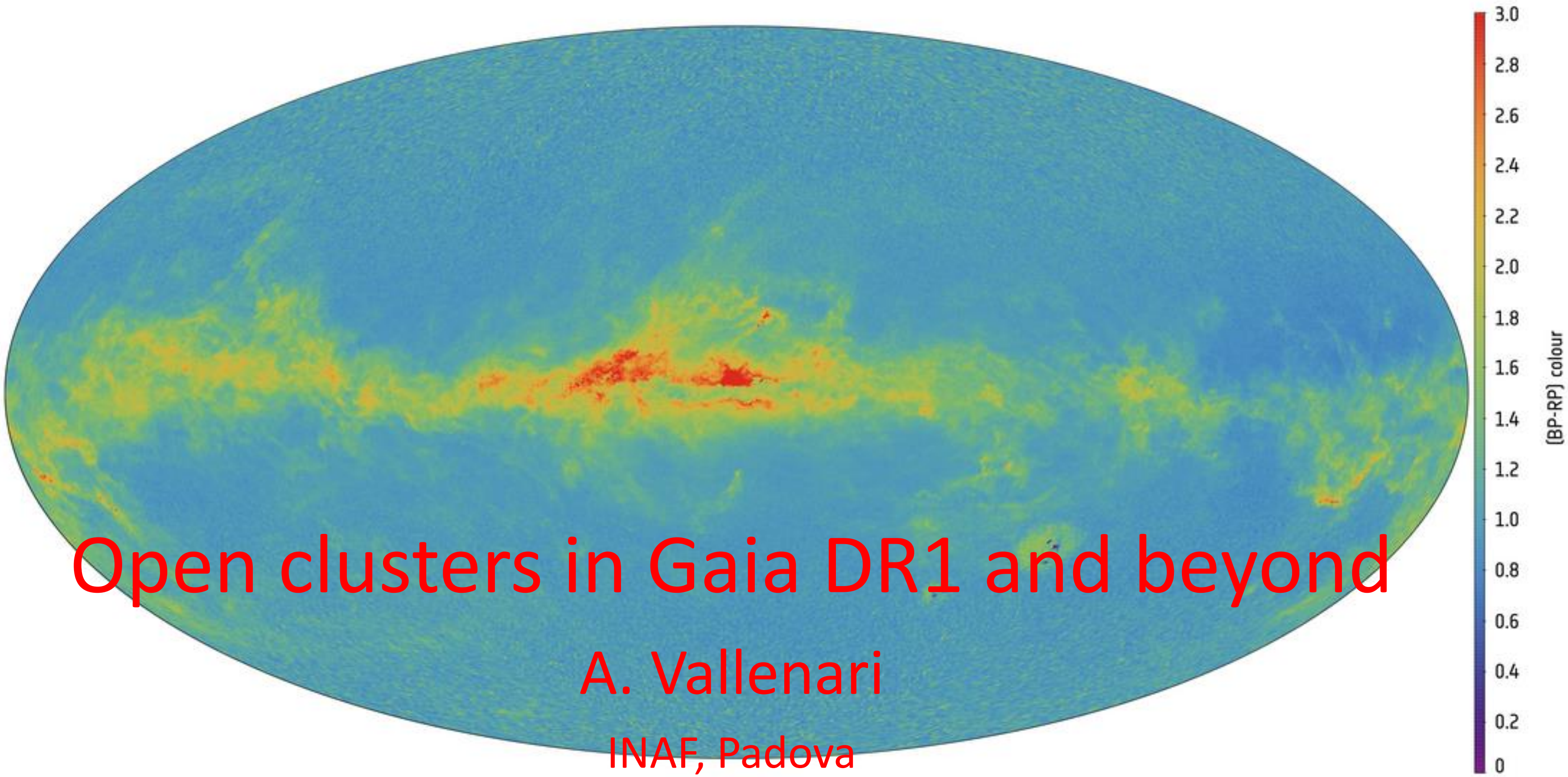


Open clusters in Gaia DR1 and beyond

A. Vallenari

INAF, Padova

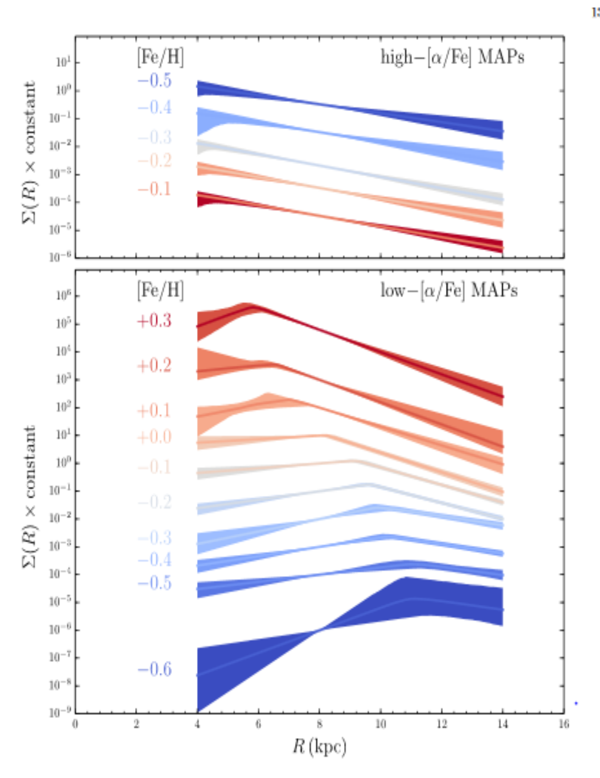
Credits: ESA/Gaia/DPAC/CU5/DPCI/CU8/F. De Angeli, D.W. Evans, M. Riello, M. Fouesneau, R. Andrae, C.A.L. Bailer-Jones

Content and overview

- OCs in the Galaxy: pre-Gaia state
- DR1 view of OCs
- Looking forward DR2: a few science cases

The new Disk(s) view

- Disk related specific questions:
  - respective roles of hierarchical formation and secular evolution in shaping the Galaxy?
  - what are the roles of spirals (+ number of arms, pitch angle, pattern speed?) and the bar (length, pattern speed?) (Helmi+2006, Schoenrich & Binney 2009, Minchev+2015)
- Radial migration in the disks → populations using chemical abundances as tag: → Mono-abundance vs mono-age populations (Bovy+2016, Minchev 2017)
- Large amount of data requires ad-hoc modeling → J. Binney talk
- Data driven models (Anderson + 2017, Leistedt+2017)



Bovy et al 2016

OCs in the Milky Way

- Their birth, internal kinematics/ dynamical evolution, evaporation, disruption, self-pollution (if any) trace the Galactic environment

  → Tidal field (Berentzen & Athanassoula 2011, Kupper et al 2010)

  → interaction with giant molecular clouds & spiral arms

  (Gieles et al 2006, Kujissen+2011) + stellar evolution effects (infant mortality)
- Depletion of OCs in SV older than 1Gyr: dissolution time
- Mass(radius)-age relation: clarify the disruption process (de Grijs & Anders 2006; Chandar et al. 2010, Baumgardt & Makino 2003)

- The older ones, trace the kinematics/structure of the (outer) disk
- Tracing the spiral structure (Carraro+2017, Moitinho + 2010, Dias&Lepine2005, Molina-Lera+2017 on Sag-Car Arm)
- Clusters age , metallicity, positions, orbits should be compared with field star properties, to trace the disk chemical gradient → disk formation and evolution process (Minchev+2015, Jacobson+2016, Bragaglia+ 2006, Cantat+2016)
- Tracing radial migration and disk kinematics
- They can be used to derive the local mass density using the frequency of their oscillation above the GP: small amount of DM in the SV (Joshi+2016, McGaugh 2016)

Open questions

- Can we put further constraints on stellar physics to safely use stars as fossils for the Galactic formation and evolution?
- How do stars and clusters form and dynamically evolve to populate the MW field?
- What is the shape of abundance gradients and their time evolution in the MW ?
- How OCs trace the kinematics and dynamics of the disks?
- Diagnostic
  - Kinematics: membership, distances, orbit reconstruction
  - chemical information, completeness

  → Ages and time evolution of the system

  → disk properties

gaia

INAF ISTITUTO NAZIONALE DI ASTROFISICA NATIONAL INSTITUTE FOR ASTROPHYSICS

Pre-Gaia: OCs census

- Important to estimate star formation, cluster disruption, disk properties
- Known Ocs are about 3000 (Kharchenko+2013)
- A large number of apparent overdensities are detected using IR or other photometric surveys (2MASS Skrutskie et al. 2006; Froebrich et al. 2017; Dambis 2017 with IPHAS-APASS, Liu+2017 Pan-STARRS: 400 candidates)
- Assuming uniform OC distribution, the current sample might be complete inside 1.5-1.8 Kpc (Buckner & Froebrich 2014)
- Estimates of the number of OCs are of the order of 100,000 (Bonatto+2006, Bica & Bonatto 2011, Lada & Lada 2003, Chen et al. 2004,Piskunov et al. 2006, R¨oser et al. 2010).

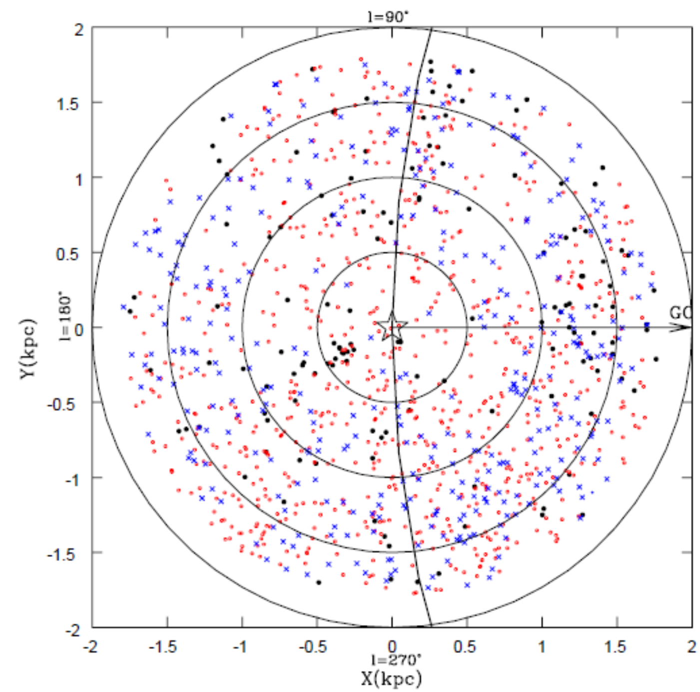
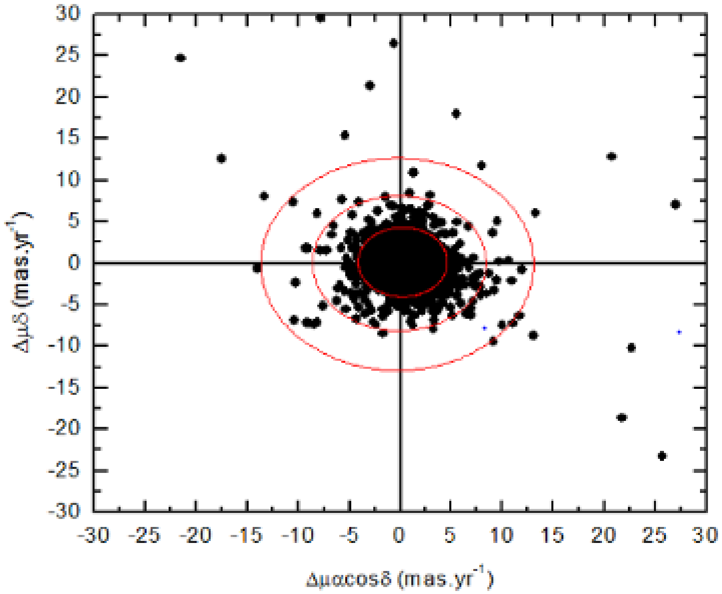


Fig. 1. Cluster distribution in the X-Y plane as projected on the GP. The filled circles, open circles, and crosses represent YOCs, IOCs, and OOCs, respectively. The asterisk at the center shows the position of the Sun, and concentric circles are drawn at an equal distance of 500 pc. The large dark circle represents the solar circle with a radius of 8 kpc, and the arrow indicates the direction to the Galactic center.

Only 1.5% of old OCs are inside 500pc from the Sun (Joshi+2016)

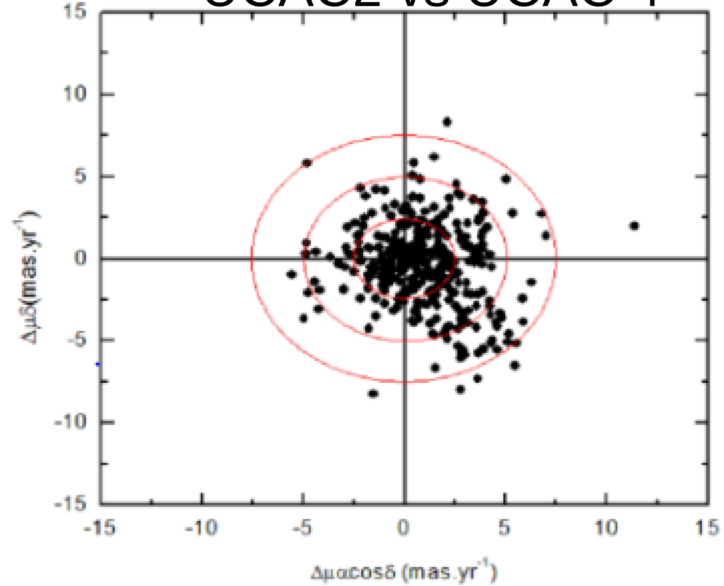
Pre-Gaia OCs: PMs

Dias 2002 vs Dias 2014



σμαcos(δ)=4.3 mas/y

Dias 2006 vs Dias 2014
UCAC2 vs UCAC 4



σμαcos(δ)=2.3 mas/y

Nominal (average) uncertainty = 0.4 mas

Pre-Gaia Ocs: parameters

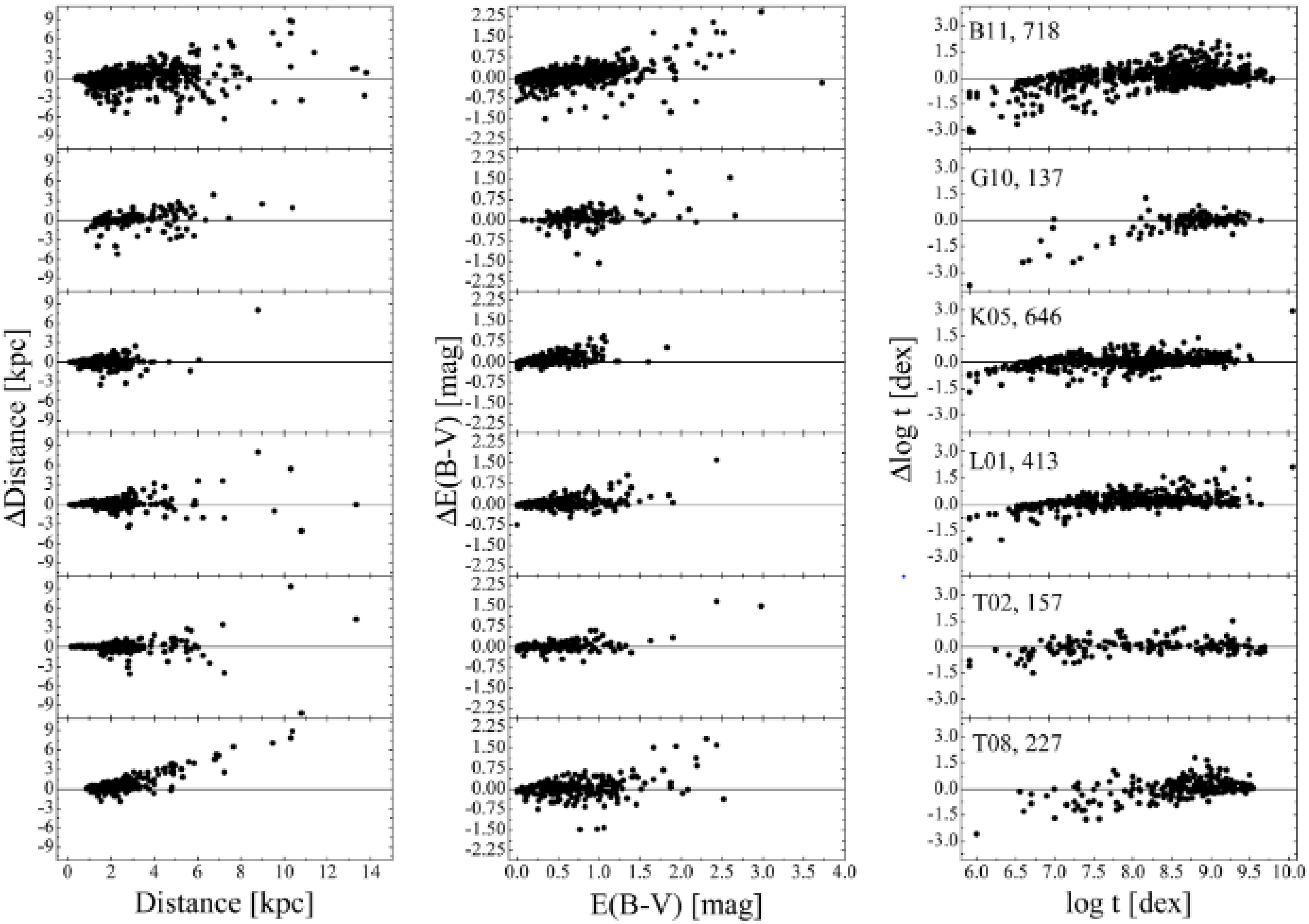
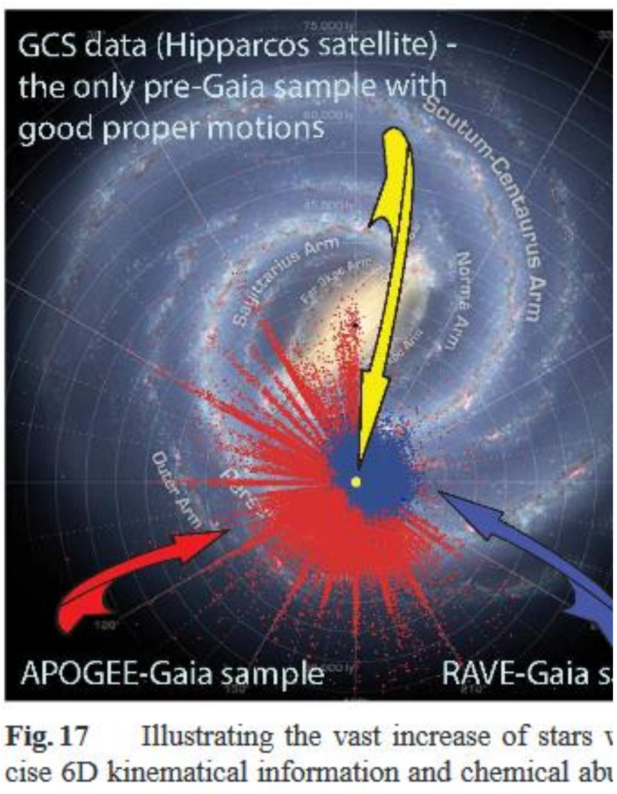
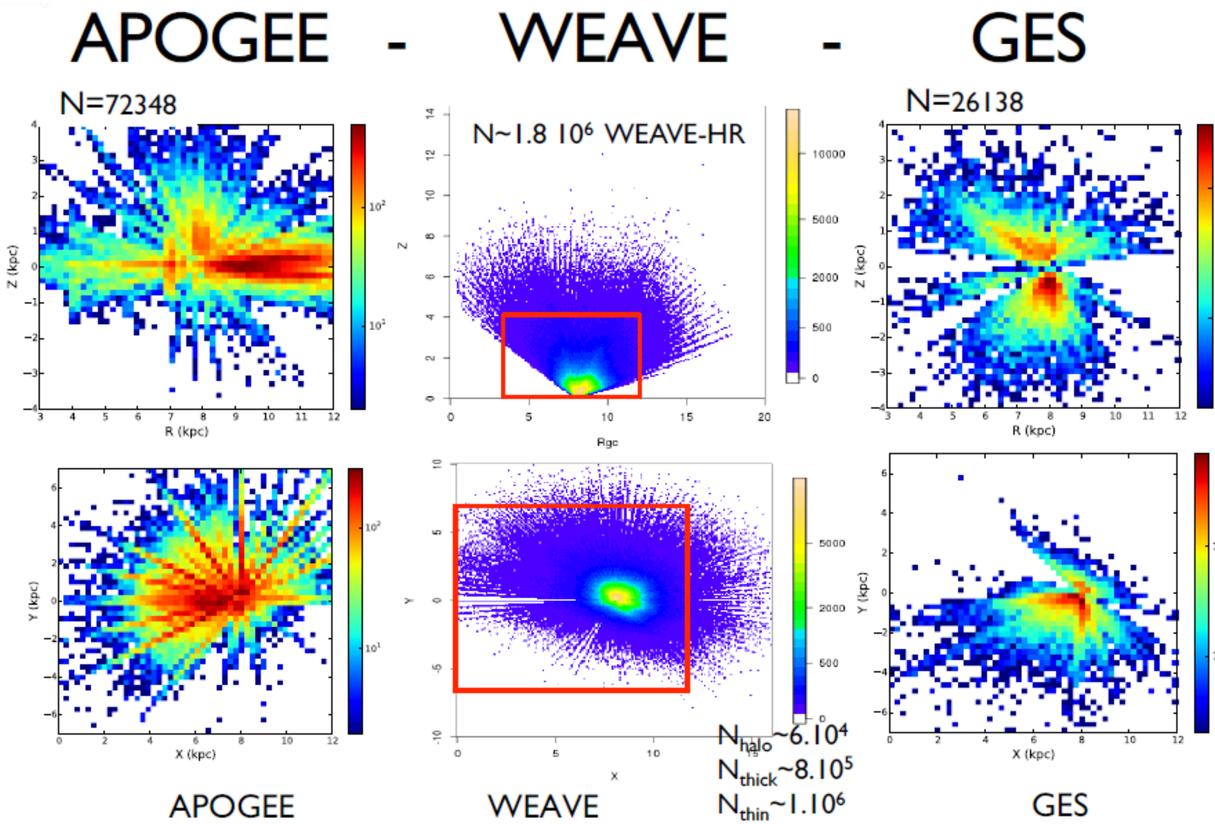


Fig. 2. Comparison of the star cluster parameters for objects in common with K13. The differences are calculated in the sense "K13 – reference". In the right-most column, the designation of the individual references (see text) and the number of clusters in common are listed.

Netopil + 2015

Not only Gaia data



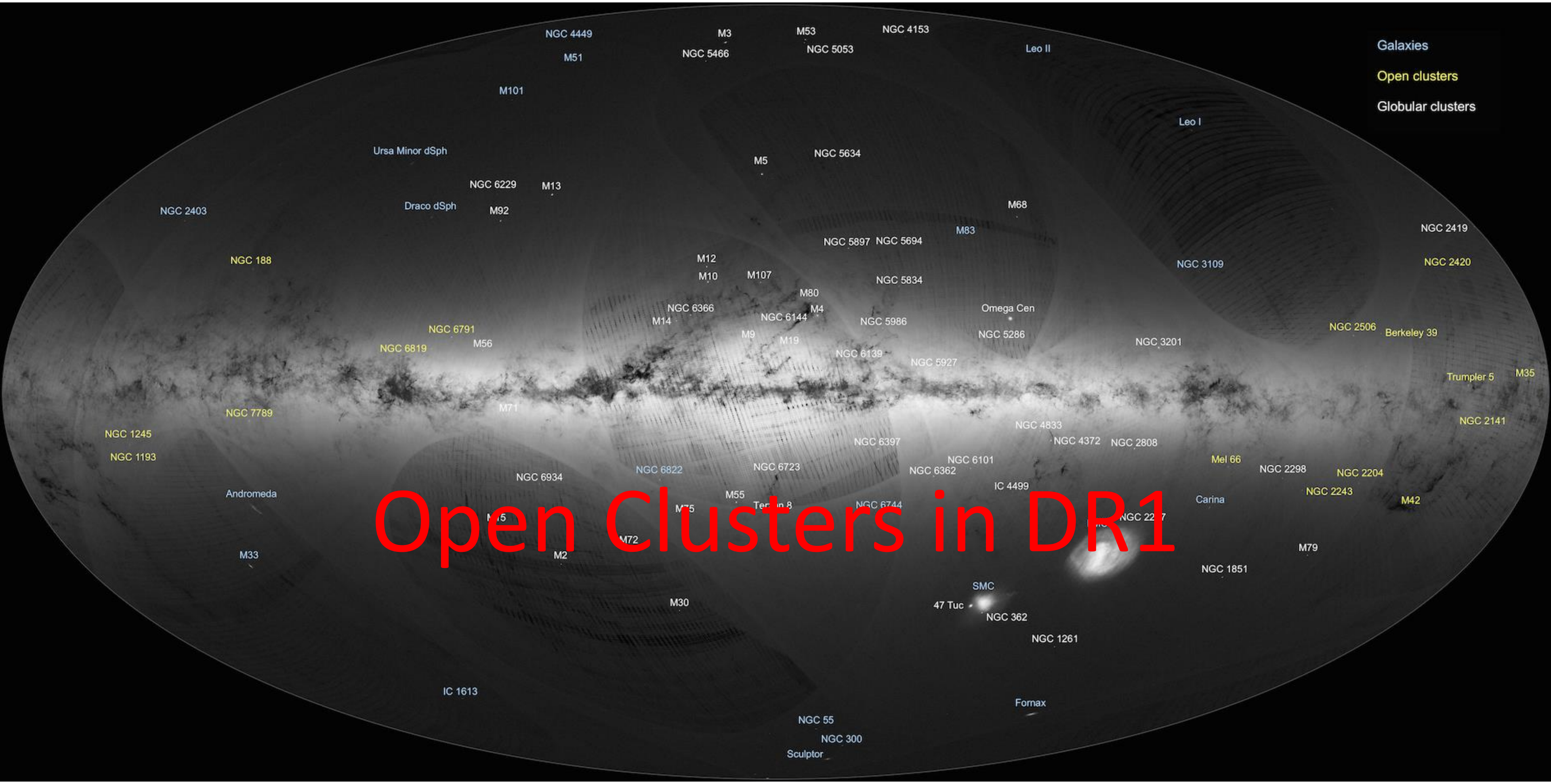


Minchev 2017

V. Hill courtesy, WEAVE science book

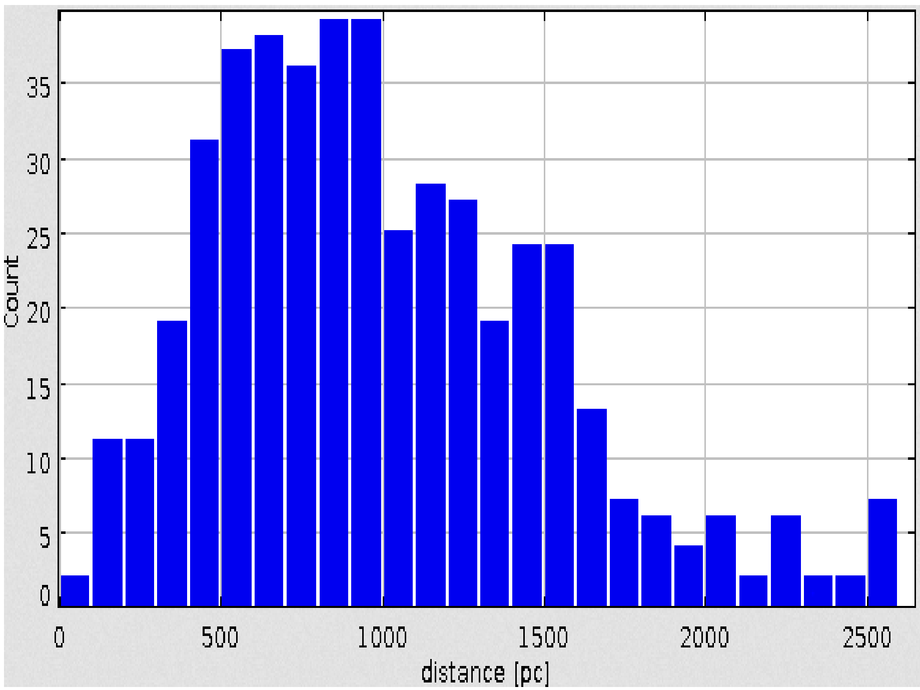
+ MOONS, 4MOST, Lamost..→ Sofia Feltzing talk.

Open Clusters in DR1



OCs in TGAS

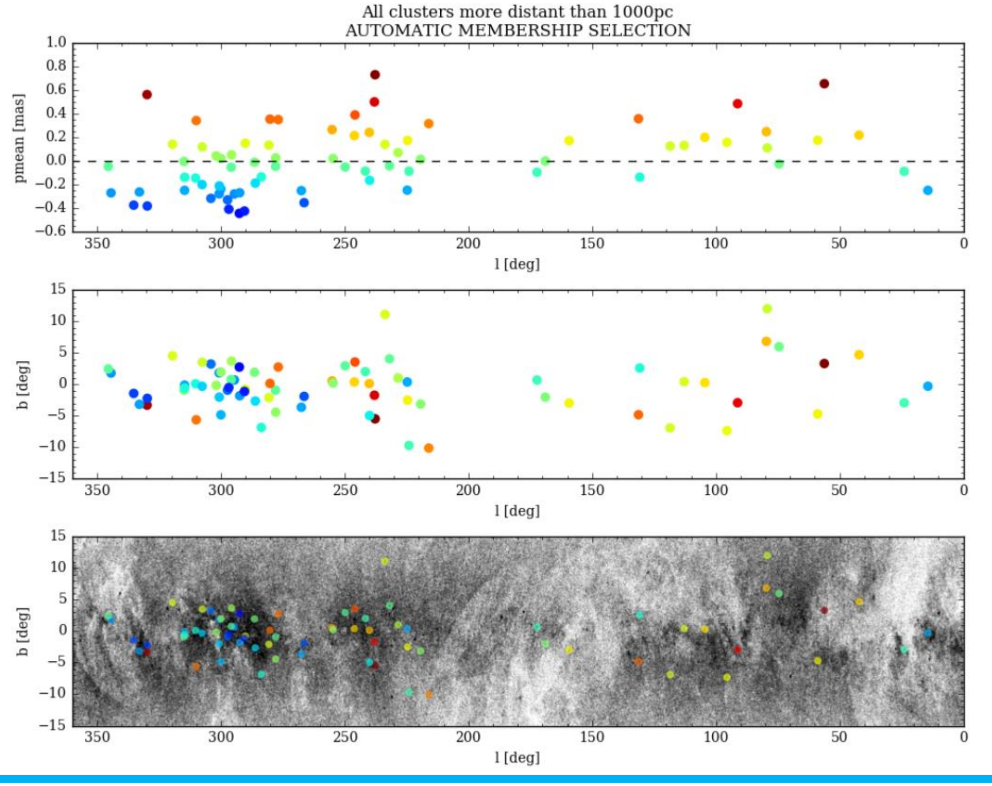
- More than 400 OC candidates in TGAS (Kharchencko+2013)



46 pc : Δπ/π=1% Hyades
46 pc Internal dispersion resolution

300 pc: Δπ/π=10%
(Gaia Collab., van Leewen+2017)

Astrometry systematics in the GP

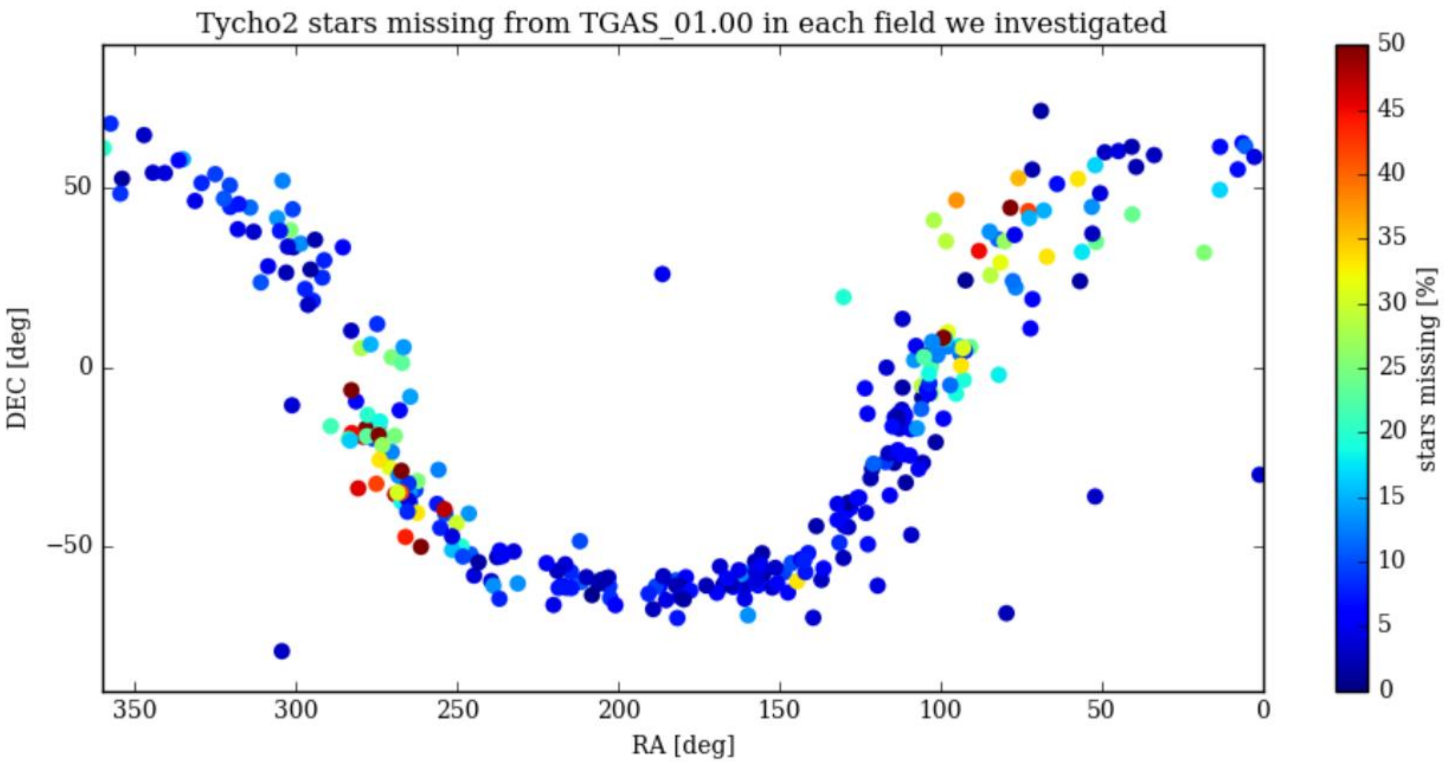


- Due to known limitations in the astrometric processing
  - a global offset below 0.1 mas
  - there are colour dependent, spatially correlated errors of ±0.2 mas
  - over large spatial scales, parallax zero point errors reach ±0.3 mas

(Arenou+2017)

Completeness:OCs

Missing stars: about 8% of Tycho-2 stars are missing (locally 50% in some fields)(Arenou et al 2017).



Parameter correlations

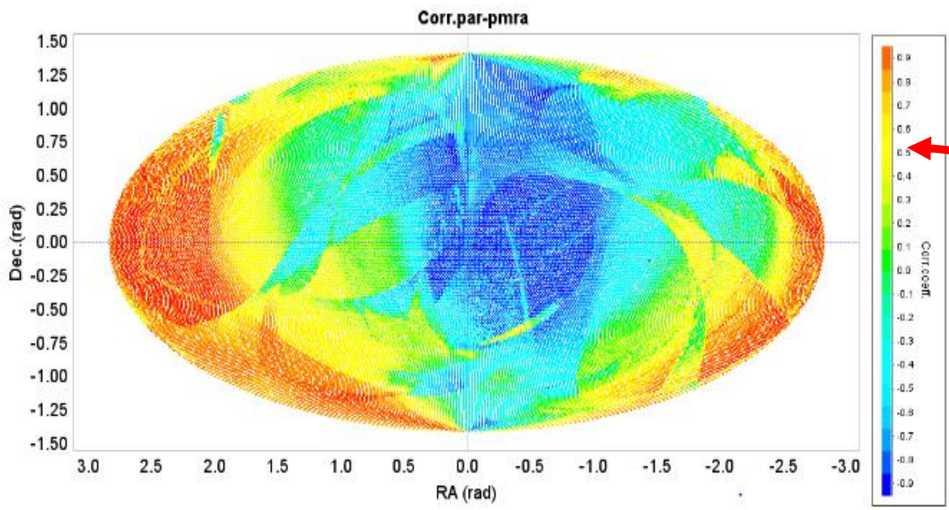
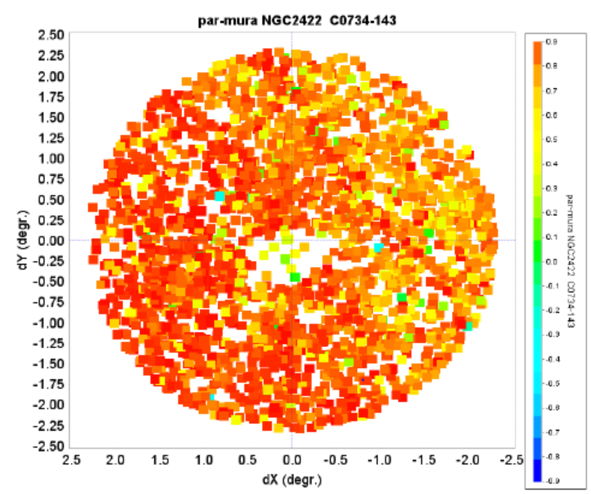


Fig. 4. Correlation coefficients between the proper motion in Right Ascension and the parallax, averaged over HEALPix level 5 pixels.

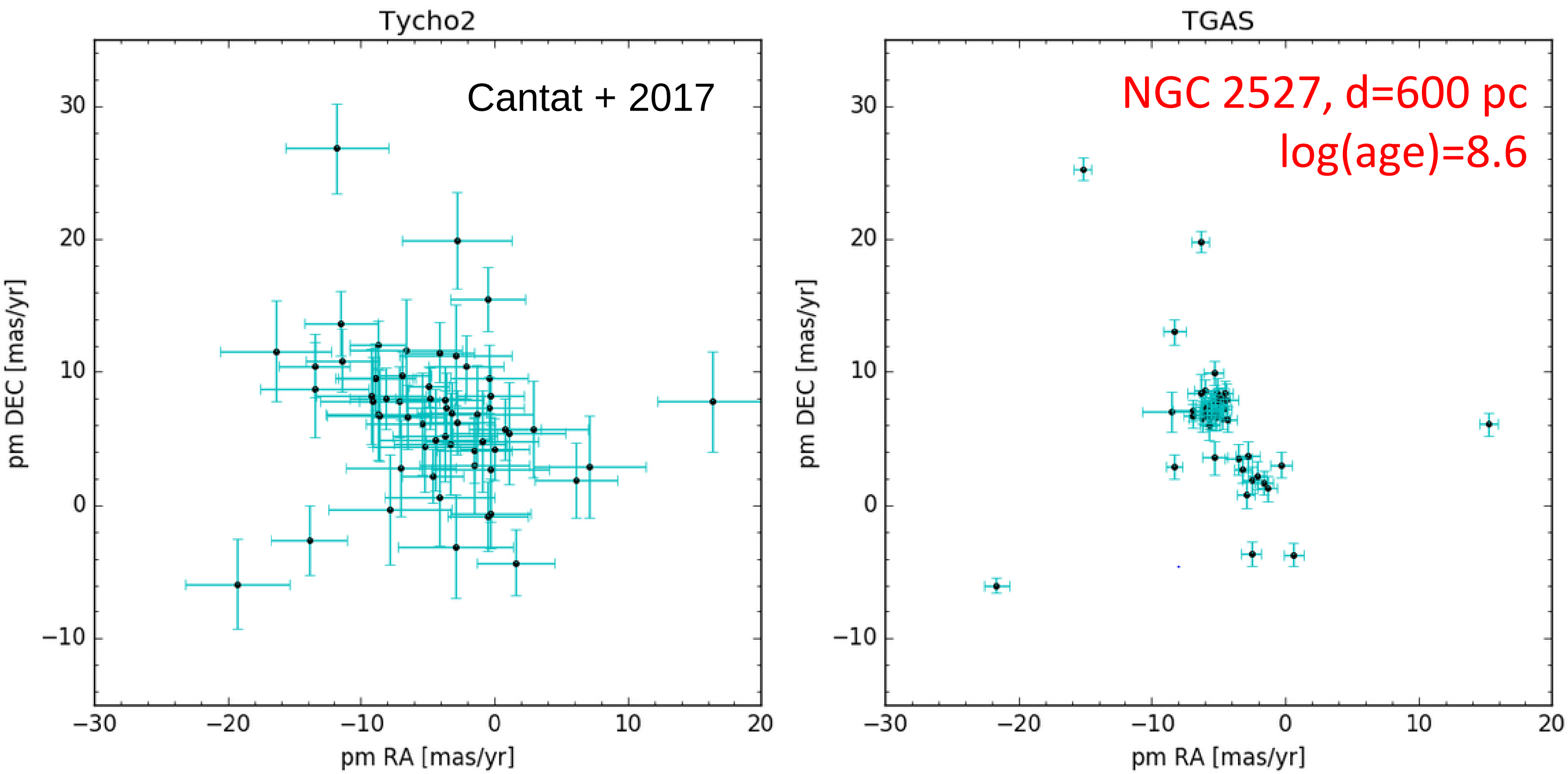
$$N_a = \begin{bmatrix} \sigma_1^2 & c_{12}\sigma_1\sigma_2 & c_{13}\sigma_1\sigma_3 \\ c_{12}\sigma_1\sigma_2 & \sigma_2^2 & c_{23}\sigma_2\sigma_3 \\ c_{13}\sigma_1\sigma_3 & c_{23}\sigma_2\sigma_3 & \sigma_3^2 \end{bmatrix}$$

Gaia Collab.Van Leeuwen + 2017



- **Averaging parallaxes e.g. in a cluster does not reduce the systematics!**

TGAS quality



M67: Catalog of PPMXL+Gaia DR1 position (580,000,000 objects ,
pm accuracy < 1 mas/yr. to 5 mas/y) (Altman, Roeser, Bastian+ 2017)

OCs vs asterisms

- Gaia will detect many new OCs and assess the reality of others
- Asterisms vs real
- Piatti+2017: using DR1 data: out of 15 candidate OCs, only 5 turn out to be real

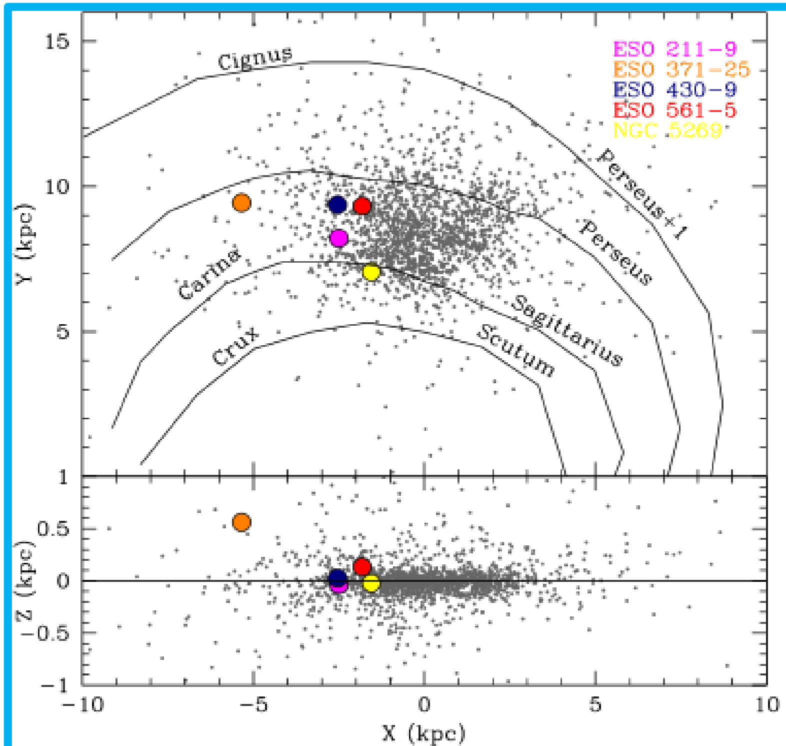
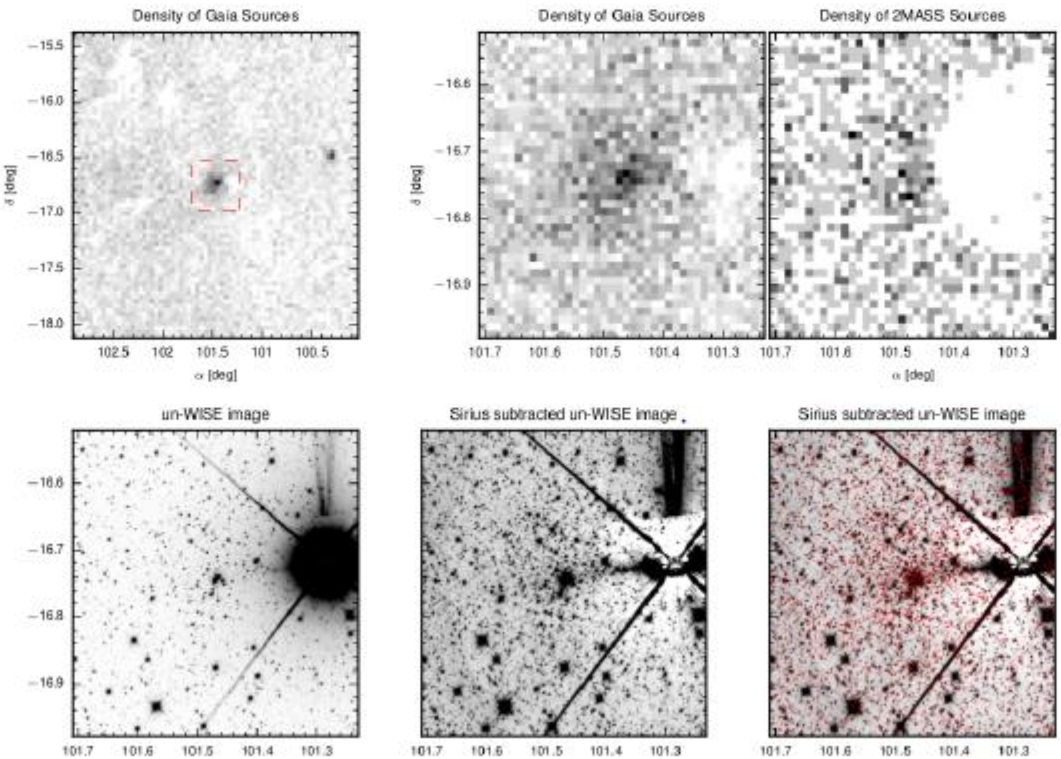
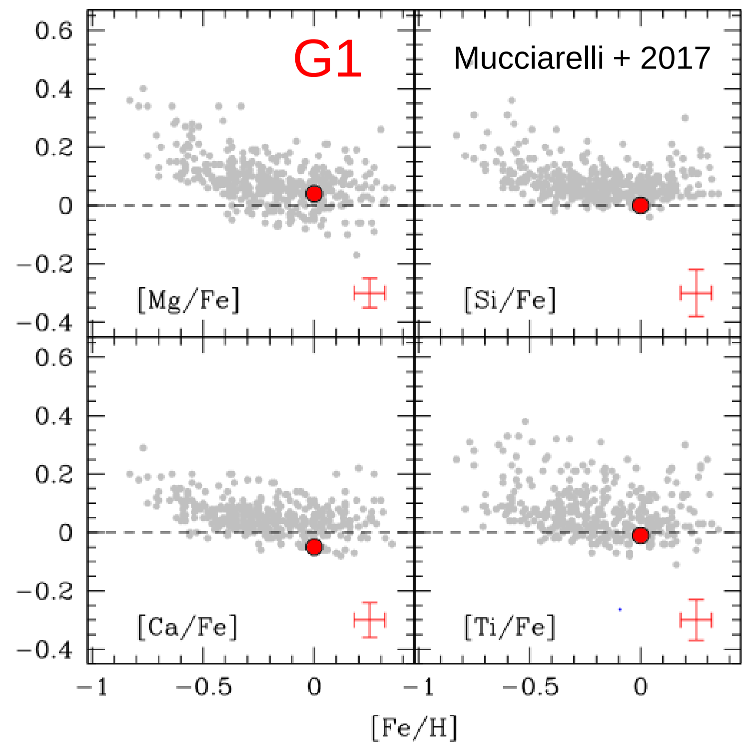


Figure 17. Galactic spatial distribution of the studied clusters. Open clusters from the catalogue of Dias et al. (2002, version 3.4 as of January 2016) are drawn with gray dots, while the schematic positions of spiral arms (Drimmel & Spergel 2001; Moitinho et al. 2006) are traced with black solid lines.

Piatti+2017

Gaia 1 and Gaia 2





Koposov+ 2017

- All sky high-resolution map
- Two OCs discovered
- Cluster hiding behind Sirius-G1

- 3Gyr old cluster(HERMES) (Simpson+2017)
- [Fe/H]=-0.13 ±0.13 (Mucciarelli+2017)

DR1 Ocs Parameter revision

- Parallax-age revision for 150 OCs in the inner 2 Kpc(Gaia collab, van Leeuwen+, 2017, Cantat+2017)
- Gaia+GES for 8 clusters(Randich + 2017)

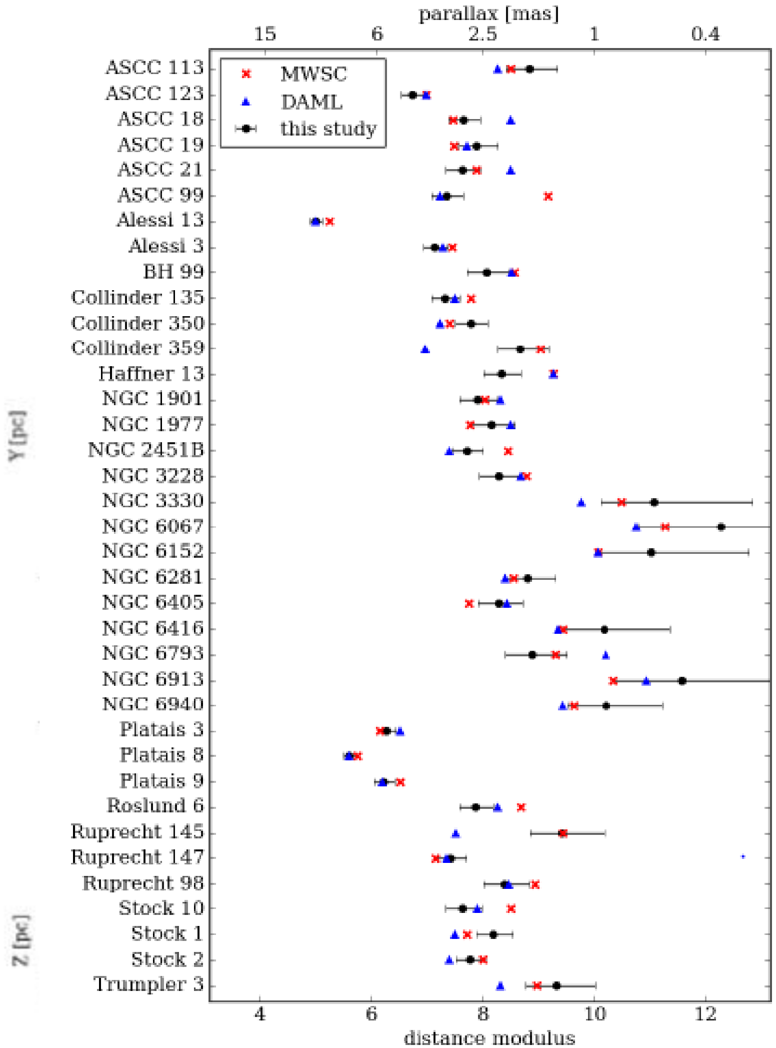
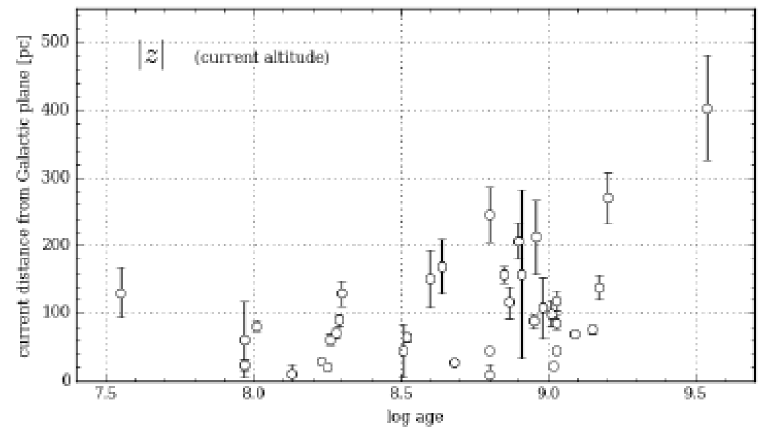


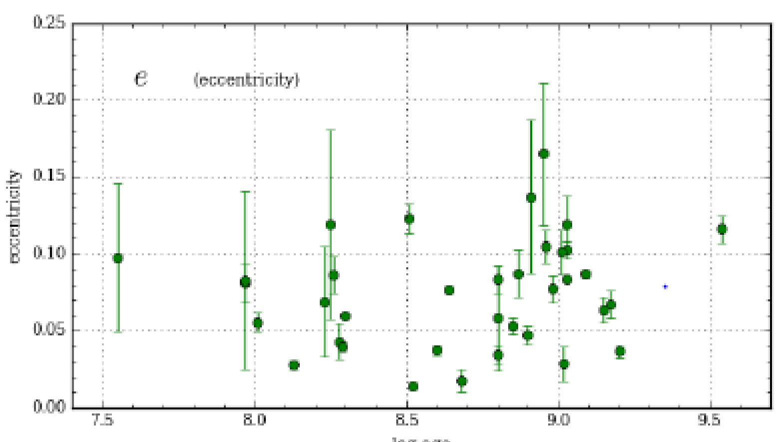
Fig. 7. Distance modulus for the OCs for which TGAS parallaxes yield values discrepant with the values listed in either MWSC or

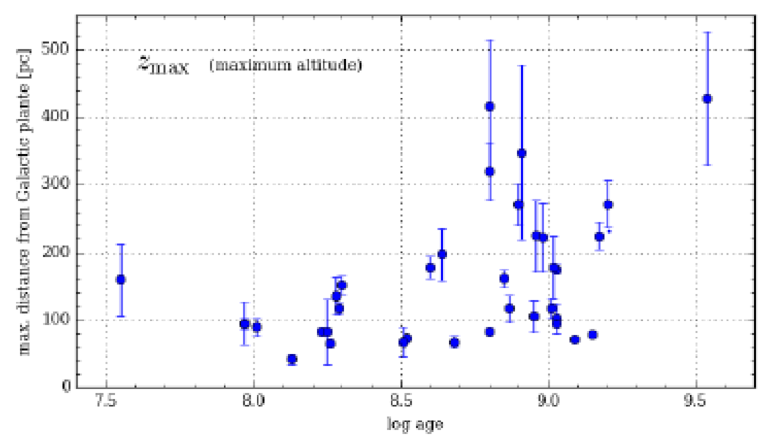
DR1 OCs orbit reconstruction

- Bovy+ 2015 static potential to reconstruct orbits+ Vrad (Mermilliod 2008, 2009) (36 Ocs)
- OCs with ages < 300 Myr →z(max)=100 pc
- OCs with ages > 300 Myr →z(max)=190 pc
- Absence of an apparent correlation age - eccentricity
- OCs ages>1Gyr→higher e (VandePutte +2010)
- the timescale for radial heating is longer than that of vertical heating.

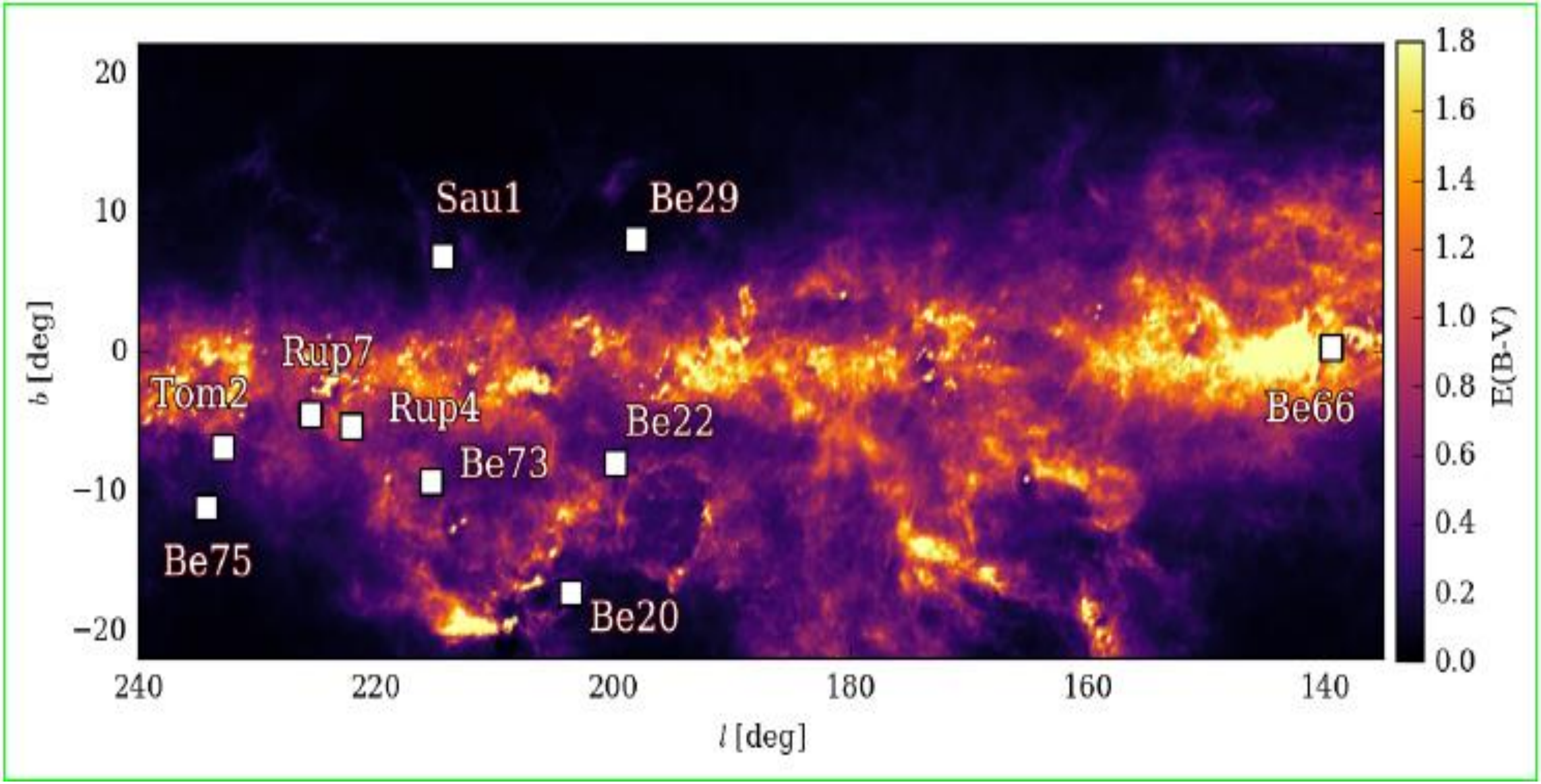
Cantat 2017



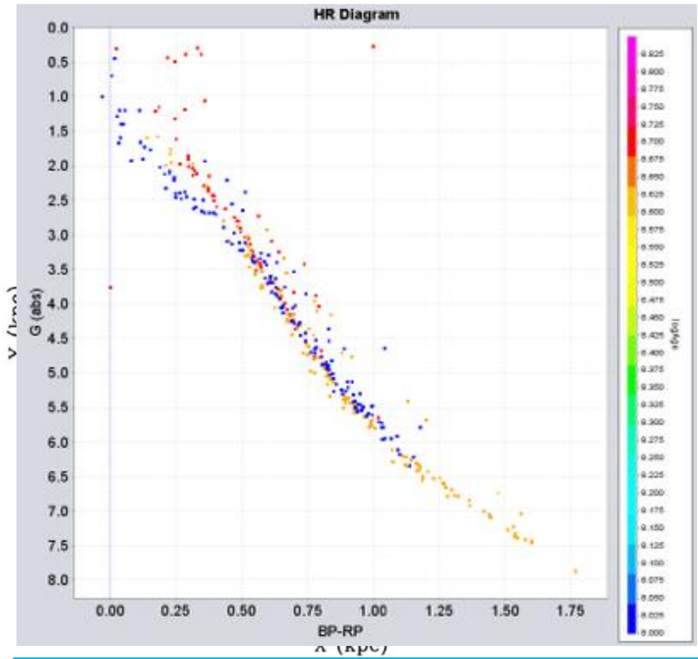




OCs in DR2 and beyond



DR2 view of OCs



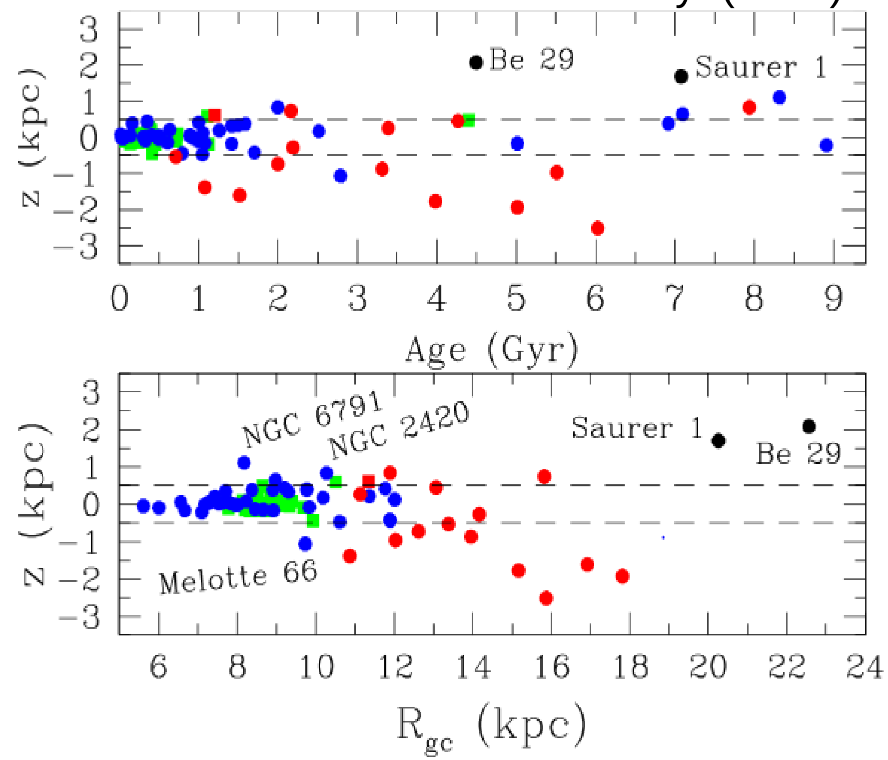
- DR2 performances
- Systematic errors <100 μas
- Typical parallax precision:
- G = 15, 30 μas;
- G = 18, 150 μas;
- G = 20, 700 μas

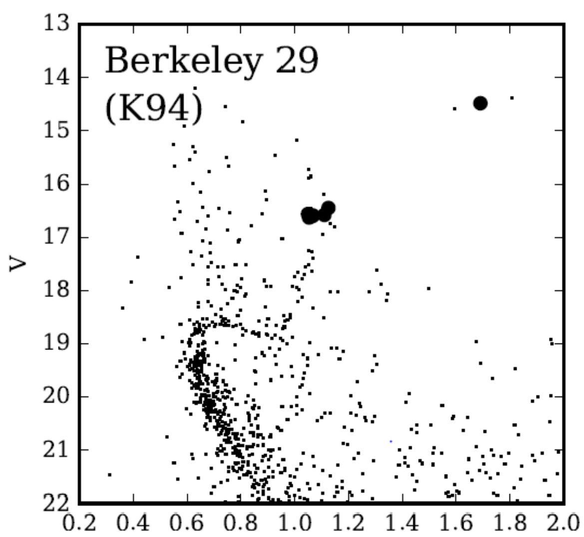
- DR2: Derive distances + pm of individual stars in OCs - little systematics and correlations:
- - at 2% for d < 500 kpc (G=16)
- -at 10% for the vast majority of OCs inside 2 kpc → more accurate orbits
- Small velocity dispersion in OCs (1 - 2 km/sec) → studies of the internal dynamics require ~ 0.2 km/sec: (d<200-300 pc)
- Improving the census
- Parallaxes, membership, exquisite photometry → Ages

OCs of extragalactic origin?

- A lot of recent work devoted to detect signs of mergers in the (outer) disk (Ibata+2017, Ruchti & Reed 2016)
- Reconstructing orbits of Ocs (+chemical tagging) can provide information about their origin
- Saurer 1 and Be 29 extragalactic origin in the past 4-5 Gyr? (Reddy+2016, vandePutte+2010)

Reddy+(2016)





Cantat +2016

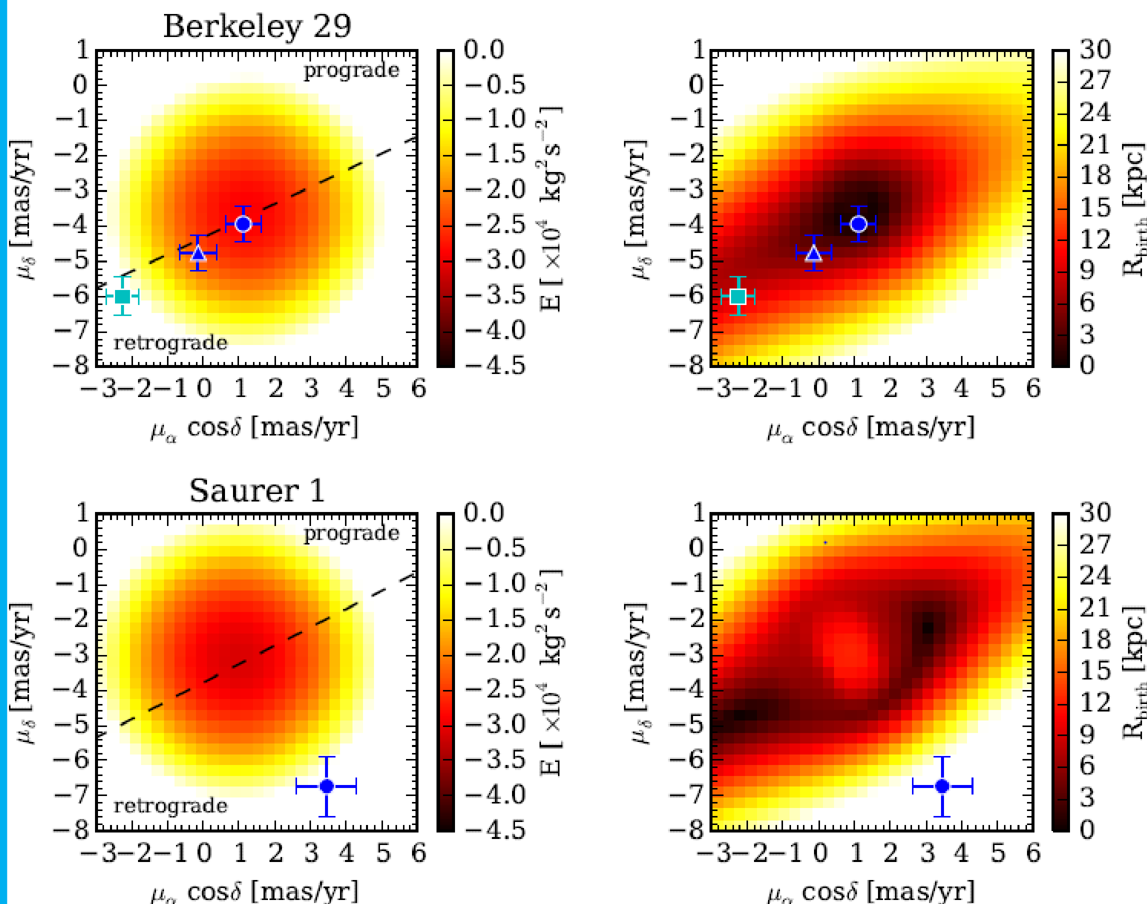
OC Orbit reconstruction

Saurer 1 and Be 29 orbits

- Retrograde orbits (Vande Putte 2010, Cantat-Gaudin+ 2016)
- However: static potential not accounting for churning
- Uncertainties in the pm: differences from 1 to 3mas/yr between VandePutte 2010, Karchenko+2013, Dias (Cantat+2016)
- Simply thick disk objects with perturbed orbits? Maybe from minor merger?

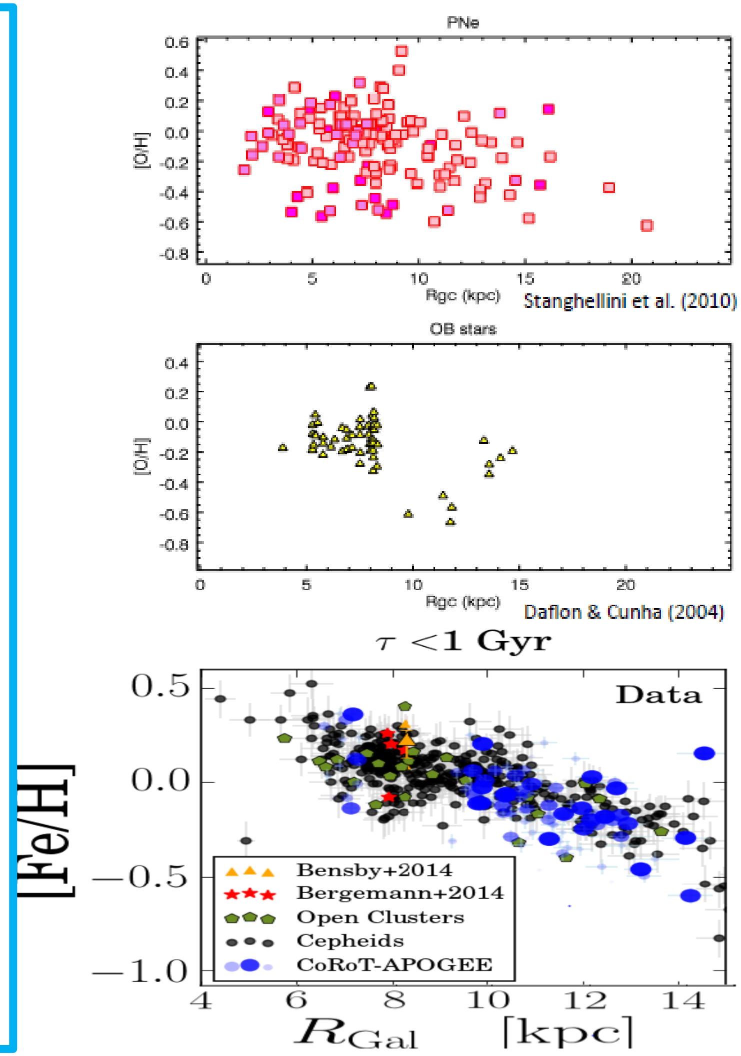
Energy

Birth radius



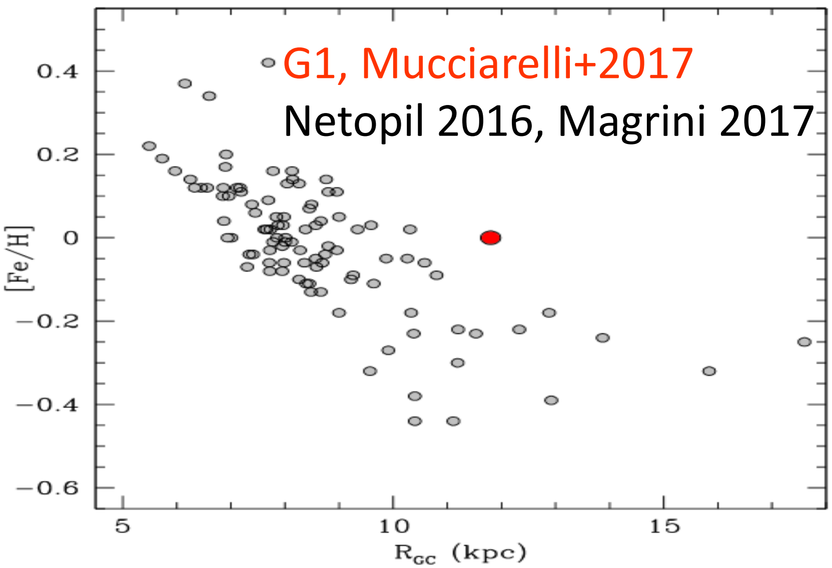
Disk metallicity Gradient and Radial Migration

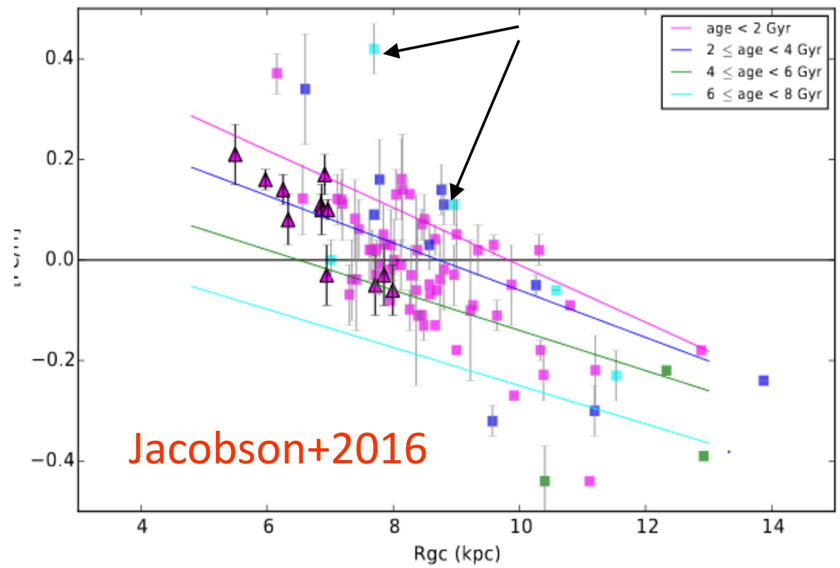
- Each indicator affect by systematics and uncertainties
- Different age, distance, and abundance scales among different groups, and between different tracer populations, especially in the case of PNe;
- Selection biases for the various tracers;
- Statistics;
- Different radial and vertical ranges of the disc considered (Reddy+2017)



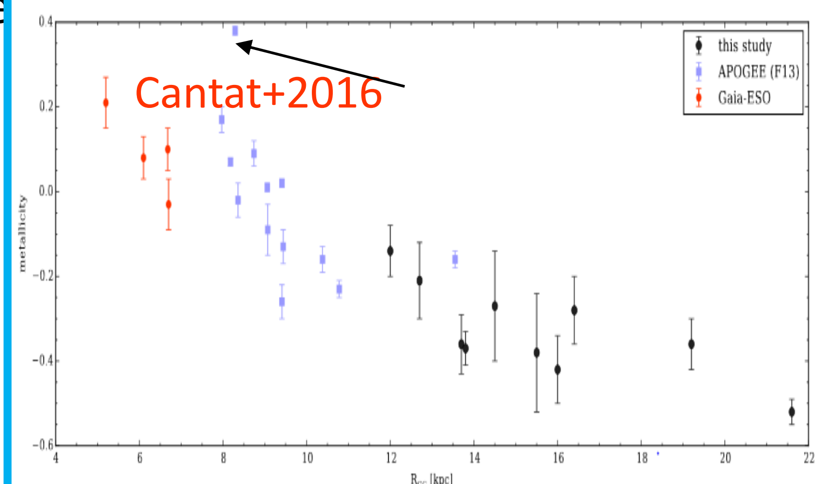
Anders 2017

GES MW radial metallicity distribution





- Old Ocs in SV have higher [Fe/H] than the younger ones (Jacobson+2016)
- super-metal-rich stars in the Solar V. (Minchev+2013; Anders +2016)
- Migrations? (Schönrich & Binney 2009; Minchev et al. 2010)
- Outer disk (R>12 Kpc) Ocs borned inside? (Reddy+2017)



Chemical gradient & Radial Migration

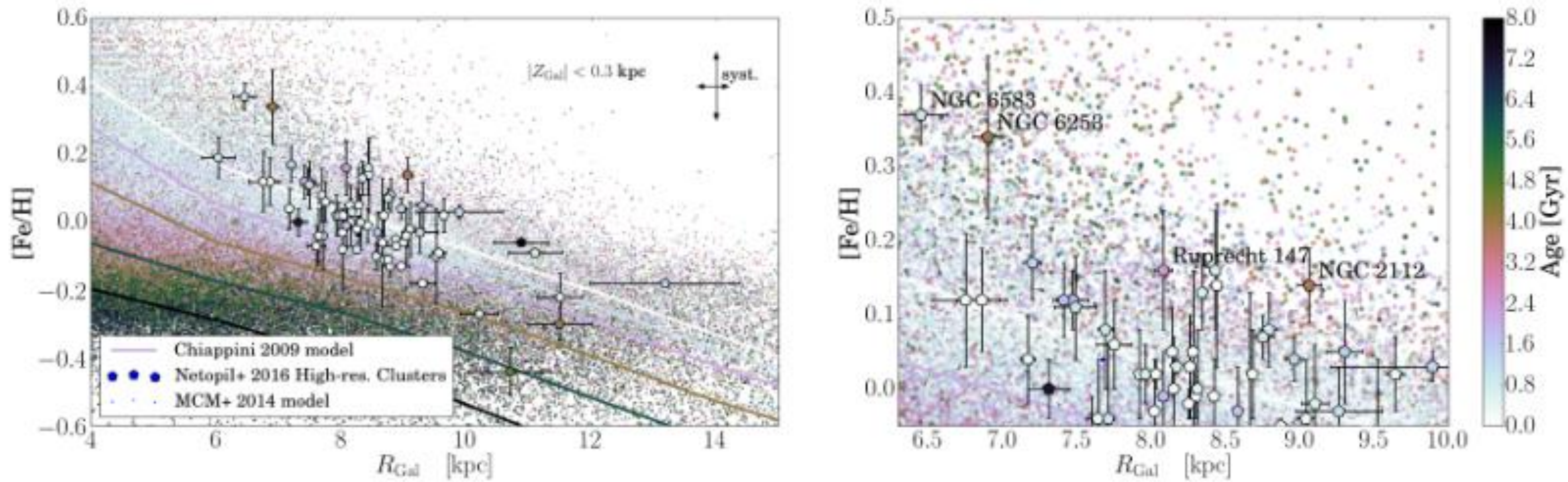
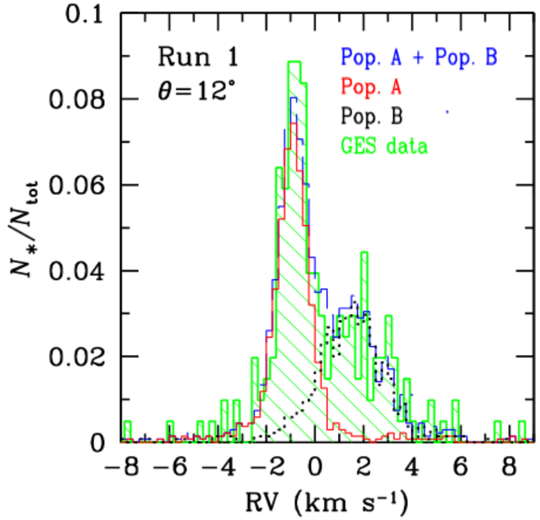


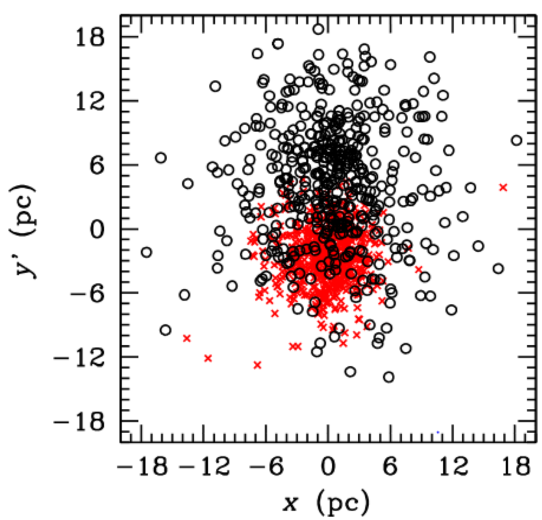
Fig. 6. The [Fe/H] vs. R_{Gal} distribution, colour-coded by age, for the high-resolution OC compilation of Netopil et al. (2016, *pentagons*), the MCM model close to the Galactic plane ($|Z_{Gal}| < 0.3$ kpc; *small dots*), and the Chiappini (2009) thin disc model at six time snapshots (*thick*

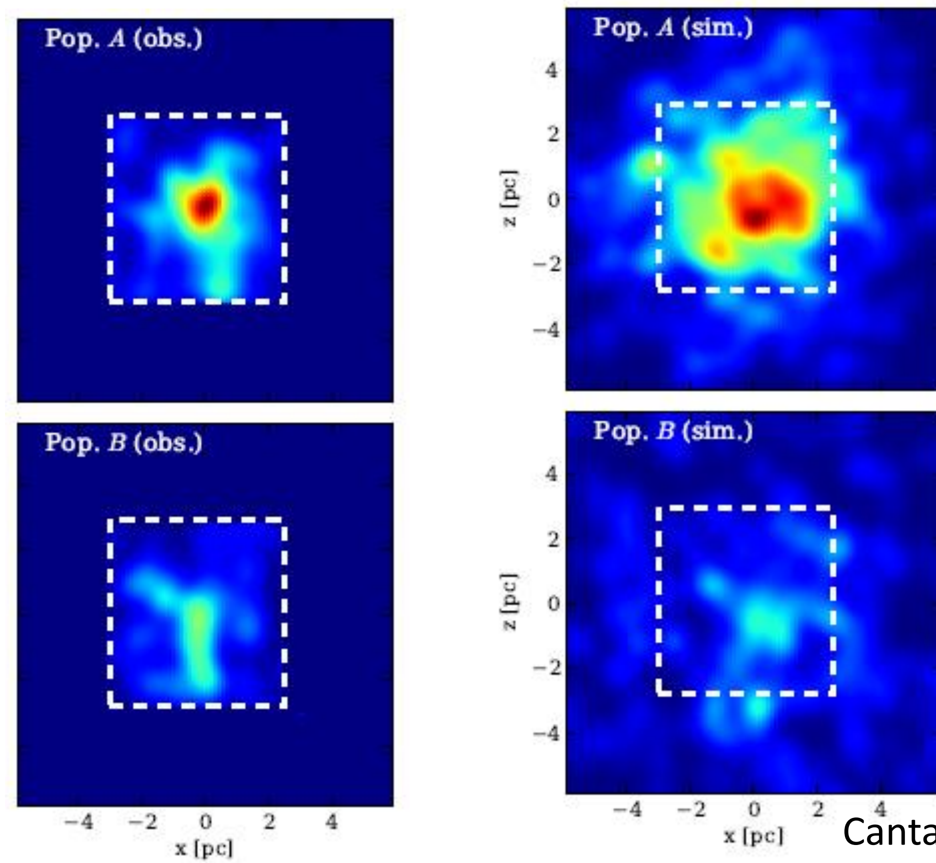
- Anders+ 2017 using Minchev+(2014) model+ error broadening
- N body simulations show that radial mixing can explain the presence of metal rich old Ocs as coming from inner disk regions
- However: cluster disruption in the inner disk not properly accounted for
- The model does not explain the spread at large RG

Young Ocs: star formation



Jeffries+2014, Mapelli+2015





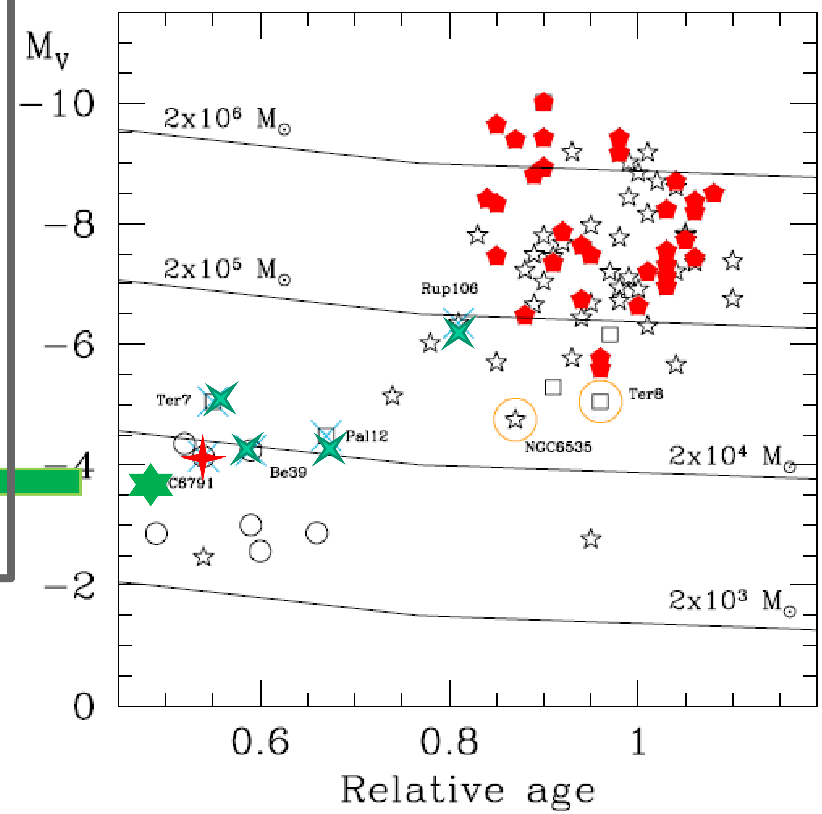
Cantat, 2017

Young OCs not in TGAS Chamaeleon I (2 Myr old, 160 pc from us, Whittet et al. 1997) or just hints of objects such as IC 2395 (6 Myr, 800 pc Clariá et al. 2003)

New insight on cluster formation from dynamical analysis of star clusters

Multiple Populations in OCs?

- Mass limit =10^{5-7} Mo(Carretta 2010, Bland-Hawthorn 2010)
- No chemical inhomogeneities in low mass clusters (Carrera+2010, Cantat +2015, Magrini+2015) regardless they are GCs or Ocs
- Data driven analysis of OC abundance spread of 0.01 - 0.03 dex (Bovy 2016)
- Hyades show inhomogeneity of 0.02 dex(Liu+2015)



Na-O anticorrelation

no Na-O anticorrelation:
- GCs of Sagittarius dSph, Ter7,Pal12 ;
- Rup 106
- massive, old OCs, Be 39

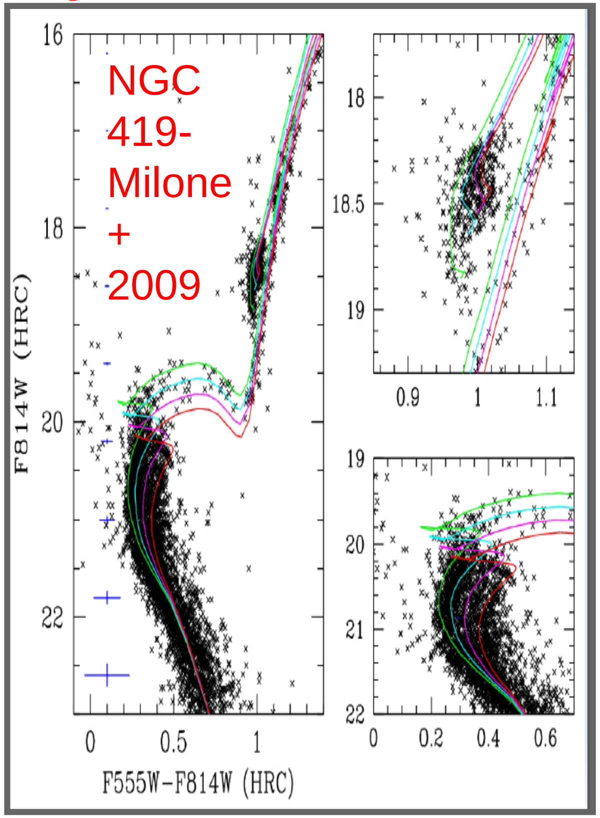
NGC 6791: unclear

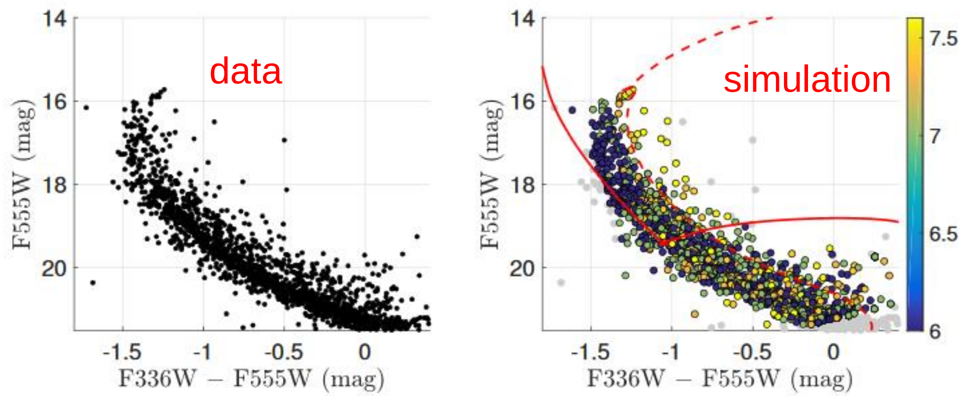
M11 ,Tr20

Masses from luminosity profiles & velocity dispersion

Is it the end of the story? See MCs

- In the Mcs, almost all clusters in the age-range 1-2 Gyr have extended Main sequence turnoff (MSTO)/extended clump(Li et al 2014, Bertelli+2003, Milone et al 2009...)
- Some Young GCs ages≤ 400 Myr have extended turnoff(Milone 2017, Li+2017)
- Not all exibit chemical abundance variation (Mucciarelli+ 2014)
- Stellar rotation + age spread (700 Myr), BSS ??? (Goudfrooij+2011, Bastian+ 2009, Li+2017..)





Li+2017
NGC 330: rotation + age spread 30 Myr

Conclusions

Thank you