Open clusters with Gaia

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The science of Gaia and future challenges, Lund, 1st Sep 2017

Open clusters

Natural groups of stars which form simultaneously within collapsing molecular clouds, hence sharing various properties like their ages, initial chemical composition, space positions, velocities, until they eventually disperse

Open clusters are key to understand the star formation mechanisms

Open clusters are excellent laboratories for testing stellar structure and stellar evolutionary theories

Open clusters are key to trace the Milky Way disk structure and to understand the formation and evolution of the galactic disks

NGC3532: image credit ESO

Known Open Clusters

The most complete updated compilations currently available are:

1. Dias et al (2002, A&A 389, 871), version 2015: 2167 entries of which 2036 are open clusters, and others are classified as associations, dubious clusters or remnants

2. Kharchenko et al (2013, A&A 558, A53): list of 3006 clusters of which 2267 are open clusters and other are classified as globular clusters, associations, asterism or remnants

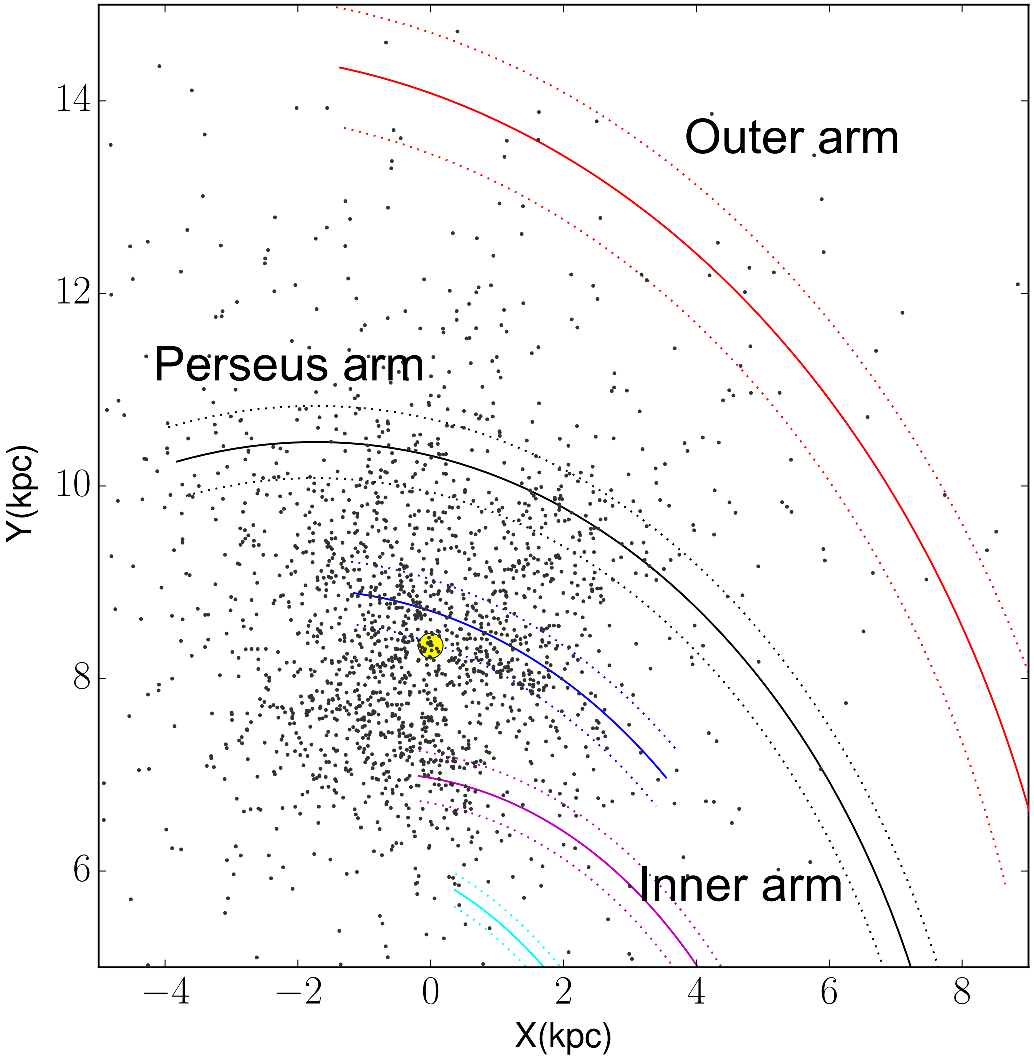
Both analysis are internally homogeneous in their determination of mean proper motions, distances, reddening and ages

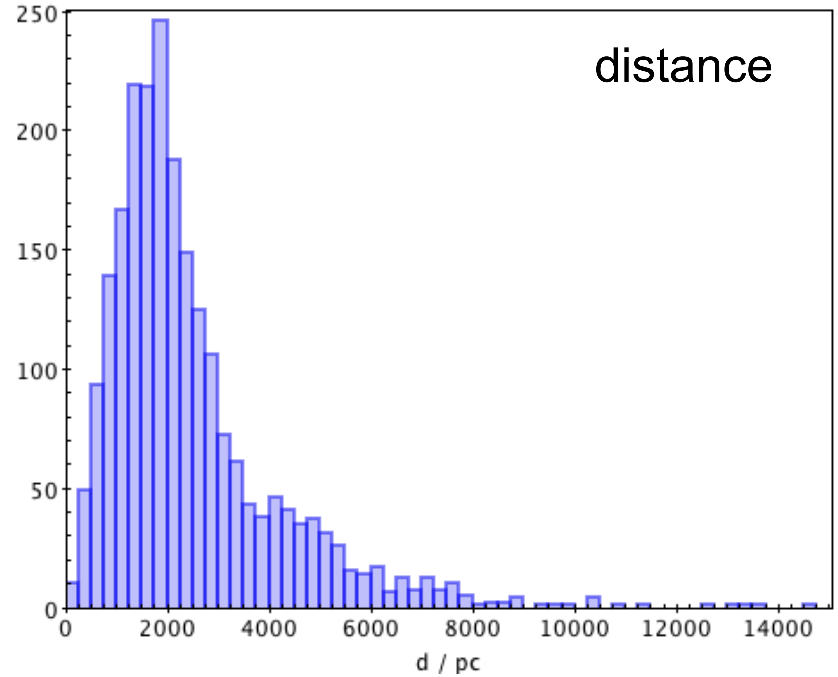
There is not a full agreement on which group is considered a cluster or an asterism between the two catalogues

+ additional ~500 clusters (Froebrich 2017, Liu et al 2017)

Known Open Clusters

Projection onto the plane

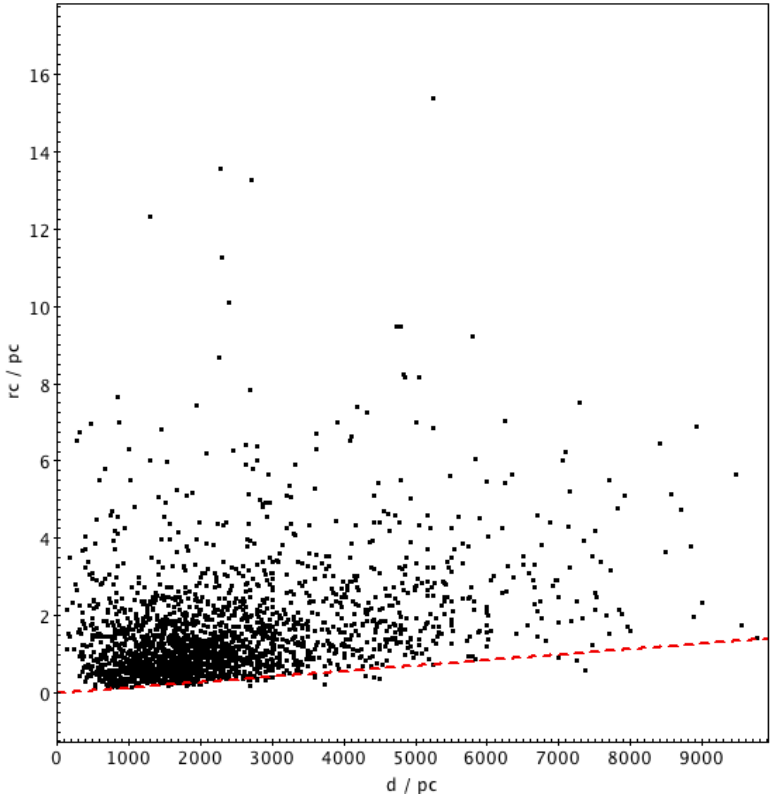


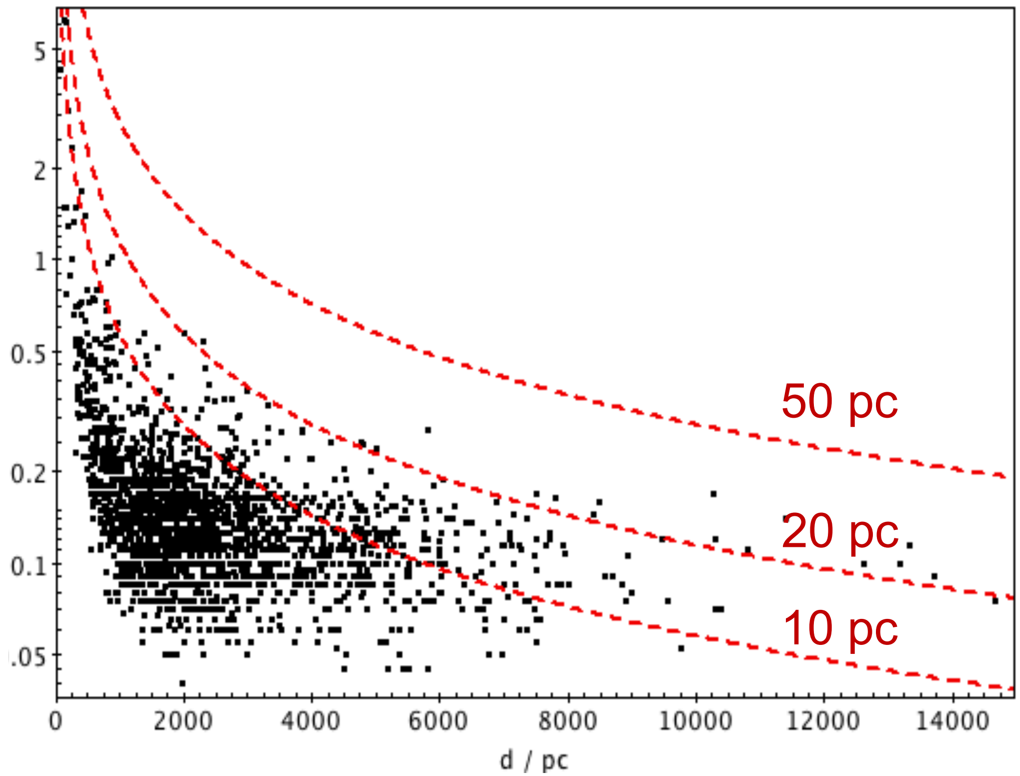


Incompleteness increases with distance

Known Open Clusters

Plenty of observational biases !!!





Sizes of the nucleus depend on the distance

From Kharchenko et al (2013) data

Known Open Clusters

The amount and precision of data available for each cluster is very different

Detailed studies are usually performed in the central region of the clusters

- Precise photometry
- Spectroscopy: radial velocity, chemical composition

Some clusters are very well studied (nearby, interesting locations in the MW, interesting ages or chemical composition, …) while others are only recognized as enhanced stellar densities in the sky

Gaia contribution

Gaia contribution

1) Detection of clusters

To build a census as much complete as possible of existing open clusters is a challenge.

2) Detection of cluster members

To determine as much complete as possible membership from low mass stars to white dwarfs.

Gaia is unique on this because of its

1. Full-sky coverage
2. Faint limiting magnitude
3. Homogeneity
4. Accuracy and precision
5. Diversity of data: astrometry, photometry, spectroscopy, physical parameters of stars, multiplicity, variability, etc

Complementary spectroscopic surveys from ground (see S. Feltzing talk)

NGC3603: Image Credit: NASA, ESA, and the Hubble Heritage

Gaia contribution

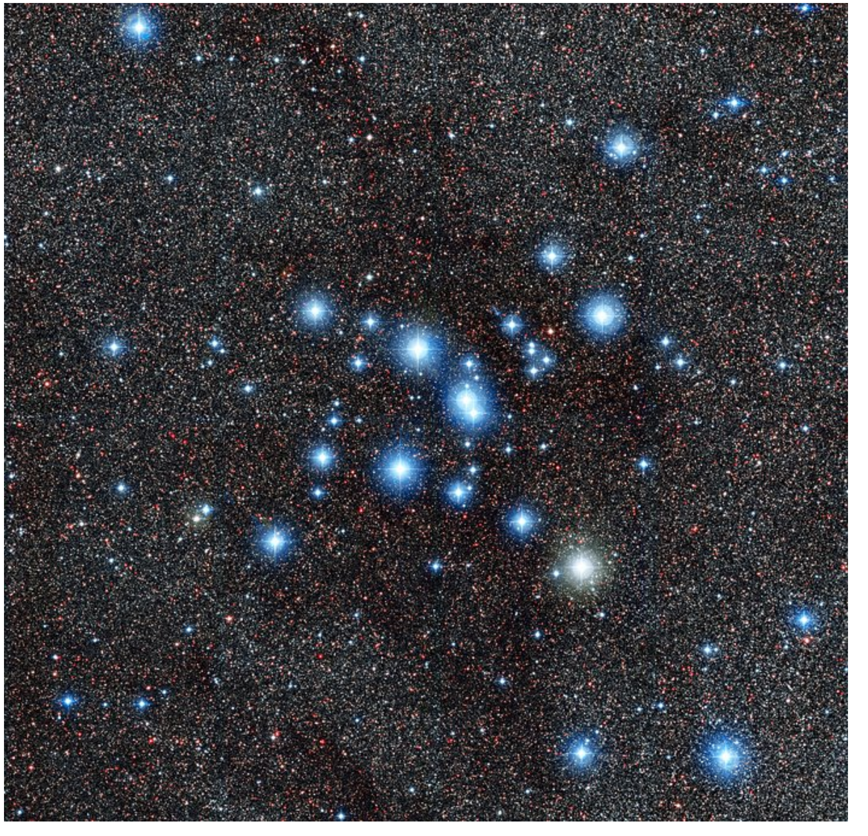
Science open clusters case is well discussed in the Red Book

Only to mention some applications:

Clusters as entities:
- Formation of clusters
- Improved luminosity and mass functions
- Internal kinematics
- Better studies of mass segregation
- Study the evaporation processes

Stellar structure and evolution
- Precise photometry will allow to study fine details in the cluster sequences

Galactic structure and evolution:
- Distances, ages, chemical composition
- Orbits



M7 = NGC6475: image credit ESO

Size of open clusters

Size of open clusters

Cores and extended coronas
Areas to study

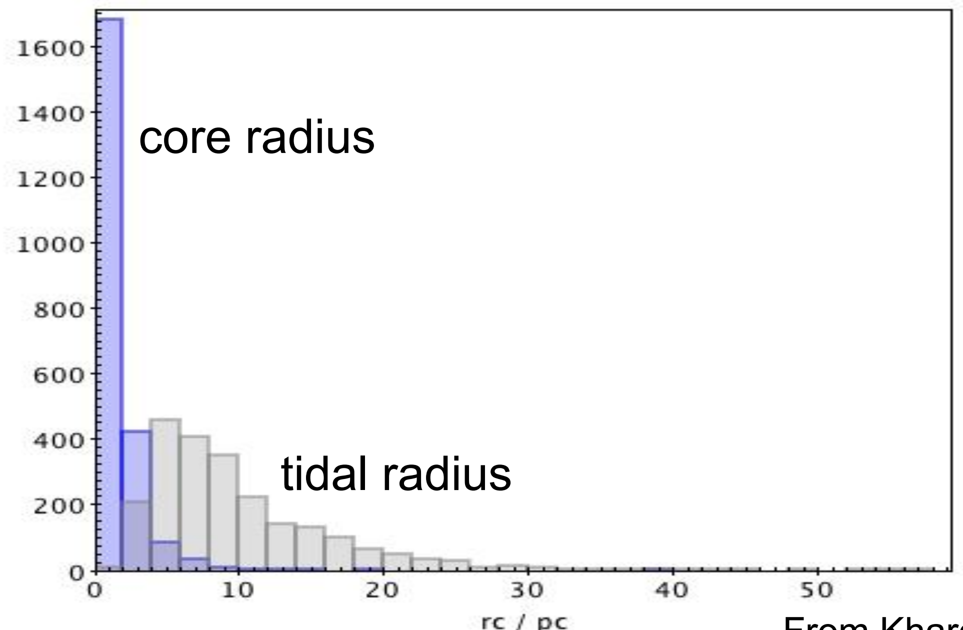
Studies of open clusters are many times focussed on the central cores, where the ratio cluster over field populations is high

How much extended are the halo/coronas of the clusters ?
Are the stars as such distances gravitationally bound to the cluster ?
Are they in the process of evaporation ?

Size of open clusters

TGAS astrometry used to determine membership of nearby clusters

1. Gaia Collaboration, van Leeuwen et al (2017) surveyed area r = 15 pc
2. Cantat-Gaudin et al (submitted) d < 2kpc surveyed area r = 20 pc



From Kharchenko et al (2013) data

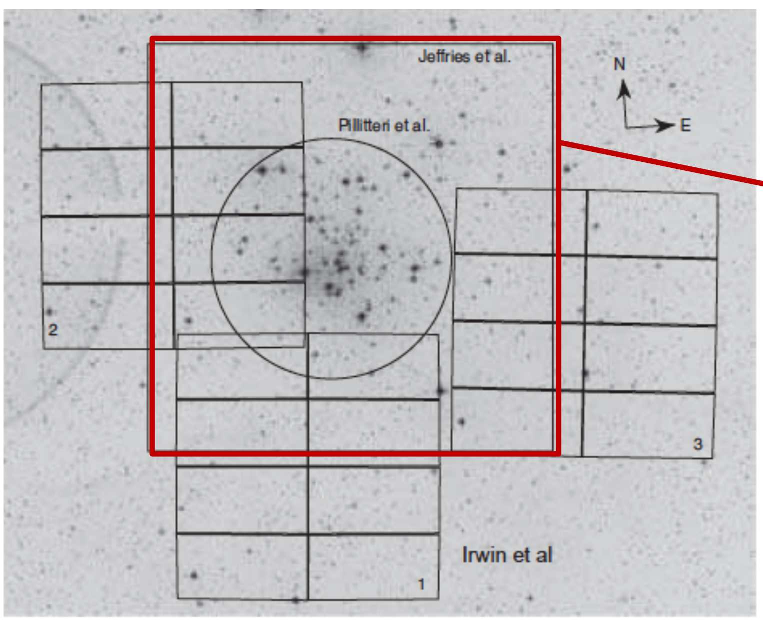
In both cases it can be seen that stars with proper motions and parallaxes compatible with <u>membership are found all over the surveyed area</u>.

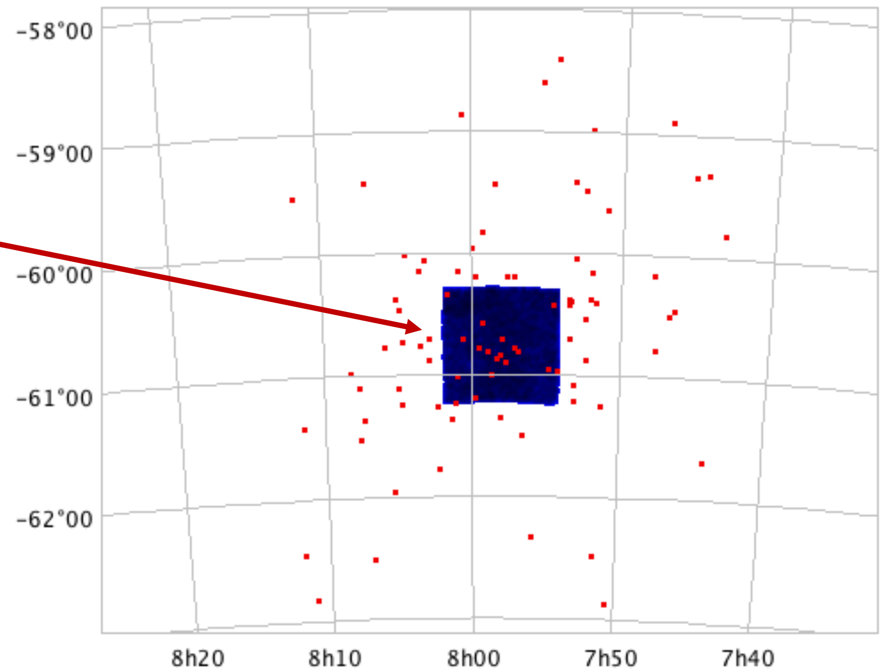
An example: NGC 2516

Located at (l,b)=(273.8º,-15.9º) at about 350 pc
Well populated cluster; relatively young cluster 300 Myr
Core radius: 0.94 pc   Tidal radius: 7.7 pc   Kharchencko et al (2013)

Scientifically interesting because its richness and properties similar to those of Pleaides. Mass function and mass segregation studies, known white dwarfs, etc

Jeffries et al (2001): 1x1 deg^2: GES





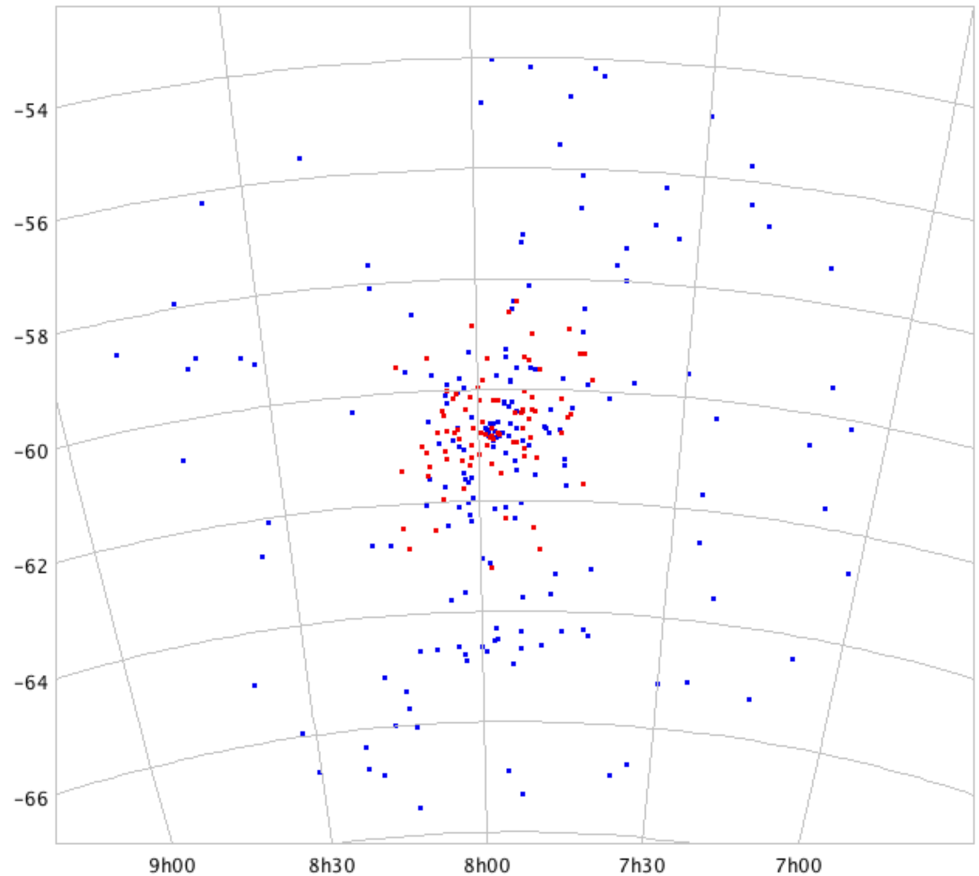
Studied in Gaia Collaboration van Leeuwen et al (2017)
Surveyed area : radius of 15 pc

An example: NGC 2516

TGAS has been re-explored in an area of 50 pc radius

Selection of members based on proper motions & parallaxes

Additional members cover all surveyed area (radius = 50 pc)

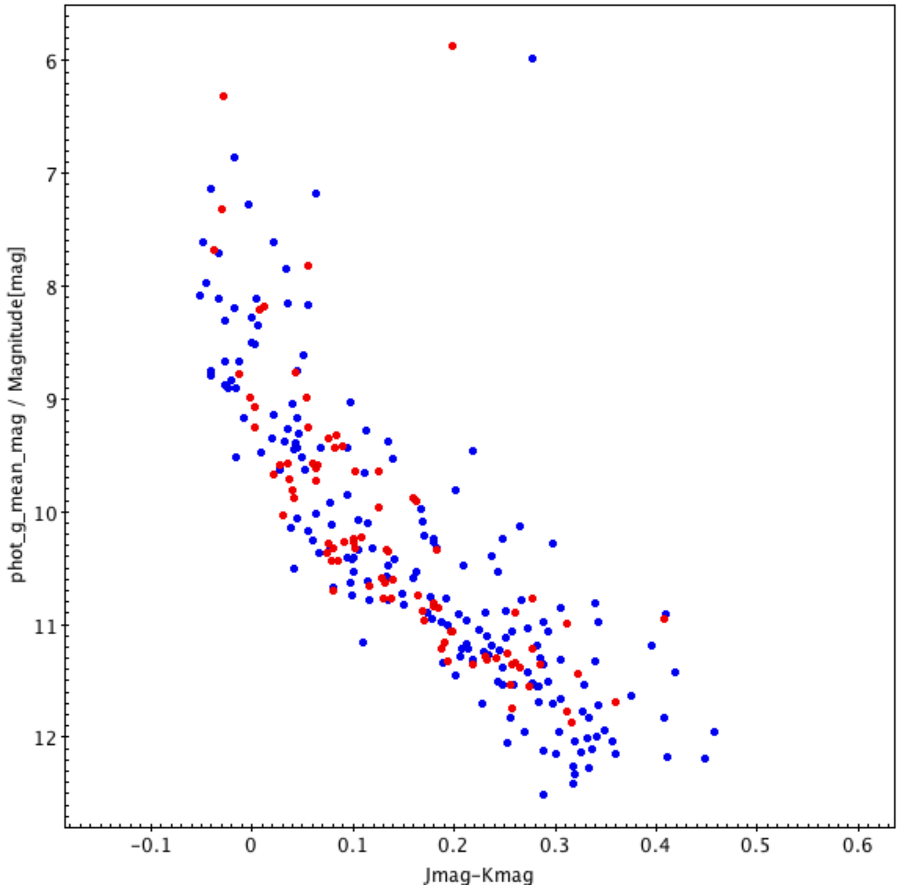


Red symbols: members in Gaia Collaboration (2017)
Blue symbols: additional members

An example: NGC 2516

Reliability of selection: check the selection in colour-magnitude diagrams

Precision of existing photometry is not good enough



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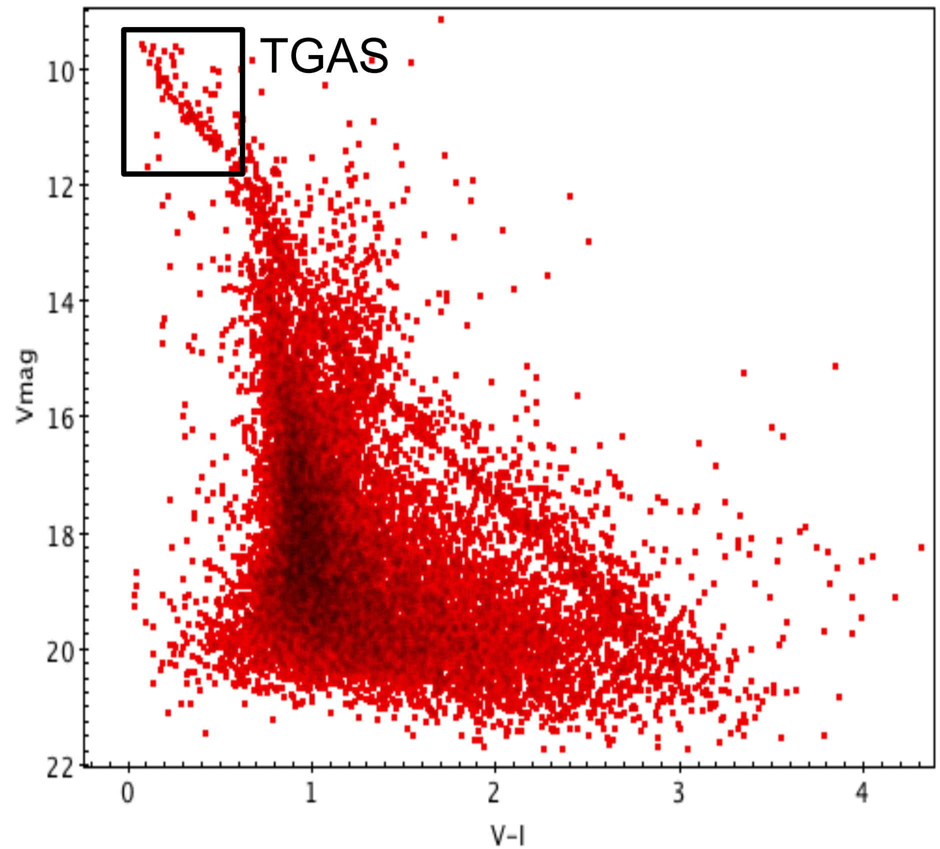
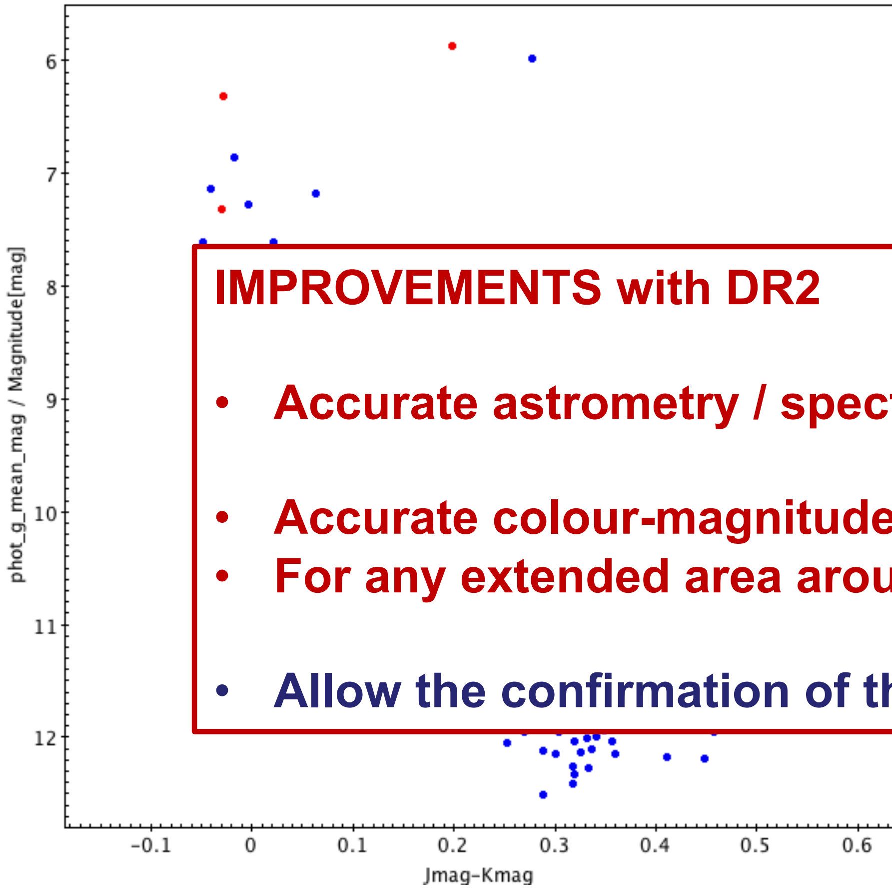


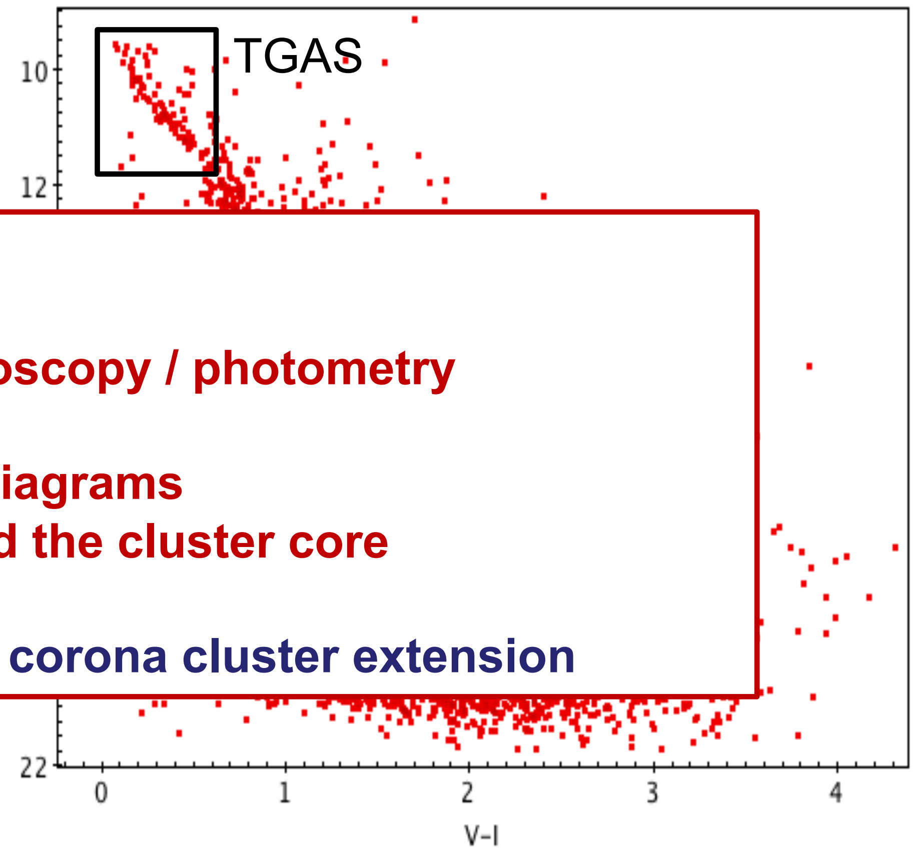
Jeffries et al (2001): area of ~ 2° x 1°

An example: NGC 2516

Reliability of selection: check the selection in colour-magnitude diagrams

Precision of existing photometry is not good enough





IMPROVEMENTS with DR2

- **Accurate astrometry / spectroscopy / photometry**
- **Accurate colour-magnitude diagrams**
- **For any extended area around the cluster core**
- **Allow the confirmation of the corona cluster extension**

Red symbols: members in Gaia Collaboration (2017)
Blue symbols: additional members

Jeffries et al (2001): area of ~ 2° x 1°

Open clusters membership

Gaia capabilities compared to existing catalogues

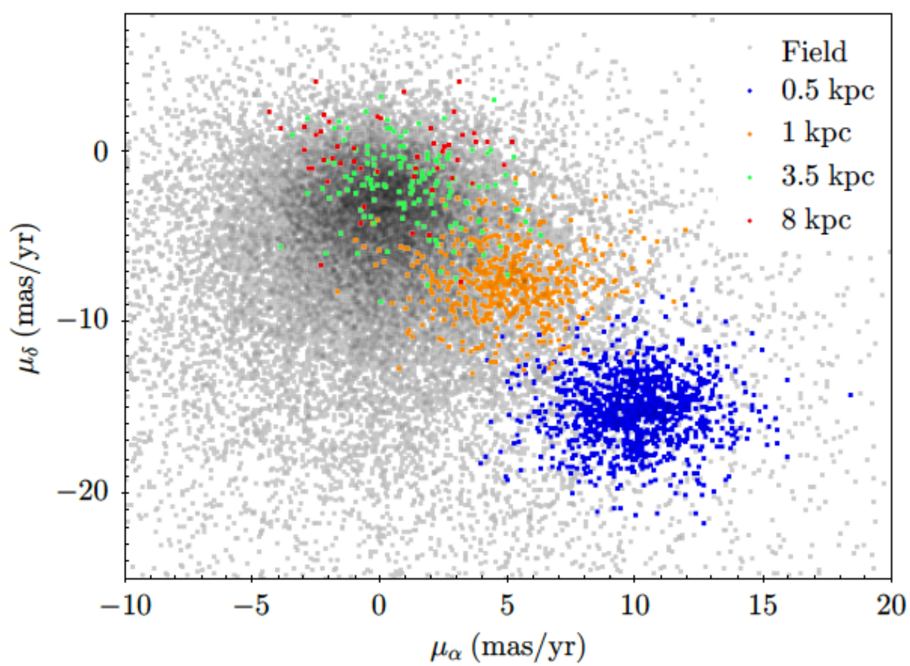
Open clusters membership

Simulation of open cluster, with a given space velocity and located at different distances

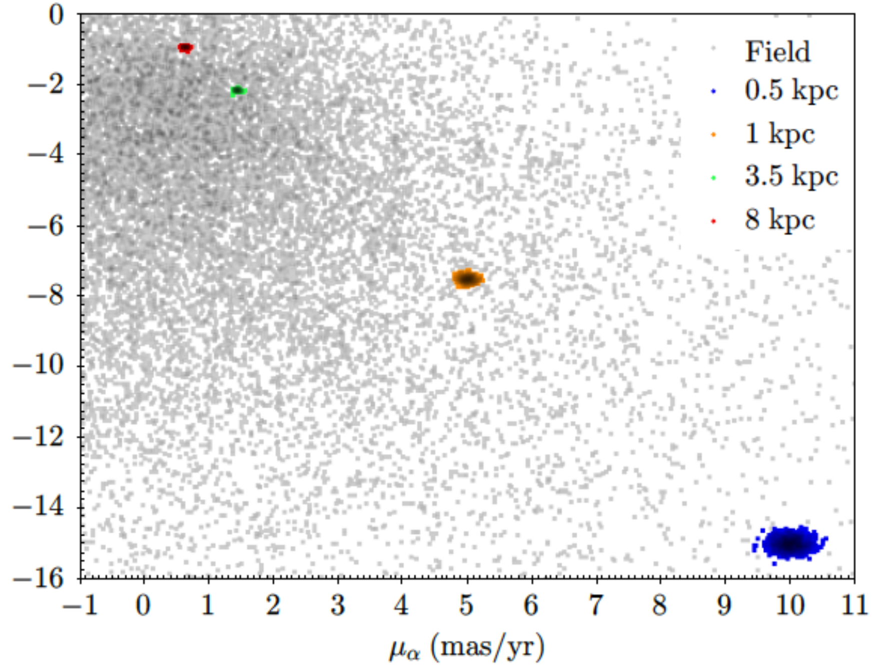
P. Massana (master thesis)

- Size: 4 pc
- Mean tangential velocity = (24,-35) km/s with sd of 0.7 km/s
- Mean position: (l, b) = (180º, 20º)
- 1000 members

HSOY uncertainties
(Altmann et al, 2017, A&A 60, 4)



Gaia end-of-mission uncertainties
Gaia web-site

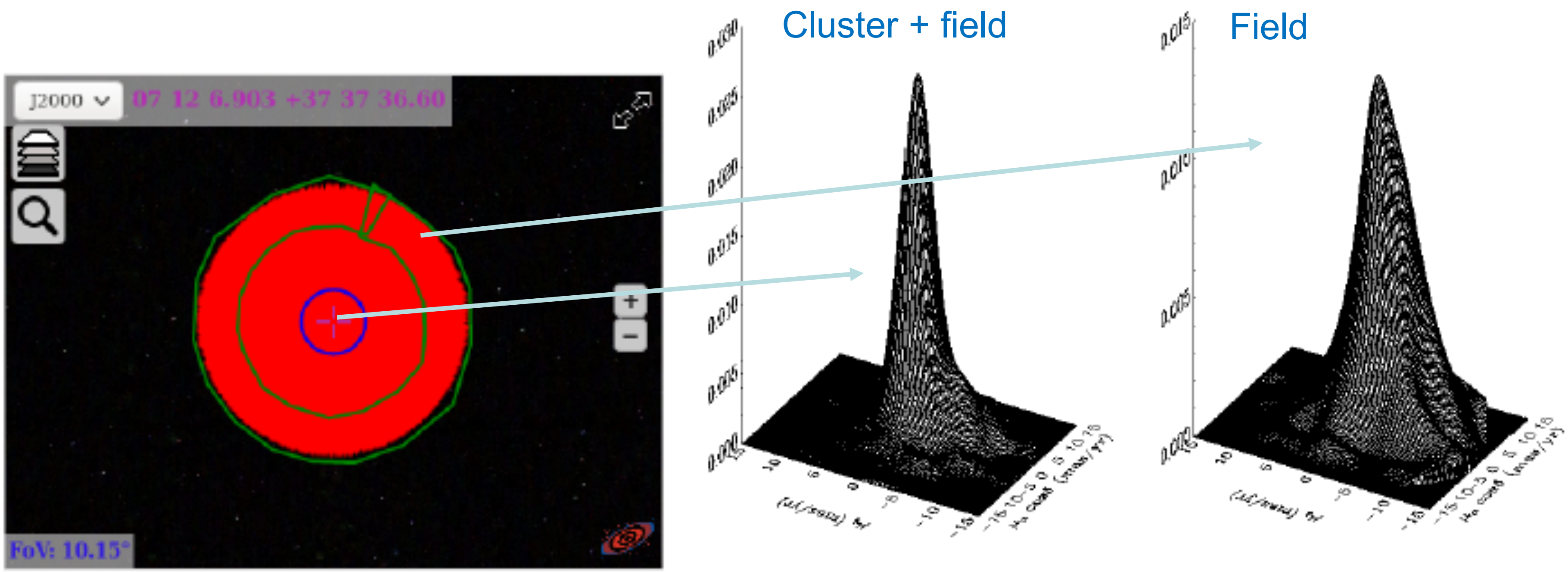


GUMS (Robin et al, 2012 A&A 543, A100) used to simulate field stars

Open clusters membership

Non-parametric approach (Galadí-Enríquez et al 1998, A&A 337, 125)

CLUSTERIX 2.0 http://clusterix.cab.inta-csic.es/clusterix



$$\Psi_c = \Psi_{c+f} - \Psi_f$$

Precision of Gaia data reveal asymmetric distributions in positional and kinematical spaces → Gaussian distributions are not valid anymore

It may be important not to impose any a priori model

Open clusters membership

Non-parametric approach (Galadí-Enríquez et al 1998, A&A 337, 125)

CLUSTERIX 2.0 http://clusterix.cab.inta-csic.es/clusterix

		Gaia		HSOY	
Distance (kpc)	# of cluster stars	ω	ε	ω	ε
0.5	1000	0.993	0.990	0.771	0.768
1	468	0.970	0.972	0.291	0.296
2	251	0.976	0.907	-	-
3.5	145	0.959	0.908	-	-
5.5	83	0.867	0.878	-	-
8	50	0.900	0.849	-	-

ω = % of true members among all stars classified as members
ε = % of stars classified as members among all true members

Open clusters membership

Non-parametric approach (Galadi-Enriquez et al 1998, A&A 337, 125)

CLUSTERIX 2.0 http://clusterix.cab.inta-csic.es/clusterix

		Gaia		HSOY	
Distance (kpc)	# of cluster stars	ω	ε	ω	ε
0.5	1000	0.993	0.990	0.771	0.768

Contributions of DR2

- **Availability of full kinematics: proper motions and radial velocity**
- **Availability of parallax**
- **Availability of accurate photometry**

ω = % of true members among all stars classified as members
ε = % of stars classified as members among all true members

Detection of open clusters

How many clusters are still undiscovered ?

Detection of open clusters

M. Morvan (master thesis)

Clusters merely correspond to increased density regions in a n-D space

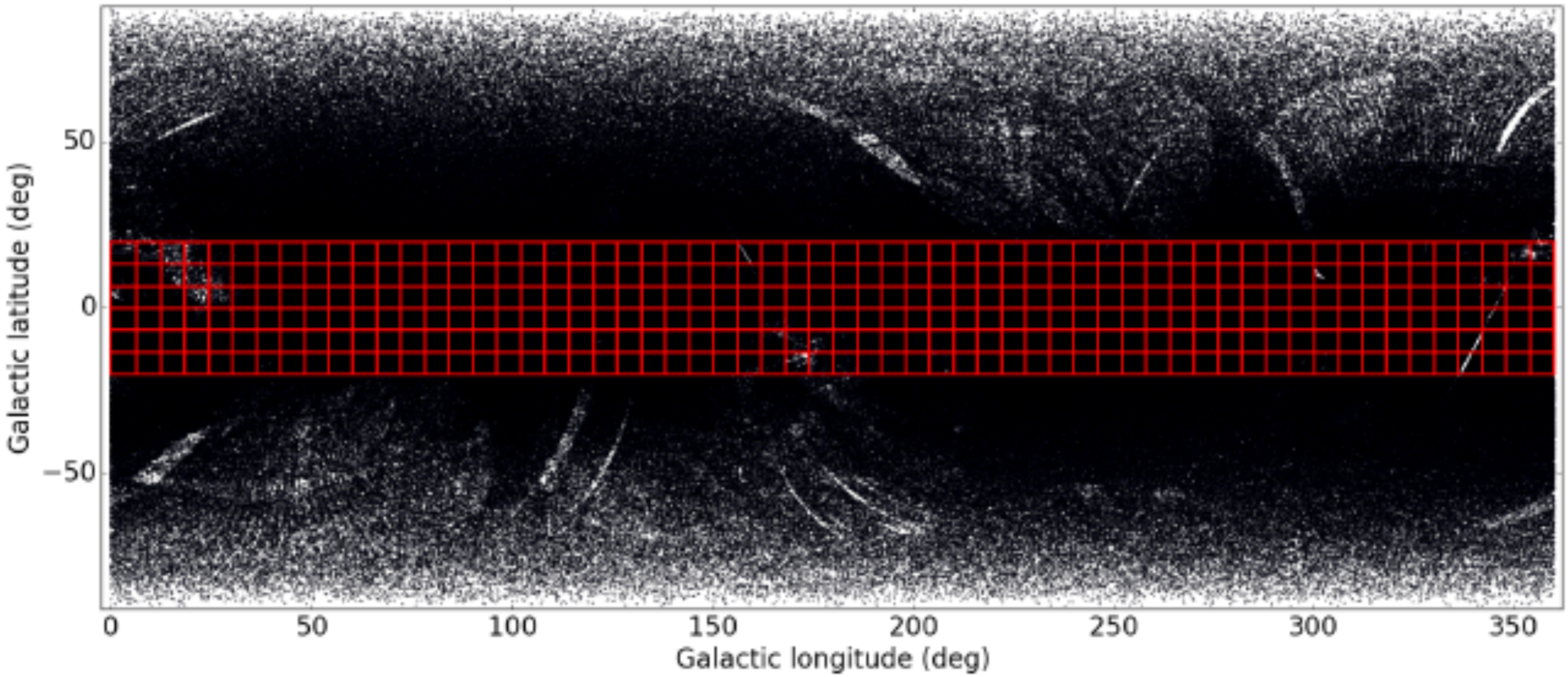
- ra, dec, parallax
- pmRa, pmDec, vrad
- age, chemical composition

Choice of a density threshold to identify clusters

Detection of open clusters

TGAS data selection:

- stars close to the disk plane $|b| < 20^{o}$ (99% of the clusters)
- rejection of extreme values $|\mu_\alpha|$ or $|\mu_\delta|$ > 30 mas/yr; ϖ > 7 mas or ϖ< 0
- partitioning the sky in rectangles of *L x L* deg^2 to get a manageable number of stars
- dithering to avoid border effects



Detection of open clusters

- Computation of distance between to stars *i* and *j* in the 5D-space ($\alpha,\delta,\mu_\alpha,\mu_\delta,\varpi$) after normalization by the s.d. in the area

- DBSCAN (Ester et al, 1996): implements kNND principle (k^{th} nearest neighbours distances); stars with at least *minPts* within a radius ε are named as cores → density-reachable cores as well as the points lying in their ε-neighbourhood
- OPTICS (Ankerst et al 1999): ordering points to identify the cluster

- Choice of threshold distance ε in each rectangle
  Assuming that its concentration has very little chance to come from a random distribution → minimum kNN distances from random stars might be higher than the typical kNN distances from any open cluster
  This provides an upper limit to ε

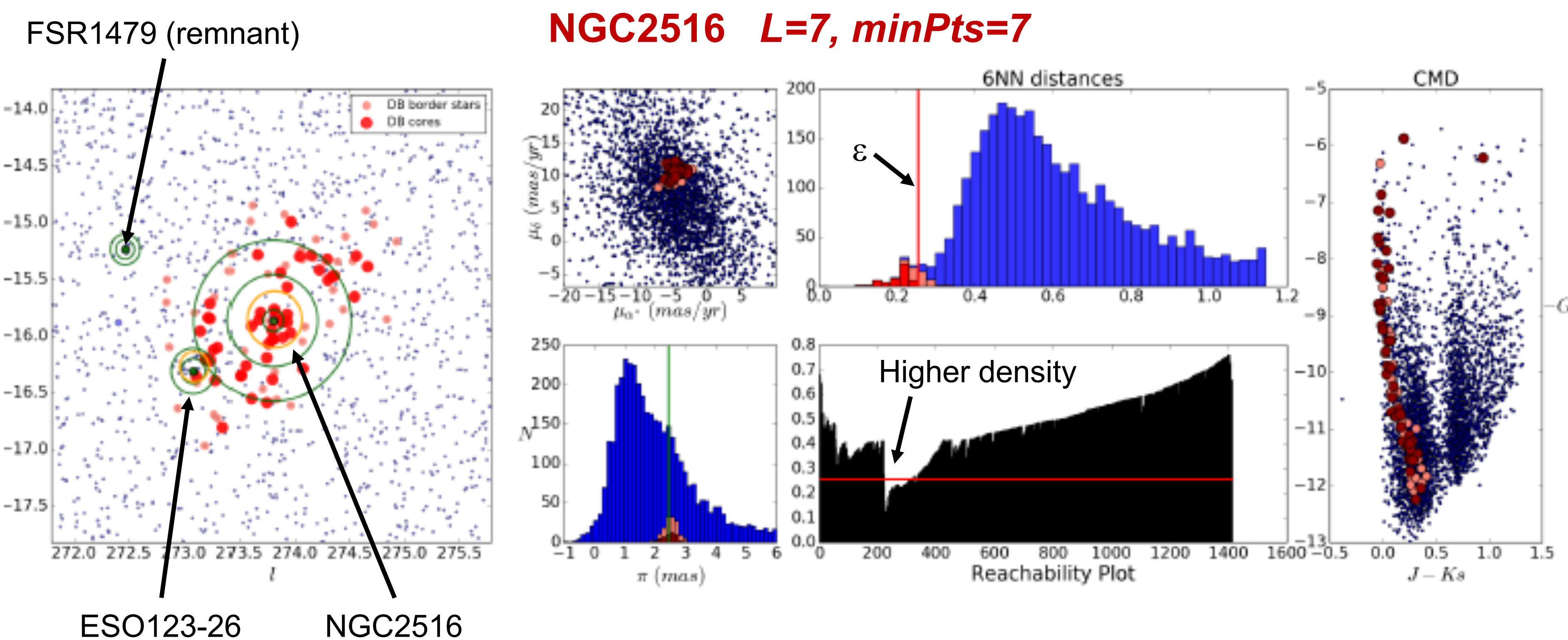
- Choice of (*L*, *minPts)* for each rectangle (+ dithering)
  15 different pairs have been tested

- <u>Output: list of detected density-based clusters</u>

Detection of open clusters

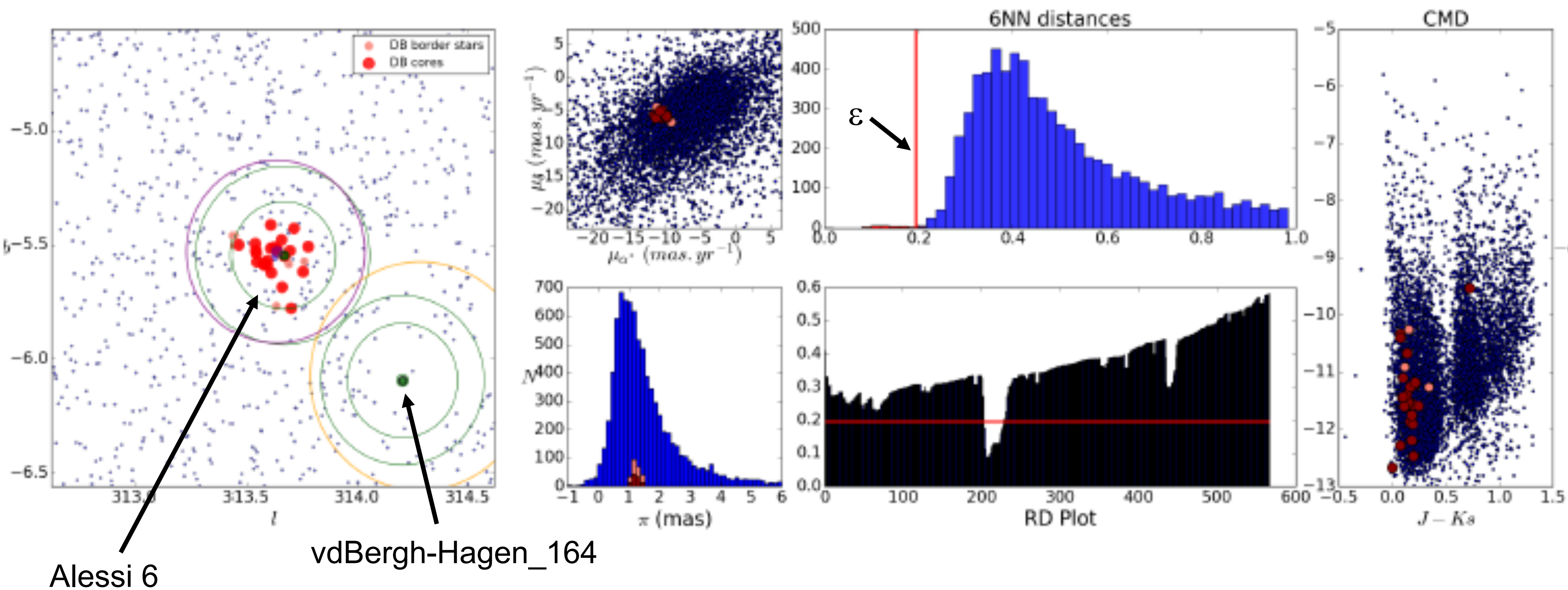
Results:

- Cross-match in 5D space with known OC (Dias et al, Kharchenko et al catalogues)
- Analysis of the colour-magnitude diagrams using 2MASS colours



Detection of open clusters

Alessi 6 *L=7, minPts=7*



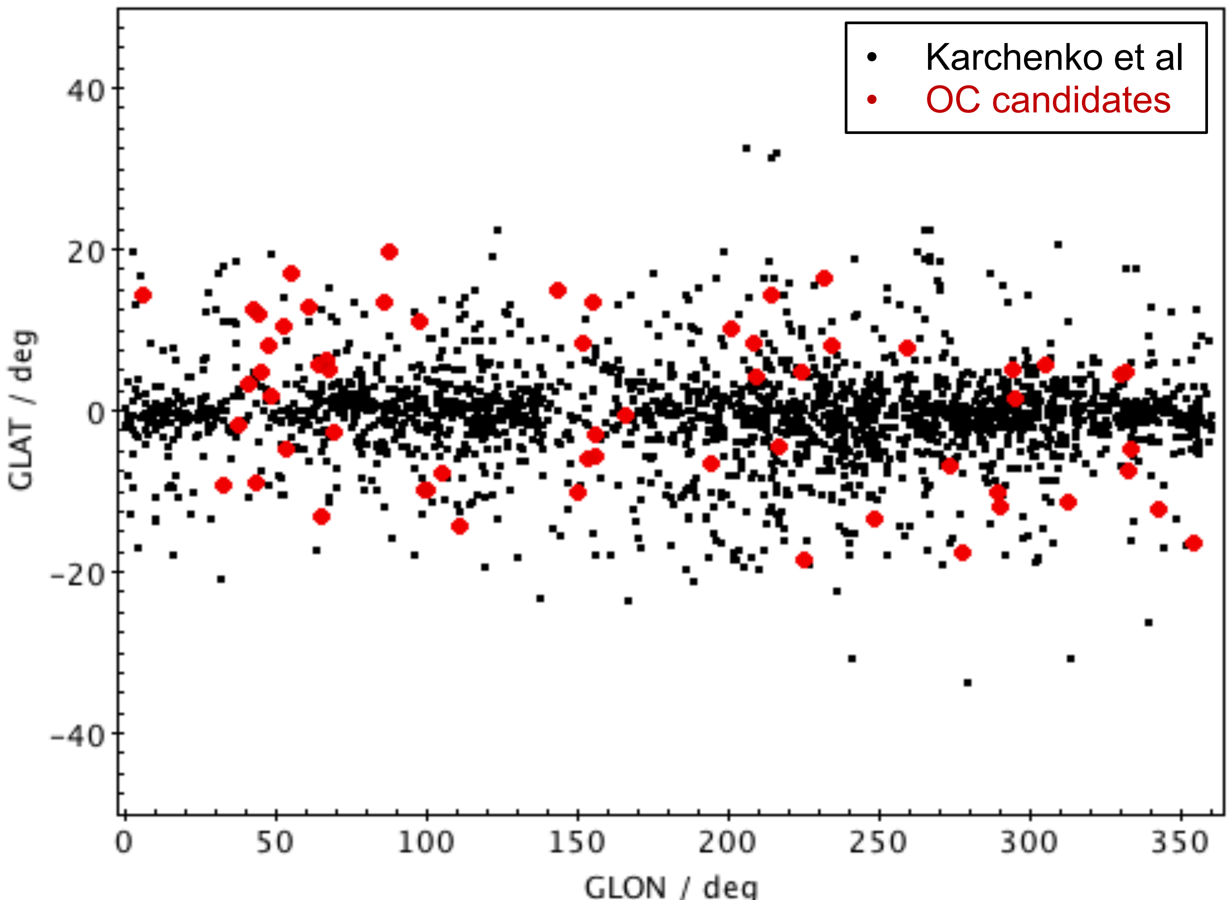
- Dias et al classify this group as an asterism
- Kharchenko et al classify this group as a cluster
- Cantat-Gaudin et al determines members for this group

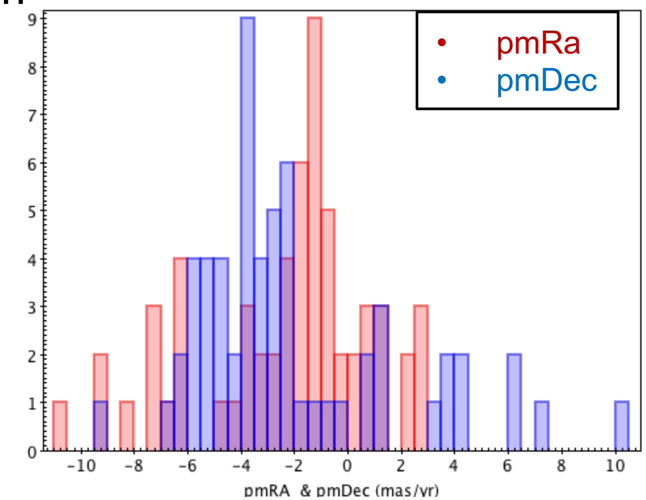
This group is most likely an open cluster

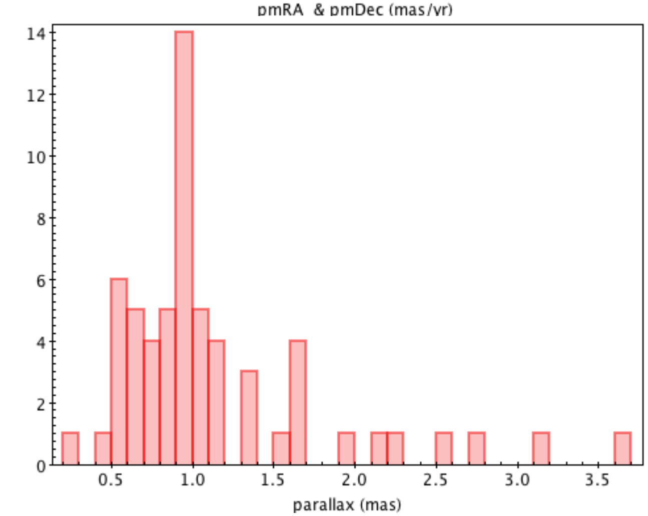
Detection of open clusters

$N_{cores} > 3$; no match with Dias et al, Kharchenko et al, Melnik et al (OB associ)

60 new density-based clusters, showing an identifiable gap in the reachability plot and probable isochrone in the colour-magnitude diagram





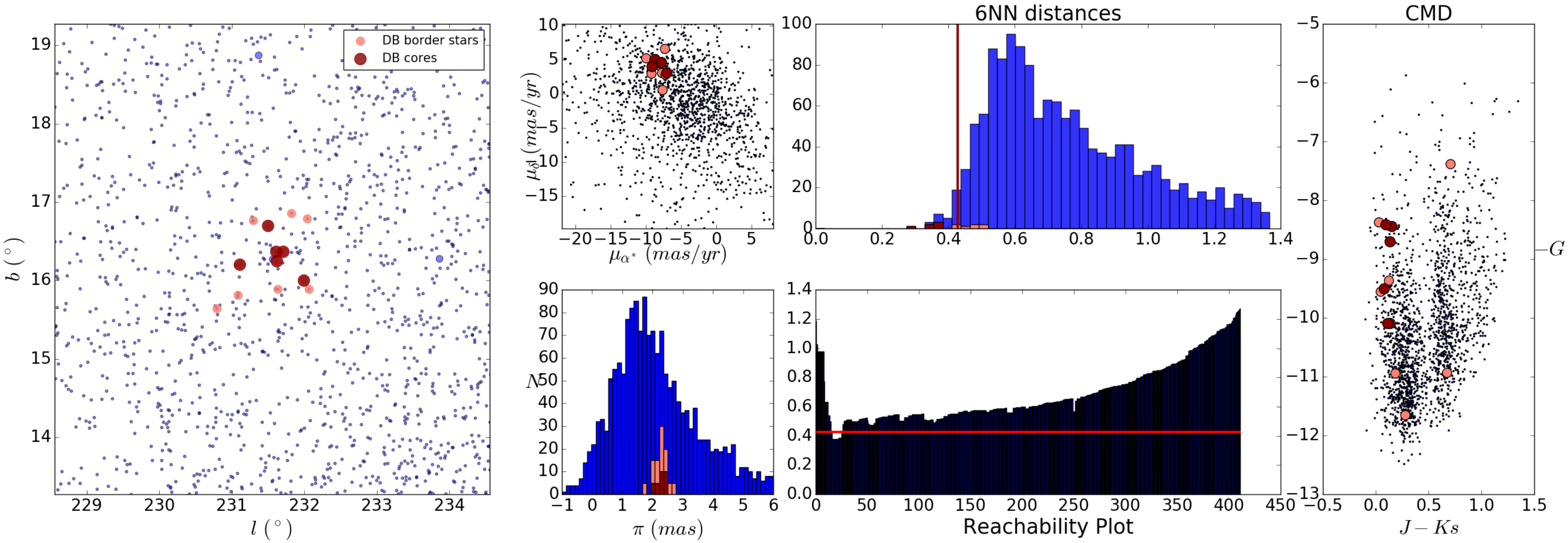


Detection of open clusters

Röser et al (2016): Nine new open clusters within 500 pc from proper motion analysis using a combination of Tycho-2 with URAT1

Our list of candidates matches two over the nine clusters: RSG3 and RSG4

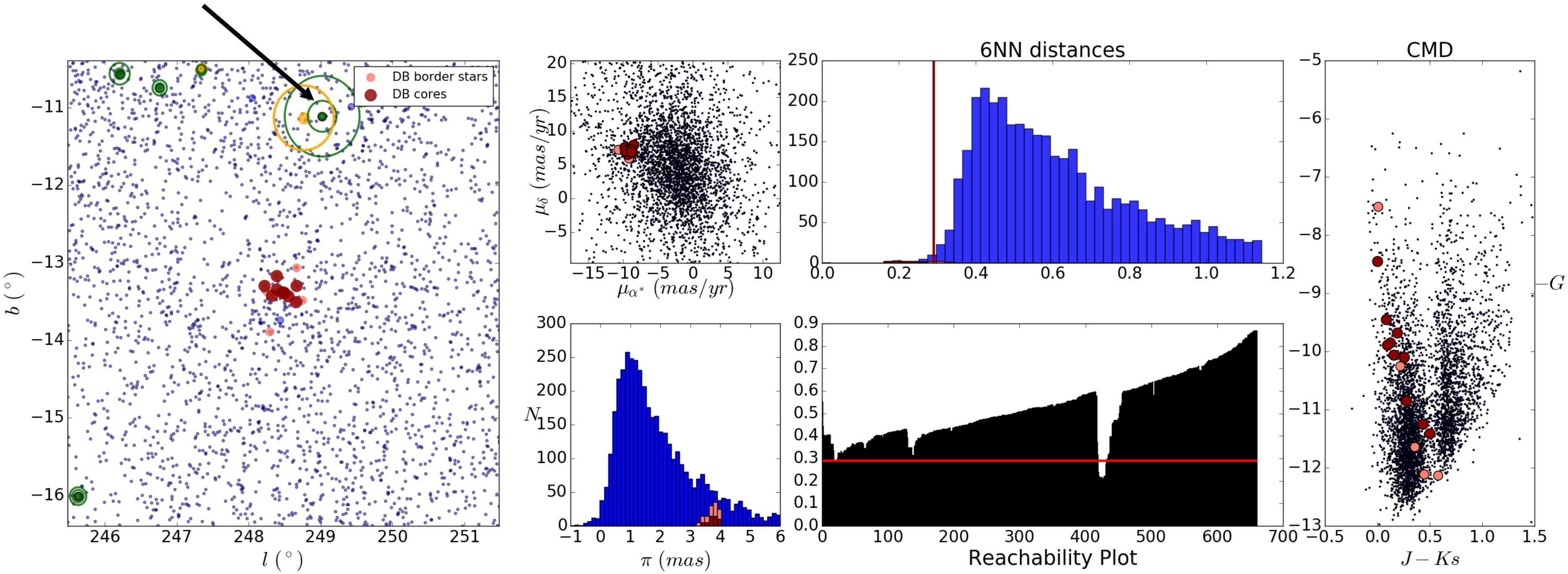
Candidate#5 *L*=7, *minPts*=7 (RSG3 in Röser et al)



Detection of open clusters

Candidate#1 ***L=7, minPts=7***

Collinder 135

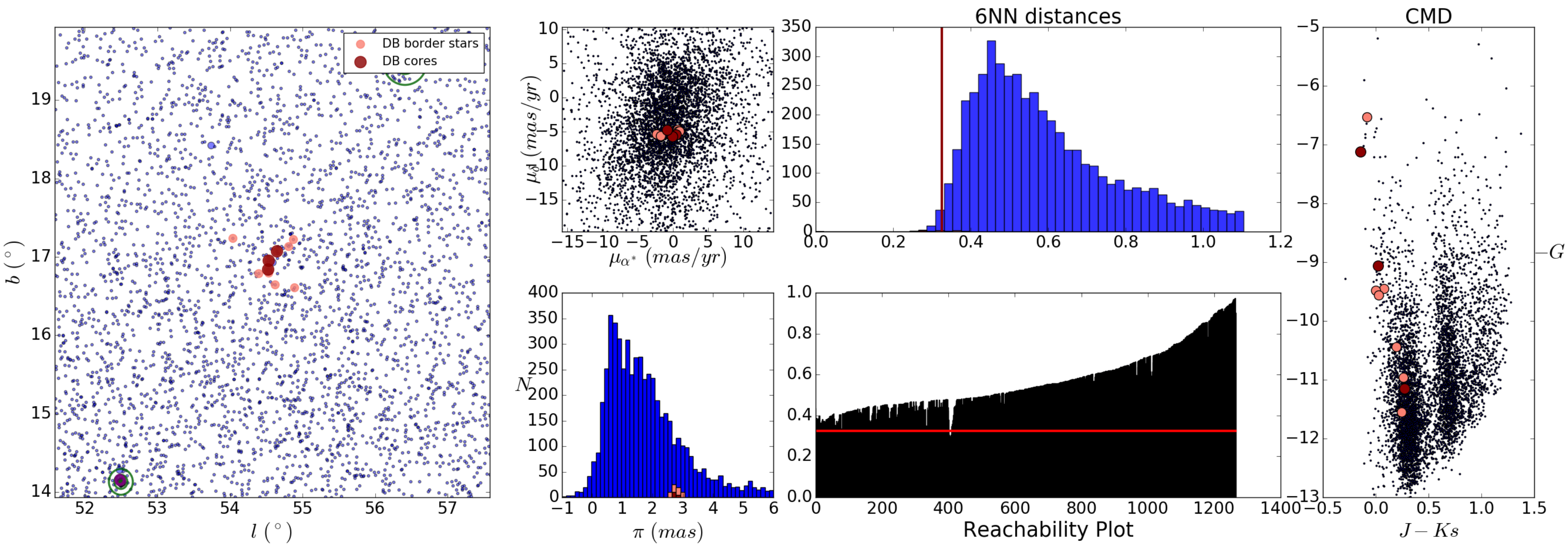


- It is a nearby cluster ϖ = 3.69 mas and relatively close in the parameter space to Col 135

- Is Col 135 much more extended than thought ?
- Is our candidate a substructure of Col 135 ?
- Is it an independent cluster ?

Detection of open clusters

Candidate#3 ***L=7, minPts=7***



Our candidates are in general poor populated clusters, at least to the GAS limiting magnitude

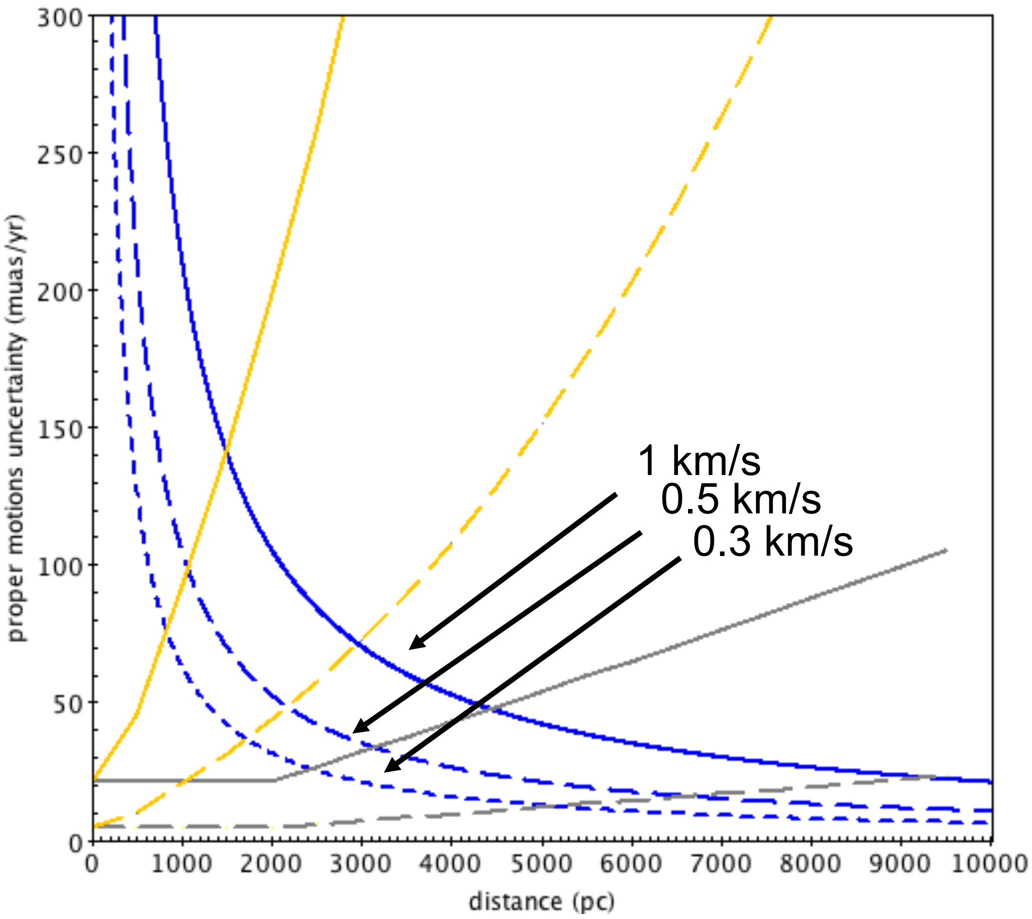
GDR2 will confirm or discard these candidates <u>and all currently catalogued clusters</u>
GDR2 will allow to find many more candidates

Internal kinematics

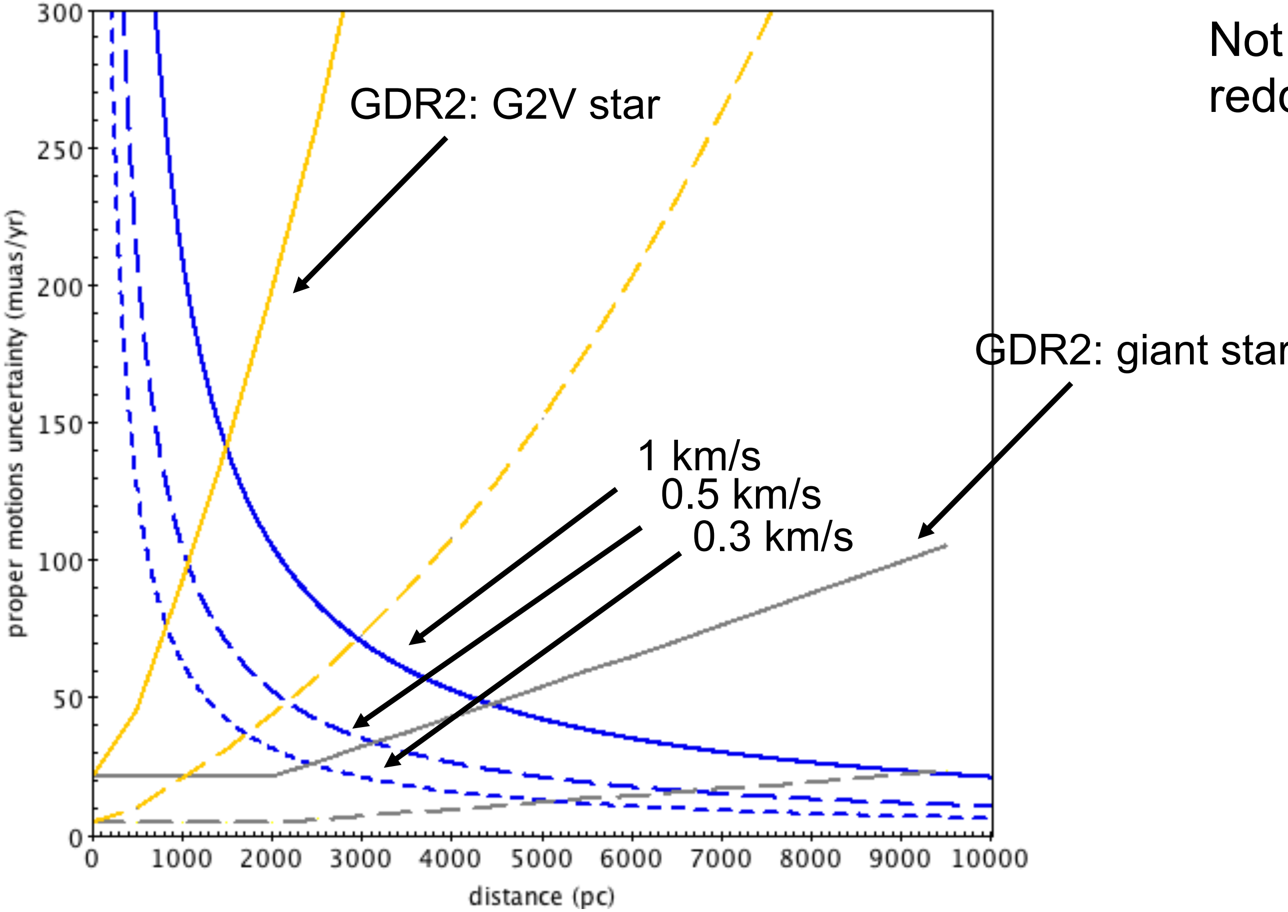
To study process of dissolution, evaporation, mass segregation and so on

At which distance, the precision of Gaia astrometry is smaller than the internal kinematic dispersion ?

Internal kinematics



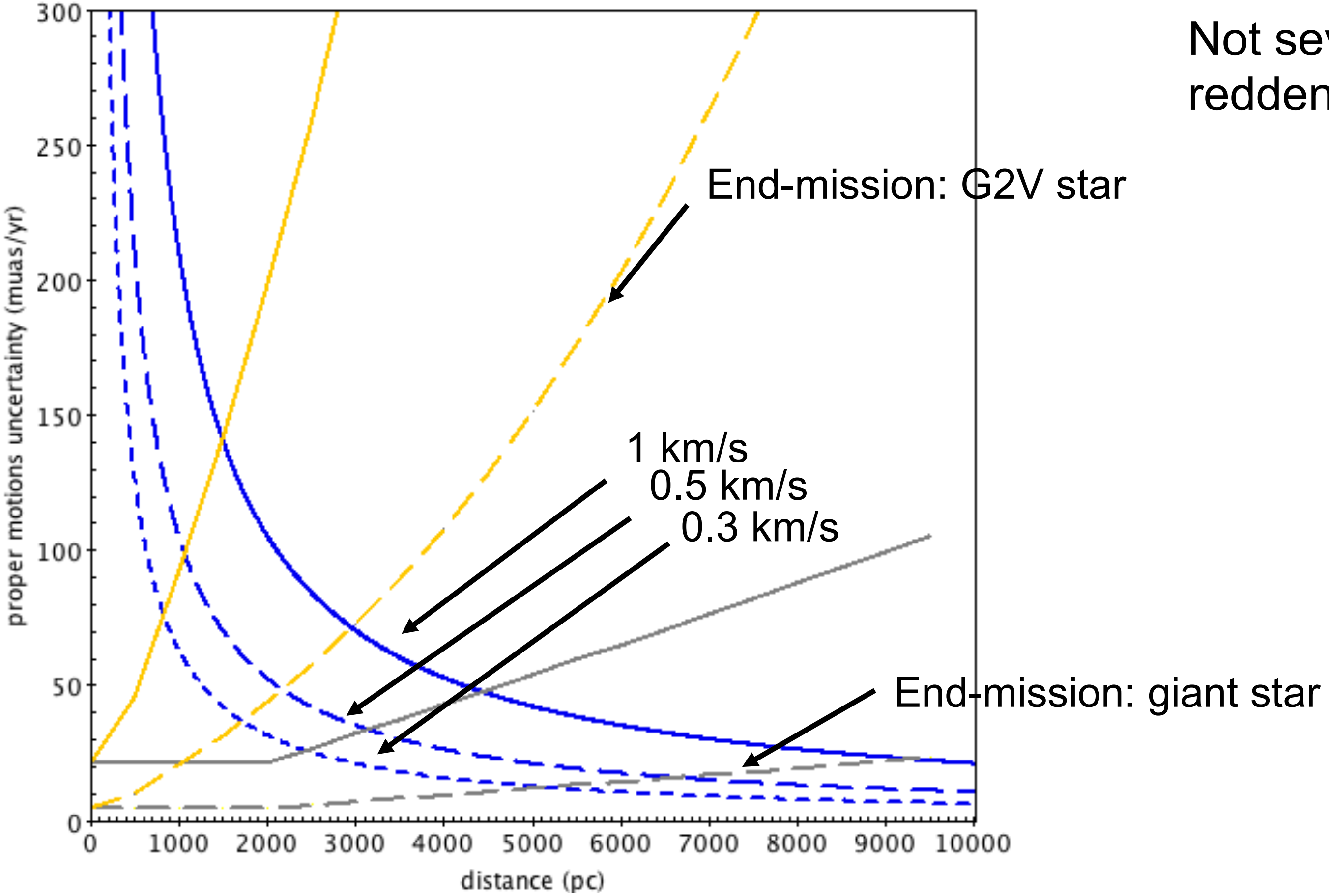
Internal kinematics



Not severe conditions of reddening

0.5 km/s: G2V type stars and brighter to 1 kpc (GDR2)
giants and brighter to 3.1 kpc (GDR2)

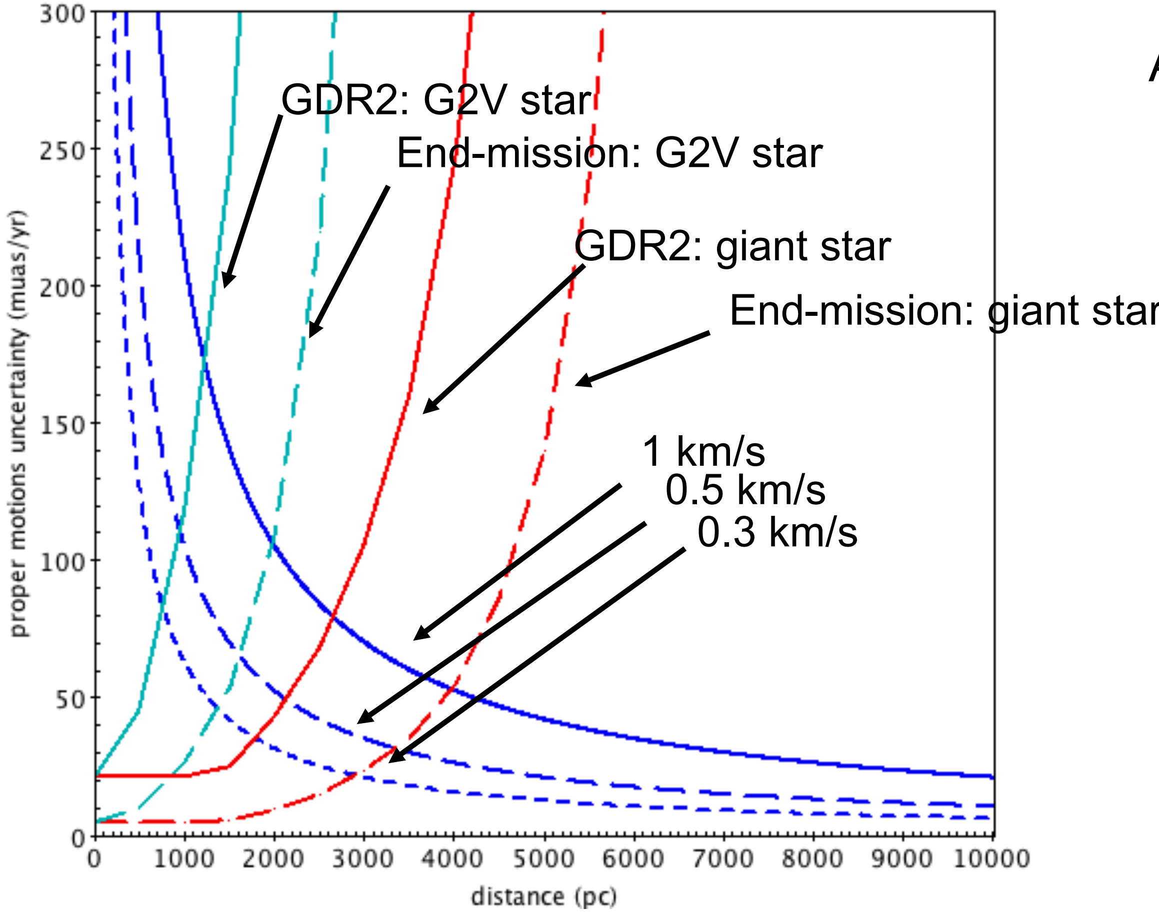
Internal kinematics



Not severe conditions of reddening

0.5 km/s: G2V type stars and brighter to 1 kpc (GDR2) and 2.1 kpc (end-of-mission)
giants and brighter to 3.1 kpc (GDR2) and 6.6 kpc (end-of-mission)

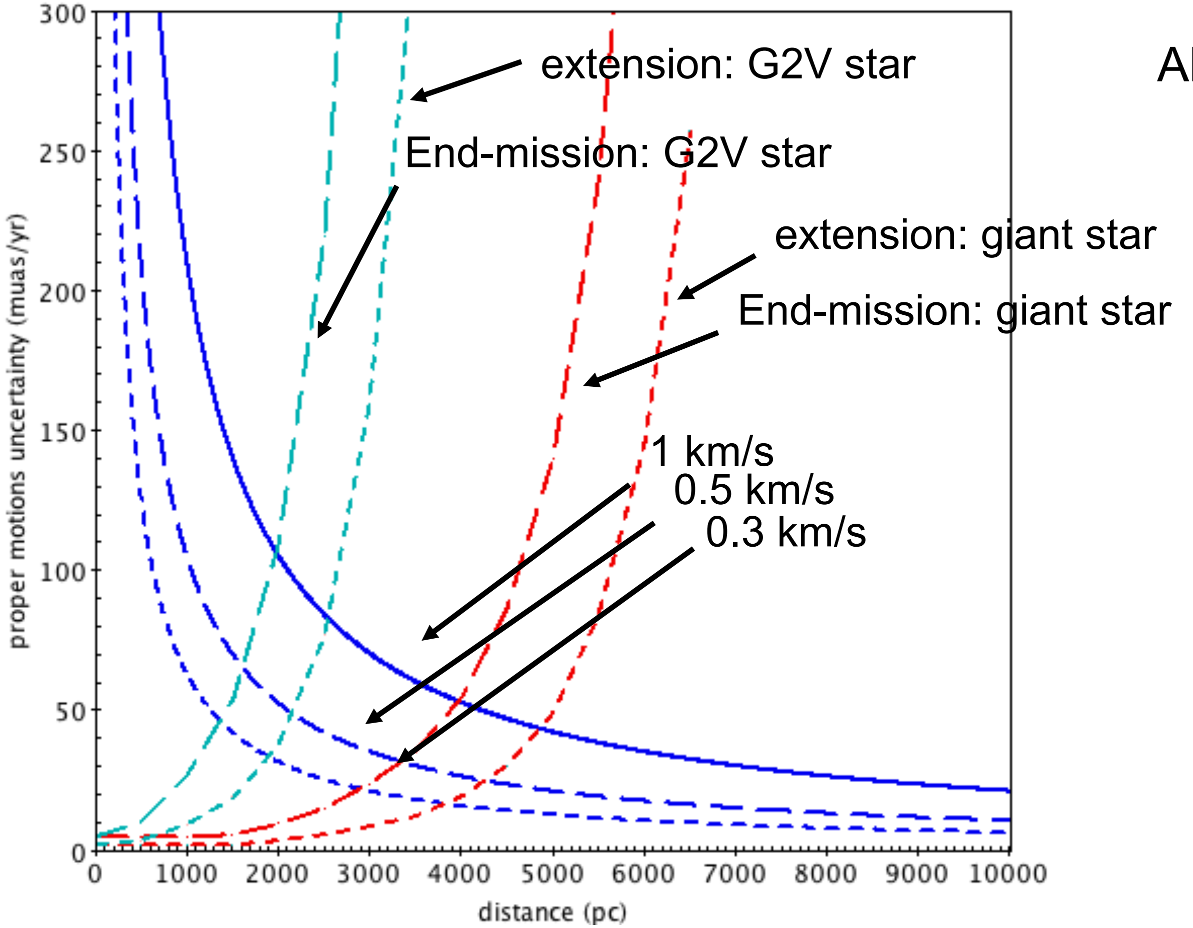
Internal kinematics



Absorption of 1 mag/kpc

0.5 km/s: G2V type stars and brighter to 1 kpc (GDR2) and 1.7 kpc (end-of-mission)
giants and brighter to 2.1 kpc (GDR2) and 3.3 kpc (end-of-mission)

Internal kinematics



Absorption of 1 mag/kpc

0.5 km/s: G2V type stars and brighter to 1.7 kpc (end-of-mission) to 2.1 kpc (extension)
giants and brighter to 3.3 kpc (end-of-mission) to 4.2 kpc (extension)

Conclusions

Gaia is unique on this because of its

1. Full-sky coverage
2. Faint limiting magnitude
3. Homogeneity
4. Accuracy and precision
5. Diversity of data: astrometry, photometry, spectroscopy, physical parameters of stars, multiplicity, variability, etc

and, in spite of the limited spectroscopic capabilities

On the use of the data

1. Account for correlations and observational biases
2. Look at the Gaia releases documentation and paper for the warnings
3. Be prepared for large asymmetries (no a priori assumptions)
4. Open clusters are really very extended

Thanks