

Getting to know the “island universes” out there.

Galaxies I

ASTR 555

Dr. n l an

Outline for Today

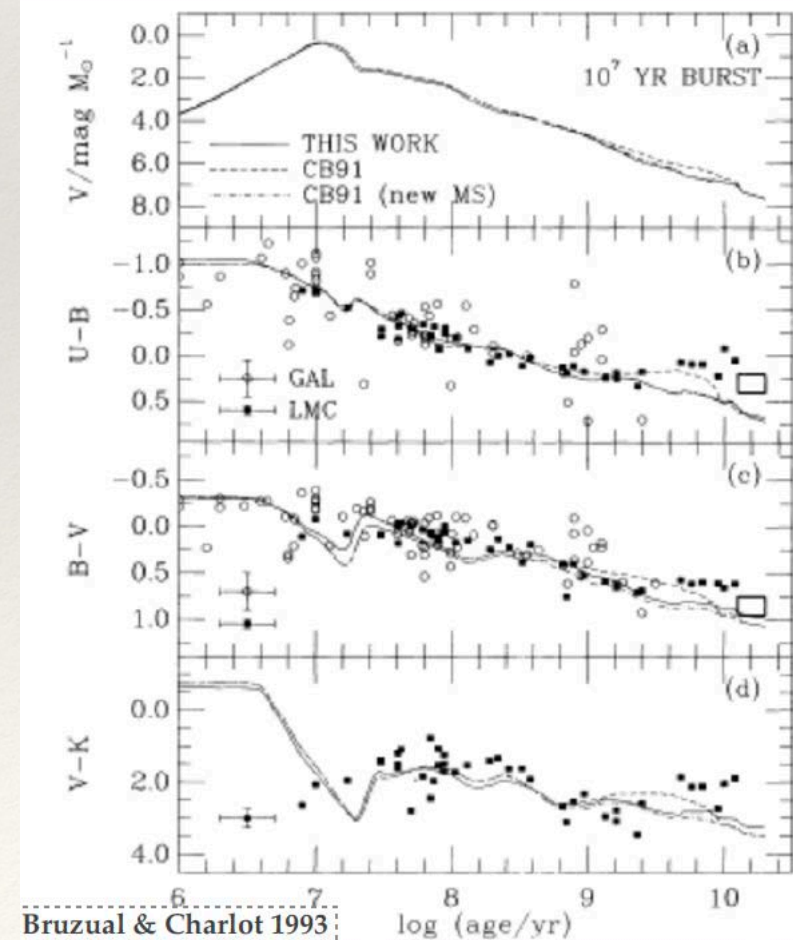
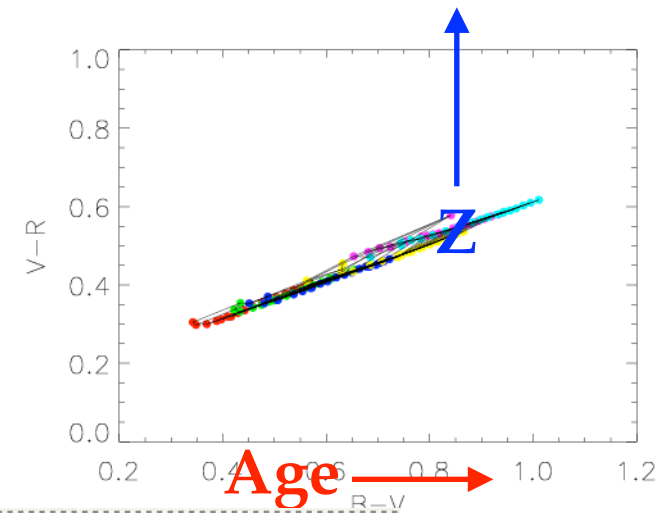
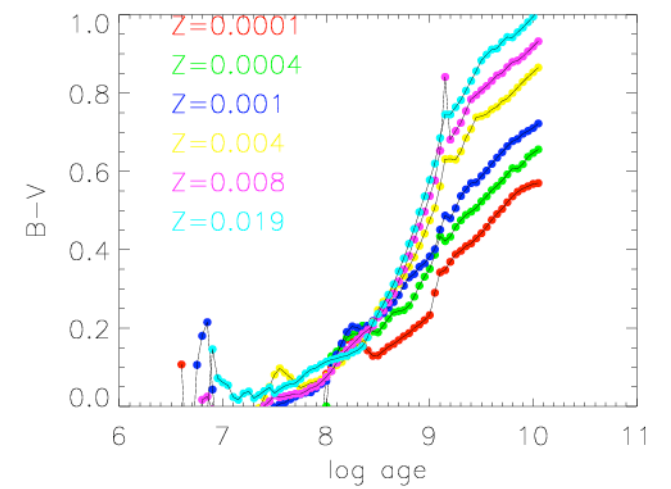
- ❖ Building Blocks - Stars and Stellar Populations:
- ❖ Stellar Population Synthesis (SPS) Modeling



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?



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.)



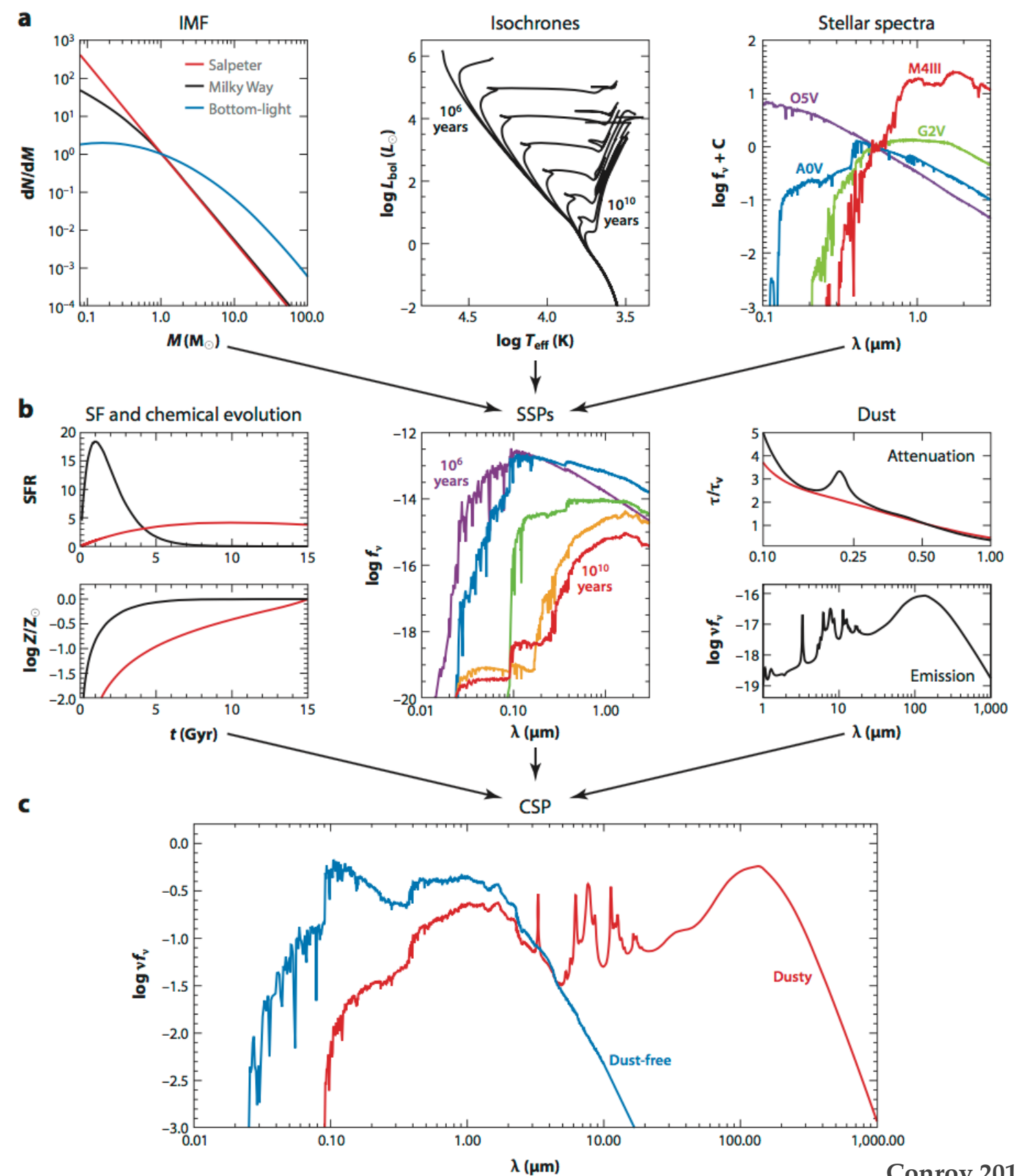
M31, Southwest arm, NGC 206 (Credit: Robert Gendler)

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)

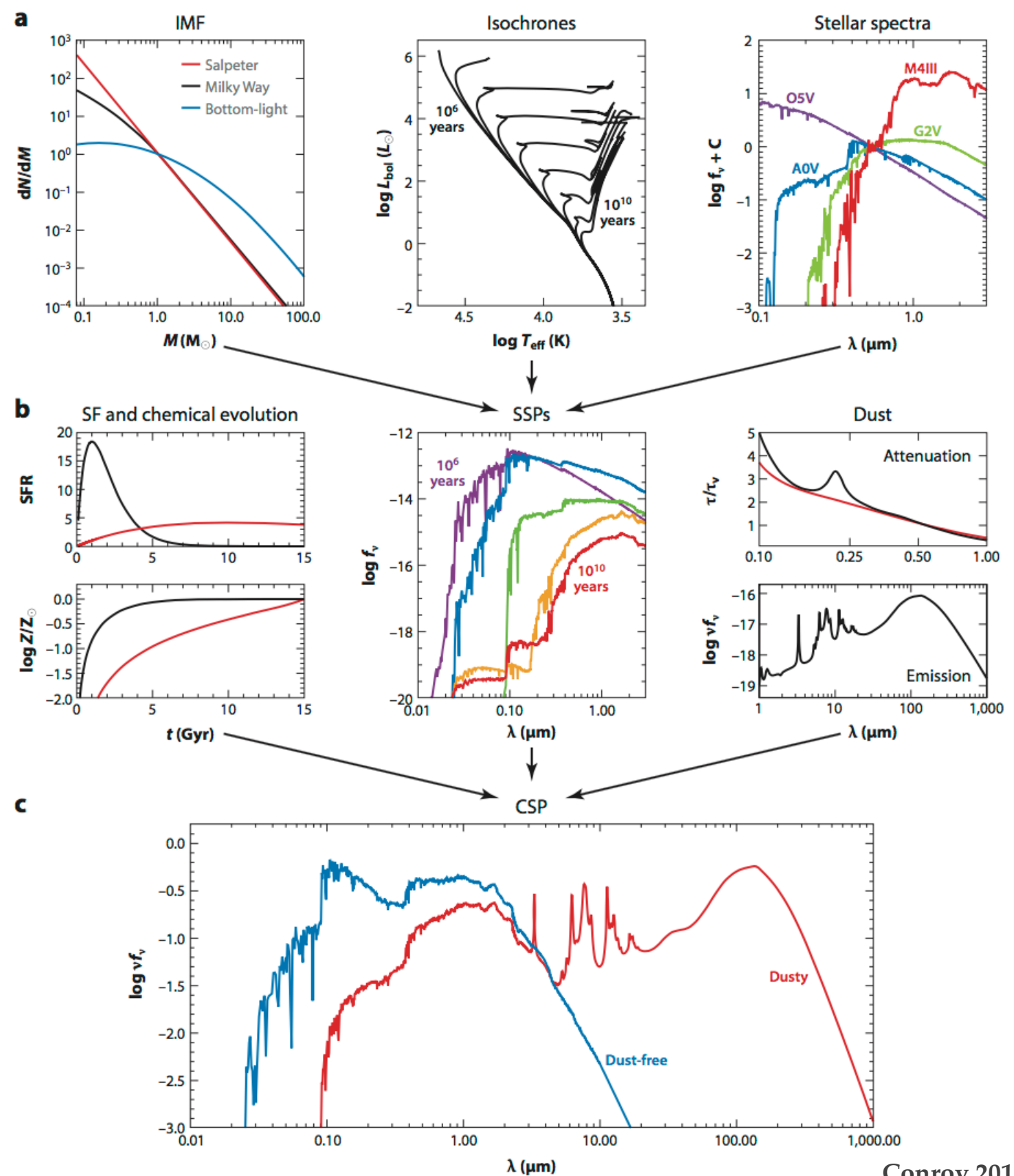


Conroy 2013

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

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



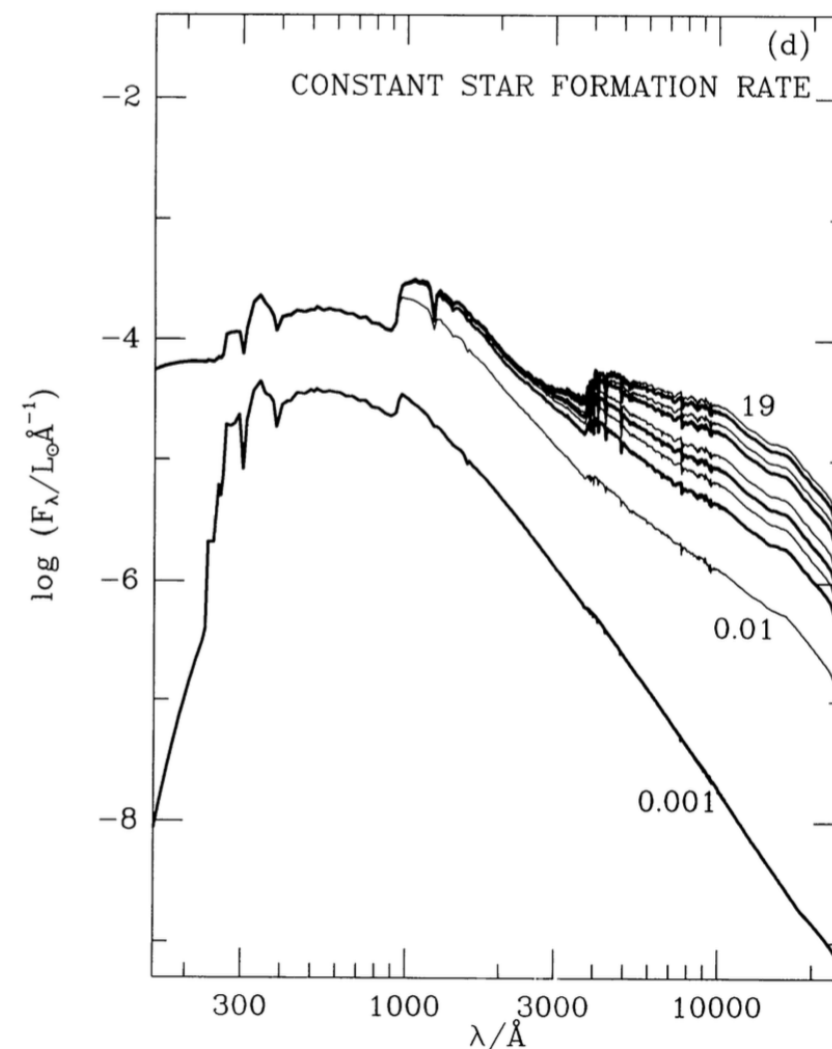
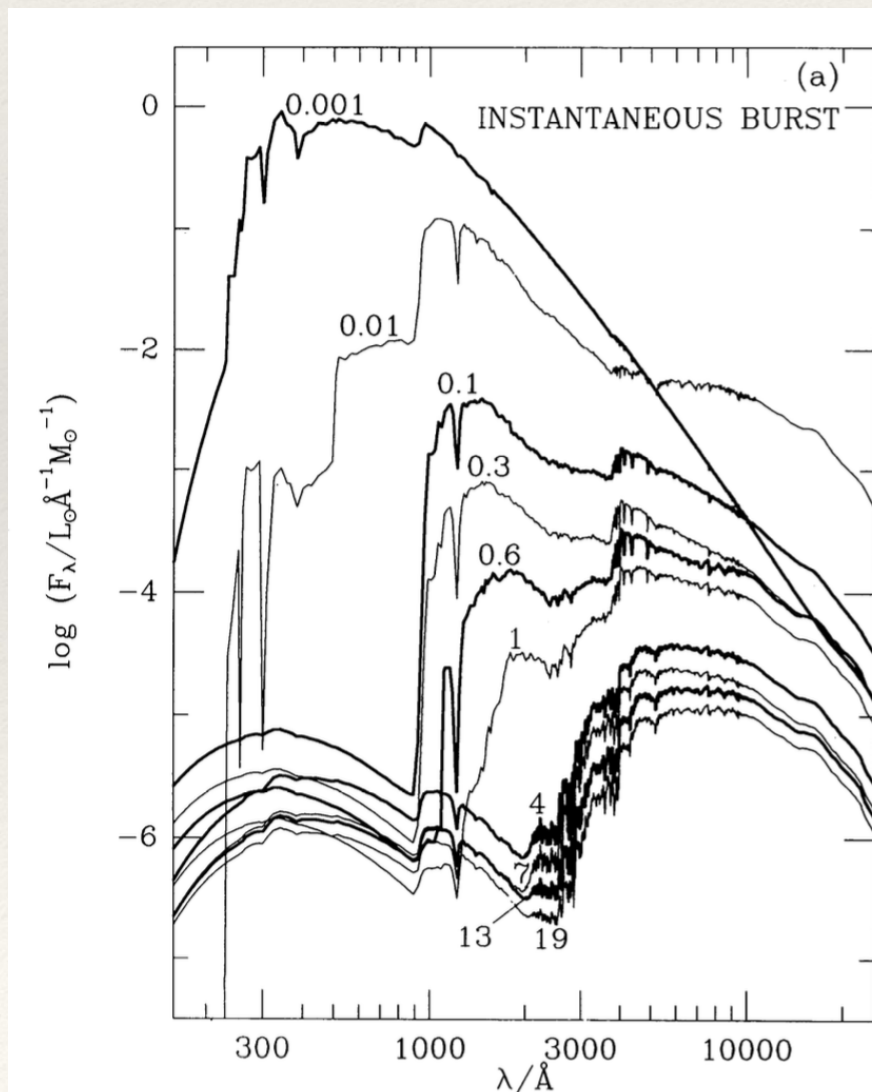
Conroy 2013

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

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 F

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

WELCOME DATA FITTING MODELS REVIEW COMMENTS AUTHORS

FITTING THE SPECTRAL ENERGY DISTRIBUTIONS OF GALAXIES

Publicly Available SED models

Missing a link?

STELLAR POPULATION MODELS

Note: There exist other webpages with link collections, e.g. at [STScI](#)

BASTI

A bag of Stellar Tracks and Isochrones

BPASS

Binary Population and Spectral Synthesis

Buzzoni

SSPs, Template Galaxy Models and more

Coelho

Spectral models for Solar scaled and α -enhanced stars

FSPS

Flexible Stellar Population Synthesis by Conroy et al.
Galadriel

The Padova GALaxies AnD single stellaR population
Galaxev

The Bruzual and Charlot Stellar Population Synthesis
Galev

GALaxy EVolutionary Synthesis models by Kotulla et al.
includes the spectral and chemical evolution of galaxies

<http://www.sedfitting.org>

WELCOME DATA FITTING MODELS REVIEW

FITTING THE SPECTRAL ENERGY DISTRIBUTIONS OF GALAXIES

Public SED fitting codes

INVERSION CODES, OPTICAL

STARLIGHT

The Spectral Synthesis non-parametric fitting code by the SEAGal Group

STECKMAP

Inversion with regularization
Ocvirk et al.

ULYSS

University of Lyon Spectral analysis Software, Koleva et al.

VESPA

VERsatile SPectral Analysis code by Edinburgh group, Tojeiro et al.
(SDSS results available via SQL)

pPXF

Penalized Pixel Fitting by Capellari et Emsellem

fit3D

Stellar Pops and emission lines
Sanchez

firefly

Fitting Iteratively For Likelihood analysis

Stars and Stellar Populations

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

But uncertainties remain...

WELCOME DATA FITTING MODELS REVIEW COMMENTS AUTHORS

FITTING THE SPECTRAL ENERGY DISTRIBUTIONS OF GALAXIES

Publicly Available SED models

Missing a link?
Send a comment!

STELLAR POPULATION MODELS

Note: There exist other webpages with link collections, e.g. at STScI or from the IAU

BASTI
A bag of Stellar Trajectories

BPASS
Binary Population and Spectral Synthesis

Buzzoni
SSPs, Template Galaxies

Coelho
Spectral models for Star Formation

FSPS
Flexible Stellar Population Synthesis

Galadriel
The Padova GALaxies Library

Galaxev
The Bruzual and Charlot models

Galev
GALaxy EVolutionary models

includes the spectral energy distribution

WELCOME DATA FITTING MODELS REVIEW COMMENTS AUTHORS

FITTING THE SPECTRAL ENERGY DISTRIBUTIONS OF GALAXIES

Public SED fitting codes

INVERSION CODES, OPTICAL

STARLIGHT
The Spectral Synthesis non-parametric fitting code by the SEAGal Group

STECKMAP
Inversion with regularization
Ocvirk et al.

ULYSS
University of Lyon Spectral analysis Software, Koleva et al.

VESPA
VErsatile SPectral Analysis code by Edinburgh group, Tojeiro et al.
(SDSS results available via SQL)

pPXF
Penalized Pixel Fitting by Capellari et Emsellem

fit3D
Stellar Pops and emission lines
Sanchez

firefly
Fitting Iteratively For Likelihood analysis

INVERSION CODES, INFRARED

PAHFIT
IDL tool for decomposing
Spitzer IRS spectra
Smith et al.

VIRTUAL OBSERVATORY

VO Spectrum Service

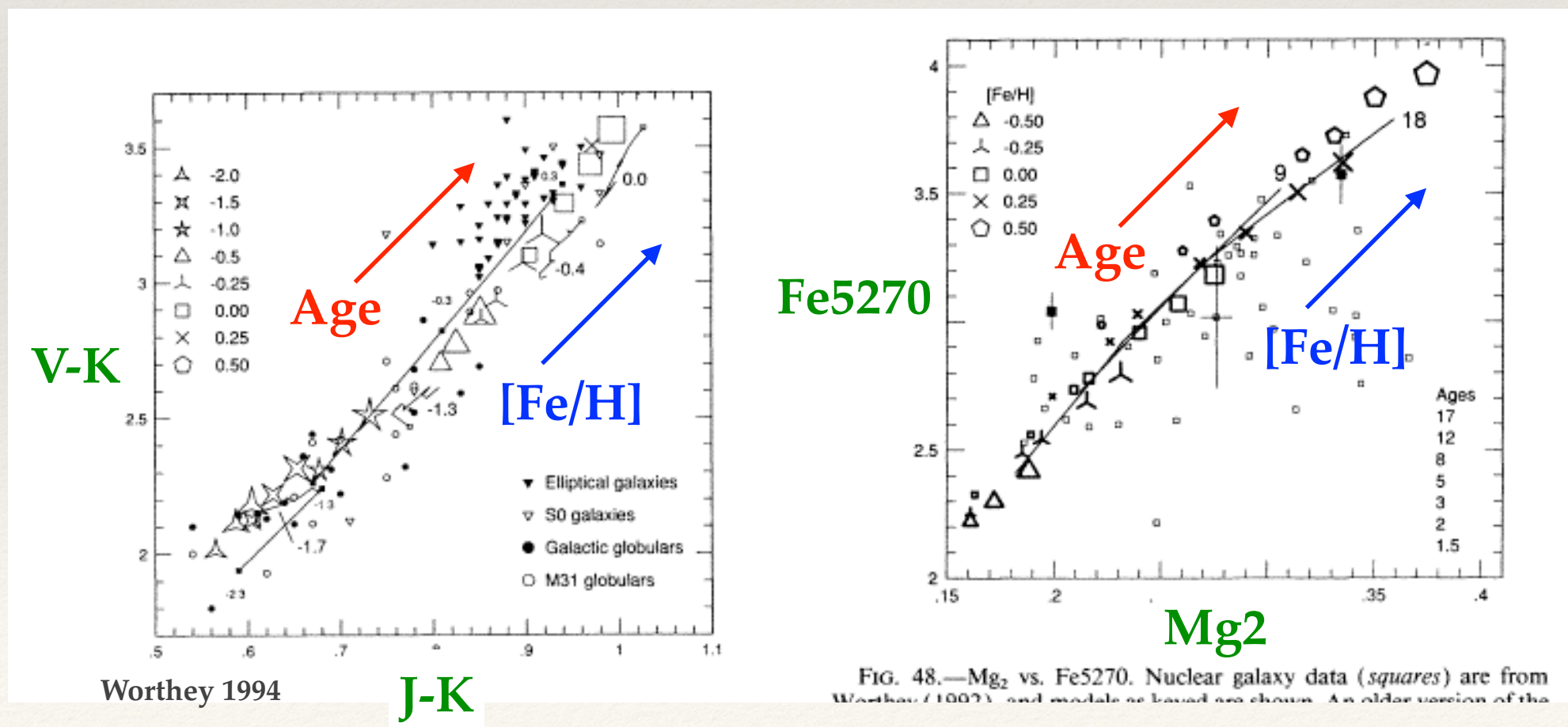
BAYESIAN INFERENCE

PHYSICAL PROPERTIES

SINOPSIS
Simulating optical
stellar populations

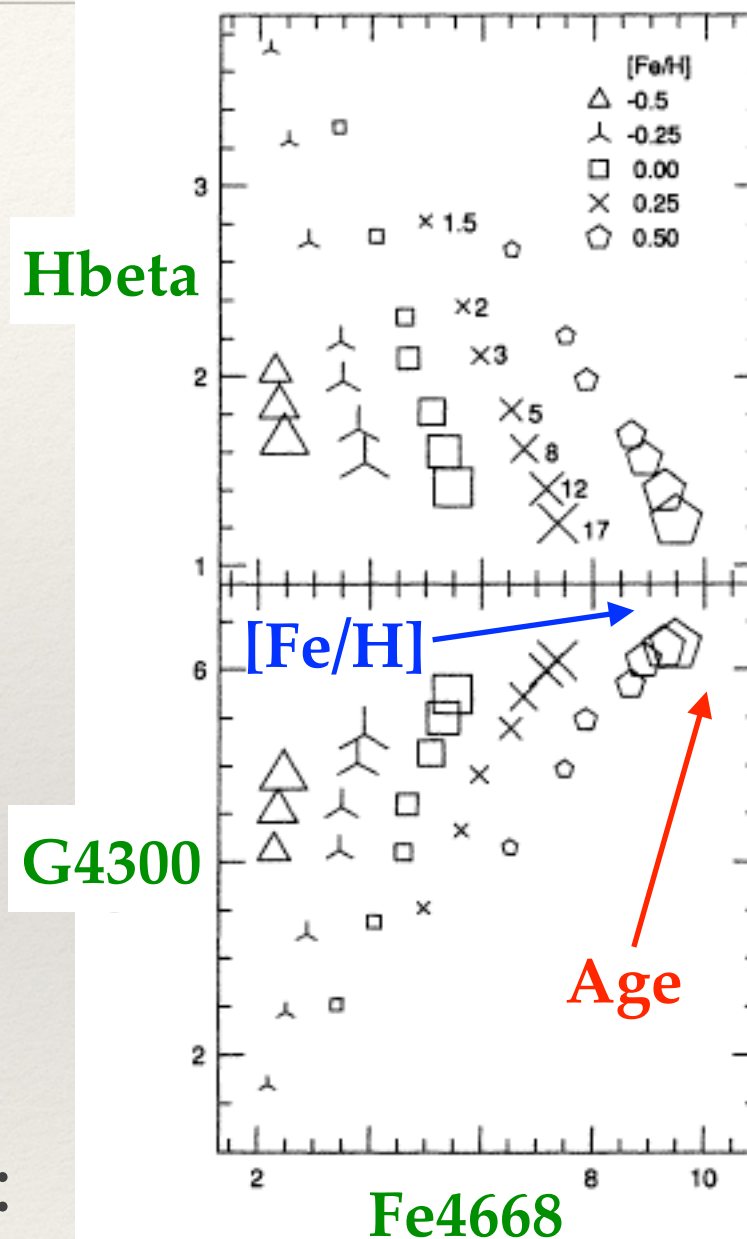
Stars and Stellar Populations

- ❖ 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



Stars and Stellar Populations

- ❖ Break the Age-Metallicity Degeneracy by using carefully chosen features
- ❖ More age-sensitive:
 - ❖ Balmer lines like $H\beta$
 - ❖ D4000 — strength of 4000Å break
- ❖ More metallicity-sensitive:
 - ❖ Fe4668, Fe5270



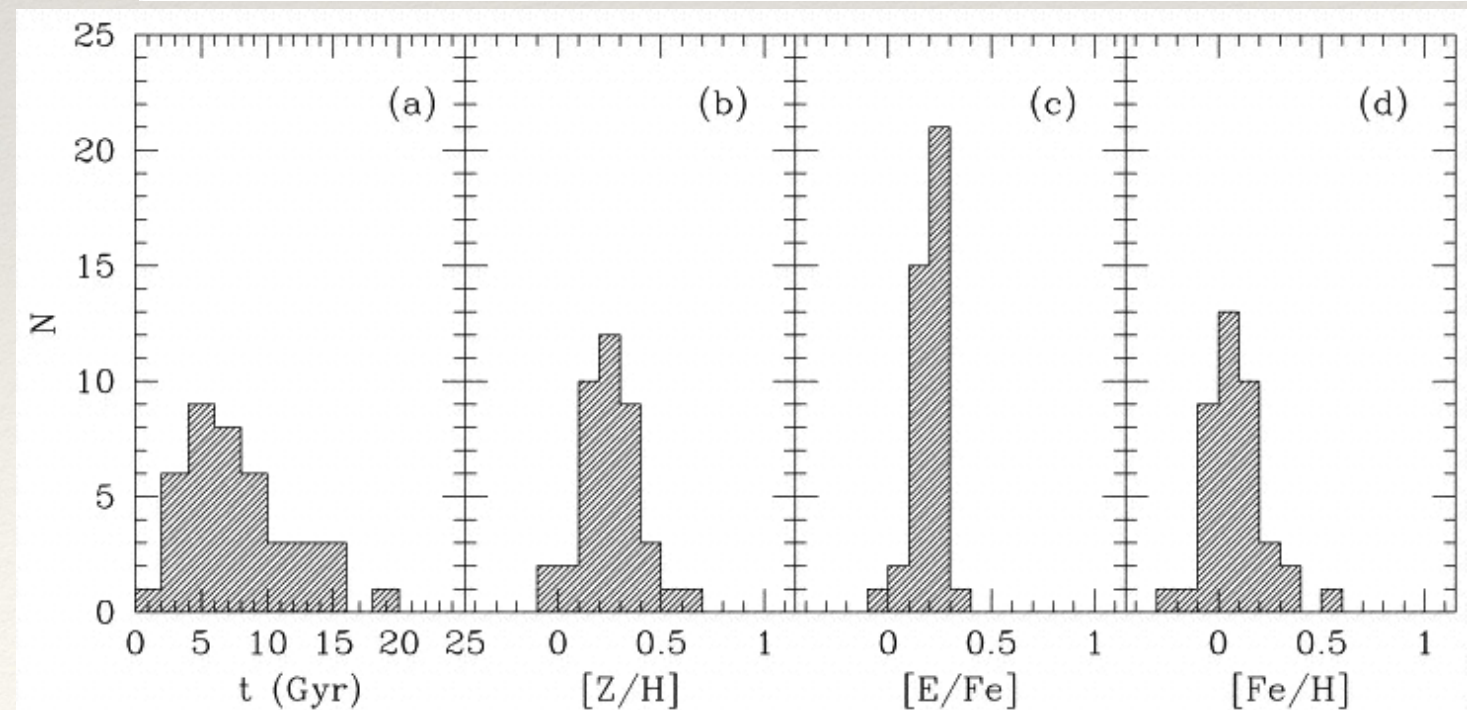
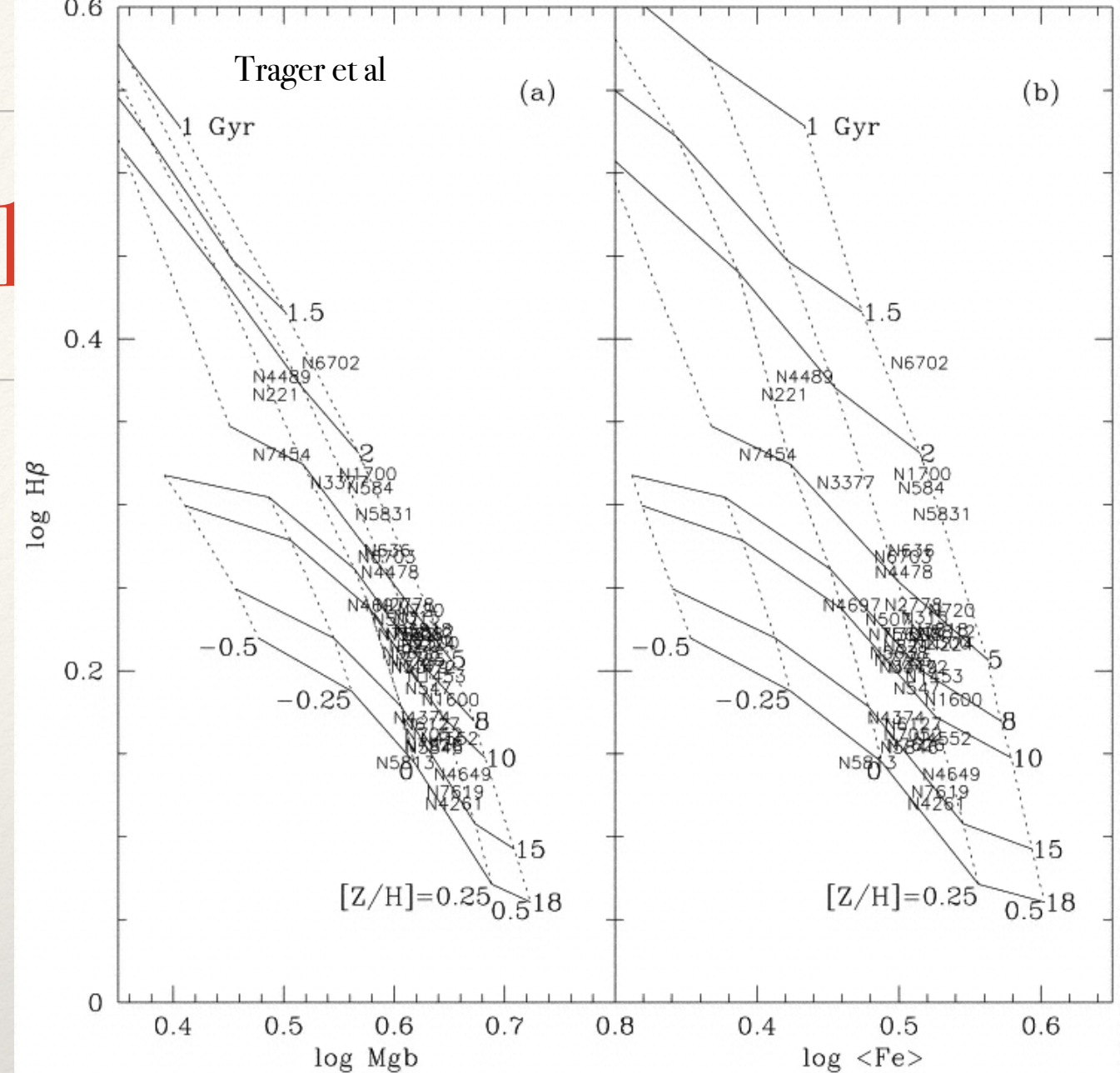
42.—(a) $H\beta$ as a function of Fe4668. $H\beta$ is the most sensitive age or uncovered in our survey, and Fe4668 is among the most sensitive metallicity indicators. (b) G4300 as a function of Fe4668. Ages 1.5, 3, 5, 8, 12, 17 Gyr are shown, except for $[Fe/H] = -0.5$, for which only the models are shown. If the symbols are separated from each other in a line, an age indicator has been discovered. If all points lie in a line, the relation is degenerate. The G band is a mixture of these effects, and is the best age indicator among the indices modeled.

TABLE 6
METALLICITY SENSITIVITIES

Index	$\left(\frac{\Delta \text{age/age}}{\Delta Z/Z}\right)_I$
$U - V$	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 $H\beta$	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

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

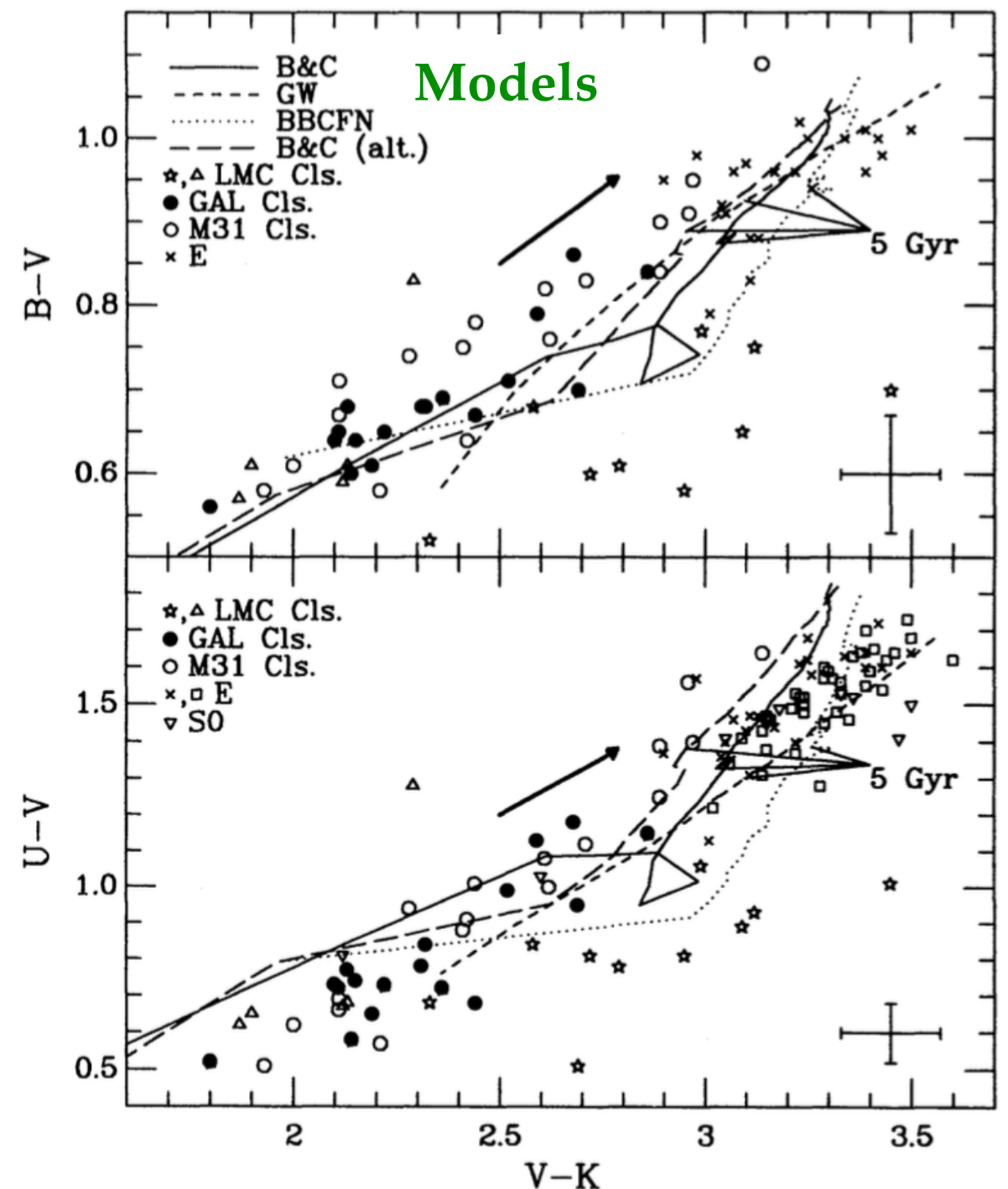


Stars and Stellar Populations

- ❖ 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**

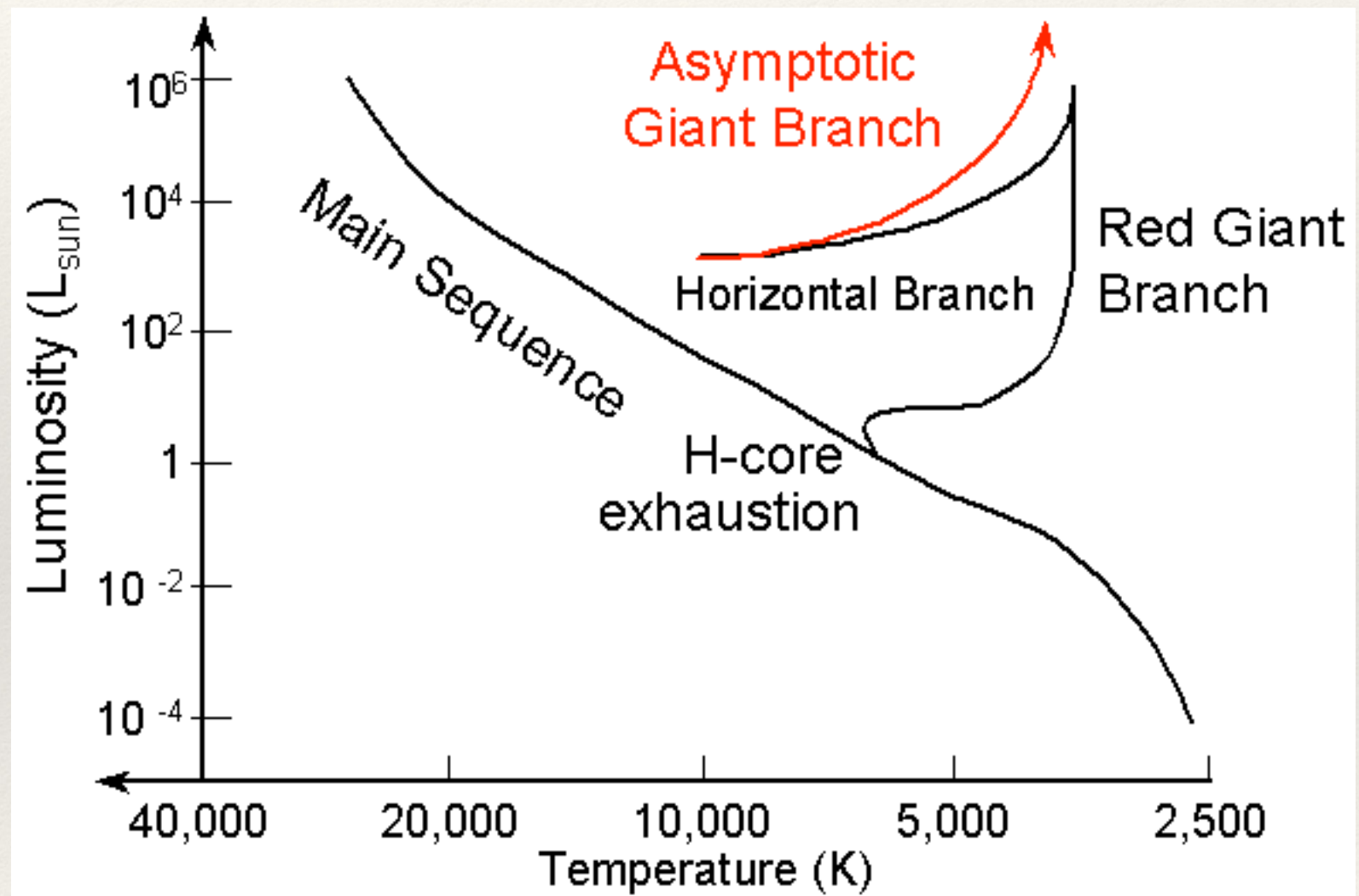
Stars and Stellar Populations

- ❖ **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



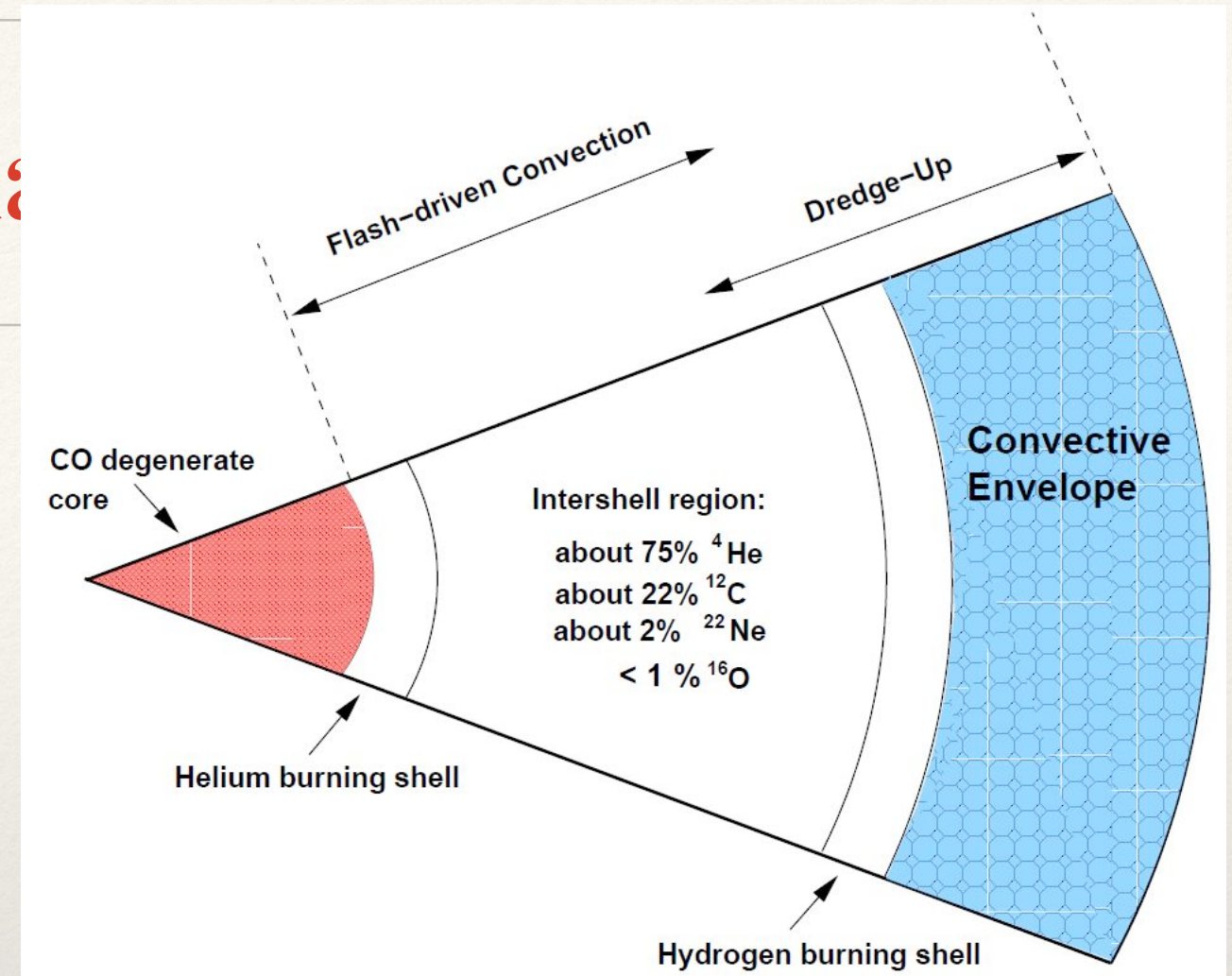
Reminder Question

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

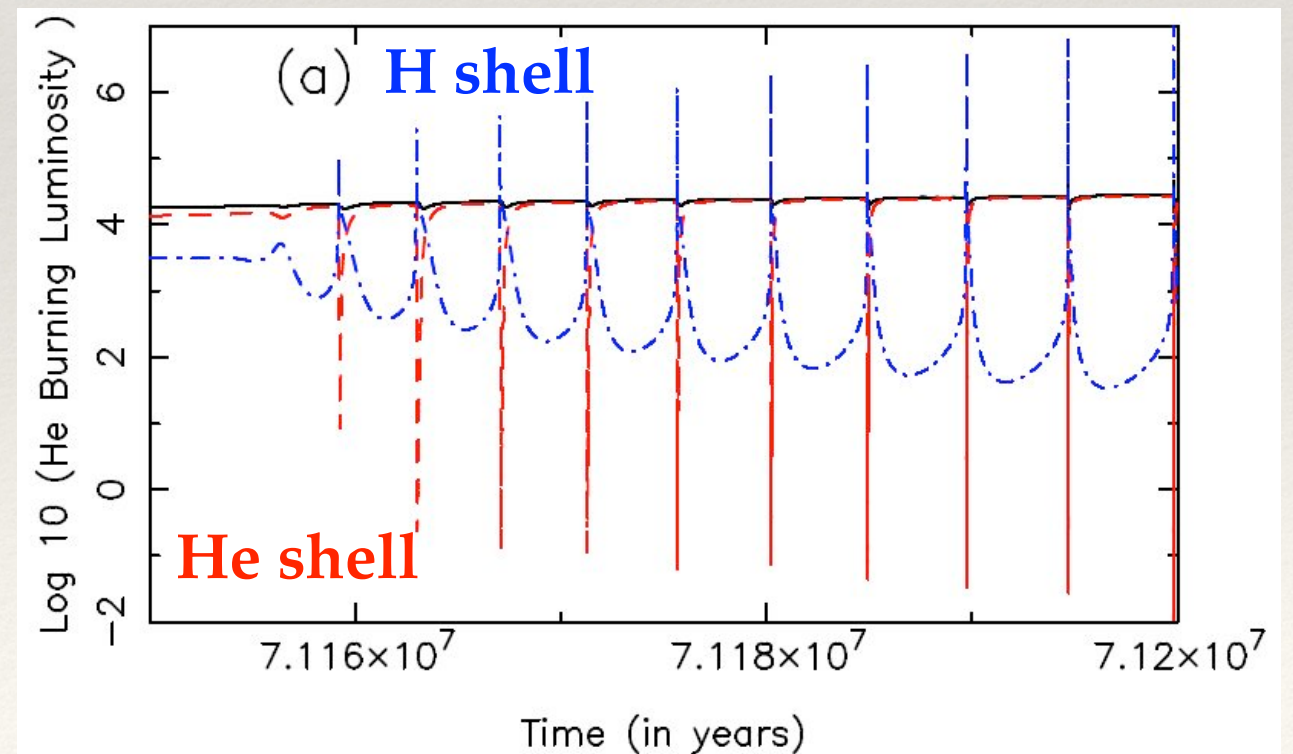


Stars and Stellar Popula

- ❖ 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!



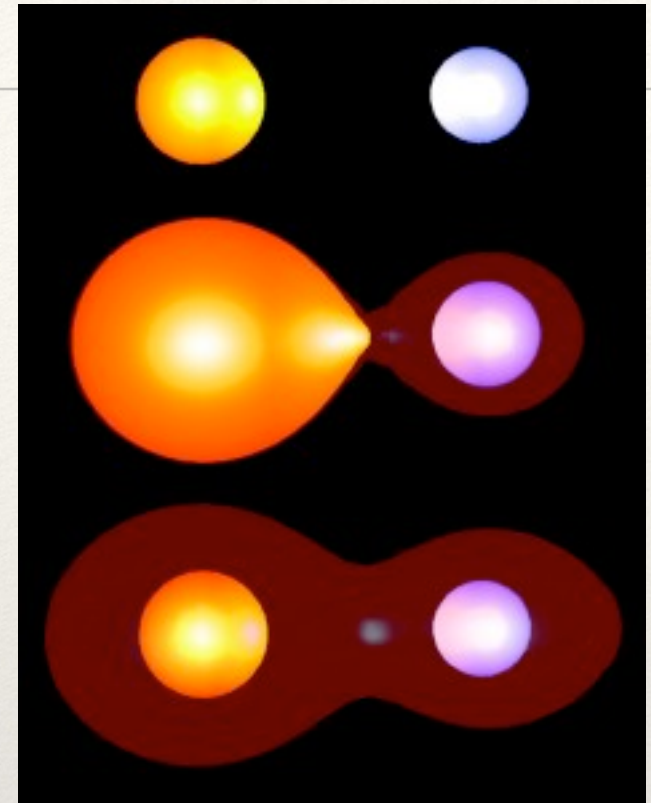
Karakas, Lattanzio, & Pols (2002)



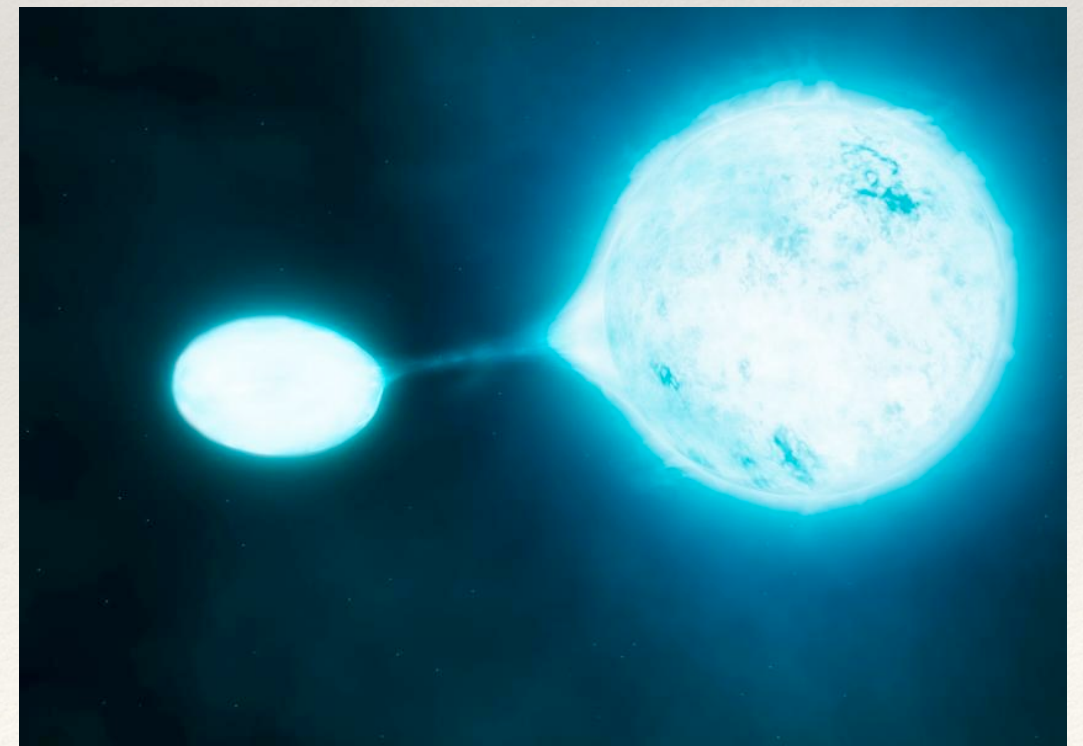
Karakas & Lattanzio 2014

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



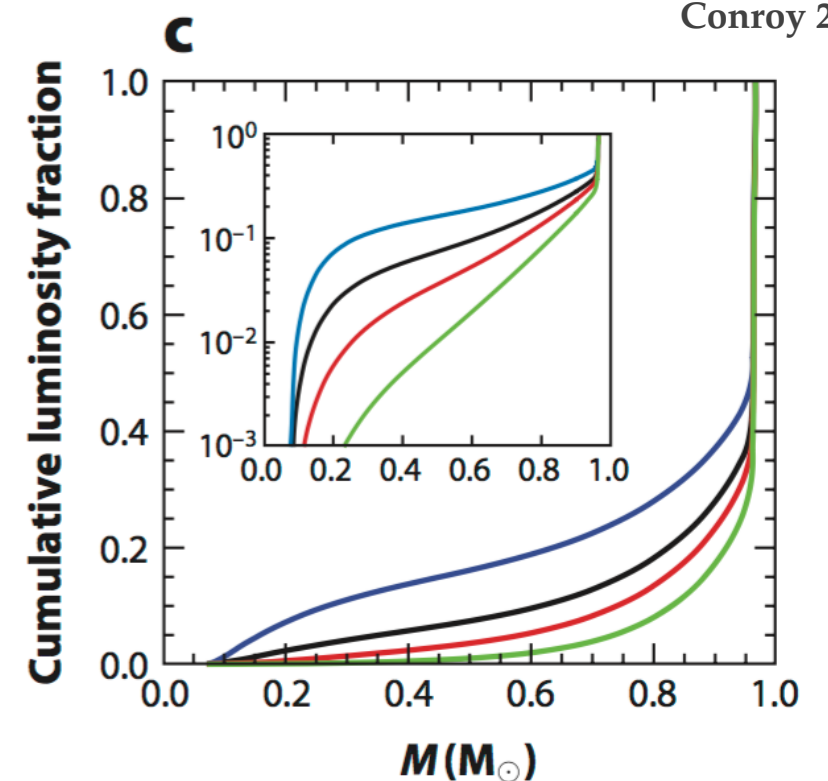
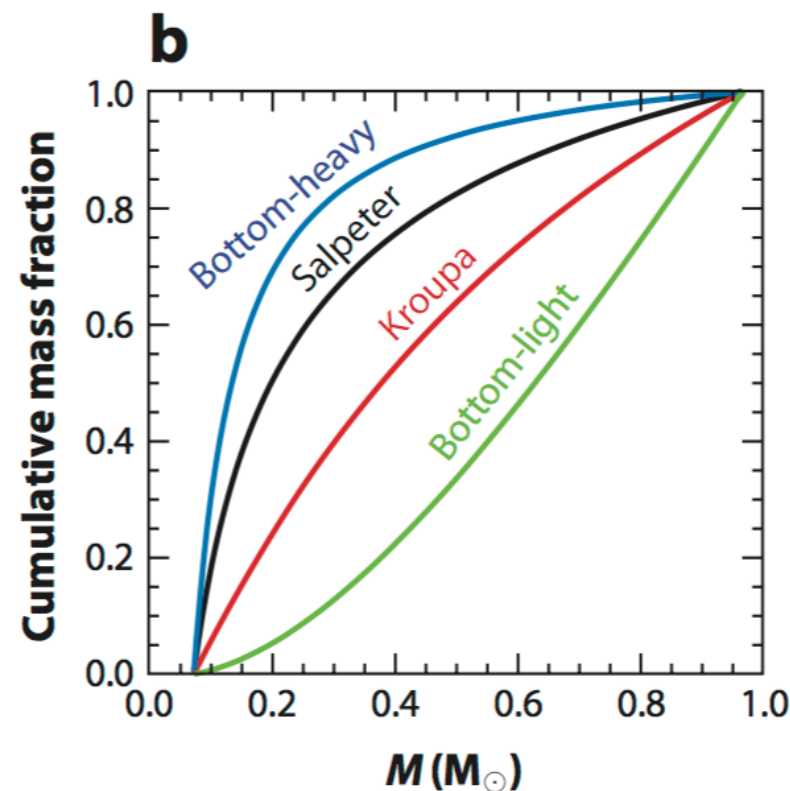
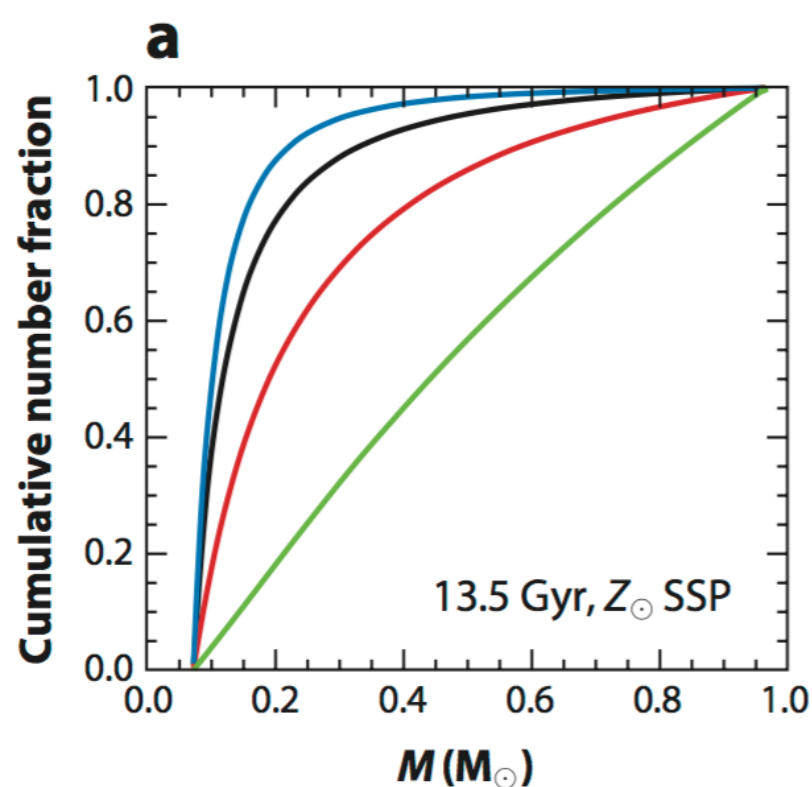
Credit: Adrien Potter



Credit: ESO/L. Calçada/S.E. de Mink

Stars and Stellar Populations

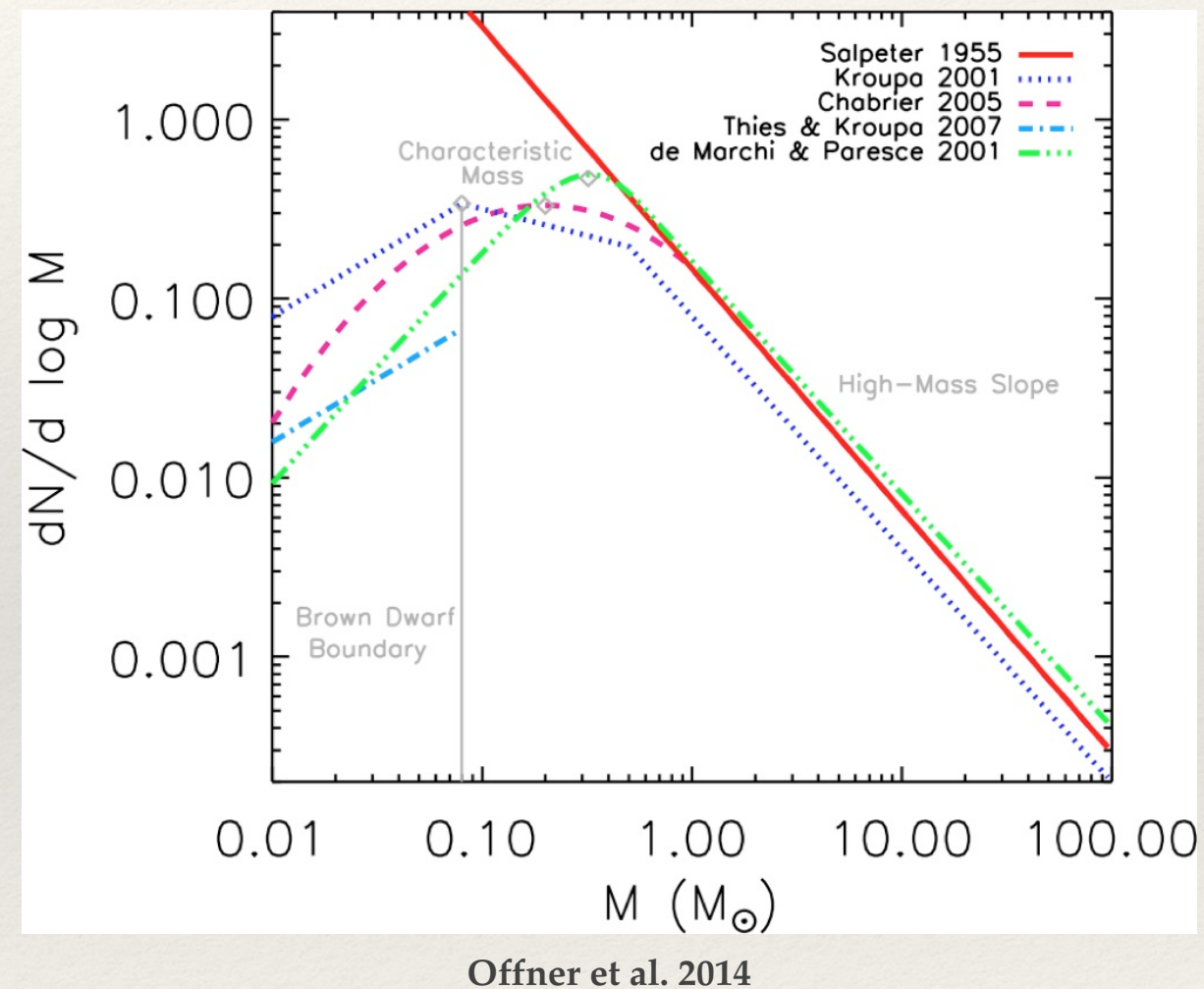
- ❖ Finally, there's the IMF:
 - ❖ determines overall normalization of the stellar M/L
 - ❖ determines rate of luminosity evolution for a passively-evolving population
 - ❖ has smaller effects on the SED (but not totally negligible)



Conroy 2013

Stars and Stellar Populations

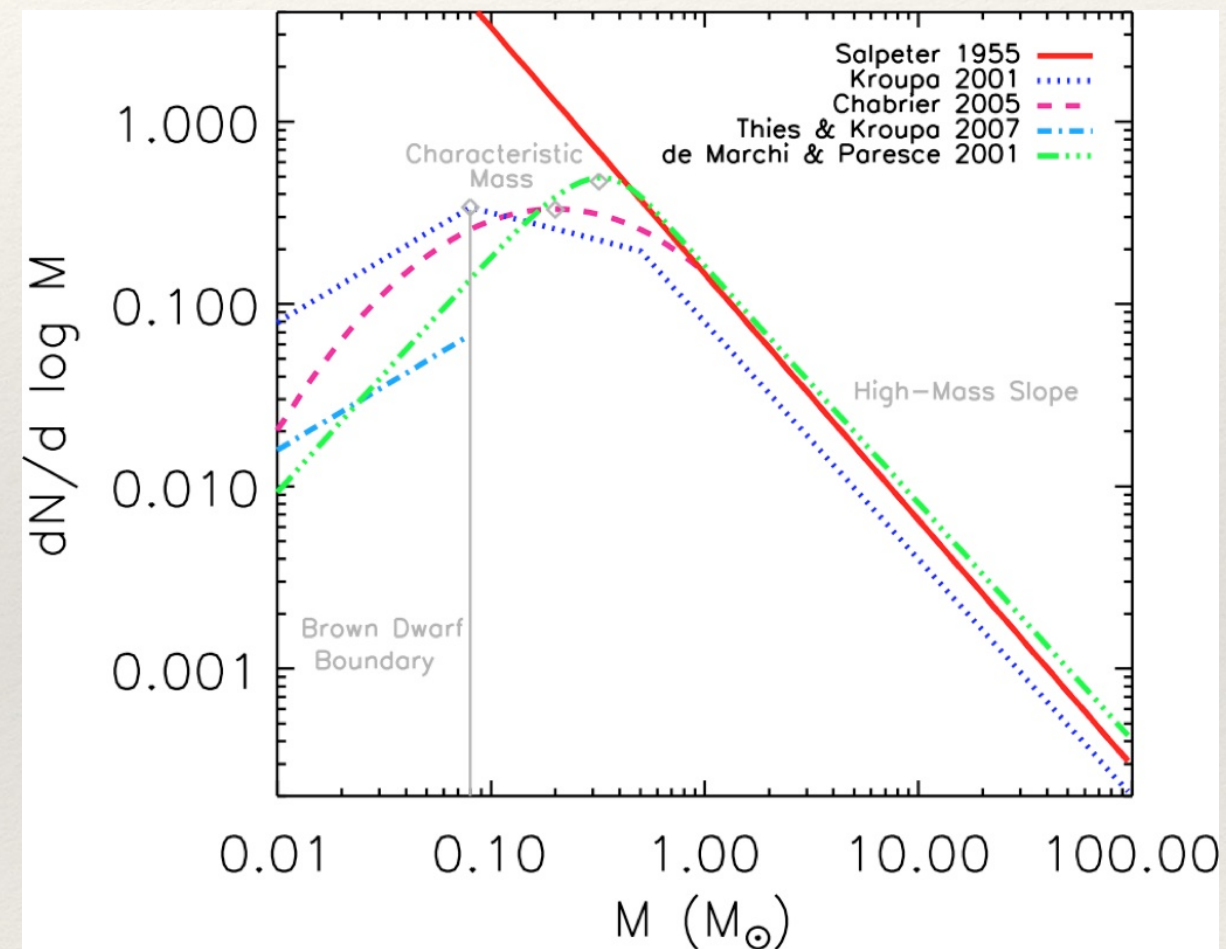
- ❖ Does the IMF vary with cosmic time or environment?
 - ❖ No compelling evidence for IMF variation from counting resolved stars (Bastian, Covey & Meyer 2010)
 - ❖ In the Solar Neighborhood, IMF deviates from the Salpeter form only at $M < 1 M_{\odot}$ (Kroupa 2001, Chabrier 2003)



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 $t=0$?

