Astr 511: Galaxies as galaxies

Winter Quarter 2017, University of Washington

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Lecture 1:

Review of Stellar Astrophysics (and other useful stuff)

Understanding Galaxy Properties and the Milky Way

Binney & Tremaine: "Always majestic, often spectacularly beautiful, galaxies are the fundamental building blocks of the Universe."

The goals of this class are:

- Understanding the correlations between various galaxy properties using simple physical principles; discussion of the formation and evolution of galaxies
- Understanding in detail the Milky Way structure (distribution of stars and ISM, stellar kinematics, metallicity and age distributions)
- Reproducing some published work

The Basics of Basics

Assumed that you are all familiar with these terms:

- general: distance modulus, absolute magnitude, bolometric luminosity, the Planck function

- types of stars: white dwarfs, horizontal branch, red giants, supergiants, subgiants, subdwarfs, etc.

- stellar properties: effective temperature, spectral class, metalicity, mass, age

Outline

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

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 - static vs. variable universe, sampling rate,...
- **p** polarization

Examples:

Imaging (photometry):

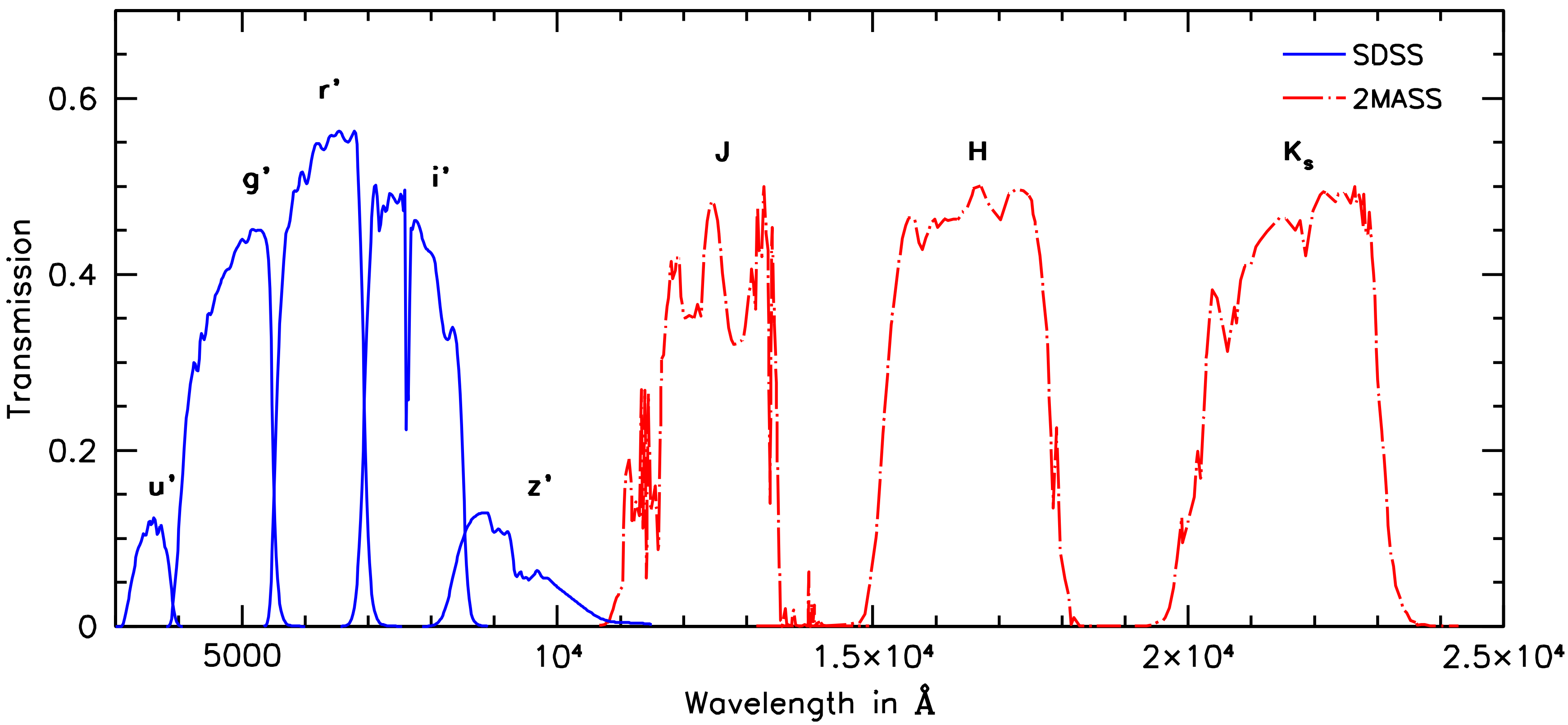
$$I_\nu^{band}(<\alpha>,<\delta>,<t>) = \int_0^\infty S(\lambda)d\lambda \int_0^T dt \int_\theta d\Omega\, I_\nu(\lambda,\alpha,\delta,t,\mathbf{p}) \tag{1}$$

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

Spectroscopy:

$$F_\nu^{object}(\lambda,<t>) = \int_0^\infty R(\lambda)d\lambda \int_0^T dt \int_A d\Omega\, I_\nu(\lambda,\alpha_0,\delta_0,t,\mathbf{p}) \tag{2}$$

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



SDSS
2MASS
u'
g'
r'
i'
z'
J
H
Ks
0.6
0.4
0.2
0
5000
10⁴
1.5×10⁴
2×10⁴
2.5×10⁴
Transmission
Wavelength in Å

An example: SDSS photometry

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

- Radial Profiles: all magnitudes are measured using circularized brightness profiles extracted for a predefined set of radii

- Do we really need all these magnitudes?

SDSS photometry

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

- Unresolved sources: aperture magnitudes are the best, 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)

The count (uncalibrated flux) extraction

- In the limit of a circular source, all fluxes (magnitudes) can be computed as:

  $flux(type) \propto \int p(x)\,\Phi(x)\,2\pi x\,dx$

- $type$: aperture, fiber, psf, Petrosian, model

- $p(x)$: circularized brightness profile

- $\Phi(x)$: type-dependent weight function

  - aperture: $\Phi(x) = 1$ for $x < 7.4$ arcsec, 0 otherwise

  - fiber: $\Phi(x) = 1$ for $x < 1.5$ arcsec, 0 otherwise

– psf: $\Phi(x)$ = psf(x) for $x < 3$ arcsec, 0 otherwise, *photo* uses 2D integration (angle dependence)

– Petrosian: $\Phi(x) = 1$ for $x < R$ arcsec, 0 otherwise, R depends on the measured galaxy profile: defined by the ratio of the local surface brightness to the mean surface brightness within the same radius

– model: $\Phi(x)$ from a best-fit (deV or exp) 3-parameter pre-computed profile (convolved with seeing); must be 2D integration

For signal-to-noise calculation, see document **An LSST document on astronomical signal-to-noise calculation and flux extraction** linked to the class webpage.

More information about SDSS galaxy photometry can be found in Strauss et al. (2002, AJ 124, 1810).

Calibrated flux and magnitudes

- Given a specific flux of an object *at the top* of the atmosphere, $F_\nu(\lambda)$, a broad-band photometric system measures the in-band flux

$$F_b = \int_0^\infty F_\nu(\lambda)\phi_b(\lambda)d\lambda, \tag{3}$$

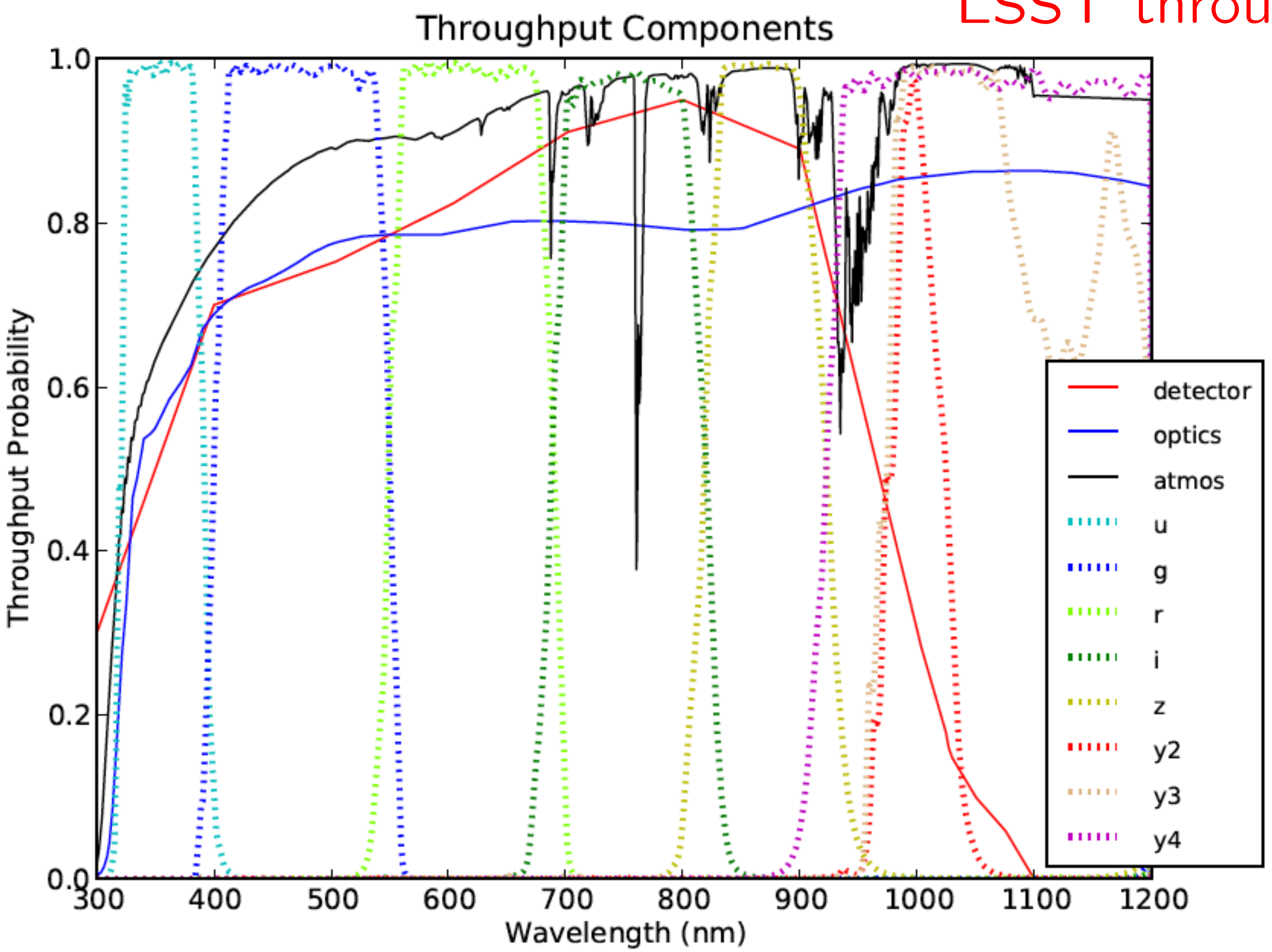
where $\phi_b(\lambda)$ is the normalized system response for a given band (e.g. for SDSS $b = ugriz$)

$$\phi_b(\lambda) = \frac{\lambda^{-1}S_b(\lambda)}{\int_0^\infty \lambda^{-1}S_b(\lambda)d\lambda}. \tag{4}$$

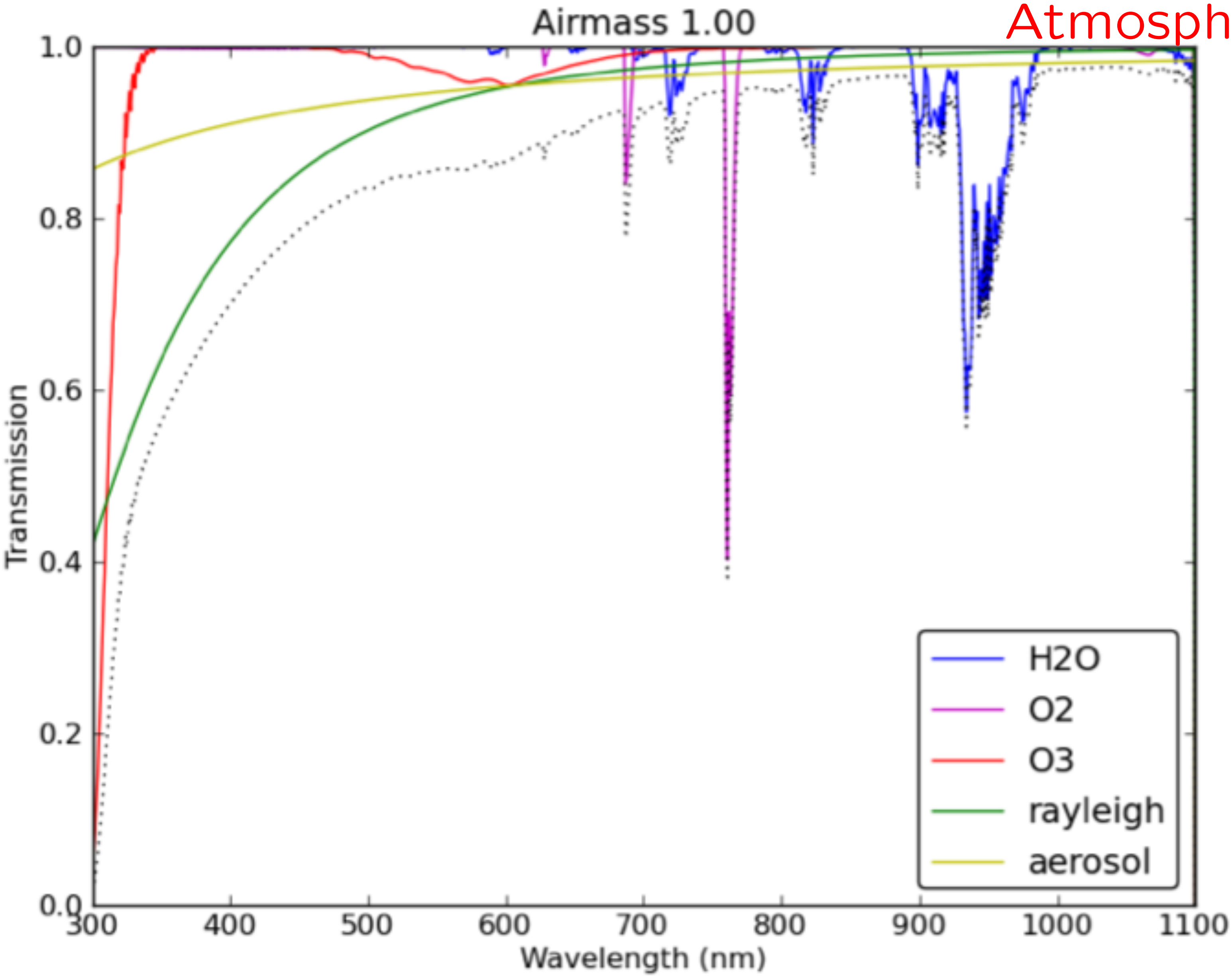
- The overall atmosphere + system throughput, $S_b(\lambda)$, is obtained from

$$S_b(\lambda) = S^{atm}(\lambda) \times S_b^{sys}(\lambda). \tag{5}$$

LSST throughput



Atmosphere



Airmass 1.00
Transmission
Wavelength (nm)
1.0
0.8
0.6
0.4
0.2
0.0
300
400
500
600
700
800
900
1000
1100
H2O
O2
O3
rayleigh
aerosol

Calibrated flux and magnitudes

- Photometric measurements are fully described by F_b and its corresponding $\phi_b(\lambda)$. The relevant temporal, spatial and wavelength scales on which $\phi_b(\lambda)$ is known determine photometric accuracy. Typically, it is assumed that $\phi_b(\lambda)$ "defines" a photometric system (e.g. Johnson, Strömgren, SDSS)

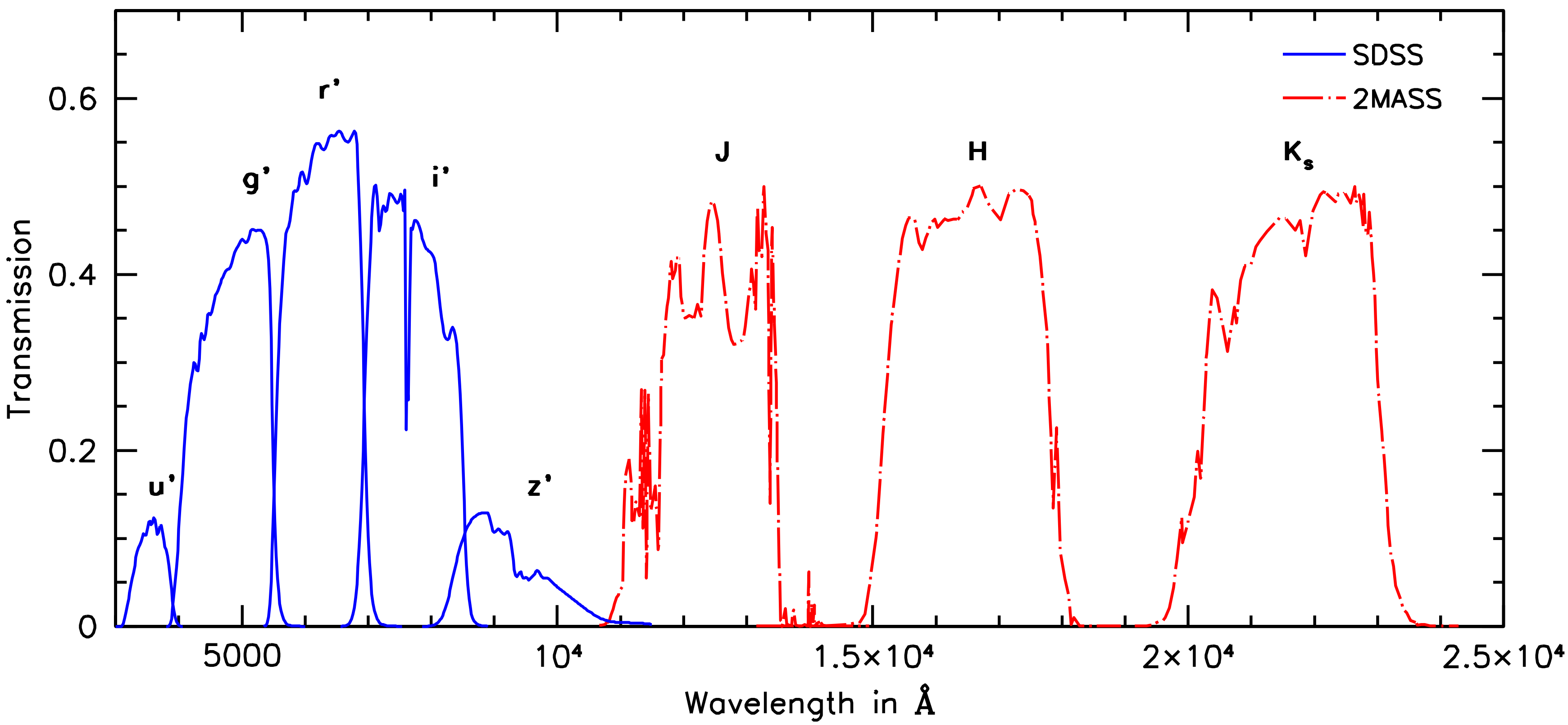
- Traditionally, the in-band flux is reported on a magnitude scale

$$m_b = -2.5 \log_{10} \left(\frac{F_b}{F_{AB}} \right). \tag{6}$$

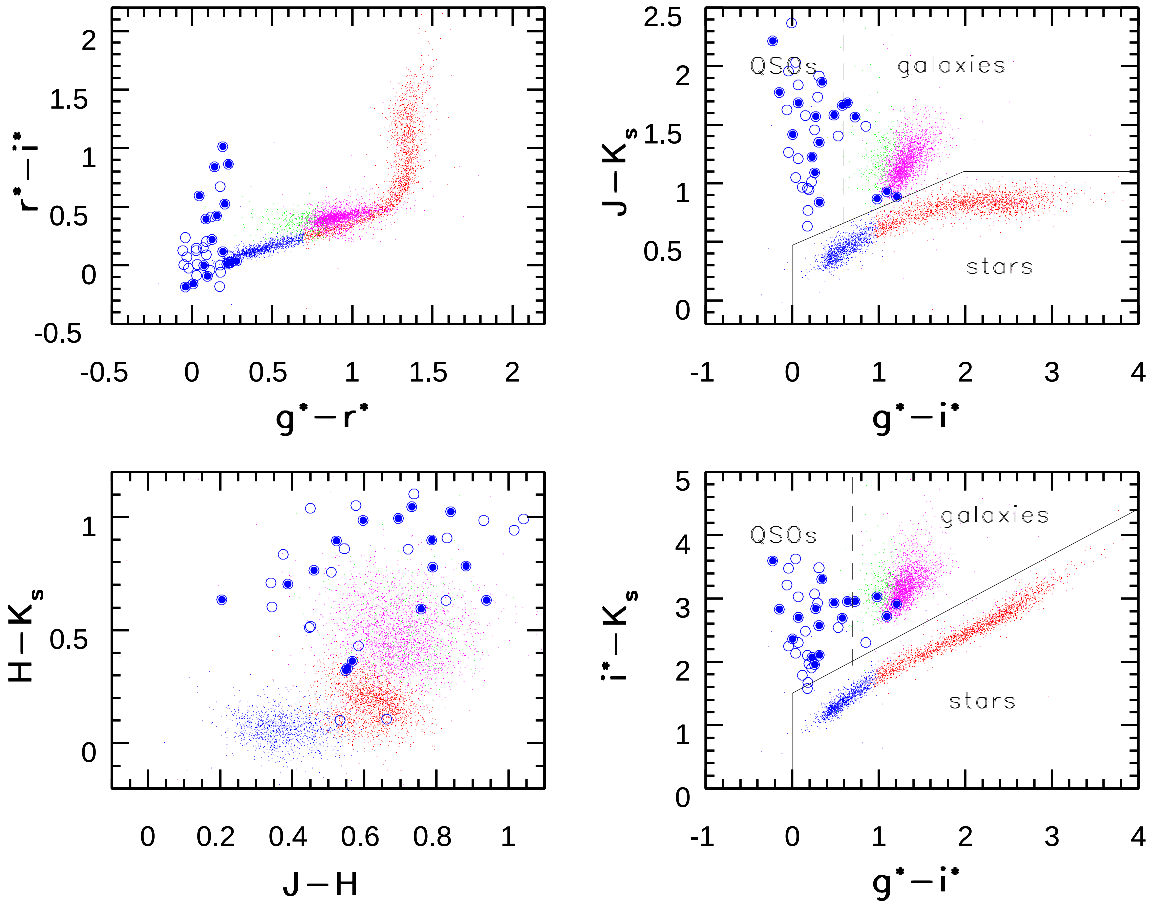
where $F_{AB} = 3631$ Jy (1 Jansky $= 10^{-26}$ W Hz^{-1} m^{-2} $=$ 10^{-23} erg s^{-1} Hz^{-1} cm^{-2}) is the flux normalization for AB magnitudes (Oke & Gunn 1983). These magnitudes are also called "flat" because for a source with "flat" spectral energy distribution (SED) $F_\nu(\lambda) = F_0$, $F_b = F_0$.

- Note: it might be a bit confusing that $F_\nu(\lambda)$ is integrated over wavelength in eq. **??**, and yet the result, F_b, has the same units as $F_\nu(\lambda)$. This happens because the product $\phi_b(\lambda)d\lambda$ is dimensionless, and eq. **??** formally represents weighting of $F_\nu(\lambda)$ rather than its area integral. Of course, this is a consequence of the definition of AB system* in terms of $F_\nu(\lambda)$.

*The fact that $F_\nu(\lambda)$ is multiplied by $S_b(\lambda)/\lambda$ and then integrated over wavelength is a consequence of the fact that CCDs are photon-counting devices. That is, the units for F_b are **not** arbitrary. For more details, see Maiz Apellániz 2006 (AJ 131, 1184).

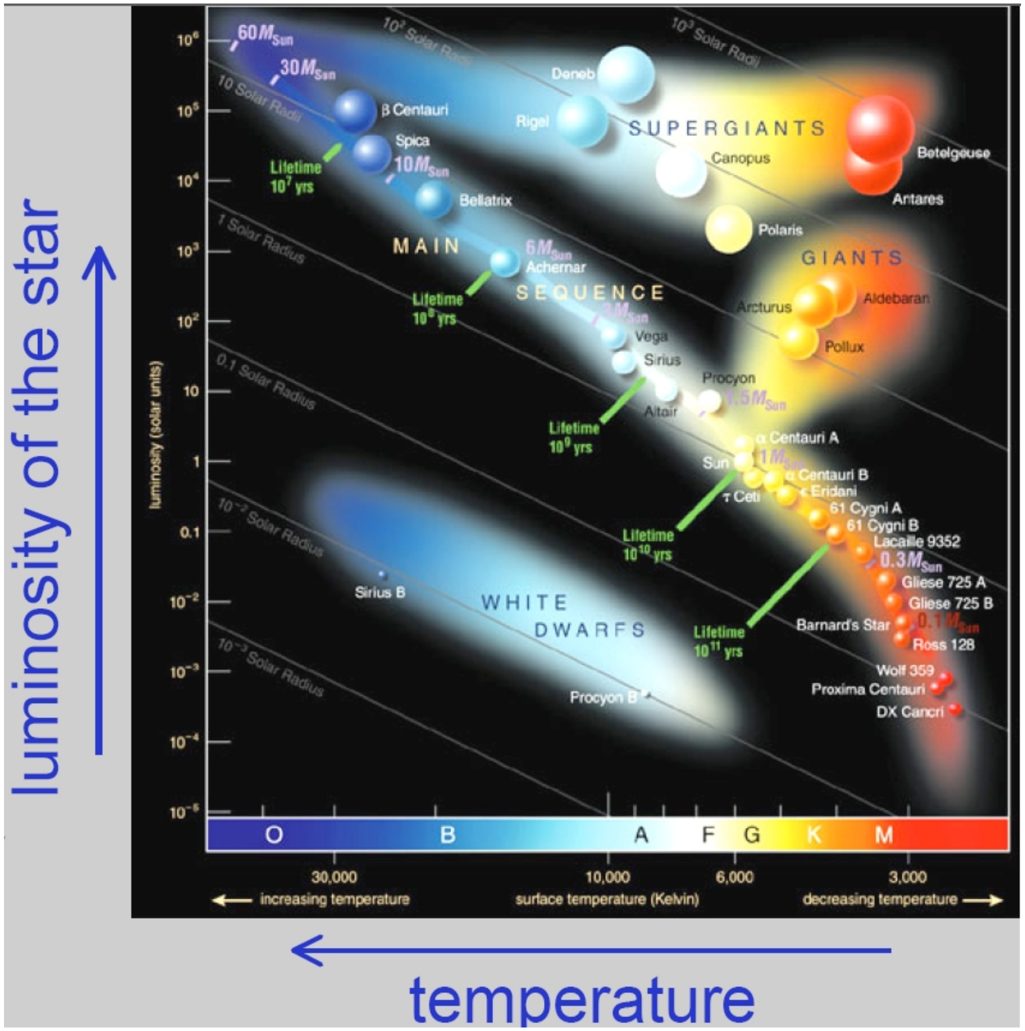


SDSS
2MASS
u'
g'
r'
i'
z'
J
H
K_s
Transmission
0
0.2
0.4
0.6
5000
10^4
1.5×10^4
2×10^4
2.5×10^4
Wavelength in Å



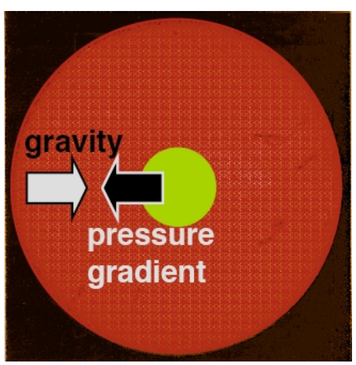
SDSS-2MASS sources

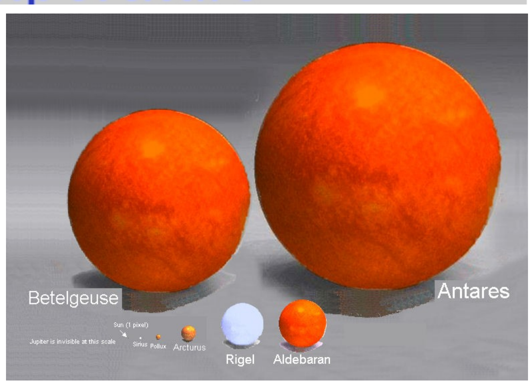
- Blue/red: blue and red stars; green/magenta: blue and red galaxies, Circles: quasars ($z < 2.5$)
- Optical/IR colors allow an efficient star-quasar-galaxy separation
- 8-band accurate and robust photometry excellent for finding objects with atypical SEDs (e.g. red AGNs, L/T dwarfs, binary stars)

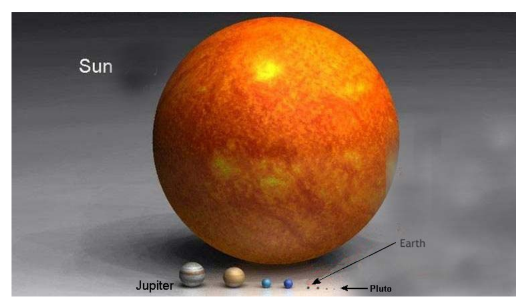


Hertzsprung-Russell Diagram

- 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
- $L =$ Area x Flux $= 4\pi R^2 \sigma T^4$
- Luminosity and size span a **huge** dynamic range!

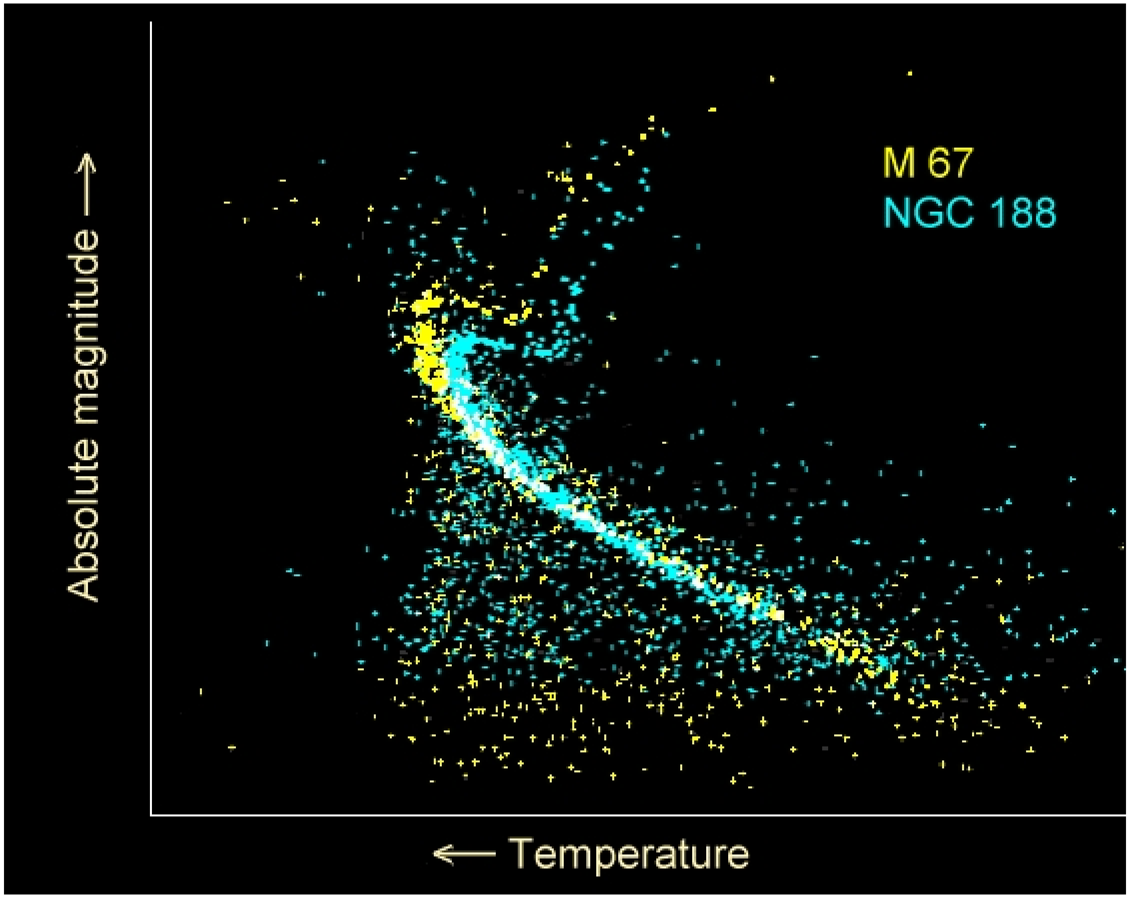


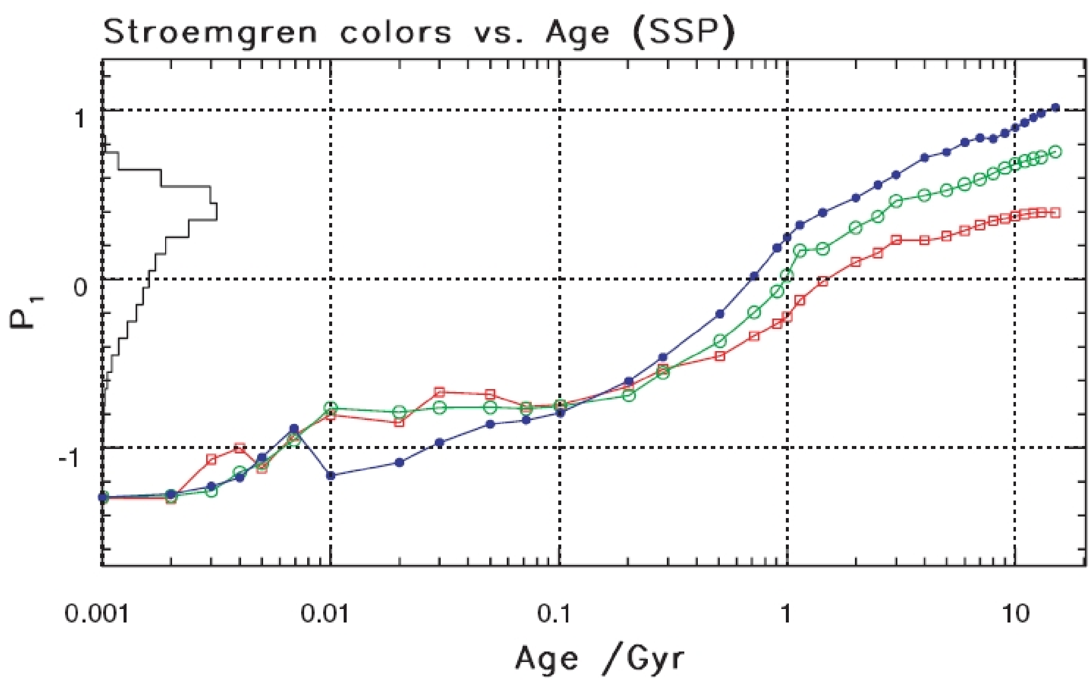




Check out HR simulator at

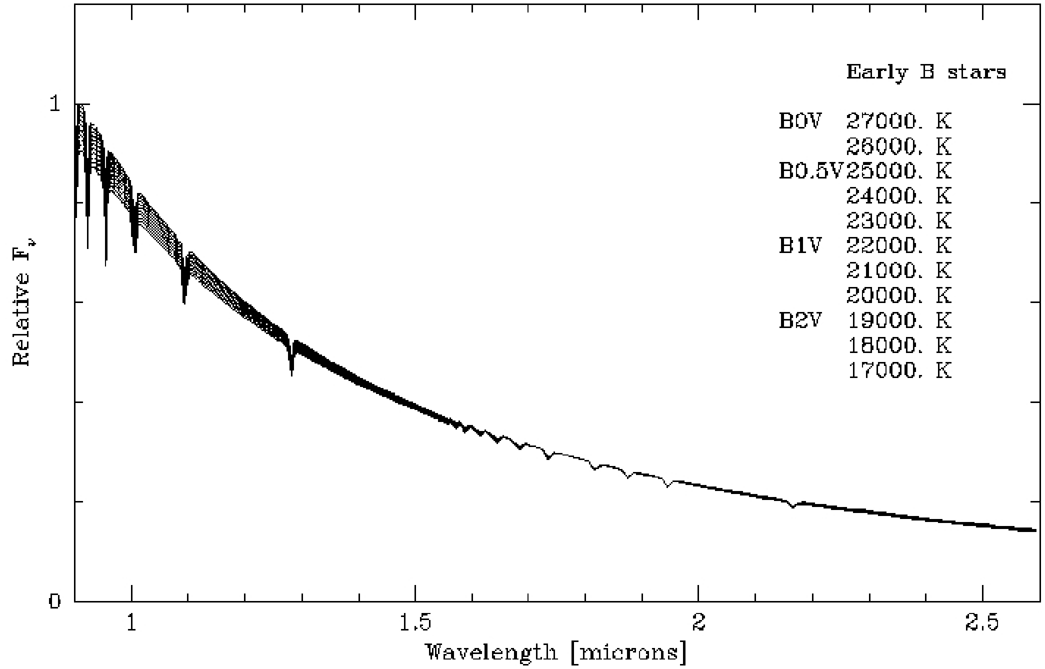
`http://www.astro.ubc.ca/~scharein/a311/Sim/hr/HRdiagram.html`

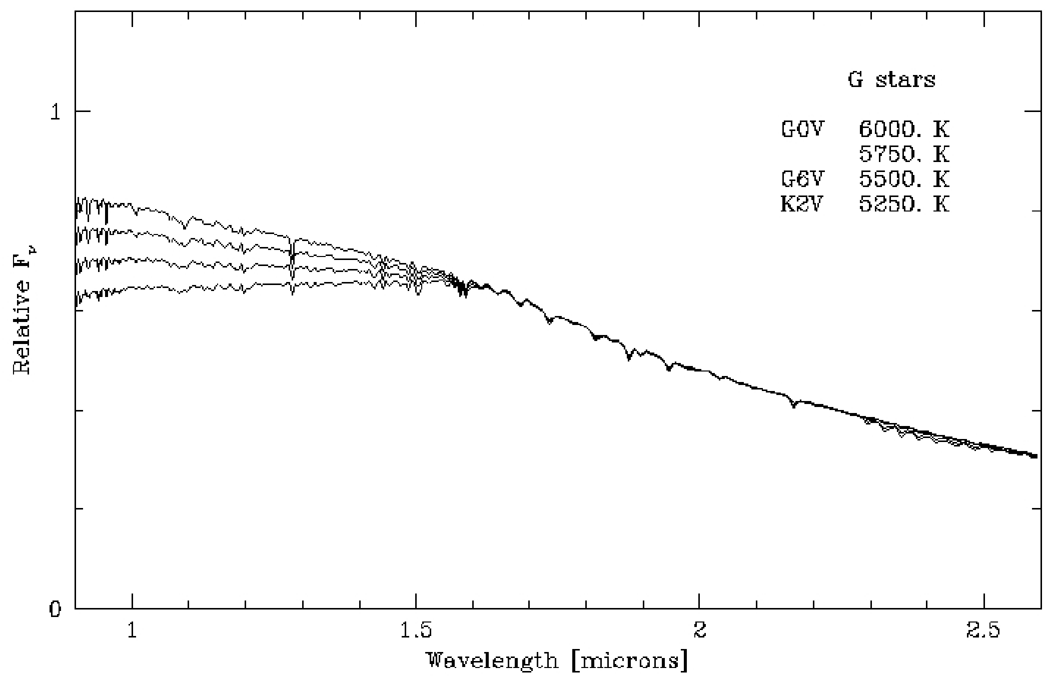




HR Diagram: Stellar Age

- 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...)

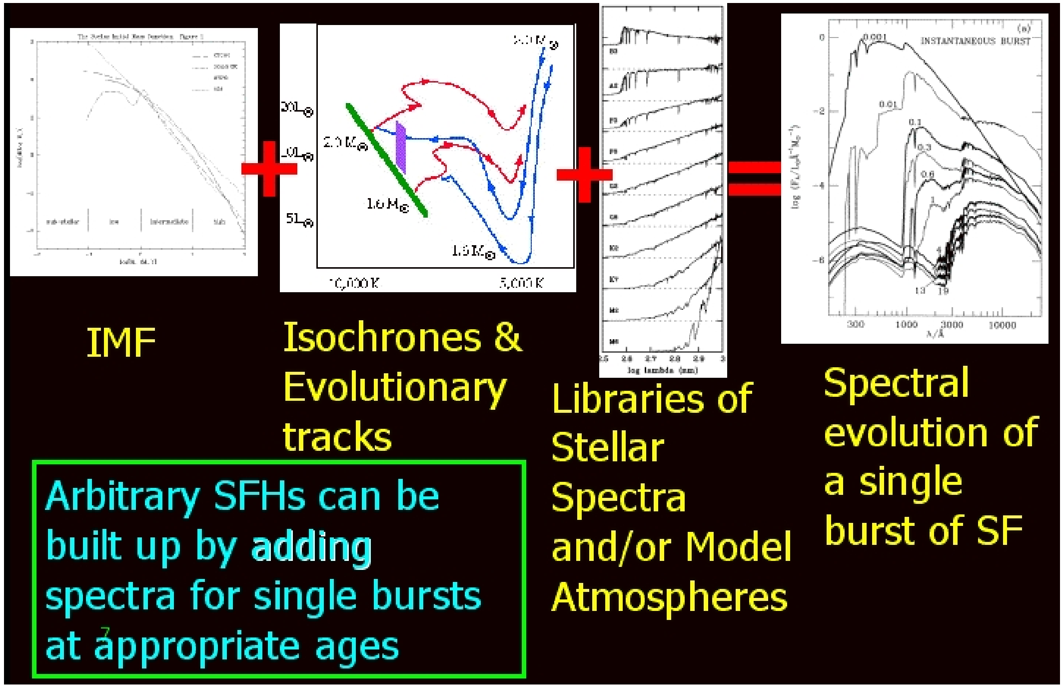


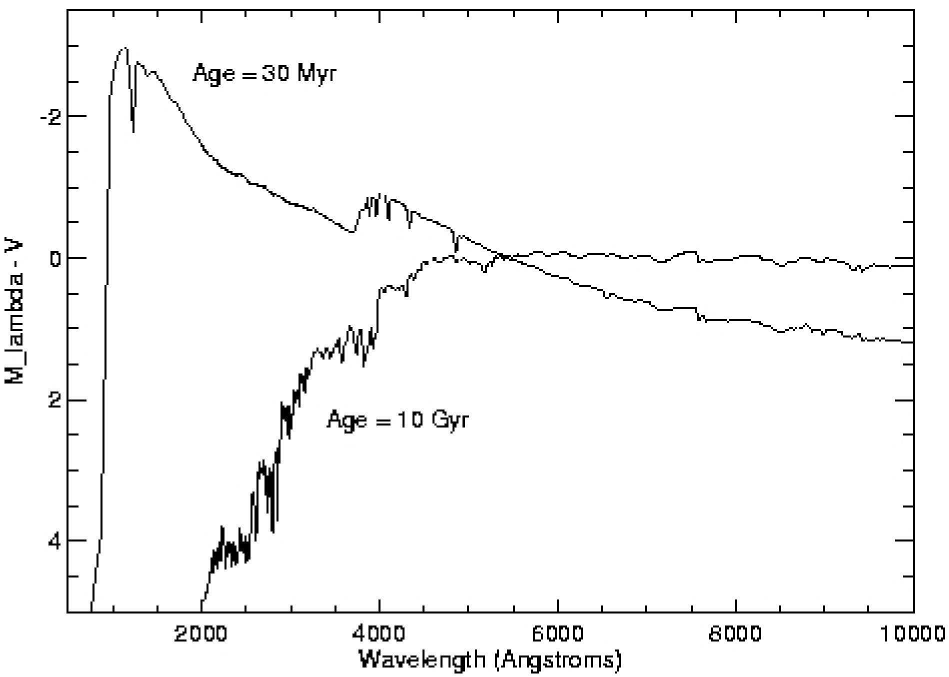


Stellar Parameters

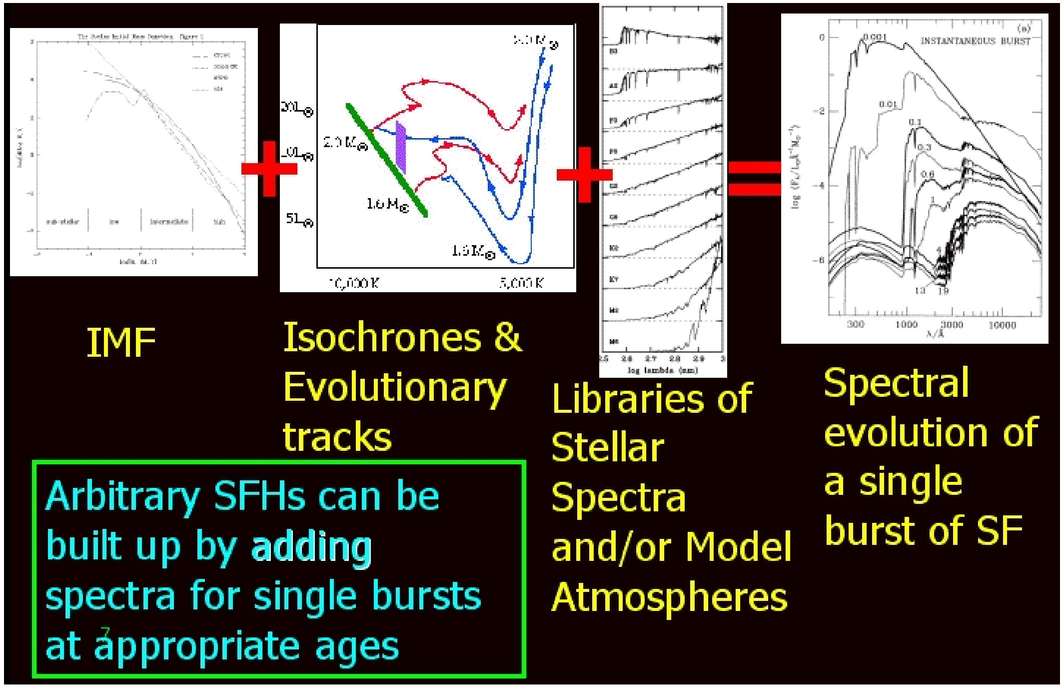
- The stellar spectral energy distribution is a function of mass, chemical composition and age, a theorist would say
- The stellar spectral energy distribution is a function of effective temperature, surface gravity and metallicity (at the accuracy level of 1%); the first two simply describe the position in the HR diagram
- Kurucz models (1979) describe SEDs of (not too cold) main sequence stars, as a function of $T_{\rm eff}$, $log(g)$ and $[Fe/H]$

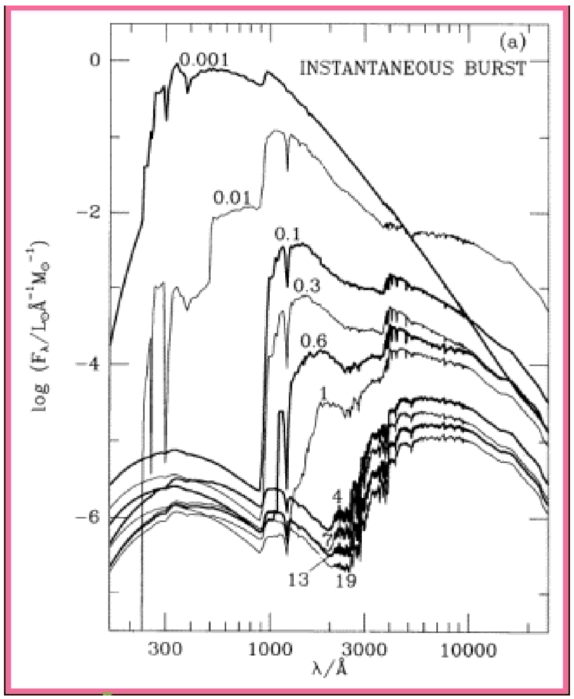
Population Synthesis: modeling SEDs of galaxies

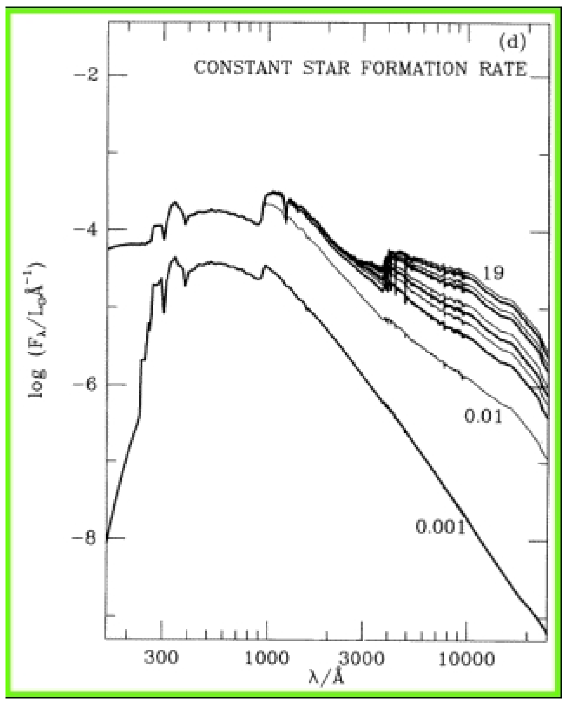




1. A burst of star formation: a bunch of stars (i.e. our galaxy) was formed some time ago: **age**
2. The mass distribution of these stars is given by a function called **initial mass function, IMF**, roughly a power-law $n(M) \propto M^{-3}$
3. The stellar distribution in the HR diagram is given by the adopted age and IMF; equivalently, can adopt a CMD for a globular or open cluster; assume **metallicity** and get a model (i.e. stellar SED, e.g. from Kurucz) for each star and add them up





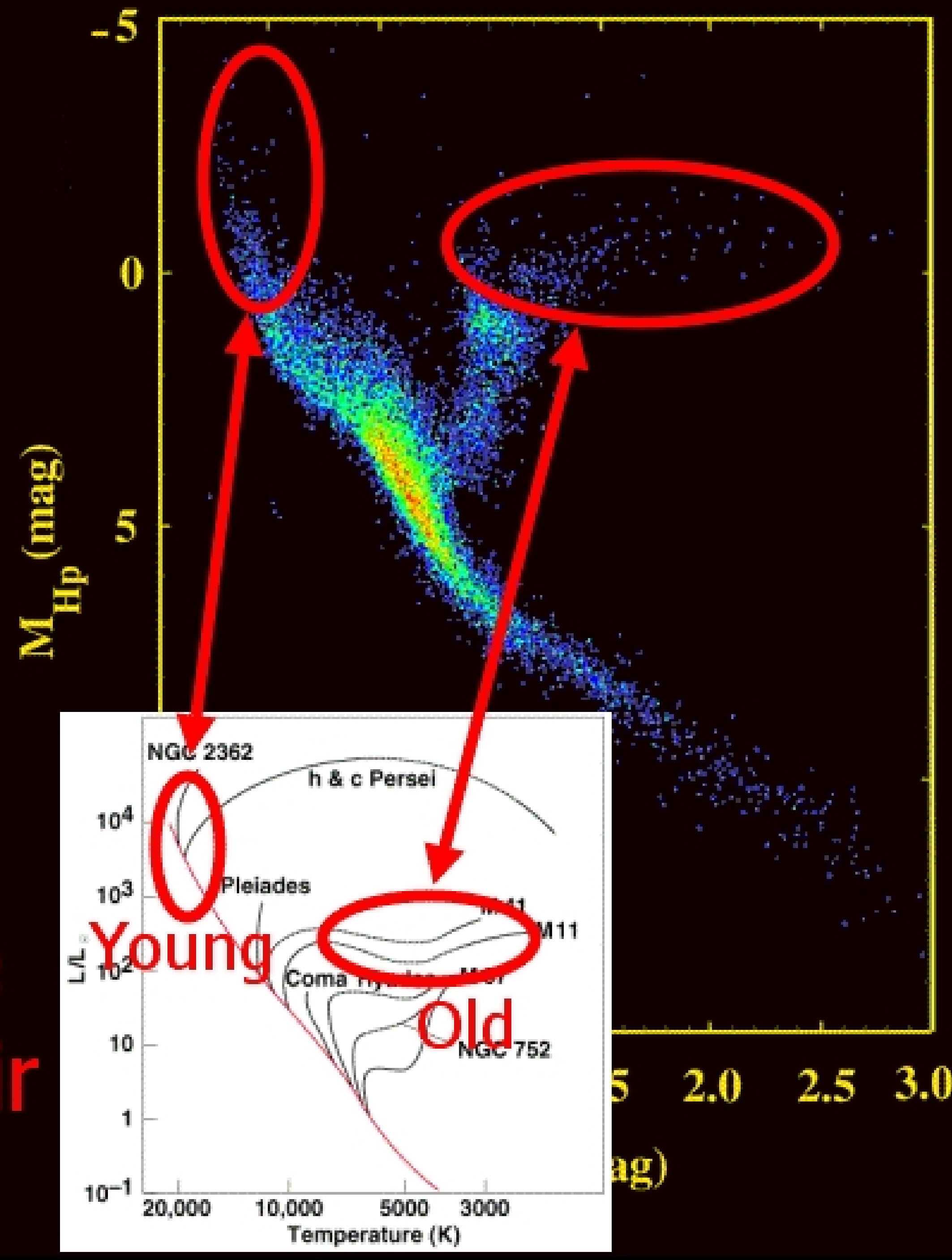


Population Synthesis: modeling SED of galaxies

1. A burst of star formation: **age**
2. The initial mass function, IMF
3. The stellar distribution in the HR diagram and metallicity: **add SEDs for all stars**, the result is
4. Simple stellar population as a function of **age** and **metallicity**
5. Star-formation history, or the distribution of stellar ages, tells us how to combine such simple stellar populations to get SED of a realistic galaxy

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

Galaxies with <u>no recent stars</u> have red giants as their brightest stars.



The Virial Theorem

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.

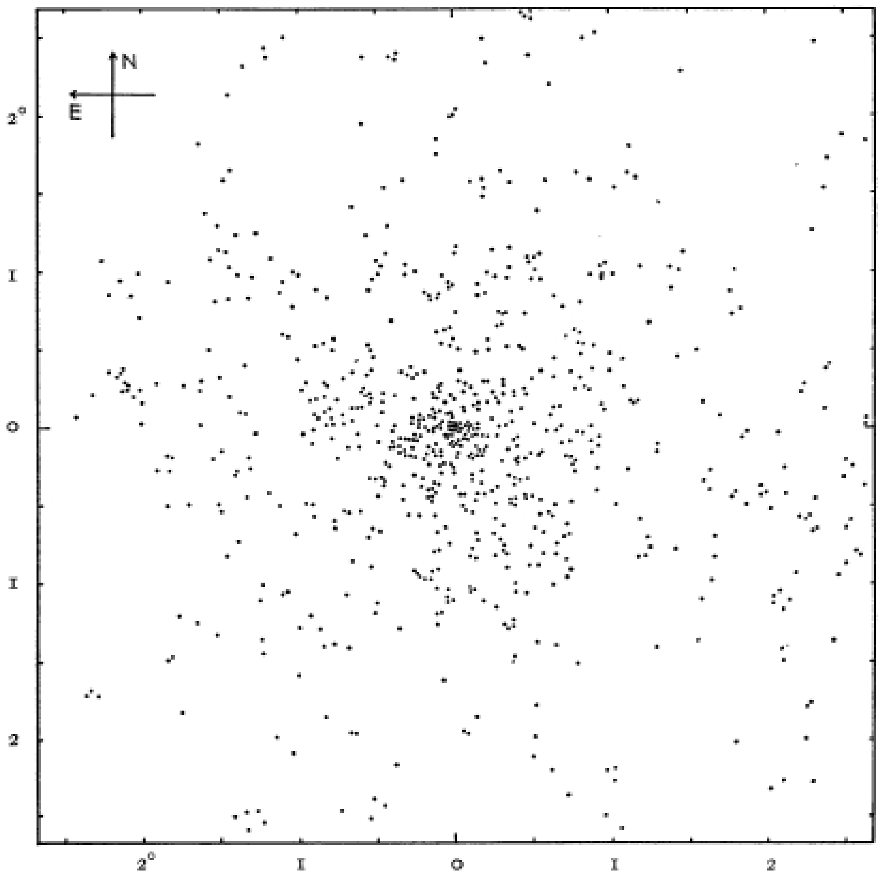


Fig. 3.—The Coma cluster of nebulae

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-

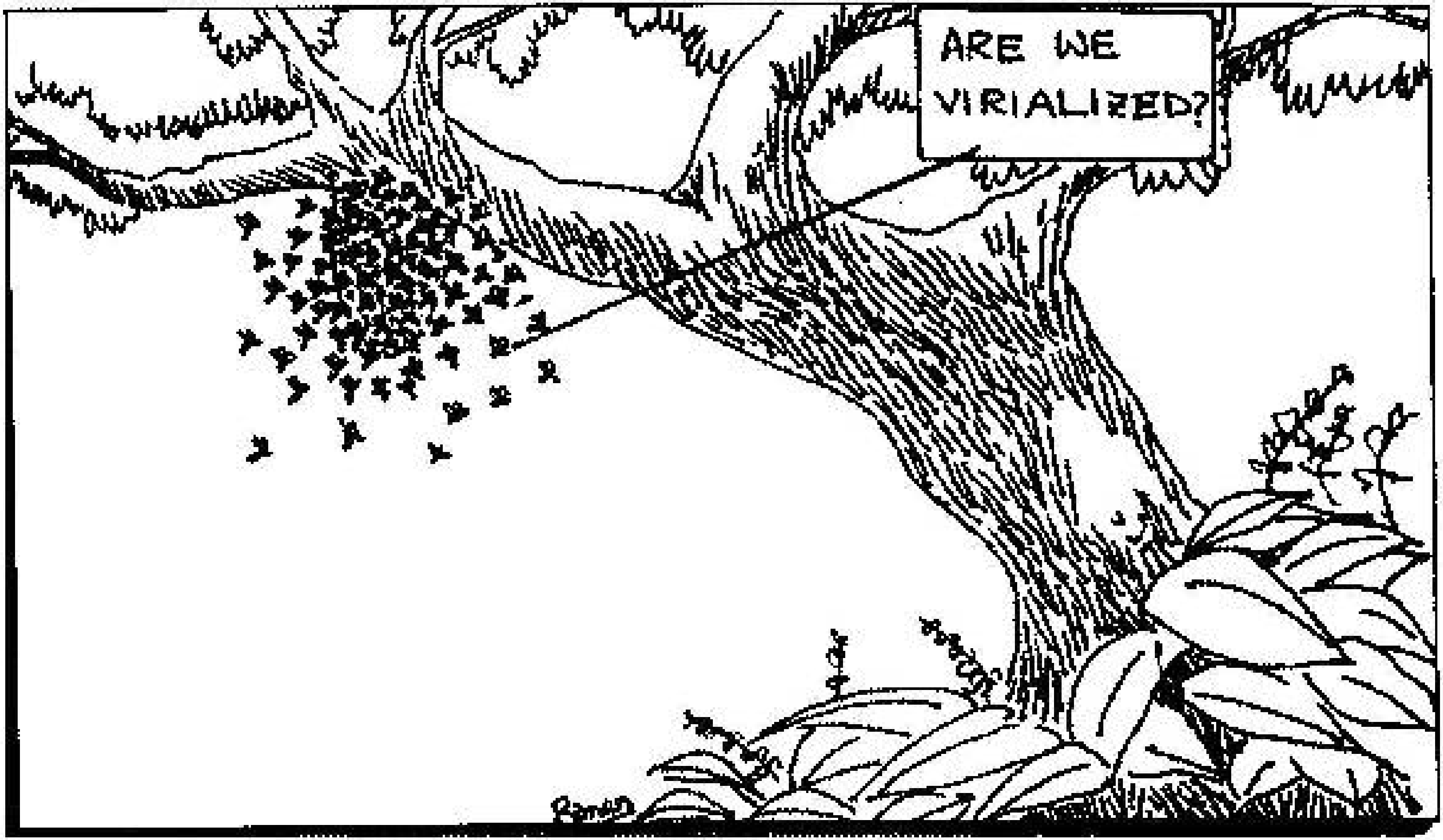
- In a system of N particles, gravitational forces tend to pull the system together and the stellar velocities tend to make it fly apart. It is possible to relate kinetic and potential energy of a system through the change of its moment of intertia
- In a steady-state system, these tendencies are balanced, 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:

$$E = K + \Phi = -K = \frac{1}{2}\Phi \tag{7}$$

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).



Cartoon courtesy of and ©1999 by B. Nath.

The Scalar Virial Theorem: Applications

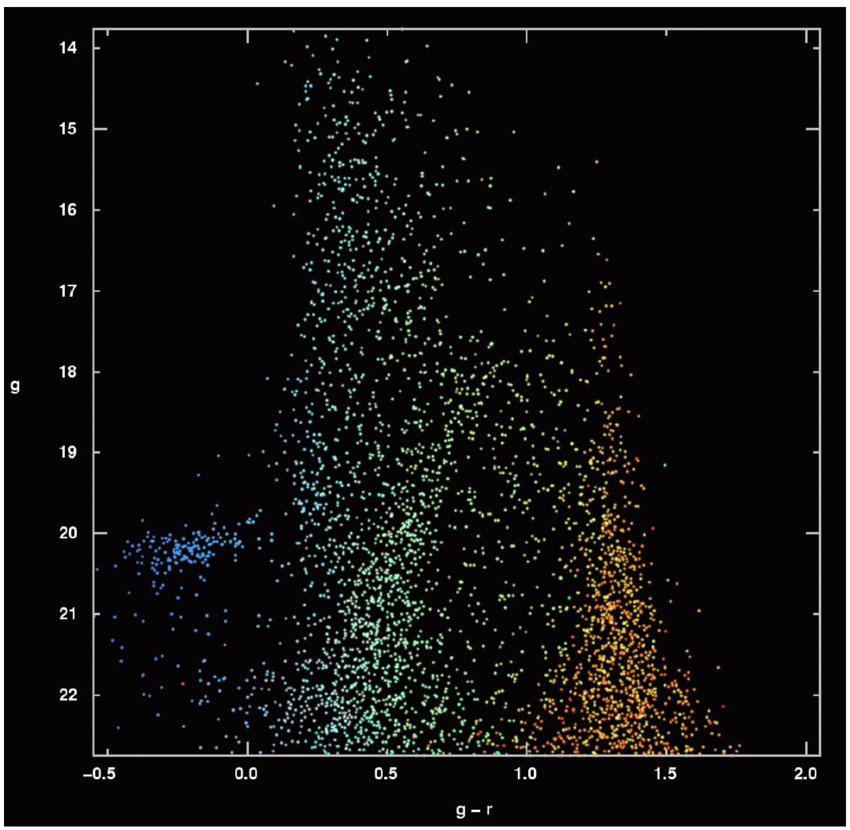
- If a system collapses from infinity, half of the potential energy will end up in kinetic energy, and the other half will be disposed of! From the measurement of the circular velocity and the mass of Milky Way (which constrain the kinetic energy), we conclude that during their formation, galaxies radiate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

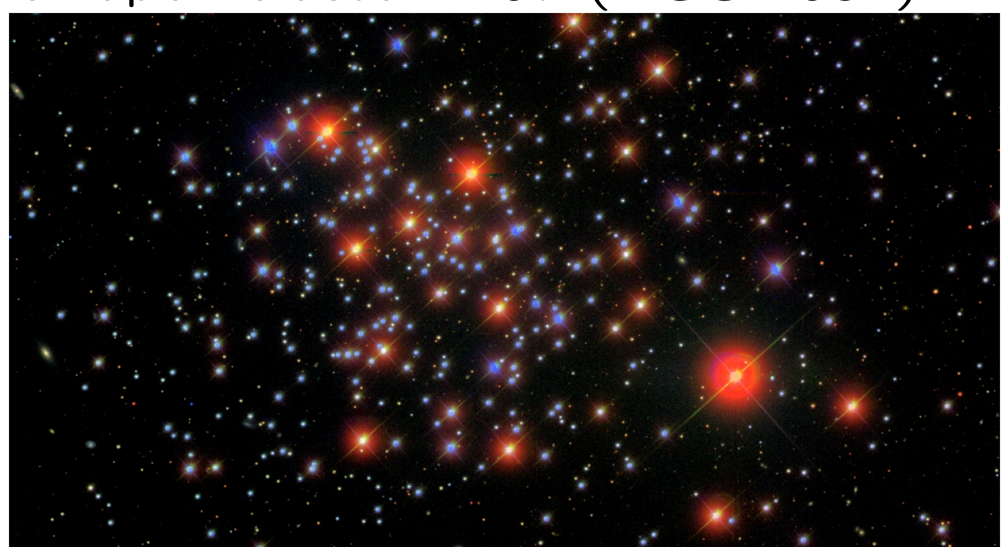
- For a virialized spherical system, $M = 2R\sigma^2/G$. We can estimate total mass from the size and velocity dispersion. E.g. for a cluster with σ=12 km/s, and R=3 pc, we get $M = 2 \times 10^5$ $M_\odot$ (note that $G = 233$ in these units)

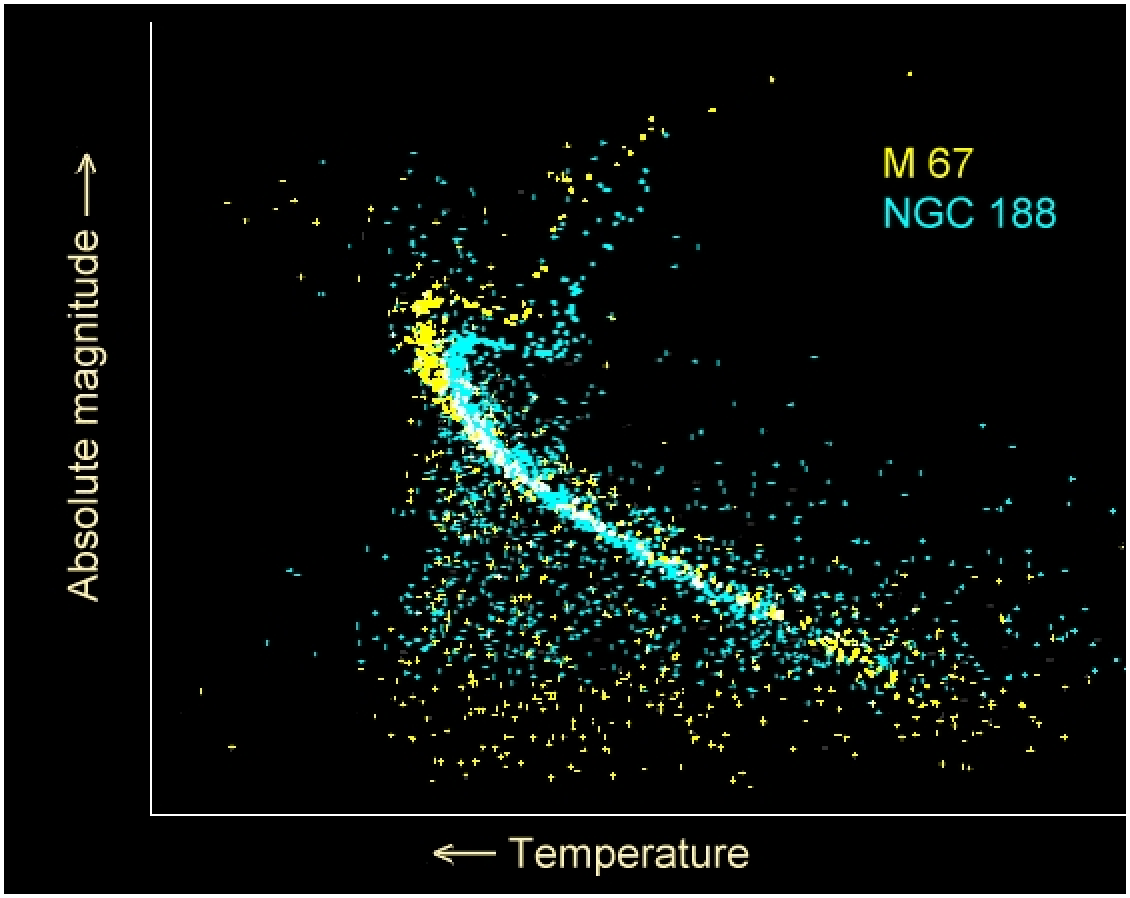
- Think about this for the next time: Evil aliens give a "kick" to our Moon that increases its kinetic energy by 10%. What will happen with its orbit?

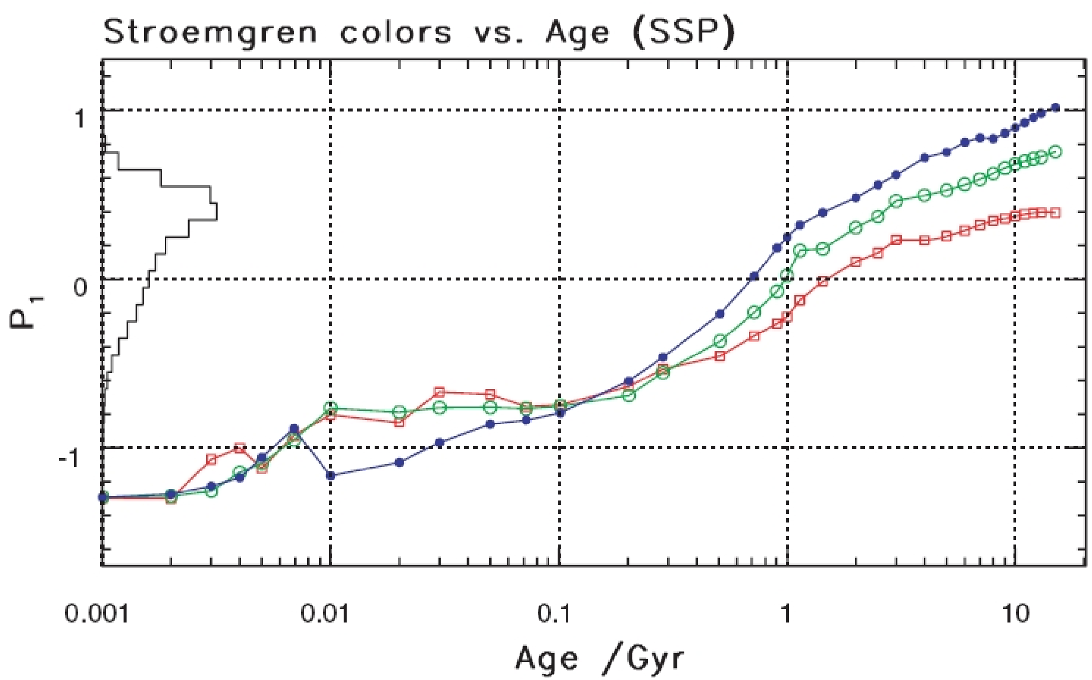
Open and Globular Clusters

- **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)



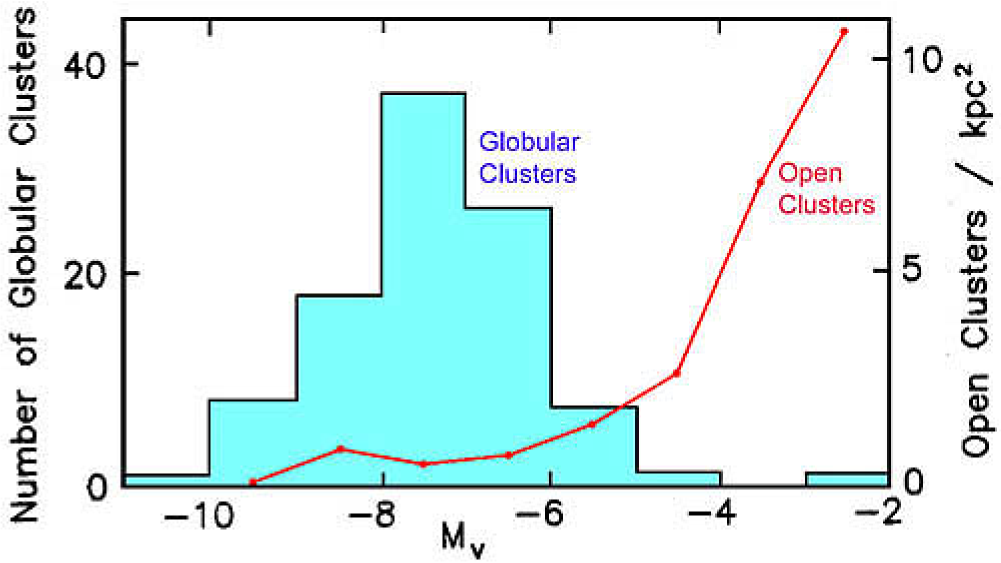






Open and Globular Clusters

- 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



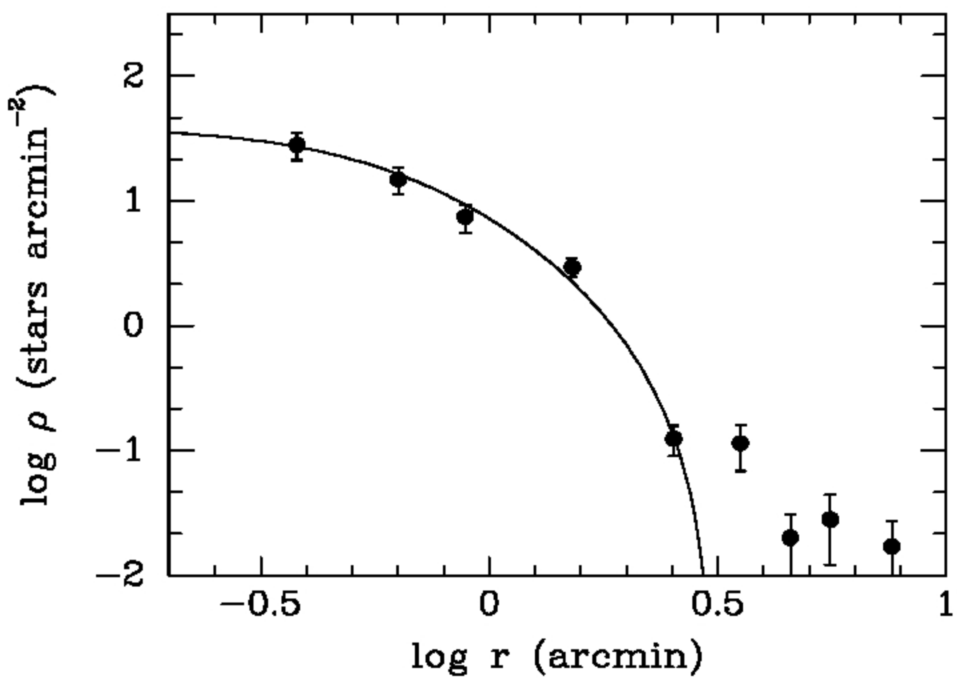


FIG. 7.—Radial star count profile of Pal 13 for stars with membership probabilities $\geq 50\%$. The line is the best-fit King profile to the cluster. Note the member stars outside the classical limiting radius.

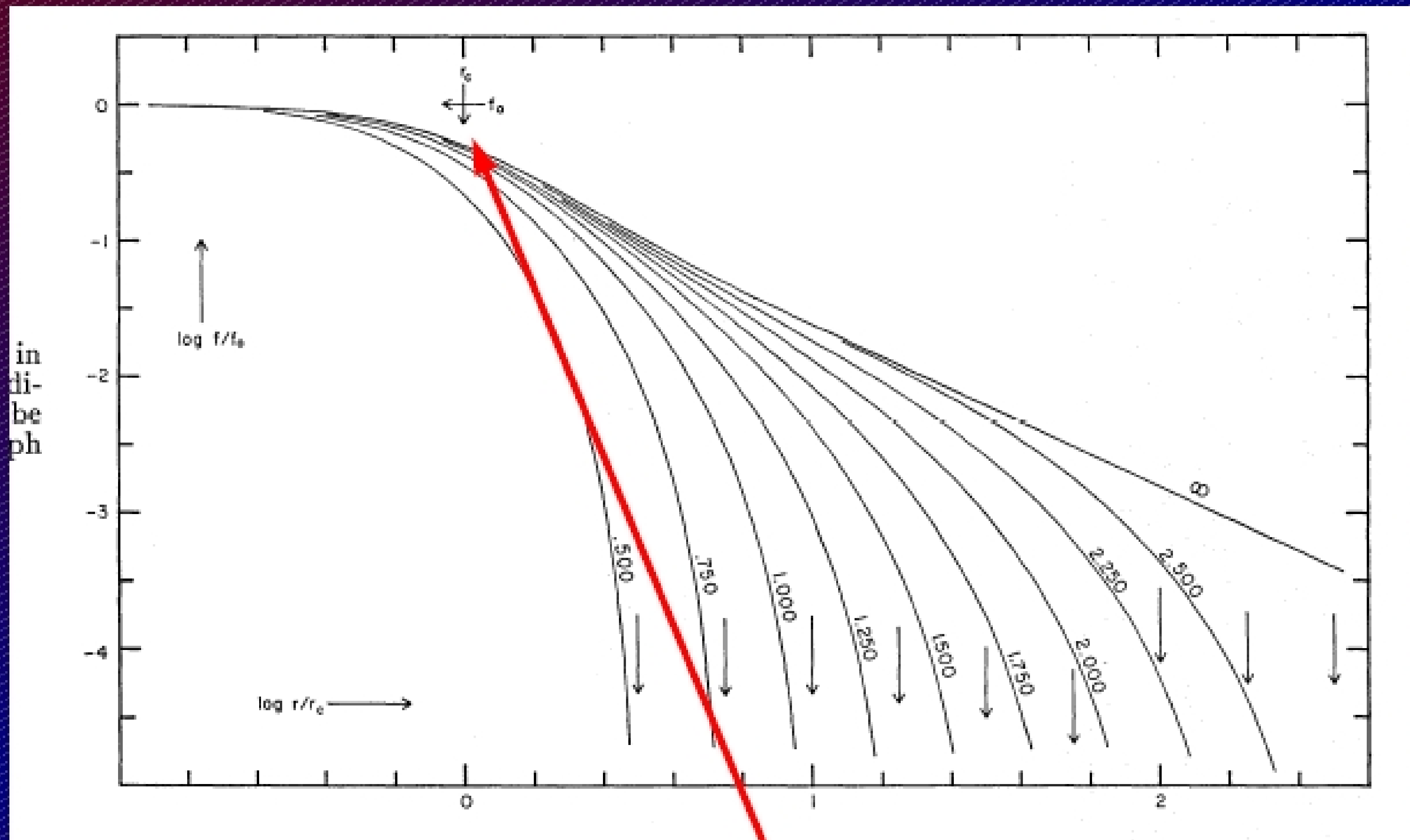
Open and Globular Clusters

- 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

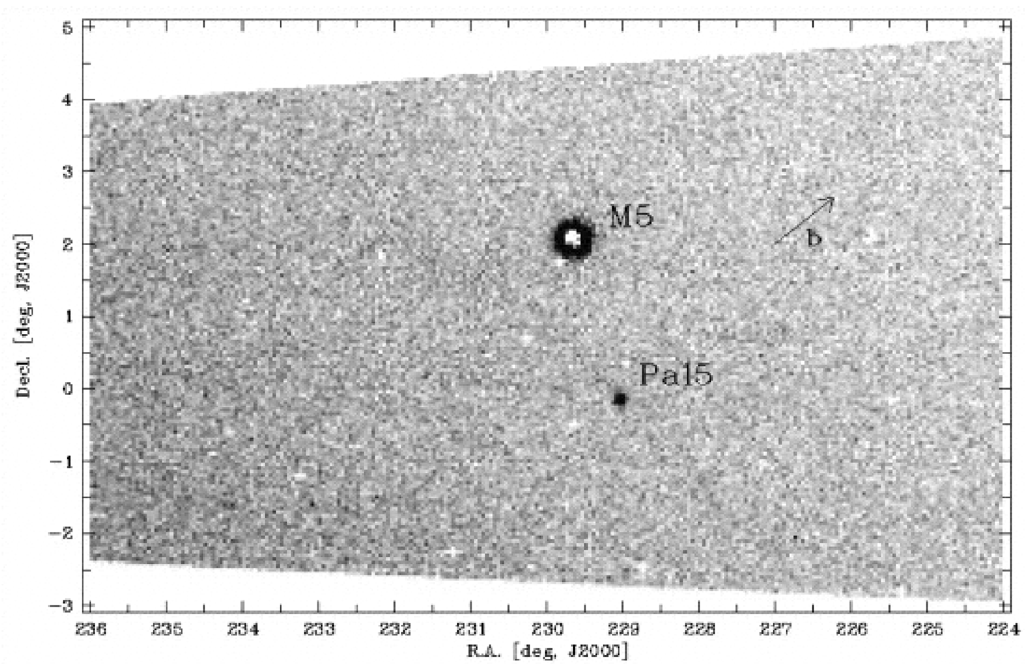
Surface brightness

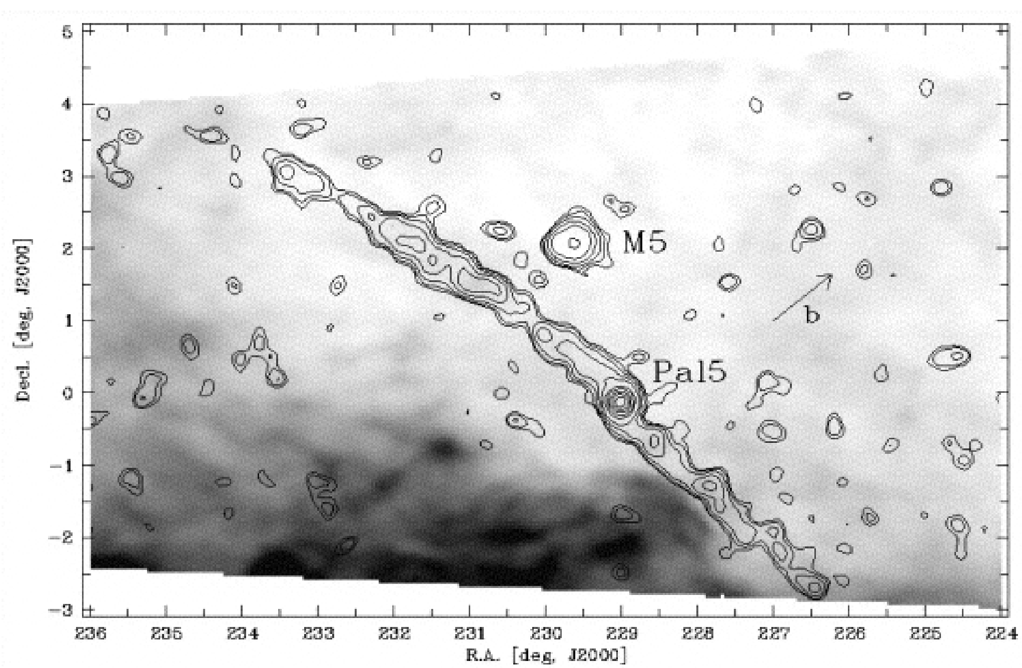


Projected radius

Ivan King

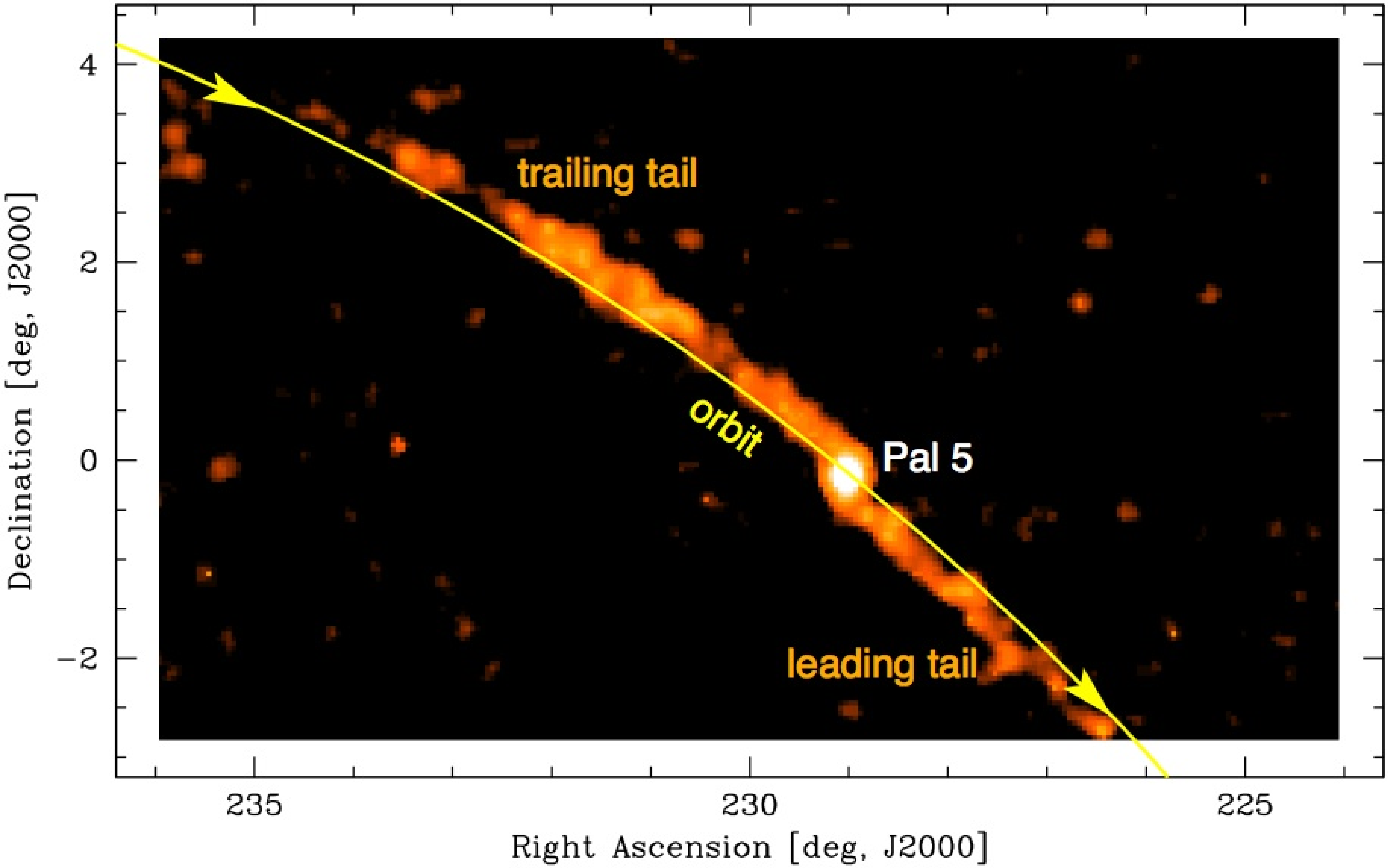
1-parameter sequence of shapes
+ 2 scale parameters (core radius; total luminosity)



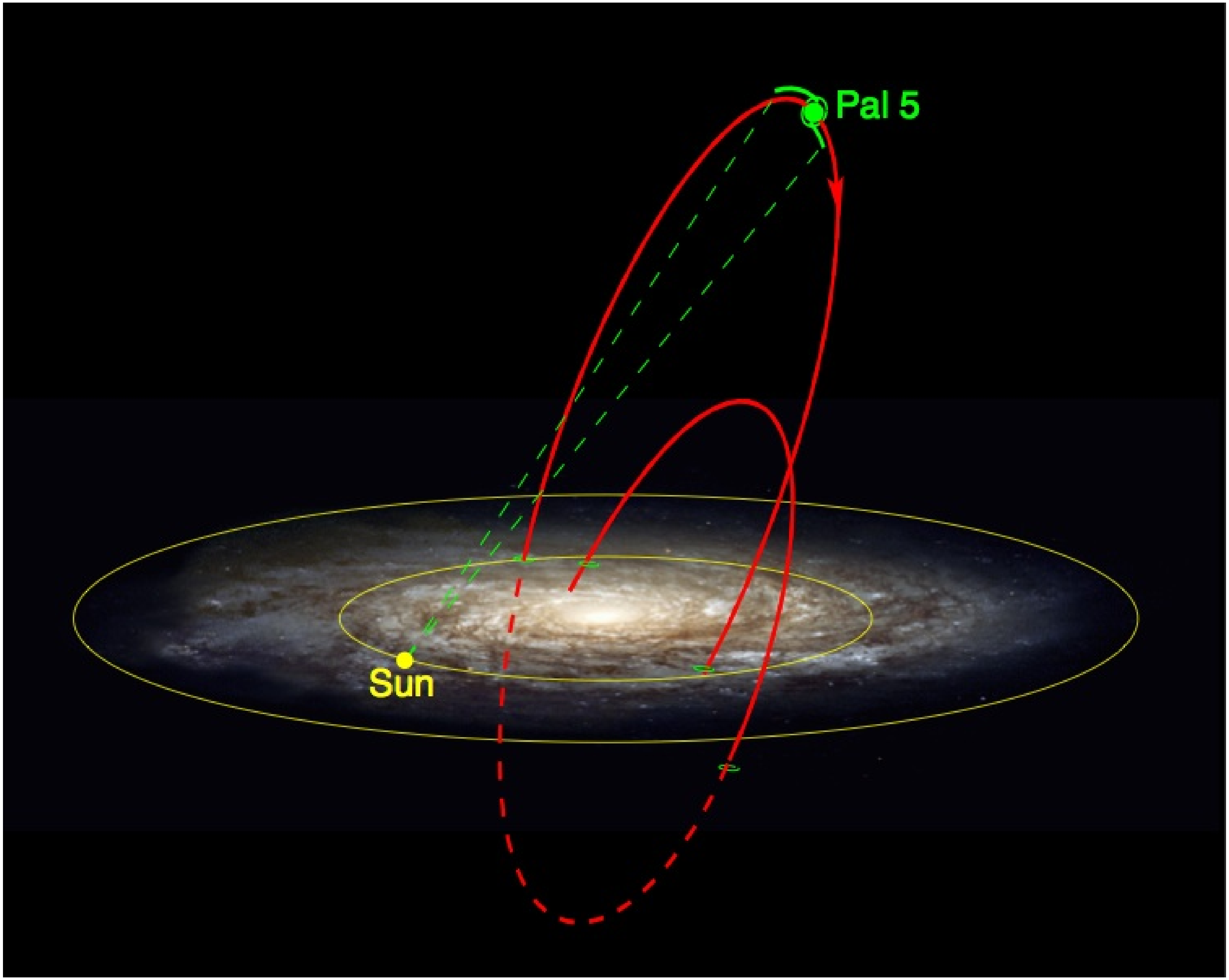


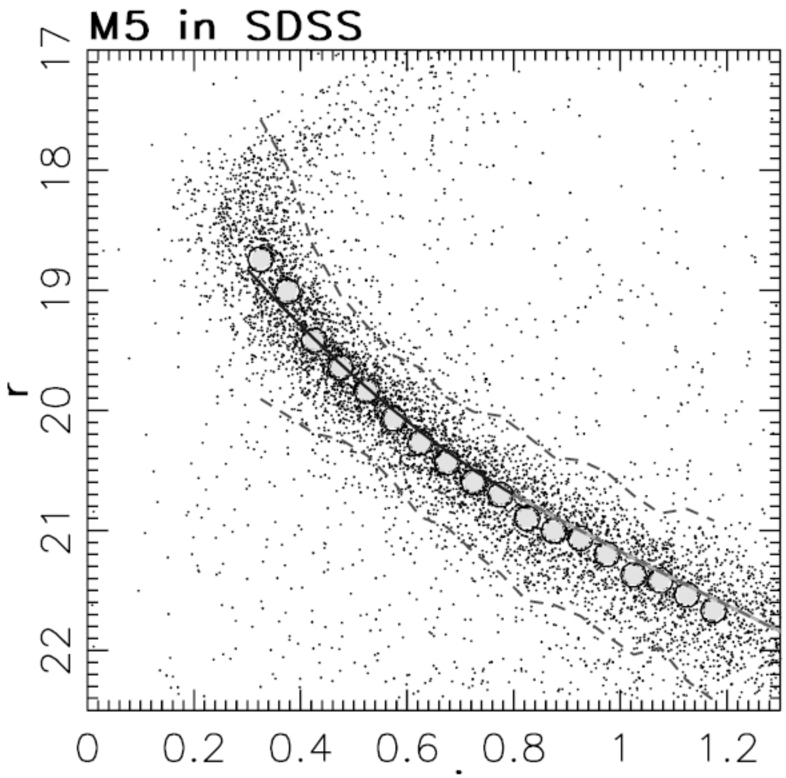
Tidal Tails around Globular Clusters

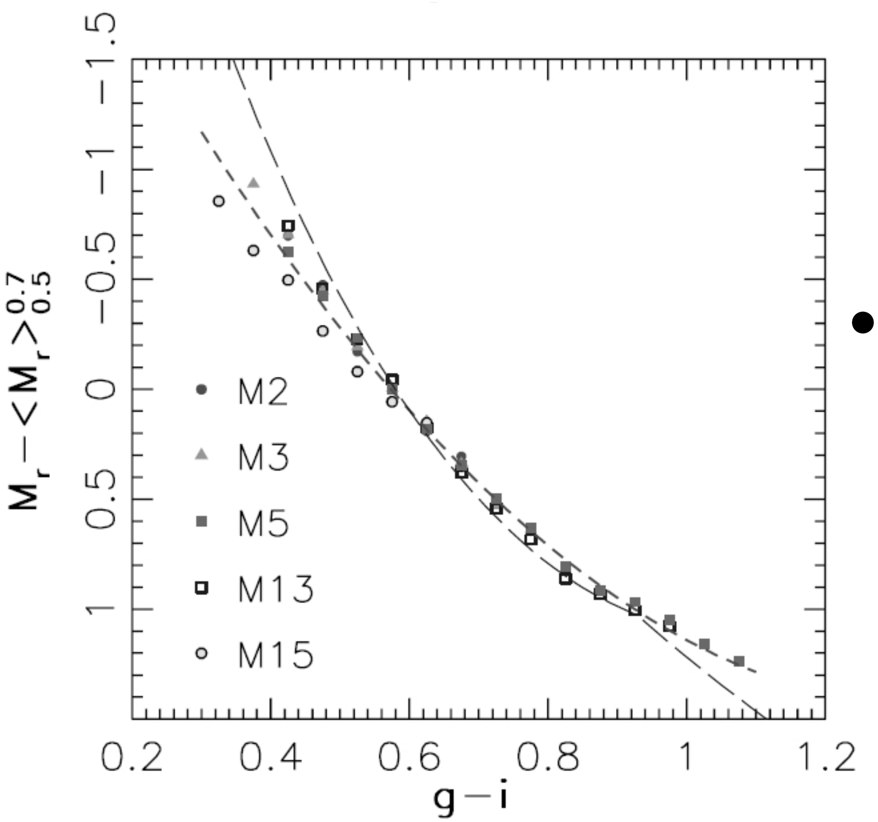
- **Top left:** SDSS stellar counts around globular clusters M5 and Pal5
- **Bottom left:** matched filter extraction of tidal tails around Pal 5 (gray: SFD E(B-V)) by Rockosi et al. (2002) and Odenkirchen et al. (2003)
- For more details about matched filter method, see Grillmair (2008, arXiv:0811.3965;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



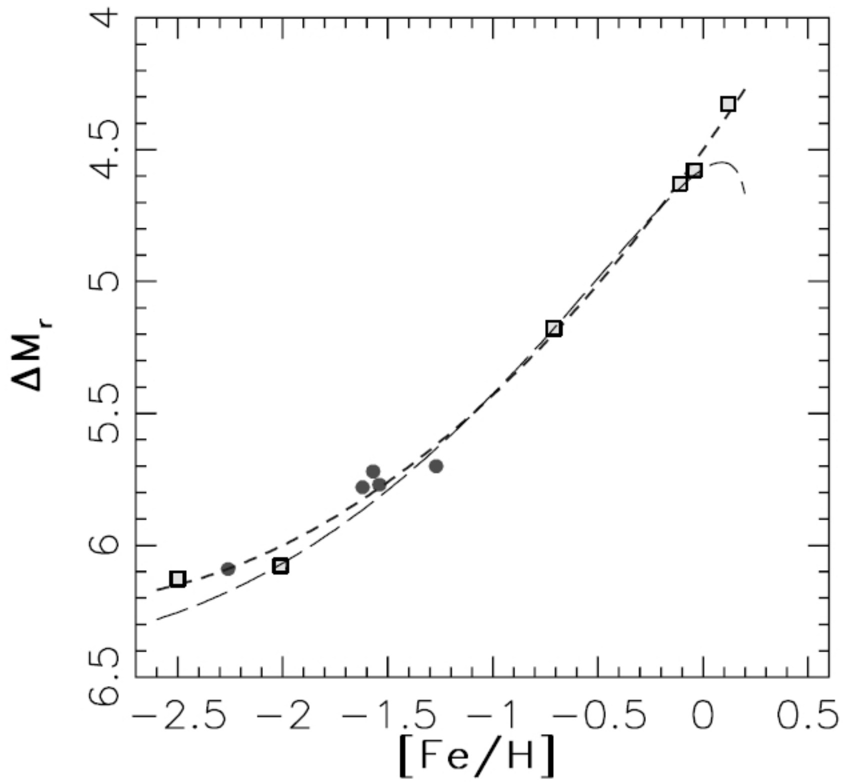


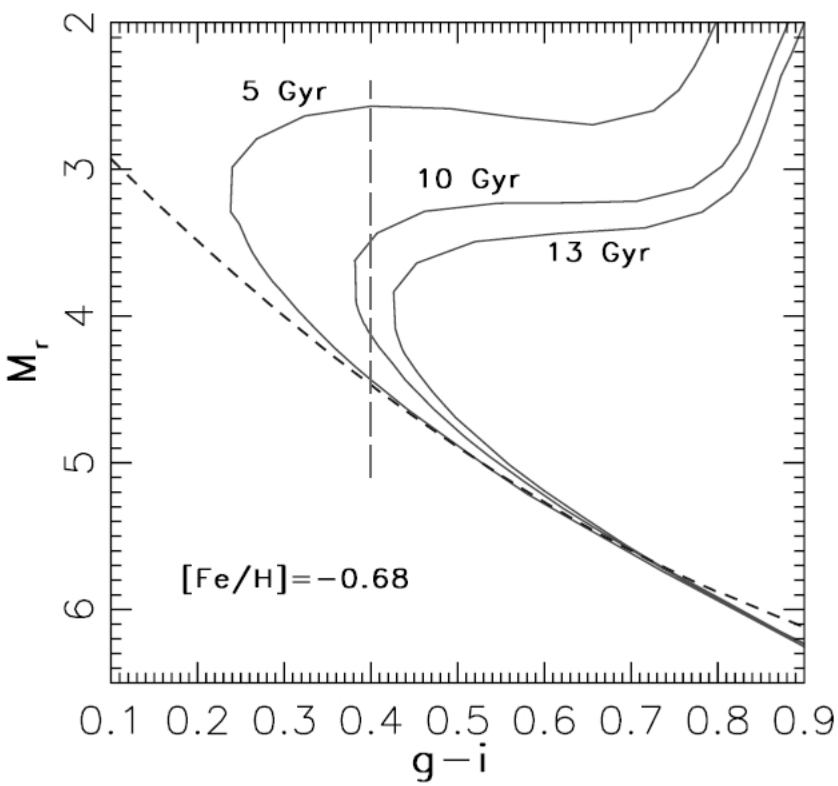
Photometric Parallax Calibration

- 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):

$$M_r = M_r^{0.6} - 2.85 + 6.29\,(g-i) - 2.30\,(g-i)^2 \quad (8)$$

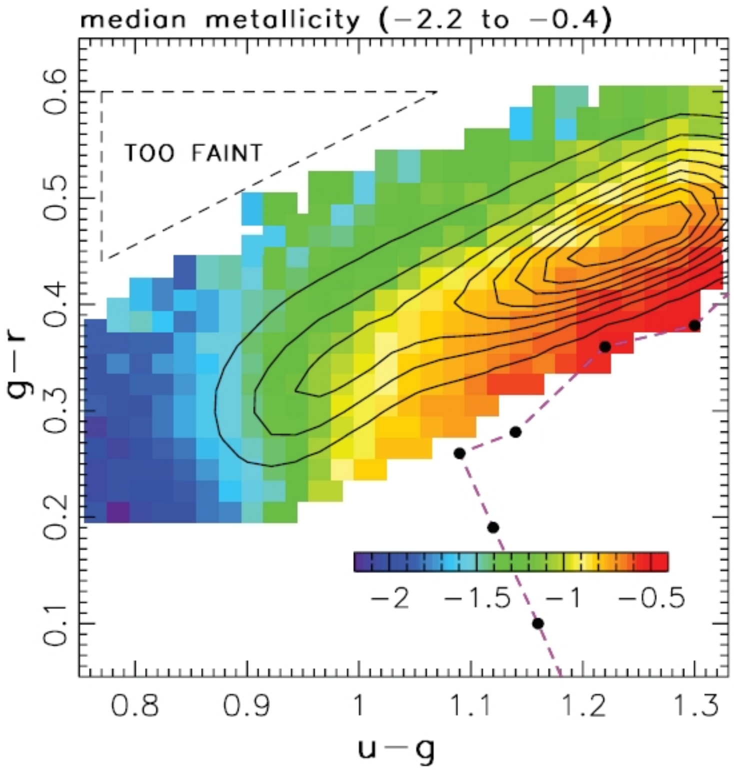
where $M_r^{0.6}$ is the median absolute magnitude for stars with $0.5 < g-i < 0.7$.
- **Bottom Left:** this is a good fit to a number of globular clusters observed by SDSS, showing that the main effect of metallicity is to slide the main sequence vertically (i.e. along luminosity axis, changing $M_r^{0.6}$),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

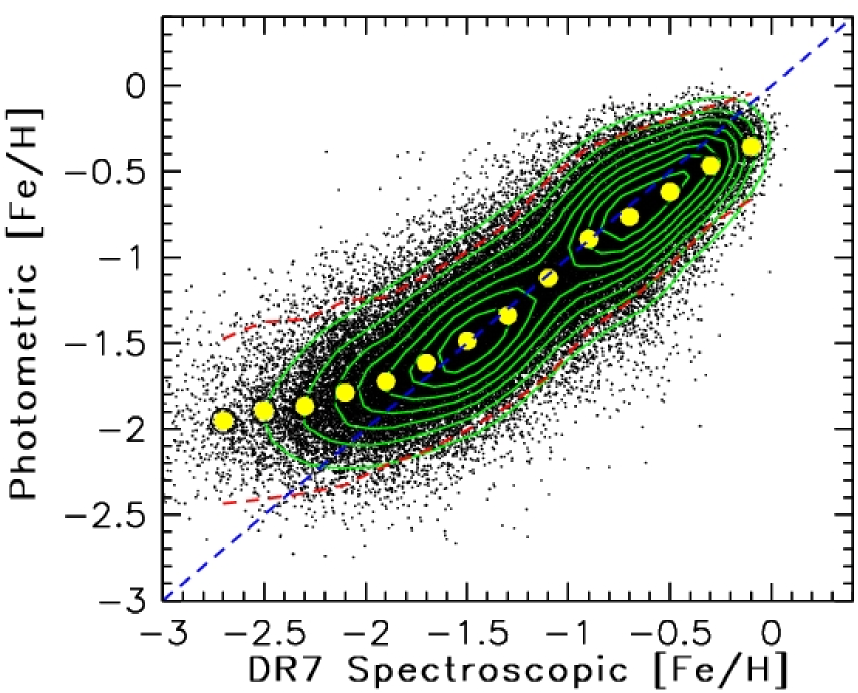




Photometric Parallax Calibration

- 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?*



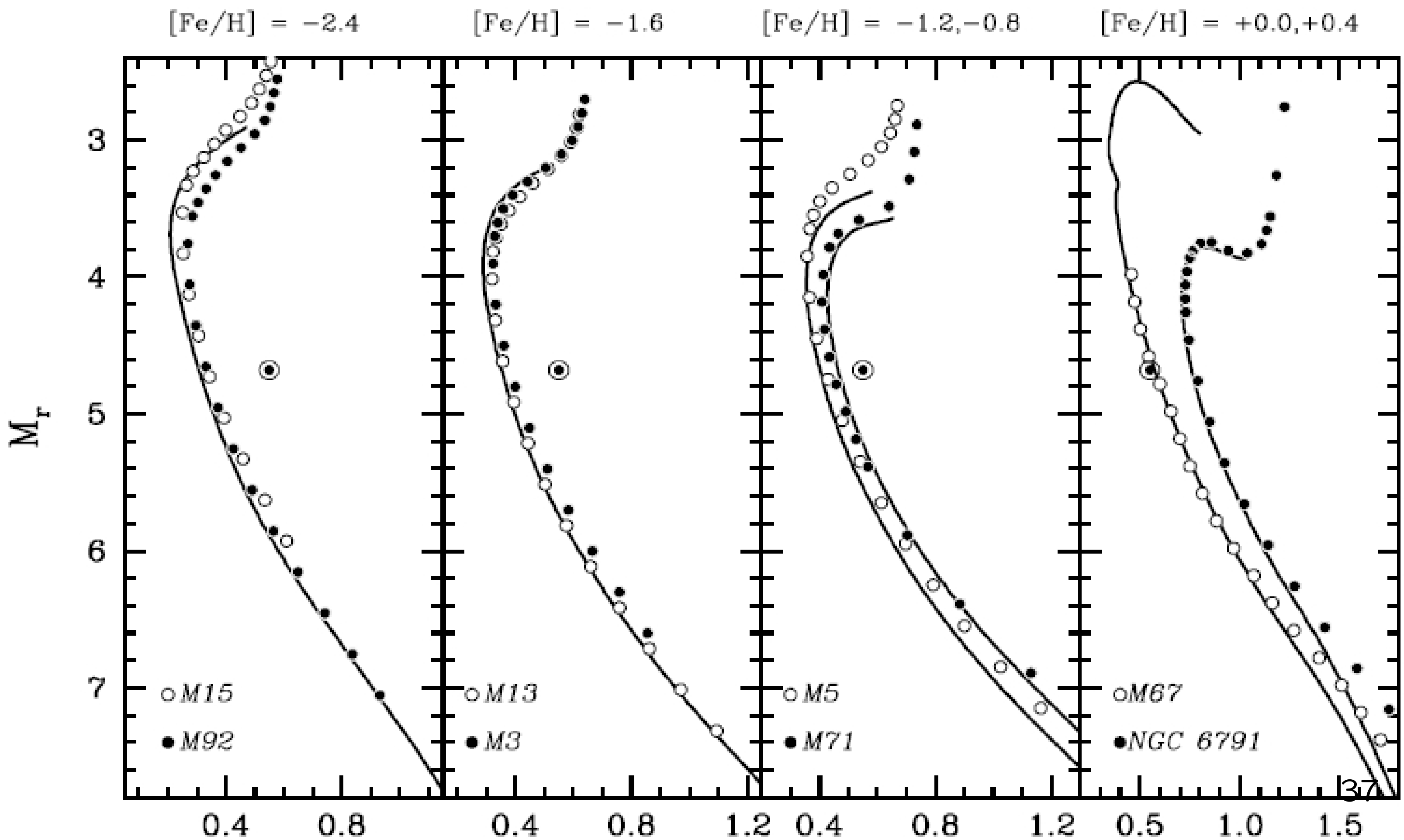


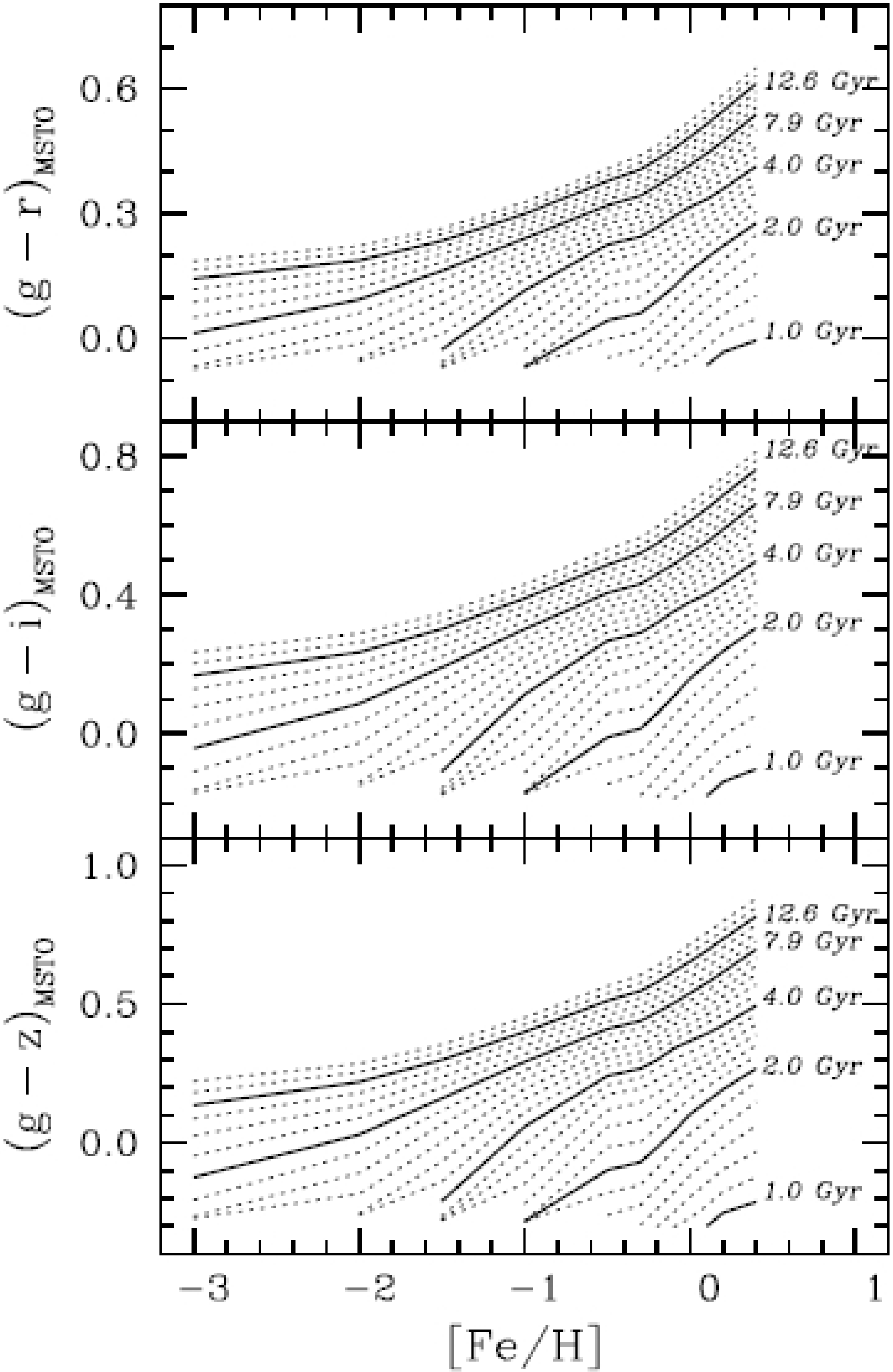
Photometric Metallicity Calibration

- 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!**

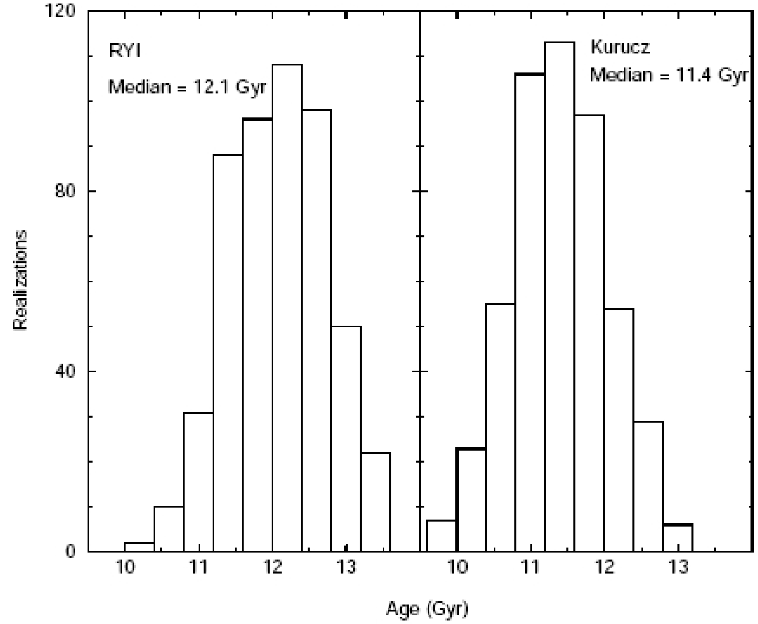


Fig. 10.— Histograms for the mean age of the oldest globular clusters, using (a) the RYI (Green *et al.* 1987) colour table, or (b) the Kurucz 1992 colour table.

An example of systematic effect: (unknown) He abundance

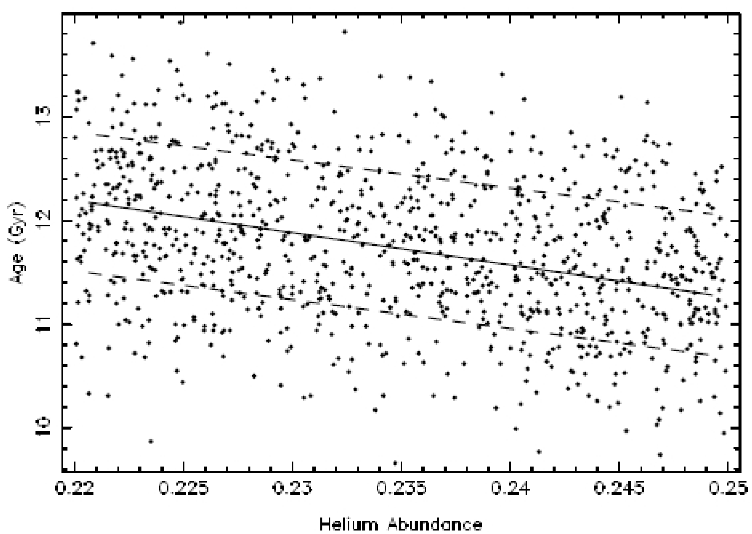
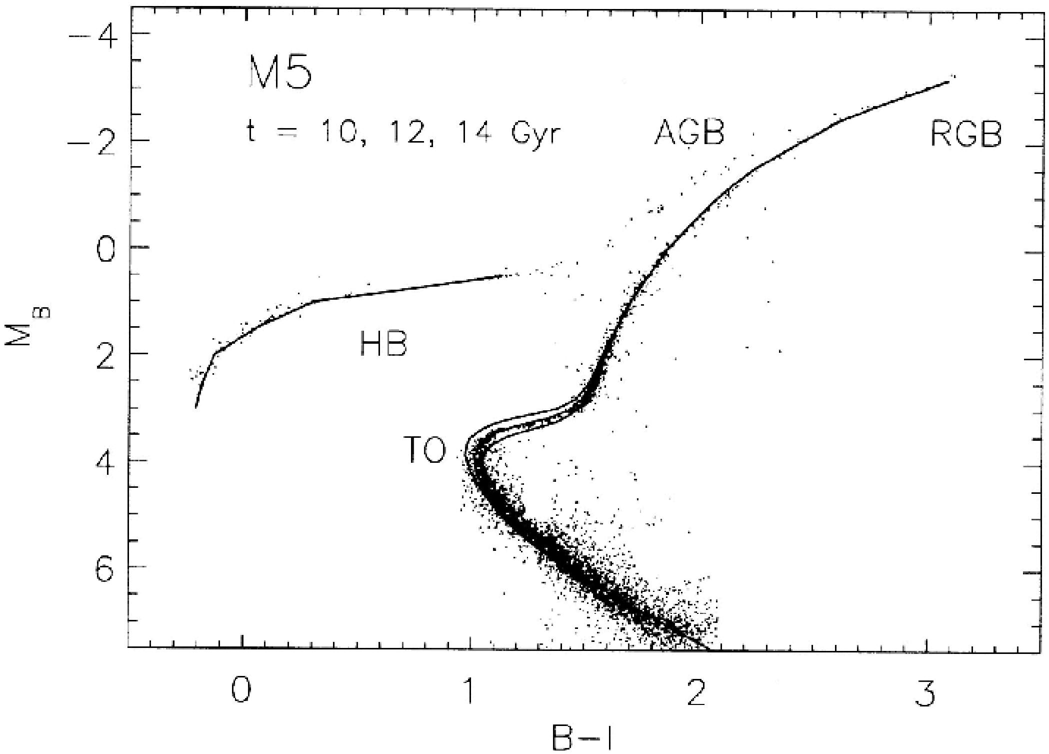


Fig. 6.— Age as a function of the helium abundance (Y) used in the stellar models. The lines of the form $t_9 = a + bY$ have the following cofficients: median $(a, b) = (19.05,\ -31.15)$; $-1\,\sigma\,(a, b) = (17.61,\ -27.73)$; and $+1\,\sigma\,(a, b) = (18.80,\ -27.04)$.

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?



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%

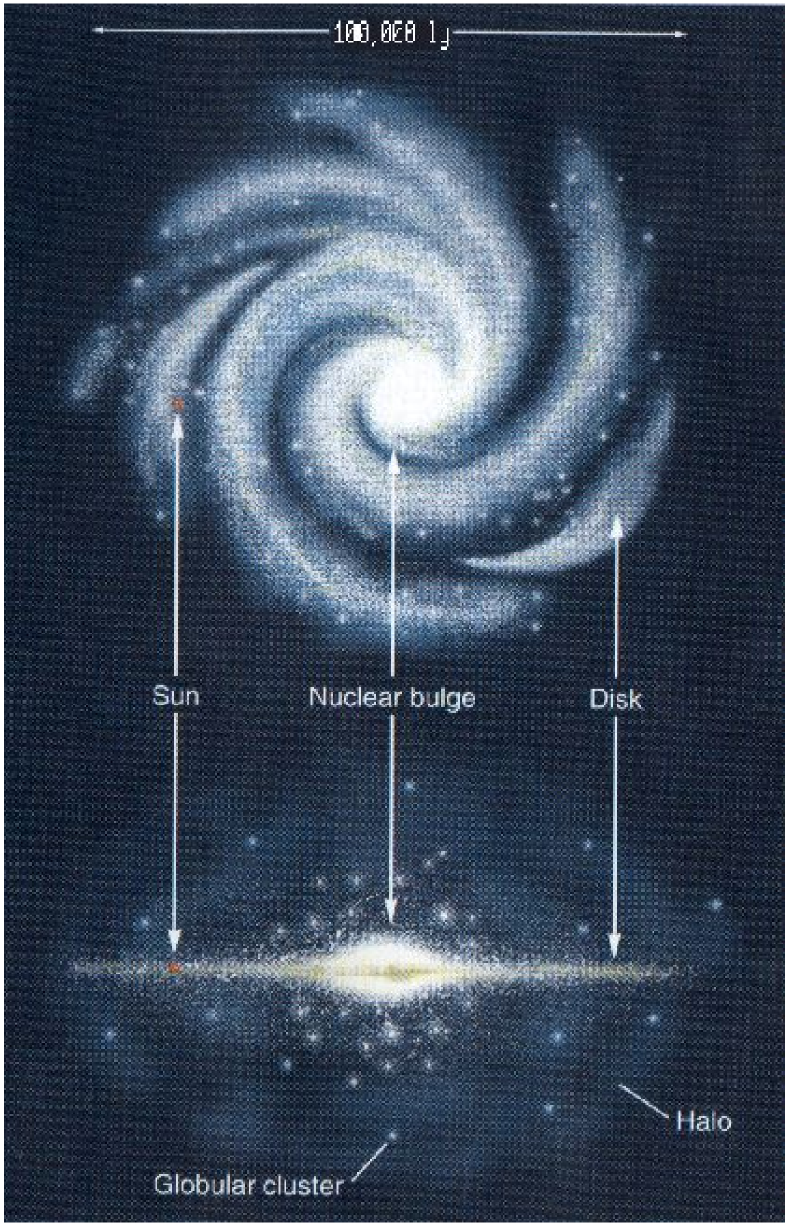
Other Age Determination Methods

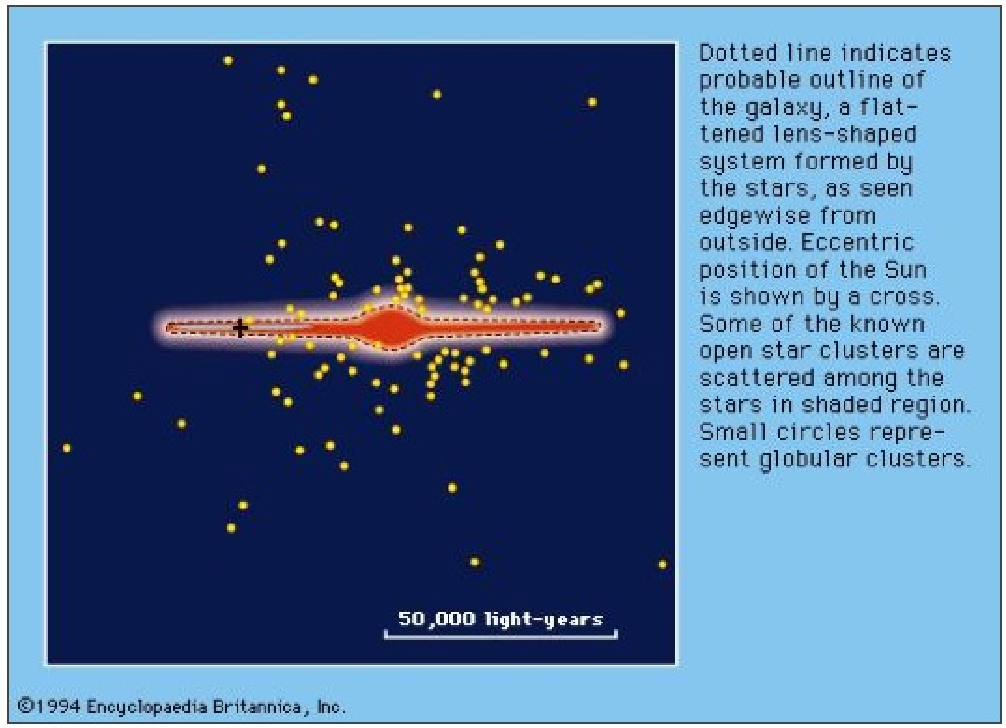
- Can we determine age and metallicity using stars that are not on main sequence? Independently of ISM extinction correction and distance scale?
- There are several other methods:

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

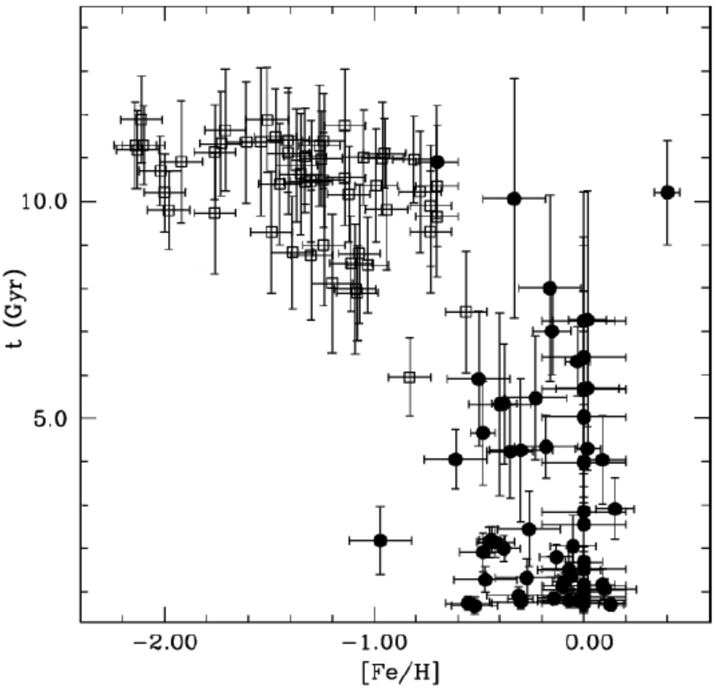
- Halo GCs claim to fame: Shapley used their distribution to demonstrate that the Sun is not in the center of the Milky Way



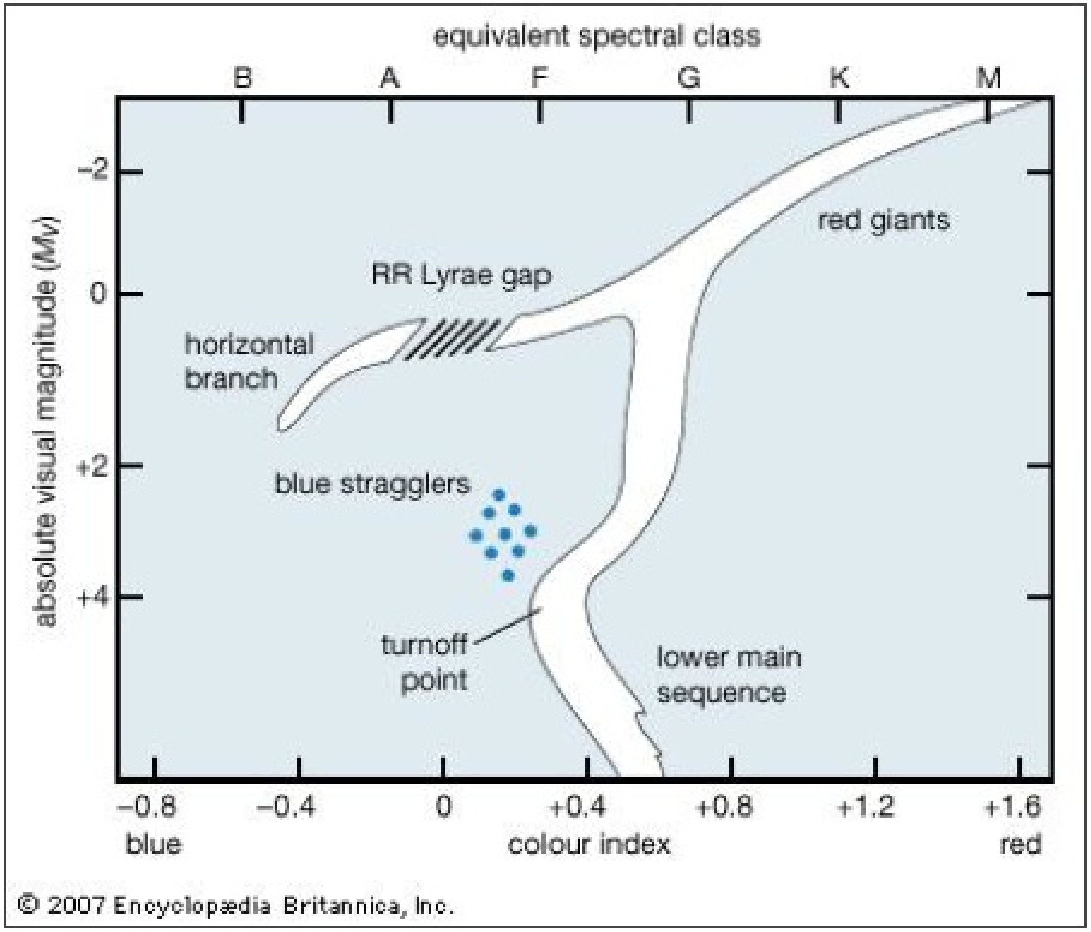


Properties of GC Population

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