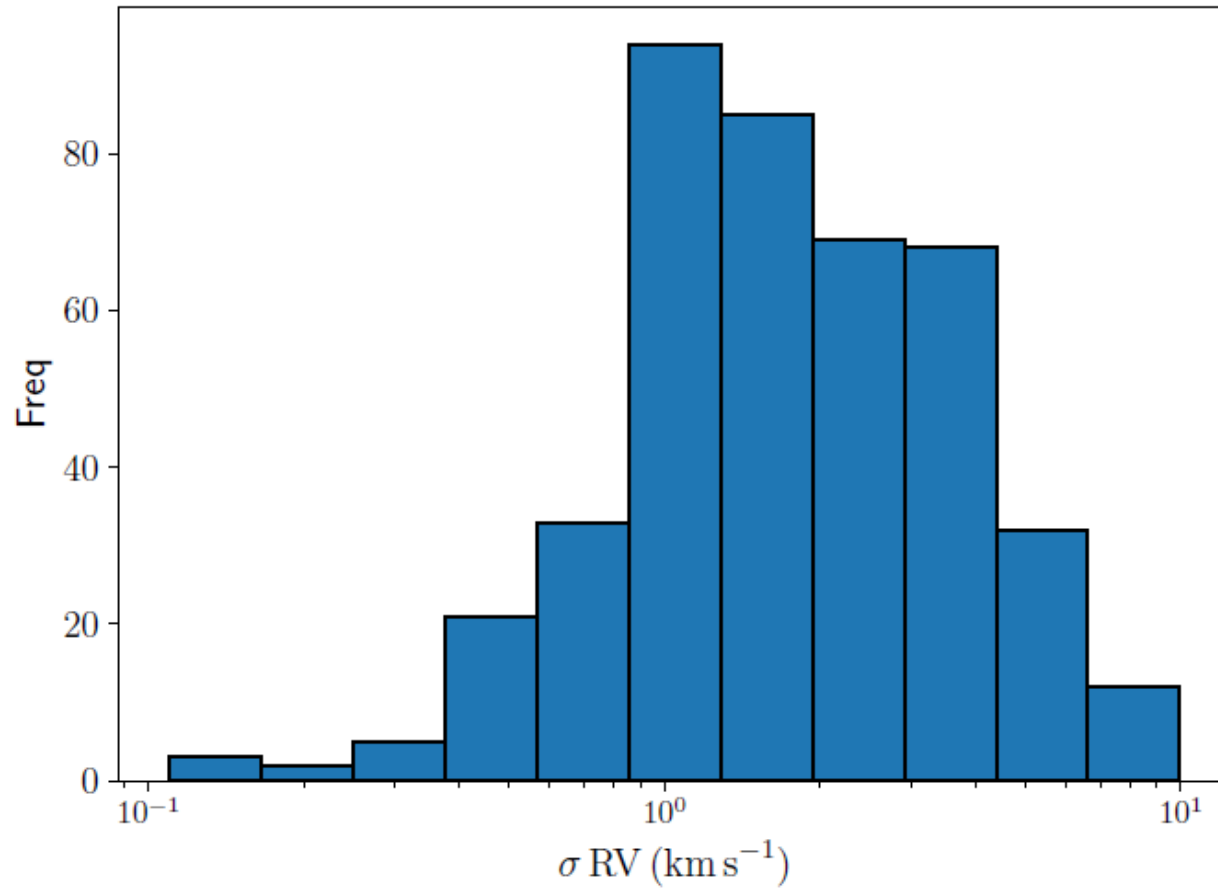


Fig. 4. Distribution of RV for members for NGC 2244.

Situation – Gaia DR2



Not
useable for
internal
distribution

Fig. 3. Histogram of the RV standard deviation, in log scale, for the OCs with at least three members.