Astr 511: Galactic Astronomy

Winter Quarter 2015, University of Washington, Željko Ivezić

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: a very useful tool

What do we measure? Radiation Intensity:

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

- 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):

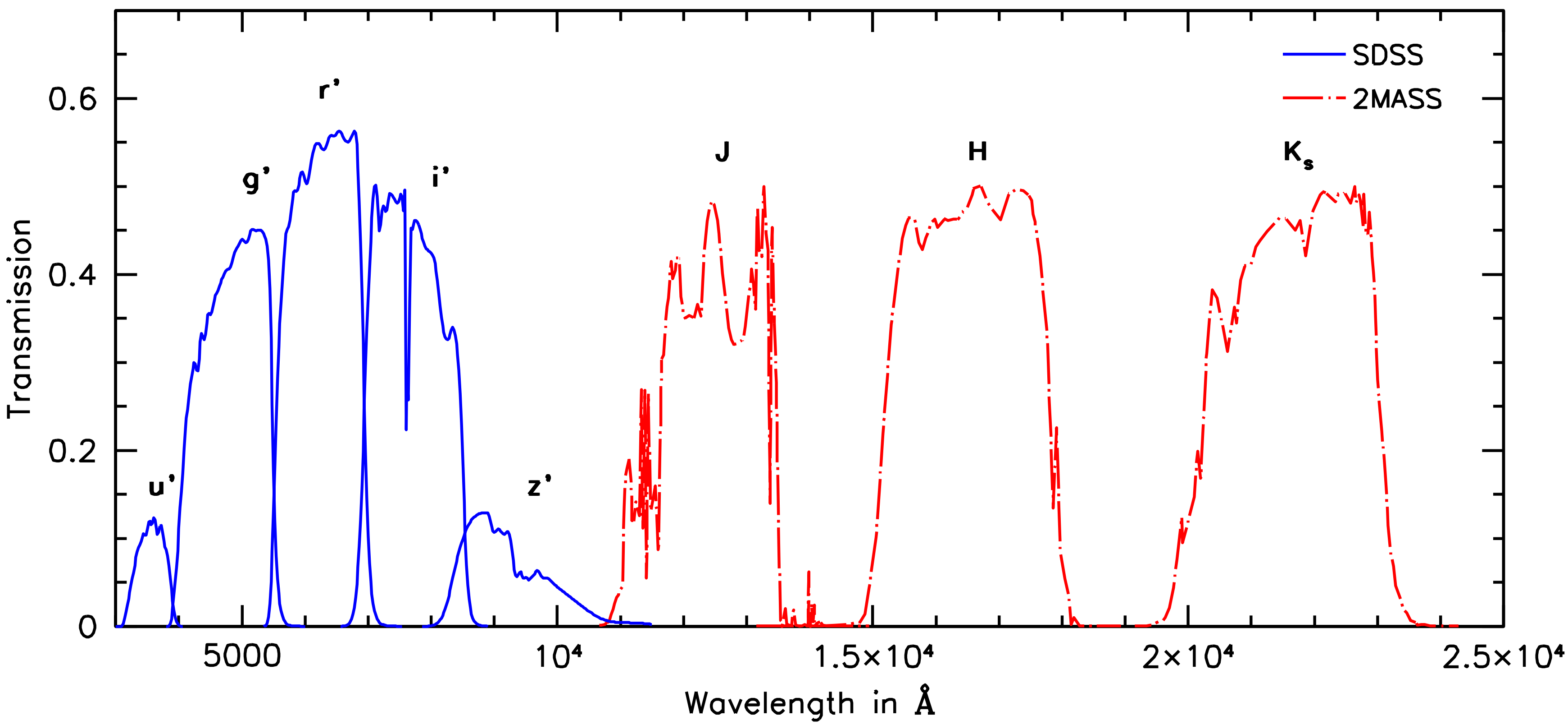
$$I_\nu^{band}(<\alpha>,<\delta>,<t>) = \int_0^\infty S(\lambda)d\lambda \int_0^T dt \int_\theta d\Omega\, I_\nu(\lambda,\alpha,\delta,t,\mathbf{p}) \tag{1}$$

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
Transmission
0
0.2
0.4
0.6
5000
10⁴
1.5×10⁴
2×10⁴
2.5×10⁴
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

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

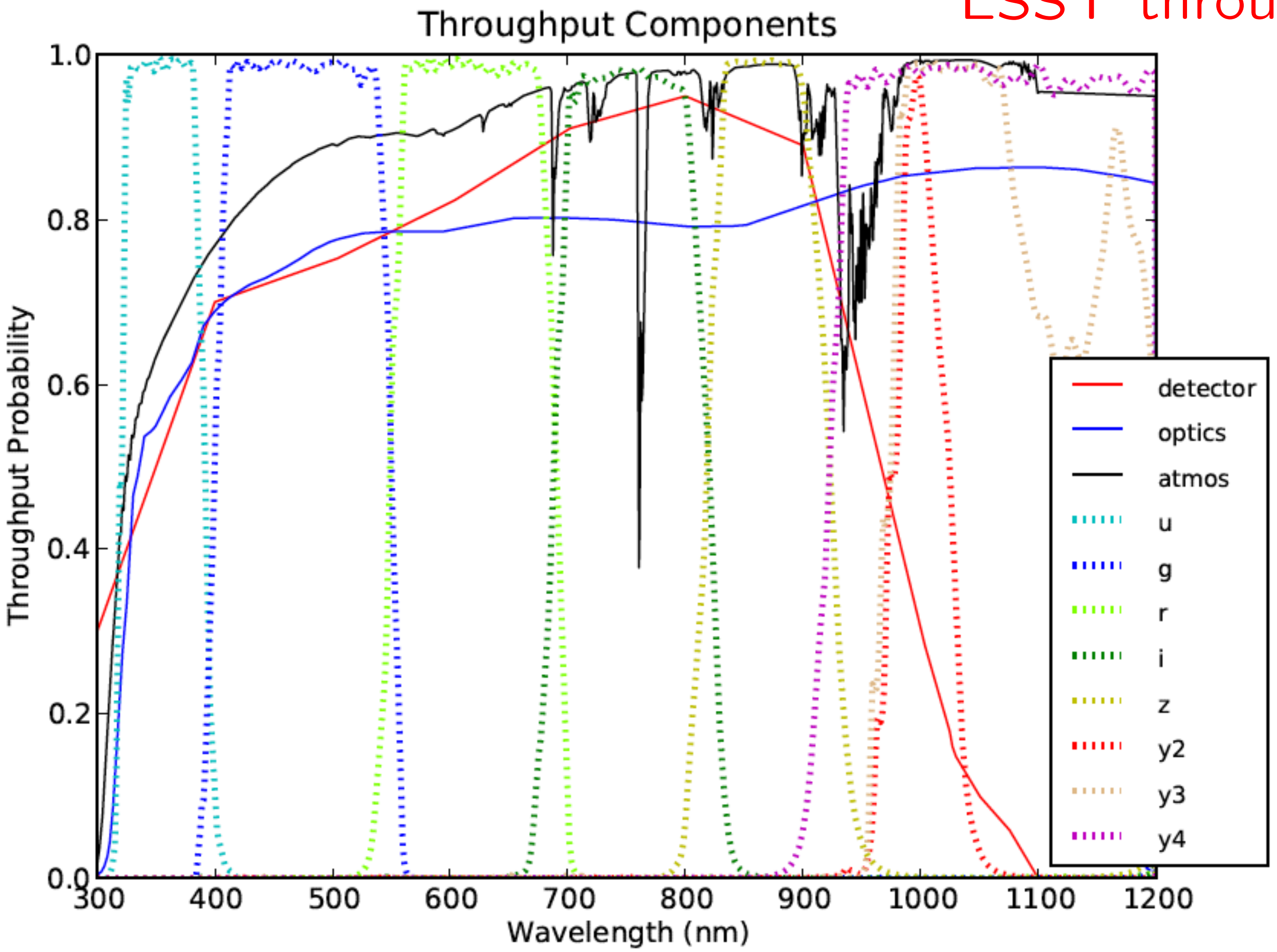
where $\phi_b(\lambda)$ is the normalized system response for a given band (e.g. for SDSS $b = ugriz$)

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

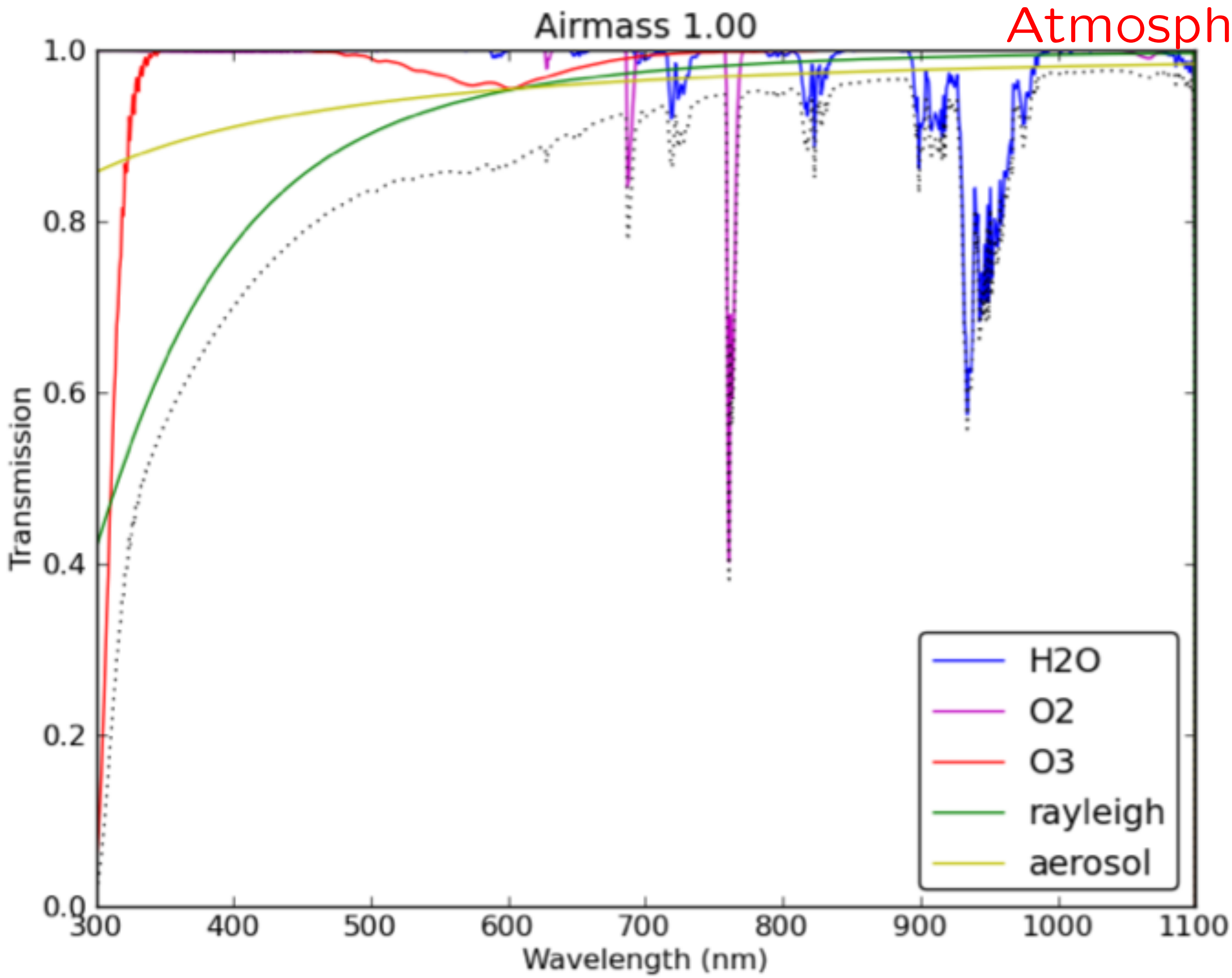
- The overall atmosphere + system throughput, $S_b(\lambda)$, is obtained from

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

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

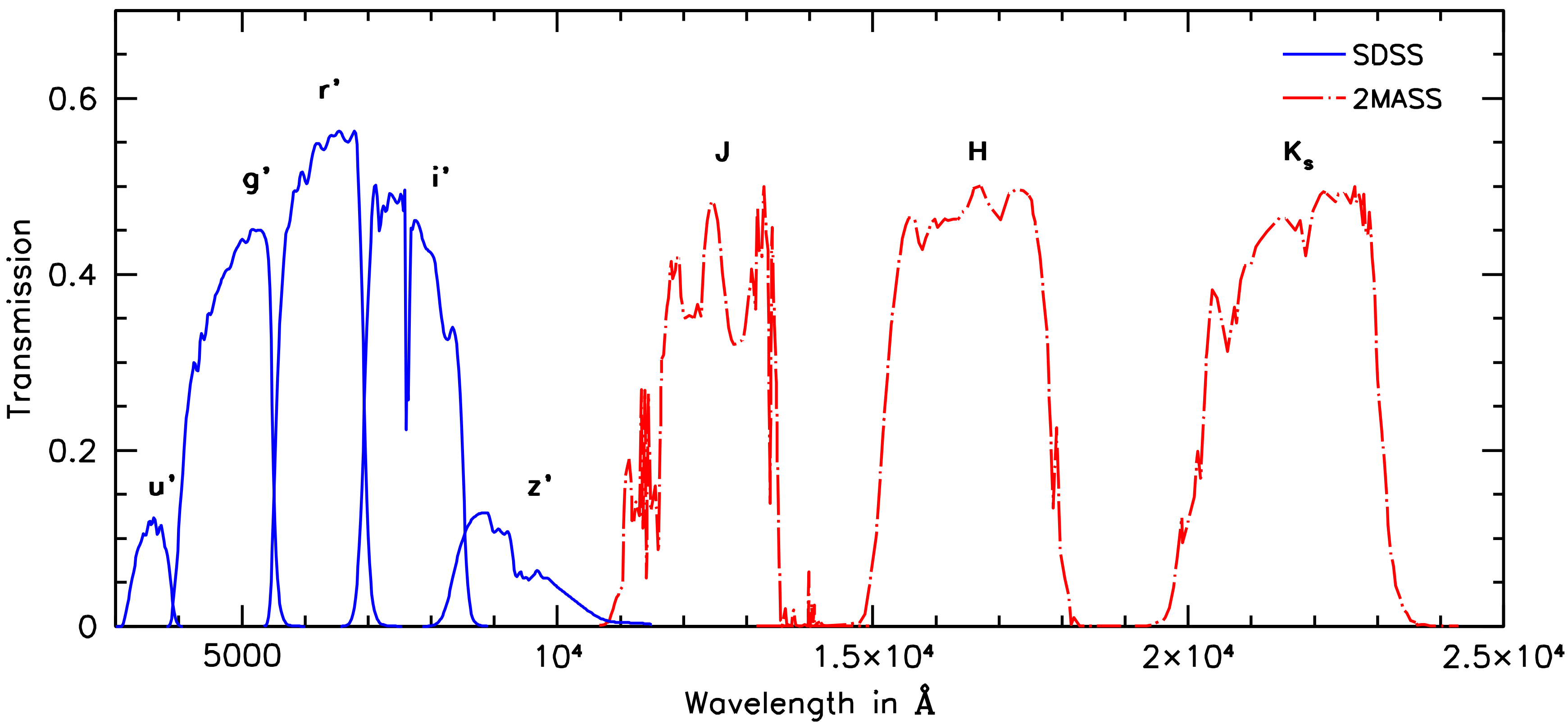
Calibrated flux and magnitudes

- 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. 3, 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. 3 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'
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K s
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Transmission
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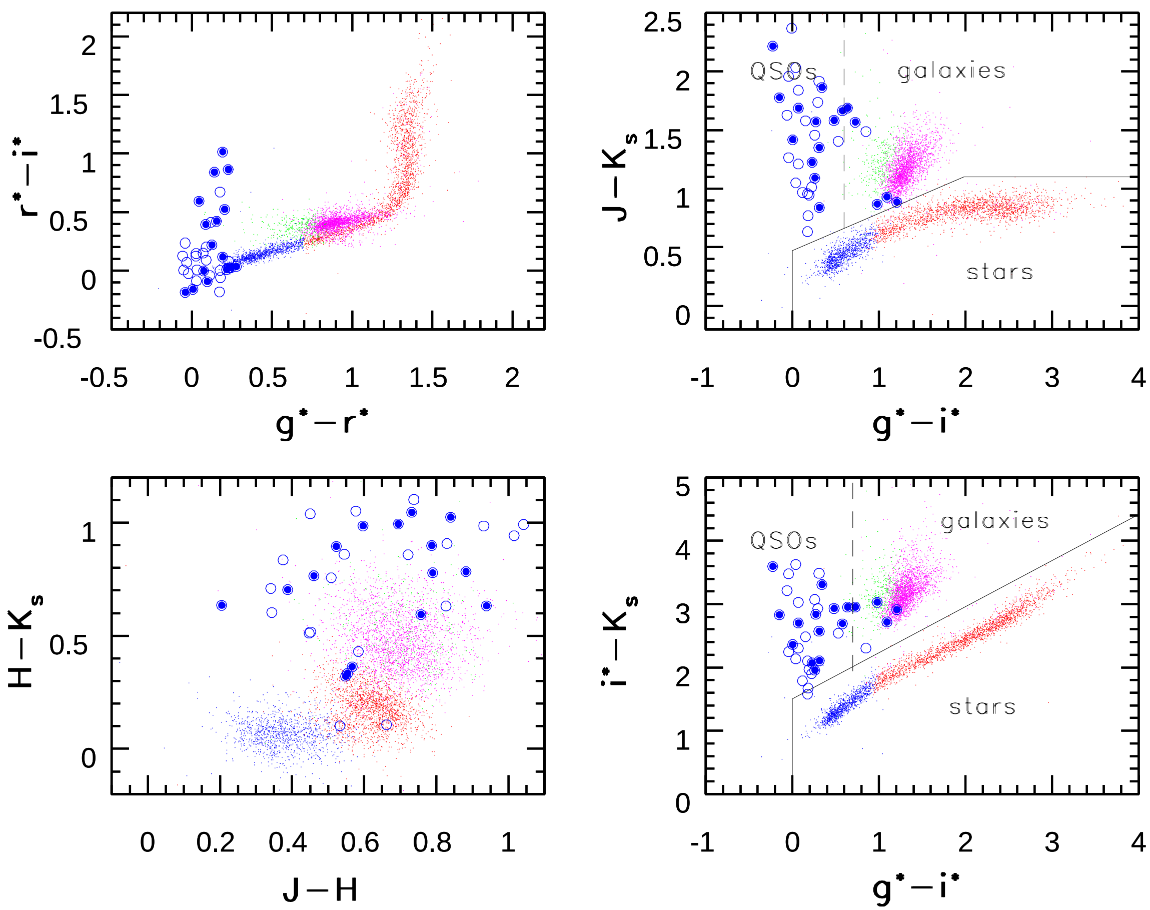
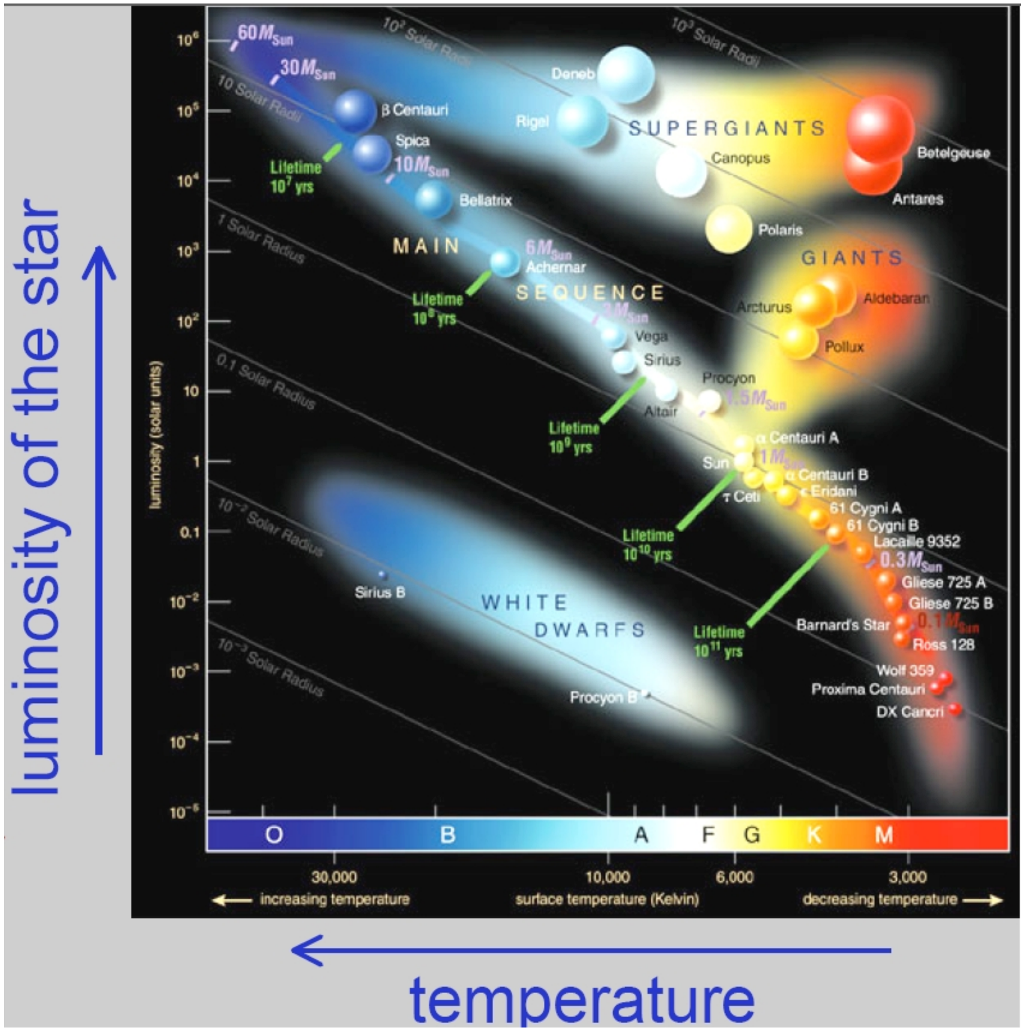
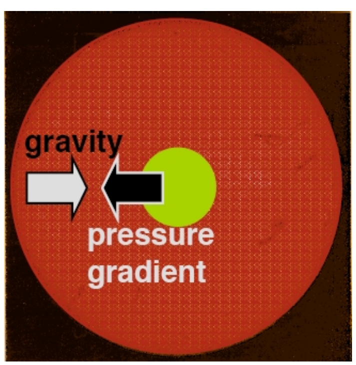
Wavelength in Å

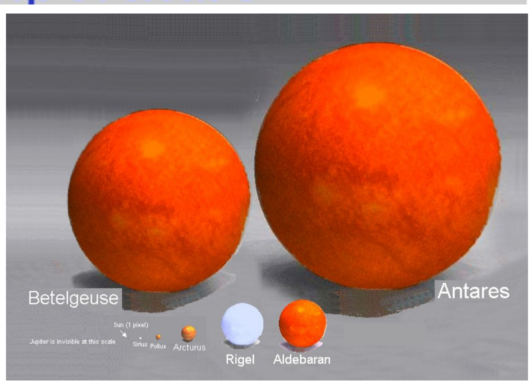


SDSS-2MASS sources

- 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)

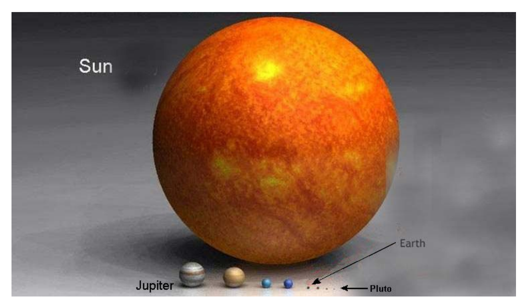






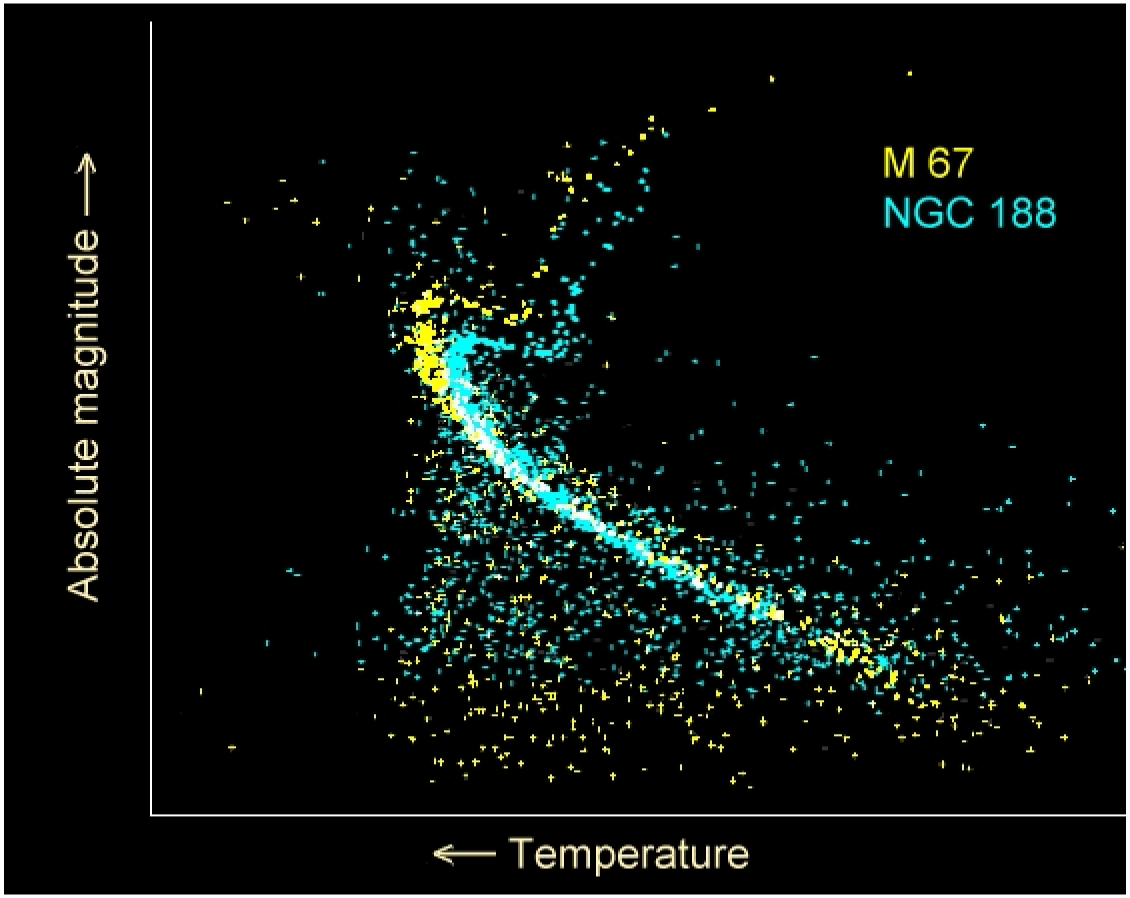
Hertzsprung-Russell Diagram

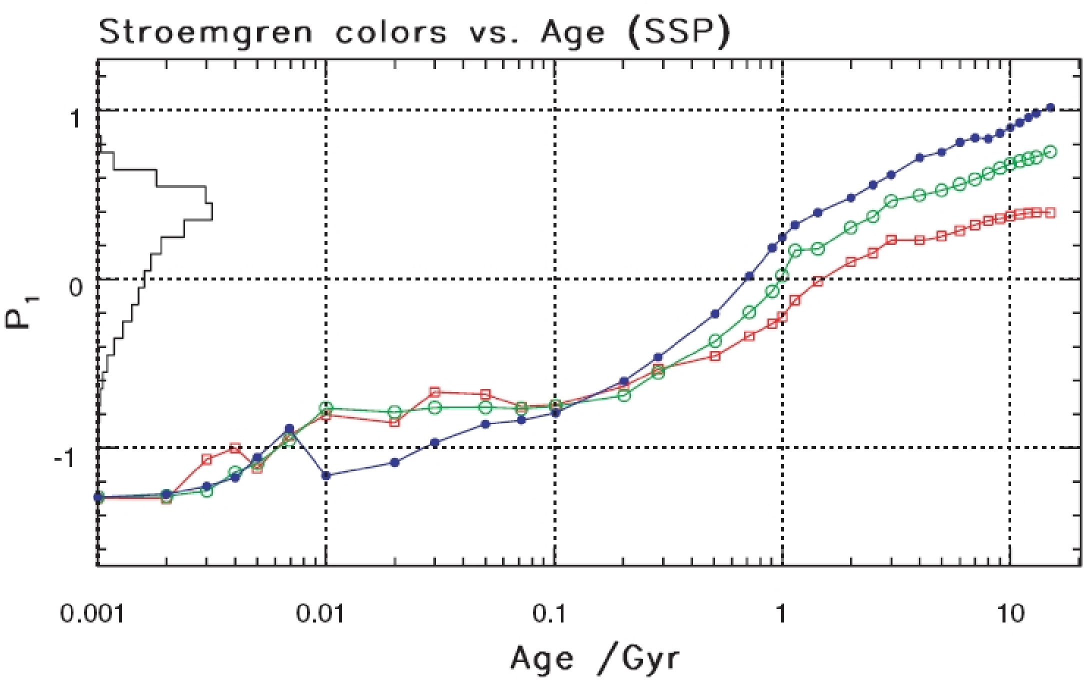
- Stars are balls of hot gas in hydrodynamical and thermo-dynamical equilibrium
- Equilibrium based on two forces, gravity: inward, radiation pressure: outward
- Temperature and size cannot take arbitrary values: the allowed ones are summarized in HR diagram
- $L = \text{Area} \times \text{Flux} = 4\pi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



Check out HR simulator at

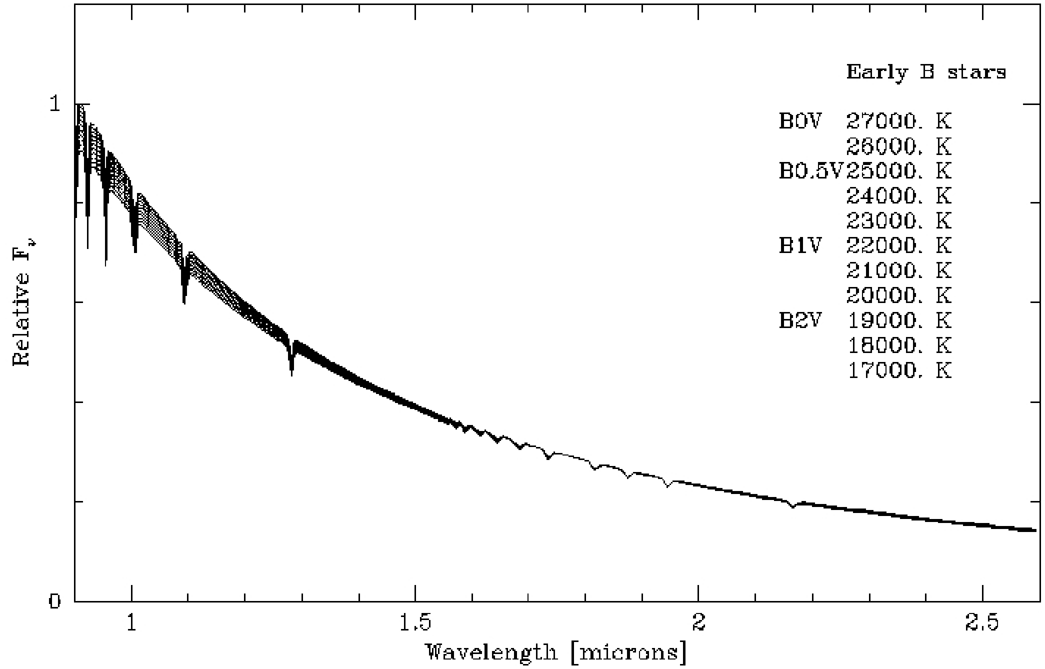
`http://www.astro.ubc.ca/~scharein/a311/Sim/hr/HRdiagram.html`

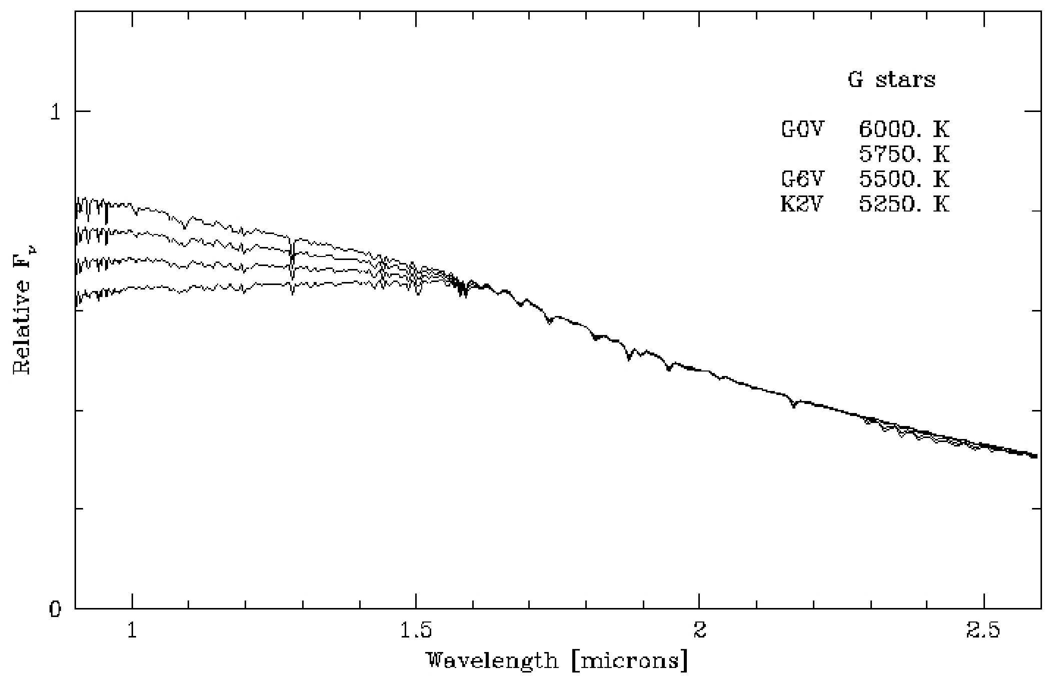




HR Diagram: Stellar Age

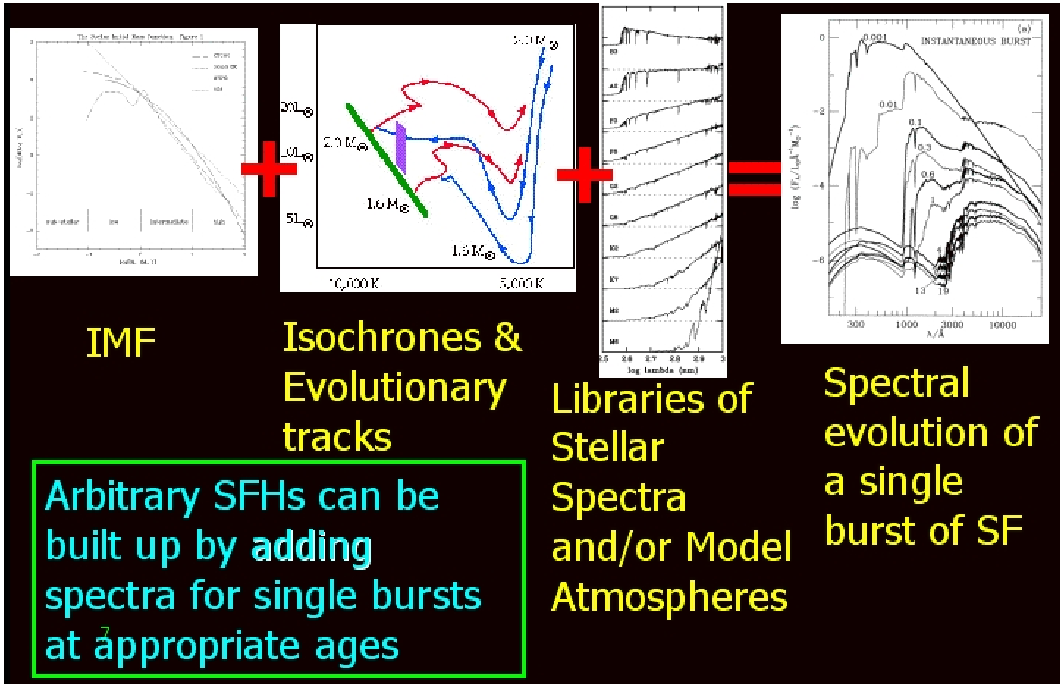
- The main sequence is where most of lifetime is spent.
- The position on the main sequence is determined by mass!
- The lifetime depends on mass: massive (hot and blue) stars have **much** shorter lifetimes than red stars
- After a burst of star formation, blue stars disappear **very quickly**, 10^8 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...)

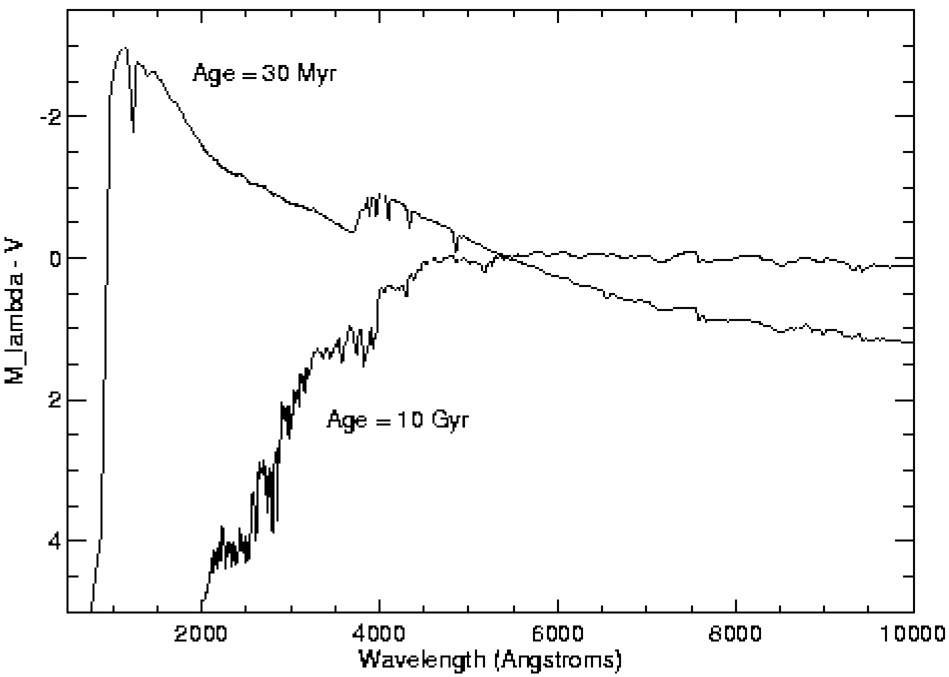




Stellar Parameters

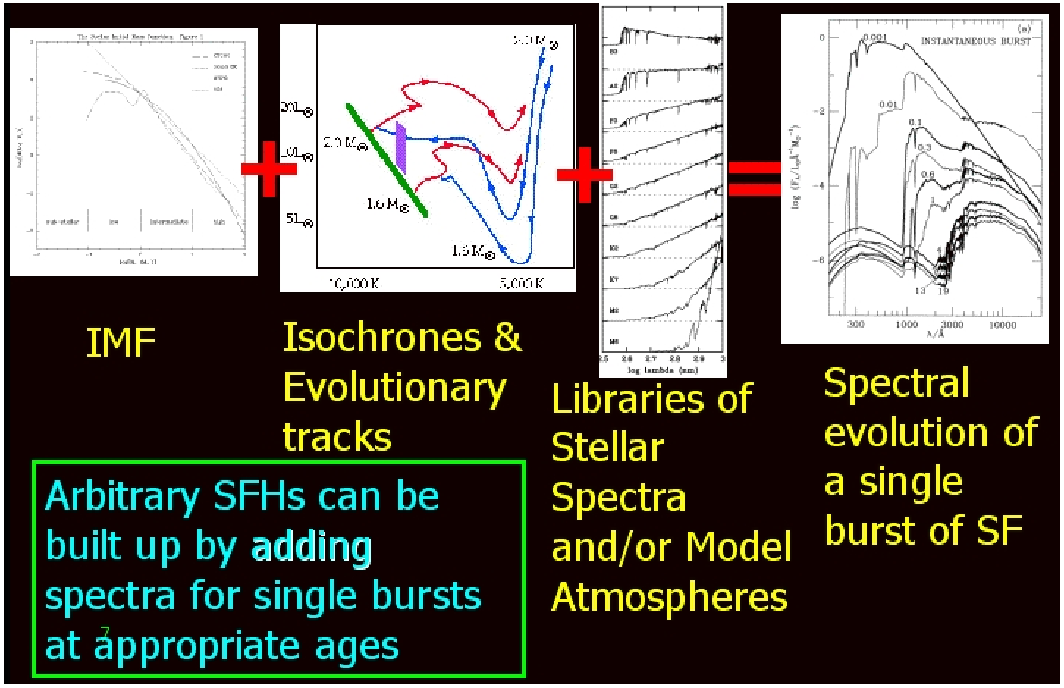
- The stellar spectral energy distribution is a function of mass, chemical composition and age, a theorist would say
- The stellar spectral energy distribution is a function of effective temperature, surface gravity and metallicity (at the accuracy level of 1%); the first two simply describe the position 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 $[Fe/H]$

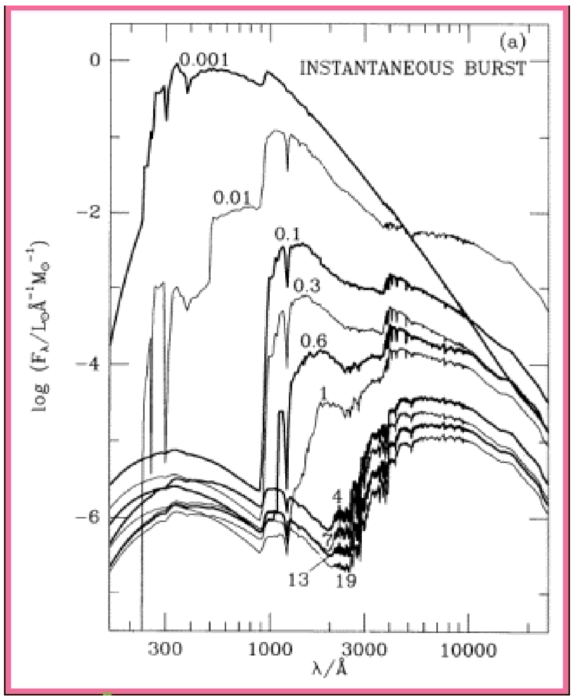


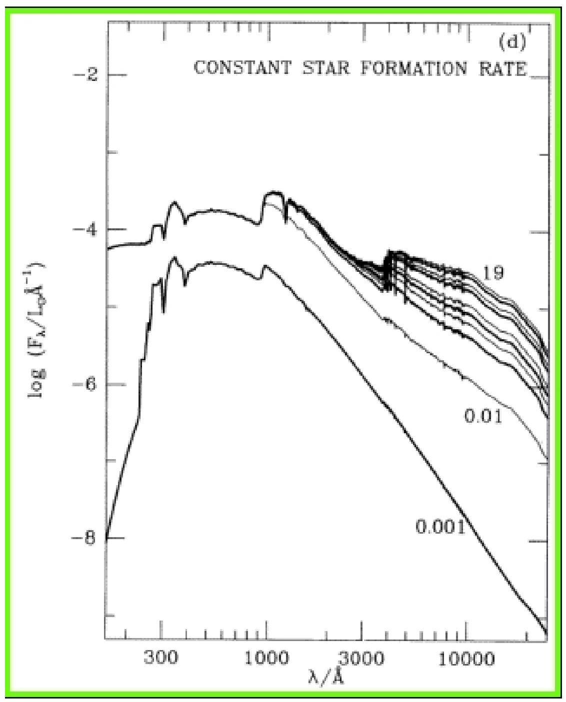


Population Synthesis: modeling SEDs of galaxies

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





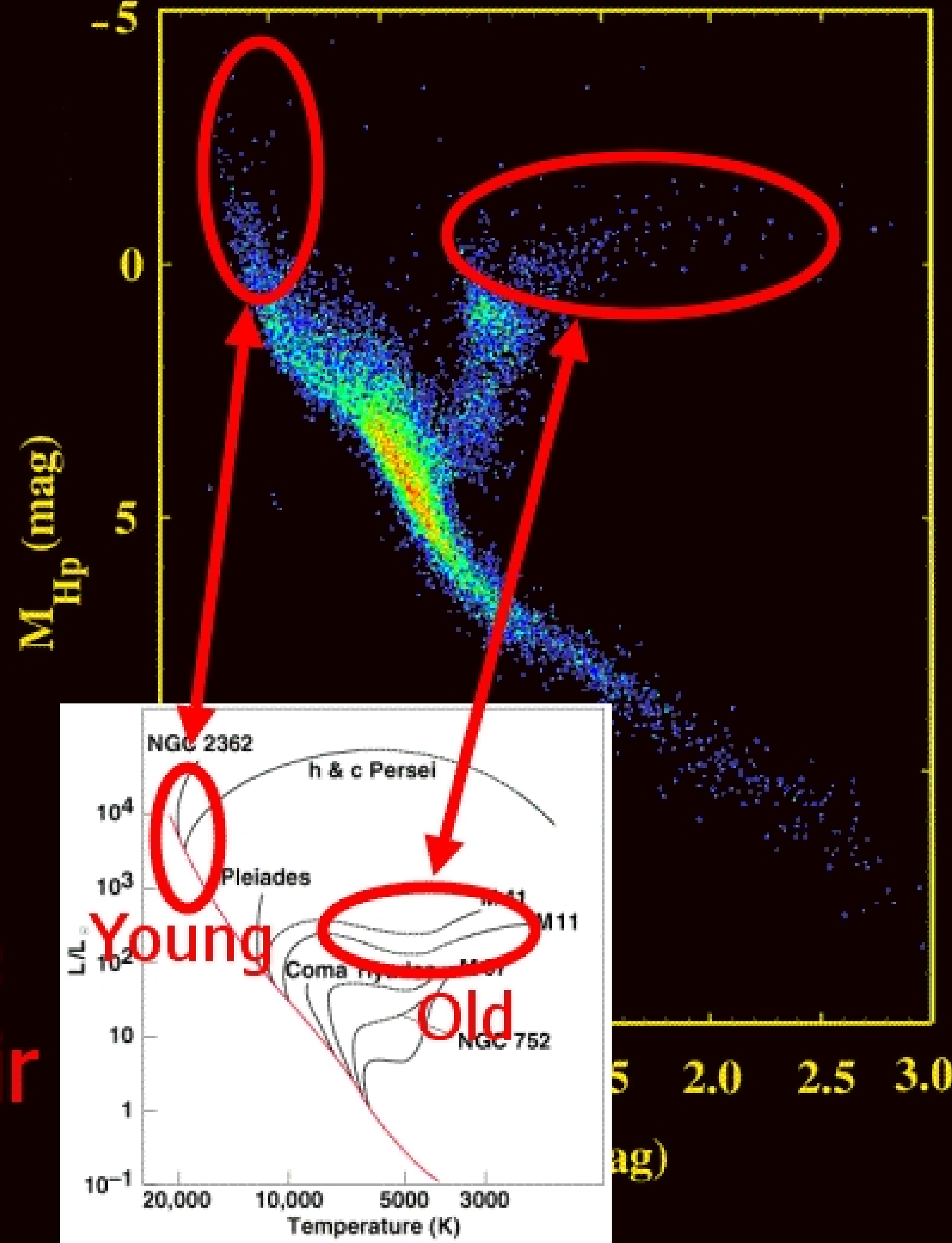


Population Synthesis: modeling SED of galaxies

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

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



The Virial Theorem

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.

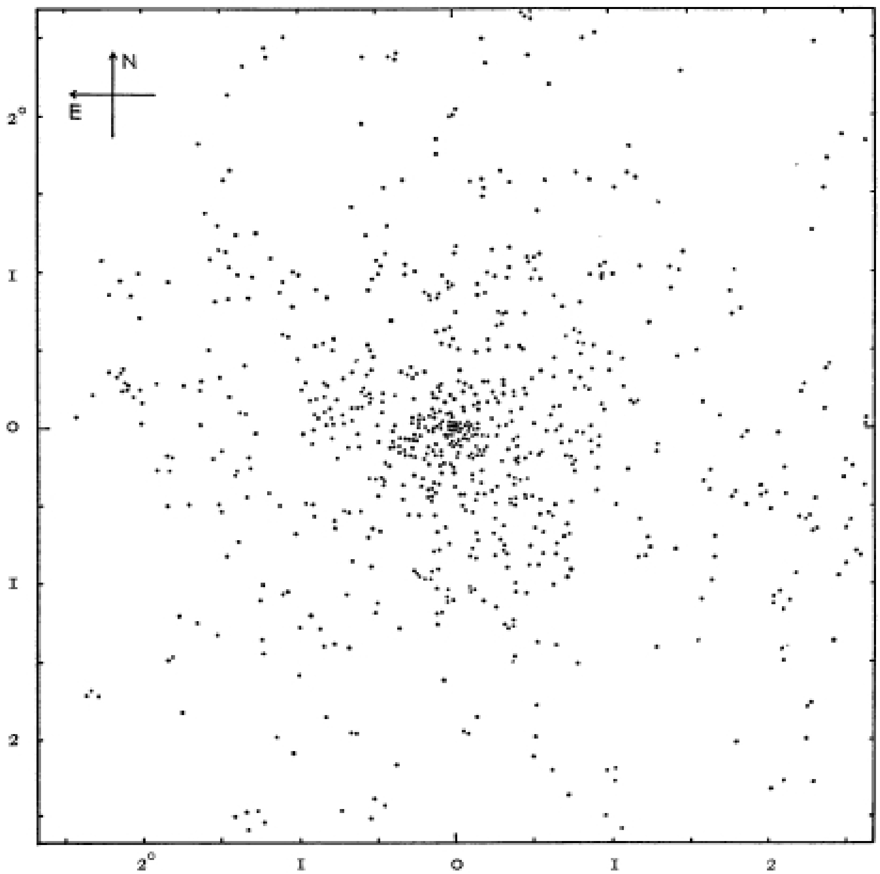
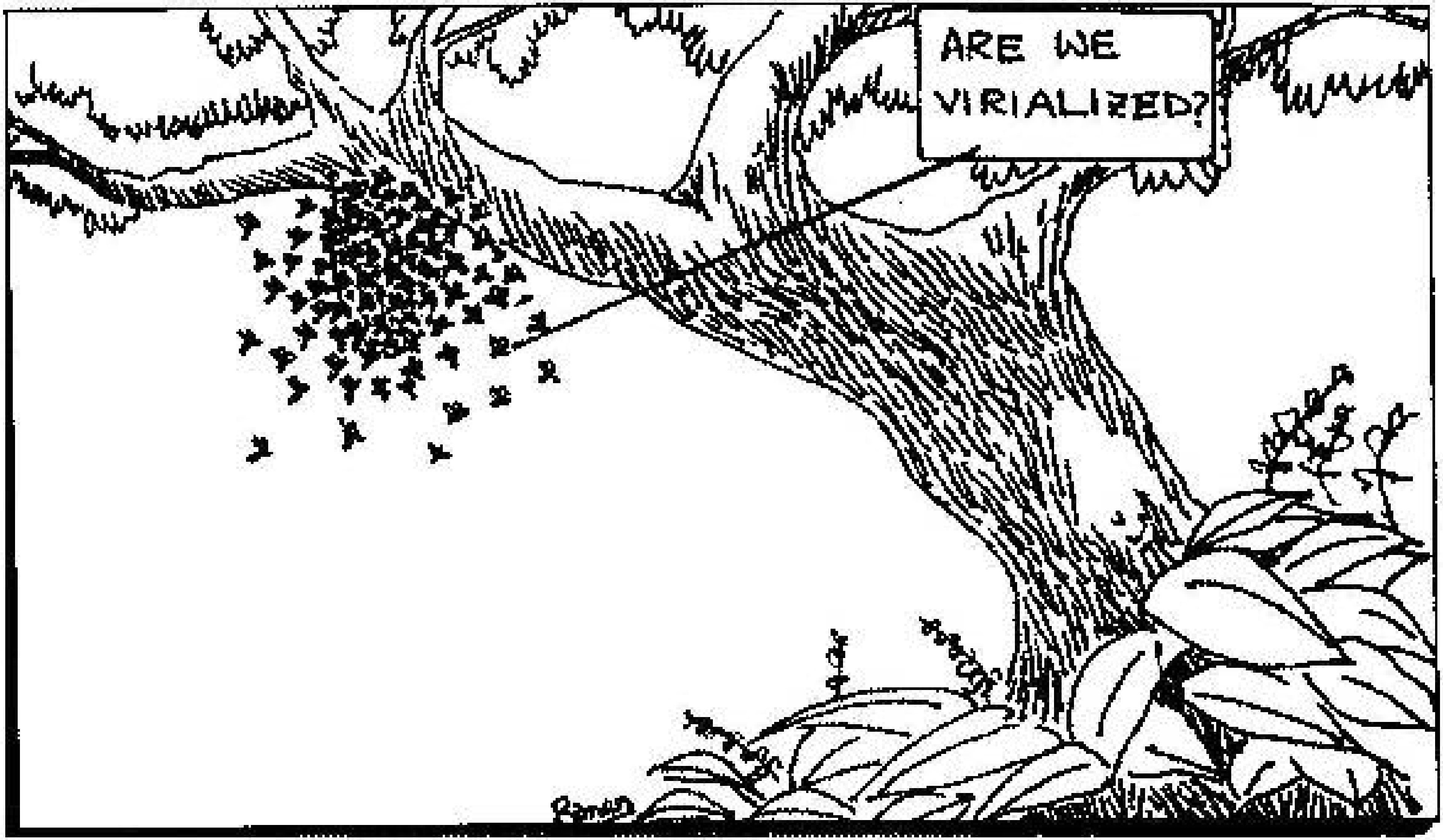


FIG. 3.—The Coma cluster of nebulae

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.



Cartoon courtesy of and ©1999 by B. Nath.

The Virial Theorem(s)

- The Scalar Virial Theorem tells us that the *average* kinetic and potential energy must be in balance.

- The tensor Virial Theorem tells us that the kinetic and potential energy must be in balance in each separate direction.

- The scalar virial theorem is useful for estimating global *average* properties, such as total mass, escape velocity and relaxation time, while the tensor virial theorem is useful for relating shapes of systems to their kinematics, e.g. the flatness of elliptical galaxies to their rotational speed (for a wide range of applications, see Chandrasekhar (1987, Ellipsodial Figures of Equilibrium, New York: Dover).

- Remember that *the virial theorem is a good intuitive tool but one that can be dangerous to put to quantitative use* (King, unpublished).

The Virial Theorem

Zwicki's derivation: (Ap. J. 1937, 86, 217)

$$m_i \frac{d^2 \vec{x}_i}{dt^2} = \vec{F}_i \tag{7}$$

where $\vec{F}_i$ is the total forces on galaxy i.

Scalar multiplication with $\vec{x}_i$ gives:

$$\frac{1}{2} \frac{d^2}{dt^2}(m_i x_i^2) = \vec{x}_i \cdot \vec{F}_i + m_i \left(\frac{d\vec{x}_i}{dt} \right)^2 \tag{8}$$

(summing over all system particles is implied). The term on the left side represents the change of the momentum of inertia, the second term on the right side is related to kinetic energy, and the first term on the right side is called *virial*.

The Virial Theorem

It can be shown (the so-called Euler theorem from classical mechanics) that for $\Phi \propto 1/r$

$$\sum \vec{x}_i \cdot \vec{F}_i = -\sum \vec{x}_i \cdot \nabla\Phi = \Phi \tag{9}$$

That is, the virial is related to potential energy of the system (true for any *homogeneous* function of the order k such that $\Phi(\lambda x) = \lambda^k \Phi(x)$ – the virial is equal to $-k\Phi$).

In a steady state,

$$\frac{1}{2}\frac{d^2}{dt^2}(m_i x_i^2) = 0, \tag{10}$$

and, for a self-gravitating system in steady state

$$2K + \Phi = 0 \tag{11}$$

where $K = M < v^2 > /2$ is the kinetic energy. Thus,

$$E = K + \Phi = -K = \frac{1}{2}\Phi \tag{12}$$

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?