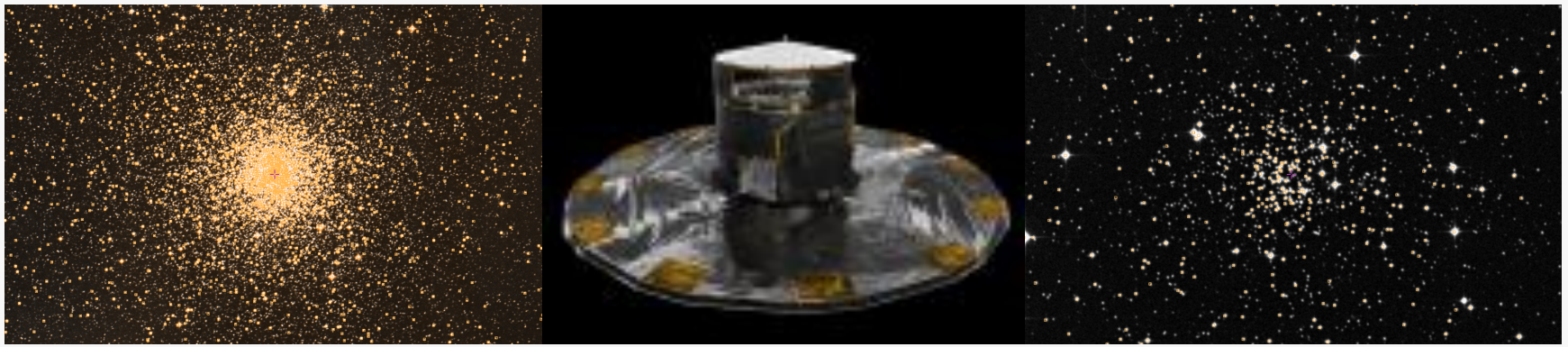


STELLAR CLUSTERS in the GAIA era

ANGELA BRAGAGLIA (INAF-OA BOLOGNA)

OUTLINE

- **The promise of Gaia for clusters** - very short
- **Clusters in DR1** - verification, science
- **Complementing Gaia with (mostly) ground-based data**
- **DR2 and later (implicit)**

THE PROMISE of *Gaia* for CLUSTERS

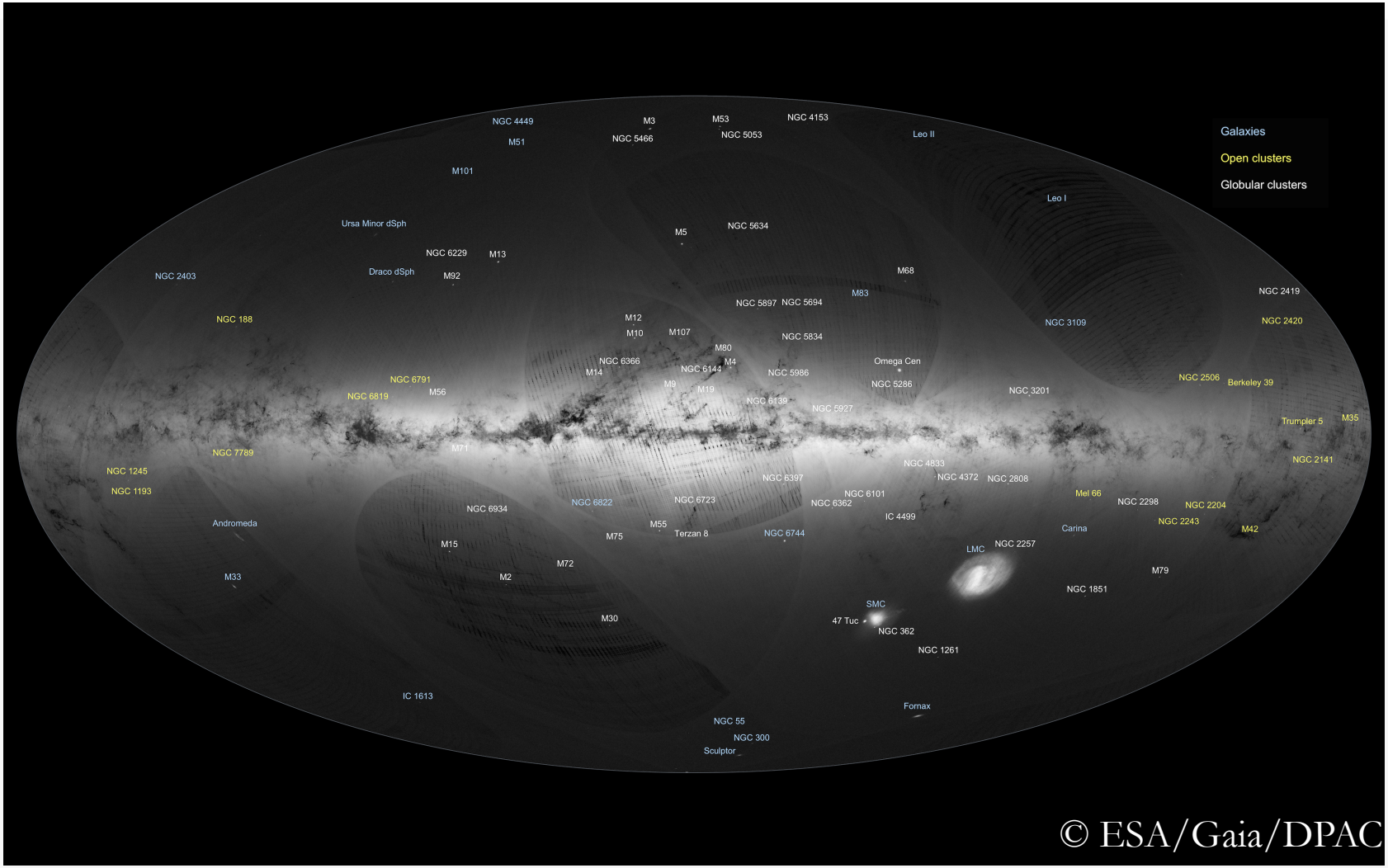
Gaia provides: accurate, precise position, distance, proper motion, (and more limited radial velocities, chemistry)

A very incomplete wish list:

- **How do clusters form**
- **How do clusters populate the field**
- **Trace stars/streams back to original cluster/association**
- **Use clusters to test stellar models (to very low mass)**
- **Use open clusters to test disk properties**
- **Variability (e.g. Cepheids, RR Lyr's, binaries)**
- **etc**

you name your favourite "cluster science" field : Gaia will be there…

Gaia's FIRST SKY MAP



HOW MANY CLUSTERS

(rule-of-thumbs) accuracy on π, PM : V≈15 star (also RV available)

1% @ 1 kpc

5% @ 5 kpc

Number		$D_\odot$<1 kpc	$D_\odot$<5 kpc
Globular clusters	(157)	none	15
Open clusters	(3000)	370	~2630

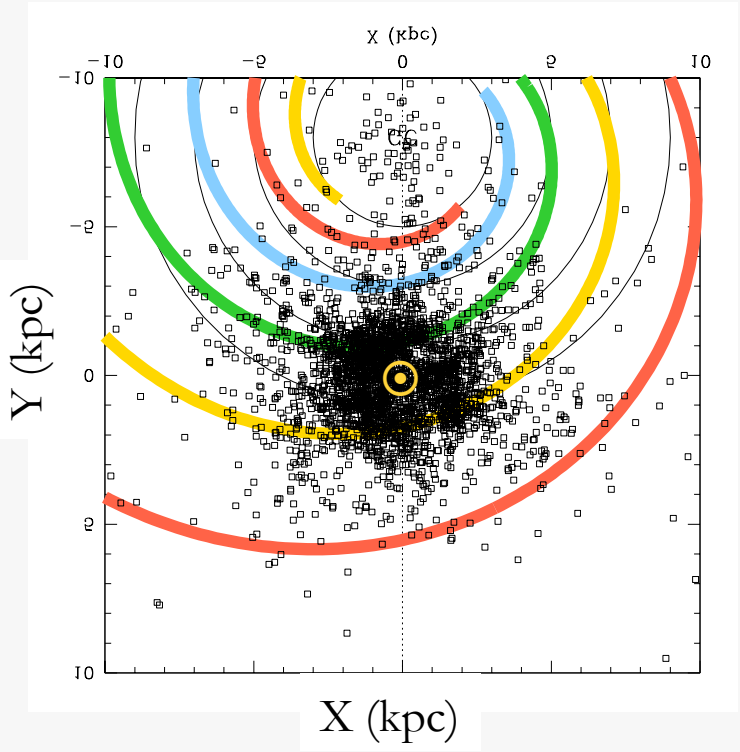
but this – surely for OCs – is only the tip of the iceberg

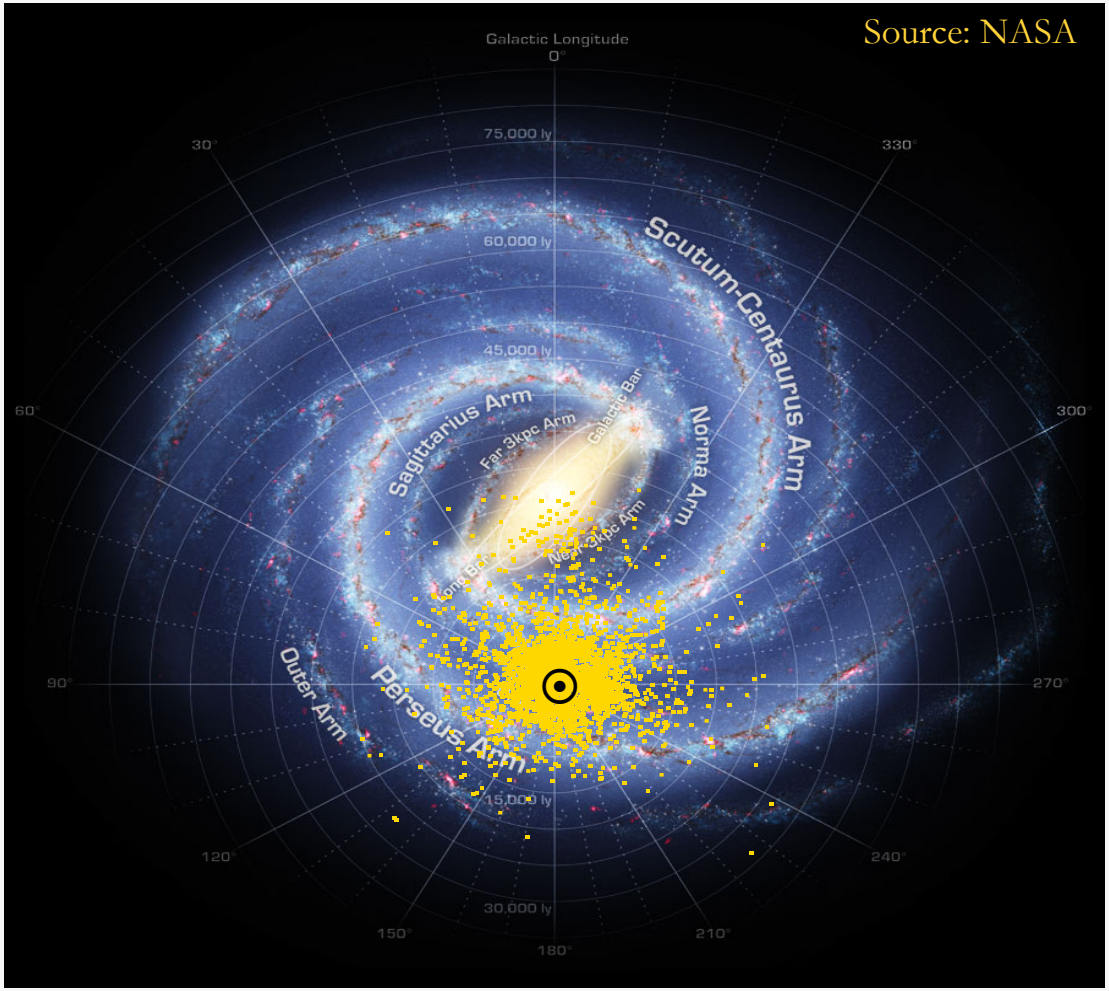
HOW MANY OPEN CLUSTERS

3000 clusters in Kharchenko+2013

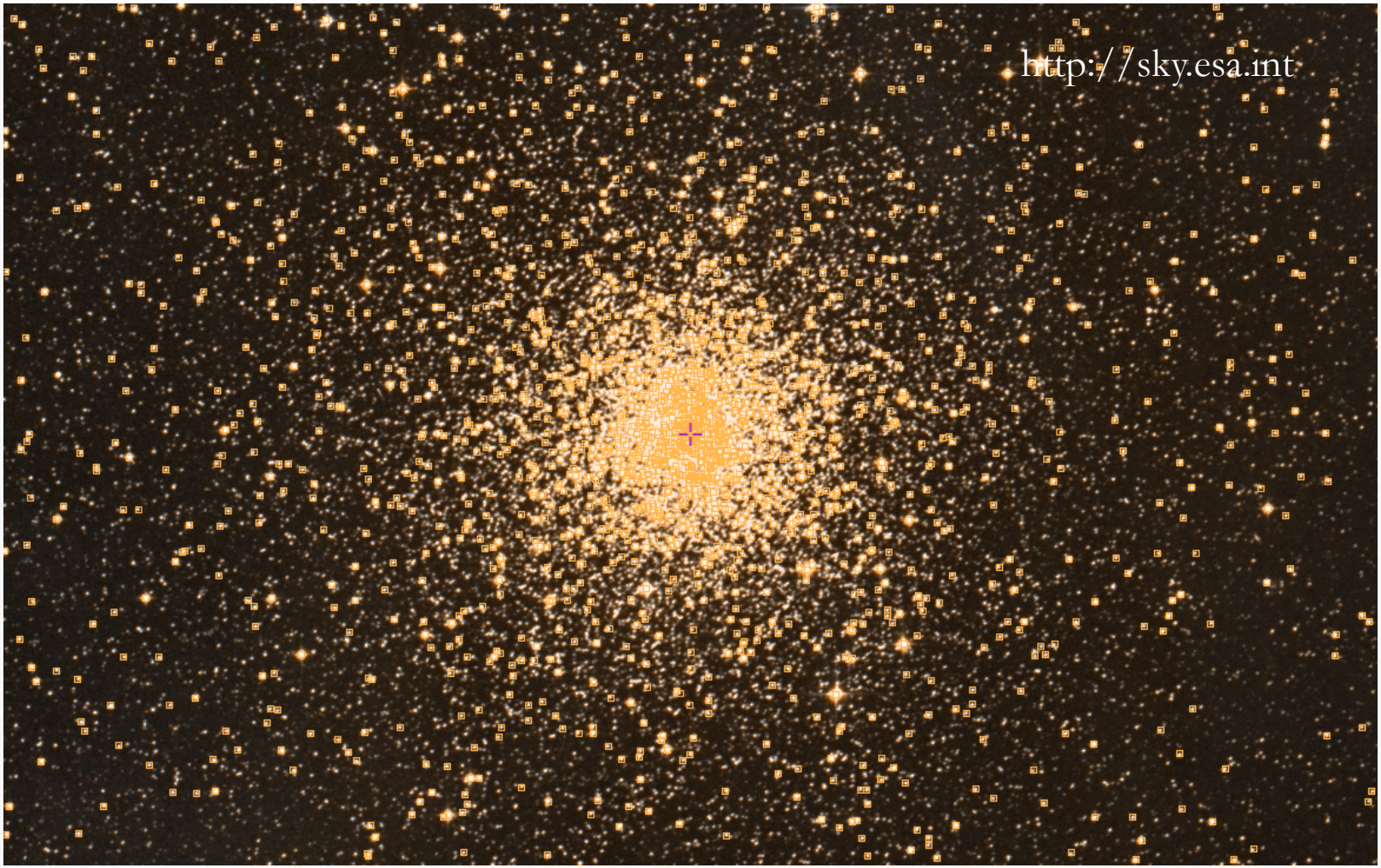
➔ ≈100000 expected

➔ Space for discovery

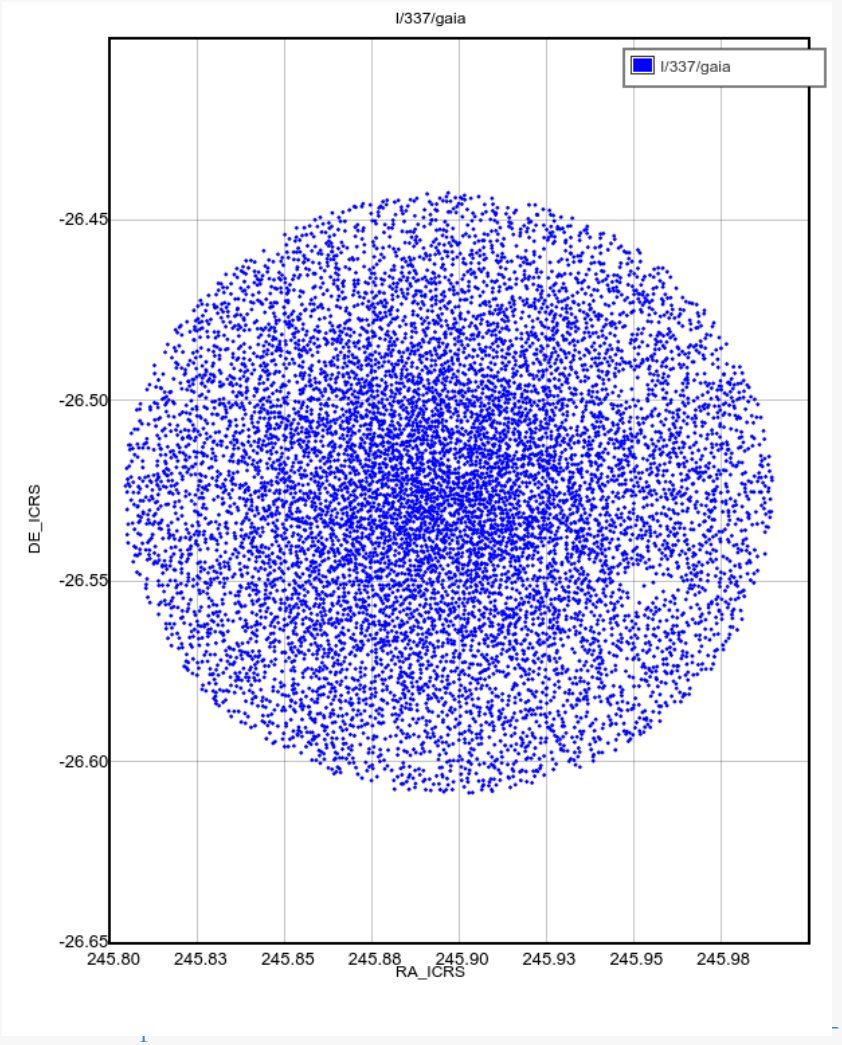


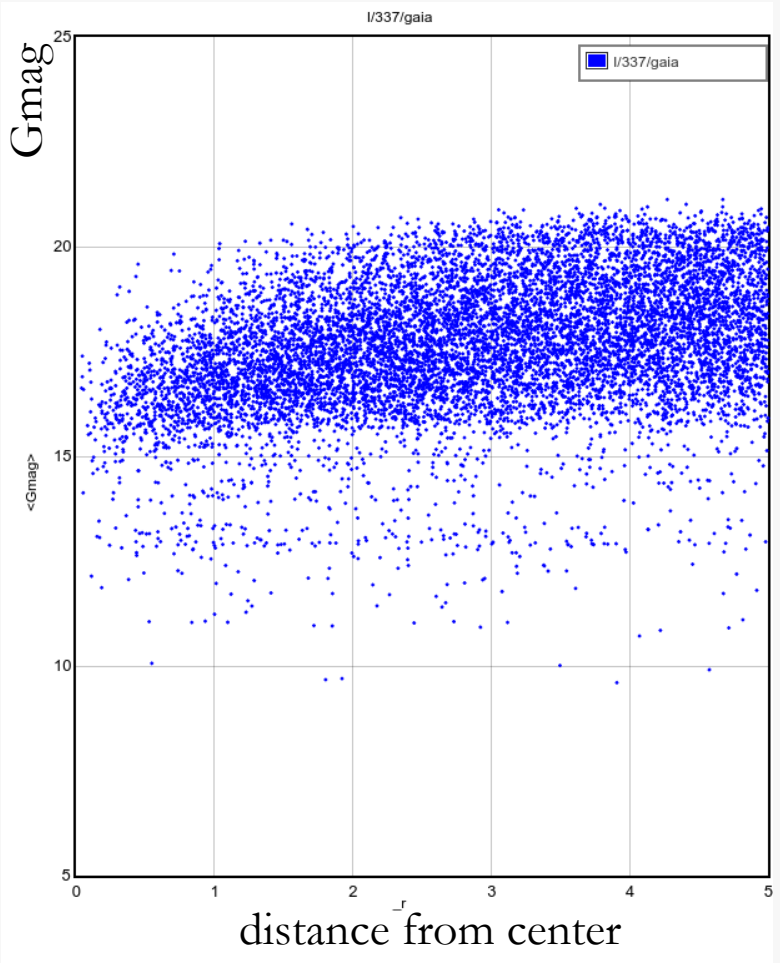


M4 – DR1



M4 in DR1 : POSITIONS & Gmag





GLOBULAR CLUSTERS IN DR1/TGAS ?

Harris 1996 and web updates : 157 MW GCs

Positions in DR1 : OK
PM, π (TGAS) : ?

exercise done by Watkins & van der Marel (arXiv:1611.03170) :

- take all MW GCs, take 2×tidal radius & search TGAS : 4268 TGAS stars in 142 GCs
- check magnitude (tip RGB for each GC and fainter) : 967 stars in 30 GCs (<10.2 kpc)
- keep only if PM, π agree with previous data : 64 stars in 15 GCs
- add RV (literature) : 59 stars in 15 GCs
- check if they lie on evolutionary sequences in CMD : 48 stars in 11 GCs
- check with field stars model : **20 stars in 5 GCs**

➔ **wait for DR2+**

GLOBULARS: LOOKING FORWARD TO END-OF-MISSION

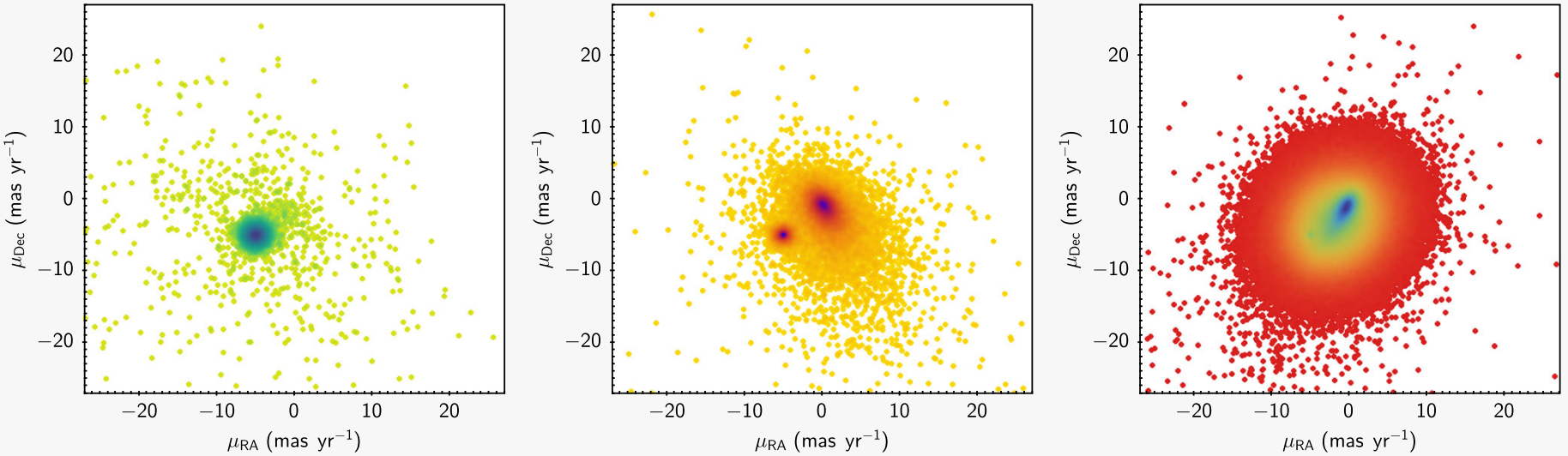
Pancino+2017 : simulations to reproduce typical GCs as observed by *Gaia*

c=1, c=2.5

$D_{\odot}$=5 (10% of MW GCs), 10 (50%), 15 (70%) kpc

background: "halo", "disk", "bulge"

"Only the latest few DRs are expected to produce a real breakthrough in GC research"



proper motions in 3 cases :

(a) easy (b) intermediate (c) difficult

GLOBULARS: LOOKING FORWARD TO END-OF-MISSION

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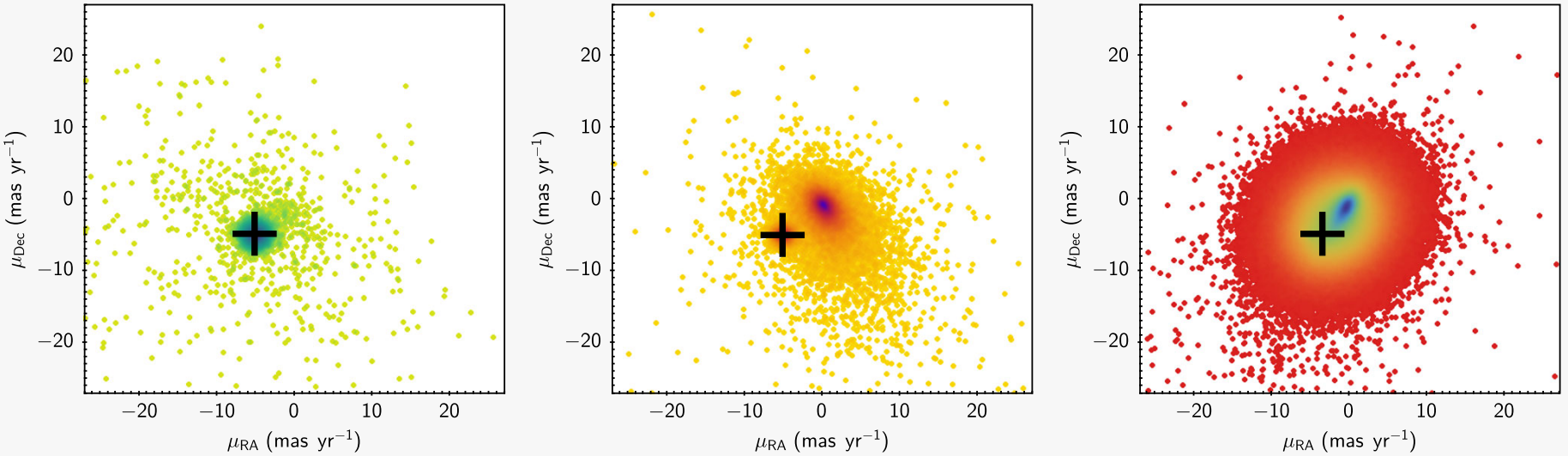

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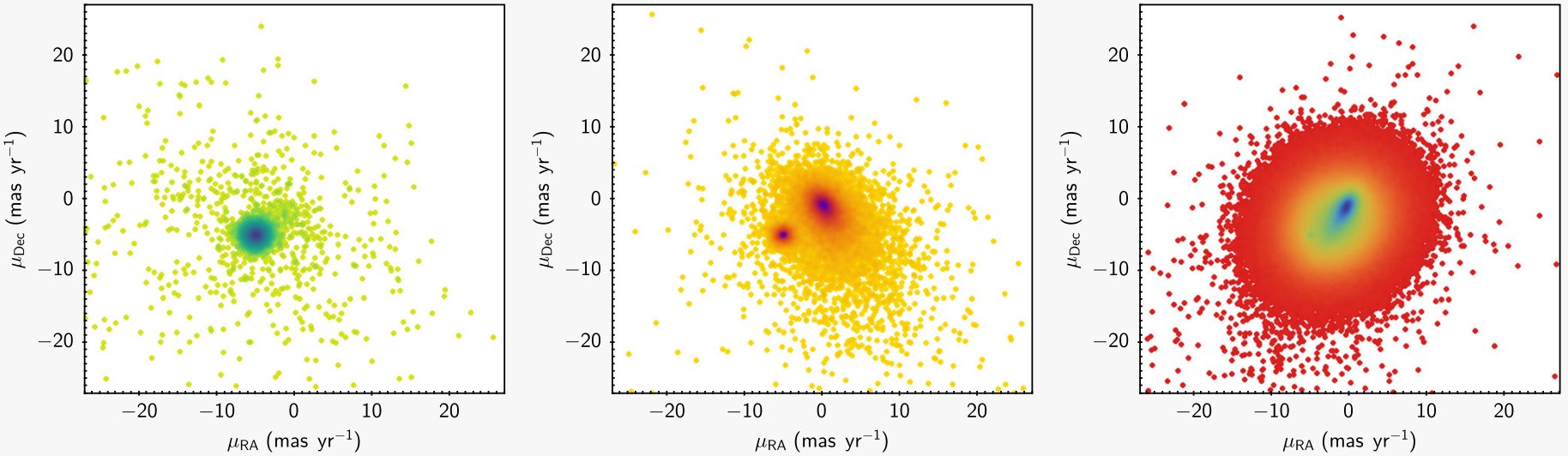


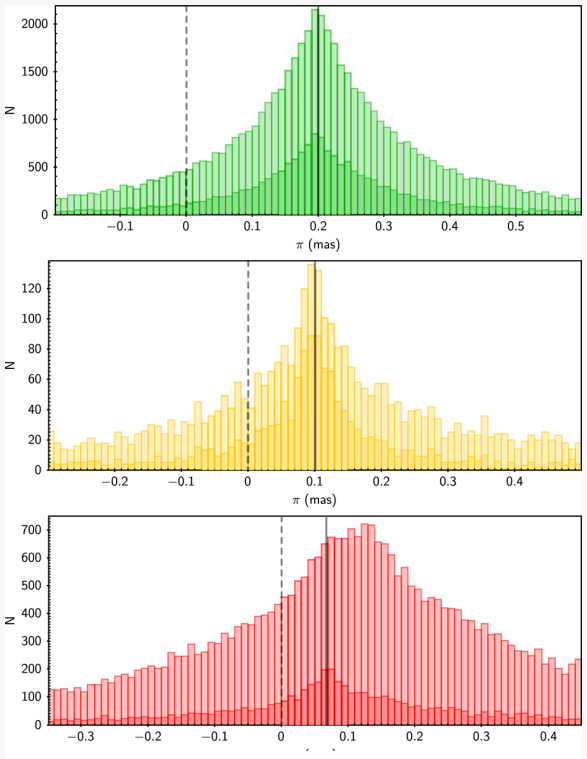
proper motions in 3 cases :

(a) easy (b) intermediate (c) difficult

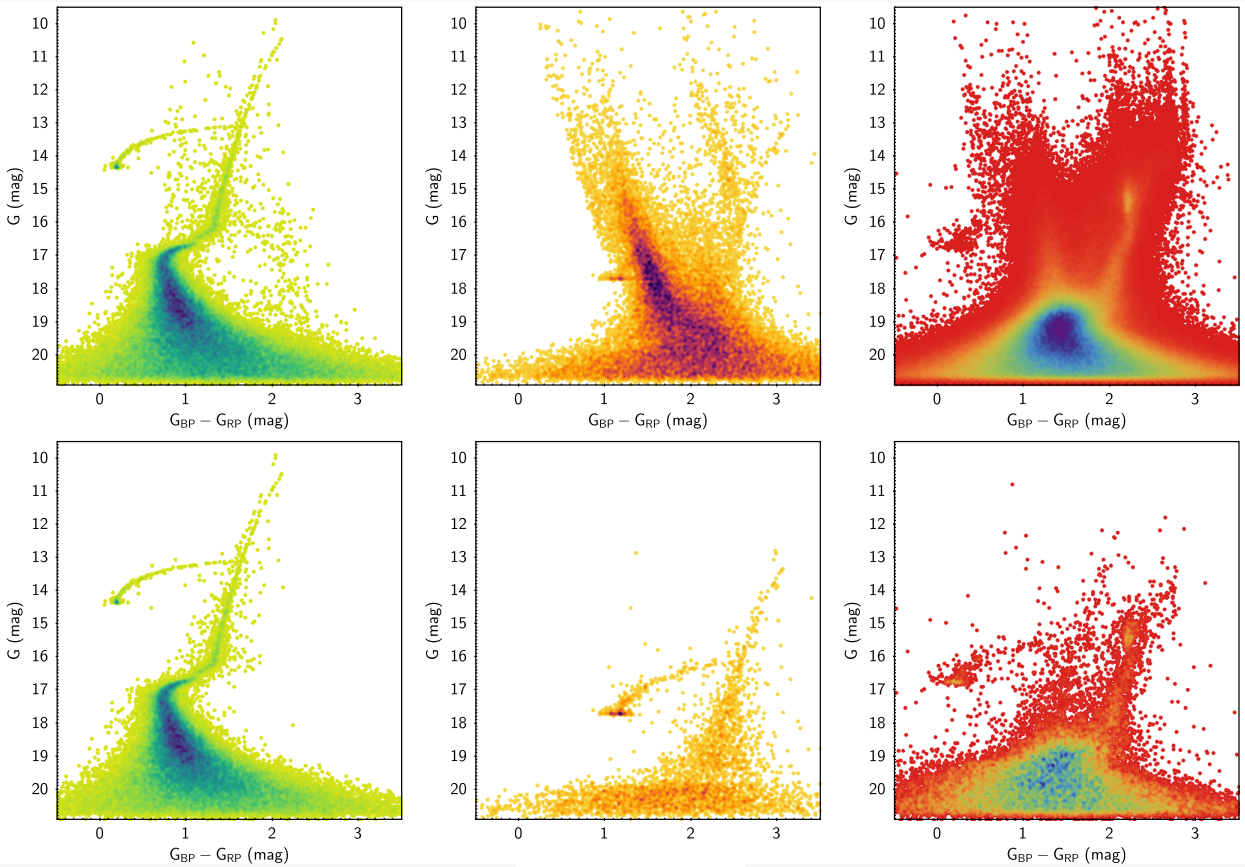
GLOBULARS: LOOKING FORWARD TO END-OF-MISSION

Pancino+2017

easy intermediate difficult



π (mas)



G_{BP}-G_{RP}

GLOBULARS: LOOKING FORWARD TO END-OF-MISSION

- 10^3-10^4 stars/GC : astrometric performance not touched by crowding
- but worst cases only ~100 clean stars
- limiting factor : background crowding (not cluster crowding)

- systemic PM, π to <1% or better up to 15kpc (i.e. 70% of MW GCs)
  e.g. dynamical relaxation from PMs to 5kpc (10% of GCs)
- 1% distance ➔ 10% absolute age (and relative ages of subpops)
- nearby GCs : velocities to a few km/s (complement from ground)
- internal kynematics of unprecedented precision
  e.g. masses to 10% to 15kpc ; kin differences in subpops to 10 kpc
- orbits from PMs, π , position, RV
  e.g. extra-tidal stars, tidal tails
- bright stars (V<17-18) : 1 mmag precision in photometry (also at centers)
- all stars have 1-3% error on absolute photometry

Pancino+2017

VALIDATION: OPEN CLUSTERS IN TGAS

Gaia Data Release 1. Open cluster astrometry: performance, limitations, and future prospects ⋆

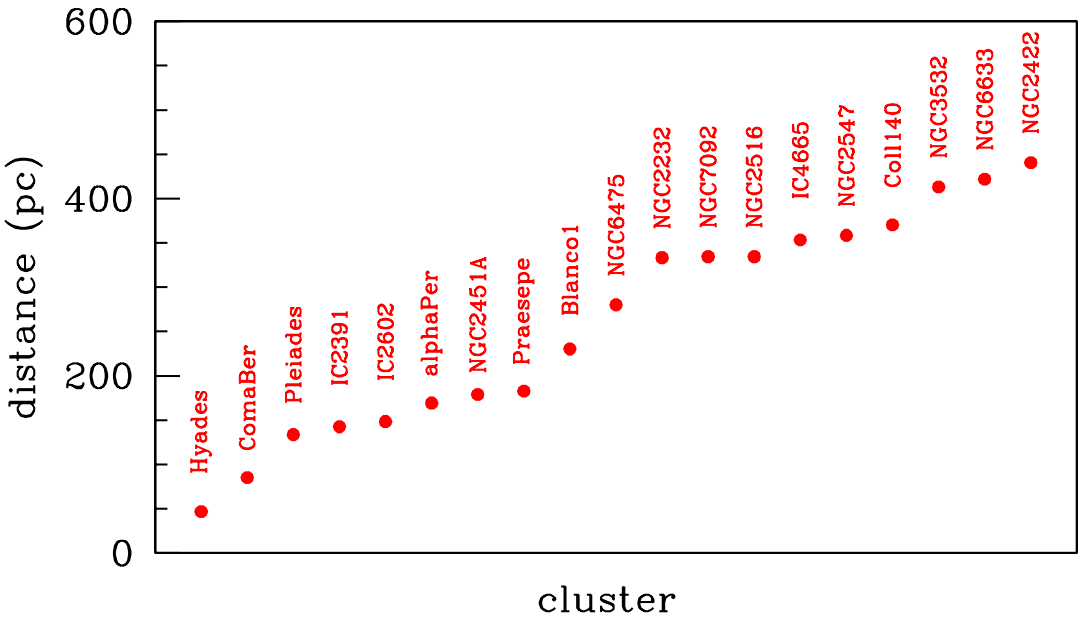
Gaia Collaboration, F. van Leeuwen[1], A. Vallenari[2], C. Jordi[3], L. Lindegren[4], U. Bastian[5], T. Prusti[6], J.H.J. de Bruijne[6], A.G.A. Brown[7], C. Babusiaux[8], C.A.L. Bailer-Jones[9], M. Biermann[5], D.W. Evans[1], L. Eyer[10], F. Jansen[11], S.A. Klioner[12], U. Lammers[13], X. Luri[3], F. Mignard[14], C. Panem[15], D. Pourbaix[16,17], S. Randich[18], P. Sartoretti[8], H.I. Siddiqui[19], C. Soubiran[20], V. Valette[15], N.A. Walton[1], C. Aerts[21,22], F. Arenou[8], M. Cropper[23], R. Drimmel[24], E. Høg[25], D. Katz[8], M.G. Lattanzi[24], W. O'Mullane[13], E.K. Grebel[5], A.D. Holland[26], C. Huc[15], X. Passot[15], M. Perryman[6], L. Bramante[27], C. Cacciari[28], J. Castañeda[3], L. Chaoul[15], N. Cheek[29], F. De Angeli[1], C. Fabricius[3], R. Guerra[13], J. Hernández[13], A. Jean-Antoine-Piccolo[15], E. Masana[3], R. Messineo[27], N. Mowlavi[10], K. Nienartowicz[30], D. Ordóñez-Blanco[30], P. Panuzzo[8], J. Portell[3], P.J. Richards[31], M. Riello[1], G.M. Seabroke[23], P. Tanga[14], F. Thévenin[14], J. Torra[3], S.G. Els[32,5], G. Gracia-Abril[32,3], G. Comoretto[19], M. Garcia-Reinaldos[13], T. Lock[13], E. Mercier[32,5], M. Altmann[5,33], R. Andrae[9], T.L. Astraatmadja[9], I. Bellas-Velidis[34], K. Benson[23], J. Berthier[35], R. Blomme[36], G. Busso[1], B. Carry[14,35], A. Cellino[24], G. Clementini[28], S. Cowell[1], O. Creevey[14,37], J. Cuypers[36], M. Davidson[38], J. De Ridder[21], A. de Torres[39], L. Delchambre[40], A. Dell'Oro[18], C. Ducourant[20], Y. Frémat[36], M. García-Torres[41], E. Gosset[40,17], J.-L. Halbwachs[42], N.C. Hambly[38], D.L. Harrison[1,43], M. Hauser[5], D. Hestroffer[35], S.T. Hodgkin[1], H.E. Huckle[23], A. Hutton[44], G. Jasniewicz[45], S. Jordan[5], M. Kontizas[46], A.J. Korn[47], A.C. Lanzafame[48,49], M. Manteiga[50], A. Moitinho[51], K. Muinonen[52,53], J. Osinde[54], E. Pancino[18,55], T. Pauwels[36], J.-M. Petit[56], A. Recio-Blanco[14], A.C. Robin[56], L.M. Sarro[57], C. Siopis[16], M. Smith[23], K.W. Smith[9], A. Sozzetti[24], W. Thuillot[35], W. van Reeven[44], Y. Viala[8], U. Abbas[24], A. Abreu Aramburu[58], S. Accart[59], J.J. Aguado[57], P.M. Allan[31], W. Allasia[60], G. Altavilla[28], M.A. Álvarez[50], J. Alves[61], R.I. Anderson[62,10], A.H. Andrei[63,64,33], E. Anglada Varela[54,29], E. Antiche[3], T. Antoja[6], S. Antón[65,66], B. Arcay[50], N. Bach[44], S.G. Baker[23], L. Balaguer-Núñez[3], C. Barache[33], C. Barata[51], A. Barbier[59], F. Barblan[10], D. Barrado y Navascués[67], M. Barros[51], M.A. Barstow[68], U. Becciani[49], M. Bellazzini[28], A. Bello García[69], V. Belokurov[1], P. Bendjoya[14], A. Berihuete[70], L. Bianchi[60], O. Bienaymé[42], F. Billebaud[20], N. Blagorodnova[1], S. Blanco-Cuaresma[10,20], T. Boch[42], A. Bombrun[39], R. Borrachero[3], S. Bouquillon[33], G. Bourda[20], H. Bouy[67], A. Bragaglia[28], M.A. Breddels[71], N.

and many authors more (2017, A&A, 601, A19)

Gaia DR1 : OPEN CLUSTERS ASTROMETRY

Name	Fe/H	E(B−V)	log(age)
Hyades	0.15 ± 0.004	0.00	8.90
Coma Ber	0.00 ± 0.08	0.00	8.75
Praesepe	0.16 ± 0.004	0.01	8.90
Pleiades	−0.01 ± 0.05	0.04	8.08
α Per	0.14 ± 0.11	0.09	7.55
IC2391	−0.01 ± 0.03	0.05	7.55
IC2606	−0.02 ± 0.02	0.03	7.88
Blanco 1	0.03 ± 0.07	0.01	8.32
NGC2451A	-0.08	0.00	7.76
NGC6475	0.02 ± 0.02	0.21	8.22
NGC7092	0.00	0.01	8.57
NGC2516	+0.05 ± 0.11	0.07	8.08
NGC2232	0.11	0.03	7.49
IC4665	−0.03 ± 0.04	0.17	7.63
NGC6633	−0.08 ± 0.12	0.17	8.76
Coll140	0.01 ± 0.04	0.05	7.57
NGC2422	0.09 ± 0.03	0.10	8.12
NGC3532	0.00 ± 0.07	0.04	8.45
NGC2547	−0.14 ± 0.10	0.04	7.70

$D_\odot$<300pc $D_\odot$=300-500pc

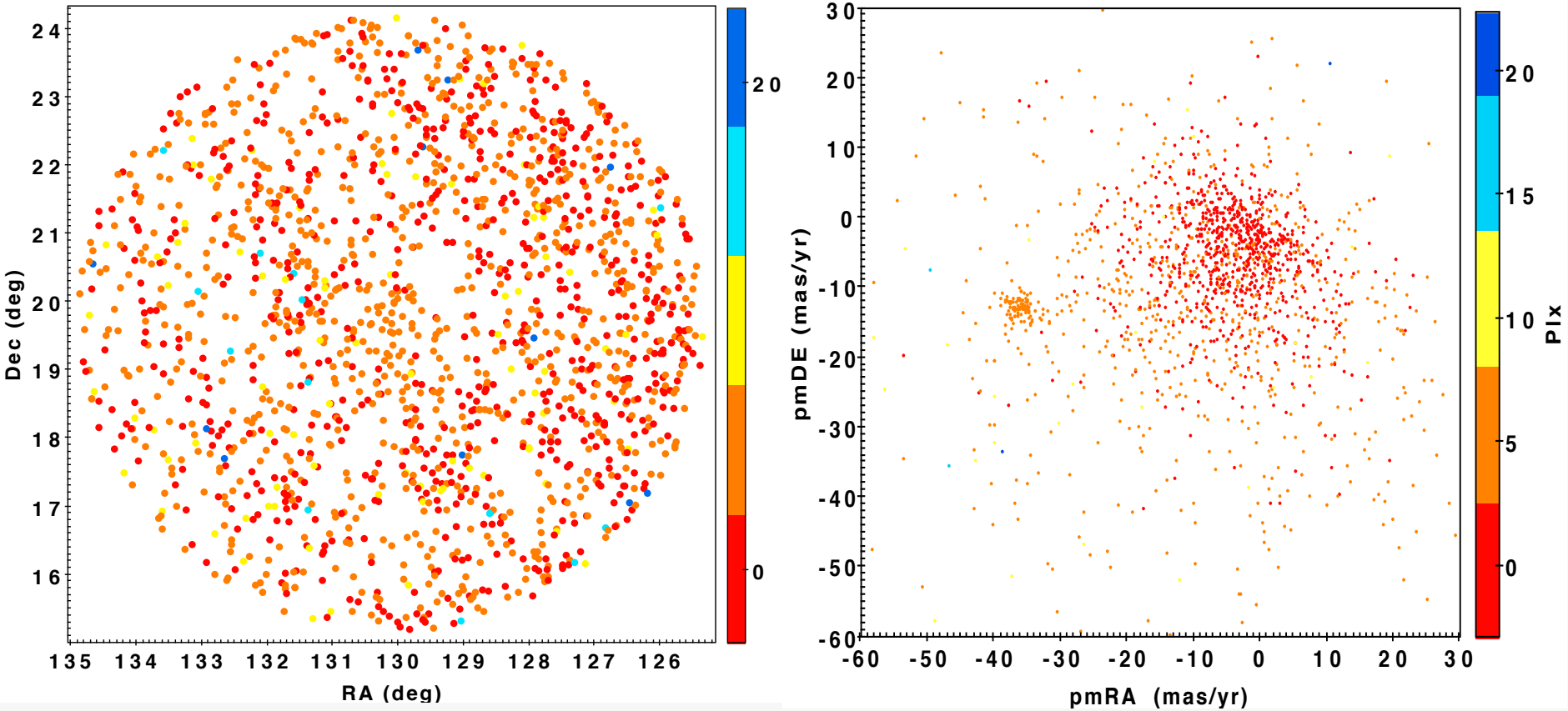


N(member)=16-152 (median ~50)
Rmax=2-17 deg (median ~ 2.7deg)
$D_\odot$=47-440 pc
van Leeuwen & Gaia collab. 2017

Gaia DR1 : OPEN CLUSTERS ASTROMETRY

Praesepe

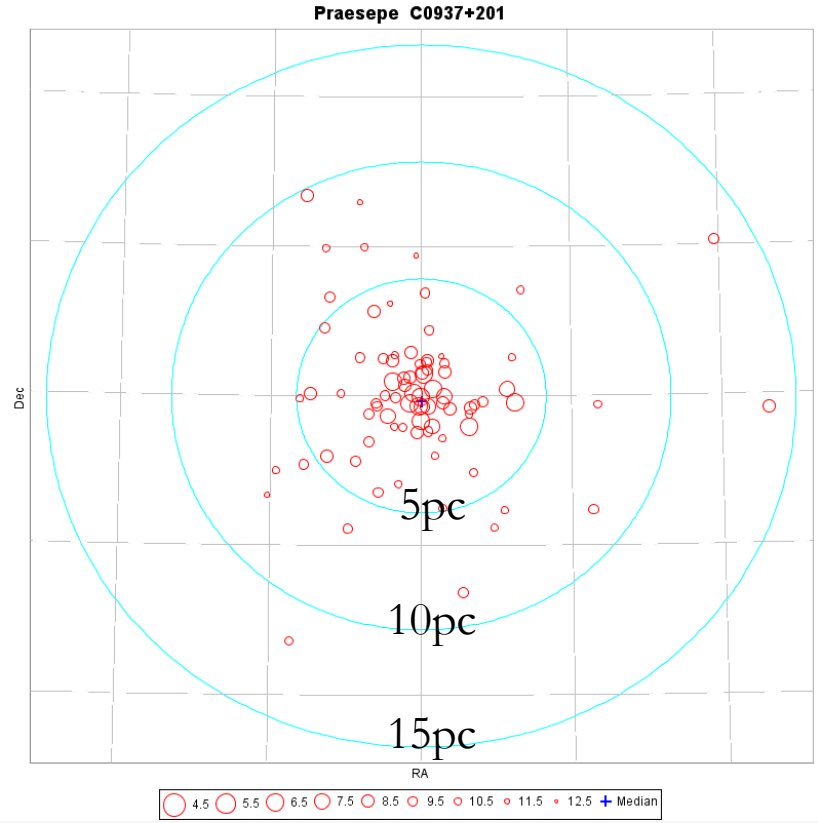
TGAS data, 4.5deg radius

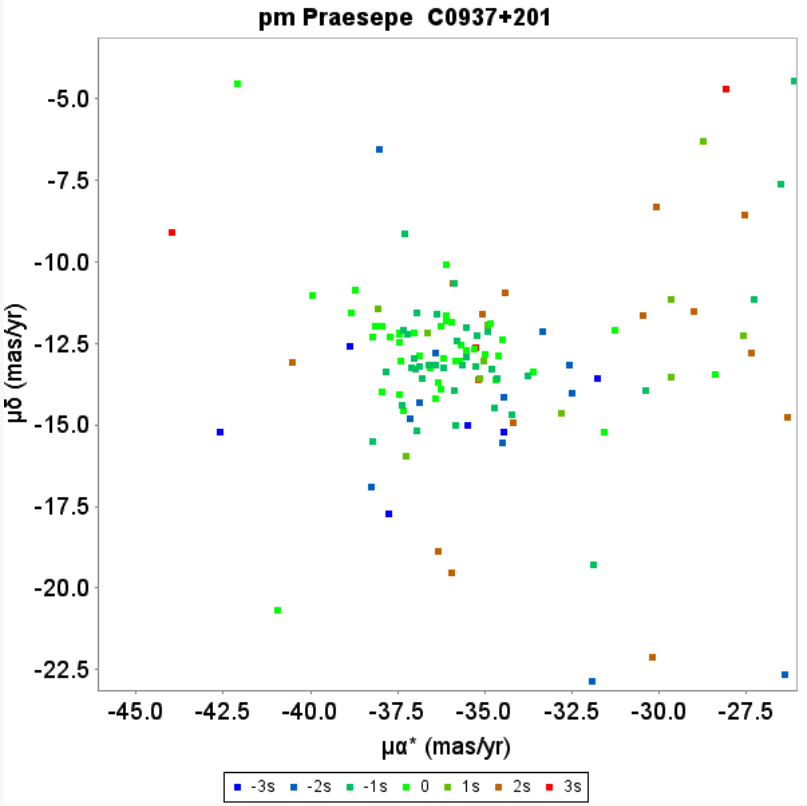


Gaia DR1 : OPEN CLUSTERS ASTROMETRY

Praesepe

79 members, $<\pi>$=5.47±0.05 mas, $D_{\odot}$=183 pc, stars to ~15pc



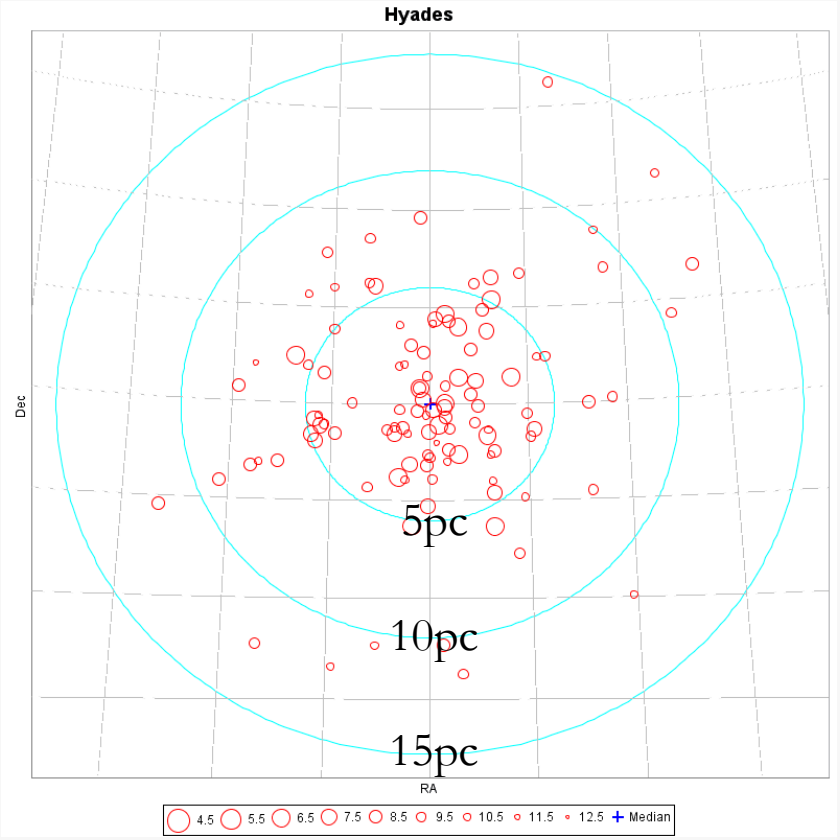


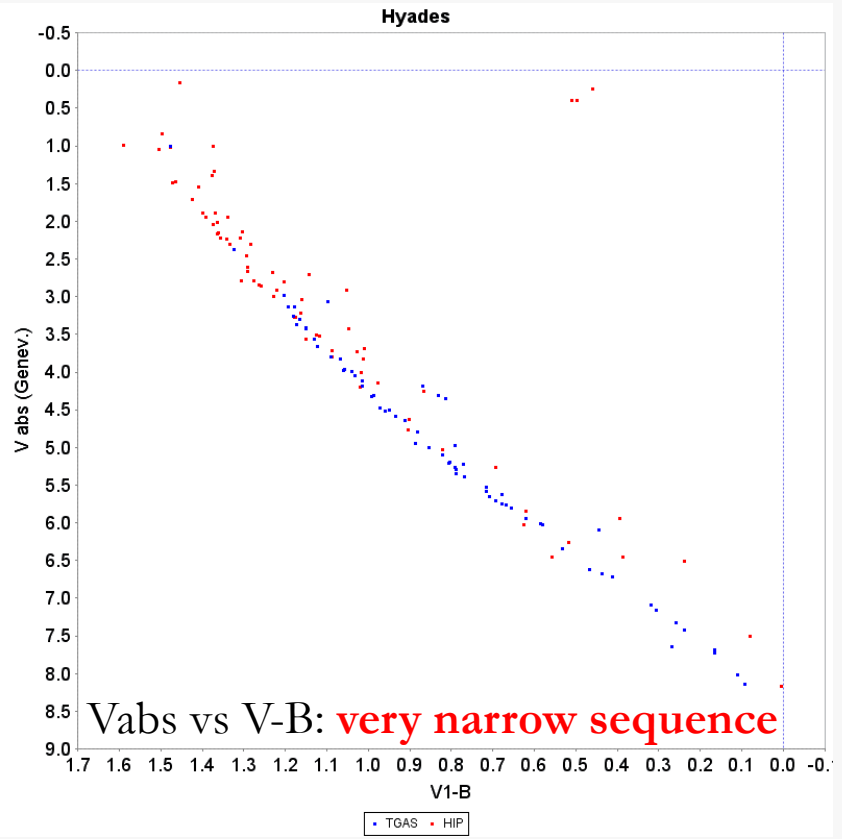
van Leeuwen & Gaia collab. 2017

Gaia DR1 : OPEN CLUSTERS ASTROMETRY

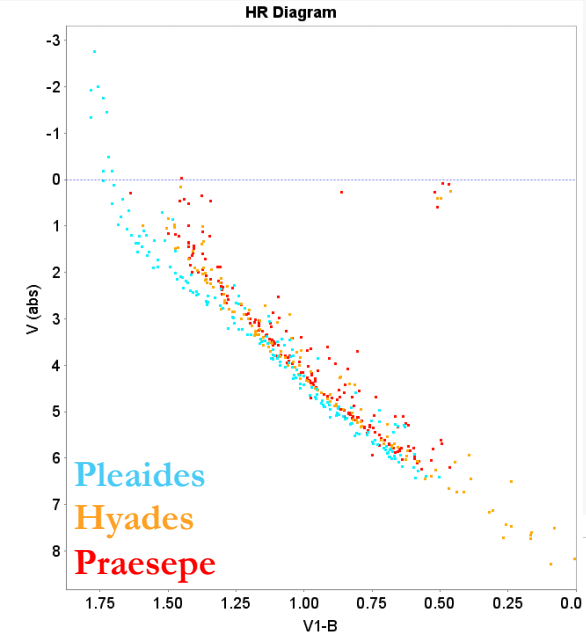
Hyades

103 members, $<\pi>=21.39\pm0.21$ mas, $D_{\odot}=46.75\pm0.46$ pc, stars at ~15pc





Gaia DR1 : OPEN CLUSTERS ASTROMETRY



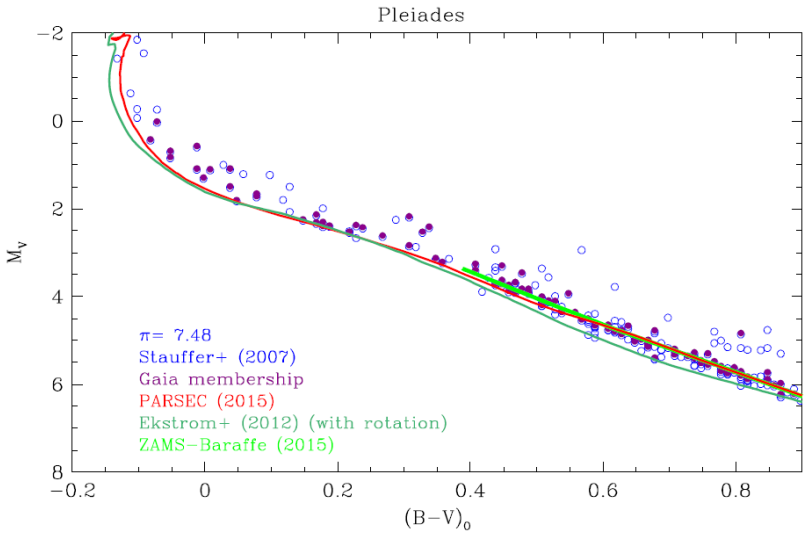
Pleiades

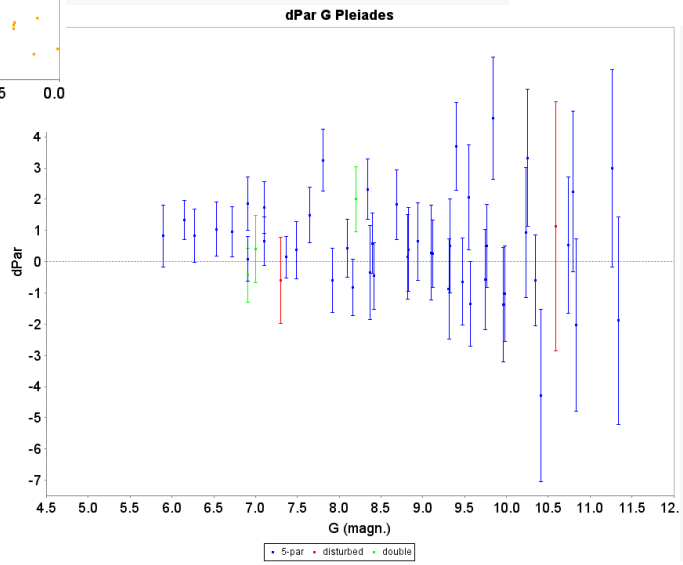
152 members,

$<\pi>$=7.48±0.03 mas,

$D_{\odot}$=134 pc

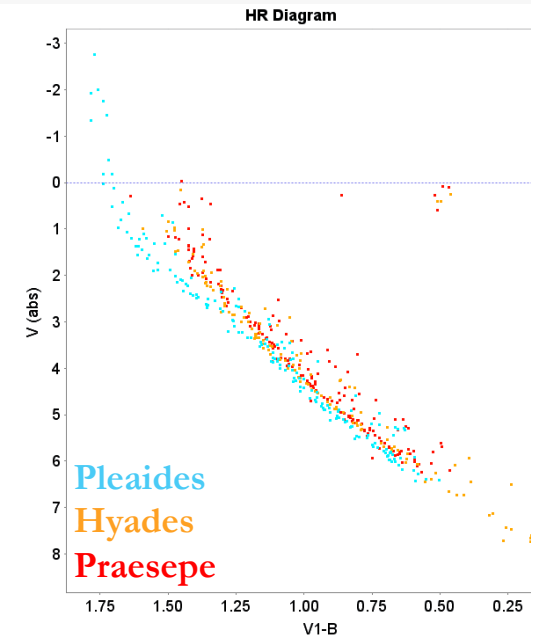
(cf VLBI: 136 pc)

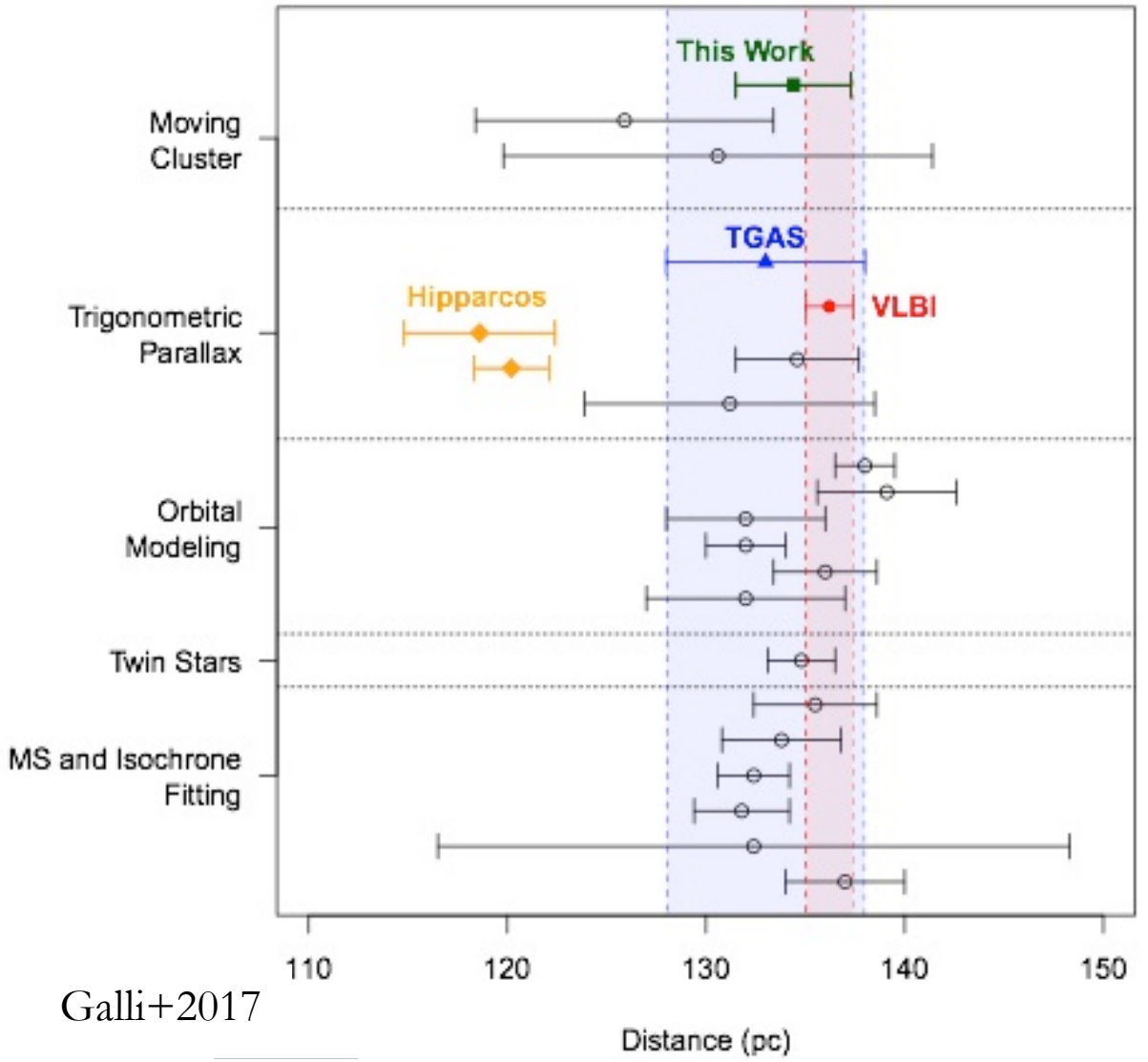




van Leeuwen & Gaia collab. 2017

Gaia DR1 : OPEN CLUSTERS ASTROMETRY



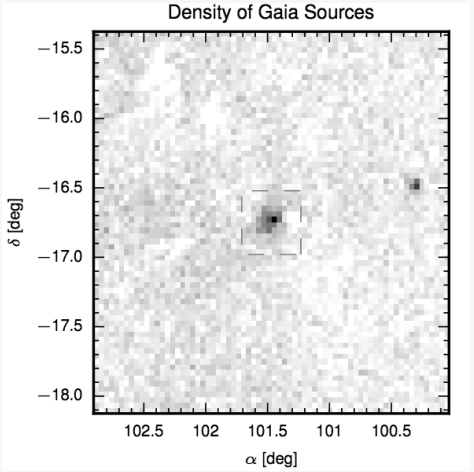


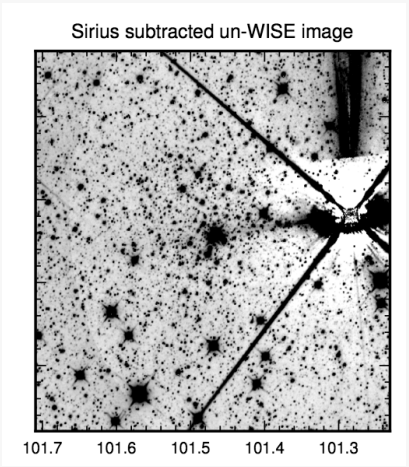
Galli+2017

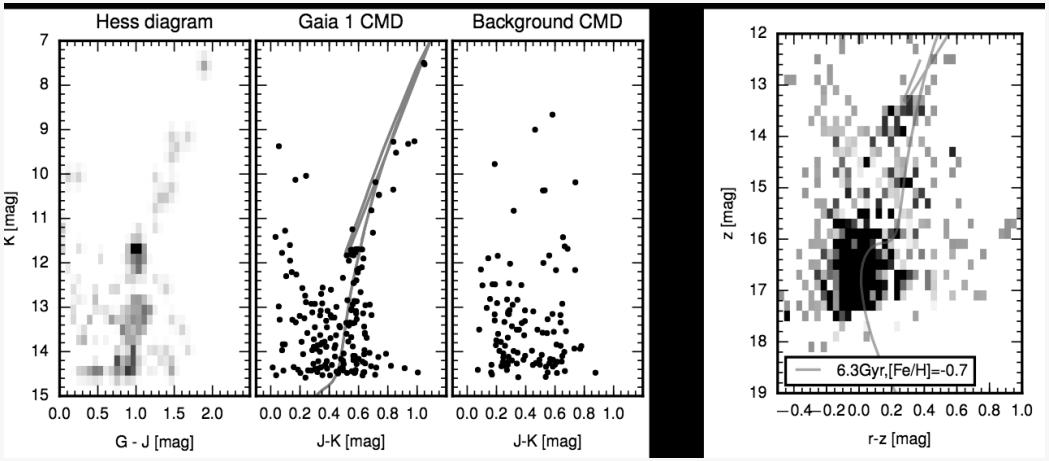
Gaia DR1 and CLUSTERS @IAUS 330

Talk - Eleonora Zari - Stellar content of the Orion OB association
C09 - Delphine Russeil - OB stars towards NGC 6357 and NGC 6334
C11 – Bertrand Goldman - What we learn from TGAS about the moving groups of the Solar neighbourhood
C16 - Joshi Yogesh - Open star clusters and Galactic structure
C20 - Lin Chien-Cheng - Open cluster dynamics via fundamental plane
C26 - David Montes - Revisiting membership of late-type stars to stellar kinematic groups using Gaia-DR1
C43 - Teixeira Ramachrisna - Revisiting TW Hydrae association in light of Gaia-DR1
C46 - Velcovsky Jaroslav - Complex study of the open cluster NGC 2281
C50 - Yen Steffi - Reanalysis of 24 Nearby Open Clusters using Gaia Data
D06 - Guo Difeng - The Sco OB2 Association in Gaia Era

Gaia 1 (behind Sirius) : a globular cluster?







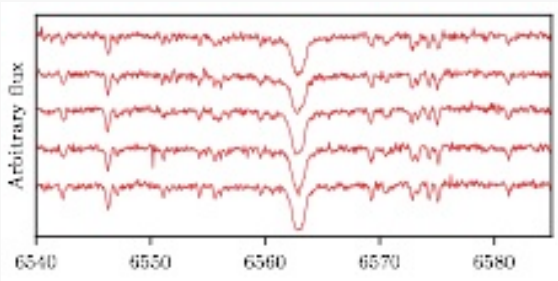
The first new stellar cluster discovered on DR1 data
Koposov+2017 (arXiv:1702.01122)

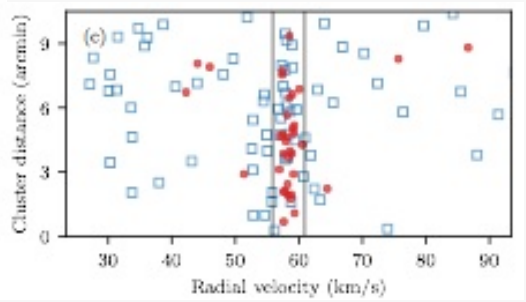
$D_{\odot}$=4.6 ± 0.2 kpc
age=6.3 Gyr, [Fe/H]=-0.7 (PARSEC)
R_h=6.5'±0.4' (=9pc)
Mv=-5.1

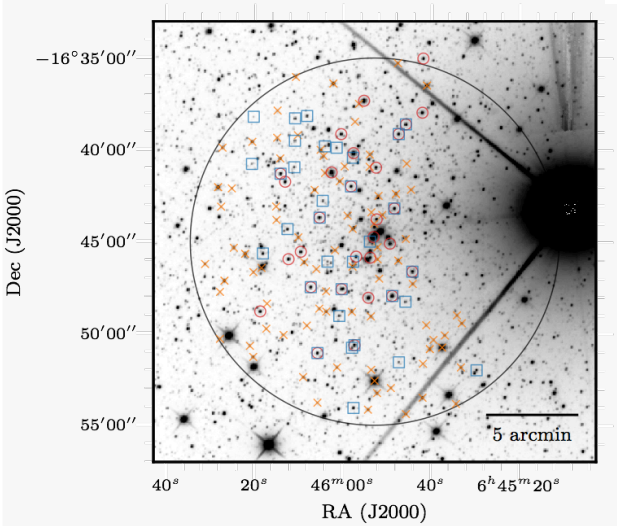
Gaia, 2MASS, WISE, PS1

We conclude that Gaia possesses powerful and unique capabilities for satellite detection thanks to its unrivaled angular resolution and highly efficient object classification.

Gaia 1 (behind Sirius) : an open cluster?



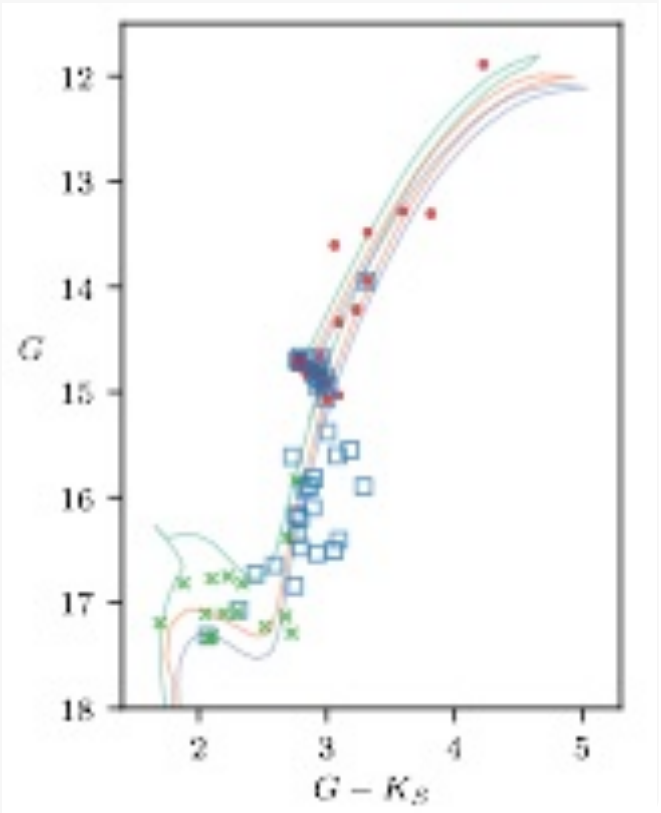




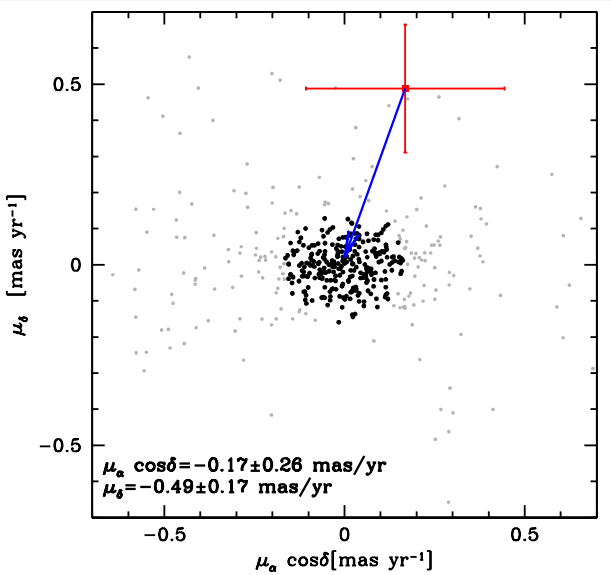
~330 stars HERMES
~660 stars AAOmega

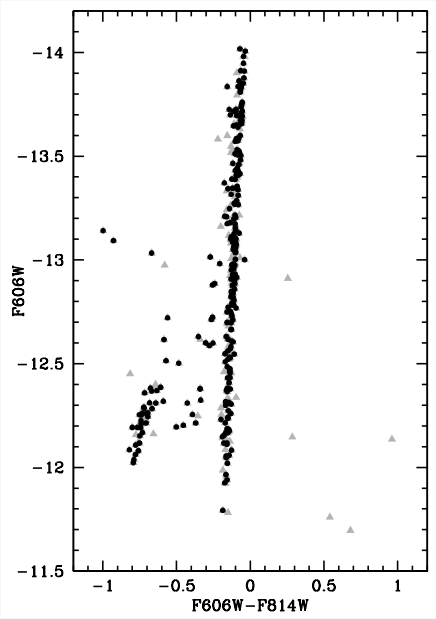
41 members
[Fe/H]=-0.13±0.13
age=3 Gyr
RV=58.3±0.22 km/s
$D_{\odot}$=4.5 ± 0.2 kpc

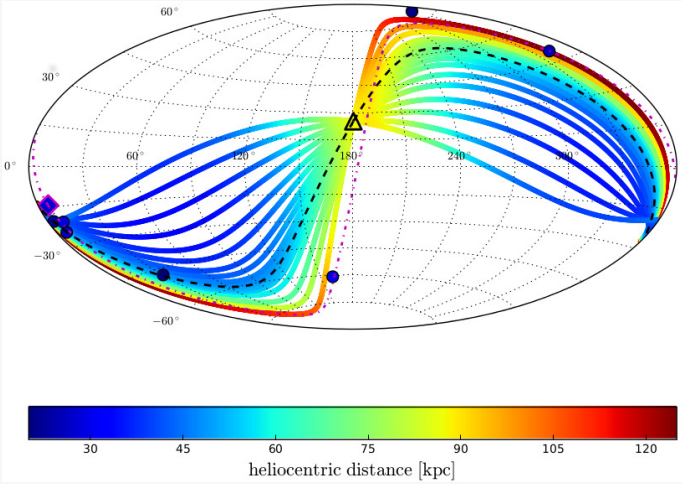
confirmed spectroscopically with HERMES & AAOmega Simpson+2017 (arXiv:1703.03823)



Gaia & HST : PMs for NGC2419







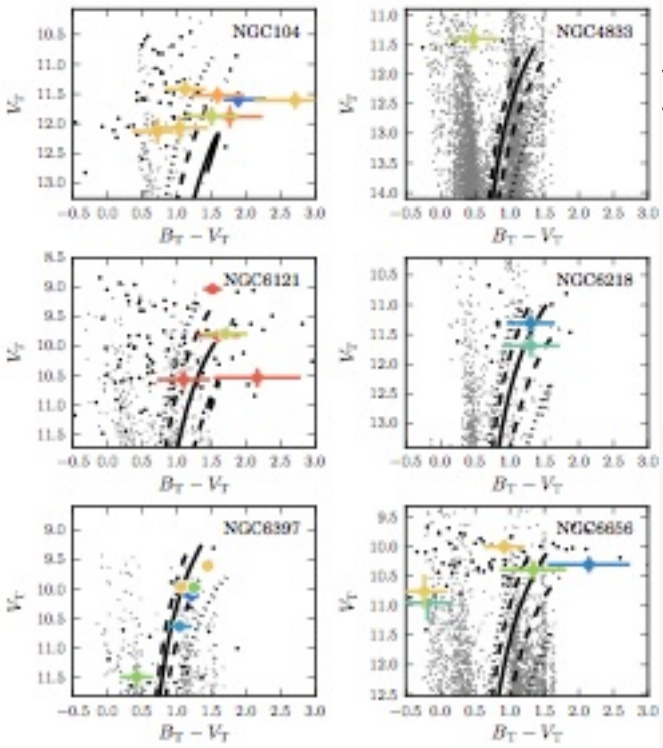
Orbit derivation:
r_P~53 kpc ; r_A~98 kpc
Sagittarius dSph?

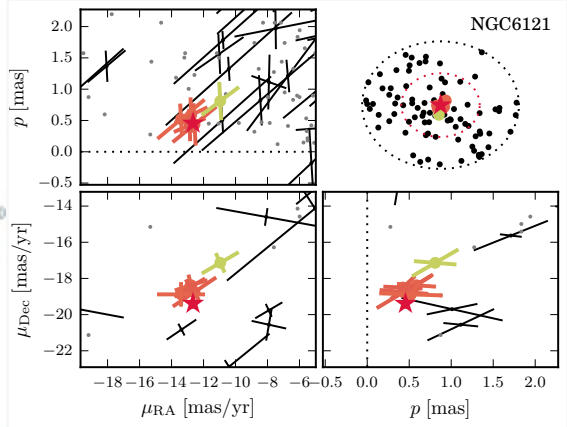
Massari+2017 : the GC NGC2419 (Mv=-9.42, Rgc=90 kpc)
$(\mu\alpha \cos(\delta), \mu\delta) = (-0.17 \pm 0.26, -0.49 \pm 0.17)$ mas yr^{-1}
First epoch : HST, second epoch Gaia DR1 (~12.5 yr baseline)

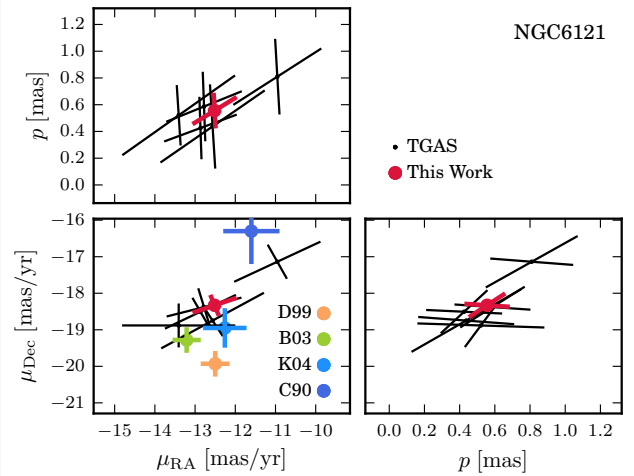
TGAS: π and PM for 5 GCs

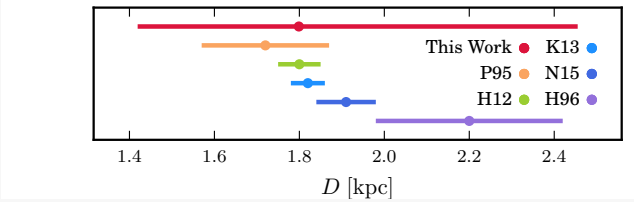
Watkins & van der Marel, subm.

Use TGAS data only









Started with ~1000 TGAS stars in 30 GCs

20 stars in 5 GCs:

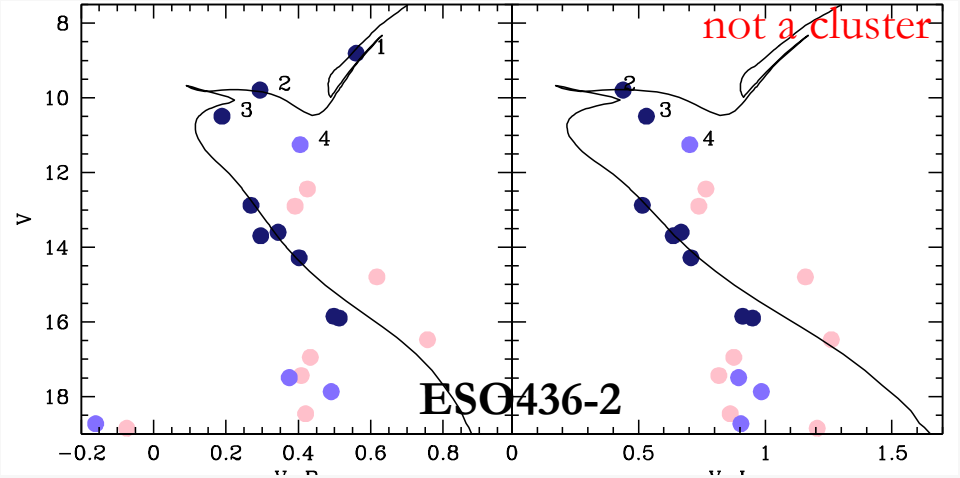
π, PM, UVW

➔ not competitive yet but potential is shown

CMDs + *Gaia* DR1 TO (DIS)PROVE OCs?

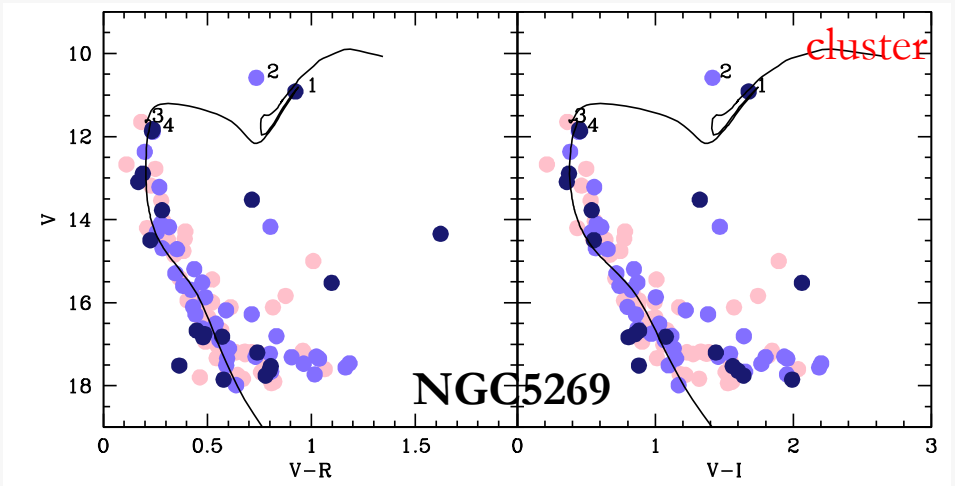
Piatti+2016, 2017 :

a) 7 candidate OCs near dissolution
Rup 3, 9, 37, 74, 150; ESO324-15, 436-2
but the 2 in Gaia DR1 are not clusters?
($\neq \pi$'s, $\neq$ PMs)



b) 15 "catalogue OCs"
8 have 1-7 *Gaia* DR1 stars
from CMD, π, PM
➔ **10 are not OCs**

4 *Gaia* DR1 stars
$\approx \pi$'s (~2.5kpc), PMs
300 Myr, 2kpc



COMPLEMENTING *Gaia*

SPECTROSCOPY, *e.g.* :
SDSS, LAMOST *(low-res)*
RAVE (*intermediate-res, not much on clusters*)

to cite only **high-res**
on-going:
APOGEE (good for IR)
Gaia-ESO ←
GALAH
future:
WEAVE
MOONS
4MOST

PHOTOMETRY, *e.g.* :
SDSS, 2MASS
ESO public surveys @VISTA, @VST
Pan-STARRS1

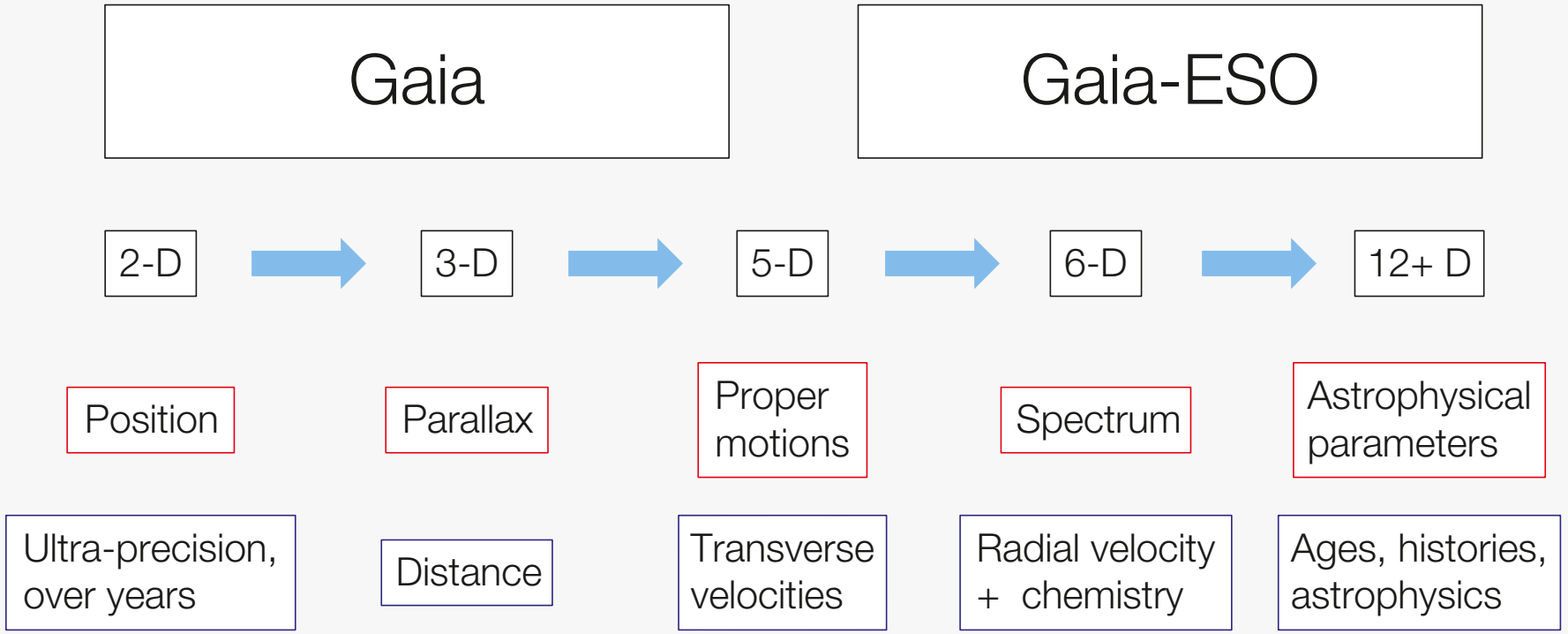
HST (*crowded centers, PM,* π)

JWST, ELTs

LSST *(Gaia's deep complement)*

Gaia-ESO SURVEY

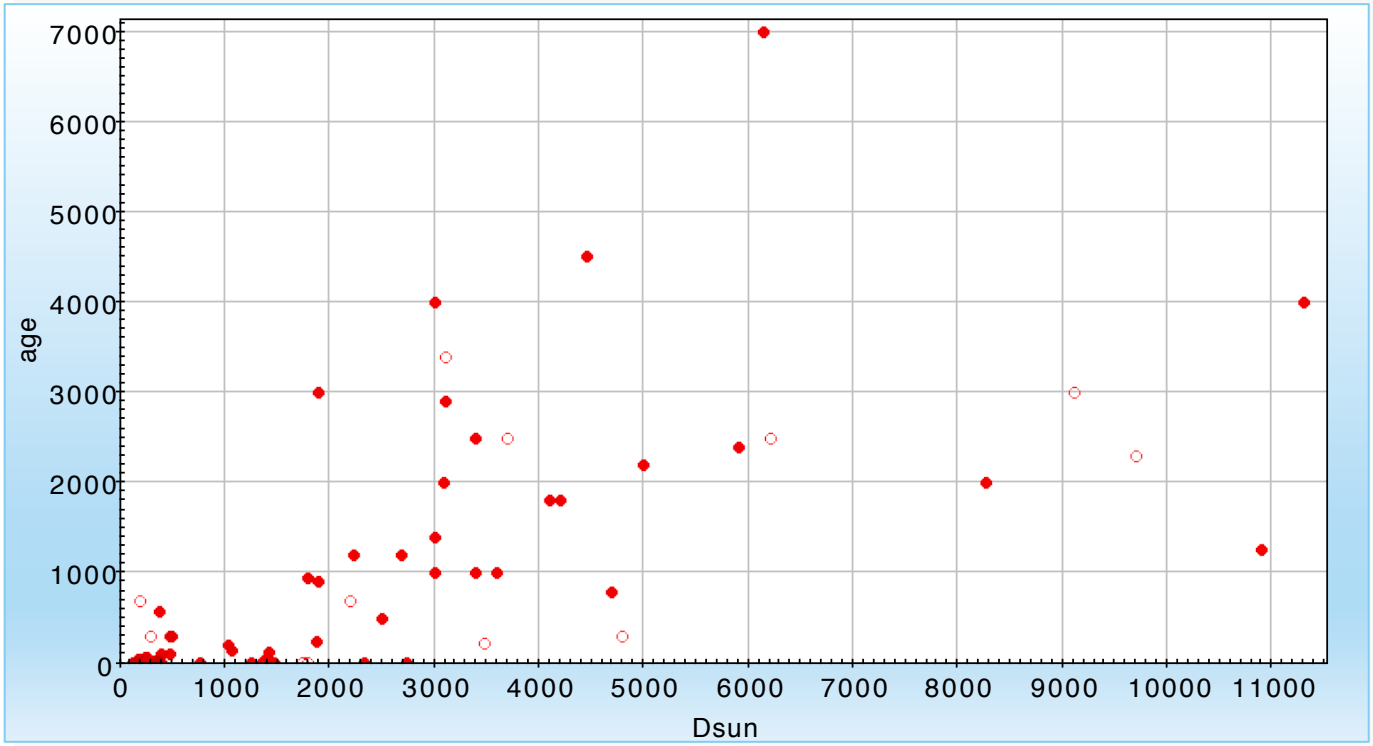
Gaia-ESO SURVEY



Gilmore, Randich, et al. 2012, The Messenger 147, 25 : "The Gaia-ESO Public Spectroscopic Survey"

Gaia-ESO SURVEY: OPEN CLUSTERS

$D_\odot$ (in pc) vs age (in Myr)

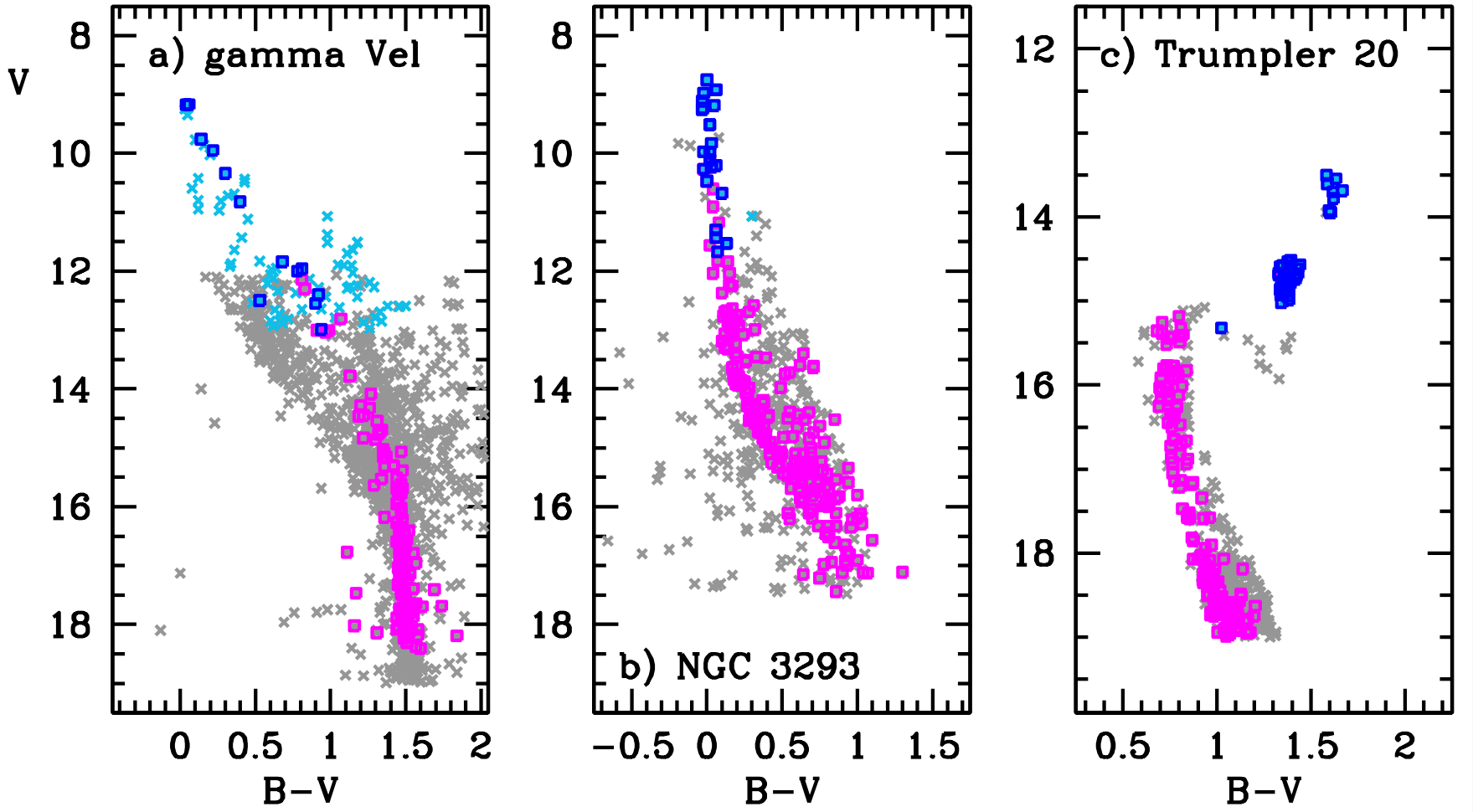


Open clusters & SFRs

- cluster formation and evolution
- Galaxy chemo-dynamics
- stellar evolution

age/metallicity/mass/Rgc range for OCs well covered

Gaia-ESO SURVEY: OPEN CLUSTERS



Gaia-ESO SURVEY and TGAS

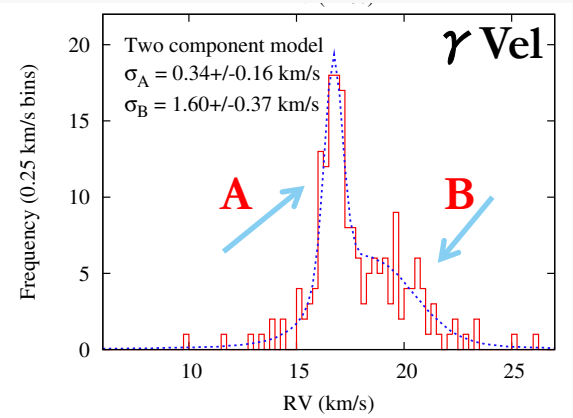
van Leeuwen & Gaia collaboration 2017 :
DR1 verification paper on open clusters

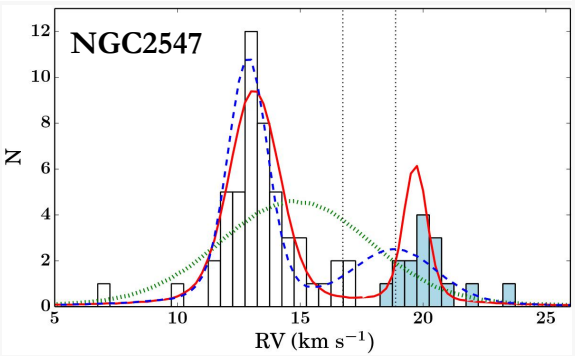
Gaia-ESO spectroscopy:

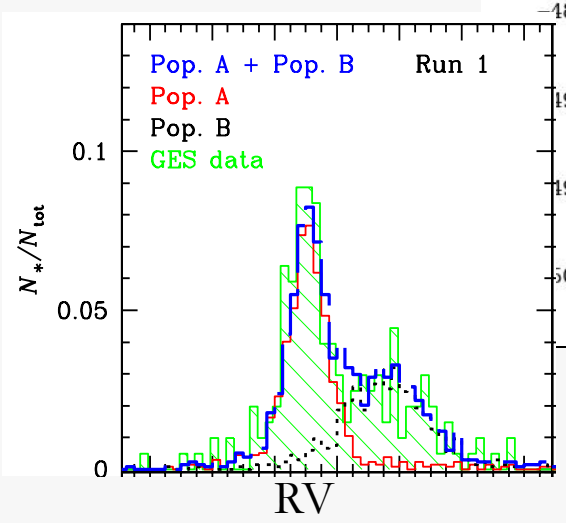
1	Hyades	(too sparse)
2	Coma Ber	(dec +26)
3	Praesepe	(TBA)
4	Pleaides	(dec +24)
5	α Per	(dec +48)
6	IC2391	
7	IC2602	
8	Blanco 1	
9	NGC2451A	
10	NGC6475	(TBA)
11	NGC7092	(dec +48)
12	NGC2516	
13	NGC2232	
14	IC4665	
15	NGC6633	
16	Cr 140	
17	NGC2422	
18	NGC3532	
19	NGC2547	

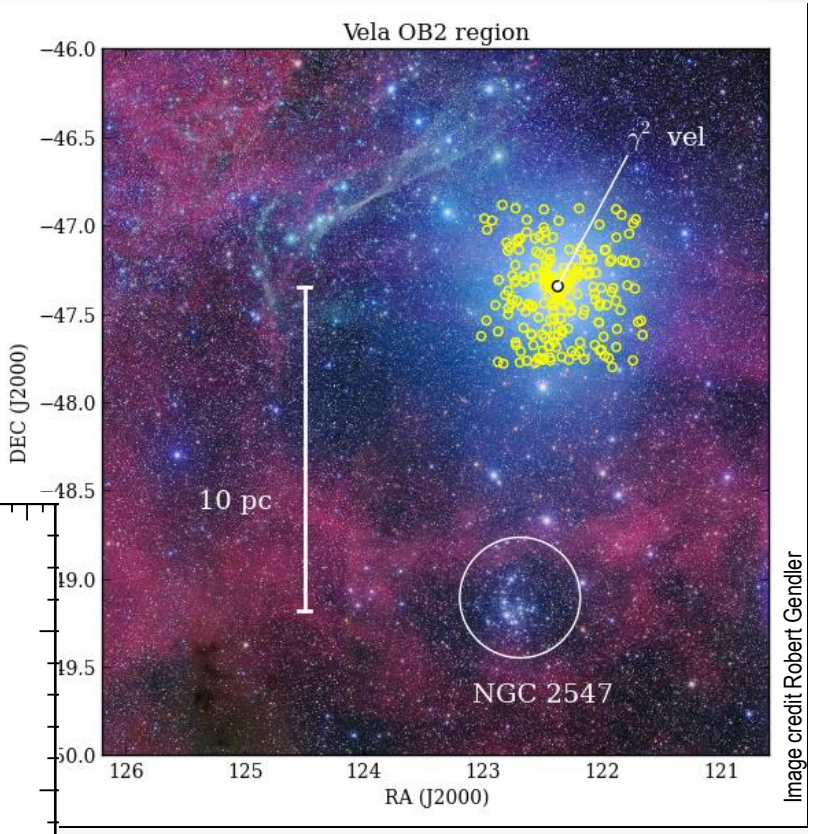
Gaia-ESO SURVEY: KINEMATICS

Jeffries+2014; Sacco+2015; Mapelli+2015 :
γ Vel has 2 subgroups [$\neq$RV, $\neq \sigma$ (RV)]
group B is visible in NGC2547 data
models : 2 subclusters from same cloud



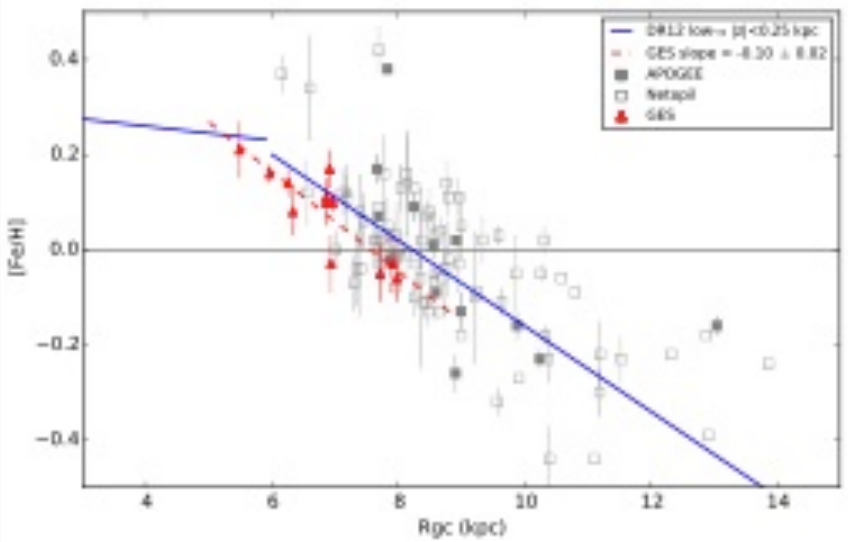






only RV used
Gaia **π , PM : more robust result**

Gaia-ESO SURVEY: MW DISK

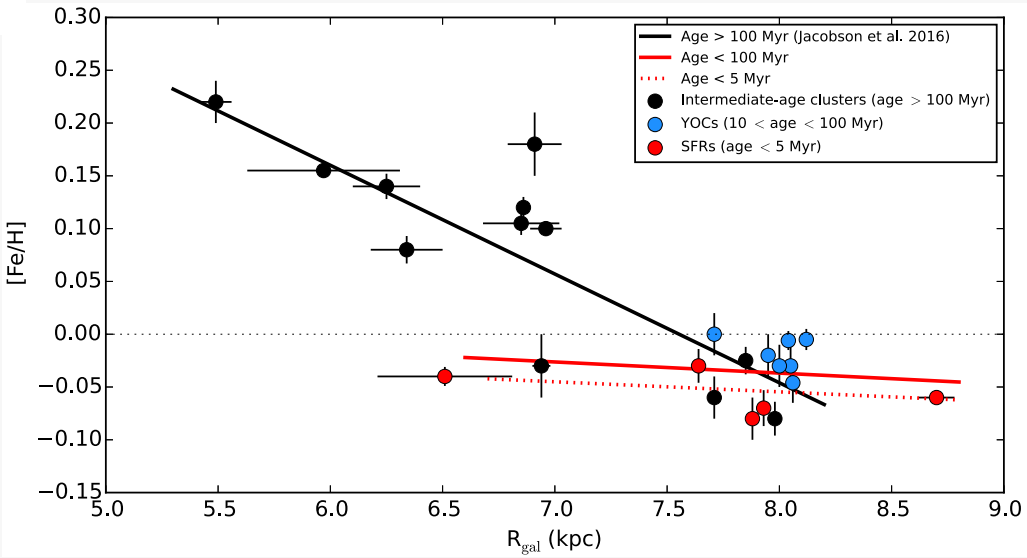


Jacobson+2016: inner disk metallicity gradient with GES open clusters (age > 100 Myr)

[Fe/H] vs Rgc

Gaia-ESO: RV, metallicity, chemistry

Gaia: distance, PM

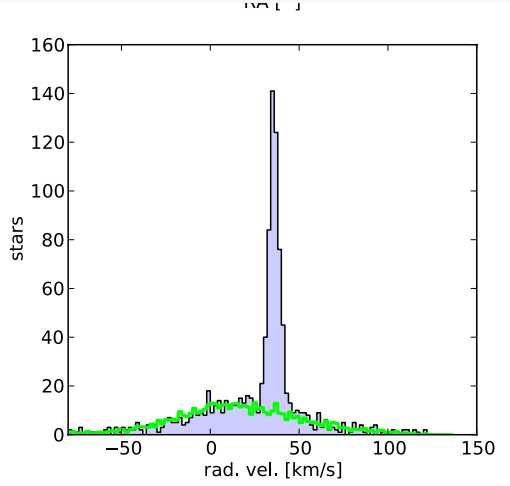


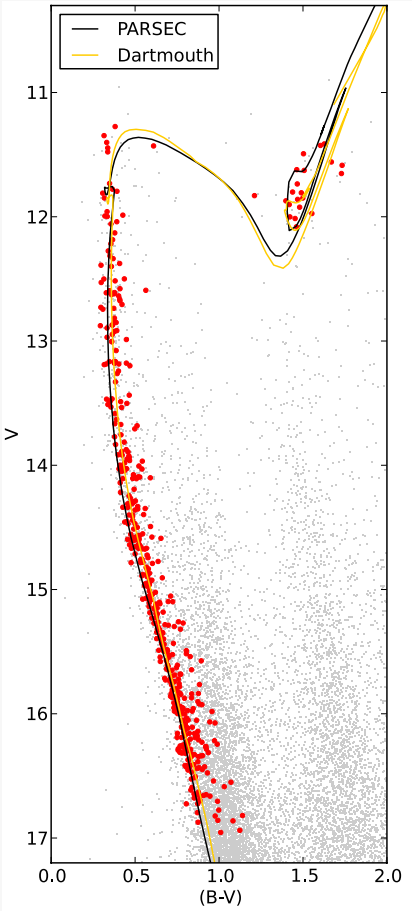
Spina+2017: present-day gradient with PMS clusters

Based on GES iDR4 – by now already 50 observed, 12+ TBO, a few more to come)

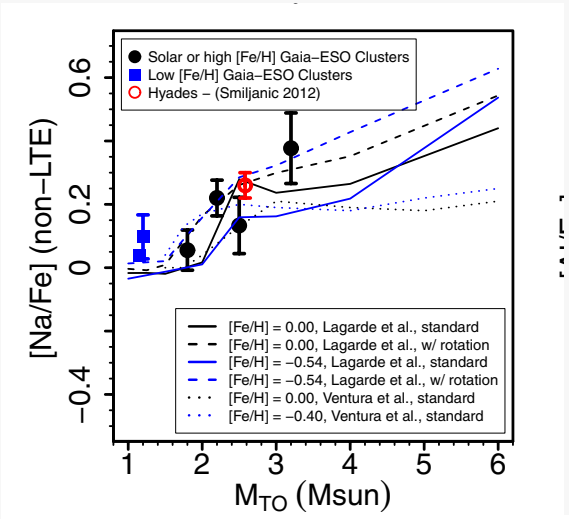
Gaia-ESO SURVEY: STELLAR MODELS

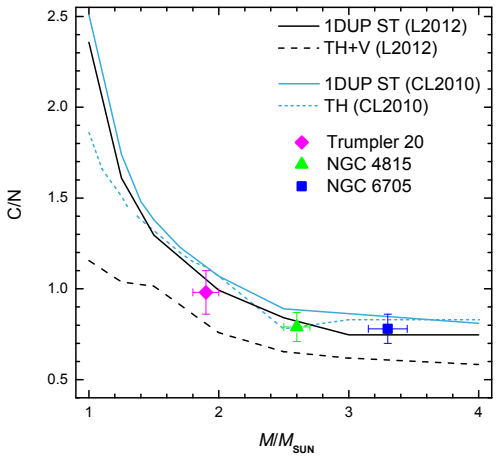
Cantat-Gaudin+2014 :
M11 as test of stellar evolution models
(*Gaia* π, PM very useful)





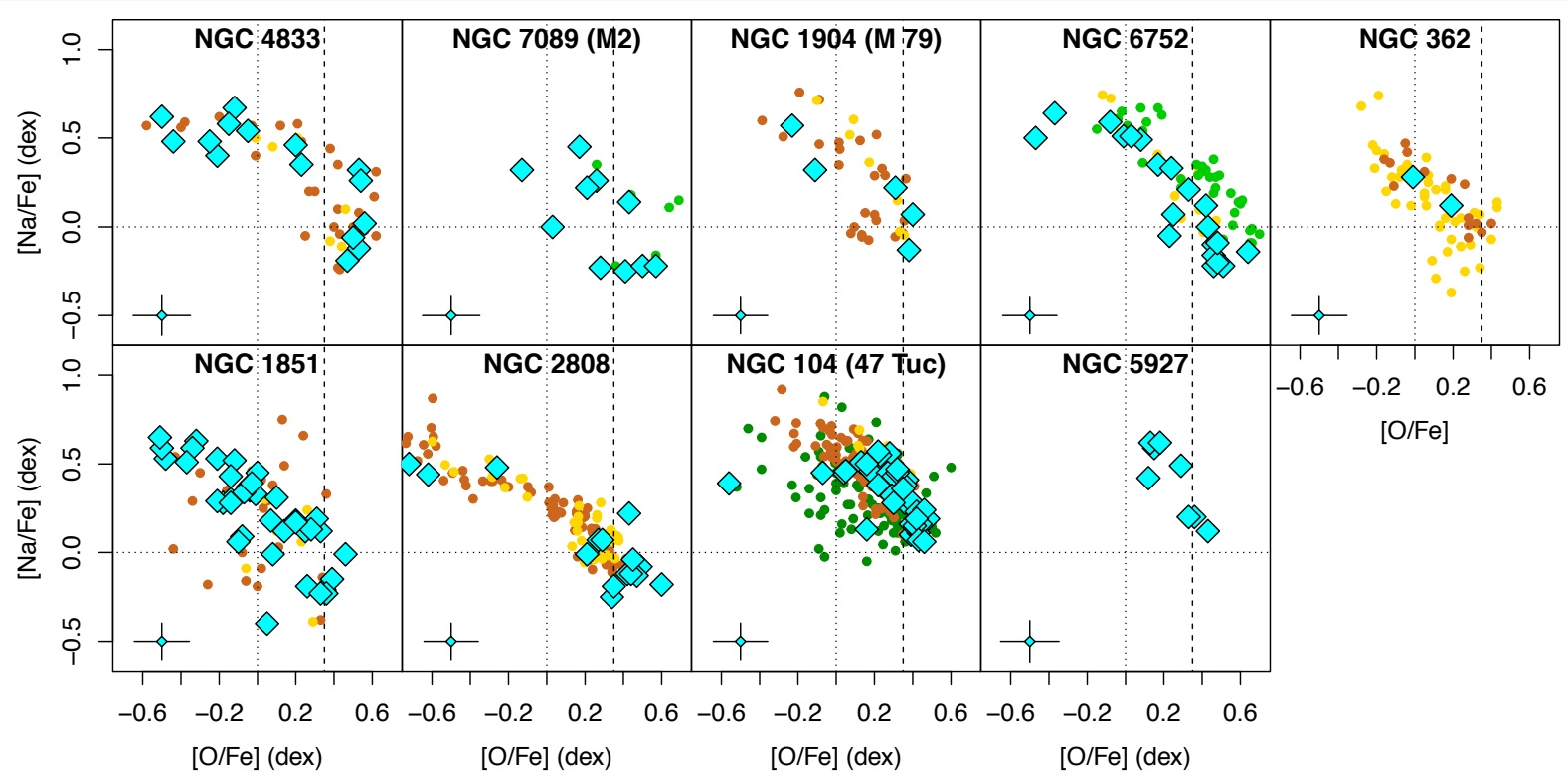
Smiljanic+2016, Tautvaisiene+2014 :
Na; C,N as test of mixing models





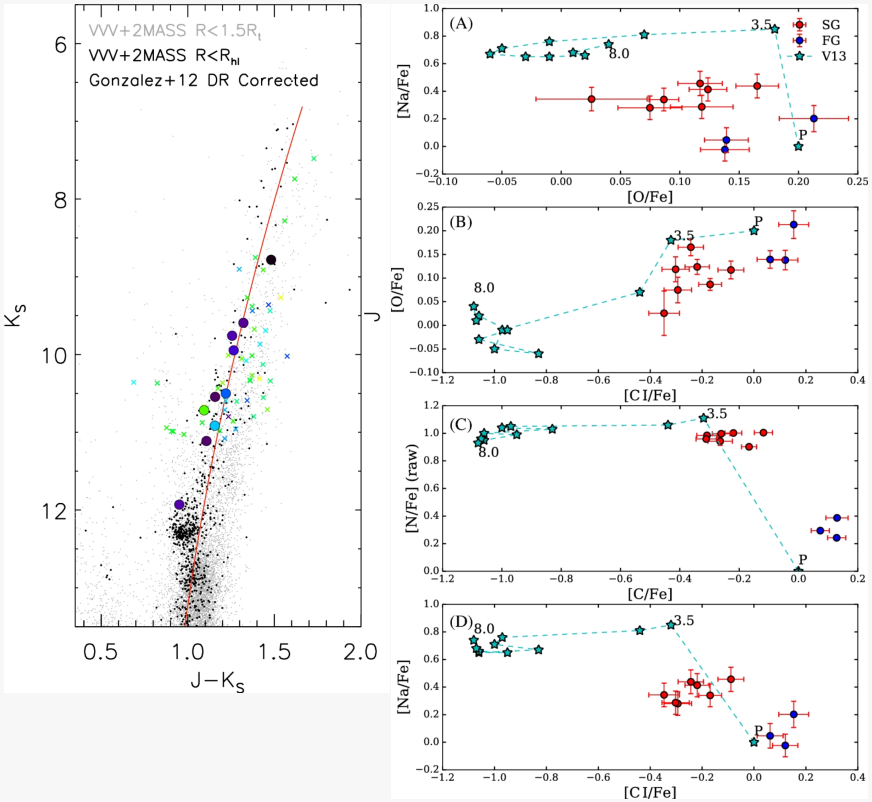
Gaia-ESO SURVEY: GLOBULAR CLUSTERS

Pancino+2017

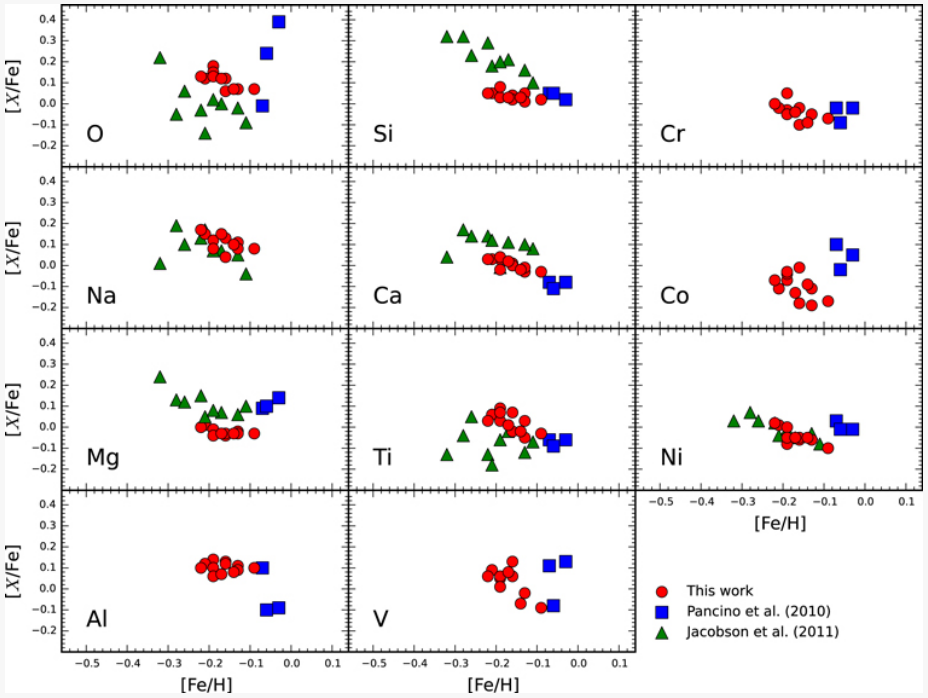


APOGEE

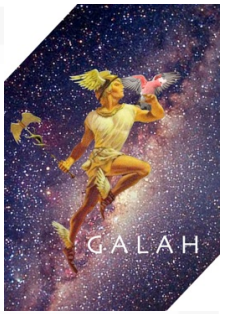
Tang+2017: two populations in the bulge GC NGC6553



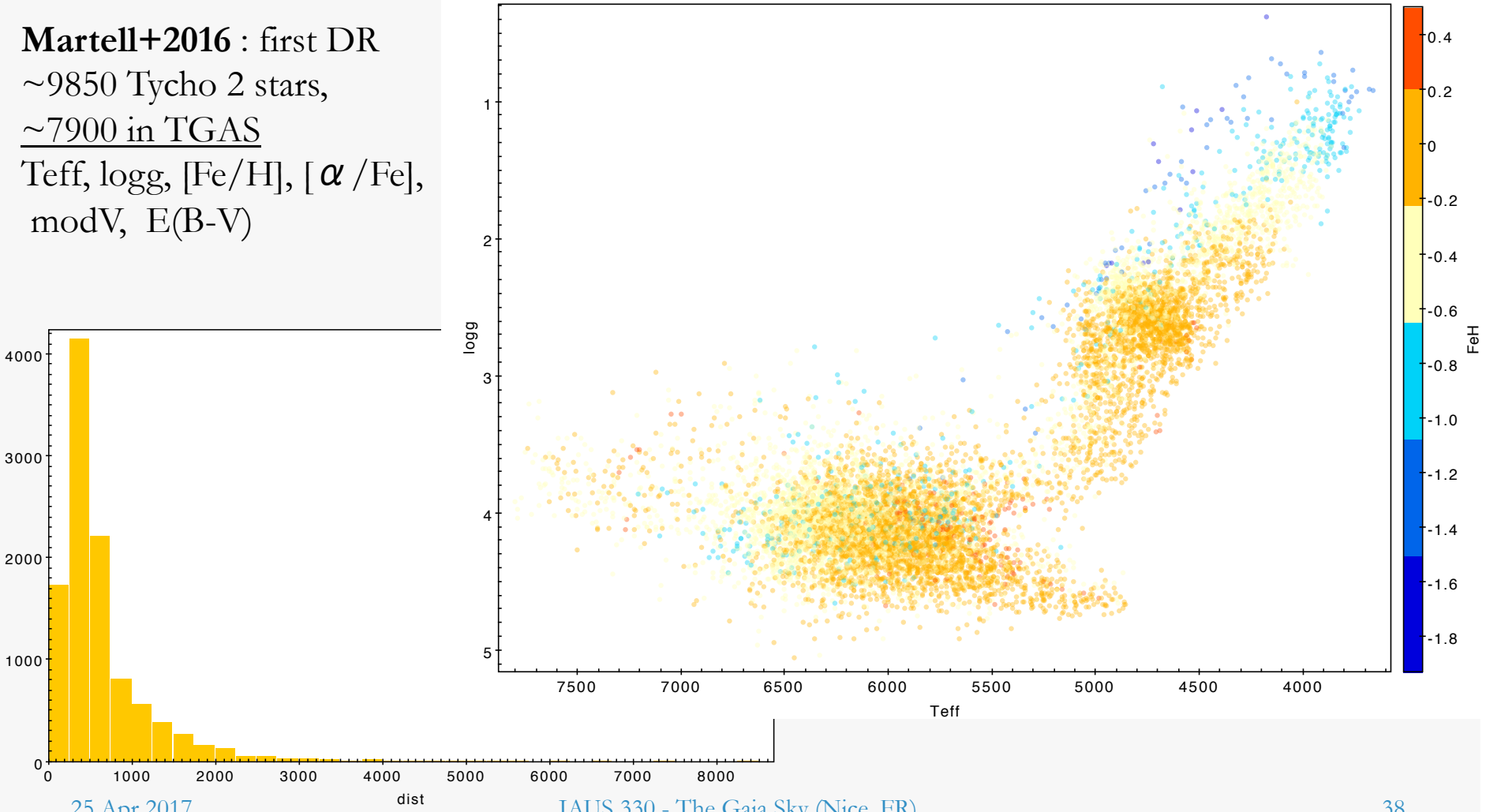
Souto+2016: RGB stars in NGC2420



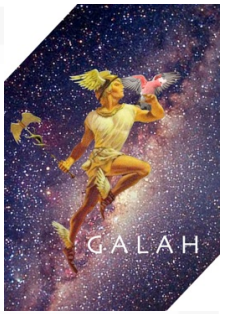
GALAH



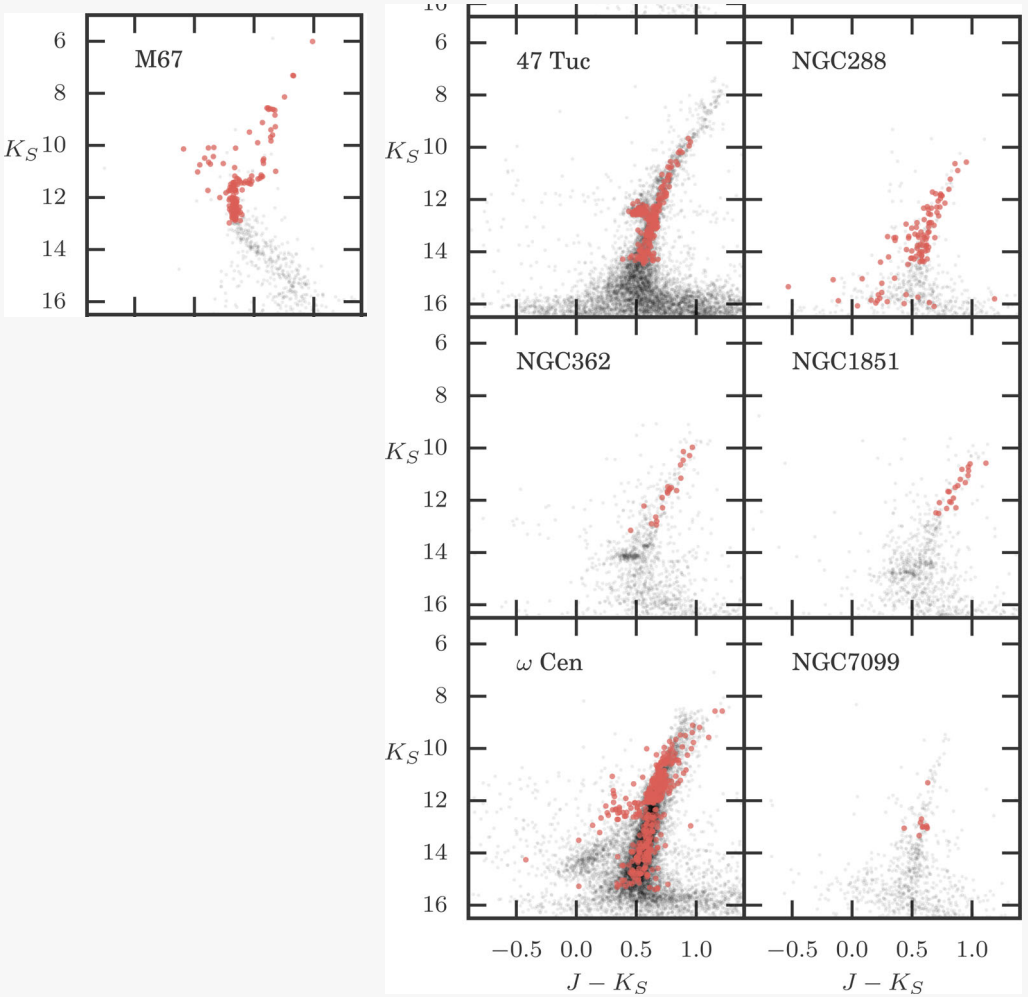
Martell+2016 : first DR
~9850 Tycho 2 stars,
~7900 in TGAS
Teff, logg, [Fe/H], [α/Fe],
modV, E(B-V)



GALAH

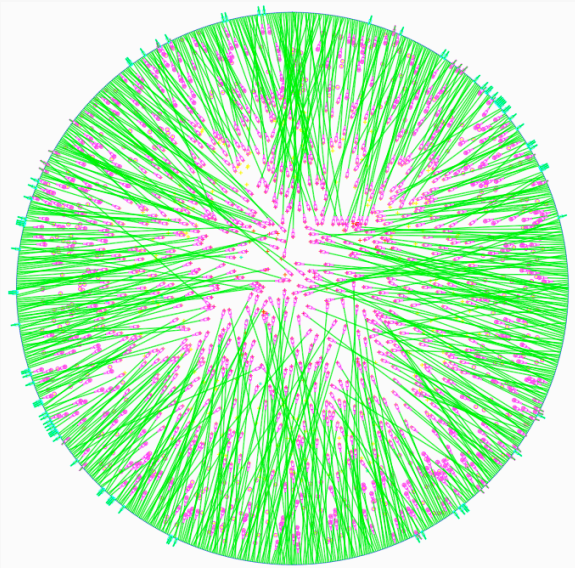


Martell+2016 :
as part of pilot/calib survey
6 GCs (NGC104, NGC1851, NGC362, NGC288, ωCen, NGC7099)
and M67



WEAVE

WEAVE = WHT Enhanced Area Velocity Explorer



@ 4.2m WHT, La Palma
2º diameter
960 (plate A)/940 (plate B) fibers
1.3" fiber diameter + mIFUs, LIFUs
LR (R~5000) : 366-959 nm
HR (R~20000) : 404-465/473-545 + 595-685nm

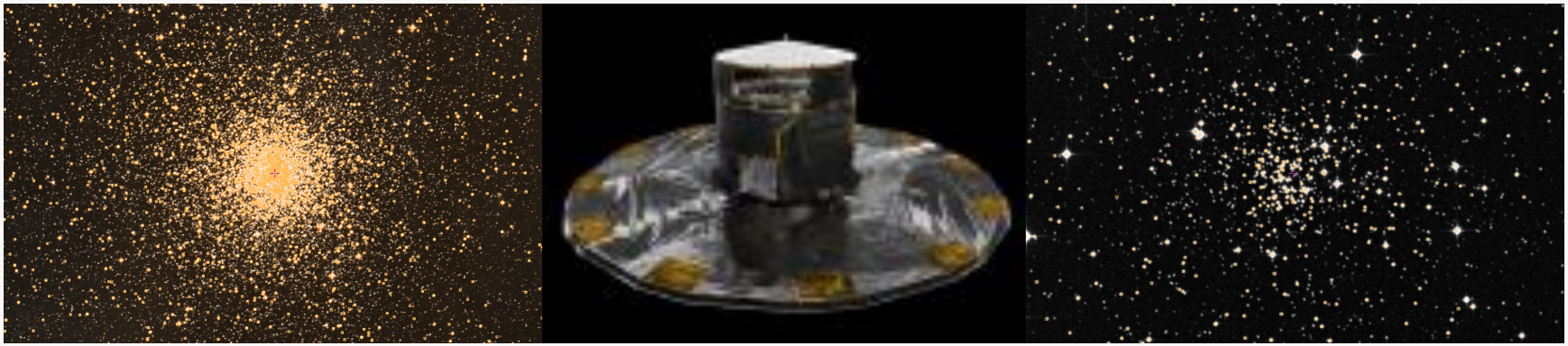
Has dedicated survey for open clusters and for star forming regions
Will observe globulars

THIS IS NOT A SUMMARY

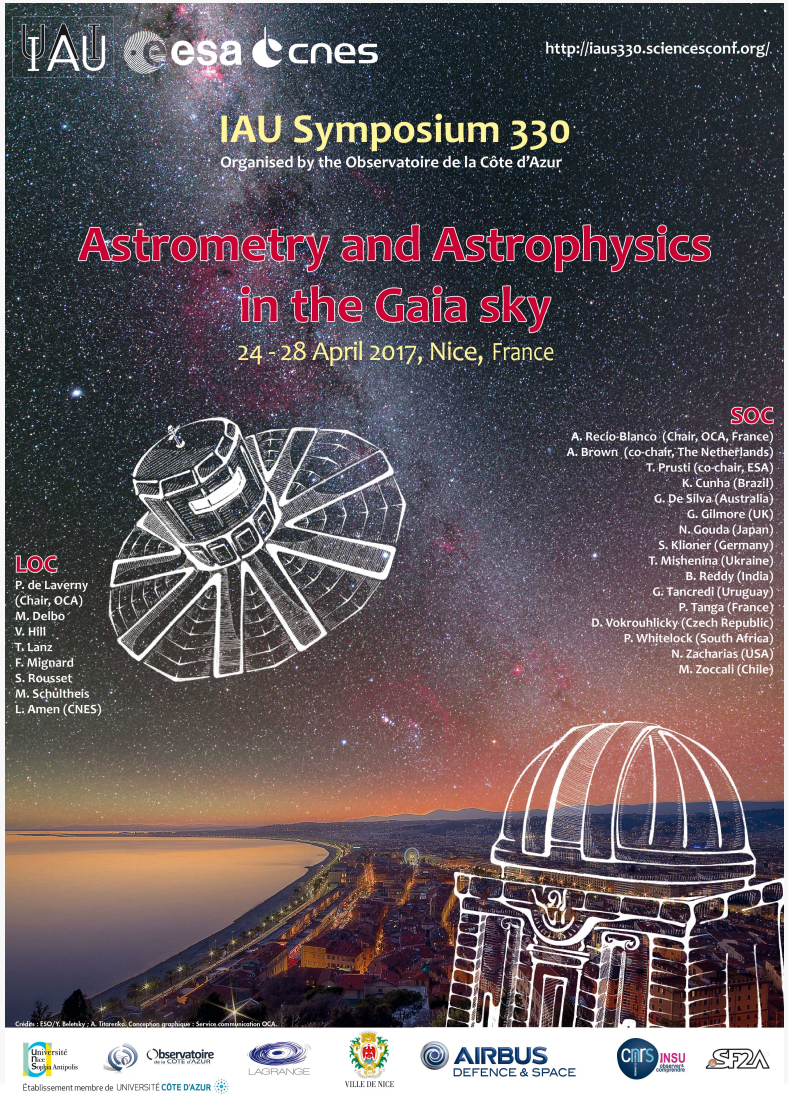
Already results on clusters, considering Gaia and complementing surveys

Let's get more from Gaia DR1

Let's get ready for Gaia DR2



THANK YOU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Organised by the Observatoire de la Côte d'Azur
Astrometry and Astrophysics in the Gaia sky
24 - 28 April 2017, Nice, France
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