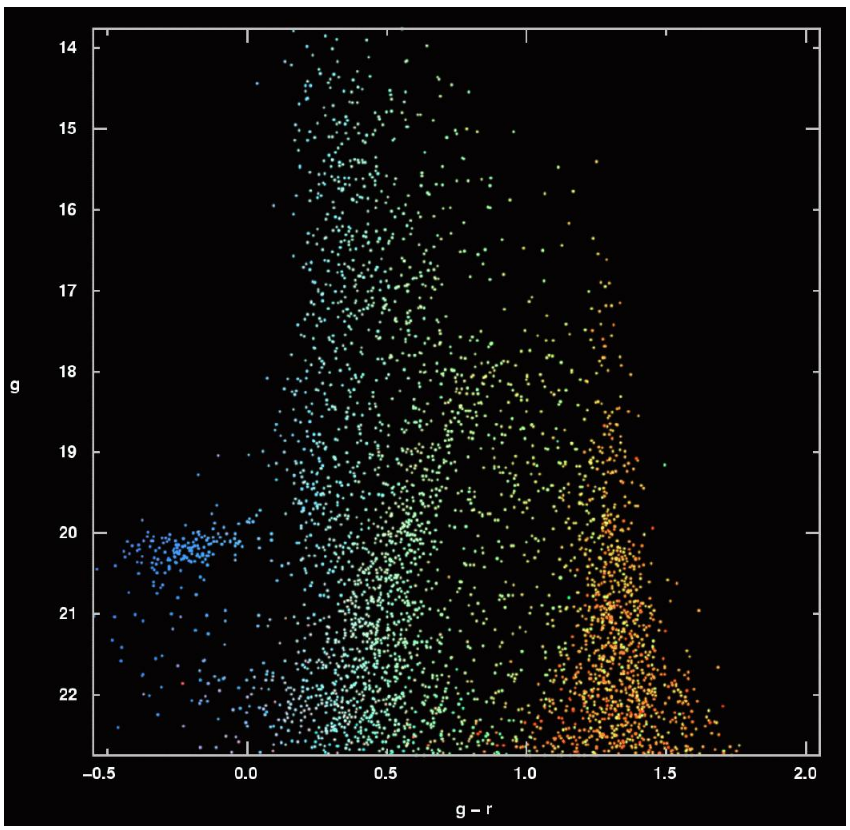
Astr 511: Galactic Astronomy

Winter Quarter 2015, University of Washington, Željko Ivezić

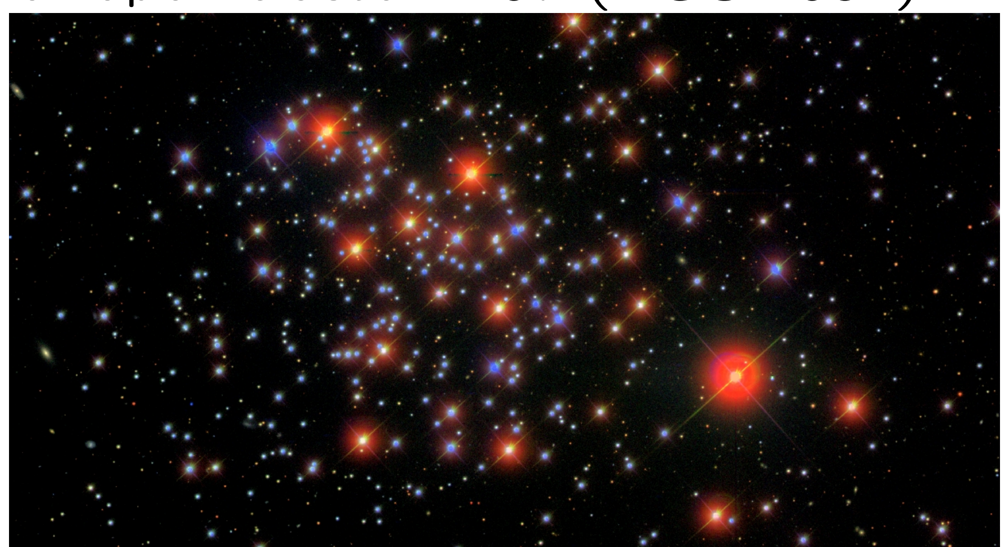
Lecture 2:

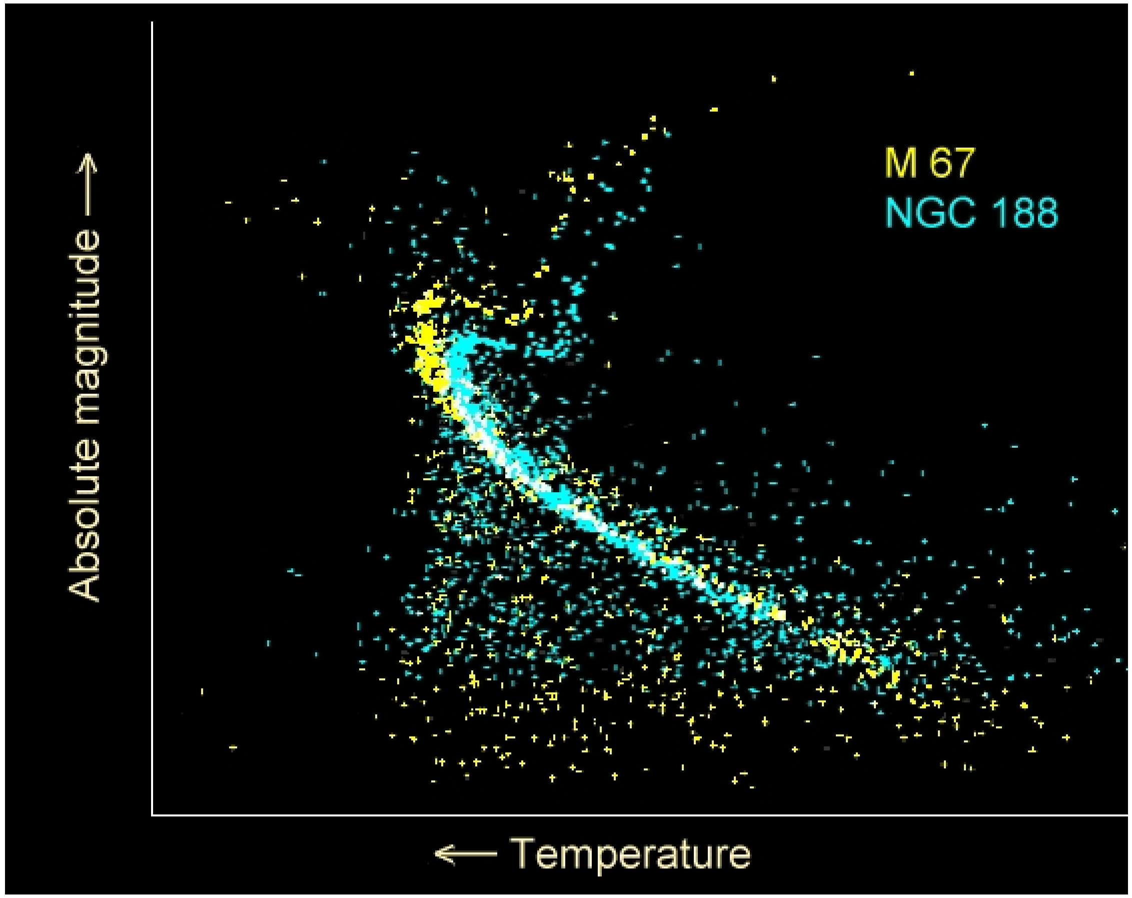
Open and Globular clusters and other simple stellar populations

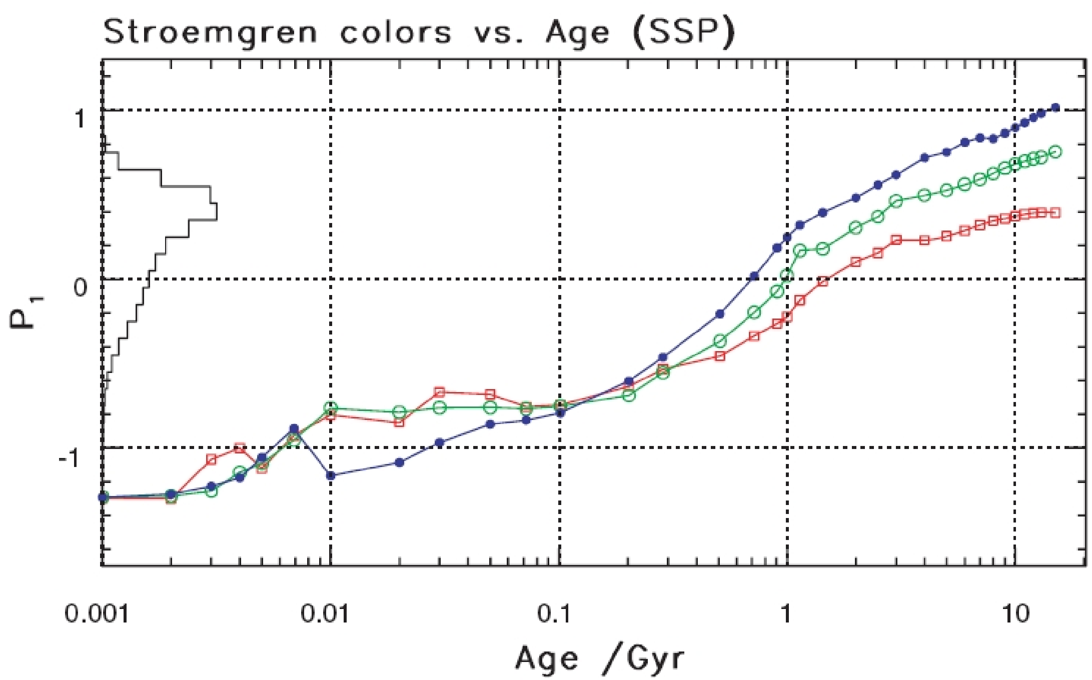


Open and Globular Clusters

- **Top left:** SDSS gri composite image of globular cluster NGC 2419; note blue (literally) horizontal branch stars and yellowish (red) giants; the image is color-coded by the observed g-r
- **Bottom left:** the SDSS g vs. g-r color-magnitude diagram of the area surrounding NGC 2419; the dots are color-coded by the observed SDSS g-r color
- **Below:** the SDSS gri composite image of open cluster M67 (NGC 2682)

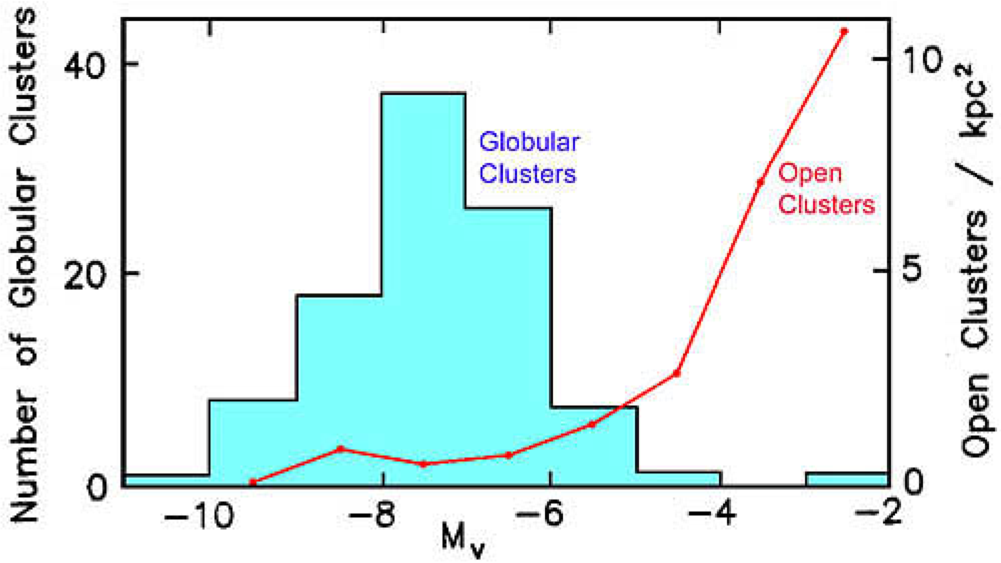






Open and Globular Clusters

- Stellar clusters are excellent probes of stellar astrophysics
- The three main advantages:
  1. All stars at roughly the same distance
  2. All stars have roughly the same composition
  3. All stars have roughly the same age
- The position of the main sequence, at a given color, depends on metallicity
- The turn-off color depends on age and metallicity
- Other features, such as morphology of blue horizontal branch and red giant branch, also depend on age and metallicity



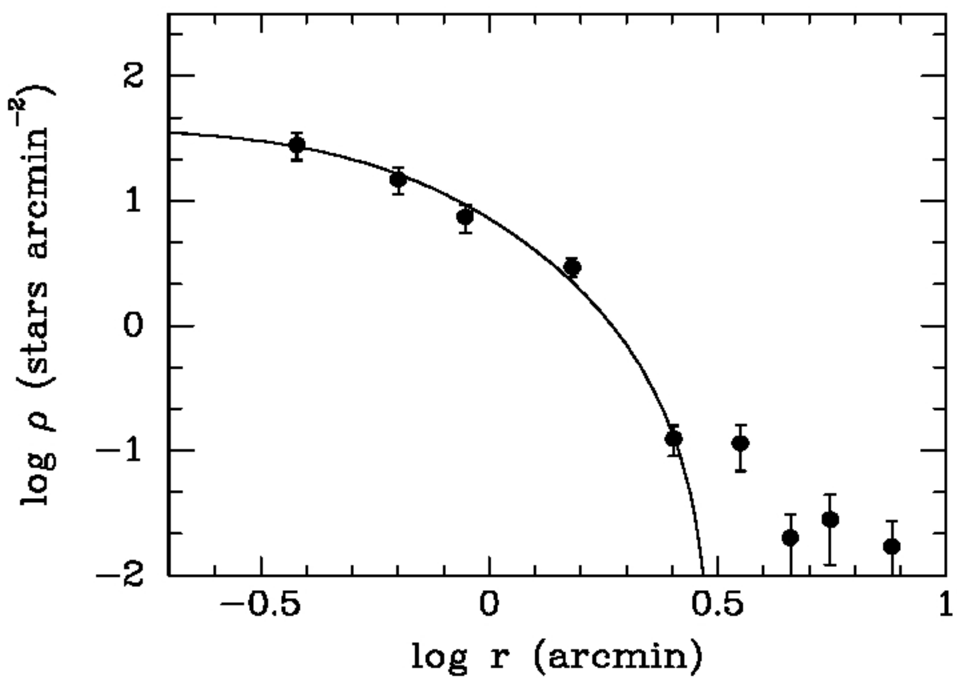


FIG. 7.—Radial star count profile of Pal 13 for stars with membership probabilities ≥50%. The line is the best-fit King profile to the cluster. Note the member stars outside the classical limiting radius.

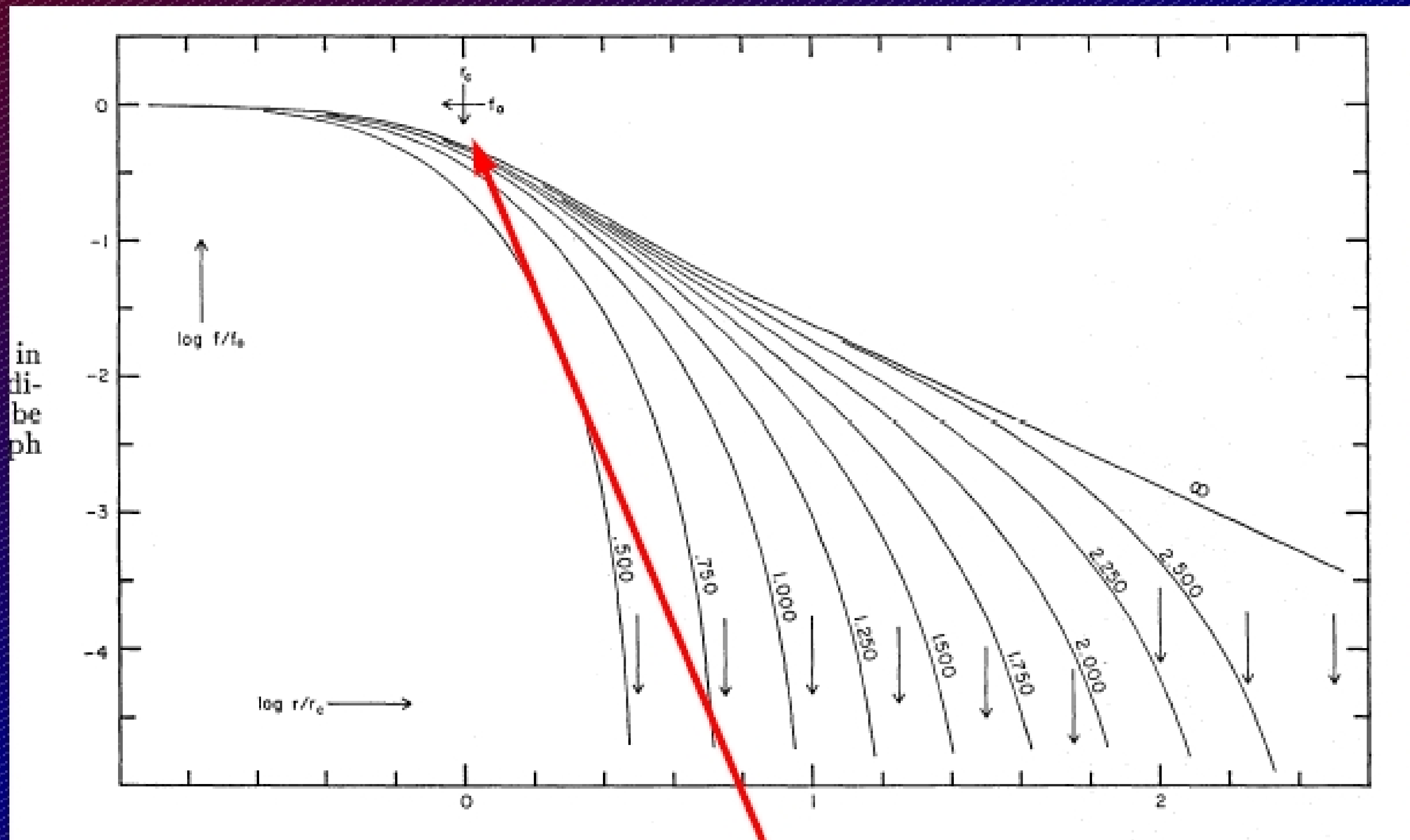
Open and Globular Clusters

- Open clusters are younger and concentrated towards the Galactic plane; globular clusters are more spherically distributed, at larger distances from the galactic center, have much lower metallicity and are much older
- **Top left:** luminosity functions for globular and open clusters are very different
- **Bottom left:** dying globular cluster Pal 13 (Siegel et al. 2001, AJ 121, 935): Spatial profiles of globular clusters usually closely follow King profiles (c.f. Tom's class on stellar dynamics); next slide stolen from Doug Heggie

KITP

King models

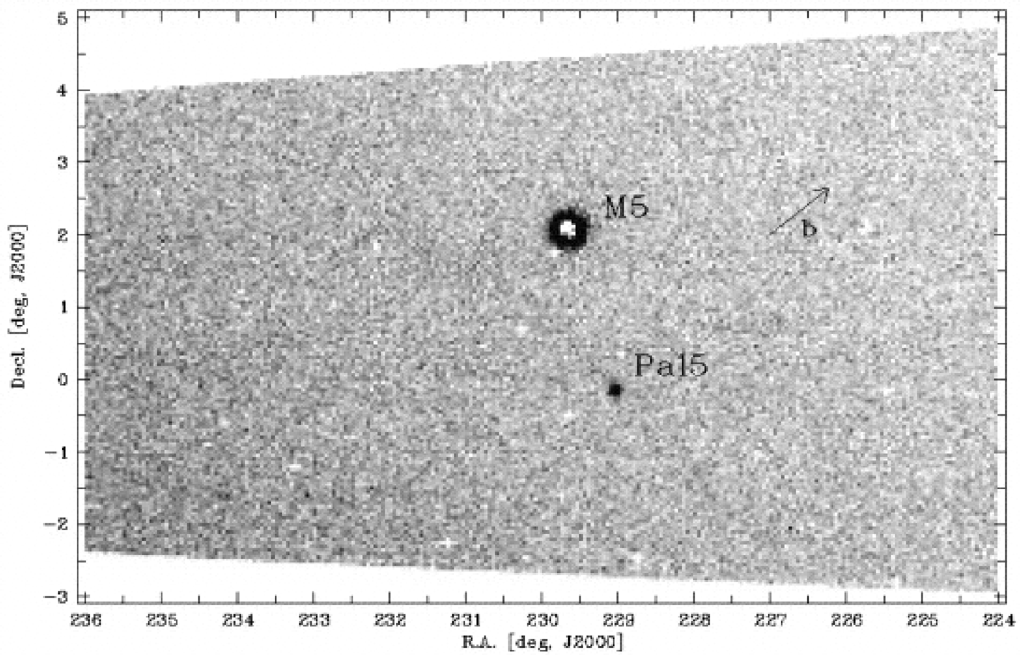
Surface brightness

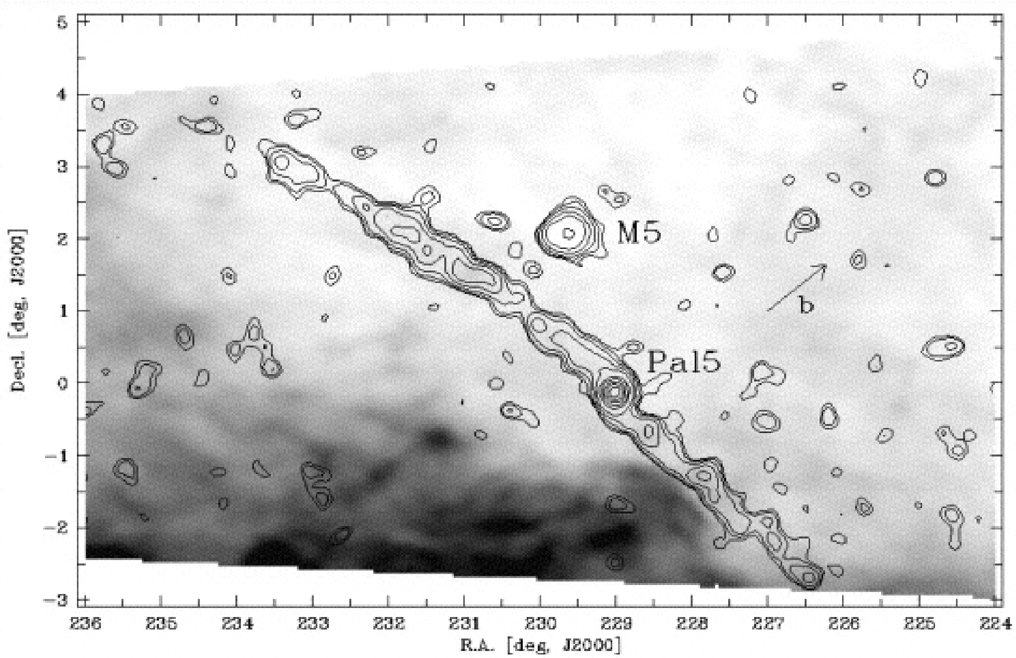


Projected radius

Ivan King

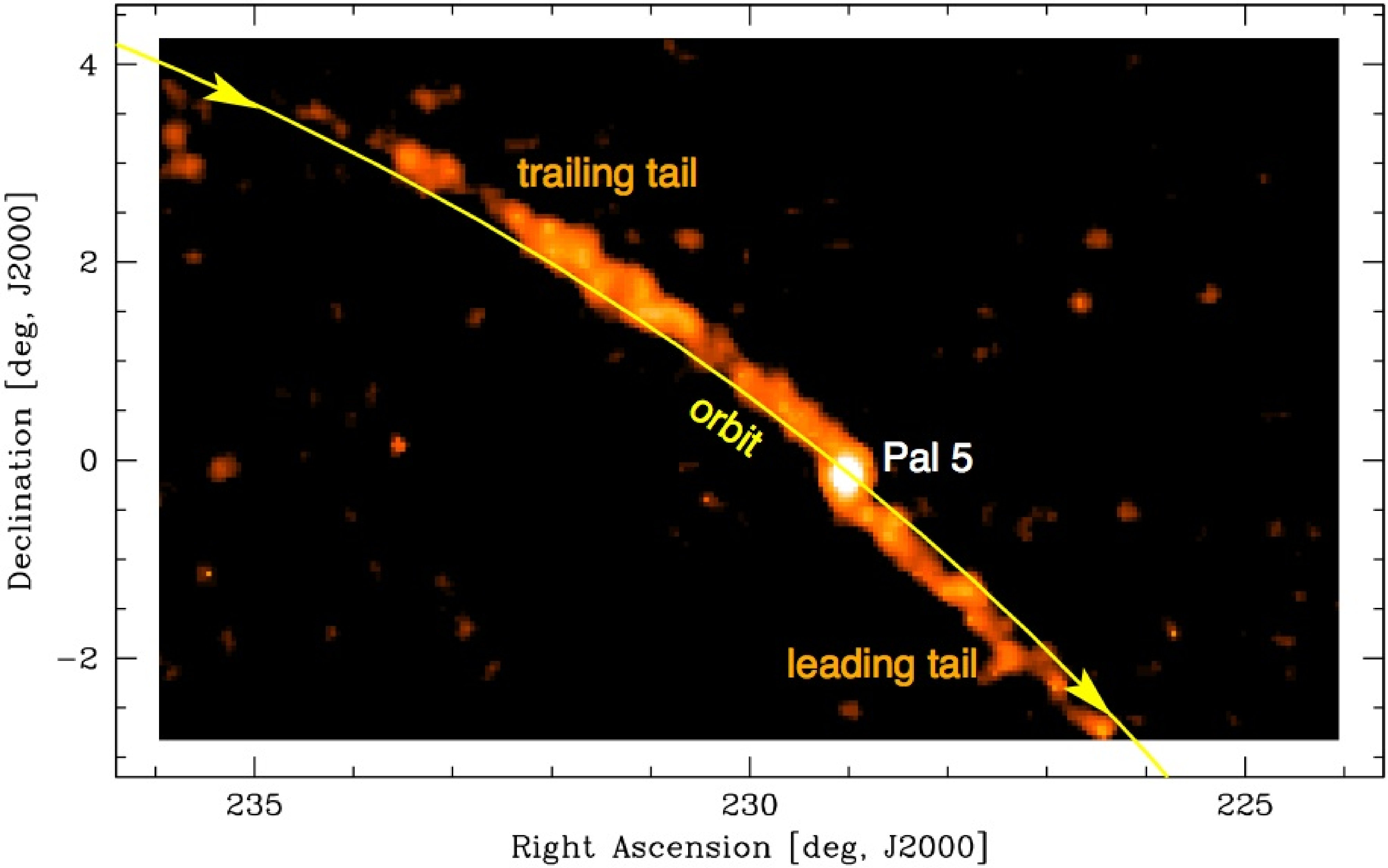
1-parameter sequence of shapes
+ 2 scale parameters (core radius; total luminosity)



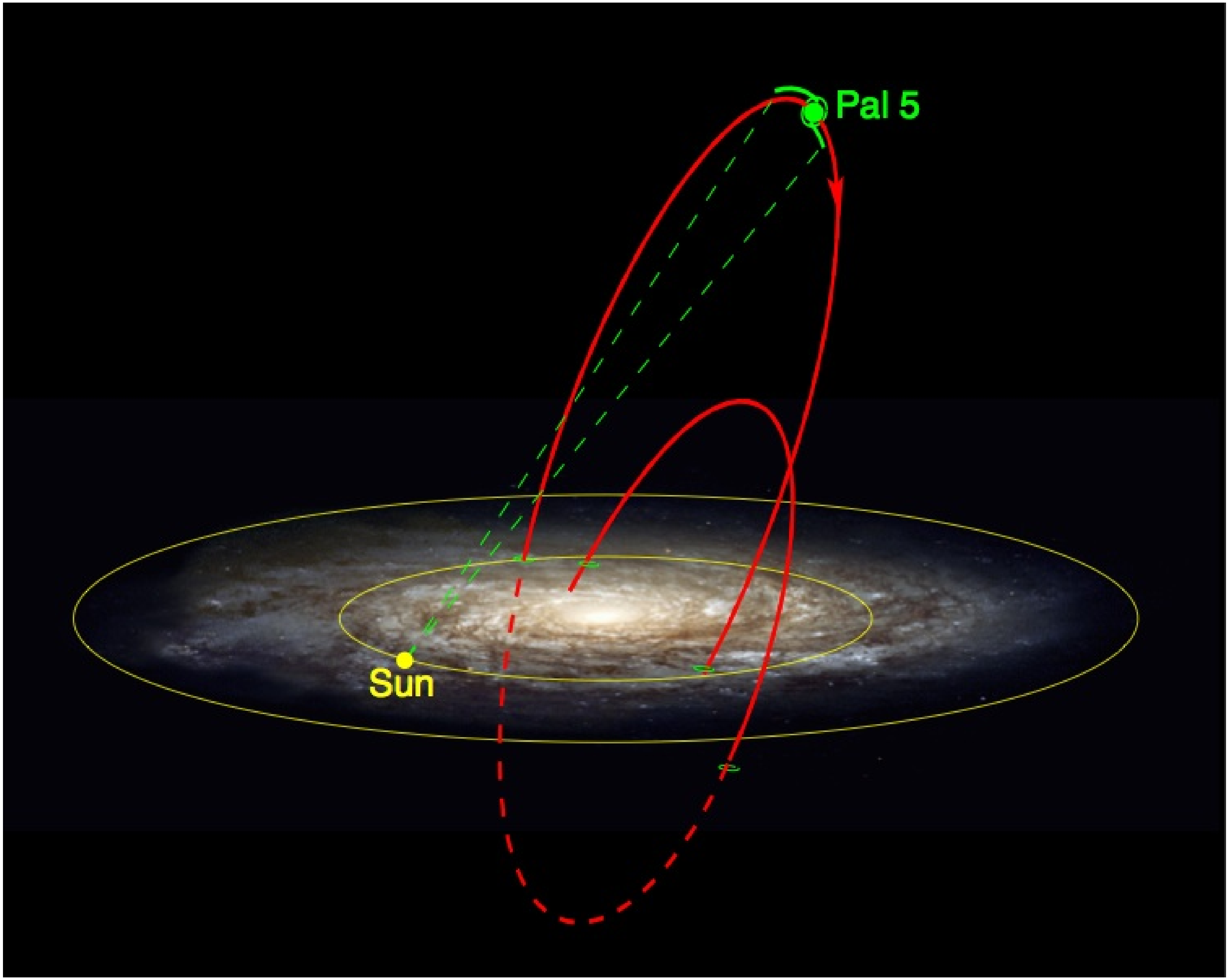


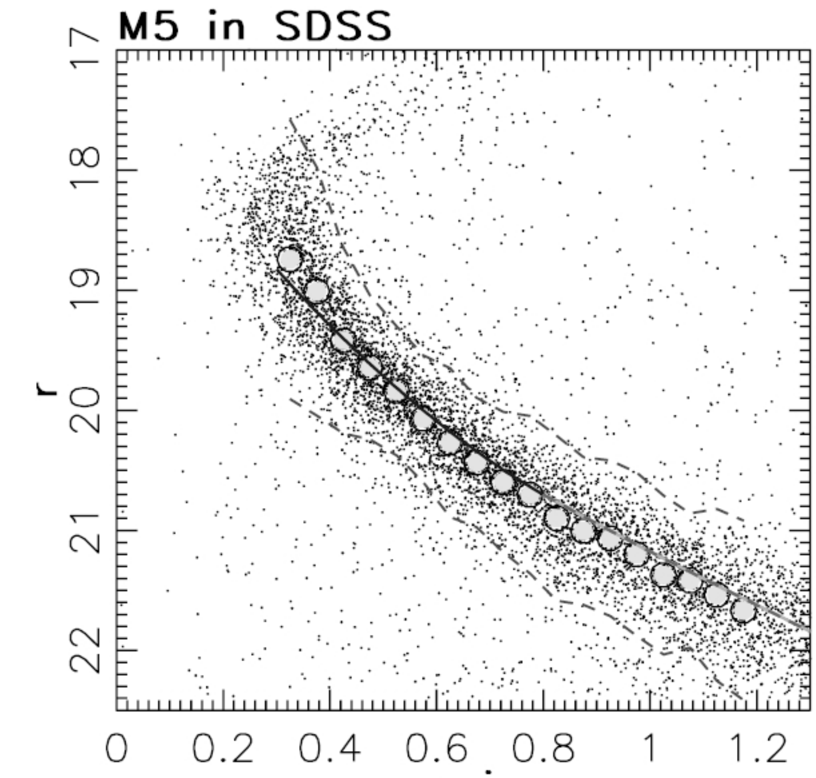
Tidal Tails around Globular Clusters

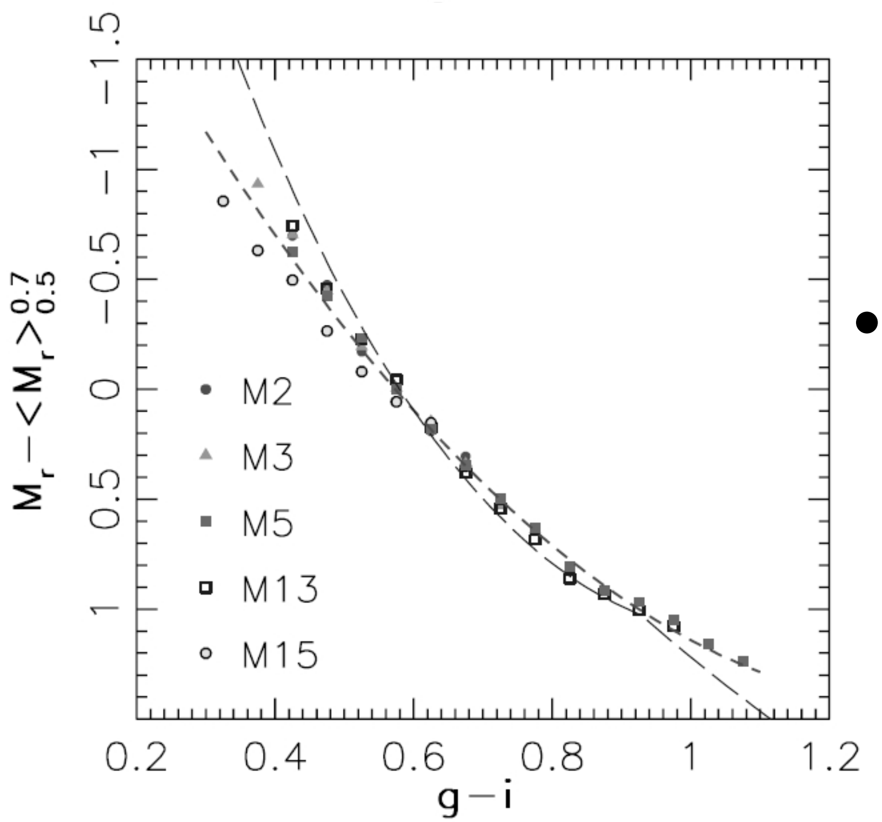
- **Top left:** SDSS stellar counts around globular clusters M5 and Pal5
- **Bottom left:** matched filter extraction of tidal tails around Pal 5 (gray: SFD E(B-V)) by Rockosi et al. (2002) and Odenkirchen et al. (2003)
- For more details about matched filter method, see Grillmair (2008, arXiv:0811.3965; and references therein)
- Tidal tails provide strong constraints on the Milky Way gravitational potential.



trailing tail
orbit
Pal 5
leading tail
Declination [deg, J2000]
Right Ascension [deg, J2000]
4
2
0
−2
235
230
225


Pal 5
Sun



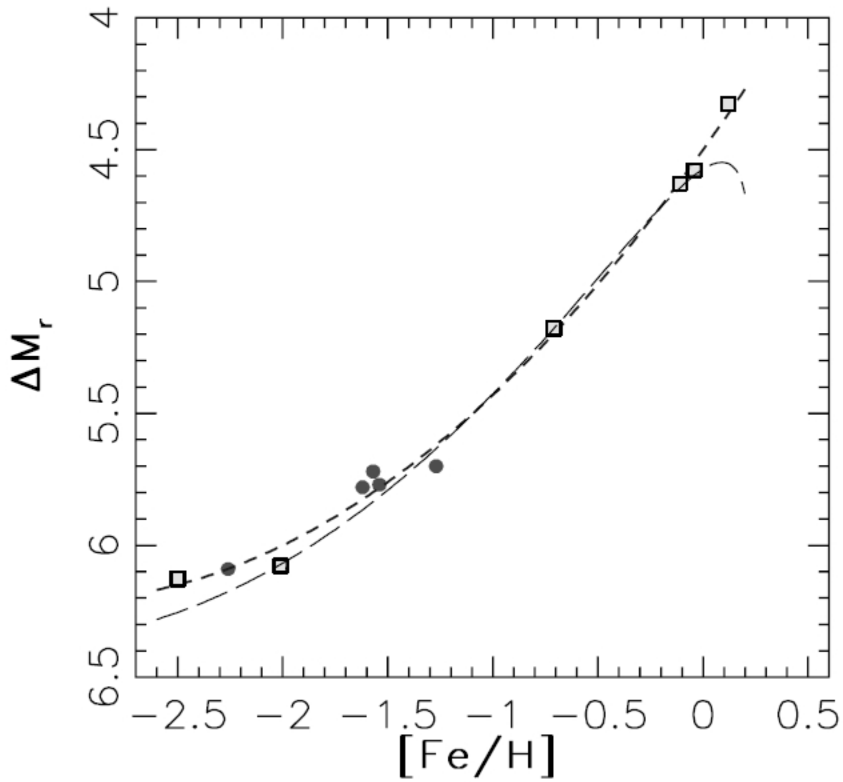


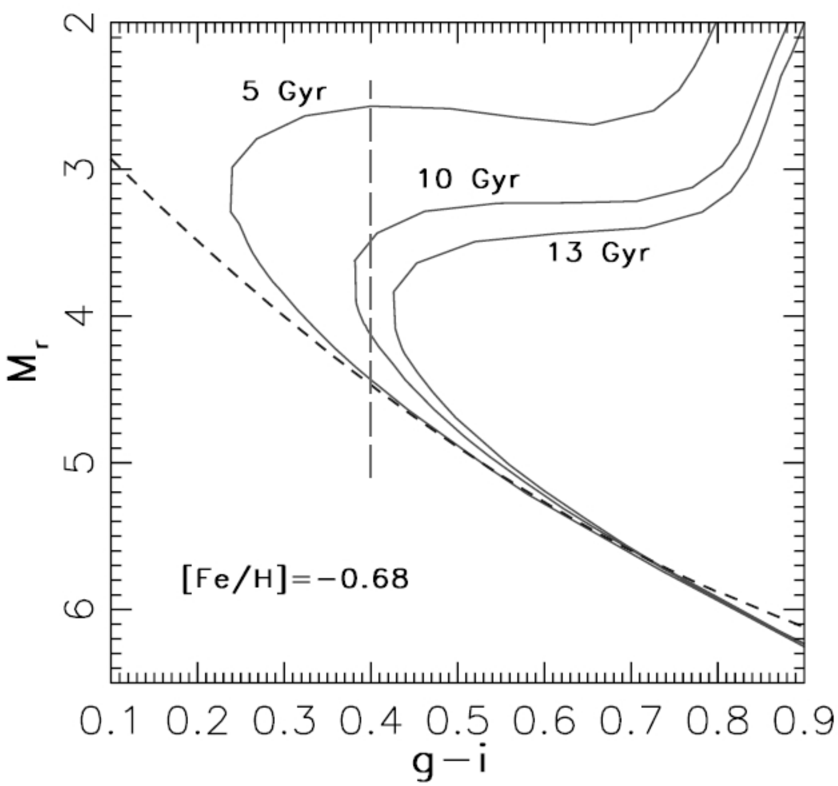
Photometric Parallax Calibration

- Using a large sample of globular clusters, we can calibrate $M_r(g - i, [Fe/H])$, and then apply it to field stars to get their distances.
- **Top Left:** an example of a globular cluster (M5) as observed by SDSS; the line is a polynomial fit to the median main sequence (large circles):

$$M_r = M_r^{0.6} - 2.85 + 6.29\,(g - i) - 2.30\,(g - i)^2 \quad (1)$$

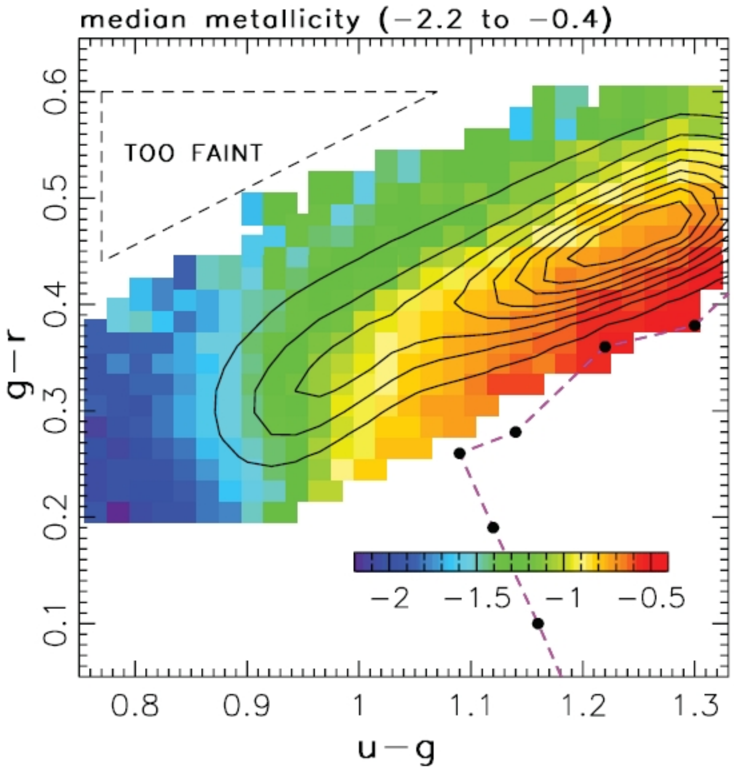
  where $M_r^{0.6}$ is the median absolute magnitude for stars with $0.5 < g - i < 0.7$.
- **Bottom Left:** this is a good fit to a number of globular clusters observed by SDSS, showing that the main effect of metallicity is to slide the main sequence vertically (i.e. along luminosity axis, changing $M_r^{0.6}$), without much effect on its *shape*.

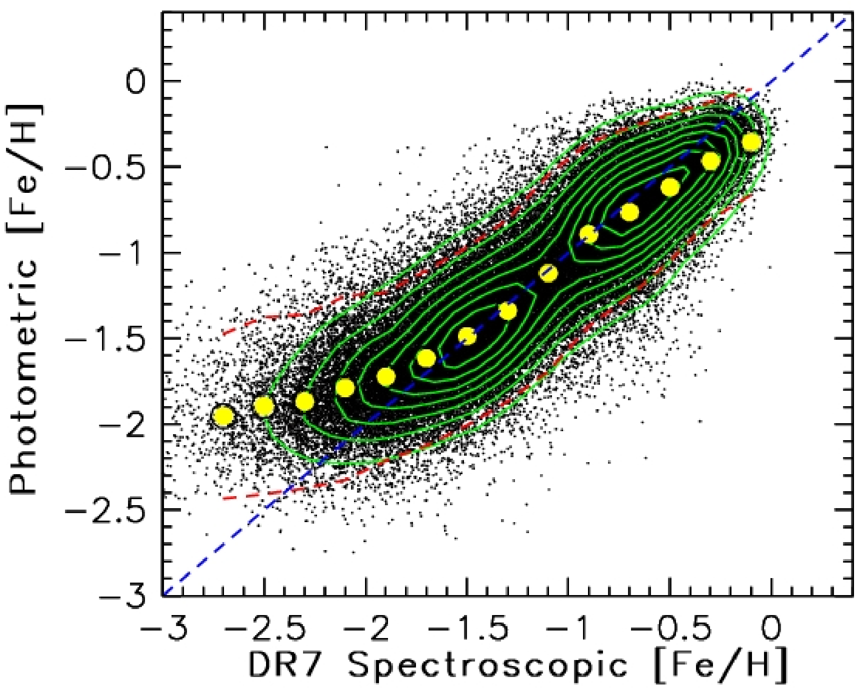




Photometric Parallax Calibration

- The position of the main sequence depends on [Fe/H]
- **Top Left:** calibration (short-dashed) based on SDSS data (dots) and VandenBerg & Cleam (2003; squares). The shift is huge: >1 mag between median halo metallicity ($[Fe/H] = -1.5$) and local disk metallicity ($[Fe/H] = -0.2$). Must know [Fe/H] to within 0.2 dex to know distances within 10%!
- **Bottom Left:** at a **fixed** [Fe/H], the turn-off depends on the age of a stellar population (based on models!).
- For a relation appropriate for age of 10 Gyr (at halo metallicity) see eq. A7 in Ivezić et al. (2008, ApJ, 684, 287)
- *What about metallicity?*



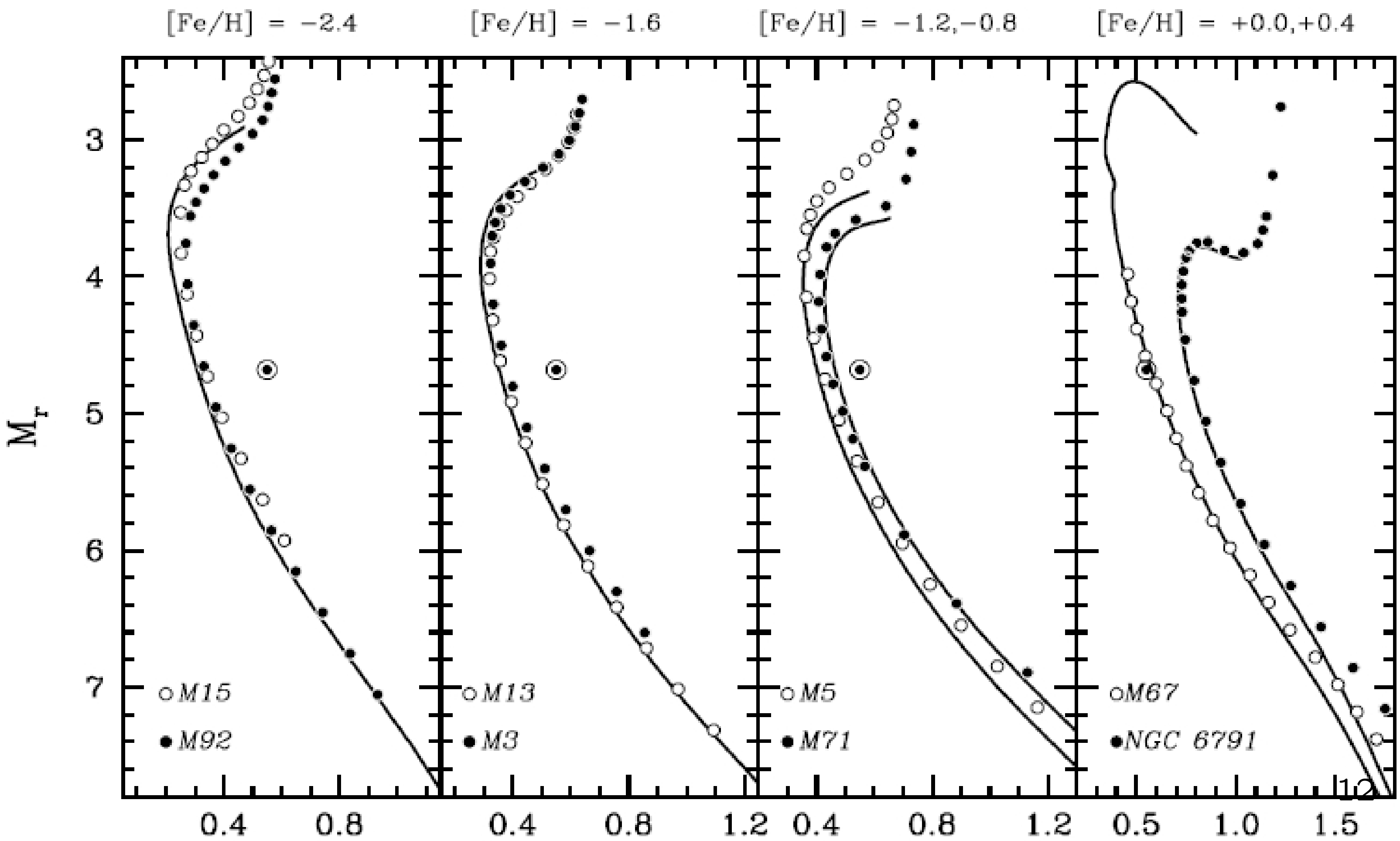


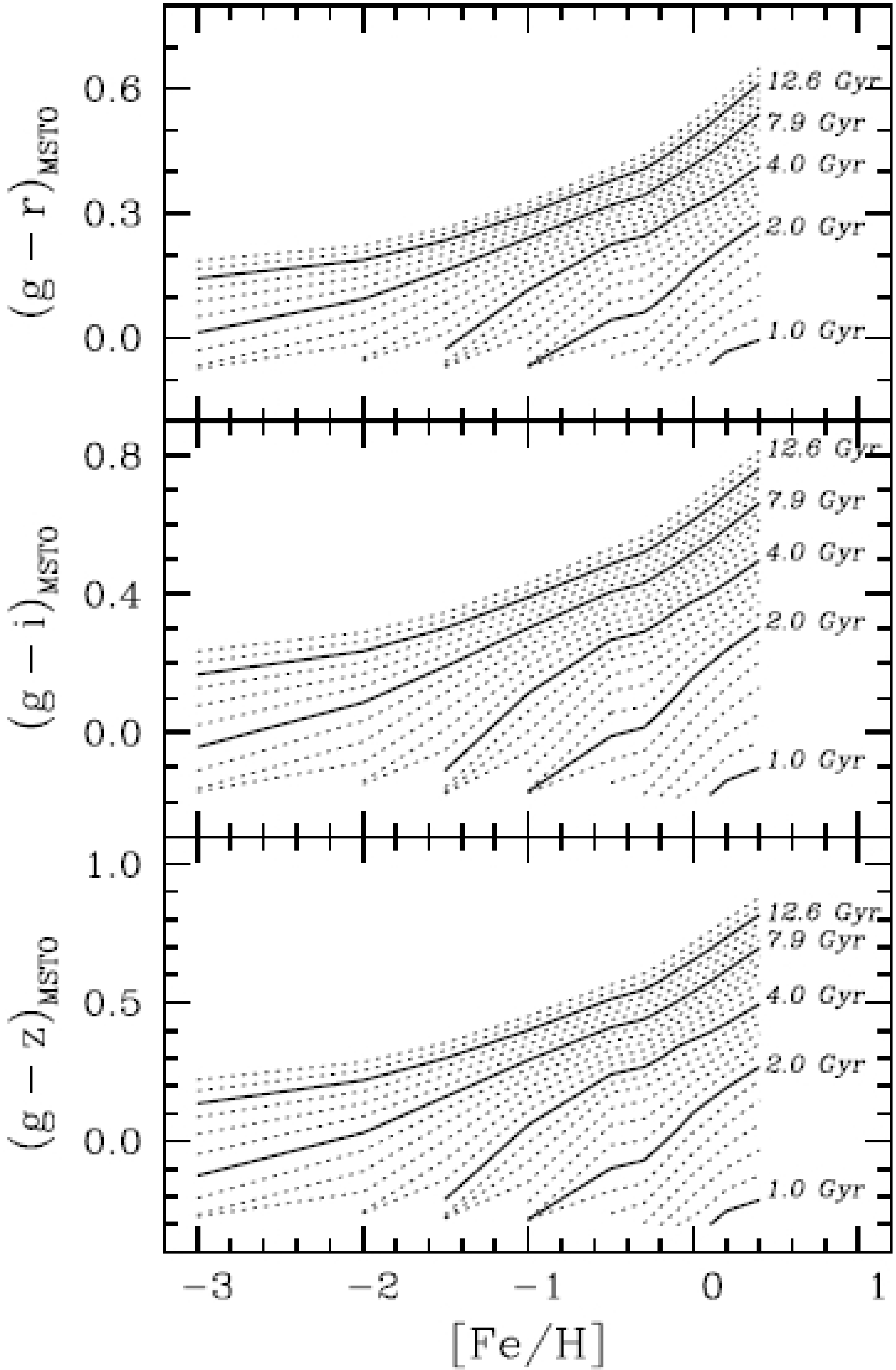
Photometric Metallicity Calibration

- At a fixed effective temperature, the amount of UV flux ($\lambda < 4000\mathring{A}$) for F/G main-sequence stars is very sensitive to metallicity (Wallerstein 1962)
- **Top Left:** the dependence of spectroscopic metallicity (using 60,000 SDSS stellar spectra) on the position in the $g-r$ vs. $u-g$ color-color diagram
- **Bottom Left:** the correlation between photometric metallicity, estimated using a two-dimensional third-order polynomial fit to the map shown in the top left panel, and spectroscopic metallicity; the individual values agree with an rms of 0.26 dex (includes errors from both methods)
- For stars with $0.2 < g-i < 0.8$, [Fe/H] can be estimated if the u band photometry (or U in Johnson system) is available.

How good are stellar models?

- Good at predicting absolute magnitudes of main-sequence stars to within 0.1-0.2 mag for stars with $T_{eff} > 4000$ K.
- An excellent model database: Percival et al. (2009, ApJ, 690, 427)
- **Bottom:** fig. 5 from An et al. (2009): lines are YREC+MARCS models for age of 12.6 Gyr; bulls-eye symbol marks the Sun





The turn-off color

- At a fixed metallicity, the turn-off color depends on age (the color-age translation can be obtained from models).
- **Left:** the dependence of turn-off color on metallicity and age for YREC+MARCS models (fig. 28 from An et al. 2009)
- For example, at [Fe/H]=0, the turn-off color changes from $g-i=-0.2$ to $g-i=0.6$ as the age increases from 1 Gyr to 10 Gyr
- For age∼10 Gyr, the change of color with age is very small for all [Fe/H]. The gradient is about 0.02 mag/Gyr: requires **exquisite photometry!**

Other Age Determination Methods

- Globular cluster absolute ages provide a strong constraint on the age of the Universe; however, the simultaneous effects of metallicity, distance, ISM extinction, He abundance, and various model parameters such as mixing length (see Chaboyer et al.; astro-ph/9706128), make age estimates uncertain by about 25% (Jimenez 1998, PNAS 95, 13)
- Can we determine age and metallicity using stars that are not on main sequence? Independently of ISM extinction correction and distance scale?

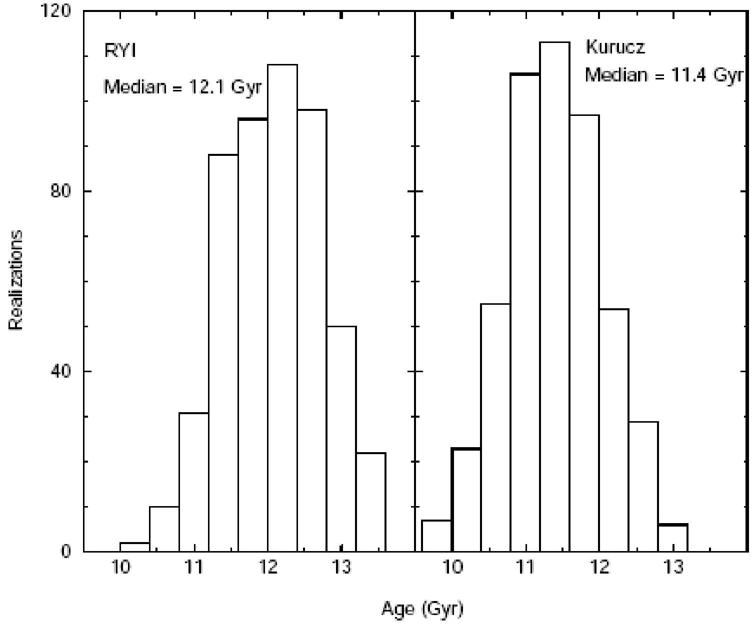


Fig. 10.— Histograms for the mean age of the oldest globular clusters, using (a) the RYI (Green *et al.* 1987) colour table, or (b) the Kurucz 1992 colour table.

An example of systematic effect: (unknown) He abundance

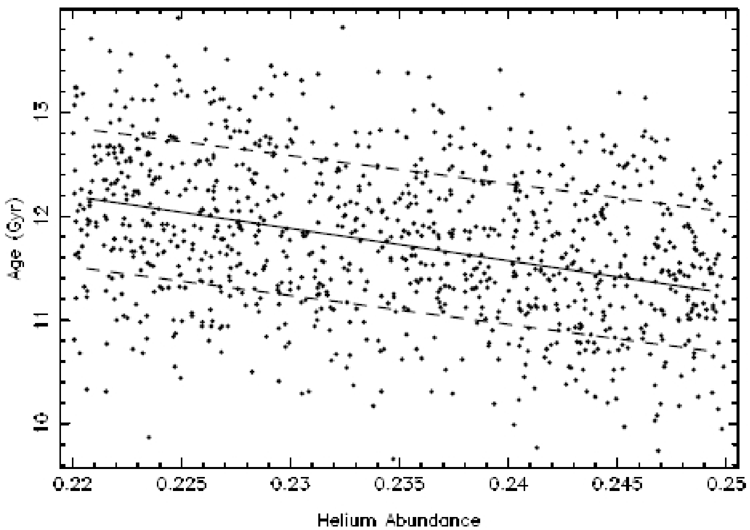
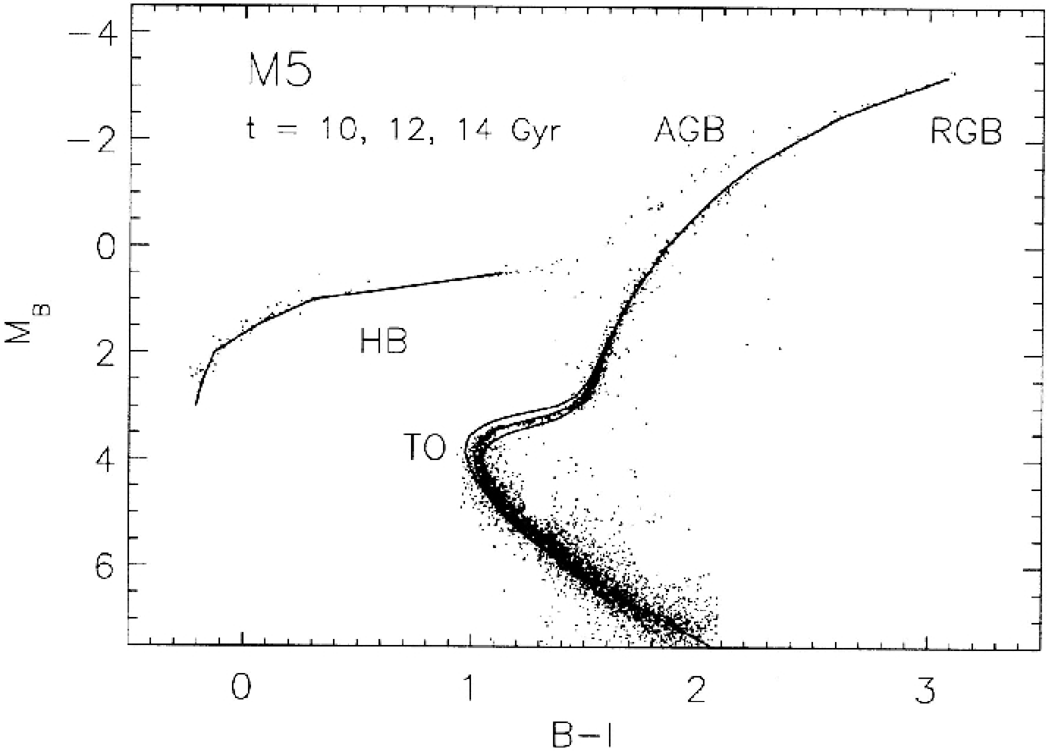


Fig. 6.— Age as a function of the helium abundance (Y) used in the stellar models. The lines of the form $t_9 = a + bY$ have the following cofficients: median $(a, b) = (19.05, -31.15)$; $-1\,\sigma\,(a, b) = (17.61, -27.73)$; and $+1\,\sigma\,(a, b) = (18.80, -27.04)$.



A comparison of errors for different methods (Jimenez 1998):

Proc. Natl. Acad. Sci. USA 95 (1998)

Table 2. Errors associated with different methods used to compute the age of the oldest GCs

Uncertainties	MSTO	HB	LF
Distance modulus	25%	0%	3%
Mixing length	10%	5%	0%
Color-$T_{\rm eff}$	5%	5%	0%
Heavy elements diffusion	7%	2%	7%
α-elements	10%	5%	10%
Reddening	5%	10%	0%

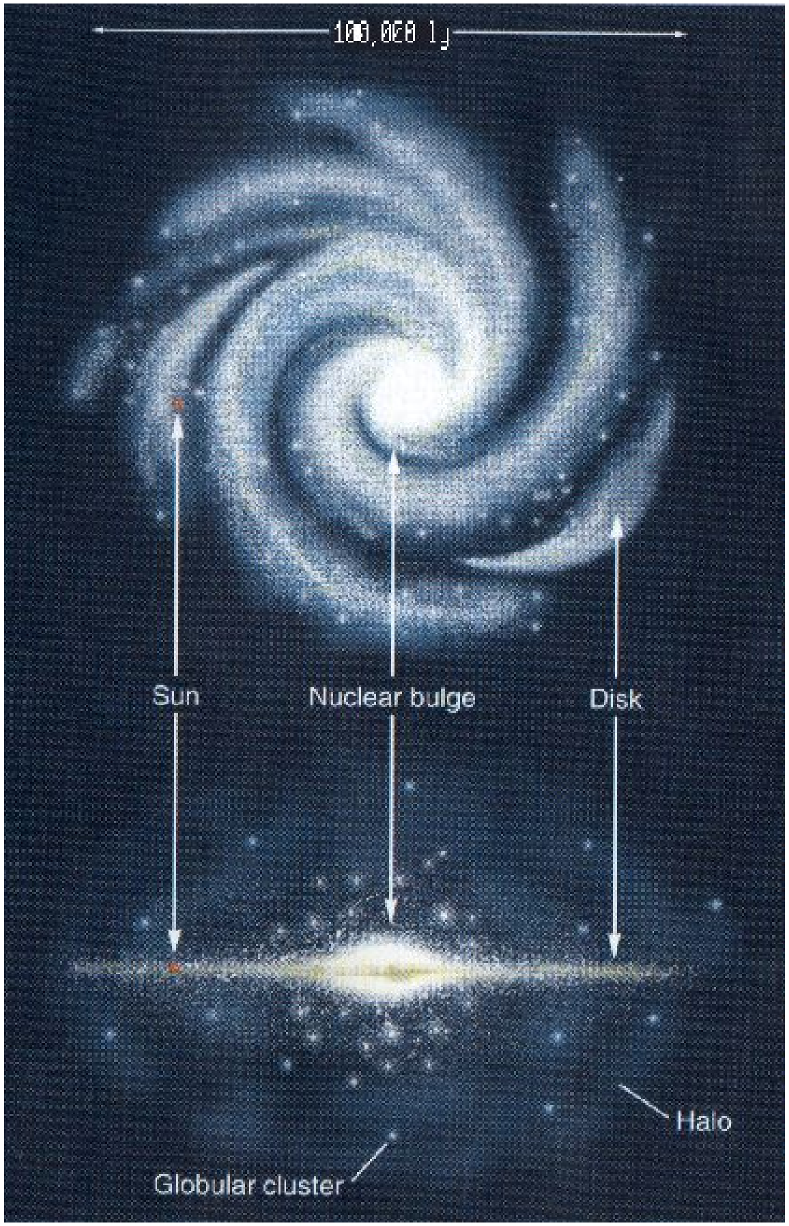
Other Age Determination Methods

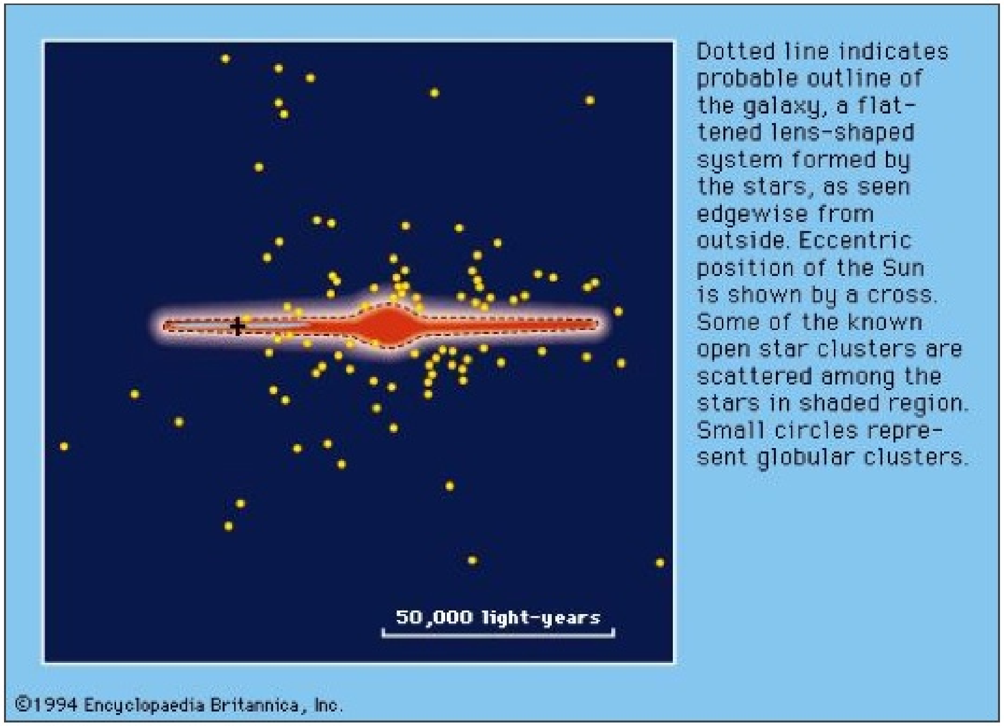
- Can we determine age and metallicity using stars that are not on main sequence? Independently of ISM extinction correction and distance scale?
- There are several other methods:

1. ΔV method: measure the magnitude difference between the Horizontal Branch and the subgiant branch (Iben & Renzini 1984); about 0.1 mag/Gyr (but also depends on FeH, about 0.2 mag/dex)
2. Morphology of the Horizontal Branch (Jimenez 1998)
3. Luminosity Function (Jimenez 1998)

Properties of GC Population

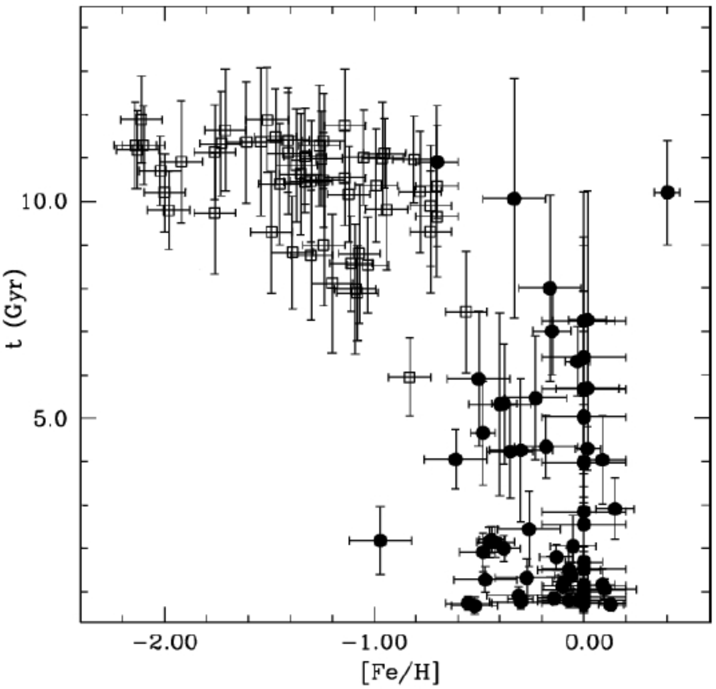
- Halo GCs claim to fame: Shapley used their distribution to demonstrate that the Sun is not in the center of the Milky Way





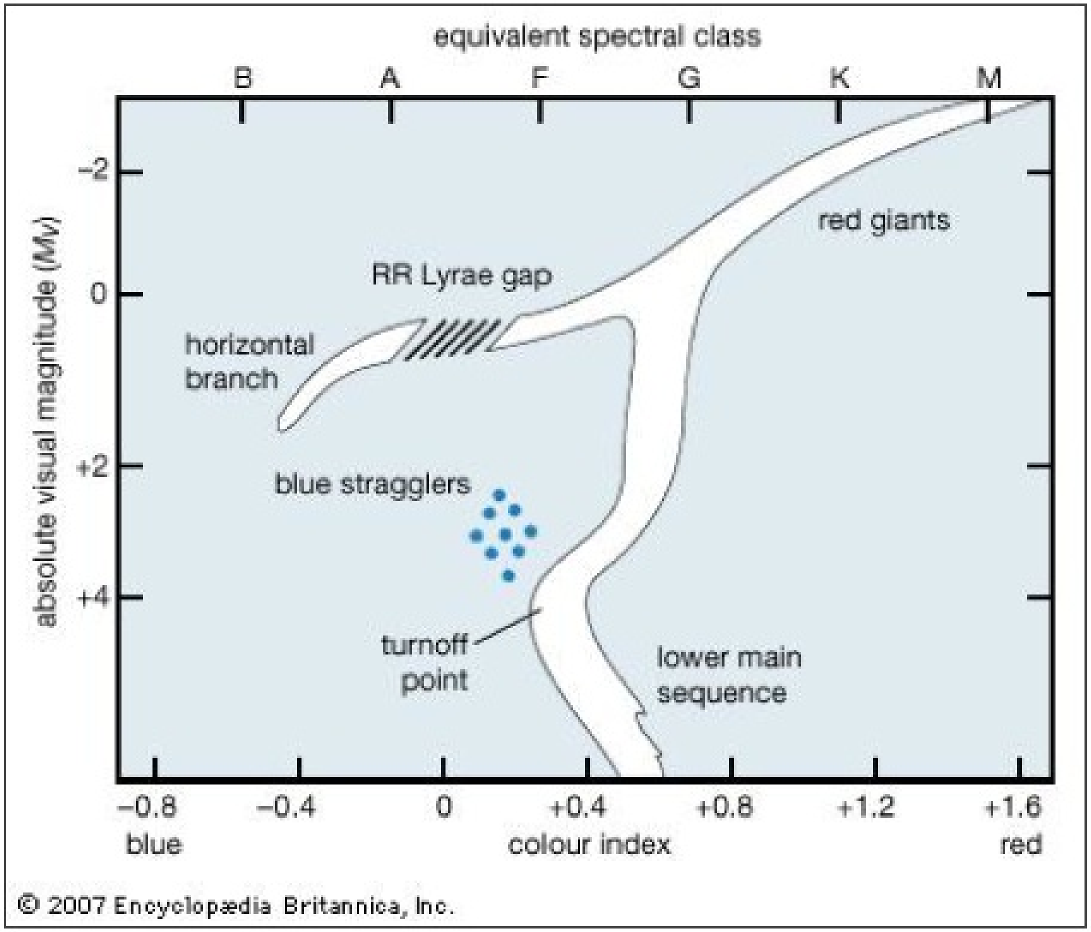
Properties of GC Population

The age vs. metallicity distribution of globular clusters from Percival & Solaris.



- Halo GCs claim to fame: Shapley used their distribution to demonstrate that the Sun is not in the center of the Milky Way
- Most globular clusters are metal-poor, and thus resemble halo stars. Their spatial distribution is also halo-like: roughly spherically distributed, and at distances of tens of kpc from the galactic center. Kinematics are similar to halo stars: randomly oriented eccentric orbits.
- About 20% of GCs have higher metallicities ($-1 < [Fe/H] < 0$) and are found within 1-2 kpc from the galactic plane. Their distribution and kinematics are very similar to thick disk.
- These differences are probably due to processes that happened early in the history of the Milky Way. It is likely that "thick disk clusters" formed after halo clusters.

Properties of GC Population



- Standard modern compilation of globular cluster properties (n=157): Harris, W.E. 1996, *A Catalog of Parameters for Globular Clusters in the Milky Way*, Astronomical Journal, 112, 1487 (updated in 2010)
- Note the existance of the so-called *blue straggler* population in the H-R diagram (left): it shouldn't exist given the cluster turn-off age; it could be the result of stellar collisions and mergers