The Stellar Population Synthesis Technique

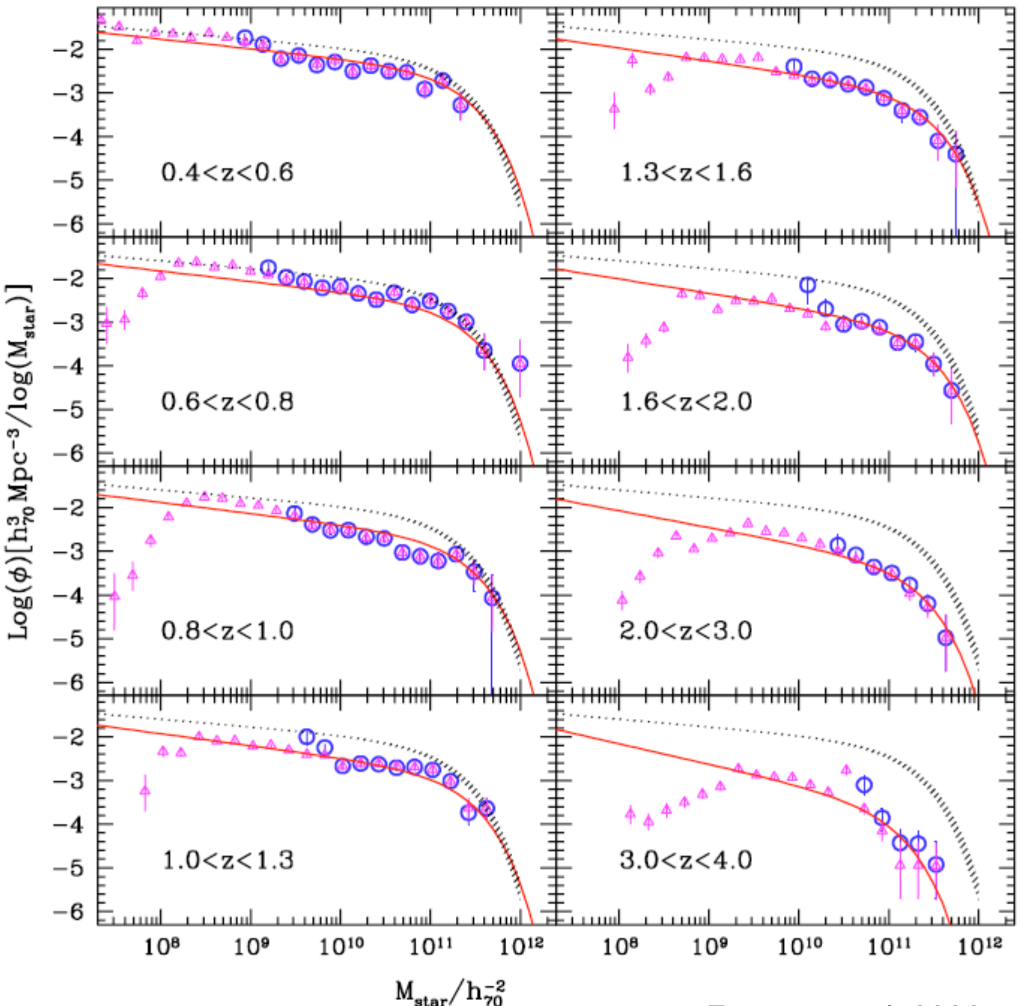
Charlie Conroy
Princeton

Outline

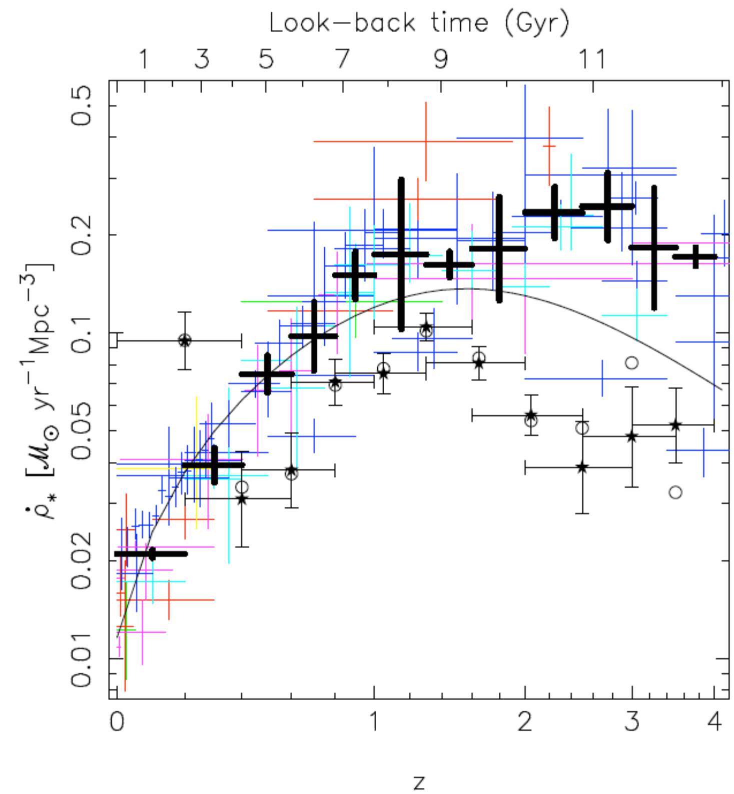
1. Introduction to stellar population synthesis (SPS)
   - What's the matter?
2. Flexible SPS
   - Propagation of uncertainties in SPS
   - Constraining models
     - i.e. comparing to star clusters
   - Assessing models
     - i.e. comparing to galaxies
3. Dust
   - Effects on mass estimates
   - Constraints from disk-dominated galaxies

Galaxies, then and now

Galaxy stellar mass function from z~4 to z~0



Fontana et al. 2006

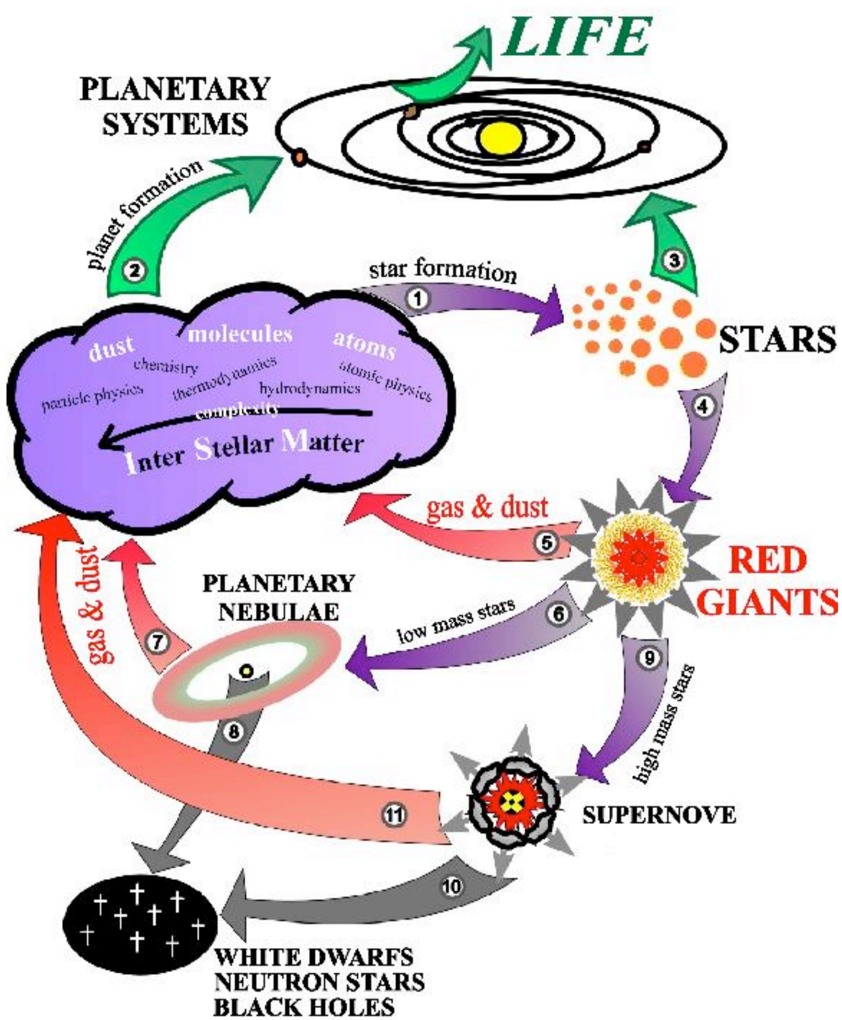


Perez-Gonzalez et al. 2007

How are these physical properties derived?

Stellar Population Synthesis: Overview

- Stellar population synthesis (SPS) utilizes the fact that galaxies are made of dust and stars
  - Gas largely ignored unless considering emission lines
  - We simply need to know the number of stars as a function of their mass, age, and metallicity
  - Starlight attenuated by dust
    - Focus on UV, optical, near-IR data, and so ignore dust emission
- **SPS provides the fundamental link between theory/models and observations**
  - Used extensively in extragalactic astrophysics



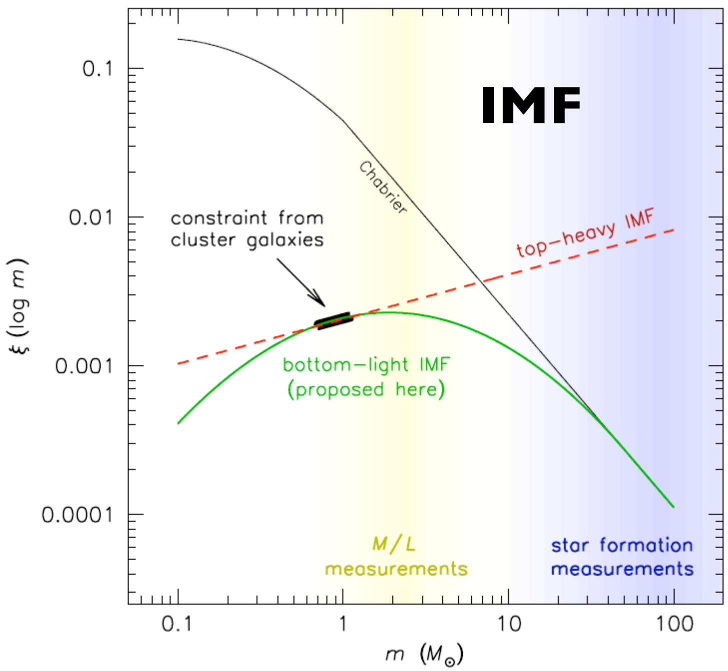
Stellar Population Synthesis - I

- Single/simple stellar populations (SSPs):

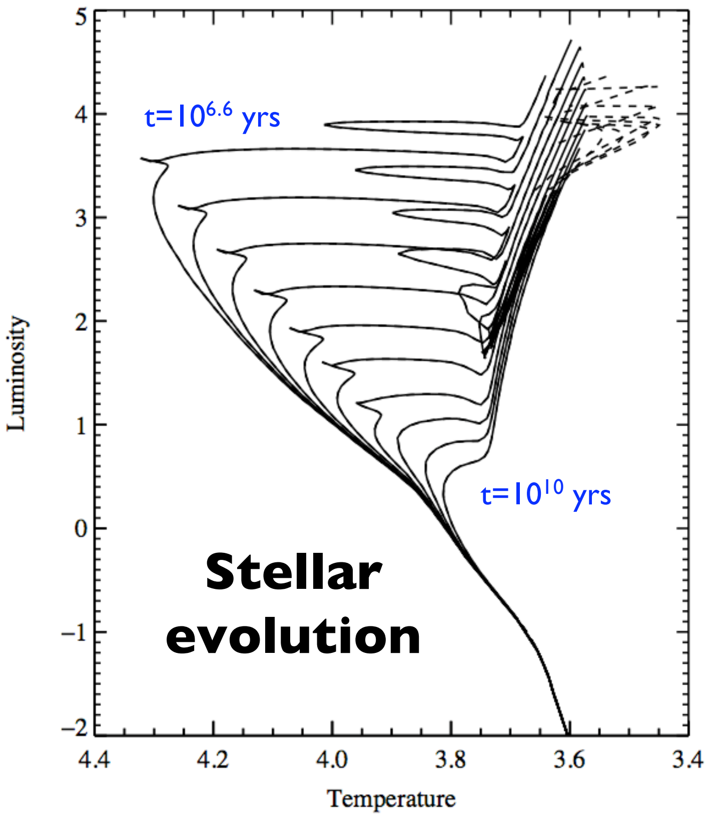
$$S(t,Z)=\int_{M_i^l}^{M_i^u(t)}\Phi(M_i)\Lambda[L(M_i,Z,t),T(M_i,Z,t),Z]\,\mathrm{d}M_i$$

IMF x spectra(stellar mass)

→ star clusters



Van Dokkum 2008



Stellar Population Synthesis - II

- Composite stellar populations (CSPs):

$$F_\lambda(t,Z) = \int_0^t \Psi(t-t')S_\lambda(t',Z)\,e^{-\tau_\lambda(t')}\,\mathrm{d}t'$$

SFR x SSP x dust

Integrate over stellar ages t'

galaxies

An example: a galaxy made of two populations:

$$\boxed{F_\lambda \sim \Phi(M_1)\Psi(t_1)S_\lambda(M_1,t_1) + \Phi(M_2)\Psi(t_2)S_\lambda(M_2,t_2)}$$

Stellar Population Synthesis: Challenges

SPS Model: IMF, spectral library, stellar evolution, SFH, dust, metallicity

↓ fit parameters of model to data

Observations: Spectral energy distributions, magnitudes, etc.

→ physical properties

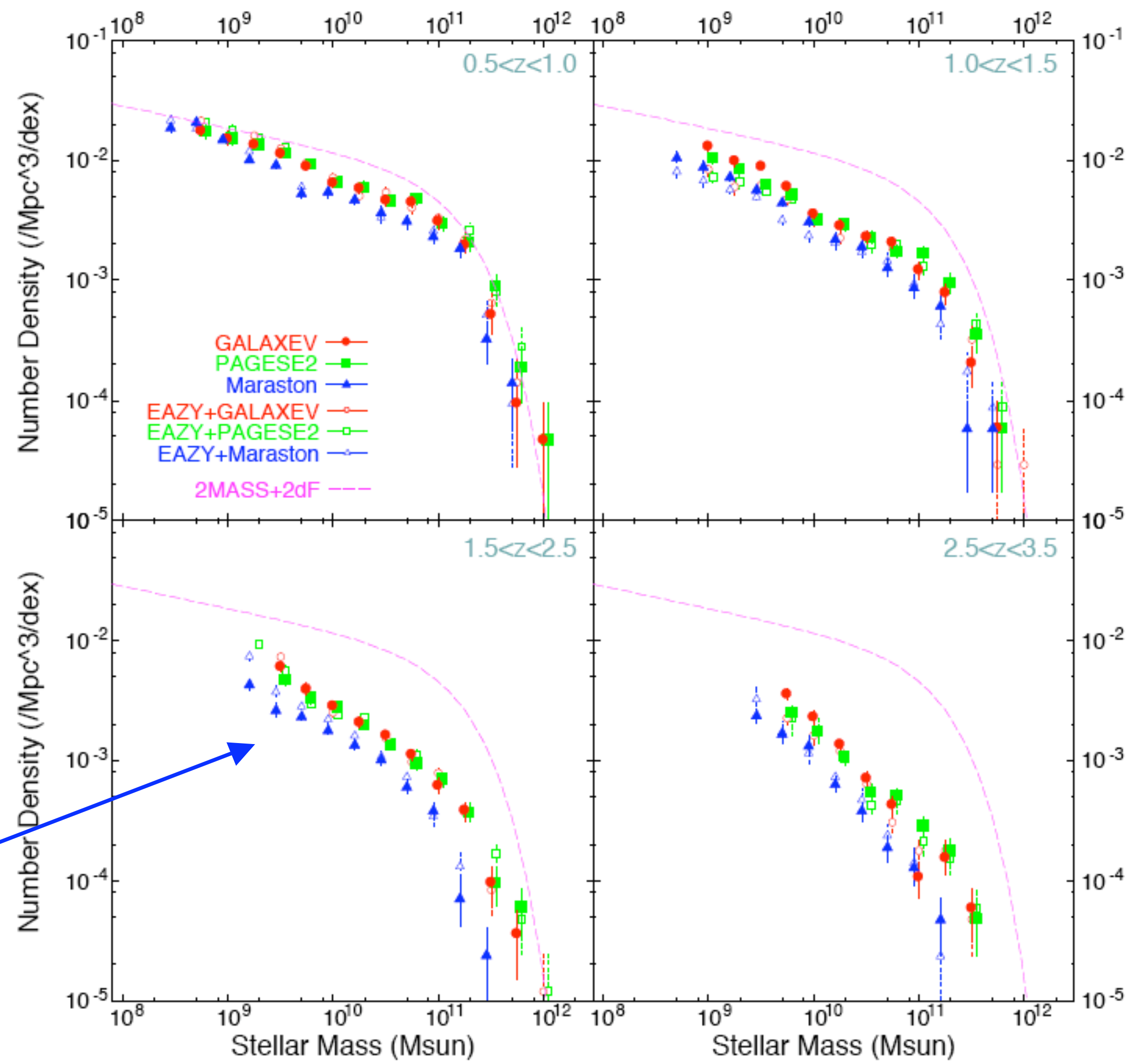
- *But how robustly can we make this transformation between observables and physical properties??*
  - How do uncertainties in SPS propagate into uncertainties in physical properties?
    - Systematic vs. statistical uncertainties
  - What inputs do we need to know better in order to make this translation more precise?

The Propagation of Uncertainties

- Recent work has shown that the stellar masses estimated from different SPS models do not agree
  - Offsets of a factor of ~2
  - The effect is a function of the age of the stars
    - Worse at higher redshift (Maraston et al. 2006)
  - Thought to be due to the differing treatment of the thermally-pulsating AGB (TP-AGB) phase

M05 - Maraston 2005	
BC03 - Bruzual & Charlot 2003	

Systematic shifts arise from different SPS models

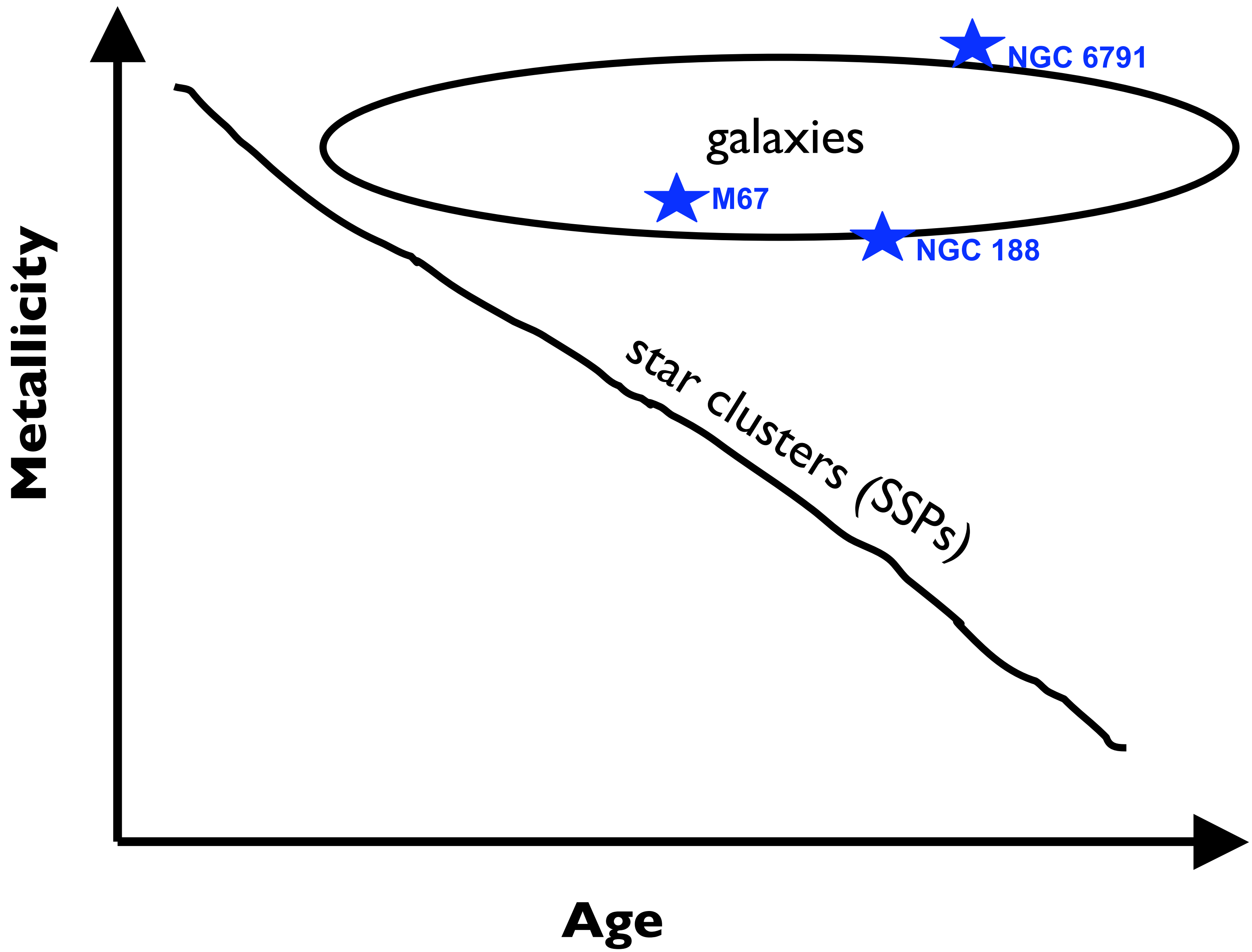


Kajisawa et al. 2009

(Some) Relevant Uncertainties

1. Stellar evolution
   - (TP-)AGB, HB, BS, post-AGB, WR, convection, rotation, binary evolution, etc.
2. Dust
   - Extinction law (i.e. properties of dust grains)
   - Molecular clouds vs. cirrus dust; optical depths, transition times
   - Geometry of dust (clumpiness)
3. Metallicity evolution and distribution
   - Rarely discussed, but metallicity distributions are *observed*
4. IMF
   - Effects normalization, *and* SED shape - degenerate with SFH
5. Stellar spectral libraries
   - Theoretical *and empirical* libraries have known flaws
6. Non-solar abundance patterns (α-enhancement)
   - Impacts both stellar evolution and the spectral libraries

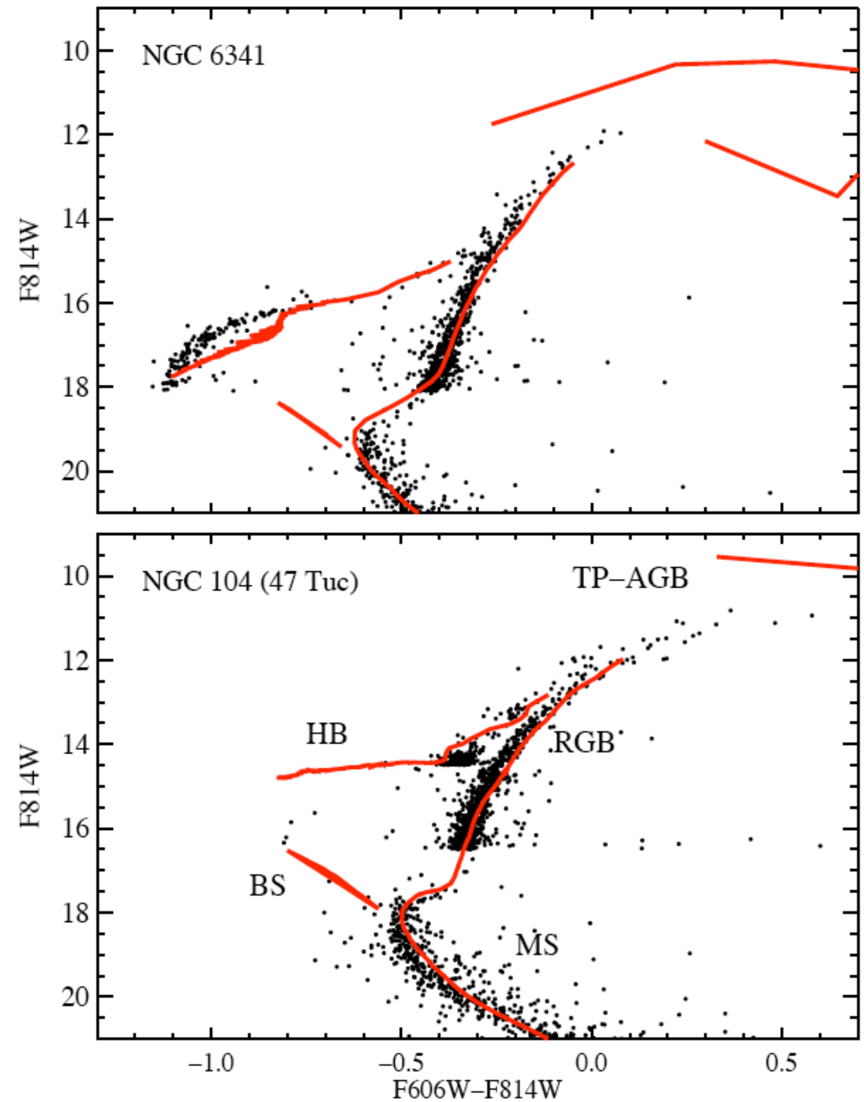
The Challenge of SPS Calibration



Stellar Evolution Uncertainties

- Use base stellar evolution calculations from:
  - Padova group (2007 models)
  - BaSTI/Teramo group
- Introduce parameters:
  - **f_{bhb}**: fraction of blue horizontal branch stars
    - Extended HBs common at low metallicity, also seen at higher Z
    - Neglected in nearly all SPS modeling
  - **S_{bs}**: specific frequency of blue straggler stars
    - Several scenarios for their existence
    - May be very common in the field
    - Ubiquitous in GCs (where S_{bs}~a few)
    - Neglected in nearly all SPS modeling
  - Δ_T: shift in log(T) along TP-AGB phase
    - T extremely uncertain owing to the complexities of this phase. Low T means a very complex atmosphere. Dust formation important
  - Δ_L: shift in log(L) along TP-AGB phase
- To control uncertain phases of stellar evolution, i.e. parameterize our ignorance

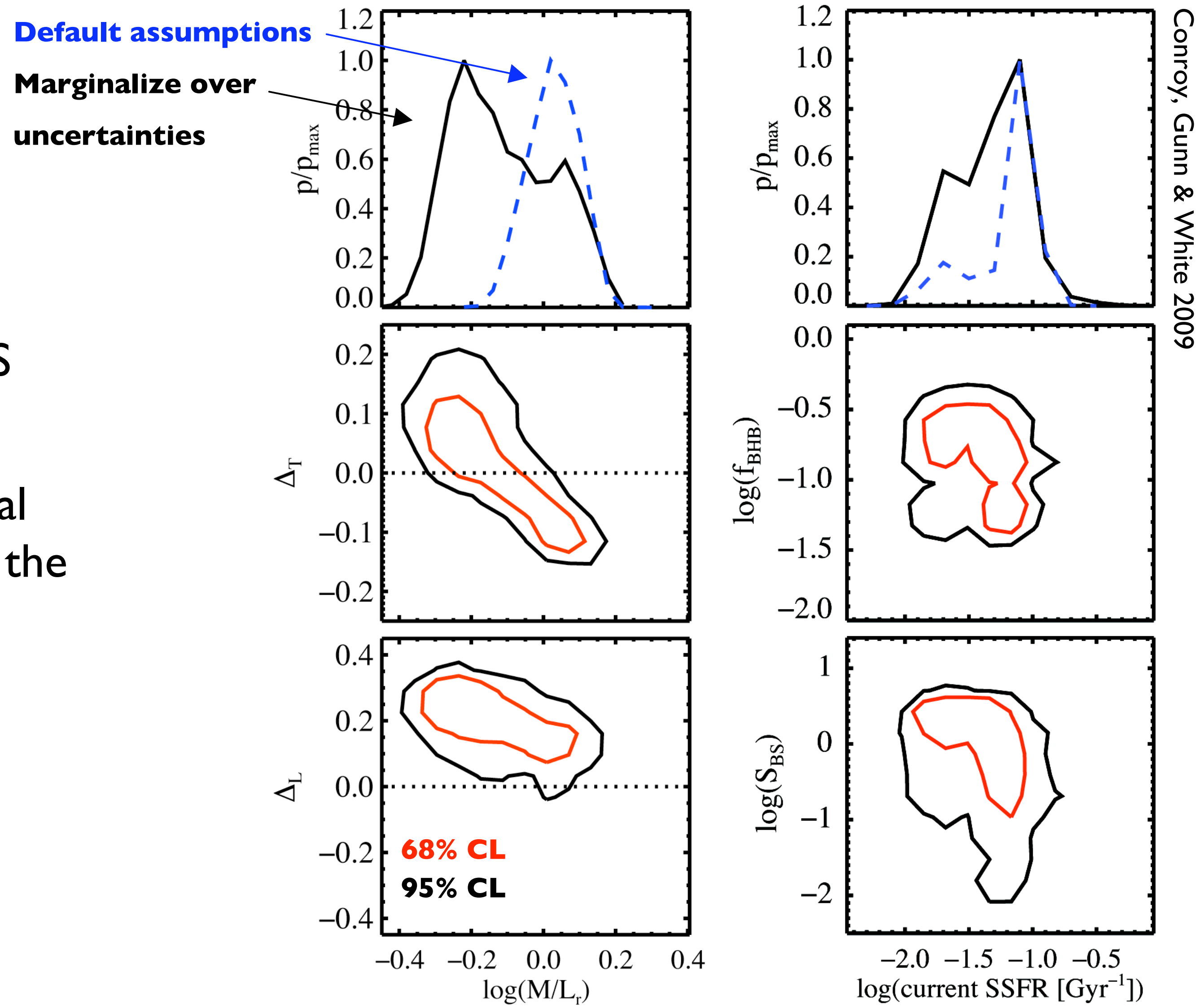
→ **"flexible SPS" = FSPS**



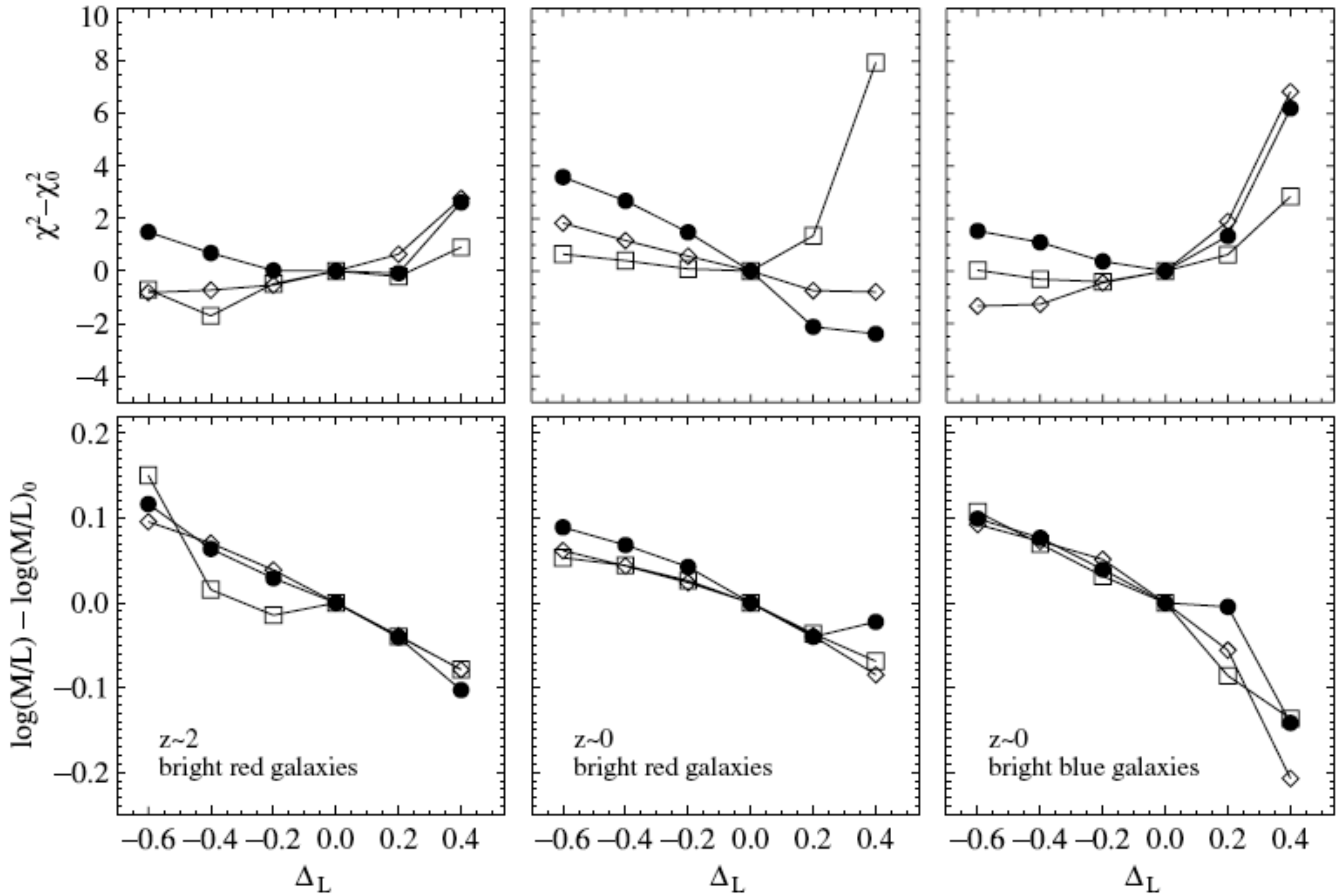
The Propagation of Uncertainties: I

An Example: fitting GALEX+SDSS+2MASS photometry at z~0

Dependence of physical properties (x-axis) on the uncertainties in stellar evolution (y-axis)



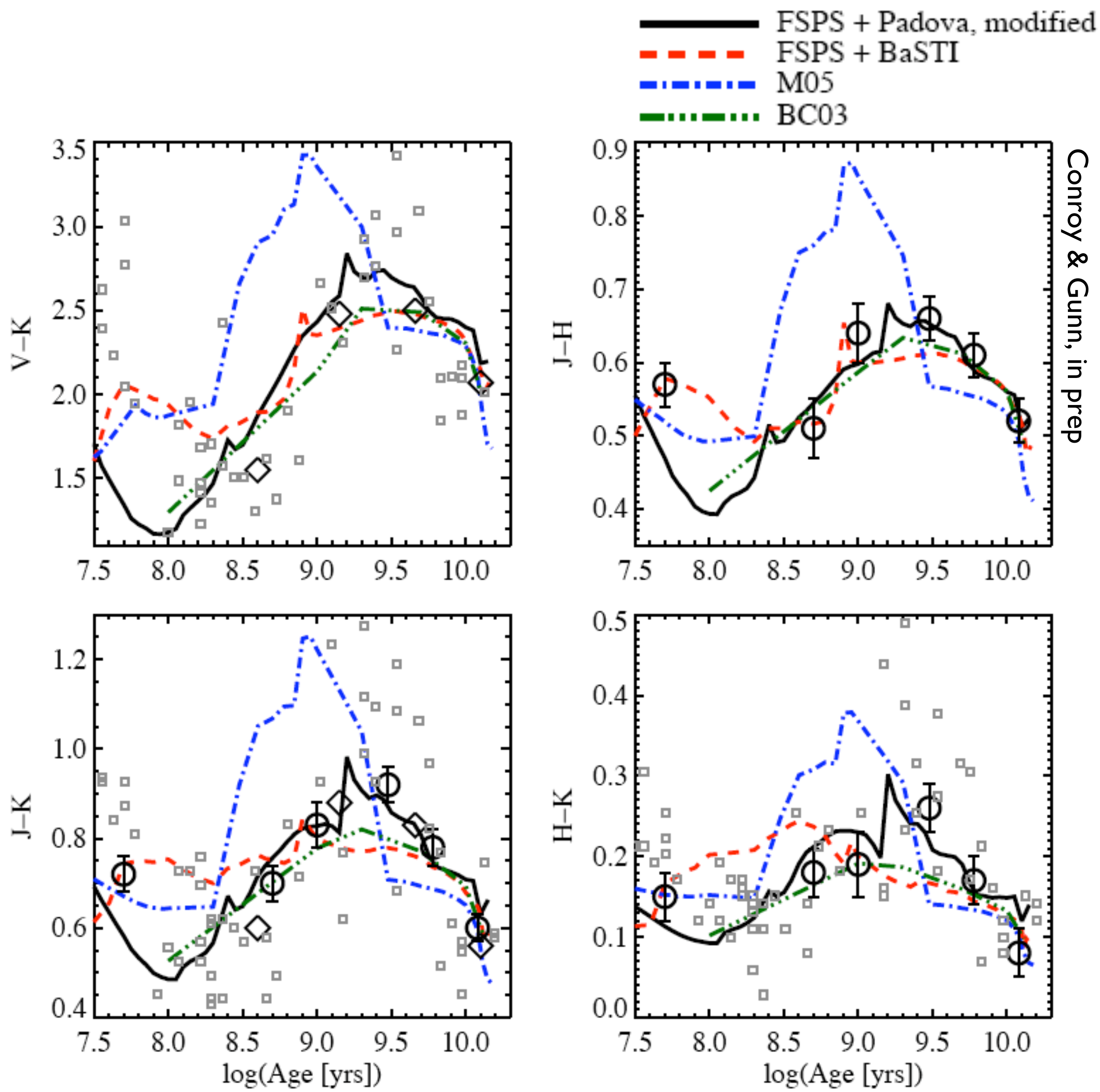
The Propagation of Uncertainties: II



Conroy, Gunn & White 2009

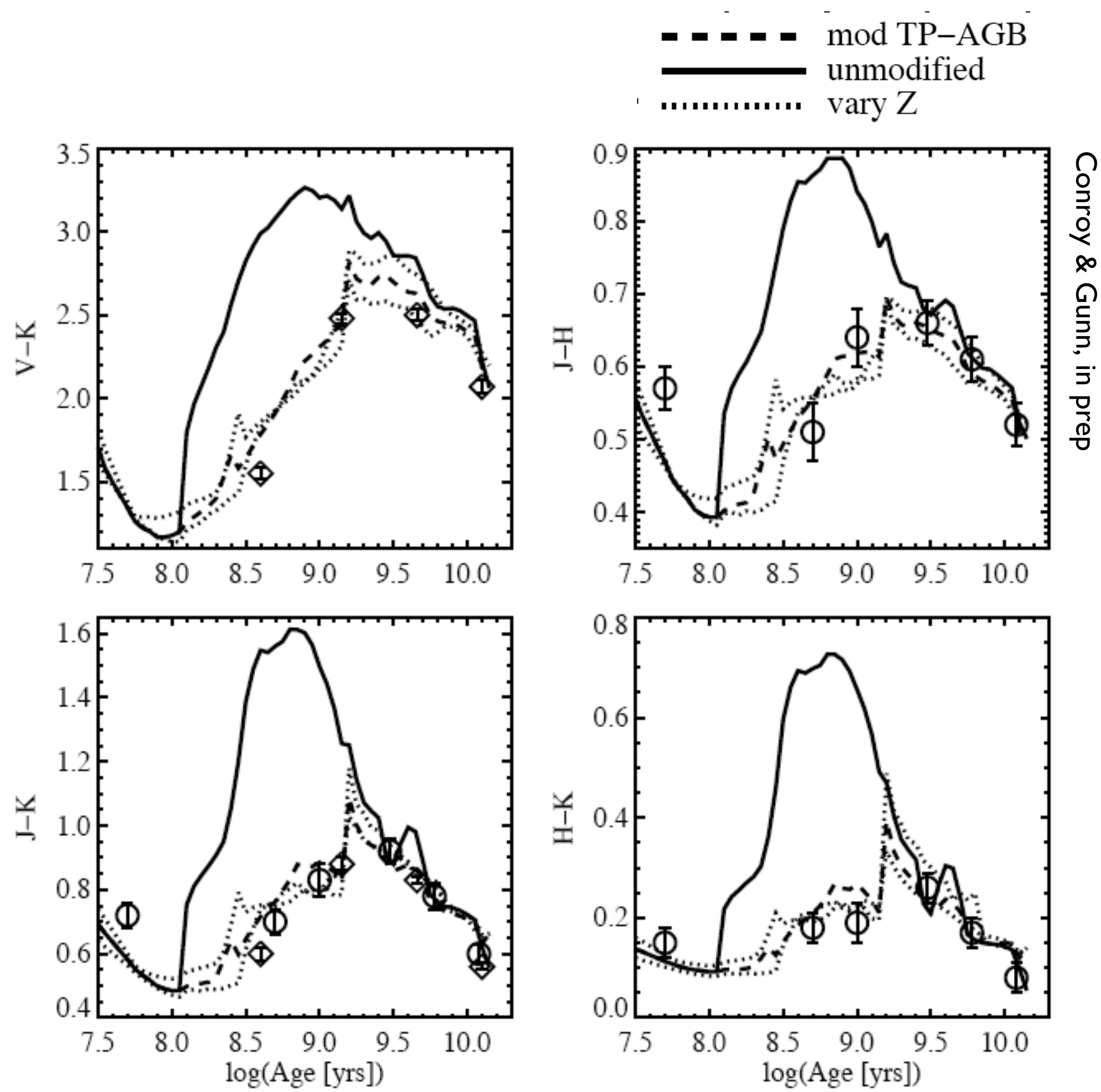
Calibrating SSPs: I

- Calibrating against star clusters in the Magellanic Clouds
- Lots of data issues
  - Old data not reliable
  - Stochastic effects must be accounted for
- Maraston's model and the default Padova isochrones provide poor fits to the data
- BaSTI stellar evolution calculation assume *no* convective core overshooting, which results in colors too red at young ages



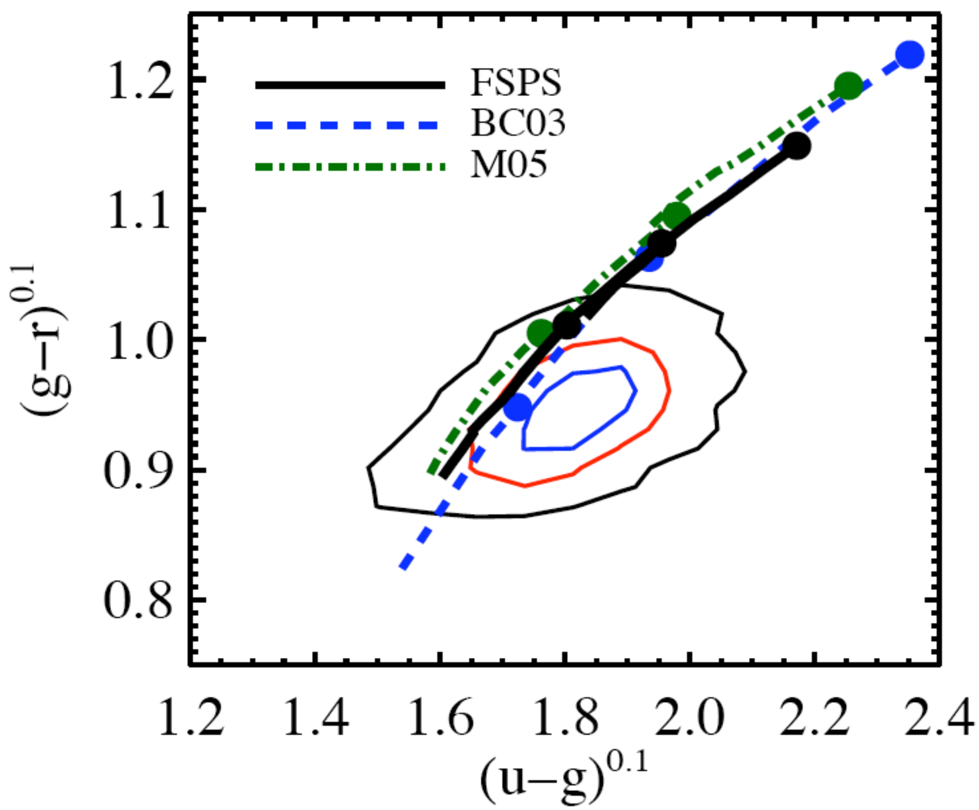
Calibrating SSPs: II

- Current stellar evolution calculations do not reproduce the observed MC data
- Luminosities and/or lifetimes of TP-AGB phase overestimated in Padova calculations
- Flexible SPS provides a straightforward platform to deal with these discrepancies
- *But how do we extend these calibrations to other metallicities??*



Modeling the Red Sequence: I

- Optical colors of massive red sequence galaxies cannot be reproduced by model SSPs
  - Old problem
  - Generic to all SPS models
- Not due to inadequacies in stellar libraries
- Probably not due to uncertainties in stellar evolution, such as the main sequence and sub-giant branch
  - Although, there are few observed star clusters at these metallicities with which to calibrate SSPs

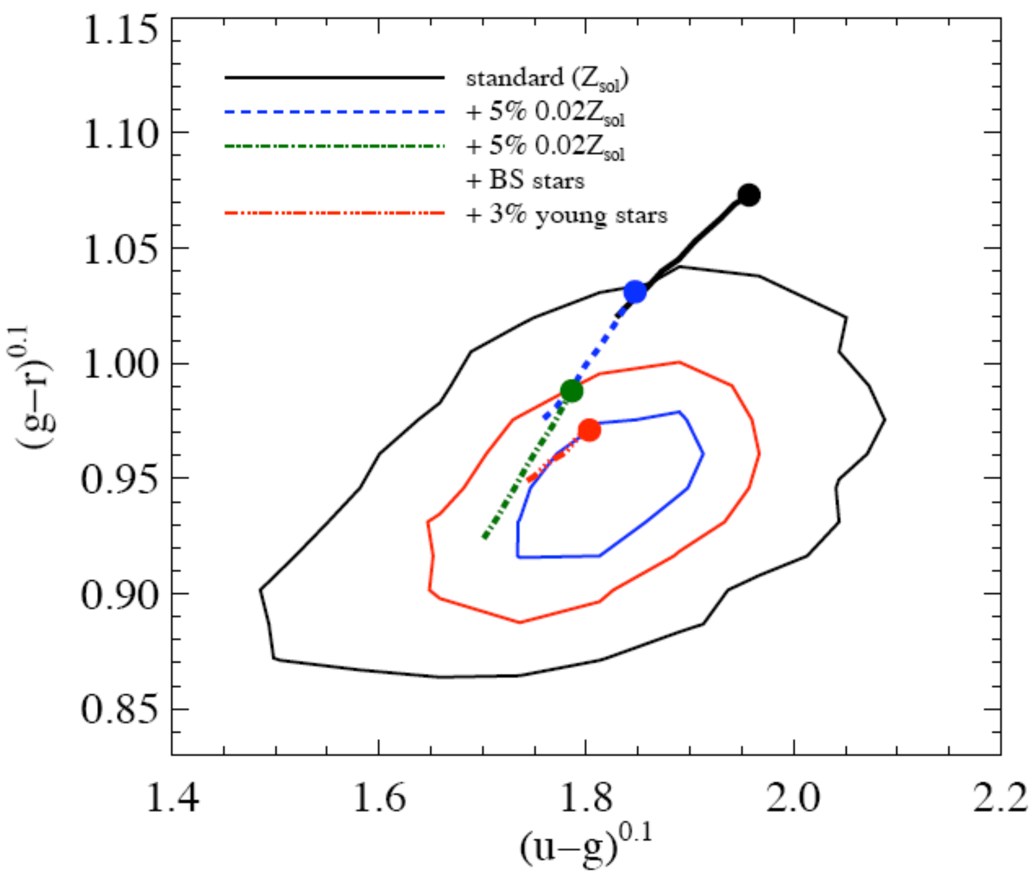


Models are shown for ages >5 Gyr and $0.5Z_{sol}$, Z_{sol}, $1.5Z_{sol}$

Modeling the Red Sequence: II

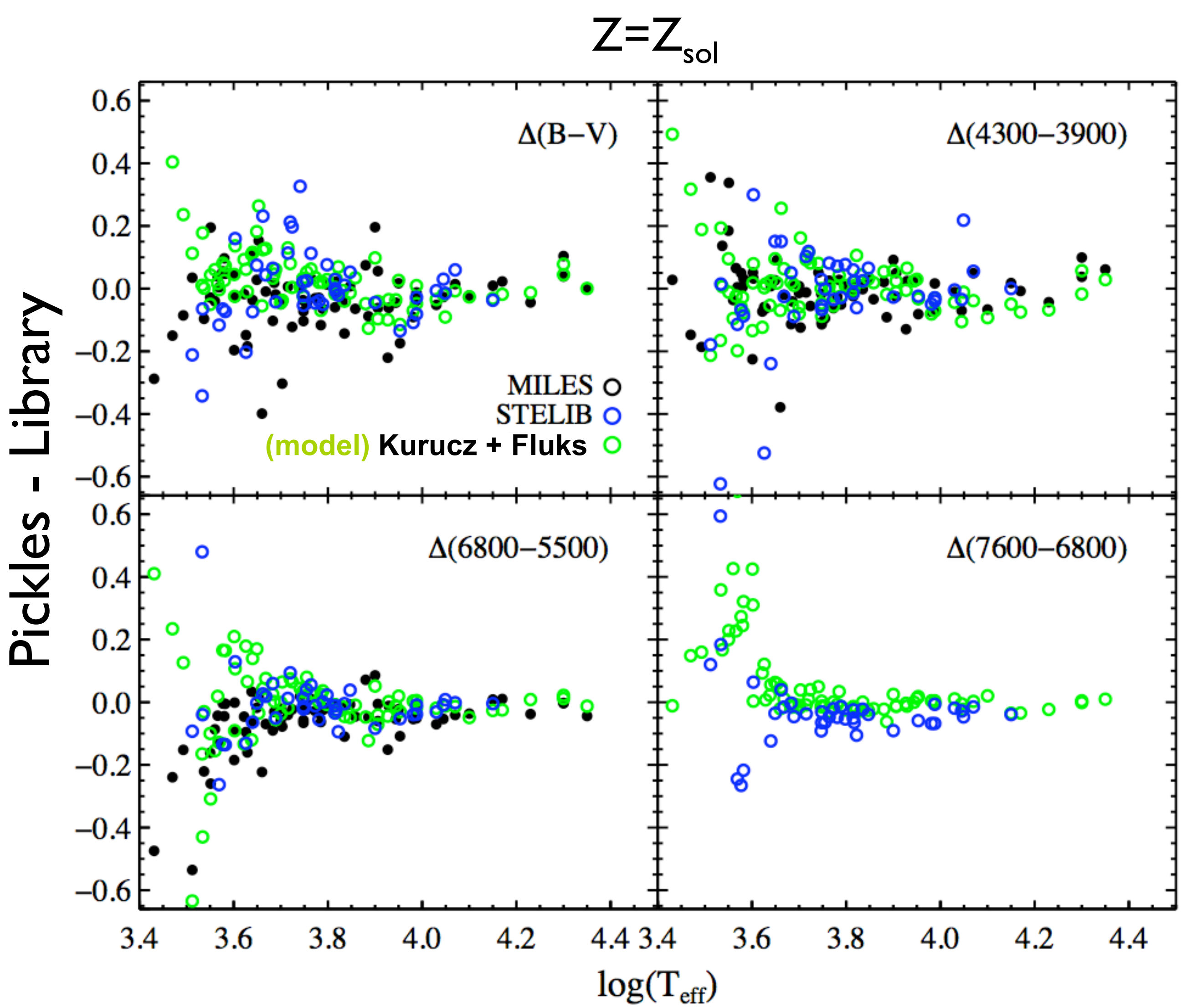
- Non-canonical additions move the models in the correct direction
  - Metal-poor stars
  - Blue straggler stars
  - Young stars (e.g. ~1 Gyr old)

- Implies that we cannot even fit the broadband photometry of galaxies to simple models. Must include the possibility for “exotic” populations.



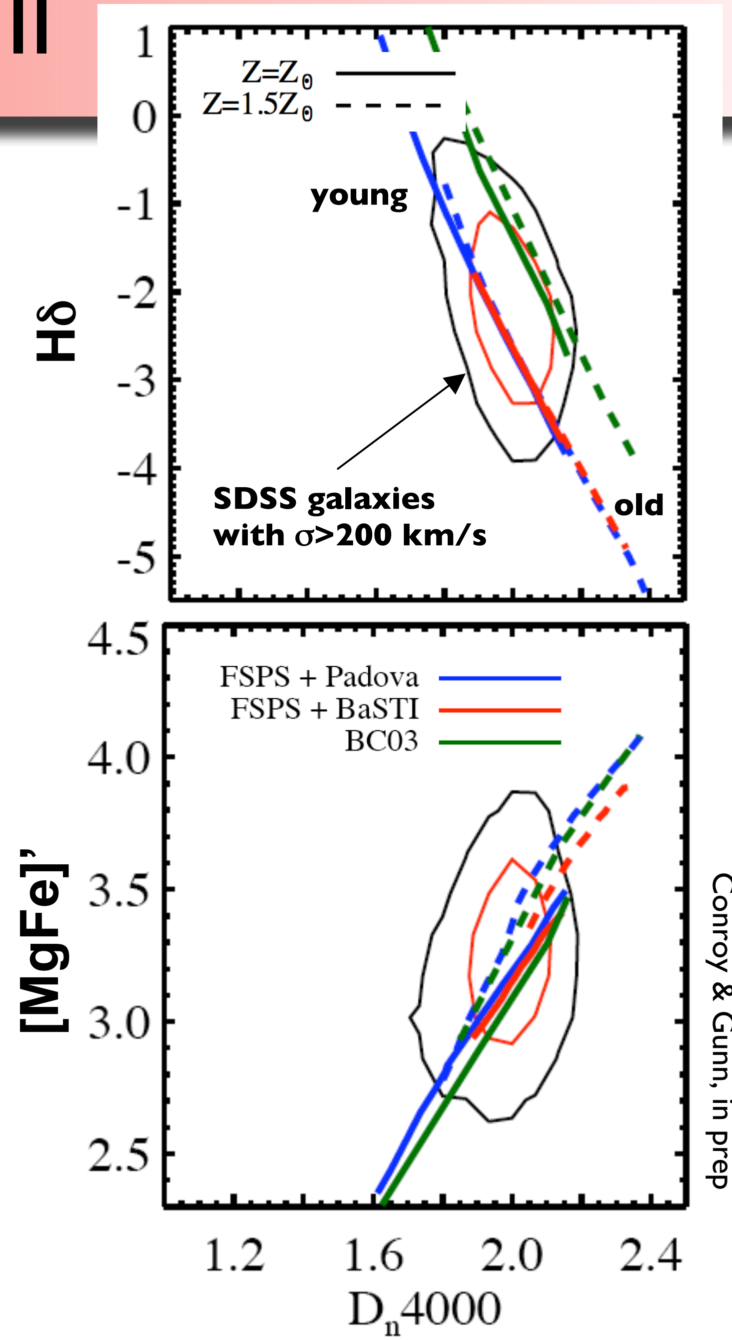
Assessment of Spectral Libraries

- Empirical stellar spectral libraries do not agree
  - Probably caused by difficulty in estimating log(g), T_{eff}, Z
- Worse at non-solar Z
- FSPS has been coupled to the Miles empirical library to produce predictions for optical spectra at moderate resolution



Modeling the Red Sequence: III

- *Different empirical spectral libraries result in different index predictions*
- Different stellar evolution calculations predict similar behavior (just reflects similar turn-off points and RGB temperatures)
- All models predict D_n4000 strengths in excess of observations
  - [α/Fe] not a likely explanation (Coelho et al. 2008)
- All models fail to reproduce the locus of galaxies in the D_n4000 - Hδ plane, although the BC03 model performs least well



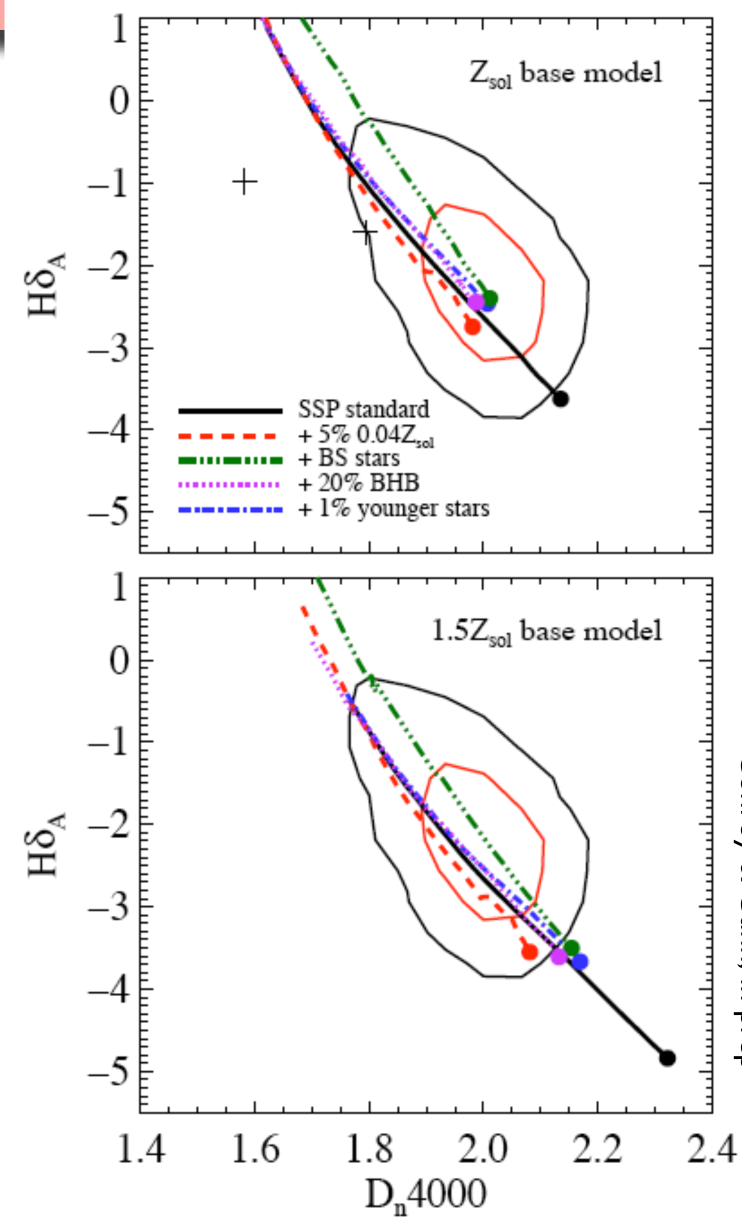
D_n4000 - age and Z sensitive

Hδ - age sensitive, particularly to small bursts

[MgFe]' - Z sensitive, *not* sensitive to [α/Fe]

Modeling the Red Sequence: IV

- A variety of non-canonical additions can yield better agreement with the observed locus, including:
  - blue HB stars
  - blue straggler stars
  - metal-poor stars
  - young stars (age of ~1 Gyr)
- How to disentangle these effects?
  1. Look-back studies
     - These populations evolve very differently
  2. Compare metal lines in the blue and red
     - Young stars, and metal-poor stars, will have a different Z compared to the bulk population
  3. SBFs in the blue?



Conroy & Gunn, in prep

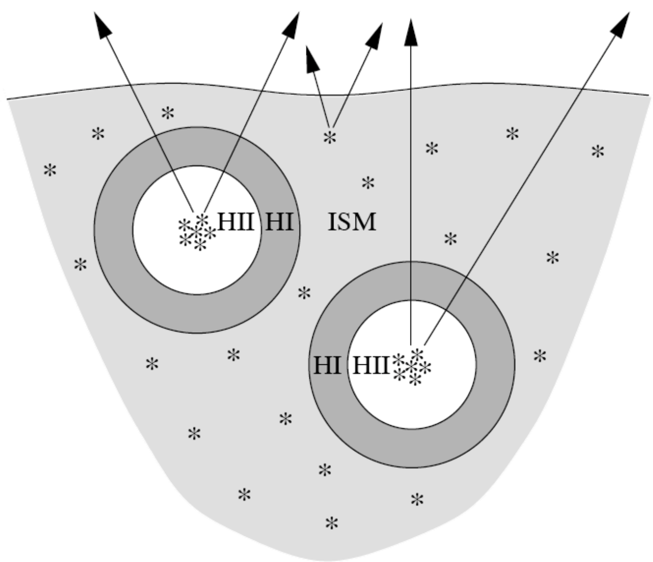
A Parametric Dust Model

Lets construct a flexible dust model:

- Two dust components:
  1. dust around young stars with optical depth τ_1
     i.e. stars embedded in birth cloud
  2. dust around all stars with optical depth τ_2
     i.e. cirrus dust

- Birth cloud disrupts at a time t_{esc}~10^7 yrs

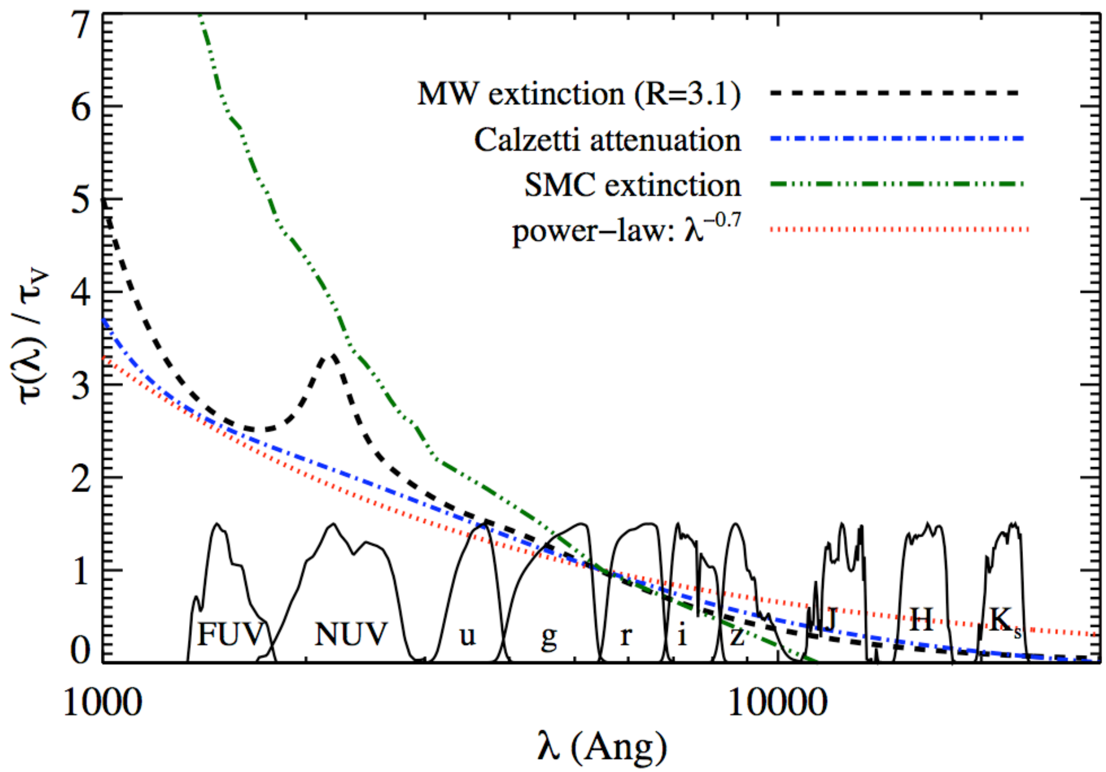
- Associate attenuation curves, $\tau(\lambda)$, with each component



i.e., Charlot & Fall 2000

Dust: Attenuation Curves

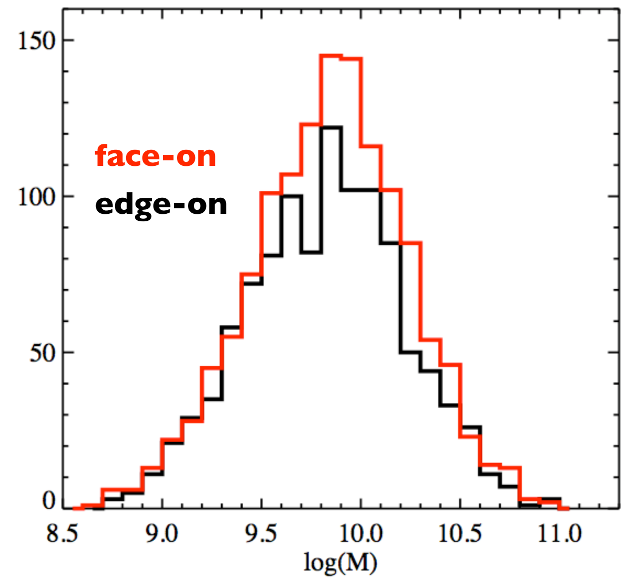
- Attenuation curve depends on:
  - Size distribution of grains
    - Metallicity
    - Intensity of UV radiation
  - Geometry
    - Scattering
    - Large-scale and local geometries matter
- In general, we do not know what the attenuation law "should" be

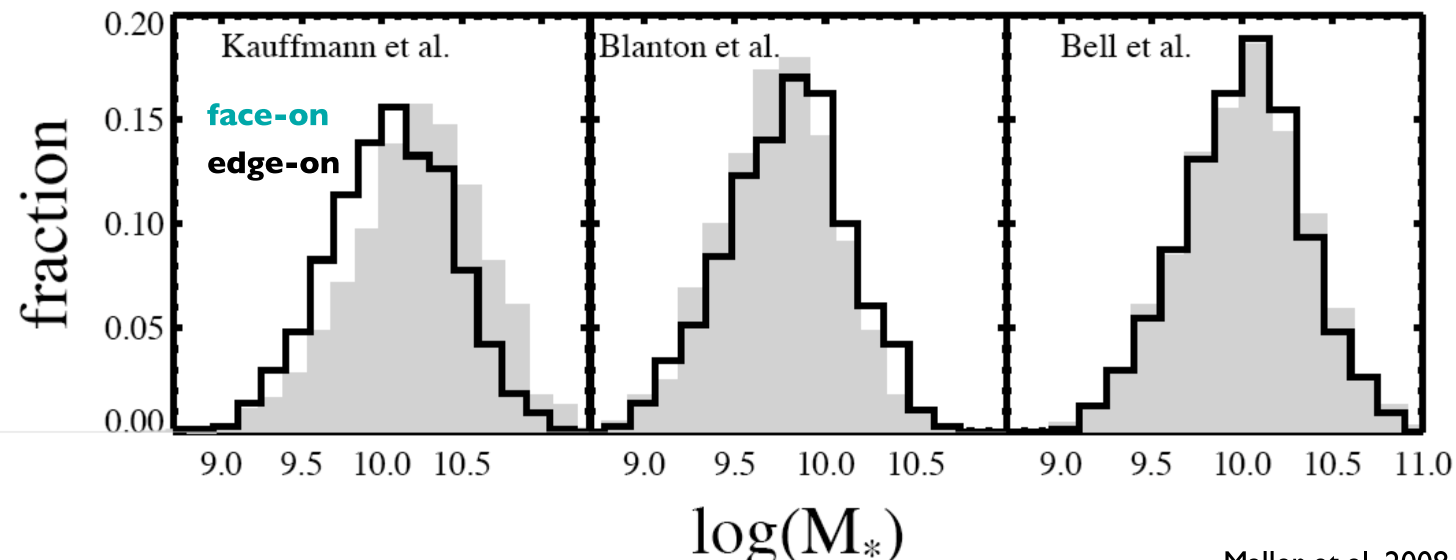


- *UV bump* is an important feature in MW and LMC extinction curves, and shows considerable variation amongst environments. Is this feature ubiquitous in the integrated spectra of galaxies?
  - If UV bump is carried by PAHs (e.g. Weingartner & Draine 2001), then we might expect variation in bump strength for different galaxies because PAH fraction varies from galaxy to galaxy (Draine et al. 2008)
  - No evidence for UV bump from local starburst galaxies (Calzetti et al.), but seen at high-z (e.g. Noll et al.)

Effects of Dust Assumptions on Mass Estimates

- One example:
  - – Stellar mass dependence on galaxy inclination
  - – Should be uncorrelated
  - – But heavily-used public stellar mass catalogs **do** show a correlation
  - – Fitting with a sufficiently flexible dust model resolves this issue
    - – Vary τ_2, τ_1, power-law attenuation curve

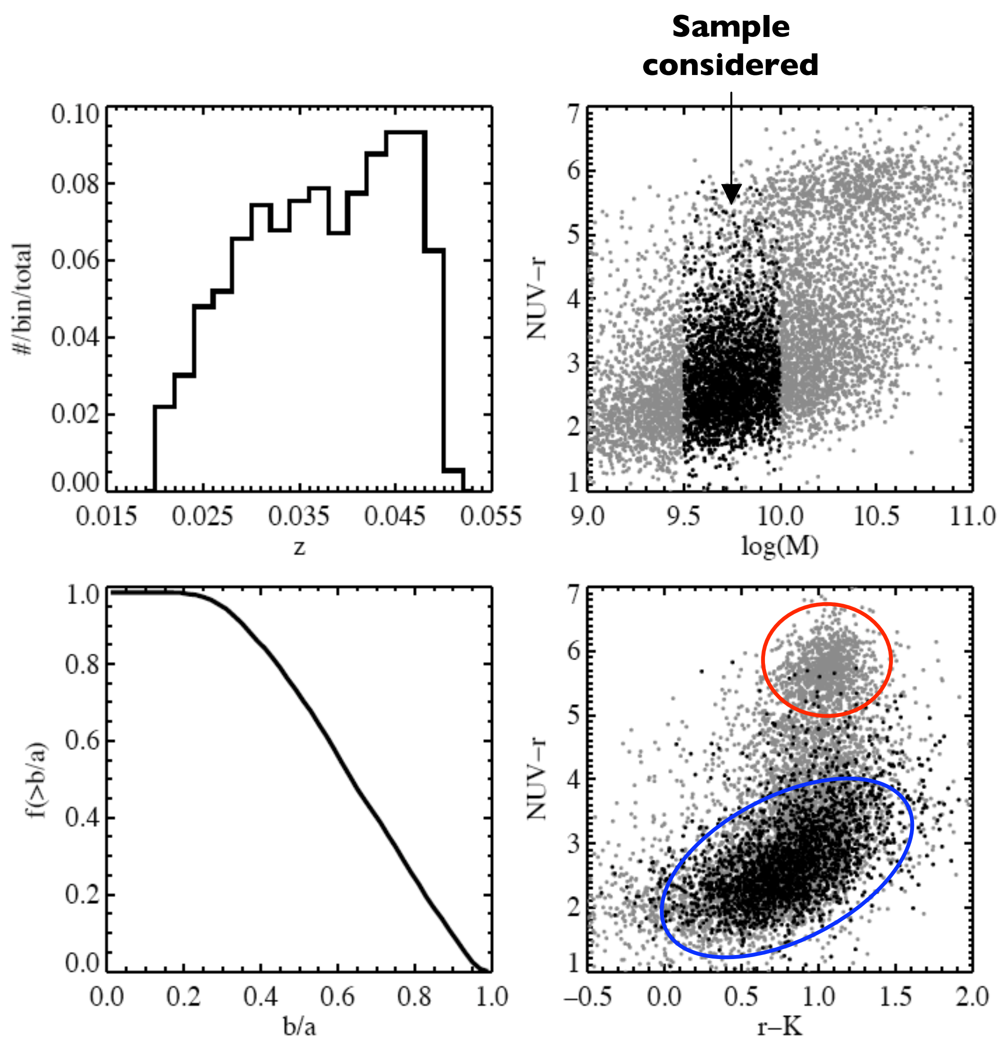




Maller et al. 2008

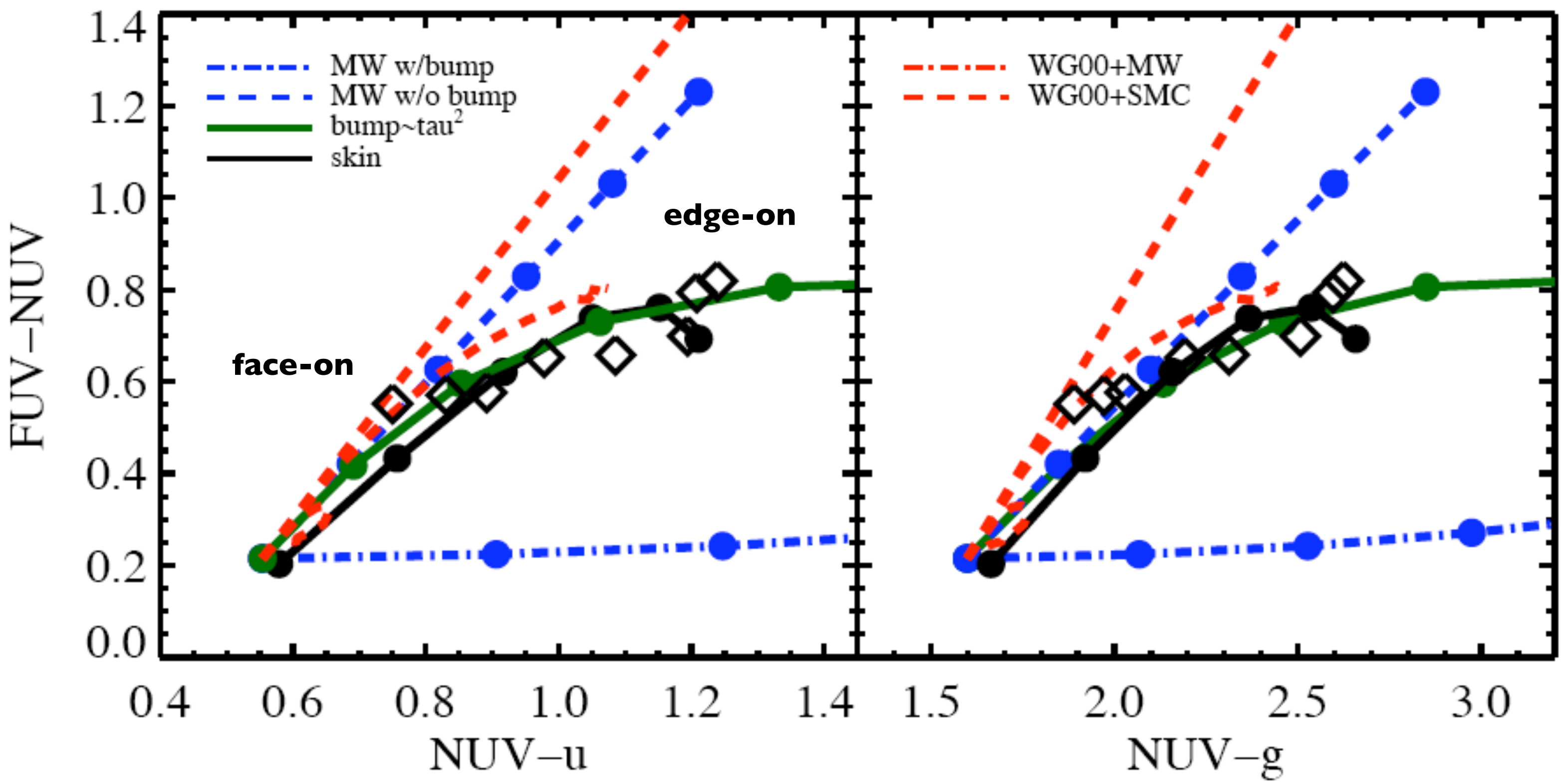
Dust in Disks: I

- Consider a sample of disk-dominated galaxies at z<0.05
  – Sersic index n<2.5
  – Narrow stellar mass bin
    ➢ Volume limited
  – GALEX+SDSS+2MASS
  – Measured inclinations (b/a)
  – Star-forming only
- Consider average photometric properties in bins of inclination
  – *Trends with inclination will depend only on dust properties*



Dust in Disks: II

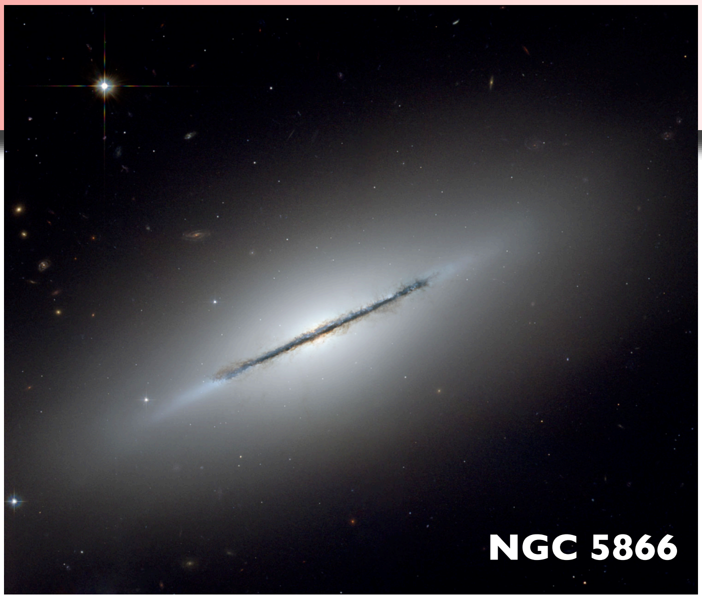
- Models assume a constant SFH, $Z=Z_{sol}$. Vary dust optical depth associated with cirrus (diffuse dust), and dust attenuation curve
- Observed inclination-dependent colors cannot be described by canonical attenuation curves. Two models do work:
  - Model with varying UV bump strength
  - Model with a small amount (~3%) of completely unobscured stars

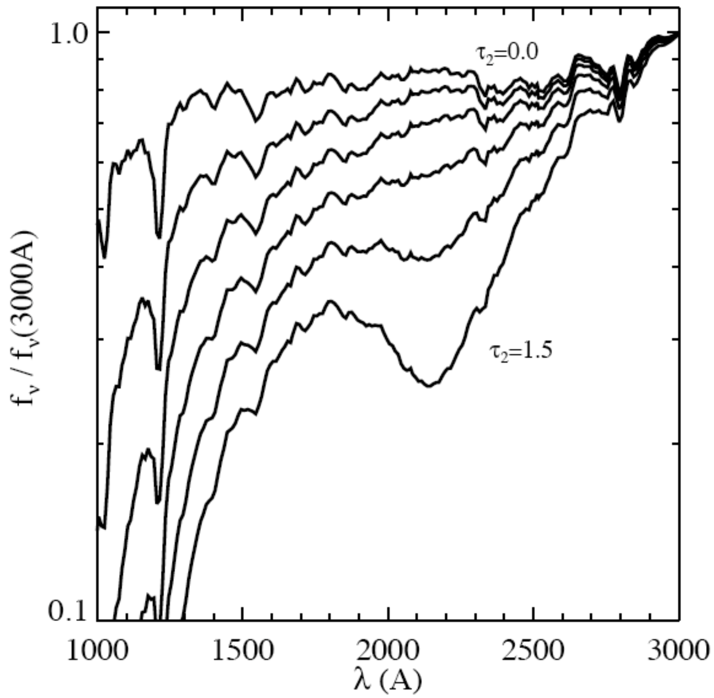


Dust in Disks: Implications

- Commonly used simple dust models are unable to reproduce the observed inclination-dependent colors of disk-dominated galaxies

1. Data are being incorrectly dust-corrected
    - Biases introduced, especially when using FUV/NUV fluxes
2. Possibility that UV bump becomes relatively more important for highly inclined systems
    - Implications for dust formation/destruction, star-dust geometry, etc.
    - Should be observable in UV spectra
3. Or, there is a skin of completely unobscured starlight





Summary and the Future

1. The ingredients of SPS are sufficiently uncertain to warrant further detailed study
   - Stellar evolution, stellar atmospheres, etc. are not solved problems!
2. We have presented a new flexible SPS code that is well-calibrated against a largest set of observational data
3. Substantial uncertainties in SPS remain even when considering all available constraining data
   - It is not obvious that the necessary constraining data exists even in principle
   - SDSS-III will probably provide a next generation spectral library
4. Constraints on dust attenuation curves in the UV will afford unique insight into dust properties and our ability to correct for the effects of dust obscuration
5. These results will hopefully spawn a revival of interest in old subjects such as stellar evolution, stellar atmospheres, high quality star cluster data, etc., etc.

w/ Jim Gunn (Princeton) & Martin White (Berkeley)