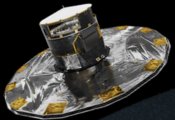

Using Gaia for studying Milky Way star clusters

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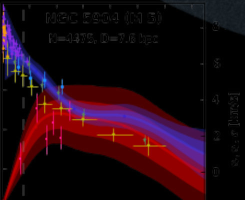
IAU 351 / MODEST-19, Bologna, 27 May 2019



Internal kinematics and galactic orbits

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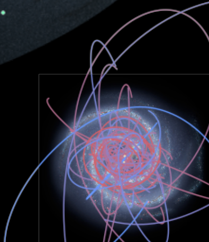
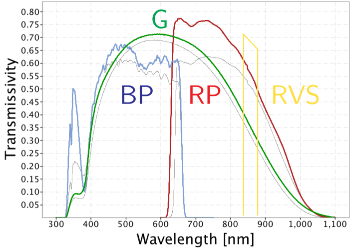
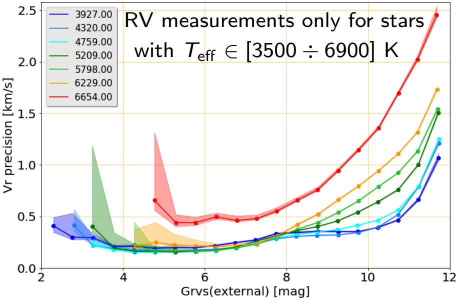


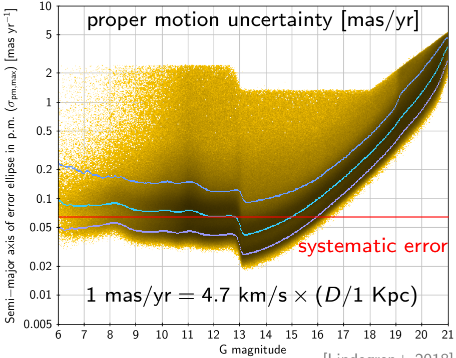
Overview of Gaia mission and Data Release 2

- ▶ Scanning the entire sky every couple of weeks
- ▶ DR2 based on 22 months of observations
- ▶ Astrometry for sources down to 21 mag (1.3×10^9)
- ▶ Broad-band blue/red photometry (1.4×10^9)
- ▶ Radial velocity down to ~ 13 mag ($\sim 7 \times 10^6$ stars)
- ! No special treatment of binary stars
- ! Poor completeness in crowded fields



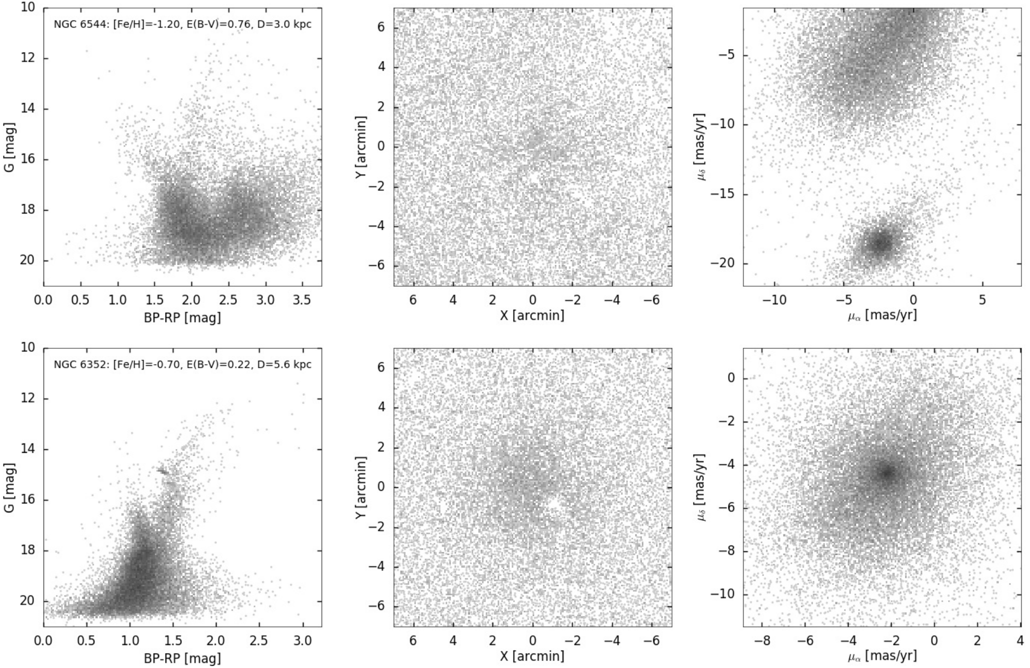


[Katz+ 2018]

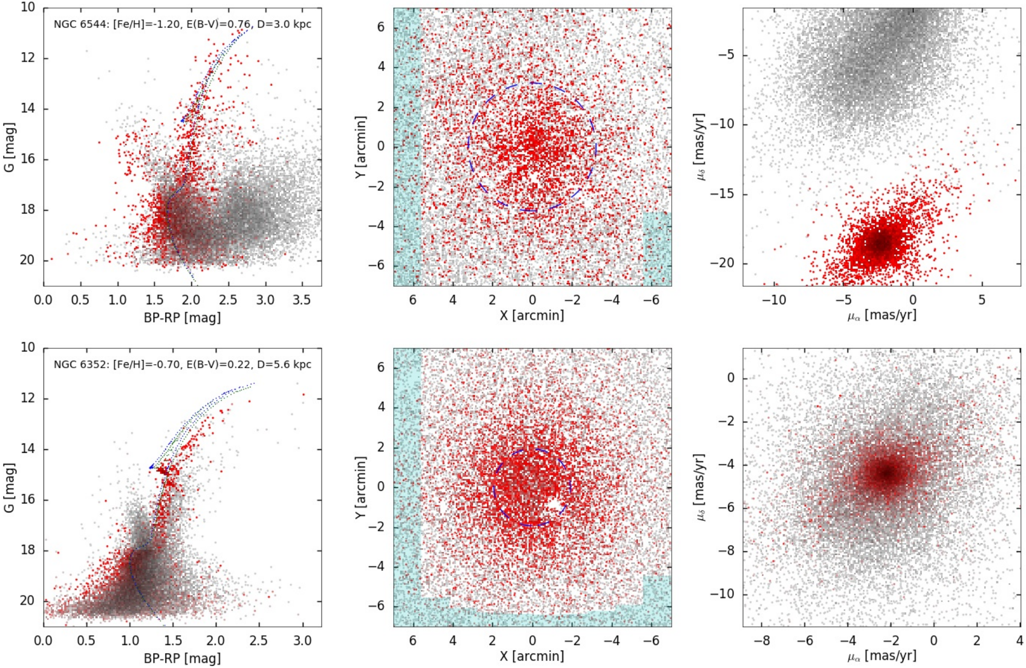


[Lindegren+ 2018]

Determination of cluster membership



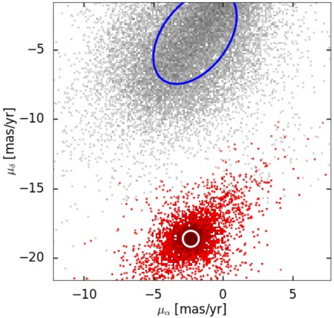
Determination of cluster membership



Probabilistic membership determination

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

A more mathematically well-grounded alternative: gaussian mixture modelling.



$$f(\boldsymbol{\mu}_i) = q_{\rm cl}\,\mathcal{N}(\boldsymbol{\mu}_i \mid \overline{\boldsymbol{\mu}_{\rm cl}}, \Sigma_{{\rm cl};i}) + (1 - q_{\rm cl})\,\mathcal{N}(\boldsymbol{\mu}_i \mid \overline{\boldsymbol{\mu}_{\rm fg}}, \Sigma_{{\rm fg};i})$$

$$\mathcal{N}(\boldsymbol{\mu} \mid \overline{\boldsymbol{\mu}}, \Sigma) \equiv \frac{\exp\left[-\frac{1}{2}(\boldsymbol{\mu} - \overline{\boldsymbol{\mu}})^T\,\Sigma^{-1}\,(\boldsymbol{\mu} - \overline{\boldsymbol{\mu}})\right]}{2\pi\sqrt{\det\Sigma}},$$

where the mean PMs $\overline{\boldsymbol{\mu}}$ and dispersions Σ of the cluster and foreground distributions, and the fraction of cluster members $q_{\rm cl}$, are all inferred by maximizing the likelihood of the observed stellar PMs.

Probabilistic membership determination

Take into account the measurement errors $\epsilon_{\mu_\alpha}, \epsilon_{\mu_\delta}, \rho_{\mu_\alpha \mu_\delta}$ for each star i:

$$\Sigma_{\mathrm{cl};i} = \begin{pmatrix} \sigma_{\mathrm{cl}}^2(\mathbf{r}_i) + \epsilon_{\mu_\alpha}^2 & \rho_{\mu_\alpha \mu_\delta}\, \epsilon_{\mu_\alpha}\, \epsilon_{\mu_\delta} \\ \rho_{\mu_\alpha \mu_\delta}\, \epsilon_{\mu_\alpha}\, \epsilon_{\mu_\delta} & \sigma_{\mathrm{cl}}^2(\mathbf{r}_i) + \epsilon_{\mu_\delta}^2 \end{pmatrix}$$

$$\Sigma_{\mathrm{fg};i} = \begin{pmatrix} S_{\alpha\alpha} + \epsilon_{\mu_\alpha}^2 & S_{\alpha\delta} + \rho_{\mu_\alpha \mu_\delta}\, \epsilon_{\mu_\alpha}\, \epsilon_{\mu_\delta} \\ S_{\alpha\delta} + \rho_{\mu_\alpha \mu_\delta}\, \epsilon_{\mu_\alpha}\, \epsilon_{\mu_\delta} & S_{\delta\delta} + \epsilon_{\mu_\delta}^2 \end{pmatrix}$$

And allow for a spatially-dependent density of cluster members: $q_{\mathrm{cl}}(\mathbf{r}_i)$.

Maximize $\ln \mathcal{L} \equiv \sum_{i=1}^{N_{\mathrm{stars}}} \ln f(\boldsymbol{\mu}_i)$ by adjusting free parameters:

$\overline{\boldsymbol{\mu}_{\mathrm{cl}}}$, $\overline{\boldsymbol{\mu}_{\mathrm{fg}}}$, $S_{\alpha\alpha}, S_{\delta\delta}, S_{\alpha\delta}$, radius and normalization of $q_{\mathrm{cl}}(\mathbf{r})$, normalization of $\sigma_{\mathrm{cl}}(\mathbf{r})$.

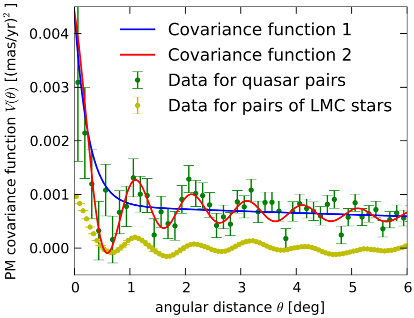
Posterior membership probability for each star:

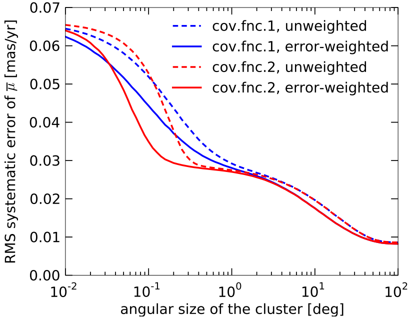
$$p_{\mathrm{cl};i} = \frac{q_{\mathrm{cl}}(\mathbf{r}_i)\, \mathcal{N}(\boldsymbol{\mu}_i \mid \overline{\boldsymbol{\mu}_{\mathrm{cl}}}, \Sigma_{\mathrm{cl};i})}{q_{\mathrm{cl}}(\mathbf{r}_i)\, \mathcal{N}(\boldsymbol{\mu}_i \mid \overline{\boldsymbol{\mu}_{\mathrm{cl}}}, \Sigma_{\mathrm{cl};i}) \;+\; [1 - q_{\mathrm{cl}}(\mathbf{r}_i)]\, \mathcal{N}(\boldsymbol{\mu}_i \mid \overline{\boldsymbol{\mu}_{\mathrm{fg}}}, \Sigma_{\mathrm{fg};i})}$$

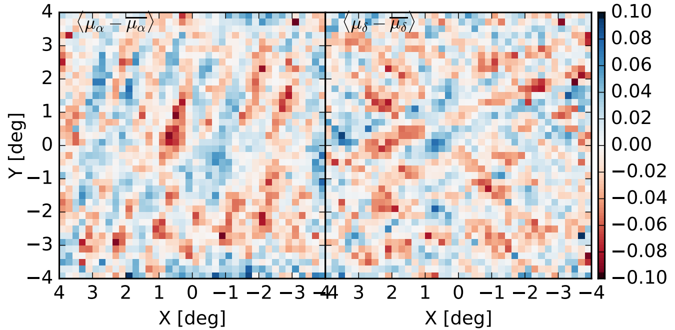
Caveat: spatially correlated systematic errors in astrometry

Covariance function $V(\theta_{ij}) = \langle \mu_i \, \mu_j \rangle$, averaged over pairs of sources separated by angular distance θ: quasars at large scales, LMC stars at small scales.

$$V(\theta) = 0.0008 \exp(-\theta/20^\circ) + \left[\begin{array}{ll} 0.0036 \exp(-\theta/0.25^\circ) & \text{(cov.fnc.1)} \\ 0.004 \,\mathrm{sinc}(\theta/0.5^\circ + 0.25) & \text{(cov.fnc.2)} \end{array} \right.$$







How to properly account for correlated systematic errors

Likelihood function for the entire dataset ($\boldsymbol{\mu} \equiv \{\mu_i\}_{i=1}^{N}$):

$$\mathcal{L} = \mathcal{N}(\boldsymbol{\mu} \mid \mathbf{1}\,\overline{\mu}, \Sigma)$$

$$\Sigma = \begin{pmatrix} V(0)+\epsilon_1^2 & V(\theta_{12}) & V(\theta_{13}) & \cdots & V(\theta_{1N}) \\ V(\theta_{21}) & V(0)+\epsilon_2^2 & V(\theta_{23}) & \cdots & V(\theta_{2N}) \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ V(\theta_{N1}) & V(\theta_{N2}) & V(\theta_{N3}) & \cdots & V(0)+\epsilon_N^2 \end{pmatrix}$$

($\epsilon_1..\epsilon_N$ are statistical errors of each datapoint).

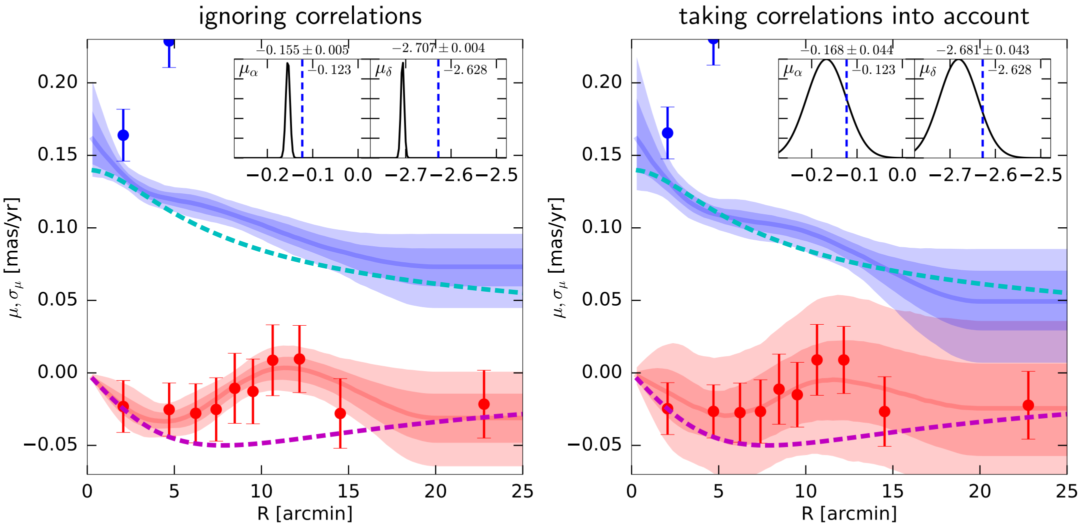
This is easily generalized to 2d case with 2×2 covariance matrices of statistical errors, and allowing for spatially-dependent internal dispersion and mean value of μ.

The downside is that one needs to invert the $N \times N$ covariance matrix Σ for the entire dataset (for the optimal error-weighted estimate).

Alternatively, an unweighted estimate of the uncertainty on $\overline{\mu}$ is $\frac{1}{N}\sqrt{\sum_{i=1}^{N}\sum_{j=1}^{N}\Sigma_{ij}}$.

Spatial correlation should not be ignored!

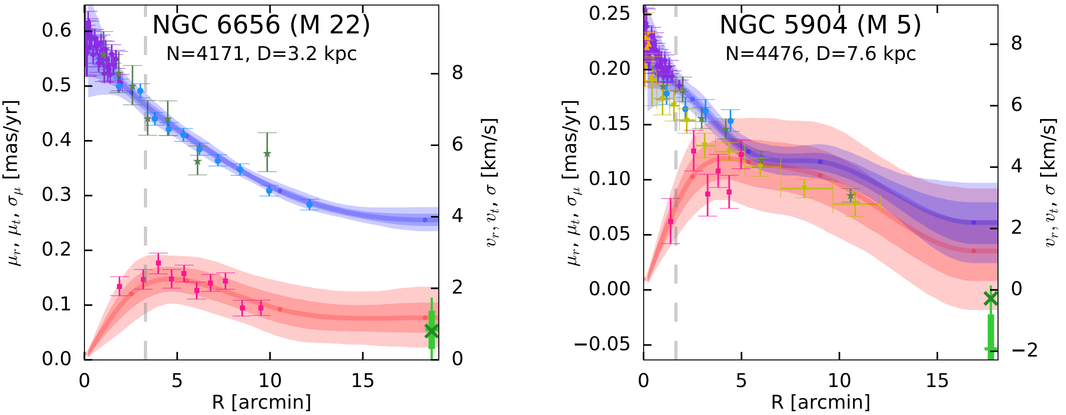
Doing so underestimates the error bars on fit parameters,
even when systematic errors are much smaller than statistical errors.



Internal kinematics of globular clusters

Clear signature of rotation in ~ 10 clusters:

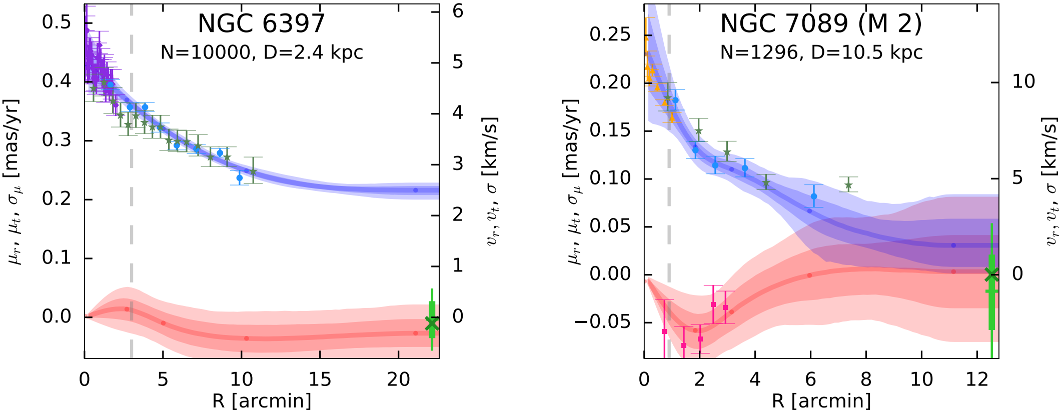
see also Bianchini+ 2018, Sollima+ 2019, Jindal+ 2019, all based on Gaia data



Internal kinematics of globular clusters

Good match between line-of-sight velocity dispersion and PM dispersion:

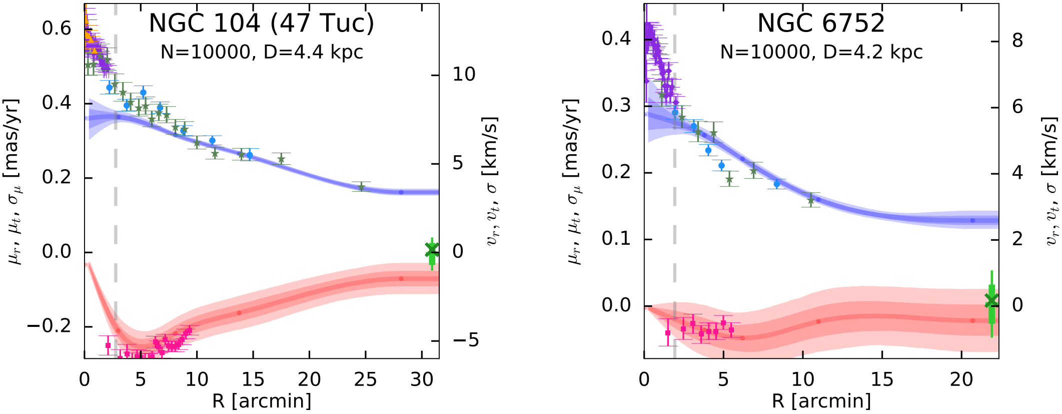
see also Baumgardt+ 2018, Jindal+ 2019 (Gaia PM) and
HST measurements in central parts [Bellini+ 2014, Watkins+ 2015]



Internal kinematics of globular clusters

Mismatch between $\sigma_{\rm los}$ and PM dispersion in central parts:

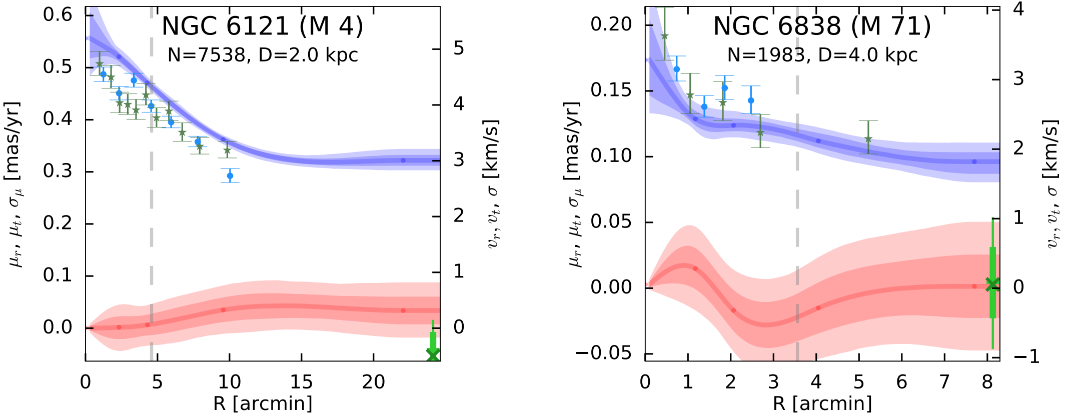
likely due to crowding issues and aggressive sample cleanup



Internal kinematics of globular clusters

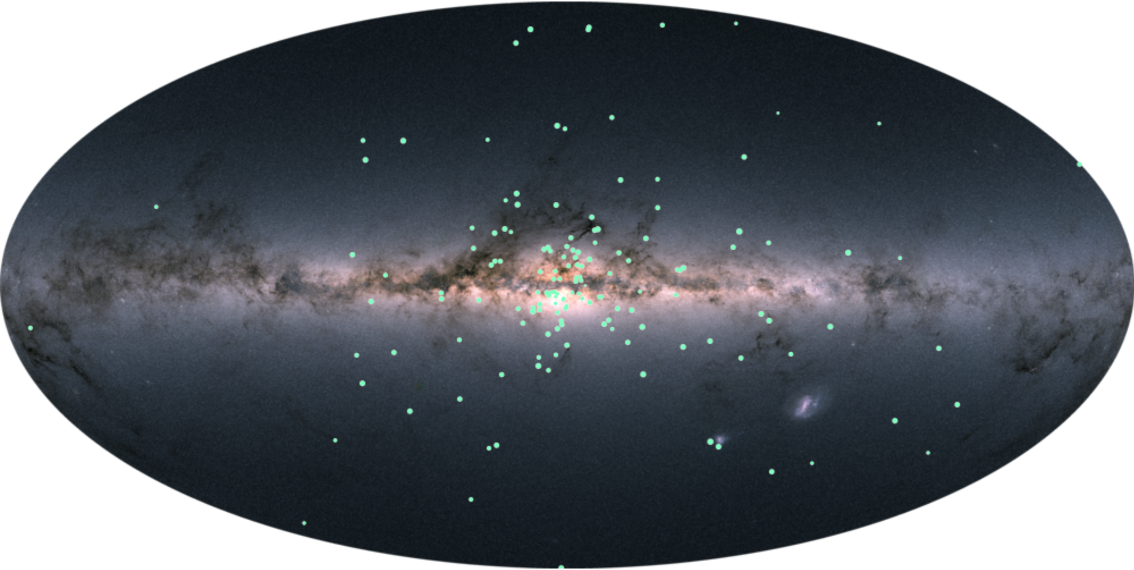
Overall scale mismatch between σ_{los} and σ_μ:

a prime method for measuring the distance from kinematic analysis



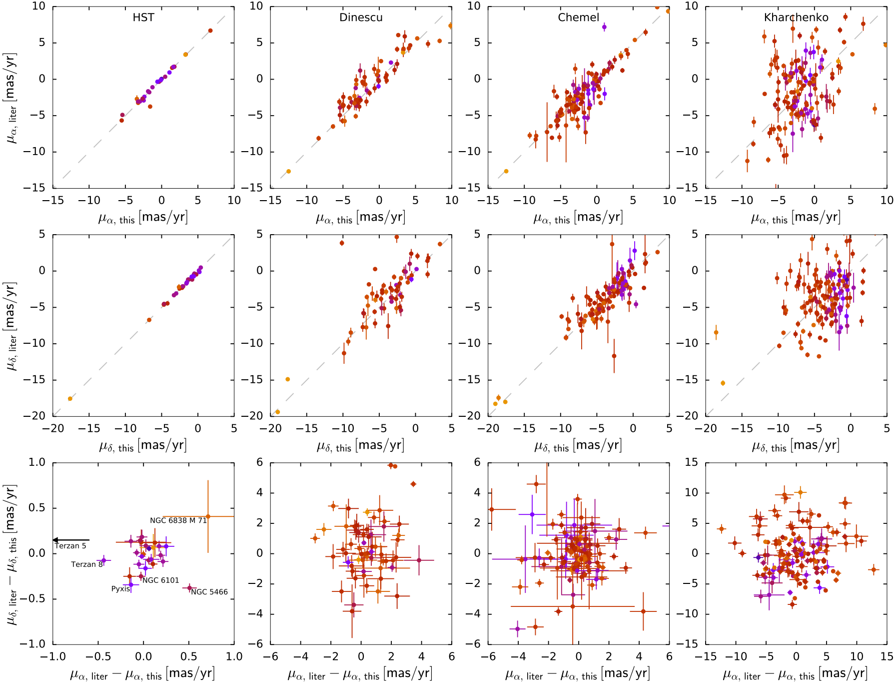
Kinematics of the entire Milky Way globular cluster system

see also Gaia Collaboration (Helmi+) 2018, Baumgardt+ 2018, de Boer+ 2019

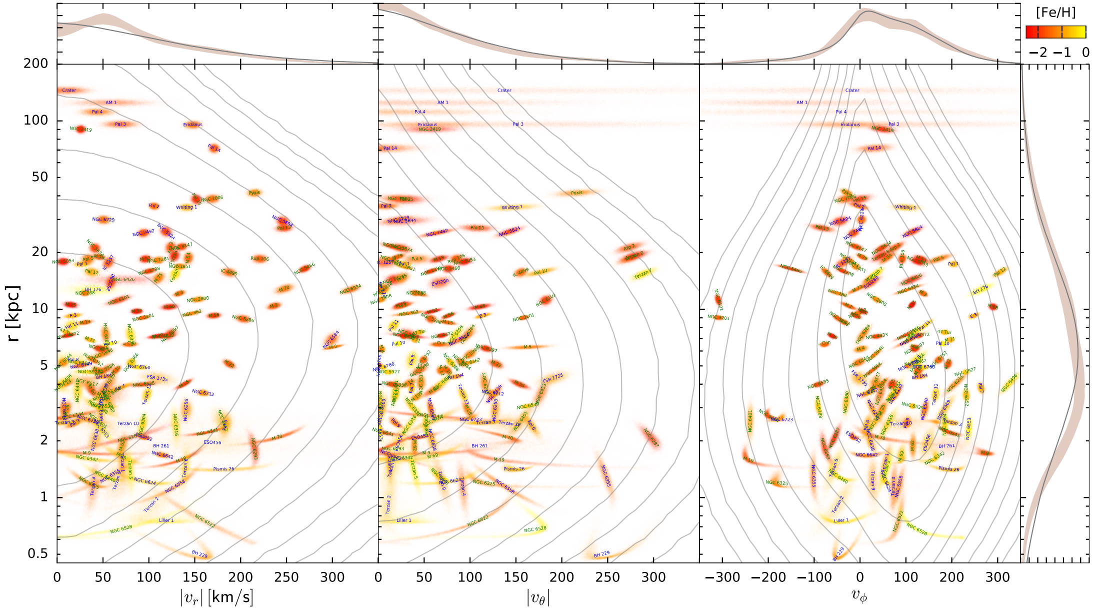


$\sim$ 150 globular clusters in the Milky Way

Previous measurements of mean PM of globular clusters



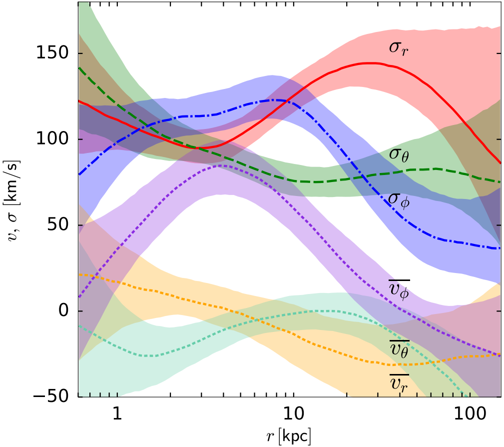
Distribution of globular clusters in position/velocity space



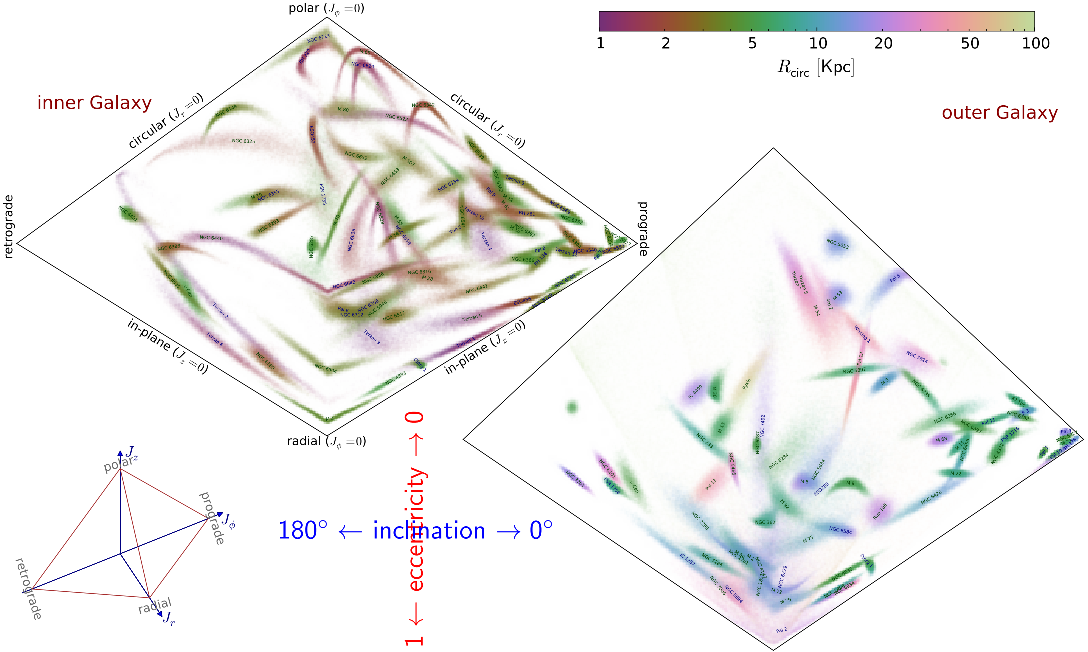
Velocity dispersion and rotation profiles

Main kinematical features of the entire population of globular clusters:

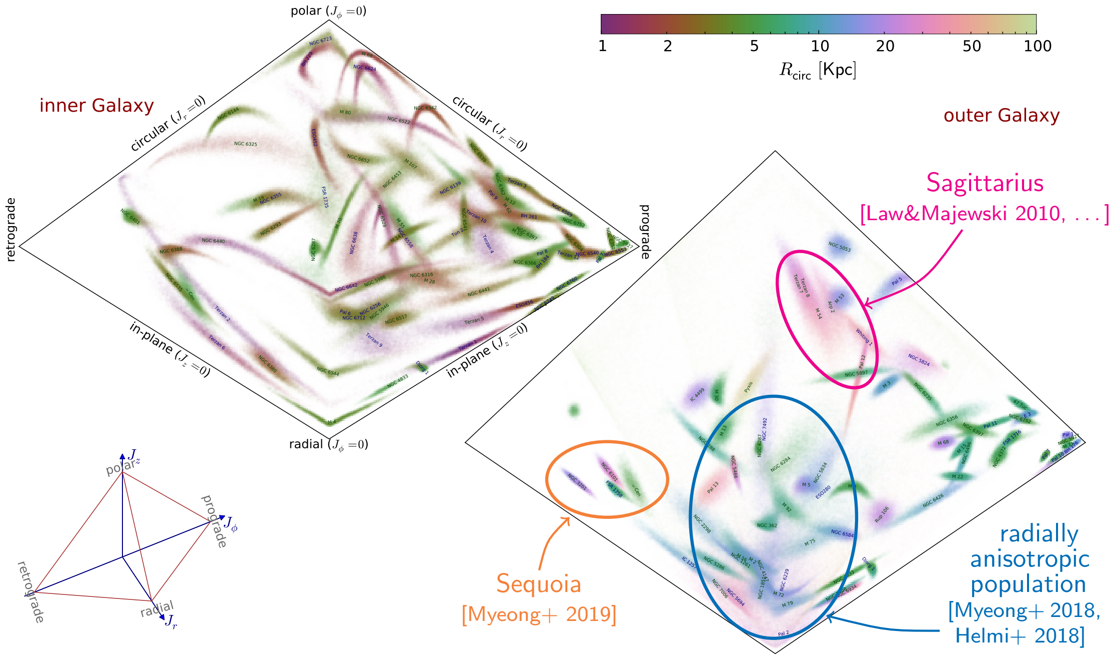
- Significant overall rotation, especially within the central 10 kpc (more prominent for metal-rich clusters).
- Nearly isotropic dispersion at $r < 10$ kpc, more radially anisotropic in outer parts; a population of ~ 10 clusters on eccentric orbits [Myeong+ 2018].
- Correlated orbits (e.g., Sgr stream: M 54, Terzan 7, Terzan 8, Arp 2, Pal 12, Whiting 1).



Distribution of globular clusters in action space



Distribution of globular clusters in action space



Distribution of globular clusters in action space

Jackson Pollock

Kliment Redko

Dynamical modelling of the entire globular cluster population

Assume an equilibrium distribution function (in action space):

$$f(\mathbf{J}) = \frac{M}{(2\pi\, J_0)^3} \left[1 + \left(\frac{J_0}{h(\mathbf{J})}\right)^{\eta}\right]^{\Gamma/\eta} \left[1 + \left(\frac{g(\mathbf{J})}{J_0}\right)^{\eta}\right]^{-\mathrm{B}/\eta} \left(1 + \tanh\frac{\varkappa J_\phi}{J_r + J_z + |J_\phi|}\right),$$

$$g(\mathbf{J}) \equiv g_r J_r + g_z J_z + (3 - g_r - g_z)\,|J_\phi|, \quad h(\mathbf{J}) \equiv h_r J_r + h_z J_z + (3 - h_r - h_z)|J_\phi|,$$

and a potential – bulge, disk and a flexible halo profile:

$$\rho(r) = \rho_\mathrm{h} \left(\frac{r}{r_\mathrm{h}}\right)^{-\gamma} \left[1 + \left(\frac{r}{r_\mathrm{h}}\right)^{\alpha}\right]^{(\gamma-\beta)/\alpha}.$$

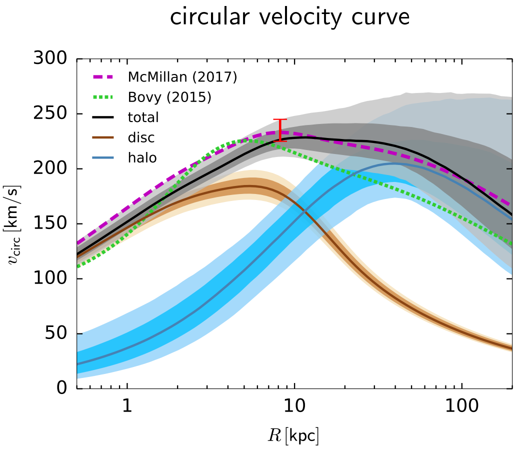
Maximize the likelihood of drawing the observed positions and velocities of clusters (taking into account their uncertainties) by varying the parameters of potential and DF.

Results: constraints on the Milky Way potential

Results are broadly consistent with other studies based on globular clusters [Binney&Wong 2017, Sohn+ 2018, Watkins+ 2019, Posti&Helmi 2019, Eadie&Juric 2019];

the potential from McMillan(2017) is acceptable, the one from Bovy(2015) has too low rotation curve.

Clusters should be combined with other dynamical tracers (dSph, halo stars) for a more robust inference on the potential.



Summary

- *Gaia* revolutionized the study of Milky Way in general, and its star clusters in particular
- Internal kinematics (velocity dispersion, anisotropy, rotation) available for a few dozen globular clusters within 10–20 kpc
- Full 6d phase-space information for almost all globular clusters: orbital properties, groups, constraints on the Milky Way potential

credit: Amanda Smith, IoA