Pseudo-photometric distances of 30 open clusters

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Distance measurements: 2 types of methods

- Direct methods: astrometry (Gaia), binary systems
  - Robust & model independent
  - Bound by the sensitivity of the instruments → « small » volume coverage
- Indirect methods: Cepheids, Photometric
  - Require star modelling & reddening corrections, but volume coverage far more extended than for direct methods → permits to fill the gap between galactic & inter-galactic distances.
- Indirect method: pseudo-photometry
  - Require the knowedge 2 magnitudes, the spectral type & the luminosity class
  - Require an Interstellar extinction law
  - Does not require the Knowledge of interstellar extinction
  - Does not require star modelling

Pseudomagnitudes

- Introduced by Van der Bergh (1975) and Madore, 1982 to derive a reddening- free period-luminosity relation for Cepheids → Wesenheit quantity

- Pseudomagnitudes are linear combinations of 2 magnitudes built in such a way as to eliminate interstellar extinction:

$$pm_{ij} = \frac{c_i m_j - c_j m_i}{c_i - c_j} = \frac{c_i \times \left(m_j^0 + c_j A_v\right) - c_j \times \left(m_i^0 + c_i A_v\right)}{c_i - c_j} = \frac{c_i m_j^0 - c_j m_i^0}{c_i - c_j} \quad \text{with} \quad c_i = \frac{A_i}{A_v}$$

- pm_{ij} is a reddening-free quantity that have magnitude properties

- We use pseudomagnitudes to infer angular diameters & stellar distances

Angular radius from Brigthness surface

- Method → Model with a polynom the brigthness surface

$$S_i = 5\log(\theta) + m_i^0$$

of a database of stars with known angular diameter as a function of the intrinsic color,

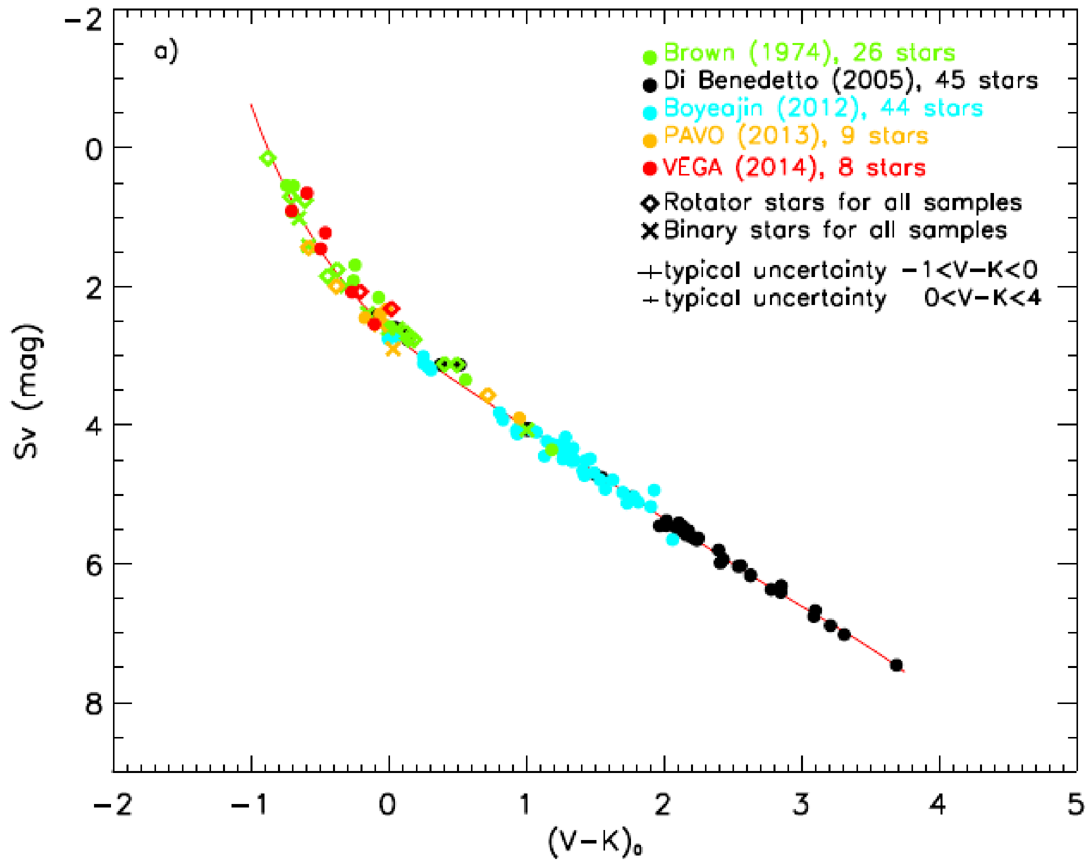
$$C_{ij} = m_i^0 - m_j^0$$

- Next → Apply the polynom to stars with known intrinsic colors to infer angular radius

- Require → interstellar extinction correction → knowledge of spectral type & luminosity class

- Reduce considerably the database of known angular diameters

Brightness surface vs intrinsic color



Challouf et al. A&A, 2014

Angular radius from pseudomagnitudes

$$S_i = 5\log(\theta) + m_i^0 \quad + \quad m_i = m_i^0 + c_i A_v \quad + \quad A_v = \frac{m_i - m_j}{c_i - c_j} - \frac{m_i^0 - m_j^0}{c_i - c_j}$$

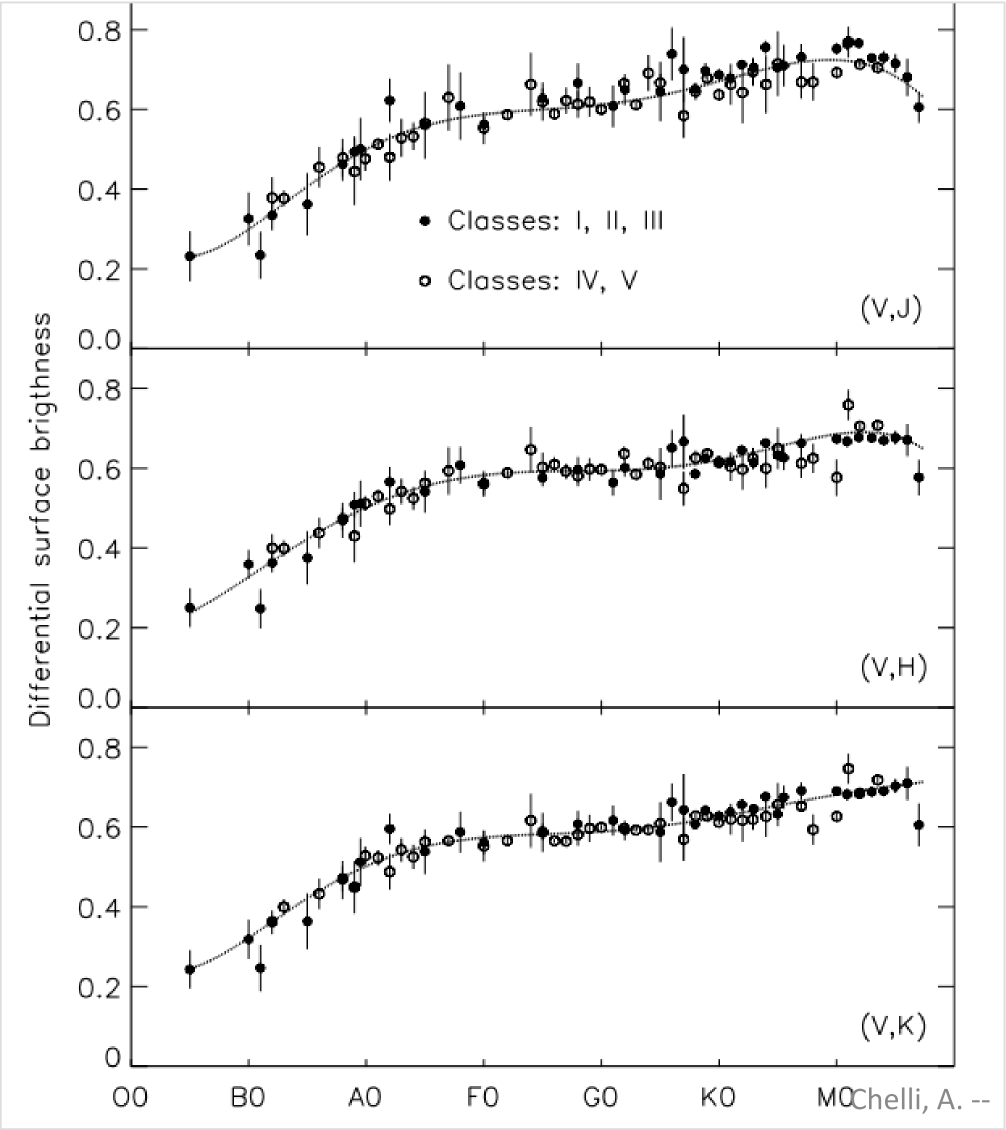
⇩

$$S_i = 5 \times \left(\log(\theta) + 0.2 \times \frac{c_i m_j - c_j m_i}{c_i - c_j} \right) + \frac{c_i}{c_i - c_j} C_{ij}$$

$$\underbrace{pm_{ij} = \frac{c_i m_j - c_j m_i}{c_i - c_j}}_{\text{Pseudomagnitude}} \quad + \quad \underbrace{\mathrm{DSB}_{ij} = \log(\theta) + 0.2\, pm_{ij}}_{\text{Differential surface brightness}} \quad ⇨ \quad S_i = 5 \times \mathrm{DSB}_{ij} + \frac{c_i}{c_i - c_j} C_{ij}$$

- Model with apolynom the differential surface brigthness of a database of stars with known angular diameter as a function of the spectral type number
- Within 2% there is no difference between main sequence stars & giants
- Apply the polynom to stars with known spectral type → no need to correct for interstellar extinction & within 2% no need to know the luminosity class

Application: JSDC_V2



JSDC_V2: JMMC Stellar Diameter Catalog available at CDS

- We use a database of ~ 1000 stars with measured angular diameters from Interferometry & lunar occultations
- From Tycho catalogue → we infer the angular radius of about 1 million stars with a 2.5% median relative error
- Main application: catalog of calibrators for Interferometric
- References: Chelli et al., A&A 2016 & Bourges et al., 2016

Pseudomagnitudes as distance indicators

- Pseudomagnitudes are reddening-free distance indicators

$$pm_{ij} = \frac{c_i\, m_j - c_j\, m_i}{c_i - c_j} = \frac{c_i\, m_j^0 - c_j\, m_i^0}{c_i - c_j} = \frac{c_i M_j^0 - c_j M_i^0}{c_i - c_j} + DM$$

- Absolute pseudomagnitudes

$$APM_{\{i,j\}} = \frac{c_i M_j - c_j M_i}{c_i - c_j} = pm_{\{i,j\}} - DM$$

- The mean absolute peudomagnitudes of a set of stars with the same physical properties may be estimated from the knowledge two magnitudes and the distance modulus *DM*
- Conversely: the knowledge of pseudo and absolute pseudomagnitudes allow to estimate the distance modulus

Absolute pseudomagnitudes of main sequence stars

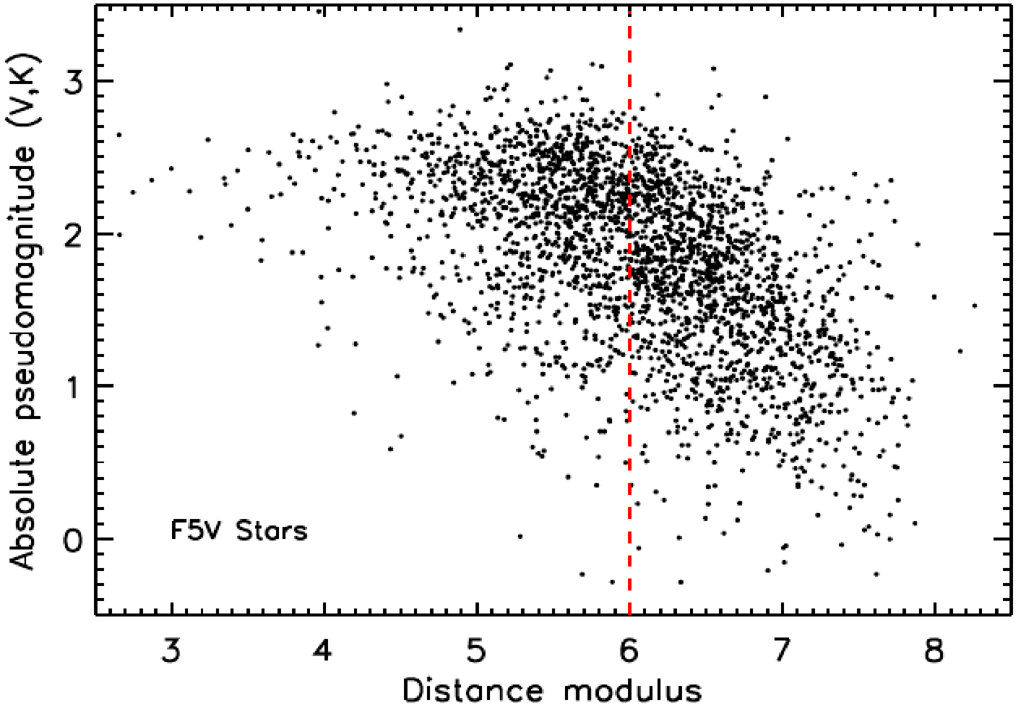


Fig. 1. Observed (V,Ks) APMs of 2533 TGAS F5V stars with a parallax error less than 10%, as a function of their distance modulus. For the stars located at a distance modulus less than 6, the dispersion of the APMs is 5 times larger than the dispersion due to the photometric and the astrometric noises. Beyond a distance modulus of 6, indicated by the vertical red broken line, the APMs begin to decrease. This behavior together with the large APMs dispersion may be explained by both multiplicity and observational bias (see text).

- We adopt the mean interstellar extinction law of Fitzpatrick (1999) and the parallaxes of TGAS
- For *DM* smaller than 6, the *APM*'s have a dispersion of 0.5 mag, i.e. 5 times larger than the dispersion due to photometric & astrometric noises → Multiplicity
- Beyond a DM of 6, the APM's seems to decrease → observational bias related to the sensitivity limit of the system which detect less and less single stars to the benefit of multiple stars as the distance increases.

Absolute pseudomagnitude distribution

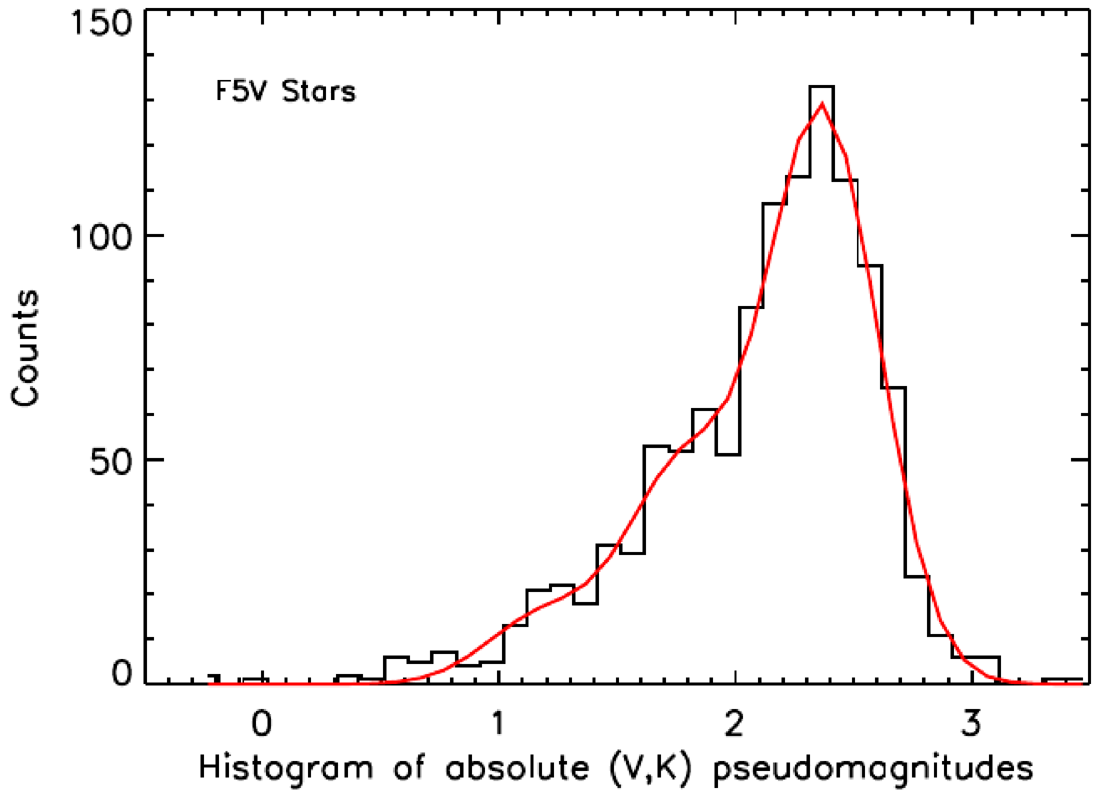


Fig. 2. (V,Ks) APMs distribution of the 1141 TGAS F5V stars located at a distance modulus smaller than 6. The red curve represents the fit of the distribution with 3 Gaussian functions of the same variance. In this case, the positions of the secondary and the tertiary Gaussian functions are smaller by 0.63 and 1.26 magnitude with respect to that of the primary Gaussian function.

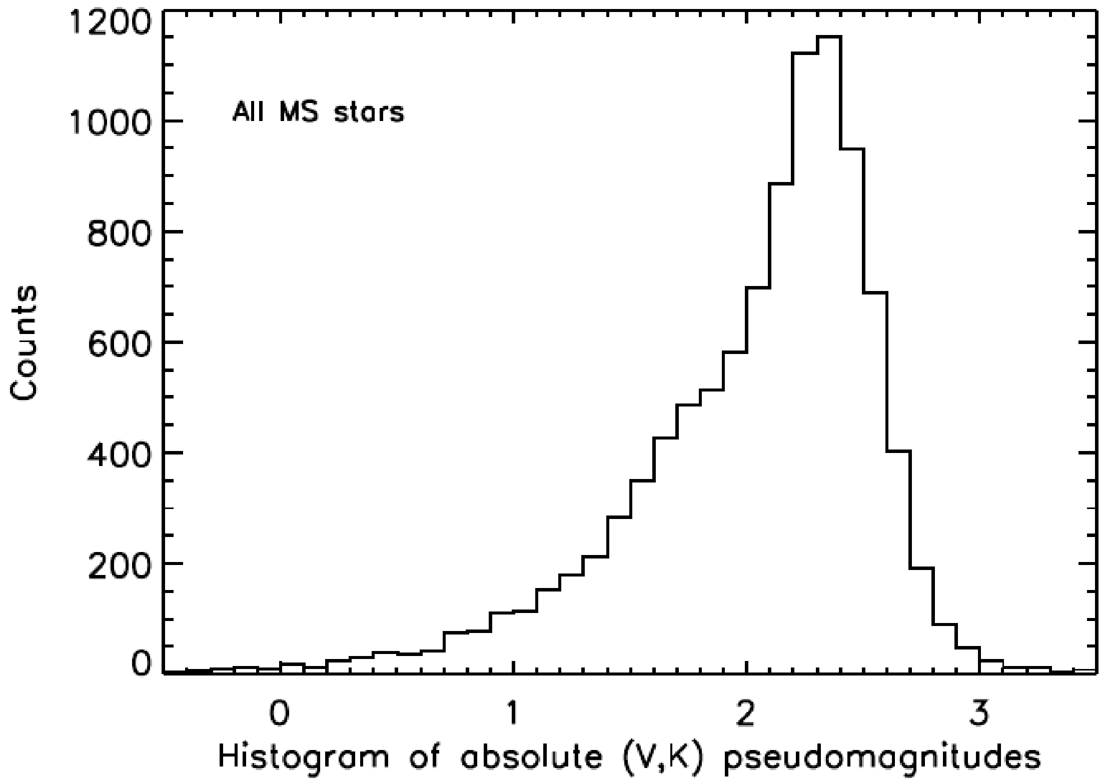


Fig. 3. (V,Ks) APMs distribution for all spectral types from B1 to K7, the APMs distribution of each spectral type having been previously shifted to that of F5V stars. The morphology of this distribution, with a main peak and an extended component to the left, is that we expect for the pseudo-photometric distance distribution of a complete open cluster.

APM's of main sequence stars versus spectral type

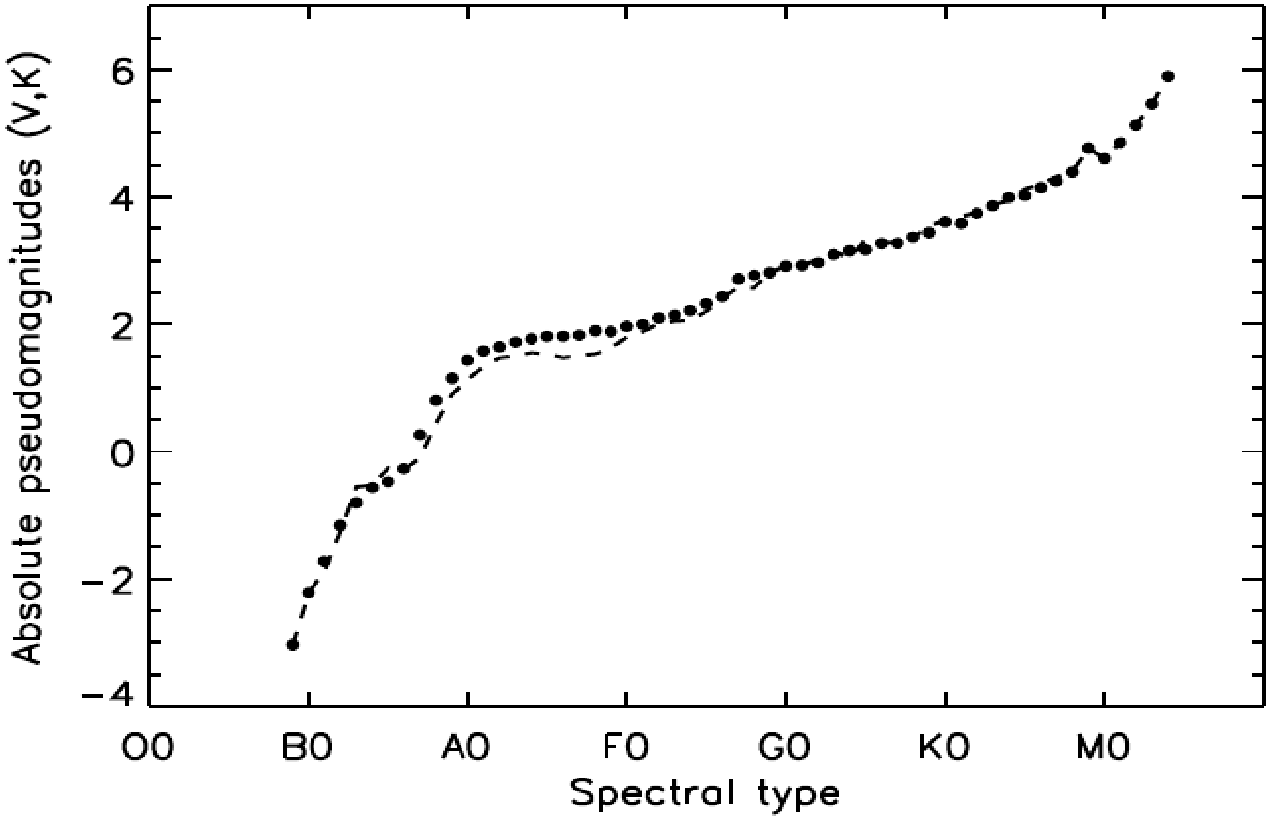


Fig. 4. Full circles: (V,Ks) $\overline{\text{APMs}}$, computed from the TGAS catalog stars, as a function of the spectral type (this paper); b) broken line: (V,Ks) $\overline{\text{APMs}}$ issued from the Hipparcos catalog stars (Chelli & Duvert 2016).

Clusters data retrieval

- Use the virtual observatory (VO)

- From the list of open clusters of Diaz et al. (2002), we select 239 clusters with more than 5 stars identified by SIMBAD as pertaining to a cluster.

- These data are complemented with a set of catalogs from Vizier

- All stars are caracterised by a spectral type and magnitudes (V,J,H,Ks)

Distance modulus estimate: methodology

- Basic hypothesis: we assume that all selected stars are main sequence stars
- We use the pseudomagnitudes (V,J), (V,H) & (V,Ks) to derive 3 pseudo-photometric distances
- We compute for each star the mean distance and the distance dispersion and we retain only the stars whose distance dispersion smaller than 0.1 magnitude
- We fit the distance distribution with one or more Gaussian functions with the same variance
- The distance modulus is set to the position of the main peak of the distances distribution (at the right of the distribution)
- For each cluster, we compute 2 distance moduli:
  - ppdm1: without proper motion constraints
  - ppdm2: with proper motion constraints

Distance distribution morphology of 30 open clusters

A. Chelli and G. Duvert: Pseudo-photometric distances of 30 open clusters

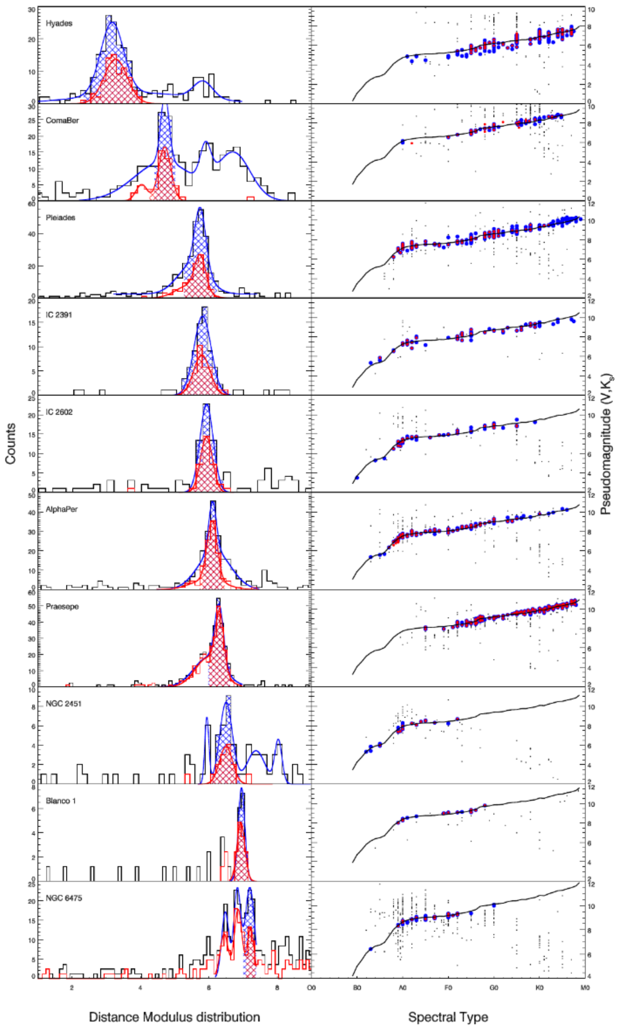


Fig. 6. Left. Pseudo-photometric distance distributions of open clusters from the list of fvl17 (first part: 10 clusters); black and red hist dd$_1$ and dd$_2$, without and with proper motion constraints, respectively (see text); full blue and red lines: Gaussian fits; the blue and red regions correspond to the selected stars to compute ppdm$_1$ and ppdm$_2$, respectively. Right. Black points: (V,Ks) pseudomagnitudes as a f of spectral type; blue and red points: stars used to compute ppdm$_1$ and ppdm$_2$, respectively.

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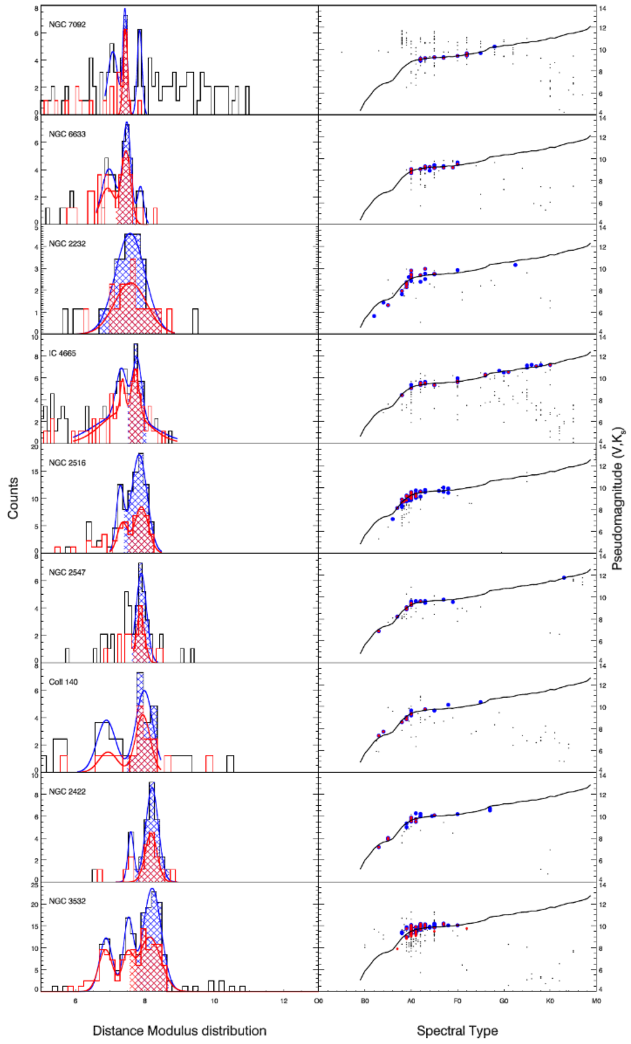


Fig. 7. Left: pseudo-photometric distance distributions of open clusters from the list of fvl17 (second part: 9 clusters); Right: (V,Ks) pseudor nitudes as a function of spectral type. See caption of figure 6 for details.

A. Chelli and G. Duvert: Pseudo-photometric distances of 30 open clusters

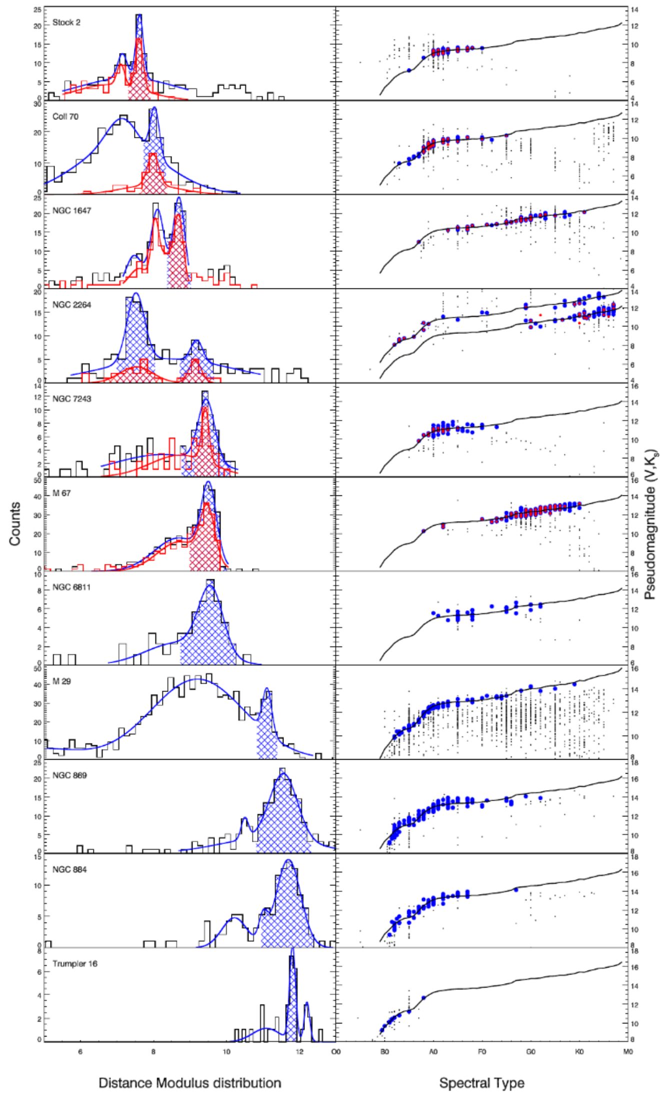


Fig. 8. Pseudo-photometric distance distributions of 11 additional open clusters. Left: pseudo-photometric distance distributions; Right: (V,Ks) pseudomagnitudes as a function of spectral type. See caption of figure 6 for details.

Distance distribution morphology of 30 open clusters

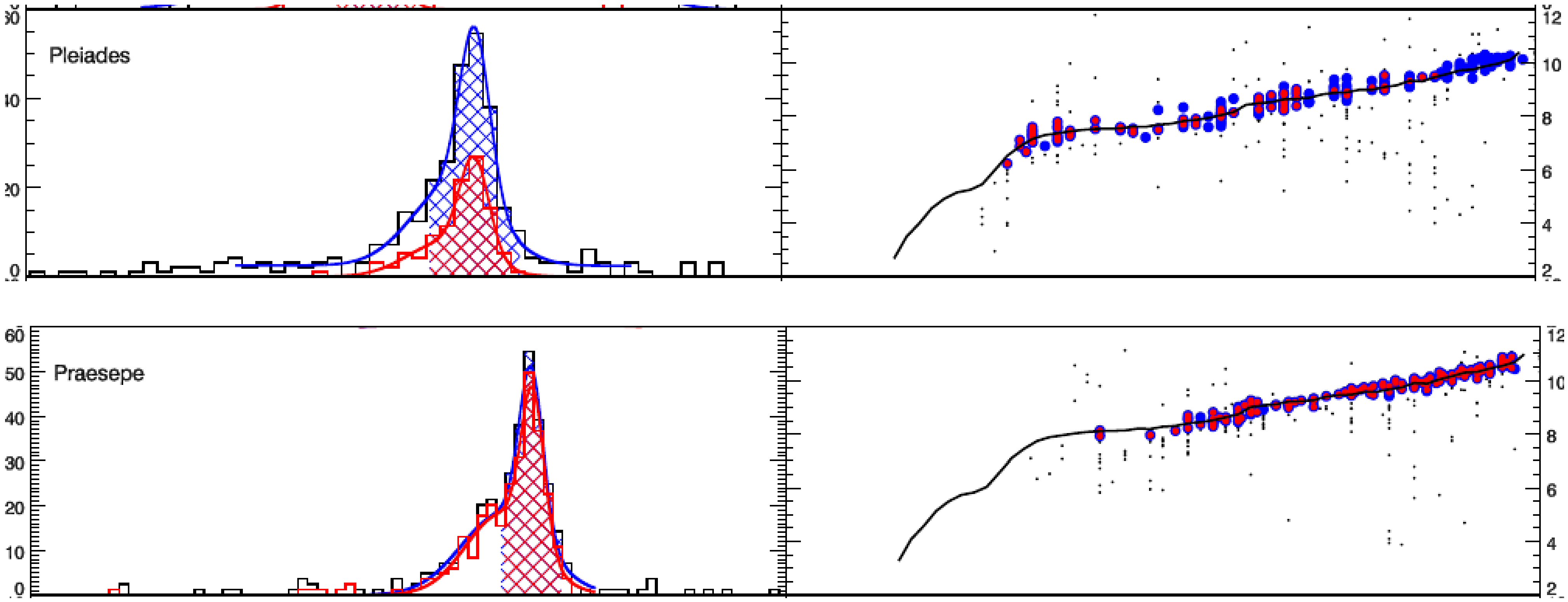
- The distributions exhibit a main peak with an with extended component to the left and/or multiple peaks:

- Limiting case 1:
  - Pleiades, Praesepe & M67: the distributions exhibit a main peak and an extended component on the left shifted by about 0.75 mag → similar to the recentered *APM* (V,Ks) distribution of all Tgas spectral types
  - For the Pleiades & Praesepe, the mean Tgas distance moduli of the stars from the extended component and the main peak are similar within 0.05 mag

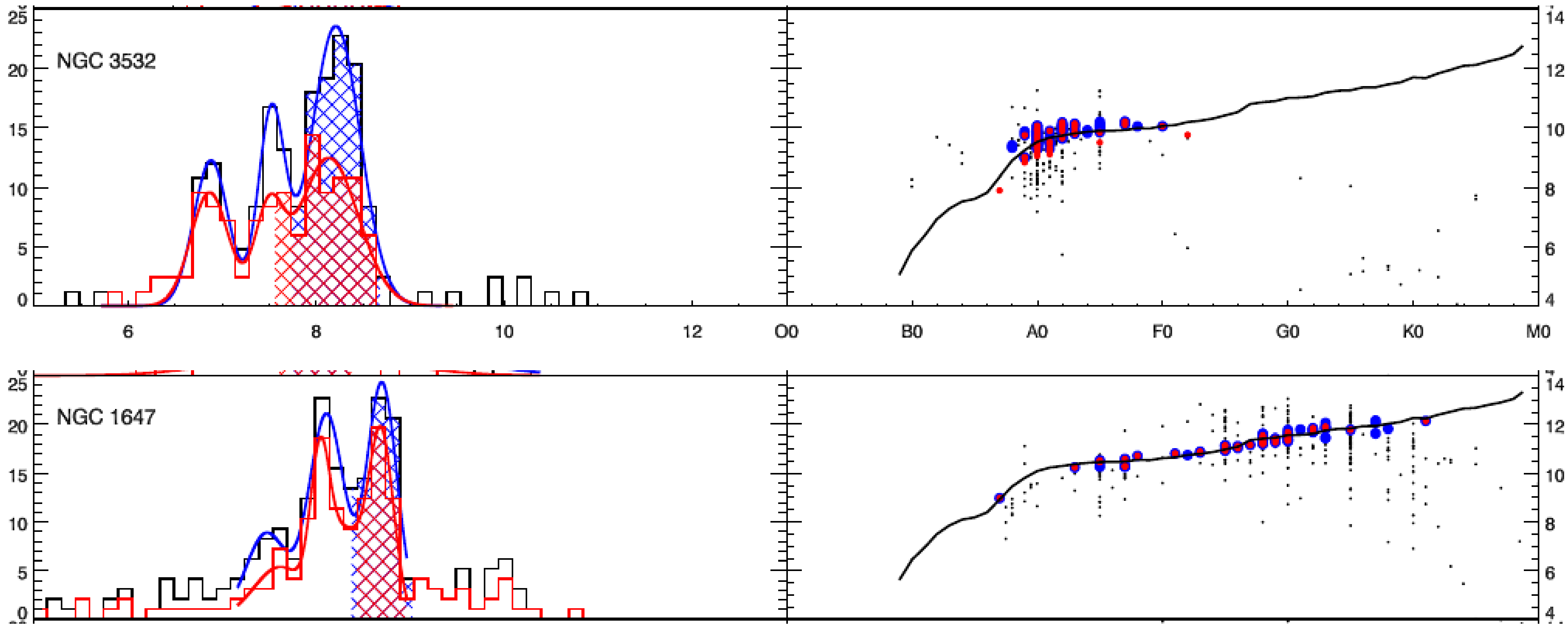
- Limiting case 2:
  - NGC3532 & NGC1647: the distance distributions exhibit a triple peaked structure with secondary and tertiary peaks shifted down by 0.62 and 1.19 mag (twins & triplets)
  - For NGC3532, the mean distance modulii of the stars from the 3 peaks are similar within 0.1 mag.

- Conclusion: the extended component and the secondary peaks are due to multiplicity

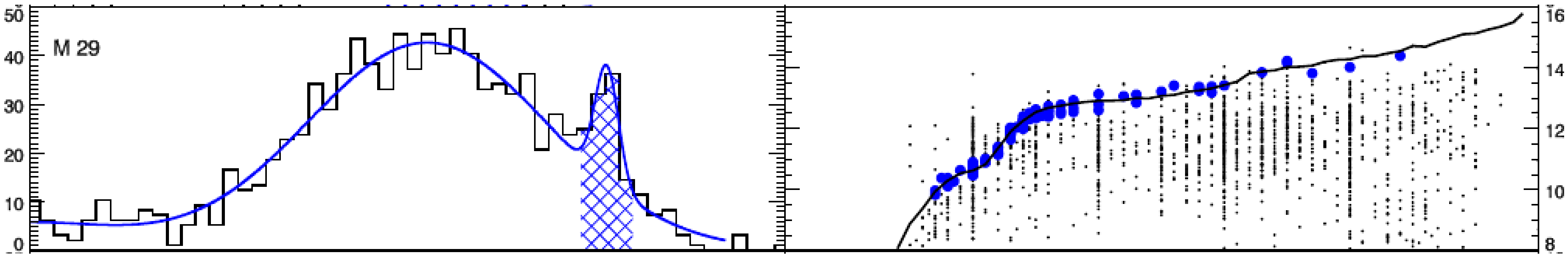
Distance distribution: Pleiades & Praeseppe



Distance distribution: NGC3532 & NGC1647



Distance distribution: M29: no pm info



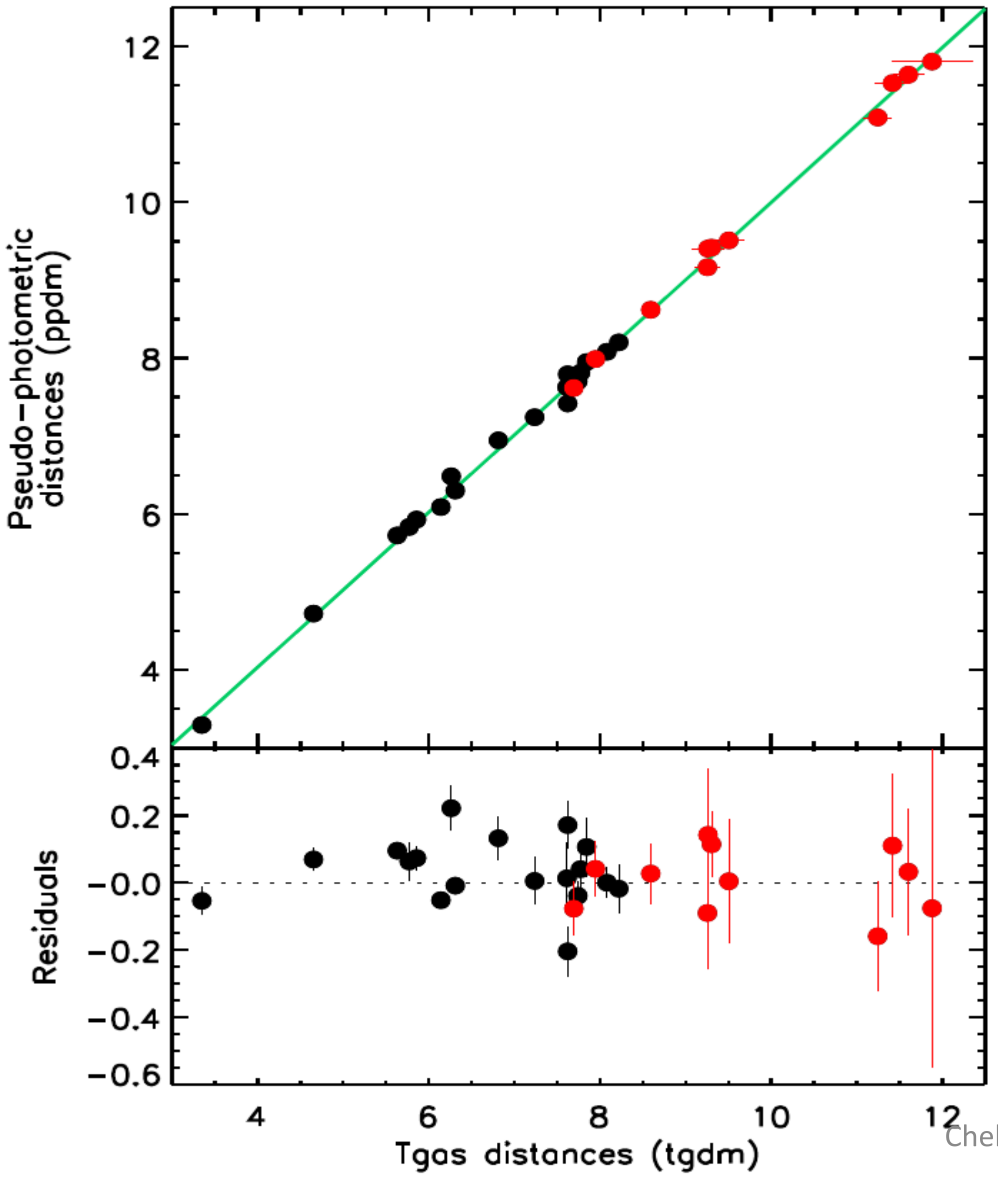
Systematic errors

- Influence of PMS on distance estimates
  - We recomputed the pseudo-photometric distances of the 30 selected clusters, excluding the stars whose time arrival on the main sequence (Jung & Kim 2007) is larger than the cluster age (WEBDA database)
  - For 20 clusters containing mainly early type stars, we found a ppdm difference smaller than 0.01 mag
  - For the other 10 clusters, the distance differences vary between -0.08 mag (Coll70) and 0.04 mag (Alpha Persei), with a rms difference of 0.02 mag.
  - Conclusion: with respect to the selected clusters, the influence of PMS on distance estimates is negligible compared to systematic errors

- Systematic errors: incompleteness, multiplicity, systematic errors on *APM's* (0.05 to 0.1 mag), mismatches between our simple Gaussian model and the real *APM's* distribution, spectral mismatches & presence of PMS stars.

- Global systematic error on pseudomagnitude distances estimates: 0.05 mag

Comparison with Tgas distances



- Tgas distances: black points (Van Leeuwen et al. 2017), red points (this work)
- Statistical linear fit:

$$ppdm = (0.023 \pm 0.047) + (0.999 \pm 0.007) \times tgdm.$$

- Dispersion: sigma(ppdm-tgdm) = 0.1 mag
- References:
  - Chelli & Duvert, A&A 2016
  - Chelli & Duvert, A&A, 2018

Summary

- Pseudomagnitudes are distance indicators free of reddening effets

- Combining absolute pseudomagnitude (from Tgas parallaxes) with Simbad and Vizier databases allow us to compute the pseudo-photometric distance of 30 open clusters

- Peudo-photometric distance estimates agree within 0.1 mag with Tgas distances

- Our approach does not need sophisticated modelling: based on a statistical analysis of quasi purely experimental quantities:

  - magnitude, spectral type & luminosity class
  - mean interstellar extincton law

Perspectives

- The pseudomagnitude concept can routinely be used in all large scale surveys where statistical distances on a set of stars, such as an open cluster, are required (Globular clusters?)

- It may also be advantageously used to study the frequency of multiplicity among stars

- The releases of Gaia DR2 & DR3 will allow to refine the absolute pseudomagnitude estimates of main sequence stars and to extend the pseudomagnitude concept to other luminosity classes and then to larger distances (Extragalactic?)