Astr 511: Galaxies as galaxies

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Lecture 1:

Review of Stellar Astrophysics, Star Clusters, and more...

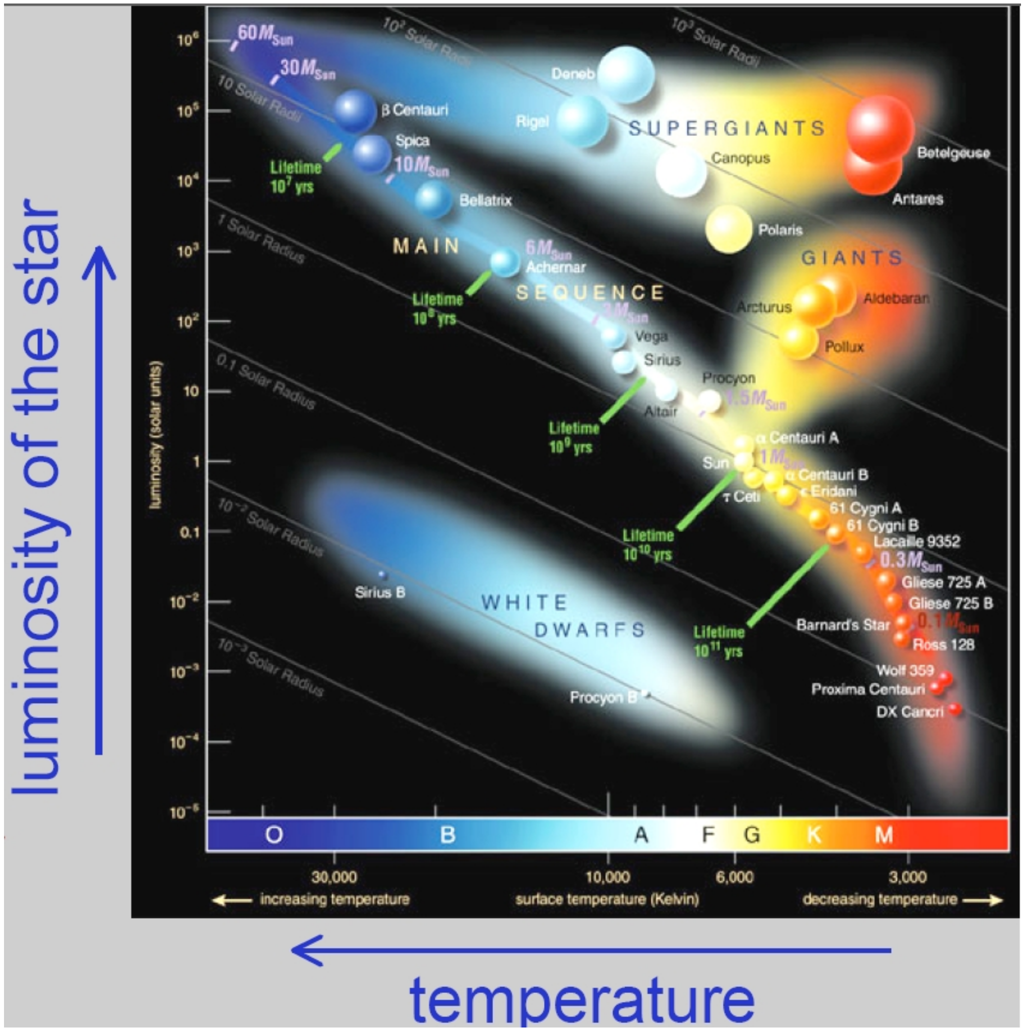
Outline

1. Stars: a 5-minute review of stellar physics
2. Stellar parameters: (mass, age, chemical composition) vs. (temperature, surface gravity, metalicity)
3. Open and Globular clusters: simple stellar populations
4. Population Synthesis: cooking up a galaxy
5. What do we observe: a summary of the measurement process
6. Virial Theorem: very brief intro to a very useful tool

Flash Review: the Basics

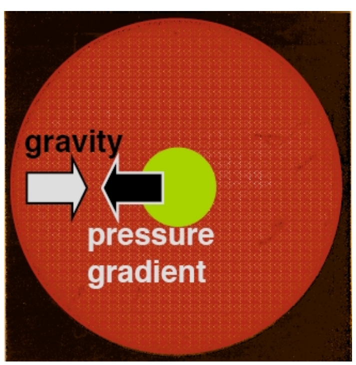
I believe you're generally familiar with these terms (at an undergraduate level):

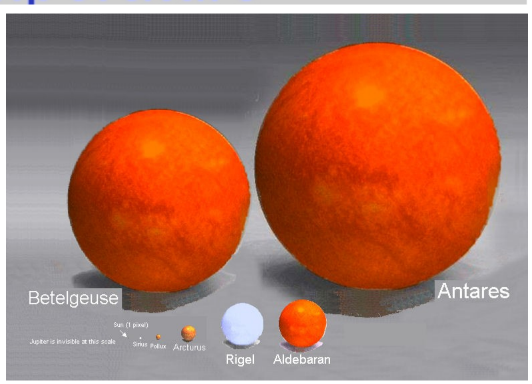
- general: absolute magnitude, distance modulus, bolometric luminosity, the Planck function
- types of stars: main sequence, white dwarfs, horizontal branch, red giants, supergiants, subgiants, subdwarfs, etc.
- stellar properties: effective temperature, spectral class, metallicity, mass, age, MK (MorganKeenan) spectral classification

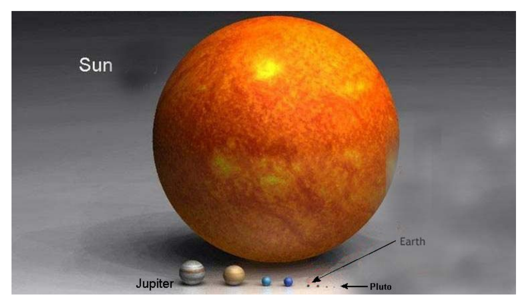


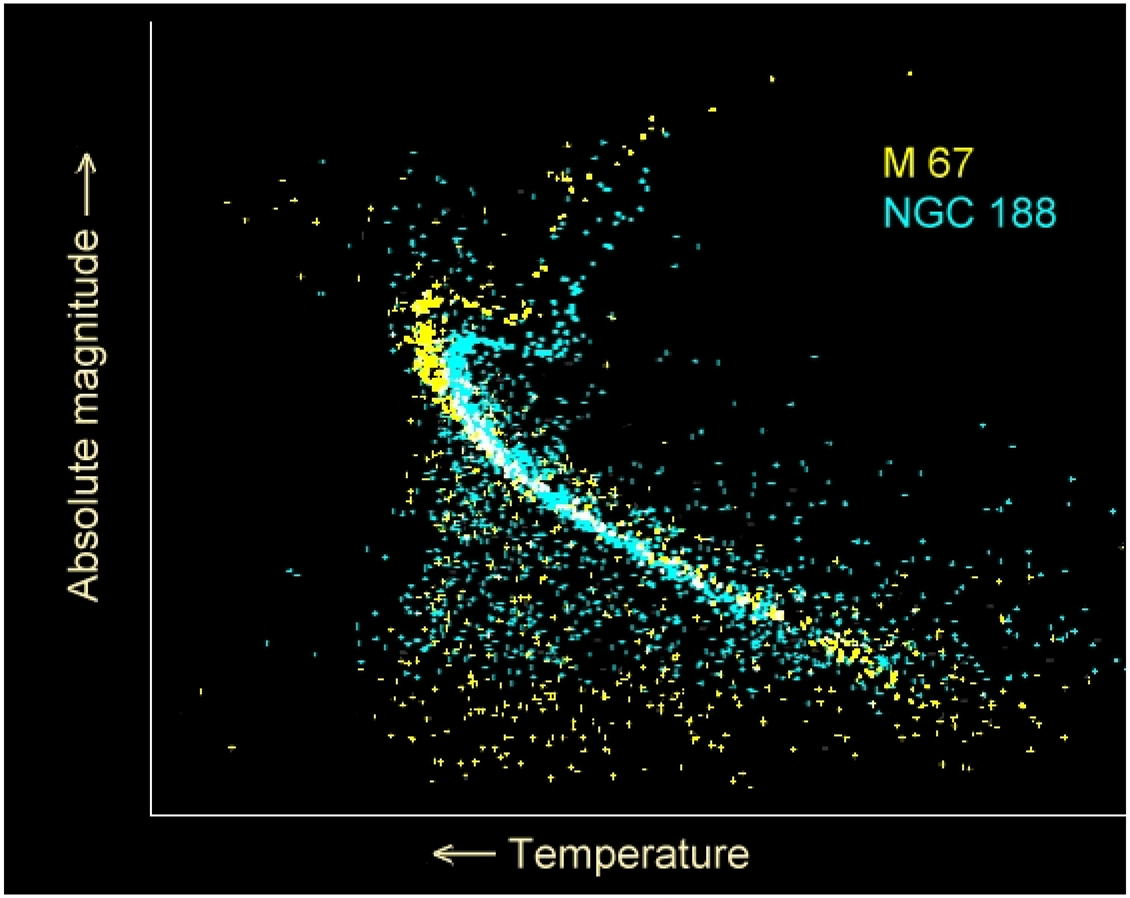
Hertzsprung-Russell Diagram

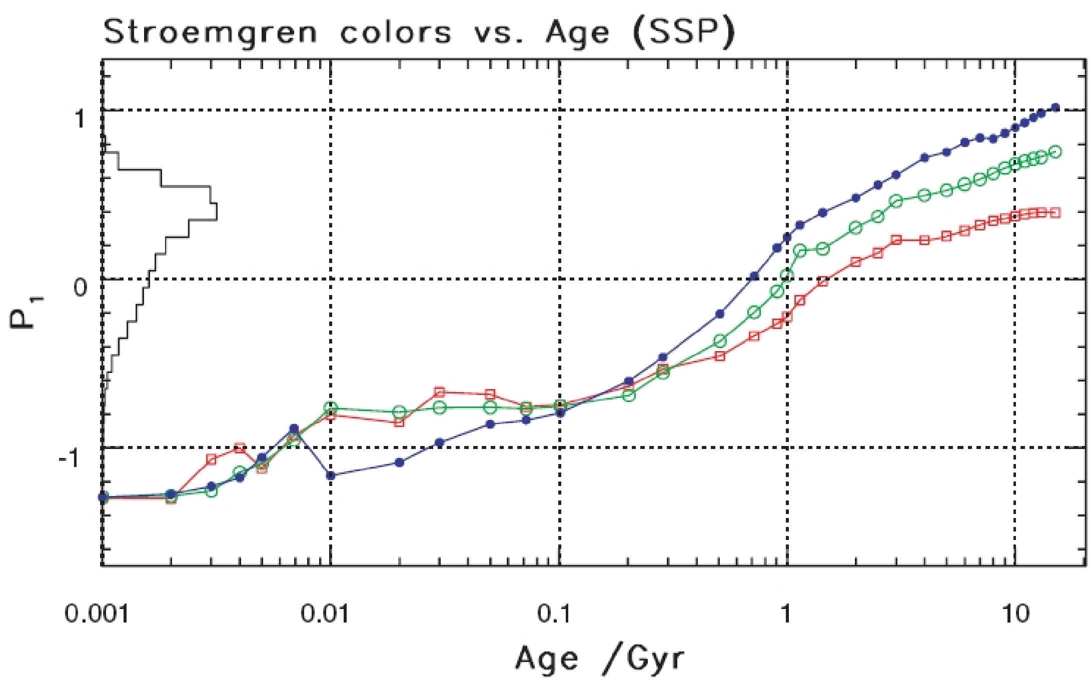
- Stars are balls of hot gas in hydrodynamical and thermo-dynamical equilibrium
- Equilibrium based on two forces, gravity: inward, radiation pressure: outward
- Temperature and size cannot take arbitrary values: the allowed ones are summarized in HR diagram
- $L = \text{Area} \times \text{Flux} = 4\pi R^2 \sigma T^4$
- Luminosity and size span a **huge** dynamic range!











HR Diagram: Stellar Age

- The main sequence is where most of lifetime is spent.
- The position on the main sequence is determined by mass!
- The lifetime depends on mass: massive (hot and blue) stars have **much** shorter lifetimes than red stars
- After a burst of star formation, blue stars disappear **very quickly**, 10^8 years or so
- Galaxies are made of stars: if there is no ongoing star formation, they are red; if blue, there **must** be actively making stars!
- Turn-off color depends on both age and metallicity (later...)

Gaia Early Data Release 3!

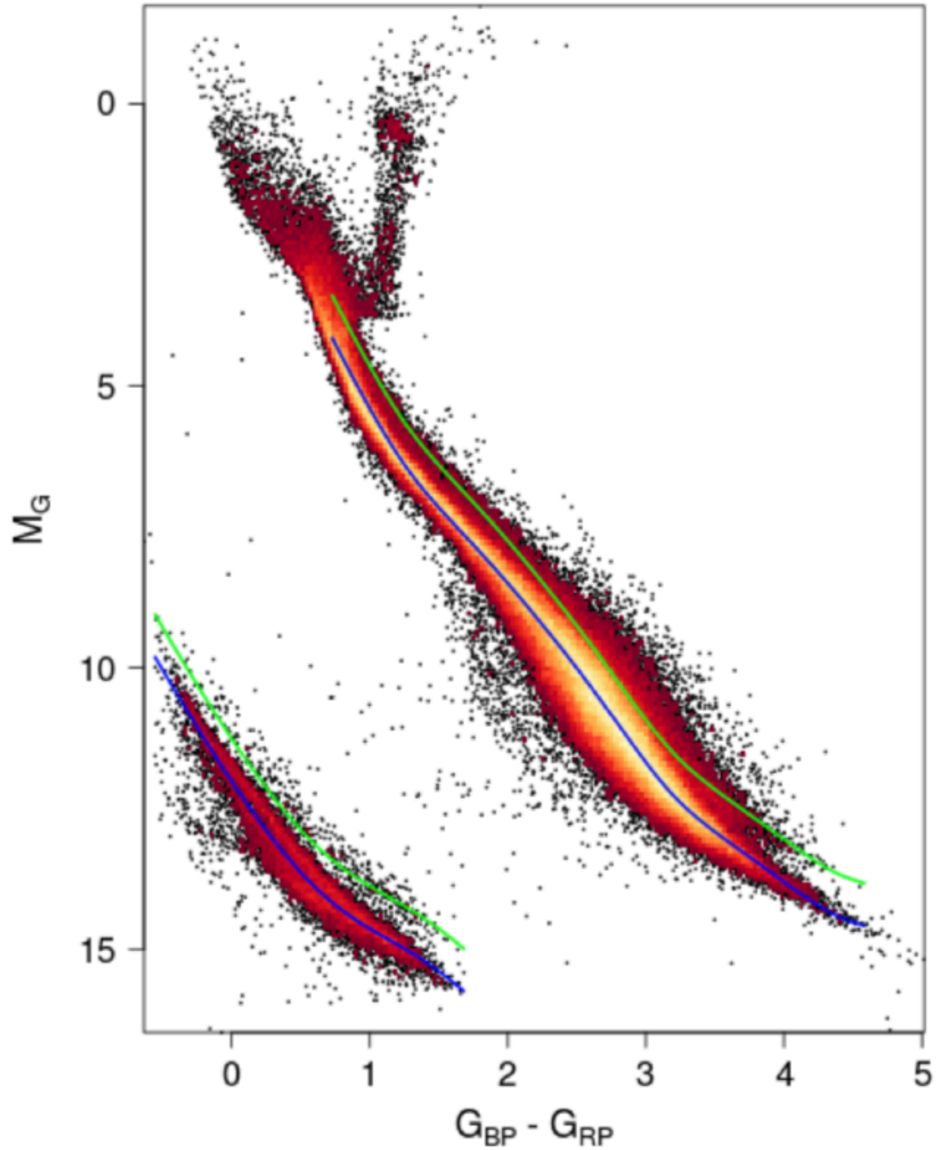


Fig. 8. Same as Fig. 6c, overlaid in blue with the median fiducial and in green with the same fiducial shifted by −0.753 mag, corresponding to an unresolved binary system of two identical stars.

- EDR3 released in Dec 2020
- 1,811,709,771 sources
- Pan-STARRS and Gaia catalogs now contain more than a billion sources each!
- Unprecedented combination of sky coverage, depth and astrometric accuracy (trigonometric parallax and proper motion measurements)
- Figure from Babusiaux et al. (2018, A&A 616, A10): a breath-taking HR diagram for field stars!

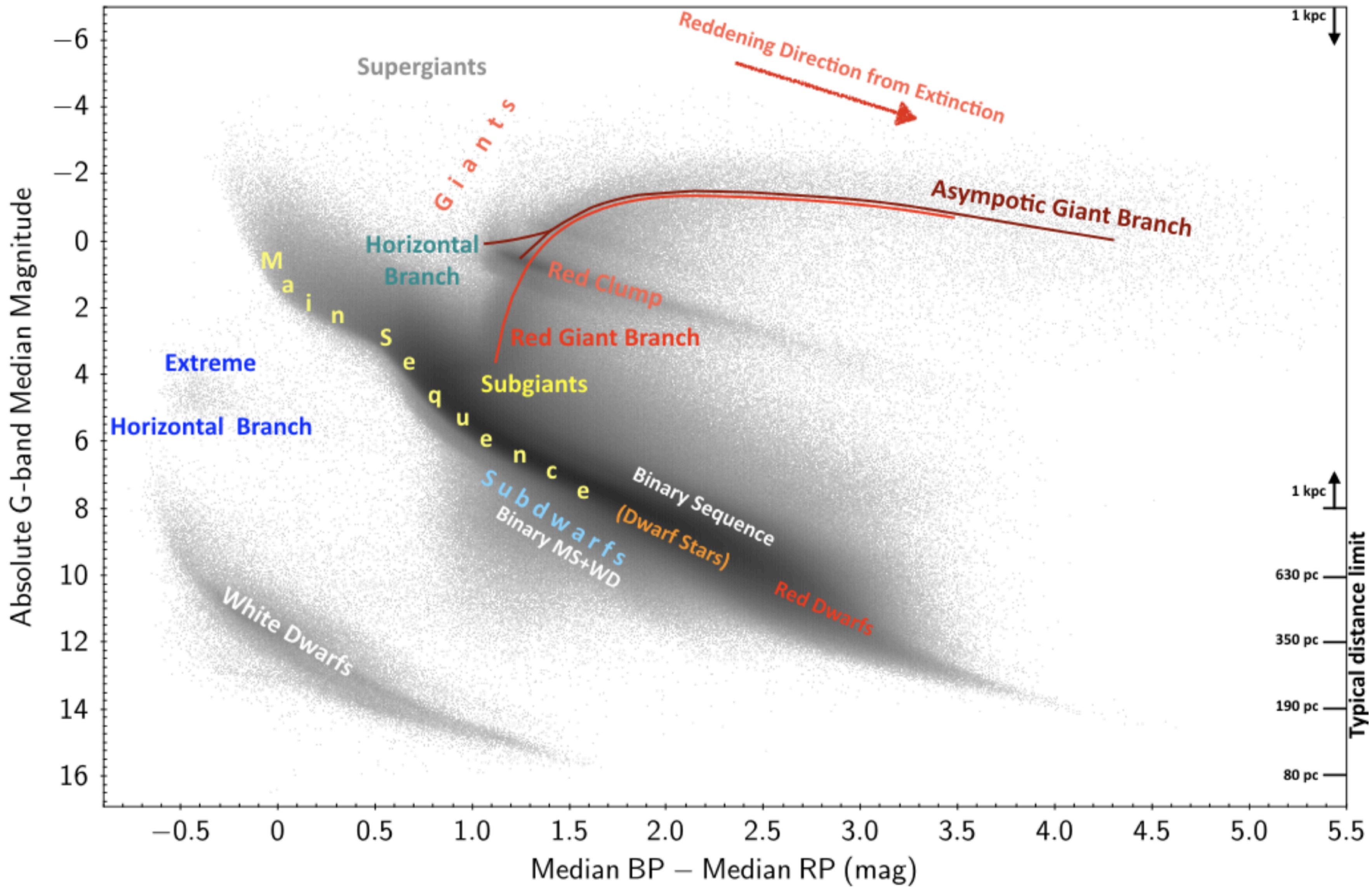
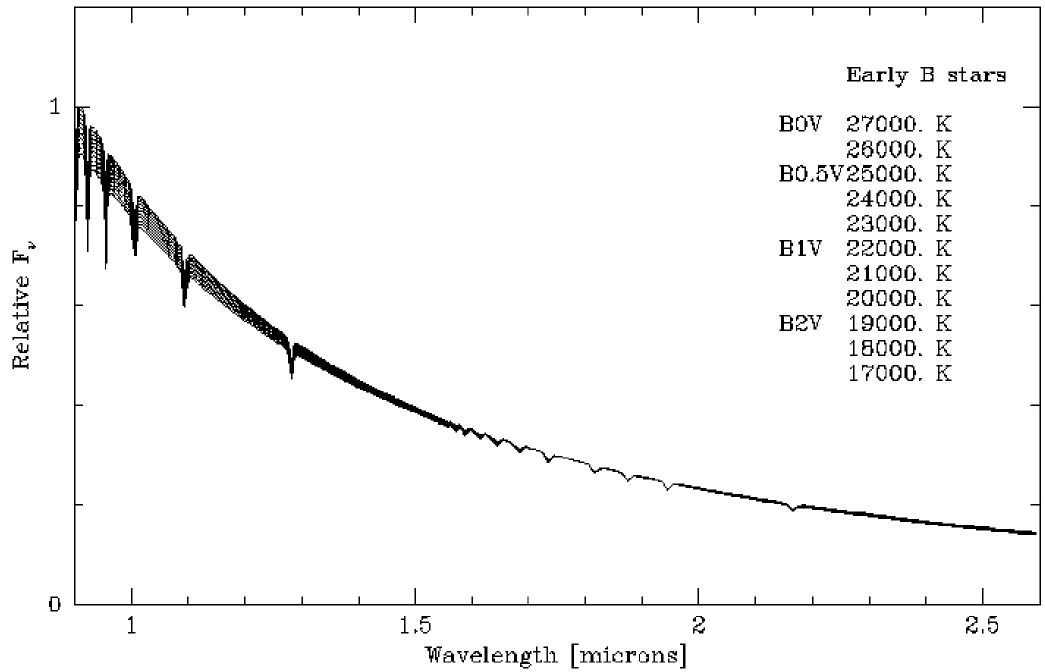
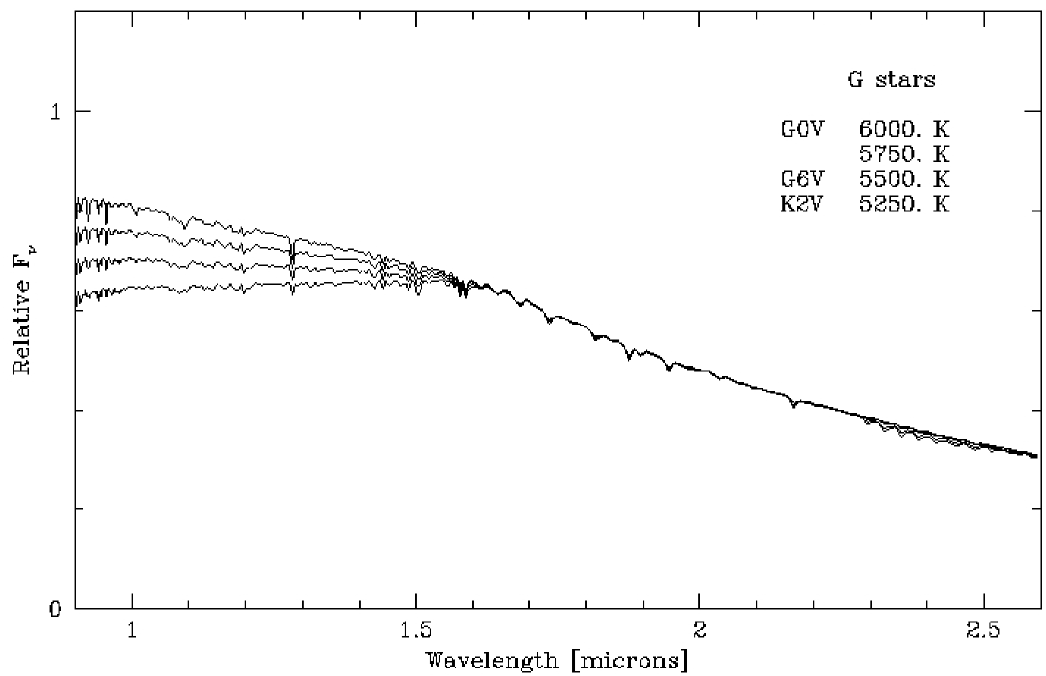


Fig. 2. CaMD with its most striking known features (see text). The points in grey denote objects with parallax greater than 1 mas, with relative parallax precision better than 20% and other criteria described in Appendix B.

Eyer et al. (2019, A&A 623, A110)



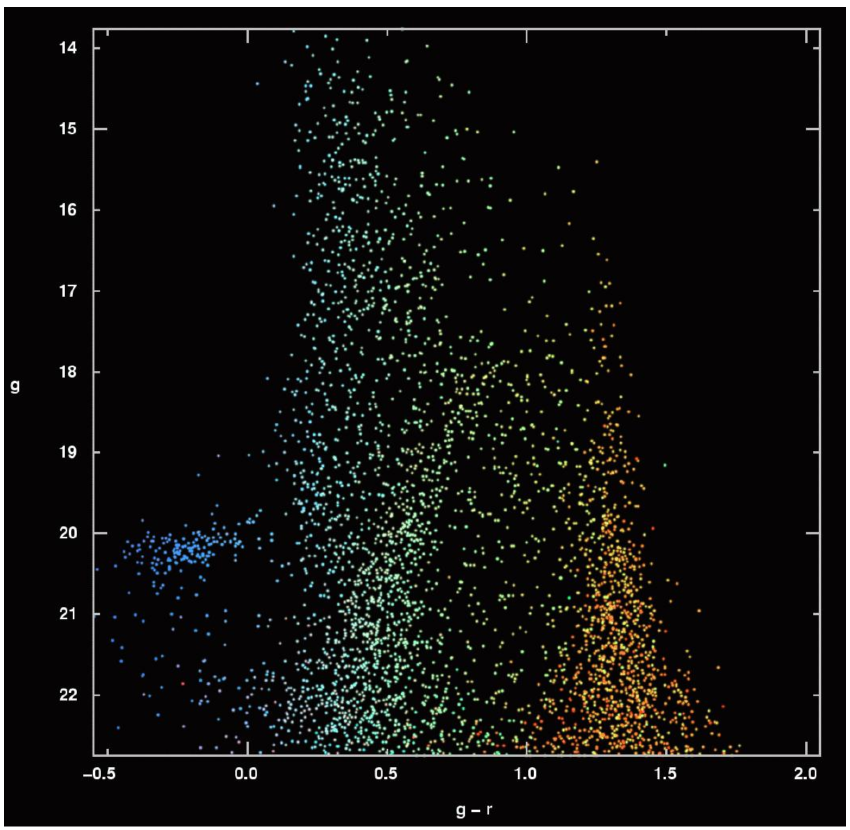


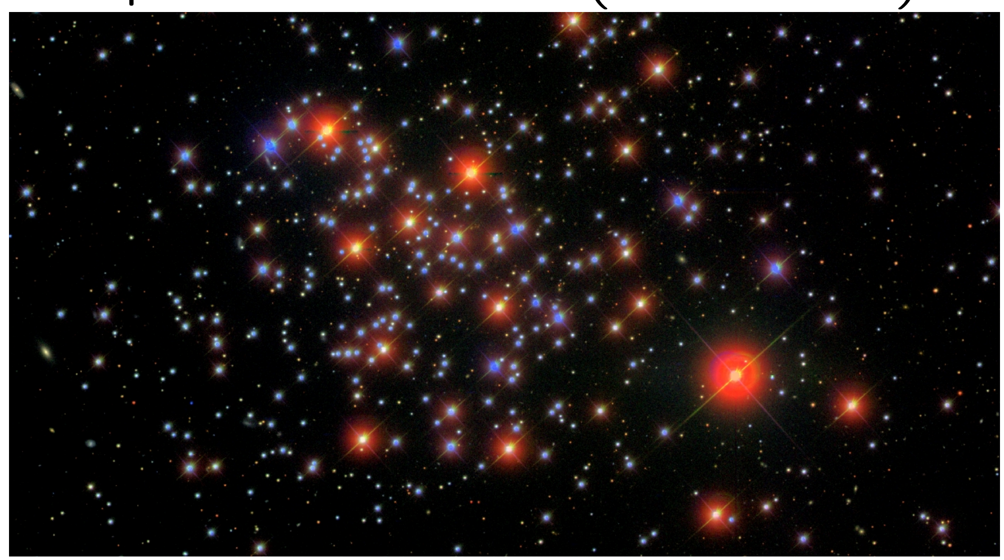
Stellar Parameters

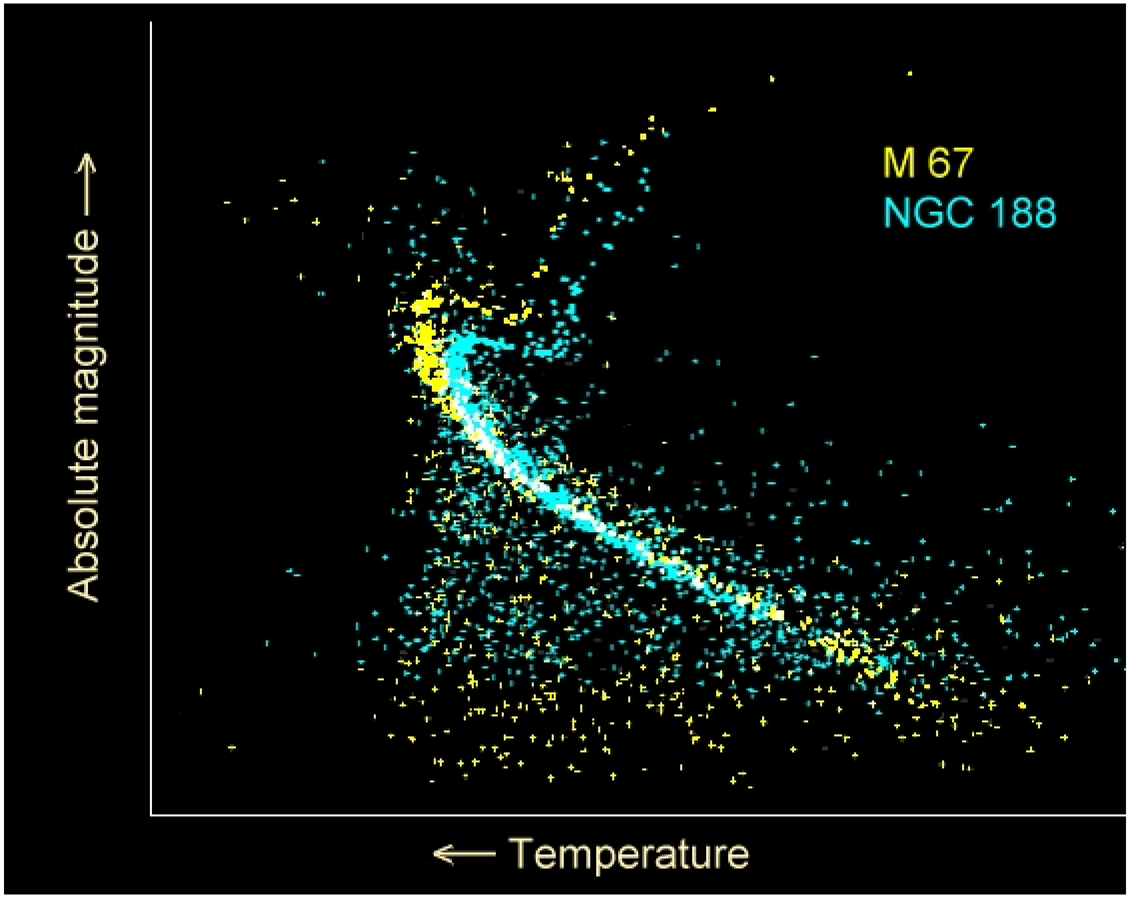
- The stellar spectral energy distribution is a function of **mass**, **chemical composition** and **age**, a theorist would say
- The stellar spectral energy distribution is a function of **effective temperature**, **surface gravity** and **metallicity**; an observer would observe. E.g., Kurucz models (1979) describe SEDs of (not too cold) main sequence stars, as a function of $T_{\rm eff}$, $log(g)$ and $[Fe/H]$ at the accuracy level of 1%.
- These two parametrizations are connected by stellar evolution models.

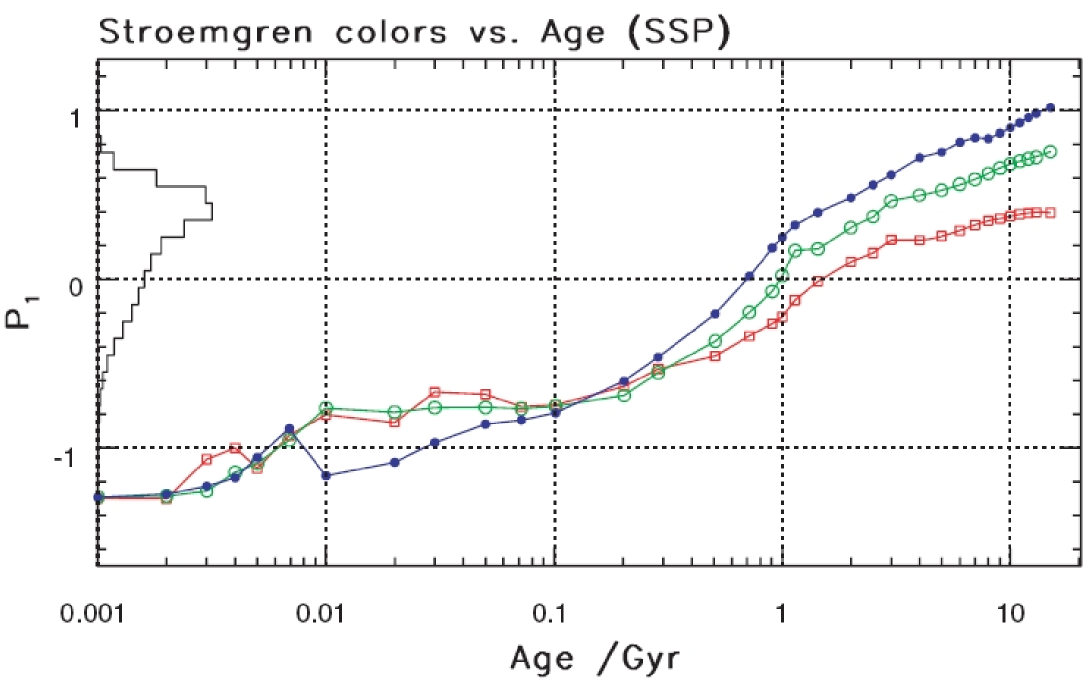
Open and Globular Clusters

- **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 around 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
- Some key properties:
  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

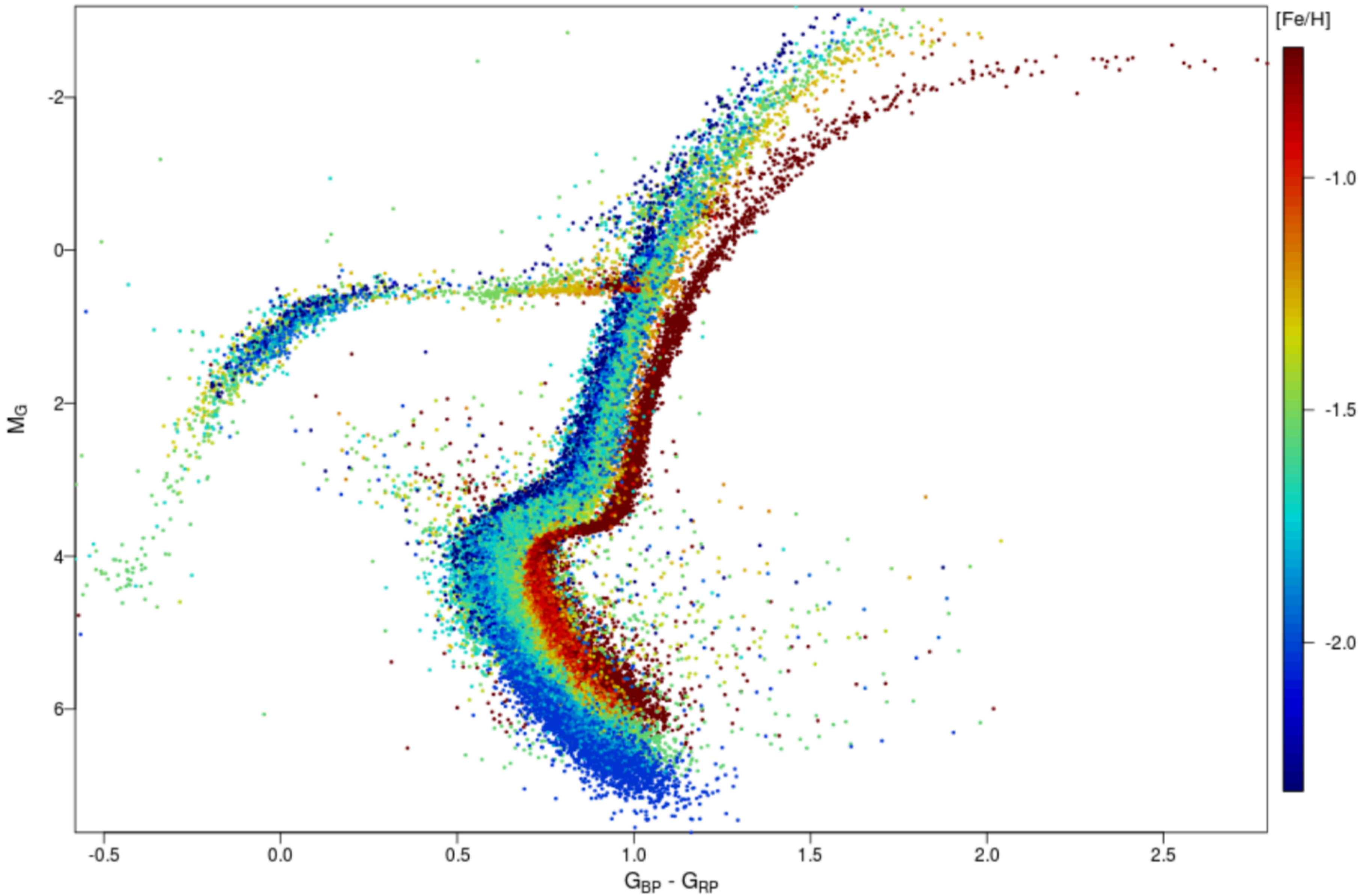
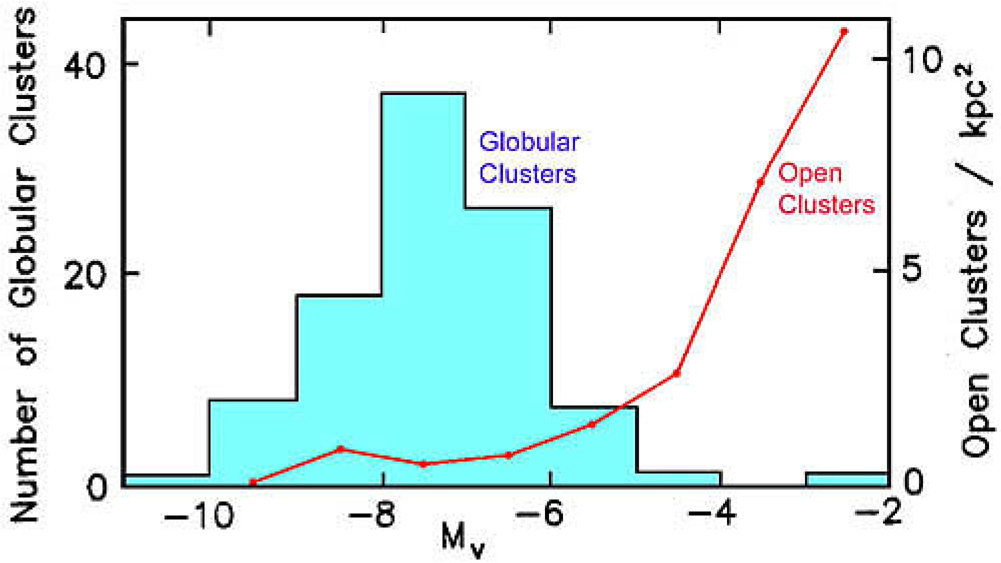


Fig. 3. Composite HRD for 14 globular clusters, coloured according to metallicity (Table 3).

Gaia EDR3 data for 14 GCs vs [Fe/H]:
Babusiaux et al. (2018, A&A 616, A10)



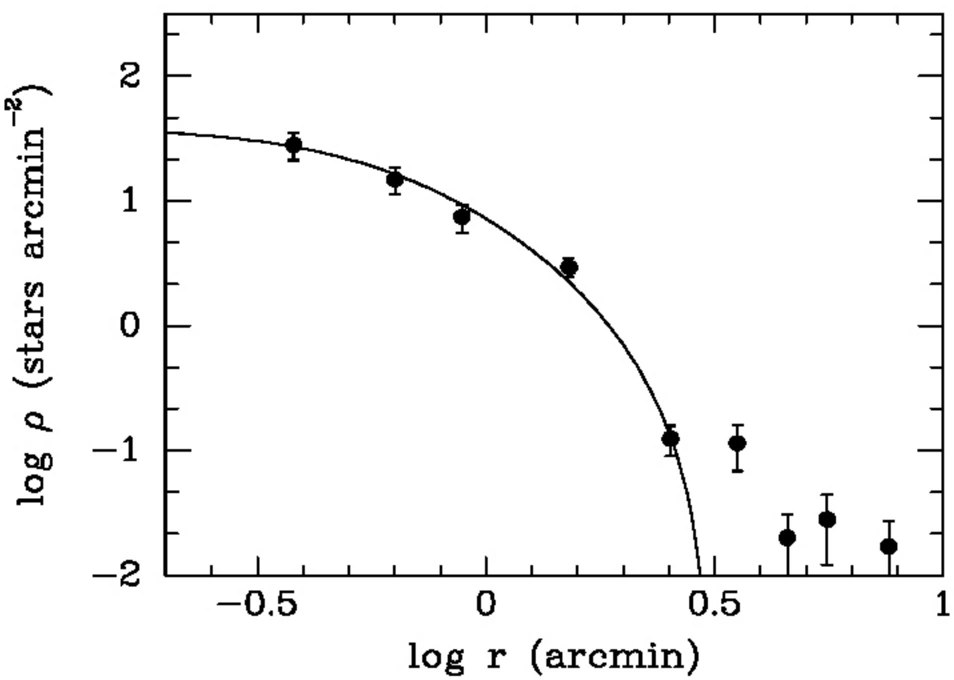


FIG. 7.—Radial star count profile of Pal 13 for stars with membership probabilities ≥50%. The line is the best-fit King profile to the cluster. Note the member stars outside the classical limiting radius.

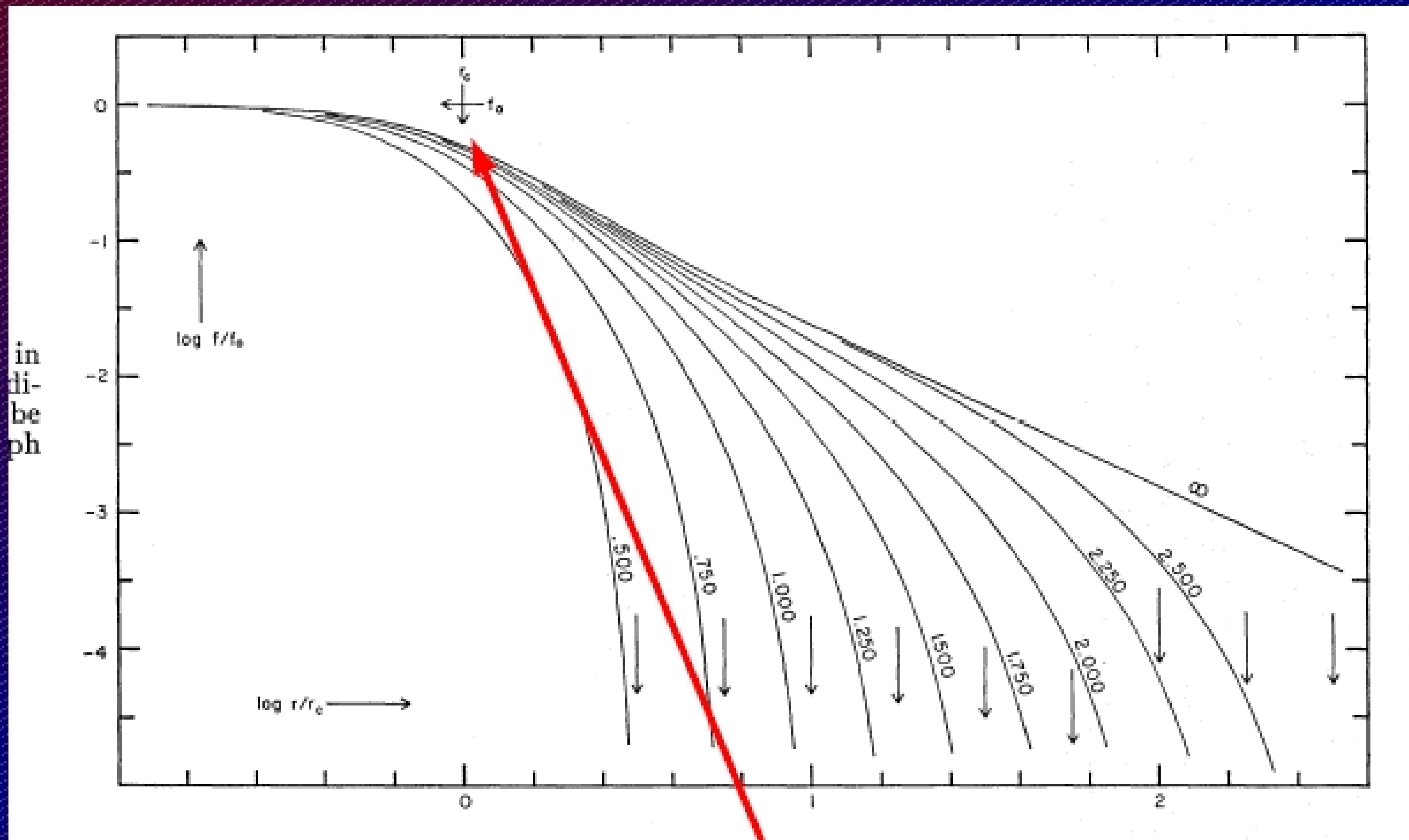
Open and Globular Clusters

- 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:** globular cluster Pal 13 (Siegel et al. 2001, AJ 121, 935): Spatial profiles of globular clusters usually closely follow **King profiles** (c.f. later lecture on stellar dynamics); next slide stolen from Doug Heggie

KITP

King models

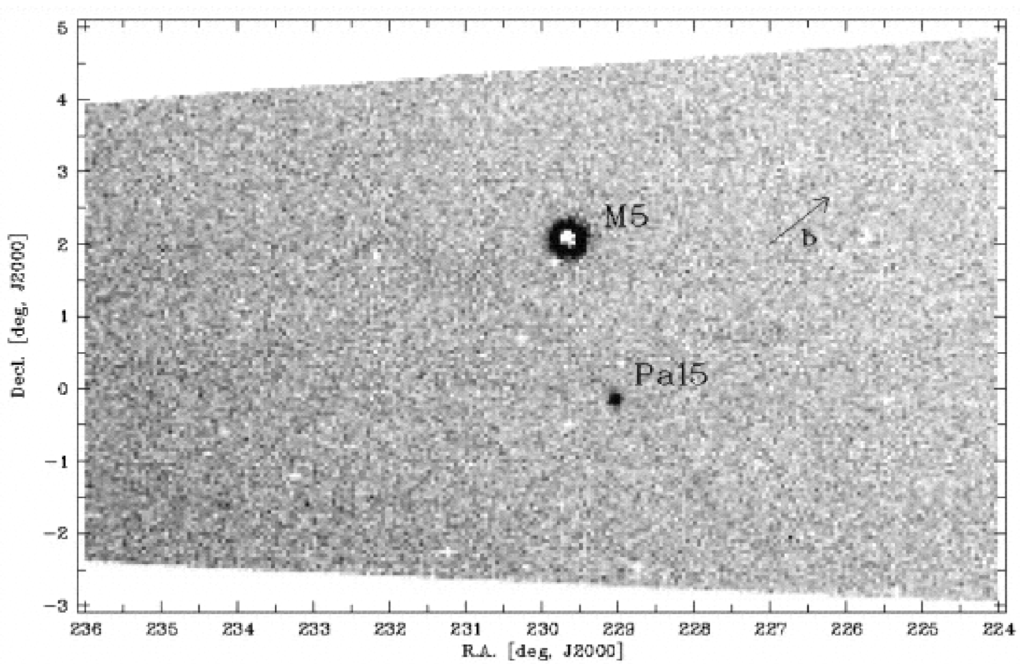
Surface brightness

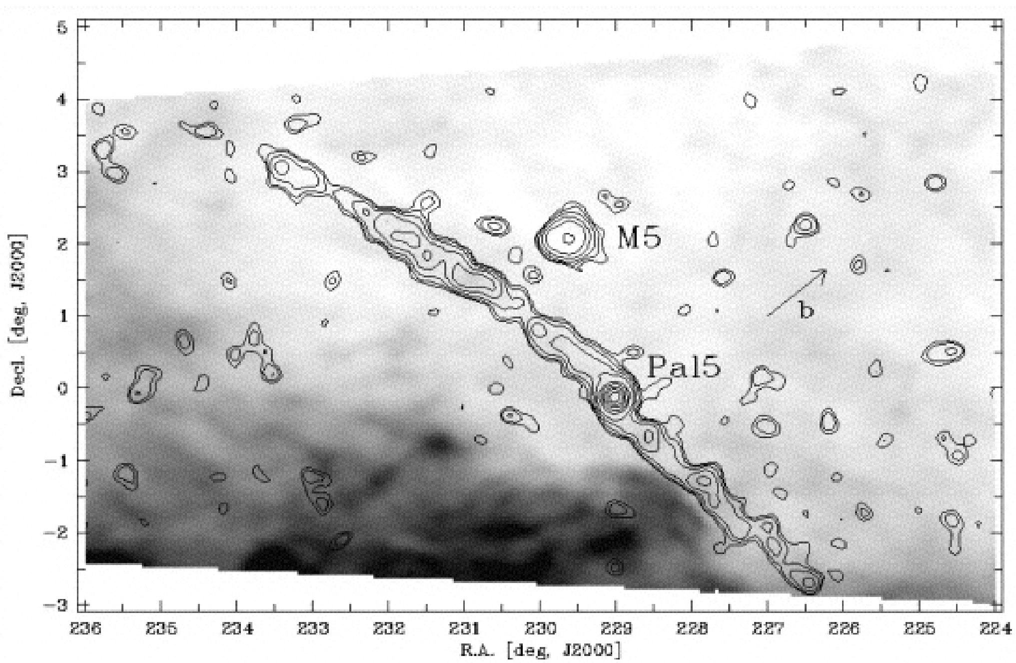


Projected radius

Ivan King

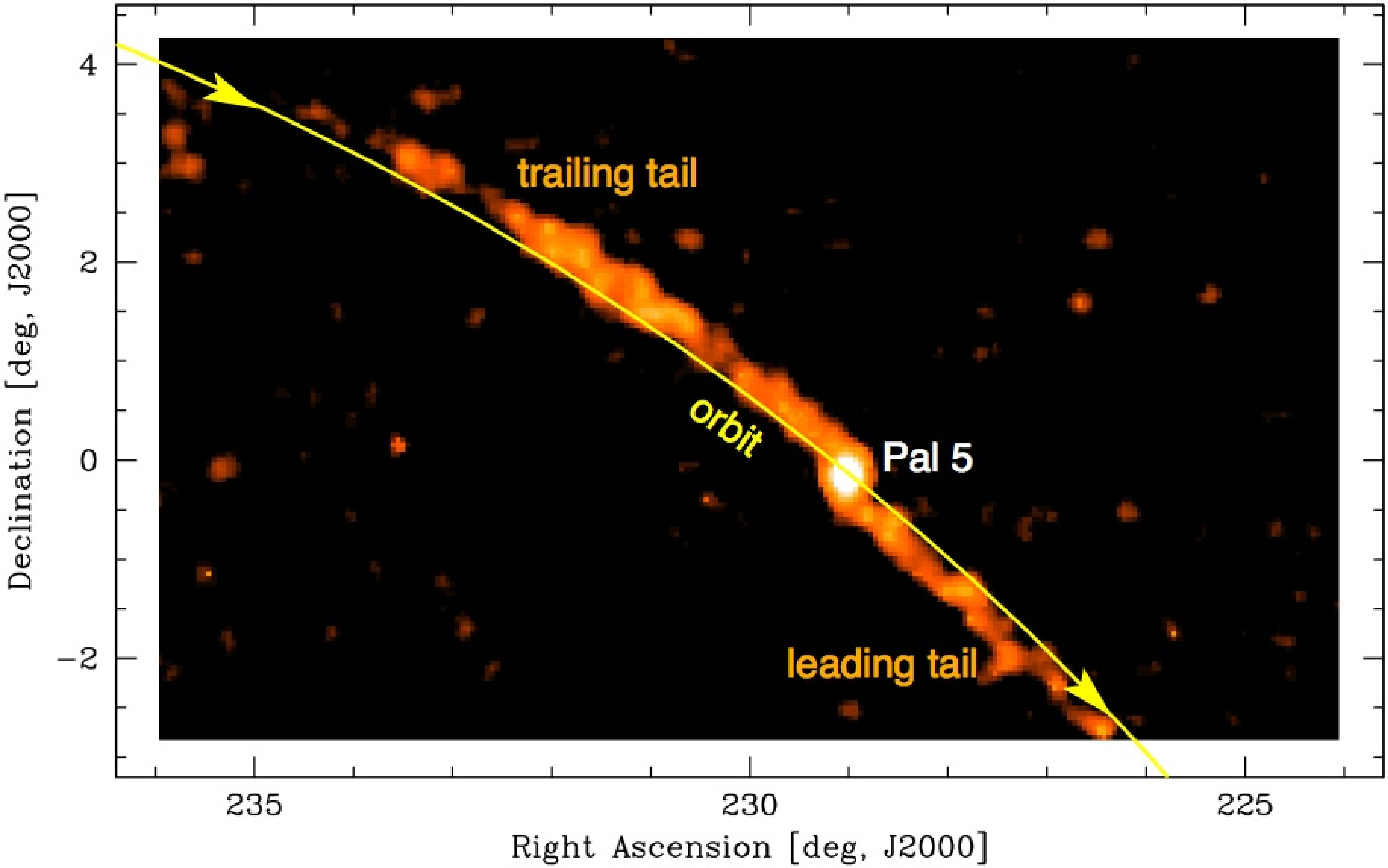
1-parameter sequence of shapes
+ 2 scale parameters (core radius; total luminosity)



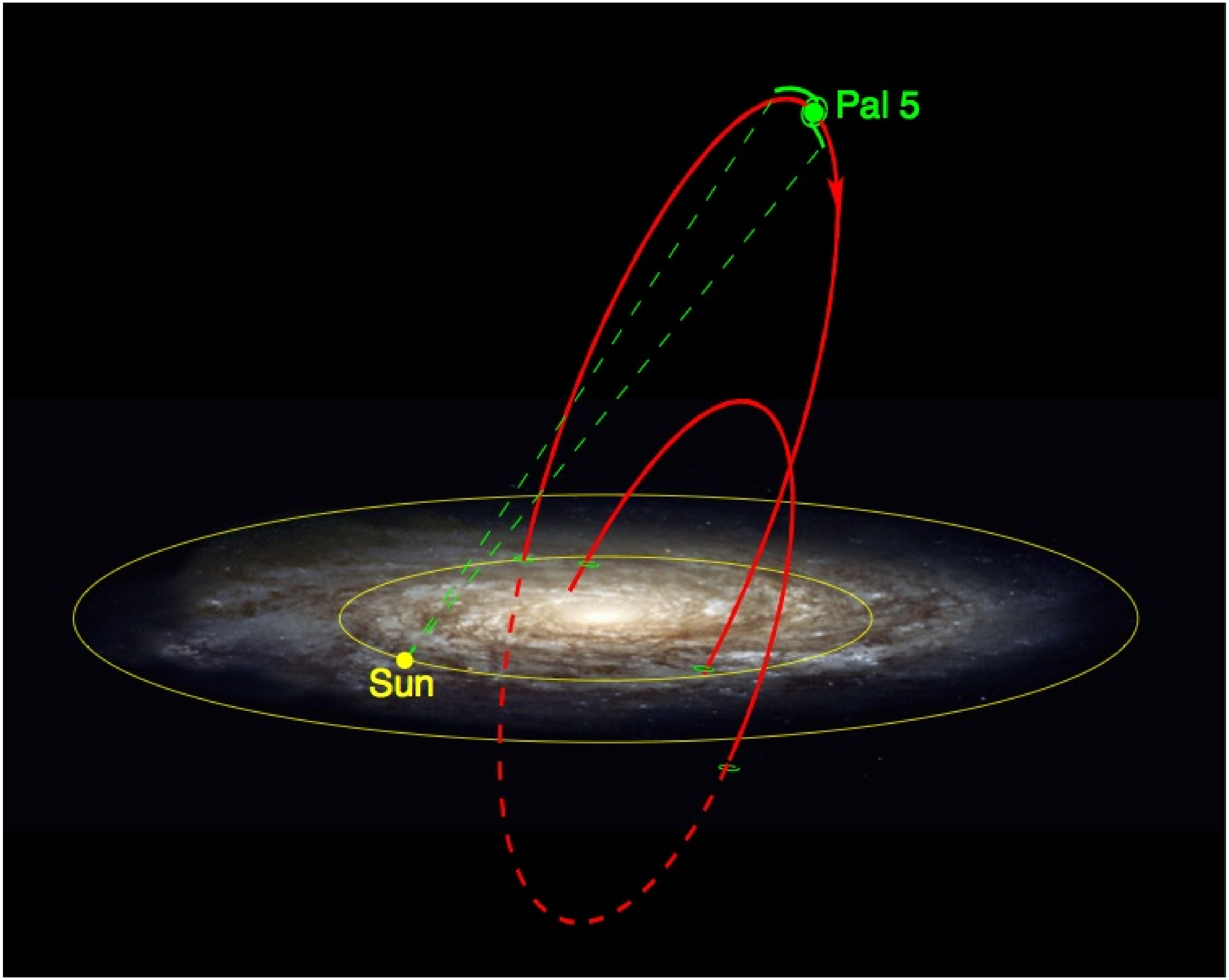


Tidal Tails around Globular Clusters

- **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.
- Overall distribution constrains the mass (e.g., Eadie & Jurić 2019, ApJ, 875, 159).

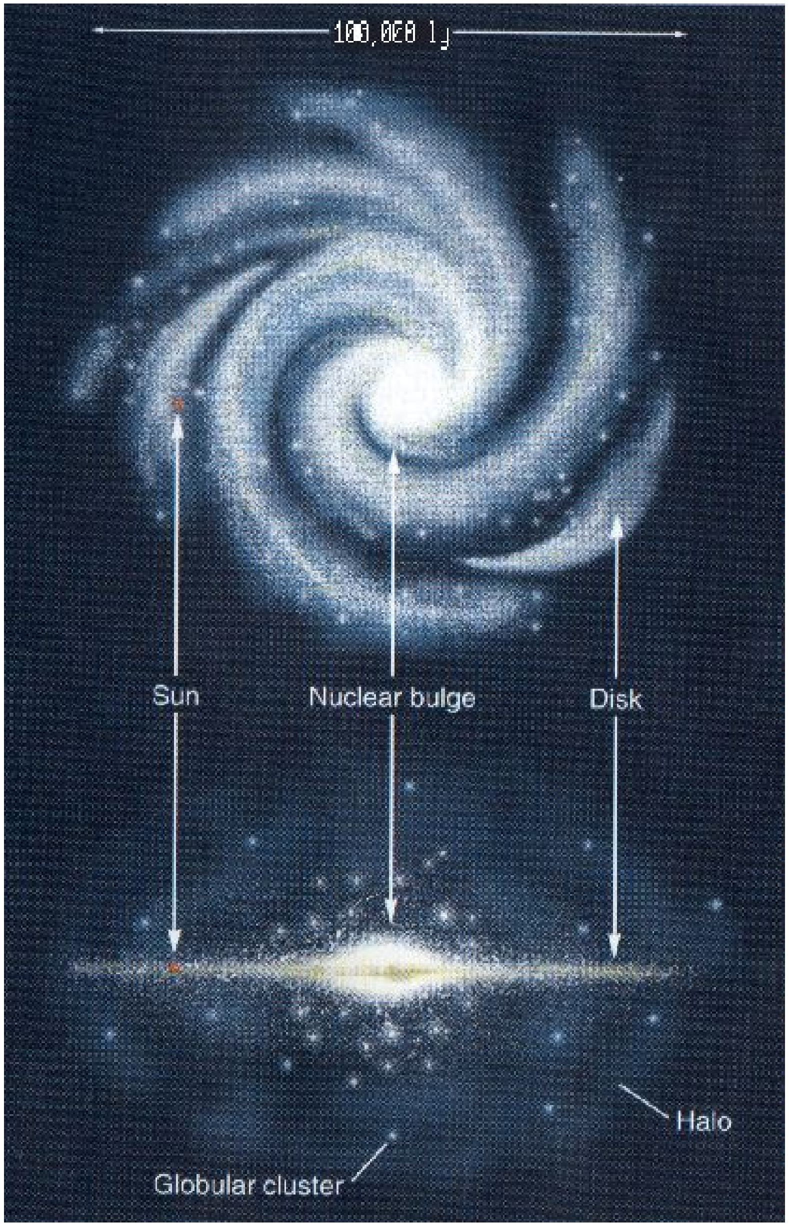


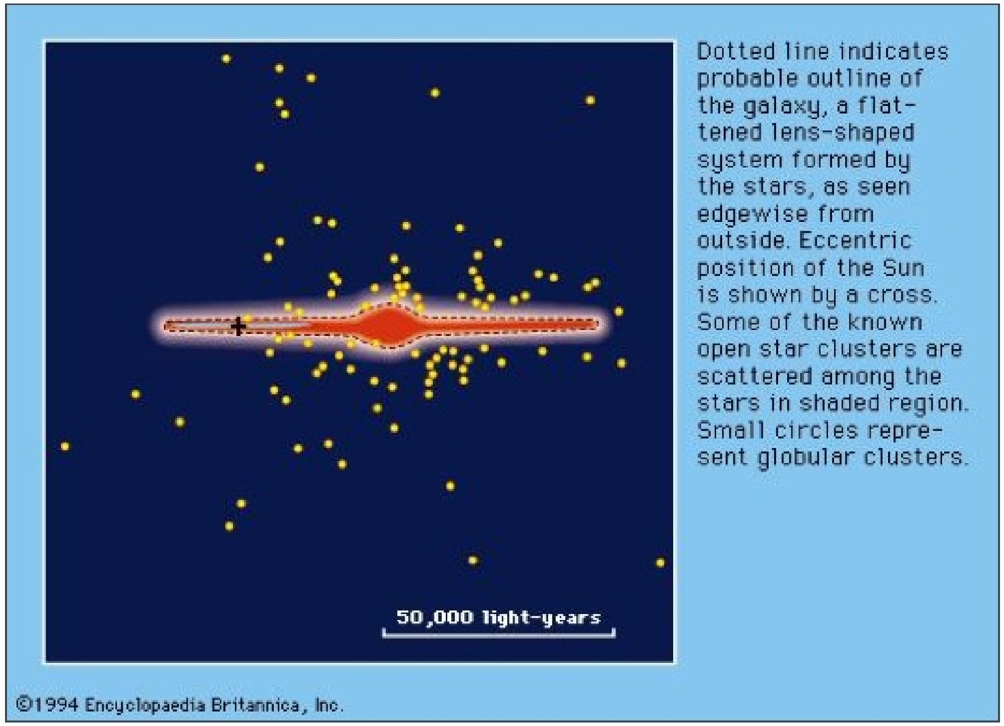
trailing tail
orbit
Pal 5
leading tail
4
2
0
−2
235
230
225
Declination [deg, J2000]
Right Ascension [deg, J2000]


Pal 5
Sun

Properties of GC Population

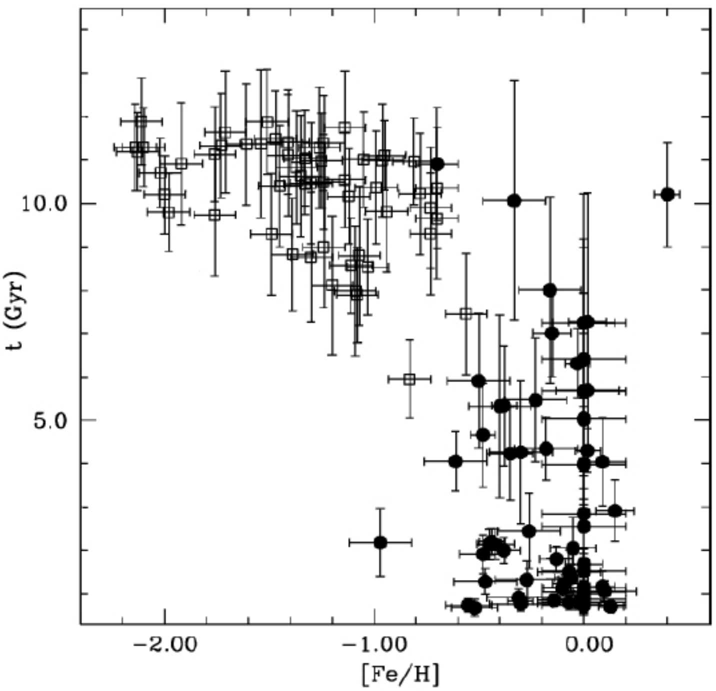
- Halo GCs claim to fame: Shapley used their distribution to demonstrate that the Sun is not in the center of the Milky Way



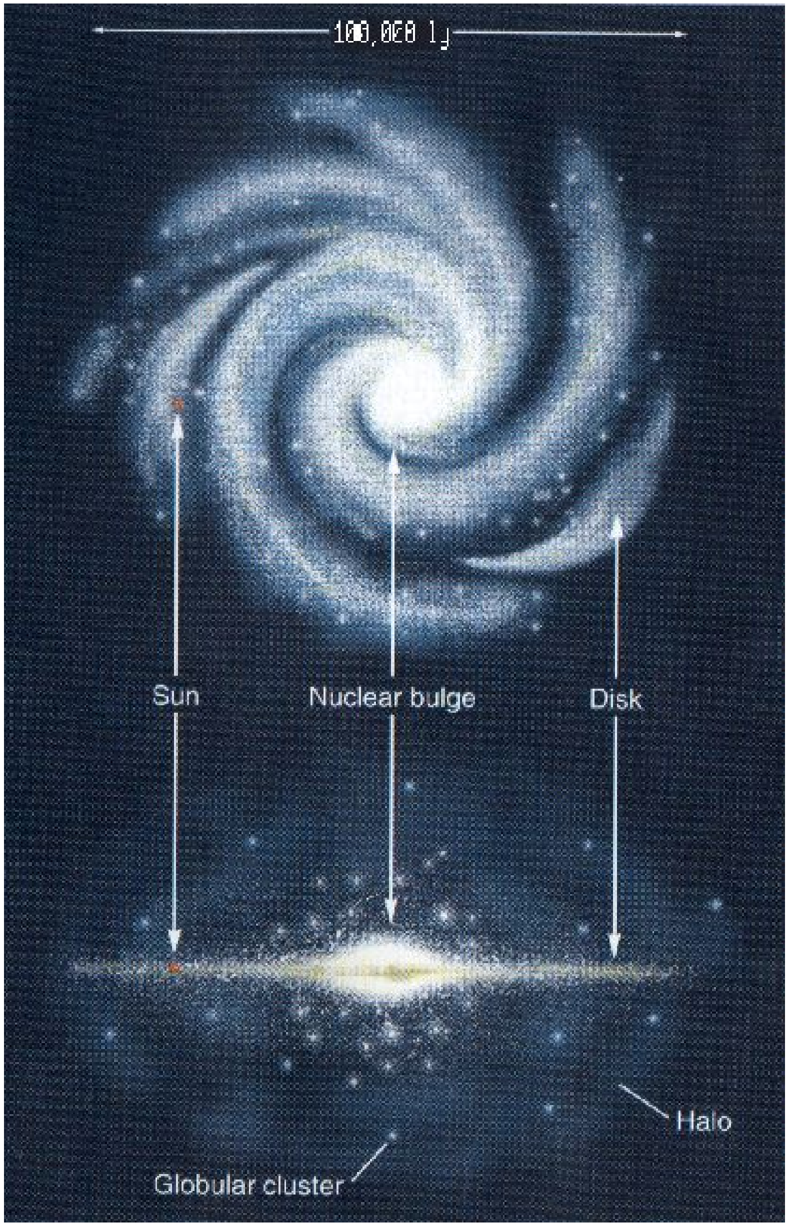


Properties of GC Population

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

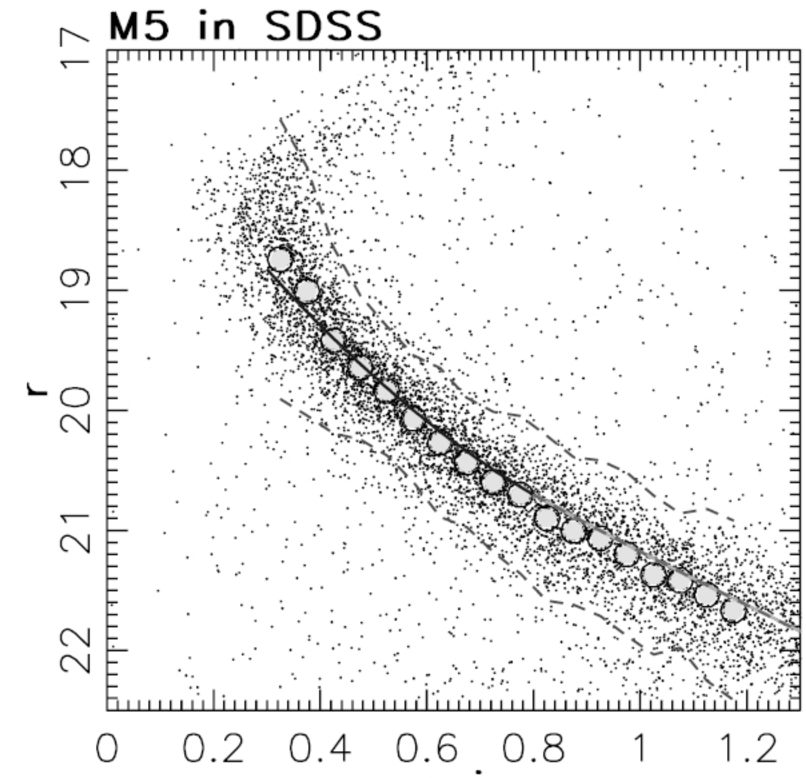


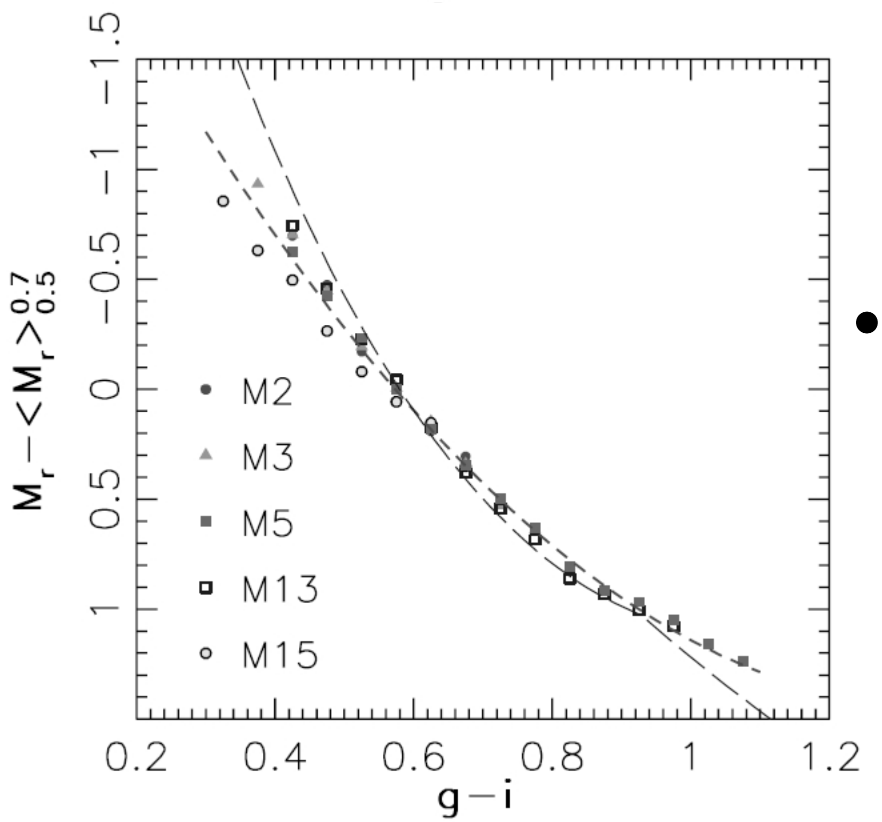
- Halo GCs claim to fame: Shapley used their distribution to demonstrate that the Sun is not in the center of the Milky Way
- Most globular clusters are metal-poor, and thus resemble halo stars. Their spatial distribution is also halo-like: roughly spherically distributed, and at distances of tens of 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.



From Clusters to Field Stars:

Calibrating Distances





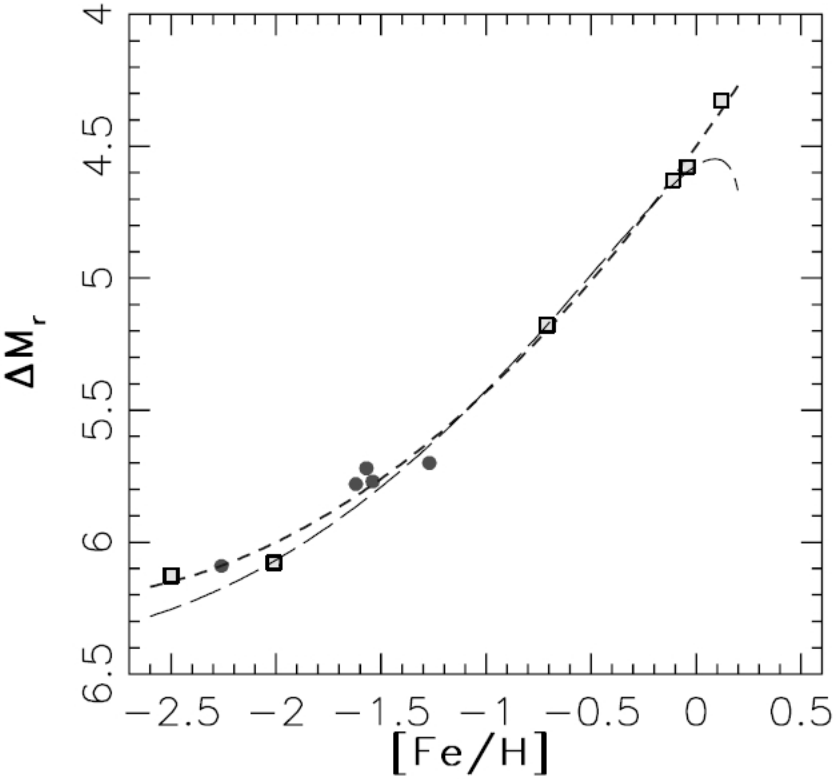
Photometric Parallax Calibration

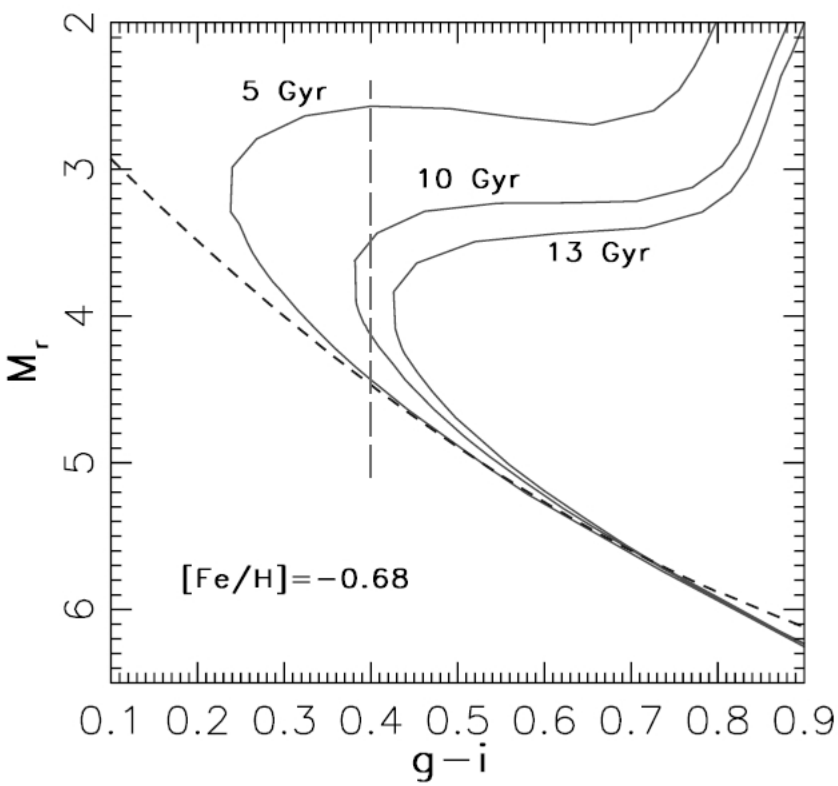
- With a sufficiently large sample of globular clusters, we can calibrate $M_r(g-i, [Fe/H])$, and then apply it to field stars to get their distances.
- **Top Left:** an example of a globular cluster (M5) as observed by SDSS; the line is a polynomial fit to the median main sequence (large circles):

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

where $M_r^{0.6}$ is the median absolute magnitude for stars with $0.5 < g-i < 0.7$.

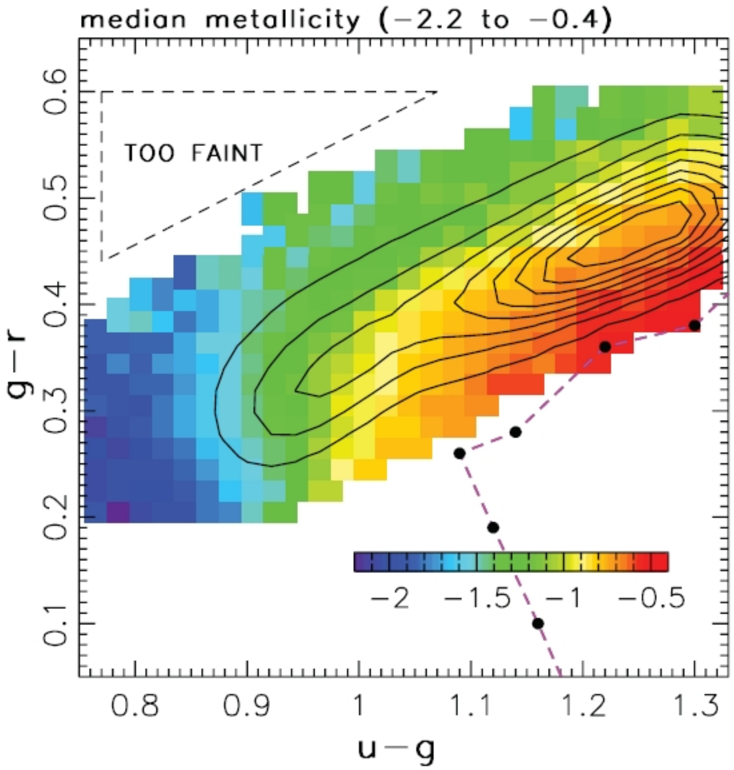
- **Bottom Left:** this is a good fit to a number of globular clusters observed by SDSS, showing that the main effect of metallicity is to slide the main sequence vertically (i.e. along luminosity axis, changing $M_r^{0.6}$), without much effect on its *shape*.

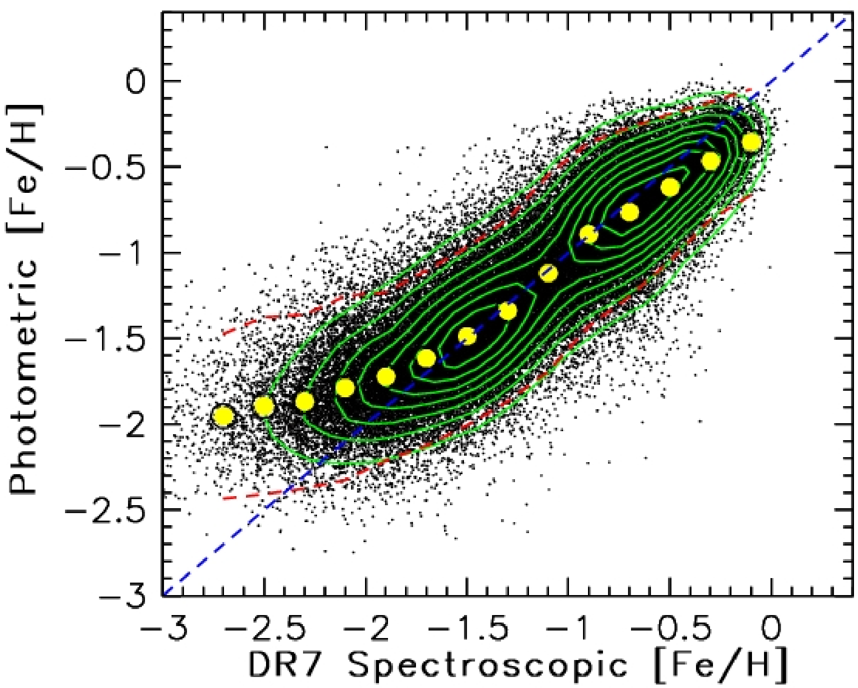




Photometric Parallax Calibration

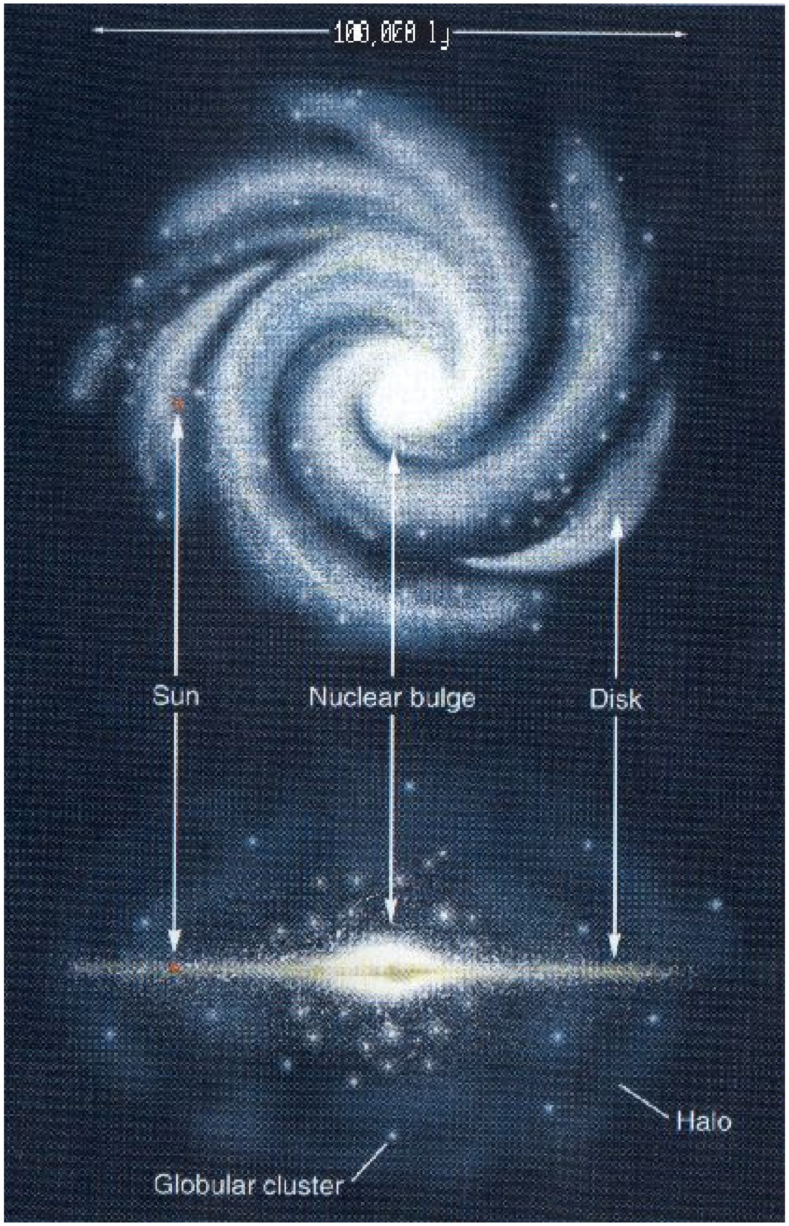
- The position of the main sequence depends on [Fe/H]
- **Top Left:** calibration (short-dashed) based on SDSS data (dots) and VandenBerg & Cleam (2003; squares). The shift is huge: $>$1 mag between median halo metallicity ($[Fe/H] = -1.5$) and local disk metallicity ($[Fe/H] = -0.2$). Must know [Fe/H] 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

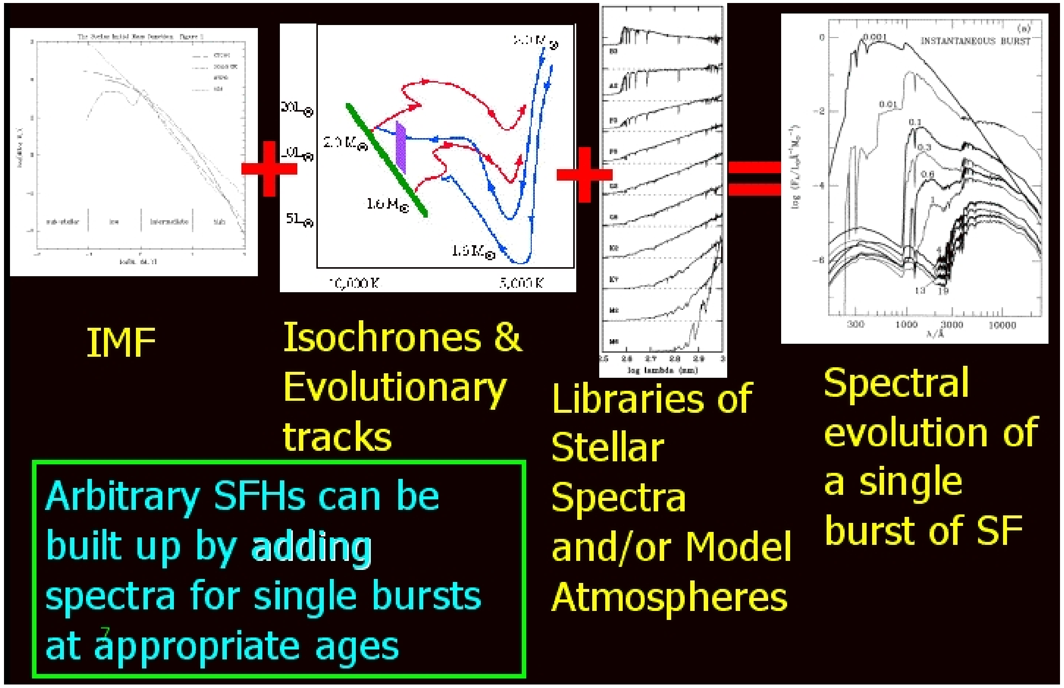
- At a fixed effective temperature, the amount of UV flux ($\lambda < 4000\AA$) for F/G main-sequence stars is very sensitive to metallicity (Wallerstein 1962)
- **Top Left:** the dependence of spectroscopic metallicity (using 60,000 SDSS stellar spectra) on the position in the $g-r$ vs. $u-g$ color-color 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.

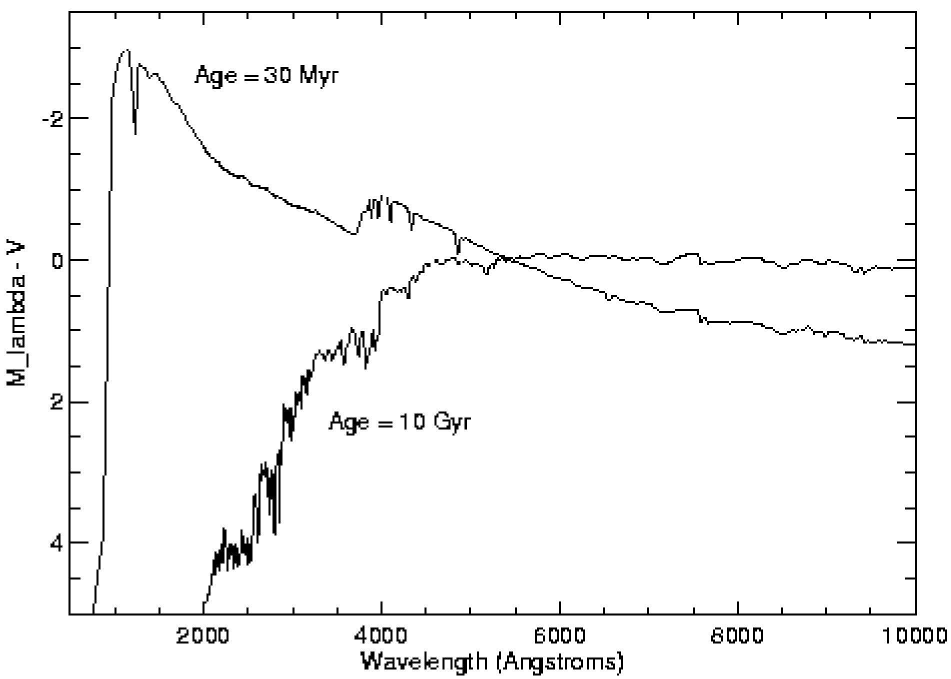


From Clusters to Galaxies:

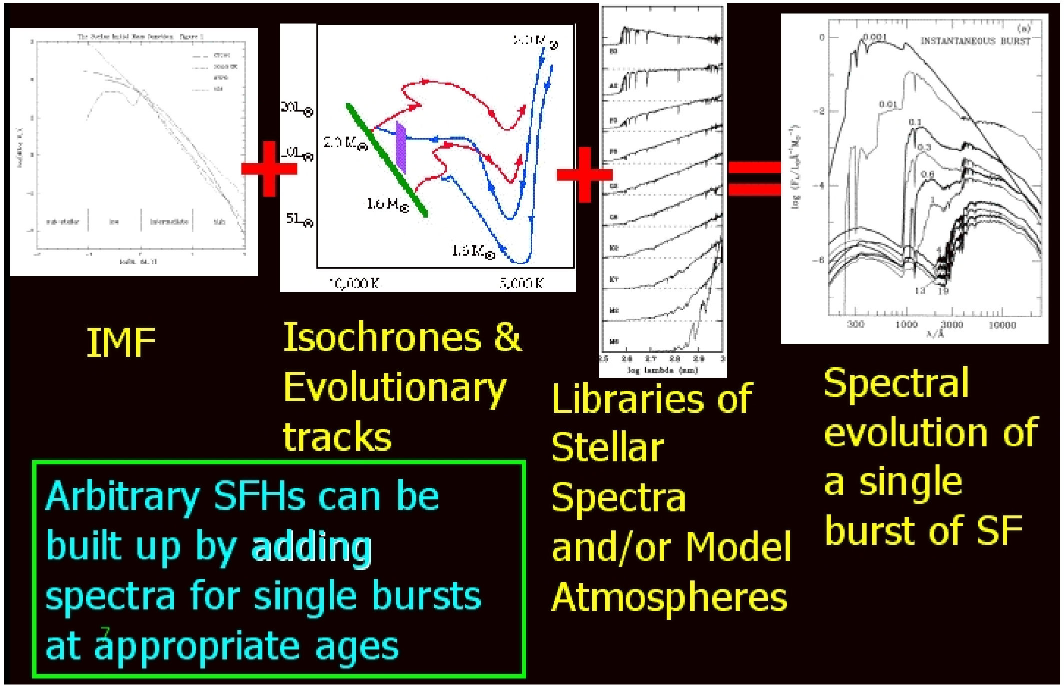
Population Synthesis

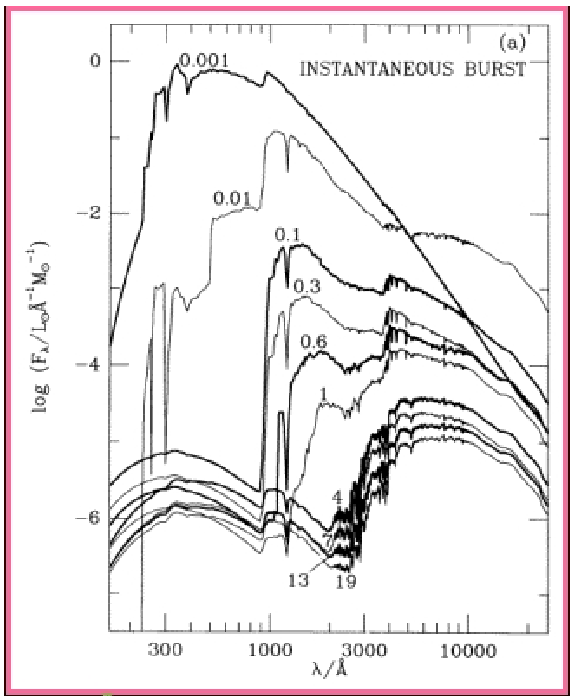
Population Synthesis: modeling the SED of a stellar system

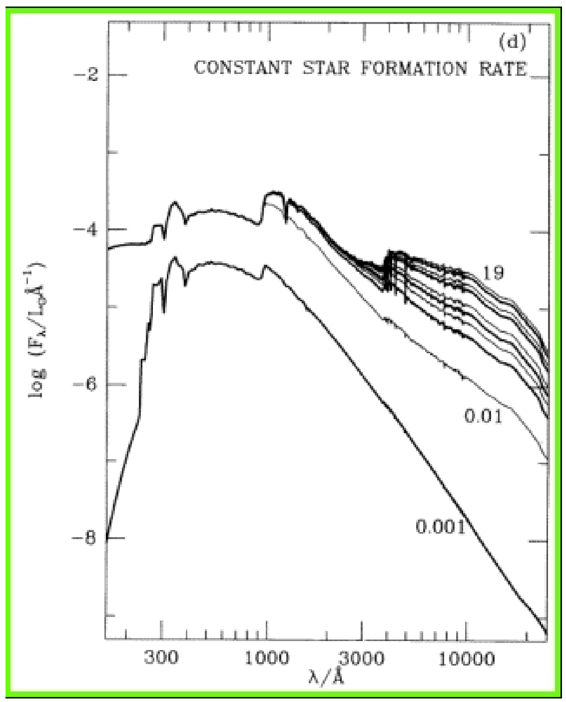




1. A burst of star formation: a group of stars (arbitrarily large) was formed some time ago: **age**
2. The mass distribution of these stars is given by a function called **initial mass function, IMF**, roughly a power-law $n(M) \propto M^{-3}$
3. The stellar distribution in the HR diagram is given by the adopted age and IMF.
4. Metallicity also has a small but measurable effect.
5. This makes up a Simple Stellar Population (SSP)





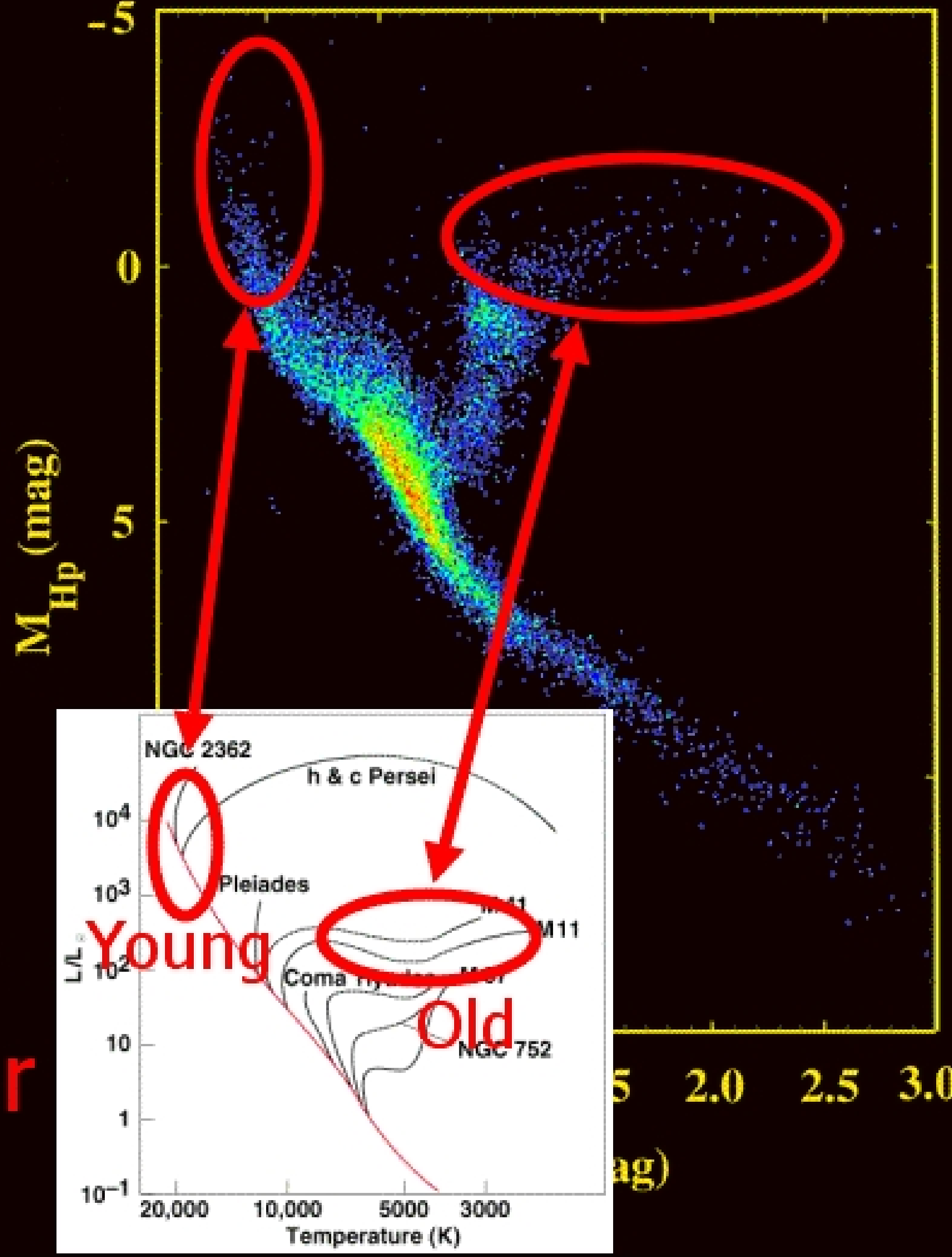


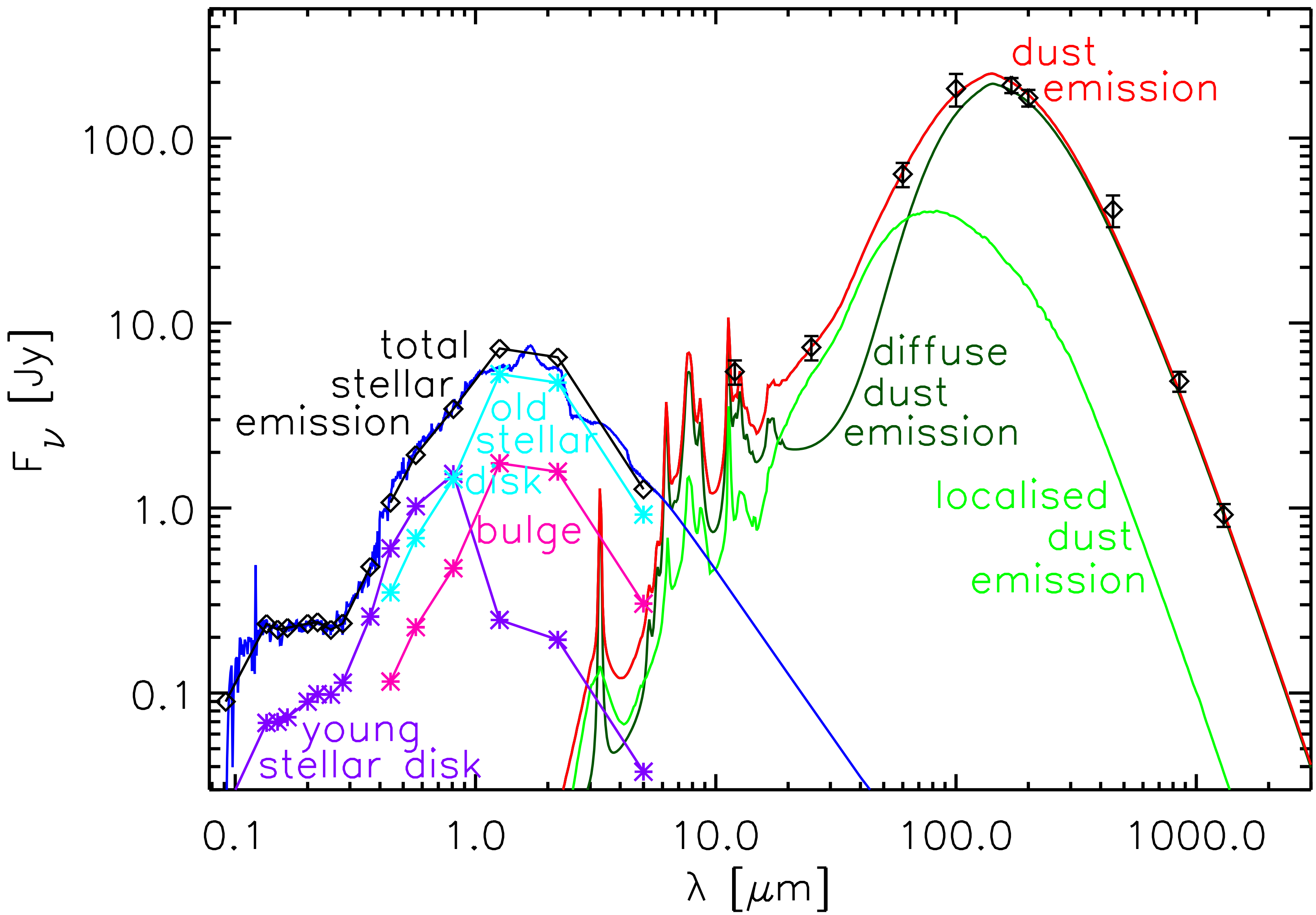
Population Synthesis: modeling SEDs of galaxies

1. Adding the SEDs of stars within an SSP gives us the SSD of an SSP. Globular clusters are a good approximation of a single stellar population (more later).
2. Star-formation history, or the distribution of stellar ages, tells us how to combine such simple stellar populations to get the SED of a realistic galaxy

Galaxies with more recent star formation have a large fraction of young main sequence stars.

Galaxies with no recent stars have red giants as their brightest stars.





Above: NGC891 (Popescu et al. 2011)

What do we measure? Radiation Intensity.

$$I_\nu(\lambda, \alpha, \delta, t, \mathrm{p})$$

- I_ν - energy (or number of photons) / time / Hz/ solid angle
- λ - γ-ray to radio, depending on resolution: spectroscopy, narrow-band photometry, broad-band photometry
- α, δ - direction (position on the sky); the resolution around that direction splits sources into unresolved (point) and resolved; interferometry, adaptive optics,...
- t - time variability of emission
- **p** polarization

Instruments measure various integrals of this quantity. Examples:

Imaging (photometry):

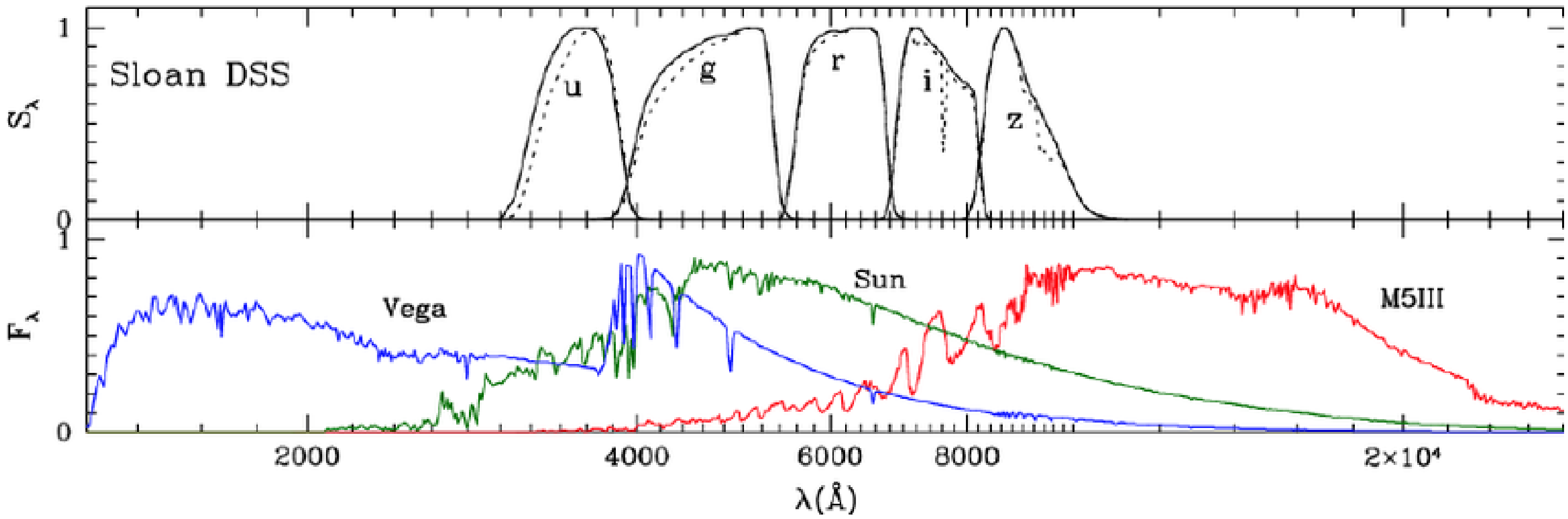
$$I_\nu^{band}(<\alpha>, <\delta>, <t>) = \int_0^\infty S(\lambda) d\lambda \int_0^T dt \int_\theta d\Omega \, I_\nu(\lambda, \alpha, \delta, t, \mathbf{p}) \tag{2}$$

SDSS: T = 54.1 sec, θ ∼1.5 arcsec, filter width ∼1000 Å

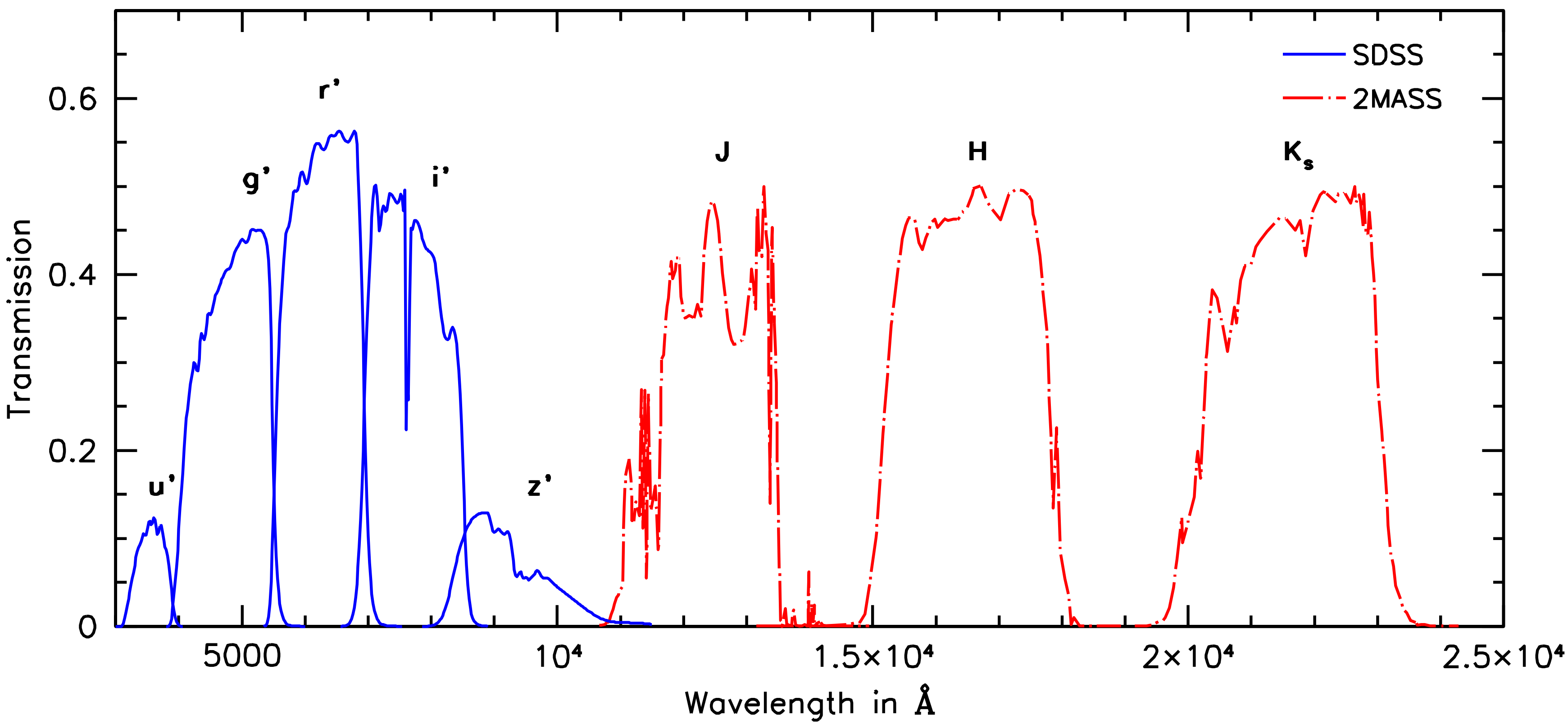
Spectroscopy:

$$F_\nu^{object}(\lambda, <t>) = \int_0^\infty R(\lambda) d\lambda \int_0^T dt \int_A d\Omega \, I_\nu(\lambda, \alpha_0, \delta_0, t, \mathbf{p}) \tag{3}$$

SDSS: T = 45 min, A: 3 arcsec fibers (∼6 kpc at the redshift of 0.1), R∼2 Å (∼70 km/s)



SDSS filters and stellar SEDs


SDSS
2MASS
u'
g'
r'
i'
z'
J
H
K_s
Transmission
0
0.2
0.4
0.6
5000
10^4
1.5×10^4
2×10^4
2.5×10^4
Wavelength in Å

Even with the same instrument, multiple measurements are made

- Magnitudes: $m = -2.5 log(I_\nu / I_0)$

- Magnitudes: there are five different types in SDSS! Aperture, fiber, psf, model and Petrosian magnitudes.

- Do we really need all these magnitudes?

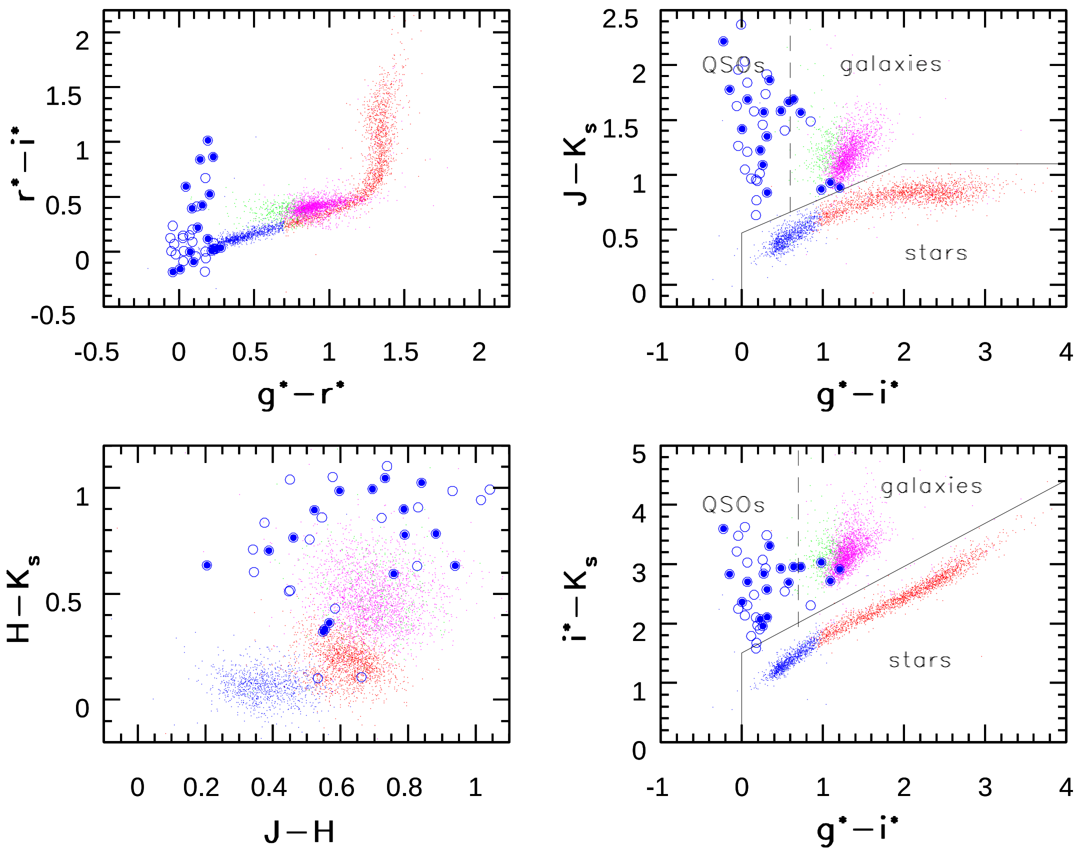
An example: SDSS photometry

- Magnitudes: we need different magnitudes because, depending on an object's brightness profile, they capture different information and have different noise properties.

- Unresolved sources: aperture magnitudes work well, but only for bright stars; for a given error, psf magnitudes go 1-2 mags deeper; fiber magnitudes measure flux within 3 arcsec aperture, and thus estimate the flux seen by spectroscopic fibers

- Resolved sources: psf magnitudes don't include the total flux, actually none of the various magnitudes includes the total flux for resolved sources! Petrosian magnitudes include **the same** fraction of flux, independent of galaxy's angular size, however, they are very noisy for faint galaxies; model magnitudes have smaller noise for faint galaxies (especially if you are interested only in colors)

Sources in Color-Color Diagrams (example: SDSS-2MASS)



- Blue/red: blue and red stars; green/magenta: blue and red galaxies, Circles: quasars ($z < 2.5$)
- Optical/IR colors allow an efficient star-quasar-galaxy separation
- 8-band accurate and robust photometry excellent for finding objects with atypical SEDs (e.g. red AGNs, L/T dwarfs, binary stars)

THE MASSES OF NEBULAE 227

III. THE VIRIAL THEOREM APPLIED TO CLUSTERS OF NEBULAE

If the total masses of clusters of nebulae were known, the average masses of cluster nebulae could immediately be determined from counts of nebulae in these clusters, provided internebular material is of the same density inside and outside of clusters.

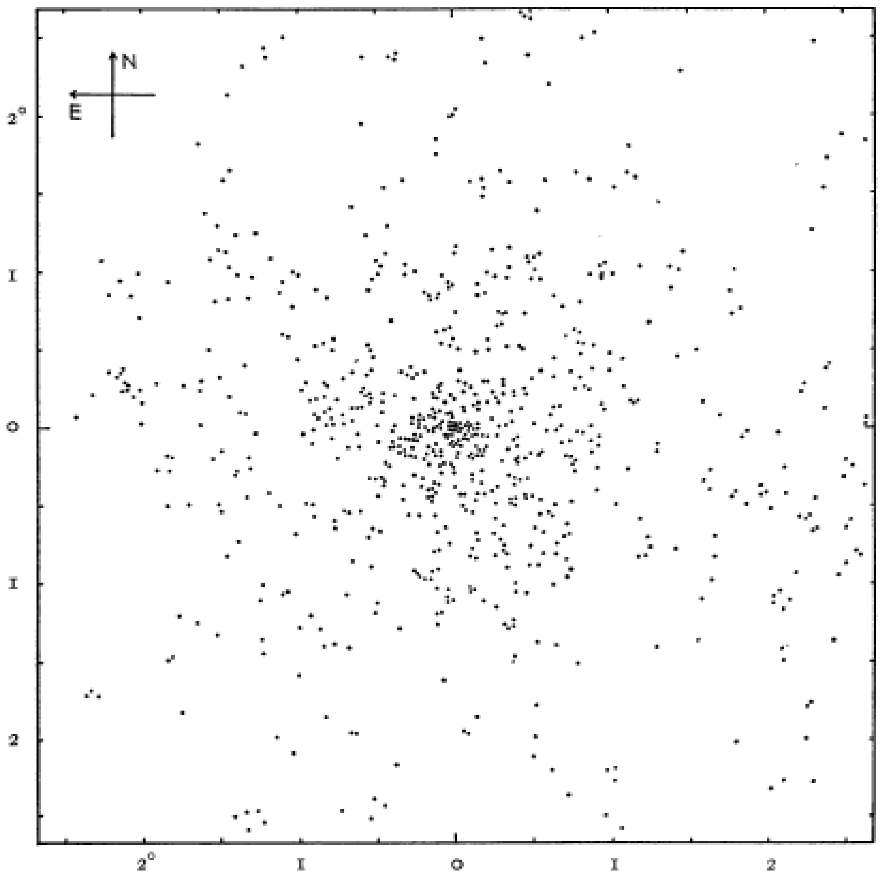


FIG. 3.—The Coma cluster of nebulae

As a first approximation, it is probably legitimate to assume that clusters of nebulae such as the Coma cluster (see Fig. 3) are mechanically stationary systems. With this assumption, the virial theorem of classical mechanics gives the total mass of a cluster in terms of the average square of the velocities of the individual nebulae which constitute this cluster.[5] But even if we drop the assumption that clus-

The Virial Theorem

- In a system of N particles, gravitational forces tend to pull the system together and the stellar velocities tend to make it fly apart. It is possible to relate kinetic and potential energy of a system through the change of its moment of intertia
- In a steady-state system, these tendencies are balanced, which is expressed quantitatively through the the Virial Theorem.
- A system that is not in balance will tend to move towards its virialized state.

The Scalar Virial Theorem

The Virial Theorem will be discussed in detail later in this class. For now, all we need to know is the final result for the Scalar Virial Theorem: the *average* kinetic and potential energy must be in balance:

$$E = K + \Phi = -K = \frac{1}{2}\Phi \tag{4}$$

where $K = M < v^2 > /2$ is the kinetic energy, Φ is the gravitational potential energy, and E is the total energy (negative for a gravitationally bound system).

For a bound system, the "potential well" is "half full": K brings the level up from Φ to $\Phi/2$ (e.g. from -100 J to -50 J).

Recall that Φ for two masses is

$$\Phi = -G\frac{mM}{r}. \tag{5}$$

The Scalar Virial Theorem: Applications

- If a system collapses from infinity, half of the potential energy will end up in kinetic energy, and the other half will be disposed of! From the measurement of the circular velocity and the mass of Milky Way (which constrain the kinetic energy), we conclude that during their formation, galaxies radiate away about 3×10^{-7} of their rest-mass energy.

- For a virialized spherical system, $M = 2R\sigma^2/G$. We can estimate total mass from the size and velocity dispersion. E.g. for a cluster with σ=12 km/s, and R=3 pc, we get $M = 2 \times 10^5$ $M_\odot$ (note that $G = 233$ in these units)

- Think about this for the next time: Evil aliens give a "kick" to our Moon that increases its kinetic energy by 10%. What will happen with the radius of its orbit (smaller or larger)?