# Stellar populations

## Galaxies are made of stars

- appearance of galaxies is due to their composition
    - type of stars
    - amount of gas
    - dark matter, bh ....
- due to their kinematics & dynamics

=> SHOW IMAGES OF GALAXIES

- spectra: source of informations

=> SHOW SPECTRA OF
- ELLIPTICAL
- SPIRAL
- STARBURST

-> why are these spectra different?

① amount of gas: emission lines

② very different shape
- E: no light blueward of 4000Å
- SB: lots of light in the blue

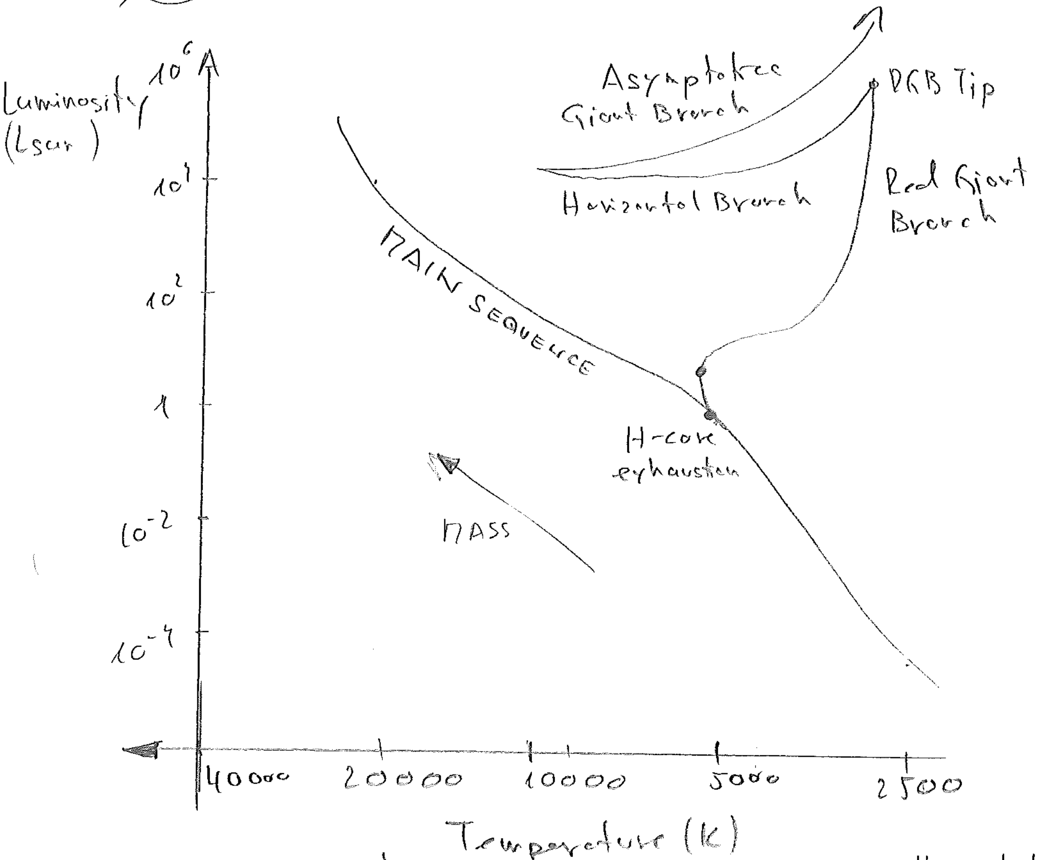
- in order to understand galaxies one has to:
    - know Newtonian dynamics (last lecture)
    - understand stars and stellar populations

- stellar populations
    - a link between stellar astrophysics and properties of galaxies

stellar astrophysics: theory that explains the structure and working of stars

properties of galaxies: observed characteristics of galaxies

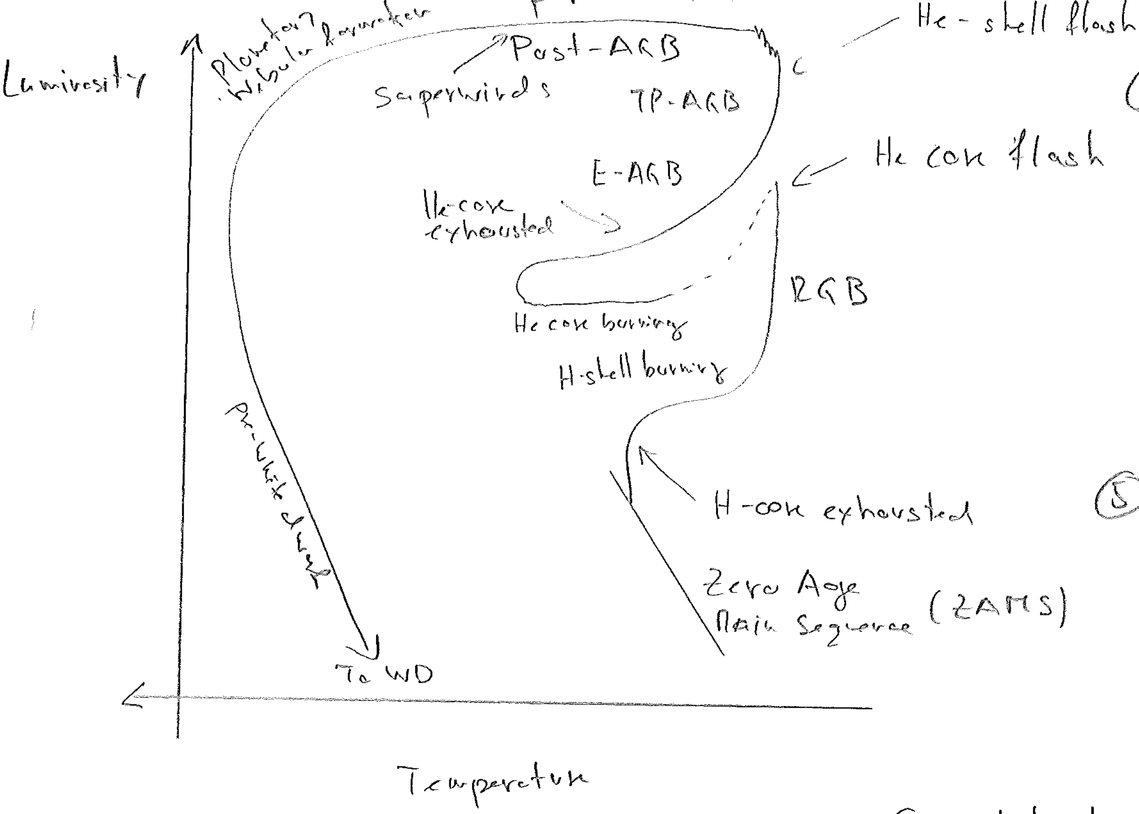
# Phases of stellar evolution: a reminder



① Main sequence: (MS)
- core H burning
- longest phase of evolution

② Turn-off (TO)
- H exhausted in core
-> beginning of interesting evolution

③ Red Giant Branch (RGB)
- H burning in shell around inert He core
- growth of He core



④ RGB Tip
- end of RGB phase
- He core massive and hot enough to ignite He-burning (He flash)

⑤ Horizontal Branch (HB)
- core He burning
- details depend on metallicity & mass loss during RGB pha

⑥ Asymtotic Giant Branch (AGB)
- He burning in shell around inert C/O core
- very complex (not fully understood) evolution dependent on mass

⑦ White dwarf sequence (WD)
- low mass stars eject envelope and leave inert C/O core which cools as a WD

⑧ Supernovae [more on this later]
- massive stars explode
- neutron stars, black holes

## Stellar lifetimes depend on their masses

- each evolutionary phase has ist duration, which is sensitive to the initial mass.

- MS: $t \sim 10^{10} (M/M_{sun})^{-2.5}$

  for $M = 1 M_\odot \Rightarrow t \sim 10$ Gyr

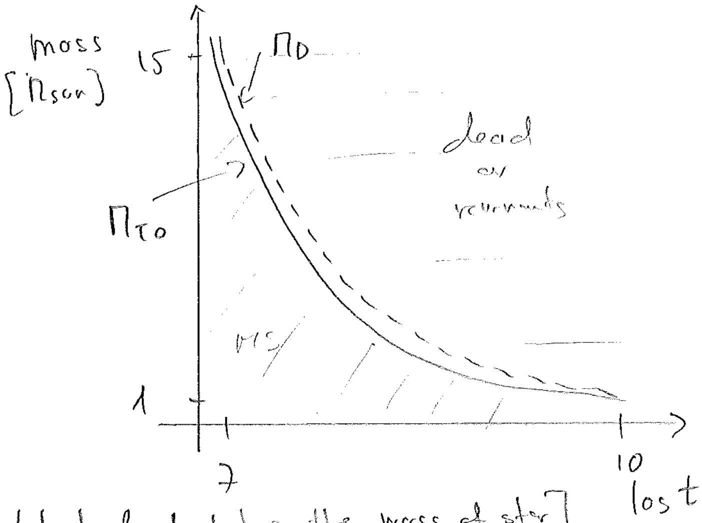
  for $M = 10 M_\odot \Rightarrow t \sim 30$ Myr

- subsequent phases short lived
- time on MS

  $\log M_{TO} = 0.0434 \log t^2 - 1.146 \log t + 7.119$   turn of Mass

- total life time of a star

  $\log M_D = 0.0379 \log t^2 - 1.048 \log t + 6.119$   Mass of lived star
  dying mass



$\Rightarrow M < M_{TO}$
→ all stars are still on main sequence burning H

$\Rightarrow M > M_D$
→ dead stars, remnants
WD, neutron stars, BH

[plot it, find what is the mass of star that has life time > $t_{universe}$]

$\Rightarrow M_{TO} < M < M_D$
→ stars going through post-MS evolutionary stages

$\Rightarrow M \approx M_{TO} \approx M_D$ - initial mass for all post-MS phases is the same, and is equal to the turn-off mass
- it could be used as a time indicator

# Stellar evolutionary tracks and isochrones

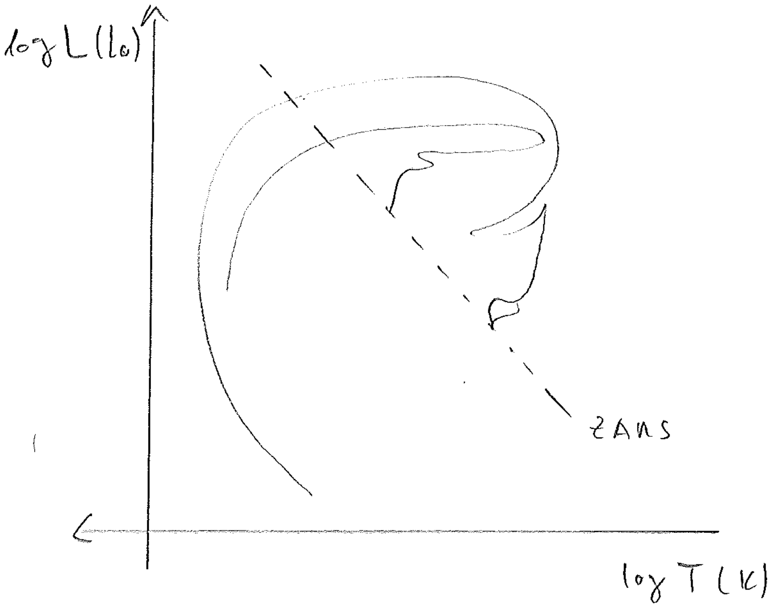
Track:
- describe evolution of a single star with time
- output of a stellar modelling code
- table with stellar parameters:
  - luminosity
  - temperature
  - surface gravity (dwarf / giant)
  - core temperature
  - core consumption
  - current mass
  - ....

track: locus of stars of given initial mass $M_i$ as a function of age t

isochrone: locus of stars of a given age t as a function of initial mass $M_i$

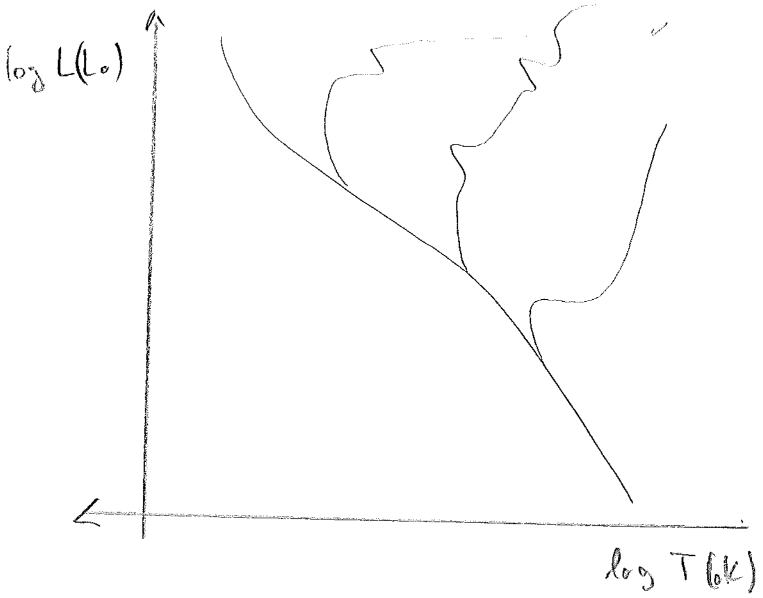
$$a(t)\Big|_{M_i=\mathrm{cte}} \longrightarrow a(M_i)\Big|_{t=\mathrm{cte}}$$

- grid of tracks has to be very dense $\Delta M_i \to 0$
- interpolation between equivalent evolutionary status in adjacent tracks.



- tracks depend on mass
- low mass stars $M < 0.9 M_\odot$ stay on ZAMS
- high mass stars move through different evolutionary phases

=> SHOW example isochrones
=> SHOW example tracks

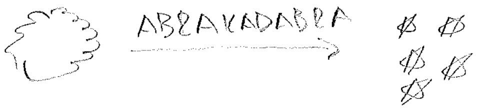


ISCHRONES
- lines that join parameters of stars of <u>different masses</u> but the <u>same age</u>
- tables: same content as for evolutionary tracks but rearranged
- made from dense grids of evolutionary tracks $M_i(t)$ via <u>interpolation</u>, for every evolutionary property (L, $T_{eff}$, $M_{core}$, chemistry)

# Single Stellar population ≡ SSP

SSP - stellar population described by a single age, single metallicity, an Initial Mass Function, and a total mass (initial or present)

imagine: convert a homogenous package of gas instantaneously into stars



- all same age
- different masses

SSP = essentially the isochrone
↳ all stars of various mass that have the same age & metalicities
↳ this is given by IMF (more later)

⇒ for example: Globular Clusters
↳ are typically SSP

# Composite stellar population

CSP - a sum of SSPs, each age and metallicity weighted by the star formation history (SFH)

⇒ now we have to explain these terms:

1) metallicity
2) IMF
3) SFH & element abundances

## What is metallicity?

"Metal" content of the gas the stars formed from

- core of stars changes during life time (as stars burn fuel)
- surface layers reflect the original composition (at least until late evolutionary phase)

"Metal" - for astronomers

- H
- He
- metals (oxygen is a metal...)

chemical mixtures of stars expressed as mass fractions

X or H = mass fraction of H

Y or He = mass fraction of He

Z = mass fraction of everything else = metals

empirically: measurments of metallicity in stellar atmospheres usually expressed in terms of number density (NOT mass fraction)

$$[Z/H] = \log_{10} \frac{N_Z}{N_H} - \log_{10}\left(\frac{N_Z}{N_H}\right)_{sun}$$

$Z/H = 0$ = solar metallicity

$Z/H = +0.3$ ≡ 2 × solar

$Z/H = -1$ = $\frac{1}{10}$ solar

- what is Z? → which element should be used
  - ⇒ many possibilities
  - ⇒ O → very important for stellar evolution, but hard to measure
    - Fe → easier to measure in spectra
    - $[Fe/H]$ is proportional to $[O/H]$ or $[Z/Fe]$ if all elements are varied proportionally

## Where do metals come from?

=> SHOW slide
with PN,
SN remnant
SN Ia art

① Big Bang nucleosynthesis

=> $^4$He + some traces of D, $^3$He, $^3$Be, $^7$Li, $^6$Li

=> everything else comes from stars

② Low-mass stars: AGB / planetary nebula

$1 < M < 8\ M_{sun}$

- outer layers enriched in C, N, O (AGB phase of He-shell burning)
  -> ejected into ISM
- core: C-O -> post AGB (luminous) cooling to WD
  -> outer layers ionised by p-AGB -> shine as PN
- $t \sim 10^9$ yr

③ High-mass stars: Type II supernova

$M > 8\ M_{sun}$

- collapse of Fe core -> neutron star / BH ->shockwave ejects outer layers (SN explosion)
- major producer of O, Mg ($\alpha$-elements)
- elements heavier than Fe synthesised in the SN explosion
- $t \sim 10^7$ yr [massive stars]

④ Binary stars: Type Ia supernova

- accretion of a companion star to a WD pushes WD over Chandrasekhar limit [could be also a merger of WD]
- WD made of C+O undergoes nuclear fusion all the way to Fe
  => all ejected into ISM
- $t \sim 10^9$ yr
- production of Fe

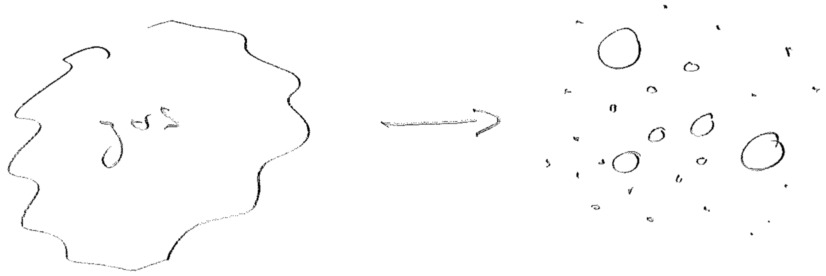
=> different types of SN give different types of metalls!

SN II -> O, Ne, Mg -> $\alpha$-elements [nuclei multiples of $\alpha$ particles, He nuc.]

SN Ia -> Fe

[come back to this in SF]

# Initial mass function – IMF



- how does gas get distributed among stars
- what are the sizes of new born stars

- not yet predicted from first principles
- need to understand: fragmentation of gas cloud, accretion to prestellar cores influence of turbulence, self gravity, magnetic fields feedback from radiation...

- but we see the outcome
  - stars in open clusters have various sizes and masses

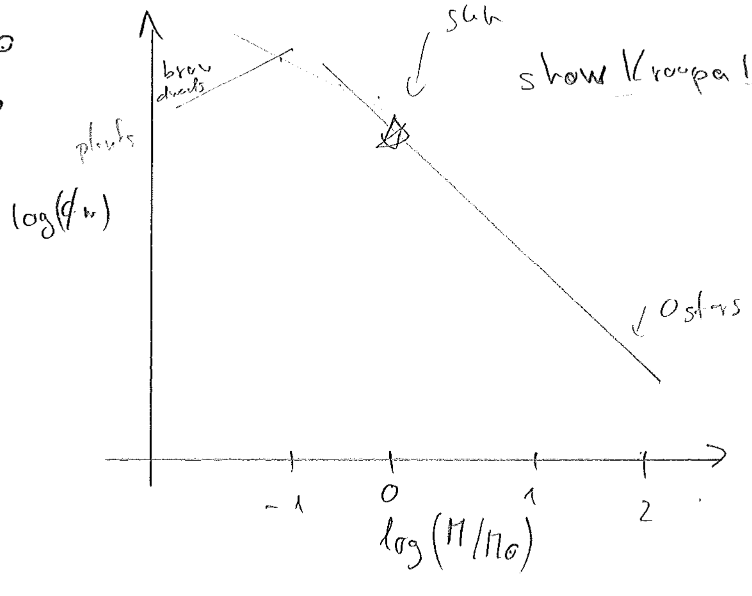
Initial mass function – initial mass distribution at the time of the birth of stars

$\phi(m)\,dm$ is the number of stars born with masses between $m$ and $m+dm$ $\quad \phi(m) = \frac{dN}{dm} \sim m^{-(1+x)}$

$$\int_{m_L}^{m_u} dm\, m\phi(m) = 1\,M_\odot$$ normalization of IMF (arbitrary)

$\left.\begin{matrix} m_L \\ m_u \end{matrix}\right\}$ lower & upper mass cutoffs are not well defined.

Typically $m_L = 0.1\,M_\odot$
$m_u = 100\,M_\odot$



show Kroupa IMF

- constrained from detailed observations of star-forming regions in MW

## IMF continued

$\phi(m) = \frac{dN}{dm} = A\, m^{-(1+x)}$ is a good representation of the observed in the solar neighbourhood

number of stars with mass $M$, $M + dM$

$dN = N_0\, \phi(m)\, dm$

- $\phi$ normalized in sense of the total mass, not total number

$\int dm\, m\, \phi(m) = 1 M_\odot$

- $N_0$ is the number of solar masses contained in the SB

there are several variants on the IMF

a) Salpeter - single power-law

$x = 1.35$ over the entire mass range

b) Salpeter - diet (bi-modal distribution)

$x = 1.35$ $m > 0.5 M_\odot$

$x = 0.3$ $m < 0.5 M_\odot$

c) Kroupa

$x = -0.7$ $m < 0.08$

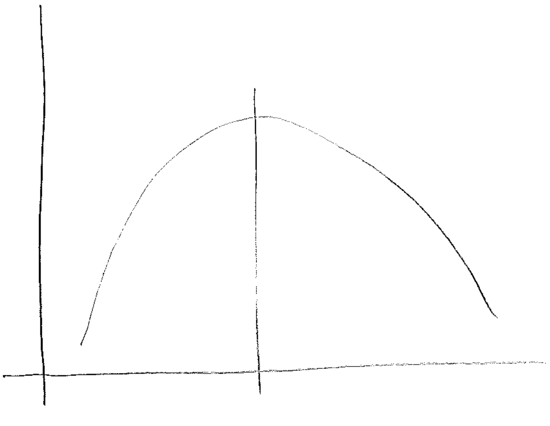
$x = 0.3$ $0.08 < m < 0.5$

$x = 1.3$ $m > 0.5$

d) Chabrier

$\phi(\log m) \sim e^{-\frac{[\log m - \log 3.5]^2}{2 \cdot 0.2^2}}$ $m < 4.0 M_\odot$

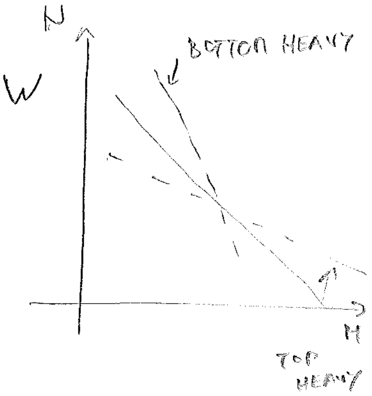
$\phi(\log m) \sim m^{-1.7}$, $m \geq 4.0 M_\odot$



$\chi(m) = \frac{dN}{dm} \sim m^{-\alpha} \left[ 1 - e^{\left(-\frac{m}{m_p}\right)^{\beta}} \right]$

# IMF continued

- is it universal → the same SLOPE! in all star-forming regions in all galaxies(?)
  - → it could be
  - → there is no reason to be universal
    - ⇒ at high redshift SF conditions could be different (amount of gas, metallicity, turbulence)



- it is very challenging to "observe" IMF beyond MW
  - → new facilities E-ELT very important
  - → are there other ways to explore IMF

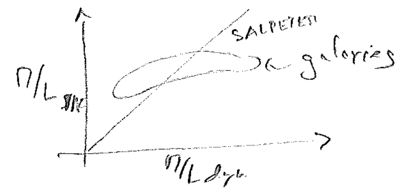
① spectral features

- we will discuss spectra later, now just to say:
- slope of IMF depends on how many massive (giants) and how many low-mass (dwarfs) stars there are
- dwarfs & giants differ in SURFACE GRAVITY
  - ⇒ they will have different spectra
  - ⇒ look for spectral features that are sensitive to surface gravity (to coming from giants / dwarfs)
  - ⇒ TiO, CaH, (FeH 9916)
  - ⇒ (NaI 8190), CaI, CaII

prominent in dwarfs
[SHOW SLIDE AFTER PAGE 16]

② determine total & stellar mass (stars, DM, gas...)

- total mass: from kinematics + dynamics
- stellar mass: from stellar populations (more about this in lecture 2)
  - ⇒ look what is the M/L predicted from dynamical models
  - compare it to M/L from stellar populations given a certain IMF



# Star formation rate & Star formation history

SFR ≡ gas mass converted to stars per unit time

$$\psi(t) = -\frac{dM_g}{dt}$$

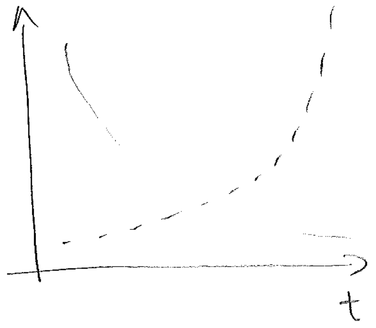
SFH : - how is gas converted to stars in a system as a function of time (a history of star formation)

- describes the evolution of SF in a system (GC, galaxy)
- traces variation of metals vs. time and interactions, accretions and other evolutionary processes.
- number of stars (mass of stars) formed as a function of time

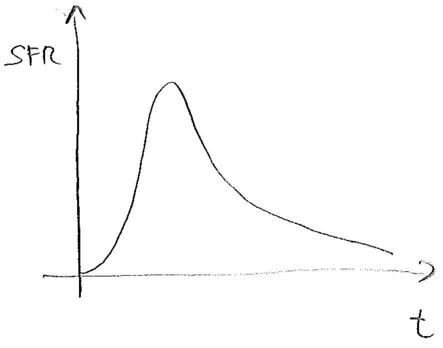
many possible SFH

① $SFR \sim e^{-\frac{t}{\tau}}$ decrease with time

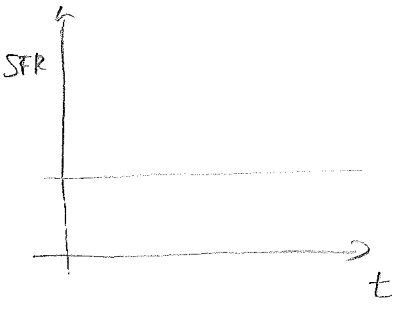
$\sim e^{+\frac{t}{\tau}}$ increase with time



② $SFR \sim \frac{t}{\tau^2} e^{-\frac{t^2}{2\tau^2}}$ galaxy that formed its stars long time ago

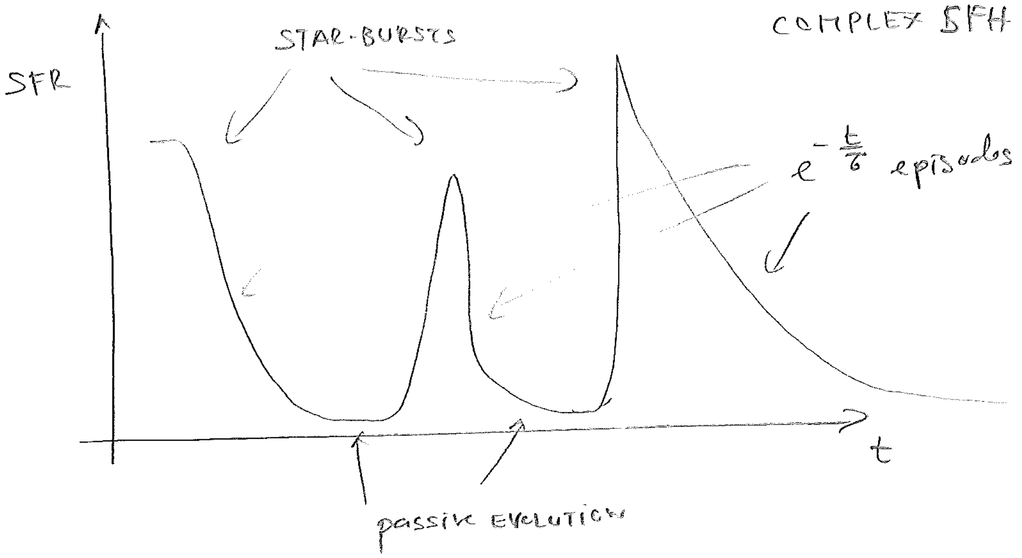


③ SFR ~ constant galaxy that is forming stars now



## SFR continued

- it is very unlikely that these simple mathematical functions are true representatives of SFH in galaxies } but are decent aproximat.
- SFH is likely characterised by EPISODES of SF which could be described as burst followed by exp. decay and passive evolution



COMPLEX SFH ⇒ end product is a composite of many SSP

## Star formation and abundance of elements

1) progenitors of SN Ia & SN II have diffent life-times.
($10^9$ yr) ($10^7$ yr)

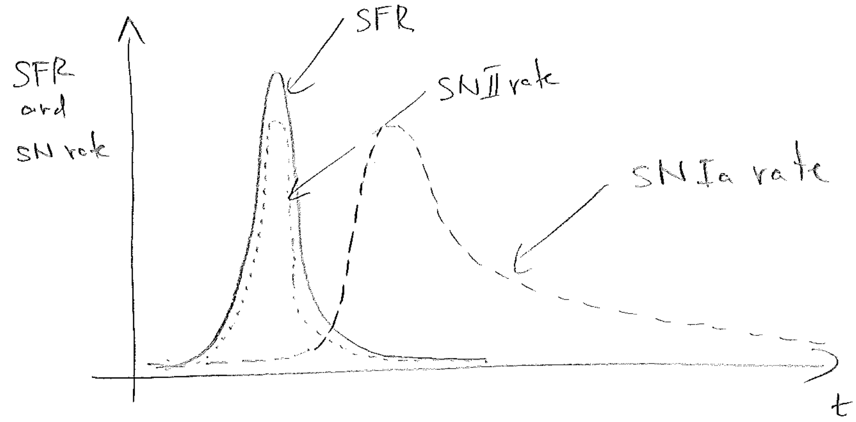
2) SN Ia & SN II synthesise different elements
↓ Fe — 50% of all elements produced
↓ O, Mg ⇒ α elements (multiple of He nuclei = α particles)
└ ~60% O; 20% Ne, 10% Mg ⇒ details depend on progenitor (mass)

⇒ timing of various SN will change the chemical composition of the system [chemical evolution]

# SF & abundances continued !

Two types of SFHs:

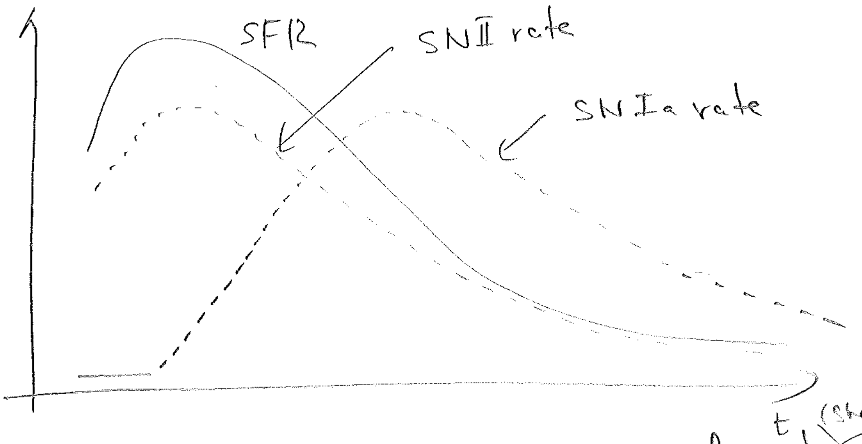
## Ⓘ short burst



- SNII rate follows SFR (as the progenitors live short)
- SNIa follow after a delay of ~$10^{8-9}$ yr (broad distribution of precursor lifetimes)

- SNII make α-elements
- as the burst is short, and SNIa products (Fe) is released after the stars are made, only α-elements are incorporated into stars

## Ⅱ long burst



- SNII rate follow SFR.
- SNIa again offset

- as the SB is longer, both α-elements (SNII) and Fe (from SNIa) can get absorbed in new stars

⇒ $[\underbrace{\alpha}_{\text{avg of element}}/\mathrm{Fe}]$ or $[\mathrm{Mg}/\mathrm{Fe}]$ → element abundances
→ trace duration & type of SF (SFH)

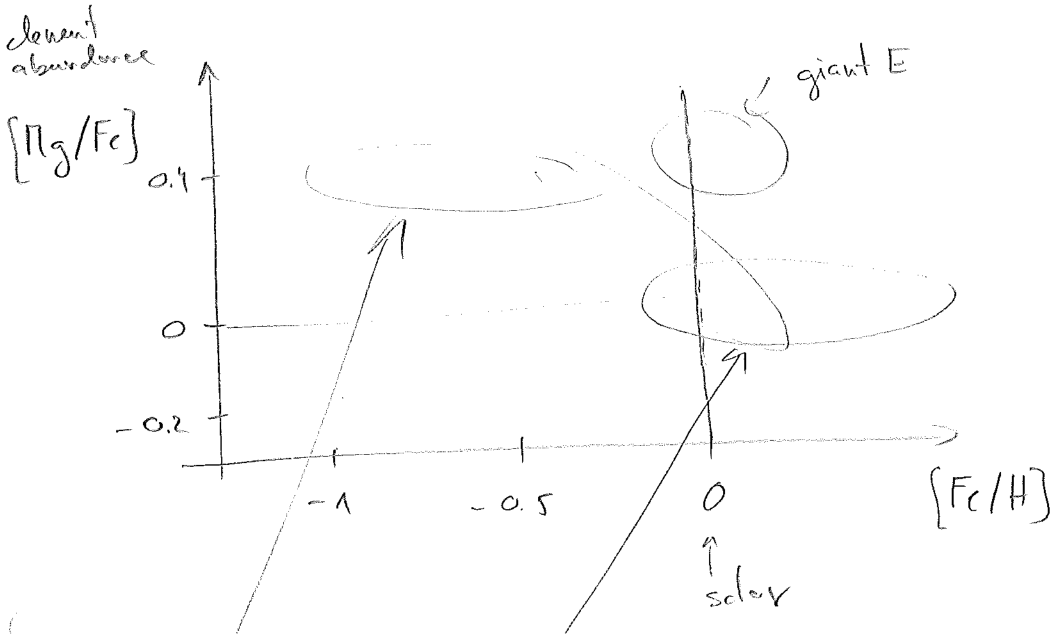
case I: higher [Mg/Fe]
case II: lower [Mg/Fe]

⇒ show MW

[skip if no time]

## SF & abundances continued II

(show slide)

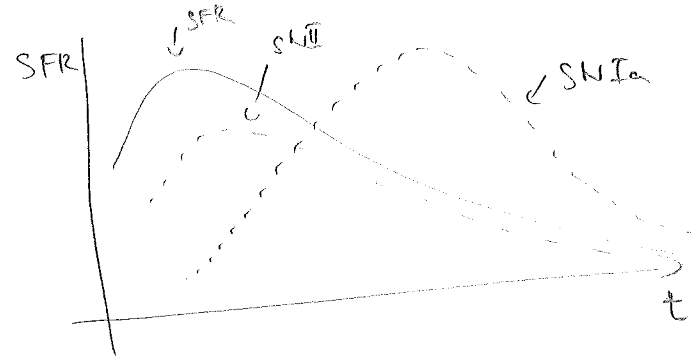


- earlier stars (low metalicity, high α fraction): form from SNII material

- later stars "poluted" by SNIa Fe ejecta (higher metalicity, lower α fraction)

⇒ MW SFH is in the „long burst" mode

- metalicity is rising



## Metal poor stars: Population III (a digression)

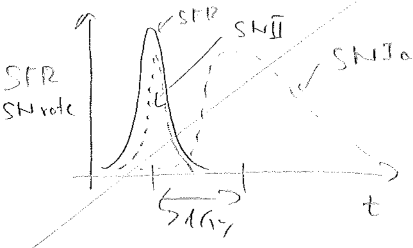
- first stars that were born: no metals → Pop III (- very unusual properties
  - very massive ($150\,M_\odot$)
  - possible progenitors of SNe)
- most metal poor star: [Fe/H] ~ -5
  ↳ allready poluted

(show slide on stellar metalicities)

## SFR continued

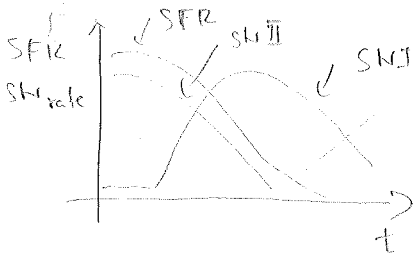
- it is very unlikely that these simple mathematical functions are true representation of SFH in galaxies
- but they seem to be decent aproximation

## SF & abundance of α-elements



- short burst of SF
  - SNII make α elements that get incorporated in stars

  => high [α/Fe] ratio



- Longer burst
  - -> SNIa happen while there is still star formation going on => Fe (from SNIa) can get incorporated in stars

  => lower [α/Fe] ratio

passive evolution

this looks like a combination of SSP

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## Spectral energy distribution - spectra of stars

spectrum - distribution of electro-magnetic radiation emitted or absorbed by a particular object

$S_\lambda$ - spectrum of a star

$S_\lambda = S_\lambda(X_i, g, T)$ ; a function of
- chemical composition
- surface gravity
- effective temperature

$\downarrow$ often written as Z if given by one number

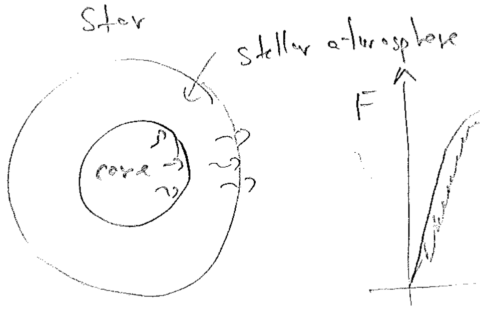
=> show spectra of stars (Miles library Sánchez-Blázquez+2006 ~~Falcon-Barroso+2011~~ Young+2003)

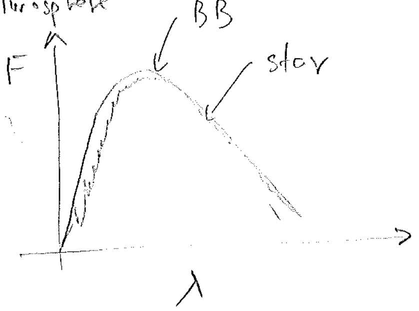
## SED continued

① effective temperature $T_{eff}$ – dominant influence on stellar spectra

↳ show star-BB comparison ((Charlot 1996)

- spectral classes: O B A F G K M
- continuum shape → black body
- modified by atomic/molecular process





② metallicity effects

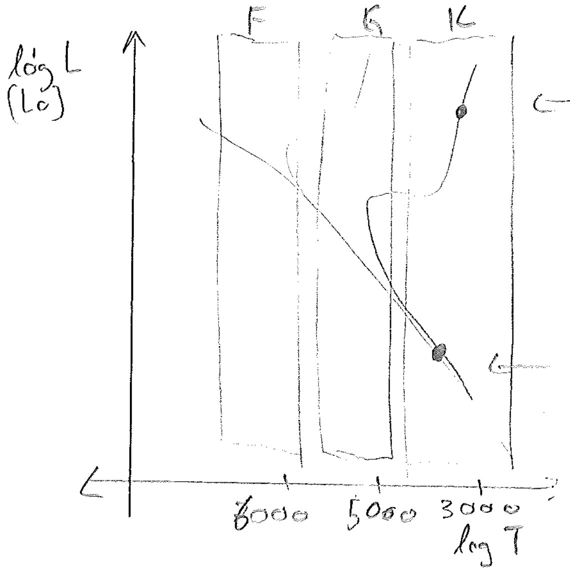
- increasing metallicity – changes opacities in stellar interiors
  - increases absorption in atomic/molecular transitions in stellar atmosphere

=> show example of F star Youry+(2009)

③ surface gravity

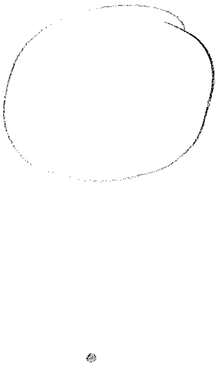
- a measure of stellar size: dwarfs vs giants

↳ luminosity classes I – $\overline{V}$
giants dwarfs



← KIII giant

← KV dwarf



-> difference in size =
= difference in surface gravity

=> link to IMF
- features in spectra sensitive to abundance of elements from dwarfs and giants

show slide Conroy & van Dokkum
(also Rayner+ (IRTF spectra))

SED continued

## Stellar libraries

need: good signal-to-noise, flux calibrated, covering the full atmospheric window, covering the full range of $(X_i, g, T)$

1) empirical libraries
   - based on spectroscopic observations of nearby stars
     -> solar neighbourhood

     ↳ typically in limited spectral range ~ 3500 - 7000 Å
   - spread of ages, [Fe/H], [α/Fe]
   - problems
     - limited spectral range: e.g. 3500 - 7500
       -> no continuous UV - IR spectrum
       ↳ also important for high z galaxies with redshifted spectra
     - insufficient coverage at high-metallicity (e.g. only young stars, no old metal rich. stars typical for Es)
     - only solar [α/Fe]

2) synthetic (model) libraries
   - any $(X_i, g, T)$ parameter can be produced !
   - not all stages of stellar evolution are well understood
     -> chemical composition of cool stars .... -> ⇒ tens of millions of abs. lines; many not measured in lab, but only predicted
   - still limited to produce spectra of all stars

what is better
- a matter of taste
- NOTE: - empirical libraries have to be fitted with synthetic spectra to derive $(X_i, g, T_{\rm eff})$ !
  - synthetic libraries don't have contributions of all $X_i$ well taken into account

END OF LECTURE I.

# Stellar population synthesis

CASE FOR CONSTANT metallicity -> SKIP it

$F_\lambda(t)$ - spectral energy distribution, age $t$, of a stellar population with a SFR, a chemical enrichment rate [a spectrum representation for some stellar population]

$$F_\lambda(t) = \int_0^t \psi(t') \cdot S_\lambda(x_i, t-t')\, dt'$$

① $S_\lambda(x_i, t)$ - spectrum of a SSP, of chemical composition $x_i$, born at $t$

② $\psi(t)$ - SFR, describing the SFH which defines the final stellar population

## ① Synthesis of SSP spectra

Ingredients:

a) isochrones (stellar evolution theory)

b) IMF (star formation observation - i.e. theory does not exist)

c) spectral library (empirical or theoretical from stellar evolution theory)

How is it done:

i) assign a spectrum $S_\lambda$ to each point on the isochrone

- isochrone gives dependence on $T_{eff}$, $g$, and metallicity as a function of stellar mass

$- S_\lambda(T_{eff}(M), g(M) \mid t, Z)$

↳ this is what I called before $x_i$

## SSP synthesis cont.

ii) distribution of mass is given by assumed IMF
=> sum spectra of stars weighted by IMF, $\phi(M)$, along the isochrone

spectrum of a SSP
$$f_{SSP} = \int_{m_{LO}}^{m_{up}(t)} S_\lambda \left( T_{eff}(M), \log g(M) \mid t, z \right) \phi(M) \, dM$$

$M$ - initial mass on the MS

$\phi$ - IMF

$S_\lambda$ - spectrum which depends on age and metallicity

$m_{LO} \sim 0.1$ ( depends on IMF)

$m_{up}$ ~ depends on stellar evolution

- relation between Teff, log g, M, for a given age & metalicity is defined by an isochrone -> integration along a isochrone

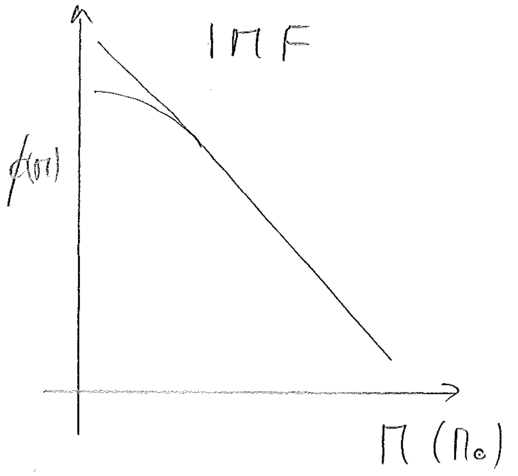
## from SSP to Composite Stellar Pop.(CSP)

CSP has (and SSP doesn't):
- stars of a range of ages given by their SFH
- stars of a range of metallicities given by chemical enrichment function
- dust

spectrum of a CSP
$$f_{CSP} = \underset{\text{age}}{\int_{t'=0}^{t'=t}} \underset{\text{metalicity}}{\int_{z=0}^{z_{max}}} \Big[ \overset{\text{SFR}}{\psi(t-t')} \cdot \overset{\text{chemical enrichment}}{\rho(Z, t-t')} \cdot \overset{\text{SSP spectra}}{f_{SSP}(t', z)} \, \overset{\text{obscuration (attenuation) by dust}}{e^{-\underset{\text{optical depth}}{\tau_{eff}(t')}}} + \overbrace{A \cdot f_{dust}(t', Z)}^{\text{dust emission}} \Big] dt' dz$$

## Stellar pop. synthesis

## What is all needed



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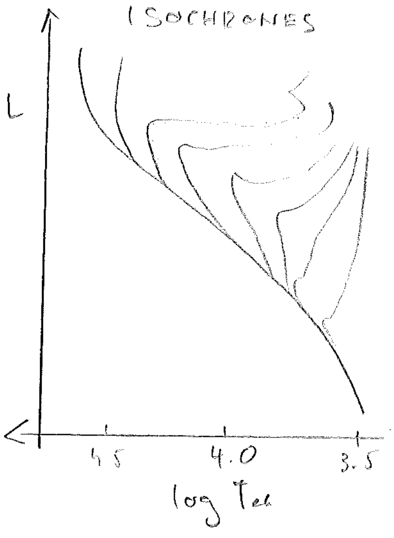

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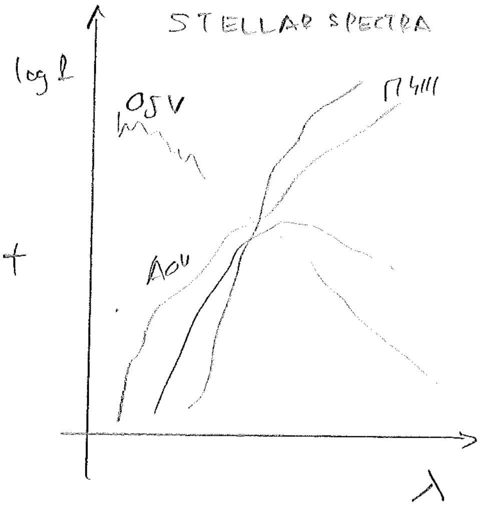
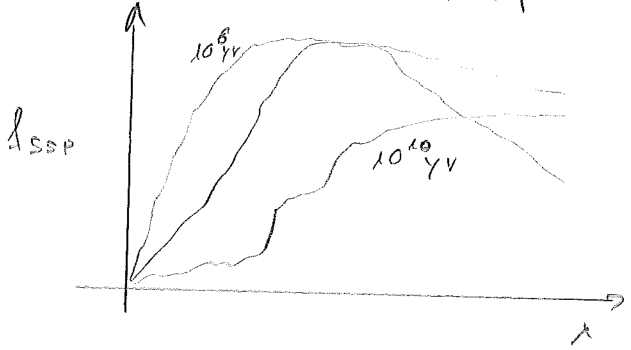
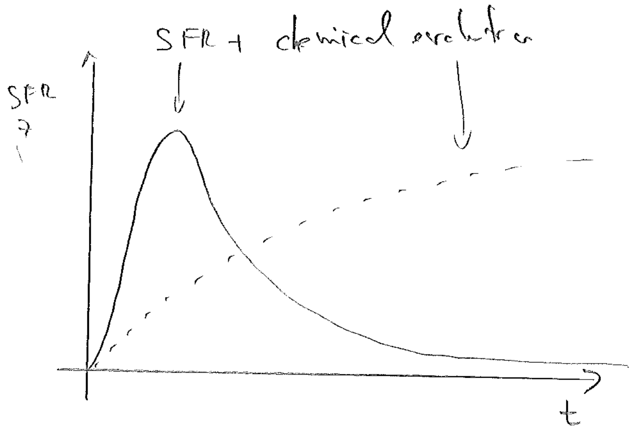


= SSP spectra





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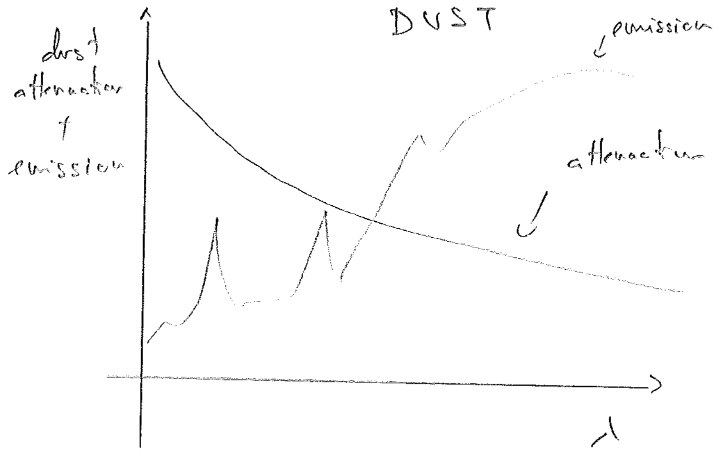
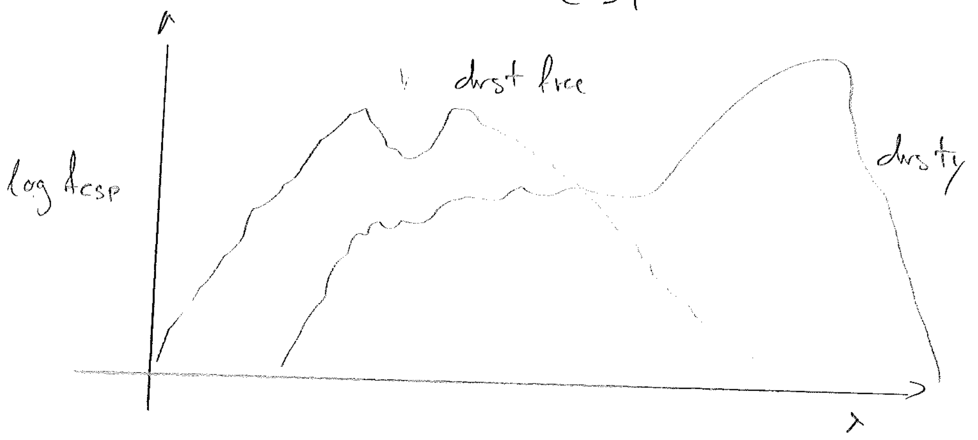


= CSP



## To worry about

1) are isochrones correct for stellar phases that contribute a lot

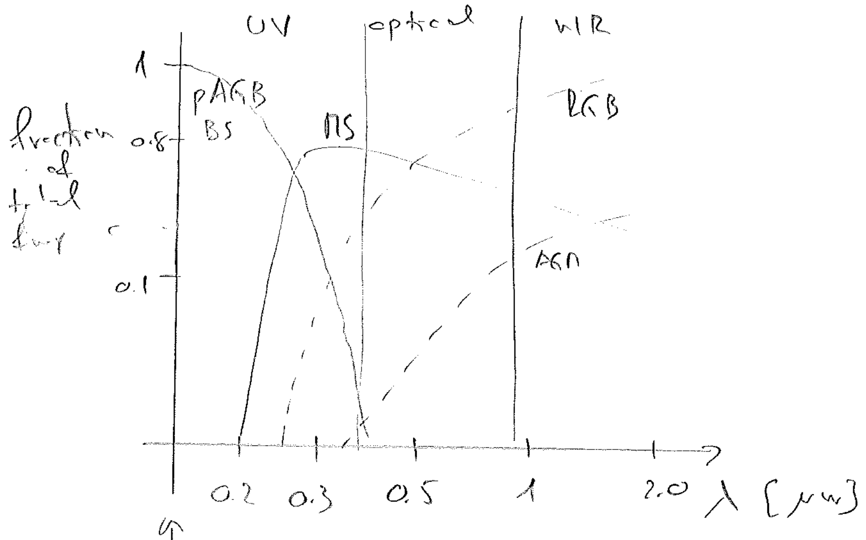
2) do we have spectra for all relevant phases & parameters (Teff, log g, M, Z, t) + that will be in galaxies we wish to investigate

3) can we attach the right spectra to right point on the isochrones (do we know the stellar parameters)

4) can we "interpolate" reasonably, or are there significant technical problems when doing the isochrone integration

## Which stars contribute most to spectra

- stellar luminosity depends on age (time after star burst)
- contributors also depend on the wavelength

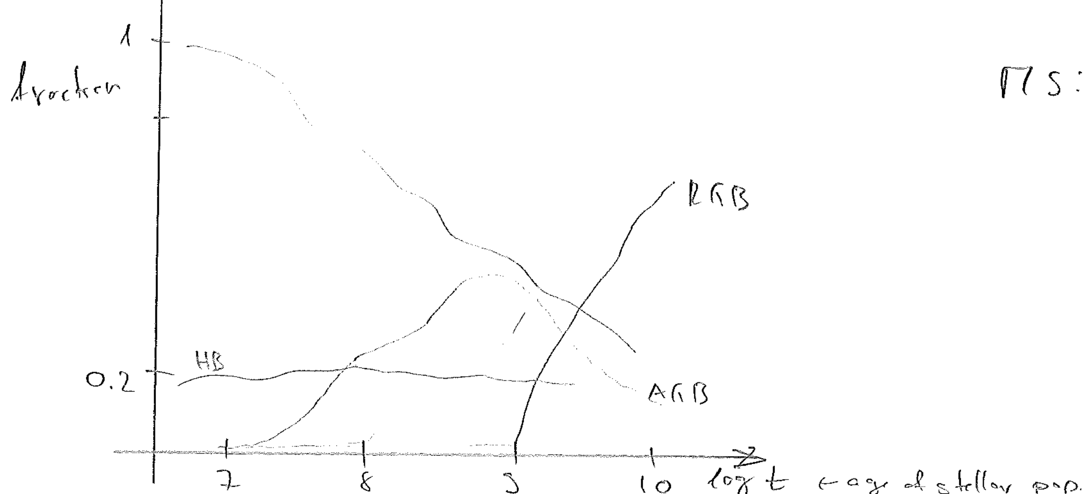


optical: - MS & RGB
bluer ↙ ↘ redder
- AGB → also important

IR : RGB & AGB & MS

UV : post AGB
↳ Horizontal Branch

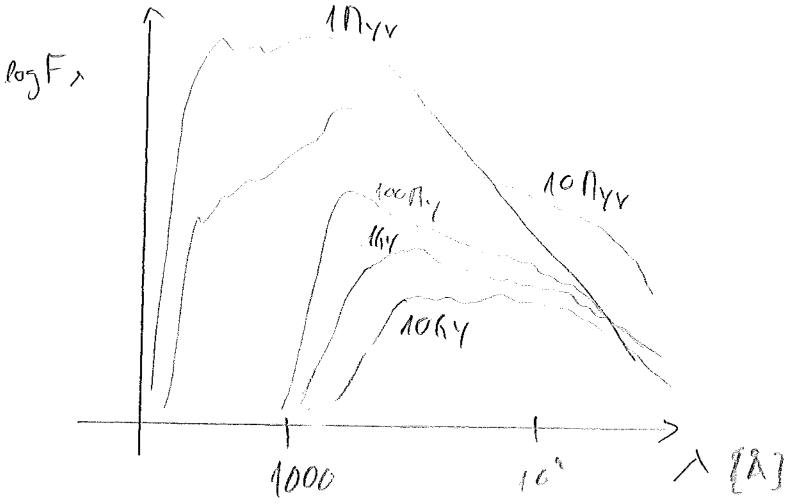
MS: important for young populations



(show slides)

## Spectral evolution of a SSP

- instantaneous burst stellar pop. at solar metallicity



- aging of an SSP

=> show fig 5.1 from Greggio & Renzini 2011

a) 1 Myr: all massive stars are still on MS; featureless SED, Ly break

b) 10 Myr: most massive stars have already died, first Red Supergiants (IR)

c) 100 Myr: development of the Balmer break + Balmer lines
-> top of main sequence is made of A stars

d) 300 Myr: fading of IR light (peak at 10 Myr by red supergiants) is stopped, due to the appearance of TP-AGB stars

e) 1 Gyr: - TP-AGB stars at strongest contribution, molecular bands in UV a possible raise of flux due to post-AGB phase, maybe HB

d) few Gyr: RGB contributes the most to NIR, gradual fading

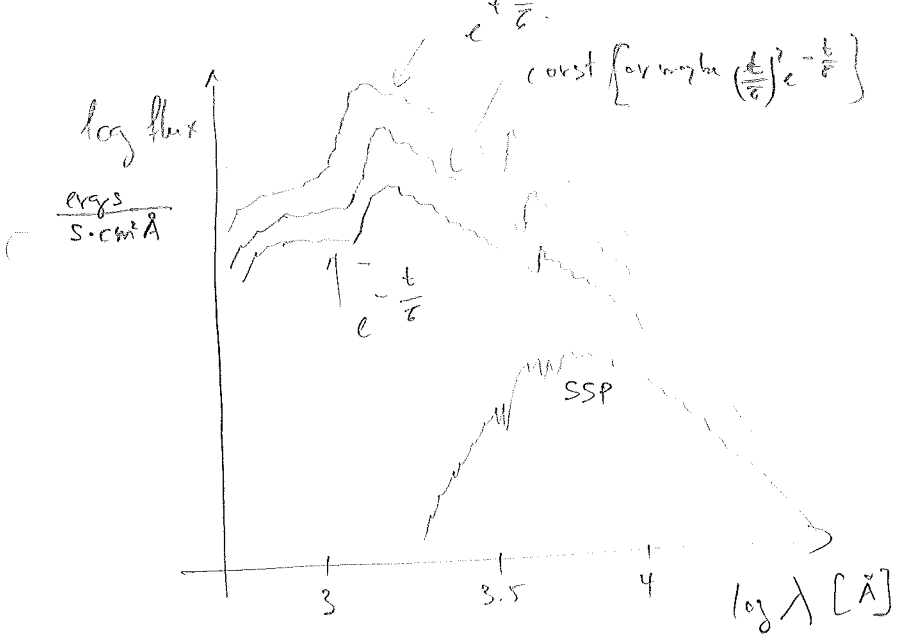
## Evolution of spectra of different SFH

cases: SSP: 1 Gyr old

CSP: made of the same SSP but with different SF laws

⇒ SED of a population that is forming stars for 1 Gyr given a SF law

⇒ very similar as long as $\tau \geq 0.5$ Gyr (not very short SF)



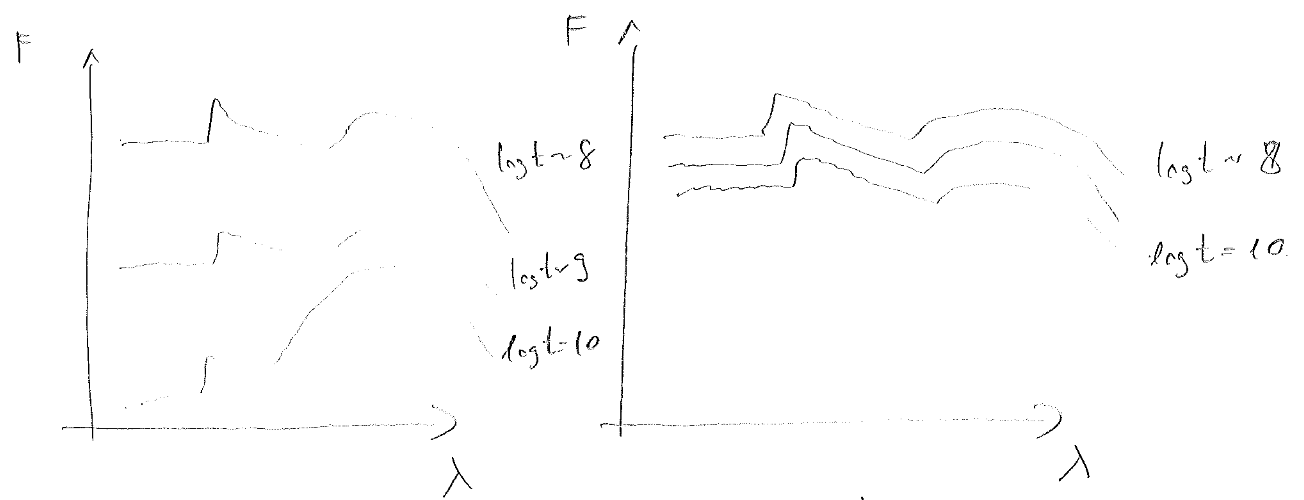
show fig 5.4 from Greggio & Renzini 2011

- as a comparison, a SSP of t = 1 Gyr is very different

⇒ all stars were created instantaneously, 1 Gyr ago, and are passively evolving since (why upper SED are from populations that still make stars)

assume SFR ~ $e^{-\frac{t}{\tau}}$ $\tau = 1$ Gyr ; $\tau = 4$ Gyr

⇒ how will SED look at different ages

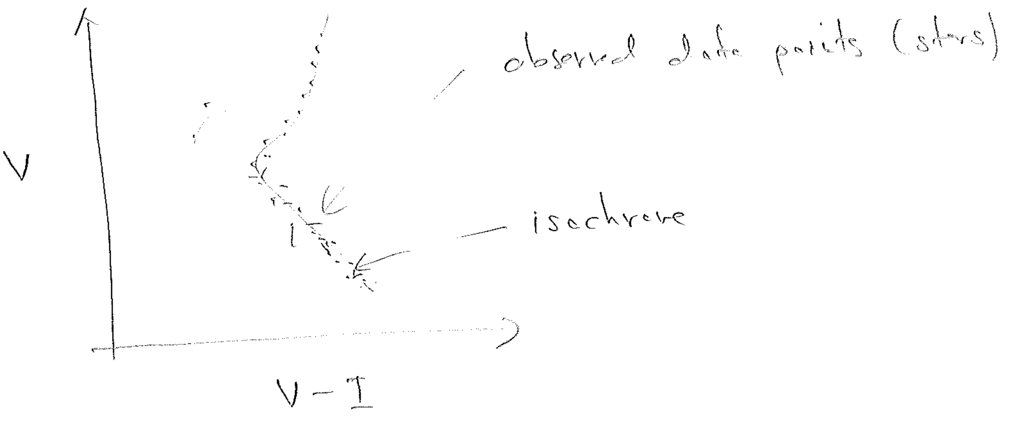


- much faster SED evolution when $\tau$ is short
- these kind of models are never "quenched" → never stop SF (exponential decay)

# Determining ages & metallicities

- spectral synthesis resulted in construction of SSP & CSP (given a SFH)
- how can we use this to determine AGE, METALLICITY (and MASS) in galaxies or stellar systems?

a) Resolved stellar populations
  - observations come from photometry: different filters.
  - CMD - colour-magnitude diagram ⇐ observational HR diagram



  - make use of isochrones

=> going from Hertzsprung-Russell diagram (theory) to CMD (observations)

=> from $(T_{eff}, \log g, L_{bol}) \rightarrow V, B-V$ or similar

=> in practice, have to convert spectra of stars in a CSP (given SFR $\psi$ and SSPs) into colours taking into account properties of the instrument (filter) flux in a „k"-band

SED of CSP

$$F_k = \int d\lambda \, R_{k,\lambda} \cdot F_\lambda$$

Response function of a filter for „k"-band

SFR

spectrum of SSP

$$F_\lambda = \int_0^t dt' \, \psi(t') \, f_{SSP}(x_i, t-t')$$

colour index $M_i - M_j$ for colour centered around wavelengths $\lambda_i, \lambda_j$

$$M_i - M_j = \text{zeropoint} - 2.5 \log \frac{F_i}{F_j}$$

↳ depends on the photometric system

- lets assume we can plot an isochrone in CMD (show slide)

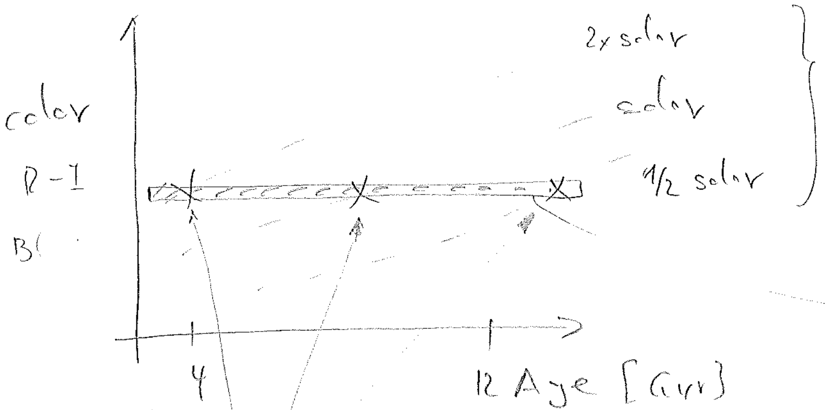
⇒ what is needed to fit it

- deep CMD - below MS turn-off
- age - position of the turnoff
- metalicity - position & shape of RGB
- distance to the system: overall magnitude match
- reddening of the system (dust): overall colour

## b) Unresolved stellar populations

- if we can't resolve individual stars (to make CMD of stellar pop.), we can try to image regions of galaxies (of the full galaxy) and see how these colours are predicted from theory

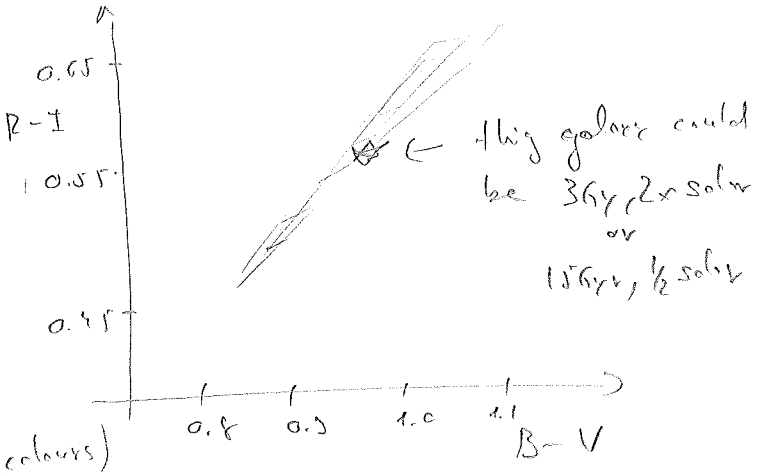
=> construction of model grids



} different curves for different metalicities, as function of age

=> measured colour

- 1 colour doesn't give sufficient info to determine age and metallicity
  - => multiple possibilities
- 2 colour are not much better
  - a bit better in NIR



(show slide with IR colour-colour)

=> AGE - METALLICITY DEGENERACY
- can't distinguish between (when using colours)
  - old-but-metal-poor
  - young-but-metal-rich
- both age & metallicity cause a SSP to redden (same effect on overall colour)

- to break/lift the age-Z degeneracy one should use spectra (even then there are difficulties, as systems are not SSP)

## c) Spectra: Breaking the age-Z degeneracy

- spectra of good signal-to-noise can show difference between age & metalicity, as some absorption lines are sensitive to age, some to metalicity

  => [show slide SSP t=10, Z=-0.4, t=2.5 Z=0.0]

  => difference in Balmer lines (age), Fe lines (metalicity)

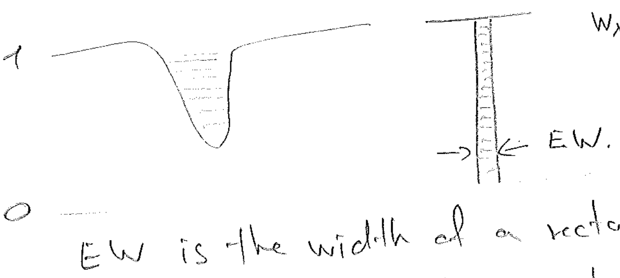
- two aproaches
  a) use „absorption indices"
  b) fit full spectrum to recover SFH

a) degeneracy breaking power in spectra is localised to some features

=> define „indices" which isolate these features

1) define a pseudo-continuum (real continuum not known)

2) express absorbed flux as an EQUIVALENT WIDTH (EW)



spectrum

$$W_\lambda = \int \left(1 - \frac{F_\lambda}{F_0}\right) d\lambda$$

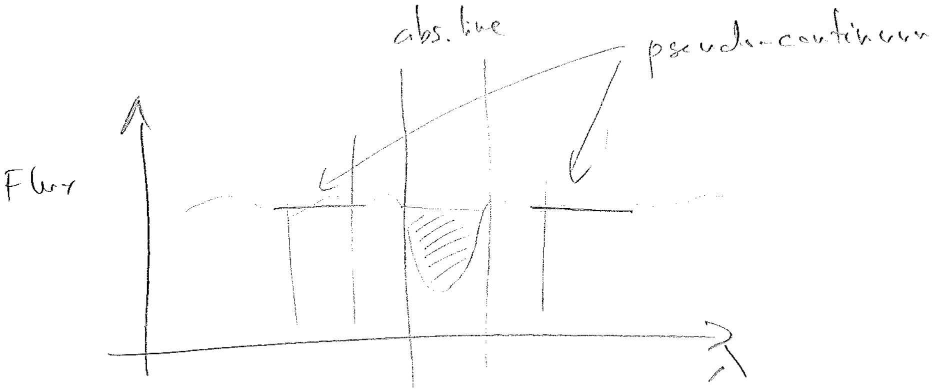
continuum

EW is the width of a rectangular, completely absorbed segment of the spectrum with the same integrated absorption (AREA) as the line itself.

3) calibrate by measuring same features on models (SSP) exactly as for the observed spectra (instrumental effects!)

↳ or maybe stars of known Z,t

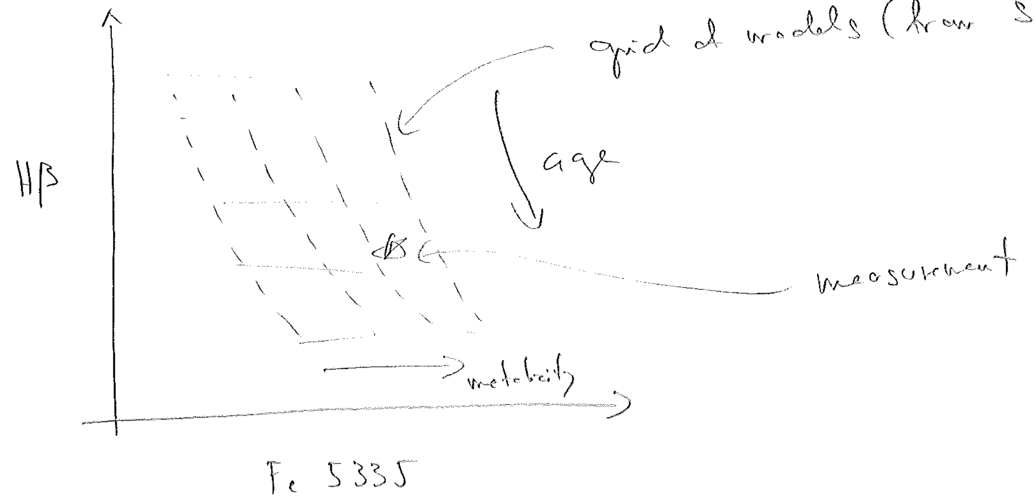
## Breaking degeneracy age-Z continued



Hβ, Mgb, Fe 5335 ....

historically important:
Lick Observatory
Stellar Library
(Worthey + 1994)

4) measured indices are plotted on a grid of models;
↳ need to choose right indices that follow mostly only age or metalicity



show slide

- how to get model predictions: (two ways)
  1) create a SSP (sum stellar library along an isochrone) and measure the same indices on this synthetic spectrum
  2) measure indices on each stellar spectrum in the library, compute luminosity-weighted average index along the isochrone

b) full spectrum fit
- use a set of models to fit the spectrum
-> estimate the average (mass-weighted) age & metalicity from those spectra that were used in the fit
(more about it soon: mass estimate + kinematics)

## How to estimate the stellar mass?

- assume: we observe a galaxy with $L = 10^{10} L_{sun}$
- what is it?
  - an old giant galaxy with $M \sim 10^{10} M_\odot$
  - a young dwarf that is making stars w/ $M \sim 10^{8} M_\odot$

(show 1st slide with galaxies)

- conversion between M & L ≡ mass-to-light ratio $M/L$
  - each star has a $M/L$; sun $1 L_\odot$ for $1 M_\odot$

- SSP: a $M/L$ is obtained by summing all stellar masses and all stellar luminosities of stars along an isochrone

  $M/L$ depends - IMF, age, metallicity

- CSP: $M/L$ depends on SFH, IMF, age, metallicity

## What mass is measured?

given by SSP or CSP, and used as a number

- multiple options: - baryonic mass that made stars ($M_i$) → initial mass
  - actual mass in stars & stellar remnants
    $M_i$ - mass return
  - actual mass in living stars

=> for comparison with dynamical models: living stars + remnants but no gas from mass loss

$$M_* = \int_{t_0}^{t} \overset{\text{SFR}}{\psi(t')}\, dt' - R(t)$$

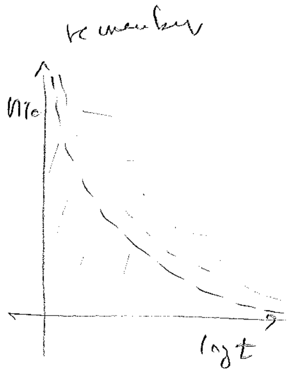
stellar mass = integral of SFR - mass return

$$\underset{\text{mass return}}{R(t)} = \int_{t_0}^{t} dt \int_{M_{TO}(t'-t_0)}^{120} dM \; \overset{\text{IMF}}{\phi(M)} \underbrace{[M - \overset{\text{final mass}}{M_f(M)}]}_{\text{mass loss}} \underbrace{\psi[t - t_0 - \overset{\text{lifetime of stars of mass }(M)}{\tau(M)}]}_{\text{SFR}}$$

=> present $M(t)$: $M(t) = M_{in}$ for $M_{in} < M_{TO}(t)$

$M(t) = \underset{\text{remnant mass}}{M_{Rem}}$ for $M_{in} > M_{TO}(t)$

remember



=> $M_{Rem}$:

$M_{in} < 8.5 M_\odot$ => white dwarf $M_R = 0.077 M_{in} + 0.48$

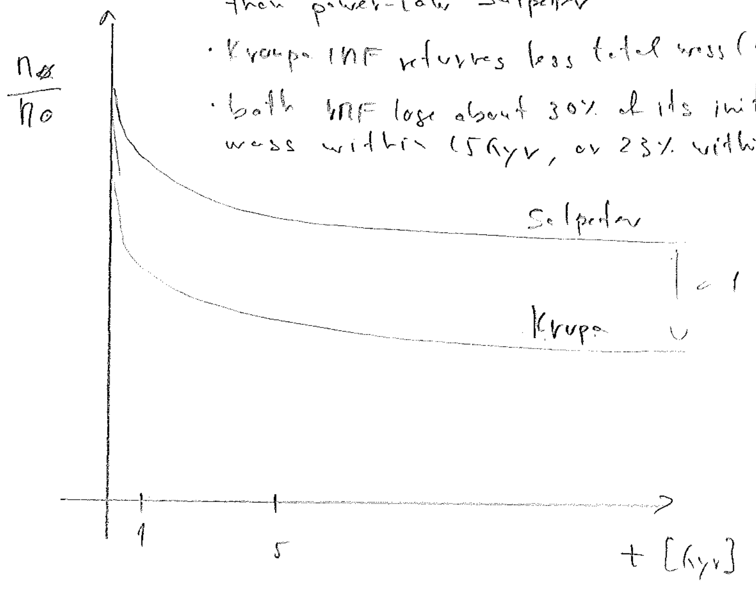
$8.5 \leq M_{in} < 40 M_\odot$ => neutron star $M_R = 1.4 M_\odot$

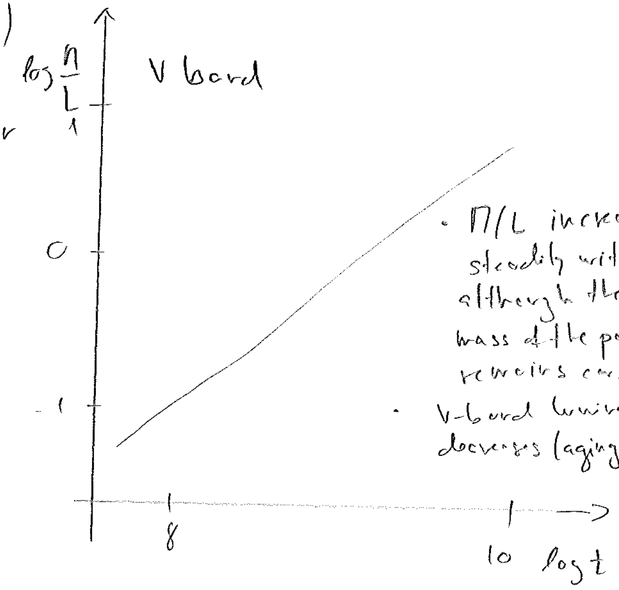
$M_{in} > 40 M_\odot$ => BH $M_R = 0.5 M_{in}$

(one prescription)

---

- Kroupa IMF has less low mass stars than power-law Salpeter
- Kroupa IMF returns less total mass (16% less)
- both IMF lose about 30% of its initial mass within 15 Gyr, or 23% within 1 Gyr





- M/L increases steadily with time although the total mass of the popul. remains constant
- V-band luminosity decreases (aging)

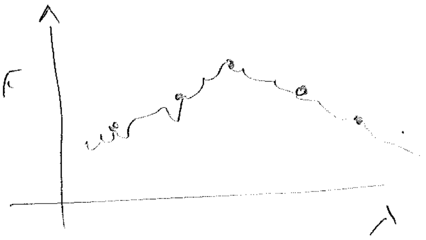
stellar mass estimate ctd

## How to derive mass/light?

① use colour, say B, V: B − V

- M/L depends on age/SFH, metallicity of a galaxy
- colour also depends on age & metallicity

② have multiple-colours and fit a CSP (with SFH) to it



③ fit the full spectrum by a CSP, or look for specific features
e.g. 4000 Å break and Hδ
↓ varies with age smoothly
↳ recent SF (100 Myr)

THIS IS REPEATED LATER: SKIP IT NOW!

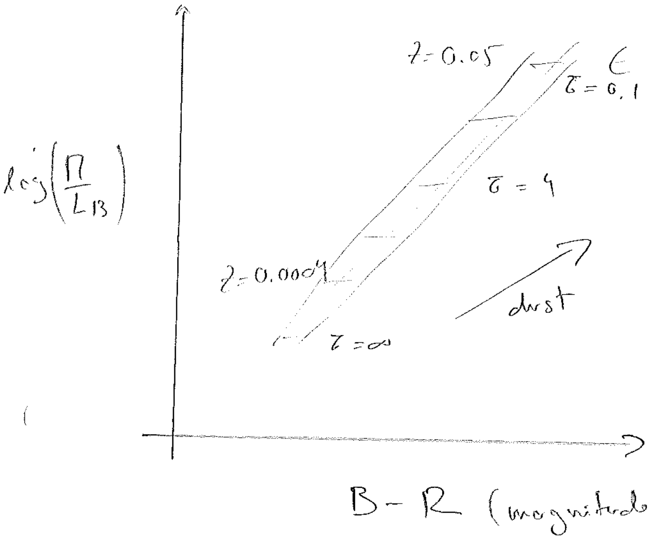
⇒ final M/L is a combination of M/L of individual SSP, but not trivially
↳ for a chosen IMF

⇒ luminosity weighting:

$$\left\langle \frac{M}{L} \right\rangle = \frac{\sum_{i=1}^{N} w_i \frac{M_i}{L_i} \cdot L_i}{\sum_{i=1}^{N} w_i L_i} = \frac{\sum_i w_i M_i}{\sum_i w_i L_i}$$

## ① Broad band colours – easy stellar masses

- $M/L$ depends on age/SFH, metallicity of a galaxy
- colours also depend on age & metallicity



models for a given
- IMF (constant for all models)
- Z (varying) [but age-metallicity degeneracy helps here
- SFR τ

$$\log\left(\frac{M}{L_B}\right) = a_B + b_B\,(B-R)$$

e.g. Bell et al. (2003)

=> B−R colour is a good predictor of $M/L_B$

-> dust not a big problems
-> it reddens the galaxy, but makes it dimmer
=> approximately preserves colour-$M/L$ relation

=> cheap $M/L$ (only observations in 2 bands)

=> uncertainties:
- SFR -> works well only for SFR ~ $e^{-\frac{t}{\tau}}$
-> large errors for other types of SFH
crucial for understanding results

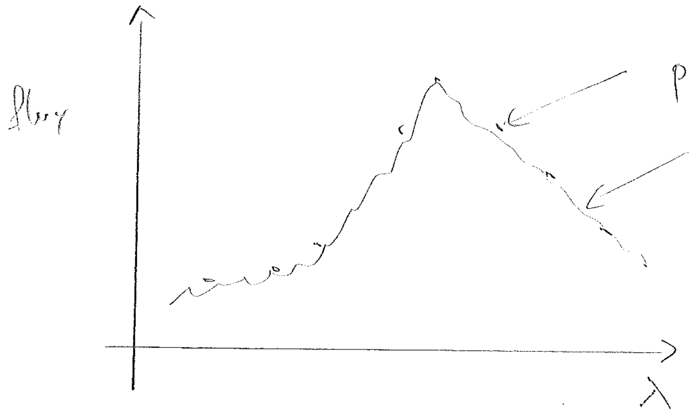
=> general expression

$$\log \frac{M}{L}\bigg|_i = a_i + b_i\,\underbrace{(m_j - m_k)}_{\text{colour (e.g. B-R)}}$$

i, j, k: can all be different (B, V, K), or some can be similar i = j

=> $a_i, b_i$ depend on the choice of colour and are obtained from models

## (7) Stellar masses from SED fitting



photometric measurements [ a poor man's spectru

SSP or CSP models that fit the
multi-band photometry
↳ many different SFH often very important
L 7 models ...

- photometry from many bands: UV/optical/NIR

⇒ method
- find SFH compatible with the observed flux
- M/L from the best fit model [will show later the formula]

⇒ caveat
- we don't know the redshift of the source
- has to be fitted simultaneously or determined by other means (e.g. spectra)

⇒ photo-z

⇒ precision:
- comparable to colour
- better handle on SFH
- a poor-man's spectrum

## 3) Stellar masses from spectroscopy

i) looking for some special features in the spectra

e.g. 4000 Å break and Hδ line index

↳ recent SF (100 Myr)

↓ varies smoothly with age

⇒ determining the population of stars (e.g. SSP that best represents them) and get its mass

ii) fitting the full spectrum (in a non-parametric way)

- real galaxies don't respect our SFR (smooth) parametrizations

⇒ show example Shetty & Cappellari+16

- how to do it
  - similar to kinematics
  - use a library of SSP models
  - use a similar code as for kinematics
    - use a similar code as for kinematics
    - find a combination of stars that best reproduce the observations
    - need some sort of tunning or smoothing of the results

- result: a set of $\underbrace{\text{SSP templates}}_{\to \text{ pre chosen IMF}}$, each with $L_i$ and $M_i$ and a weight $w_i$
- what is the final M/L

$$M/L_R = \frac{\sum_{j=1}^{N} w_j M}{\sum_{j=1}^{N} w_j L_j}$$

$$M/L_R = \frac{\sum_j w_j \cdot \frac{M_j}{L_j} \cdot L_j}{\sum_j w_j L_j}$$