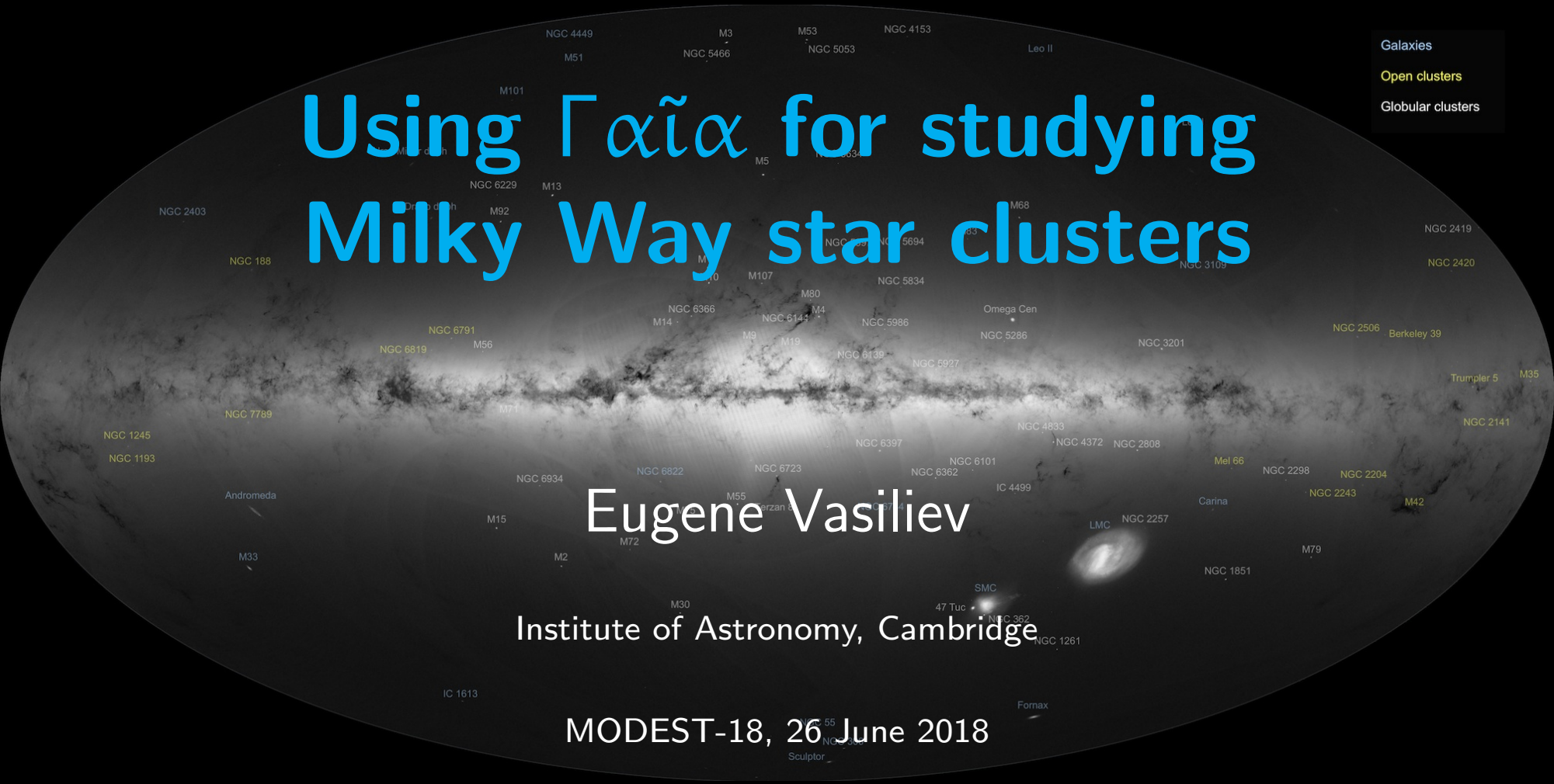


Using Γαῖα for studying Milky Way star clusters

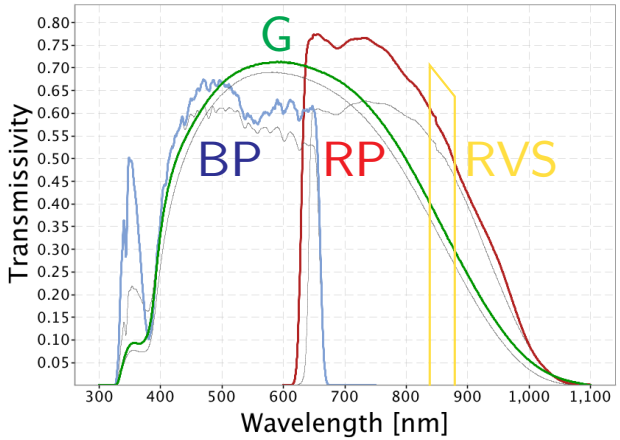
Eugene Vasiliev

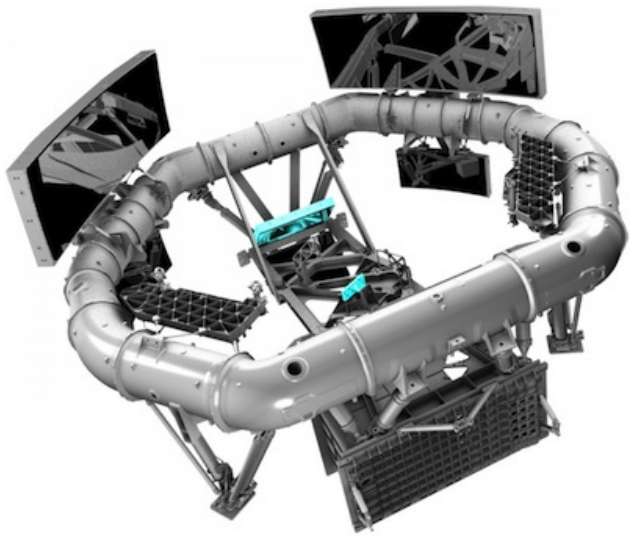
Institute of Astronomy, Cambridge

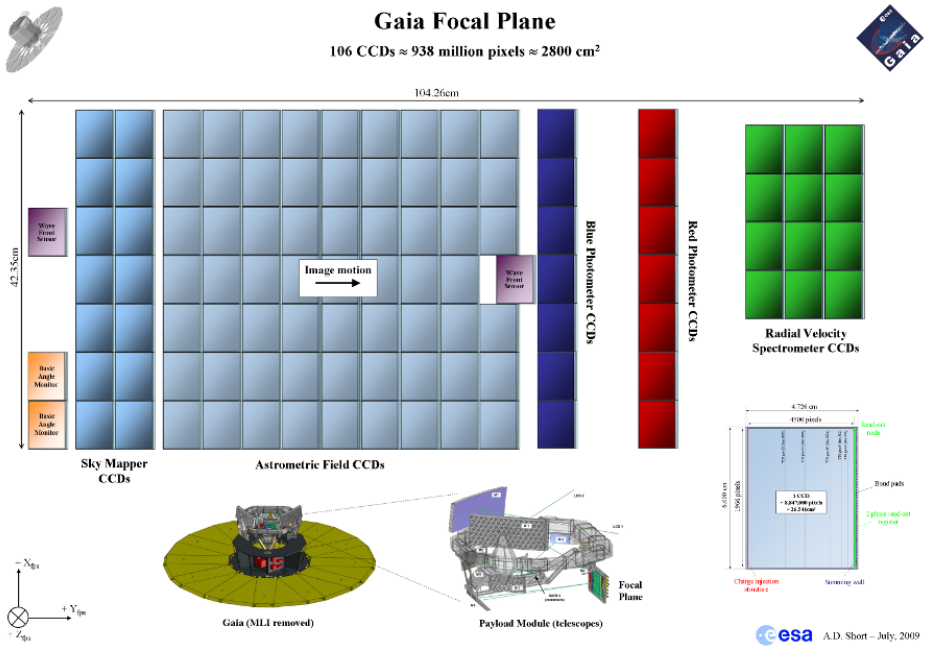
MODEST-18, 26 June 2018

Overview of Gaia mission

- Scanning the entire sky every couple of weeks
- Astrometry for sources down to 21 mag
- Broad-band photometry/low-res spectra
- Radial velocity down to $\sim$ 15 mag (end-of-mission)

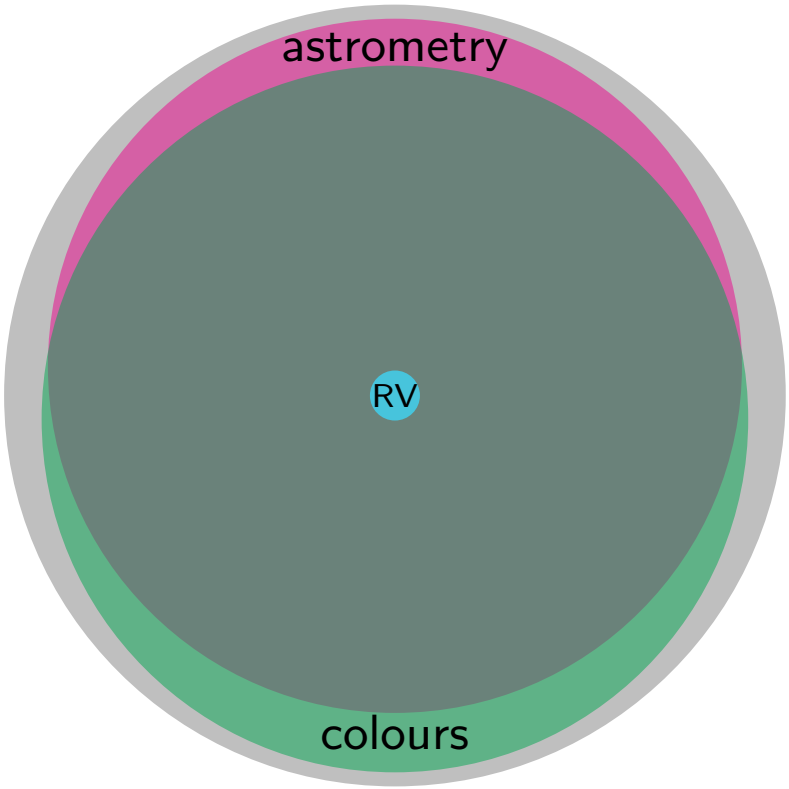




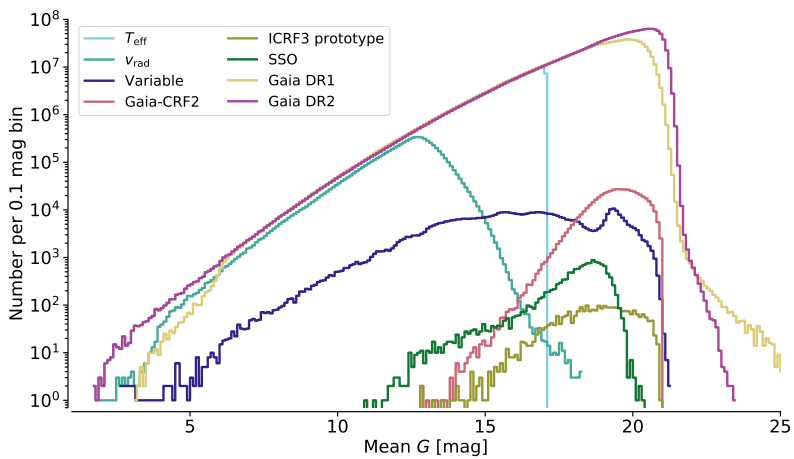


[Source: ESA]

Overview of Data Release 2

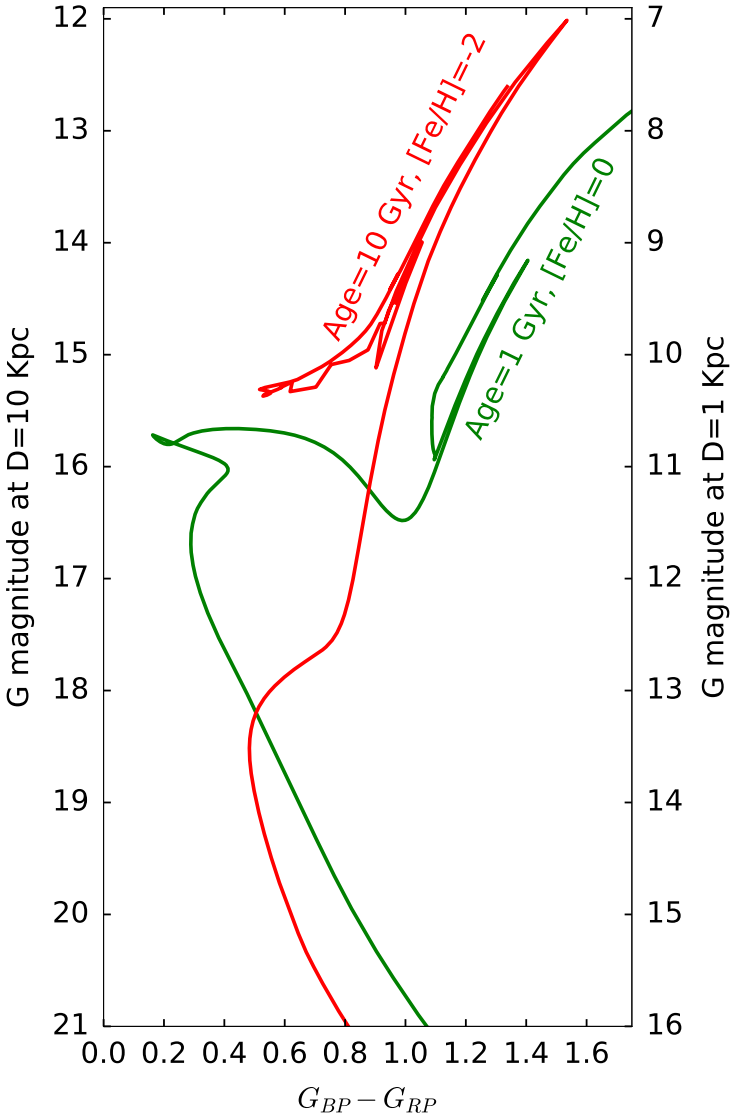


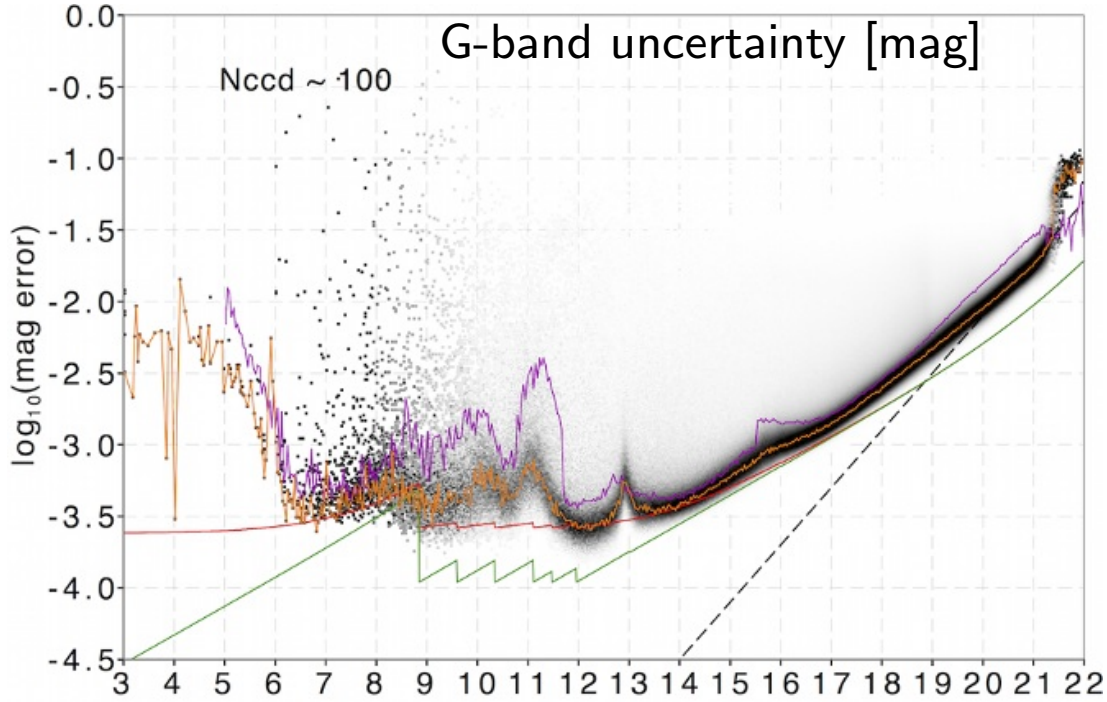
- Based on 22 months of data collection
- Total number of sources: 1.69×10^9
- Sources with full astrometry (parallax ϖ, proper motions $\mu_{\alpha*}, \mu_\delta$): 1.33×10^9
- Colours (G_{BP}, G_{RP}): 1.38×10^9
- Radial velocities: 7.2×10^6
- Effective temperature: 160×10^6
- Stellar parameters ($R_\odot, L_\odot$): 77×10^6
- Extinction and reddening: 88×10^6
- Variable sources: 0.55×10^6

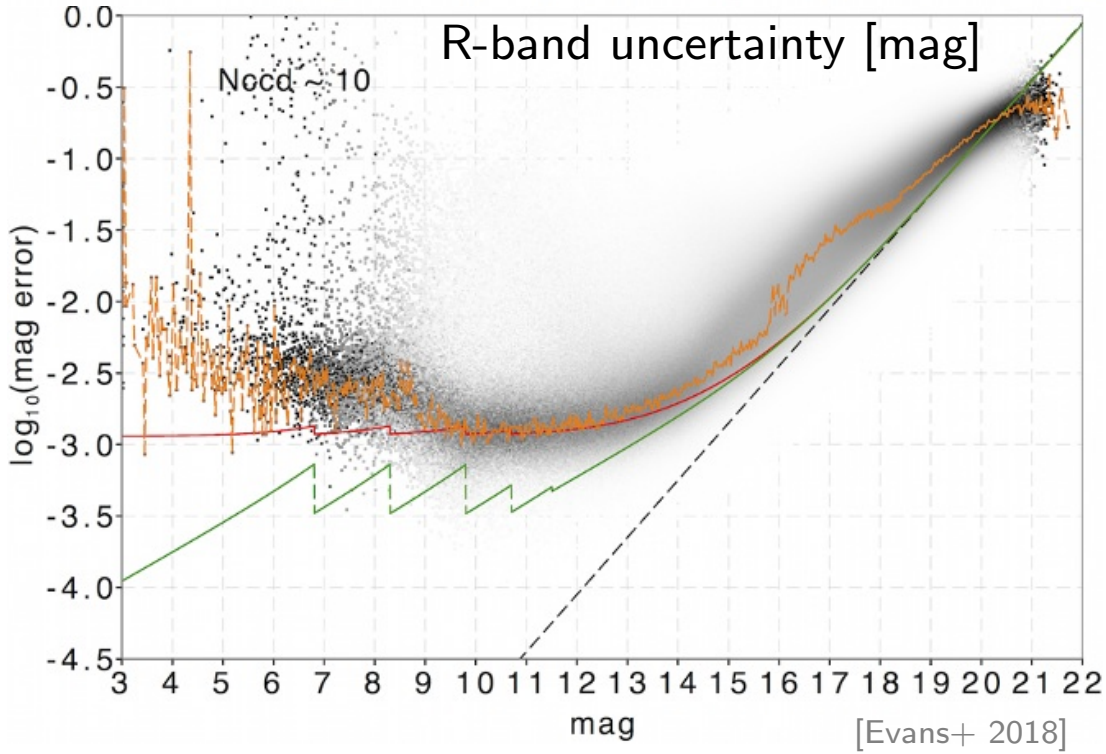


[Brown+ 2018]

Photometry

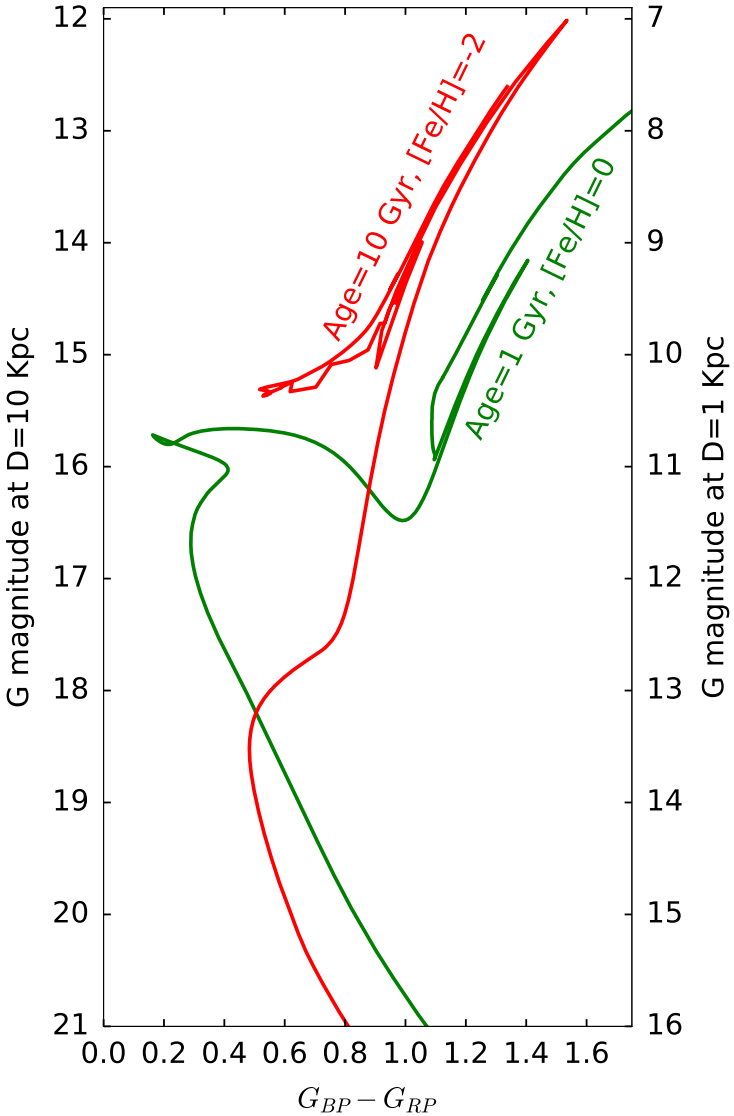


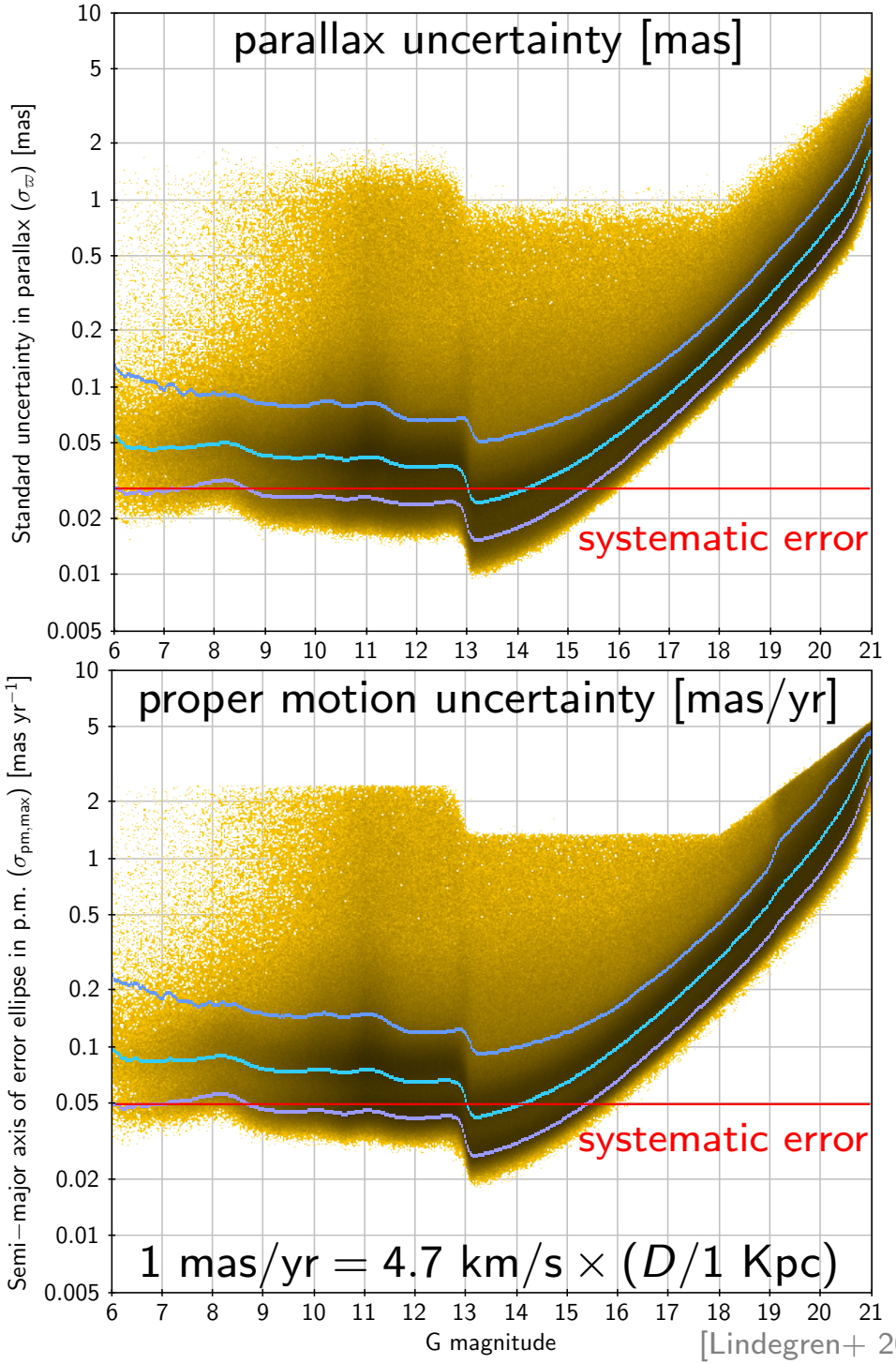




[Evans+ 2018]

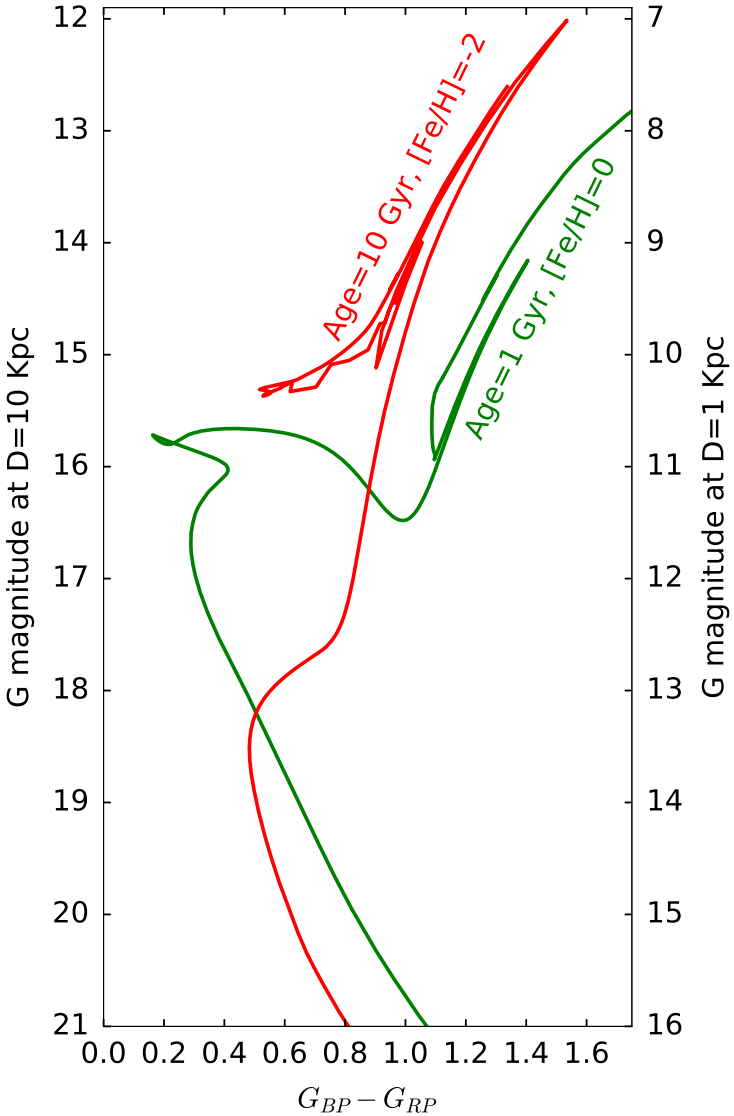
Astrometry





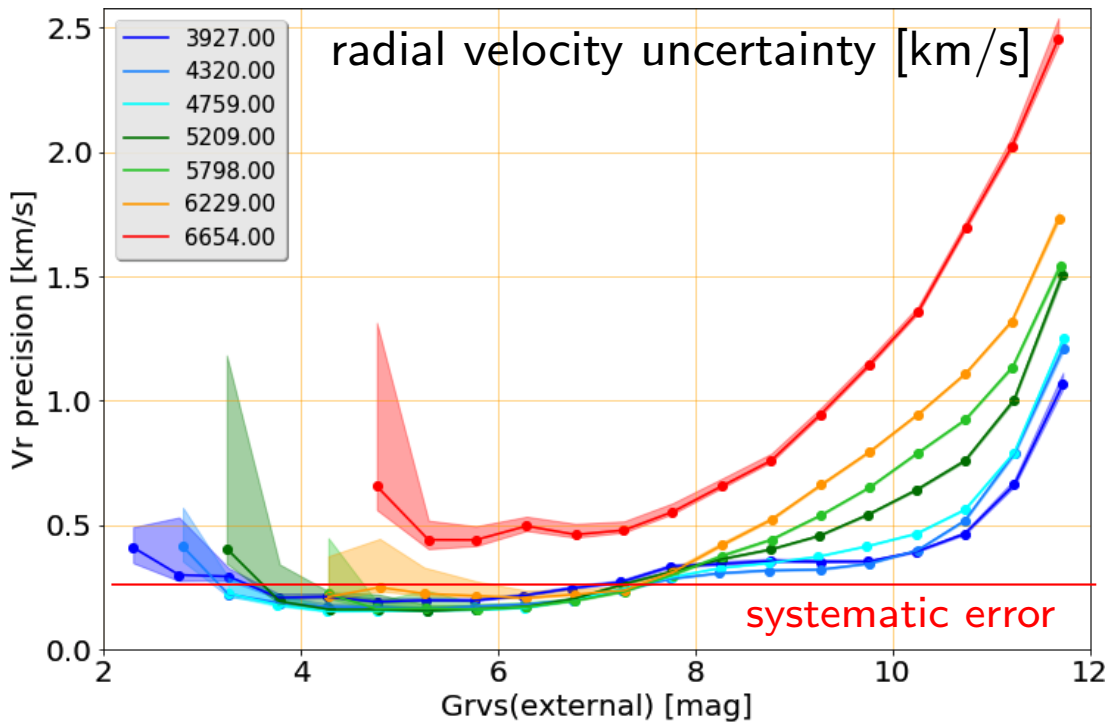
[Lindegren+ 2018]

Spectroscopy



RV measurements only for stars with

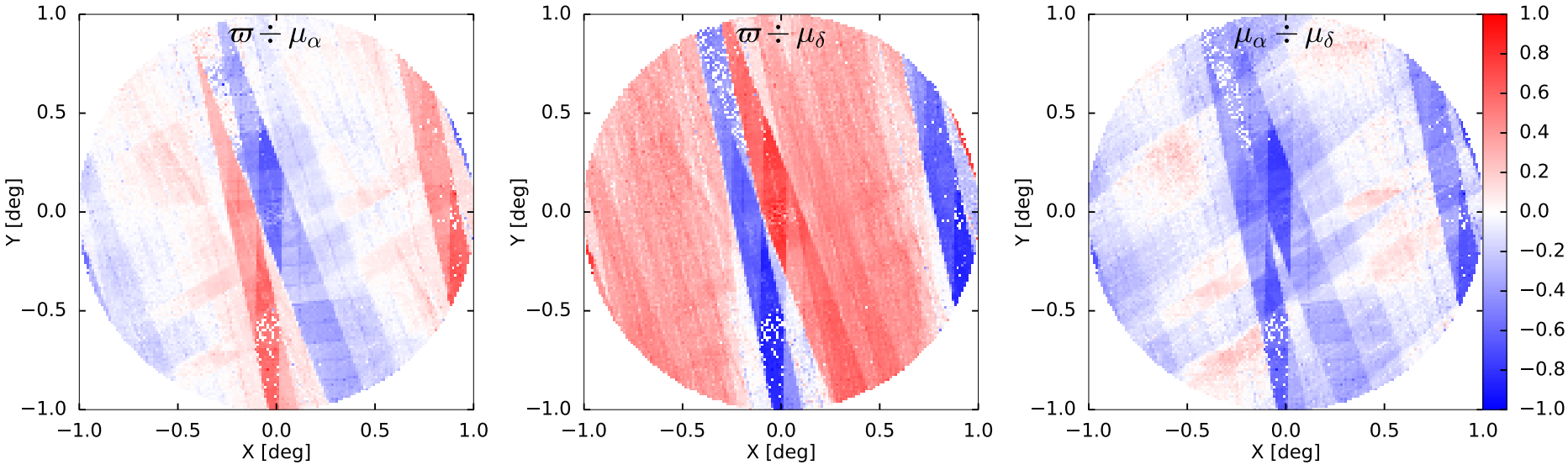
$T_{\text{eff}} \in [3500 \div 6900]$ K and $G_{\text{RVS}} \leq 12$



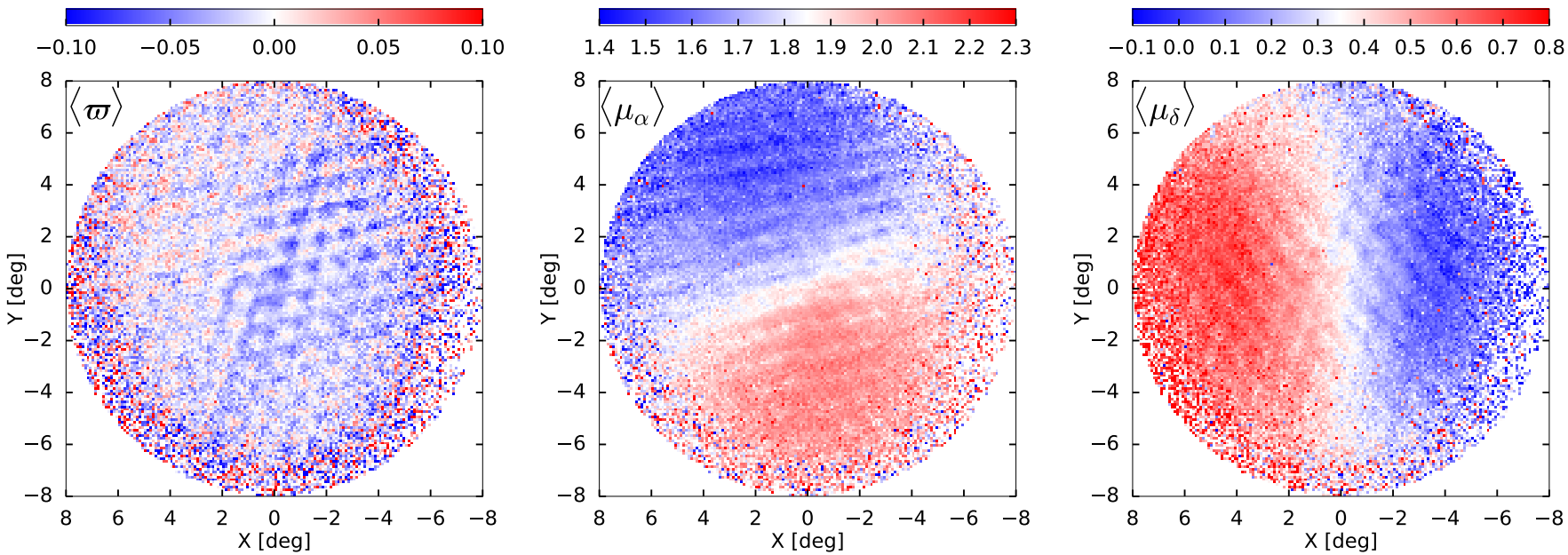
[Katz+ 2018]

Correlations and systematic errors

correlations between parallax and PM (ω Cen region)



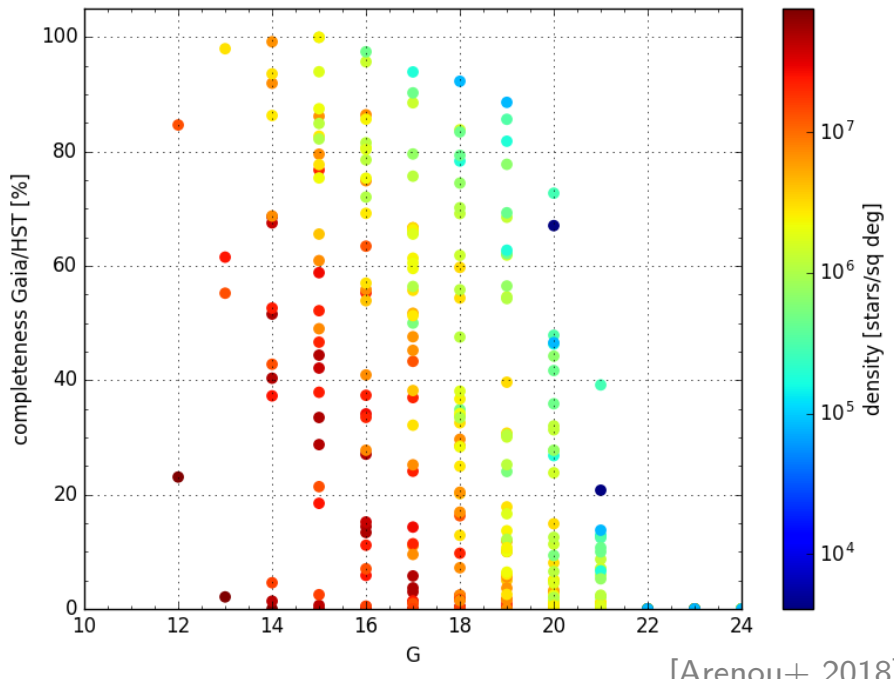
mean parallax and PM (Large Magellanic Cloud region)



Limitations

- No special processing for binary stars
  (but a poor astrometric solution is marked clearly)
- Colour photometry has lower spatial resolution
  (a quality control flag is provided)
- Poor completeness at faint magnitudes in crowded regions

- Need to apply various filters to clean up sample
  (but do it wisely, e.g.,
  don't just cut off negative parallaxes
  [see Luri+ 2018 for a discussion])



[Arenou+ 2018]

Dynamics of Milky Way globular clusters

Internal: rotation, velocity dispersion and anisotropy profiles:

- Rotation signatures from radial velocities [e.g., Fabricius+ 2014, Kamann+ 2017] now complemented by proper motion (PM) data [HST: Bellini+ 2014, Watkins+ 2015; Gaia: Bianchini+ 2018]
- Velocity anisotropy determined directly from PM
- Velocity dispersion profile in the outskirts, potential escapers [e.g., Claydon+ 2017]

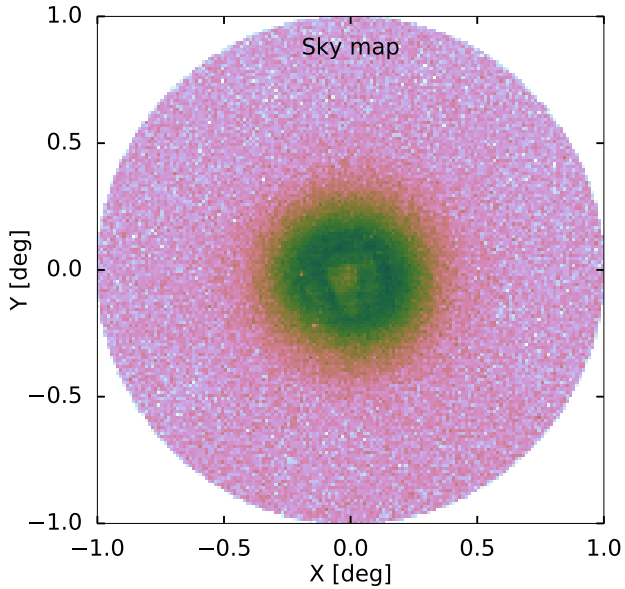
External: 3d center-of-mass velocity data:

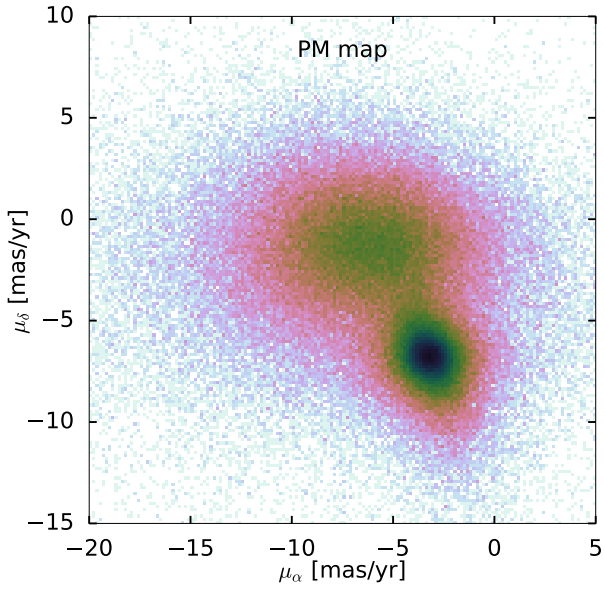
- galactic orbits [e.g., Helmi+ 2018], tidal effects
- possible correlations in phase-space distribution (cluster pairs)
- dynamical tracers of Milky Way potential

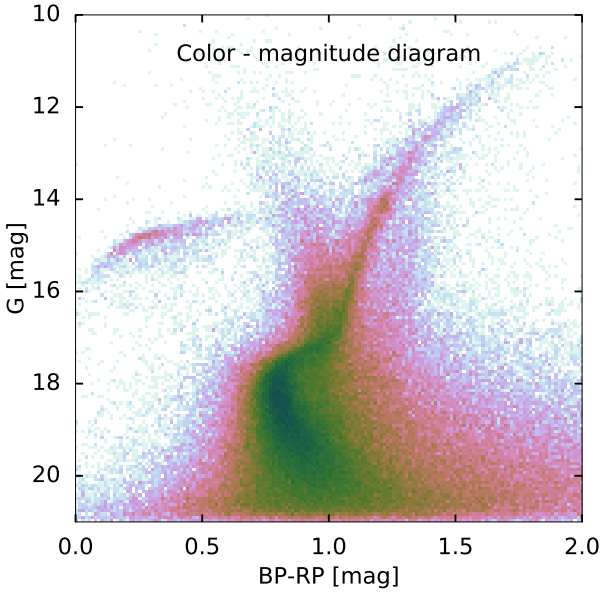
Example: NGC 5139 (ω Cen)

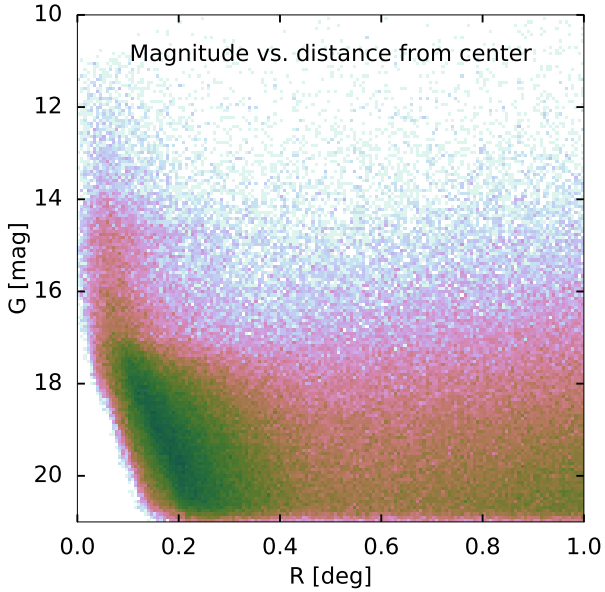
All stars

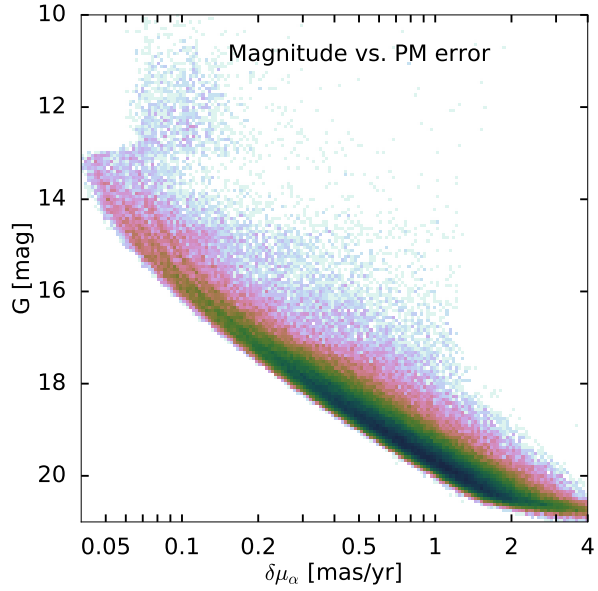
N=335469









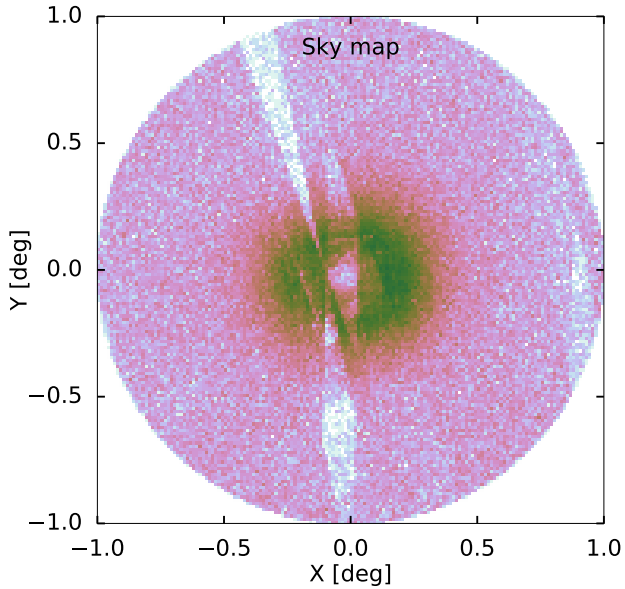


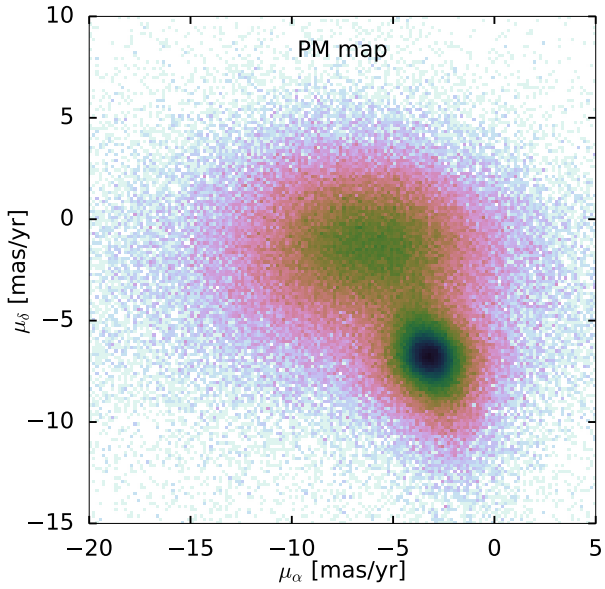
Example: NGC 5139 (ω Cen)

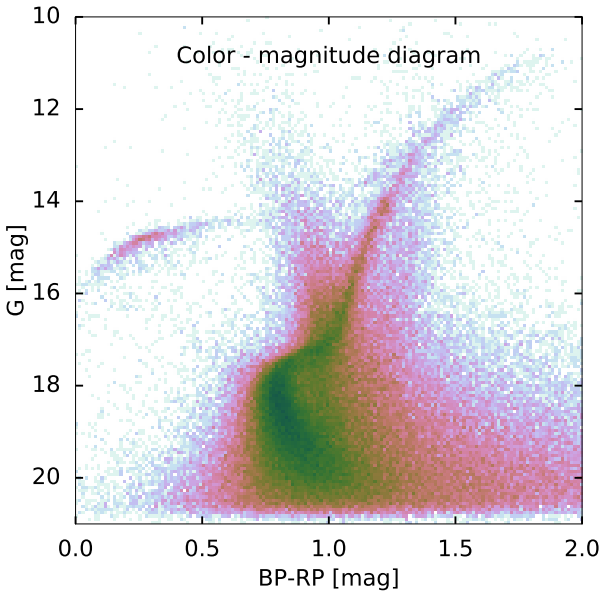
Stars with full astrometry

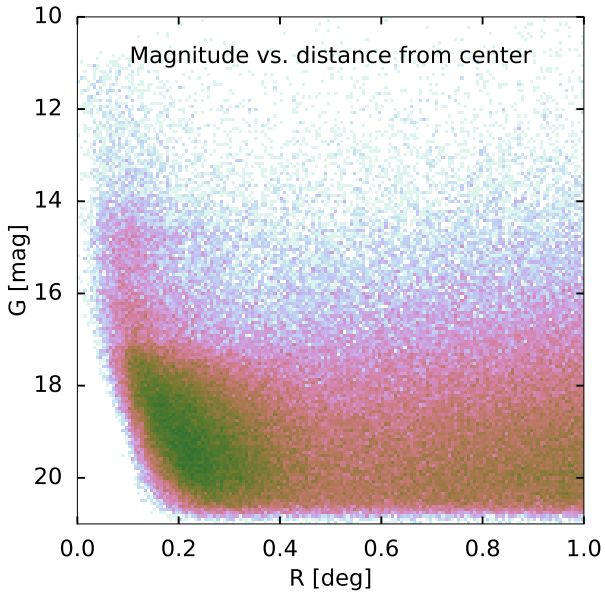
$(\varpi, \mu_\alpha, \mu_\delta)$

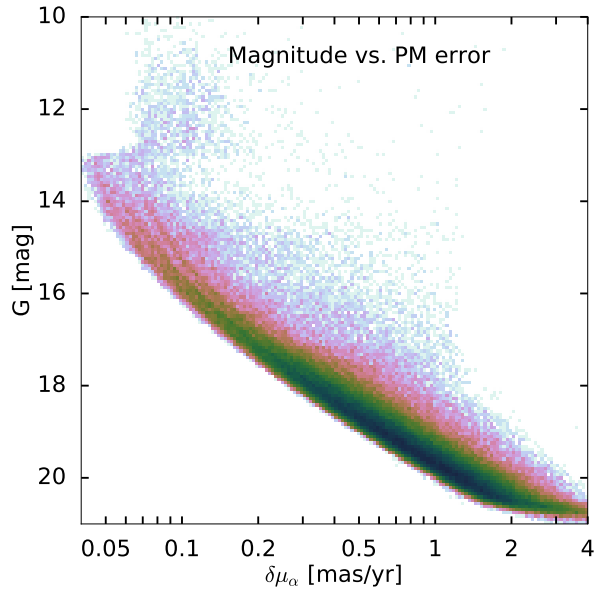
N=227754











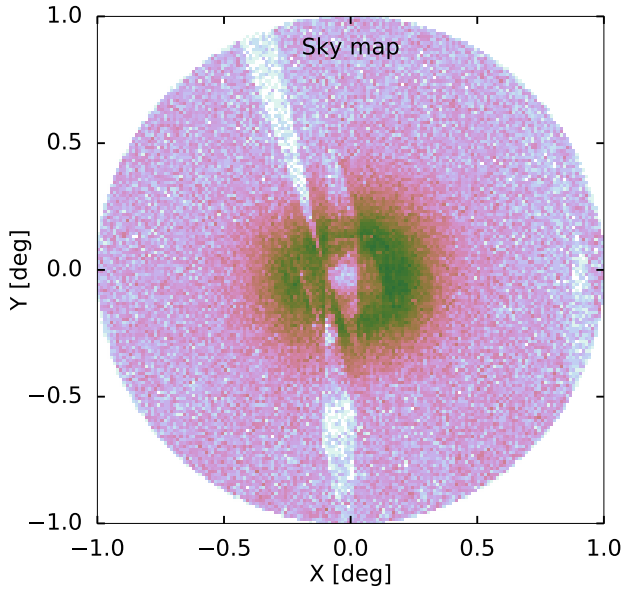
Example: NGC 5139 (ω Cen)

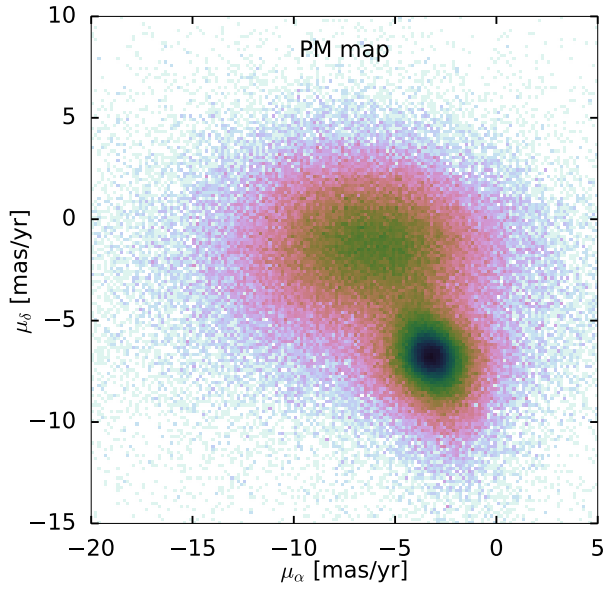
Parallax cut:

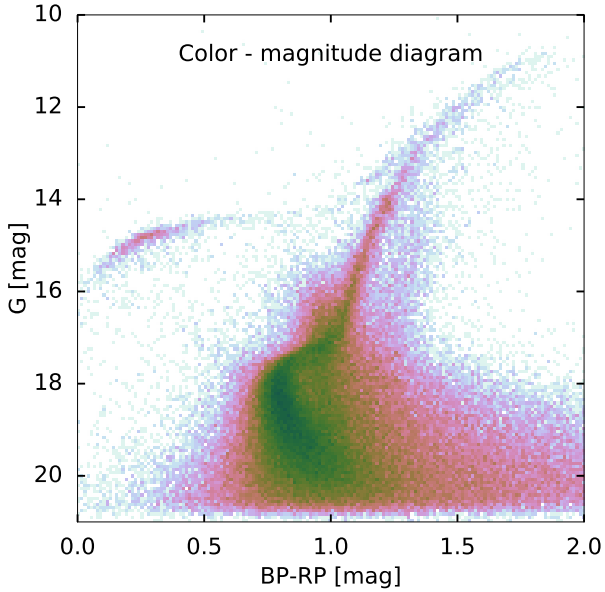
$$\varpi - \varpi_0 < 3\,\delta\varpi,$$

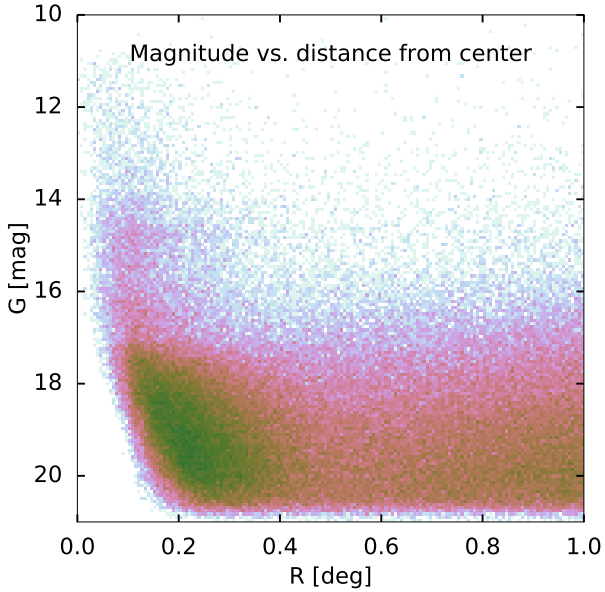
$$\varpi_0 = 0.15 \text{ mas}$$

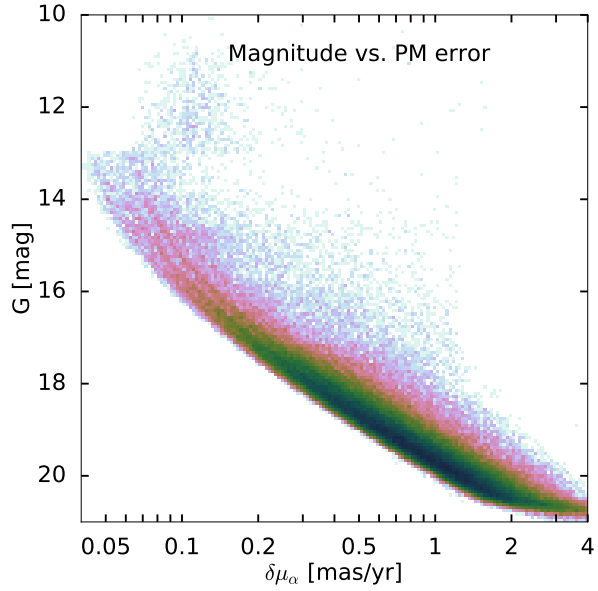
N=207980









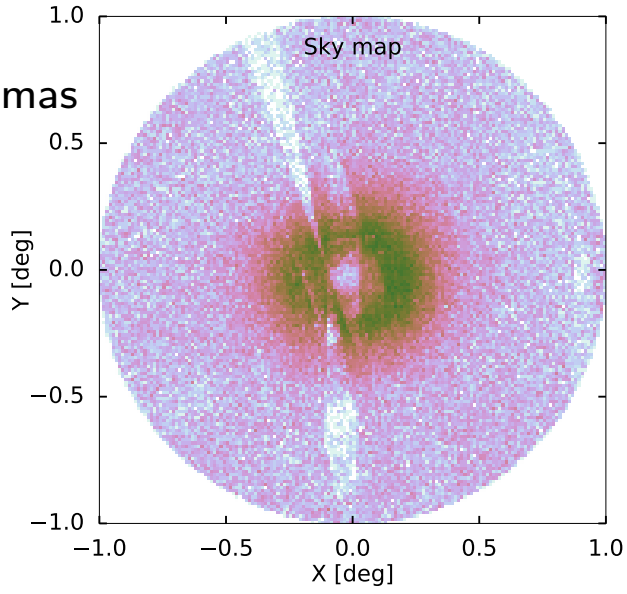


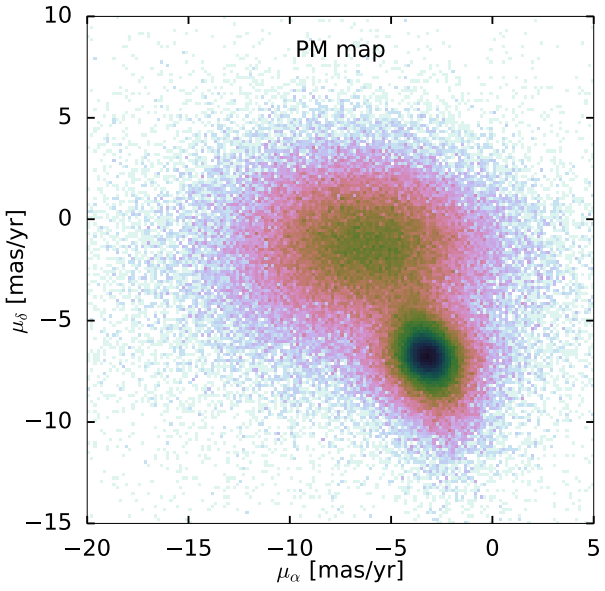
Example: NGC 5139 (ω Cen)

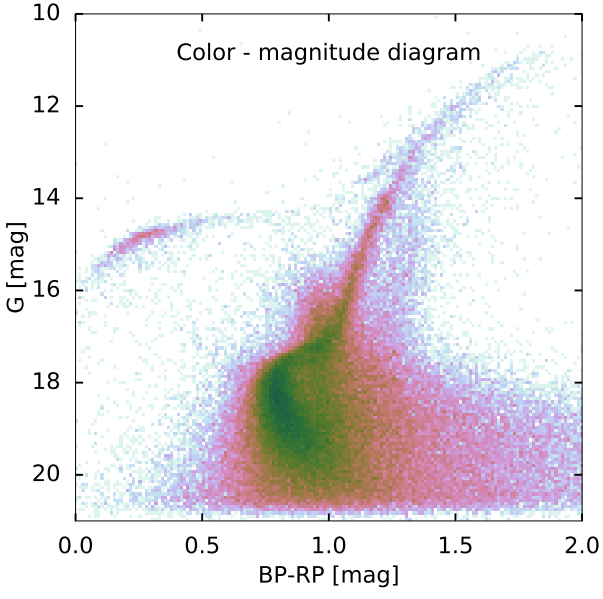
Cut on astrometric quality:

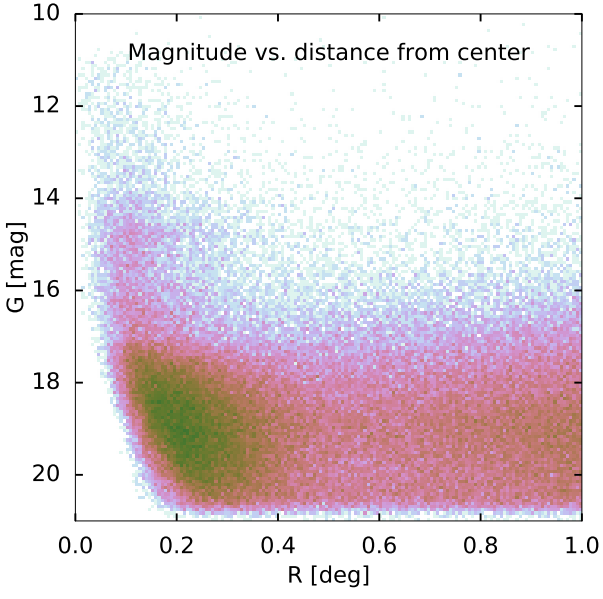
$\texttt{astrometric\_excess\_noise} < 1$ mas

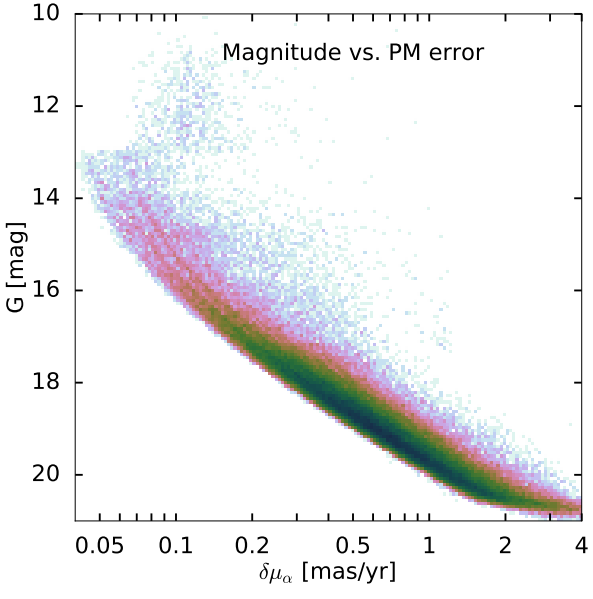
N=167376









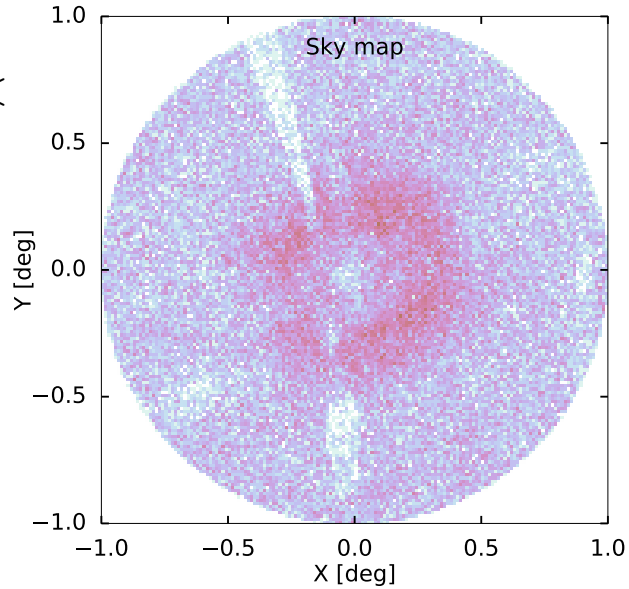


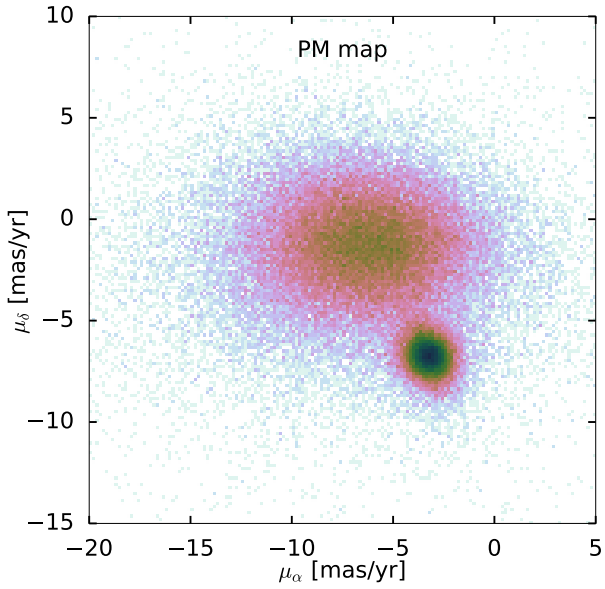
Example: NGC 5139 (ω Cen)

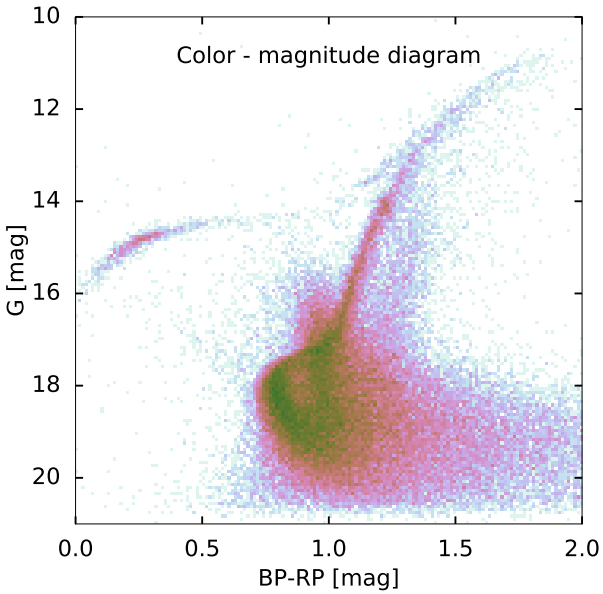
Cut on photometric quality:

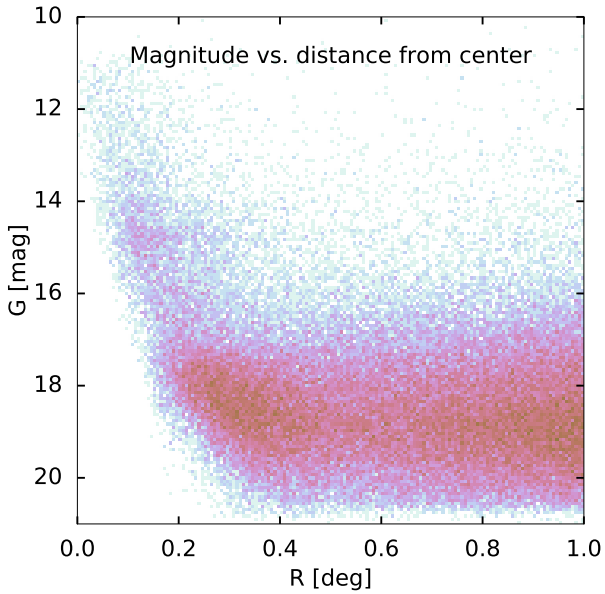
$$\texttt{phot\_bp\_rp\_excess\_factor} < 1.3 + 0.06\,(G_{BP} - G_{RP})^2$$

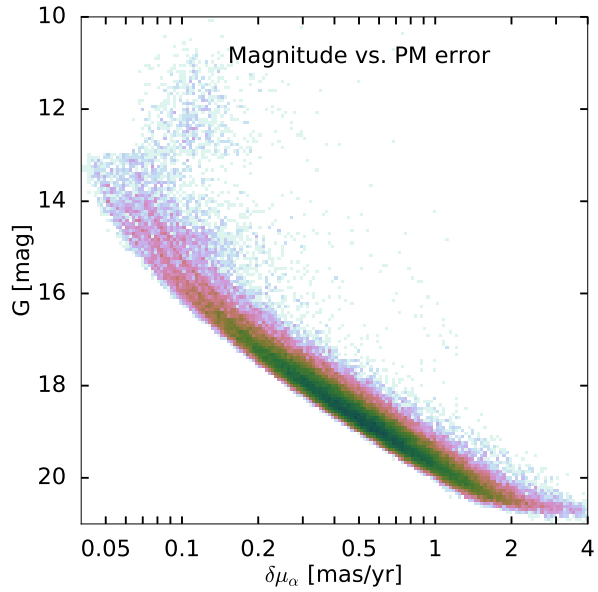
N=89686



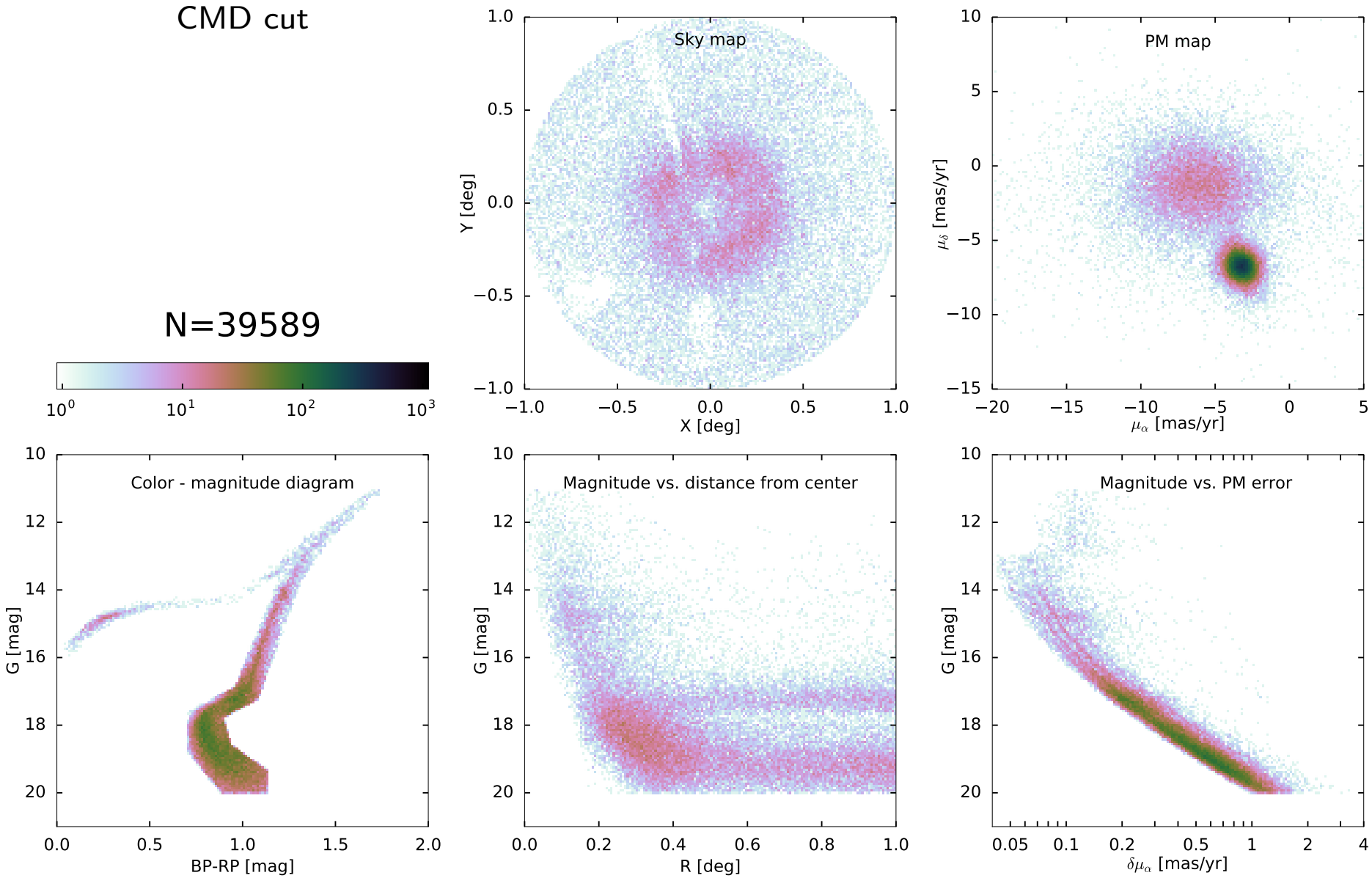








Example: NGC 5139 (ω Cen)



Example: NGC 5139 (ω Cen)

Cut on proper motions:

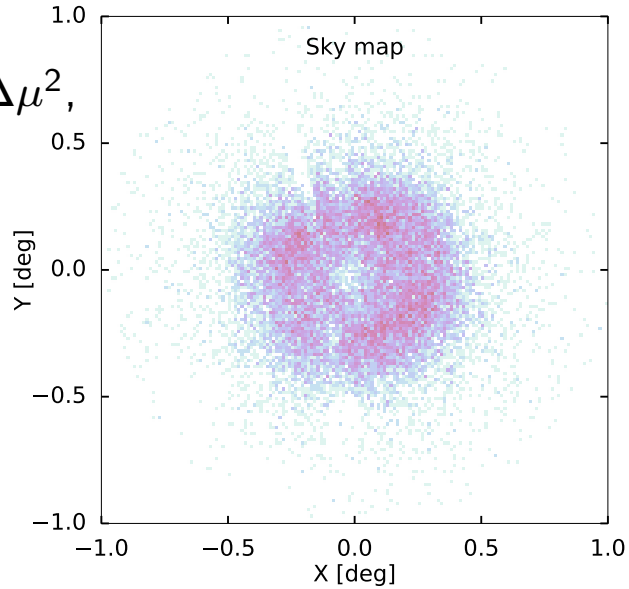
$$(\mu_\alpha - \mu_{\alpha,0})^2 + (\mu_\delta - \mu_{\delta,0})^2 < \Delta\mu^2,$$

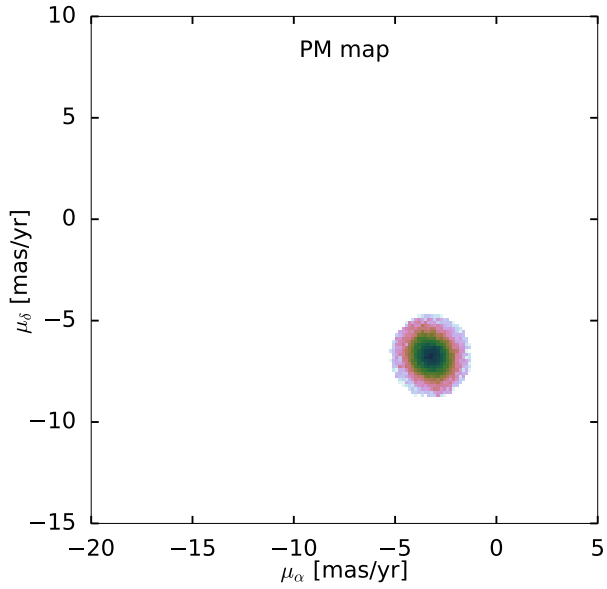
$$\mu_{\alpha,0} = -3.2 \text{ mas/yr},$$

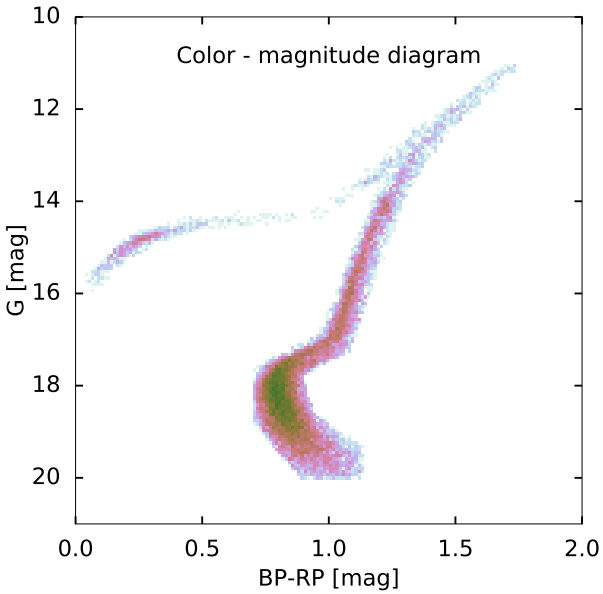
$$\mu_{\delta,0} = -6.75 \text{ mas/yr},$$

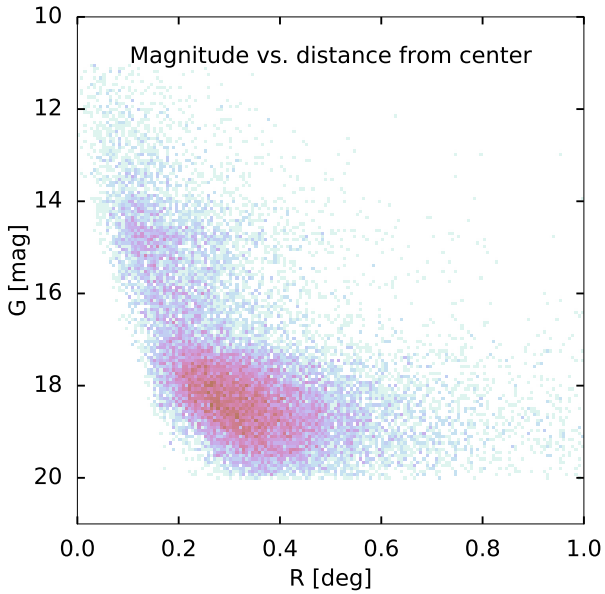
$$\Delta\mu = 2 \text{ mas/yr}$$

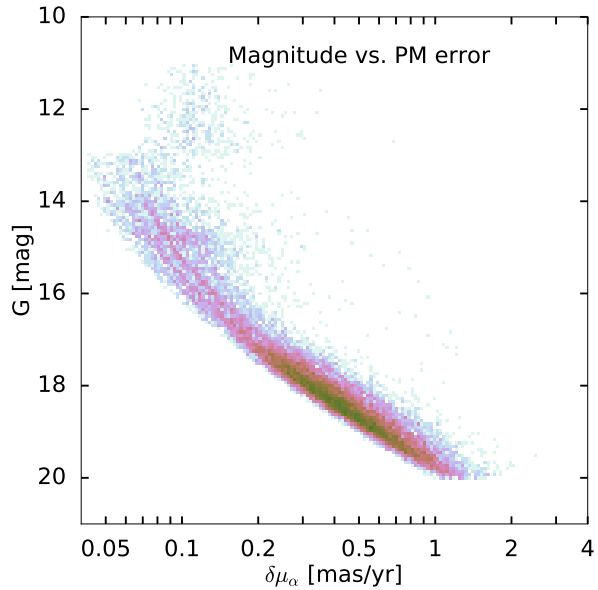
N=22342





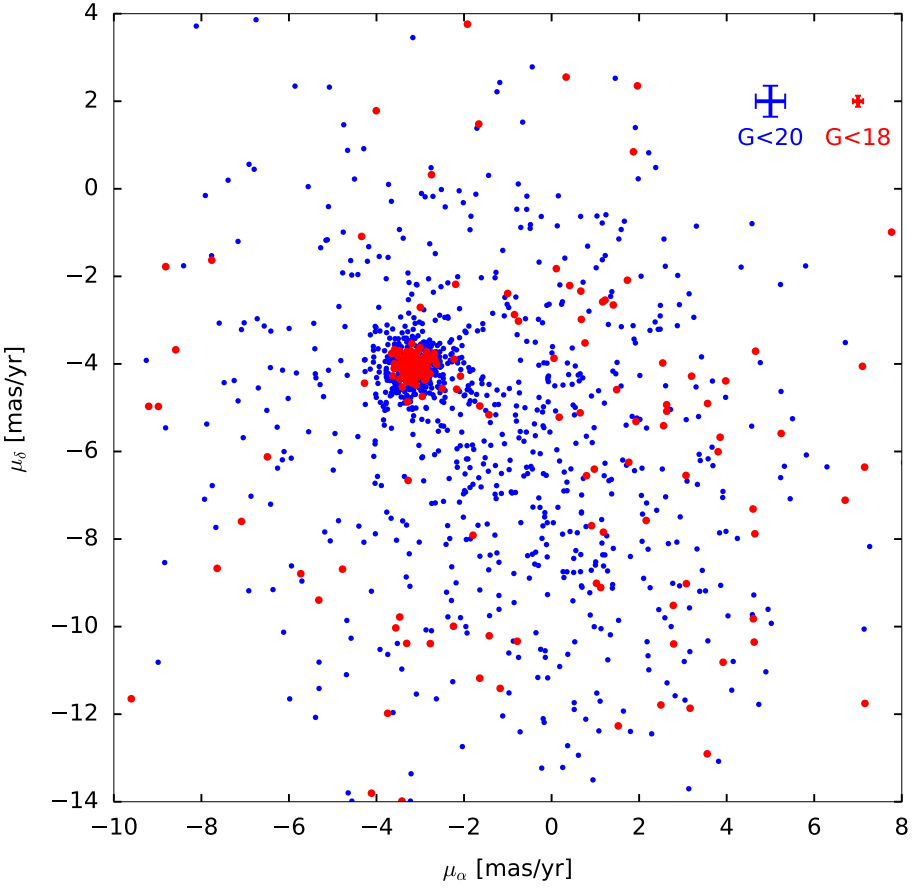


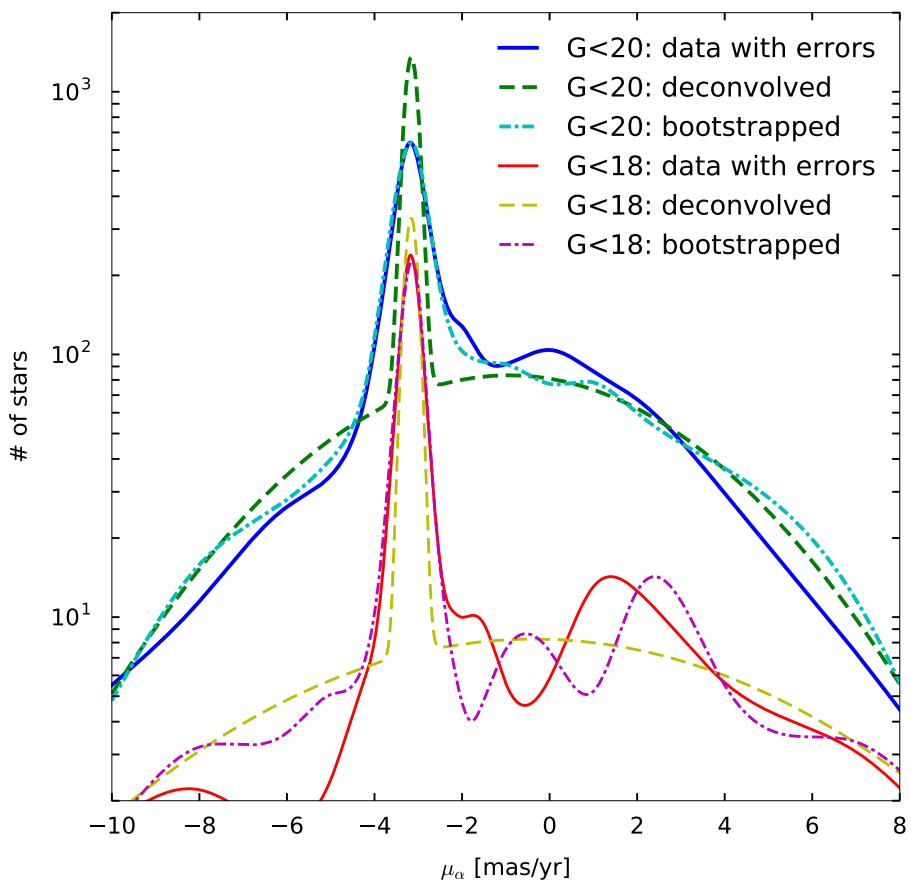




Inferring the internal velocity dispersion

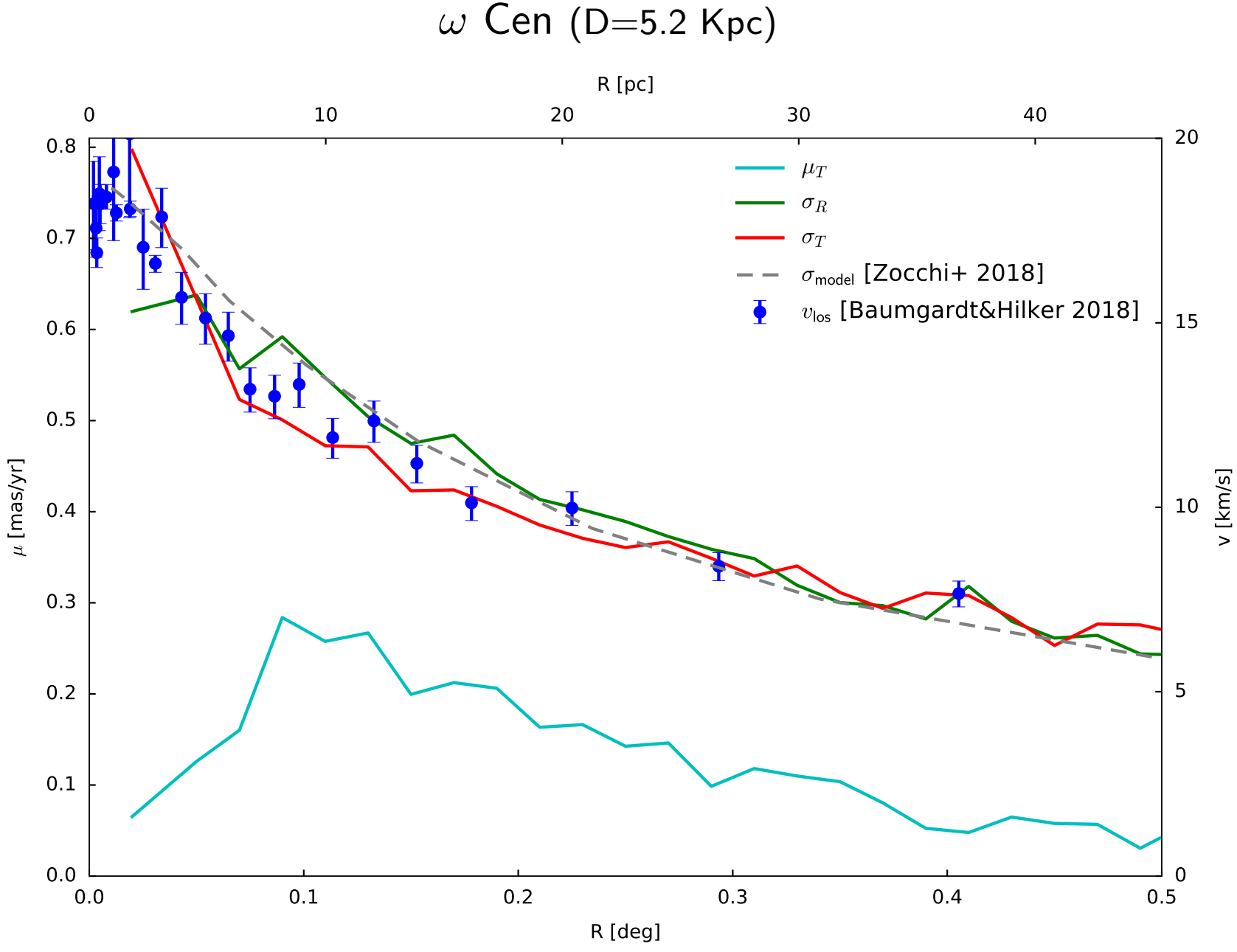
Gaussian mixture modelling of PM distribution without applying hard cuts and taking into account individual errors (Extreme Deconvolution, Bovy+ 2011)



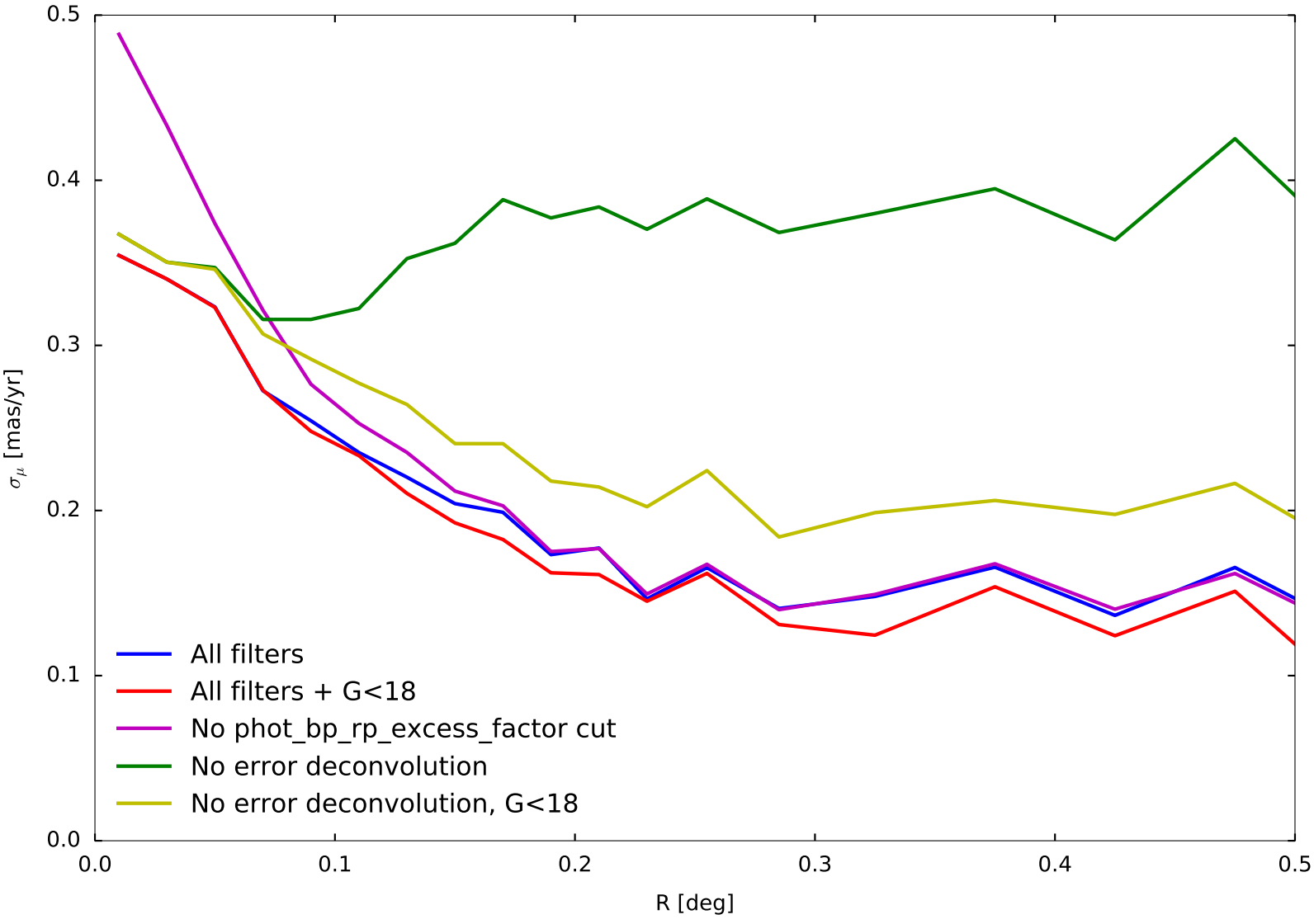


NGC 6752, $0.35^\circ < R < 0.5^\circ$

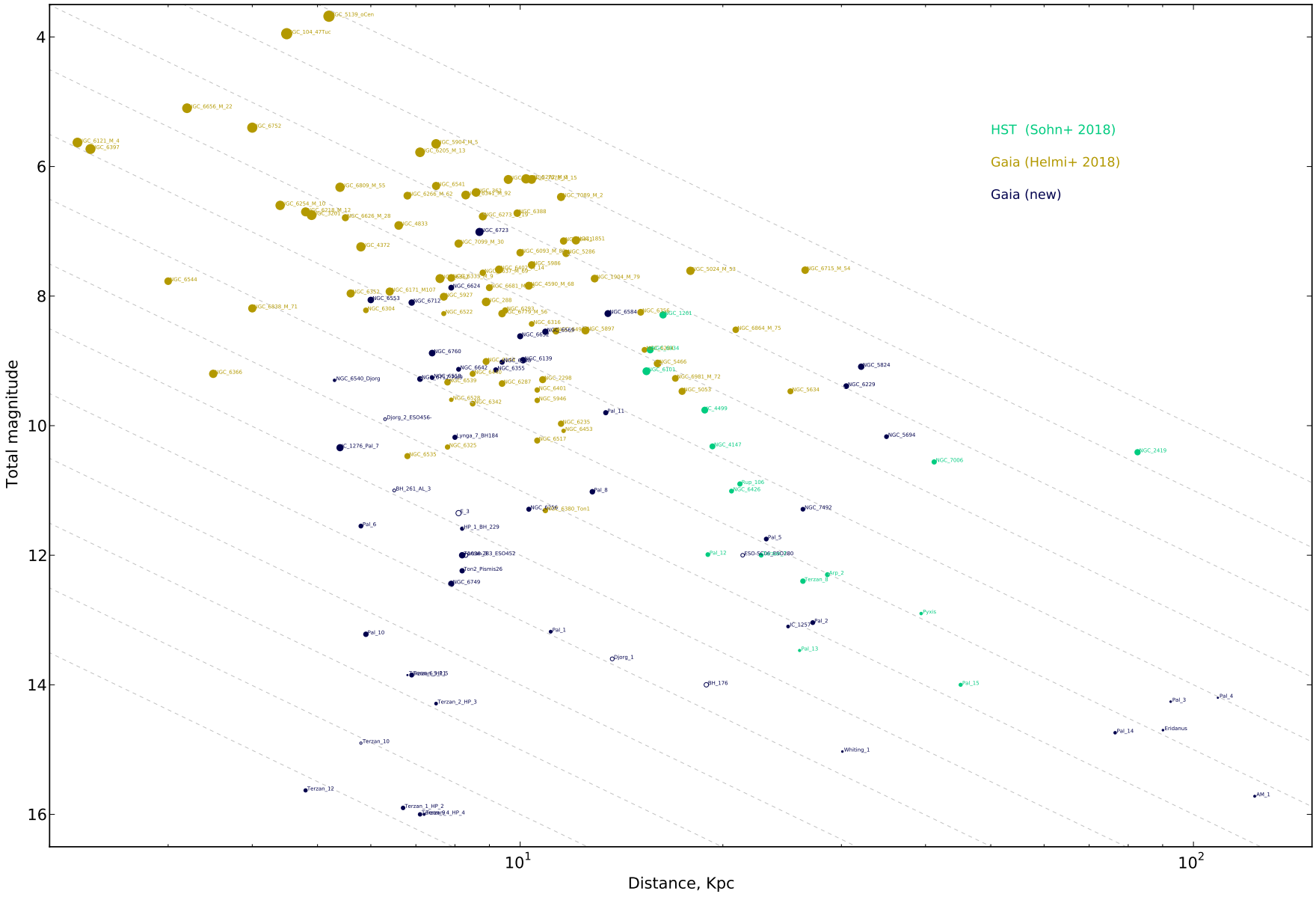
Results: radial profile of velocity dispersion and rotation



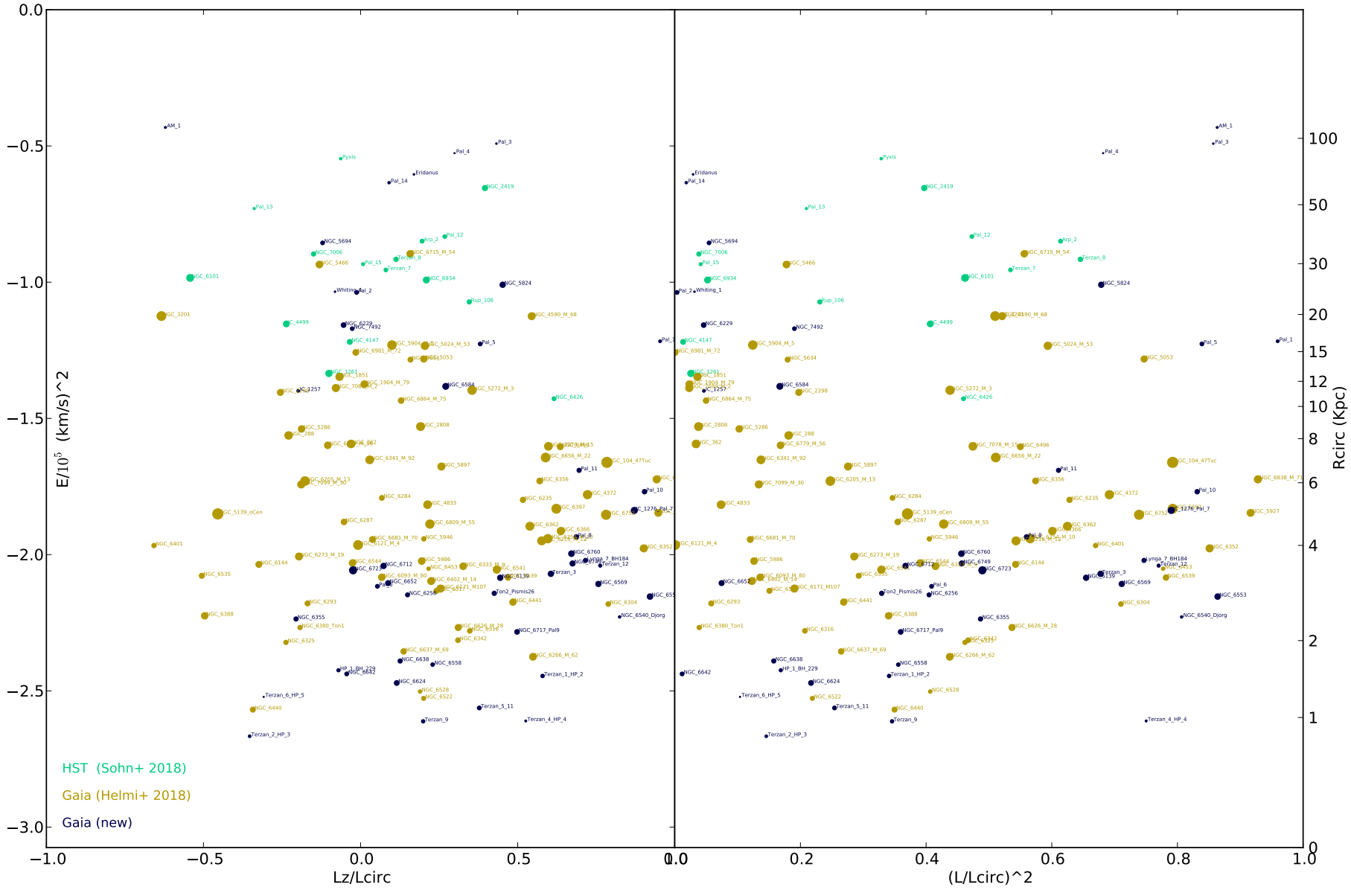
Effects of various quality cuts



Proper motions for [almost all] Milky Way globular clusters



Phase-space distribution of Milky Way globular clusters



Complementary instruments and surveys

Astrometry (mainly proper motions):

- Gaia: down to $G = 21$, but only in the outer parts;
  − central regions severely limited by crowding.
  + Provides absolute proper motions in the global reference frame
  (subject to systematic uncertainty of ~ 0.05 mas/yr).
- Hubble (*HSTPROMO*: Bellini+ 2014, Watkins+ 2015, Sohn+ 2018):
  + performs well even in crowded regions;
  + precision comparable or better than Gaia (baseline ~ 15 yr);
  + goes down to 26 mag in outer regions;
  − much smaller FoV ($3'$);
  − PMs are relative (don't provide mean motion and rotation),
  unless enough background galaxies are used to anchor them.
- Ground-based: superseded by Gaia for all practical purposes.

Complementary instruments and surveys

Radial velocities:

- Gaia: down to $G \lesssim 13$ (improved by ~ 3 mag towards the end of mission), but for the entire sky ($80 - 90\%$ compleness except dense regions).
- Ground-based: several magnitudes deeper, but more limited spatial coverage.

Chemistry, stellar parameters:

- Gaia: $T_{\rm eff}$, $R_\star$, $L_\star$, $\log g$ down to $G \lesssim 17$ – in DR2 based on parallax and broad-band photometry only (G, BP, RP);
  will be improved in future data releases with low-res spectroscopy from BP/RP.
- Ground-based spectroscopy: produces much more information.

Photometry: Gaia cross-matches with several other surveys (2MASS, SDSS, PanSTARRS, RAVE) is provided in DR2.

Future data releases

- DR3 (late 2020), DR4 (end 2022):
  binary stars;
  BP/RP and RVS spectra;
  improved calibration, PSF modelling, etc.;
  better treatment of crowded regions;
  extended spectroscopic templates for hotter/cooler stars;
  variable star classification and lightcurves;
  epoch astrometry (50 – 300 observations for each star).

- Mission extension from nominal 5 years up to 10 years:
  parallax error $\propto T^{-1/2}$, PM error $\propto T^{-3/2}$!

Summary

- *Gaia* is awesome by itself, and complementary to other surveys
- Internal dynamics of globular clusters

  (velocity dispersion profiles, anisotropy, rotation, tidal boundary)
- Motion of globular clusters in the Galaxy