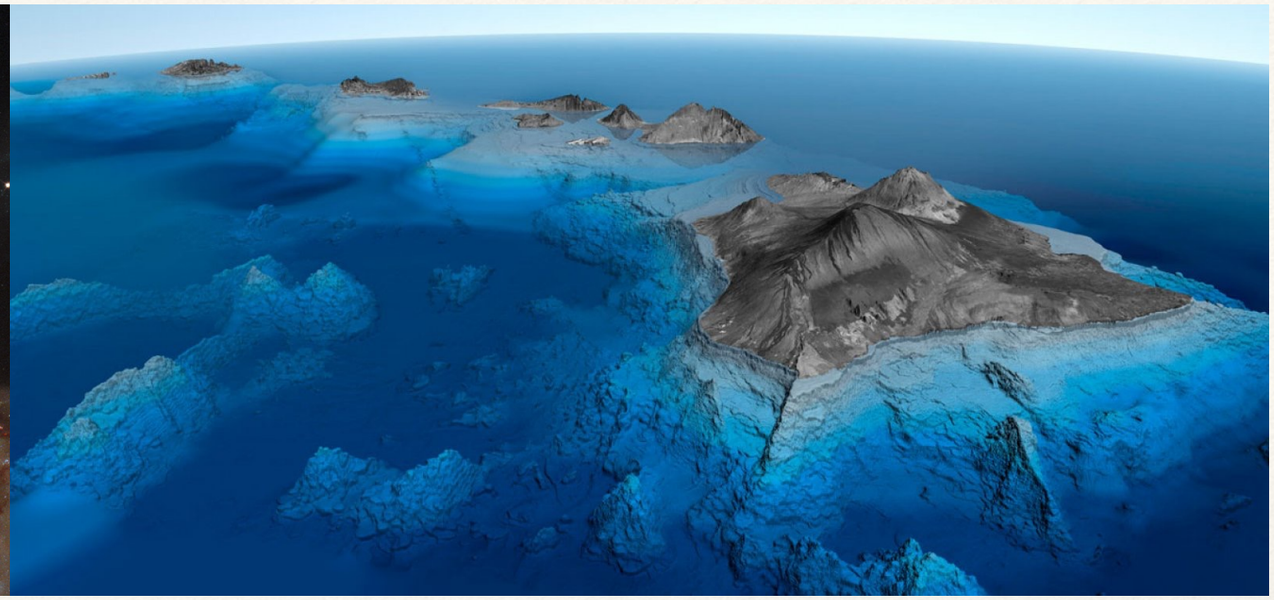


Getting to know the "island universes" out there.

Galaxies I

ASTR 555

Dr. n l an

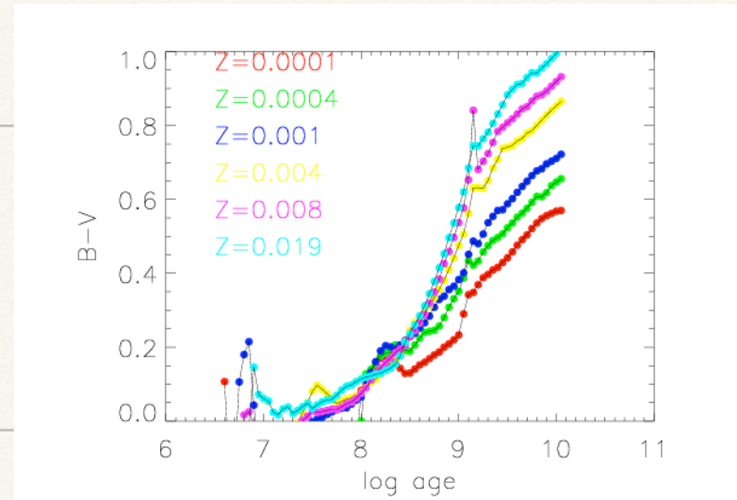
Outline for Today

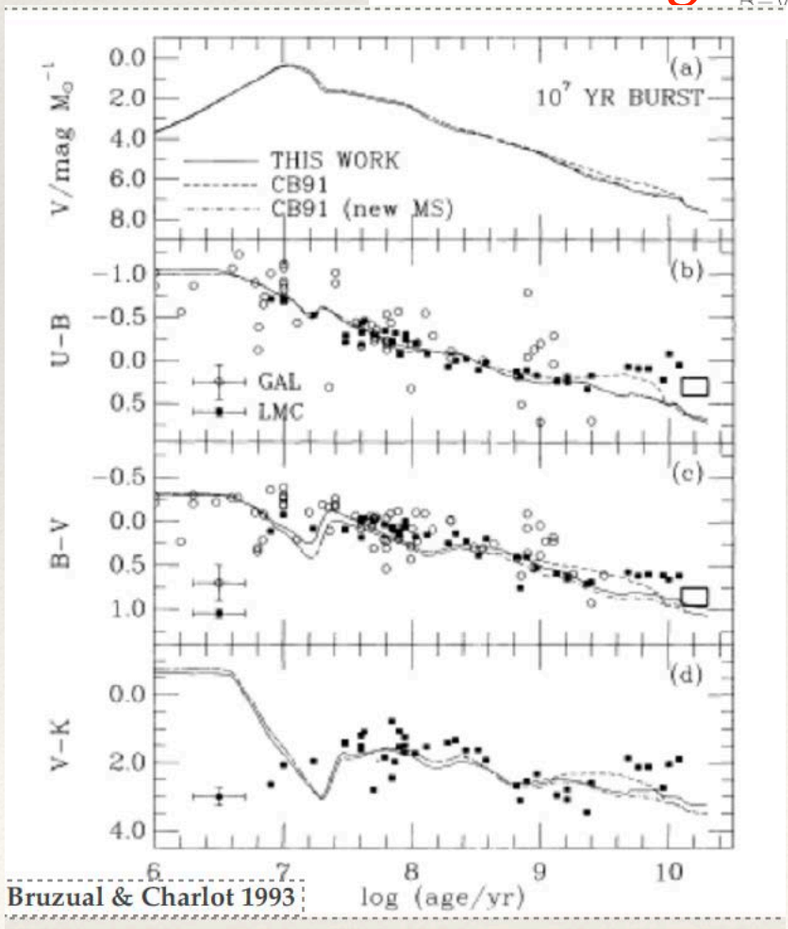
- Building Blocks - Stars and Stellar Populations:
- Stellar Population Synthesis (SPS) Modeling

M31, Southwest arm, NGC 206 (Credit: Robert Gendler)

Stars and Stellar Populations

- How can we learn about star formation histories (SFHs) from integrated colors and luminosities?
- Challenges
  - **Age-Metallicity Degeneracy:**
    - both older populations and more metal-rich populations are redder
  - **Luminosity Weighting:**
    - Even if age-metallicity were resolved, non-SSPs are weighted towards younger populations
- Can spectra resolve these?





Bruzual & Charlot 1993

Stars and Stellar Populations

- **Stellar population synthesis models**
  - predict spectrum of a composite stellar population
  - use to fit observed galaxy spectral energy distributions (SEDs) and derive properties (stellar mass, age, etc.)

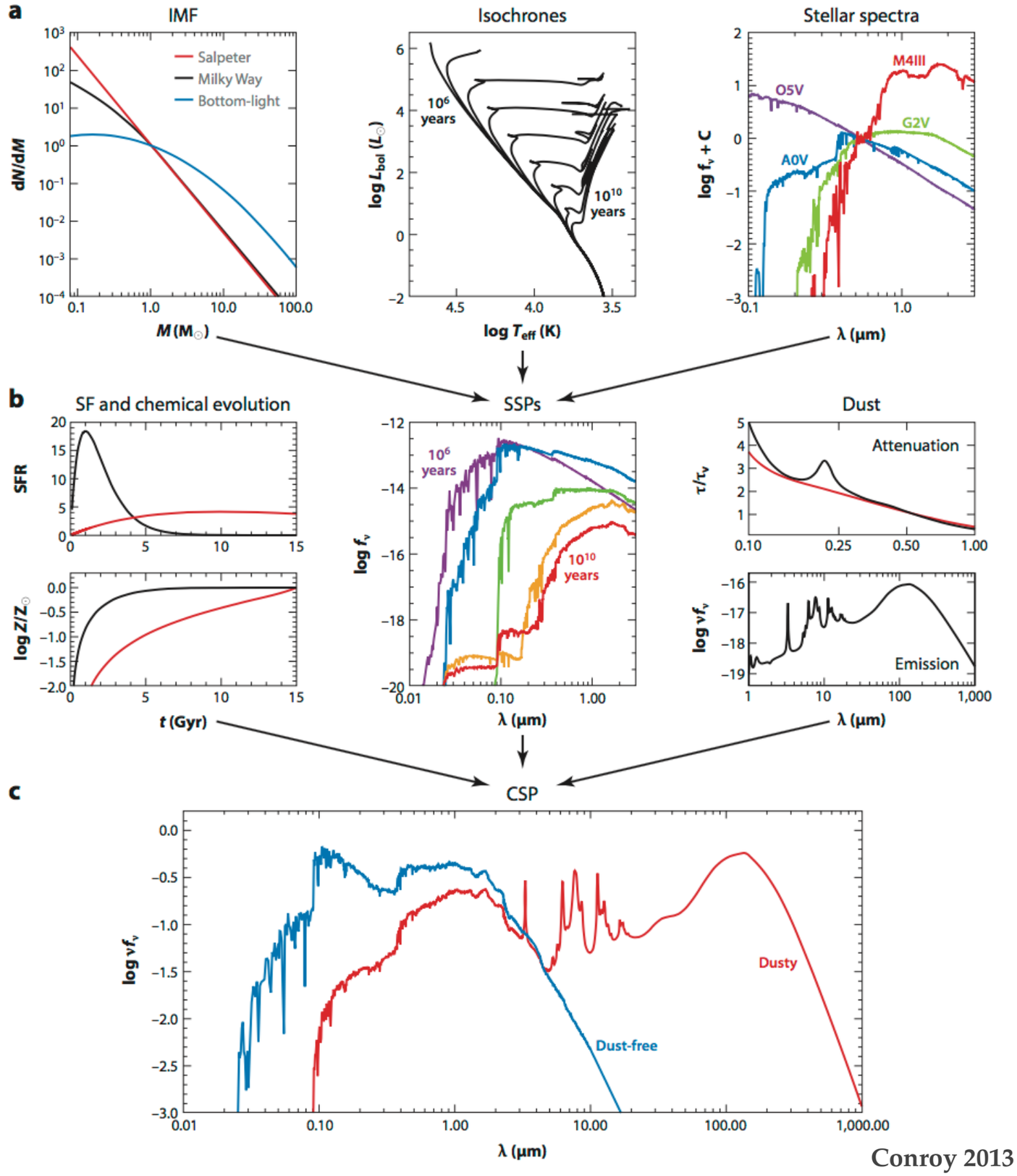
M31, Southwest arm, NGC 206 (Credit: Robert Gendler)

Thought Question

- Write down a recipe for building the spectral energy distribution (SED) of a simple stellar population (SSP).
  - What ingredients do you need?
  - How would you combine them?
- How would you build a composite stellar population (CSP)?

Stars and Stellar Pop

- **Stellar population synthesis models - SSP**
  - Isochrones from stellar evolution theory
  - Stellar spectral libraries
  - Initial Mass Function (IMF)

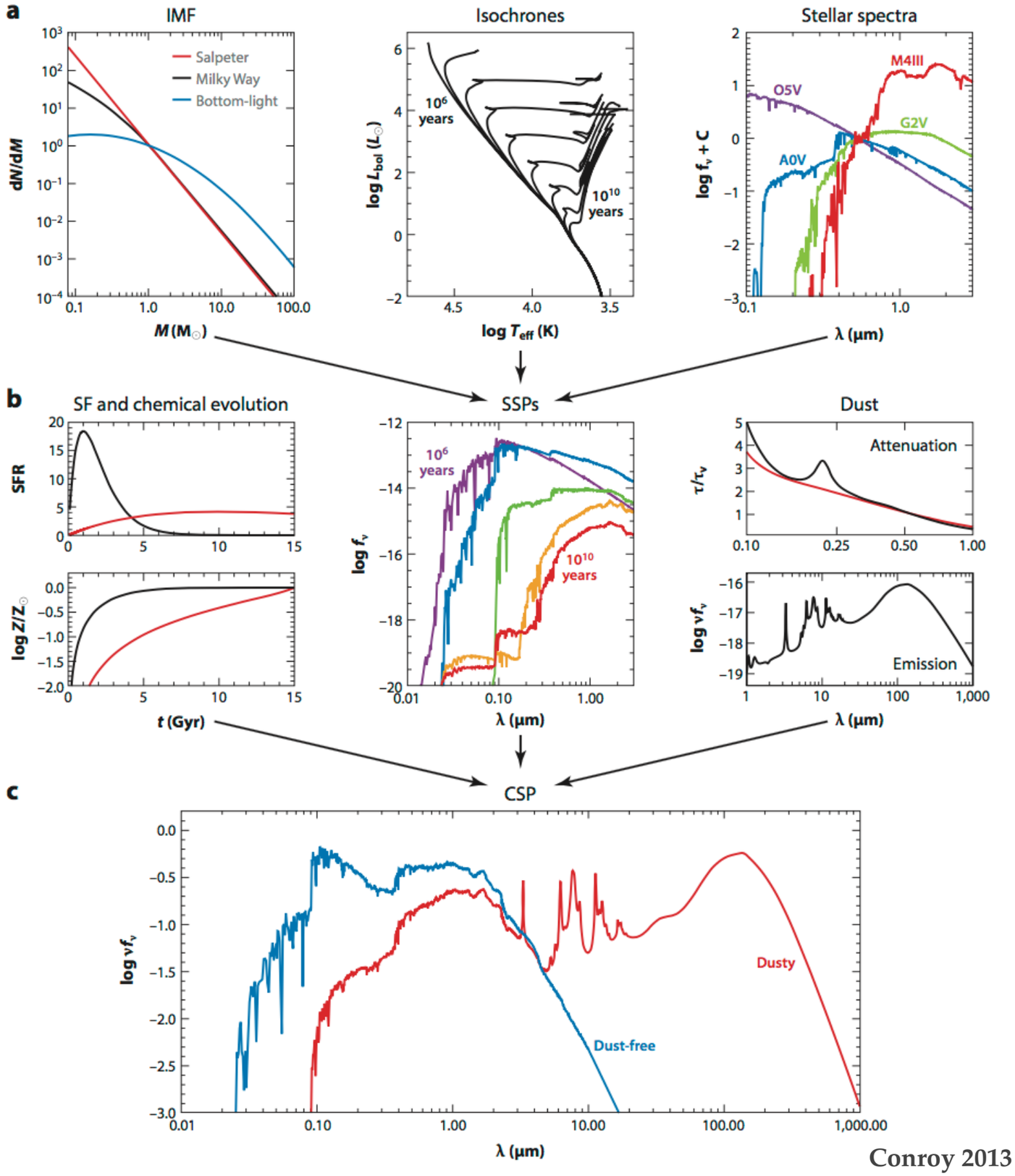


Conroy 2013

$$f_{\rm SSP}(t,Z) = \int_{m_{\rm lo}}^{m_{\rm up}(t)} f_{\rm star}\left[T_{\rm eff}(M), \log g(M) | t, Z\right] \Phi(M)\, {\rm d}M,$$

Stars and Stellar Pop

- **Stellar population synthesis models - CSP**
  - SSP library
  - Star formation rate vs. time (SFR)
  - Metallicity distribution vs. time (P)
  - Dust emission and attenuation



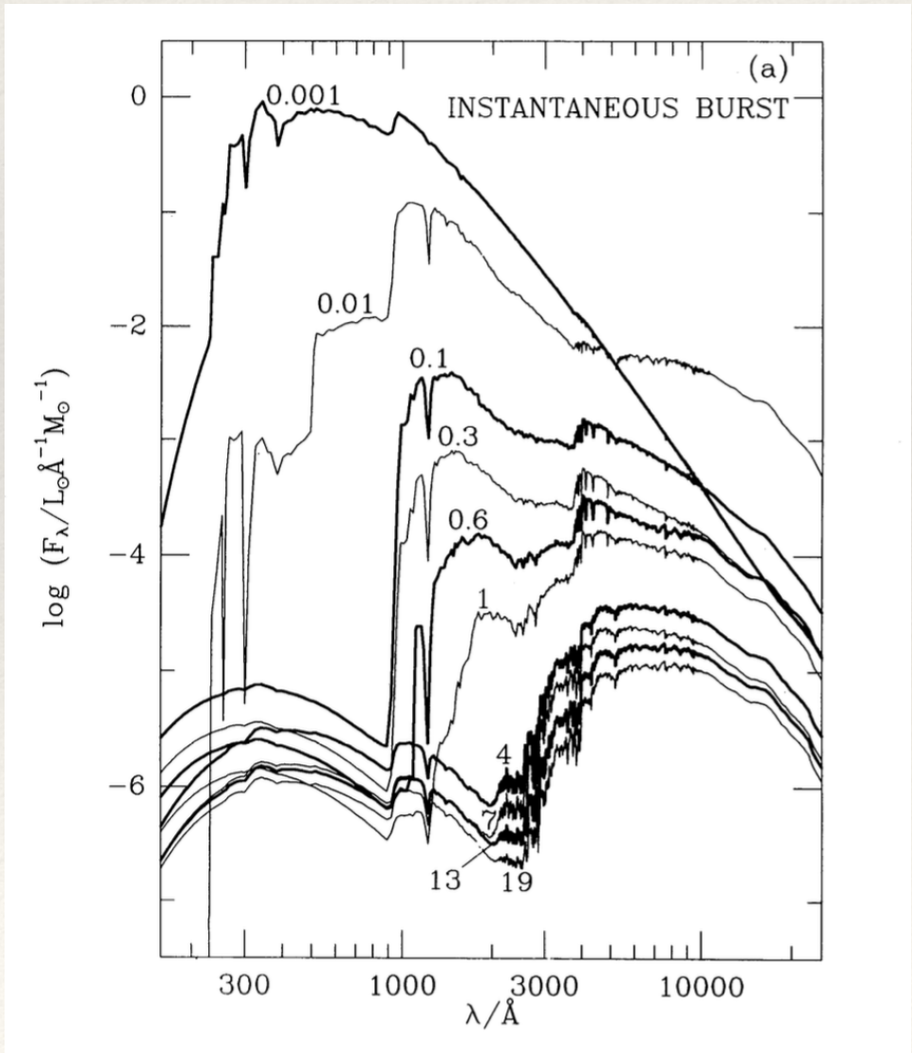
Conroy 2013

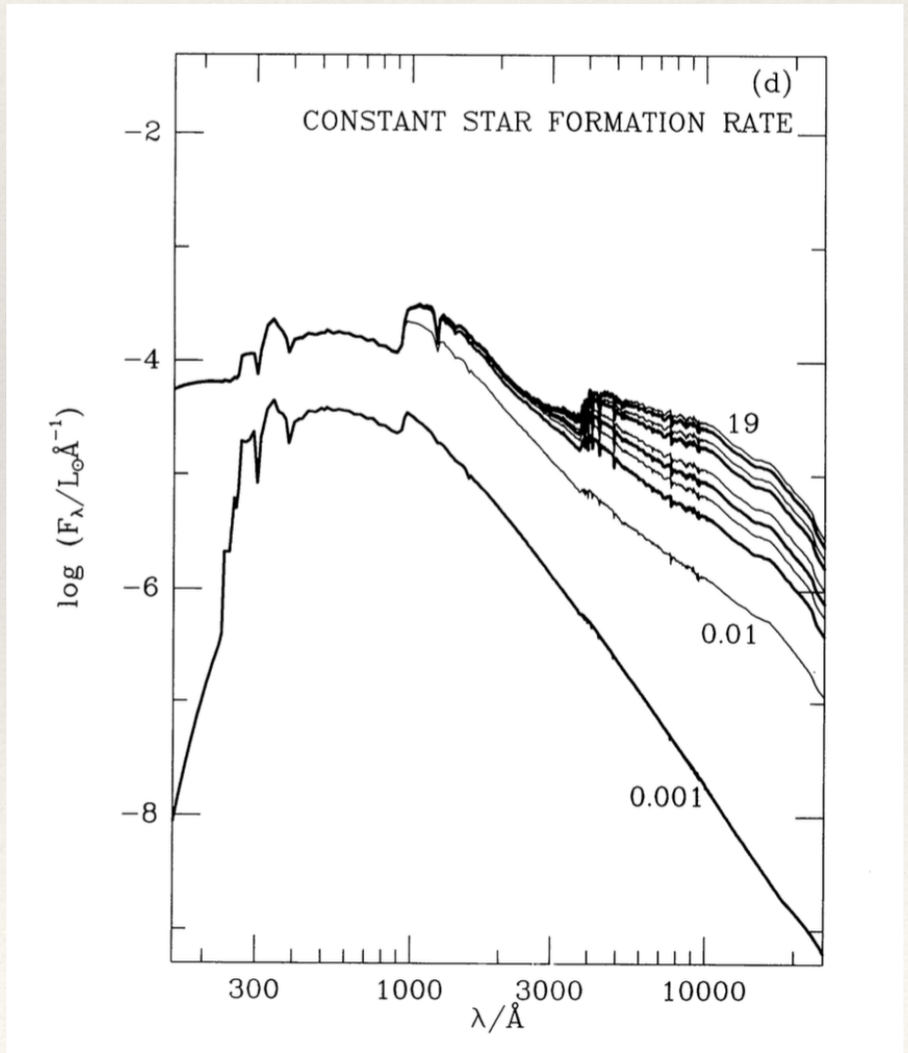
$$f_{\rm CSP}(t) = \int_{t'=0}^{t'=t} \int_{Z=0}^{Z_{\rm max}} \left({\rm SFR}(t-t')\, P(Z, t-t')\, f_{\rm SSP}(t', Z)\, e^{-\tau_d(t')} + A\, f_{\rm dust}(t', Z) \right) {\rm d}t'\, {\rm d}Z$$

Thought Questions

- What happens to the SED as the galaxy ages?
- What portions of the SED are sensitive to the SFR of the galaxy?
- What portions of the SED are sensitive to the galaxy stellar mass?

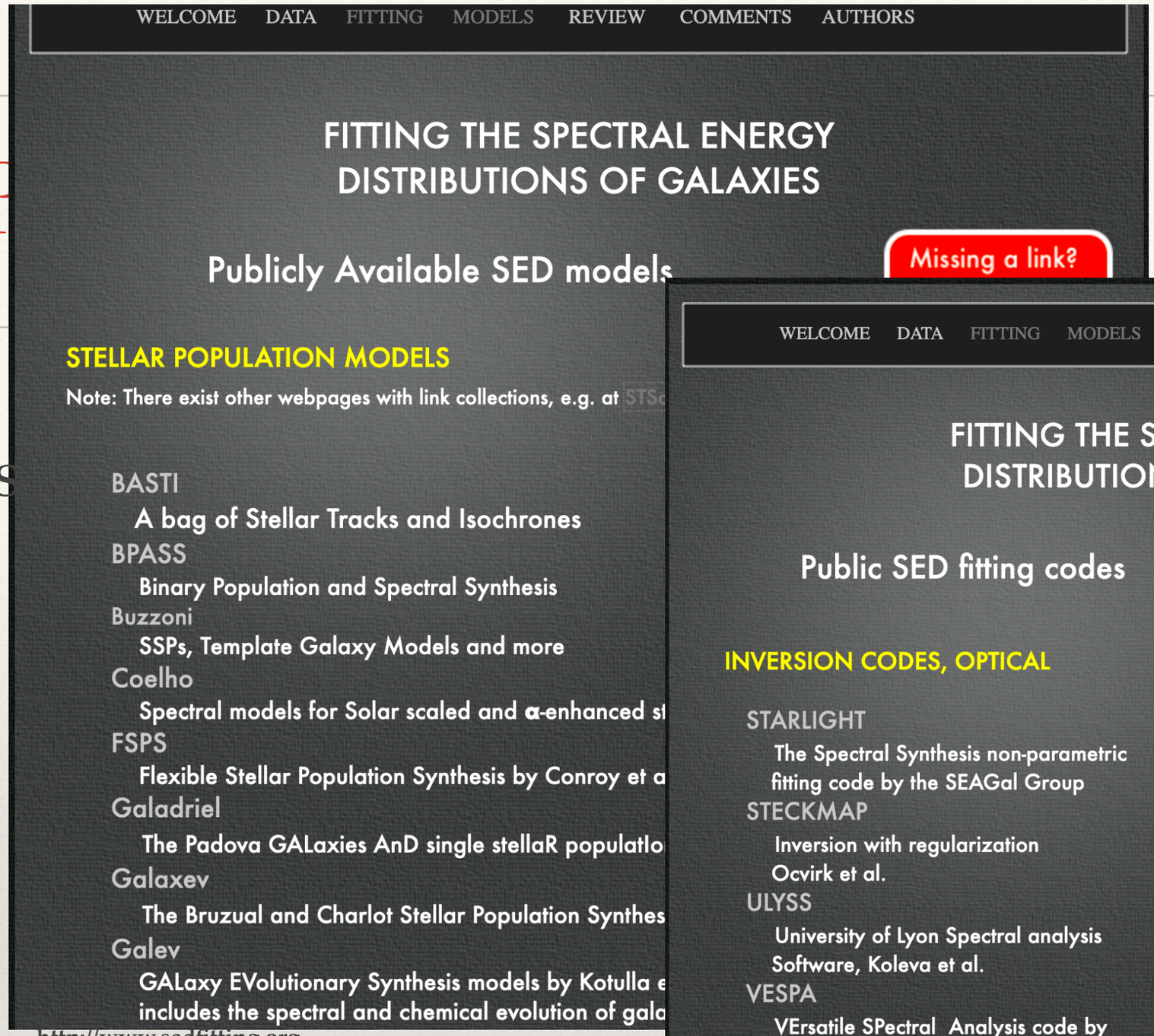
Bruzual & Charlot 1993





Stars and Stellar P

- Many stellar population synthesis (SPS) models and fitting codes exist
- SED-fitting used derive properties (stellar mass, age, etc.)

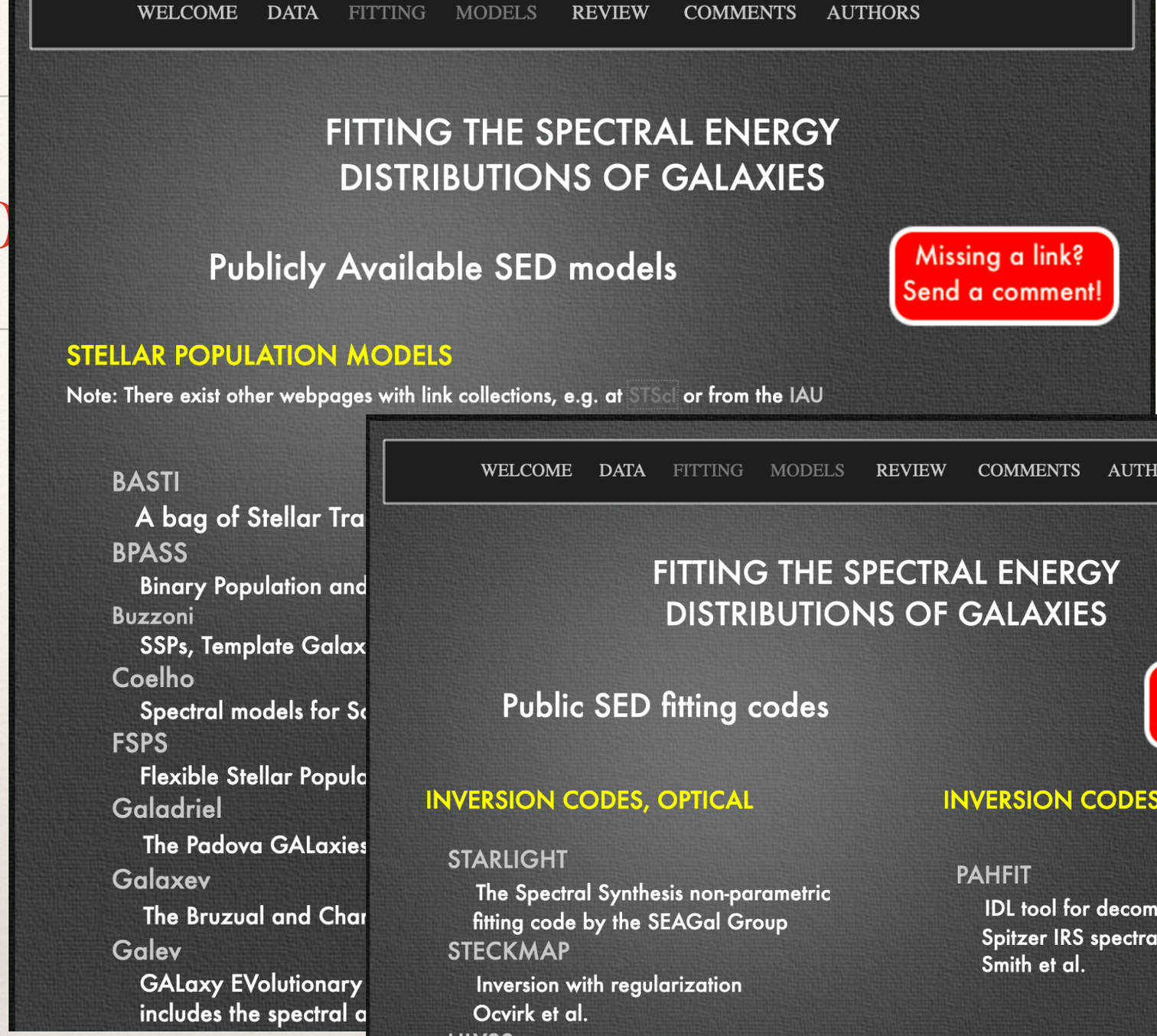


http://www.sedfitting.org

Stars and Stellar Po

- Many stellar population synthesis (SPS) models and fitting codes exist
- SED-fitting used derive properties (stellar mass, age, etc.)

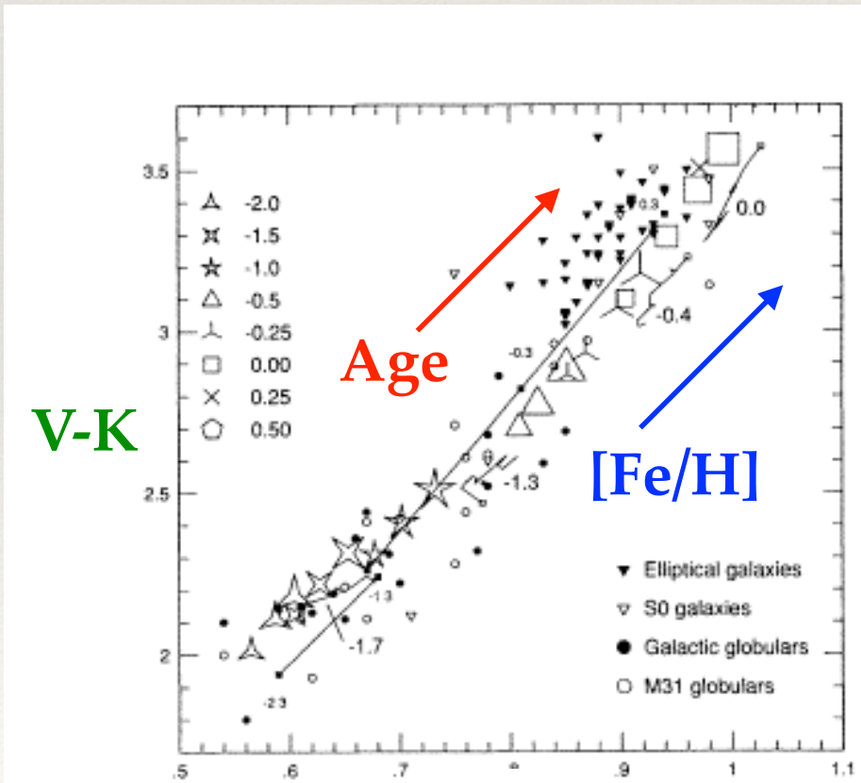
But uncertainties remain…



http://www.sedfitting.org

Stars and Stellar Populations

- Even with perfect models and many spectral features, there's still an **Age-Metallicity Degeneracy!**
  - Worthey (1994) "3/2 rule" — factor of 3 change in age almost perfectly degenerate with a factor of 2 change in metallicity for broadband colors and even many line strengths
- However, there are a few spectral features that can help



Worthey 1994

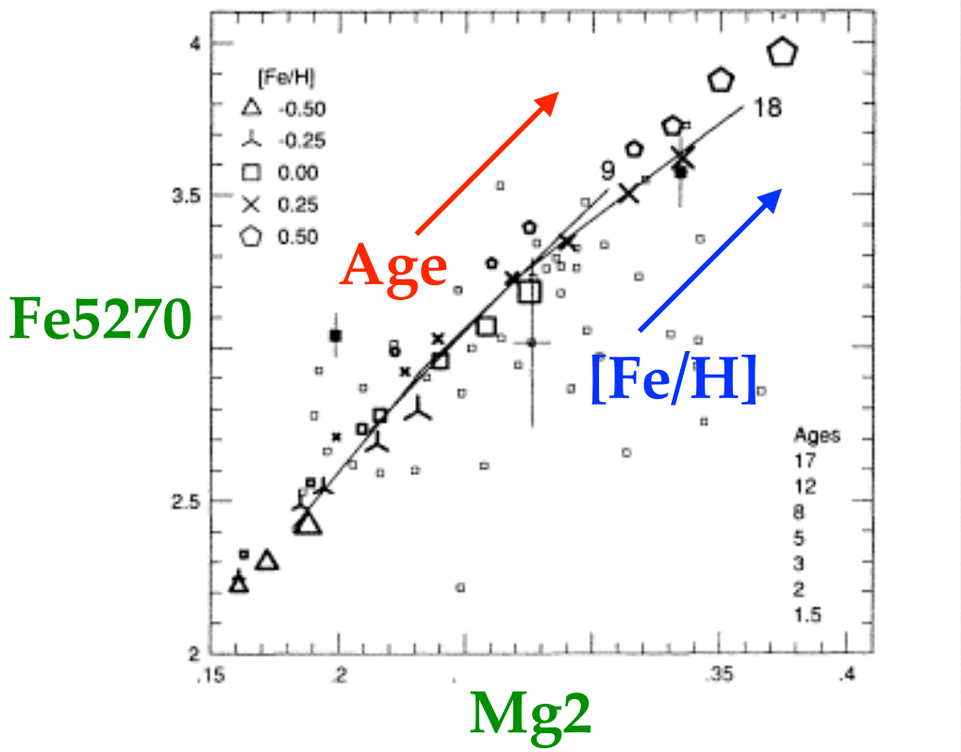


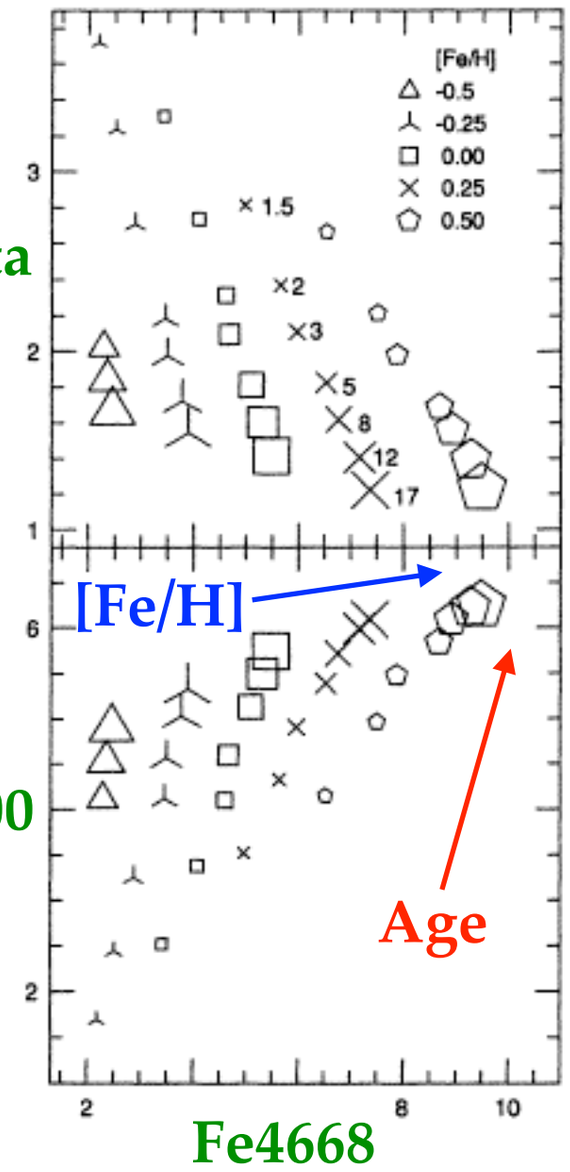
FIG. 48.—Mg_2 vs. Fe5270. Nuclear galaxy data (*squares*) are from

Stars and Stellar Populations

- Break the **Age-Metallicity Degeneracy** by using carefully chosen features

- More age-sensitive:
  - Balmer lines like Hβ
  - D4000 — strength of 4000A break

- More metallicity-sensitive:
  - Fe4668, Fe5270



42.—(*a*) Hβ as a function of Fe4668. Hβ is the most sensitive age
or uncovered in our survey, and Fe4668 is among the most sensitive
city indicators. (*b*) G4300 as a function of Fe4668. Ages 1.5, 3, 5, 8,
17 Gyr are shown, except for [Fe/H] = −0.5, for which only the
nodels are shown. If the symbols are separated from each other in
hion, an age indicator has been discovered. If all points lie in a line,
ation is degenerate. The G band is a mixture of these effects, and is
nd best age indicator among the indices modeled.

TABLE 6

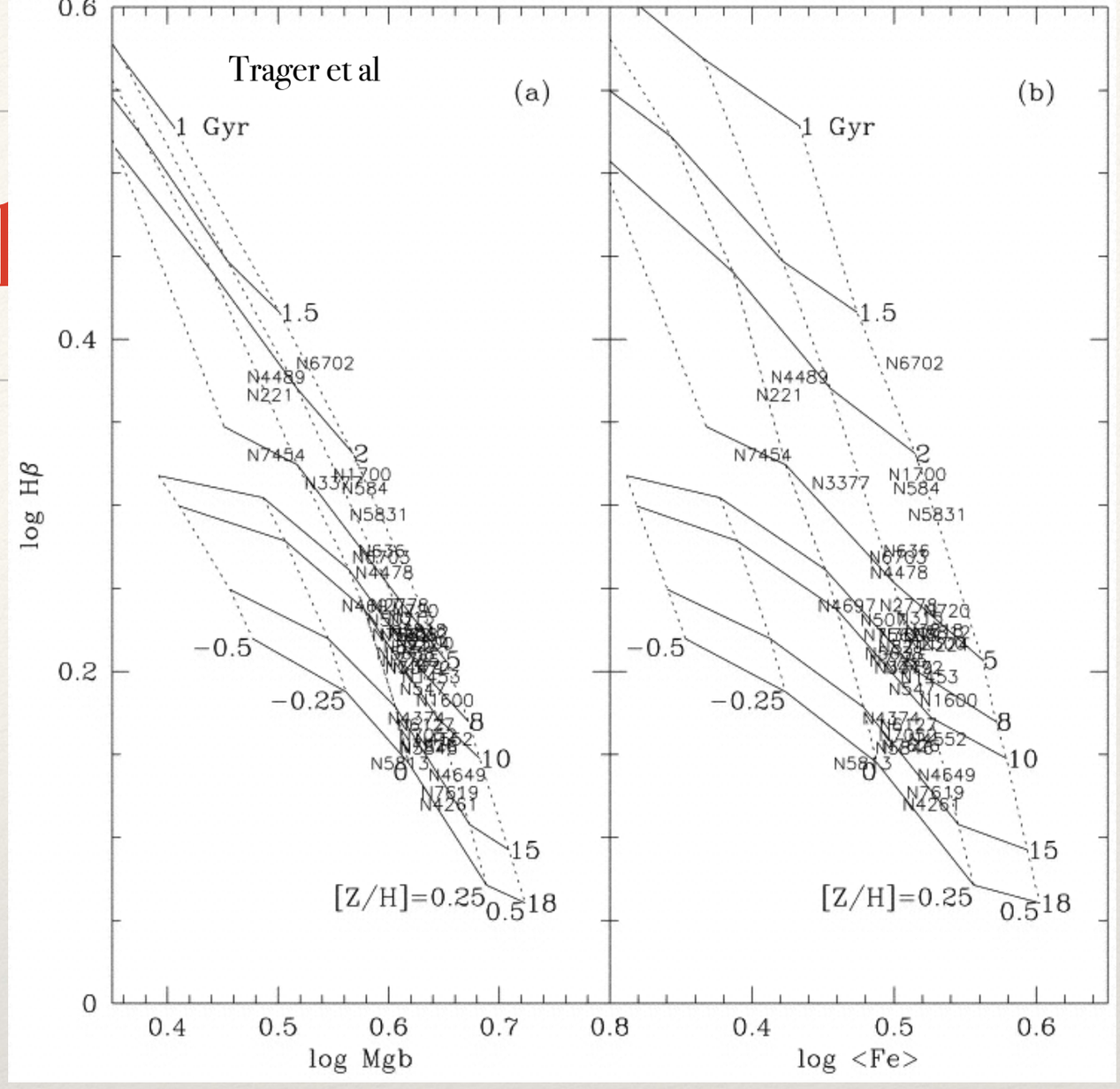
METALLICITY SENSITIVITIES

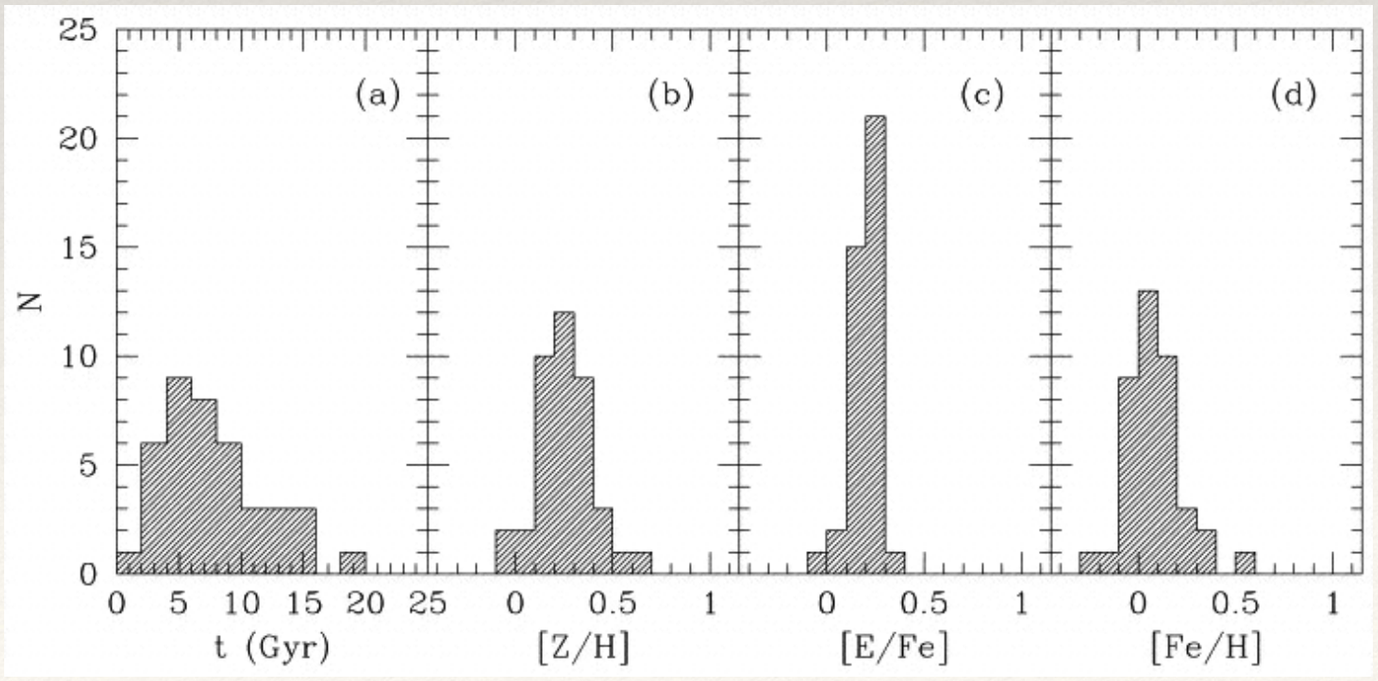
Index	$\left(\frac{\Delta age/age}{\Delta Z/Z}\right)_I$
$U-V$	1.5
$B-V$	1.4
$V-R_C$	1.3
$V-I_C$	1.4
$V-J$	1.9
$V-K$	1.9
$J-H$	1.7
$J-K$	1.9
$J-L$	1.8
$J-L'$	1.8
$J-M$	1.7
01 CN_1	1.9
02 CN_2	2.1
03 Ca4227	1.5
04 G4300	1.0
05 Fe4383	1.9
06 Ca4455	2.0
07 Fe4531	1.9
08 Fe4668	4.9
09 Hβ	0.6
10 Fe5015	4.0
11 Mg_1	1.8
12 Mg_2	1.8
13 Mg *b*	1.7
14 Fe5270	2.3
15 Fe5335	2.8
16 Fe5406	2.5
17 Fe5709	6.5
18 Fe5782	5.1
19 Na D	2.1
20 TiO_1	1.5
21 TiO_2	2.5
D(4000)	1.3

Worthey 1994

Stars and Stellar Popul

- Results from population modeling:
  - Early type galaxies, interpreted as SSPs: some range of ages, but perhaps younger galaxies are from "frosting" of younger population?
  - solar abundances are typical,
  - alpha-enhanced populations are required to match features
- Late type galaxies: much harder because of luminosity weighting!
  - broader wavelength coverage may help



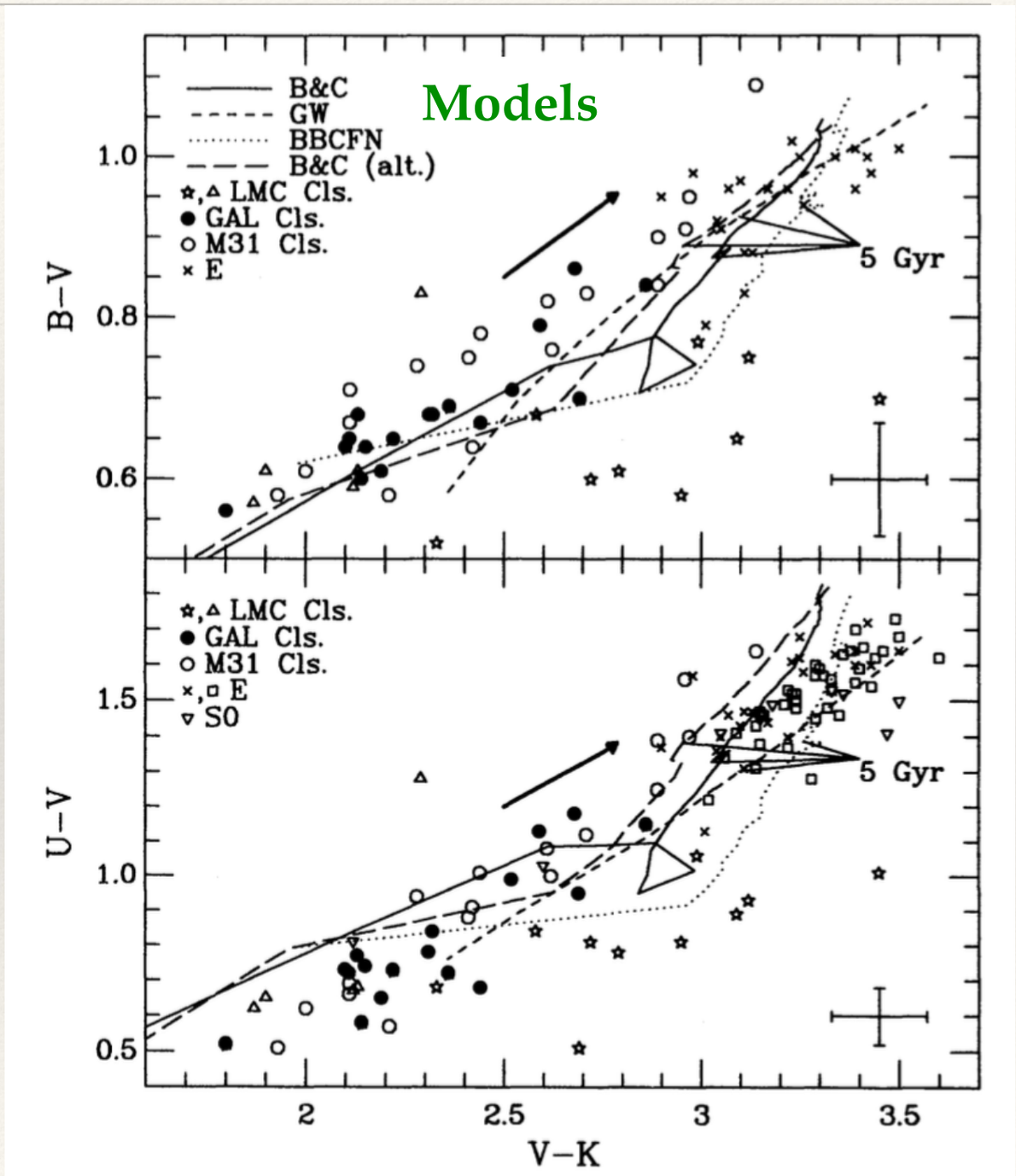


Stars and Stellar Populations

- Field is fraught with uncertainties
- Potential problems with synthetic integrated spectra:
  - **Stellar model and isochrone uncertainties**
    - opacities, convection, diffusion, mass loss, atmospheres, etc.
  - **Missing evolutionary stages (e.g., HB, AGB)**
  - **Interacting binary stars**
  - **Initial mass function**

Stars and Stellar Populations

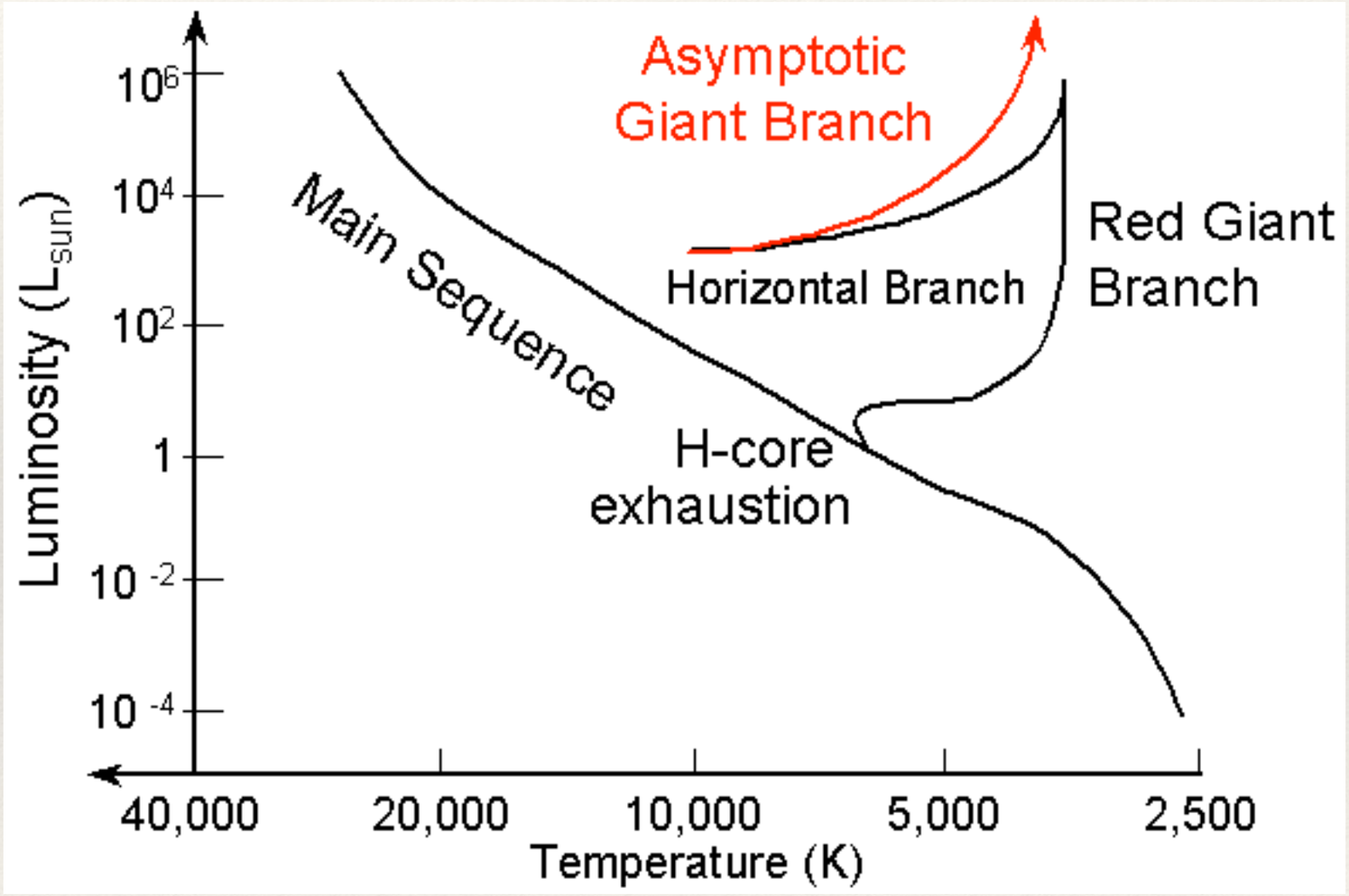
- **Stellar model and isochrone uncertainties:**
  - **opacities** — affects luminosities
  - **convection** — amount of convective "overshooting" affects MS lifetimes
  - **rotation** — increases MS lifetimes due to mixing
  - **mass loss** — affects lifetimes of advanced (luminous) evolutionary phases
- Uncertainties larger at later (luminous) stages of evolution



Charlot et al. 1996

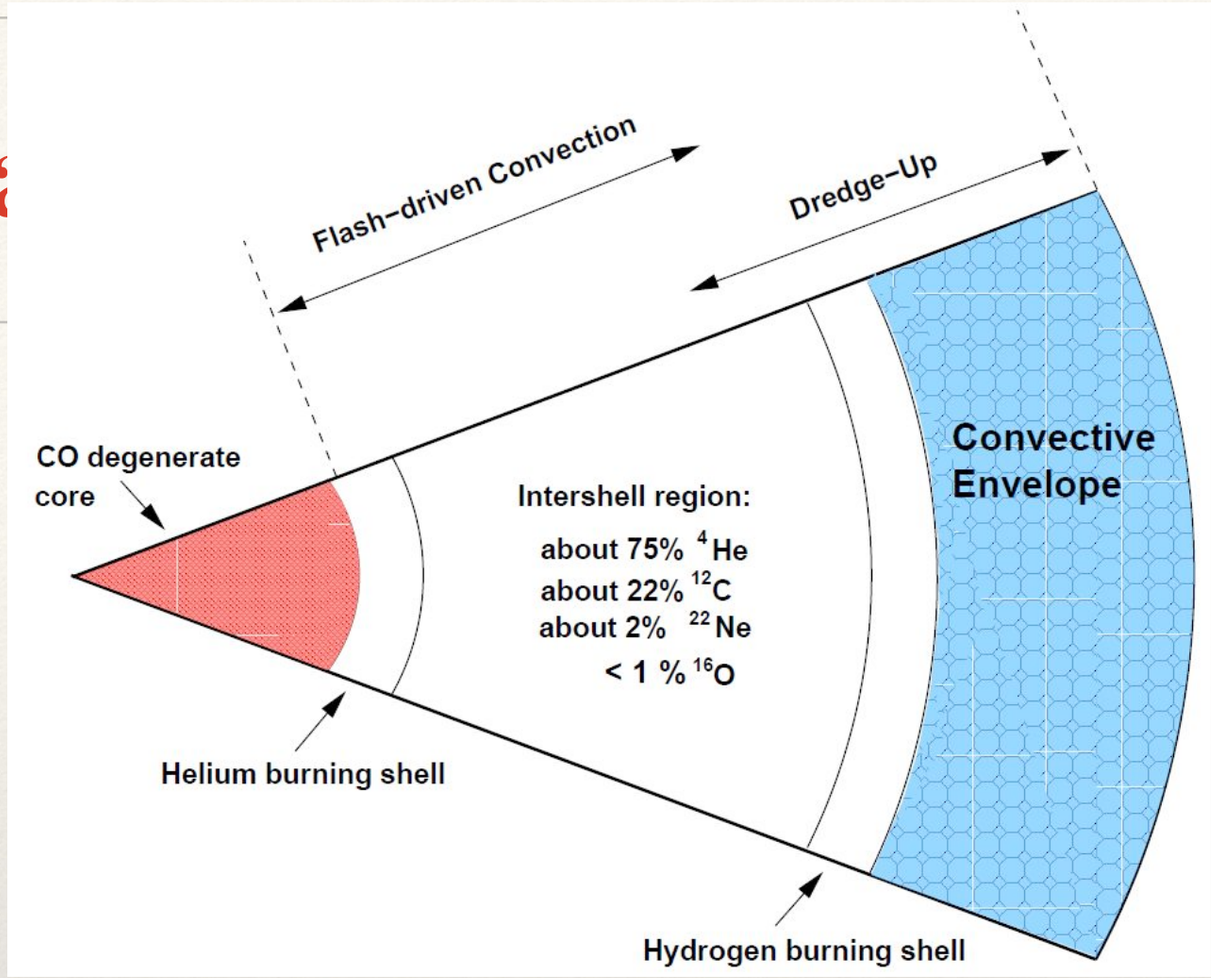
Reminder Question

- What is going on in a star during the AGB phase?
- How does this phase differ from the RGB phase?

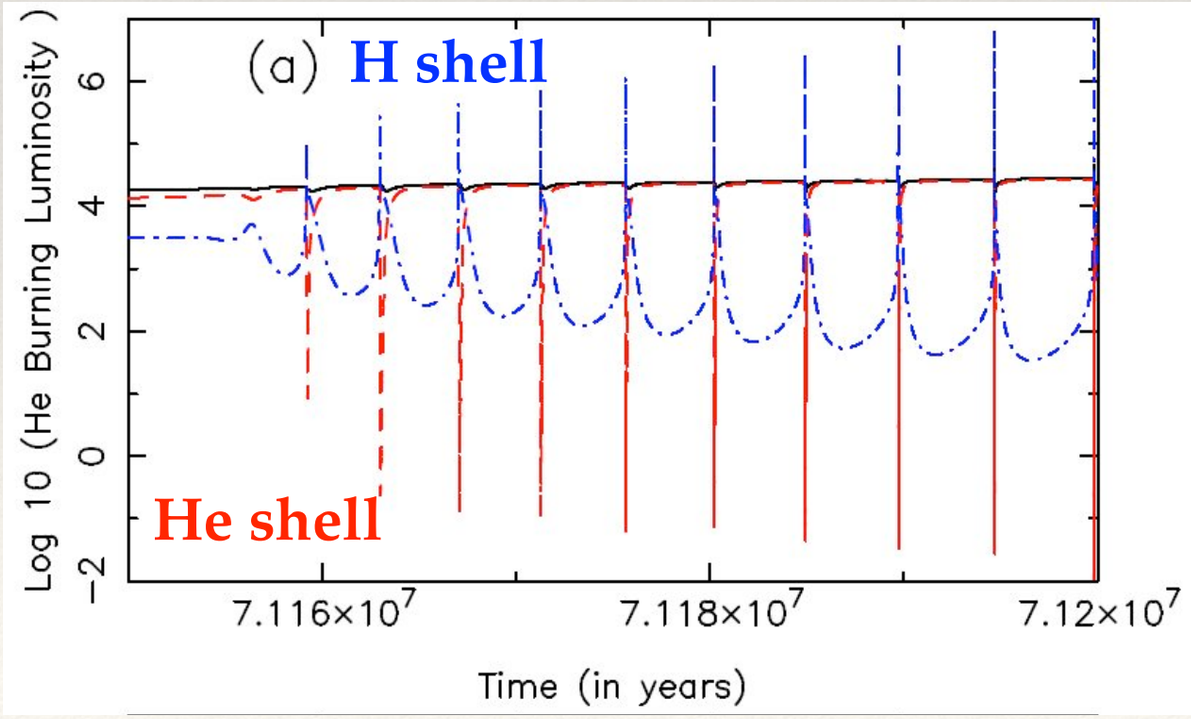


Stars and Stellar Popula

- **Missing evolutionary stages (e.g., HB, AGB)**
  - Thermally pulsating AGB stars (TP-AGB; Maraston et al. 2011)
  - Nuclear fusion in H and He shells — thermally unstable — gives rise to **thermal pulses**
  - Mass loss becomes catastrophic during this phase, terminating the life of the star
  - Difficult to model!



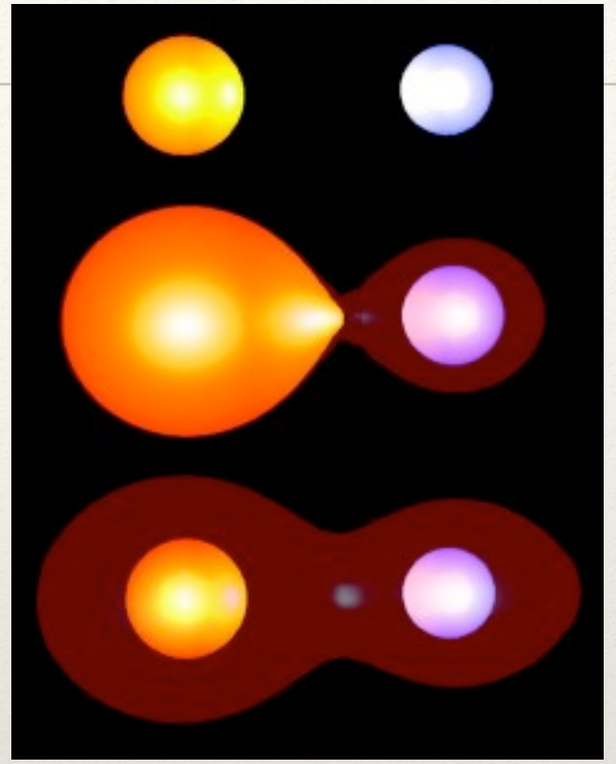
Karakas, Lattanzio, & Pols (2002)



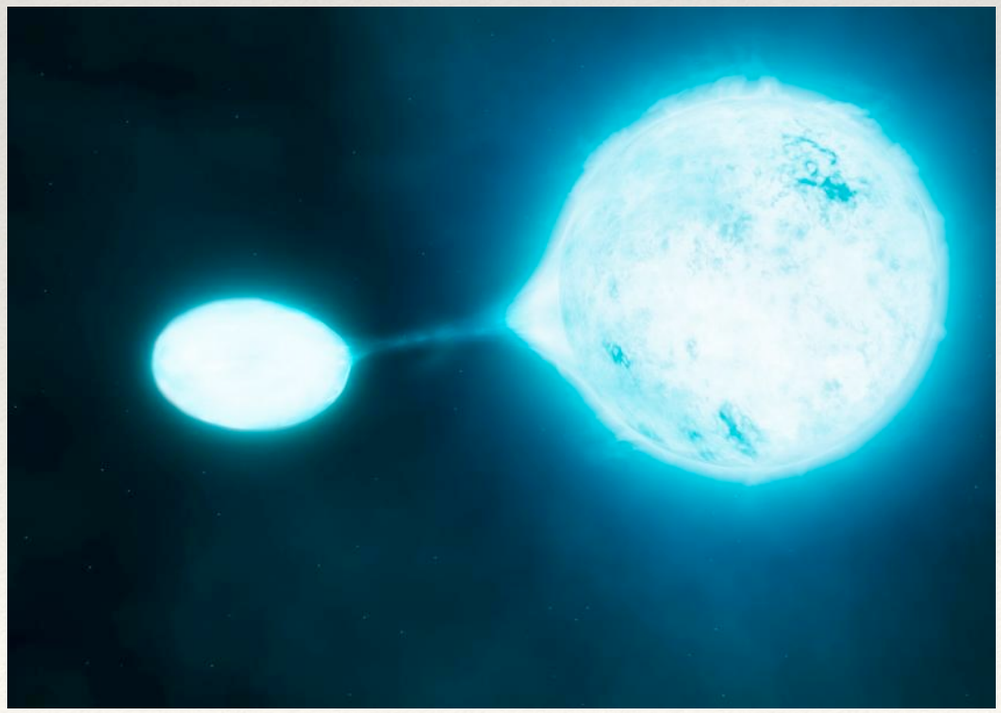
Karakas & Lattanzio 2014

Stars and Stellar Populations

- **Interacting binary stars**
  - mass transfer affects evolution and observable properties
  - leads to a “bluer” stellar population
  - may also create Blue Straggler stars and extreme Horizontal Branch (EHB) stars
  - BPASS models — Stanway & Eldridge 2018



Credit: Adrien Potter

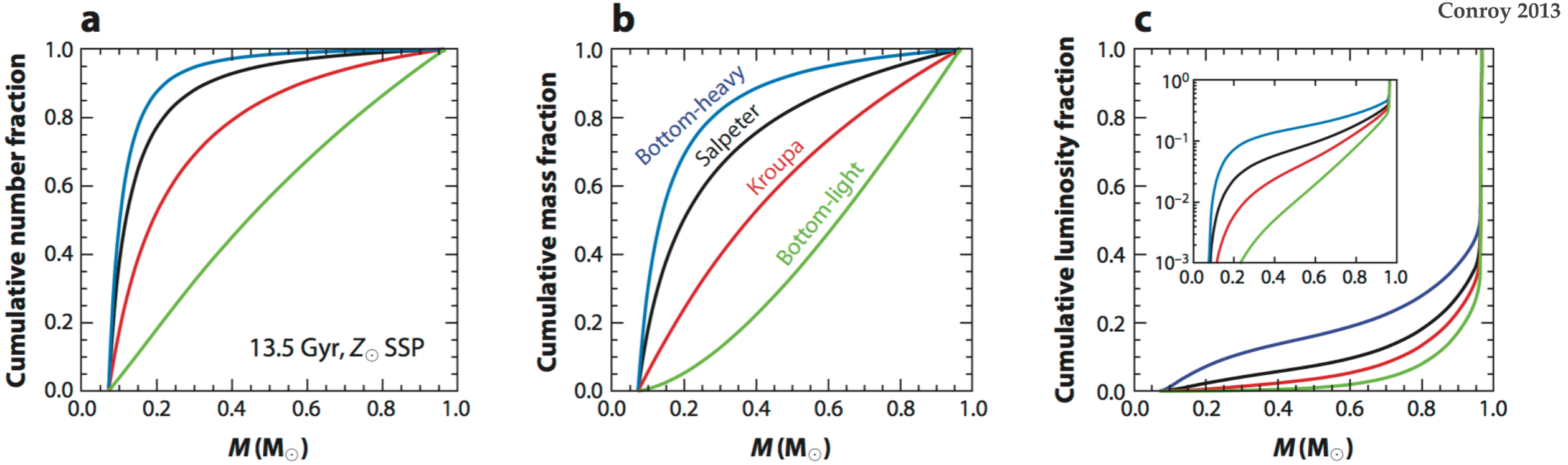


Credit: ESO/L. Calçada/S.E. de Mink

Stars and Stellar Populations

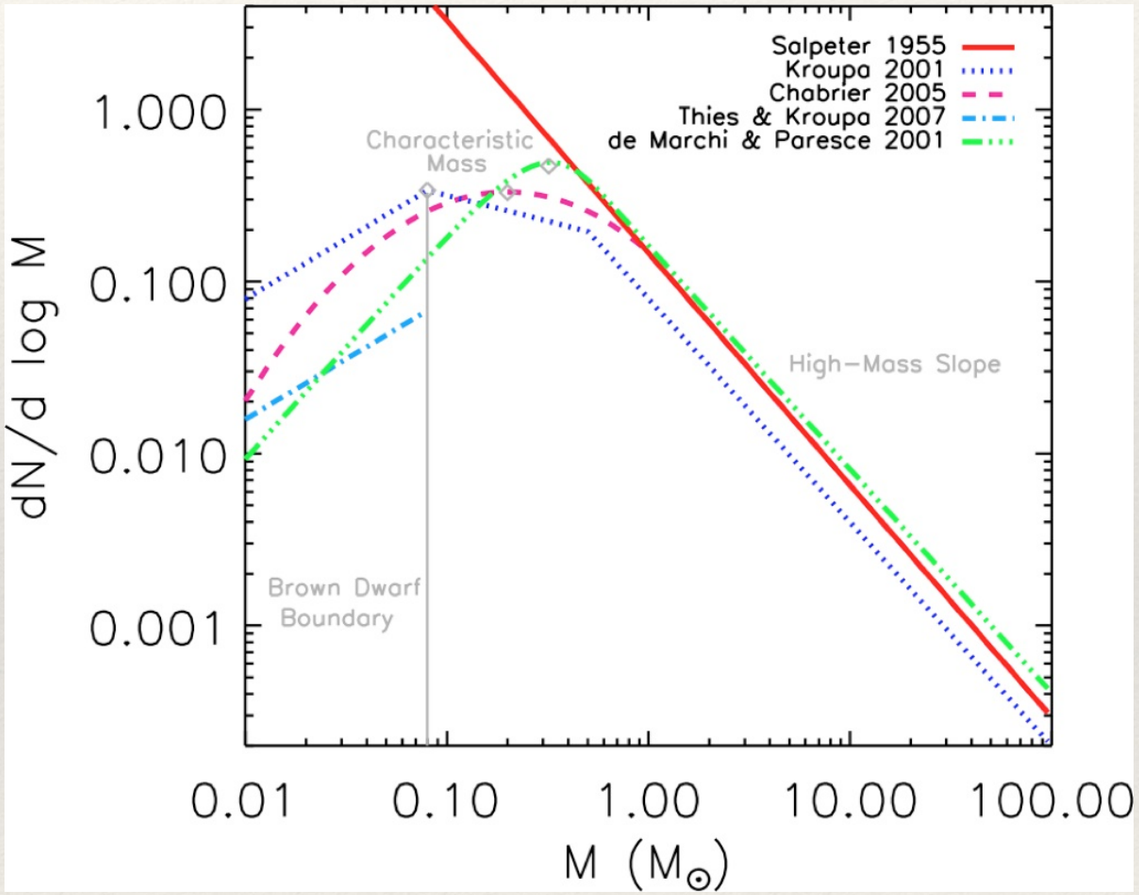
- **Finally, there's the IMF:**
  - determines overall normalization of the stellar M/L
  - determines rate of luminosity evolution for a passively-evolving population
  - has smaller effects on the SED (but not totally negligible)

Conroy 2013



Stars and Stellar Populations

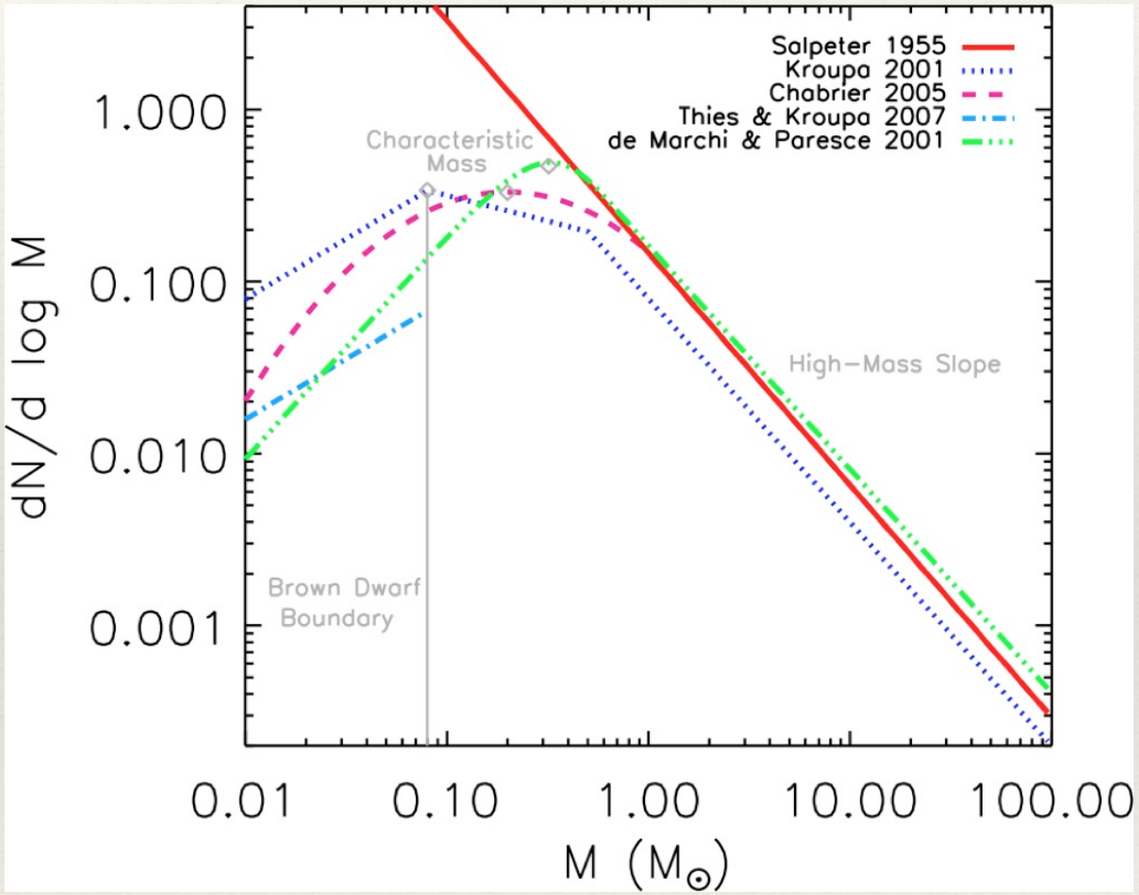
- **Does the IMF vary with cosmic time or environment?:**
  - No compelling evidence for IMF variation from counting resolved stars (Bastian, Covey & Meyer 2010)
  - In the Solar Neighborhood, IMF deviates from the Salpeter form only at $M < 1\ M_\odot$ (Kroupa 2001, Chabrier 2003)



Offner et al. 2014

Stars and Stellar Populations

- **Does the IMF vary with cosmic time or environment?:**
  - Evidence for modest IMF variations in other galaxies:
    - extra low-mass stars in elliptical galaxies via line strengths of gravity-sensitive features (van Dokkum & Conroy 2010, 2012)
    - SPS+lensing+dynamical modeling in ellipticals — relatively more low-mass stars with increasing galaxy velocity dispersion (e.g., Auger et al. 2010)

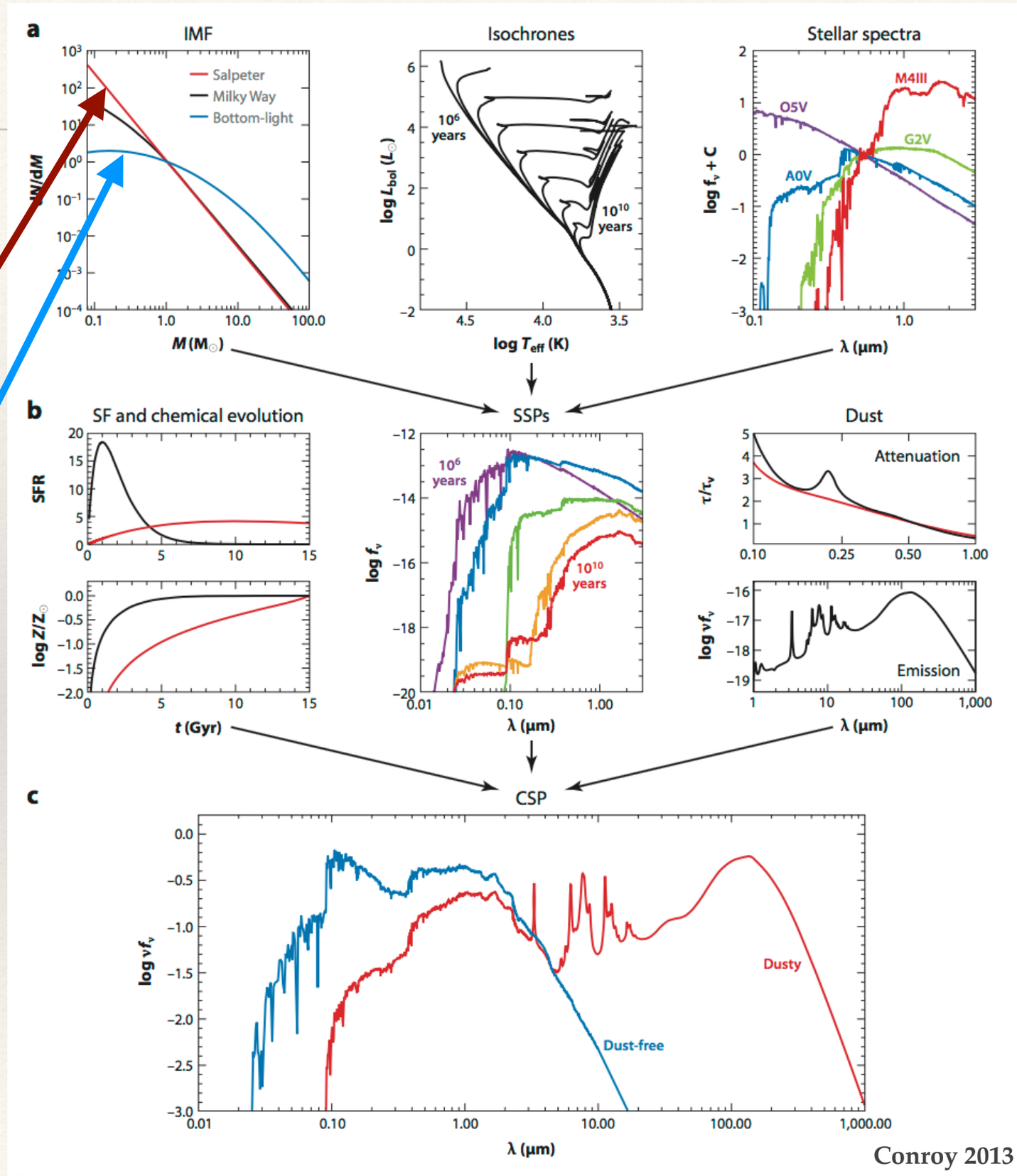


Offner et al. 2014

More work to do!

Review

- **Write for 2 minutes:**
  - Suppose the 10^9 year SSP (in orange in the middle panel) was derived with this Salpeter IMF.
  - How would the predicted SED change if this Bottom-Light IMF was used instead?
  - How would uncertainty about which IMF is correct affect estimates of the total stellar mass formed at t=0?



Conroy 2013