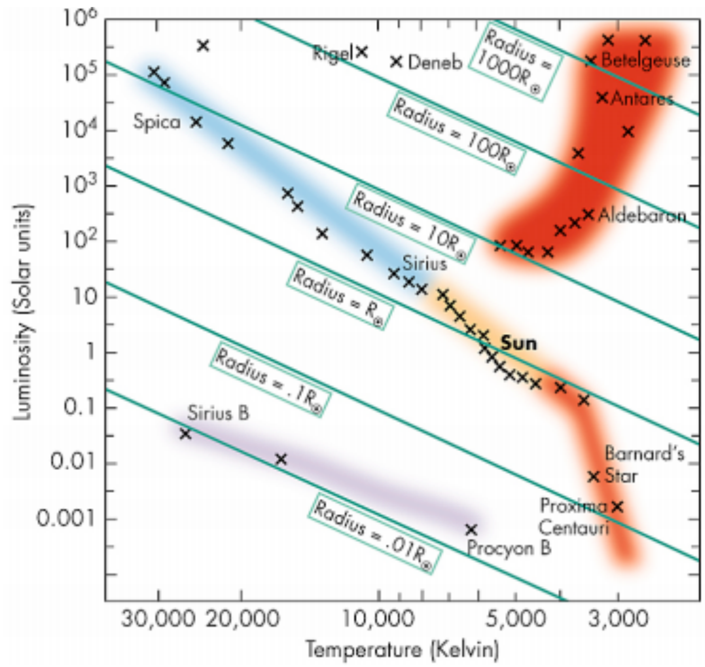
Stellar Sizes/Luminosity/Temperature

Stefan-Boltzman law- Lines L~AT^4

(T= temperature, A= area) eq. 1.3 in S&G

- 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 23

- Many spectroscopic surveys that aim to derive a complete chemo-dynamic map of our Galaxy are underway or recently completed.
  - goal of expanding the six-dimensional phase space (mass, 3-D position and 2-D velocity) by adding chemical

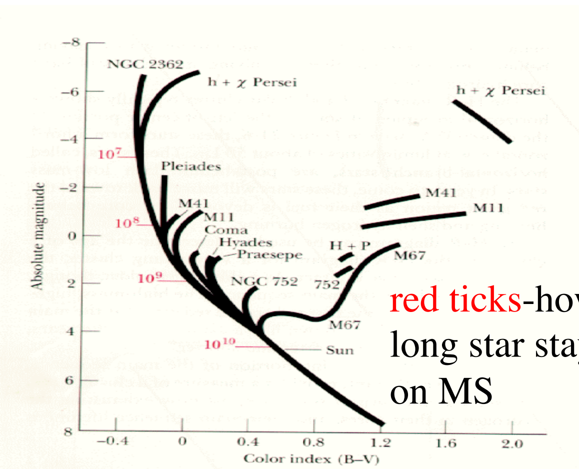
abundance measurements of a large number of tracers of chemical evolution for several hundred thousands of stars

- Survey names:RAVE (Steinmetz et al. 2006), SEGUE (Yanny et al. 2009), APOGEE (Majewski et al. 2017), GALAH (De Silva

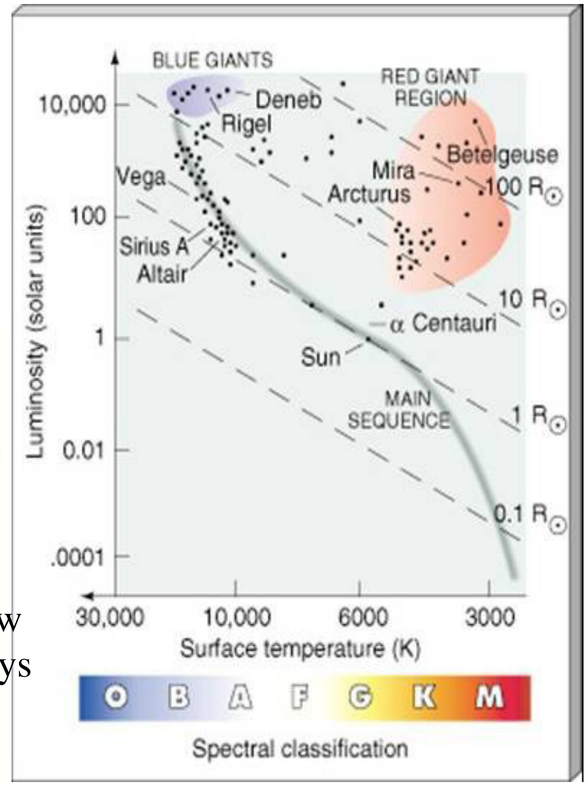
et al. 2015), Gaia-RVS (Cropper et al. 2018), LAMOST (Zhao et al. 2012), Gaia-ESO (Gilmore et al. 2012), 4MOST (de Jong et al. 2012), and WEAVE (Dalton et al. 2012).

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- S&G pg 128) or huge sample GAIA



red ticks-how long star stays on MS

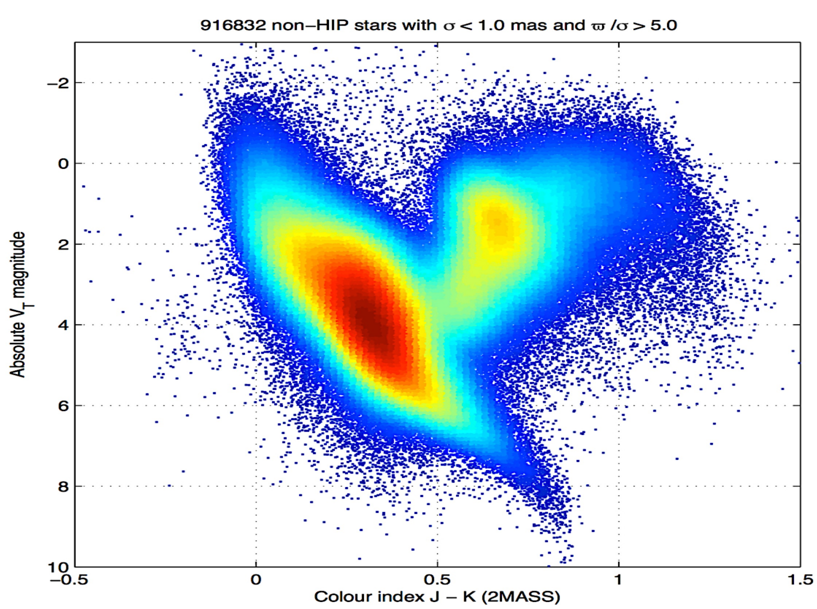


Everything Has Changed Now

- **GAIA** has surveyed the entire sky measuring the positions, proper motion, brightness and colors of stars down to 18^{th} mag
- revolutionized things study of main sequence, IMF, galactic dynamics

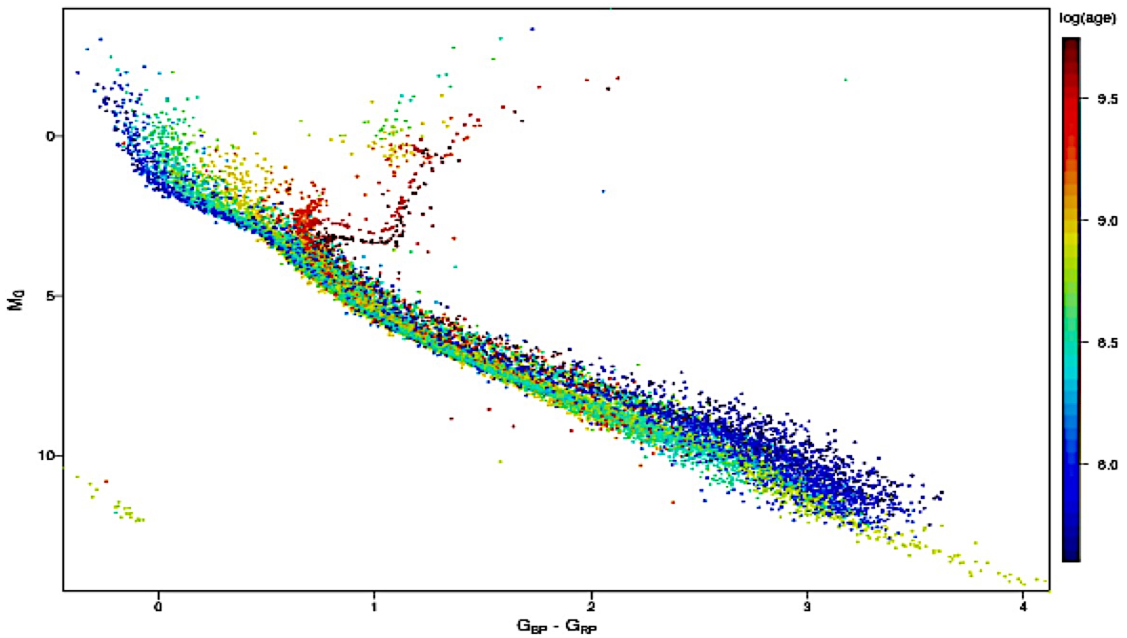
Credits: ESA/Gaia/DPAC, Carine Babusiaux and co-authors of the paper "Gaia Data Release 2: Observational Hertzsprung-Russell diagrams"

GAIA Color-mag diagram (color coded by density of points)



Gaia Data Release 2

Observational color-magnitude diagrams- color coded by age



. 2. Composite HRD for 32 open clusters, coloured according to log(age), using the extinction and distance moduli as determined fron ia data (Table 2).

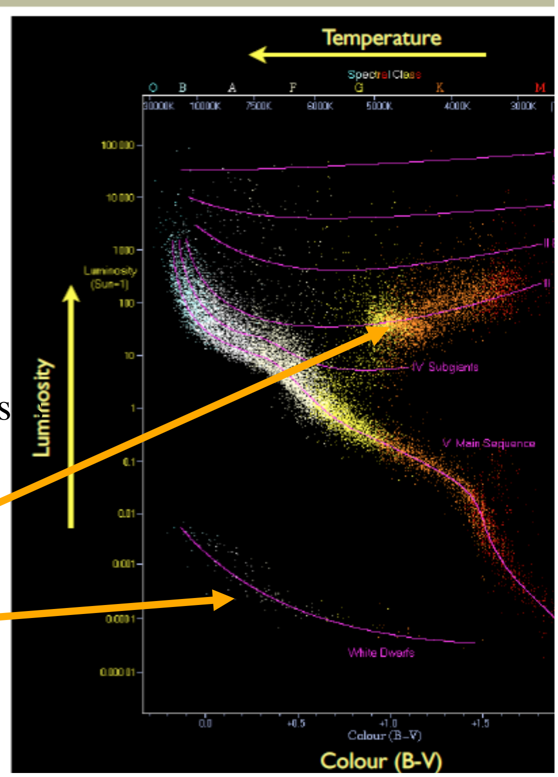
Stellar evolution reminder

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. and mass



H-R diagram organizes the observed optical properties of stars

Main sequence

white dwarfs

giant branch

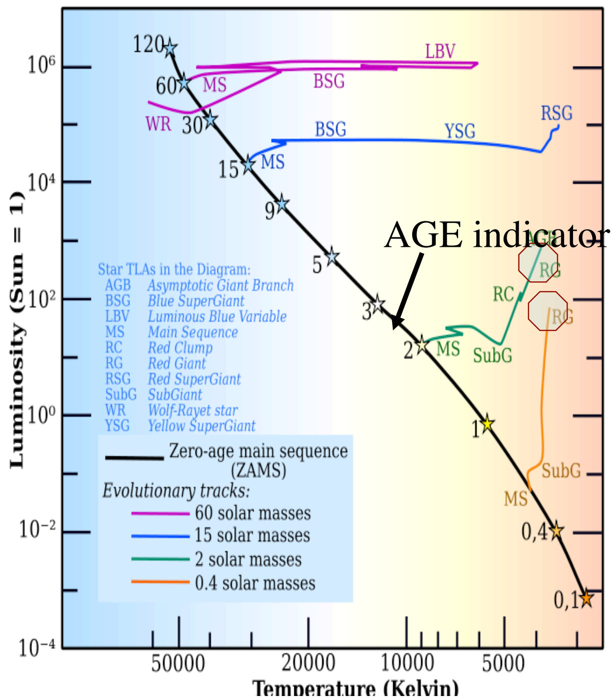
MBW 10.2)

TRACKS

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

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

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



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

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

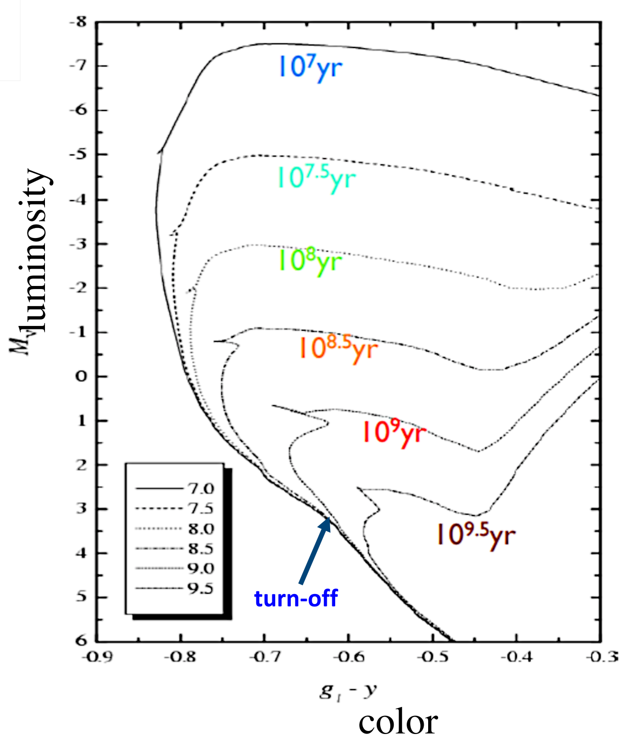
'Simple' stellar population (SSP)

has one age and metallicity

Theoretical models-allow estimate of age **from MS turn-off**

metallicity **from** giant branch color

See MBW fig 10.3



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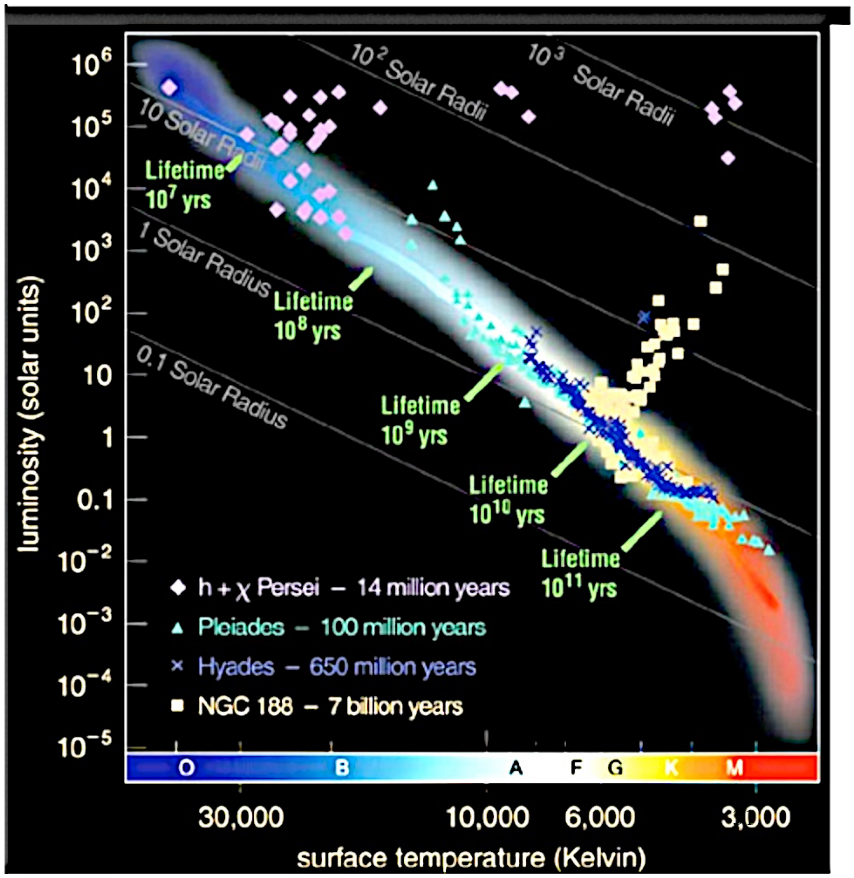
http://astro.dur.ac.uk/~rjsmith/stellarpops.html

Measuring Age of a Stellar System

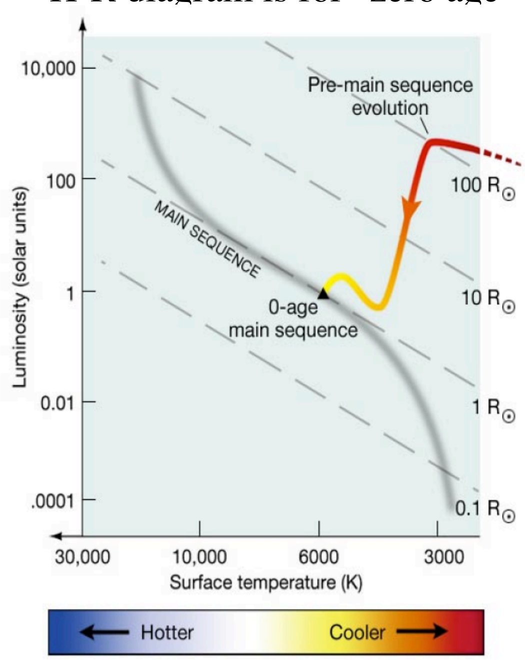
- Main sequence turnoff is <u>primarily</u> a age indicator.



- 'low' mass stars evolve slowly-'stay' on the M-S for a long time
- On the M-S hydrogen 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 slowly with time, e.g. the Sun will 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

Main Sequence

H-R diagram is for 'zero age'



A Young SSP

- H-R diagram of the Pleiades (S&G fig 2.12) a nearby young open cluster.
- Notice thinness of the H-R diagram
  - scatter probably due to binaries

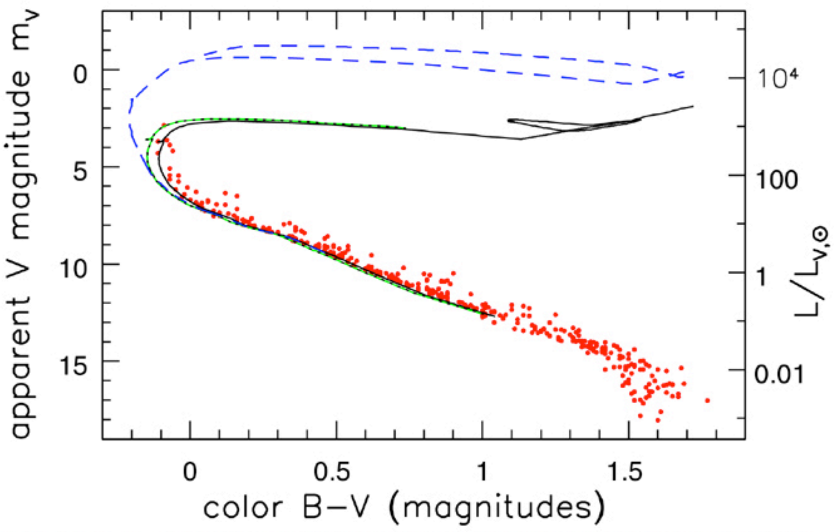
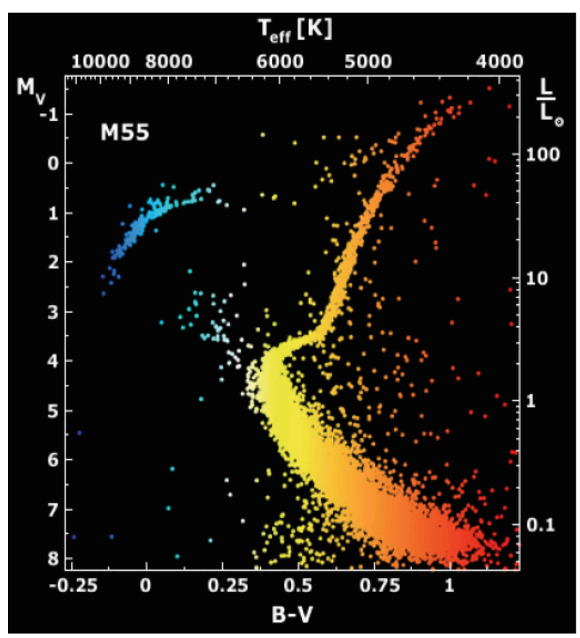


Fig 2.12 (J.-C. Mermilliod) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

A Old 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 (simple stellar population)
- To first order most Globular clusters are SSPs (some show metallicity variations)

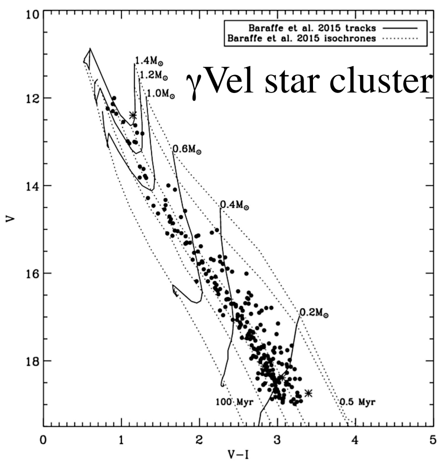


astronomy picture of the day

How Good are the Models??

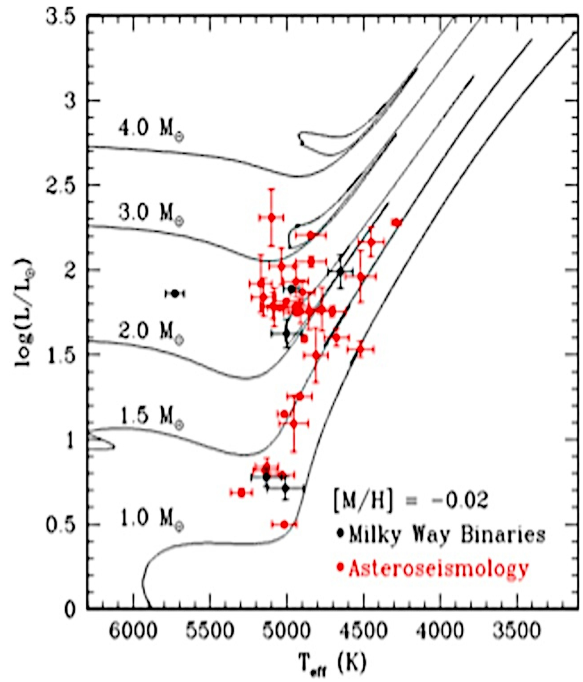
For many purposes we must reply on stellar evolution models to determine stellar parameters-

Models pretty good!



γVel star cluster

g. 10. Color magnitude diagram of the confirmed (dots) d possible members (crossed dots). Theoretical tracks and ›chrones (0.5, 1, 5, 10, 20 and 100 Myr) by Baraffe et al. 015) are also shown with solid and dotted lines, respectively.



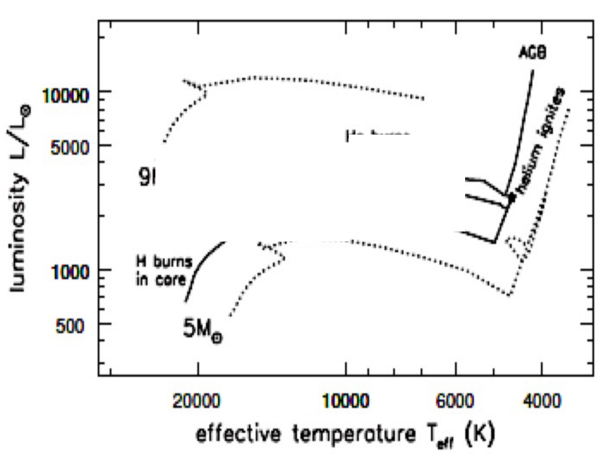
35

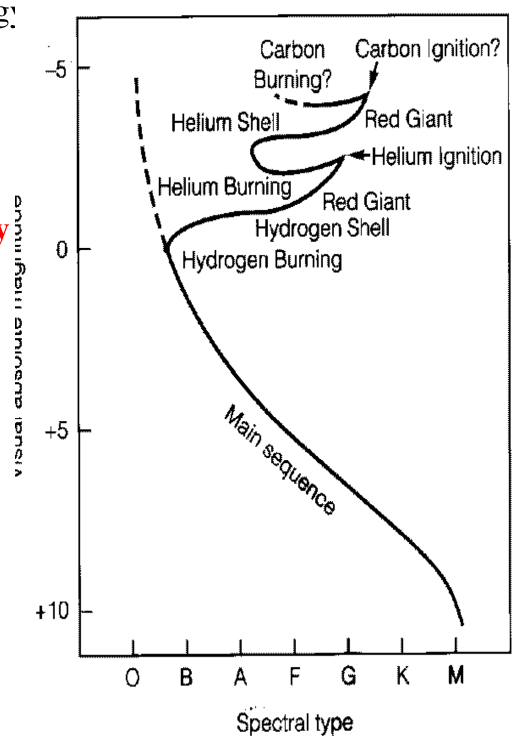
Off the MS

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

~ 2x10^9 yrs for a solar mass star

- However stars on the giant branch are *very* luminous **and can dominate the luminosity of old stellar systems**





MASS-DEPENDENT LIFETIMES

Lifetime in each evolutionary phase depends sensitively on initial mass.

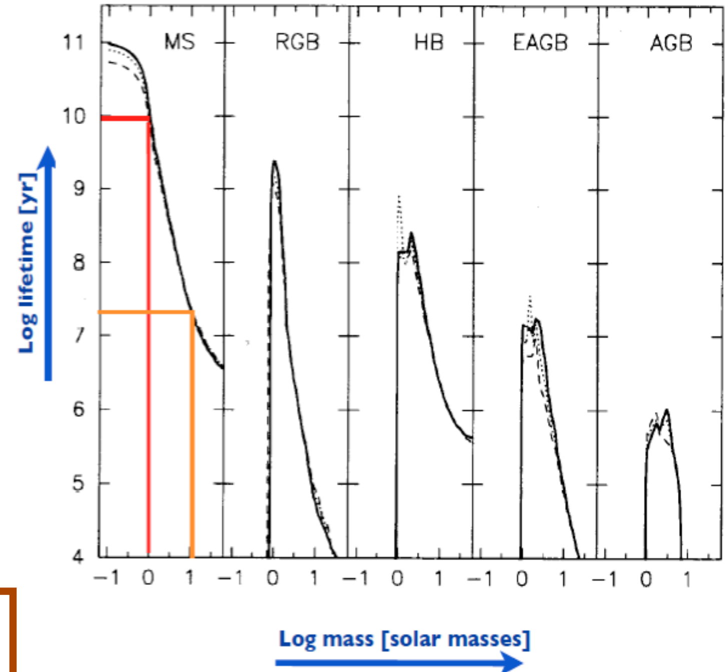
MS lifetime is ~10^{10} $(M/M_{sun})^{-2.5}$ yrs: so 10 Gyr at 1 solar mass, but only ~20 Myr for 10 $M_\odot$

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



Russell J. Smith Durham

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

Stellar Properties (S&G table 1.1)

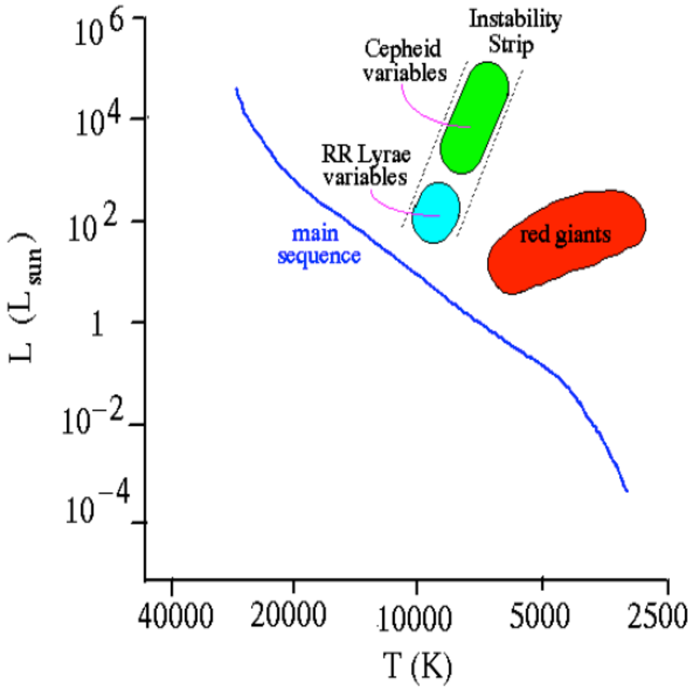
Table 1.1 Stellar models with solar abundance, from Figure 1.4

Mass ($M_\odot$)	L_{ZAMS} ($L_\odot$)	T_{eff} (K)	*Spectral type*	τ_{MS} (Myr)	τ_{red} (Myr)	$\int(L\,d\tau)_{MS}$ (Gyr × $L_\odot$)	$\int(L\,d\tau)_{pMS}$ (Gyr × $L_\odot$)
0.8	0.24	4860	K2	25 000		10	
1.0	0.69	5640	G5	9800	3200	10.8	24
1.25	2.1	6430		3900	1650	11.7	38
1.5	4.7	7110	F3	2700	900	16.2	13
2	16	9080	A2	1100	320	22.0	18
3	81	12 250	B7	350	86	38.5	19
5	550	17 180	B4	94	14	75.2	23
9	4100	25 150		26	1.7	169	40
15	20 000	31 050		12	1.1	360	67
25	79 000	37 930		6.4	0.64	768	145
40	240 000	43 650	O5	4.3	0.47	1500	112
60	530 000	48 190		3.4	0.43	2550	9
85	1 000 000	50 700		2.8		3900	
120	1 800 000	53 330		2.6		5200	

Note: L and T_{eff} are for the zero-age main sequence; spectral types are from Table 1.3; τ_{MS} is main-sequence life; τ_{red} is time spent later as a red star ($T_{eff} \lesssim 6000$ K); integrals give energy output on the main sequence (MS), and in later stages (pMS).

Some Especially Interesting Places in HR Diagram for Galaxies

- Cepheids are used to determine absolute distances out to ~30 Mpc [at 10Mpc m~24, issues of crowding and need for multiple observations)
- Red giants are very luminous **with narrow range of parameters**- can be used for distance determinations (called 'tip of red giant branch' TGB)

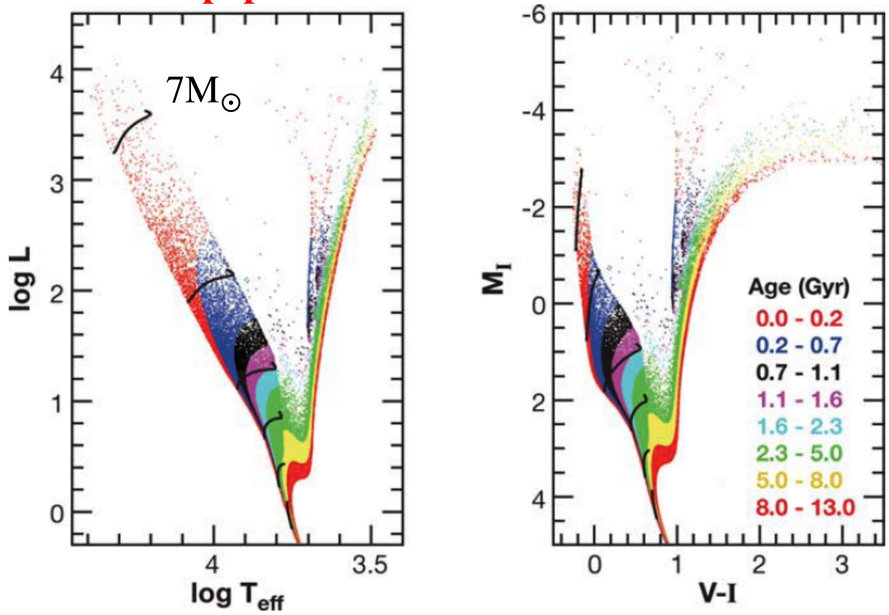


Important for Galaxies

- stars of different masses have different main-sequence lifetimes
- massive stars have main-sequence lifetimes much shorter than the age of the Universe
- thus when we observe a galaxy today (i.e. at redshift $z = 0$), we are observing the light from the stars that have evolved to the present time.
- stars on the main-sequence today with $M \sim M_\odot$ include all stars of similar masses that have formed during the past **9x10^9 yr**
- But stars on the main-sequence today with $M \sim 10M_\odot$ have formed during the past **10^7** yr.
- **Consequently, the stellar population observed from a galaxy depends strongly on its star-formation history**
- **Inverting this idea we can learn a lot about the star formation history of a galaxy from studying its stellar population.**

394 GALLART ▪ ZOCCALI ▪ APARICIO

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



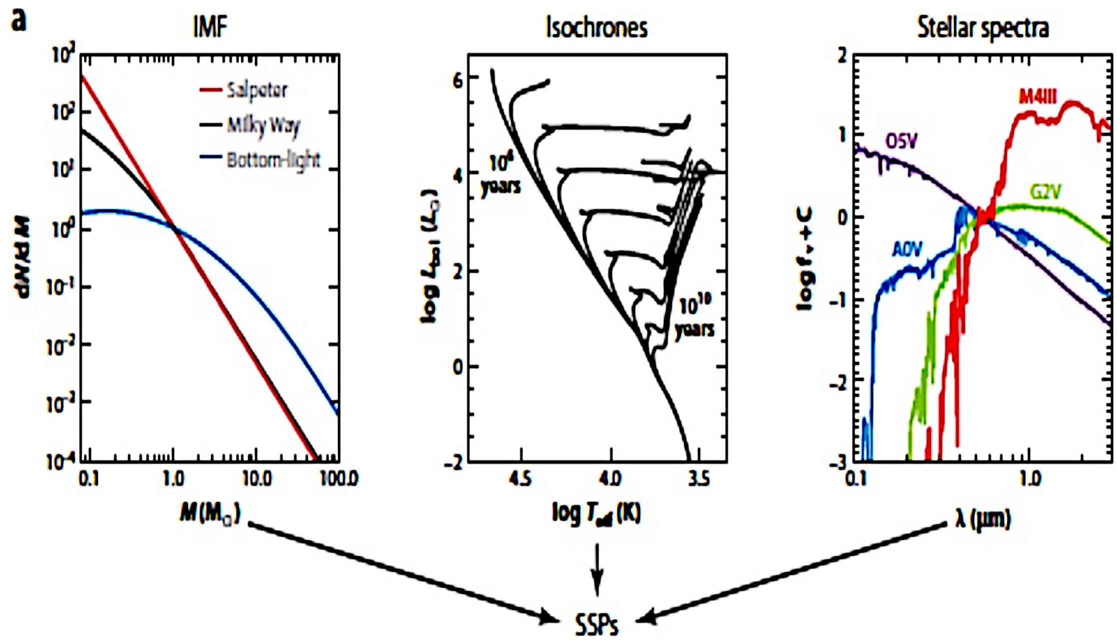
- **Theoretical space (left), observational space (right)-notice width of "MS"**
- **Constant SFR** from 13Gyr ago to the present time, Z =0.0198, IMF slope-2.3 41
- **stellar evolutionary tracks for stars of masses 7, 3, 1.9, 1.5, 1.2, and1$M_\odot$**

Where are We Going

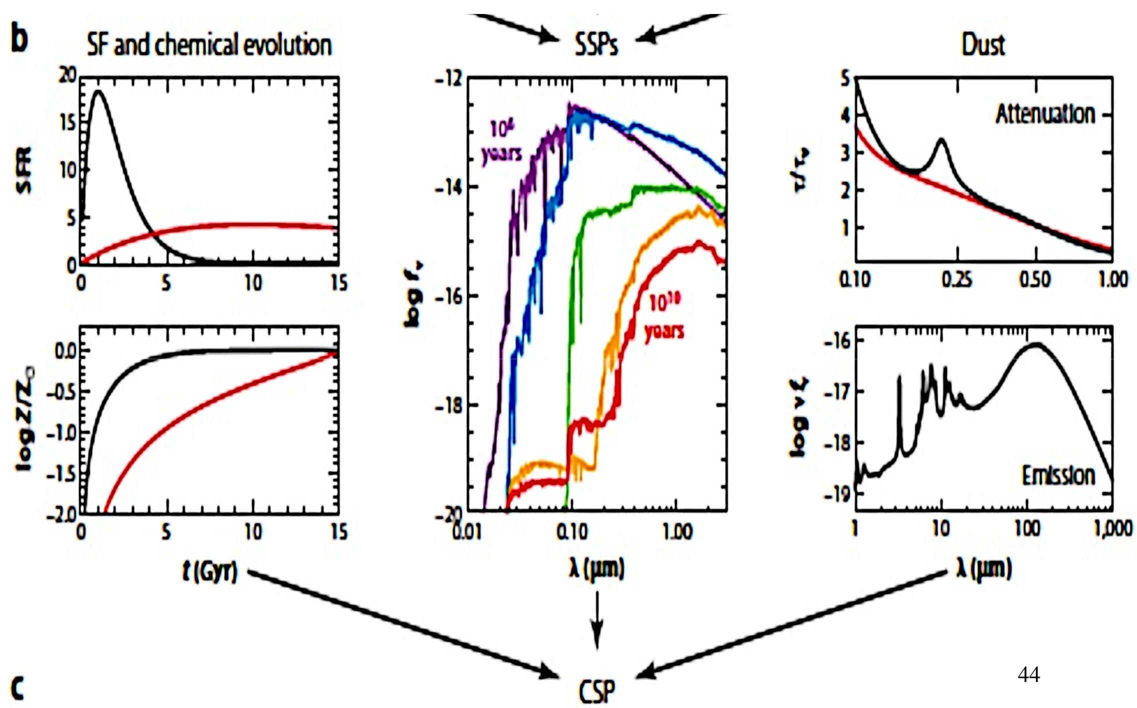
- How to build up the galaxies we observe from what we know about stars !

What is the Process –MWB sec 1.3 Conroy 2013

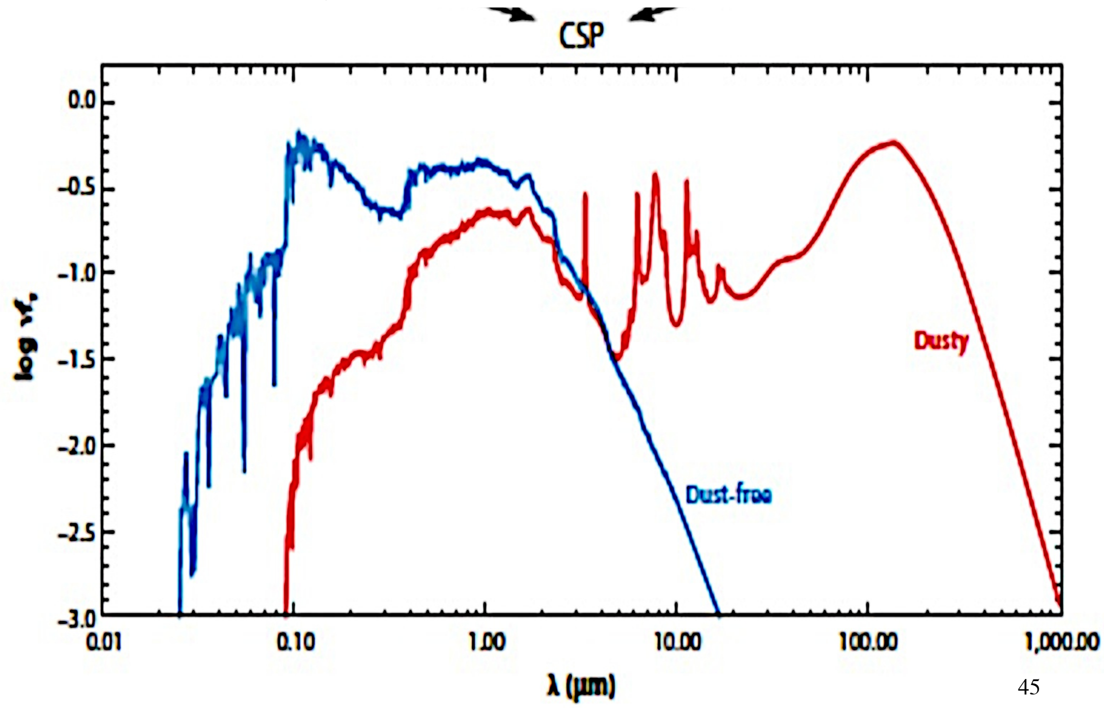
Taking stellar models
and data and constructing a galaxy spectrum



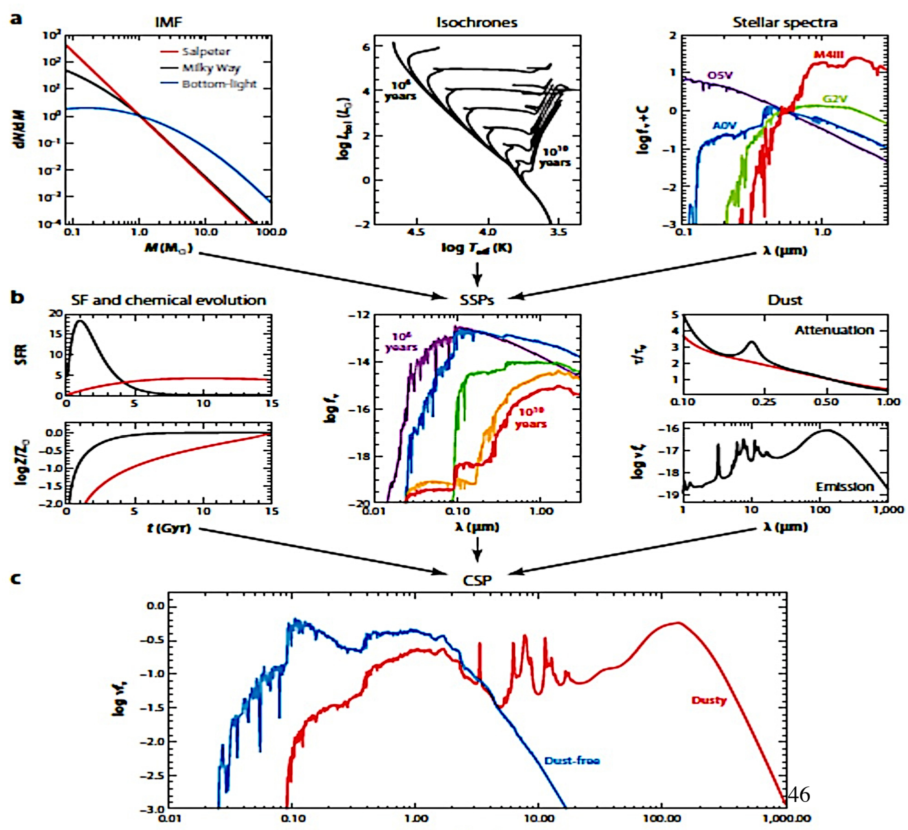
What is the Process –MWB
sec 1.3 Conroy 2013



What is the Process –MWB sec 1.3 Conroy 2013

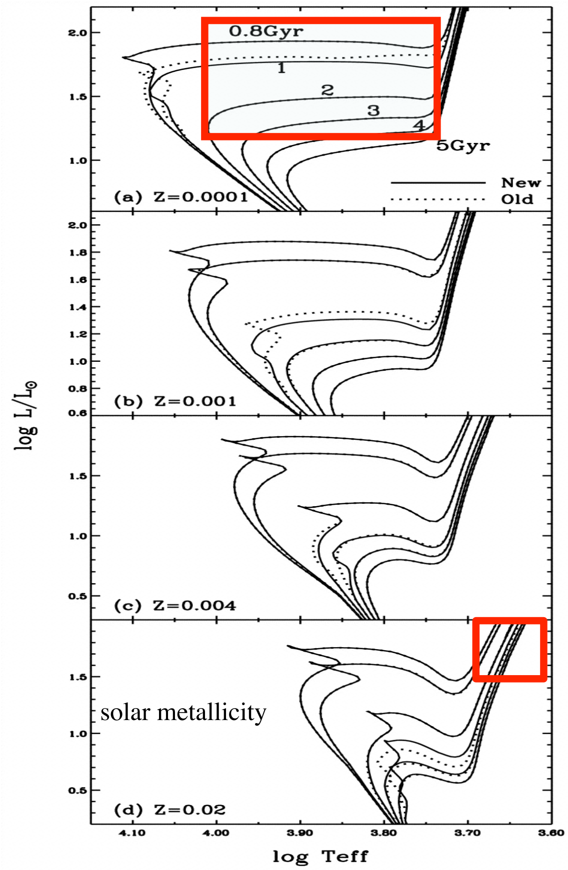


What is the Process – MWB sec 1.3 Conroy 2013



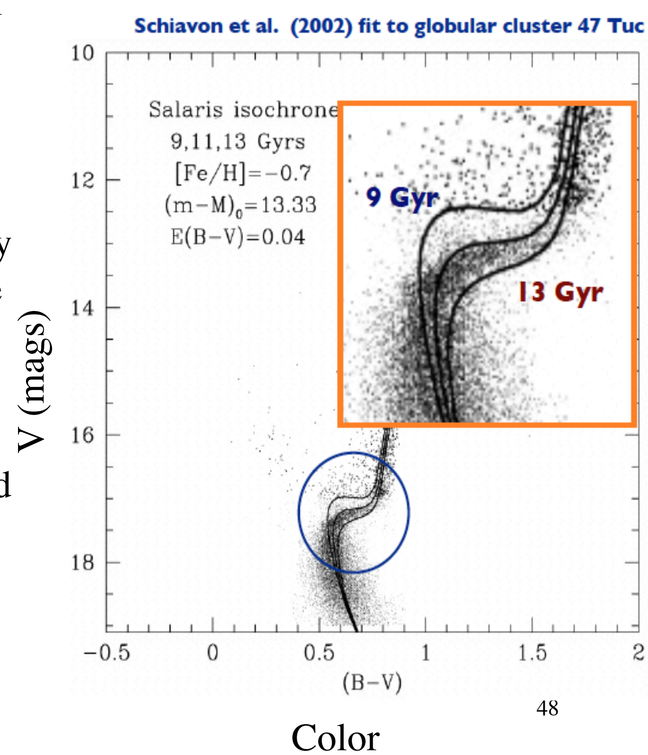
Theoretical Isochrones

- 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)



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.
  - (because stars at same distance, can use observed brightness, V, instead of absolute luminosity)



Isochrones for Omega Cen a Globular Cluster
Showing sensitivity to metallicity

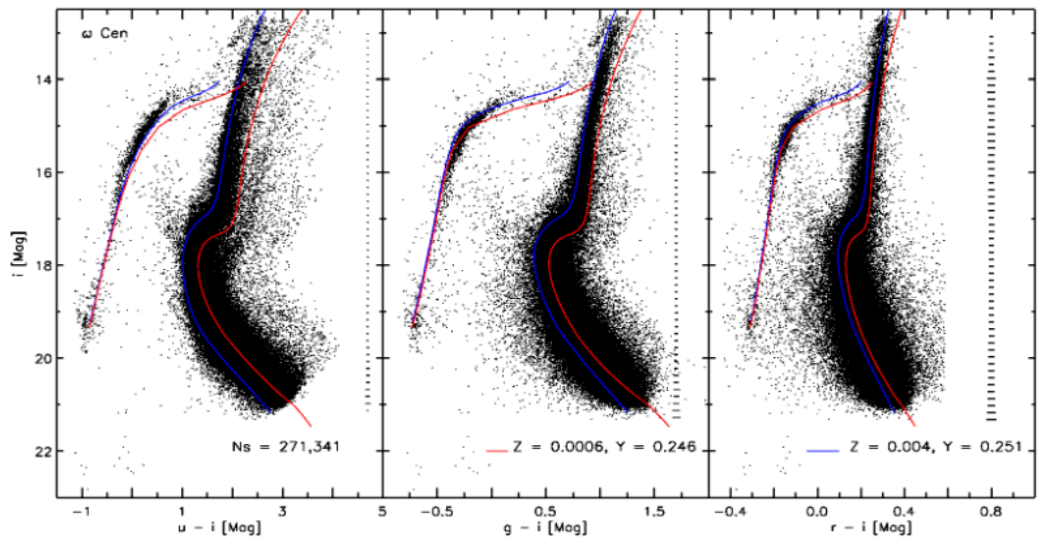
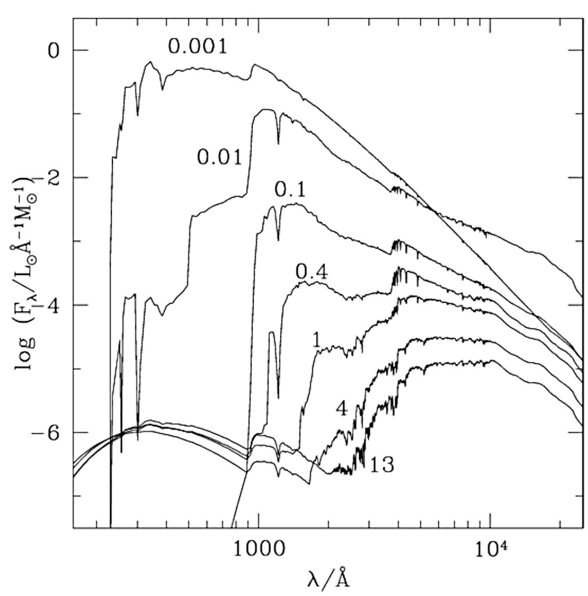


FIG. 6.— DECam *ugri* color-magnitude diagrams of ω Cen cluster members. Isochrones for the same age, t = 12 Gyr, and different metallicities are over-plotted (see labeled values). The respective zero age horizontal branch (ZAHB) tracks are also shown. Error bars are marked.

Galaxy Spectra

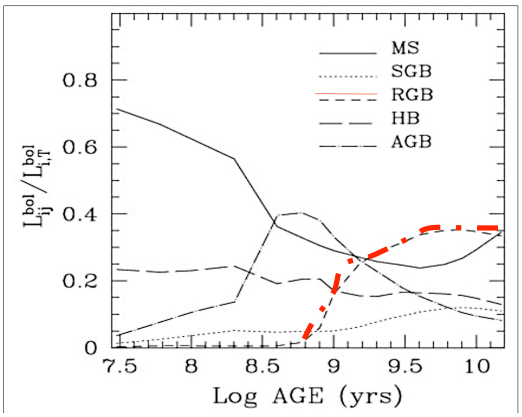
- Of course the galaxy spectrum is the sum of the stars, weighted by their luminosity.
- The spectra changes radically with the age of the system (MBW fig 10.5) and weakly with chemical composition
- After a ~fewx10^9 yrs stars on the red giant branch dominate the ~1μ flux; stars on the red giant branch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

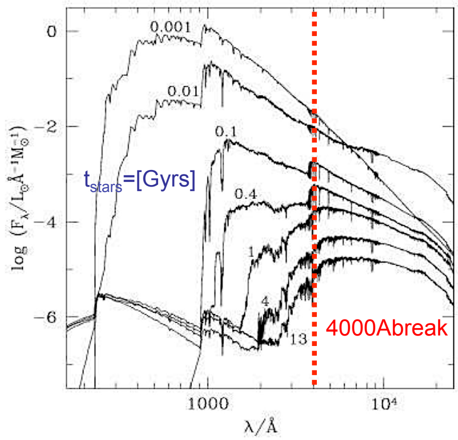


Theoretical spectrum of a SSP with a Saltpeter IMF and solar metallicity at a variety of ages 0.001-13 Gyrs

Luminosity and Colors Changes of a SSP

- As SSP ages the <u>relative luminosity due to different parts of the H-R diagram changes</u>
  - young systems MS dominated by massive stars
  - Older systems(>2Gyrs)-dominated by 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>





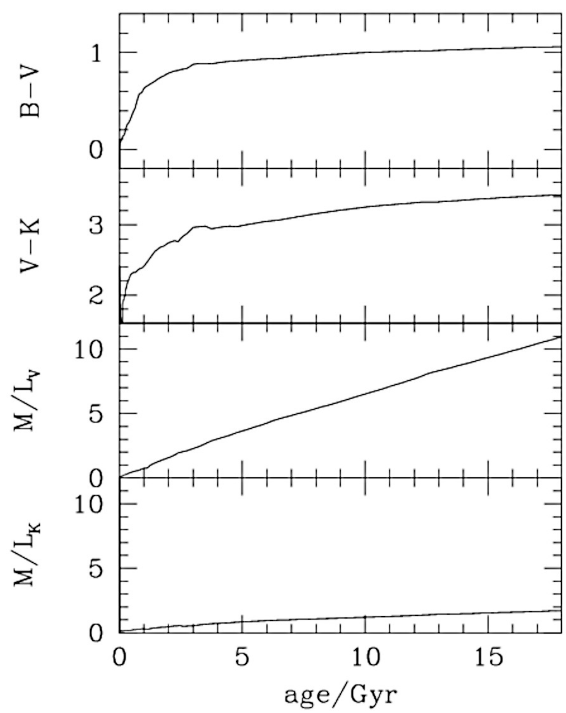
Spectral energy distribution UV-IR of a SSP as it ages

Notice the enormous changes in the UV and blue

A slow fading in the IR

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
- ***why? please explain why these plots look like they do.***
  - ***Hints: K band is in the near IR, V band is in the optical***



IMF- **MBW 9.6**
S&G 2.1.2

INITIAL Mass Function

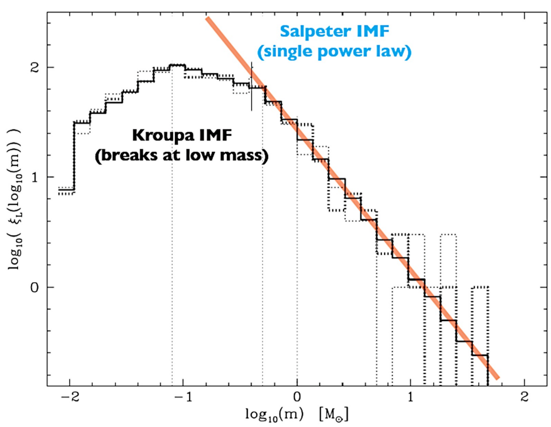
- The physical origin of the form of the IMF is not well understood
- Use the stellar mass-luminosity relation and present day stellar *luminosity* function together with a model of how the star formation rate varies with time.
- Simplest description: Salpeter- pure power law $\Phi(m)=N(M)\sim M^{-\alpha}\,dM$ for $M>M_\odot$ (Salpeter 1953)- total mass diverges $\alpha\sim 2.35$ (eq 2.5 S&G)
- Near the sun one can observe several 'open' star clusters (Scalo 1986)
  - one finds that the slope changes below ~ $1M_\odot$ (e.g. flattens)
- 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 !

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 $M_\odot$	

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

Initial Mass Function-IMF S&G sec 2.12

- 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/Scalo/Chabrier IMFs- flatten at low masses
- At present it is controversial if the IMF is universal or a function of age, metallicity, density etc



Luminosity function
$\Phi(x)$ = [number of stars with $M_V - 1/2 < x < M_V + ½$]/]volume Vmax(MV) over which these could be seen]

Salpeter Mass Function

- The Initial Mass Function for stars in the Solar neighborhood was determined by E.Salpeter in **1955.**
- $\Phi(m)=\Phi(0)M^{-2.35}$: $\Phi(0)$ is a constant which sets the local stellar density
- Using the definition of the IMF, the number of stars that form with masses between M and M + ΔM is: $\Phi(m)\Delta M$
- To determine the total number of stars formed with masses between M_1 and M_2 integrate the IMF between these limits:
- $N=\int\Phi(m)dM=\Phi(0)\int M^{-2.35}dM =[\Phi(0)/1.35][M_1^{-1.35}-M_2^{-1.35}]$

and total mass is $\int M^*\Phi(m)dM=[\Phi(0)/0.35][M_1^{-0.35}-M_2^{-0.35}]$

- most of the stars (by number) are low mass stars
- most of the mass in stars resides in low mass stars
- following a burst of star formation, most of the luminosity comes from high mass stars

Steps to the IMF-adapted from Djorgovski/Scalo-http://www.astro.caltech.edu/~george/ay20/Ay20-Lec17x.pdf

Determining the IMF is difficult- no more GAIA

• Start with observed star counts

– Understand your selection effects, completeness

– Get the distances

– Correct for extinction

– Correct for unresolved binaries

Take the data and determine the luminosity function (LF),

Then apply: correction for main sequence lifetimes, and evolved stars no longer visible

• Get the Present-Day Luminosity Function (PDLF)

– Assume a mass-luminosity relation

which is a function of metallicity, bandpass, …

– Theoretical models tested by observations

and the mass-luminosity (m-L) relation using stellar structure theory

• Convert to Present-Day Mass Function (PDMF)

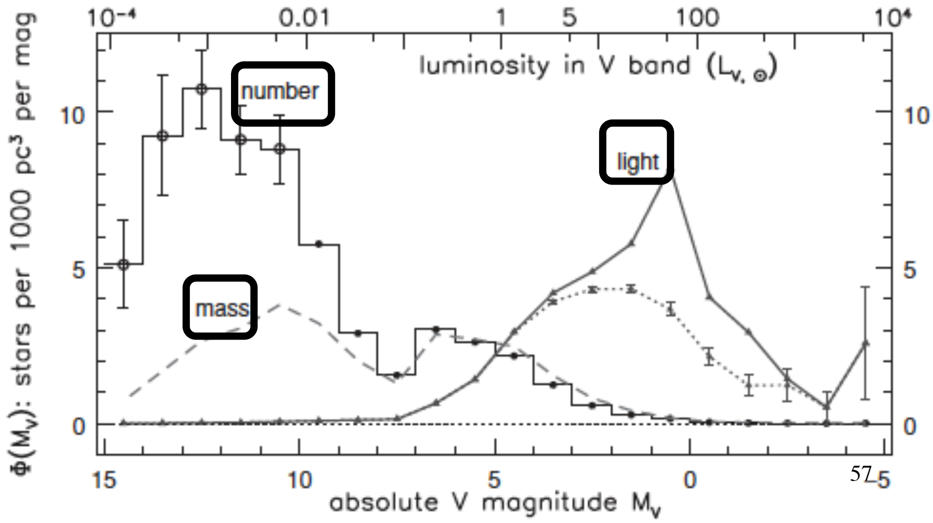
– Use the evolutionary tracks from the same theoretical models

– Iterate over a star formation history

• Get the Initial Mass Function (IMF)

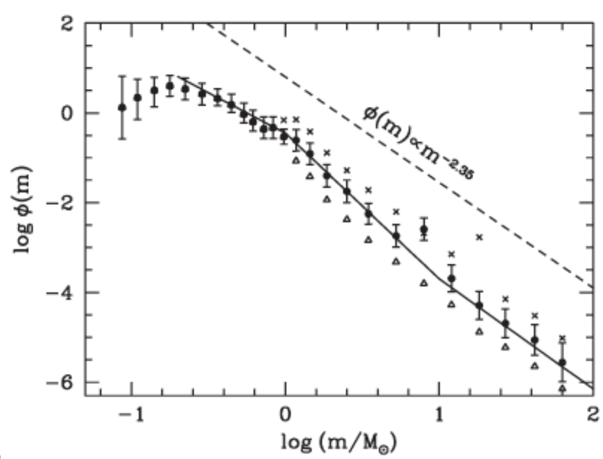
Number, Luminosity and Mass Functions

- S&G Fig 2.3 The histogram shows the luminosity function (MV) for nearby stars: solid dots
- Lines with triangles show $L_V\Phi(M_V)$, light from stars in each magnitude bin; the dotted curve is for main-sequence stars alone, the solid curve for the total. The dashed curve gives $M_{MS}\Phi(M_V)$, the mass in main-sequence stars. Units are L or M per 10 pc cube.



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



5. The IMF from Scalo (1986) for field stars in the solar neighborhood. For $m > 1\,M_\odot$ the thı
ıts represent results assuming different ratios of the current star-formation rate to the average o
ıe of the solar neighborhood. The solid lines show the broken power law (9.41), while the dash

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

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

Kroupa IMF has 1.6x less total mass than the Saltpeter IMF for the same normalization but ~ same amount of light

$\langle M\rangle=0.6M_\odot$

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.

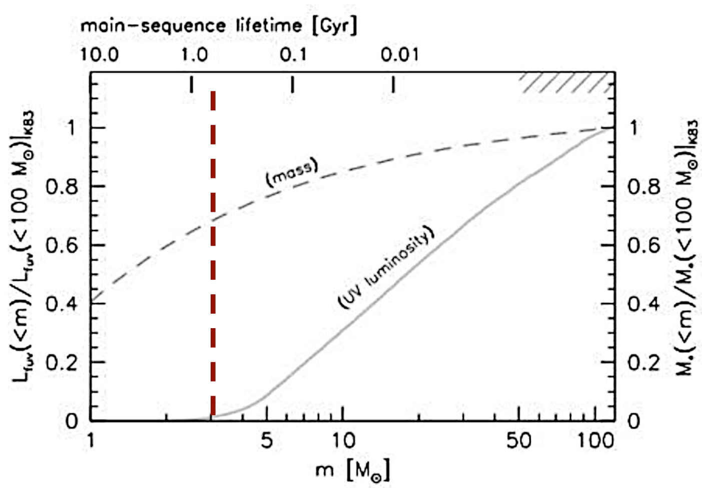
- This change in the number of massive stars is very important for the chemical enrichment of the galaxy since only stars of $M>8M_\odot$ produce type II SN.

  – 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 and Kroupa.

- The slope of the IMF is, critical for converting the observed light to stellar mass - 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

What We Covered

- Age of a SSP
- SSP spectra as a function of time
- Initial Mass Function (IMF)
- Composite spectra of galaxies

Stellar Populations I & II- Baade 1942 (pg 56 MBW) S&G sec 6.3

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

Population I

– Young

– Metal rich

– in disks

- Rotationally supported

Population II-' red'

– Old

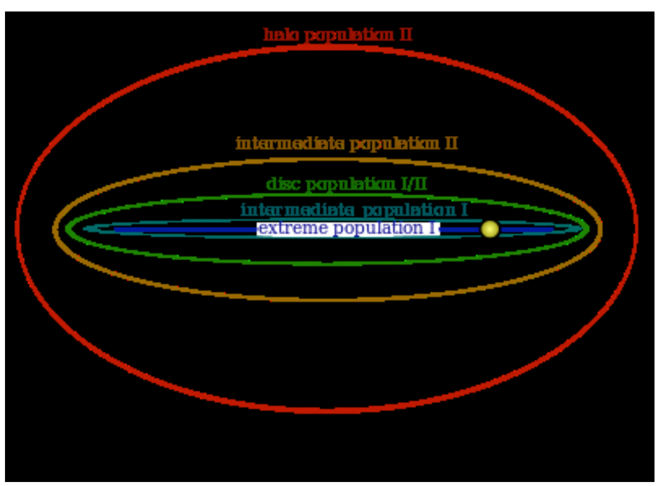
– Metal poor- non-solar abundances

– 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



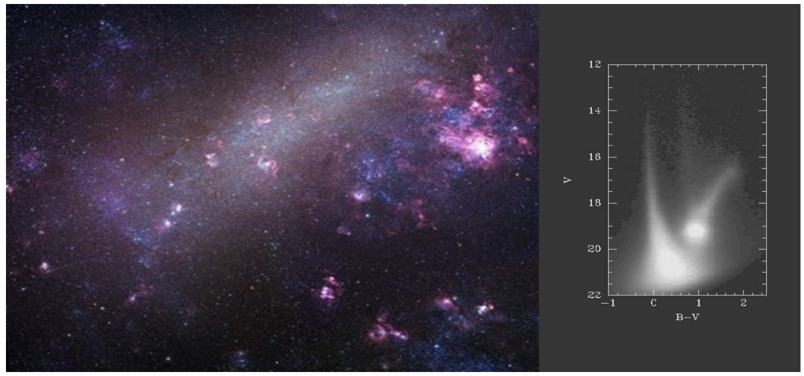
Schematic picture of stellar pop's in Milky Way

- 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

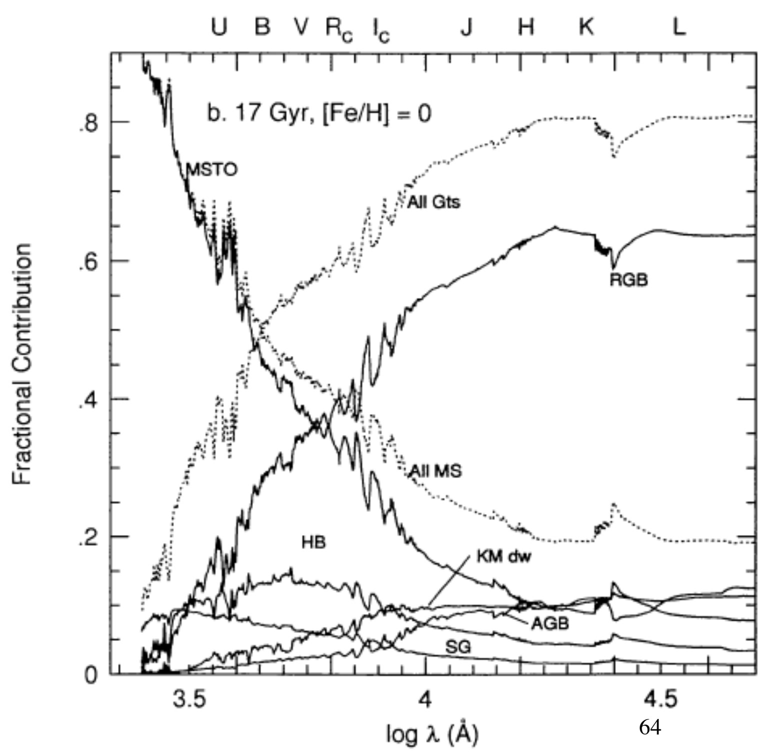


LMC:Zaritsky&Harris2004-2009

Origin of Light

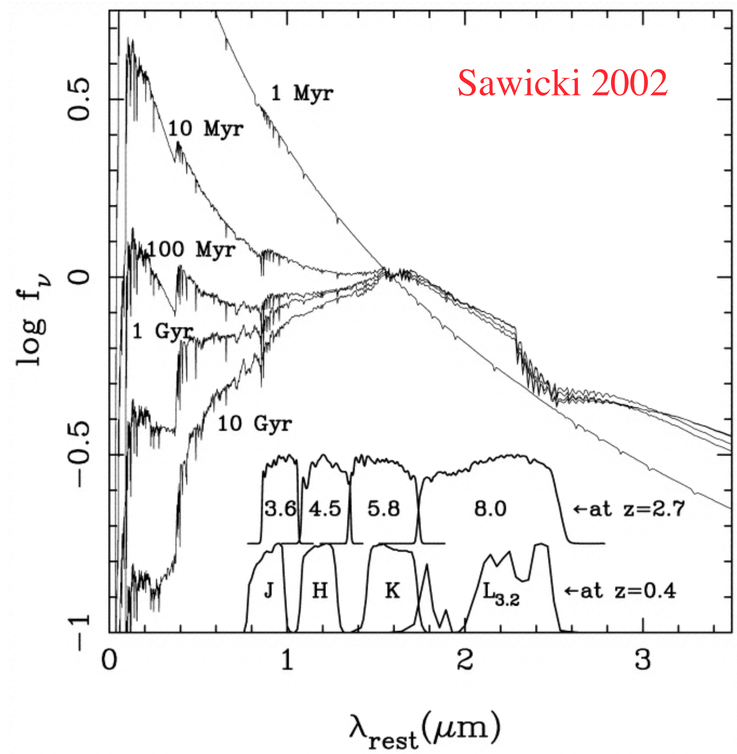
In a SSP which stars produce the observed light as a function of wavelength

Graph is a snap shot at an age of 17 Gyrs !) (Worthey 1994)



How Much Light at Which Wavelengths

- As a SSP system ages the spectrum changes strongly at short wavelengths but remains ~ constant at long wavelengths
  - K band (2.2μ) is thus a good proxy for stellar mass at all times

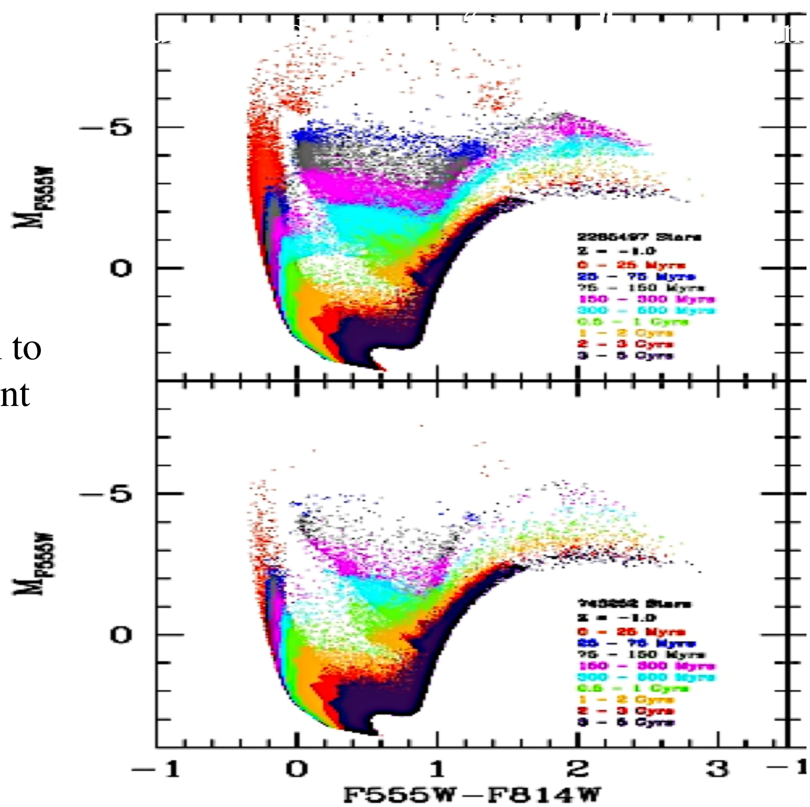


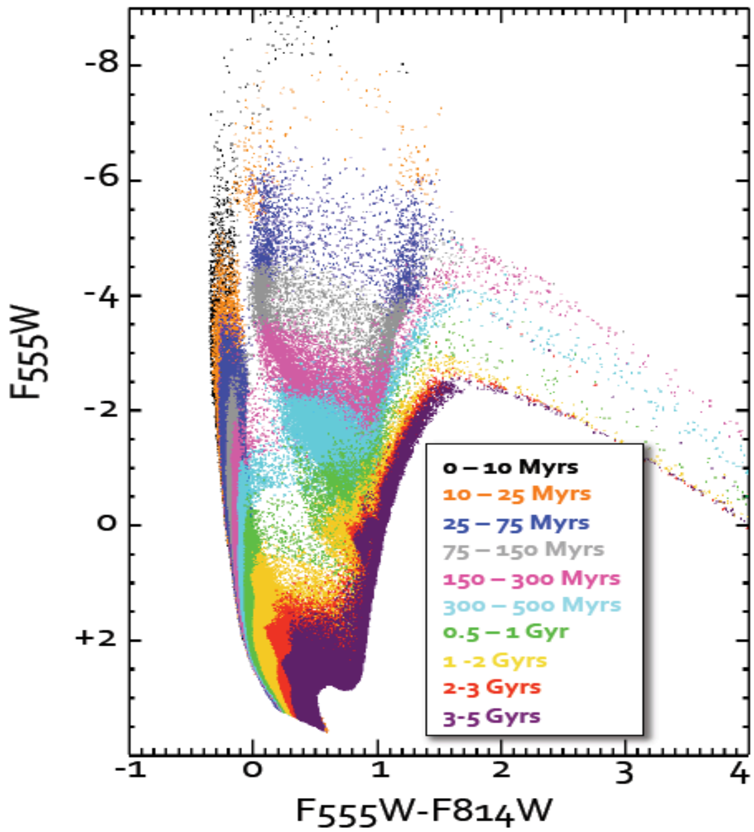
What does CMD of a composite population look like?
SFR * IMF * flux for individual stars (before it's integrated over all stars…)
(Eric Bell)

Top panels: Increasing SFR to emphasize recent star form

Bottom panels: constant SFR

CMDs created by D. Weisz using Dolphin's codes





- Galaxy $=\Sigma_{(time)}SFR(t) \times SSP(t;Y;Z;IMF)$
- Y the Helium abundance and Z the abundance of heavier elements (metallicity)

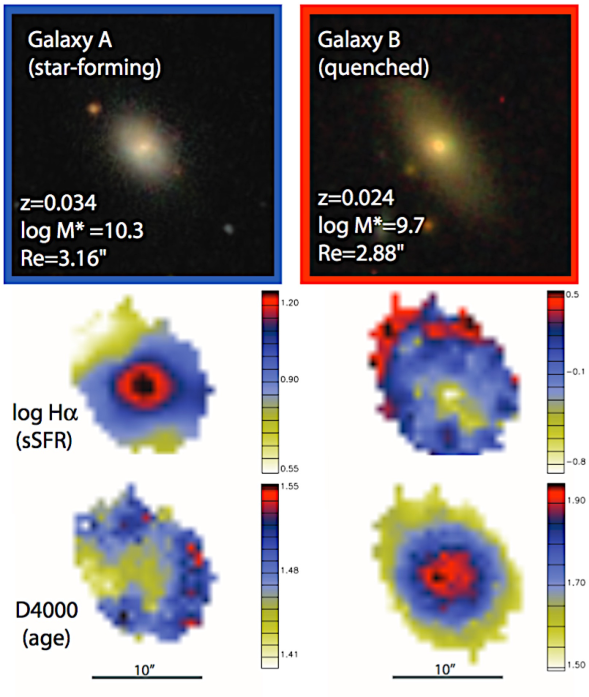
Synthetic CMD; D.Weisz- constant SFR

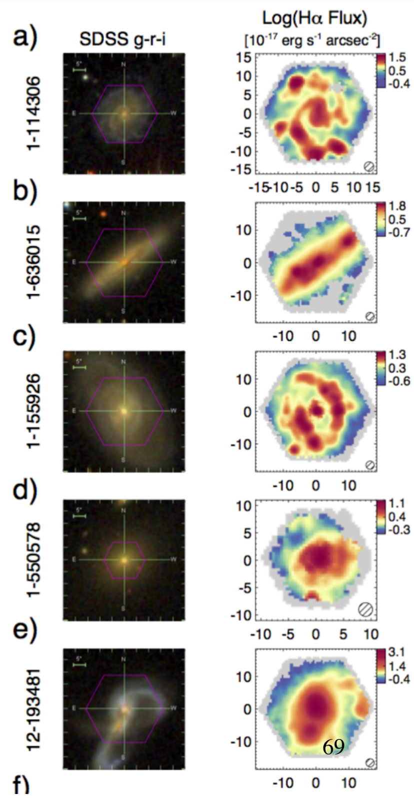
Color Magnitude Diagrams

- Need to measure individual stars- only possible in local group
- <u>But Very powerful</u>
  - If get to main sequence turn off for old stars
    - Star formation history
      - Resolution good for recent star formation, worse for ancient times
  - If you don' t get to main sequence turn off (more distant objects)
    - Some SFH information remains but tricky to do well because it' s all post-main sequence based

- However for the vast majority of galaxies just have integrated spectra/ color images
  - New data with spatially resolved spectra (IFUs)- e.g MANGA (more later) sub-divide galaxy into ~100 places (~1 kpc) for 10,000 (!!) galaxies

MANGA Galaxy Data



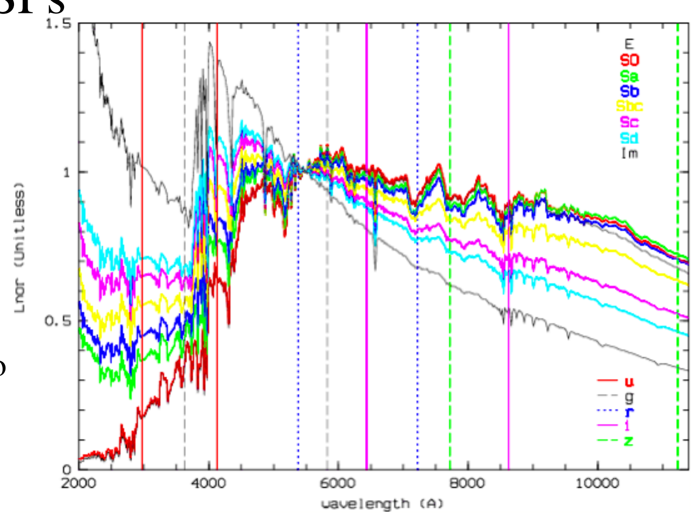


General Trends for SSPs

- 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.

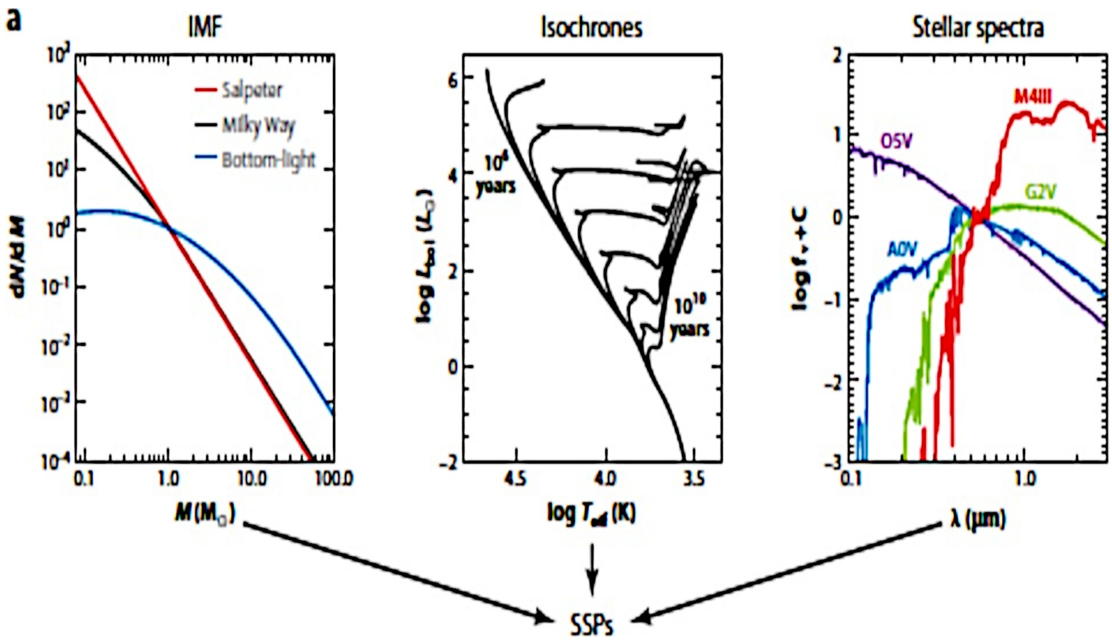
Higher 'metallicity' and dust also 'redden'



Theoretical models of galaxy composite spectra

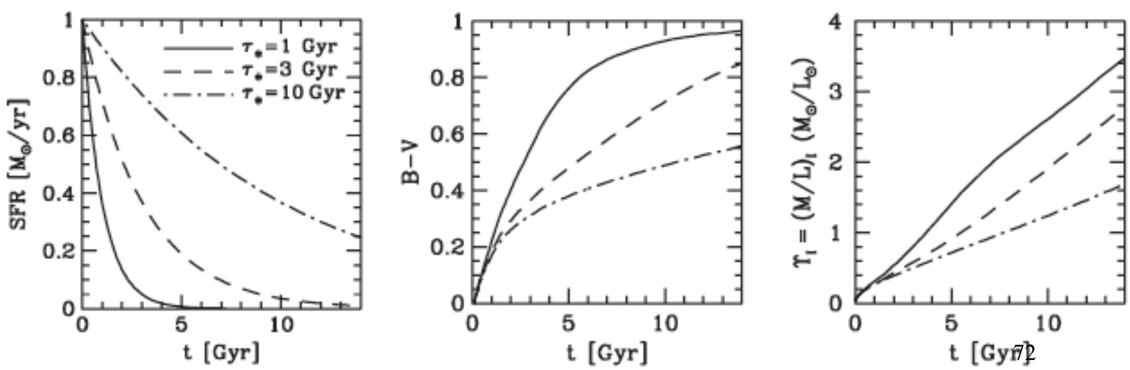
What is the Process –MWB sec 1.3 Conroy 2013

Taking stellar models and data and constructing a galaxy spectrum



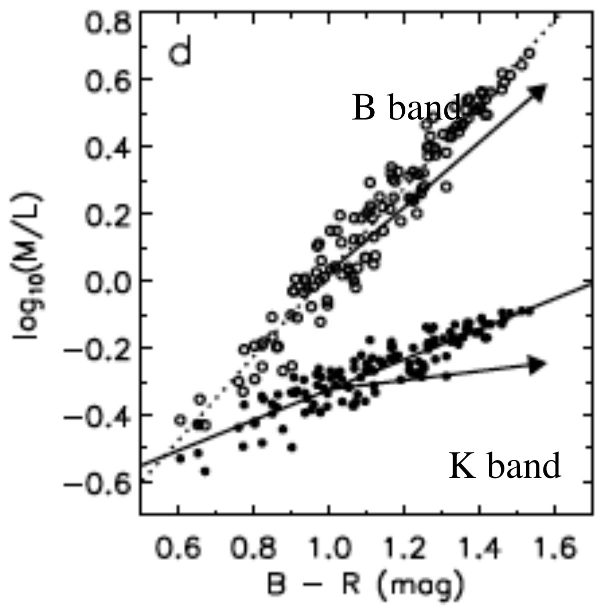
Effect of Star Formation History on Colors and Luminosity of a SSP (fig 10.9 of MBW)

- Left panel 3- different star formation histories
  - solid 1 Gyr e-folding time
  - dash 3 Gyr
  - -dash-dot .. 10 Gyr
- Middle panel B-V colors
- Right Panel mass to light ratios

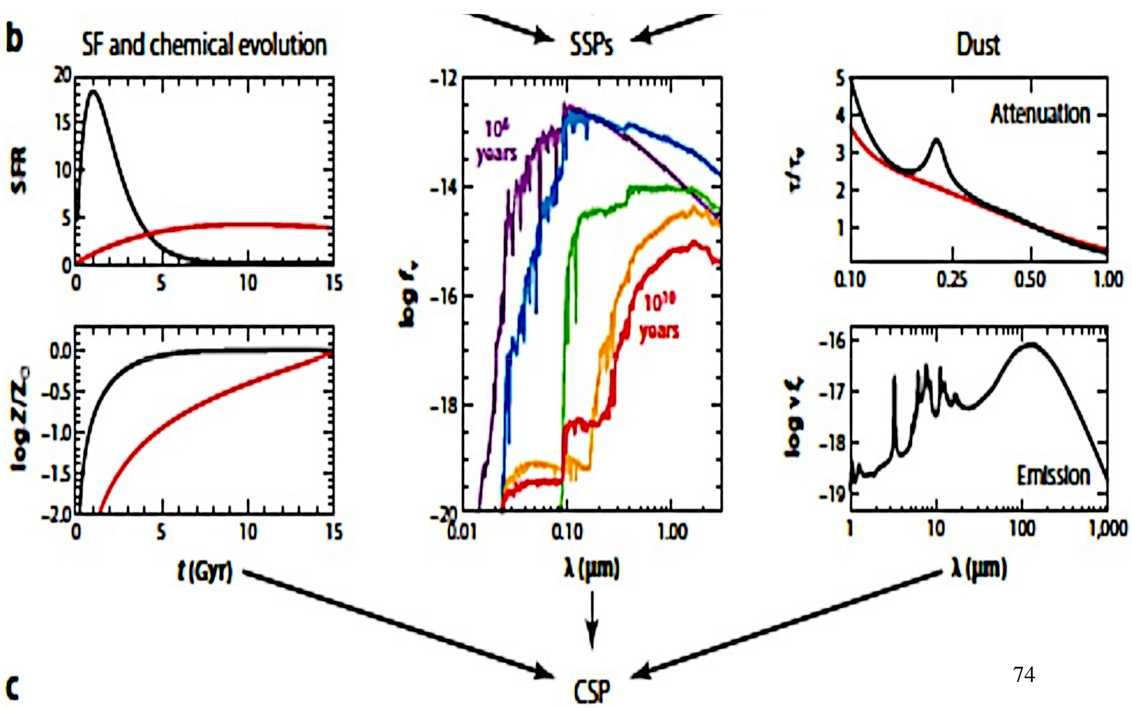


M/L(Mass to Light) Indicators

- Some colors are very sensitive to M/L
- 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
- Such techniques can be applied to large samples -



What is the Process –MWB
sec 1.3 Conroy 2013

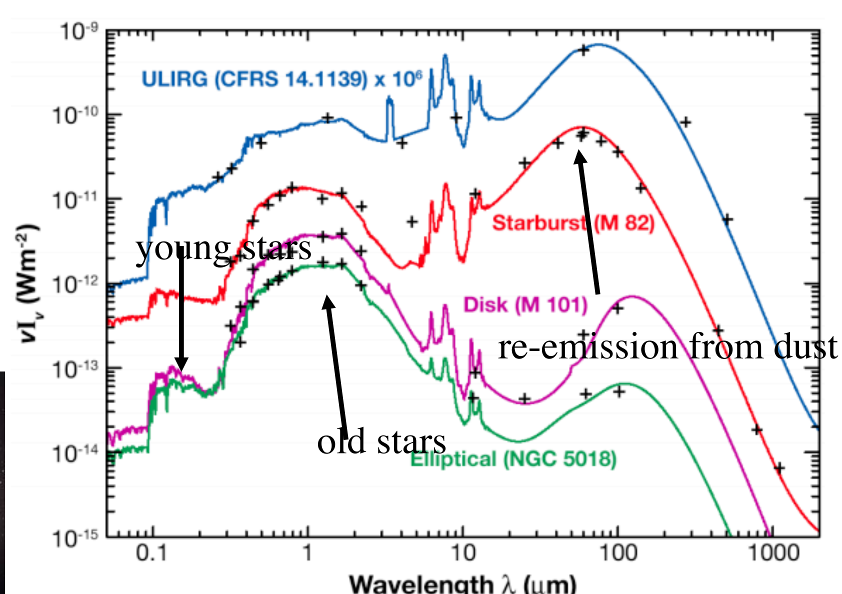


Next Time

- GAS- physics of ... S+G 2.4+5.2
- additional material in MBW sec 10.3.7,10.3.8

Put it All Together Into A Galaxy

- Even some ellipticals have dust



http://hubblesite.org/newscenter