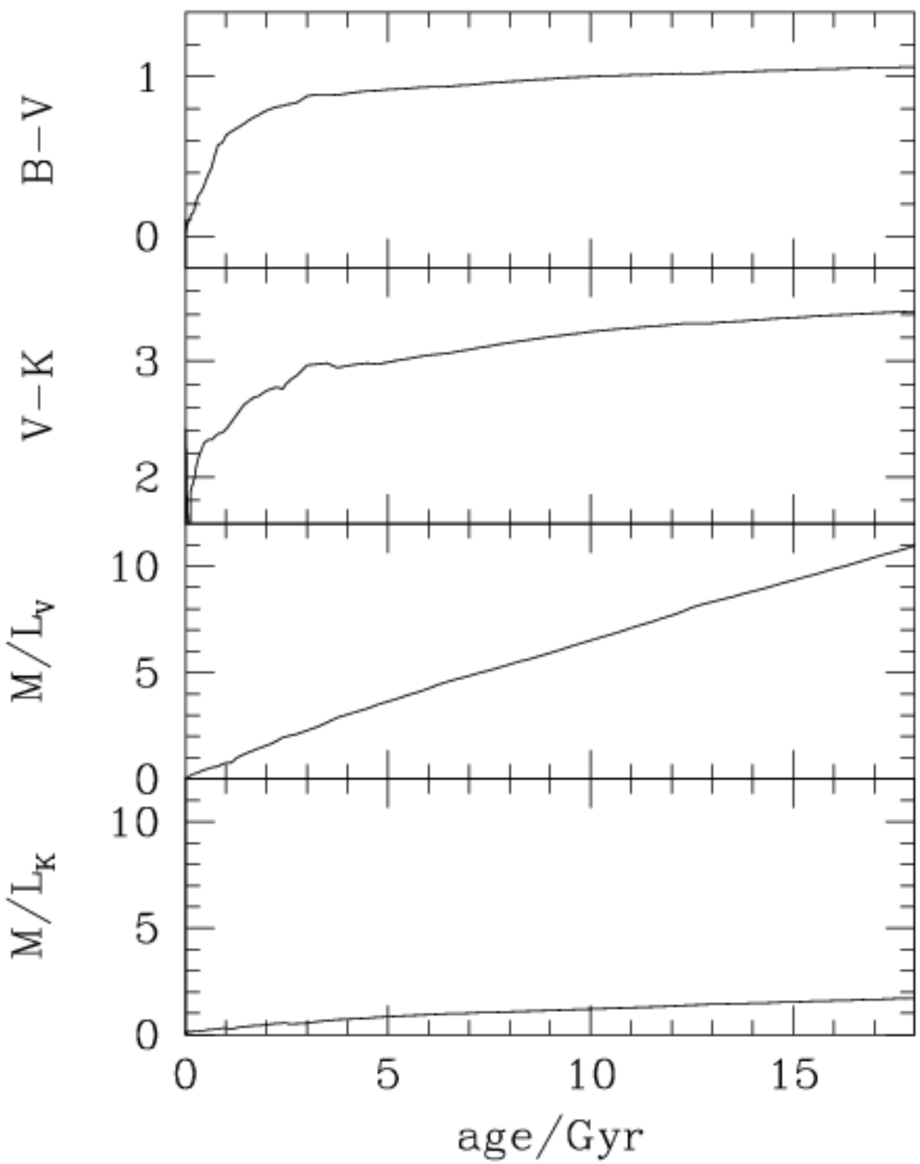
Age Dating A SSP

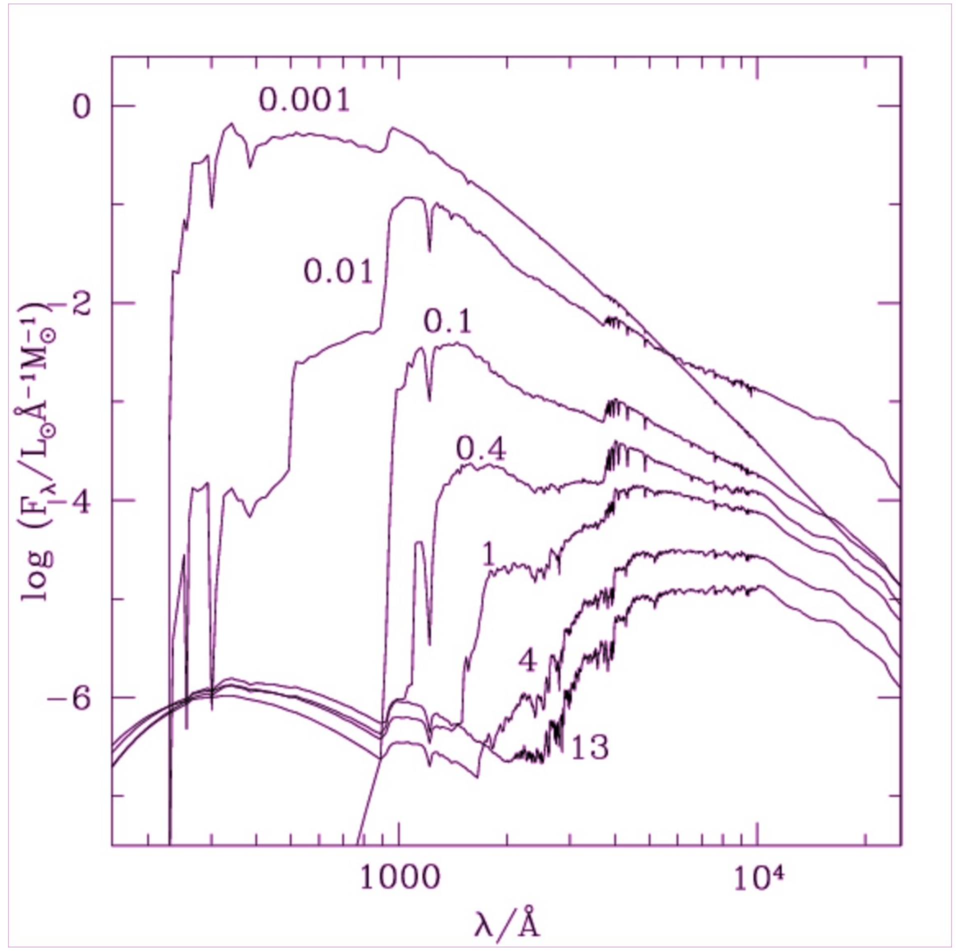
- Color is only a weak function of age after ~3Gyrs (for a given metallicity) (See MBW pg 473)
- But there is a strong change in M/L_V and weak change in M/L_K

- ***Quick quiz: please write down a 3 sentence explanation of why these plots look like they do.***



Galaxy Spectra

- Of course the galaxy spectrum is the sum of the stars, weighted by their luminosity.
- The spectra changes radically with the age of the system (MBW fig 10.5)
- After a ~fewx10^9 yrs stars on the red giant branch dominate the ~1μ flux; stars on the red giant branch have a narrow range of parameters for a large range in mass; good estimator of mass in stars (discussion in sec 10.3.3 MBW)



Theoretical spectrum of a SSP with a Saltpeter IMF and solar metallicity
at a variety of ages 0.001-13 Gyrs

IMF S&G sec 2.1

- The origin of the form of the (Initial Mass Function) IMF is not well understood
- There is a severe technical issue- it is only in the MW, MW globular clusters and the Magellanic clouds that one can measure individual stars over a large mass range. All other estimates of the IMF depend on integrated properties and thus are more model dependent
  - there is also a fundamental problem; how to handle binary stars !

INITIAL Mass Function

mass range $[M_\odot]$	% by number	% by mass
0.01 - 0.08	37.2	4.1
0.08 - 0.5	47.8	26.6
0.5 - 1	8.9	16.1
1 - 8	5.7	32.4
8 - 120	0.40	20.8
$<m>$	0.38 $M_\odot$	

70 Pavel Kroupa: A&A, Un

Review Chabrier- Publications of the Astronomical Society of the Pacific, 115:763–795

Steps to the IMF-adapted from Djorgovski/Scalo

Determining the IMF is difficult (Also S&G sec 2.1-2.2)

• Start with observed star counts

– Understand your selection effects, completeness

– Get the distances (a whole subject in itself)

– Correct for extinction

– Correct for unresolved binaries

These ingredients include the luminosity function (LF), the mass-luminosity (m-L) relation, main sequence lifetimes, the relation between scale height and mass, the correction for evolved stars etc

• Get the Present-Day Luminosity Function (PDLF)

– Assume a mass-luminosity relation

which is a function of metallicity, bandpass, …

– Theoretical models tested by observations

• Convert to Present-Day Mass Function (PDMF)

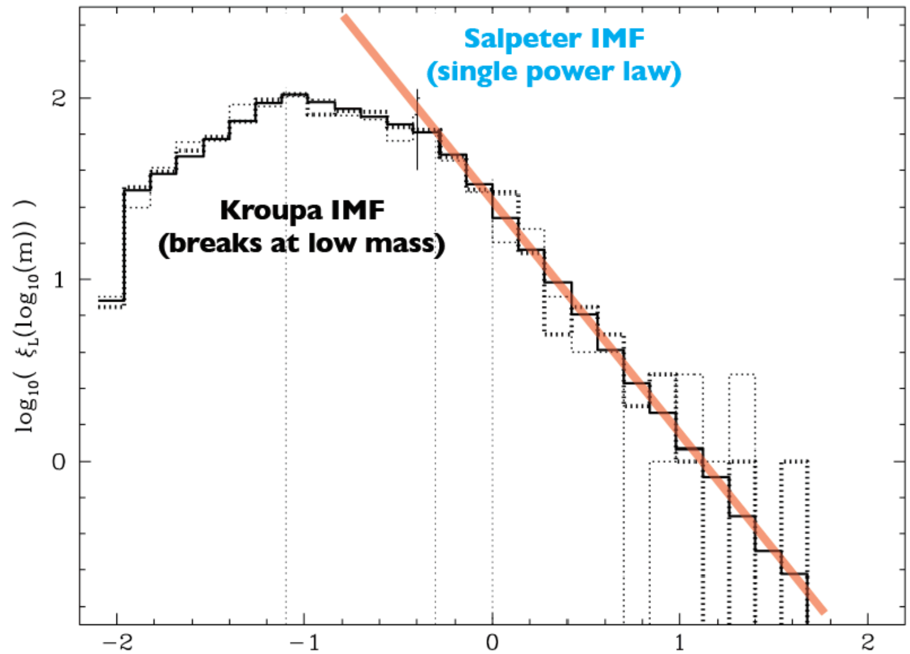
– Use the evolutionary tracks from the same theoretical models

– Iterate over a star formation history

• Get the Initial Mass Function (IMF)- correct for the ‘missing’ high mass stars

Initial Mass Function-IMF

- The distribution of stellar masses **at t=0 (birth)**
- The origin of the form of the IMF is not well understood
- There are several forms proposed
  - Saltpeter-$\Phi(m)=N(M)\sim M^{-2.35}dM$ for $M>M_{\odot}$ (Salpeter 1953)
    - much of integrated stellar mass near $1M_{\odot}$
  - Kroupa/Chabrier IMF-flattens at low masses
- At present it is controversial if the IMF is universal or a function of age, metallicity, density etc



Log M

Kroupa IMF $\Phi(M)=dN/dM = A\ M^{-1.3}\ (0.1 \leq M_{\odot} \leq 0.5)$

$= 0.5\ A\ M^{-2.3}\ (0.5 \leq M_{\odot} \leq 100)$

Kroupa IMF has 1.6x less total mass than the Saltpeter IMF for the same normalization

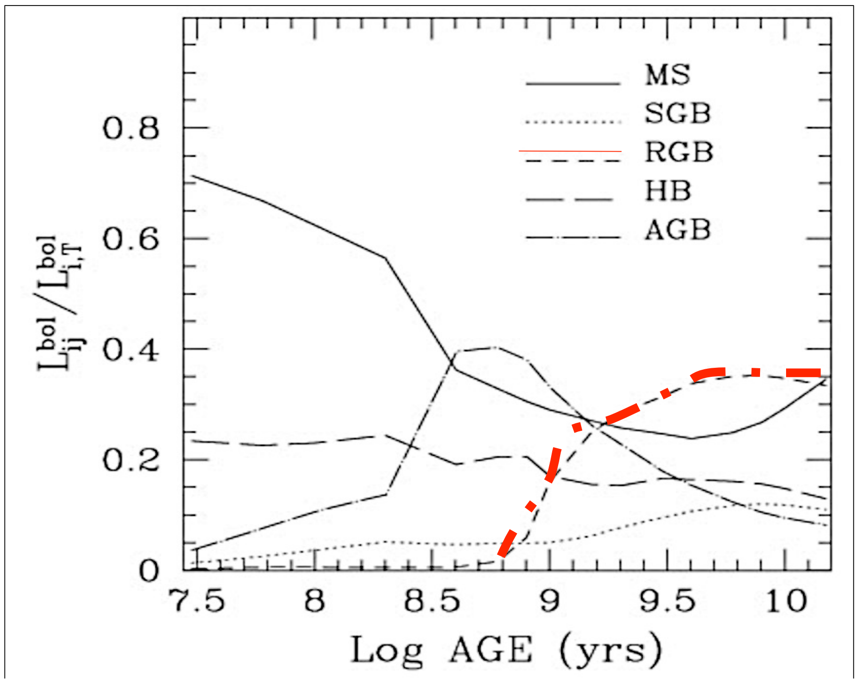
$<M>=0.6M_{\odot}$

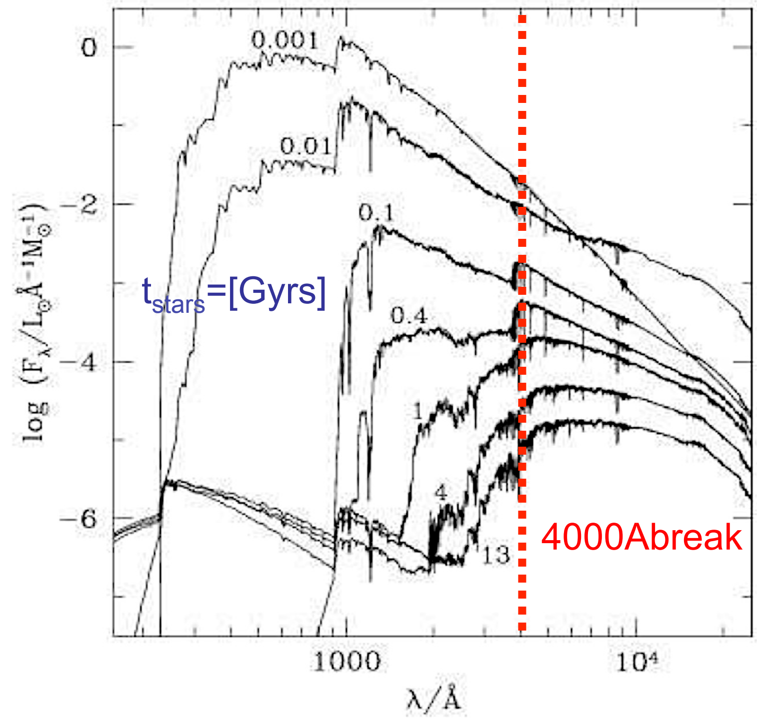
IMF-see MBW pg 440

- General form $\int m\Phi(m)dm = 1M_\odot$
- integrated over the upper and lower mass range of stars ; meaning $\Phi(m)dm$ is the number of stars born with mass m+/- $\delta m/2$ for every $M_\odot$ of newly formed stars
- Stars $M<0.08M_\odot$ - nuclear fusion not take place and $M>\sim 120M_\odot$ are unstable.

Initial Mass Function-IMF

- As SSP ages the <u>relative luminosity due to different parts of the H-R diagram changes</u>
  - Young systems MS(massive stars)
  - Older systems(>2Gyrs)-red giant branch
  - If star formation is a continuous process which stars produce most of the luminosity and where most of the stellar mass lies <u>can be quite different</u>





Spectral energy distribution UV-IR of a SSP as it ages

Notice the enormous changes in the UV and blue

A slow fading in the IR

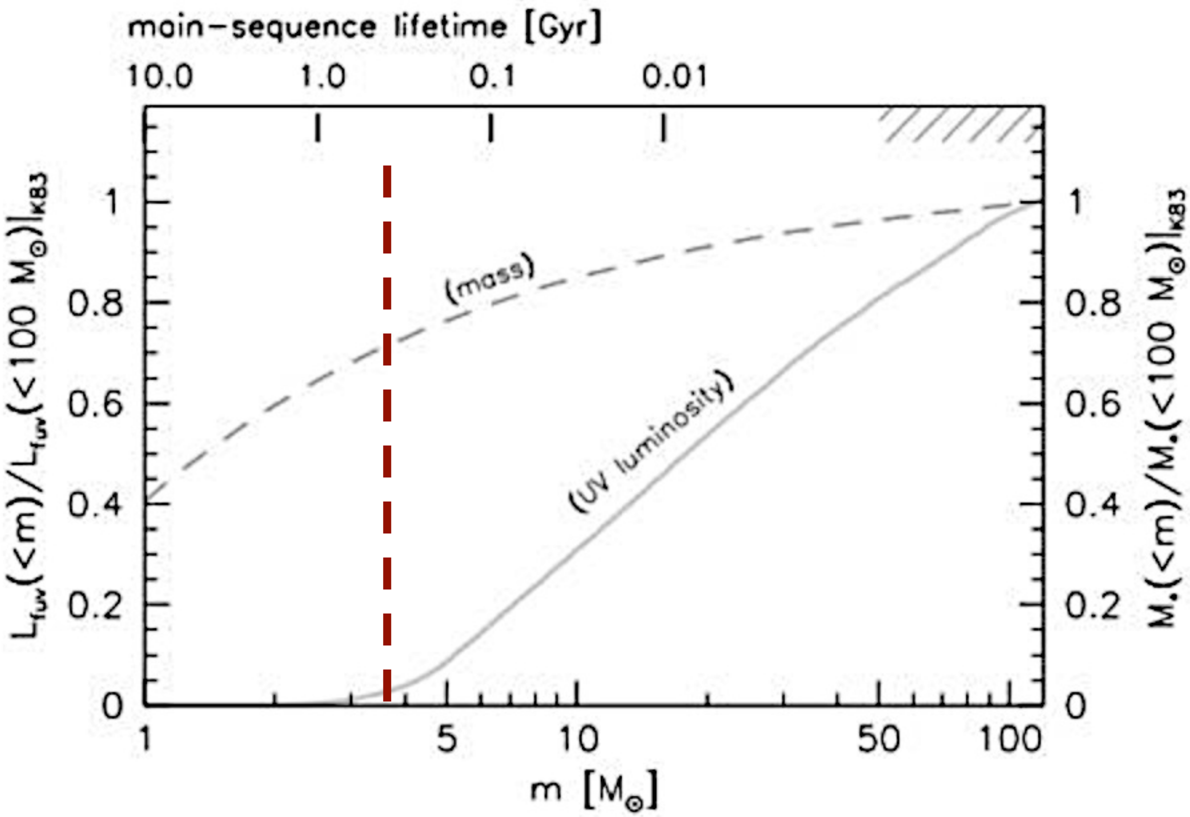
Effects of IMF

- an IMF with a slope of = 2.4 for stars above $1M_\odot$ produces 10^8 stars with $M> 8M_\odot$ for a galaxy of total stellar mass 10^{11} $M_\odot$ while a Kroupa (2001) IMF gives 10^9 such stars – a factor of 10 times more.
- This change in the number of massive stars is very important for the chemical enrichment of the galaxy since only stars of $M>8M_\odot$ produce type II SN and thus metals
- Thus, for example, the mass of O^{16} released by massive stars for the slope 2.4 case, produces a 7 times lower than solar oxygen abundance.

- The slope of the IMF is , of course, critical for converting the observed light to stellar mass. As we will discuss later this is extremely important for determining the baryonic mass in spiral and elliptical galaxies and is a major source of uncertainty.

Focus on The UV

- The UV emission of a star forming galaxy driven by high-mass stars ($M > 10M_{\odot}$).
- The short main-sequence lifetimes of these stars indicates that the UV luminosity is a diagnostic of the star formation rate.
- BUT the UV emission from a star forming galaxy is produced by stars with a range of masses, and thus main-sequence lifetimes.



Solid line- how much UV luminosity comes from stars more massive than m-
Dotted line how much of the total stellar mass comes from these objects

Wilkins et al 2012

Stellar Populations I & II- Baade 1942

<u>In spiral galaxies</u> there are 2 'types' of stellar populations

Population I

– Young

– Metal rich

– Found in galaxy disks

- Rotationally supported

Population II-' red'

– Old

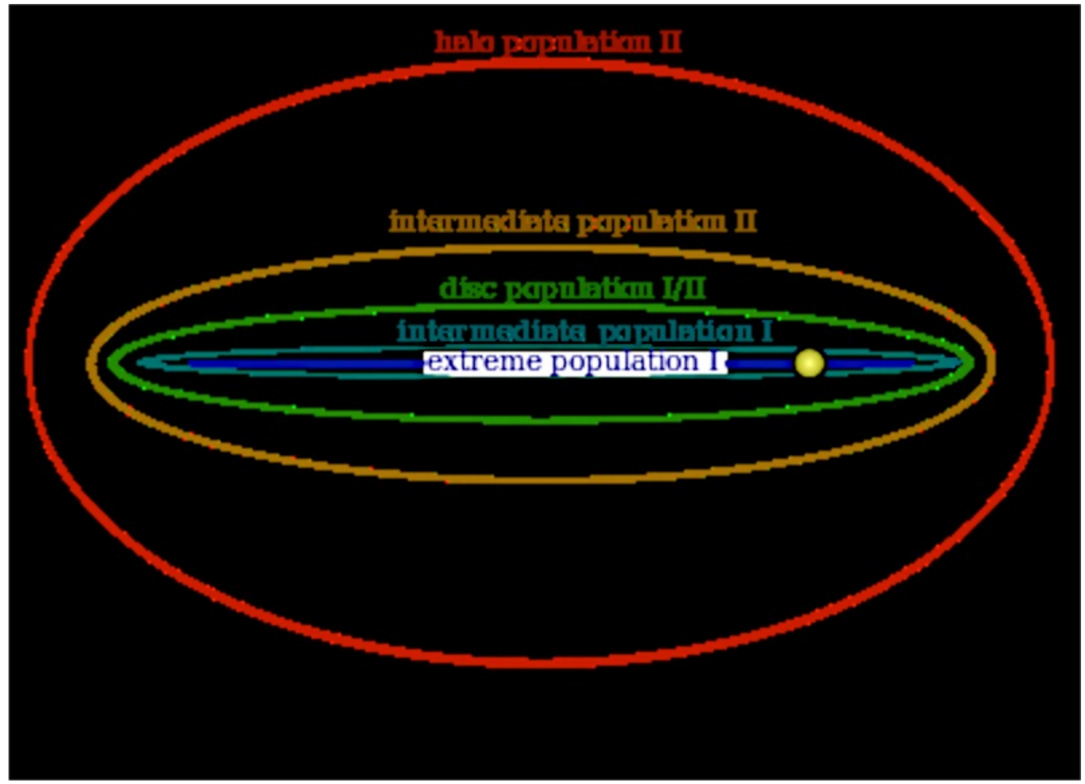
– Metal poor- non-solar abundances

– Found in Globular clusters, Spiral bulges

- dispersion supported

- But **not** in Ellipticals- these stars are old- but frequently metal rich, thus different than spiral Pop II

theoretically there is also Pop III- the first stars

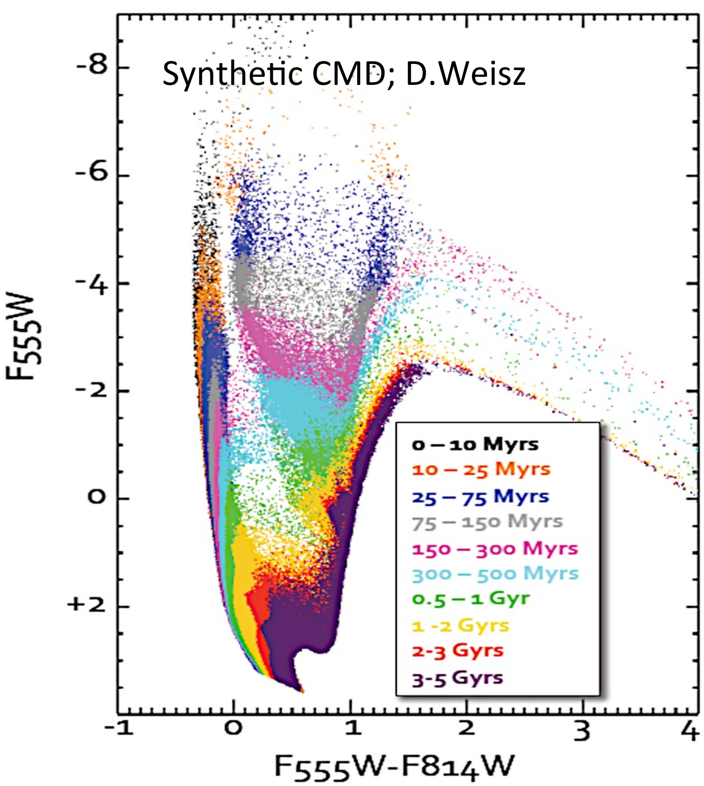


Schematic picture of stellar pop's in Milky Way

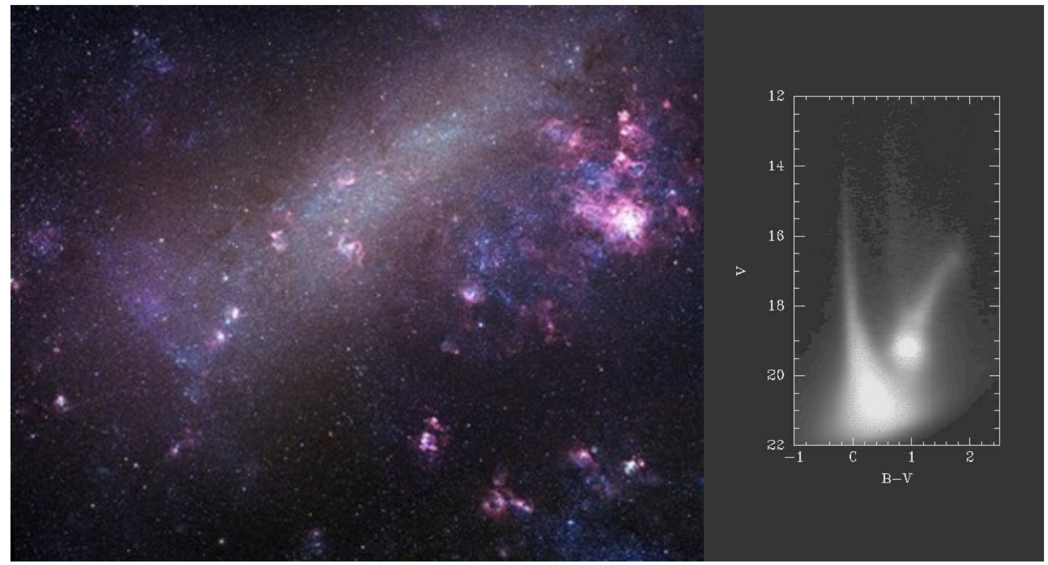
Galaxies are NOT SSPs

H.Rix2010

- Different parts of a galaxy have different ages and metallicity
- Only for the MW, SMC, LMC (and with Hubble a few nearby galaxies) can one construct a H-R diagram which shows this
- For distant galaxies we have to deal with integrated spectra colors and brightness and the effects of dust.



LMC:Zaritsky&Harris 2004-2009



LMC:Zaritsky&Harris2004-2009

Galaxy $=\Sigma_{(time)}$SFR(t) xSSP(t;Y; Z; IMF)

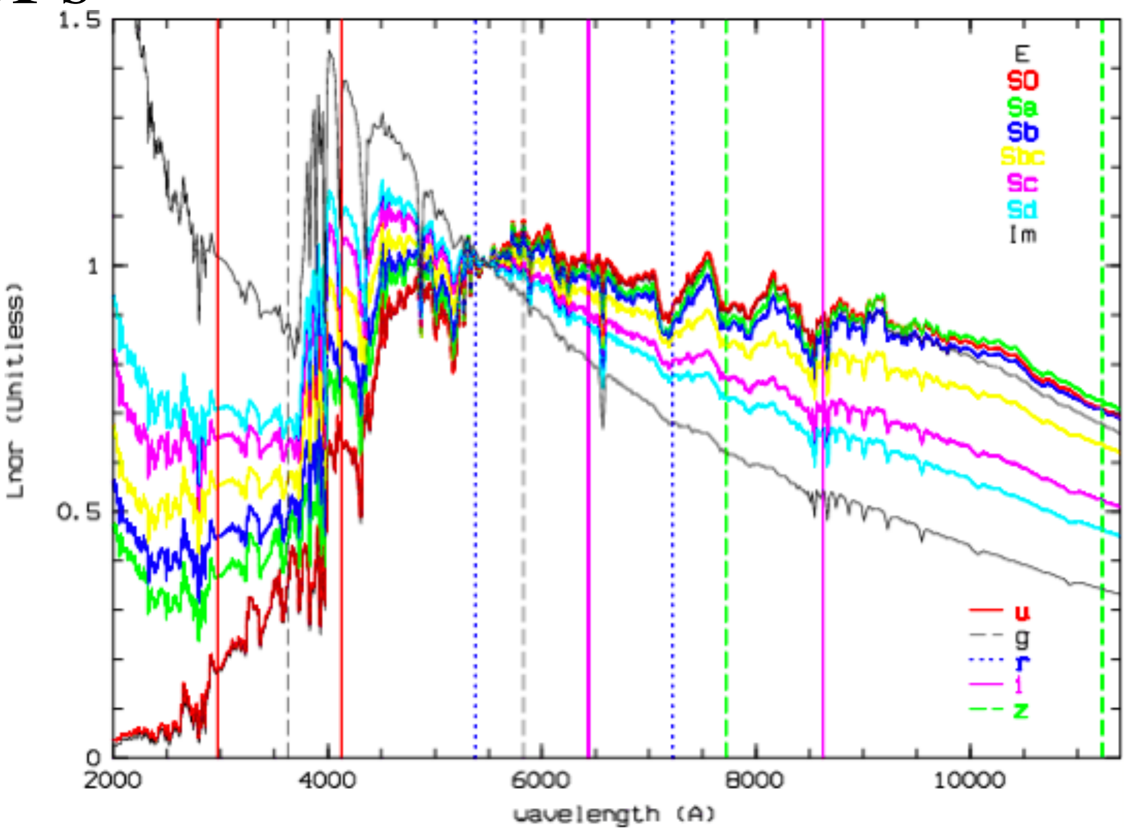
Y the Helium abundance and Z the abundance of heavier elements (metallicity)Graph synthetic CMD for a galaxy forming stars (e.g. not a SSP)

General Trends for SSPs

- Populations fade as they age
- – ionizing flux is only produced for t<20 Myrs
- – Fading by 10^5 at 3000Å from 10 Myrs to 10Gyrs

  – UV flux is only produced for 0.2Gyrs
- X 100 at 5000Å from 0.1Gyrs to 10Gyrs

X 6 at 1.5μ from 1Gyr to 10Gyrs



– populations 'redden' as they age

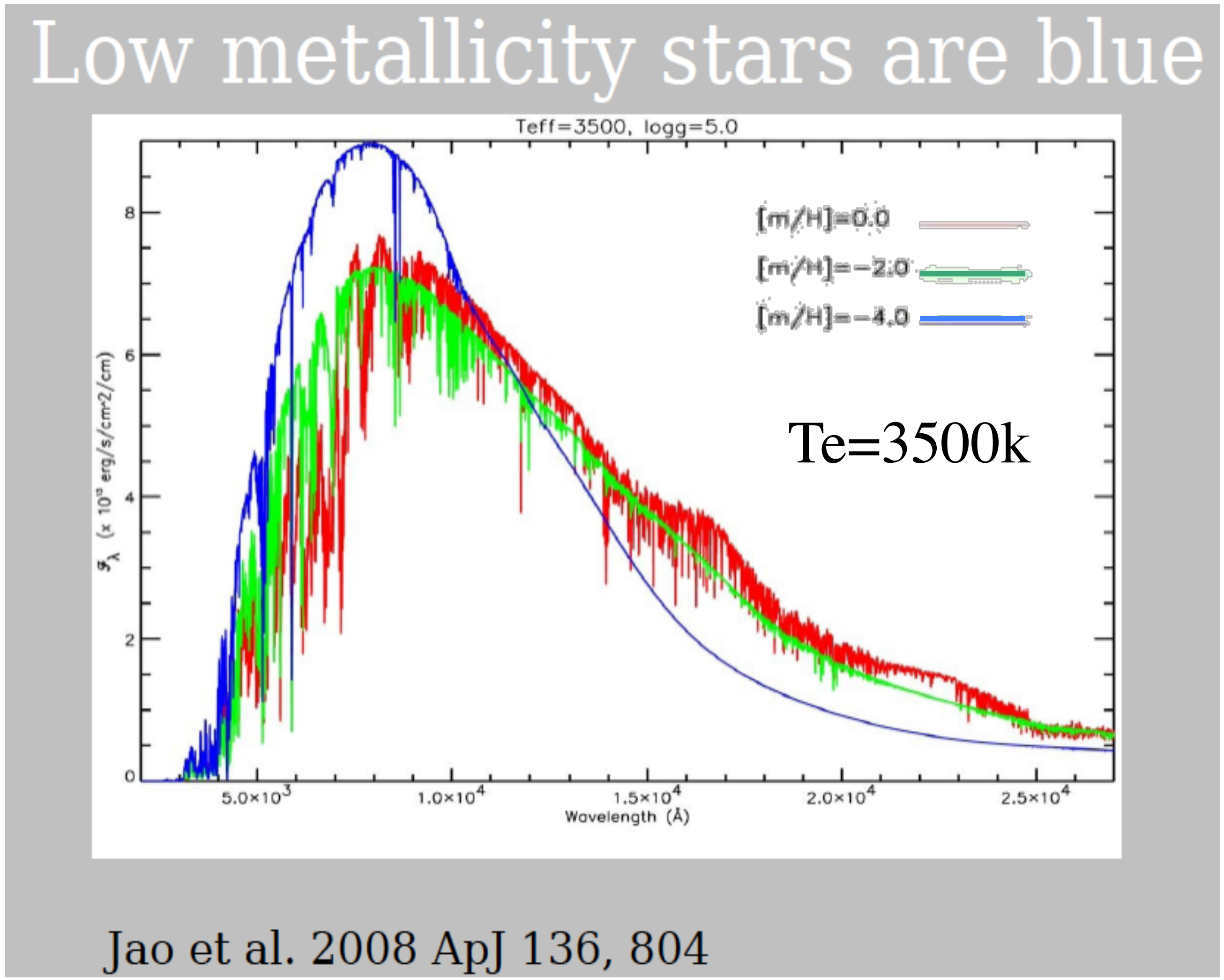
the ratio of the current SFR over the average past SFR is very important in determining the spectrum of a galaxy.

Higher 'metallicity' and dust also 'redden'

output from Pegase2 code Tsalmantza et al 2007,2009

Effects of Metallicity

- At a given mass/ temperature the colors of metal poor stars are 'bluer'- due to less line <u>blanketing*</u> in their atmospheres



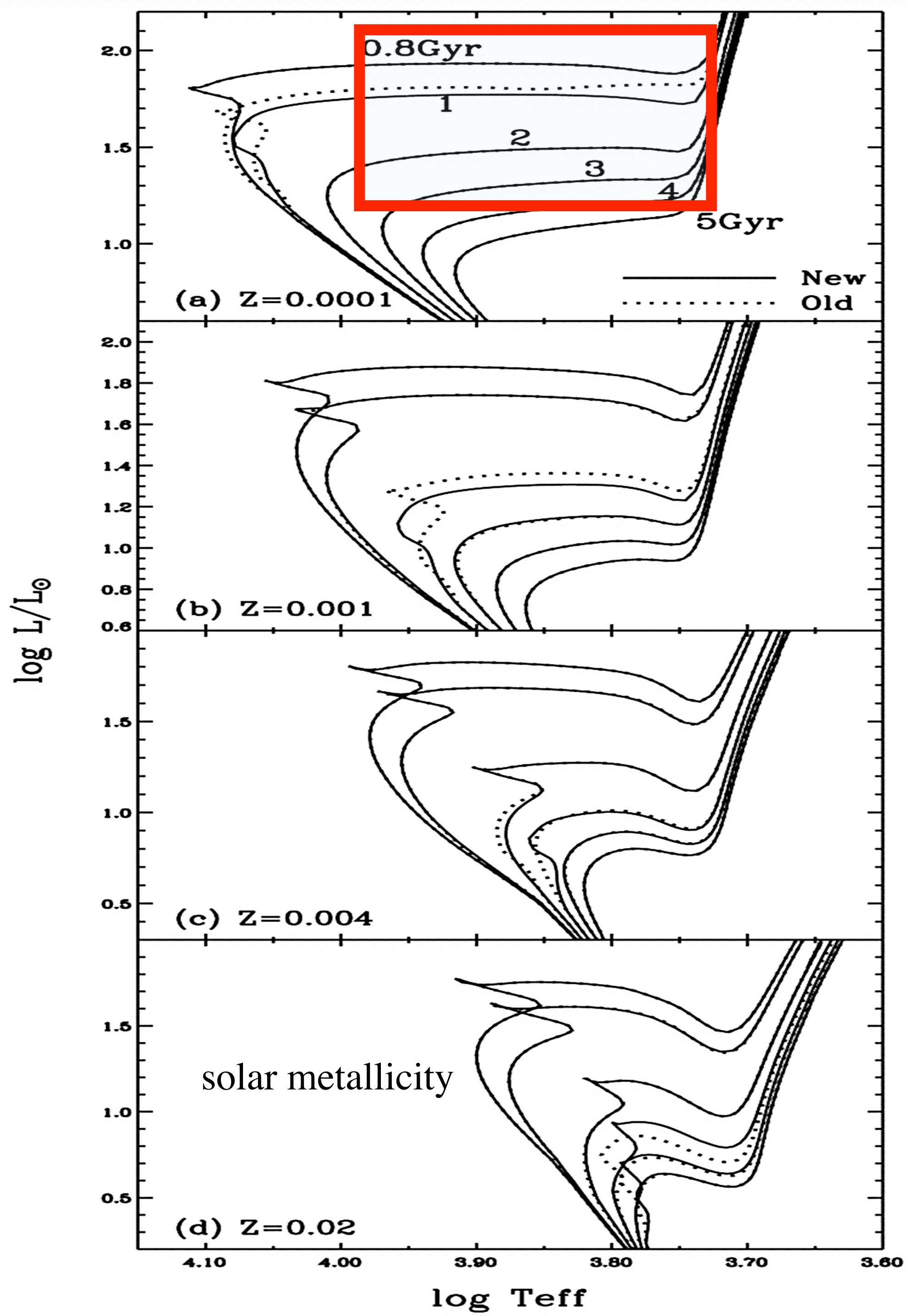
*The decrease in intensity of a star's spectrum due to many closely spaced, unresolved absorption lines.

Its important for cool stars, whose atmospheres contain many different types of atoms and molecules that tend to absorb at shorter (bluer) wavelengths and reemit in the red and infrared.

Theoretical Isochrones

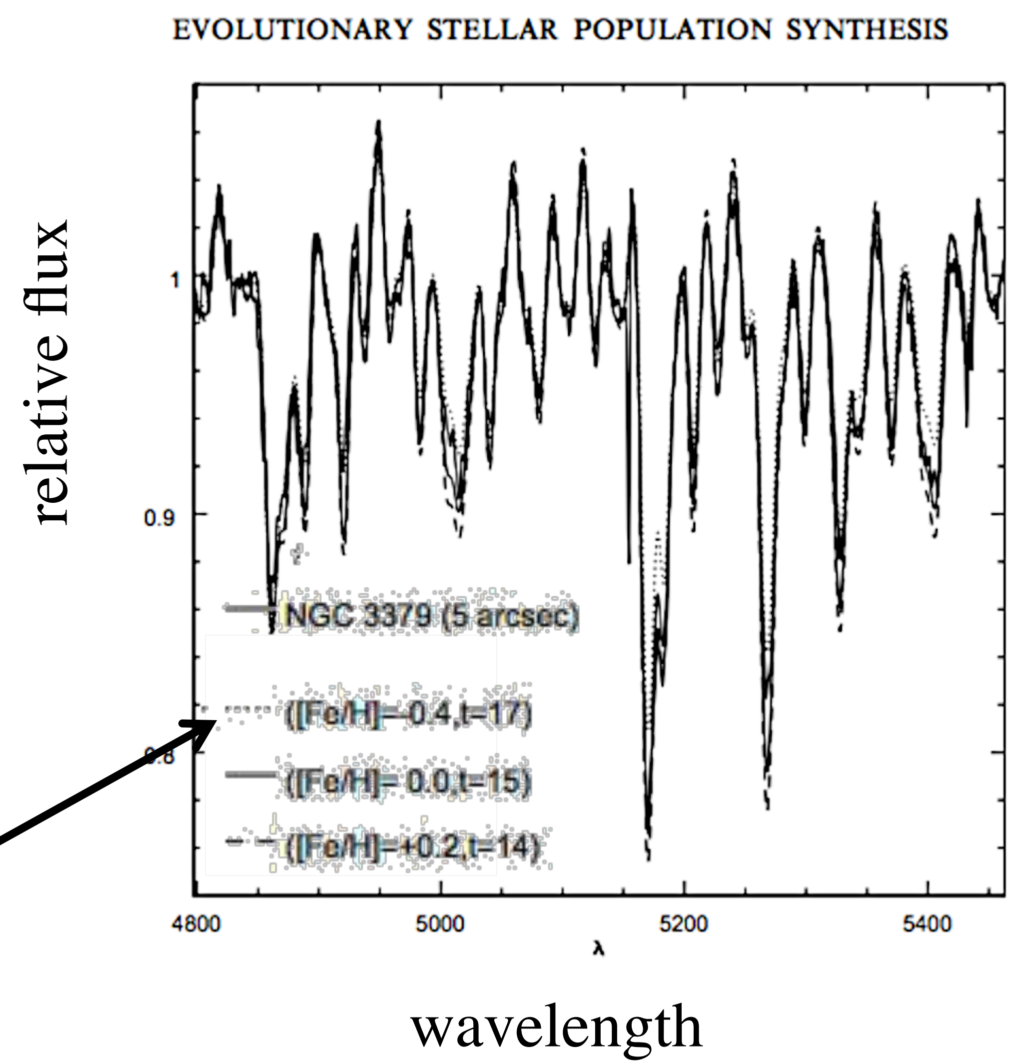
- These lines are the positions of stars from a SSP as a function of the age of the system - in the temperature/ luminosity plane **if** no new stars are born
- The shape depends on the metallicity of the stars (Demarque et al 2004)

- One can determine the '*age*' of the system by fitting an isochrone (if one has data for individual stars) or by calculating some average property (color/spectrum) averaging over the isochrone - <u>degeneracy problems with age and metallicity are obvious</u> -
- notice stars 'pile up' on the red giant branch (dominate luminosity of old systems)



Spectra of Galaxies see MWB sec 10.3.2-10.3.6

- Almost all the energy radiated by 'normal' (not AGN) galaxies is due to stars (either direct or reprocessed)
- However the stellar spectra is a triple integral over
  - IMF
  - star formation history
  - stellar library
- furthermore the observed spectrum is often strongly effected by dust
- Also there is a 'age/metallicity' degeneracy; for much of the optical band spectra young, metal-rich populations strongly resemble old, metal-poor populations
- see sec 2.2 in the 'Galaxy Mass' review paper posted on the web site.



Vazdekis 1999

Spectra of Galaxies

- Mathematically the luminosity of a galaxy at a given frequency, ν, is
- $L_\nu(\text{galaxy})=\int dt' \int dZ'(dM/dt(t,Z)xL_\nu^{(SSP)}(t\text{-}t',Z',\phi)$
- where Z is metallicity at a time t dM/dt is the formation rate of stars of metallicity Z at time t and $L_\nu^{(SSP)}$ is the luminosity at this frequency of a SSP of metallicity Z, age t and IMF ϕ
- $L_\nu^{(SSP)} =\int\phi\ (M')L_\nu^{(star)}\ )(t,,Z)dM'$ over the range of masses (e.g. M_{min}-M_{max})
- there are theoretical libraries which calculate for different ages, IMFs and metallicities
- However signficant uncertainties still exist- estimate to be about 0.4mag/unit redshift in the K band (!) for a evolving population

- see the A. Benson review article eqs 114,115

How to Use this Information

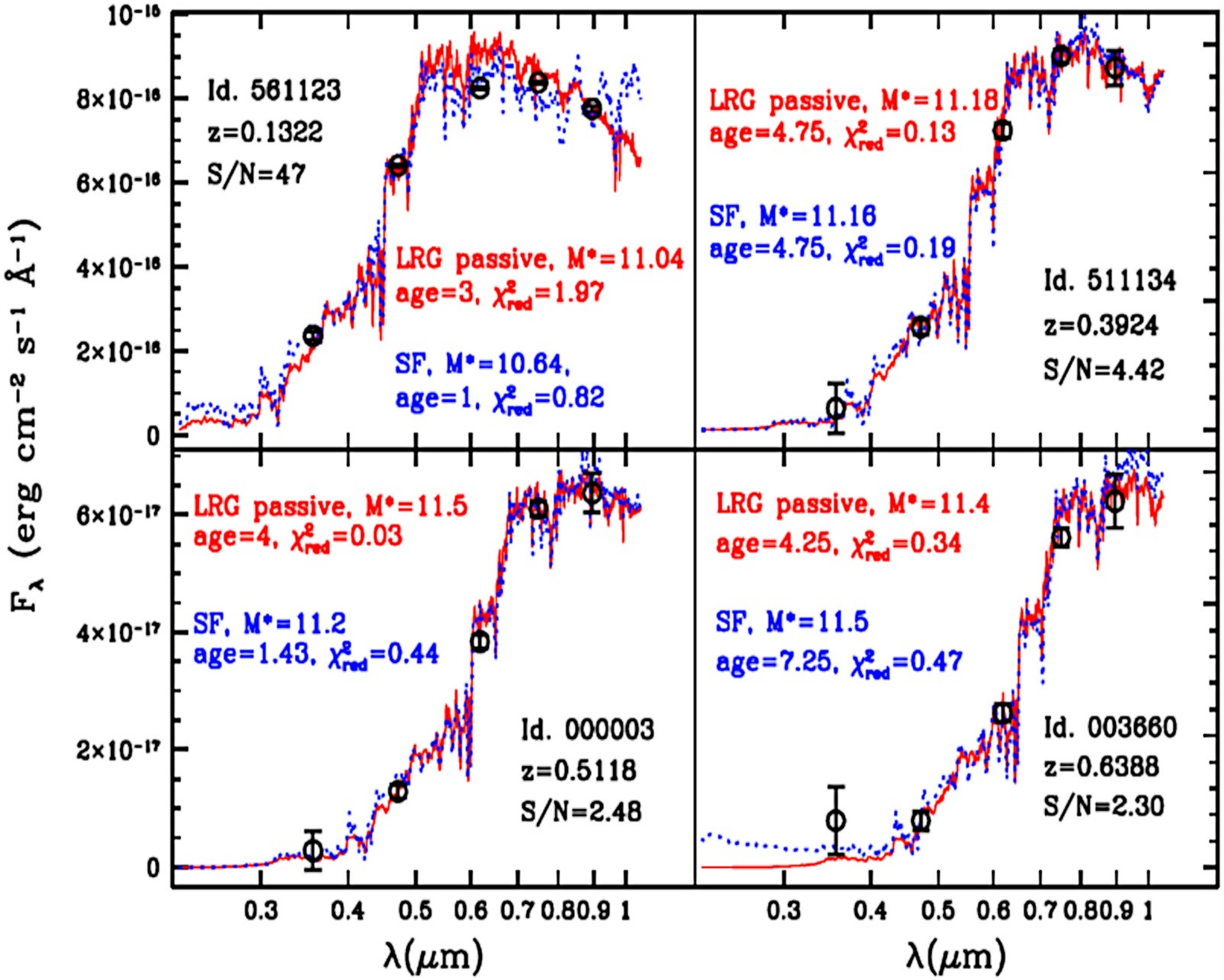
- ‘Integrated’ Stellar Populations

Crucial since only 10-100 Galaxies have resolved stars

- What can we say about stellar mass, metallicity, star formation history age– for low z galaxies can resolve 'parts' of the galaxy, for most distant objects 'whole' galaxy
- Data
  - images
  - colors, or ‘many colors’, i.e the ‘spectral energy distribution’ (SED) (R=5 spectrum)
  - Spectra (R=2000) (integrated or spatially resolved spectra or long slit)
- It is not possible to invert the data to derive the desired parameters.
- Process:
  - assume stellar formation history and IMF- generate isochrones
  - use stellar library to calculate spectra/colors
  - iterate and see if it converges

Age/Type/SF rate Degeneracies

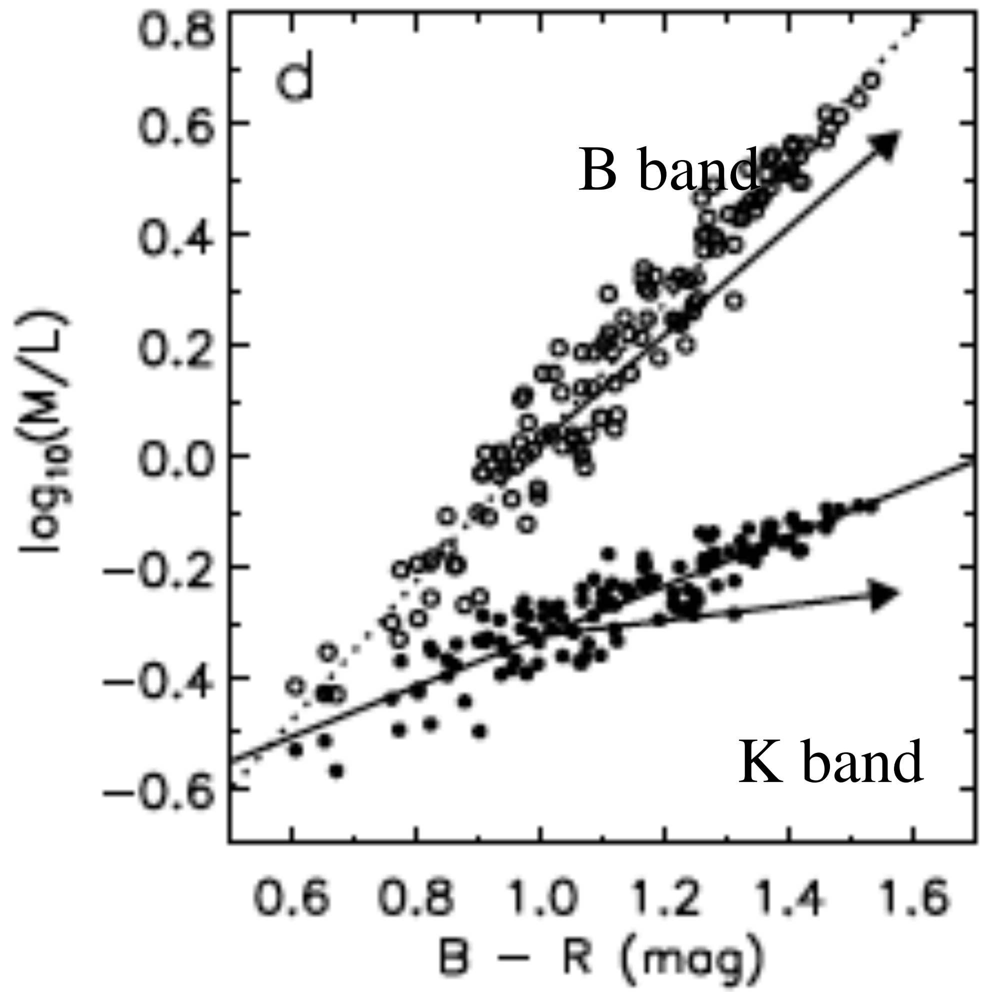
- The new BOSS galaxy sample (400,000 galaxies) has degeneracies even when using solar metallicity models.
- Notice good fits for both Star forming (SF) and 'passive' galaxies with very different ages and somewhat different stellar masses **even without including reddening (dust)**



Maraston et al 2012

M/L Indicators

- Some colors are very sensitive to M/L for spirals
- If there is a universal spiral galaxy IMF, - a strong correlation between stellar M/ L and the optical colors
- For a composite population one has to make a lot of assumptions: SF vs time law chemical evolution model, SSP model, etc etc- color is basically ratio of how much SF now to how much in the past
- Can apply such techniques to large samples -

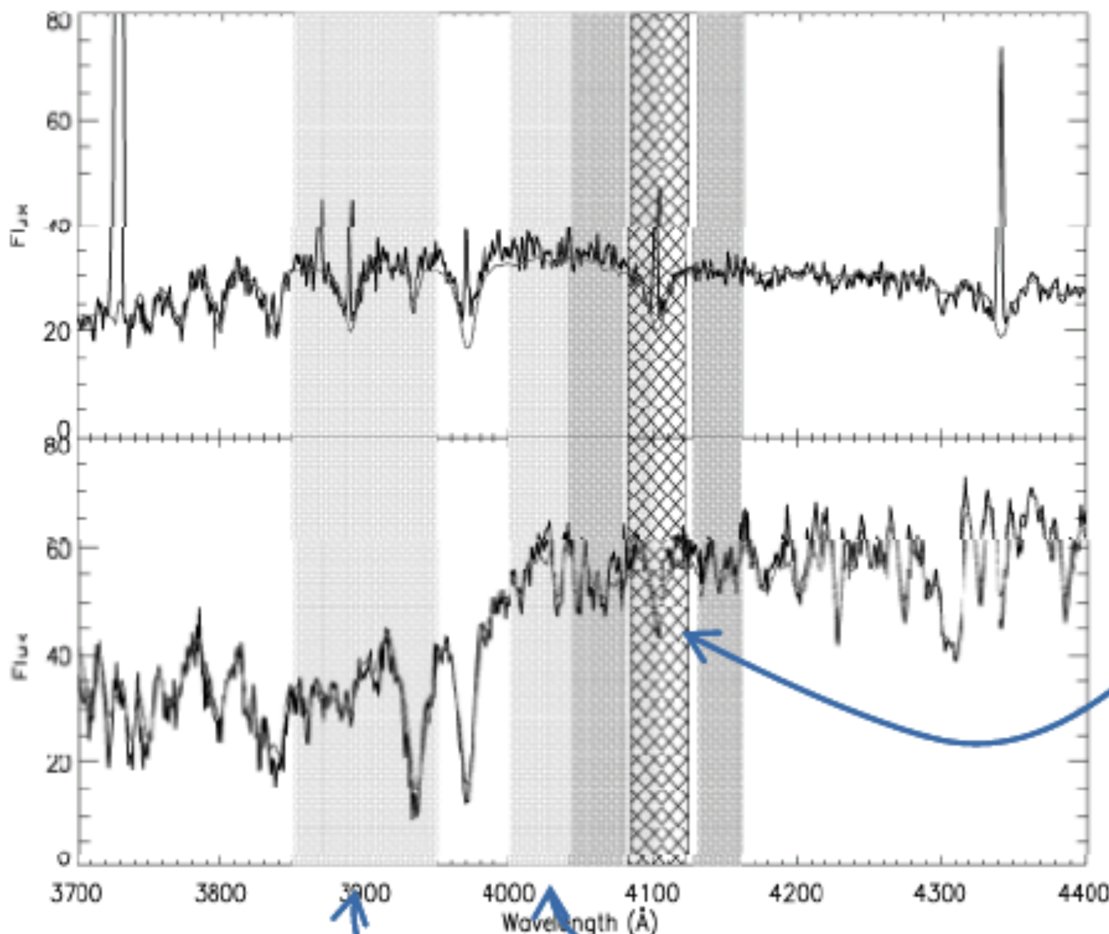


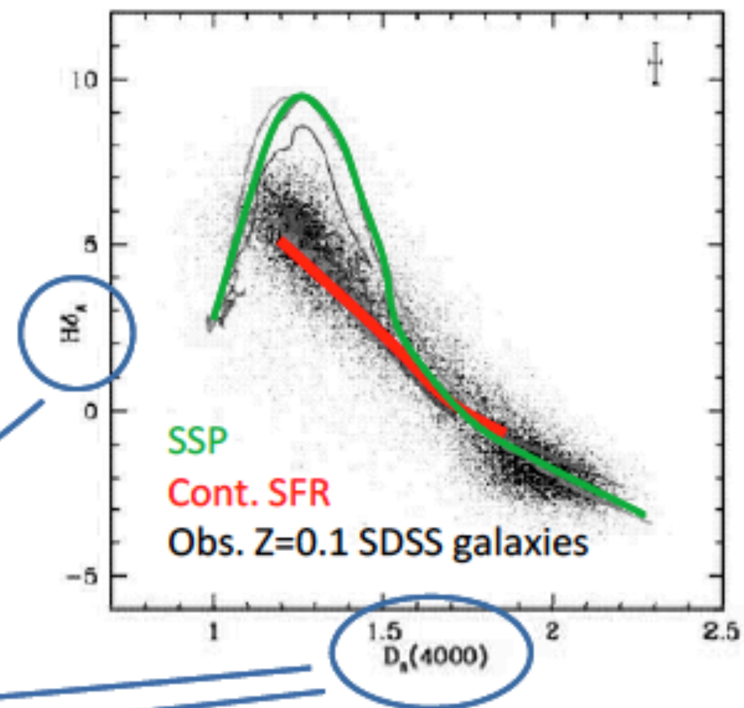
Dust and Reddening

- The effects of reddening can be complex.
- reddening law for isolated stars
  - not the same for all galaxies; e.g. MW and SMC are rather different in the UV but not in the optical;.

- It depends on how the stars and the dust are intermixed
- Since star formation occurs in dusty molecular clouds regions of high SFR show high reddening

Signatures of Stellar Evolution

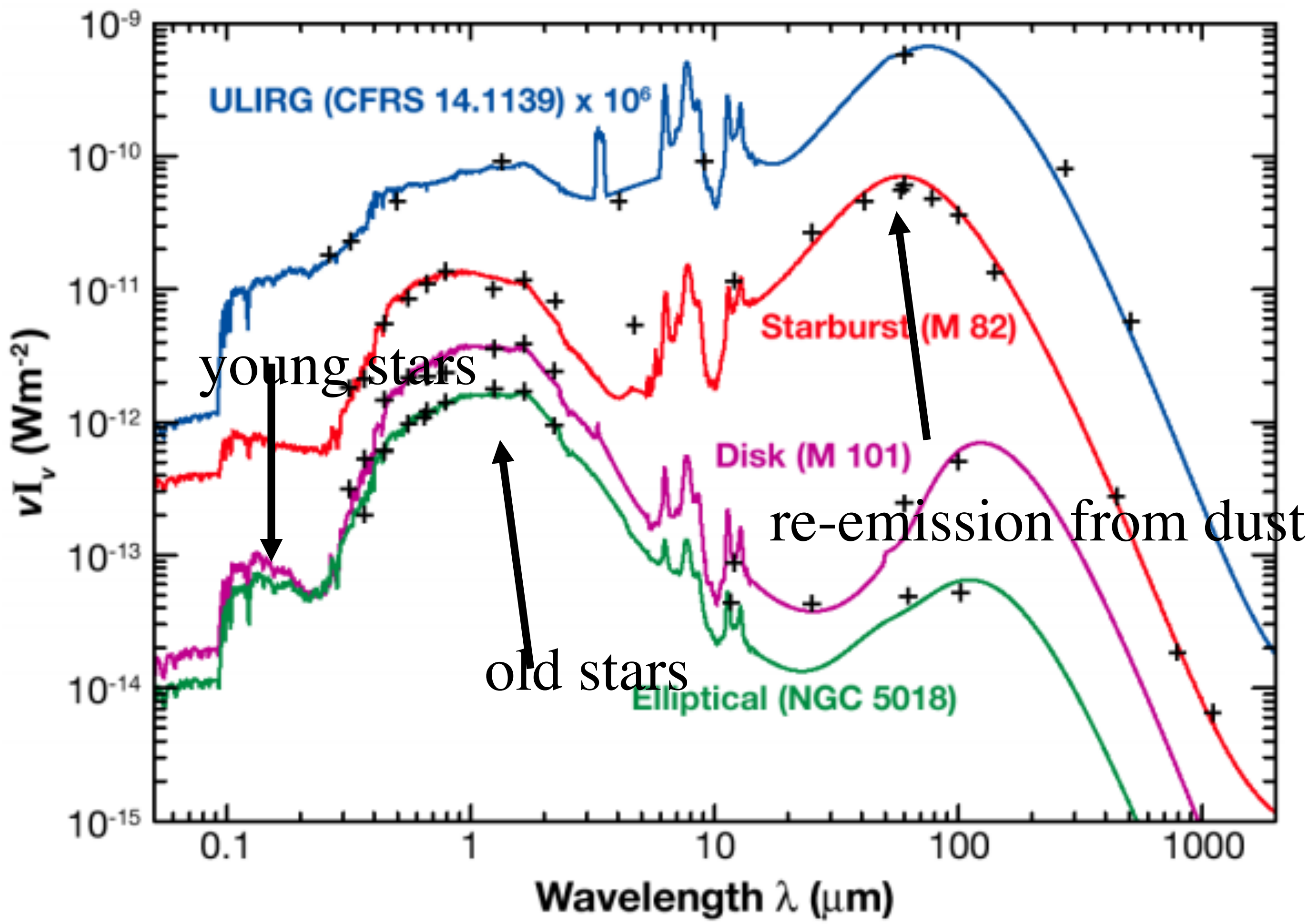




- Hδ vs D(4000)- distinguish SSP vs continuous star formation- features in summed stellar spectra

Put it All Together Into A Galaxy

- Even some ellipticals have dust



http://hubblesite.org/newscenter

Next Time

- GAS- physics of ... S+G 2.4+5.2