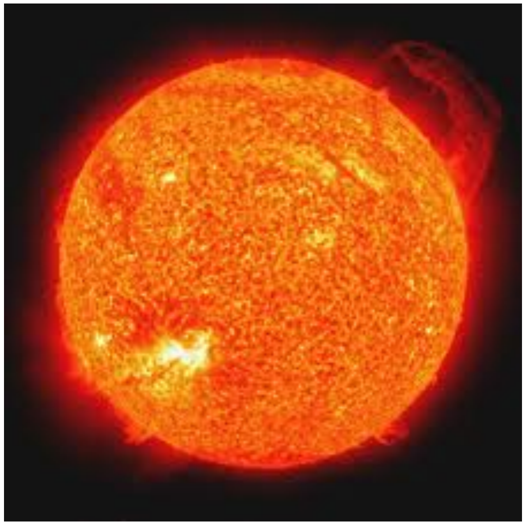


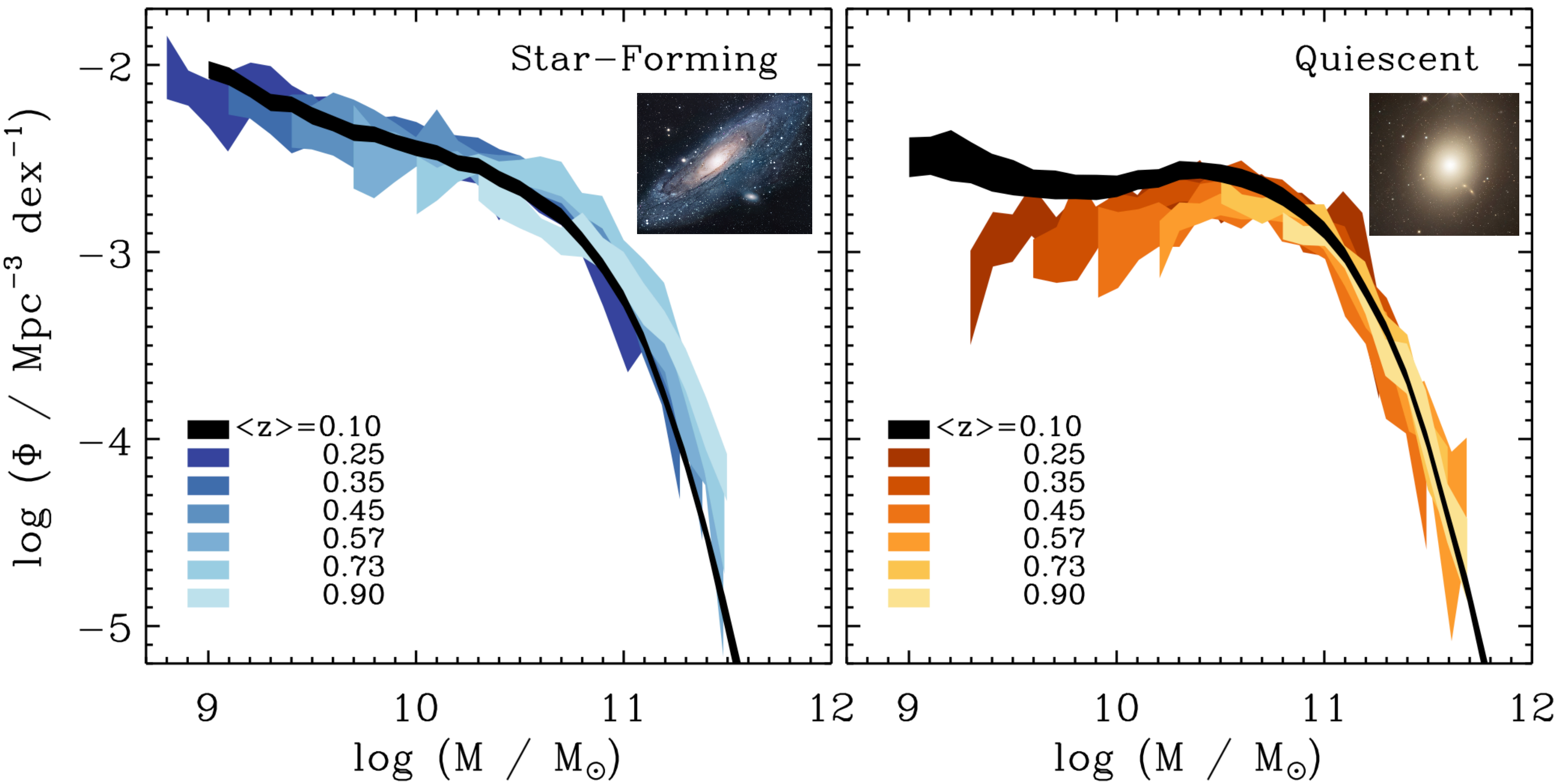
From Stars to Galaxies

Charlie Conroy (Harvard)

I. What do we think we know about galaxies*?

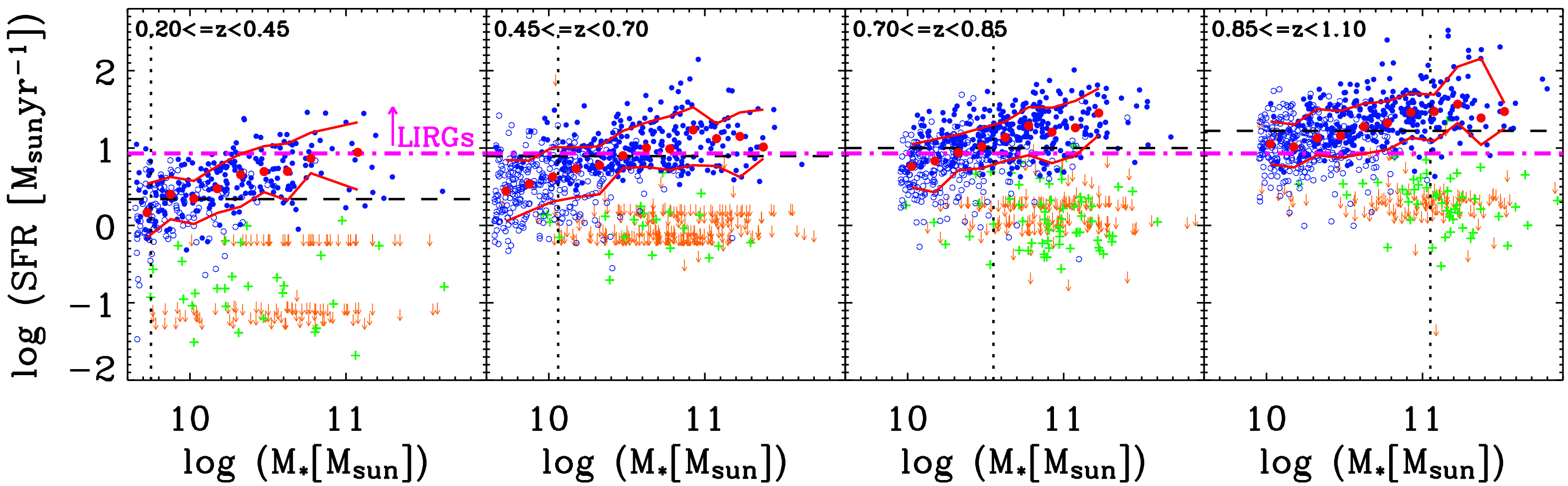
*Ignoring kinematics, lensing, explosions, gas (mostly), morphology, high energy radiation, black holes, large scale structure, and essentially all “raw” observed properties

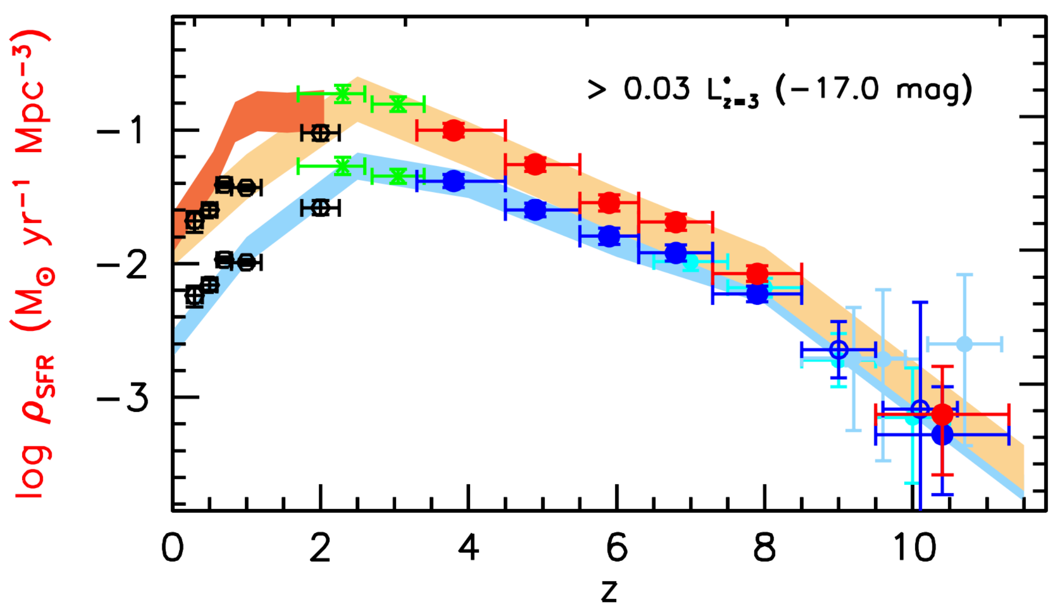
Evolution of the Stellar Mass Function



Moustakas et al. 2013

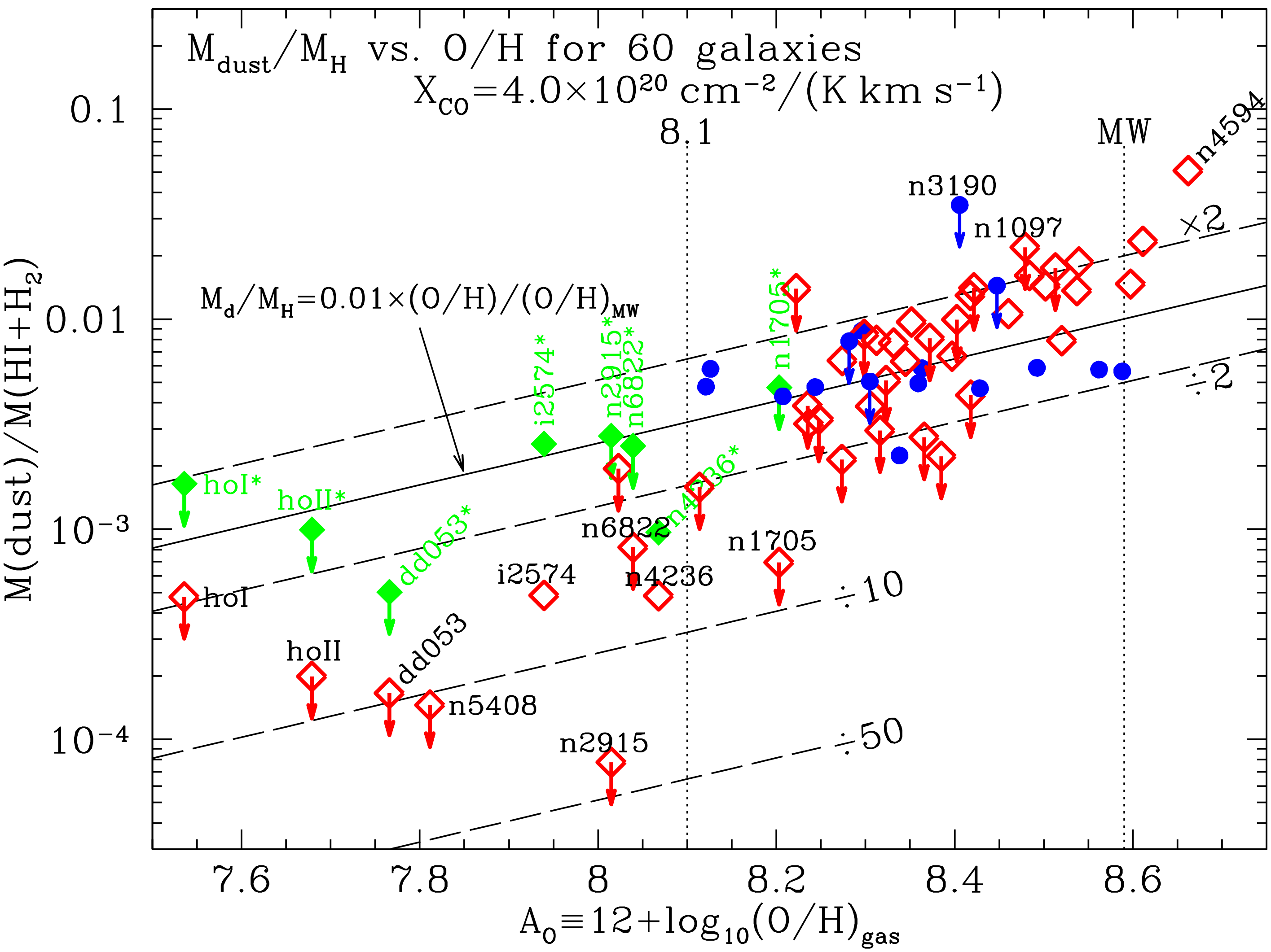
Star formation history; SF "main sequence"





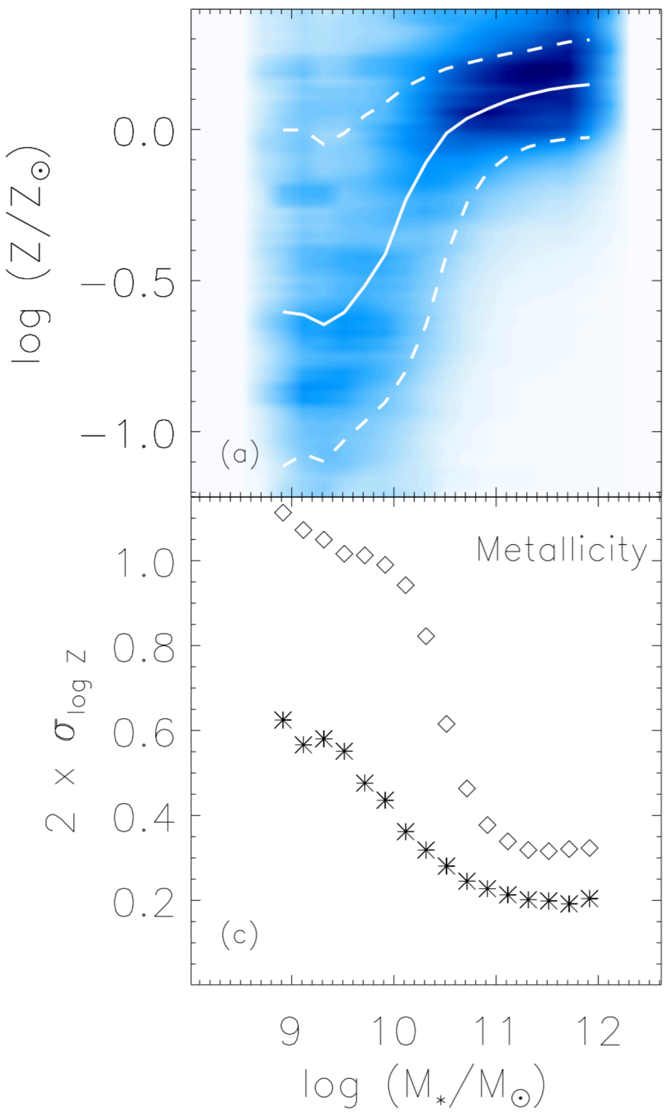
Noeske et al. 2007
Bouwens et al. XXXX

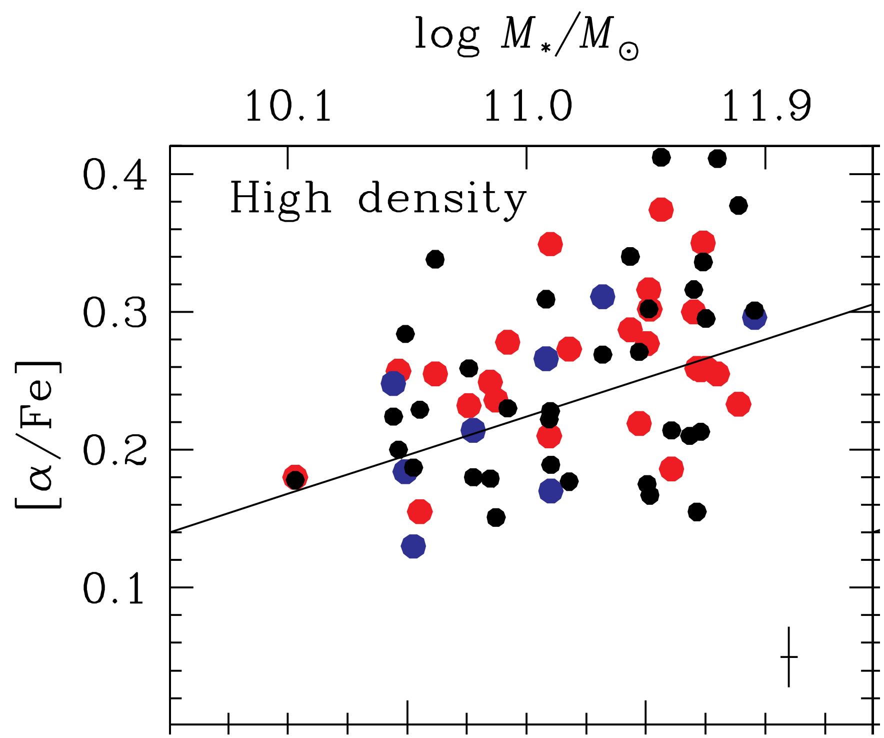
Dust scaling relations



Draine et al. 2007

Stellar Abundances, Metallicities





Gallazzi et al. 2005; Thomas et al. 2005

Connecting Galaxies To the Cosmic Web

- AGN feedback
- Supernovae feedback
- Early feedback, late feedback
- Preheating
- A star-forming “main sequence”
- Inflows, outflows, and fountains
- Photoheating (squelching)
- Inside-out growth
- Assembly bias
- Bathtub models
- Stripping
- Starvation and strangulation
- Downsizing
- Quenching; rejuvenation
- Anti-hierarchical growth

Stellar mass: 10^{7}, 10^{8}, 10^{9}, 10^{10}, 10^{11}, 10^{12}

Dark matter halo mass: 10^{10}, 10^{11}, 10^{12}, 10^{13}, 10^{14}, 10^{15}

Behroozi et al. 2013

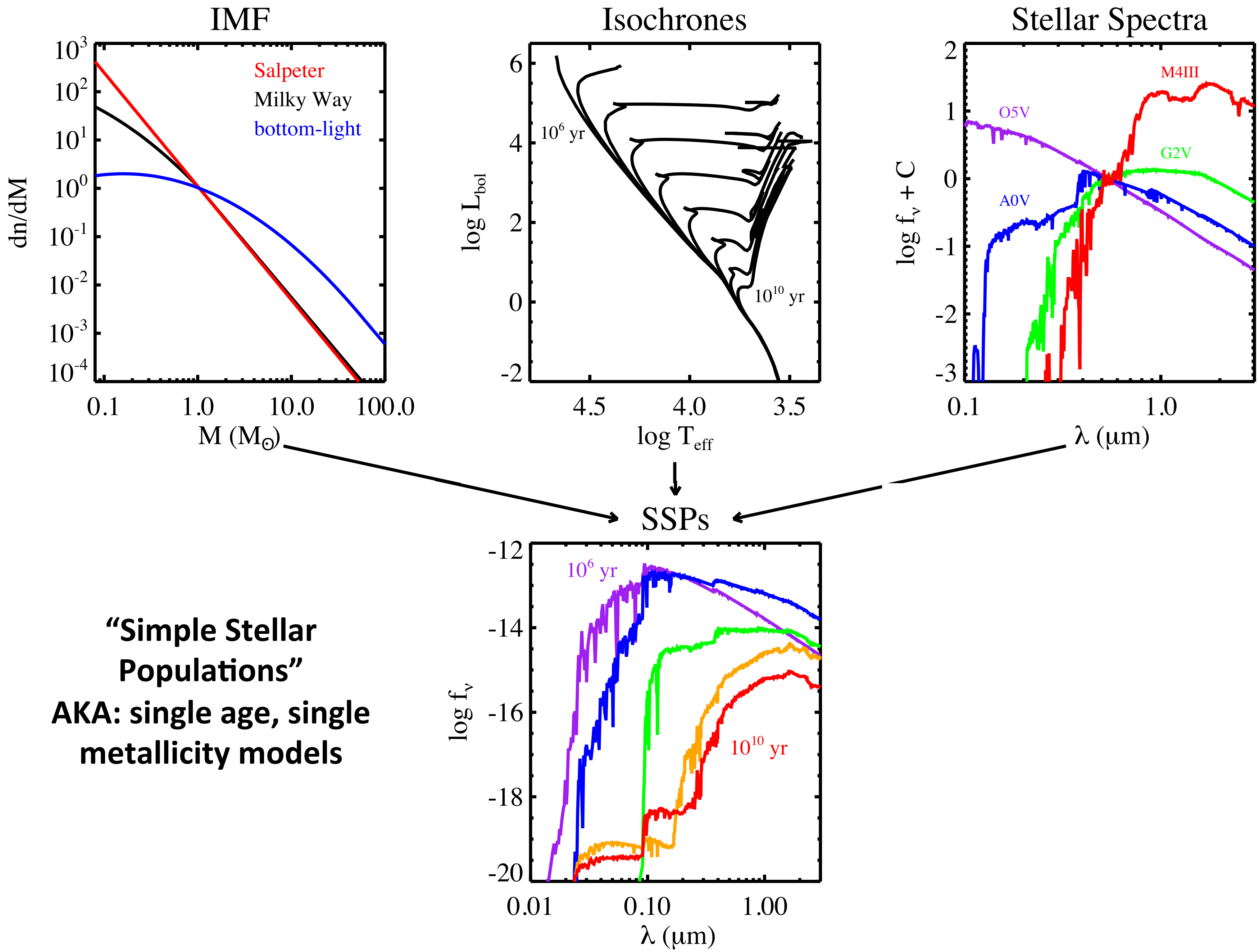
II. *How* do we know what we think we know?

Stellar Population Synthesis Models

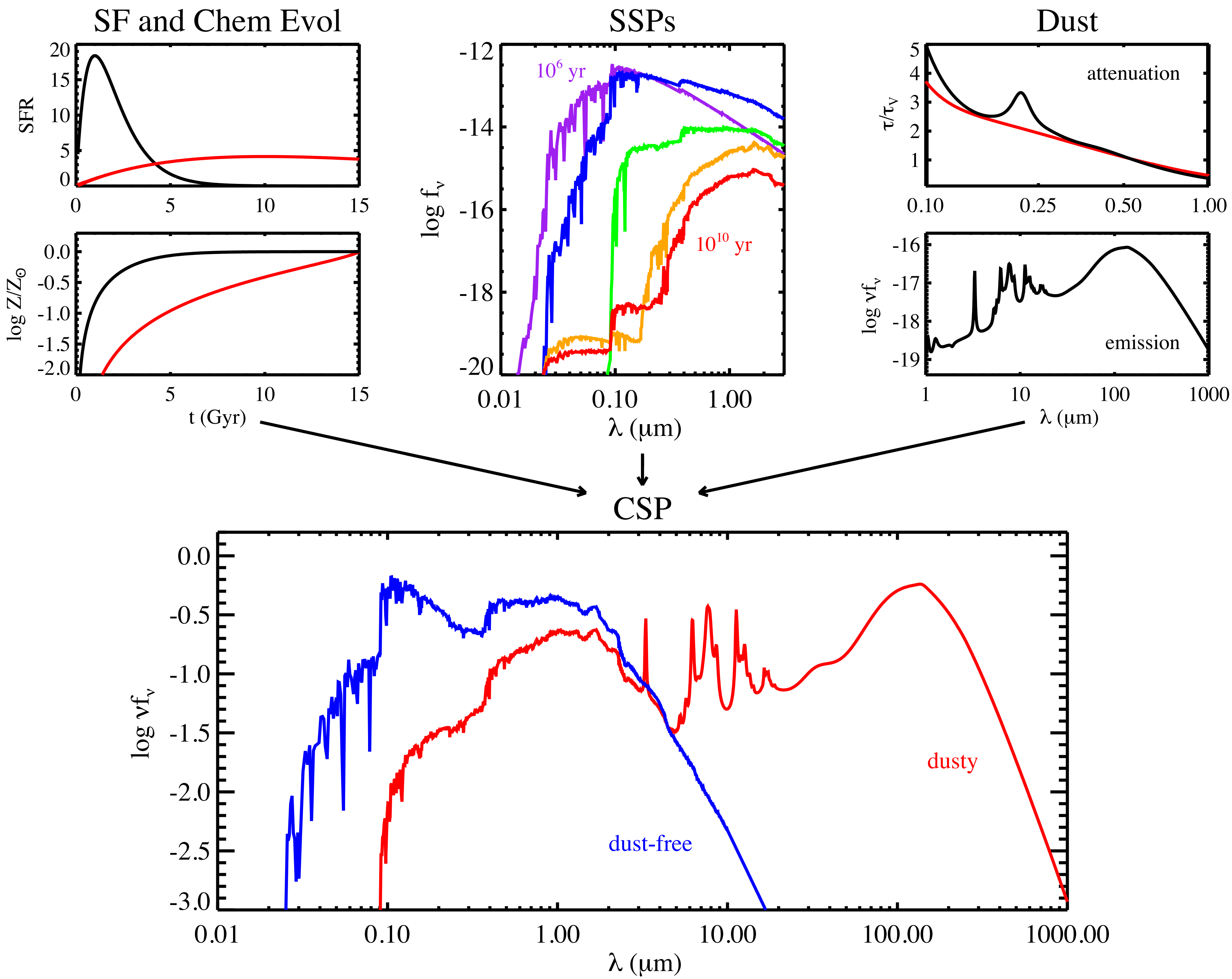
- Long history
  - Tinsley 1968, Searle et al. 1973, Tinsley & Gunn 1976, Bruzual 1983, Charlot & Bruzual 1993, Worthey 1994, Bressan et al. 1994, Fioc & Rocca-Volmerange 1997, Leitherer et al. 1999, Vazdekis 1999, Maraston 2005, Conroy et al. 2009, etc. etc.

- Necessary *both* for converting observations into physical quantities and for converting models/simulations into observables

- *We know little about the physical properties of galaxies that does not depend on stellar evolution, stellar atmospheres, and stellar spectra*



"Simple Stellar Populations"
AKA: single age, single metallicity models


SF and Chem Evol
SFR
log Z/Z⊙
t (Gyr)
SSPs
10^6 yr
10^10 yr
log f_ν
λ (μm)
Dust
attenuation
τ/τ_V
emission
log νf_ν
λ (μm)
CSP
log νf_ν
dust-free
dusty
λ (μm)

- **Simple Stellar Populations**

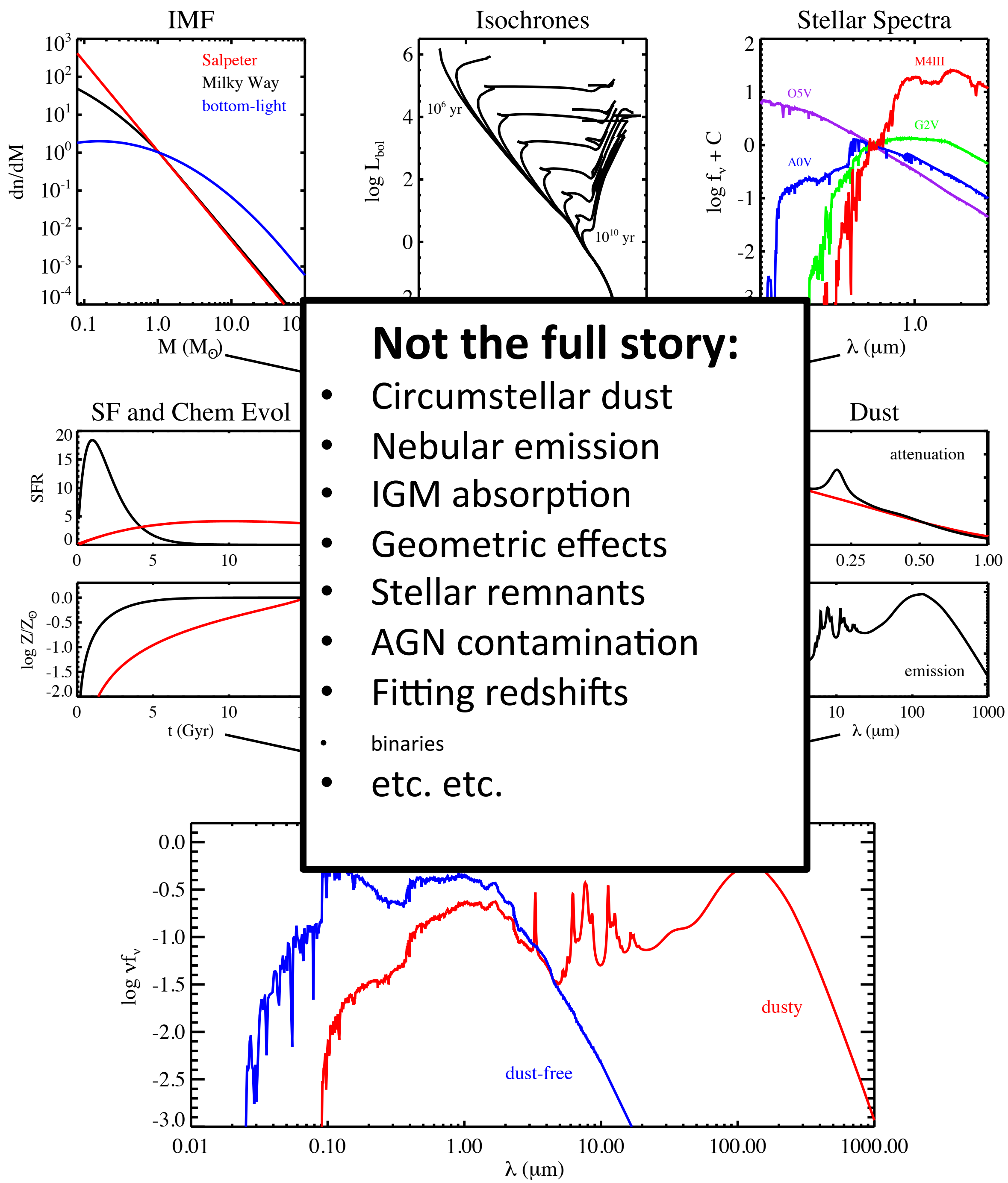
$$f_{\mathrm{SSP}}(t, Z) = \int_{m_{\mathrm{lo}}}^{m_{\mathrm{up}}(t)} f_{\mathrm{star}}[T_{\mathrm{eff}}(M), \log g(M)|t, Z]\, \Phi(M)\, \mathrm{d}M$$

IMF x spectra(stellar mass)

- **Complex Stellar Populations**

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

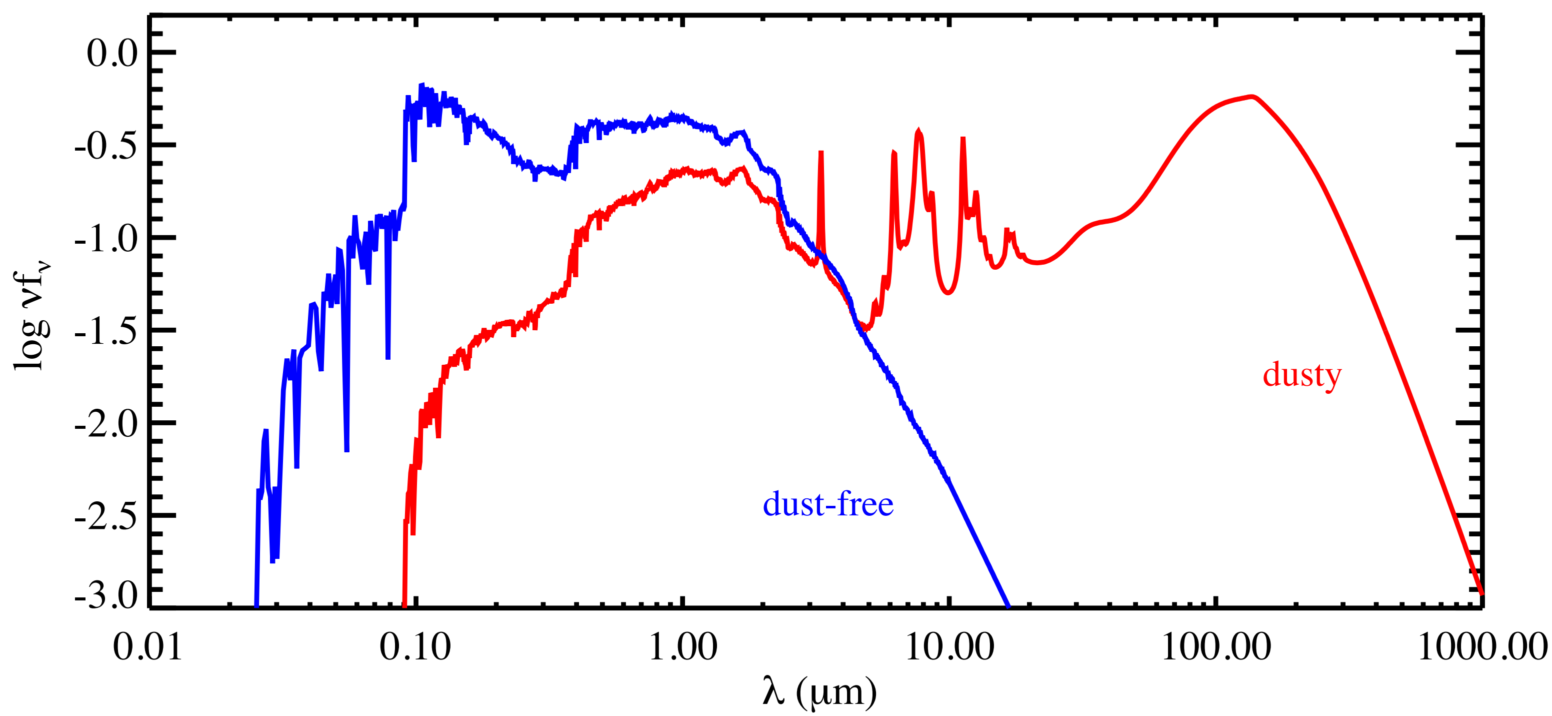
SFR x SSP x dust + dust emission



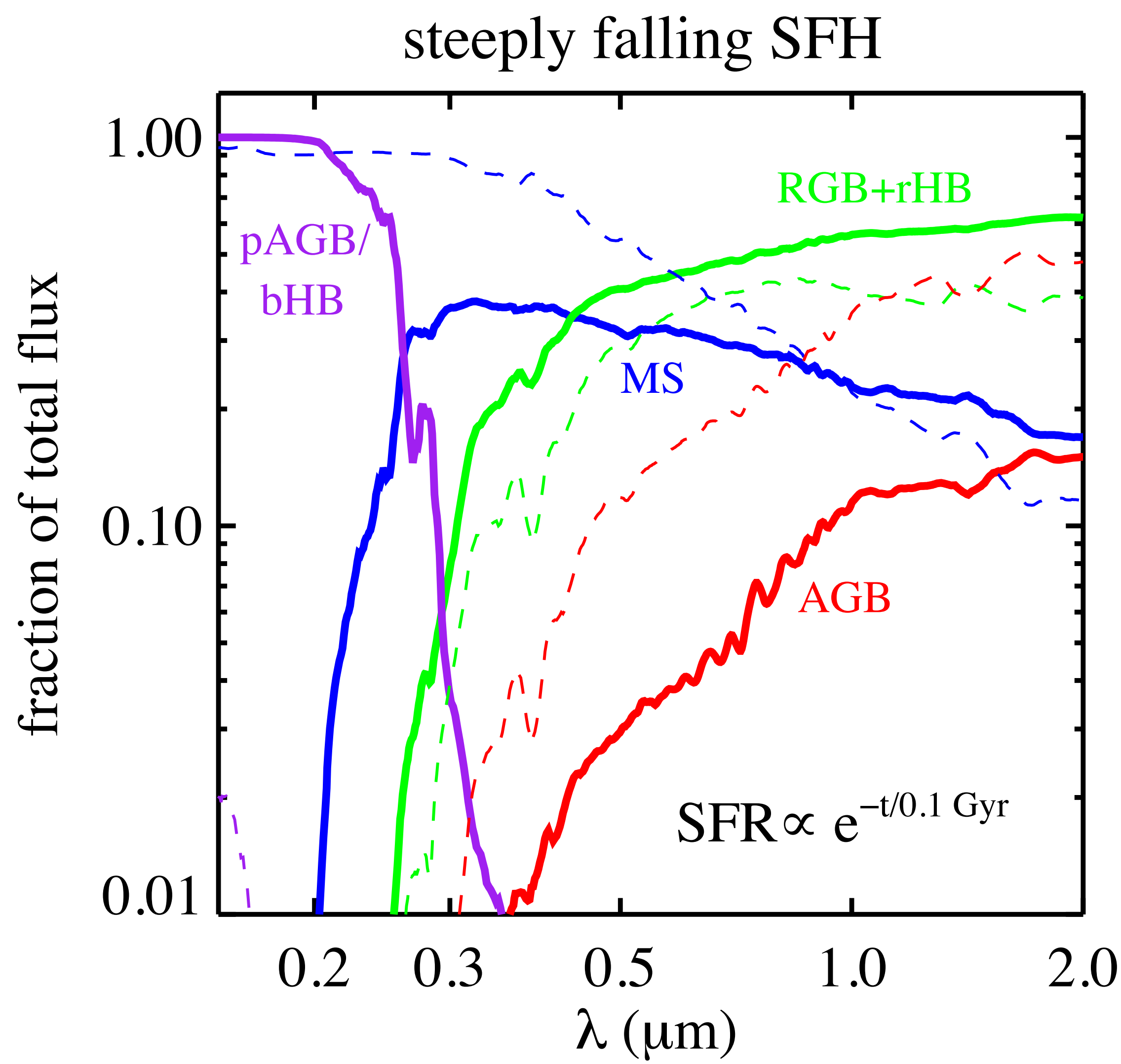
Not the full story:

- Circumstellar dust
- Nebular emission
- IGM absorption
- Geometric effects
- Stellar remnants
- AGN contamination
- Fitting redshifts
- binaries
- etc. etc.

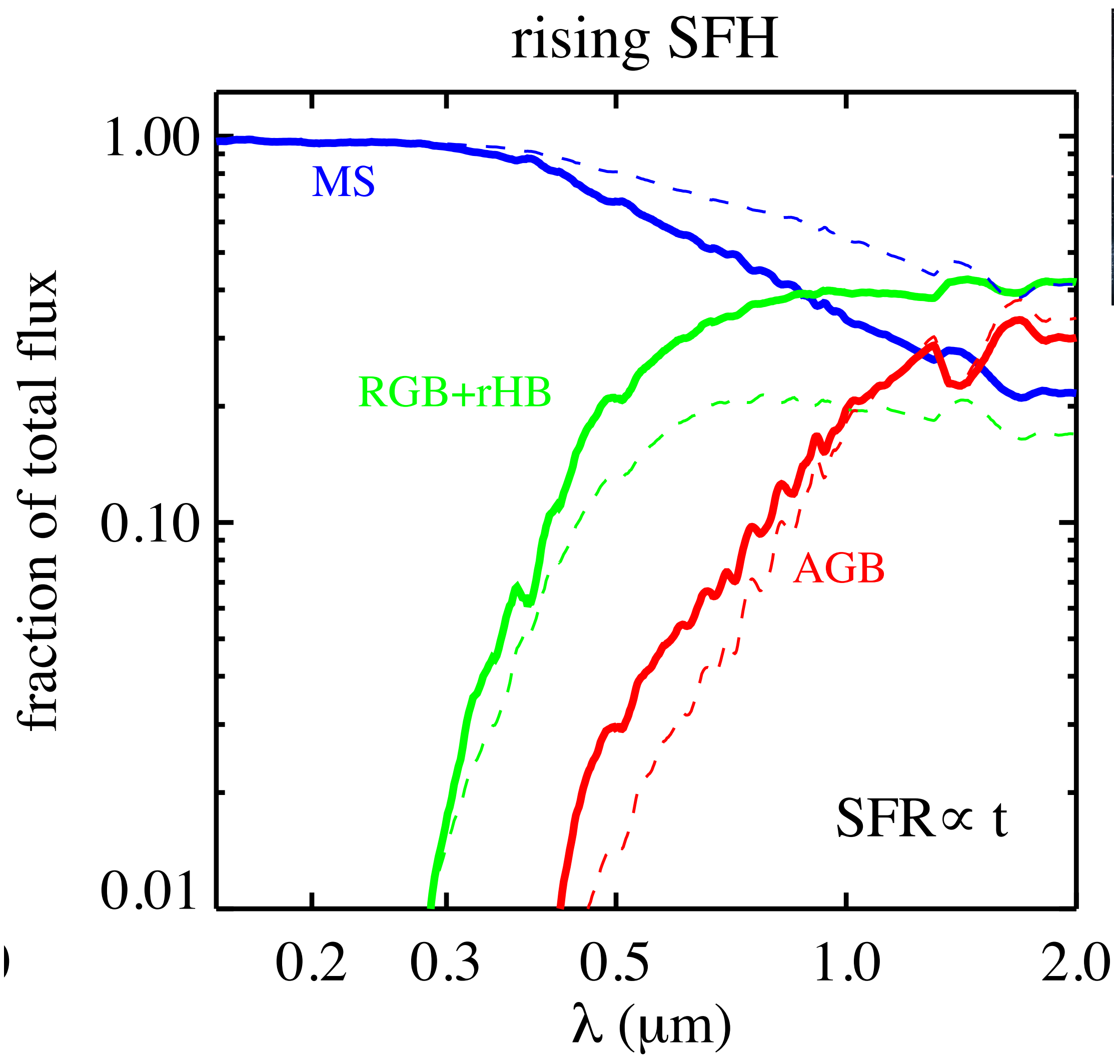
III. Information Content (in the most ideal world)



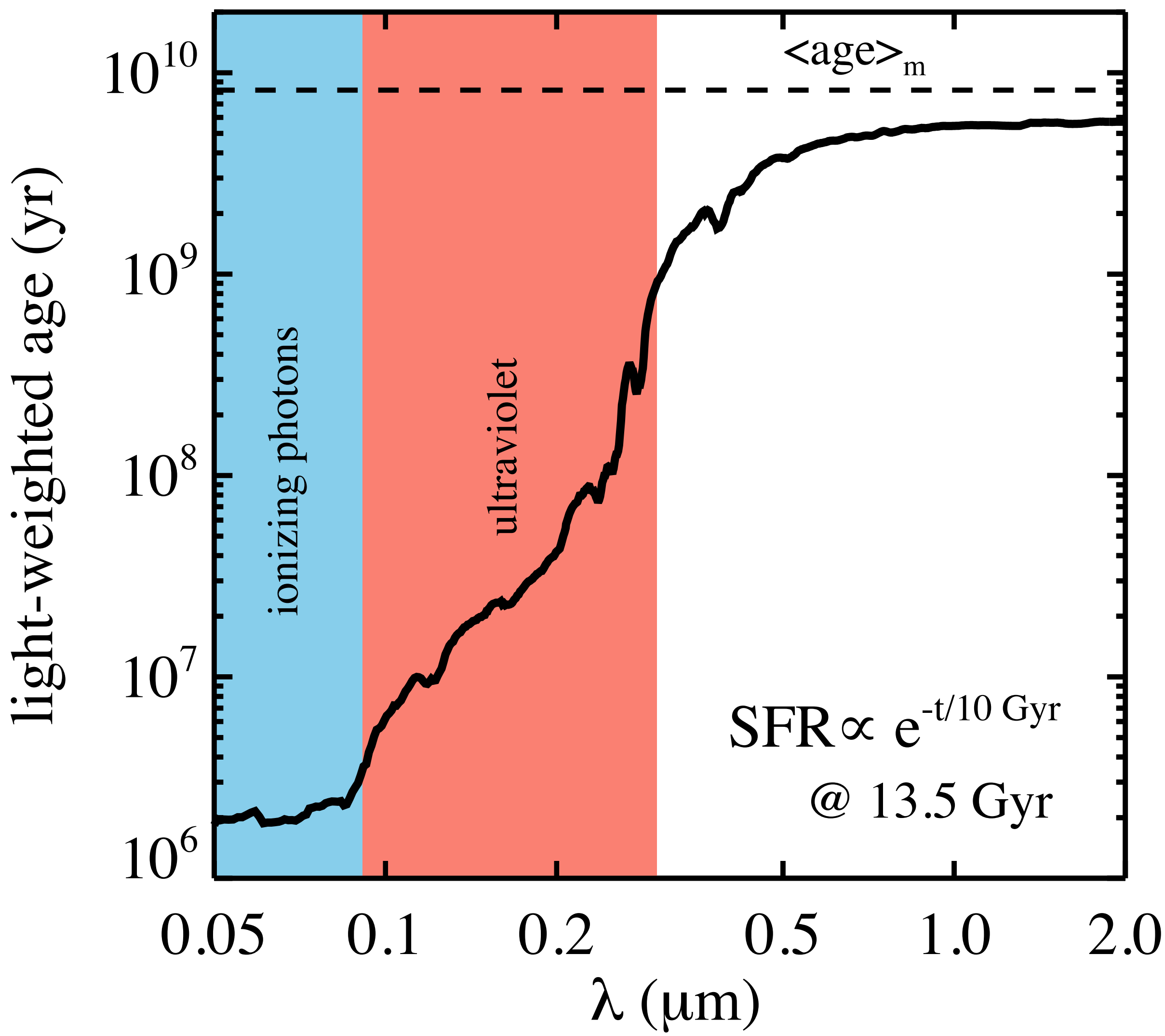
Where is the Light Coming From?



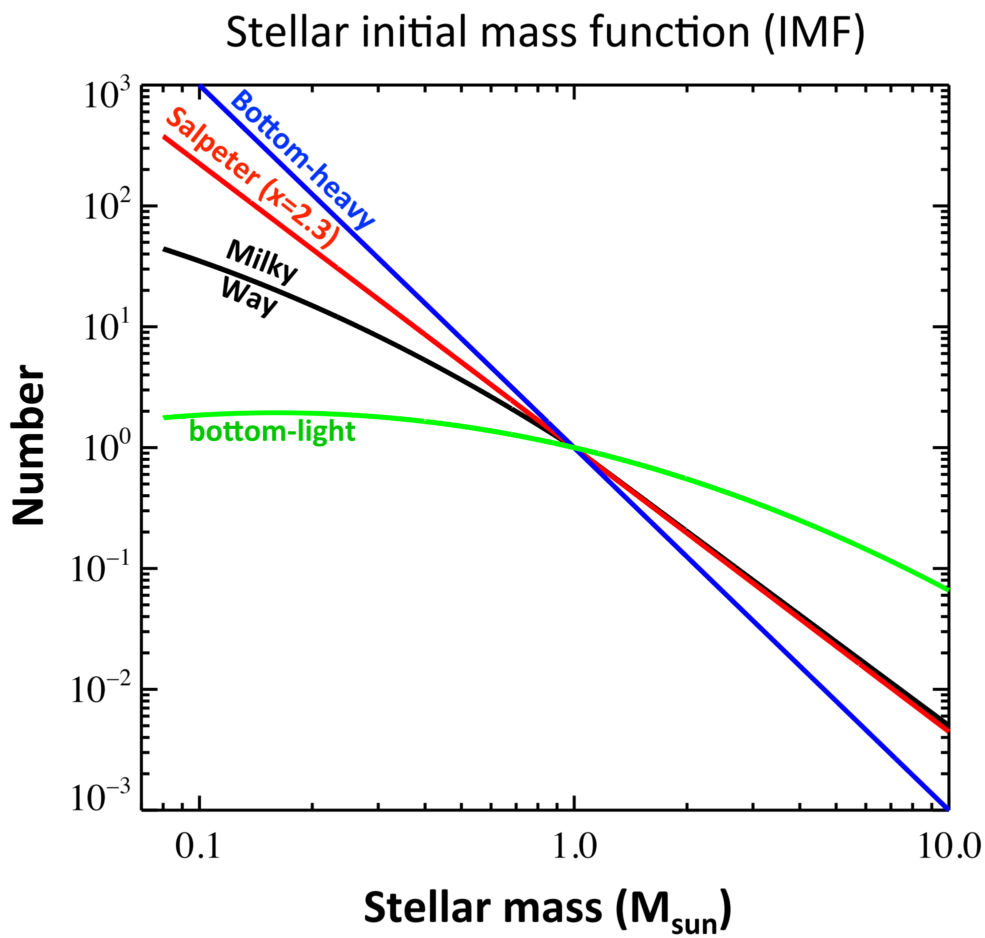
Where is the Light Coming From?

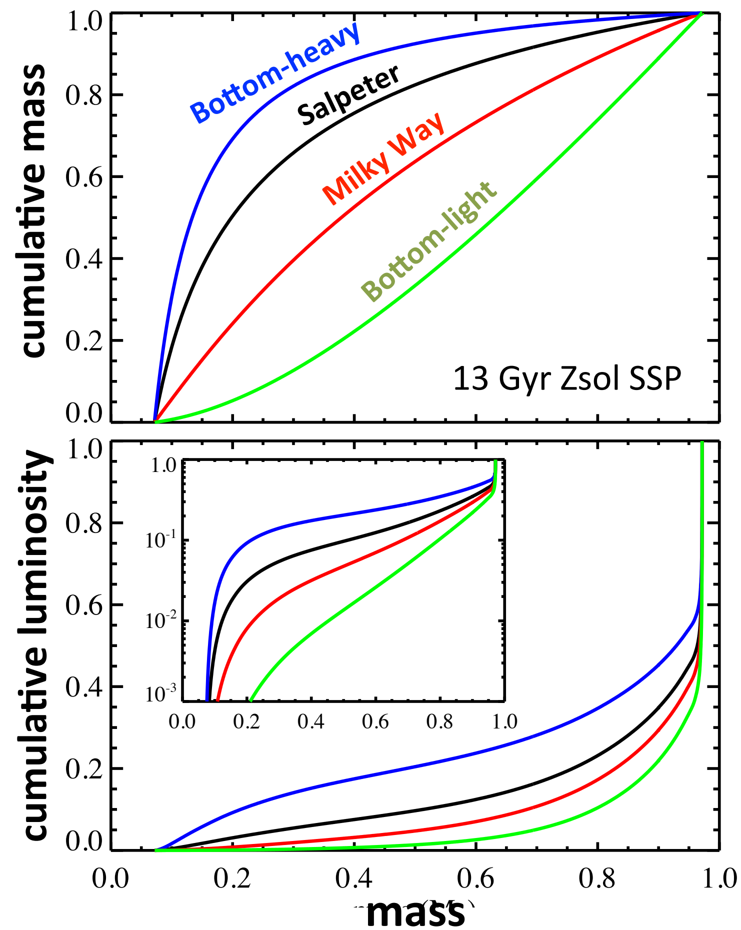


Star Formation Histories

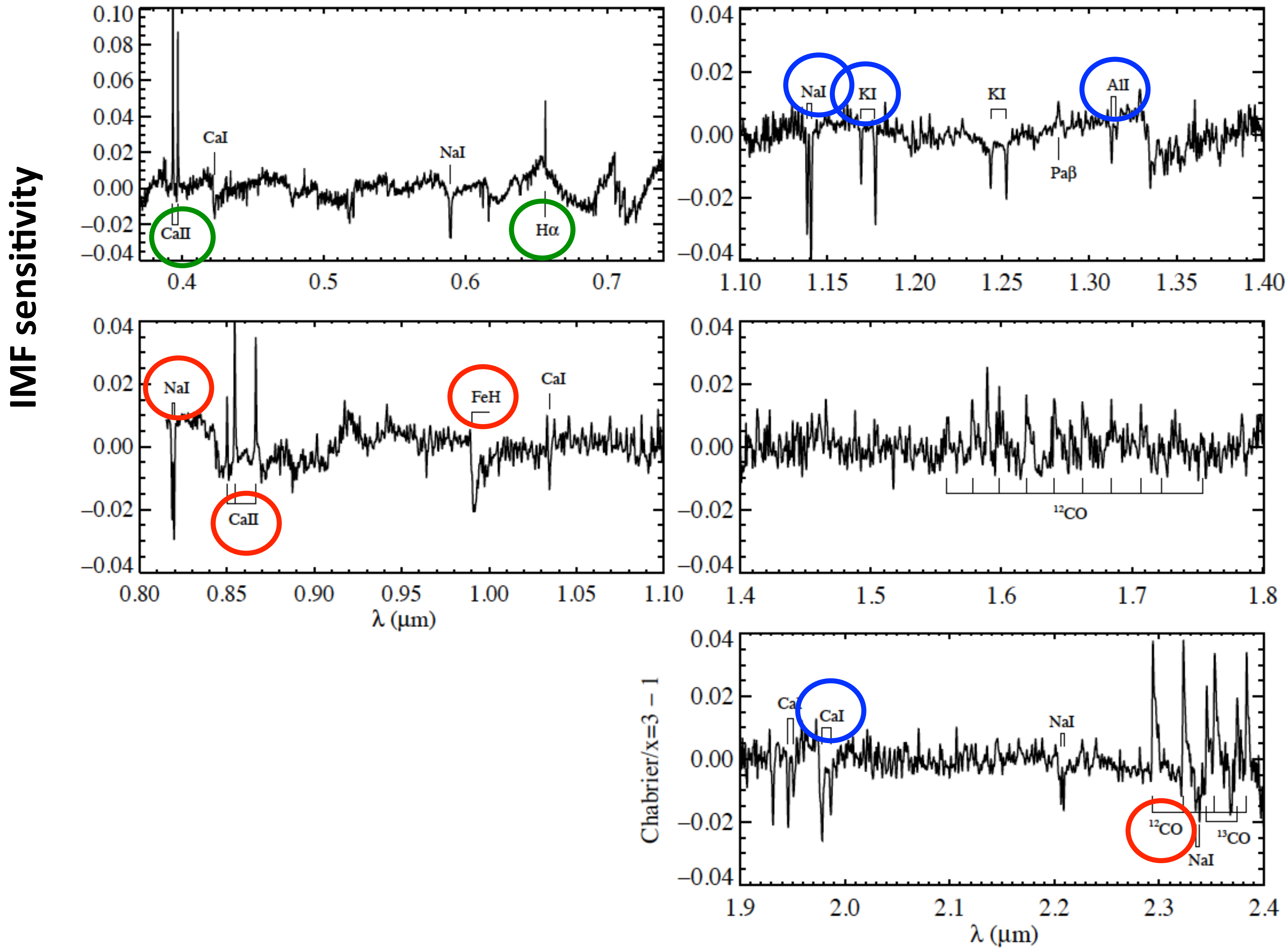


The Initial Mass Function



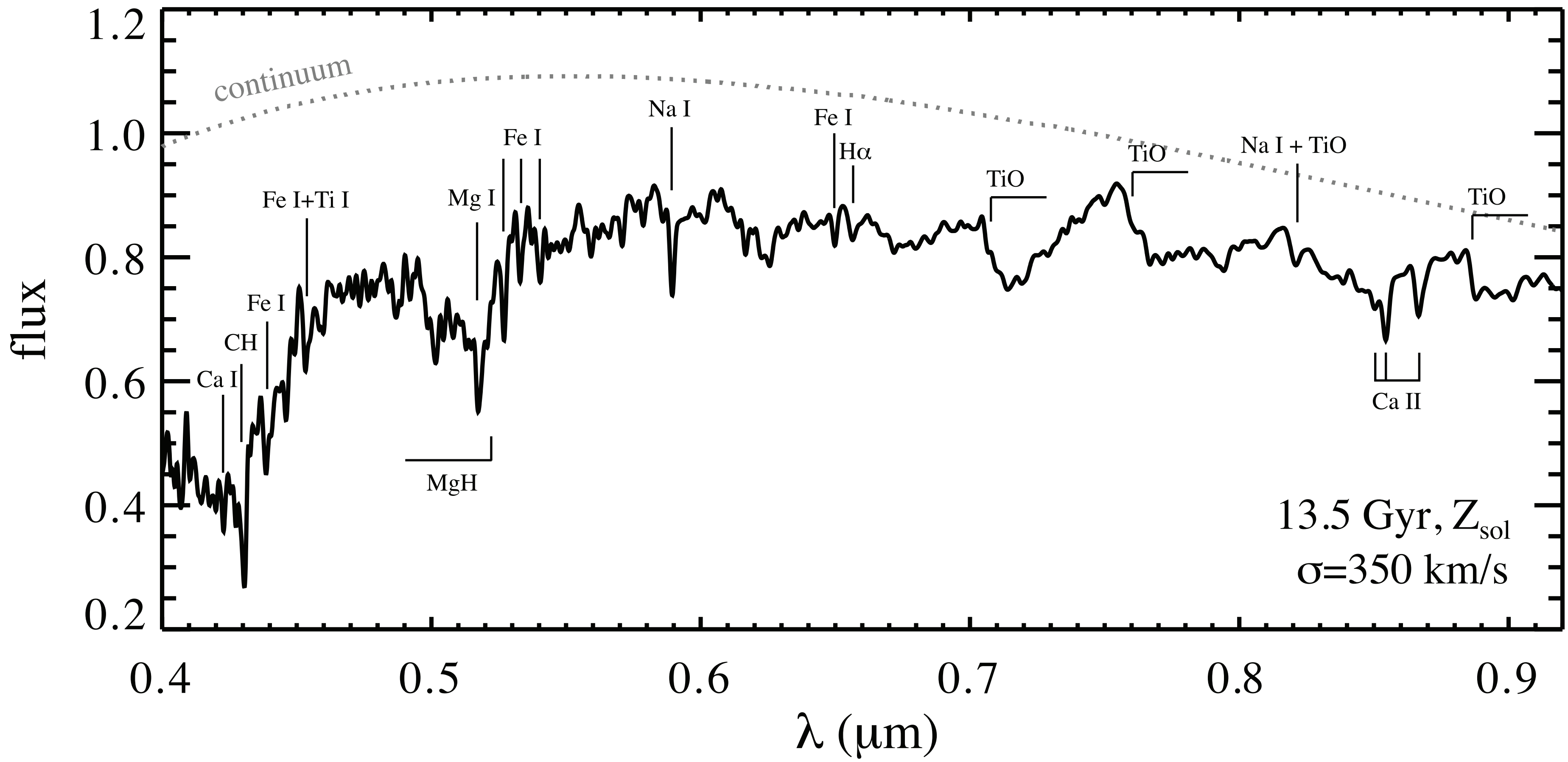


IMF Fingerprints:



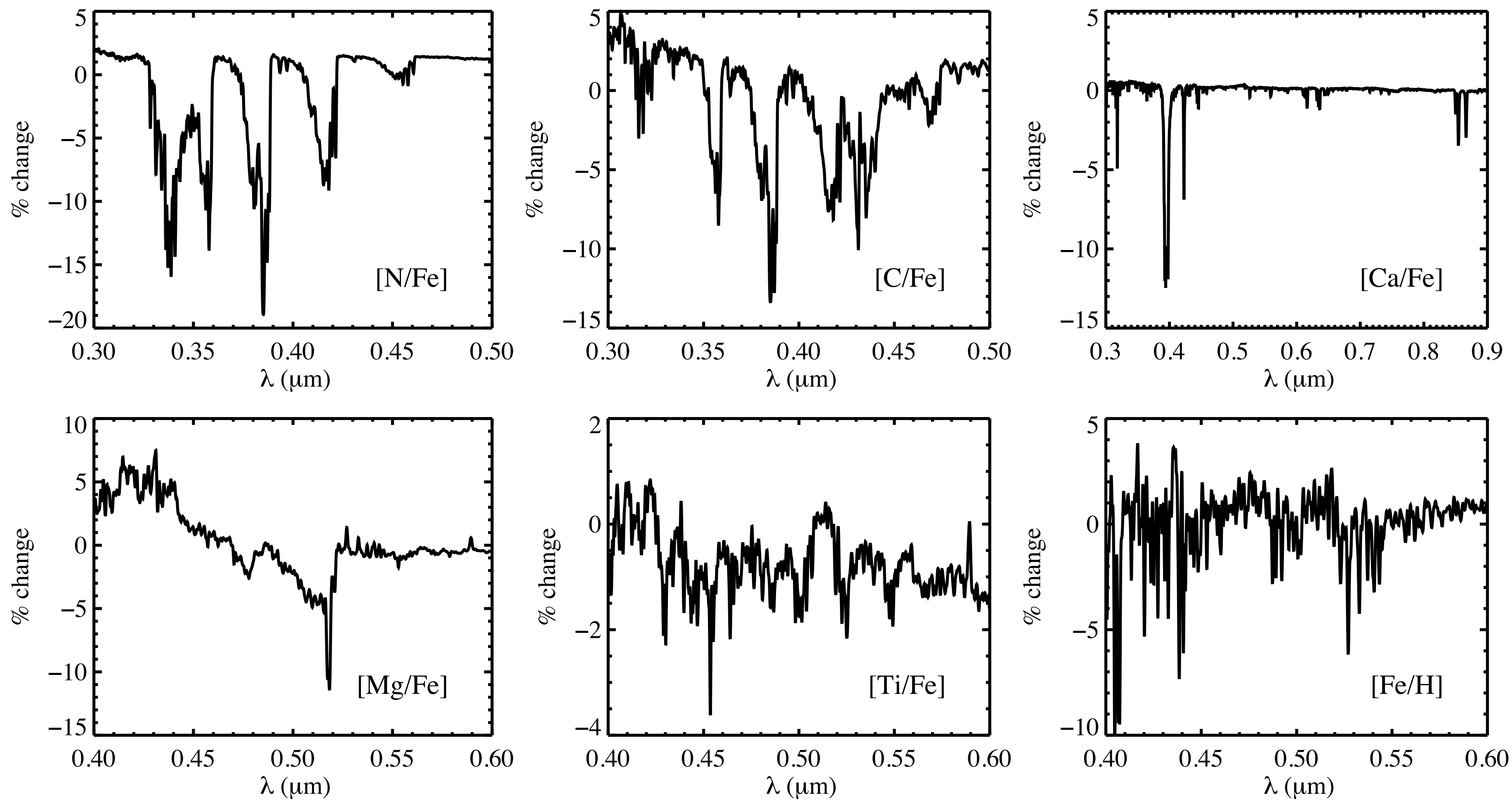
Measuring Abundance Patterns In Galaxies

Model of an early-type galaxy spectrum



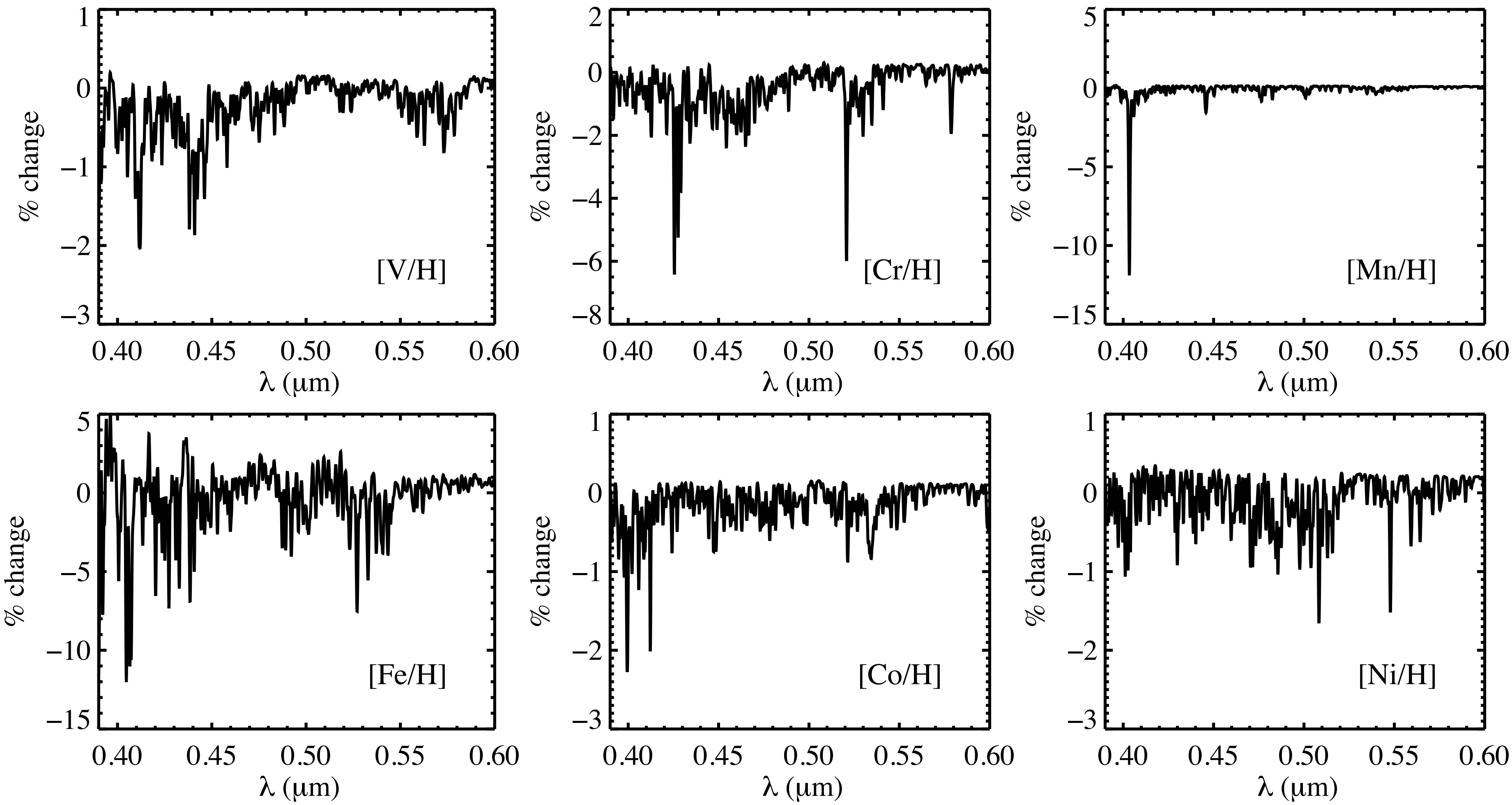
Element Fingerprints

Change in model galaxy due to 2x abundance increase:



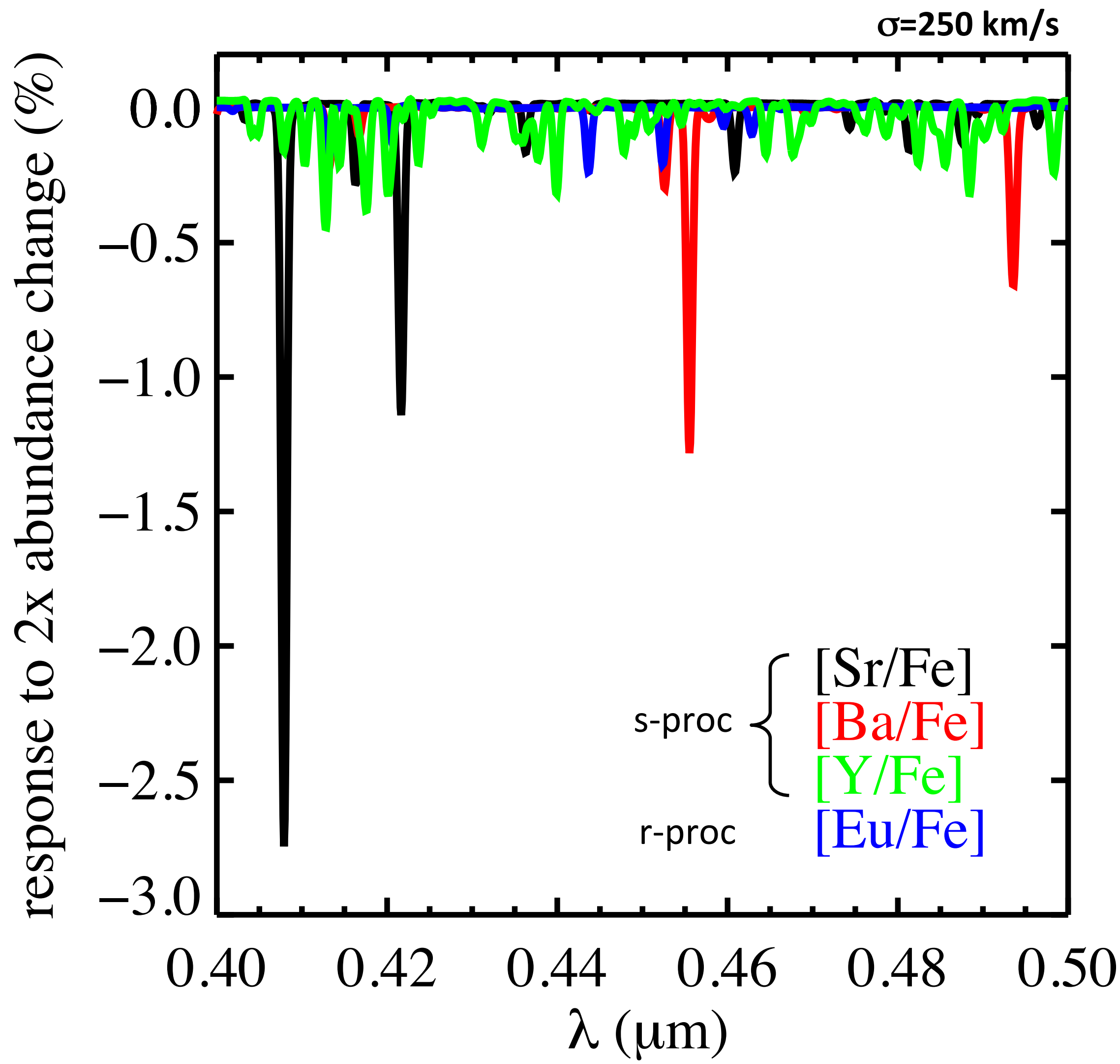
Element Fingerprints

The Iron Peak Elements:

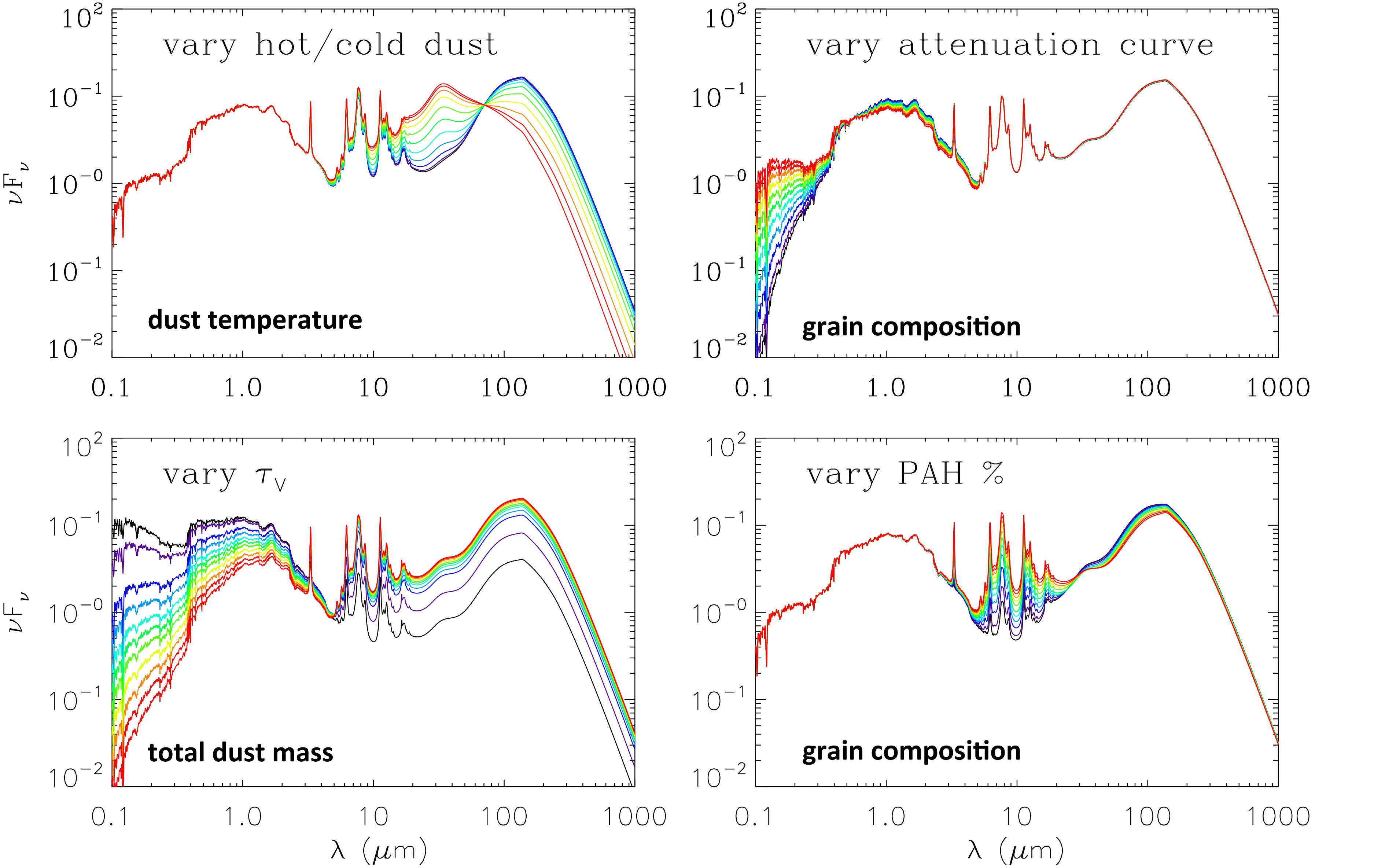


Element Fingerprints

Neutron-capture elements



Measuring Dust Properties



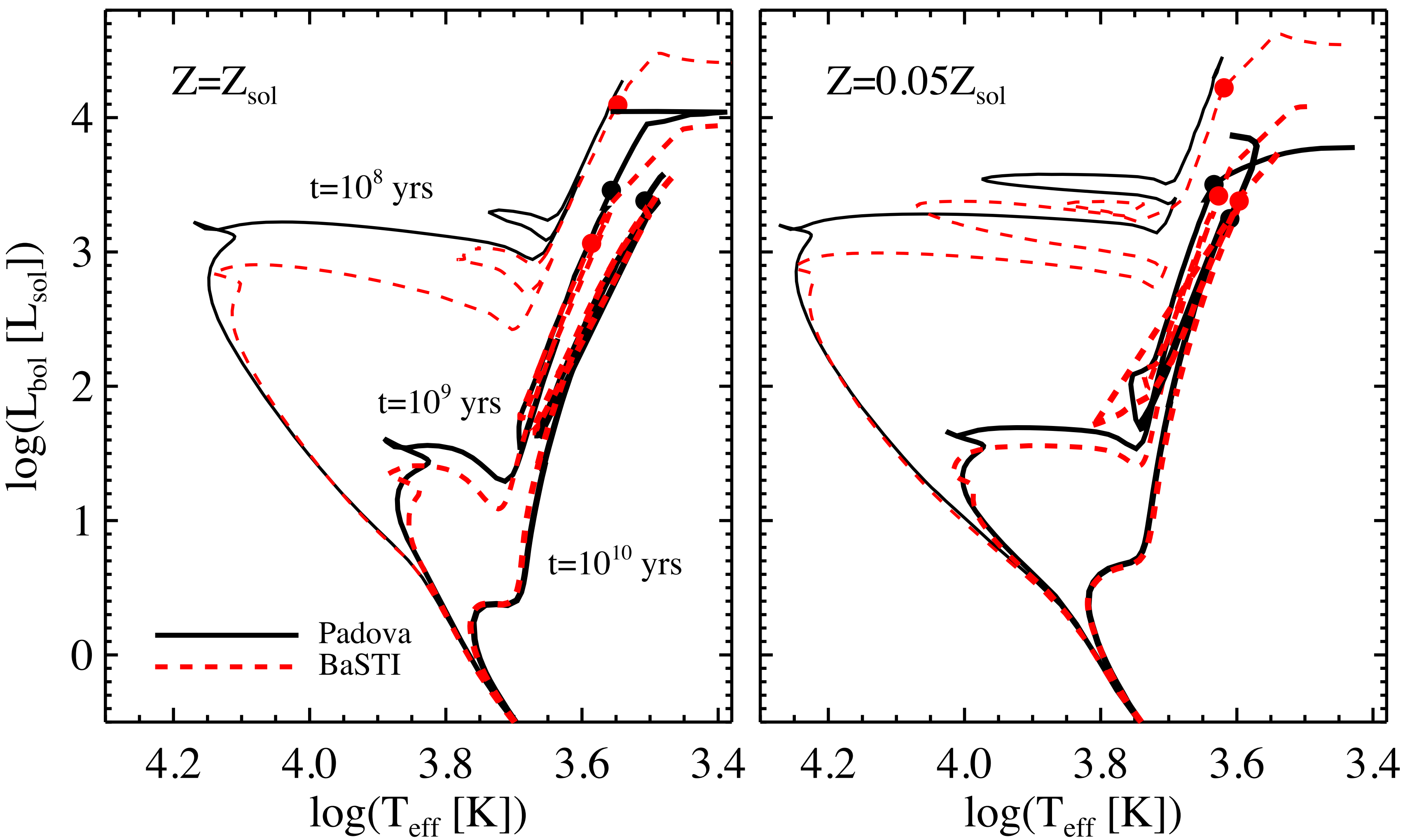
In Principle*, We Should be Able to Measure:

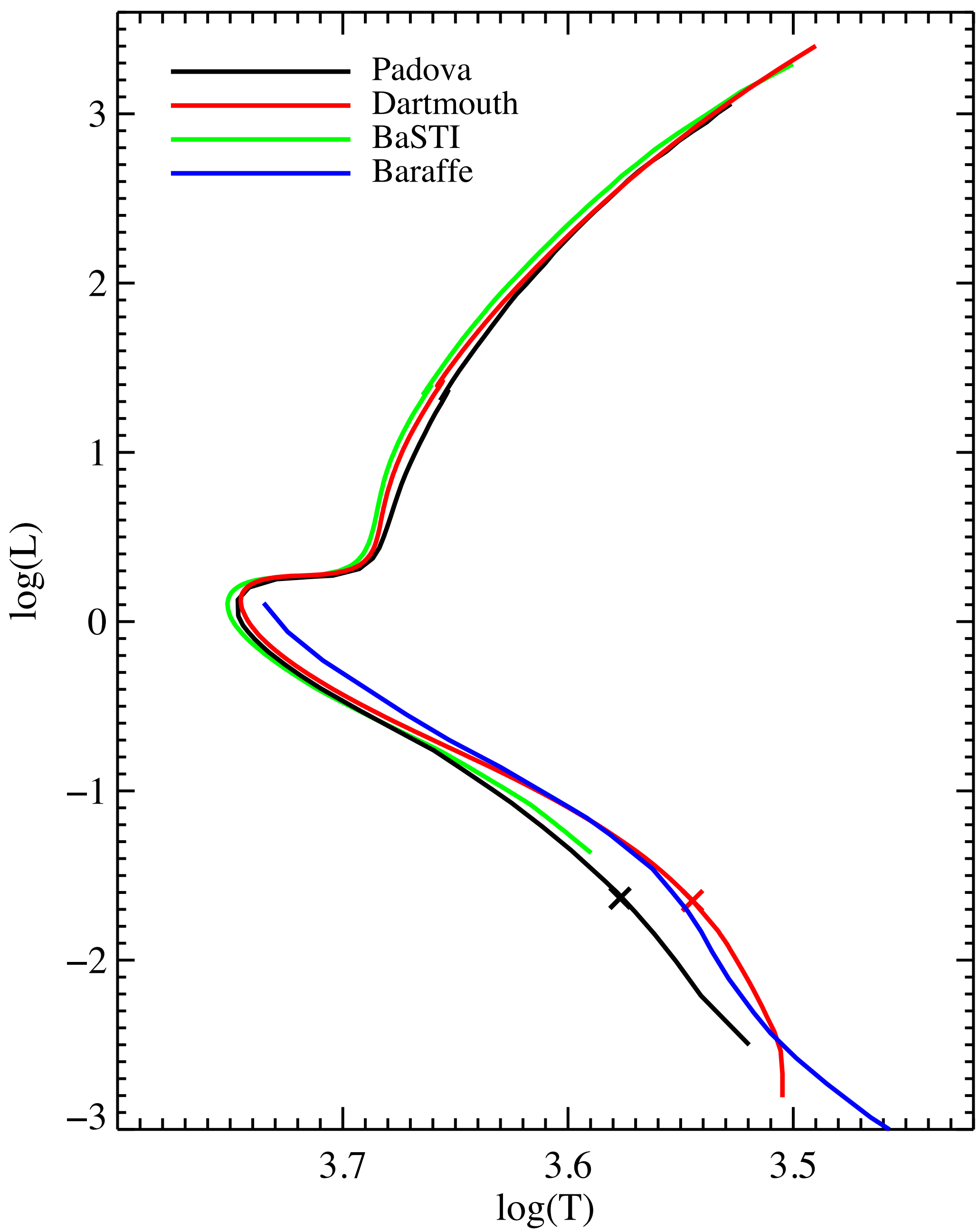
1. Non-parametric star formation histories in 5-10 age bins
2. Metallicity history and/or metallicity distribution function
3. Stellar abundances of at least 15 elements, including light, alpha, Fe-peak, and neutron capture elements
4. The stellar (initial) mass function in 2-3 mass bins
   – Hence measure the “true” stellar mass
5. Temperature, density, and elemental abundances for the “mean” HII region
6. Temperature, mass and rough grain size distribution of dust
7. Star-dust geometry

** For R=2,000 spectra with S/N>10^3 from FUV-FIR, and perfect models*

IV. Why is this hard?

Uncertainties in Stellar Evolution

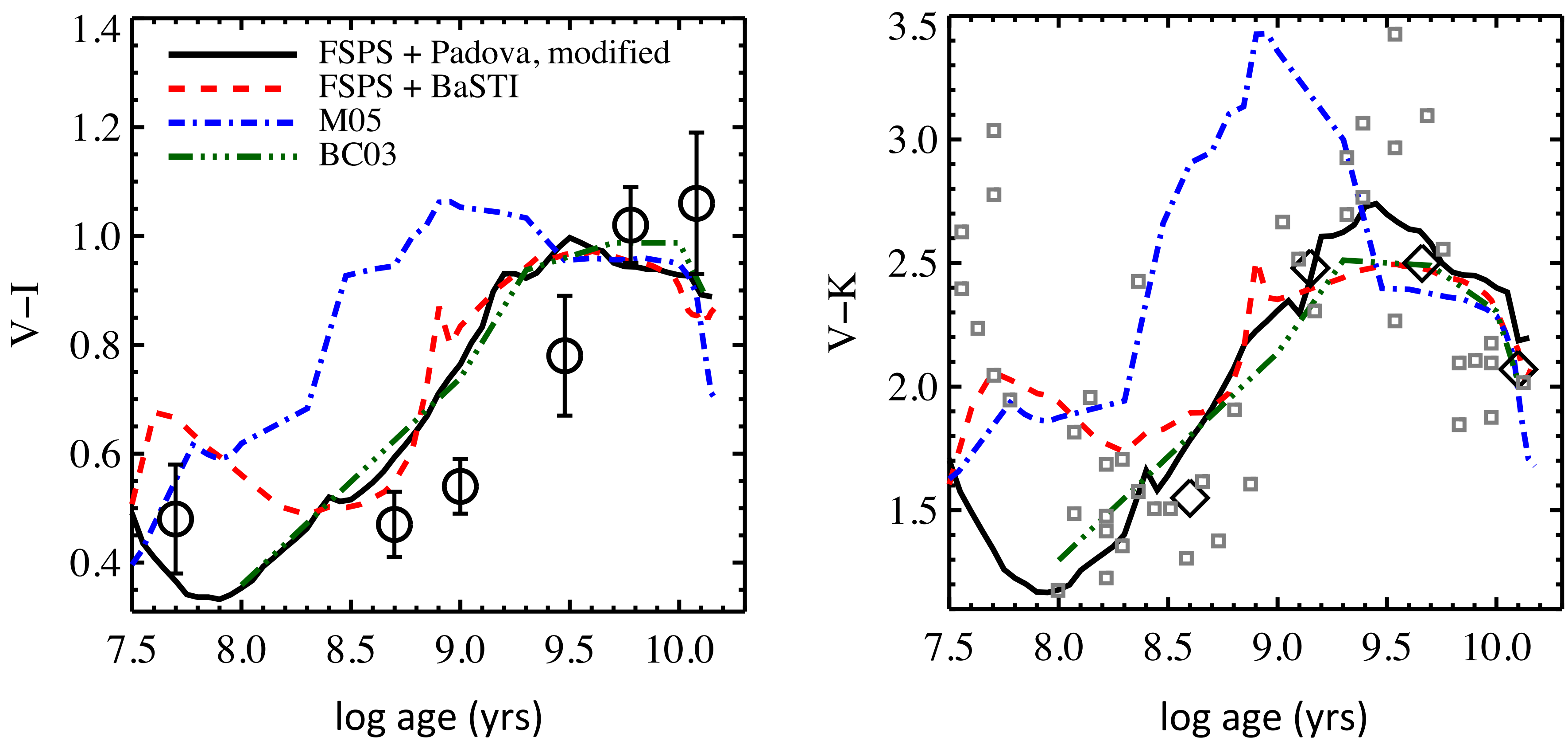




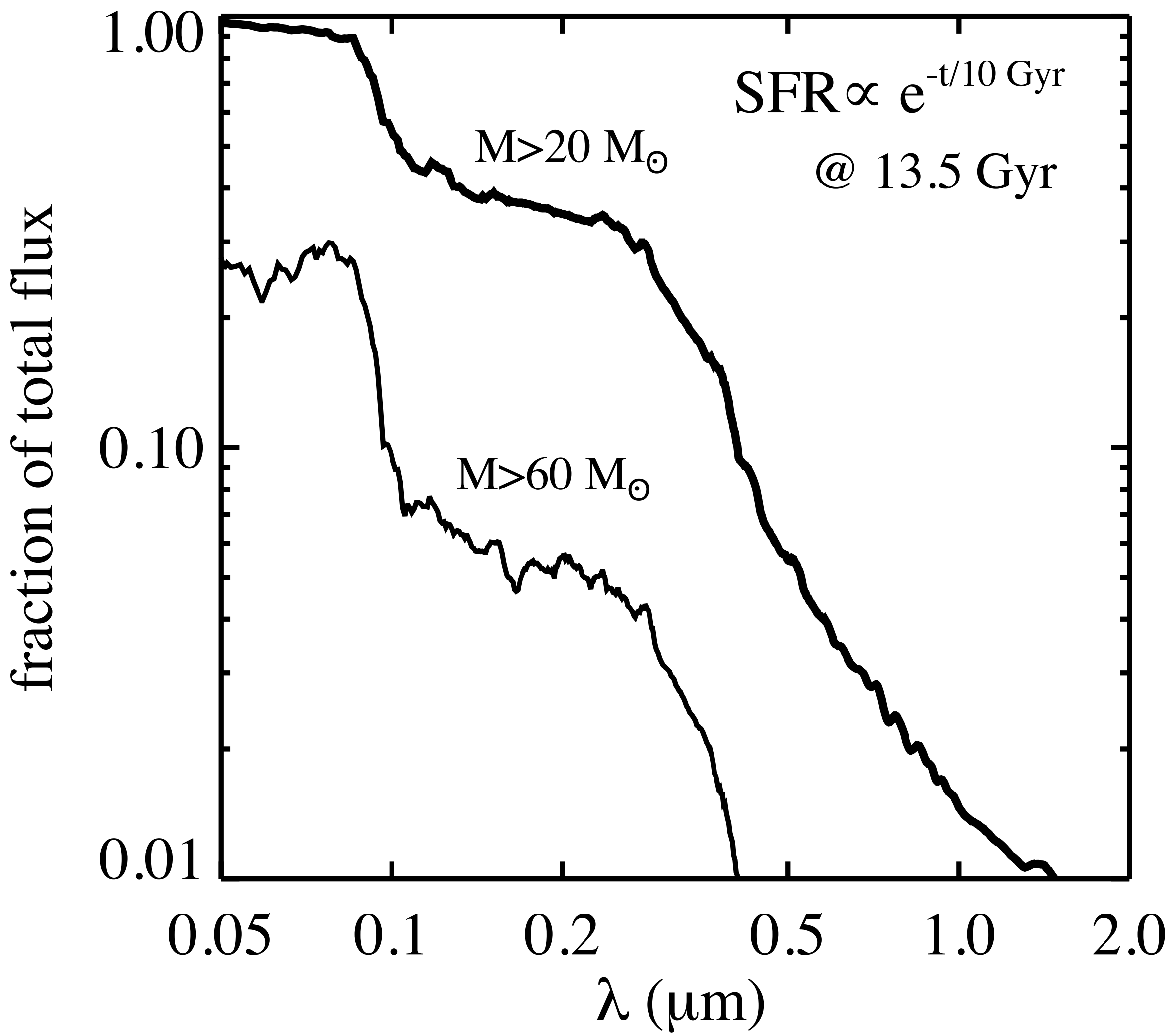
Padova
Dartmouth
BaSTI
Baraffe
log(L)
3
2
1
0
−1
−2
−3
3.7
3.6
3.5
log(T)

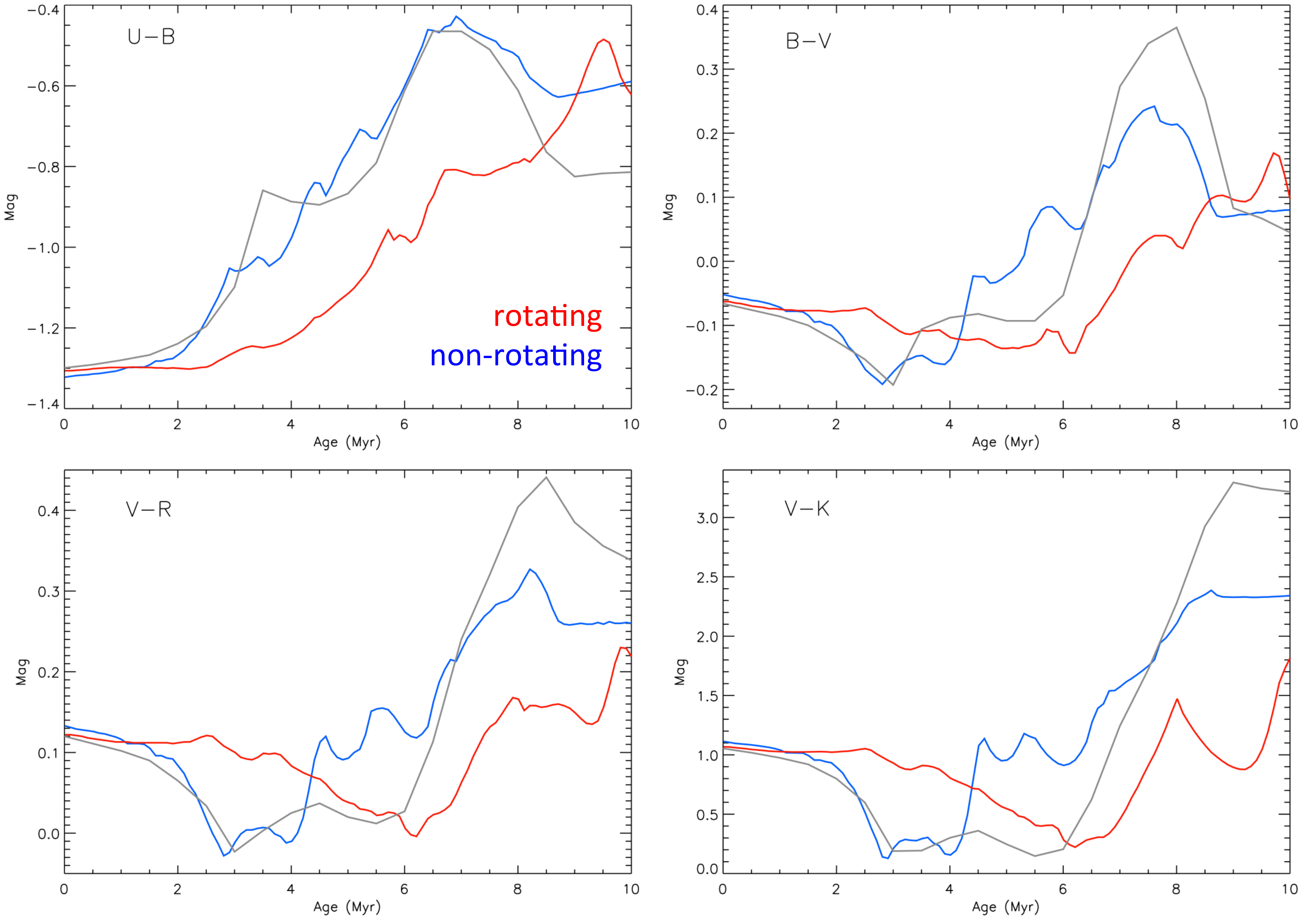
Uncertainties in Stellar Evolution

Colors of star clusters in LMC provide constraints on models



Uncertainties in Modeling Massive Stars

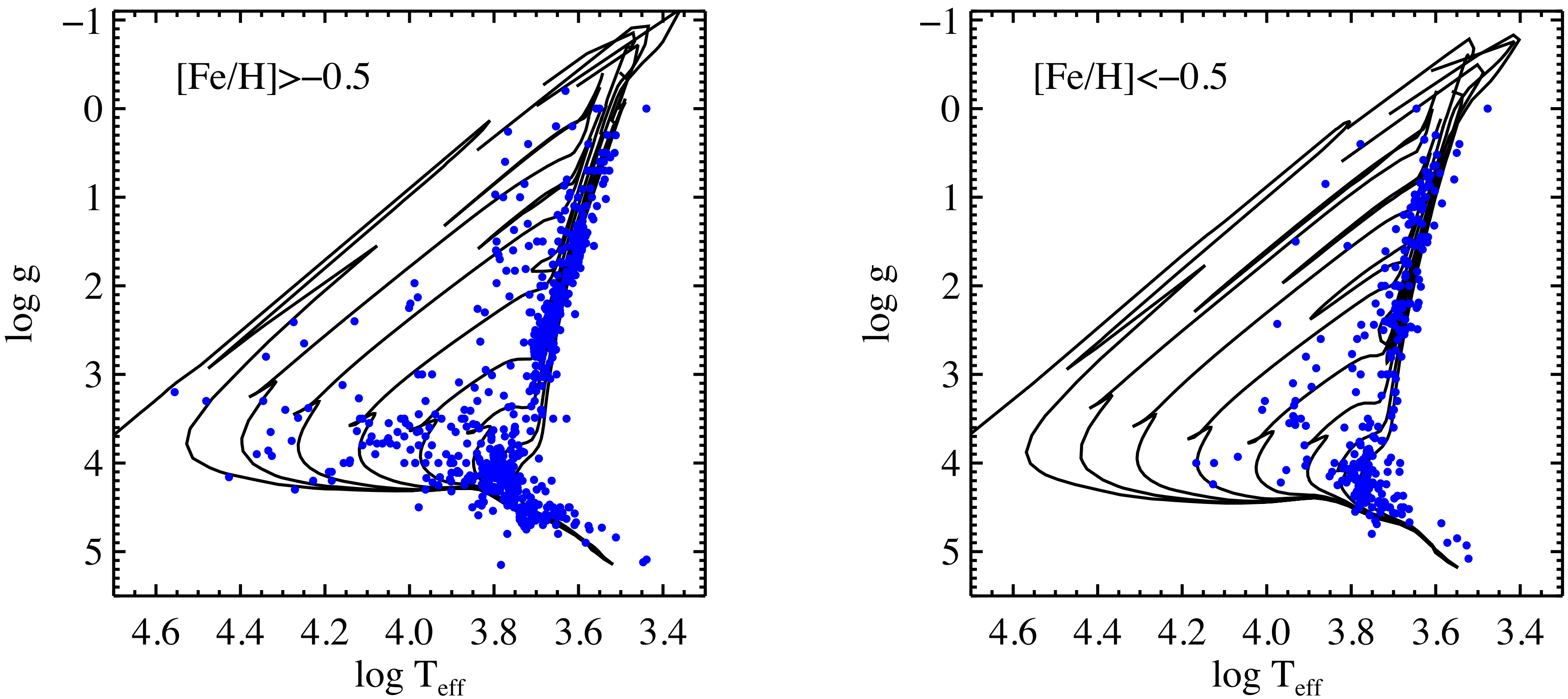




Levesque et al. 2012

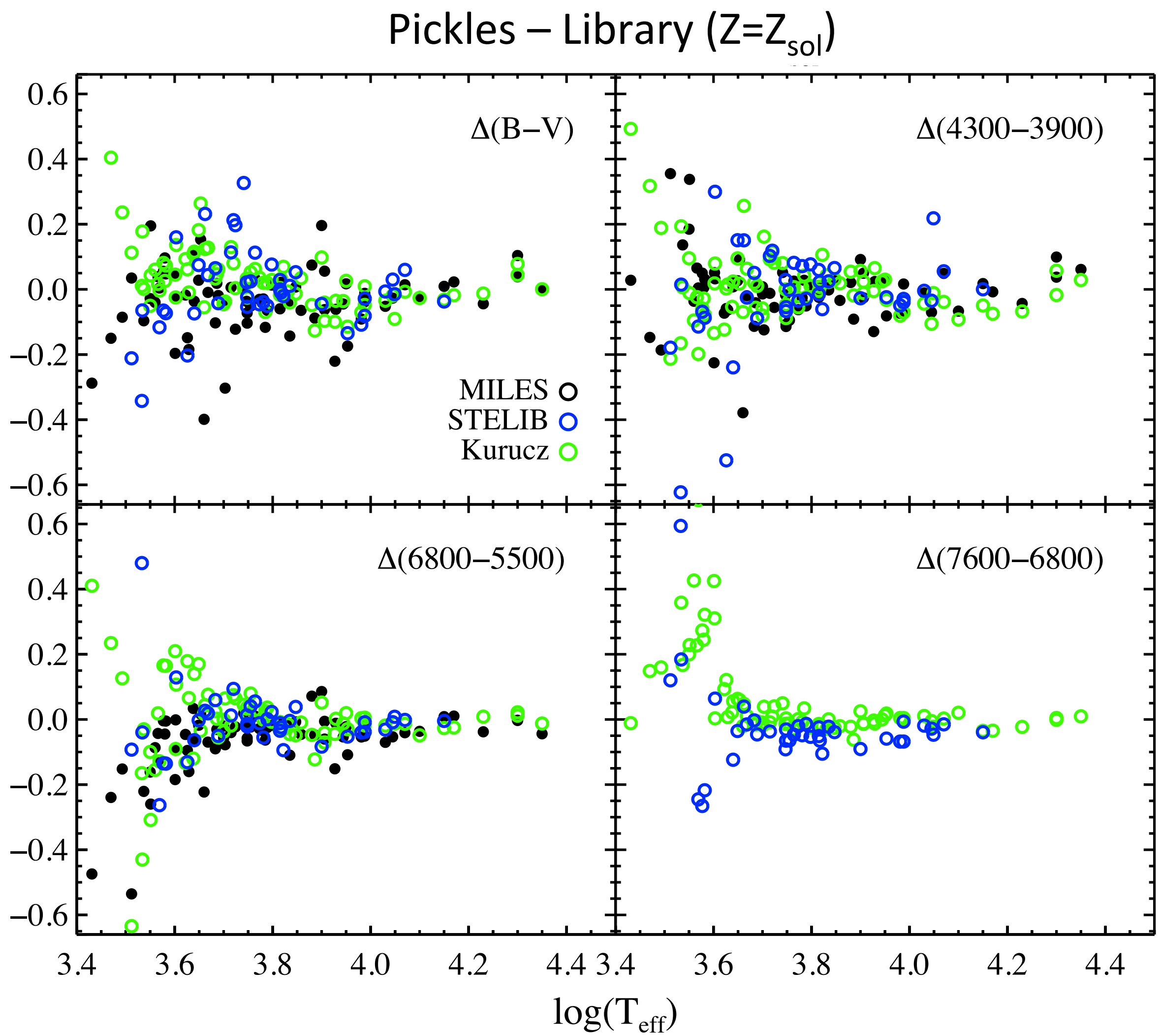
Incomplete Empirical Spectral Libraries

MILES spectral library



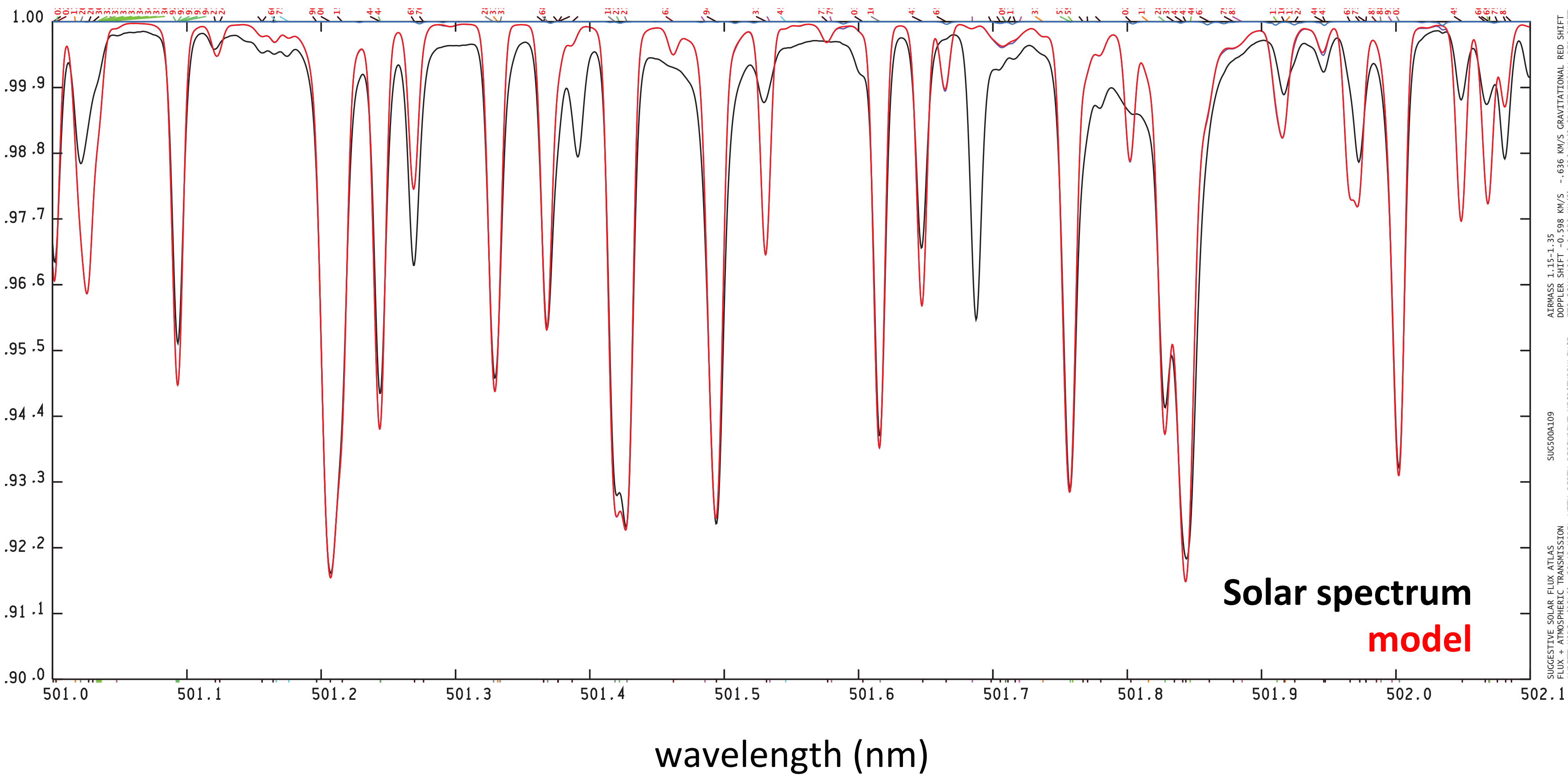
Empirical stellar libraries have sparse coverage in logg/logT/Z

Inconsistent Empirical Spectral Libraries

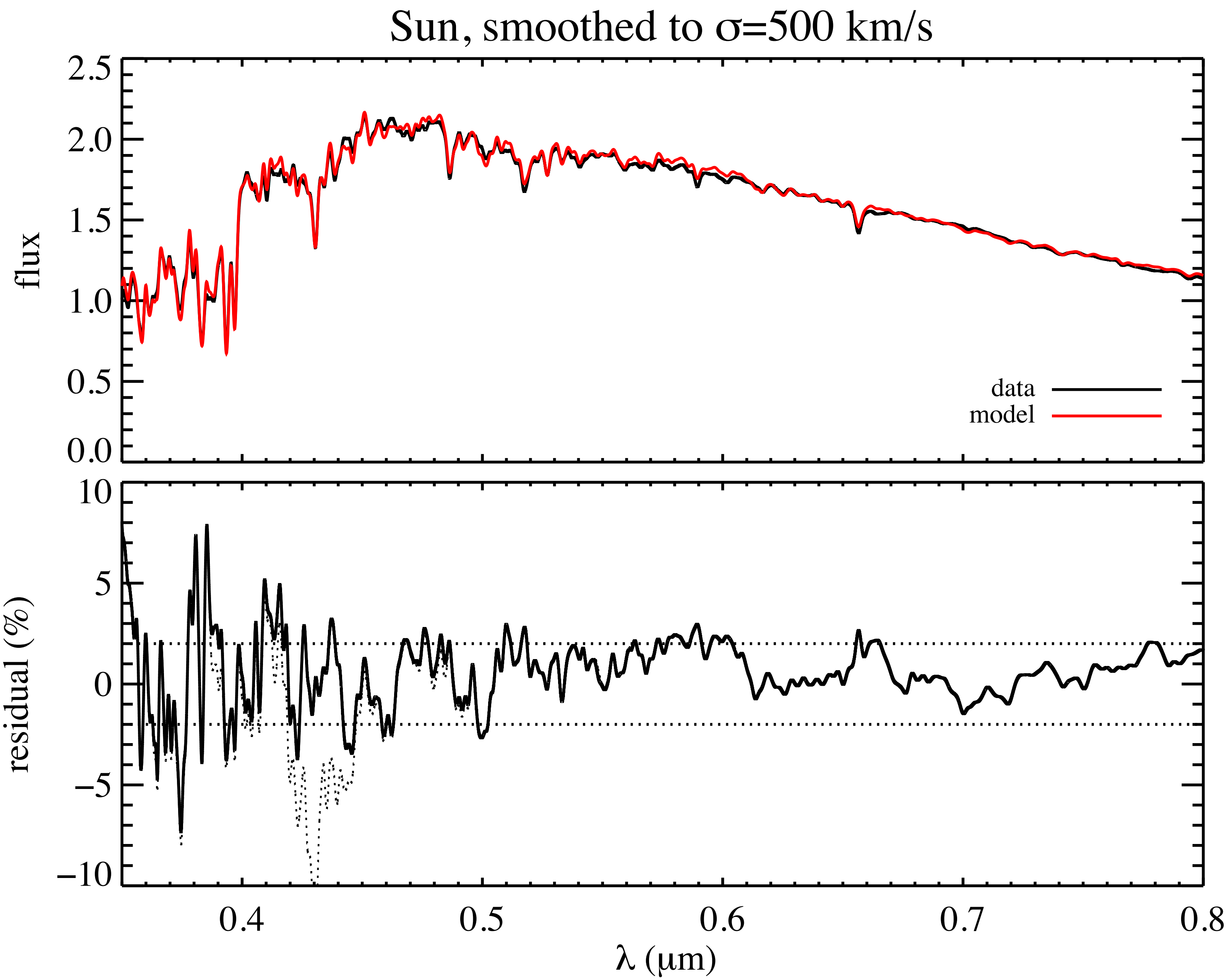


Uncertainties in Modeling Stellar Spectra

Model stellar atmospheres and spectra are uncertain: line lists, corona, B fields, NLTE, 3D, rotation, etc.

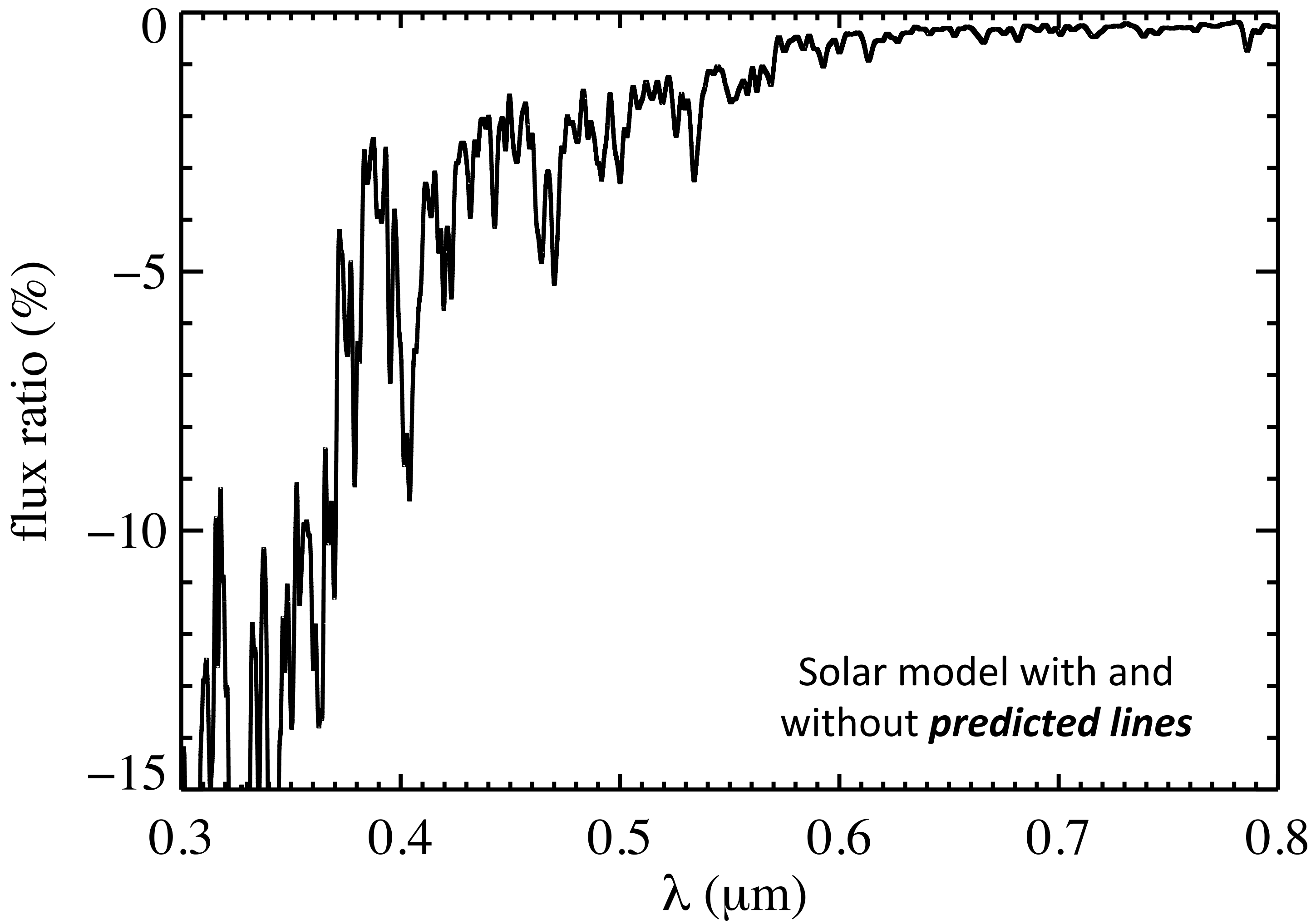


Courtesy of R. Kurucz

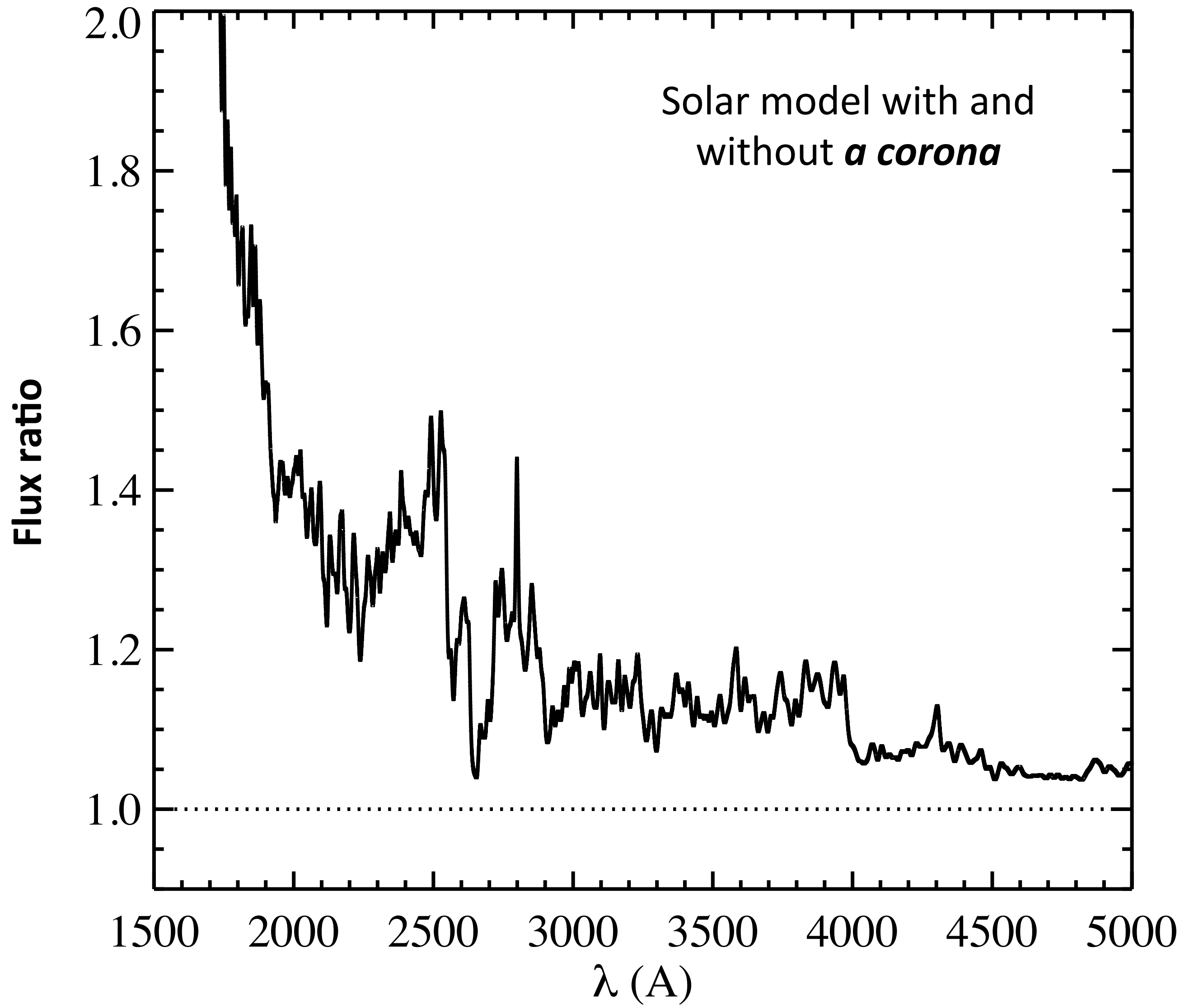


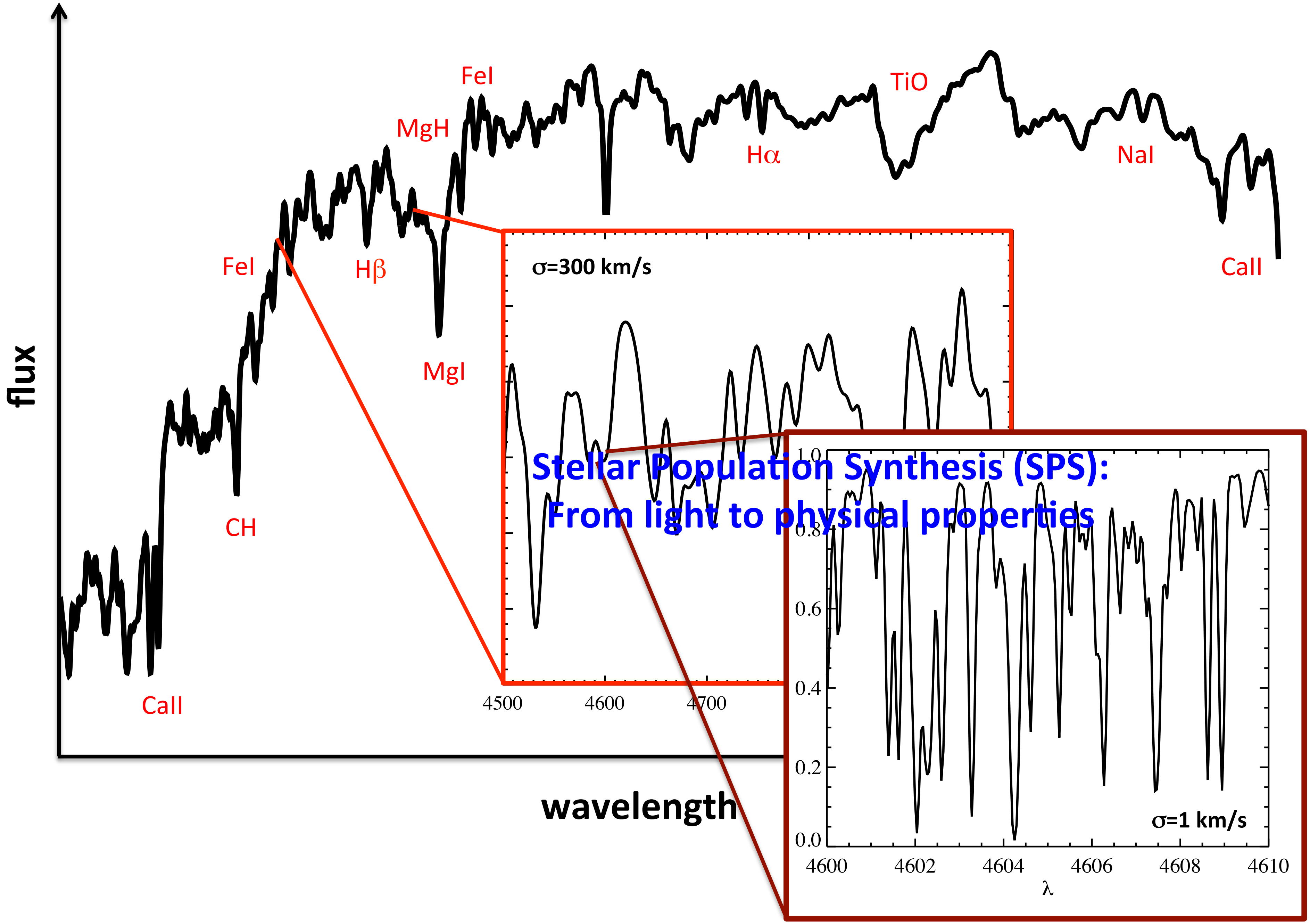
Sun, smoothed to σ=500 km/s
flux
data
model
residual (%)
λ (μm)

Uncertainties in Modeling Stellar Spectra



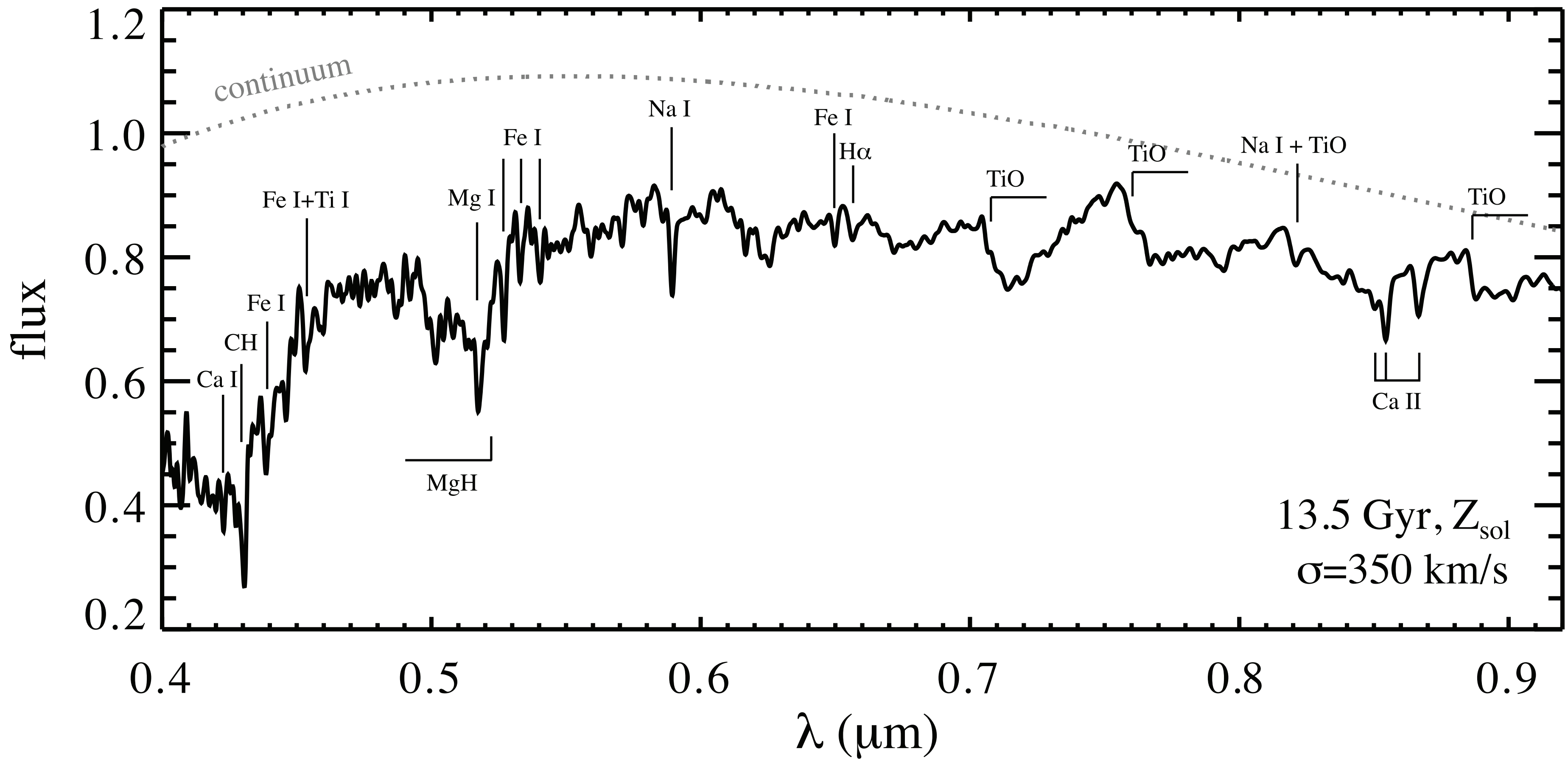
Uncertainties in Modeling Stellar Spectra



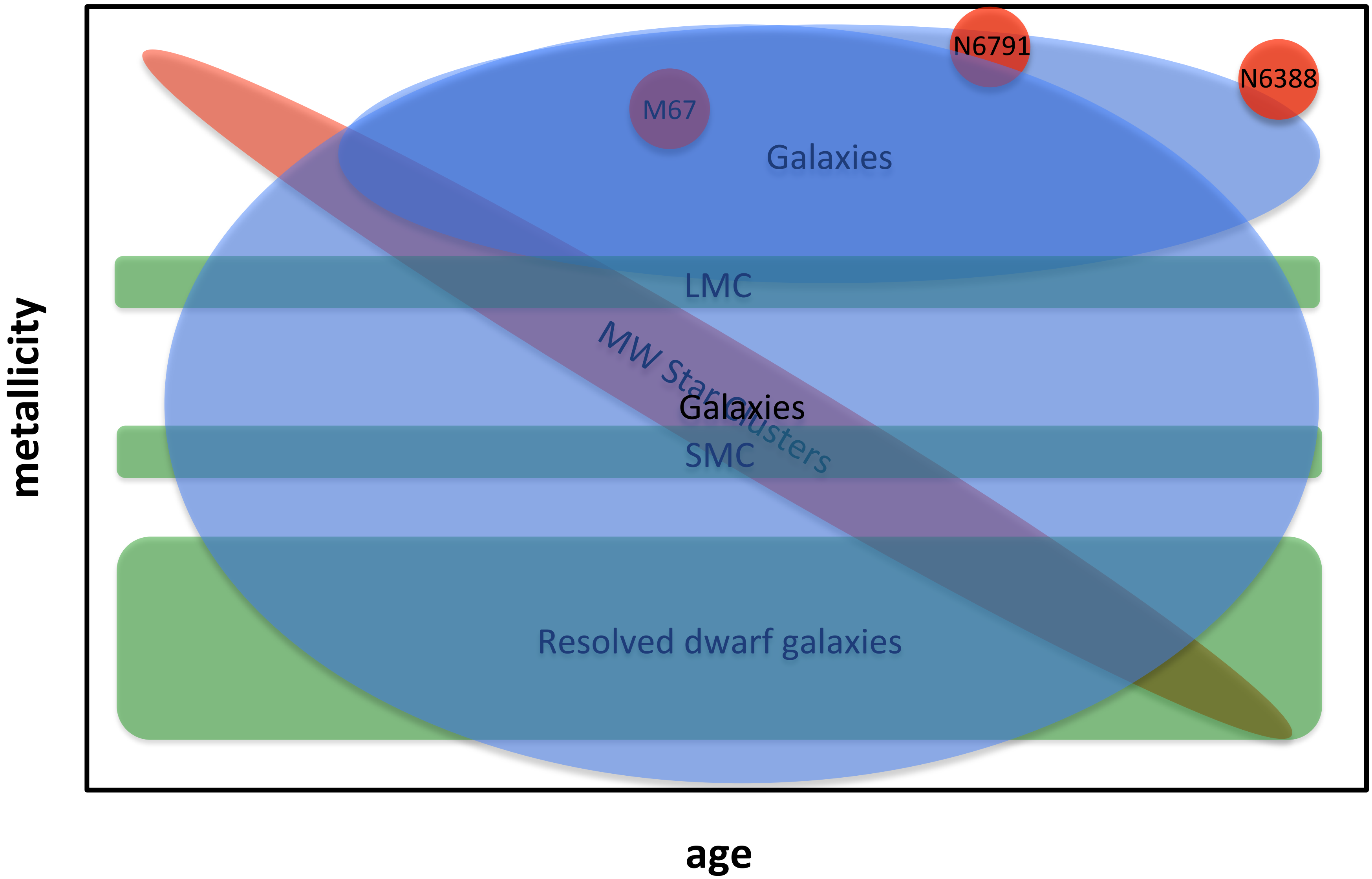


Stellar Population Synthesis (SPS):
From light to physical properties
flux
wavelength
CaII
CH
FeI
Hβ
MgH
MgI
FeI
Hα
TiO
NaI
CaII
σ=300 km/s
4500
4600
4700
σ=1 km/s
1.0
0.8
0.6
0.4
0.2
0.0
4600
4602
4604
4606
4608
4610
λ

Model of an early-type galaxy spectrum

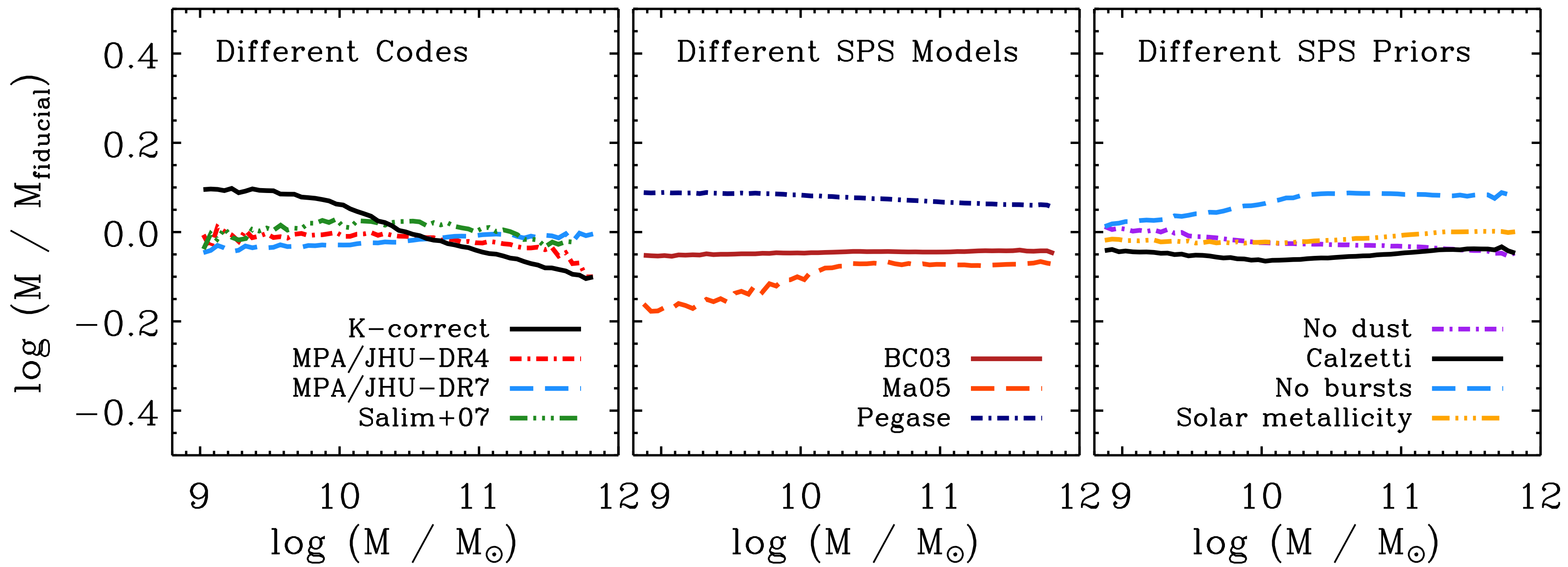


The Challenge of Model Calibration



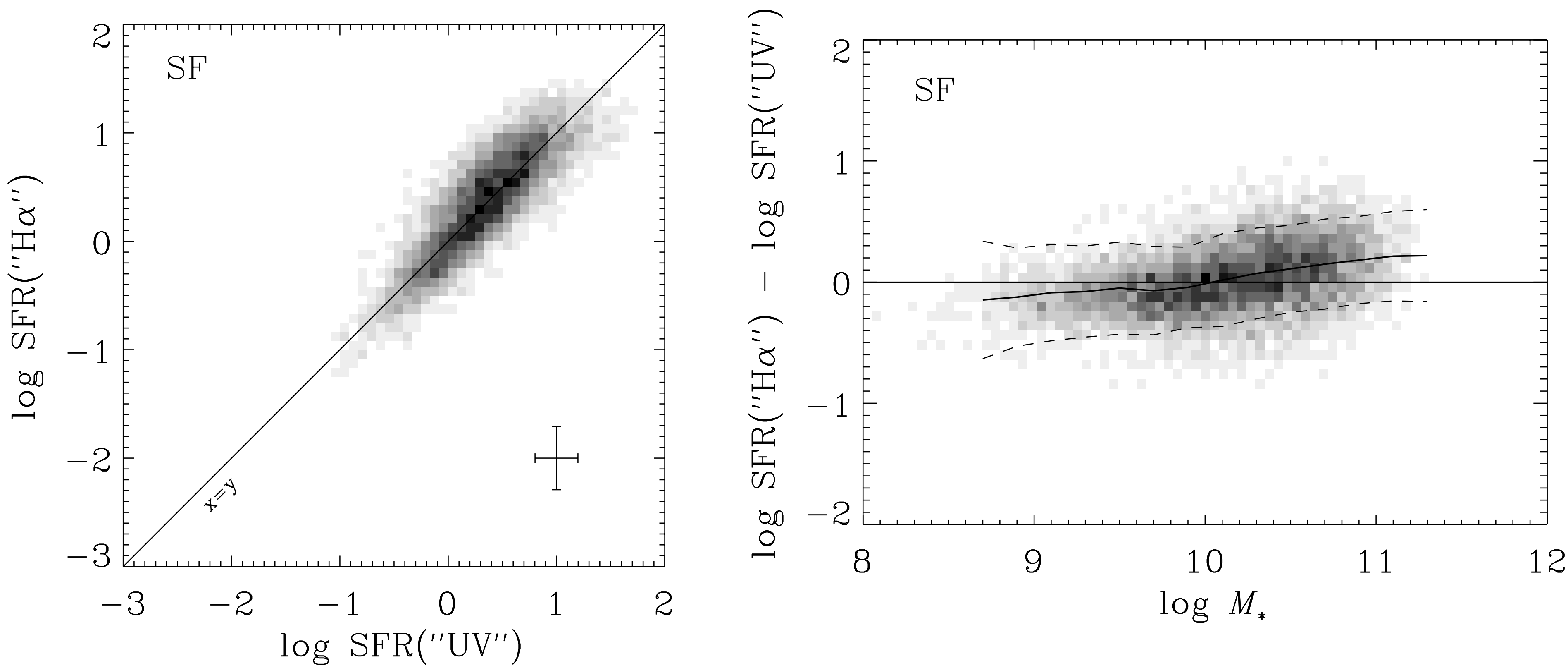
V. OK, so why should you believe anything from Part I?

Stellar Masses are Remarkably Robust



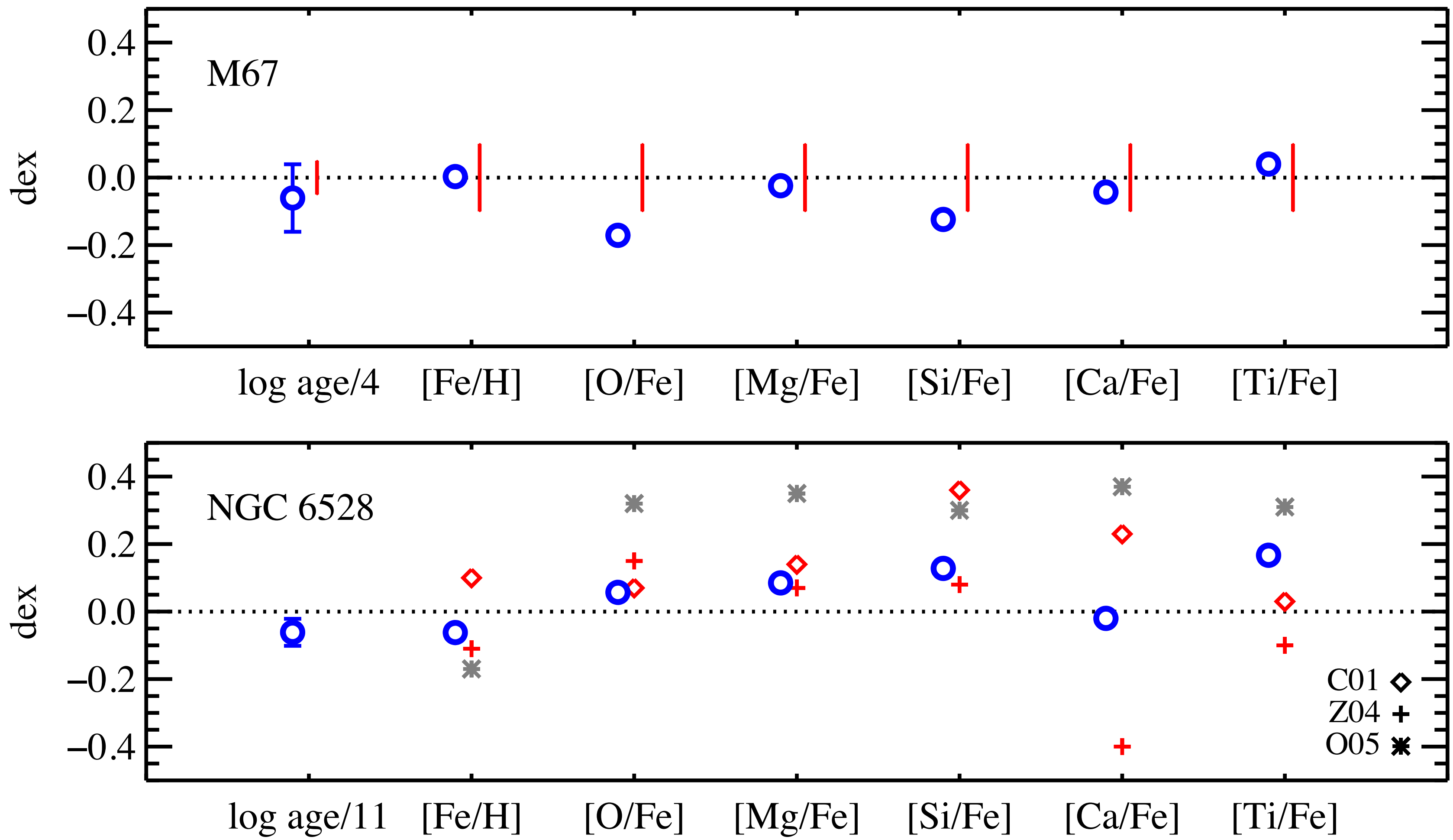
Moustakas et al. 2013

So are SFRs (more or less)



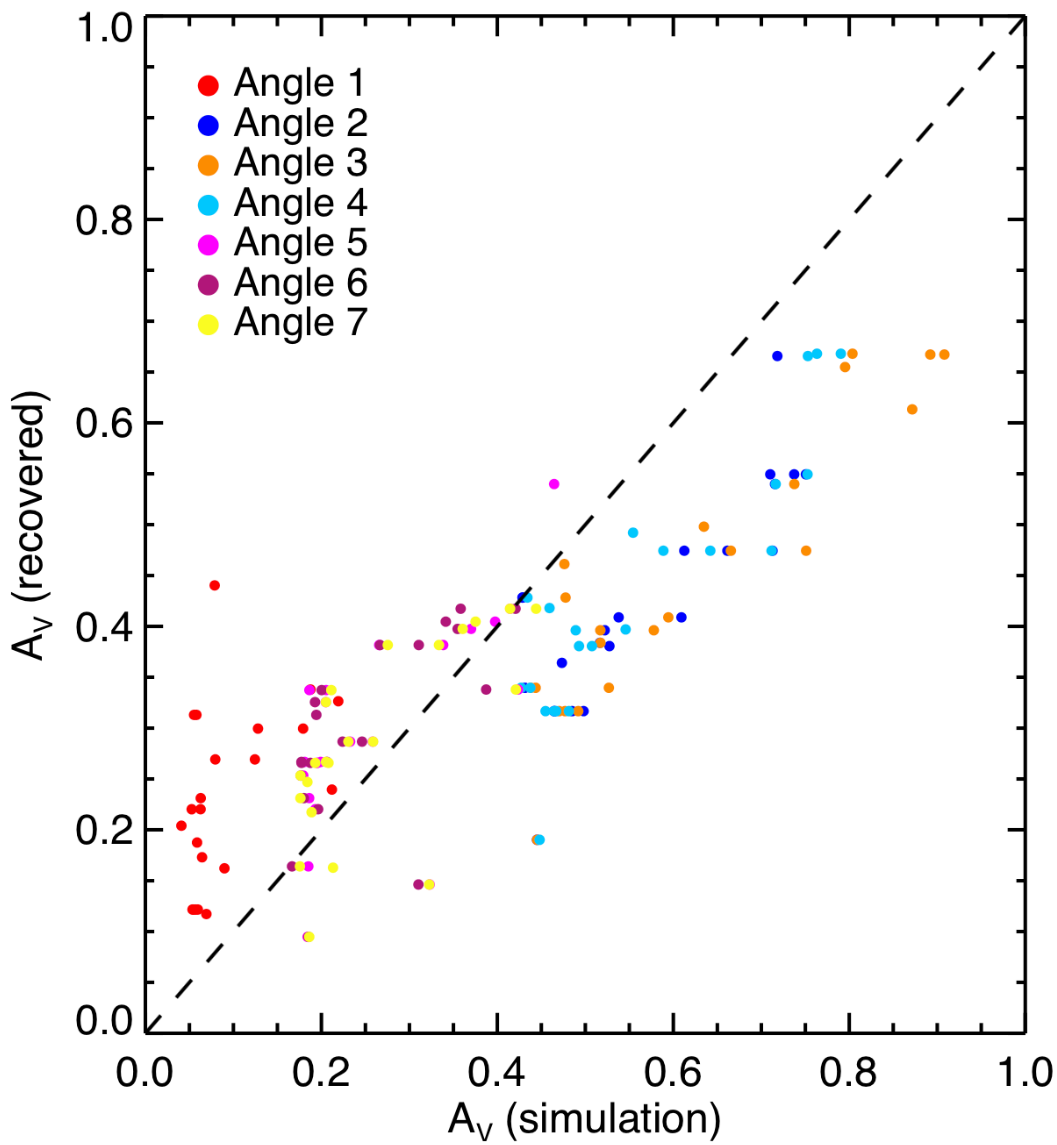
Salim et al. 2007
Brinchmann et al. 2004

Model Validation with MW Star Clusters



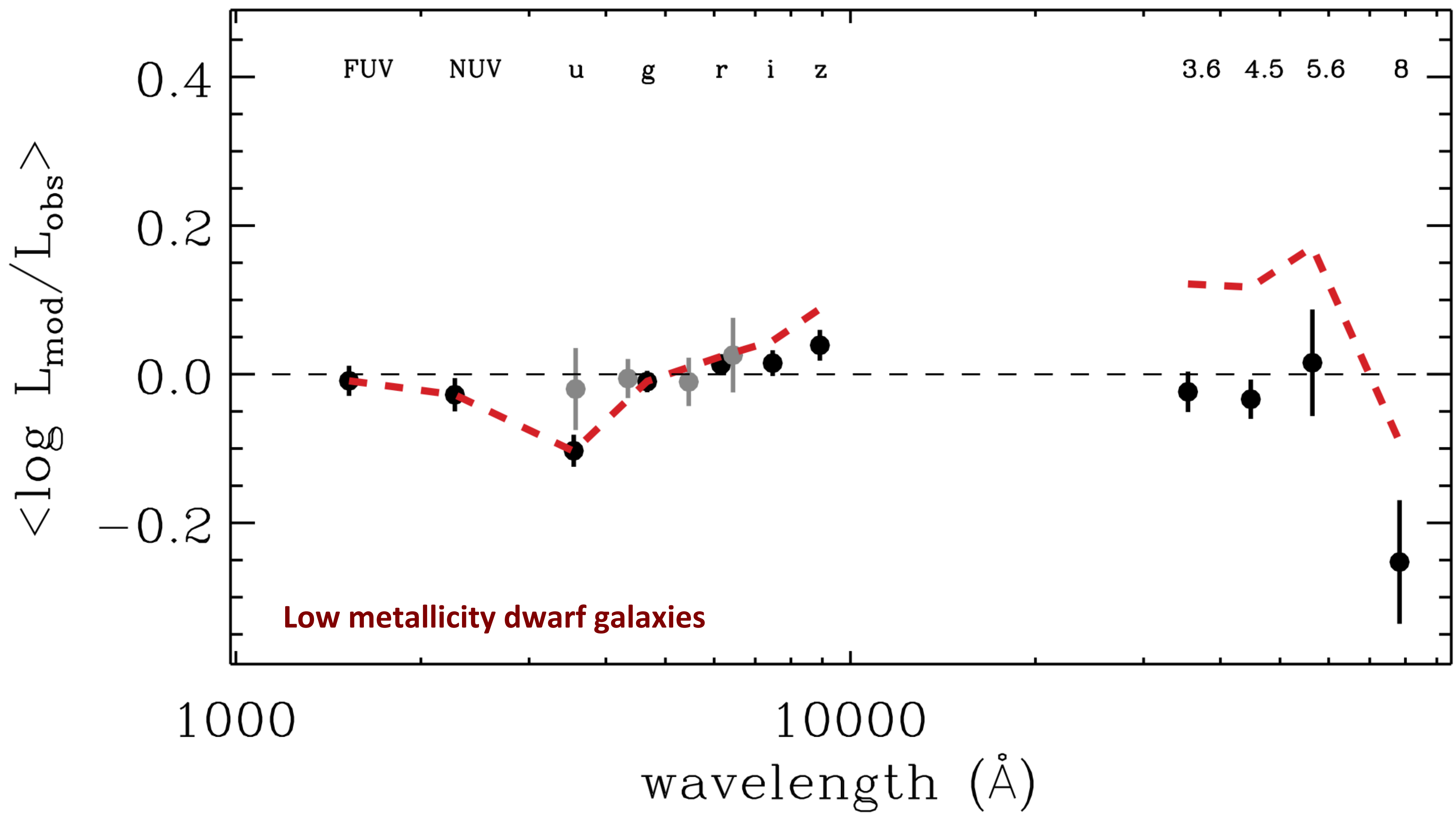
Spectral fitting an integrated light spectrum of clusters

Model Testing with Simulations



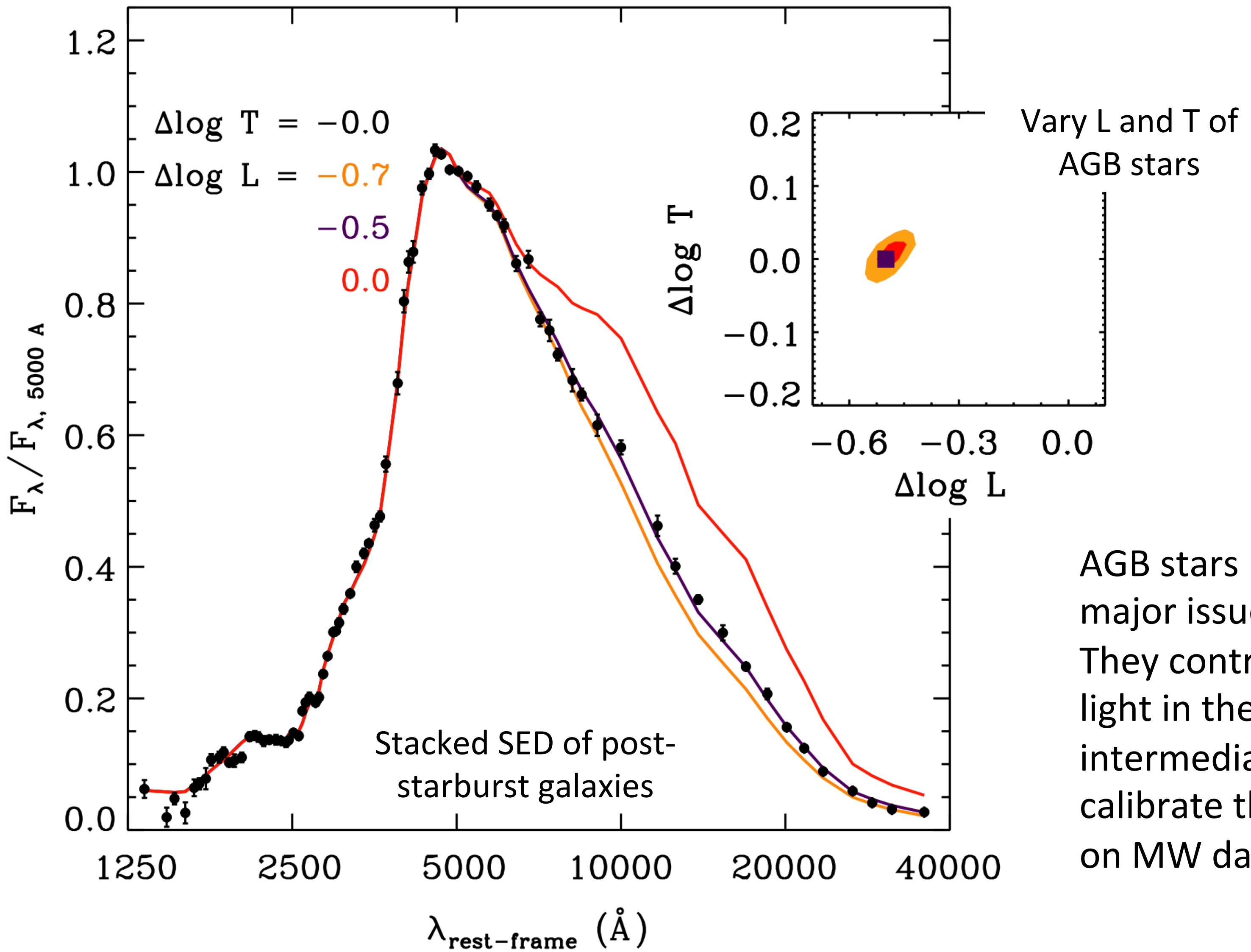
Hayward & Smith 2014

Model Testing with Resolved SFHs



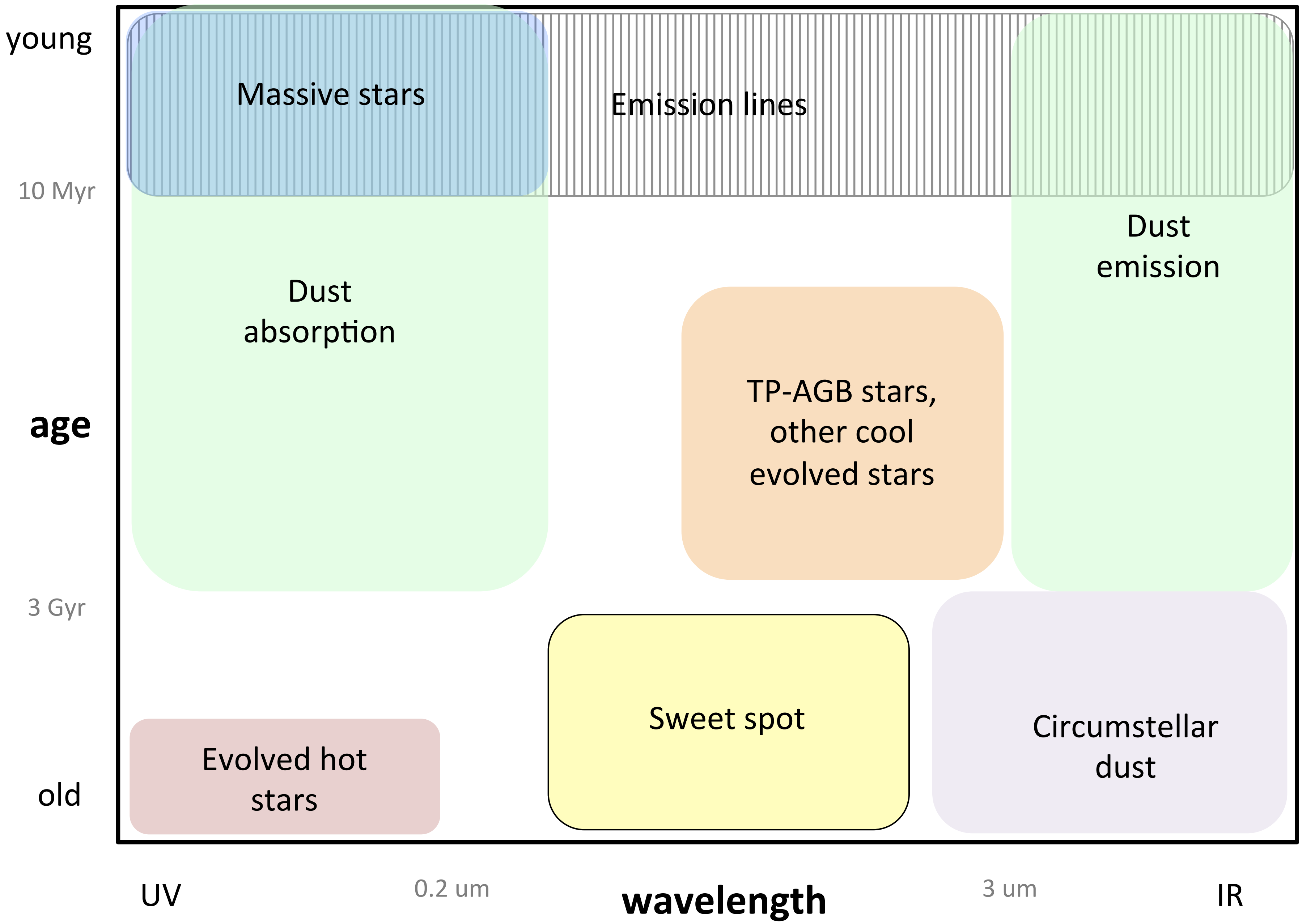
Johnson et al. 2013

Constraining Stellar Evolution with Galaxies?



AGB stars have become a major issue in this field. They contribute a lot of light in the NIR at intermediate ages. Hard to calibrate this phase based on MW data

Kriek et al. 2013


young
10 Myr
age
3 Gyr
old
Massive stars
Emission lines
Dust absorption
Dust emission
TP-AGB stars, other cool evolved stars
Evolved hot stars
Sweet spot
Circumstellar dust
UV
0.2 um
wavelength
3 um
IR