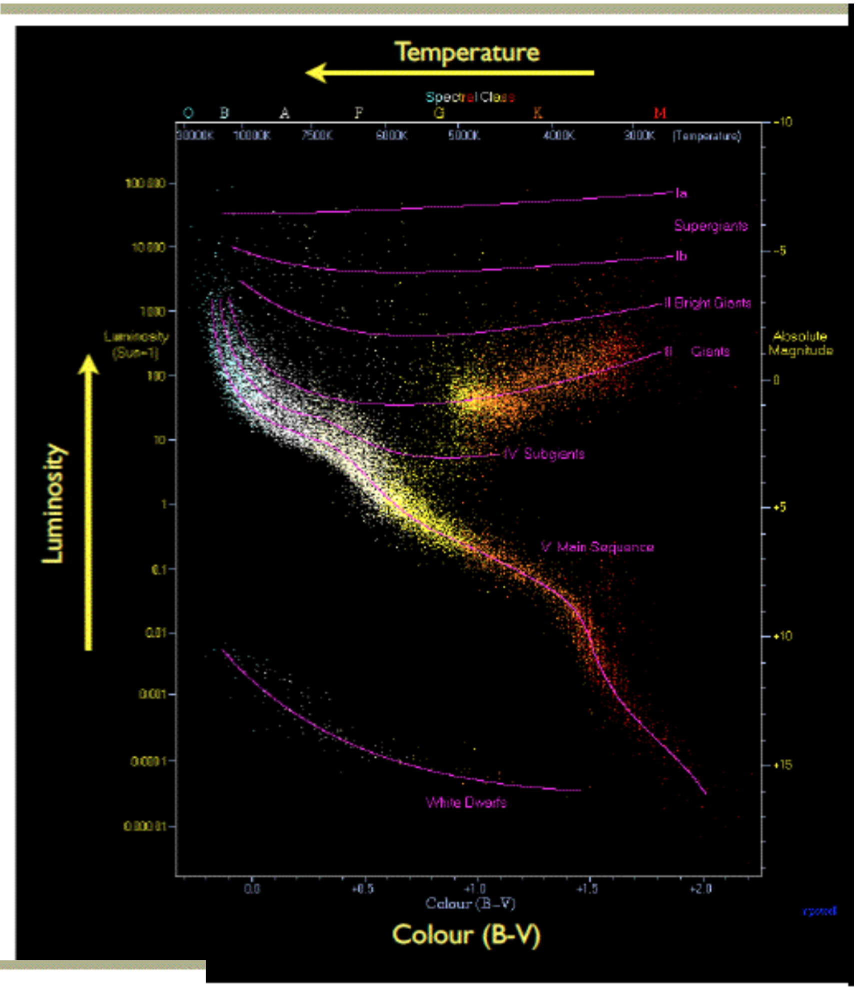
Stellar Populations of Galaxies- 2 Lectures

see MBW sec 10.1 for stellar structure theory- will not cover this

Top level summary

- stars with $M<0.9M_{\odot}$ have MS-lifetimes$>t_{Hubble}$
- $M>10M_{\odot}$ are short-lived:$<10^{8}$years$\sim 1t_{orbit}$
- Only massive stars are hot enough to produce HI–ionizing radiation
- massive stars dominate the luminosity of a young SSP (simple stellar population)

see 'Stellar Populations in the Galaxy Mould 1982 ARA&A..20...91



HERTZSPRUNG-RUSSELL DIAGRAM

Plots luminosity of stars, versus their temperature.

Stars populate distinct regions of this plane, corresponding to particular evolutionary phases.

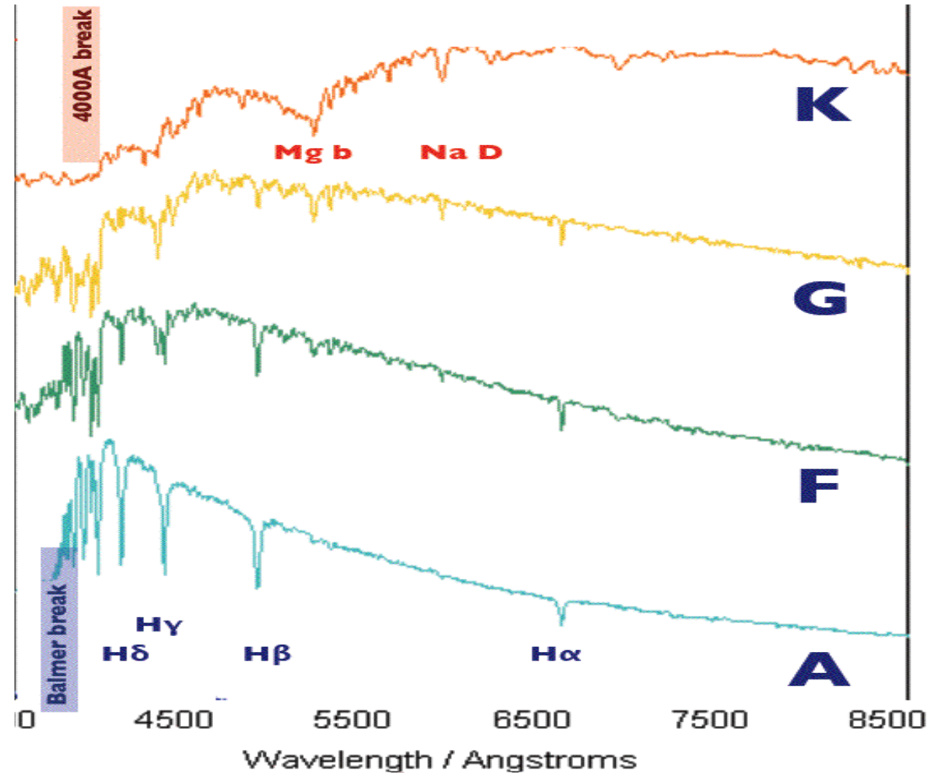
H-R(CMD) diagram of region near sun

H-R is theoretical

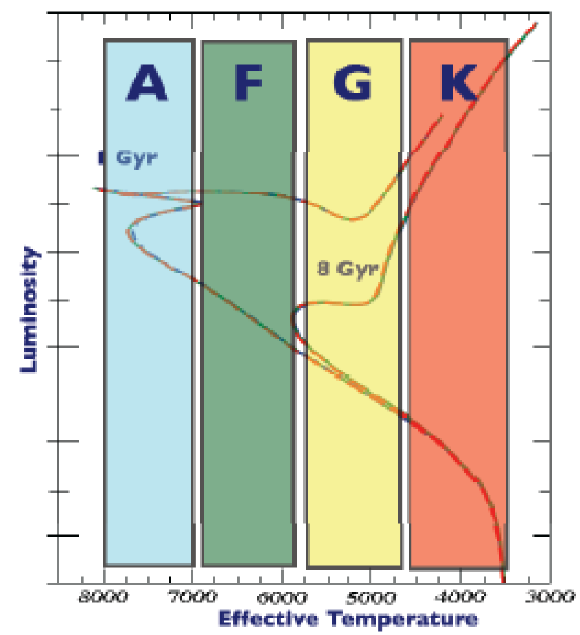
CMD is in observed units (e.g.colors)

Spectra of Individual Stars

- Stellar spectra reflect:
  spectral type (OBAFGKM)
- effective temperature T_{eff}
- chemical (surface)abundance
  - [Fe/H]+much more e.g [α/Fe]
  - absorption line strengths depend on T_{eff} and[Fe/H]
- surface gravity, log g
  - Line width (line broadening)
  - yields:size at a given mass
  - dwarf-giant distinction for GKM stars
- no easy'age'-parameter
  - Except e.g. $t<t_{MS}$

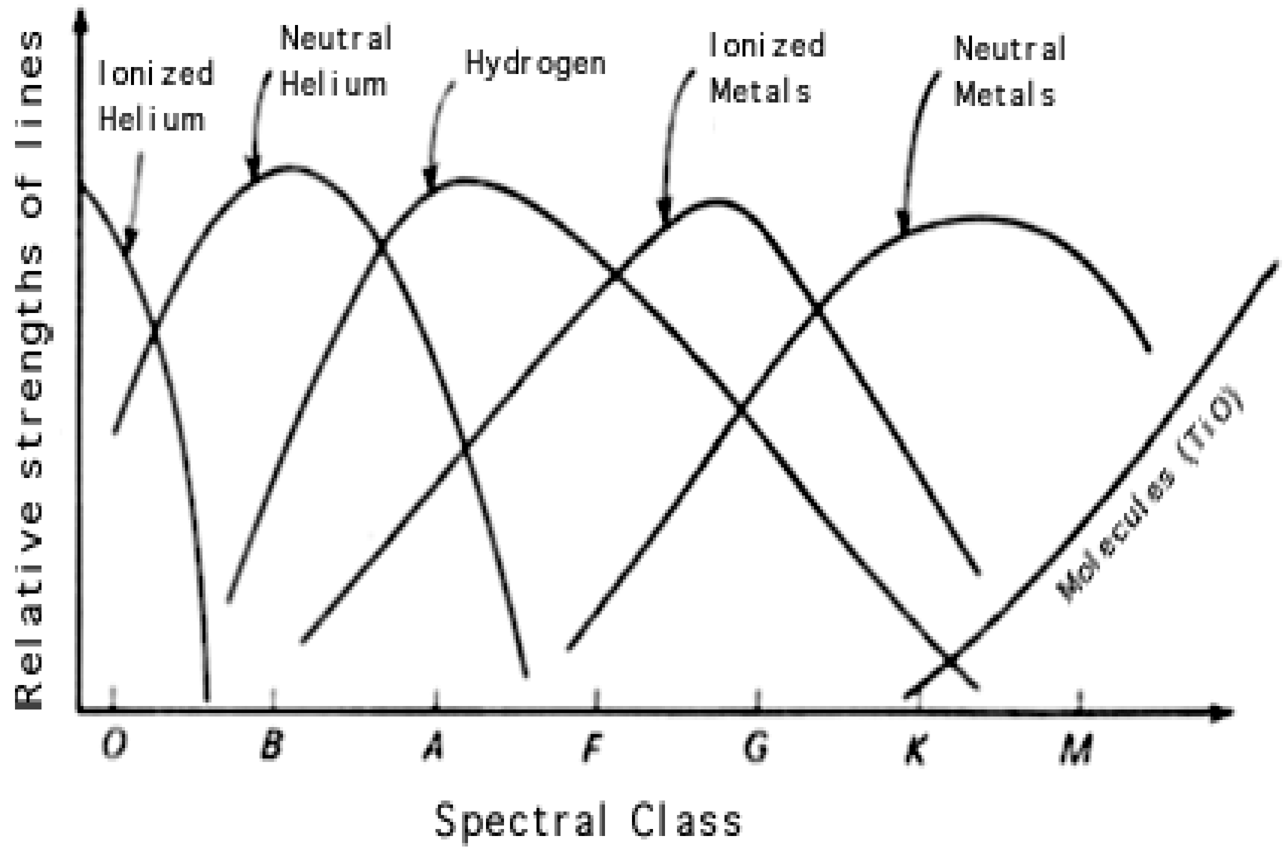


Luminosity



H.Rix

Basic Physics of Stellar Classes



- The spectra of stars from each class is dominated by different physical processes in the stars atmosphere-but there is strong overlap between classes

Again- horrible nomenclature eg. GOV, Wolf-Rayet, giants, dwarfs etc etc tables 1.4-1.6 in S+G
Huge (~ 10^9)range in luminosities (table 1.4)

Mass and age are the prime determinant of stars properties

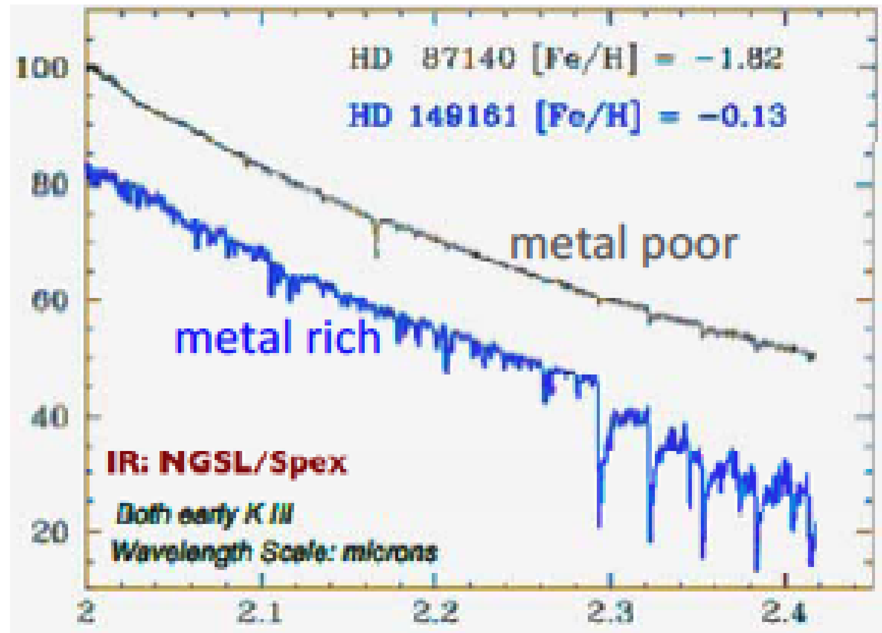
More Details

- If one has spectra of individual stars much can be learned -detailed metallicity, gravity, rotation rate
- BUT for composite stellar systems in real galaxies much harder to obtain this information due to
  - velocity of stars broadens features
  - composite spectra are not unique
- For young populations (<300 Myrs)

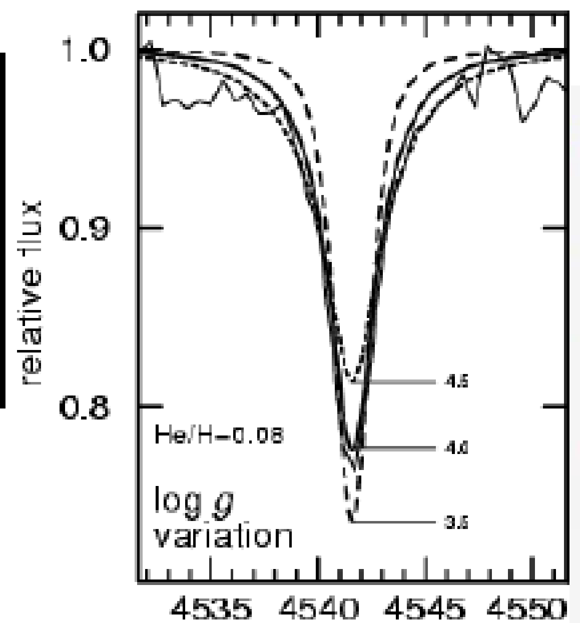
– upper MS stars (massive, young) dominate integrated L_{bol}

- For old populations (>2Gyrs)

– red giants (moderate mass, wide range of ages) dominate integrated L_{bol}

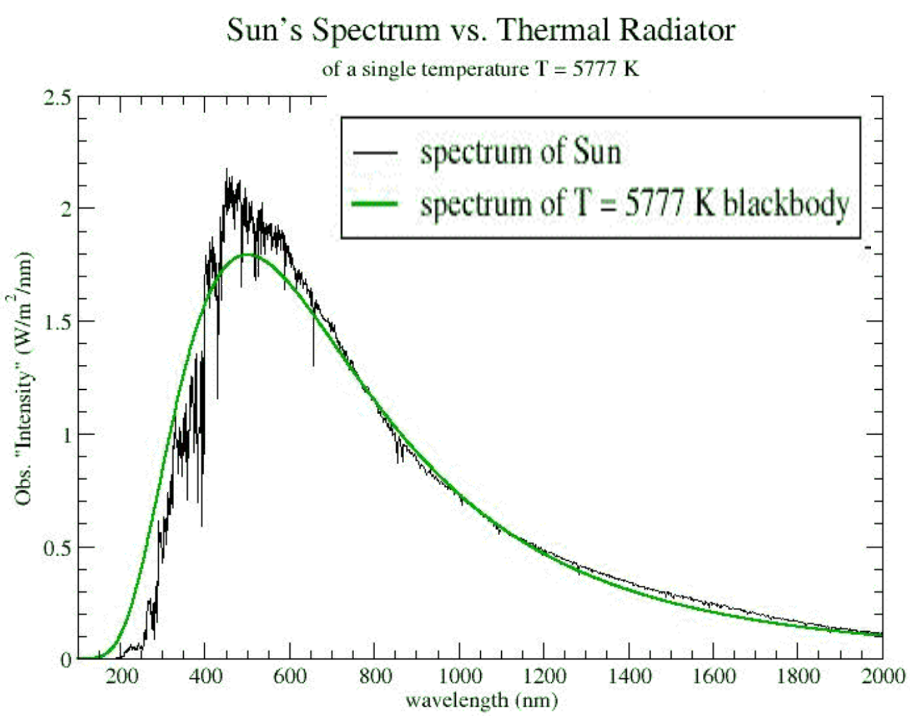


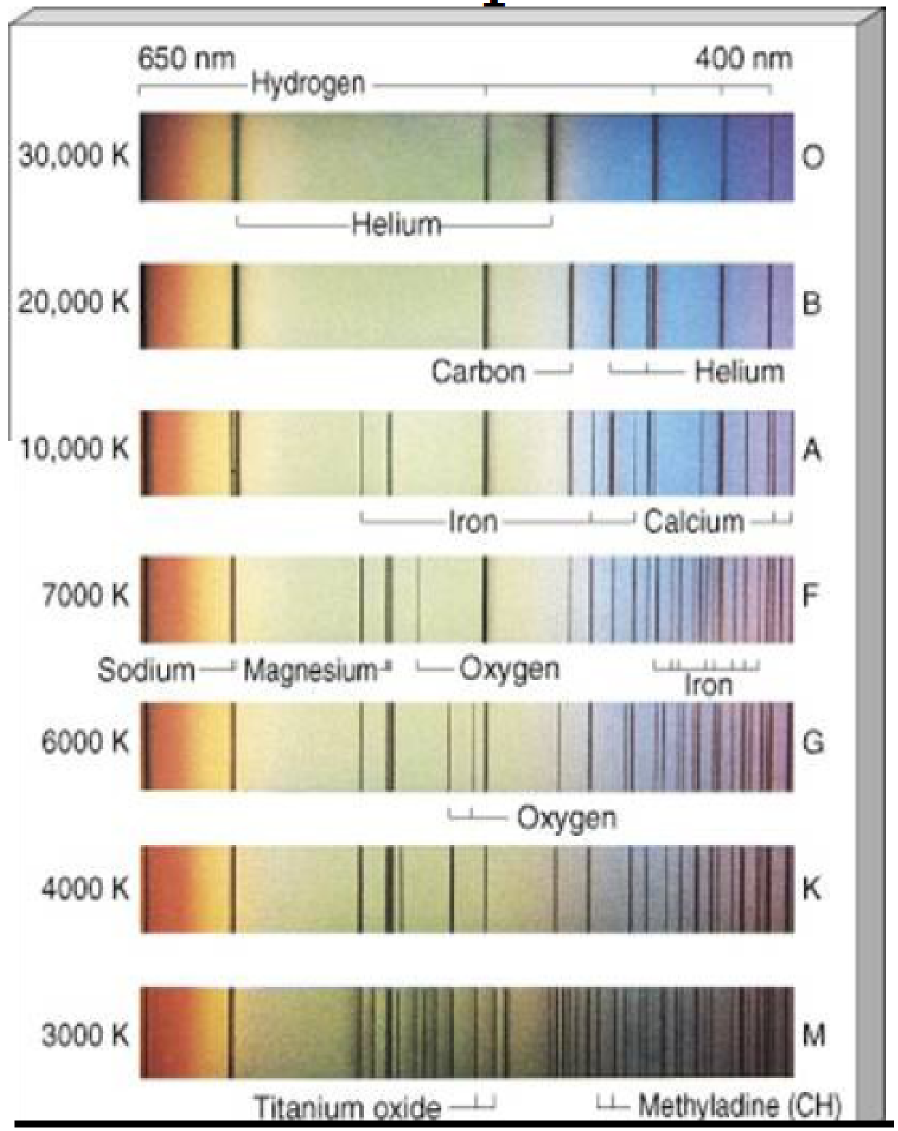
line shape as a function of surface gravity



- To zeroth order stellar spectra can be approximated as black bodies of the appropriate temperature. - If this is true comparison of flux in 2 well separated bands measures the temperature

Stellar Spectra





http://homepages.wmich.edu/~korista/sun-images/solar_specbb.jpg

discovery of quantum levels

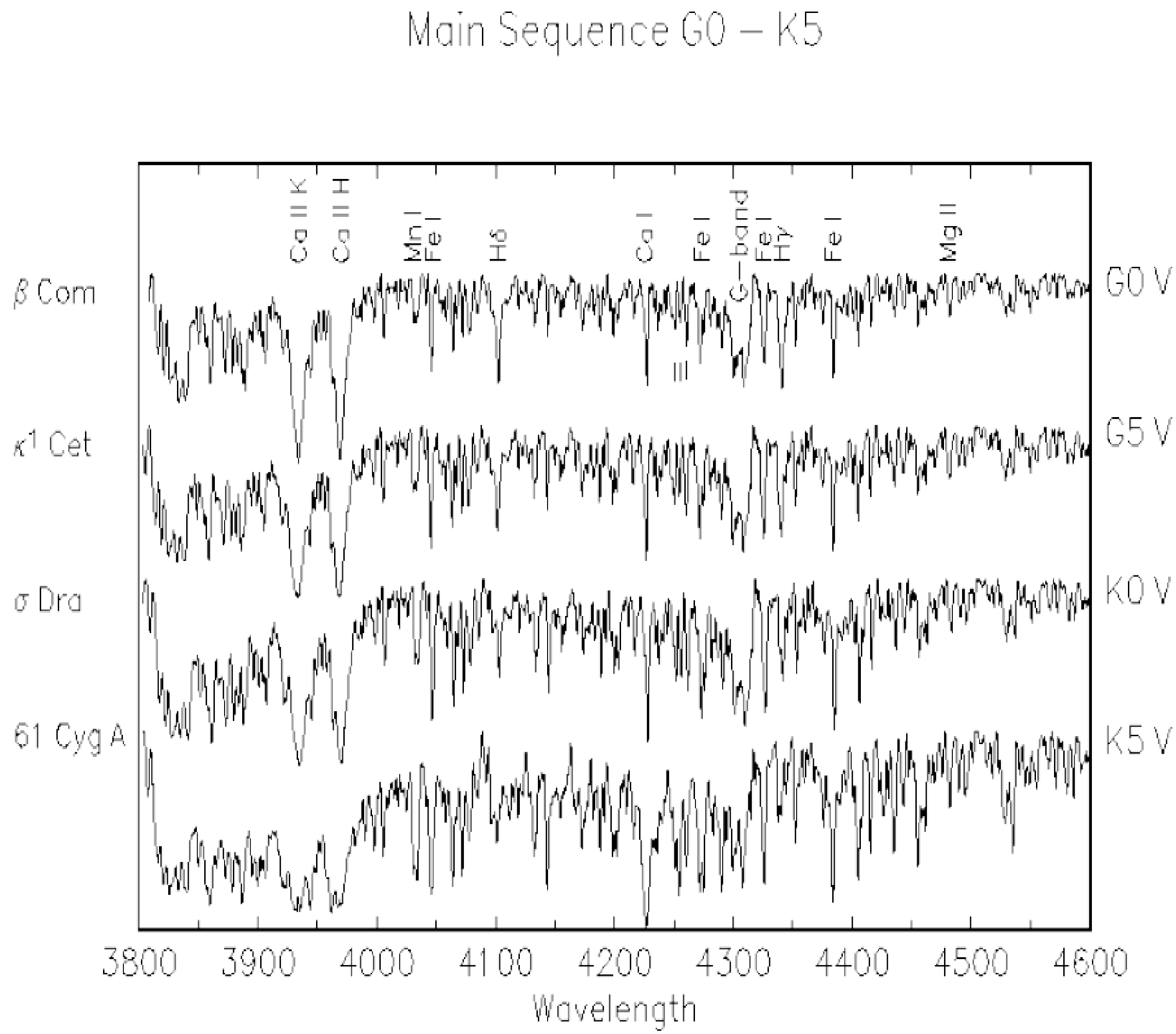
Simplest Physics of Stellar Spectra

- "hot" opaque bodies emits a continuous spectra.
- "hot" low density gas emits a sequence of emission lines. - a neon sign.

- "cold" low density gas, placed in front of a hot opaque body, produces a continuous spectrum with dark lines on top (absorption lines). - light from the sun.
- Every element (Hydrogen, Oxygen, Nitrogen etc.) produces
  - a unique set of emission and absorption lines
    - contains information on the ionization state of the element , its velocity (and with more discrimination the density of the gas and whether it is in equilibrium)

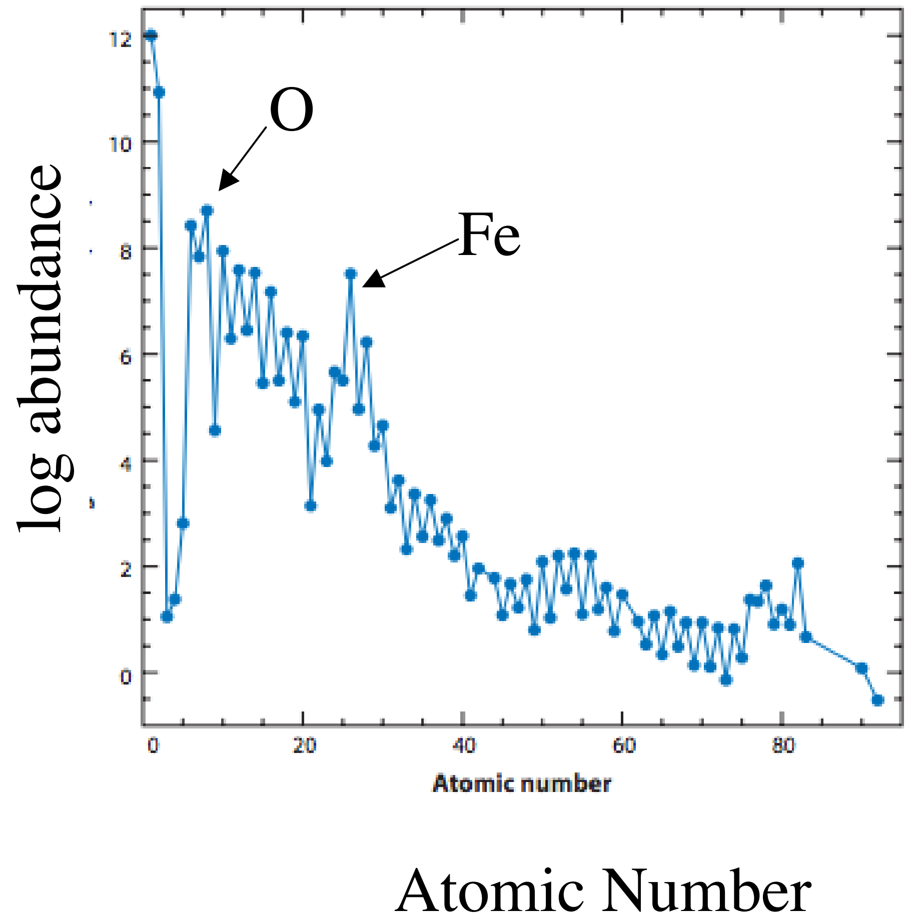
- Detailed spectra of bright stars can reveal their age, metallicity, rotation rate, size and distance.... allowing measurements of detail of MW structure, age, chemical evolution..etc

- Need very high (>30,000) spectral resolution ($\lambda/\delta\lambda$)



Chemical Composition of Stars

- It is frequent to normalize the chemical composition of an astrophysical system to the sun- The Chemical Composition of the Sun Annual Review of Astronomy and Astrophysics 47: 481-522 Asplund et al
- There are 2 types of variation: total abundance of 'metals' (elements heavier than He) and their relative abundance; total abundance of metals by mass (Z) in sun is ~0.013
- to zeroth order (more later) there are 4 sources of metals
- BBN- Li Be
- Type I SN -Fe, Ni etc
- Type II SN - O, Ne, etc
- Other (stellar winds, planetary nebulae etc) - N, C - still to be understood .



•in nearby stars, 40-80% of the carbon is due to low- and intermediate-mass stars.

•The stellar origin of carbon is thus uncertain, (e.g. Mattsson 2012)

Luminosity Mass Relation

- on the main sequence stars of the same age and metallicity have simple scaling relations (first order) between mass, luminosity and size
  - 2nd order corrections can be important
  - Basic physics of stellar structure eqs (MBW sec 10.1.4) shows that on the main sequence L~

    $81(M/M_\odot)^{2.14}$ $M>20M_\odot$

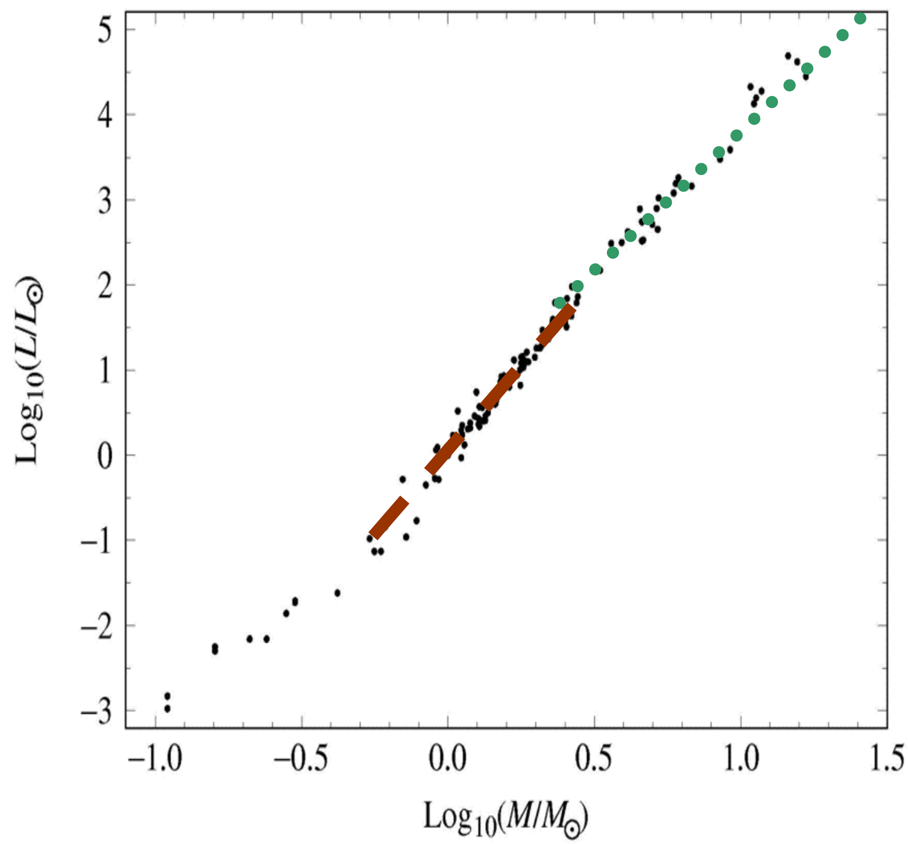
    $1.78(M/M_\odot)^{3.5}$ $2M_\odot<M<20M_\odot$

    $0.75(M/M_\odot)^{4.8}$ $M<2M_\odot$

$L \sim T^b$ with b~4.1 at low and 8.6 at high mass

Notice the very strong dependences

Lifetime on MS ~M/L~M^{-3}



$$R \propto R_\odot \left(\frac{M}{M_\odot}\right)^\alpha, L \propto L_\odot \left(\frac{M}{M_\odot}\right)^\beta$$

$\alpha \sim 0.7$, $\beta \sim 5$

Estimating Lifetimes - MS

26.7 MeV released every time 4H $\longrightarrow$ He + ν + photons

The difference in mass of 4H and He is

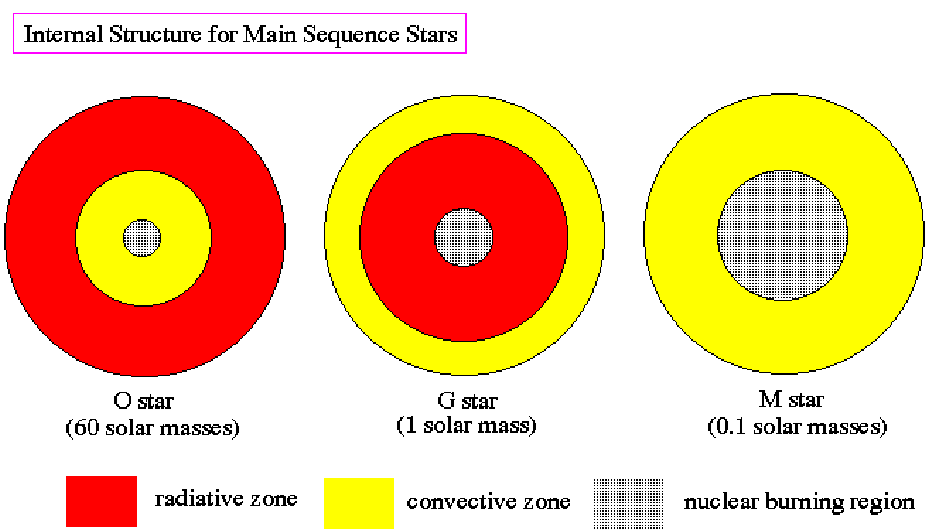
$4m_{proton} - 3.97m_{proton} = 0.0267m_{proton}$

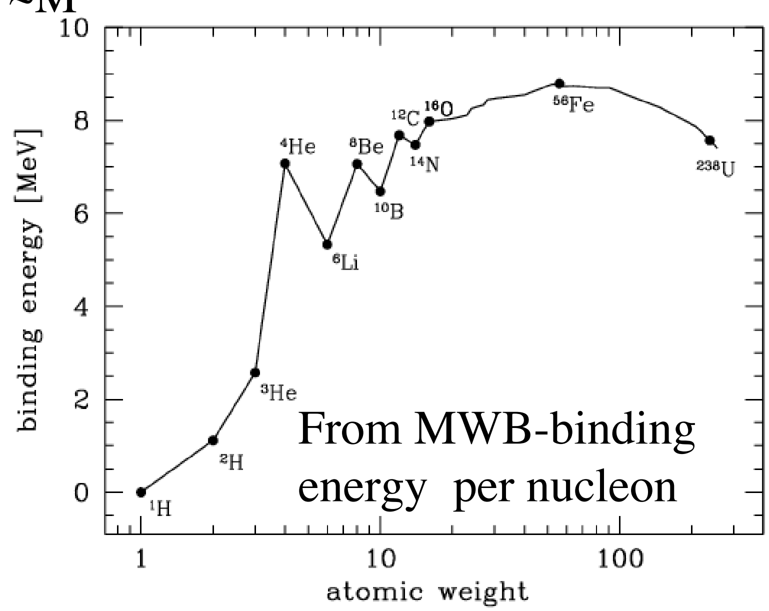
The efficiency of converting mass to energy with p-p process is 0.03 / 4 = 0.007, or 0.7% (some of the energy goes into neutrinos)

- So, $t_{MS} = (0.007\ \alpha M\ c^2) / L$

α is the total mass of H converted to He while the star is on the main sequence- varies with mass : nuclear burning regions takes up a larger percentage of the stellar interior as one goes to low mass star.

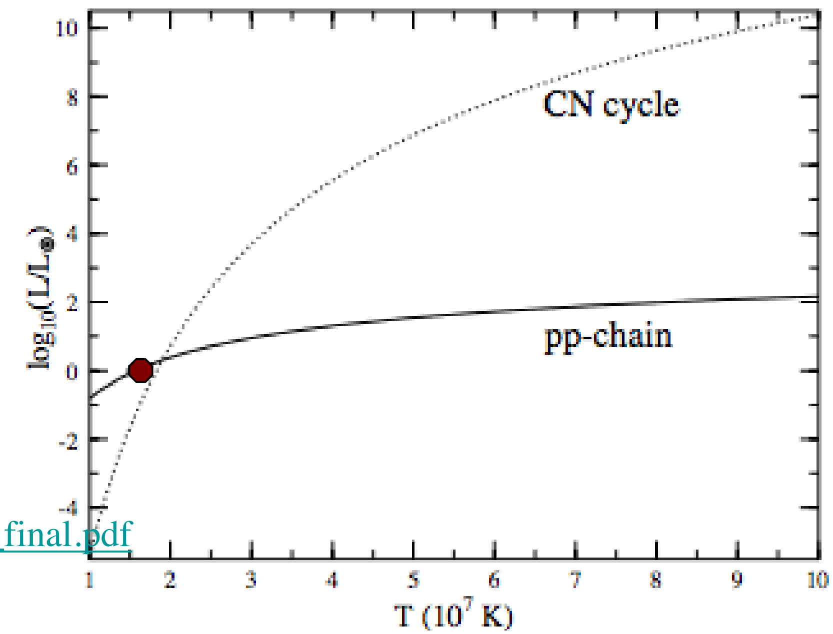
In terms of useful units, $t_{MS} \sim 10^{10}(M/M_{solar})/(L/L_{solar})$; $\sim M^{-2.5}$





Energy Generation on Main Sequence

- p-p goes at ρT^{4}- dominates in sun
- C-N-O as ρT^{17}- if $M > 1.5 M_{\odot}$ this dominates



http://www.int.washington.edu/PROGRAMS/SolarFusionII_revised_final.pdf

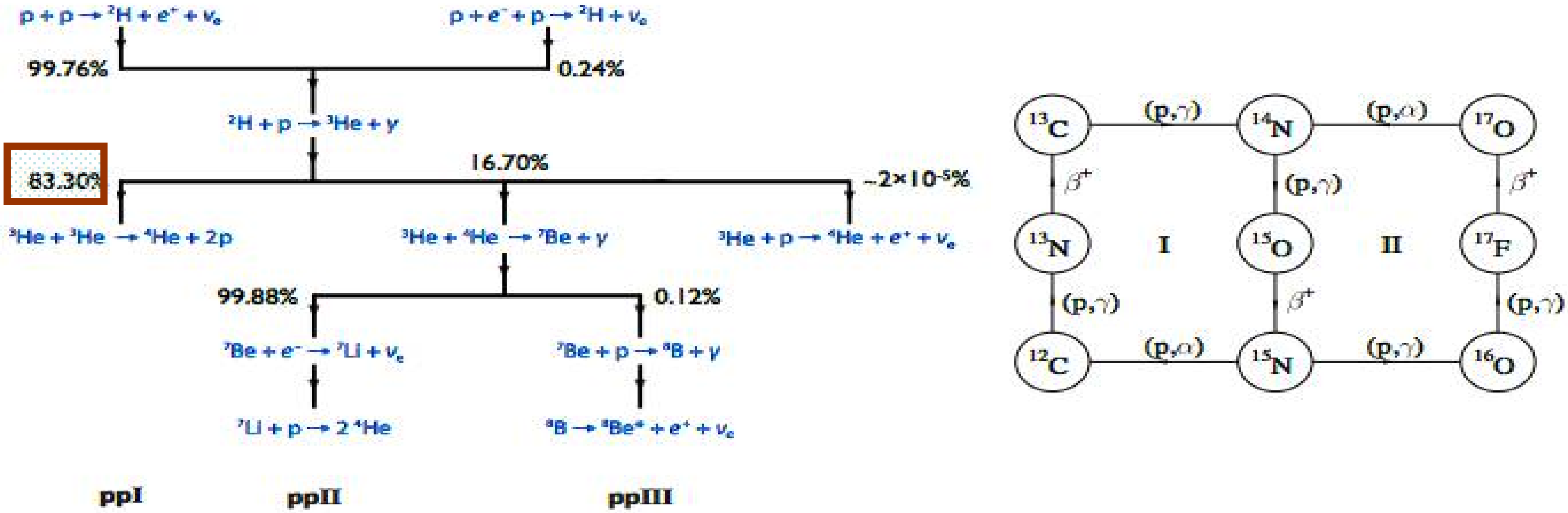
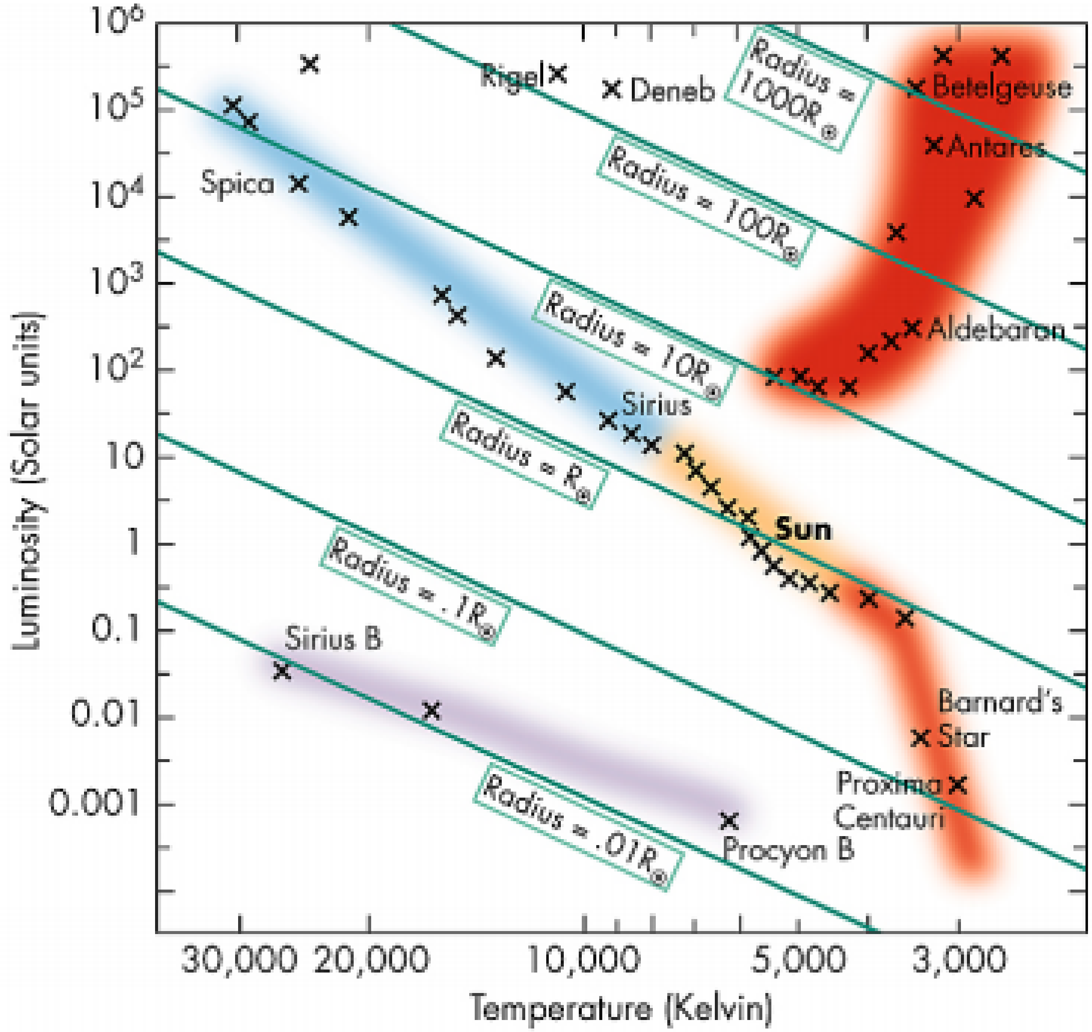


FIG. 2 The left frame shows the three principal cycles comprising the pp chain (ppI, ppII, and ppIII), with branching percentages indicated, each of which is "tagged" by a distinctive neutrino. Also shown is the minor branch ${}^3He+p \rightarrow {}^4He+e^+ +\nu_e$, which burns only $\sim 10^{-7}$ of ${}^3He$, but produces the most energetic neutrinos. The right frame shows the CNO bi-cycle. The CN cycle, marked I, produces about 1% of solar energy and significant fluxes of solar neutrinos.

Stellar Sizes/Luminosity/Temperature

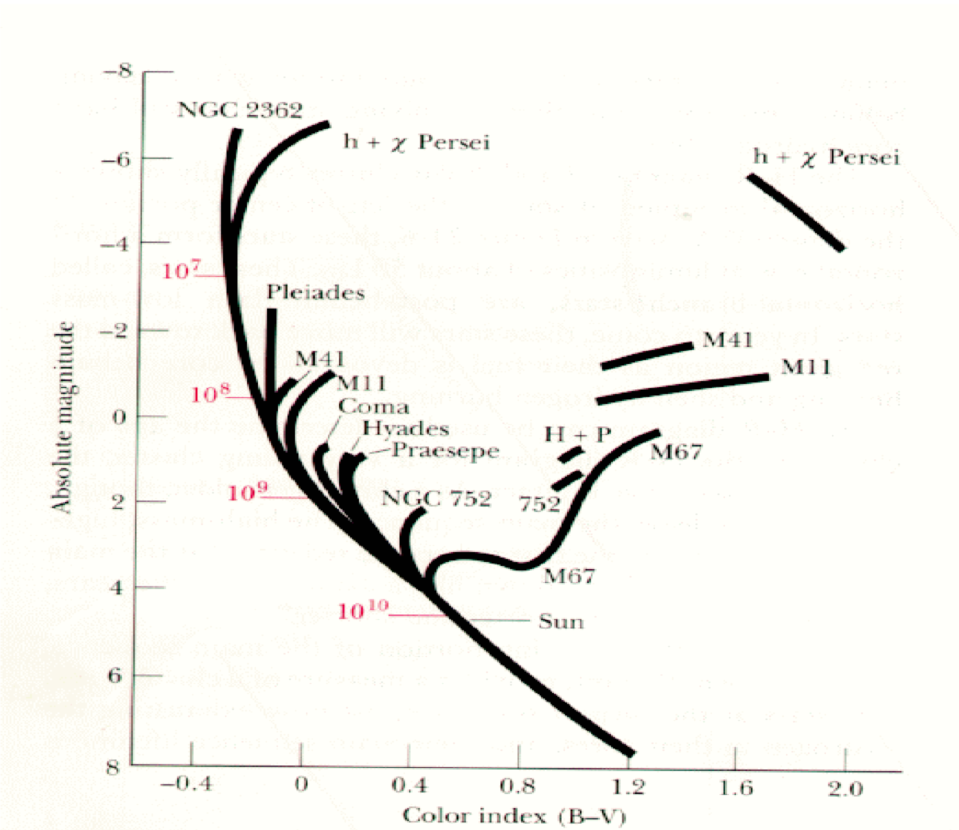
- Stefan-Boltzman law- Lines $L \sim T^4$
- Over a wide range in luminosity stars radiate close to a Black body spectrum in the optical band

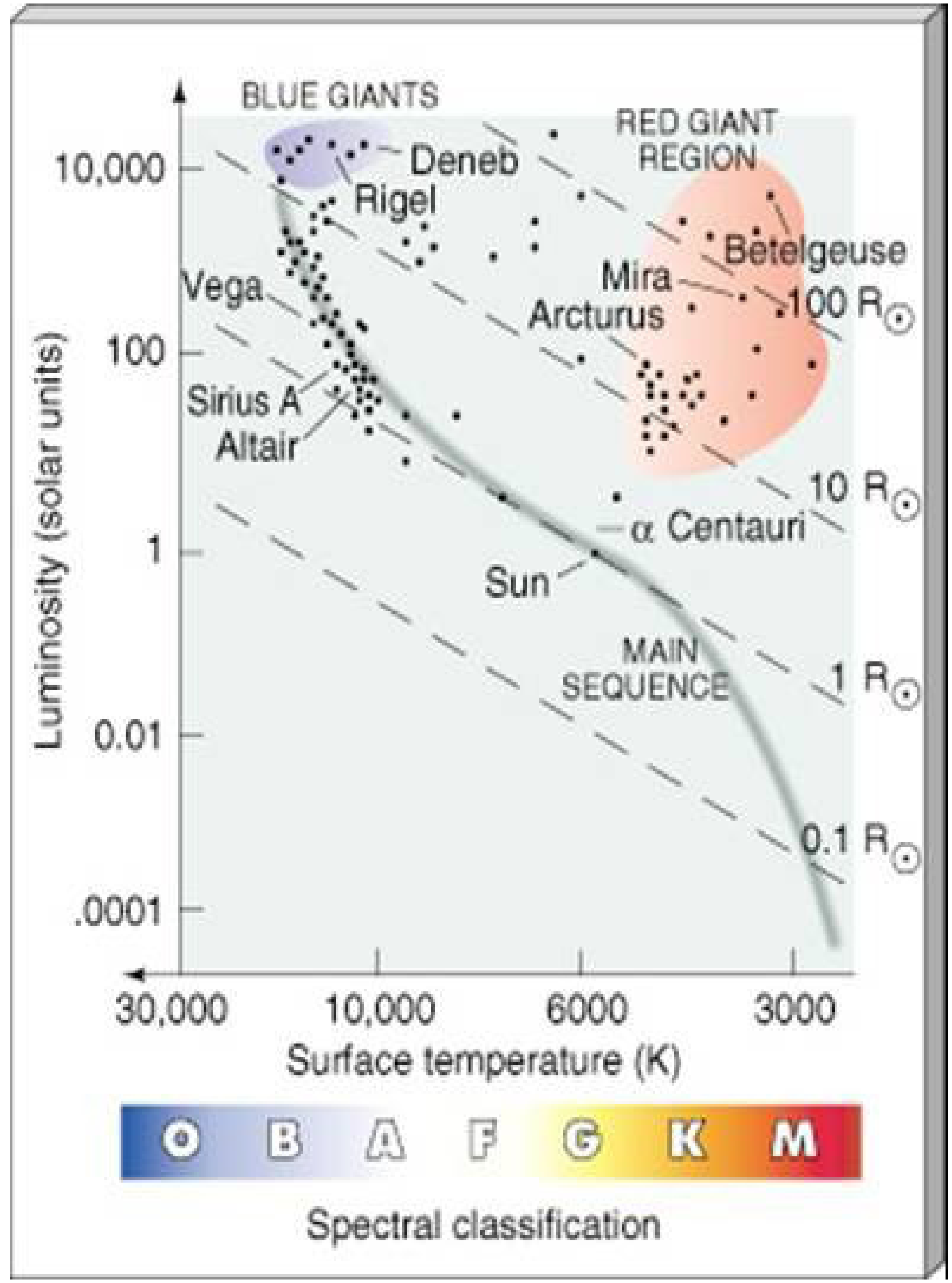


http://www.physics.isu.edu/~hackmart/spectral_class.pdf

H-R Diagram for Visible Stars in MW

- The brightest stars in the visible sky do NOT sample the H-R diagram well -how does one construct an appropriate sample?
- Need to go much fainter, find 'co-eval' populations (e.g. **open clusters** like the Hyades)





Stellar evolution reminder

HERTZSPRUNG-RUSSELL DIAGRAM

Russell Smith Durham

Plots luminosity of stars, versus their temperature.

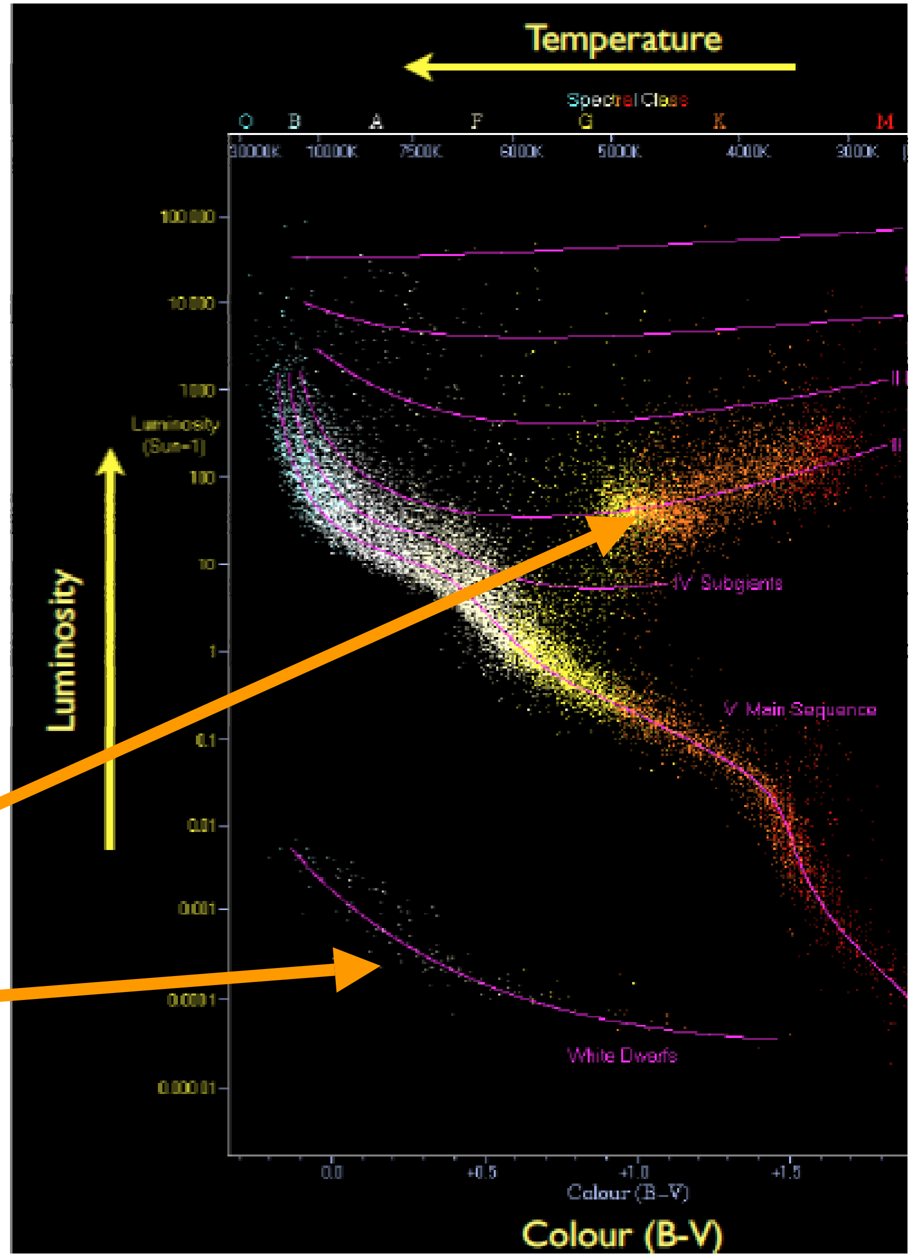
Stars populate distinct regions of this plane, corresponding to particular evolutionary phases.

H-R diagram organizes the observed optical properties of stars

Main sequence

white dwarfs

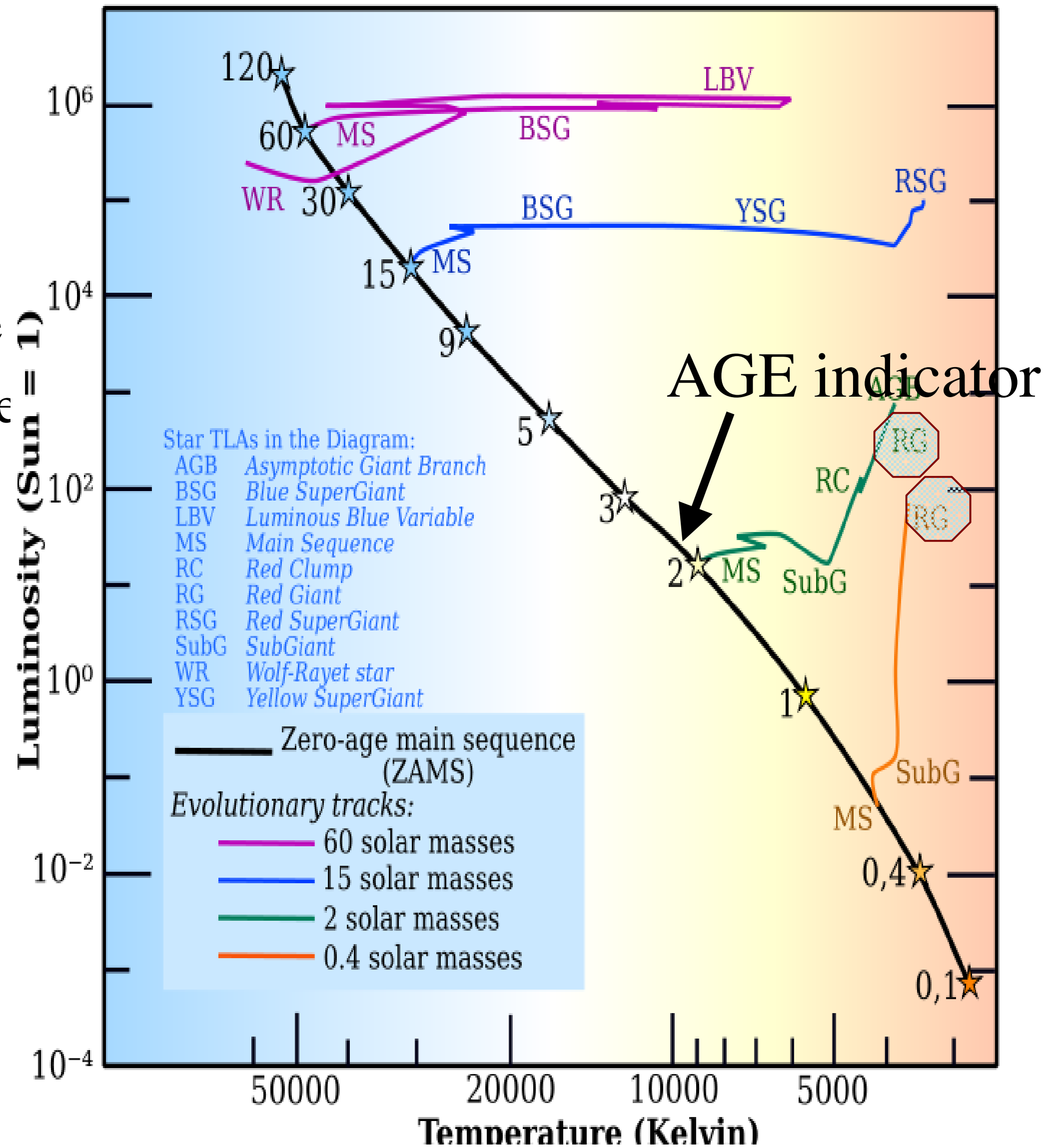
giant branch



TRACKS

"Tracks" are trajectories of individual stars in the H-R

Stellar evolutionary tracks trace the evolution of a given mass star vs time luminosity, temperature plane



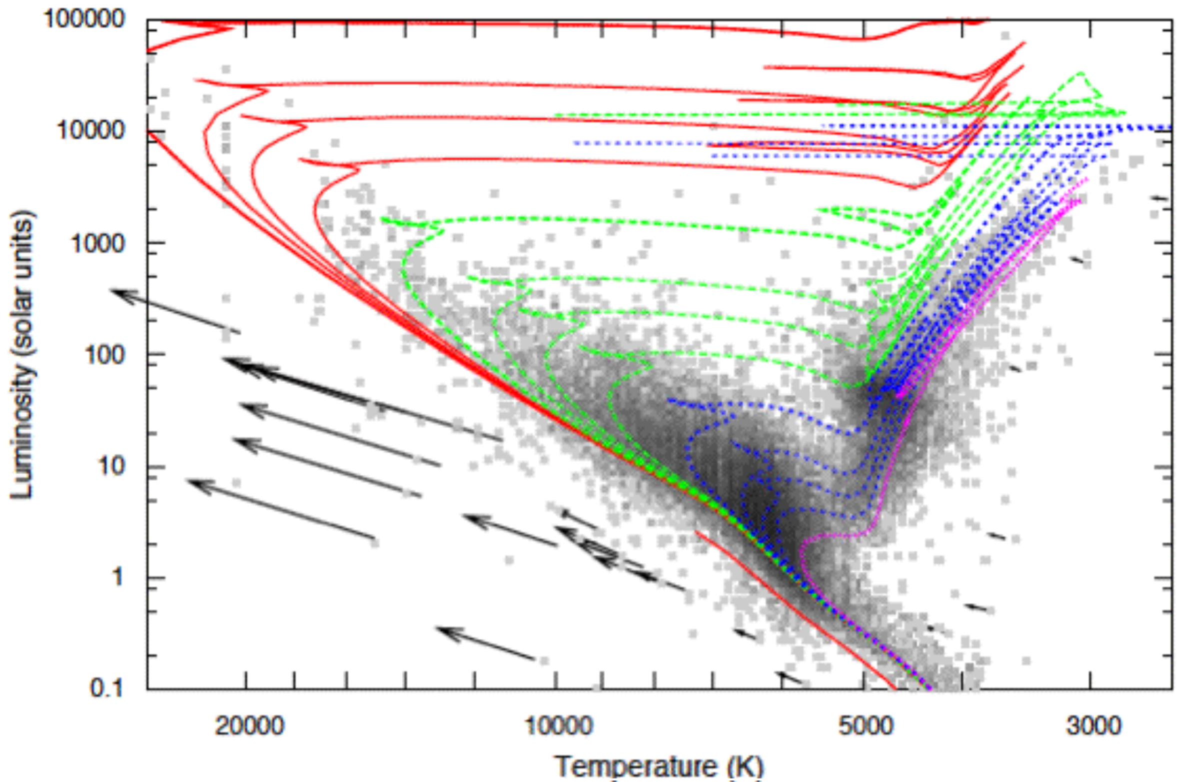
as a function of initial mass (and initial chemical composition).

In detail, the tracks are computed from stellar evolution models (Padova, Geneva, BaSTI etc).

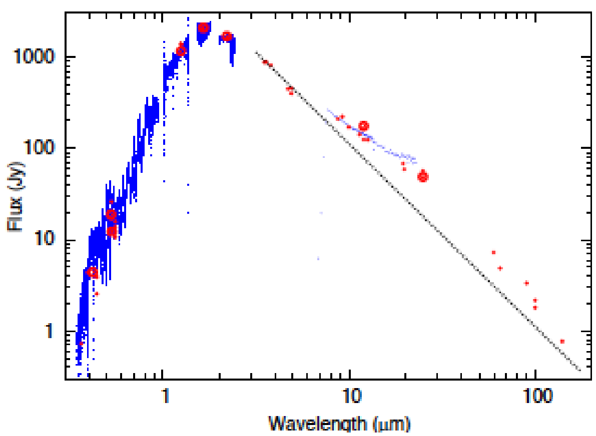
Russell J. Smith Durham
http://astro.dur.ac.uk/~rjsmith/stellarpops.html

H-R Diagram for stars d<200pc McDonald, Zijlstra, Boyer 2012

- Uses SDSS, Akari, WISE, 2MASS
- there is still a large amount of scatter in the H–R diagram. due to distance errors, causing vertical scatter



e 2. D he Pad ensity-coded Hertzsprung–Russell diagram for the 200-pc sample (greyscale). Overplotted are solar-metallicity isochrones dashed ain seq va models (Marigo et al. 2008; Bertelli et al. 2008) at 10, 20, 30 and 50 Myr (solid, red lines); 100, 200, 300 and 500 Myr he effe green lines); 1, 2, 3 and 5 Gyr (short-dashed blue lines); and 10 Gyr (dotted magenta line). The thin red line to the left of ience is a zero-age isochrone at [Fe/H] = −1 to illustrate the blueward shift caused by decreasing metallicity. Black arrows t of dereddening individual sources by $E(B-V) = 0.1$ mag.

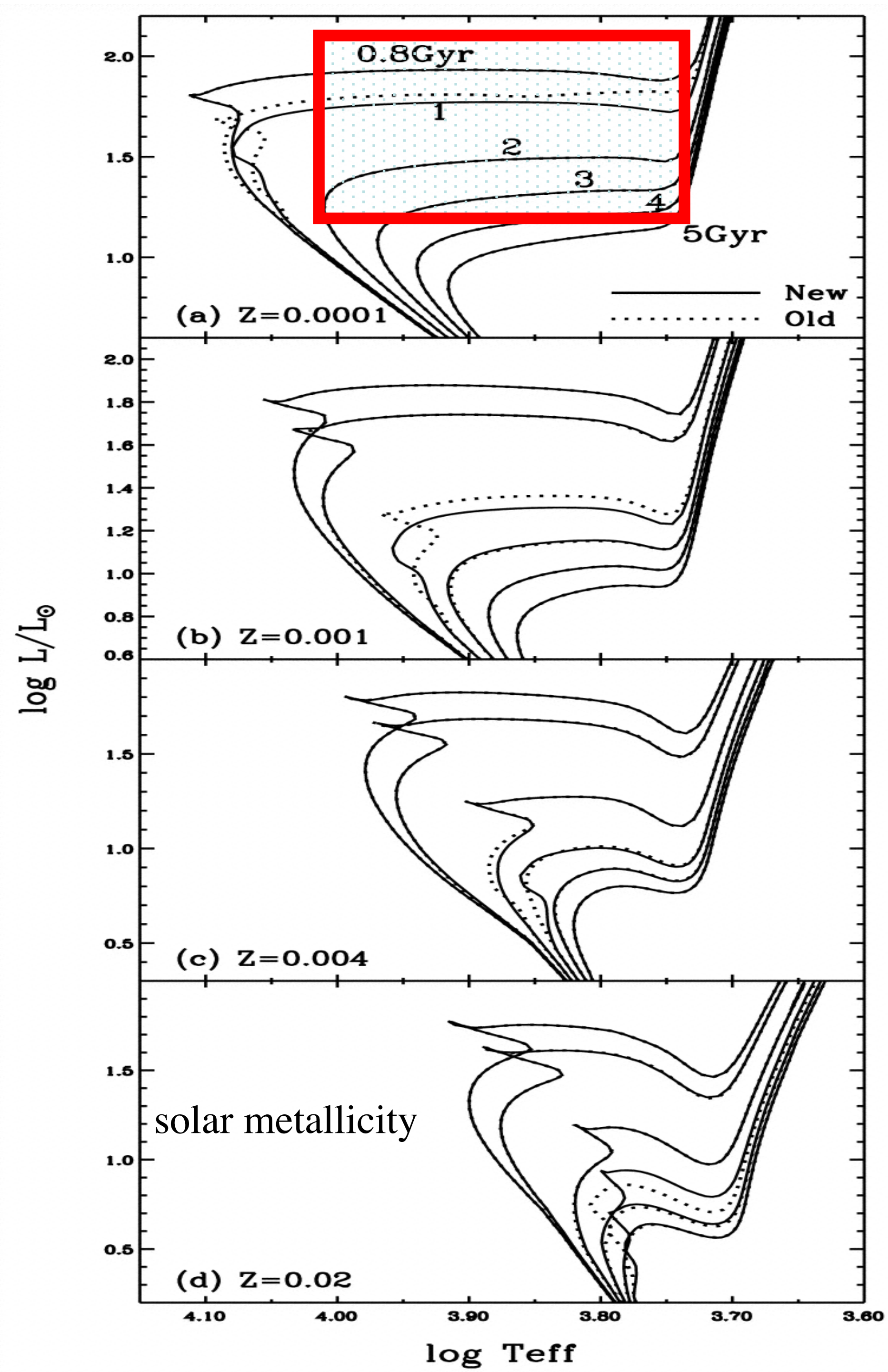


star with dust ring- IR excess not all light from stars is due to the star itself (!)

Theoretical Isochrones

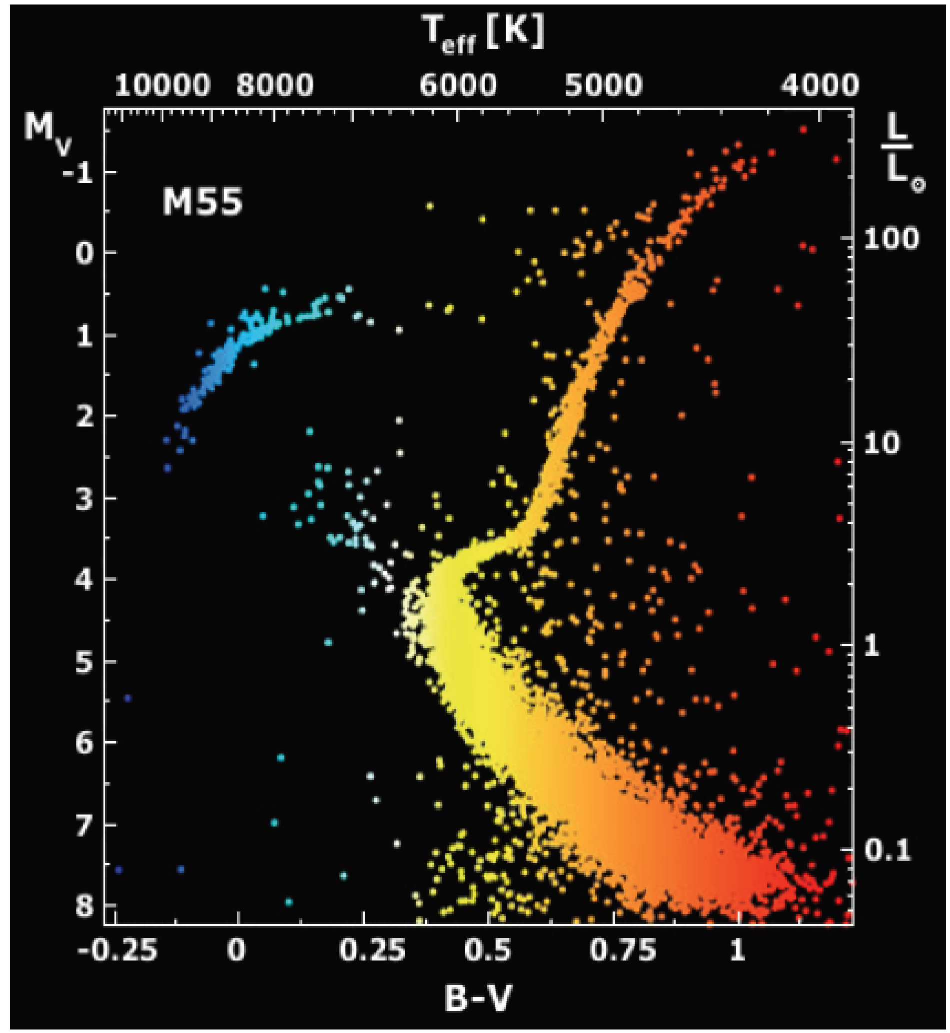
- These lines are the positions of stars from a SSP as a function of the age of the system - in the temperature/luminosity plane **if** no new stars are born
- The shape depends on the metallicity of the stars (Demarque et al 2004)

- 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)



A SSP

- Color-magnitude (H-R) diagram for stars in the globular cluster M55
- an old population of equal age+metallicity with no recent star formation ; e.g. a SSP
- To first order most Globular clusters are SSPs (some show metallicity variations)



astronomy picture of the day

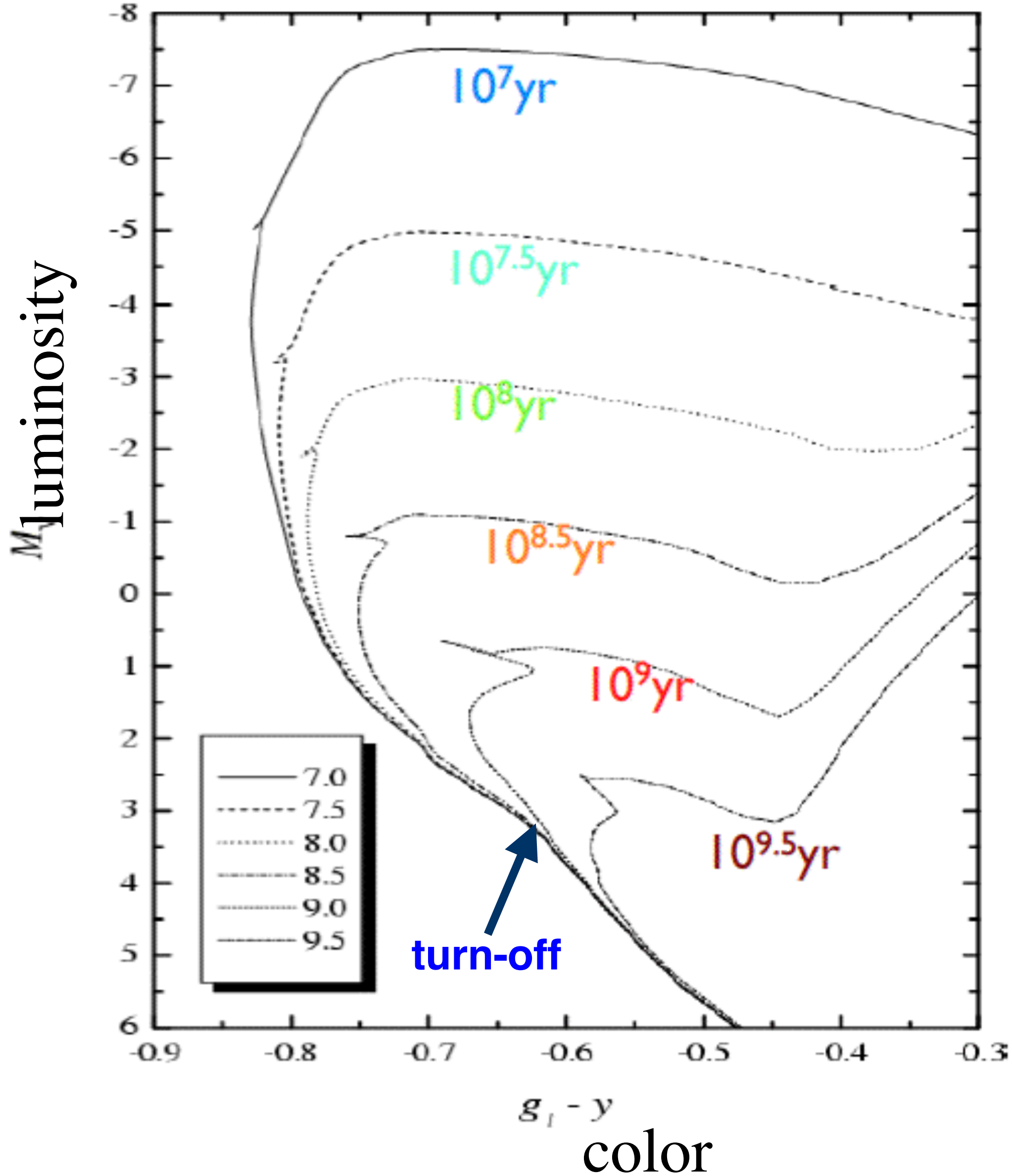
Isochrones

Theoretical lines in the H-R diagram of a given age for stars of different masses of a 'simple' stellar population

details depend on color used and stellar metallicity

'Simple' stellar population
has one age and metallicity
Theoretical models-allow estimate

- age **from MS turn-off**
- metallicity **from** giant branch color



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http://astro.dur.ac.uk/~rjsmith/stellarpops.html

MAIN SEQUENCE (MS)

Core hydrogen burning phase. Longest phase of evolution.

TURN-OFF

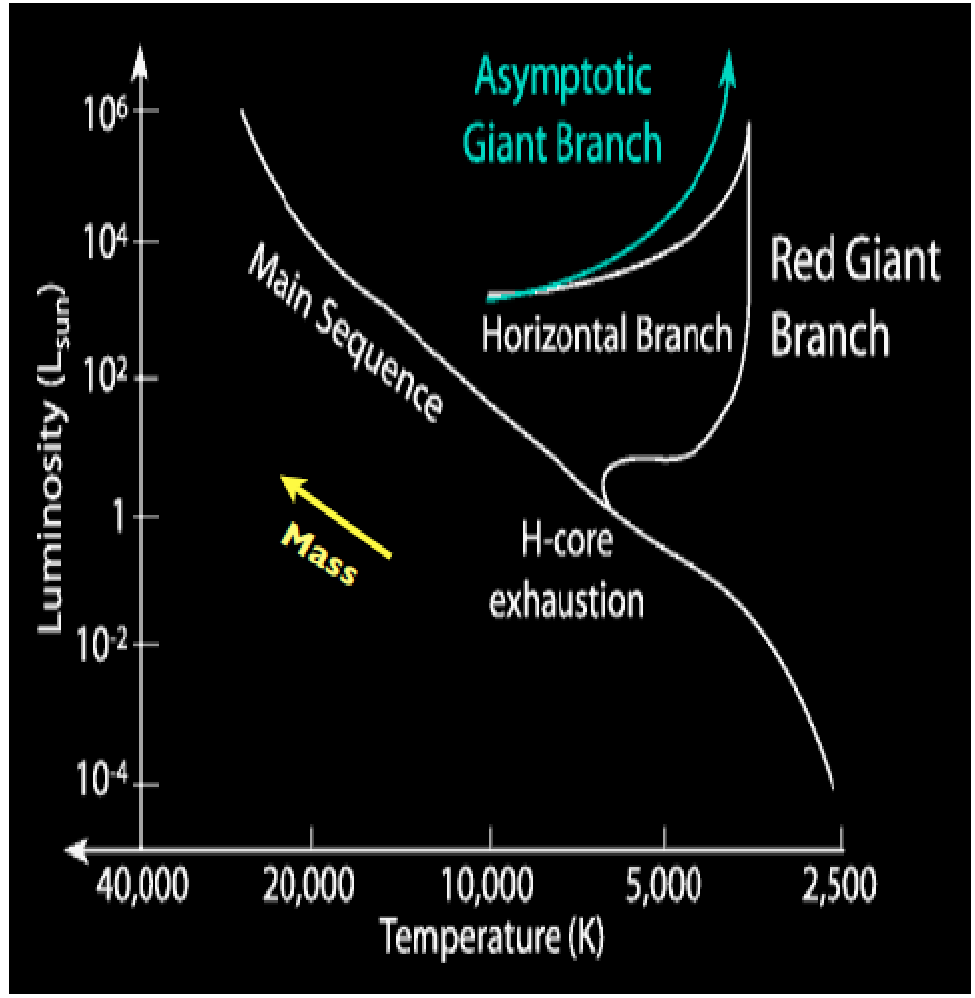
Hydrogen exhausted in core, start of "interesting" evolution.

RED-GIANT BRANCH (RGB)

Hydrogen burning in shell around inert helium core. Growth of He core.

RGB TIP

End of RGB phase: core massive and hot enough to ignite He-burning (the "helium flash")



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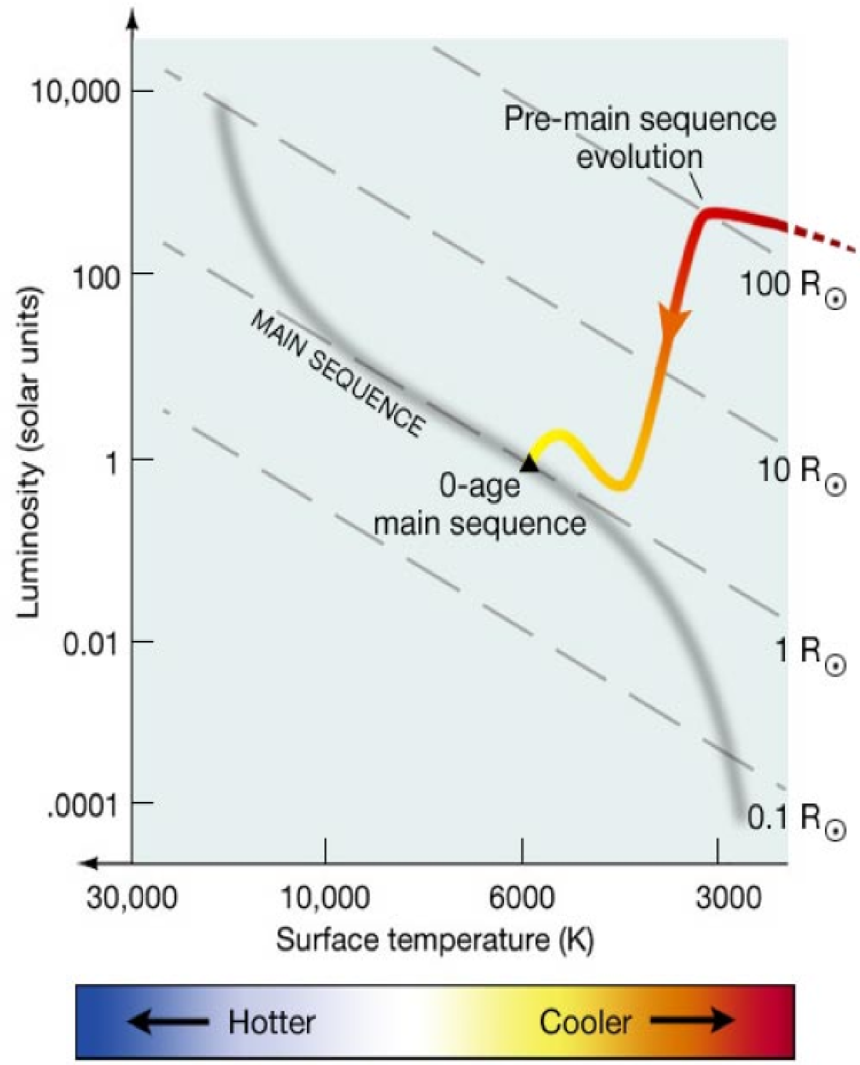
Main Sequence

H-R diagram is for 'zero age'

- 'low' mass stars evolve slowly-'stay' on the M-S for a long time
- On the M-S hydrogen burning' nuclear fusion in the core generates energy, the pressure is balanced by gravity-hydrostatic equilibrium.
- Stars spend ~80% of their lifetime on the M-S fusing hydrogen into helium.
- The position in the HR diagram changes with time, e.g. the Sun will slowly brighten and its color vary over its ~10^{10}year life on the Main Sequence. By the end of its MS lifetime, ~ twice as luminous as now

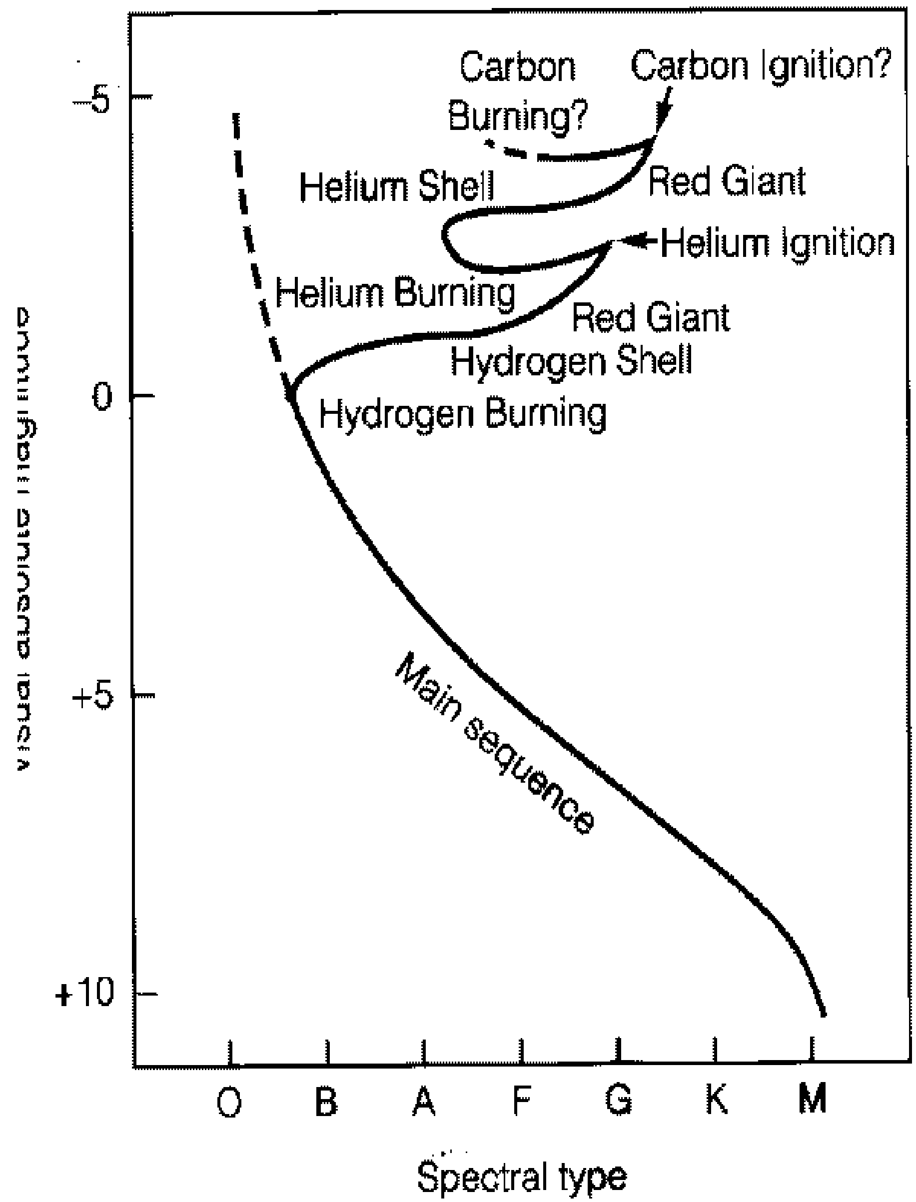


Dr. Christopher Palma PSU

Off the MS

- He burning only releases ~20% of the energy that H burning produces
- Lifetime in the He burning phase is

~ $2x10^9$ yrs for a solar mass star



MASS-DEPENDENT LIFETIMES

Lifetime in each evolutionary phase depends sensitively on initial mass.

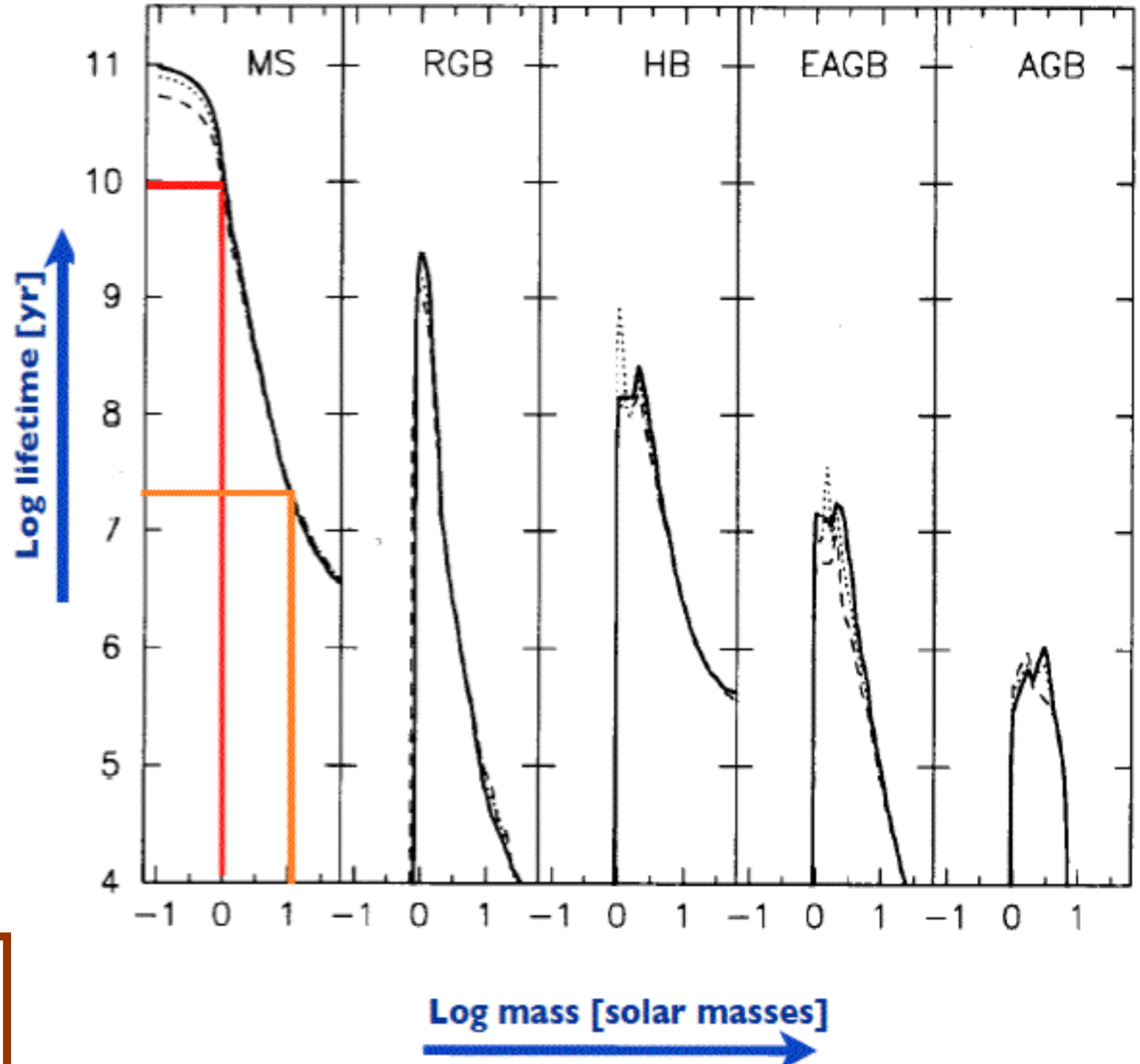
MS lifetime is ~10^{10} $(M/M_{sun})^{-2.5}$ yrs: so 10 Gyr at 1 solar mass, but only ~20 Myr for 10 $M_\odot$

Subsequent phases shorter-lived.

Below ~ 0.9 $M_\odot$, the MS lifetime is longer than age of Universe!

Mass-vs-lifetime relation is one of the crucial tools for age-dating populations.

MS= main sequence, RGB= red giant branch HB= horizontal branch etc



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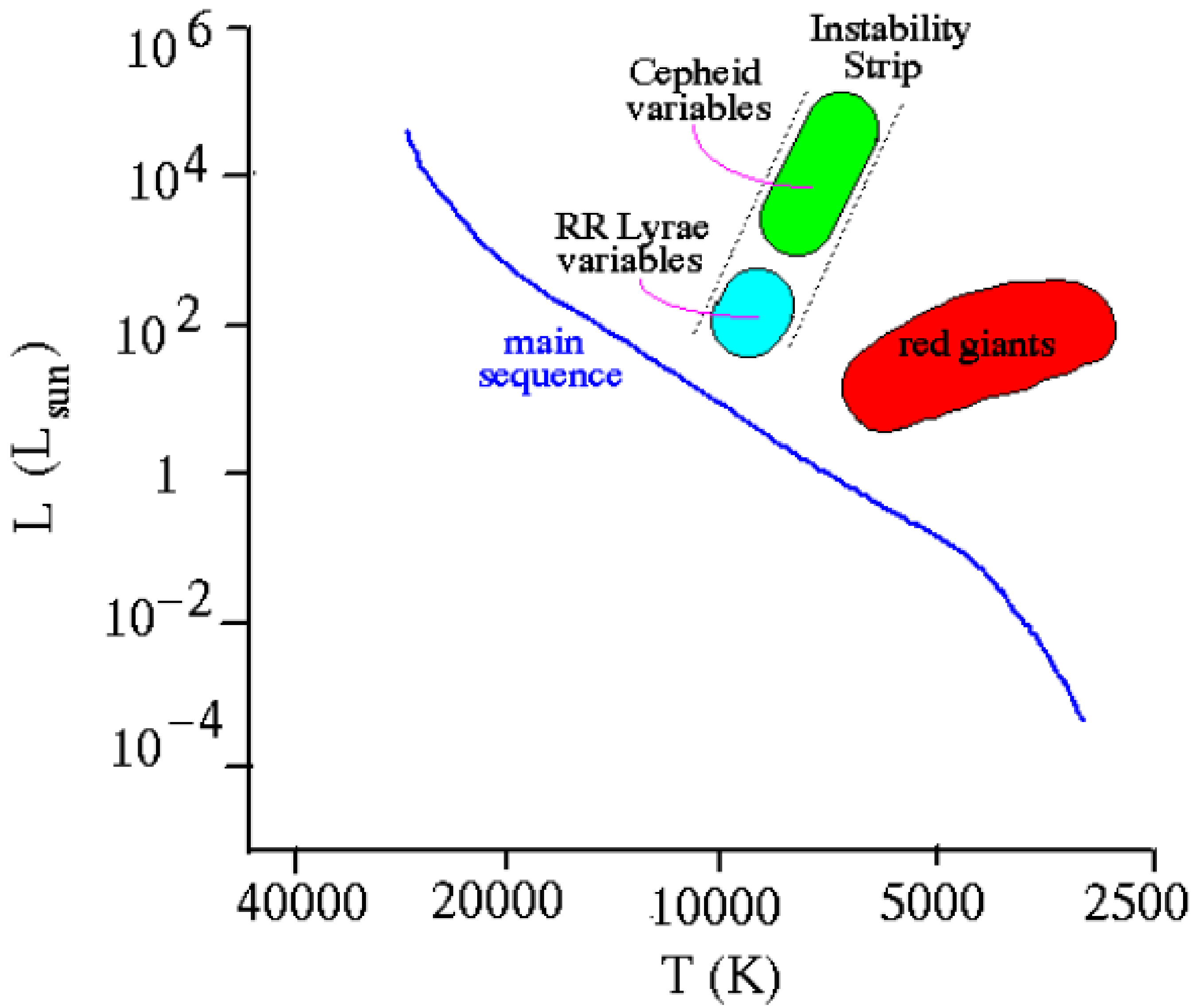
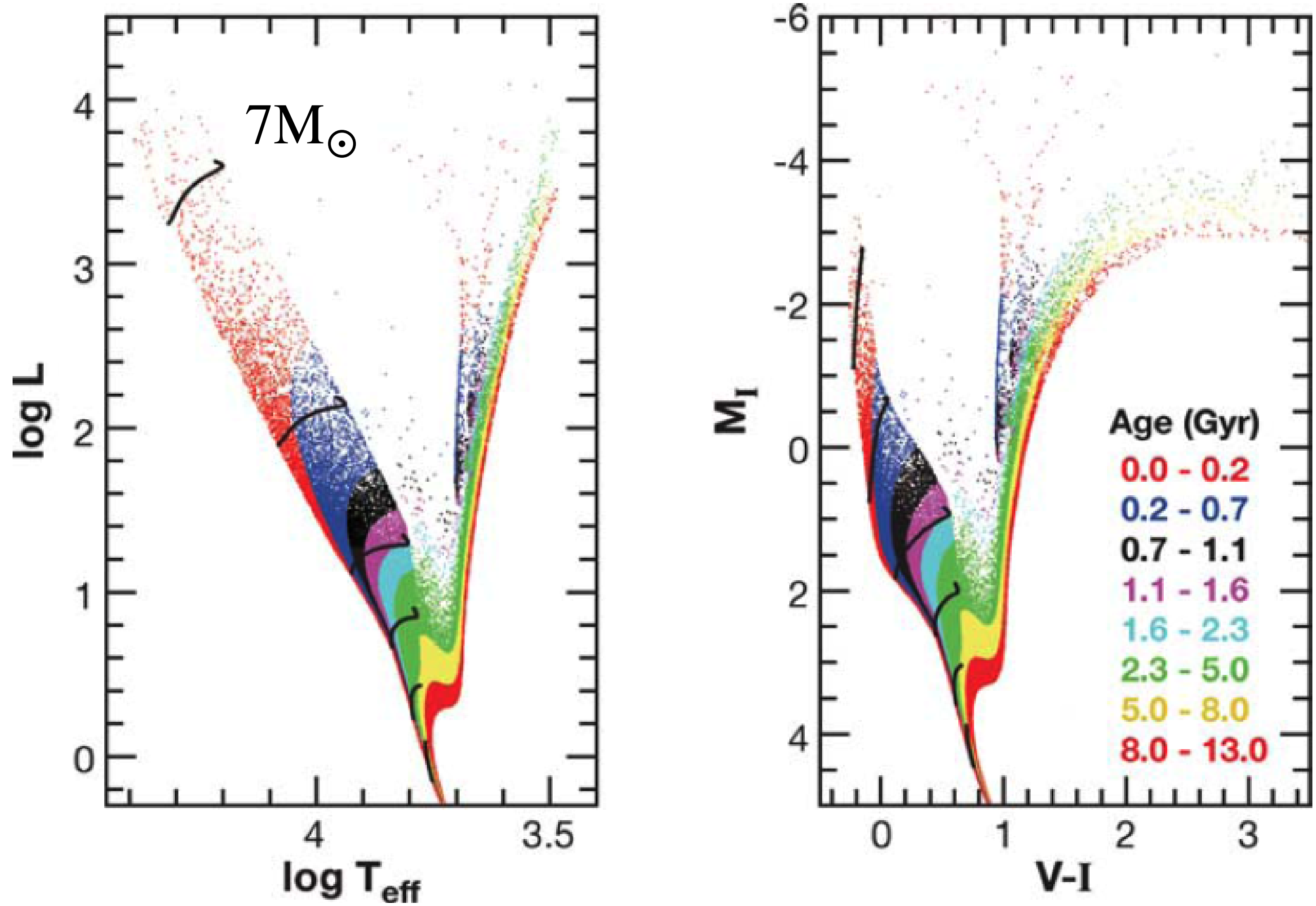
Some Especially Interesting Places in HR Diagram

- Cepheids are used to determine absolute distances
- Red giants are very luminous with narrow range of parameters- can be used for distance determinations (called 'tip of red giant branch' TGB)



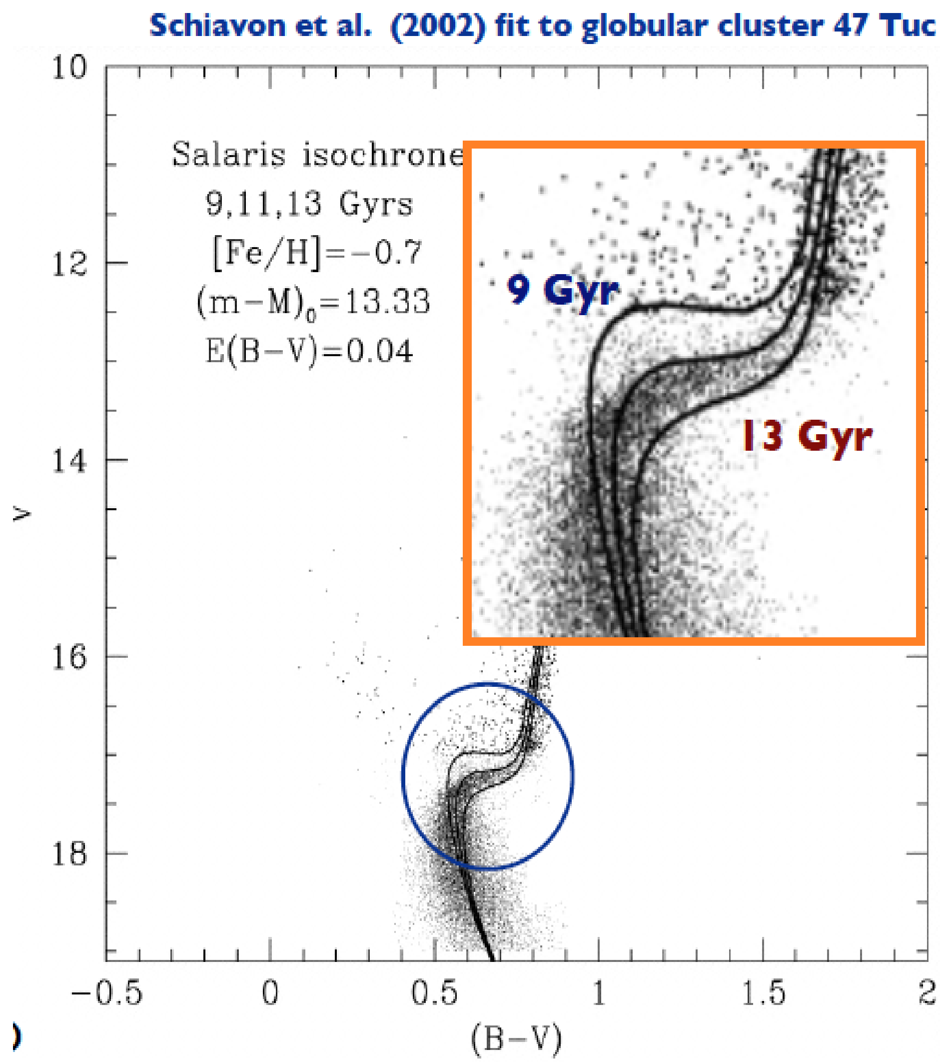
What does a population with continuous Star formation look like??



- **Theoretical space (left), observational space (right)**
- **Constant SFR** from 13Gyr ago to the present time,Z =0.0198, IMF slope-2.3
- stellar evolutionary tracks for stars of masses 7, 3, 1.9, 1.5, 1.2, and1M

Age Dating a SSP

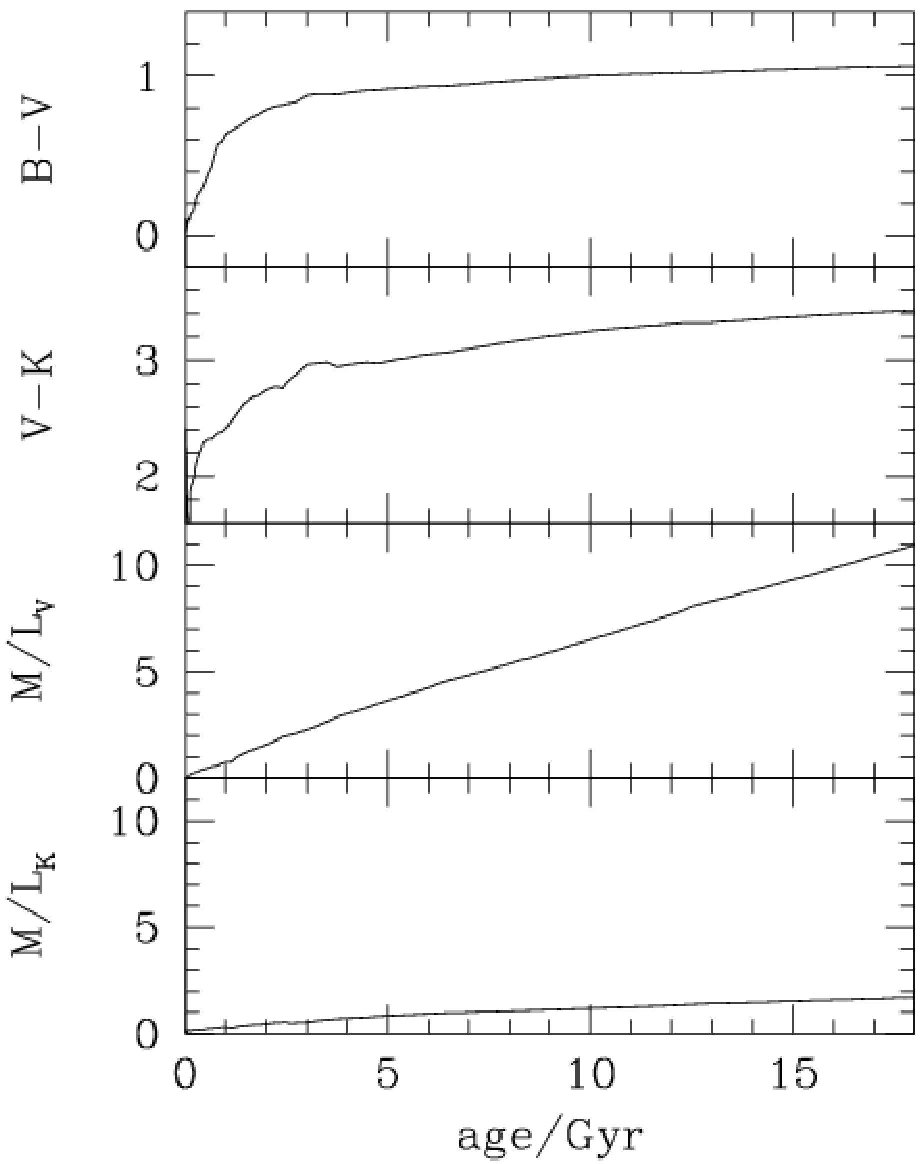
- Globular clusters can be well approximated by a SSP and are frequently chemically homogenous
- With precision photometry ages can be well estimated by measuring the location of the 'turn-off'- e.g. when the star leaves the main sequence.



Age Dating A SSP

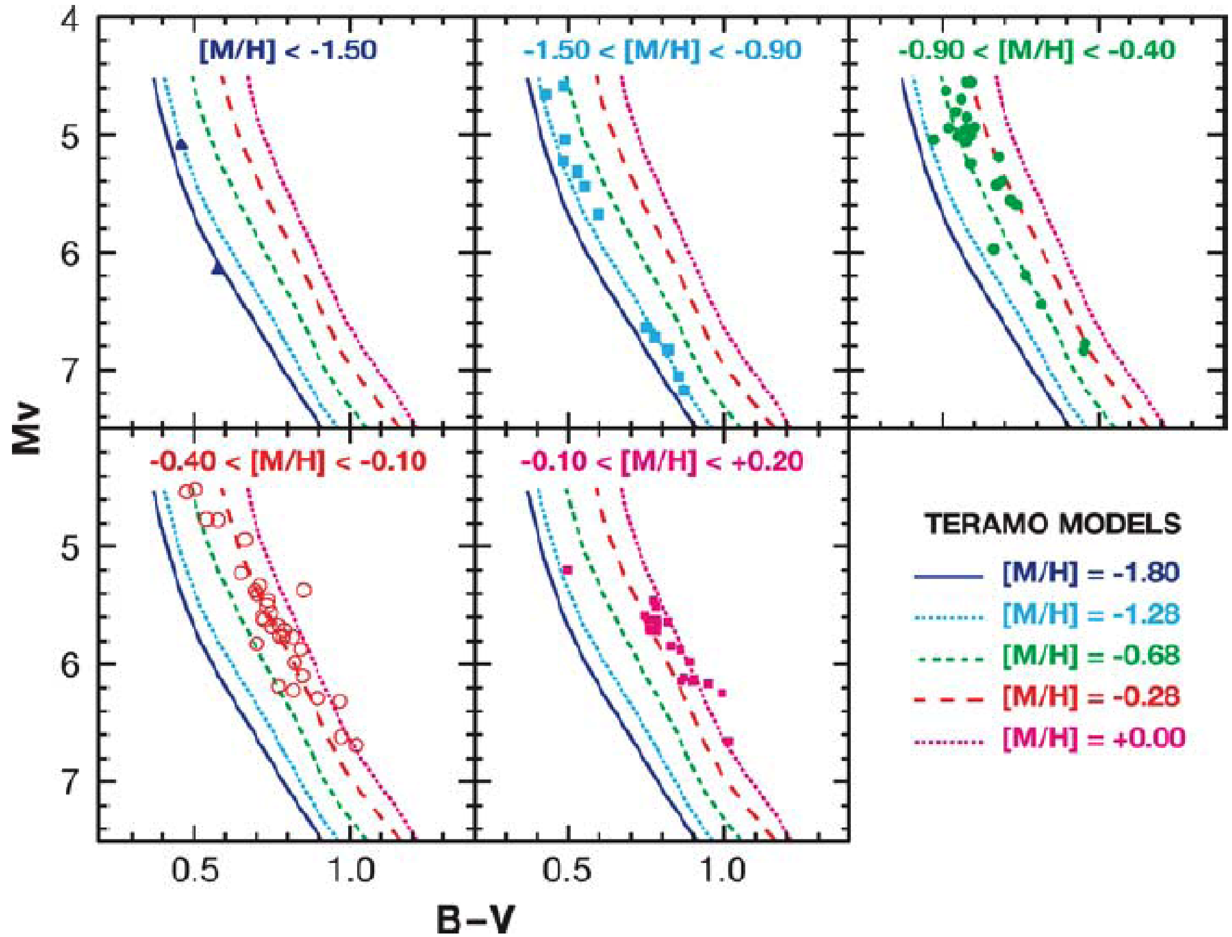
- If one just has colors then the H-R diagram is not so useful; the colors of a SSP can be calculated as a function of age (for a given metallicity) (See MBW pg 473)
- Notice the weak change in color vs age after ~3Gyrs, but the strong change in M/L_V and weak change in M/L_K

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



Effects of Metallicity

- Color distribution of stars of a fixed absolute magnitude (M_v) as a function metallicity- lines are models points are data
- lower metallicity stars are 'bluer' (both hotter and with a different spectral energy distribution) and brigh for a given mass. (fig in S+G).
- M_v :absolute magnituc in the V band



IMF

INITIAL Mass Function

- The origin of the form of the IMF is not well understood
- Use the stellar mass-luminosity relation and present day stellar *luminosity* function together with a model of how the star formation rate varies with time.
- Salpeter- pure power law $\Phi(m)=N(M)\sim M^{-\alpha}\,dM$ for $M>M_\odot$ (Salpeter 1953)- total mass diverges $\alpha\sim2.35$
- Near the sun one can observe several 'open' star clusters (Scalo 1986)
  - one finds that the slope changes below ~ $1M_\odot$ (e.g. flattens) Amount it flattens by is slightly controversial
- There is a severe technical issue- it is only in the MW, MW globular clusters and the Magellanic clouds that one can measure individual star 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 !

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: AIfA Un

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+/-dm/2 for every $M_\odot$ of newly formed stars
- Stars $M<0.08M_\odot$ nuclear fusion not take place and $M>\sim120M_\odot$ are unstable.

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

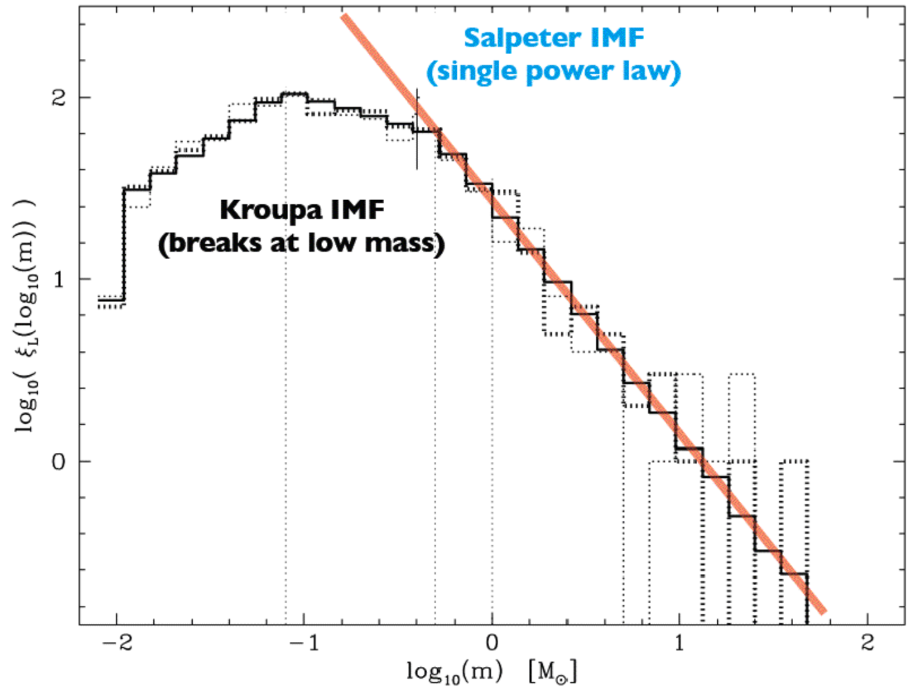
  $= 0.5\ A\ M^{-2.3}$ $(0.5 \leq M_\odot \leq 100)$

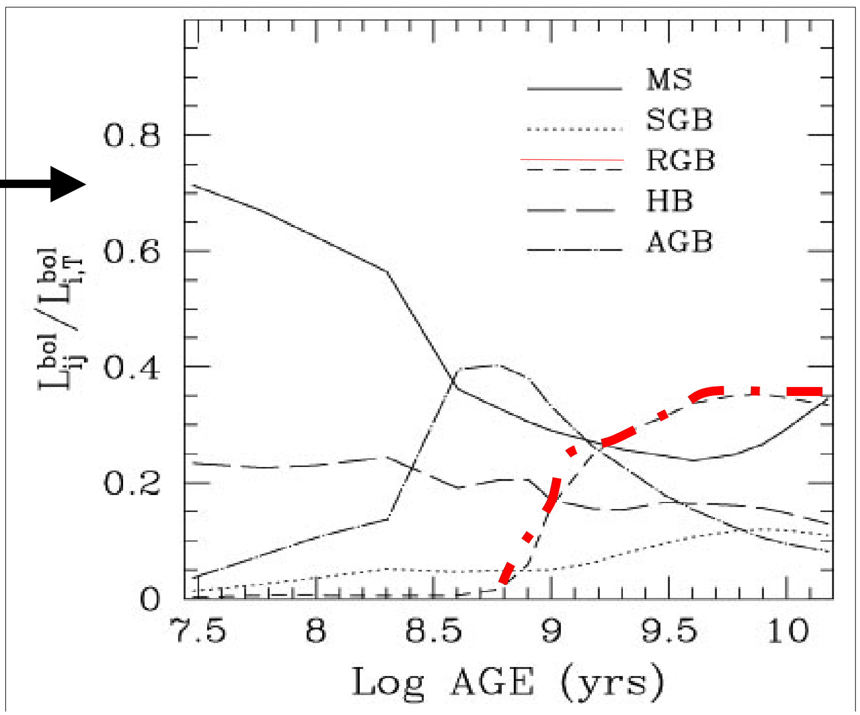
This IMF has 1.6x less total mass than the Saltpeter IMF.

$<M>=0.6M_\odot$

Initial Mass Function-IMF

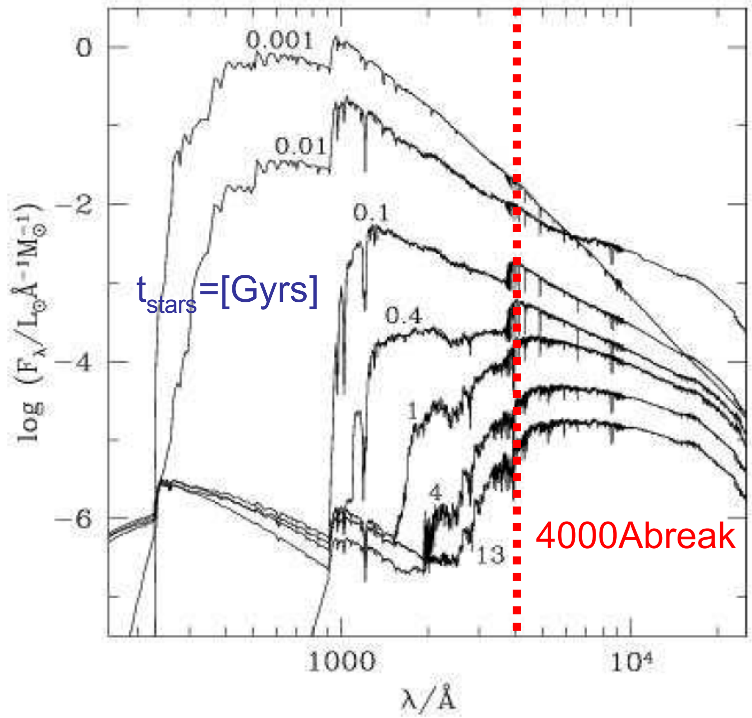
- The distribution of stellar masses at t=0 (birth)
- The origin of the form of the IMF is not well understood
- There are several forms proposed
  - Saltpeter-$\Phi(m)=N(M)\sim M^{-2.35}dM$ for $M>M_{\odot}$ (Salpeter 1953)
    - much of integrated stellar mass near $1M_{\odot}$
  - Kroupa-flattens at low masses
- At present it is controversial if the IMF is universal or a function of age, metallicity, density etc
- As SSP ages the relative luminosity due to different parts of the H-R diagram changes
  - 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 can be quite different

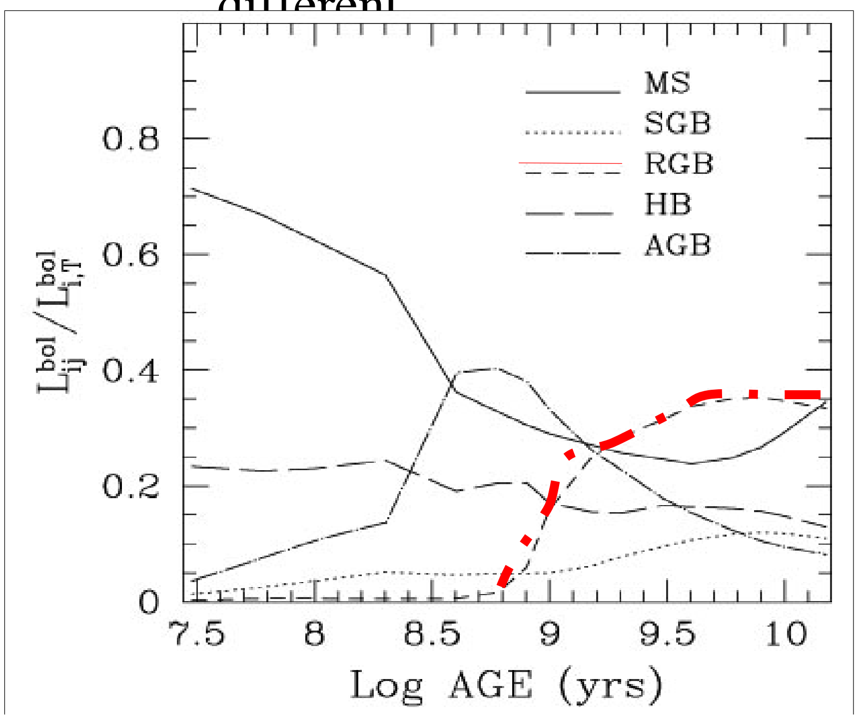




Initial Mass Function-IMF

- As SSP ages the relative luminosity due to different parts of the H-R diagram changes
    - 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 can be quite different





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

Stellar Populations I & II- Baade 1942

In spiral galaxies there are 2 'types' of stellar populations

Population I

– Young

– Metal rich

– Found in galaxy disks

- Rotationally supported

Population II-' red'

– Old

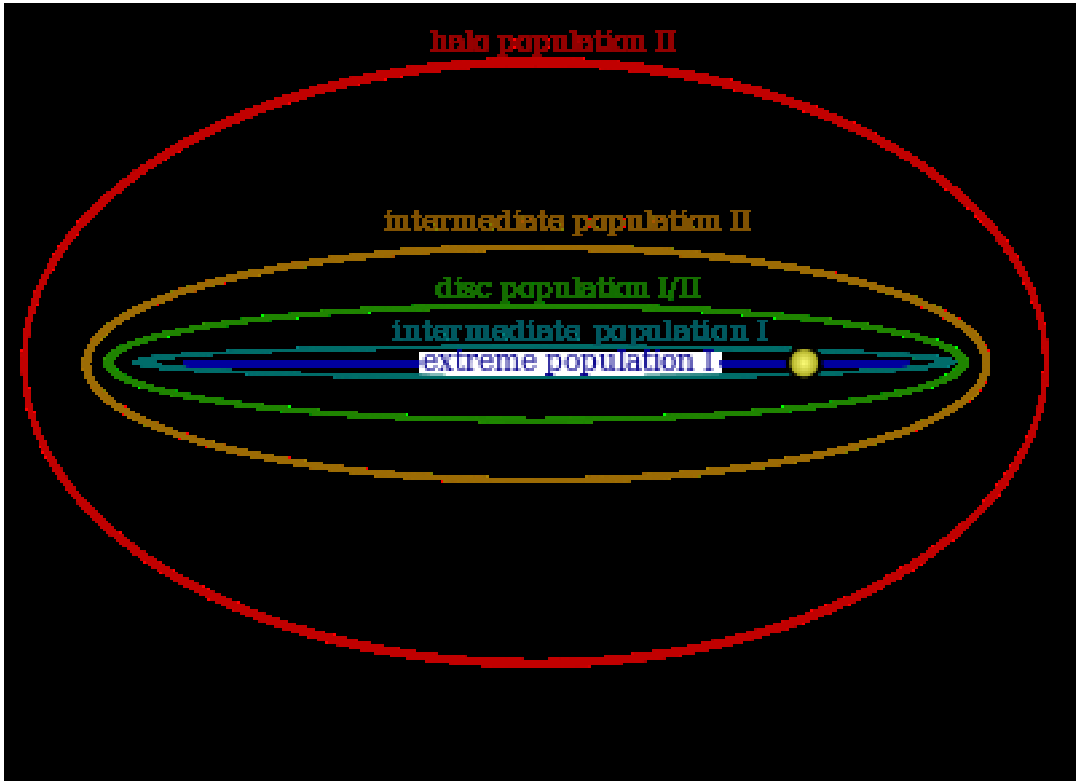
– Metal poor- non-solar abundances

– 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

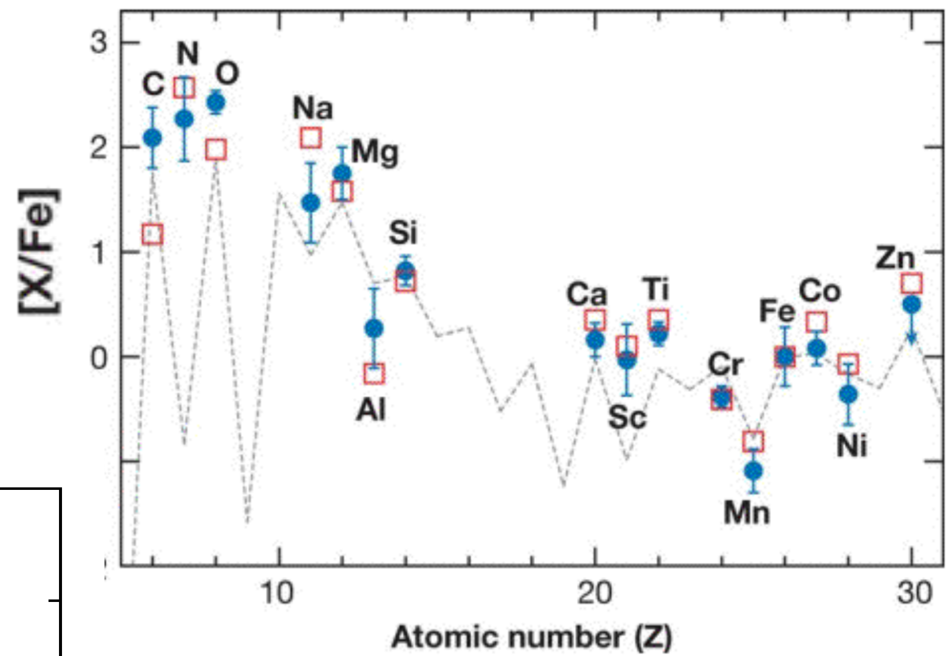
theoretically there is also Pop III- the first stars

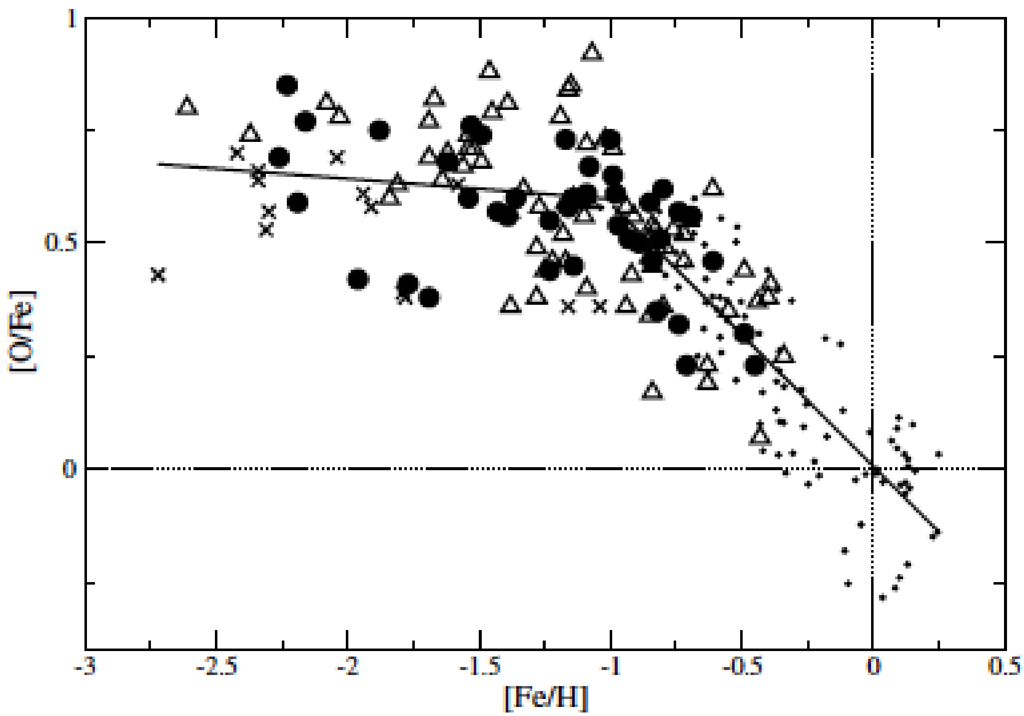


Schematic picutre of stellar pop's in Milky Way

Abundance Pattern of OLD Metal Poor Halo Stars

- A strong clue to the formation of the **first** stars - lots more C, N,O relative to Fe.





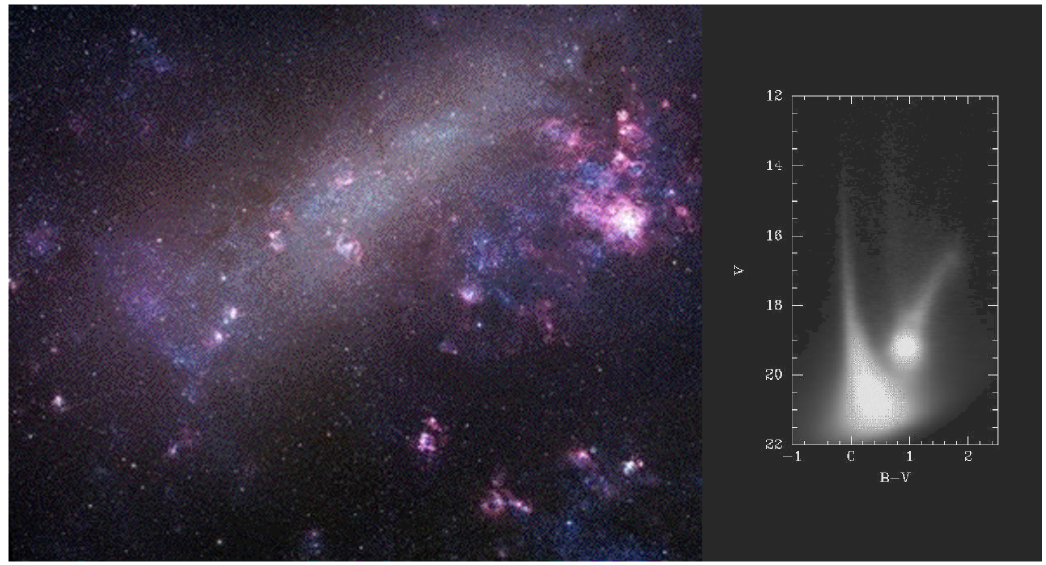
[X/Fe] is the logarithmic ratio of element X to Fe with respect to the sun's abundance pattern

- 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.

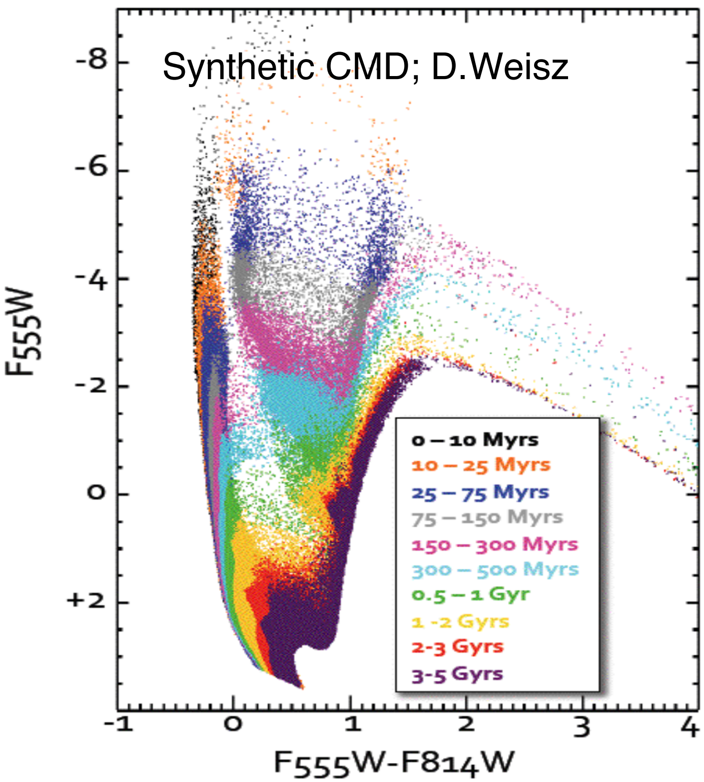
Galaxies are NOT SSPs

H.Rix2010

LMC:Zaritsky&Harris 2004-2009



LMC:Zaritsky&Harris2004-2009



We shall use this information later to see how one estimates the star formation history of a galaxy and the universe

Galaxy spectra

- Classical indicators of what is going on:
- The so-called 4000A break is produced by the absorption of metallic lines of a variety of elements in various states of ionization, including
- Ca II H and K high-order lines of the Balmer series (see Hamilton 1985, The opacity suddenly increases for photons bluer than this wavelength, which produces an intensity drop. It is enhanced in old stellar populations
- The Balmer lines become deeper and broader with time from the starburst, with a characteristic time-scale of the order of one Gyr

Does G have emission lines? if YES then

- ⋆ if the lines are broad then .... **QSO or Seyfert 1**
- ⋆ if lines are not broad then apply BPT
  - if [NII]λ6583 < Hα/2.5 then
    - . if [NII]λ6583 << Hα then .... **low-metal starburst**
    - . else .... **high-metal starburst**
  - if [NII]λ6583 > Hα/2.5 then
    - . if [OIII]λ5007 < Hβ then .... **LINER-like**[1]
    - . else .... **Seyfert 2**
- ⋆ if G does not have metal absorption lines then
  - if Hβ > 30 Å .... **young starburst / HII G**
  - else .... **starburst**

Does G has absorption lines? if YES then

- ⋆ *Does G show the Balmer break at* 3650 Å?
  - if YES then *Does G show the* 4000 Å *break*?
    - . if YES then .... **mixed young-old stellar populations**[2]
    - . if NO then .... **young stellar populations**[2]
  - if NO then *Does G show the* 4000 Å *break*?
    - . if YES then .... **old metal-rich stellar populations**[2]
    - . if NO then .... **odd**

Neither emission nor absorption? if YES then .... **BL Lac**

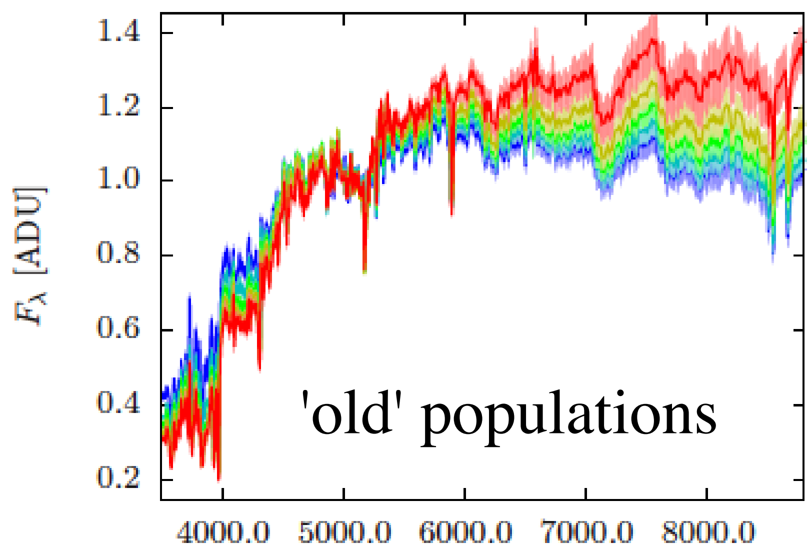
Does the continuum rise beyond 6000 Å? if YES then .... **dust reddened G**

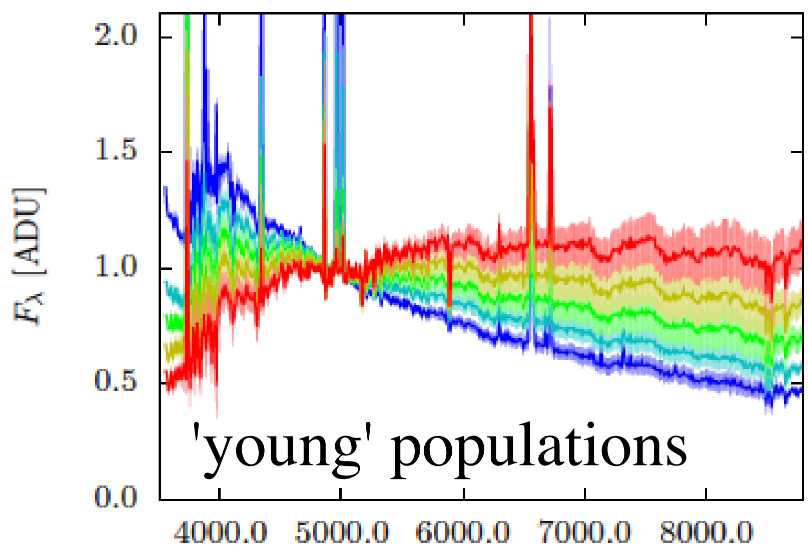
[1] LINER, or retired G, or X-ray emitting gas or ...
[2] Age and metallicity can be determined through calibrated indexes

- Historically specific stellar absorption features over narrow wavelength intervals were used when analyzing galaxy spectra to obtain the ages and metallicities of the stellar populations
- For galaxies with old stellar populations, the Lick/IDS system of ~25 narrow-band indices is often used (Worthey1994.
- For actively star-forming galaxies, the 4000A break(Balogh etal.1999) and Balmer absorption line features, such as the Hδ index, provide important information about stellar age and recent star formation history.

Galaxy spectra

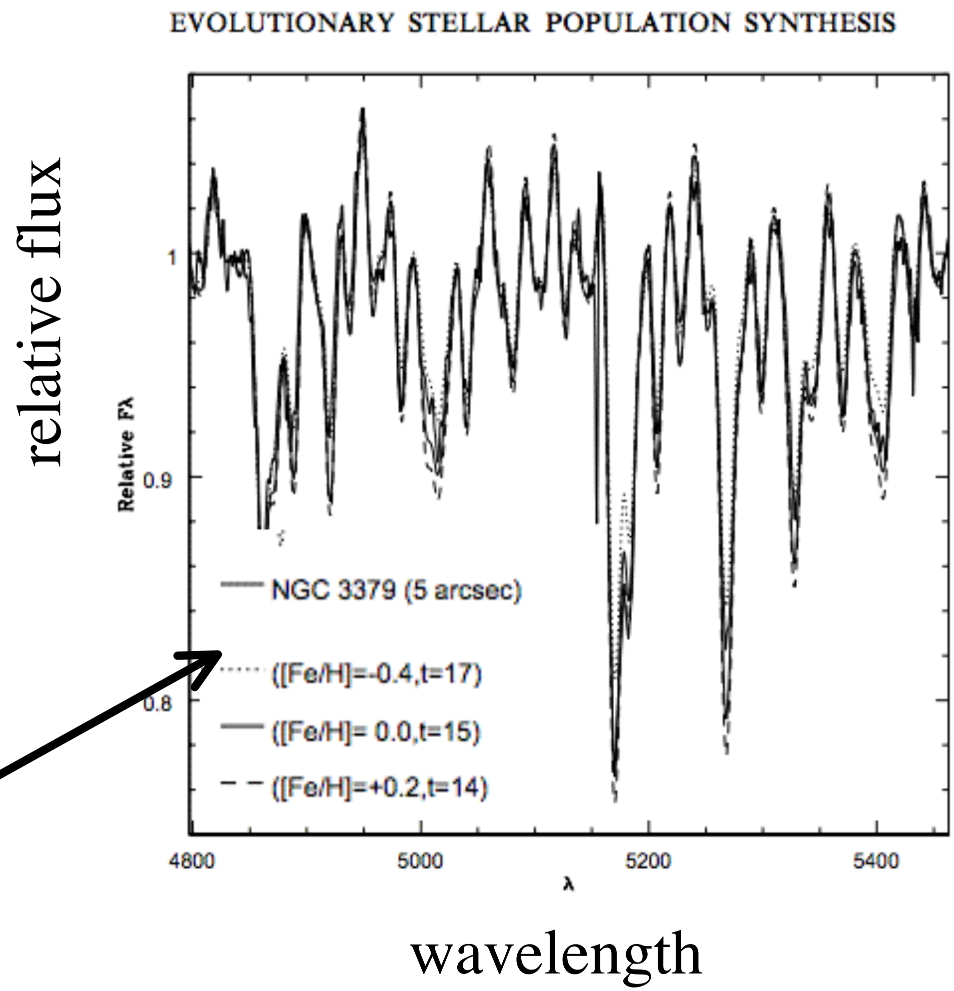
- Classical indicators of what is going on:
- The limit of the Balmer series and the blending of the high-order Balmer lines produces a discontinuity of the spectrum blueward of 3650°A. (the Balmer break) –more important in young populations, The break amplitude and position is a proxy for the age of the stellar population
- The UV continuum flux is also an age indicator for very young stellar populations. It increases with decreasing age when the ages are only a few Myr
- The ratio between the fluxes of Hα and [NII]6583 is an indicator of how the nebula is ionized
- **Dust (reddening) is a major issue**





Spectra of Galaxies

- 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



Vazdekis 1999

How to Use this Information

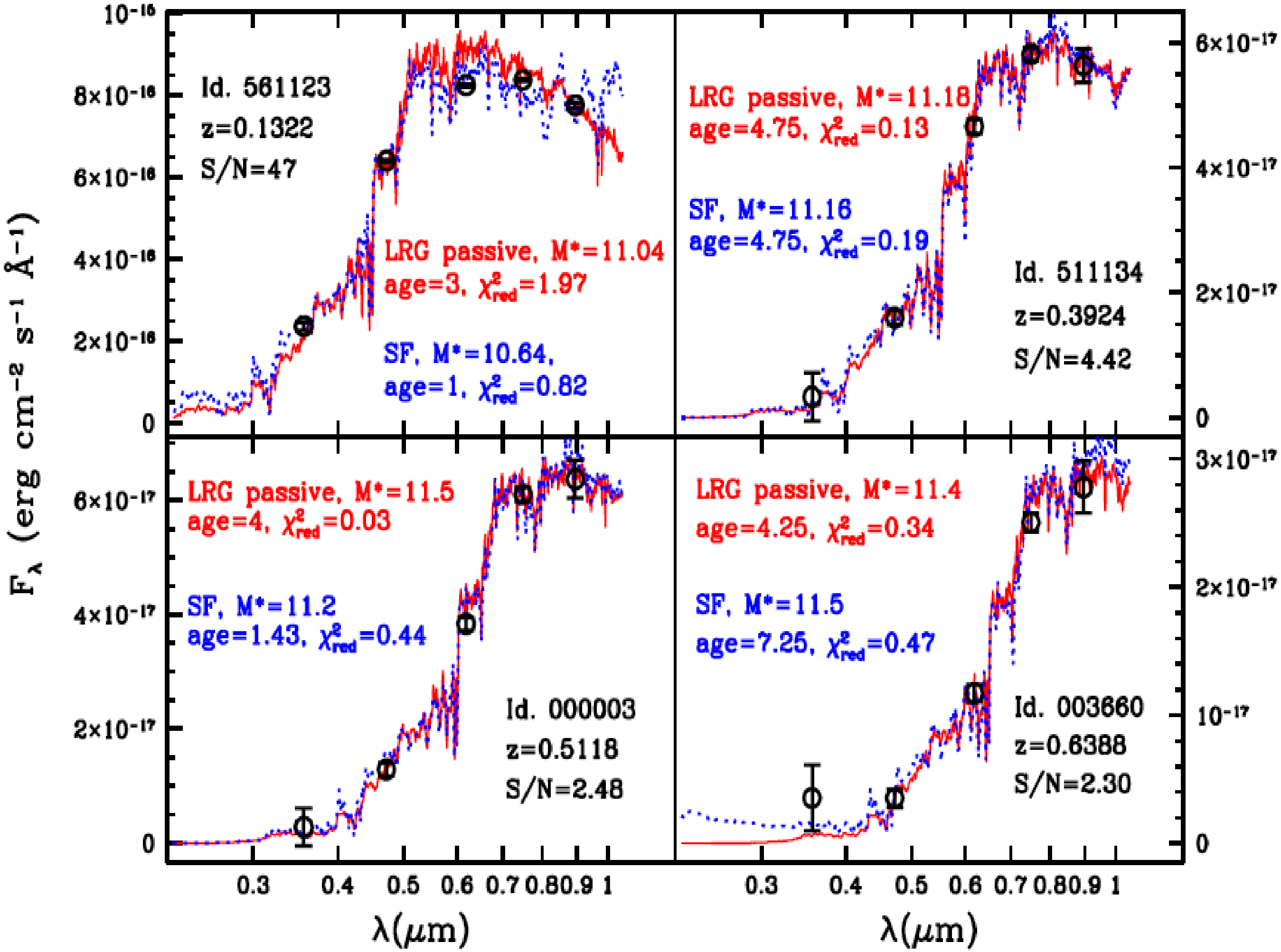
- ‘Integrated’ Stellar Populations

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 usings 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)



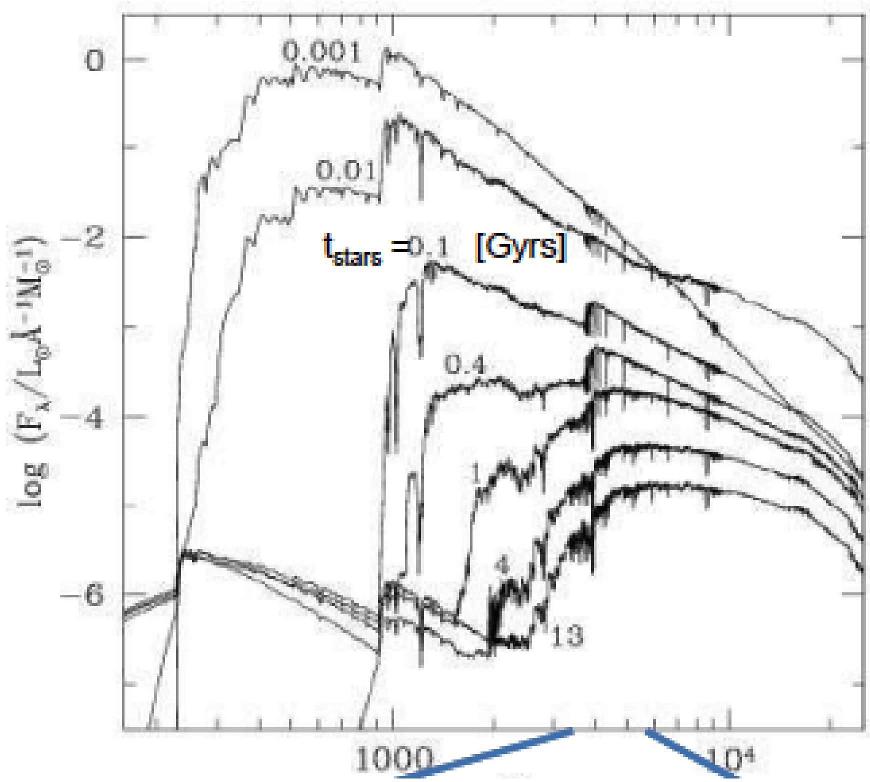
Maraston et al 2012

General Trends for SSPs

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

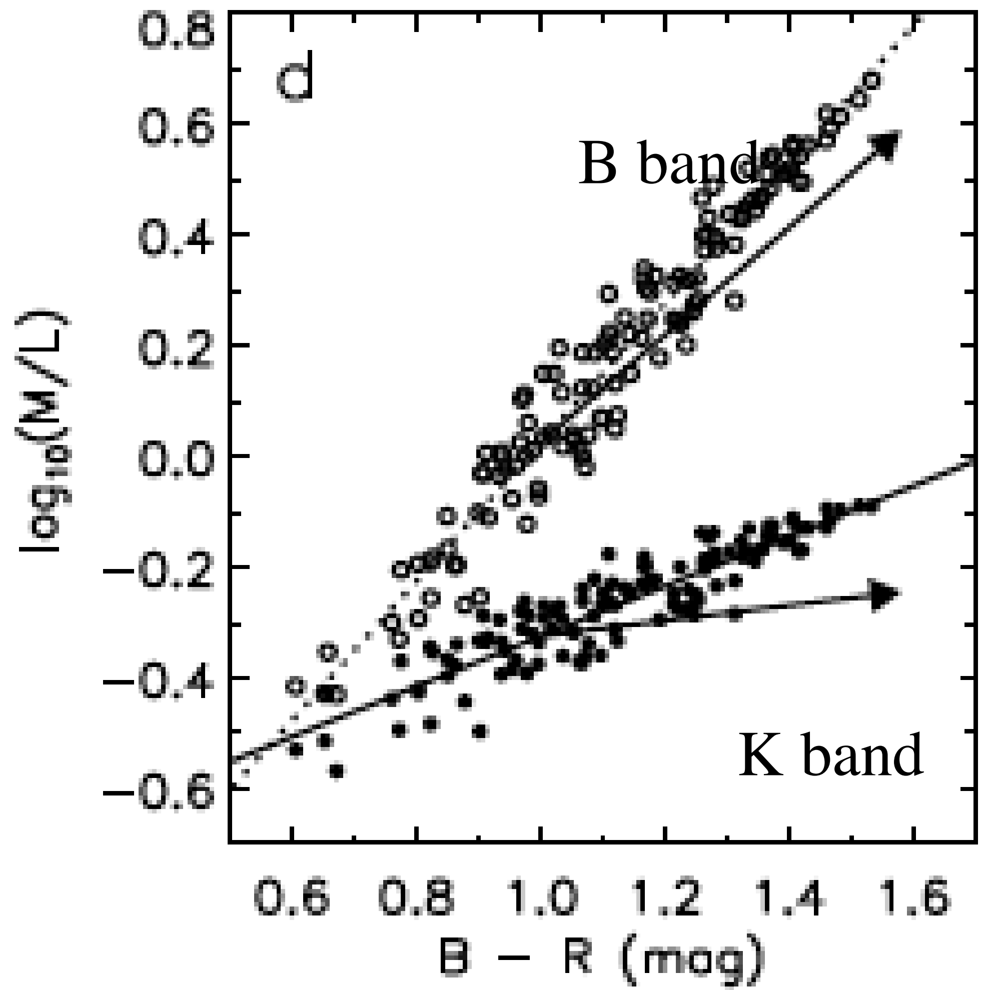
  – UV flux is only produced for 0.2Gyrs
- X 100 at 5000A from 0.1Gyrs to 10Gyrs
- X 6 at 1.5μ from 1Gyr to 10Gyrs
- – populations 'redden' as they age

Higher 'metallicity' and dust also 'redden'



M/L Indicators

- Some colors are very sensitive to M/L for spirals
- If 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
- Apply such technique to large samples -



Dust and Reddening

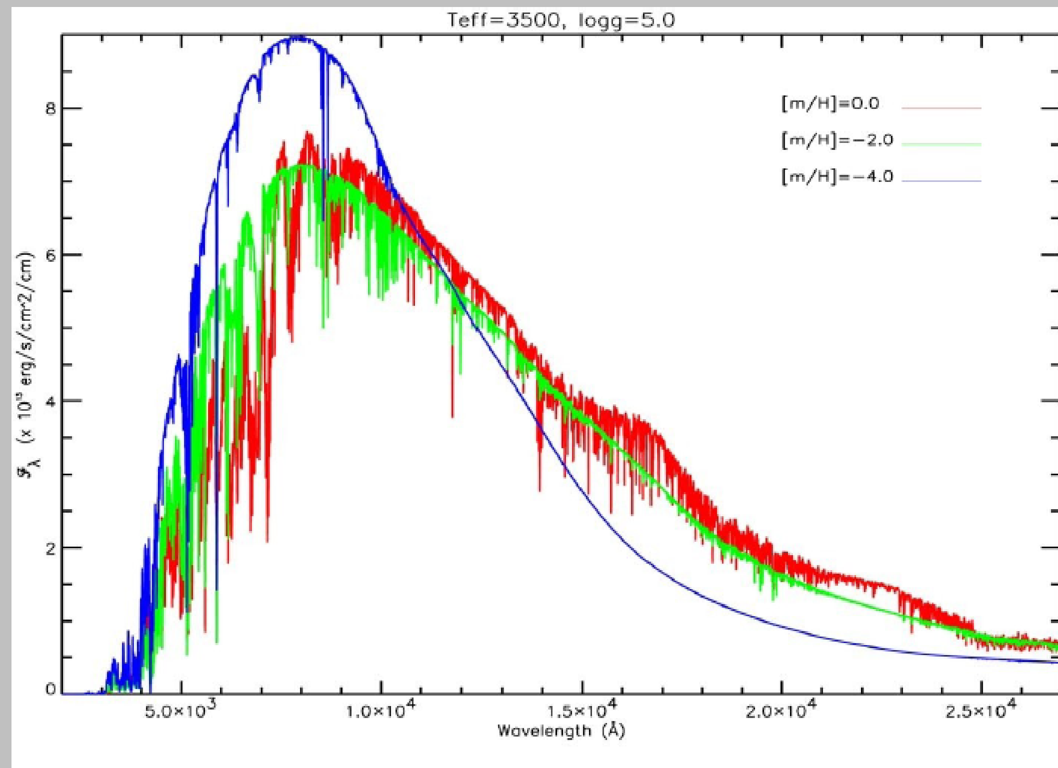
- The effects of reddening can be complex.
- reddening law for isolated stars
  - not the same for all galaxies; e.g. MW and SMC are rather different in the UV but not in the optical;.

- 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

Effects of Metallicity

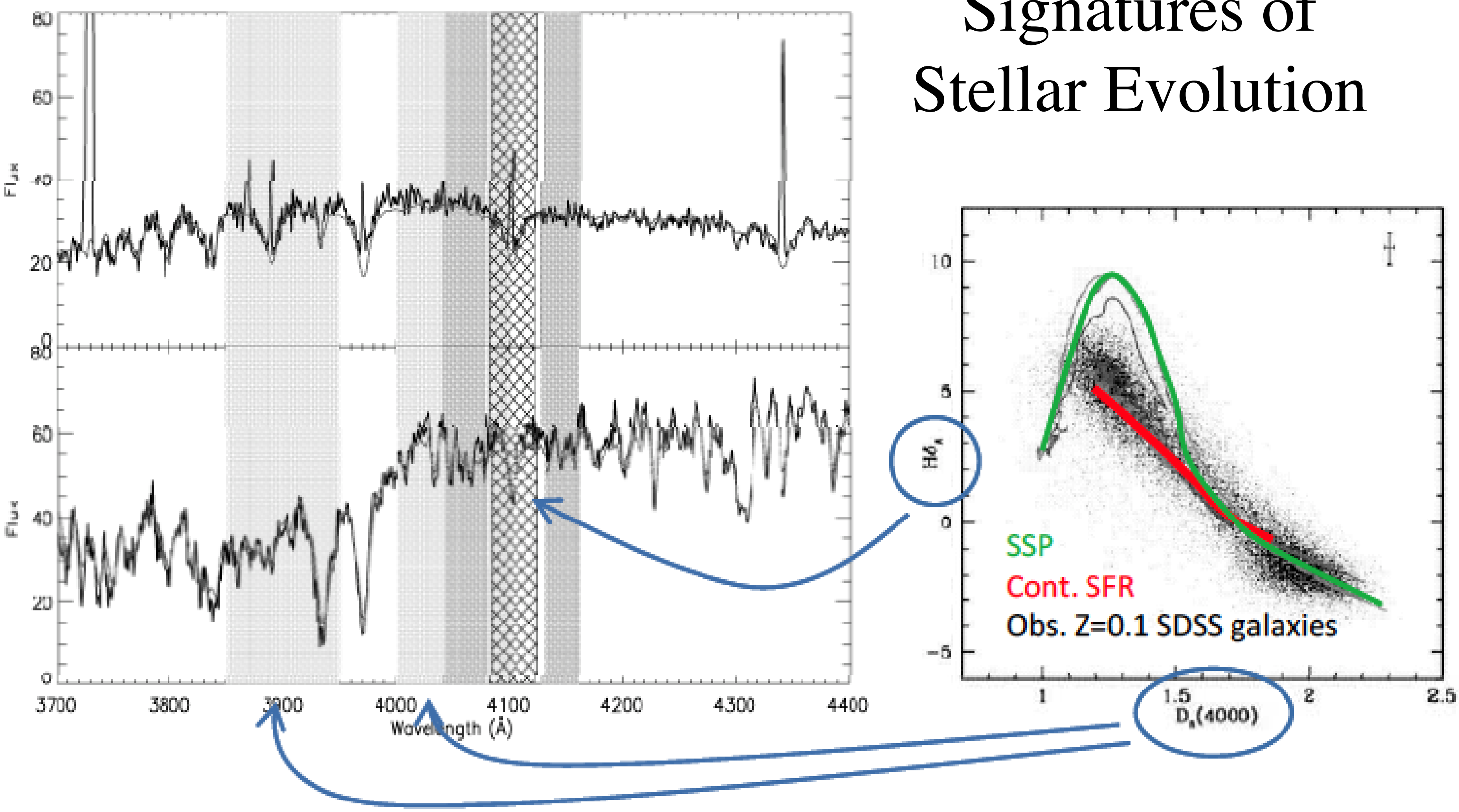
- At a given mass/temperature the colors of metal poor stars are 'bluer'- due to less line blanketing in their atmospheres

Low metallicity stars are blue



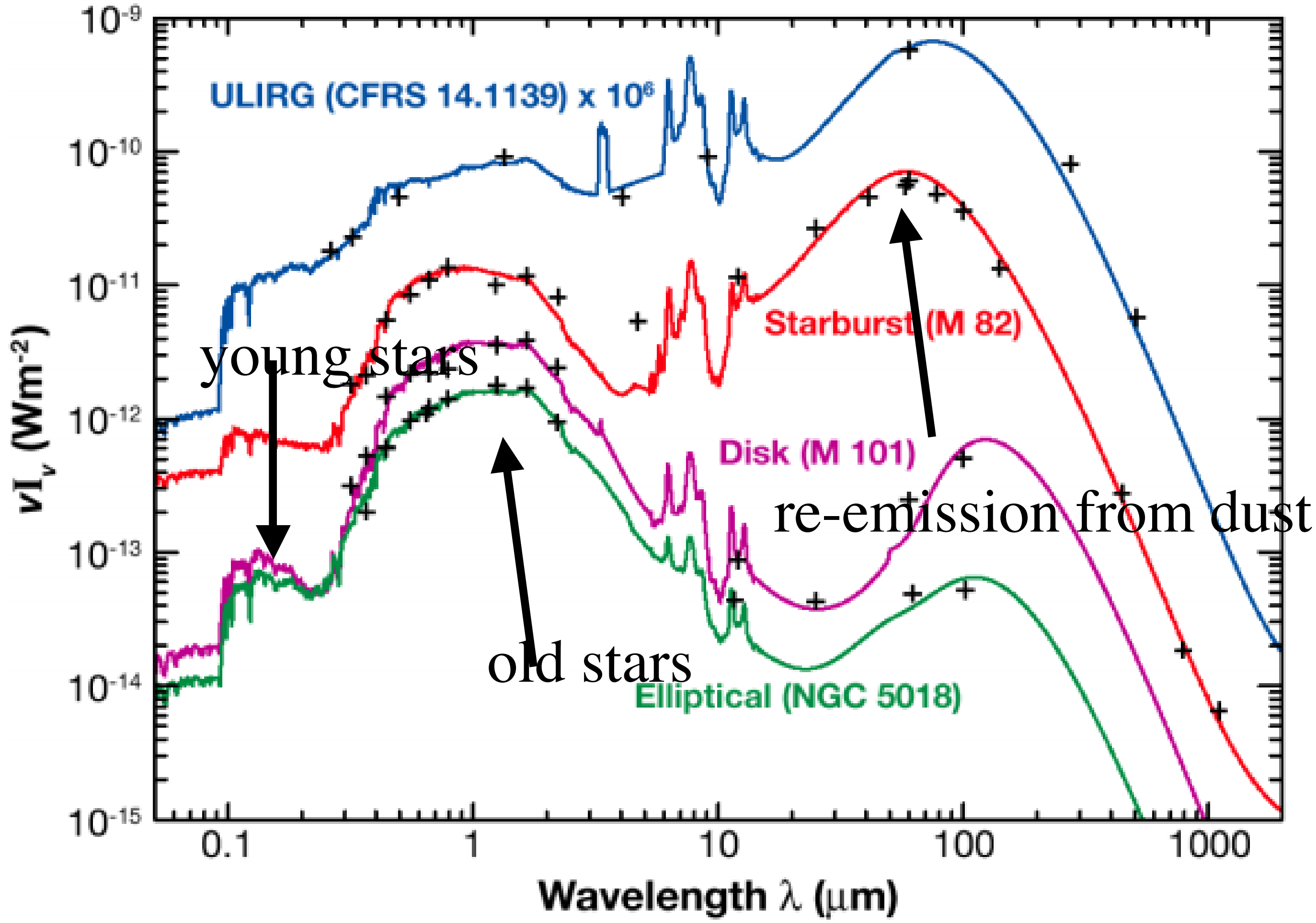
Jao et al. 2008 ApJ 136, 804

Signatures of Stellar Evolution



- Hδ vs D(4000)- distinguish SSP vs continuous star formation

Put it All Together Into A Galaxy



Next Time

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

Star formation Rate Estimates

- Depends on signatures of high mass (short lived) stars
- SFR estimates are based on

counting either

– Ionizing photons, often reflected in Hα

- UV photons only from short lived stars
- Dust heated by UV photons

- SFR estimates depend entirely o IMF

– effects from $M^*>5M_\odot$

– those stars contribute negligibly t M_{tot}

Kennicutt SFR estimators

$$\mathrm{SFR}\ (M_\odot\ yr^{-1}) = 7.9 \times 10^{-42}\ L(H\alpha)\ (\mathrm{ergs\ s^{-1}})$$

$$SFR\ (M_\odot\ yr^{-1}) = (1.4 \pm 0.4) \times 10^{-41}\ L[OII]\ (\mathrm{ergs\ s^{-1}}), (?)$$

$$\mathrm{SFR}\ (M_\odot\ yr^{-1}) = 1.4 \times 10^{-28}\ L_\nu\ (\mathrm{ergs\ s^{-1}\ Hz^{-1}})$$

L_ν(in UV)~const for very young pos.s (e.g. Kennicutt 98)

$$\mathrm{SFR}\ (M_\odot\ yr^{-1}) = 4.5 \times 10^{-44}\ L_{FIR}\ (\mathrm{ergs\ s^{-1}})$$

Generic Results

- Ellipticals tend to be massive and red and have old, metal rich stars and very little star formation at the present time
- Spirals have a wide range of stellar ages and metallicities and have 'more' star formation now.

- However star formation(SF) has varied over cosmic time with galaxy properties