IMF- **MBW 9.6**

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 $\alpha\sim 2.35$
- 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 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 $M_{\odot}$	

70 Pavel Kroupa: AIfA, 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

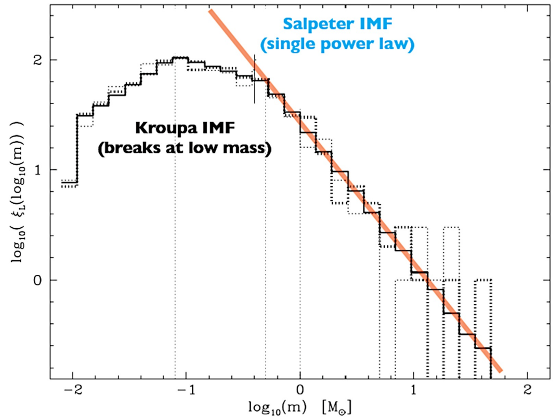
- Start with observed star counts
  - Understand your selection effects, completeness
  - Get the distances
  - Correct for extinction
  - Correct for unresolved binaries

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)

Initial Mass Function-IMF S&G sec 2.12

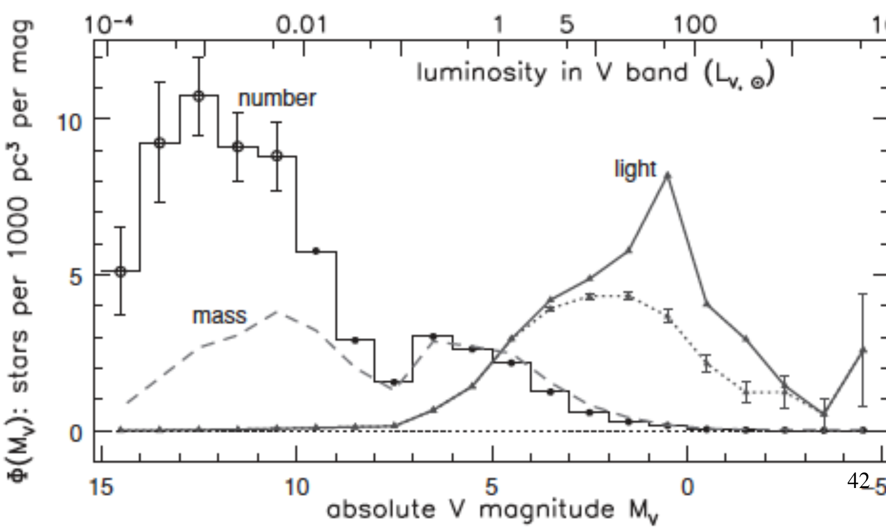
- The distribution of stellar masses at t=0 (birth)
- The origin of the form of the IMF is not well understood
- There are several forms proposed
  - Saltpeter- $\Phi(m)=N(M)\sim M^{-2.35}dM$ for $M>M_{\odot}$ (Salpeter 1953)
    - much of integrated stellar mass near $1M_{\odot}$
  - Kroupa/Scalo/Chabrier 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]

Number, Luminosity and Mass Functions

- S&G Fig 2.3 The histogram shows the luminosity function (MV) for nearby stars: solid dots from stars of Figure 2.2, open circles from Reid *et al*. 2002 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;vertical bars show uncertainty, based on numbers of stars in each bin.



IMF-see MBW pg 440

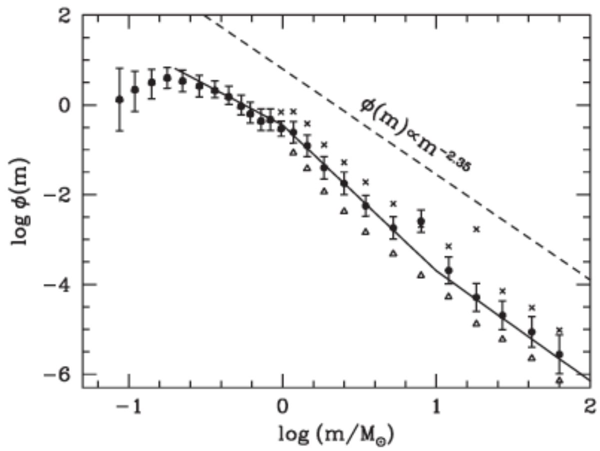
- General form $\int m\Phi(m)dm=1M_\odot$
- integrated over the upper and lower mass range of stars ; meaning $\Phi(m)dm$ is the number of stars born with mass m+/- δm for every $M_\odot$ of newly formed stars
- Stars $M<0.08M_\odot$ nuclear fusion not take place and $M>\sim 120M_\odot$ are unstable.

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

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

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

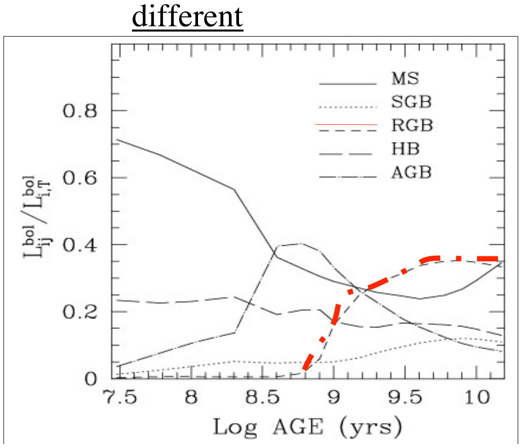
$\langle M\rangle=0.6M_\odot$

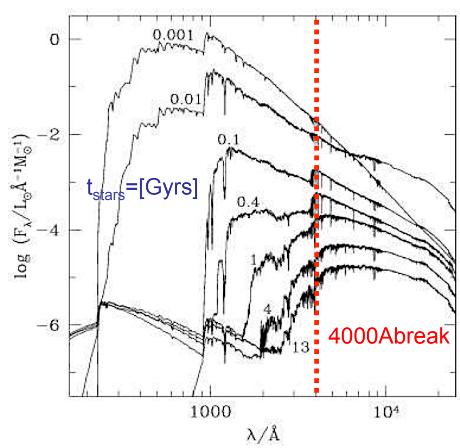


5. The IMF from Scalo (1986) for field stars in the solar neighborhood. For $m > 1 M_\odot$ the thı
ıts represent results assuming different ratios of the current star-formation rate to the average o
ıe of the solar neighborhood. The solid lines show the broken power law (9.41), while the dash

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

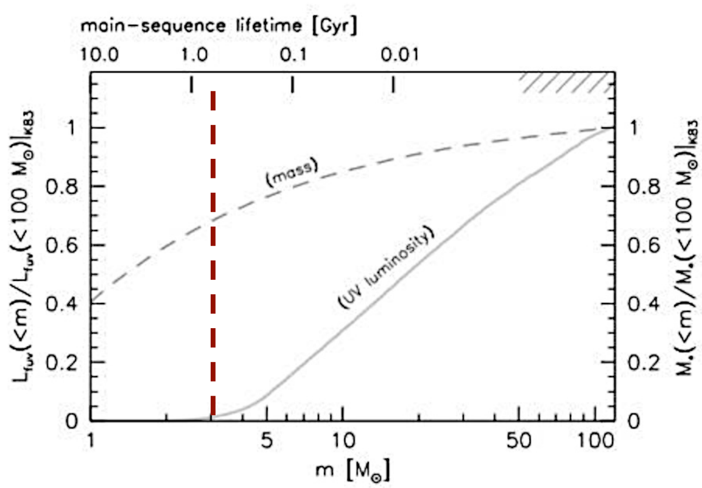
Effects of IMF

- 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.
- 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

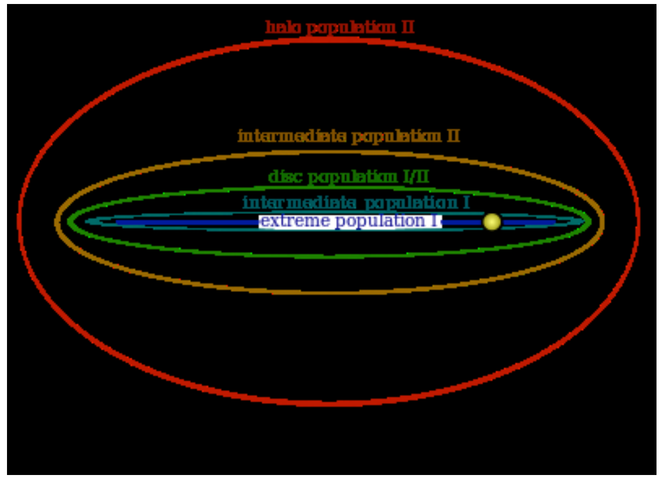
In spiral galaxies there are 2 'types' of stellar populations

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

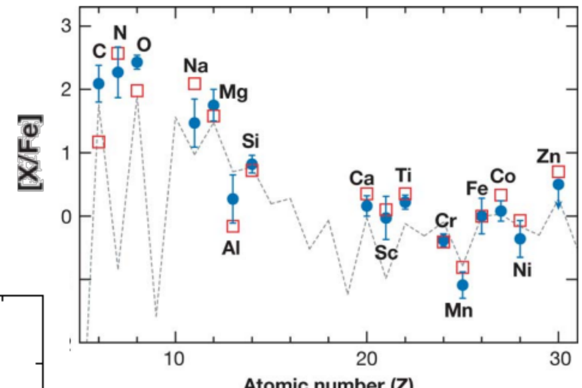
theoretically there is also Pop III- the first stars

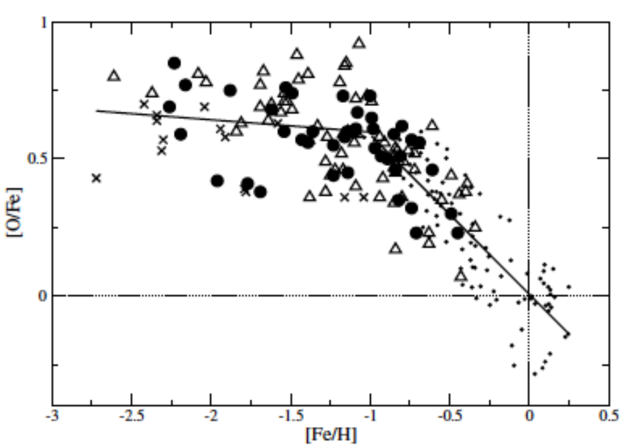


Schematic picture of stellar pop's in Milky Way

Abundance Pattern of OLD Metal Poor Halo Stars (pg 177 in S+G)

- A strong clue to the formation of the **first** stars - lots more C, N,O relative to Fe.
- *We will have a more general lecture on chemical evolution later*



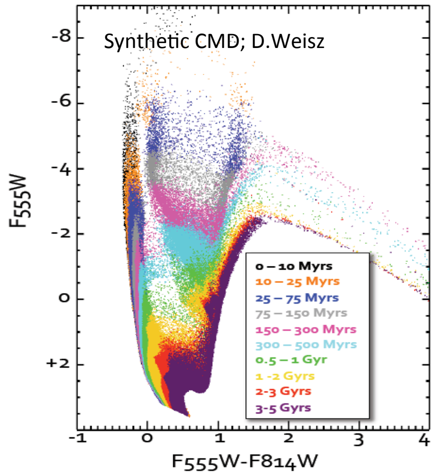


[X/Fe] is the logarithmic ratio of element X to Fe with respect to the sun's abundance pattern

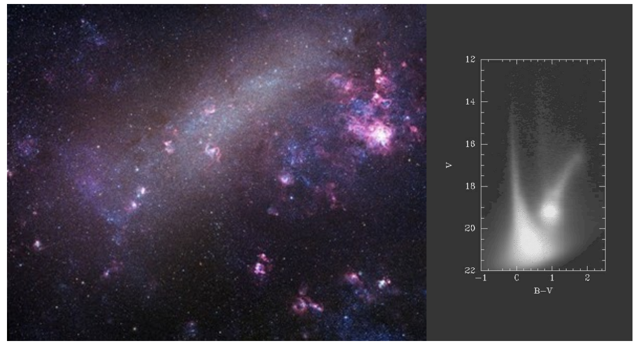
Galaxies are NOT SSPs

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



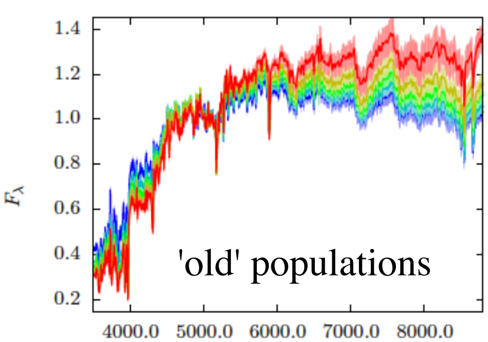
LMC:Zaritsky&Harris2004-2009

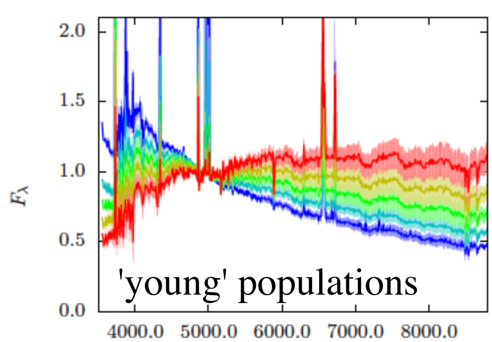
Galaxy $=\Sigma_{(time)}$SFR(t) xSSP(t;Y; Z; IMF)

Y the Helium abundance and Z the abundance of heavier elements (metallicity)

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 3650Å. (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 gas is ionized
- Balmer absorption lines such as Hγ, Hδ, and Hβ tend to trace age in old stellar populations, whereas metal-line indices such as Fe and Mgb yield information about the metallicity and α (O, Mg, Si, Ar, Ne) abundances in the stellar atmospheres.
- ***Dust (reddening) is a major issue***





Galaxy spectra-see MWB 10.3.4

- Classical indicators of what is going on:
- The so-called 4000Å 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 : 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

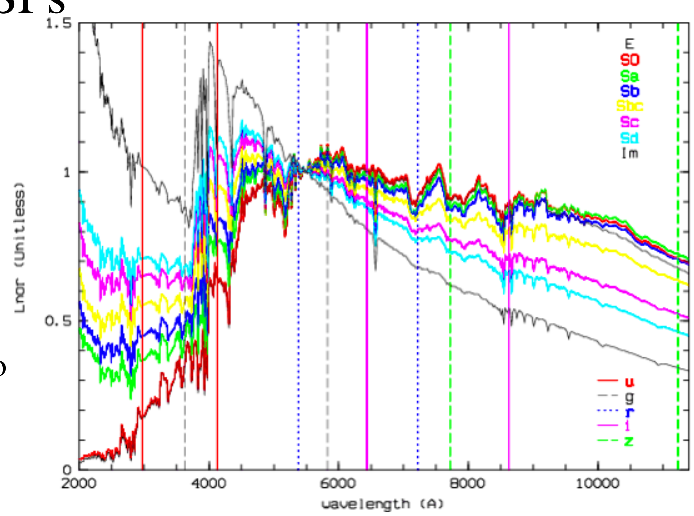
General Trends for SSPs

- 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’



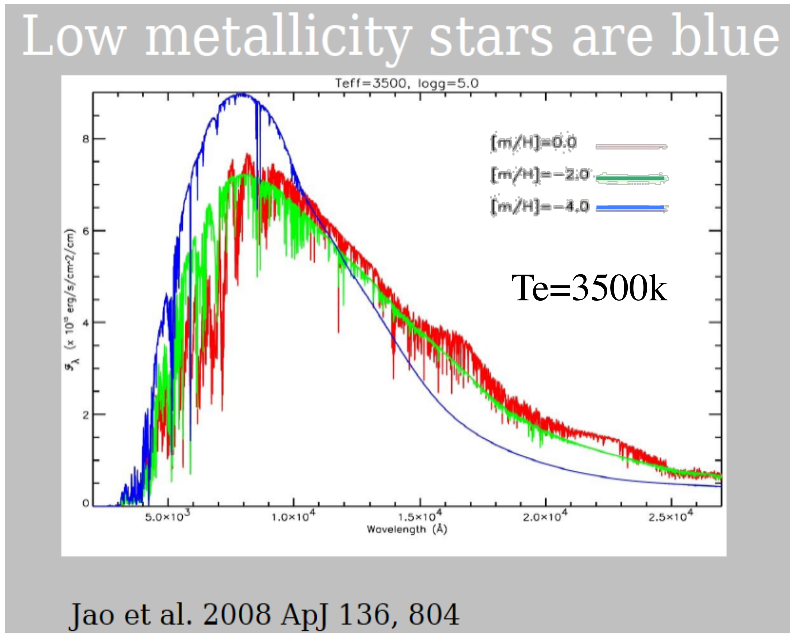
output from Pegase2 code Tsalmantza et al 2007,2009
Each spectrum in the library is defined by a set of 17 astrophysical parameters, plus the morphological type
The four most significant APs are:
the star formation scenario ,the infall timescale of gas; the age of the galactic winds

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

Effects of Metallicity

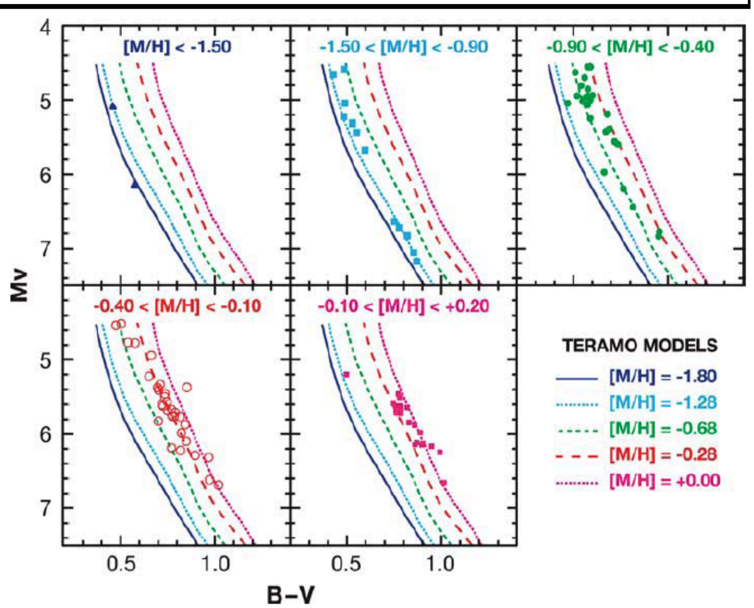


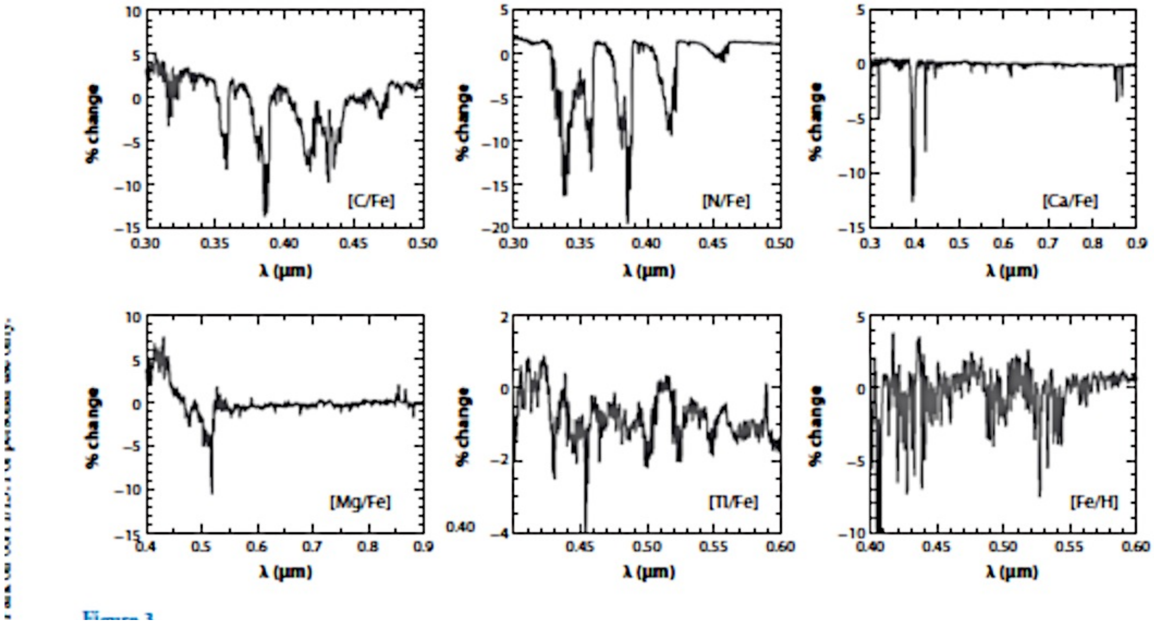
Effects of Metallicity

- 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 brighter for a given mass. (fig 1.5 in S+G).
- M_v :absolute magnitude in the V band

Age-Metallicity Degeneracy (10.3.5)

Evolution of star depends on metallicity; stars with higher metallicity evolve faster. Unfortunately stars with the same $tZ^{3/2}$ have virtually identical optical colors





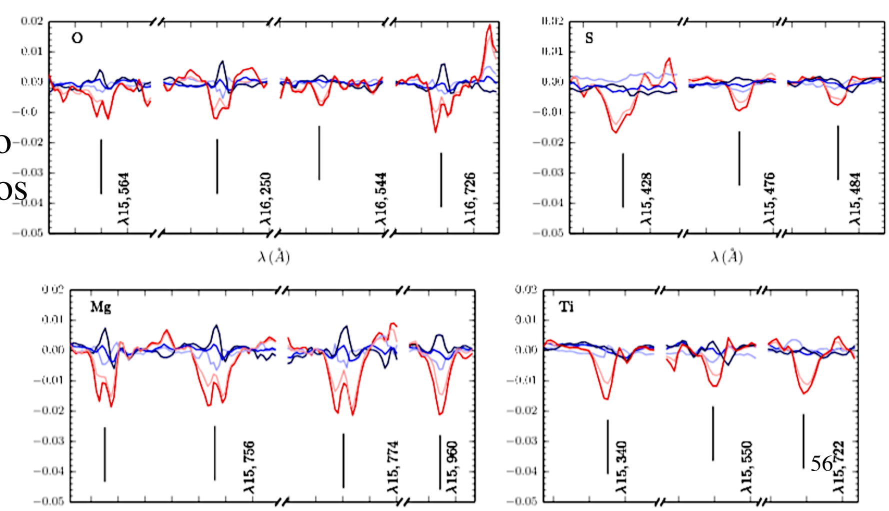
- Effects of change in abundance for different elements on a 13Gyr old stellar population

Abundance Determination

- Relies on very high S/N spectra with high spectral resolution
- Very accurate models of stellar atmospheres

Notice signatures of elements occur at the 1-2% level
Bovy et al arxiv 1509.05796

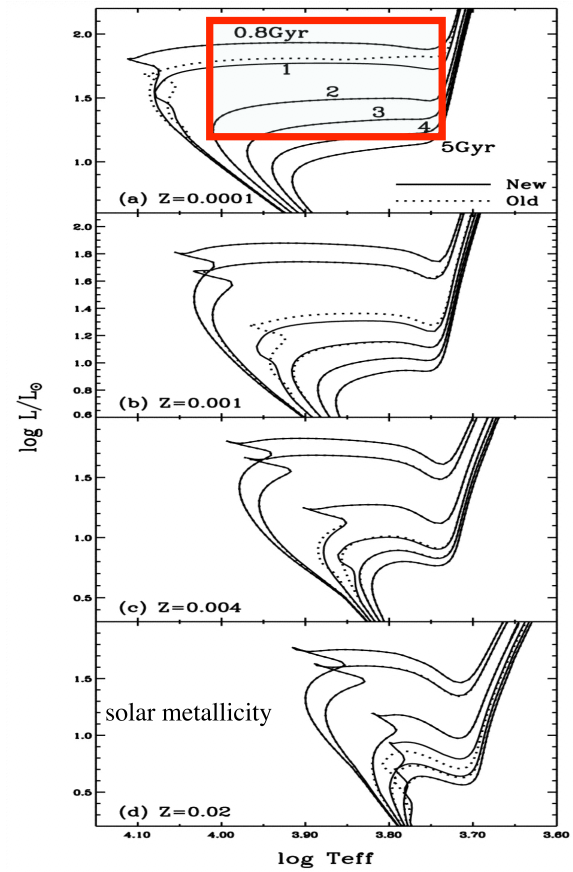
Different colors correspond to different ratios of α/Fe



Theoretical Isochrones

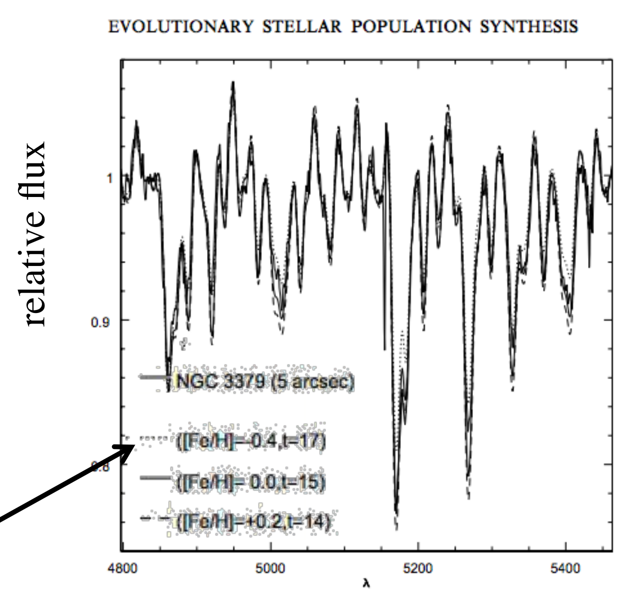
- These lines are the positions of stars from a SSP as a function of the age of the system - in the temperature/ luminosity plane **if** no new stars are born
- The shape depends on the metallicity of the stars (Demarque et al 2004)

- 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 - degeneracy problems with age and metallicity are obvious -
- 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.



wavelength

Vazdekis 1999

Spectra of Galaxies

- Mathematically the luminosity of a galaxy at a given frequency, ν, is
- $L_\nu(\text{galaxy})=\int dt' \int dZ'(dM/dt(t,Z) x L_\nu^{(SSP)}(t-t',Z',\phi)$
- 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

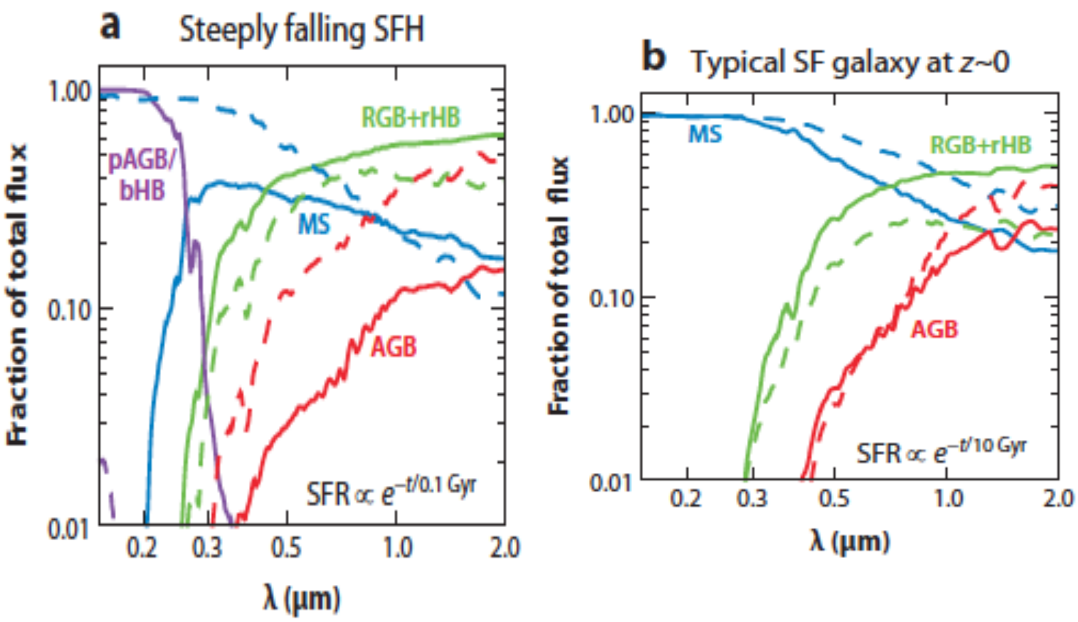
- ʻIntegratedʼ Stellar Populations

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 ʻmany colorsʼ, i.e the ʻspectral energy distributionʼ (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

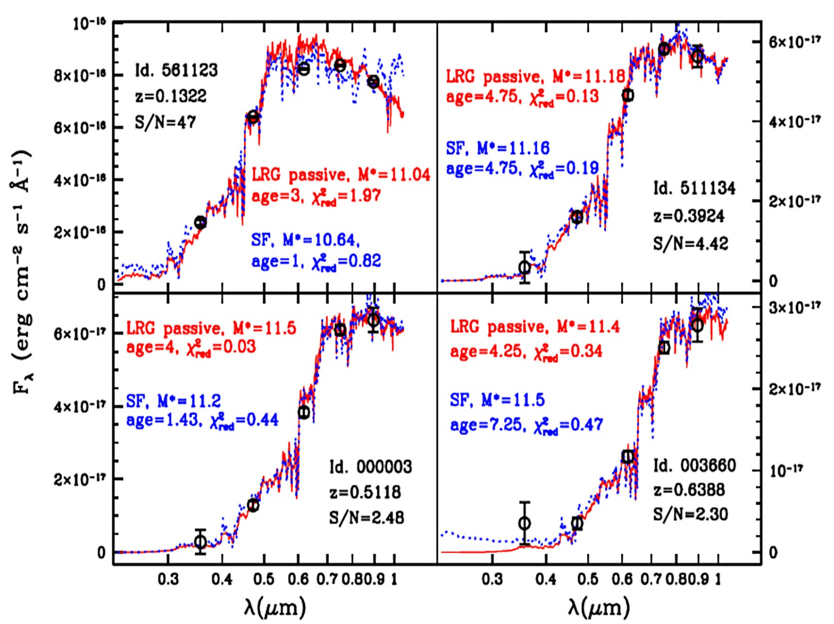
Effects of Different Star Formation Histories on Galaxy Spectra- Conroy 2013

13 Gyr solid lines, 1 Gyr dashed lines



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)**

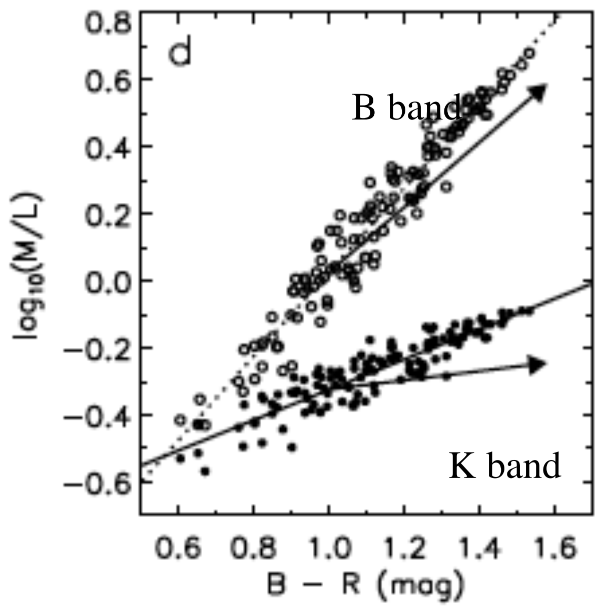


Maraston et al 2012

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
- Apply such technique to large samples -

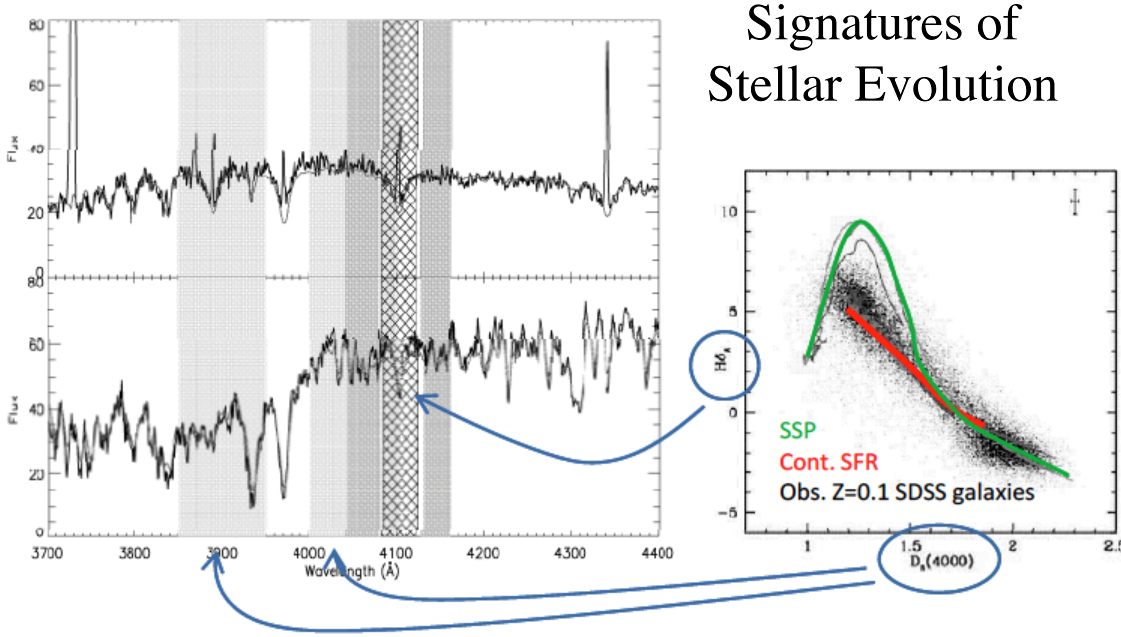


Dust and Reddening-MBW 478-481

- 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

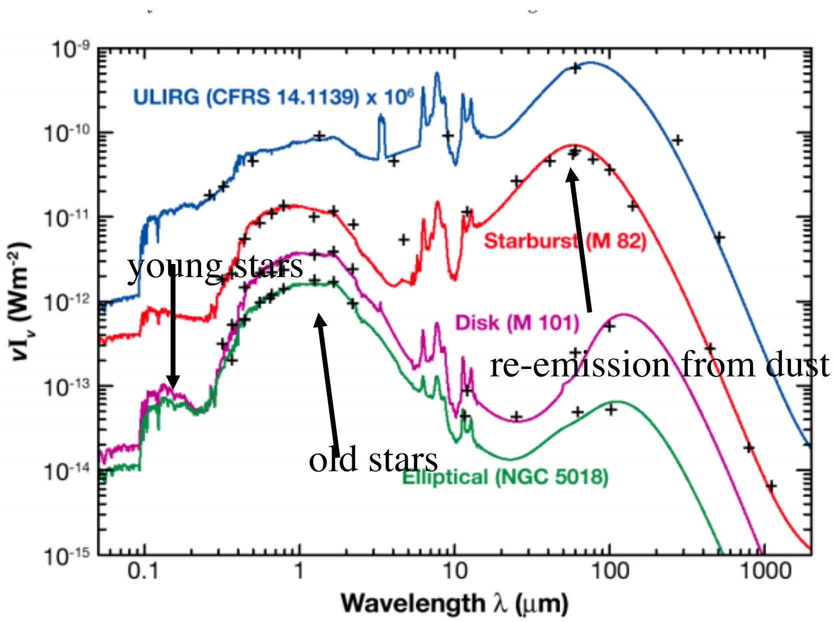


- Hδ vs D(4000)- distinguish SSP vs continuous star formation- features in summed stellar spectra

- 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 was often used (Worthey1994.
- For actively star-forming galaxies, the 4000Å 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.

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

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

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

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

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

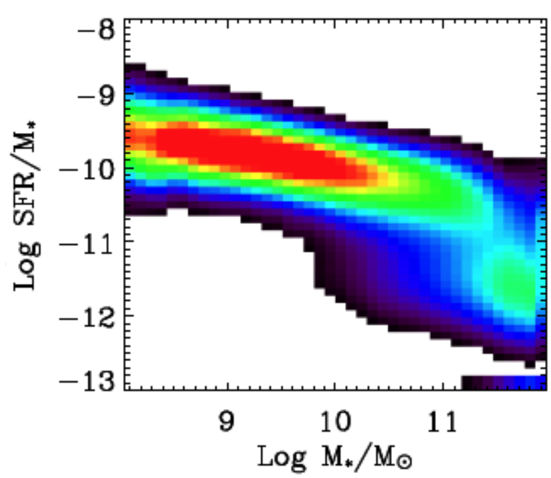
L_v(in UV)~const for very young pos.s (e.g. Kennicutt 98)

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

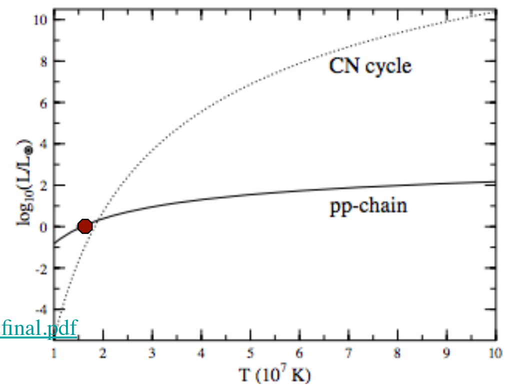
Generic Results

- 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



Energy Generation on Main Sequence



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

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

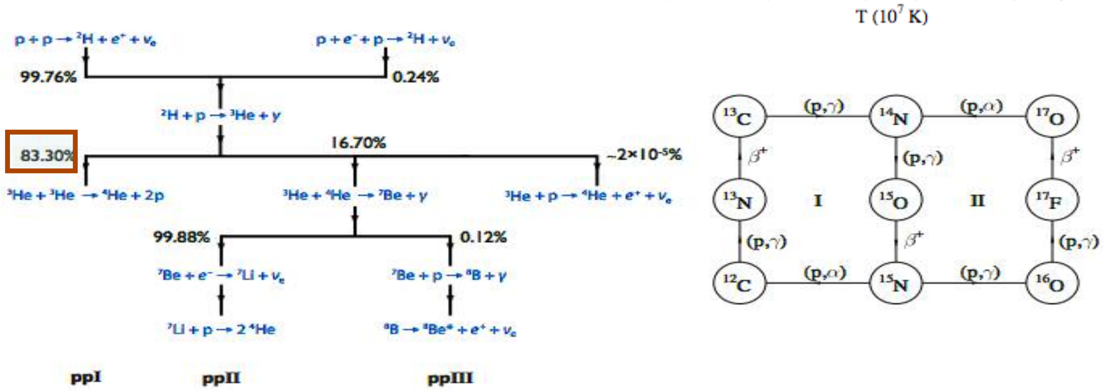


FIG. 2 The left frame shows the three principal cycles comprising the pp chain (ppI, ppII, and ppIII), with branching percentages indicated, each of which is "tagged" by a distinctive neutrino. Also shown is the minor branch ${}^3He+p \rightarrow {}^4He+e^++\nu_e$, which burns only $\sim 10^{-7}$ of ${}^3He$, 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.