The Stellar Populations of Galaxies

H.-W. Rix IMPRS Galaxies Course March 11, 2011

Goal:

Determine $\mathbf{n_*(M_*,t_{age},[Fe/H],\mathit{R})}$ for a population of galaxies

How many stars of what mass and metallicity

formed when and where in galaxies?

In particular:

# of young stars → 'star formation rate' (SFR)

stellar mass (vs. dynamical mass)

Literature:

B. Tinsley, 1972, A&A 20, 383

Worthey

G. Bruzual & S. Charlot 2003, MNRAS, 344, 1000

Mo, van den Bosch & White 2010

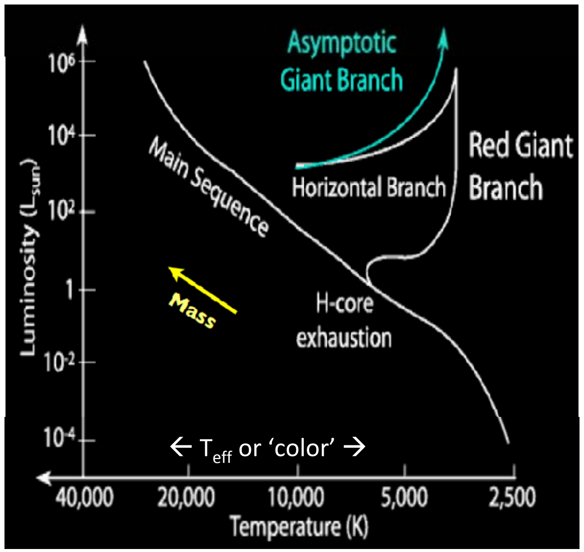
http://astro.dur.ac.uk/~rjsmith/stellarpops.html

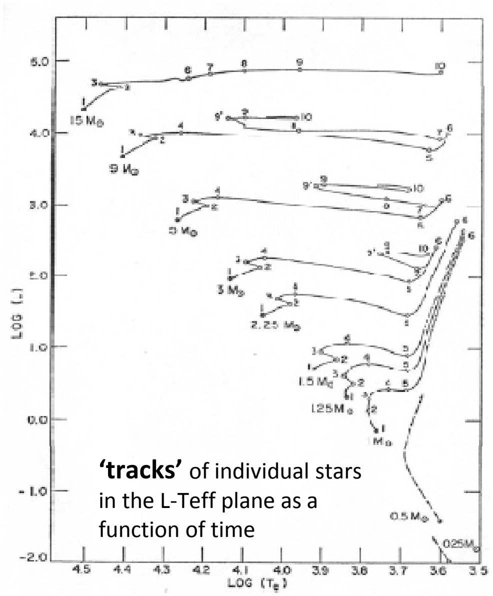
Physical vs. observable properties of stars

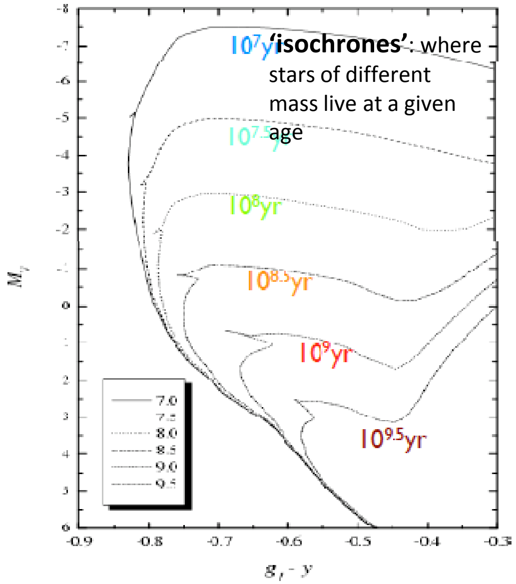
- Stellar structure: $L_{bolom} = f(M, t_{age}, [Fe/H])$, $T_{eff} = f(M, t_{age}, [Fe/H])$

- Most stars spend most of their time on the main sequence (MS),
  - stars $<0.9\ M_{sun}$ have MS-lifetimes $>t_{Hubble}$
  - $M=10\ M_{sun}$ are short-lived: $<10^8$ years ~ 1 t_{orbit}
  - Only massive stars are hot enough to produce HI – ionizing radiation
  - $L_{MS}(M) \sim M^3$ → massive stars dominate the luminosity (see 'initial mass function')

- Model predictions are given as 'tracks' (fate of individual stars) , or as isochrones, i.e. population snapshots at a given time (Padova, Geneva, Yale, etc… isochrones)



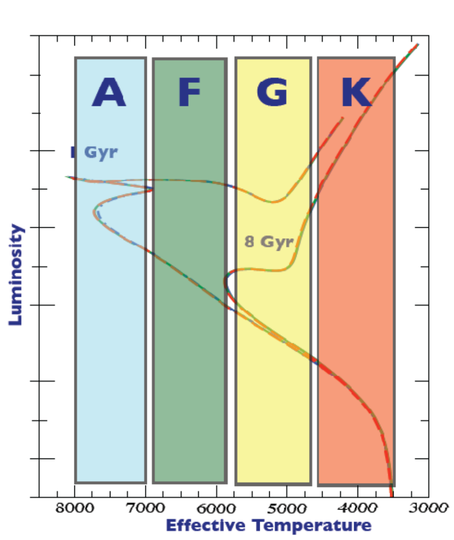


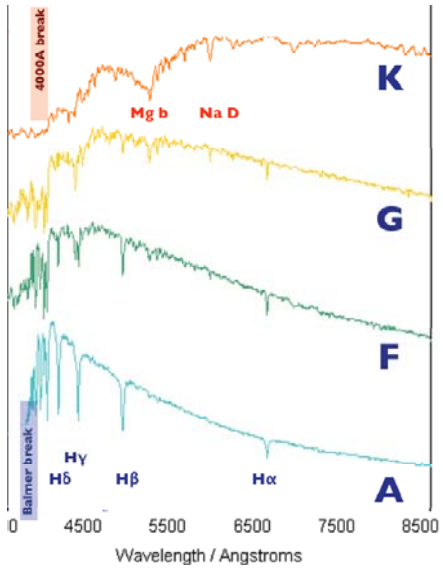


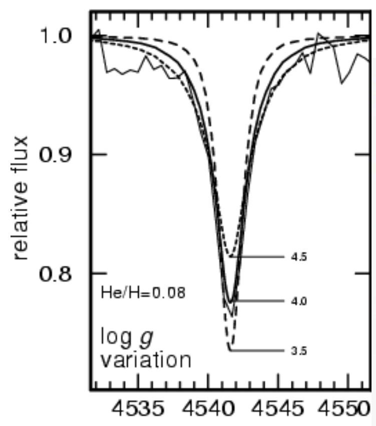
Information from Stellar Spectra

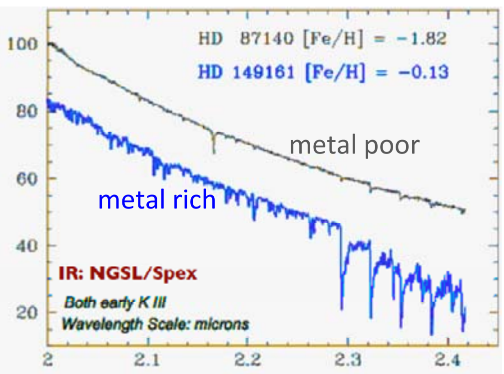
Stellar spectra reflect:

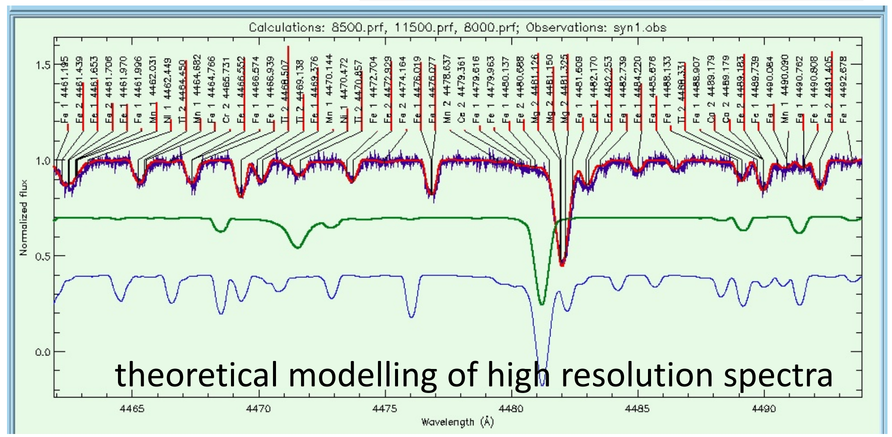
- spectral type (OBAFGKM)
  - effective temperature T_{eff}
- chemical (surface) abundance
  - [Fe/H] + much more e.g [α/Fe]
  - absorption line strengths depend on T_{eff} and [Fe/H] → modelling
- surface gravity, log g
  - Line width (line broadening)
  - yields: size at a given mass
  - → dwarf -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











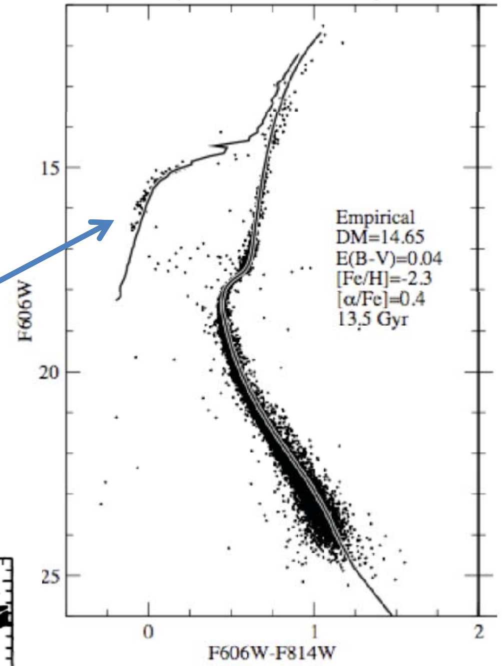
Resolved *Single* Stellar Populations

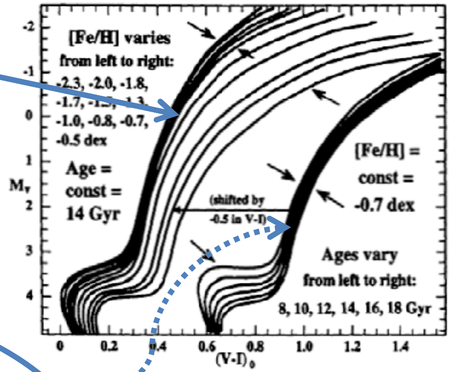
(photometry only)

- 'Single stellar populations' (SSP)
  - t_{age}, [Fe/H], [α,Fe], identical for all stars
  - open and (many) globular clusters are SSP

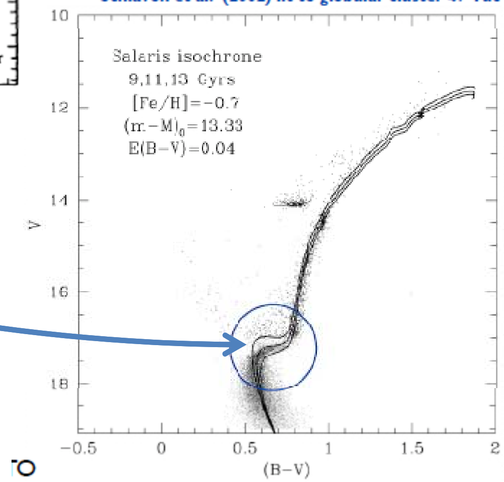
- Isochrone fitting
  - transform T_{eff} → (filter) colors
  - distance from e.g. 'horizontal branch'
  - Get metallicity from giant branch color
    - only for t>1Gyr
    - no need for spectra
  - **get age from MS turn-off**
    - **Ages only from population properties!**
  - N.B. some degeneracies

M92 (Dotter et al. 2009)



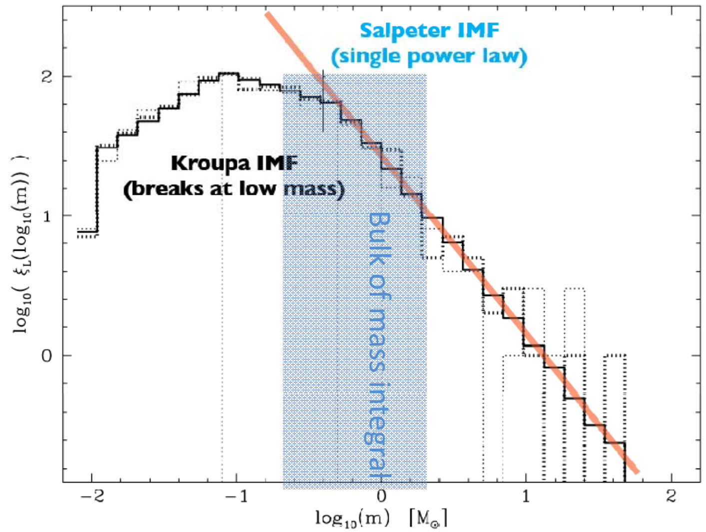


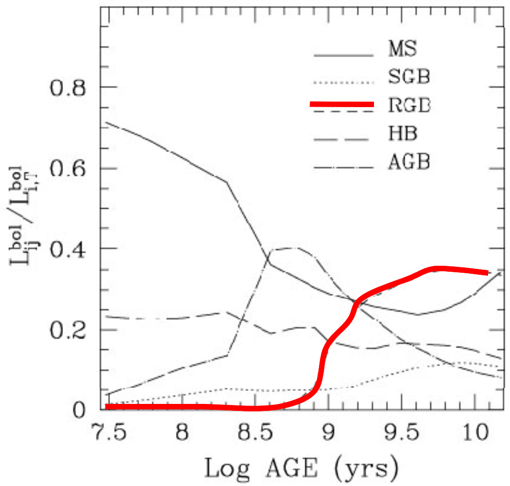
Schiavon et al. (2002) fit to globular cluster 47 Tuc



The Initial Mass Function and 'Single Stellar populations'

- Consider an ensemble of stars born in a molecular cloud (*single stellar population*)
- The distribution of their individual masses can be described piecewise by power-laws
  $N(M) \propto M^{-\alpha} dM$ (e.g. Kroupa 2001)
  - $N(M) \propto M^{-2.35}\, dM$ for $M > M_{sun}$ (Salpeter 1953)
  - much of integrated stellar mass near $1 M_{sun}$
- Massive stars dominate MS luminosity, because $L_{MS} \sim M^3$
- For young populations (<300 Myrs)
  - upper MS stars dominate integrated L_{bol}
- For old populations (>2Gyrs)
  - red giants dominate integrated L_{bol}

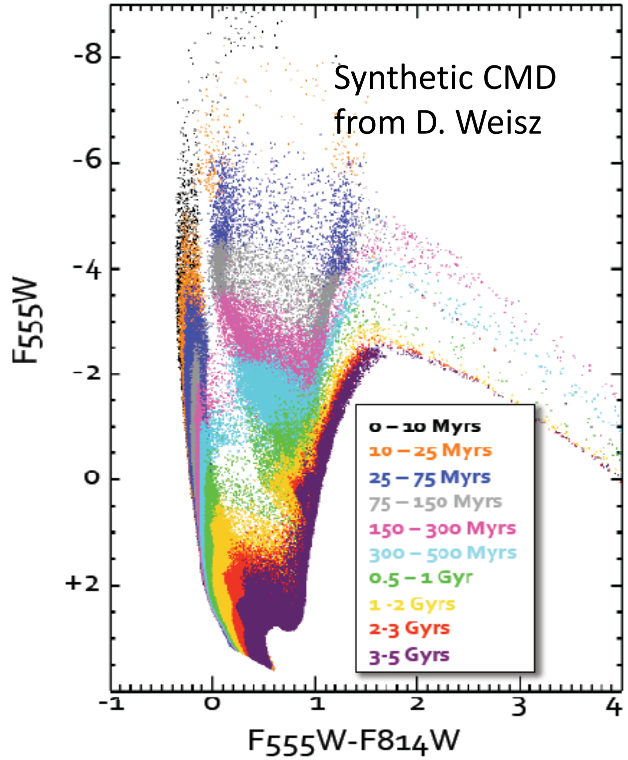


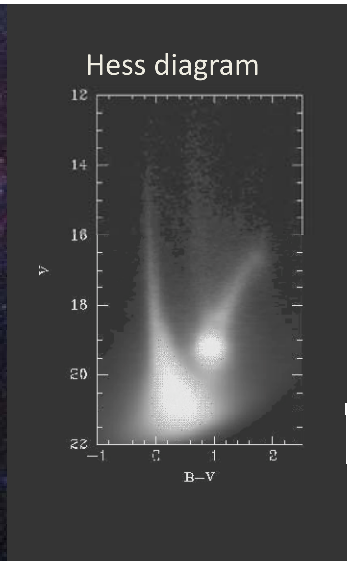


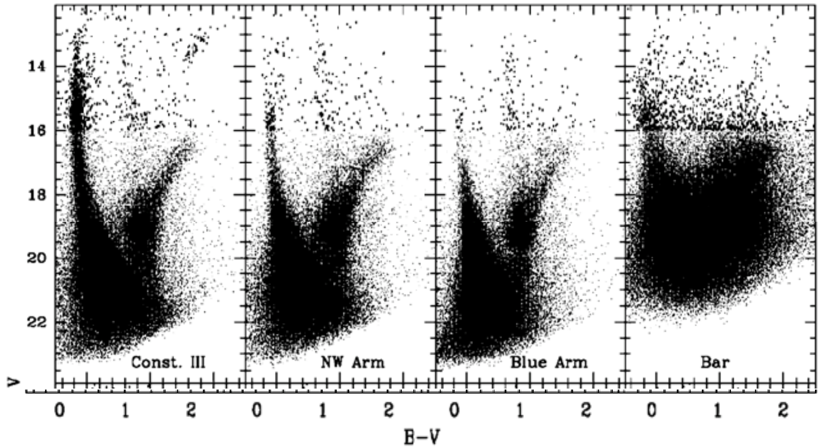
Resolved Composite Stellar Populations
(photometry only)

- ‘Composite stellar populations’
  - t_{age}, [Fe/H], [α,Fe] vary
  - stars have (essentially) the same distance
  - Examples: nearby galaxies

- Full CMD (Hess diagram) fitting
  - Both locus and number of stars in CMD matter
  - Forward fitting or deconvolution
  - Result: estimate of $f(t_{age},[Fe/H])$



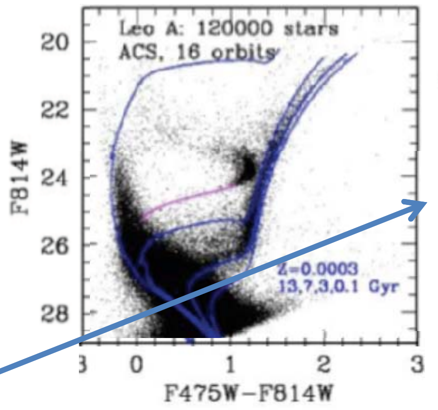


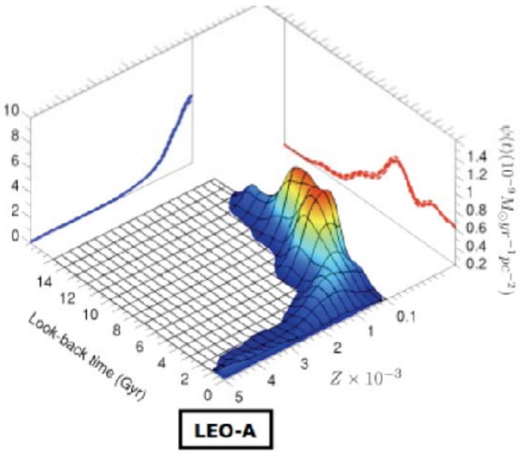


CMDs for different parts of LMC

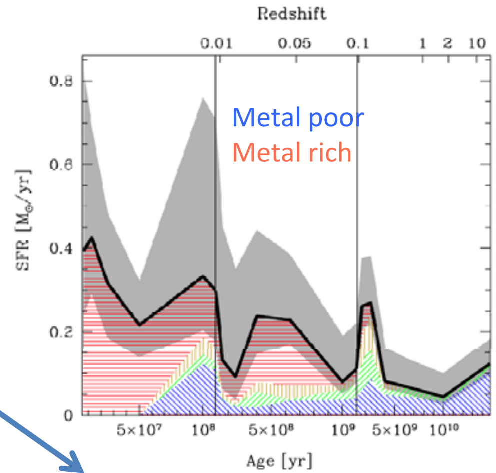
Constructing the Star-Formation History (SFH) for Resolved Composite Stellar Populations

- Convert observables to f(t_{age},[Fe/H])
  - E.g. Leo A (Gallart et al 2007)
  - LMC (e.g. Harrison & Zaritsky)

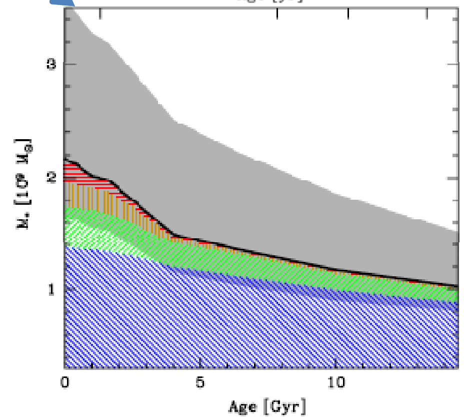




- Issues
  - Not all starlight 'gets out'
    - Dust extinction dims and reddens
    - Star light excites interstellar
  - Age resolution logarithmic, i.e. 9Gyrs =11Gyrs



- Basic Lessons (from 'nearby' galaxies, < 3Mpc)
  - All galaxies are composite populations
  - Different (morphological) types of galaxies have very different SFH
    - Some mostly old stars (t_{age} >5Gyrs)
    - Some have formed stars for t~t_{Hubble}
  - younger stars ←→higher [Fe/H]
    - Multiple generations of stars → self-enrichment

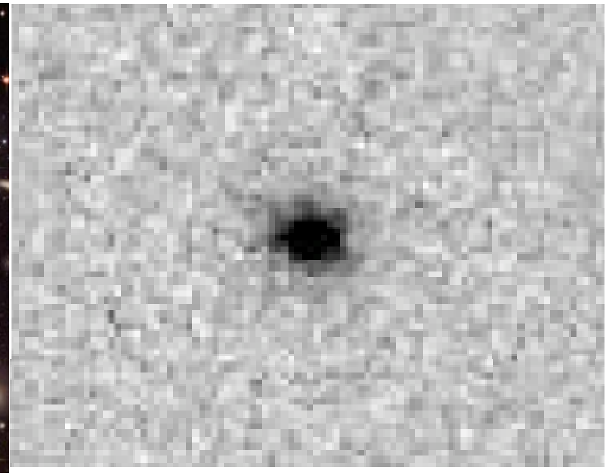


‘Integrated’ Stellar Populations

- of the $>10^{10}$ galaxies in the observable universe, only 10-100 are ‘resolved’

- What can we say about $f(t_{age},[Fe/H])$, SFR, $M_{*,total}$ for the unresolved galaxies?
  - galaxies 5-100Mpc stars are unresolved but stellar body well resolved
  - z>0.1 means that we also have to average over large parts of the galaxy





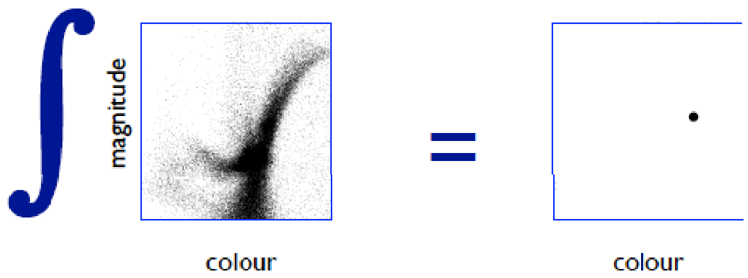
- Observables:
  - colors, or ‘many colors’, i.e the ‘spectral energy distribution’ (SED) (R=5 spectrum)
  - Spectra (R=2000)

  integrated over the flux from ‘many’ stars
  - covering a small part (e.g. the center) of the galaxy, or the entire stellar body

Describing Integrated Stellar Populations by Colors

Integrating (averaging) destroys information

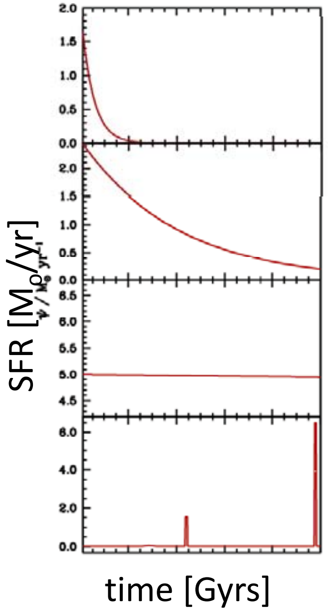
- Straightforward: *predict*
  - assume SFH, $f(t_{age},[Fe/H],IMF)$ → flux, colors
    - Isochrones for that age and [Fe/H]
    - IMF, distribution of stellar masses
    - Translate $L_{bol}.T_{eff}$ to 'colors'
  - post-giant branch phases tricky
  - Dust reddening must be included
- Impossible: *invert*
  - invert observed colors to get $f(t_{age},[Fe/H],IMF)$
- Doable: *constrain 'suitable quantities'*
  - Infer approximate $(M/L)_*$
  - Check for young, unobscured stars (UV flux)
  - Test which set of SFH is consistent with data
- NB: different colors strongly correlate
  - 'real' galaxies form a 1-2D sequence in color space



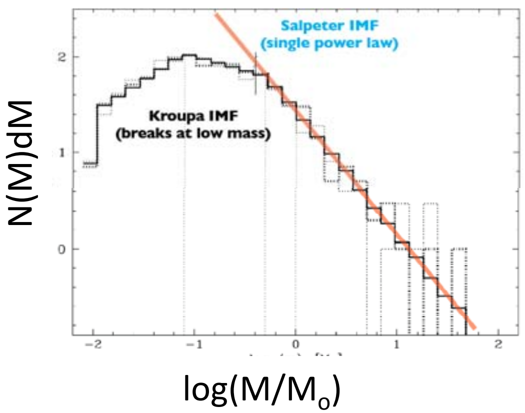
Stellar Population Synthesis Modelling

e.g. Bruzual & Charlot 2003; da Cunha 2008

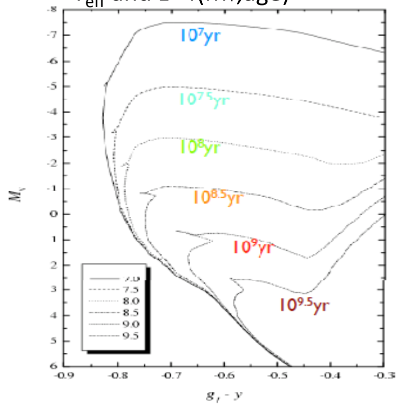
1) Assume star formation history (**SFH**) (M*,[Fe/H]) +



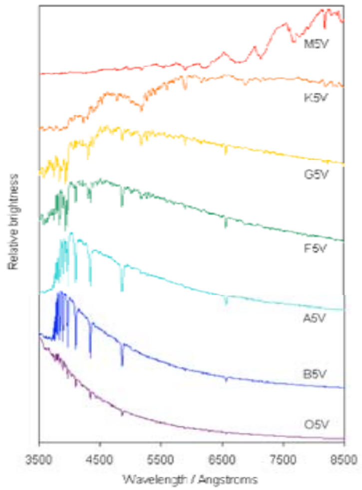
2) 'IMF': how many stars of what mass



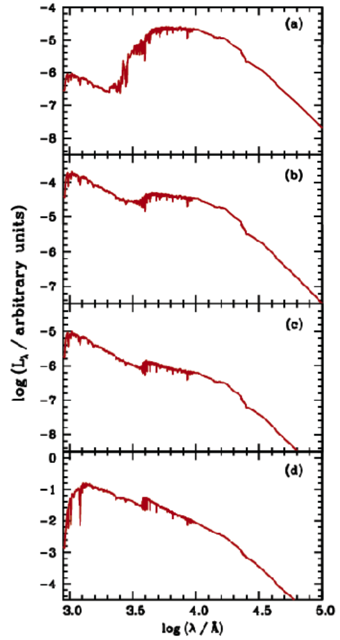
3) 'isochrones': what's T_{eff} and L =f(M*,age)



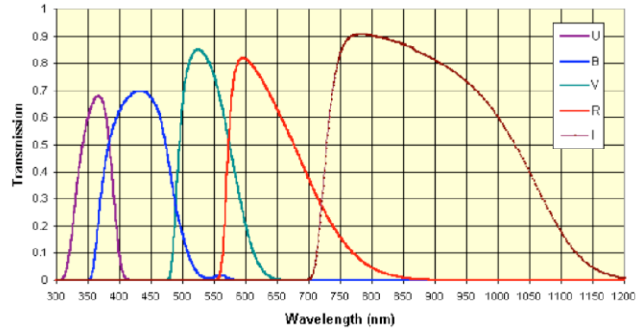
4) Spectral library:
What does the spectrum look like = f(Teff,log g, [Fe/H]



5) SED 'integrated spectrum':



6) Band-pass integration:
Integrate spectrum over bandpass to get **colors**

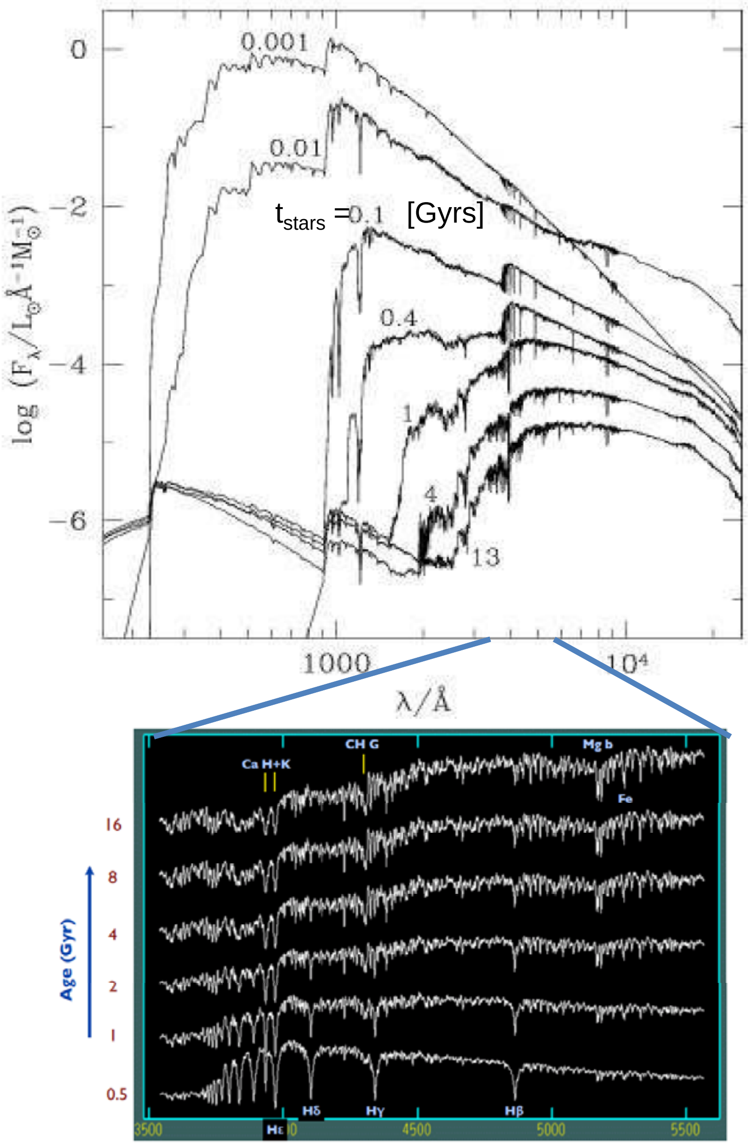


The Integrated SED's of Simple Stellar Populations

- Populations fade as they age
  - ionizing flux is only produced for t<20 Myrs
  - Fading by
    - X 10^5 at 3000A from 10 Myrs to 10Gyrs
      - UV flux is only produce for 0.2Gyrs
    - X 100 at 5000A from 0.1Gyrs to 10Gyrs
    - X 6 at 1.5μm from 1Gyr to 10Gyrs
  - populations 'redden' as they age
    - Higher 'metallicity' and dust also 'redden'

- Spectral features
  - There are 'breaks' in the spectrum:
    - Ly break 912A
    - Balmer break & 4000A break
    - 1.6mm 'bump'
  - Hydrogen vs metal lines: >1Gyr or <1Gyr
  - >1 Gyr: all signatures become sublte

- Integrated spectra of young populations also have emission lines



Vazdekis et al. (2007) models at solar Fe/H from MILES library.

SED Modelling: A worked example or z>1 galaxies

courtesy E. da Cunha

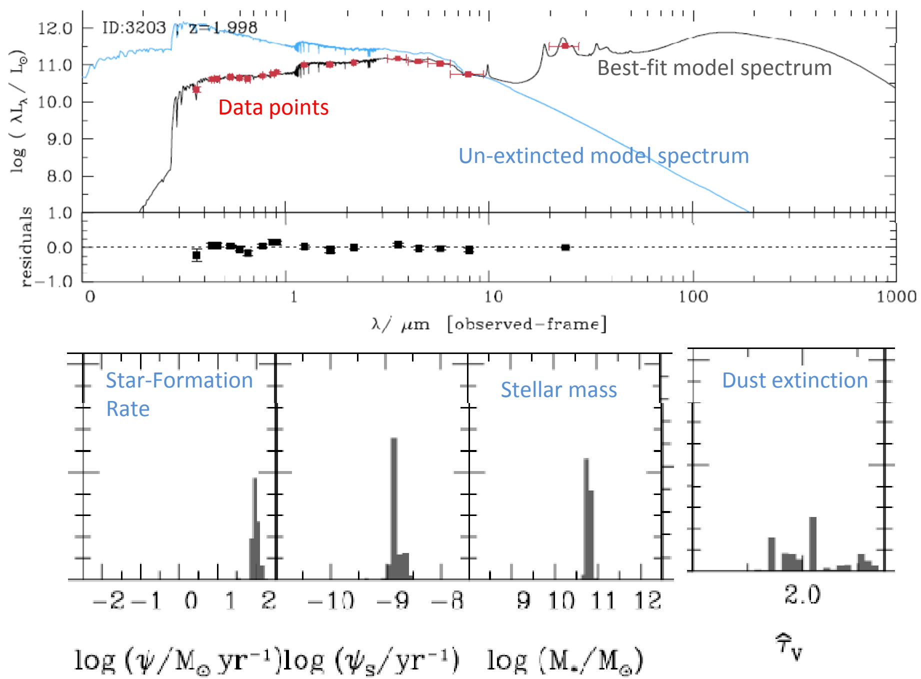
Data:

- Fluxes & errors in ~20 bands
- taken from different instruments
- averaged over the entire galaxy

What you fit for:

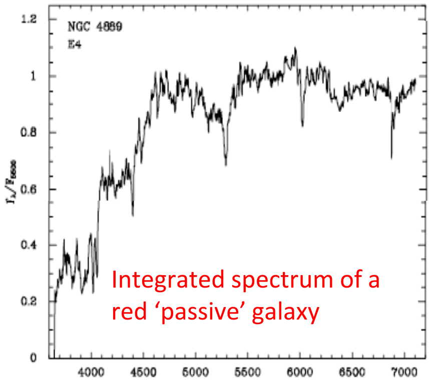
- redshift ('photometric redshift)
- Stars formation rate (t<20Myrs)
- stellar mass
- Fraction of light absorbed by dust
- (dust spectrum)

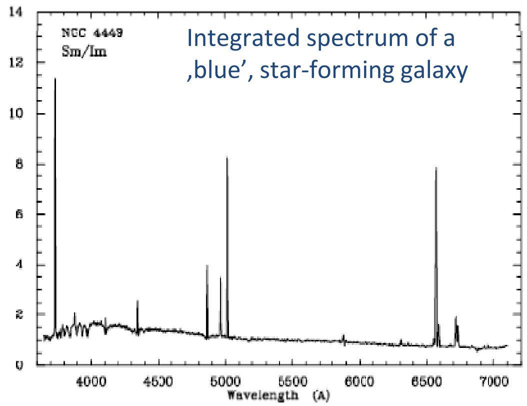
- Also:
  - 'marginalize' over possible SFHs
  - convert to physical quanities using the luminosity distance



Application I: Estimating 'Star Formation Rates'

- "SFR" = $M_*(t_{age} < \Delta t)/\Delta t$
  - Δt= 10 – 200 Myrs
  - NB: SFR may vary within Δt





- SFR estimates are all based on counting either
  - Ionizing photons, often reflected in Hα
  - UV photons (only from short-lived stars)
  - Dust heated by UV photons
    - Fraction of absorbed UV photons varies from 10% to nearly 100%
    - Higher extinction in more massive (metal rich) galaxies and at high SFR

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

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

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

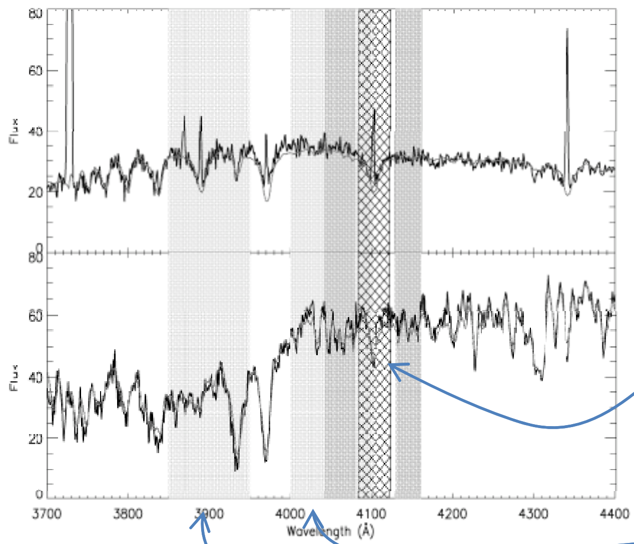
L_ν(in UV)~const for very young pos.s (e.g. Kennicutt 98)

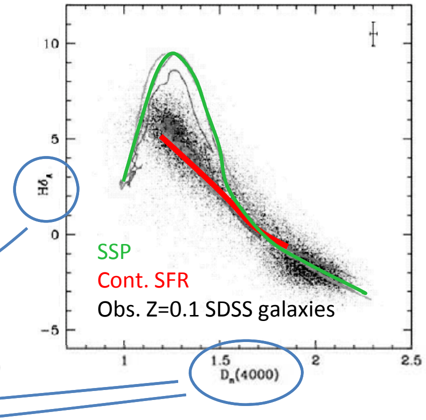
$$\mathrm{SFR}\ (M_\odot\ yr^{-1}) = 4.5 \times 10^{-44}\ L_{FIR}\ (\mathrm{ergs\ s^{-1}})$$

- SFR estimates depend entirely on IMF
  - effects from M_*>5M_o
  - those stars contribute negligibly to M_{tot}

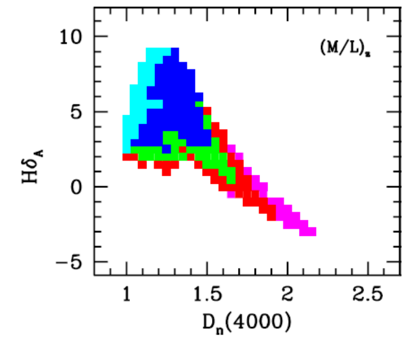
Getting Stellar Mass-to-light Ratios from spectra/colors

Bell & de Jong 2001
Kauffmann et al 2004

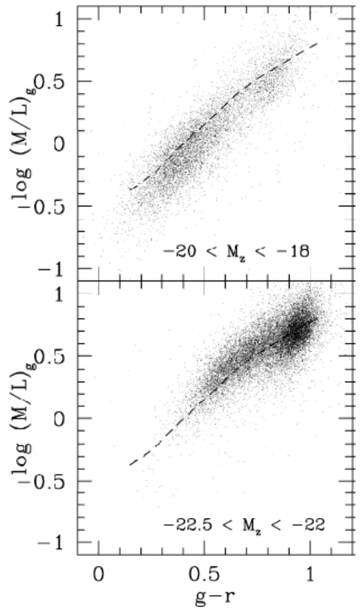




- Define 'line indices; (e.g. D4000), EW Hδ to characterize the spectrum
- Different observed spectra fall onto a 2 dimensional sequence (blue to red)



- To get a first guess at the stellar mass-to-light ratio, it is enough to measure one optical color, e.g. g-r
  - Bell & de Jong 2001

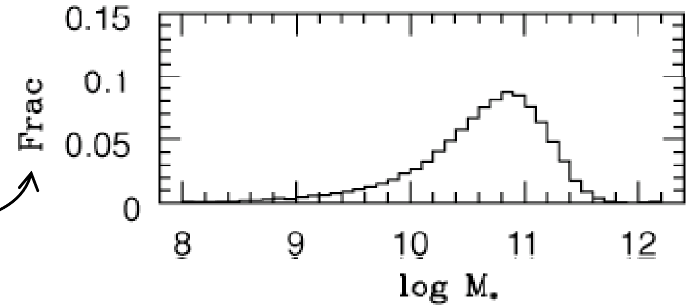


What can we learn from such modeling?

Applications from SDSS to present epoch (z~0.05) galaxies

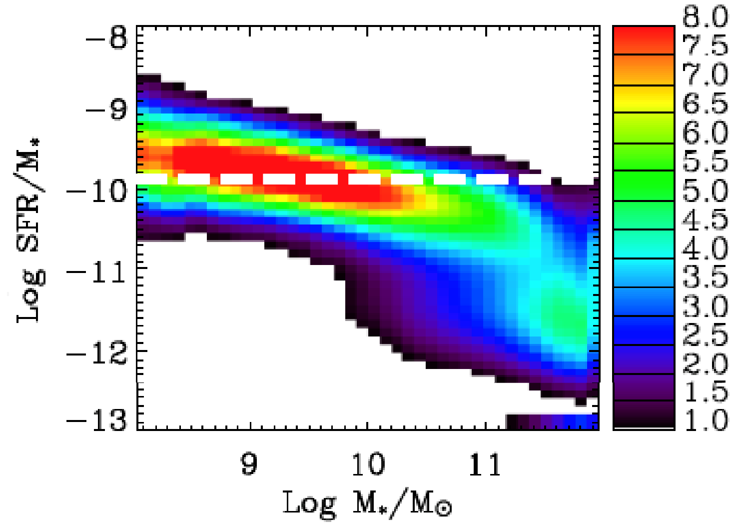
- The distribution of stellar galaxy masses
  - Take large sample of galaxies
  - Determine M_*(SED) for each galaxy
  - Correct for V/V_{max}

→ for any random star in the present day universe, what is the chance that it lives in a galaxy whose total stellar mass is M_*



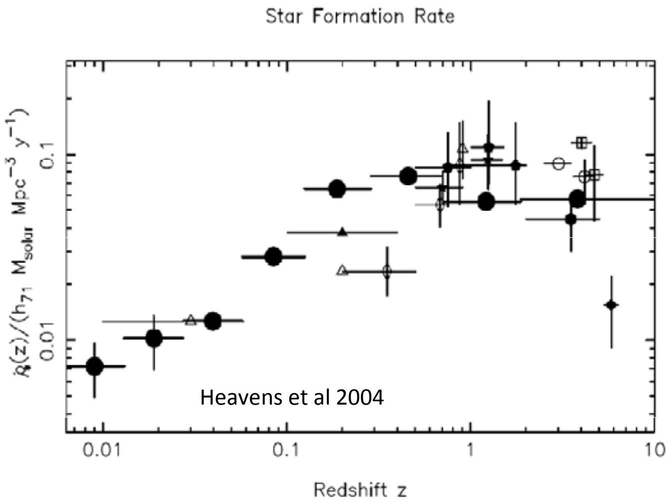
→ most stars live in galaxies with $10^{10} – 2x10^{11}M_o$

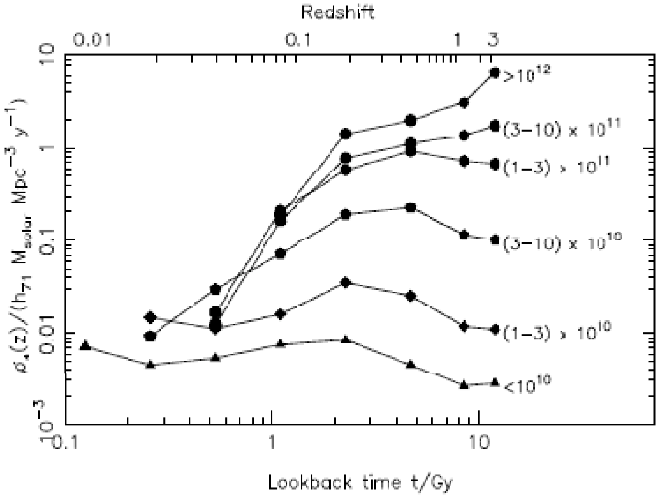
- How rapidly are galaxies making new stars now?
  - Calculate 'specific star formation rate' (SSFR) → SFR(now)/<SFR>(past)
  - Galaxies with $M^* > 2x10^{11}$ hardly form new stars



What do we learn from such modeling?

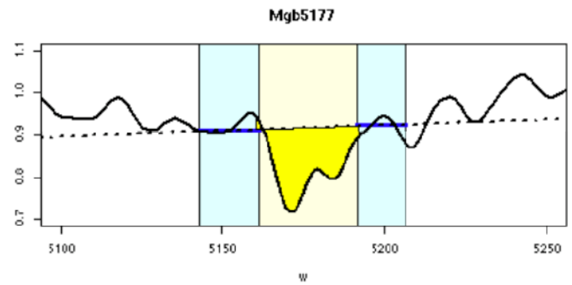
- Try to invert SFH of galaxies from present-day spectra (Heavens et al 2004)
  - Assume SFR = A x exp(- t/t_{scale}) for all galaxies
  - t_{scale} large → constant star formation rate
  - Determine A, t_{scale} for each galaxy → SFH
  - Proper average over all galaxies in sample volume
- Global (volume averaged) SFH has dropped by ~5-10 since z=1
- Lower mass galaxies have a more prolonged SFH

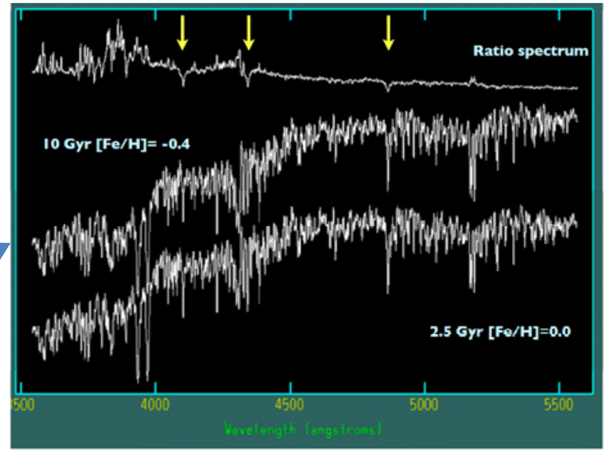




Population diagnostics in 'old' (>2 Gyrs) populations

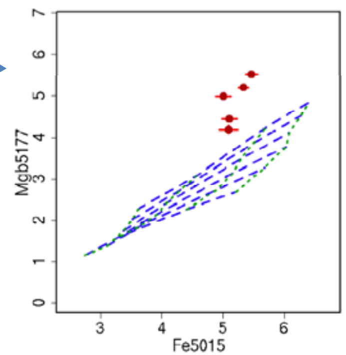
- Nowadays, the majority of stars live in galaxies with 'old' populations
  - massive 'early-type' galaxies
- Use of 'line indices'
  - Lick indices – EW measurements
  - focus on interesting parts of spectra

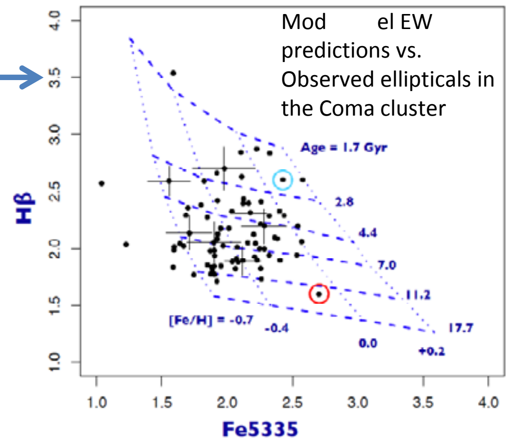




Vazdekis et al. (2007) models from MILES library

- Age and metallicity are nearly completely degenerate!
  - Balmer lines as age diagnostics
- Massive galaxies have higher Mg/Fe ratios ([α/Fe]) than the Sun
  - Enhanced [α/Fe]: SN Ia – deficient (i.e. rapid) chemical enrichment
  - Multiple generations of stars formed rapidly (?)





Grids: Schiavon et al. (2007).

Stellar populations: Summary

- For resolved populations one can reconstruct $f(t_{age},[Fe/H])$ from CMD's
  - need good distances
  - Need CMDs that reach the MS-turn-off of the oldest population
- Integrated colors or spectra
  - Cannot be robustly inverted to yield $f(t_{age},[Fe/H])$
  - $(M/L)^*$ can be robustly (better than x2) determined, for assumed IMF
  - Star formation rates (to ~ x2) can be determined, from Hα, UV, thermal IR
- SED/spectral modelling covering a wide wavelength range is best approach.

- SDSS spectra and colors have given us a clear picture of the present-day galaxy population in physical units, M_*, SFR.
  - More massive galaxies have a larger fraction of old stars
  - Massive galaxies ($5x10^{10}$) barely form new stars