IMF- MBW 9.6 S&G 2.1.2, B&M ch 5.1.9

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 $\alpha\sim2.35$ (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 !

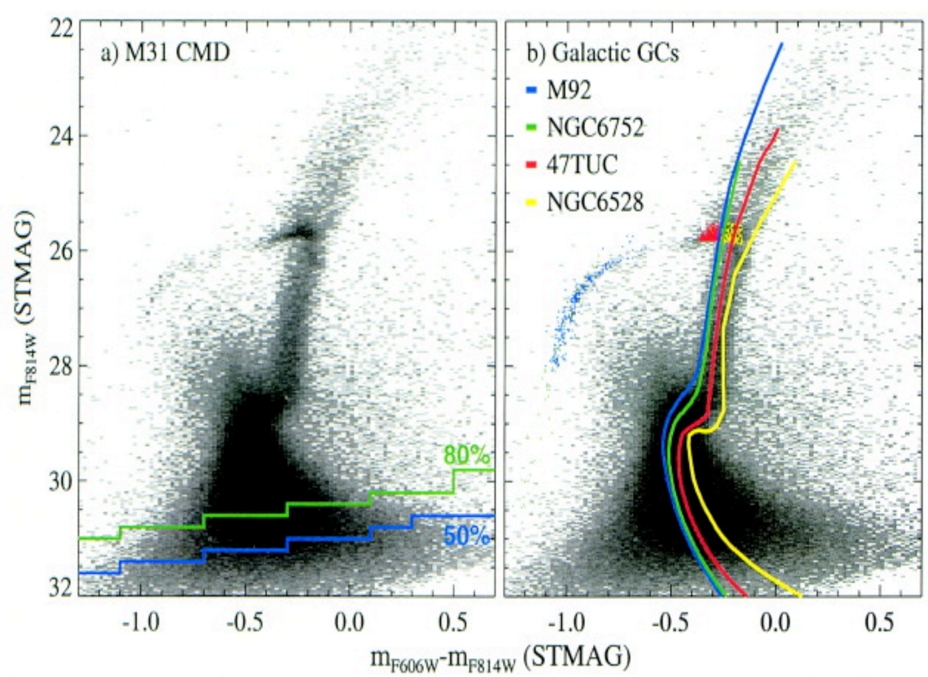
mass range $[M_\odot]$	% by number	% by mass
0.01 - 0.08	37.2	4.1
0.08 - 0.5	47.8	26.6
0.5 - 1	8.9	16.1
1 - 8	5.7	32.4
8 - 120	0.40	20.8
$<m>$	0.38 $M_\odot$	

70 Pavel Kroupa: AIfA, Uni

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

(M31 distance modulus 24.4 mag) so sun in M31 ~29.5th see 1708.02617.pdf PHAT survey

M31 Color Mag Diagram Brown et al 592:L17-L20



- Please see the review article by Krumholz (https://ned.ipac.caltech.edu/level5/Sept10/Krumholz/Krumholz_contents.html) for all the gory detail and

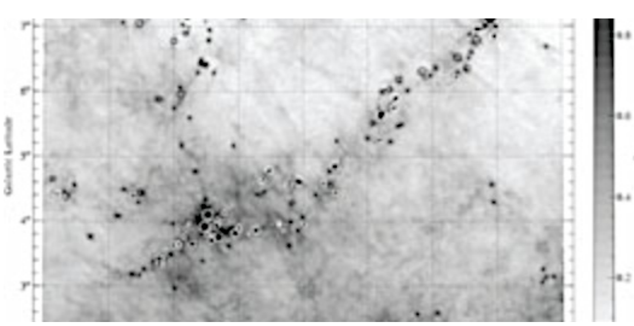
G. Chabrier, "The Initial Mass Function: from Salpeter 1955 to 2005," in *The Initial Mass Function 50 Years Later*, edited by E. Corbelli, F. Palla, and H. Zinnecker, 2005, vol. 327 of *Astrophysics and Space Science Library*, pp. 41-+. for a shorter version of the story.

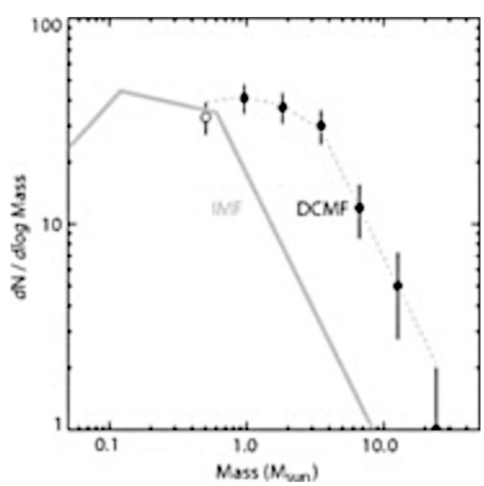
- The bottom line (sec 5.2 of Krumholz) and the Chabrier paper is that
  - The IMF definitely exhibits a similar behaviour in various environments, disk, young and globular clusters, spheroid. Small scale dissipation of large scale compressible MHD turbulence seems to be the underlying triggering mechanism for star formation (Padoan and Nordlund). Modern simulations of compressible MHD turbulence yield an IMF consistent with the one derived from observations.

(more in lecture on star formation)

Break Through Observational Result

- Direct observation of molecular clouds "cores" (e.g. collapsed structures) shows a mass distribution that is very similar to the IMF of the stars(!)

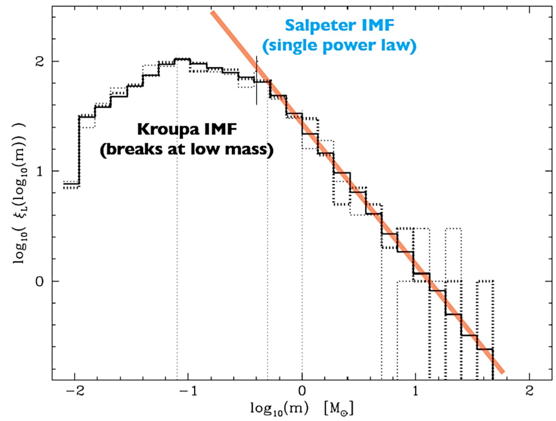




From Krumholz

Initial Mass Function-IMF MBW 9.6

- 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 $M_V - 1/2 < x < M_V + ½$]/]
in volume $V_{max}(M_V)$
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 (**5496 citations**) . 1955ApJ...121..161S
- Worth reading

The evolutionary significance of the observed luminosity function for main-sequence stars in the solar neighborhood is discussed. The hypothesis is made that stars move off the main sequence after burning about 10 per cent of their hydrogen mass and that stars have been created at a uniform rate in the solar neighborhood for the last five billion years.

Using this hypothesis and the observed luminosity function, the rate of star creation as a function of stellar mass is calculated. The total number and mass of stars which have moved off the main sequence is found to be comparable with the total number of white dwarfs and with the total mass of all fainter main-sequence stars, respectively.

Salpeter Mass Function

$\Phi(m)=\Phi(0)M^{-2.35}$: $\Phi(0)$ 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
- most of the luminosity is in massive stars

IMFs-see MBW pg 440-441

- Stars $M<0.08M_\odot$ nuclear fusion not take place and $M>\sim120M_\odot$ are unstable.

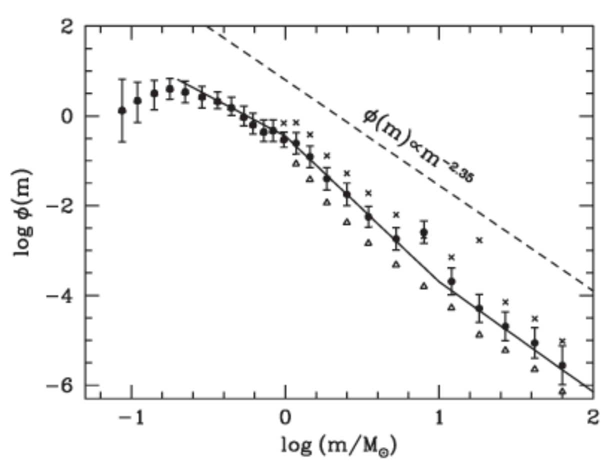
- **Kroupa IMF**
- $\Phi(M)=dN/dM = A\,M^{-1.3}$ $(0.1 \le M_\odot \le 0.5)$

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

piece-wise continuous

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

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



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

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

Determining the IMF used to be difficult before recent massive stellar surveys

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

much easier with Gaia

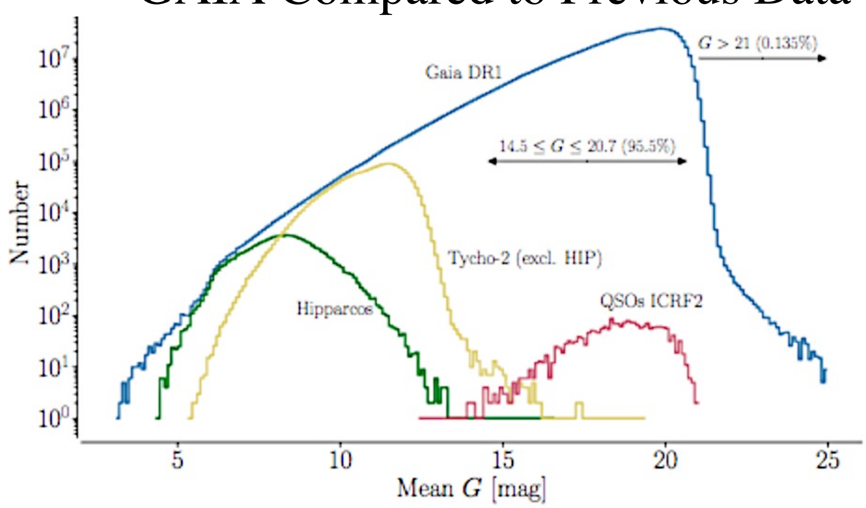
Take the data and determine the luminosity function (LF),
Then apply: correction for main sequence lifetimes, and evolved stars no longer visible

- 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)

GAIA Compared to Previous Data Sets



1. Magnitude distribution of the sources in the *Gaia* DR1 catalogue. The TGAS mag-

The astrometry (position accuracy is ~2.3 mas, parallax ~0.3mas and proper motions ~1 mas) is complemented by multi-colour photometry (better than 0.03 mag), measured for all sources observed by Gaia and radial velocities for stars brighter than ~16 A. Brown 1709.1216 as well as time variability.

New Results on IMF

- With GAIA being able to measure the multicolor brightness and absolute distance to (arxiv 1704.05063)
- Early release for ~2 million stars with parallax errors of ~0.3mas (calculate the distance out which distances can be determined to ~10% accuracy)

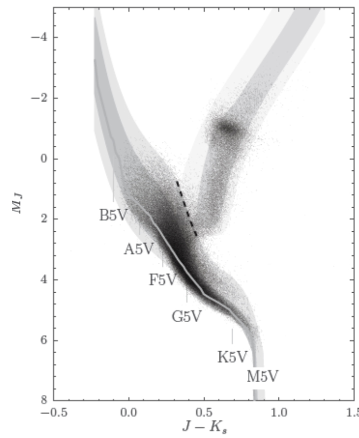
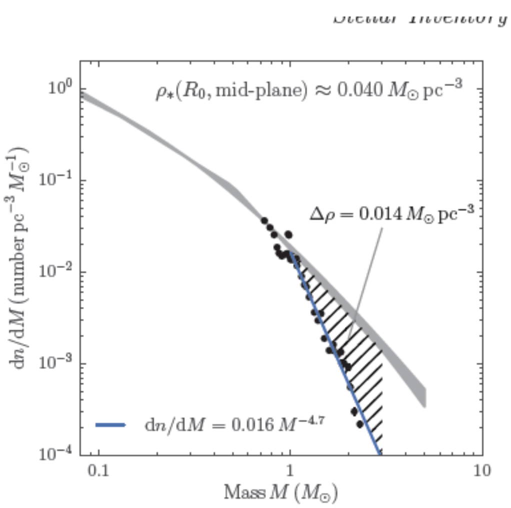


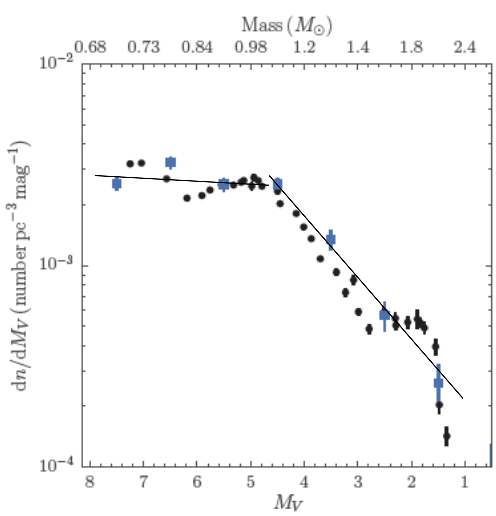
Figure 1. Near-infrared CMD for *TGAS* stars. The light gray



GAIA and the IMF (Bovy 2017)

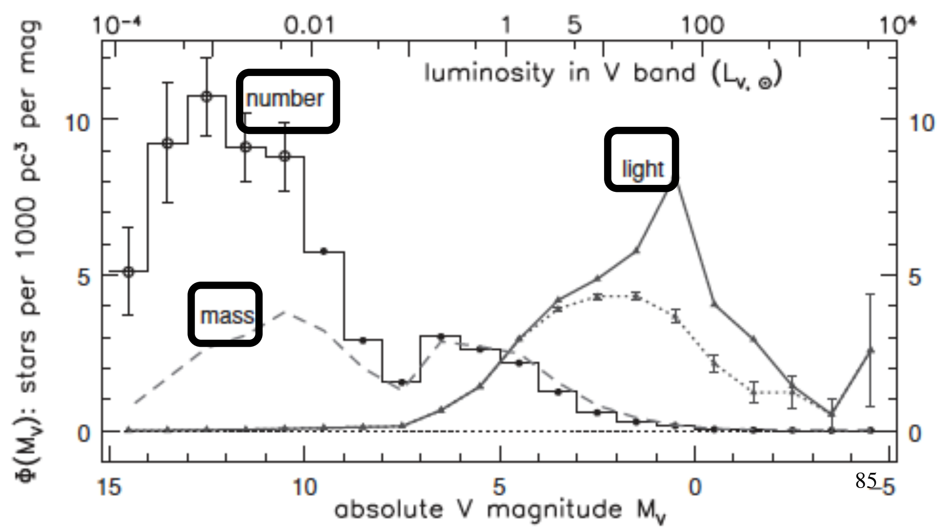
The most precise censuses of stars in the solar neighborhood were based on small, volume-complete surveys of local stars (for example, 25 pc (545 stars), Reid et al. 2002; 50 pc, Jahreiss et al. 1998), which contain only a handful of the brightest stars.

Gaia will observe more than 10^9 stars, or about 1% of all of the stars in the Milky Way.



Number, Luminosity and Mass Functions

- S&G Fig 2.3 The histogram shows the luminosity function (M_V) 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 1000 pc^3.



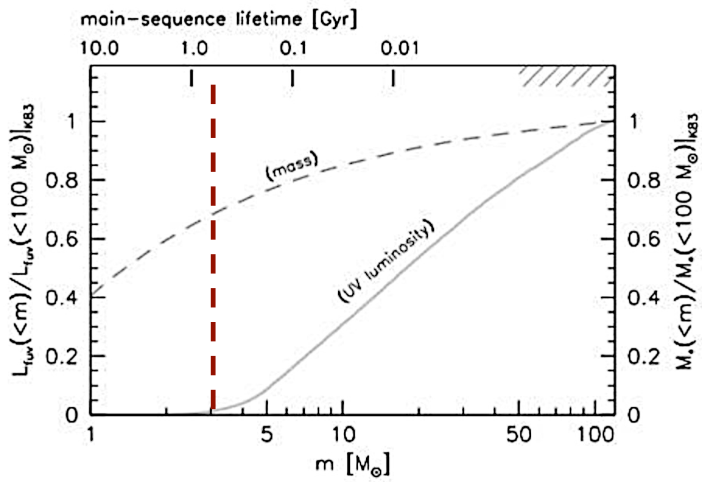
Effects of IMF

- 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 which produce (O,Ne,Mg,Si...) .
- For example, the mass of O^{16} released by massive stars for the slope 2.4 case, produces 7 times less oxygen abundance than Kroupa IMF.

- 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

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

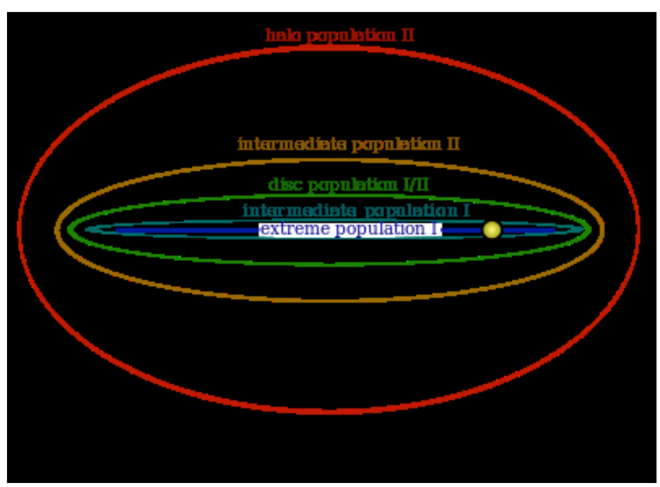
In spiral galaxies there are 2 'types' of stellar populations

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



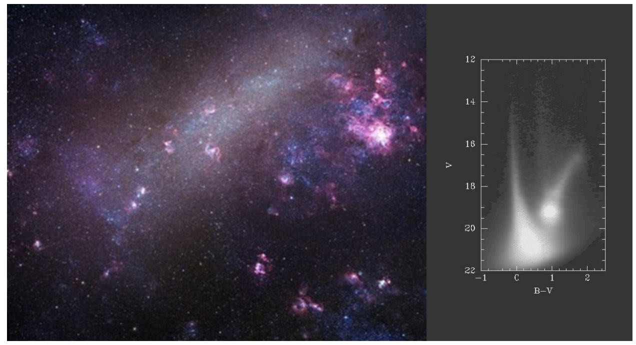
Schematic picture of stellar pop's in Milky Way

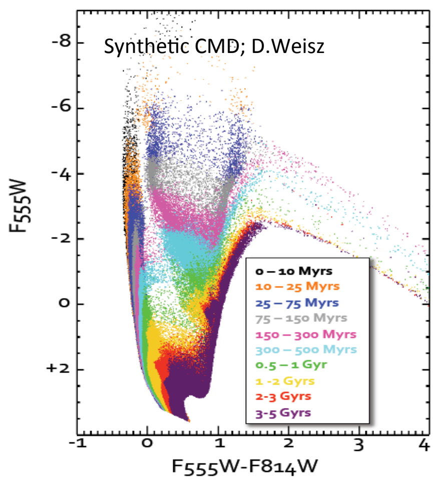
- Different parts of a galaxy have different ages and metallicity
- Only for the MW, SMC, LMC (and with Hubble a few nearby galaxies) can one construct a H-R diagram which shows this
- For distant galaxies we have to deal with integrated spectra colors and brightness and the effects of dust.

Galaxies are NOT SSPs

H.Rix2010

LMC:Zaritsky&Harris 2004-2009



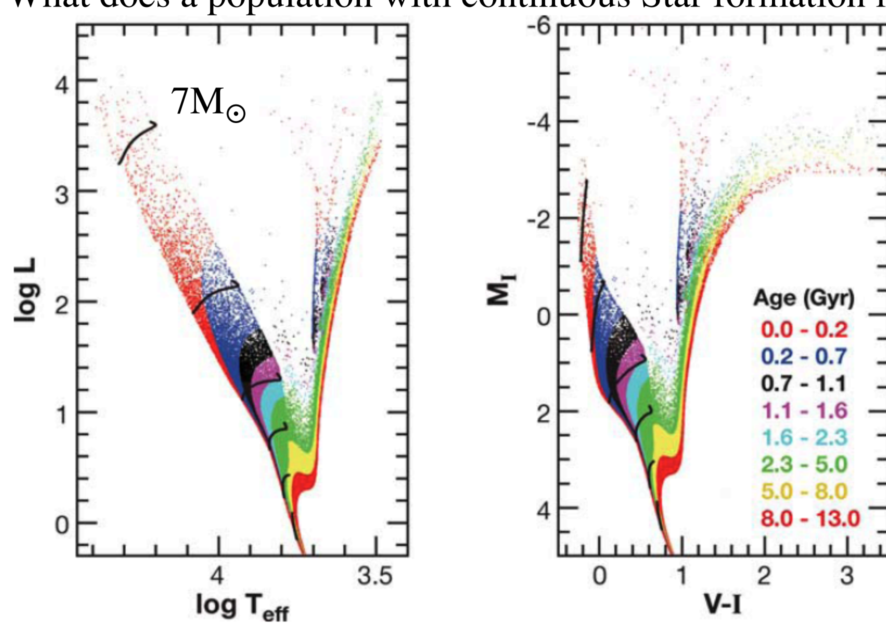


LMC:Zaritsky&Harris2004-2009

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

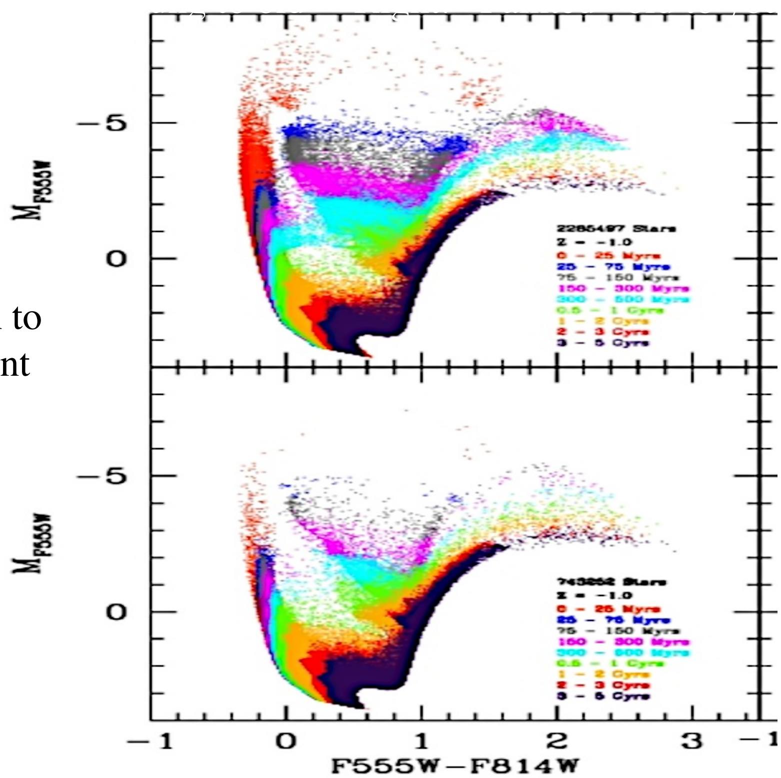
394 GALLART ■ ZOCCALI ■ APARICIO

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, and1$M_{\odot}$**

What does this 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

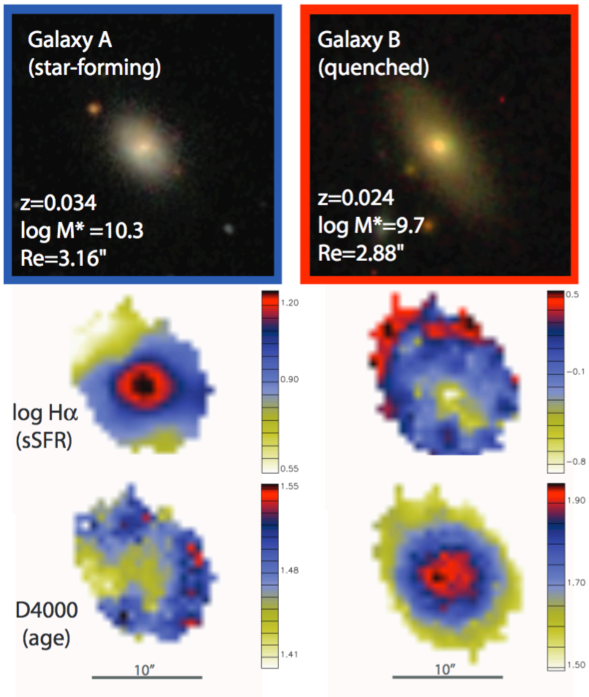
CMDs created by D. Weisz using Dolphin's codes

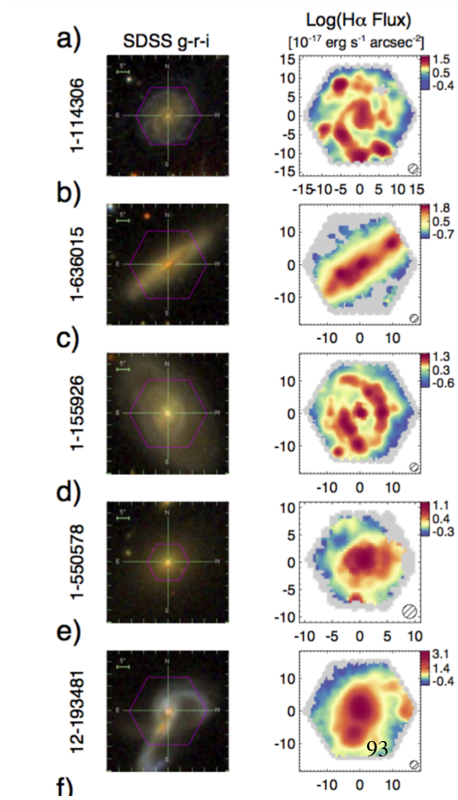
Color Magnitude Diagrams

- 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 Data

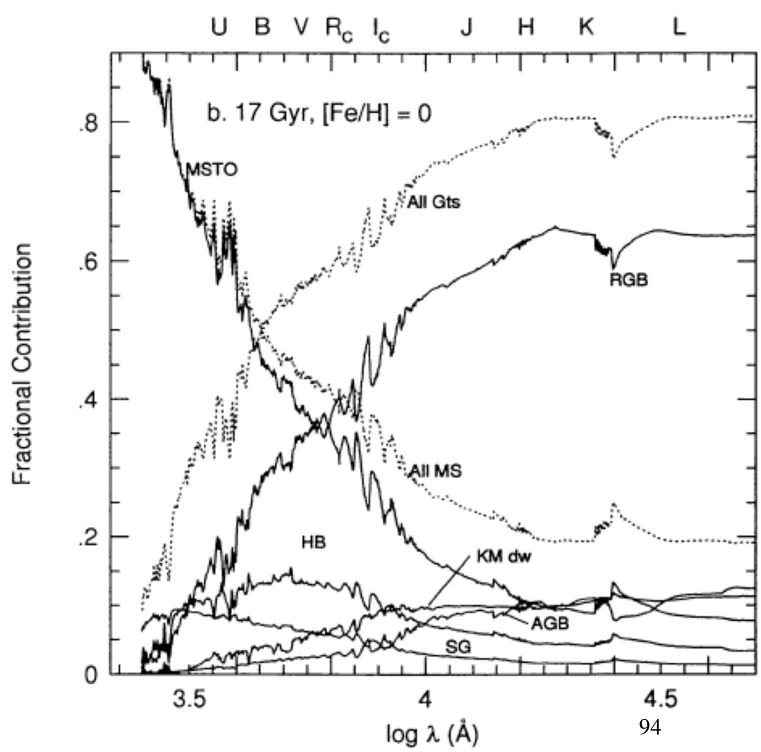




Origin of Light

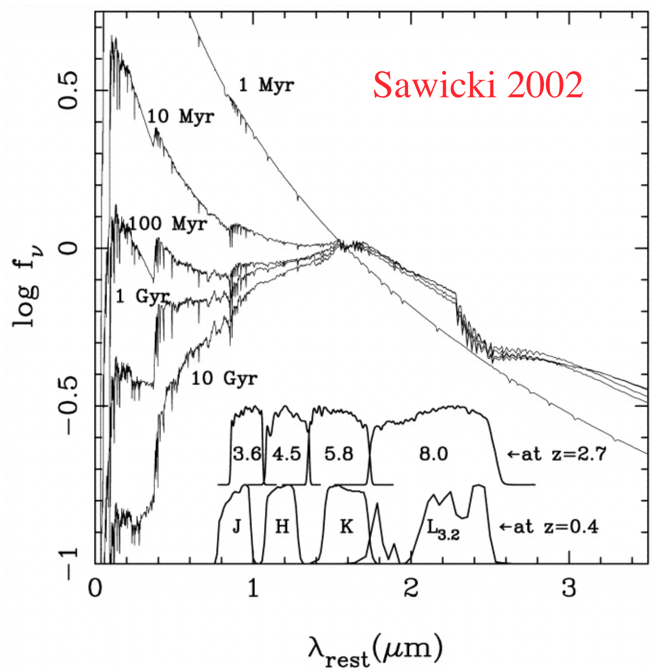
In a SSP which stars produce the observed light as a function of wavelength

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

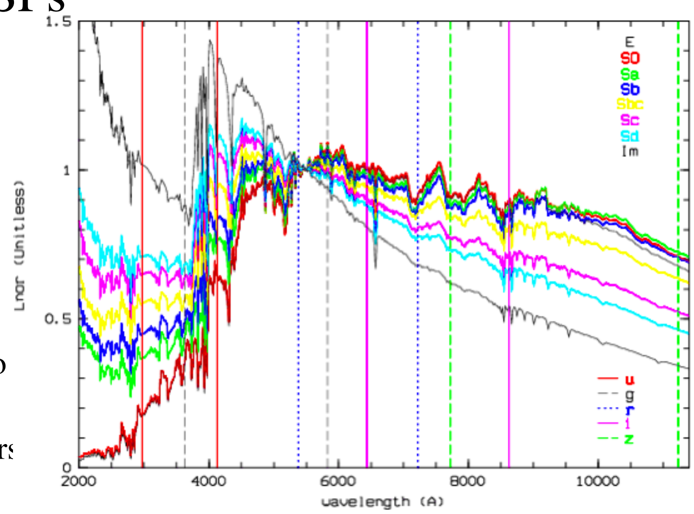


General Trends for SSPs

- 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'



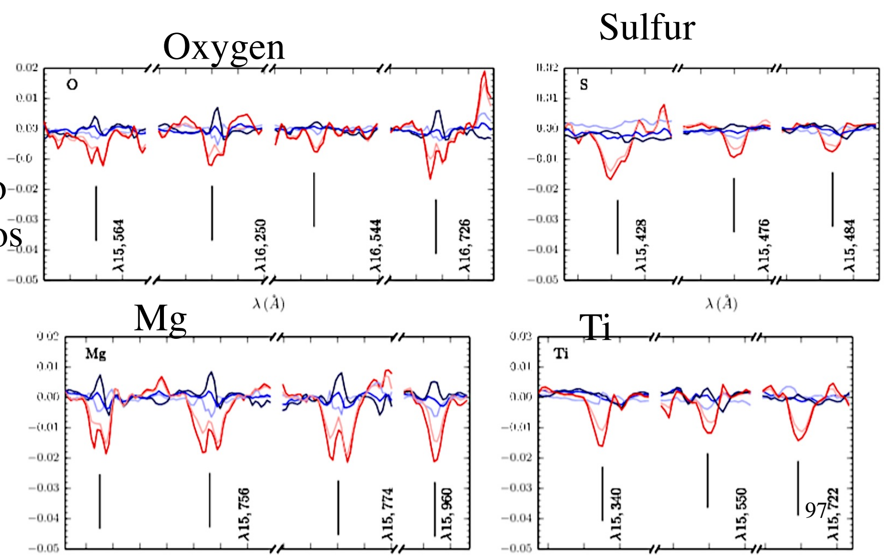
Theoretical models of galaxy composite spectra

Abundance Determination

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

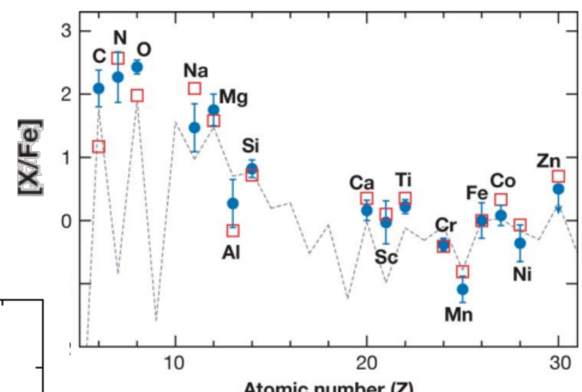
Notice signatures of elements occur at the 1-2% level
Bovy et al arxiv 1509.05796

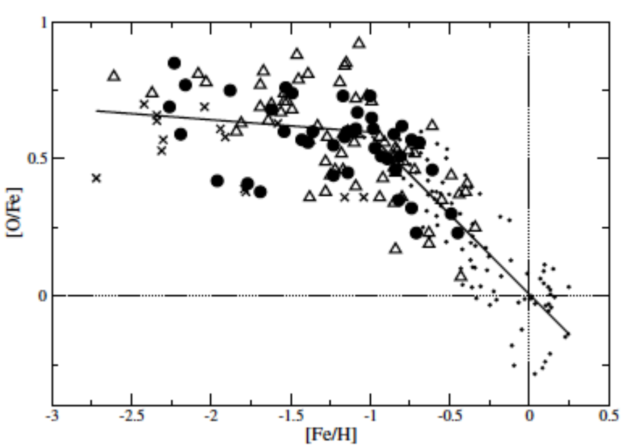
Different colors correspond to different ratios of α/Fe



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

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



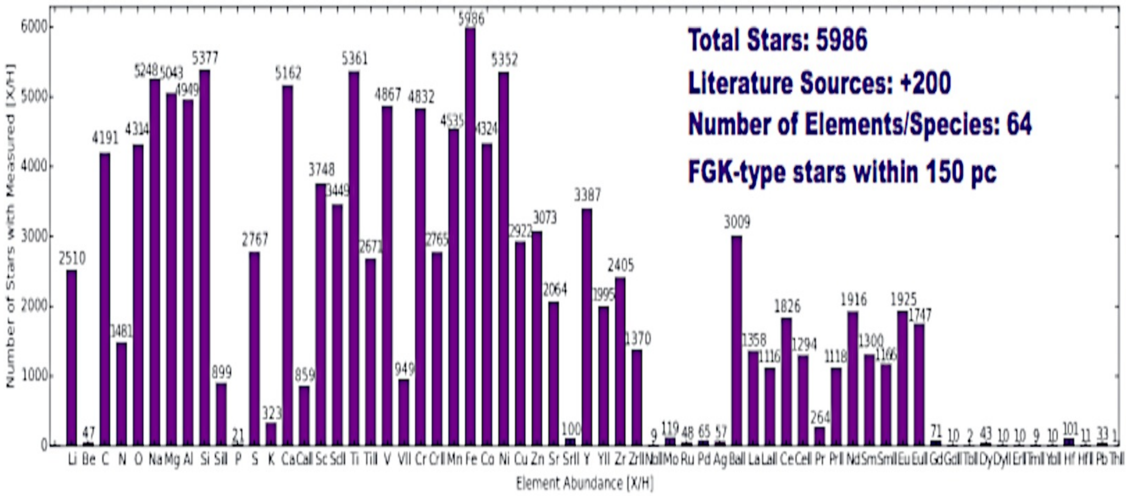


[X/Fe] is the logarithmic ratio of element X to Fe *with respect to the sun's abundance pattern*

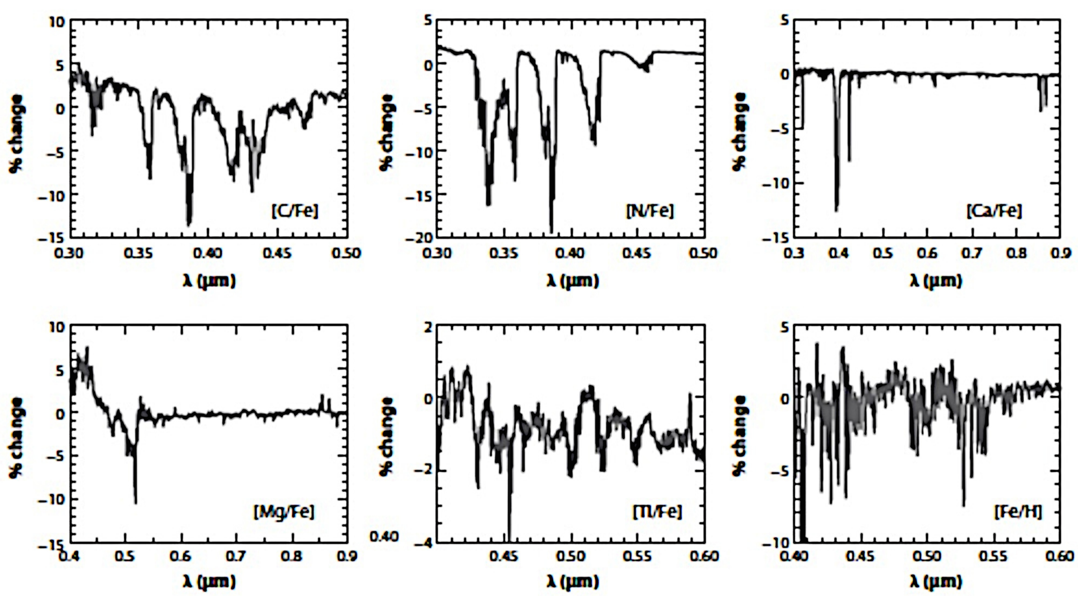
Chemical Composition

What can stars tell us about chemical composition

- With high signal to noise and excellent models the abundance of many elements can be determined



Hinkel et al.https://arxiv.org/pdf/1709.04465.pdf



- Effects of change in abundance for different elements on a 13Gyr old stellar population- effects at the few percent level at selected wavelengths

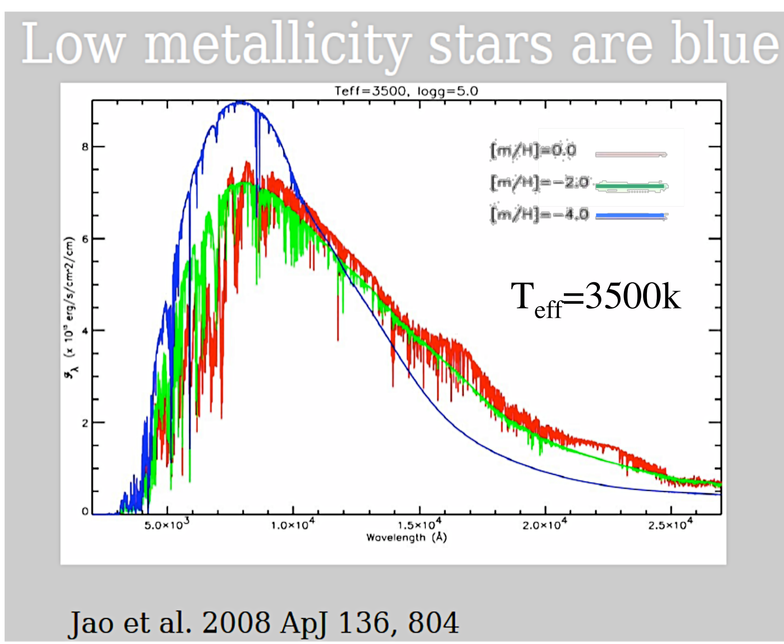
- specific stellar absorption features over narrow wavelength intervals are used to obtain the ages and metallicities of the stellar populations in galaxies.

- Extra Info
  - 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.

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.



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
- These are constructed using a combination of theoretical stellar evolution models, observations of stars of known age and metallicity and theoretical models of stellar atmospheres where no good observations exist.

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

Next Time

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