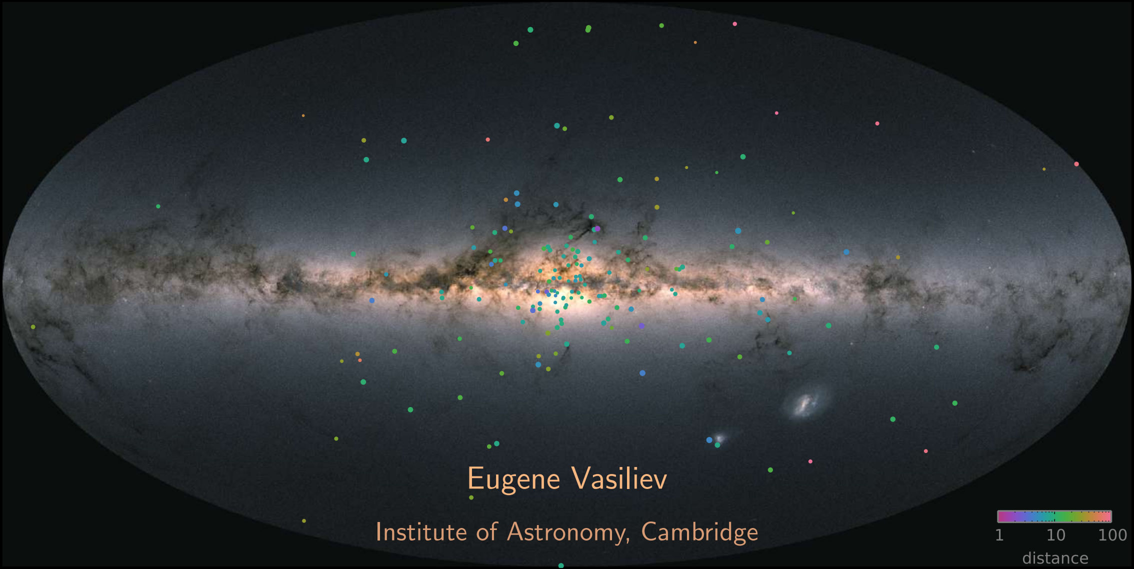
Gaia EDR3 view on Galactic globular clusters



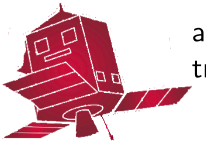
Eugene Vasiliev

Institute of Astronomy, Cambridge

IAP seminar, 17 June 2021

based on: Vasiliev & Baumgardt (2102.09568), Baumgardt & Vasiliev (2105.09526)

The Gaia [r]evolution



Hipparcos (1989–1993)

all-sky photometry: 10^9 stars

Hipparcos + Gaia = TGAS

astrometry: 2M nearby stars

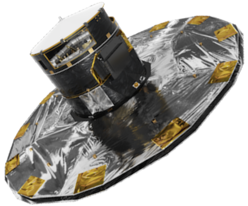
astrometry and colours: $> 10^9$, V_{los}: 7M stars with $G \lesssim 13$

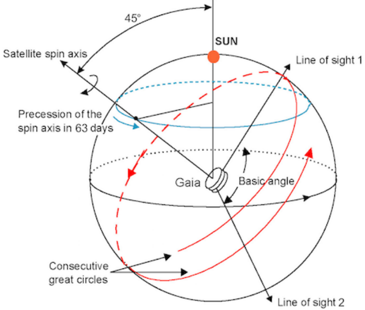
22 months

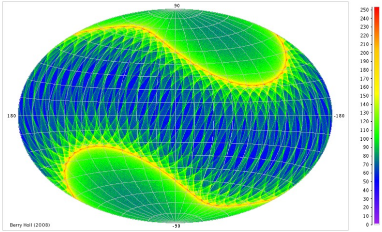
improved precision and reduced calibration errors

34 months

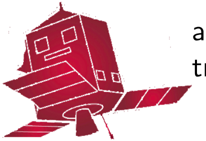
DR1 $\Longrightarrow$ DR2 $\Longrightarrow$ EDR3







The Gaia [r]evolution



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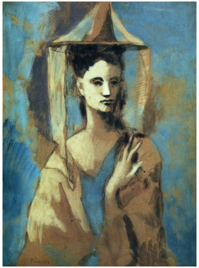
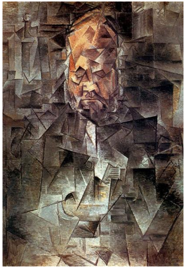
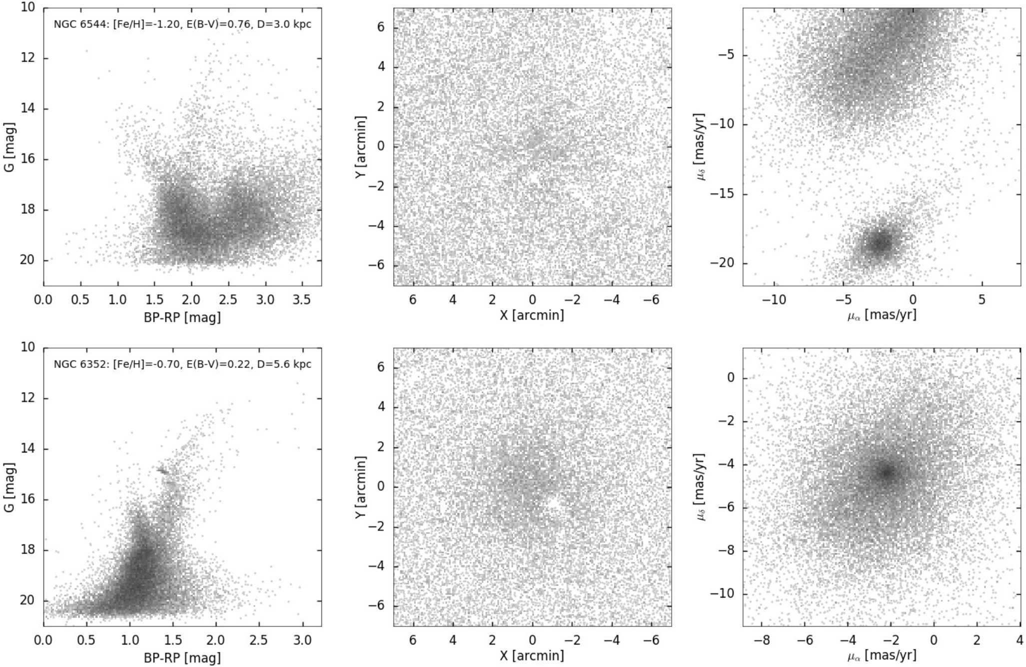
$V_{\rm los}$ for fainter stars; binary parameters; epoch astrometry and photometry...

pre-Gaia $\Longrightarrow$ DR1 $\Longrightarrow$ DR2 $\Longrightarrow$ EDR3 $\Longrightarrow$ DR3, 4, 5

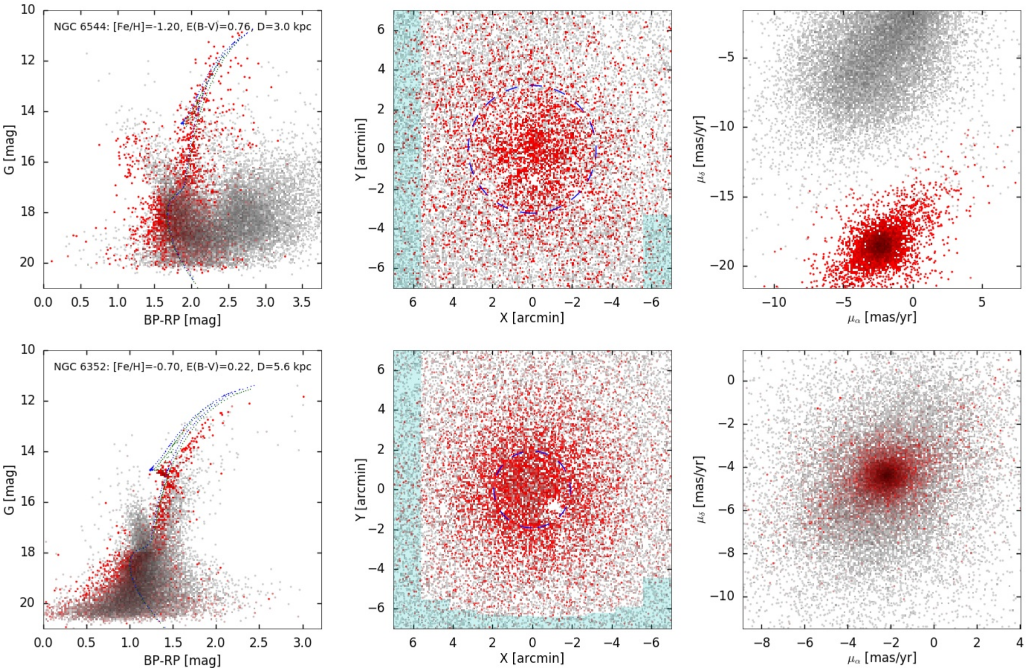




Determination of cluster membership

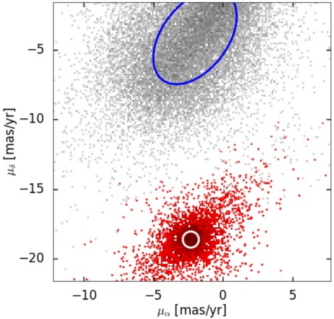


Determination of cluster membership



Determination of cluster membership and parameters

A hard cutoff in PM space is not always possible and is conceptually unsatisfactory.



A more mathematically well-grounded alternative: mixture modelling [Gaussian or more general].

Write down the distribution functions for both cluster and field populations, and vary their parameters $\boldsymbol{\theta}$ to maximize the likelihood of the observed data data:

true DF convolved with errors — measurements: $\varpi, \boldsymbol{\mu}, R$ — measurement uncertainties

$$\ln \mathscr{L} \equiv \sum_{i=1}^{N_{\rm stars}} \ln \left[\eta\, f_{\rm memb}(\mathbf{x}_i,\ \delta\mathbf{x}_i \mid \boldsymbol{\theta}_{\rm memb}) + (1-\eta)\, f_{\rm field}(\mathbf{x}_i,\ \delta\mathbf{x}_i \mid \boldsymbol{\theta}_{\rm field})\right]$$

fraction of members — parameters of distributions

Results: cluster properties $\overline{\varpi},\ \overline{\boldsymbol{\mu}},\ \sigma_\mu(R),\ \mu_{\rm rot}(R),\ \eta,\ \dots$

and membership probability of each star: $p_i = \dfrac{\eta\, f_{\rm memb}(\mathbf{x}_i)}{\eta\, f_{\rm memb}(\mathbf{x}_i) + (1-\eta)\, f_{\rm field}(\mathbf{x}_i)}$.

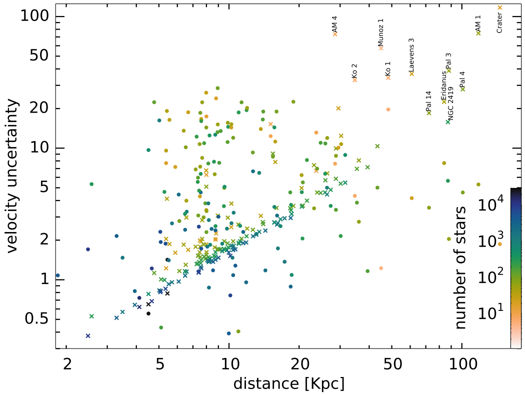
6d kinematics of star clusters

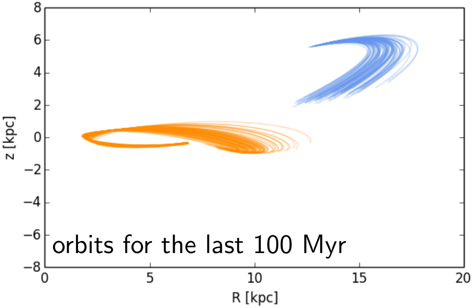
typical PM uncertainty: $\delta\mu \simeq 0.025$ mas/yr

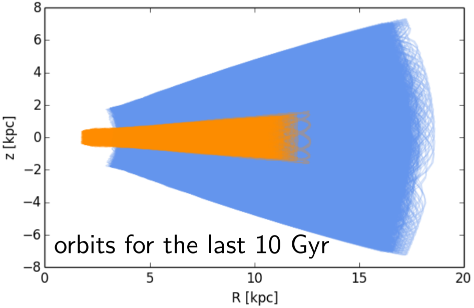
distance uncertainty: $\sim$ a few percent

$$\frac{v}{\text{km/s}} = 4.74 \, \frac{\mu}{\text{mas/yr}} \, \frac{D}{\text{kpc}}$$

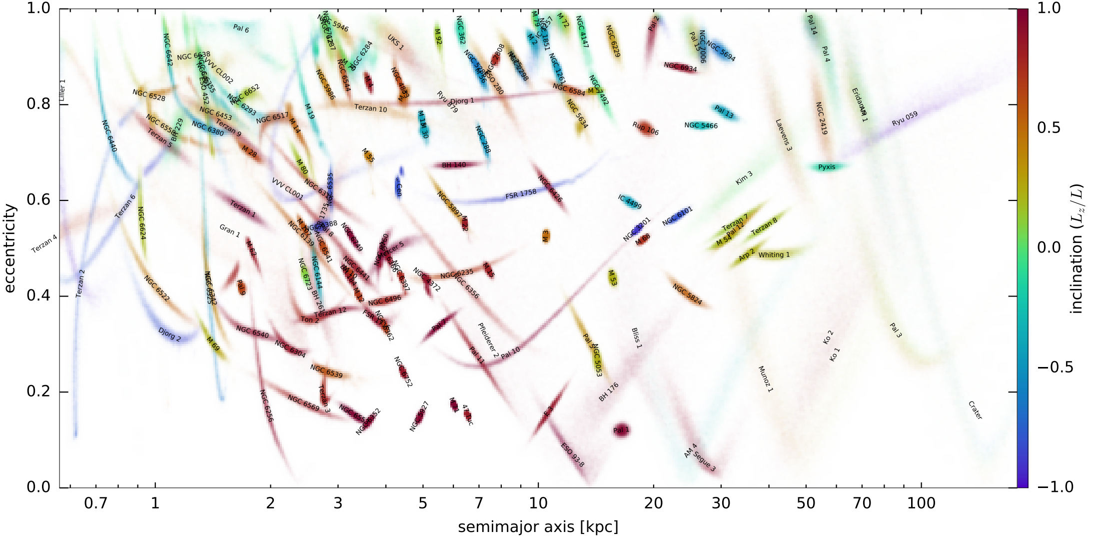
distance uncertainty usually dominates



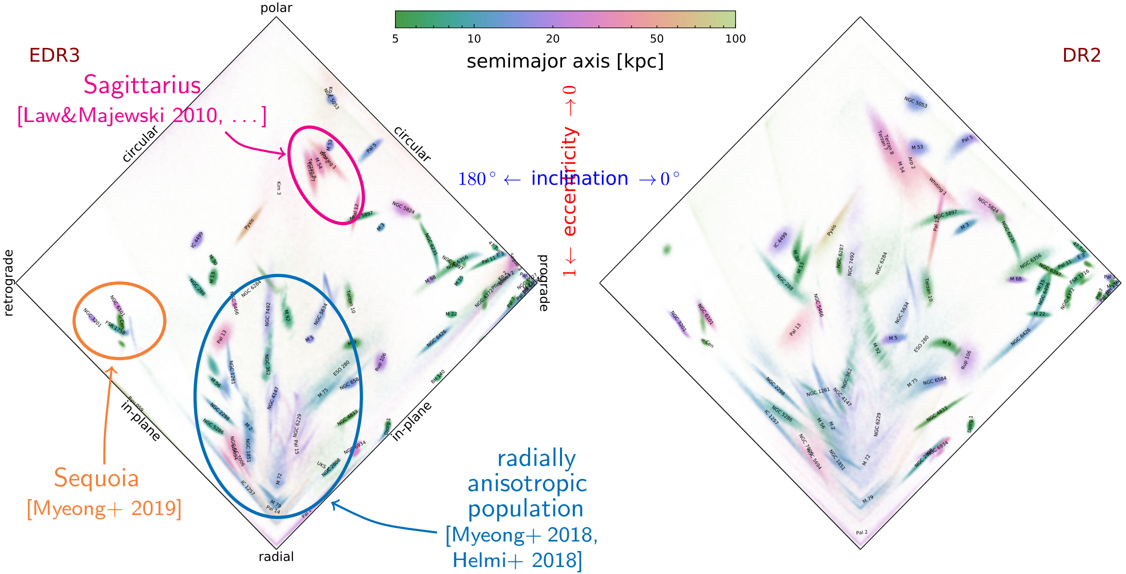




Orbits of star clusters



Clusters in the space of integrals of motion

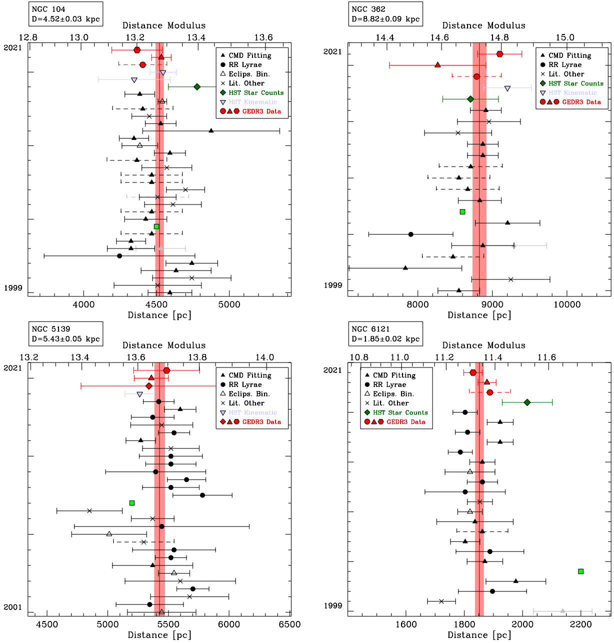


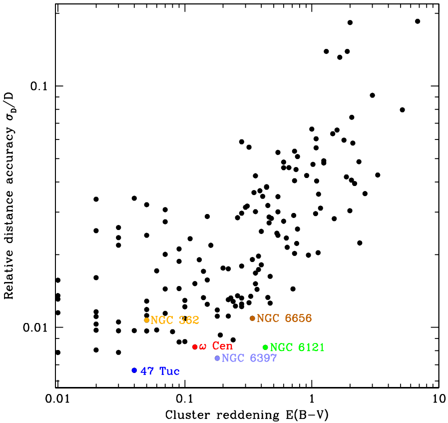
Clusters in the space of integrals of motion

Jackson Pollock, “Convergence”

Kliment Redko, “Uprising”

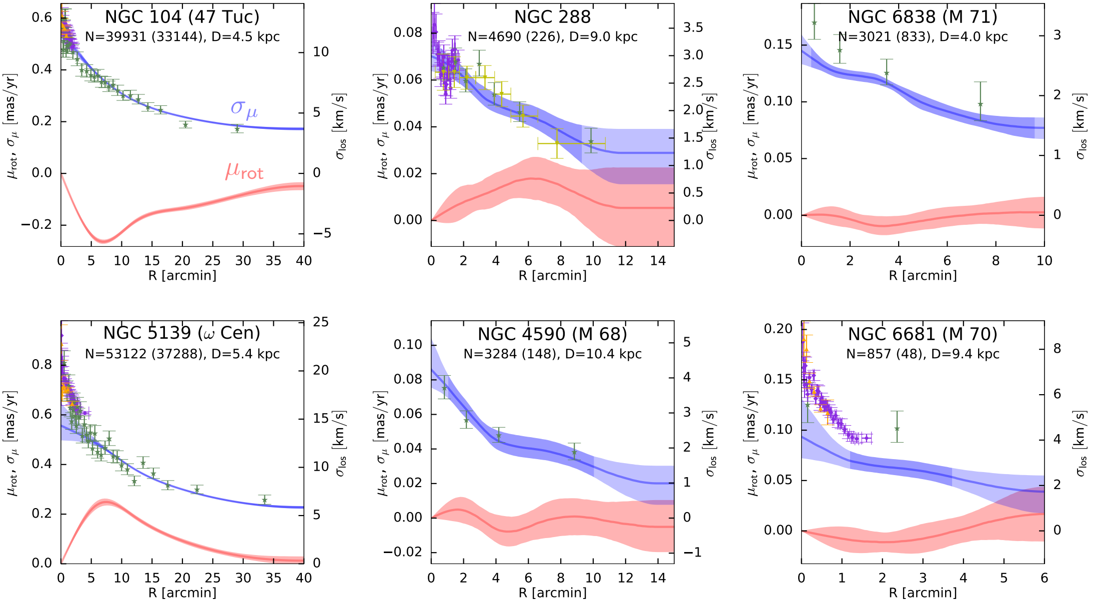
Distances to star clusters





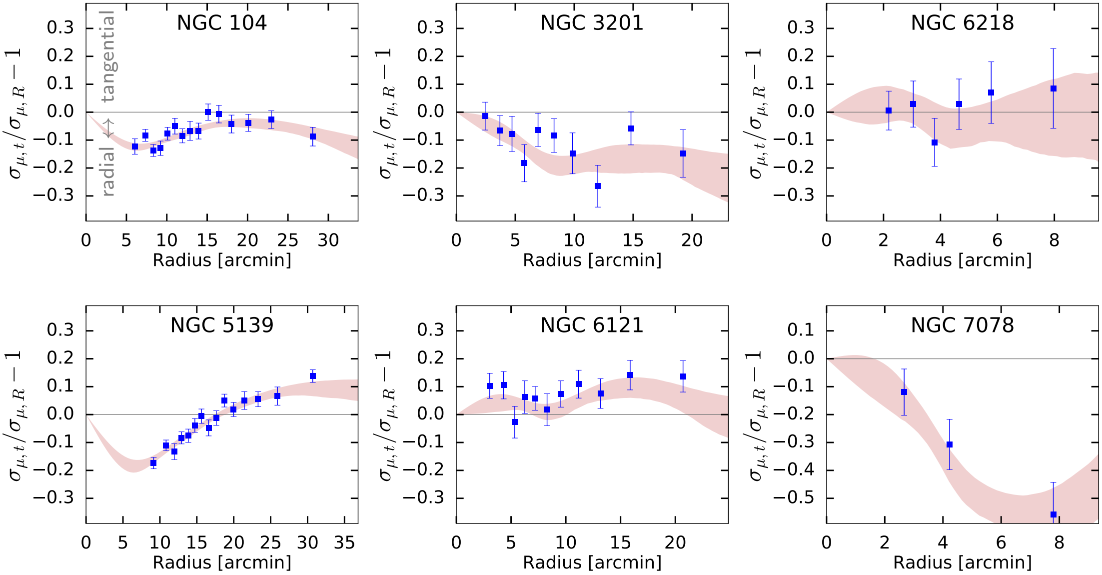
compilation of ∼ 1300 measurements from literature by Holger Baumgardt (CMD, RR Lyrae, eclipsing binaries) + HST/Gaia dynamical fits & parallaxes

Internal kinematics: rotation, dispersion



Good agreement with HST σ_μ [Watkins+ 2015, Cohen+ 2021] and σ_{LOS} from literature

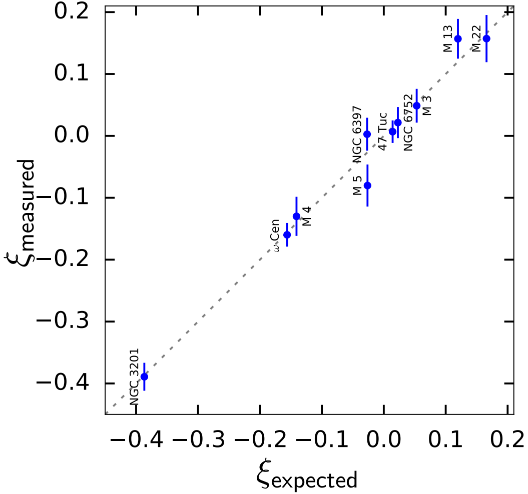
PM anisotropy profiles

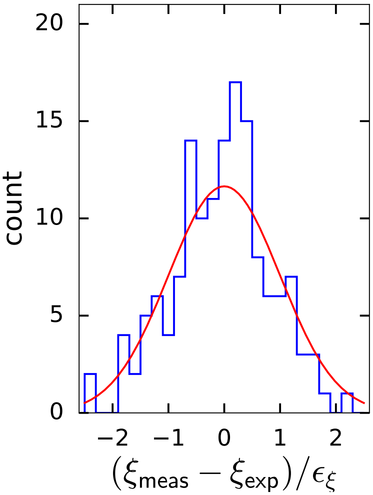


variety of profiles, mostly weakly radial or isotropic

Perspective effects in the radial PM component

Perspective contraction/expansion due to line-of-sight motion:
$\mu_R(R) = \xi\, R, \;\; \xi_{\text{expected}} = -v_{\text{LOS}}/D \times (\pi/180^\circ/4.74)$ mas/yr/degree.

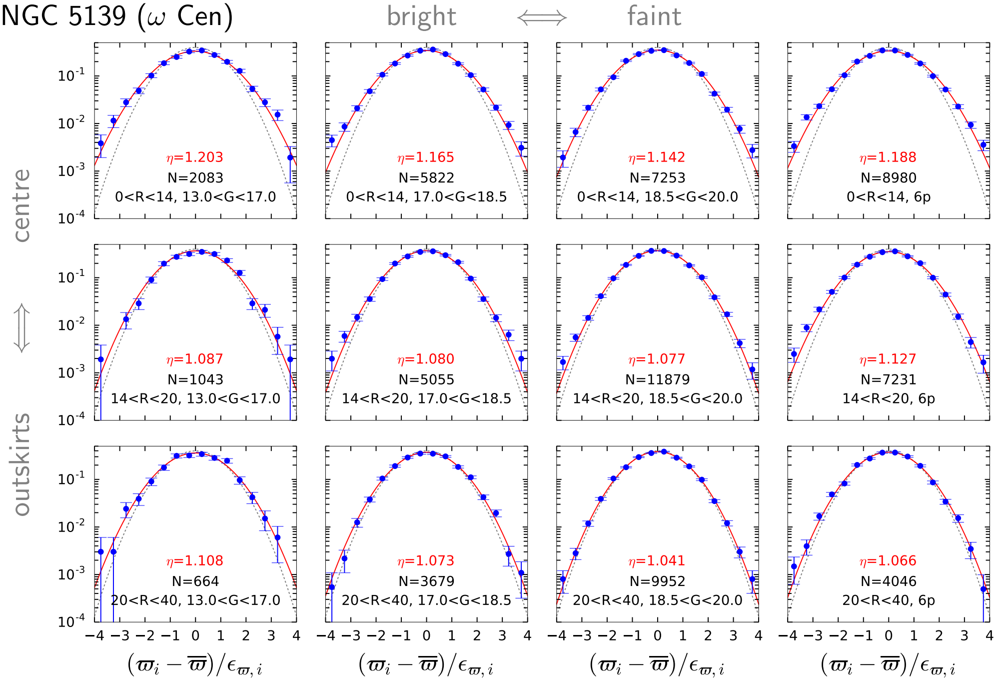




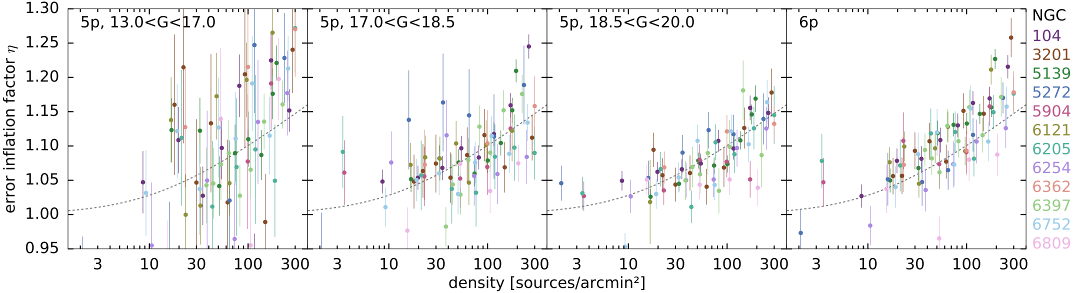
(error bars take into account spatially correlated systematics)

Caveat 1: statistical uncertainties are slightly underestimated

NGC 5139 (ω Cen)



Caveat 1: statistical uncertainties are slightly underestimated



Actual vs. formal uncertainty:

$$\epsilon^2_{\text{actual}} = \eta^2\,\epsilon^2_{\text{formal}} + \epsilon^2_{\text{add}},$$

error inflation factor

$$\eta = (1+\Sigma/\Sigma_0)^\zeta,$$

$$\Sigma_0 = 10\ \text{stars/arcmin}^2,$$

$$\zeta = 0.04,$$

$$\epsilon_{\text{add}} = 0.01\ \text{mas}.$$

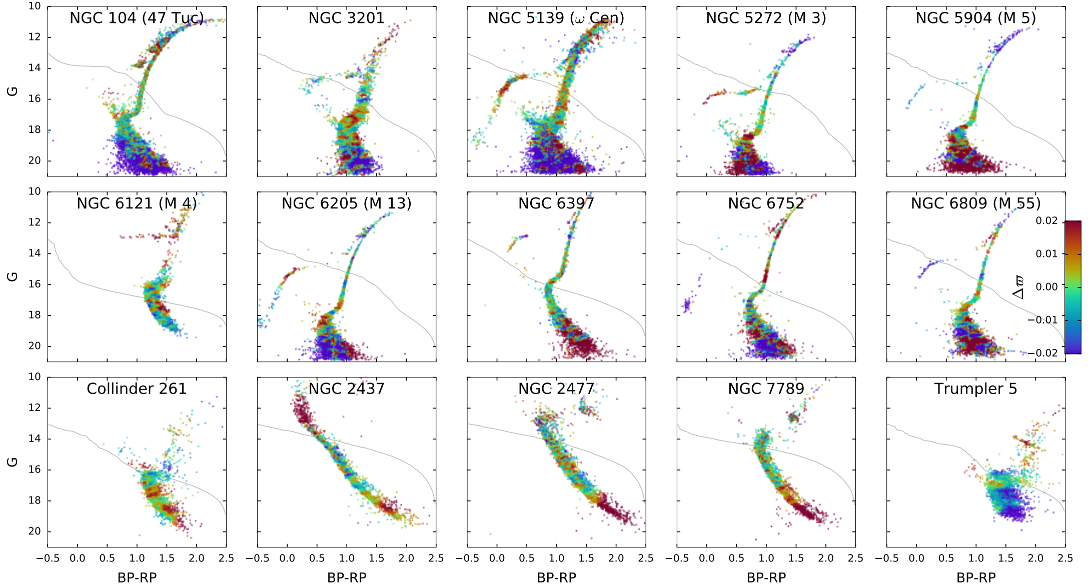
See also uncertainty calibration studies:

Fabricius+ 2012.06242,
Maíz Apellániz+ 2101.10206,
El-Badry+ 2101.05282:

$\eta \sim 1.1 - 1.3$ for well-behaved sources

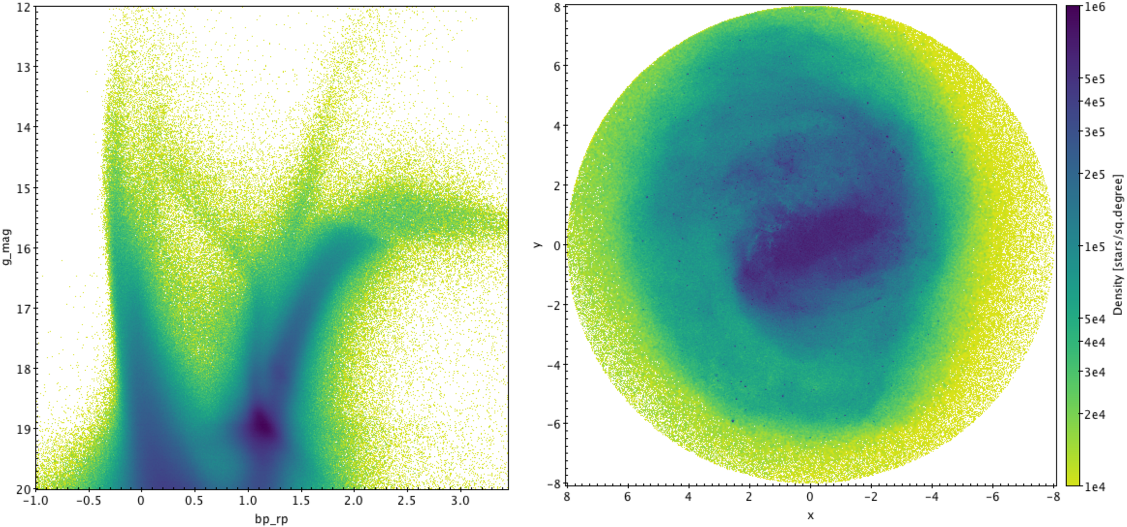
Caveat 2: variation of parallax zero point across CMD

stars coloured by the offset of ϖ from the mean value for each cluster



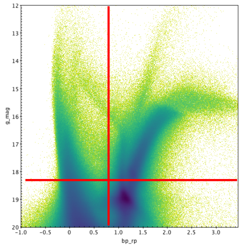
Analysis of parallaxes in the Large Magellanic Cloud

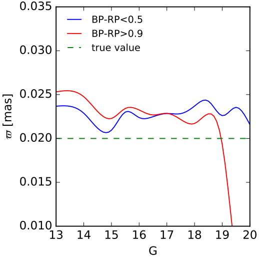
$\sim$ 9M stars in the LMC selected using a mixture model in CMD + astrometry space

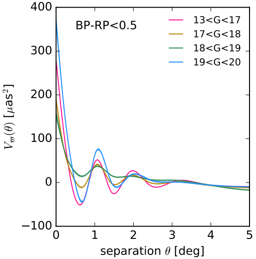


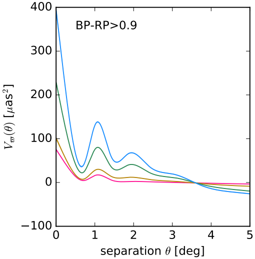
Analysis of parallaxes in the Large Magellanic Cloud

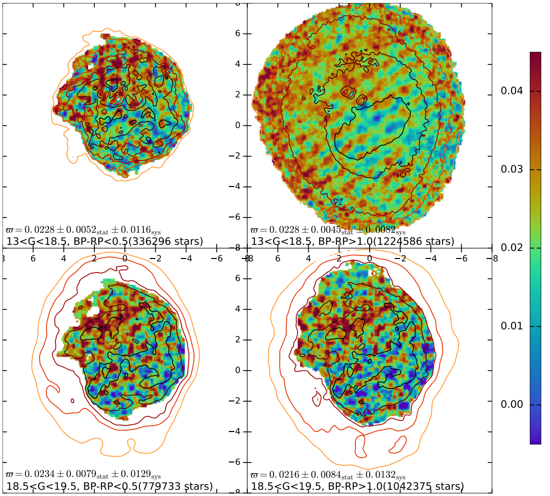
spatial correlations in the mean parallax of stars described by a covariance function $V_\varpi(\theta) = \left\langle \left(\varpi_i - \overline{\varpi}\right)\left(\varpi_j - \overline{\varpi}\right)\right\rangle$, where θ is the angular distance between stars i and j.





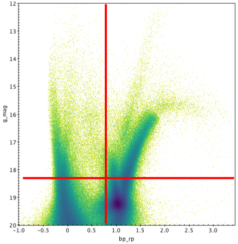


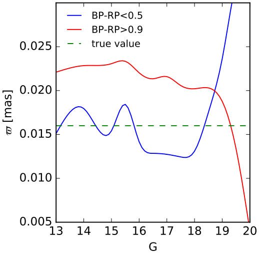


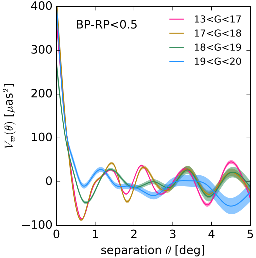


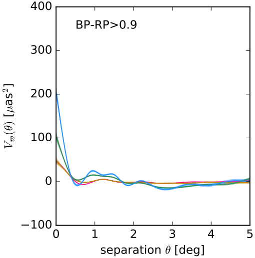
mean parallax of LMC stars

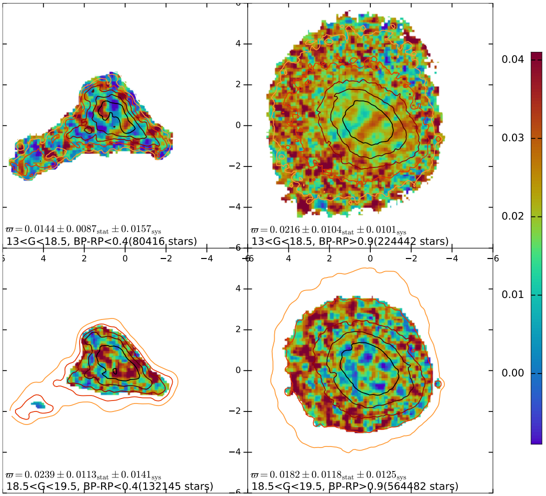
Analysis of parallaxes in the Small Magellanic Cloud





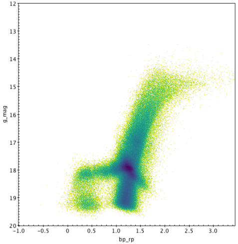


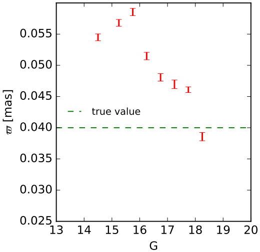


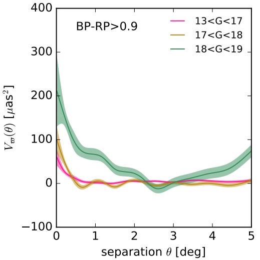


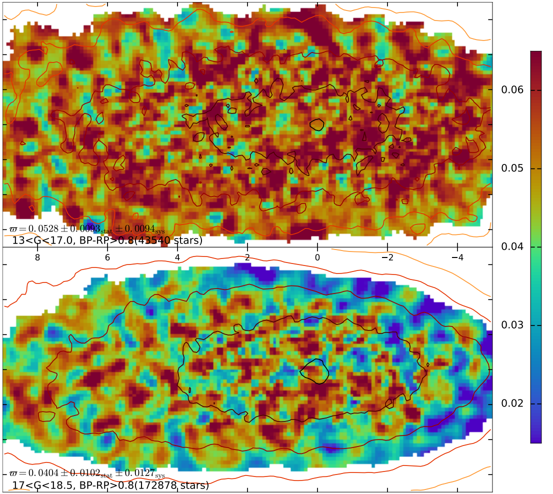
mean parallax of SMC stars

Analysis of parallaxes in the Sagittarius dSph



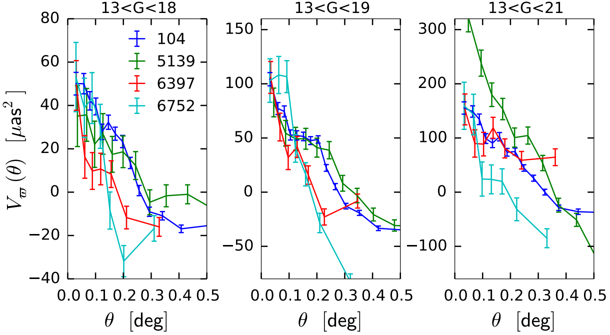


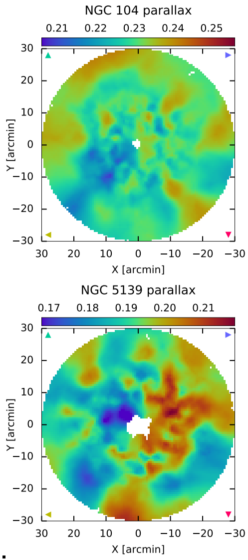




mean parallax of Sgr stars

Caveat 3: spatially correlated systematic errors





Spatial covariance function: $V_\varpi(\theta) = \langle (\varpi_i - \overline{\varpi})(\varpi_j - \overline{\varpi}) \rangle$,
where θ is the angular distance between stars i and j.

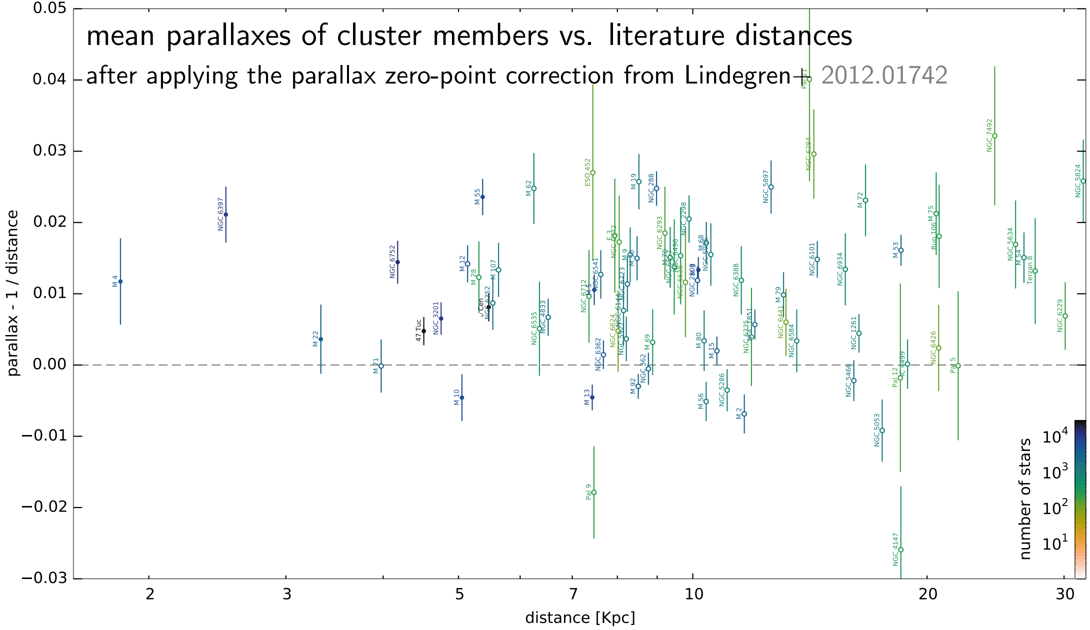
see also Lindegren+ 2012.03380, Maíz Apellániz+ 2101.10206
for $V_\varpi(\theta)$ determined on scales $\theta \gtrsim 1^\circ$ from LMC stars and quasars.

For bright stars ($13 < G < 18$): $\epsilon_{\varpi,\mathrm{sys}} \equiv \sqrt{V_\varpi(\theta=0)} \simeq 0.01$ mas;
for fainter stars it may be $\sim 1.5 - 2\times$ higher.

Same for PM: $\epsilon_{\mu,\mathrm{sys}} \simeq 0.025$ mas/yr.

DR2:
$\epsilon_{\varpi,\mathrm{sys}} \sim 0.043$
$\epsilon_{\mu,\mathrm{sys}} \sim 0.066$

Caveat 4: parallaxes appear to be slightly overestimated



Caveat 4: parallaxes appear to be slightly overestimated

$$\varpi_i - 1/D_i \sim \mathcal{N}(\Delta\varpi,\ \epsilon^2_{\varpi,i} + \epsilon^2_{\varpi,\mathrm{sys}}),$$

$$\Delta\varpi \simeq 0.01\,\mathrm{mas},$$

$$\epsilon_{\varpi,\mathrm{sys}} \simeq 0.01\,\mathrm{mas}.$$

See also zero-point calibration studies by

Riess+ 2012.08534 (cepheids),

Bhardwaj+ 2012.13495 (RR Lyrae),

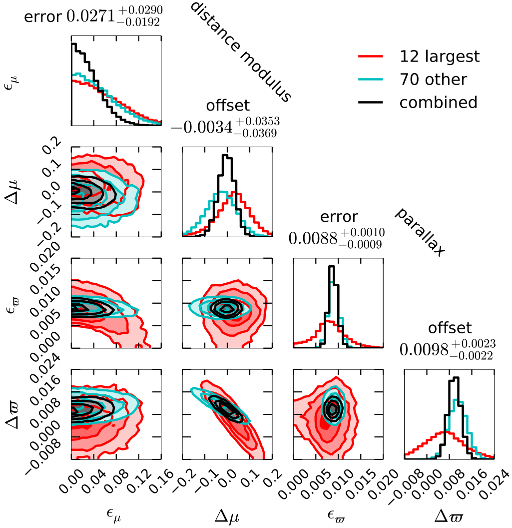
Stassun & Torres 2101.03425,

Ren+ 2103.16096 (eclipsing binaries),

Zinn 2101.07252 (asteroseismology),

Huang+ 2101.09691 (red clump stars),

Groenewegen 2106.08128 (quasars)



Summary: Gaia EDR3 $\Longleftrightarrow$ globular clusters

- Mean parallaxes, PM and orbits determined for 170 globular clusters;
- PM dispersions and dynamical distances – for $\sim$ 100 clusters;
- Rotation detected in $\sim$ 20 clusters;
- PM anisotropy measured in $\sim$ 15 clusters.

- Statistical uncertainties are underestimated by $10-20\%$ in dense regions (even for the clean subset);
- Spatially correlated systematic errors on sub-degree scales: $\epsilon_{\varpi} \simeq 0.01-0.02$ mas, $\epsilon_{\mu} \simeq 0.025$ mas/yr;
- Parallax zero-point correction overshoots by $\sim$ 0.01 mas.

Despite these caveats, *Gaia* is great and EDR3 significantly improves its quality!