ASTRONOMY &
ASTROPHYSICS

Interpreting the Properties of Starbursts with Improved Models

Elizabeth Stanway University of Warwick, UK

with

J J Eldridge University of Auckland, NZ

Lin Xiao, University of Science and Technology of China in Hefei

and many others

Outline

- The Need for New Galaxy Models
  - Challenges from the Distant Universe
- Modelling Stellar Populations
  - Modelling stellar populations
  - The binary problem
  - BPASS: Binary population and spectral synthesis

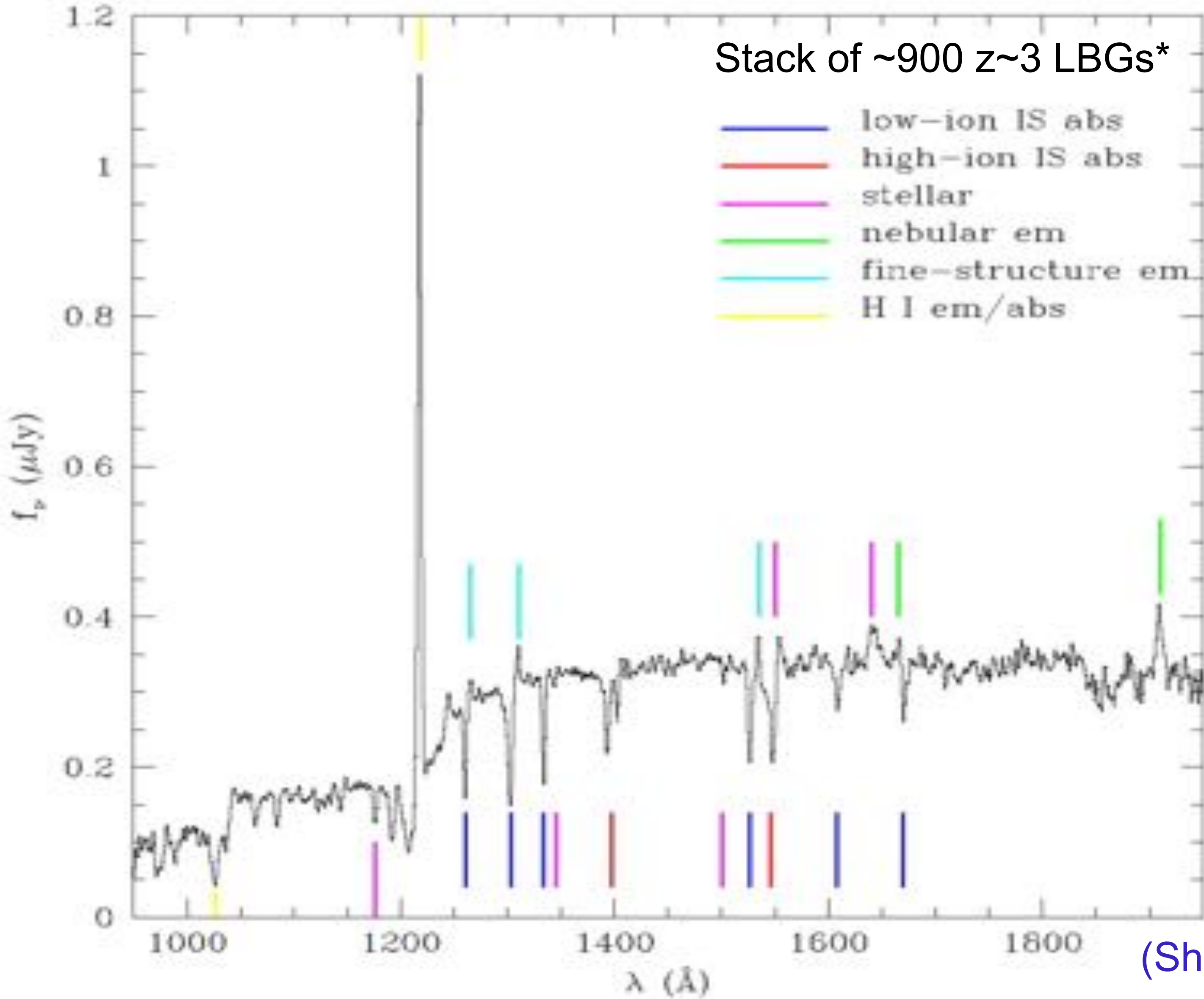
The Challenge

Distant galaxies (and local Lyman Continuum leakers) are typically intense starbursts, with emission dominated by massive stars

Their properties deviate significantly from those the nearby population… but this isn't intrinsic to redshift, more likely to specific star formation rate or surface density of star formation.

They probe low metallicity, young stellar populations

Massive stars at z~3?



*LBGs are rest-UV selected star forming galaxies at high redshift

(Shapley et al 2003)

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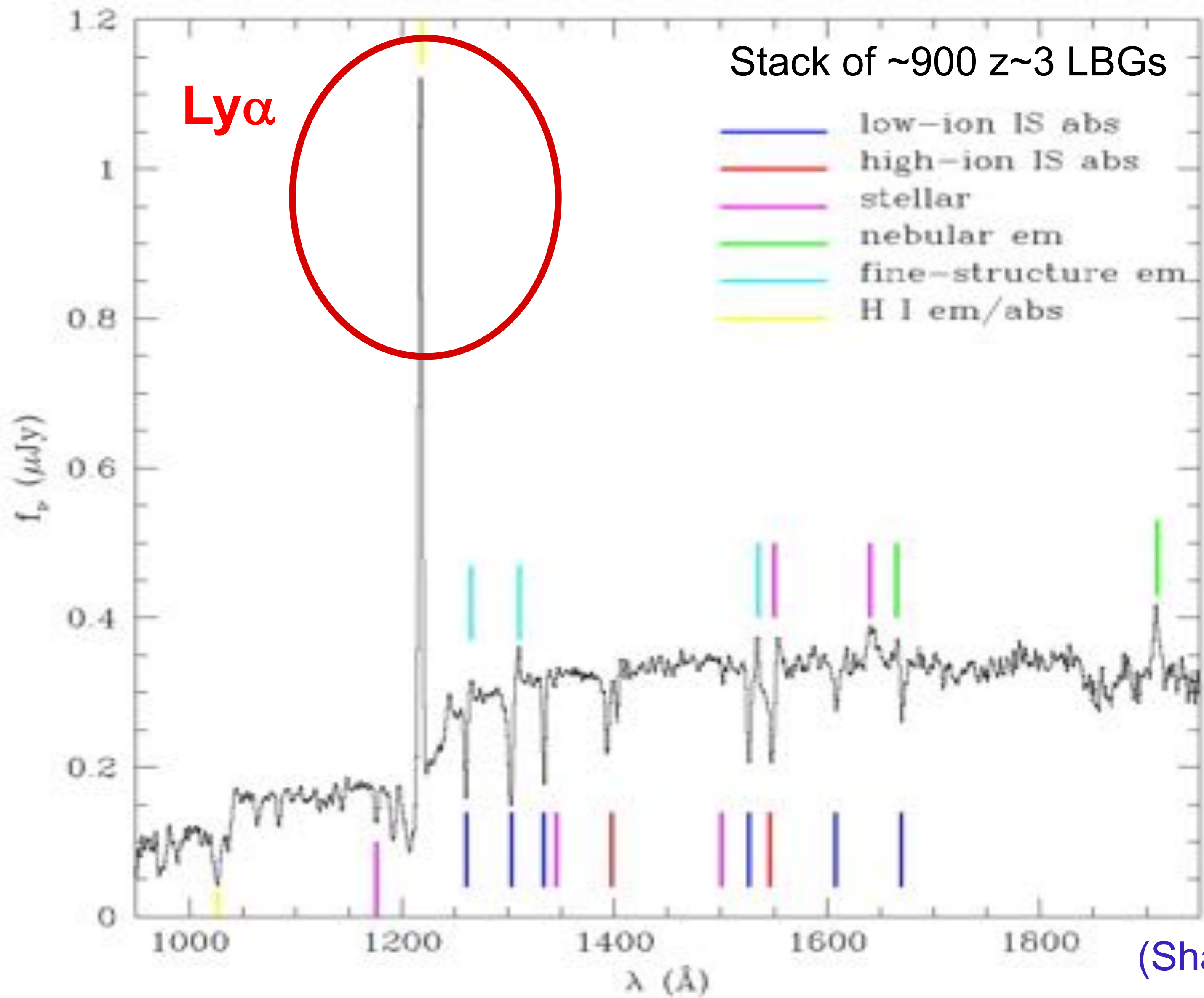
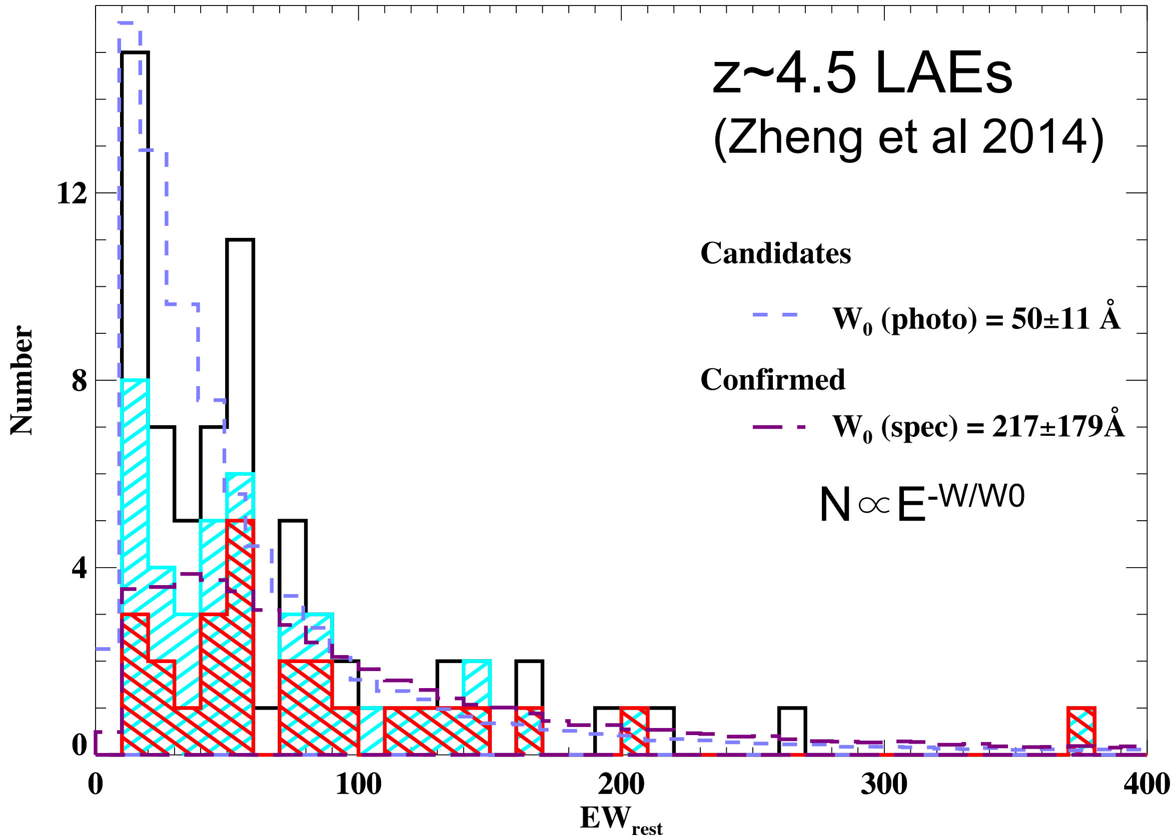


(Shapley et al 2003)

Lyman-α EW distribution



Observed EW(Ly-α) can exceed 200A

… **before** correcting for scattering and absorption.

This is challenging at moderate metallicity with single star models (which under-predict the massive star contribution)

e.g. Malhotra & Rhoads (2002), Zheng et al (2014), Dijkstra & Wyithe (2007)

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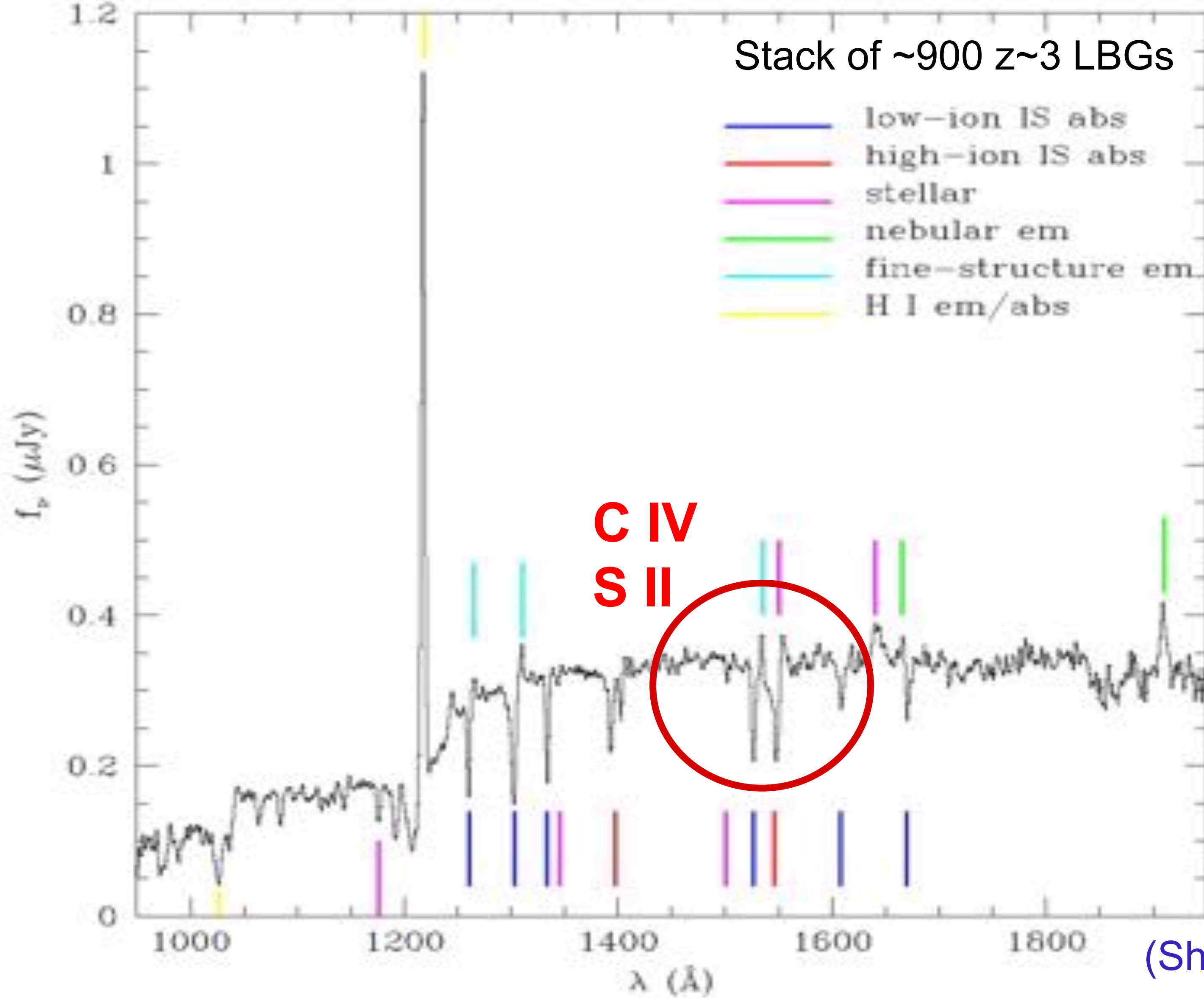

(Shapley et al 2003)

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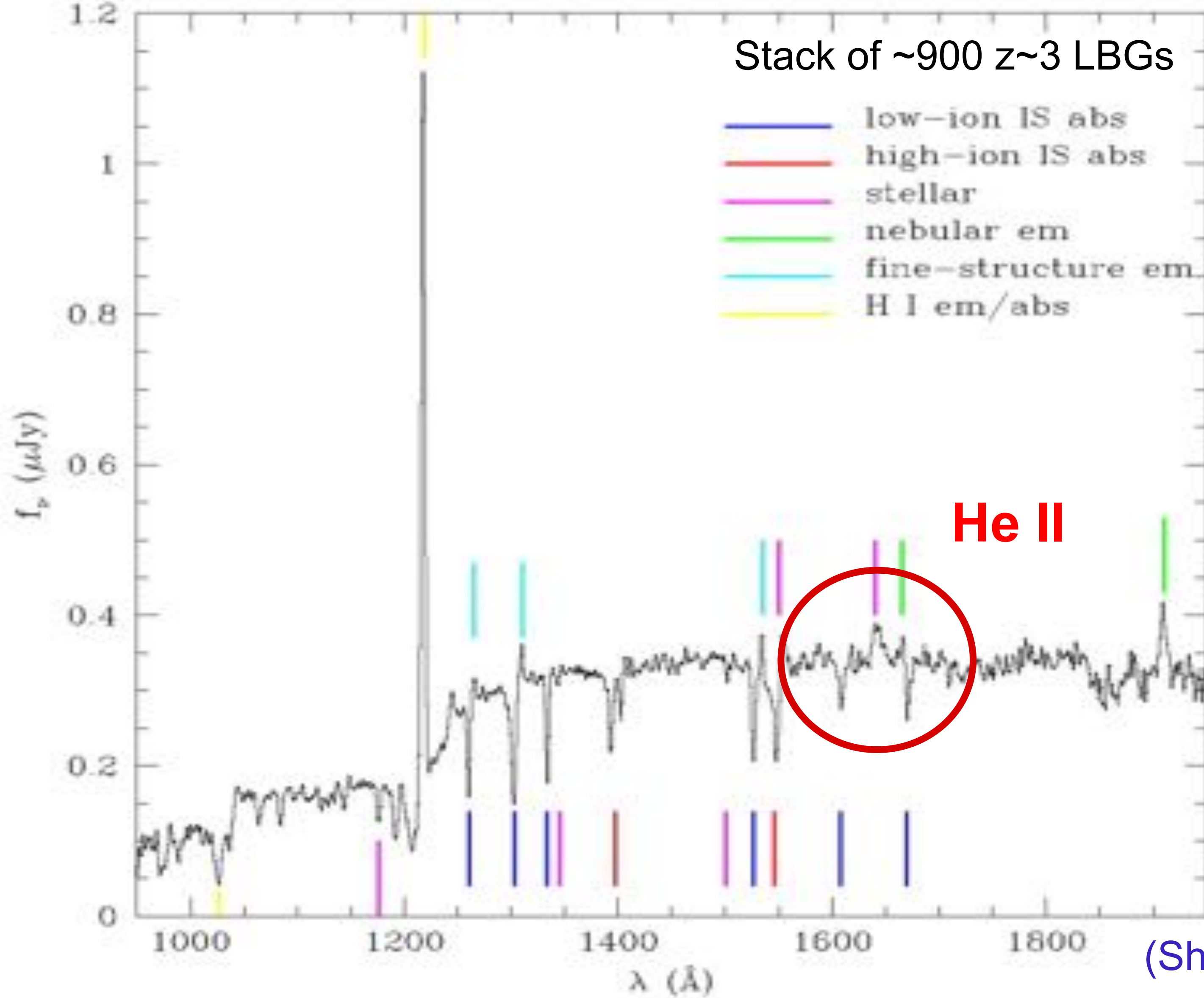

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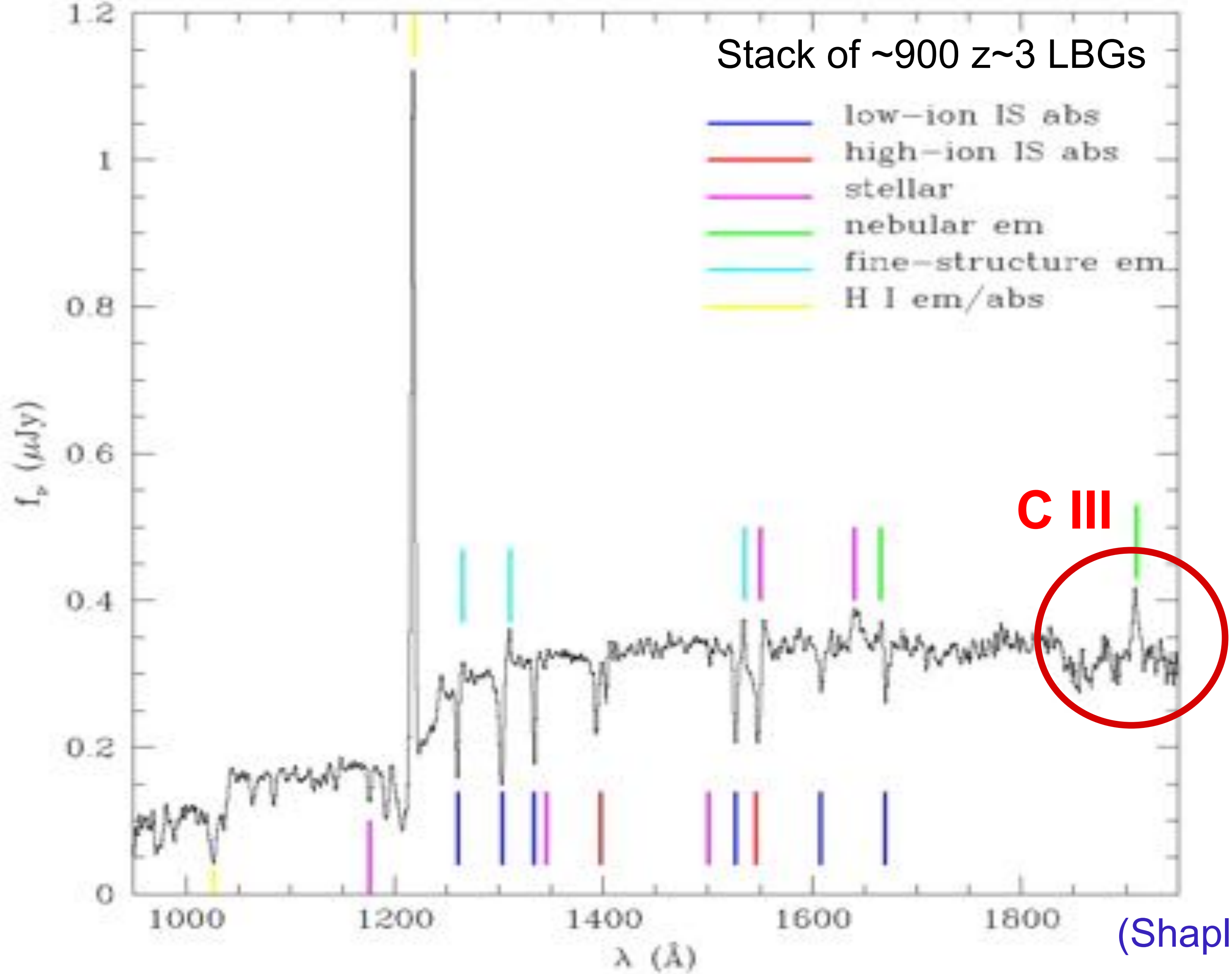
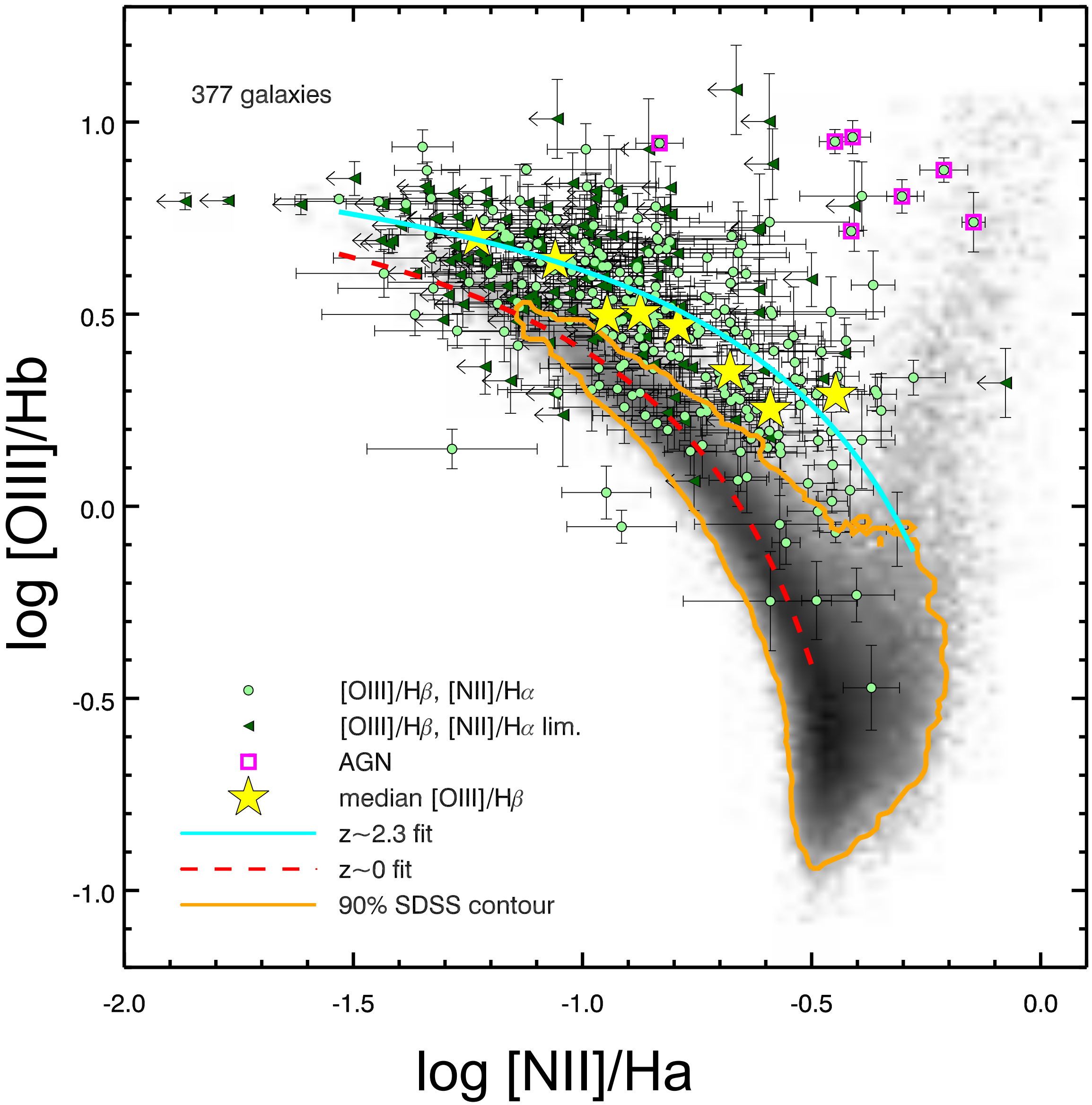


(Shapley et al 2003)

The Ionizing Spectrum at z~3



Multi-object near-IR spectrographs on 8-10m class telescopes (notably MOSFIRE on Keck) are making the high z rest-optical diagnostics accessible for the first time.

(Strom et al 2016, 2018, see also Steidel et al 2016, Kriek et al 2016, Reddy et al 2016)

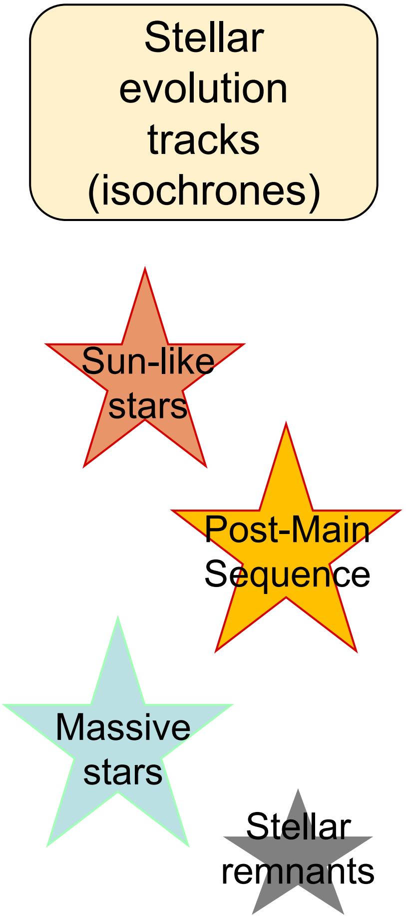
Interpreting Observations

So we know we're looking at intense, young, massive-star dominated starbursts with hard ionizing spectra.

These are also at significantly sub-Solar metallicities

To go further and interpret observations we need suitable models…

Population & Spectral Synthesis



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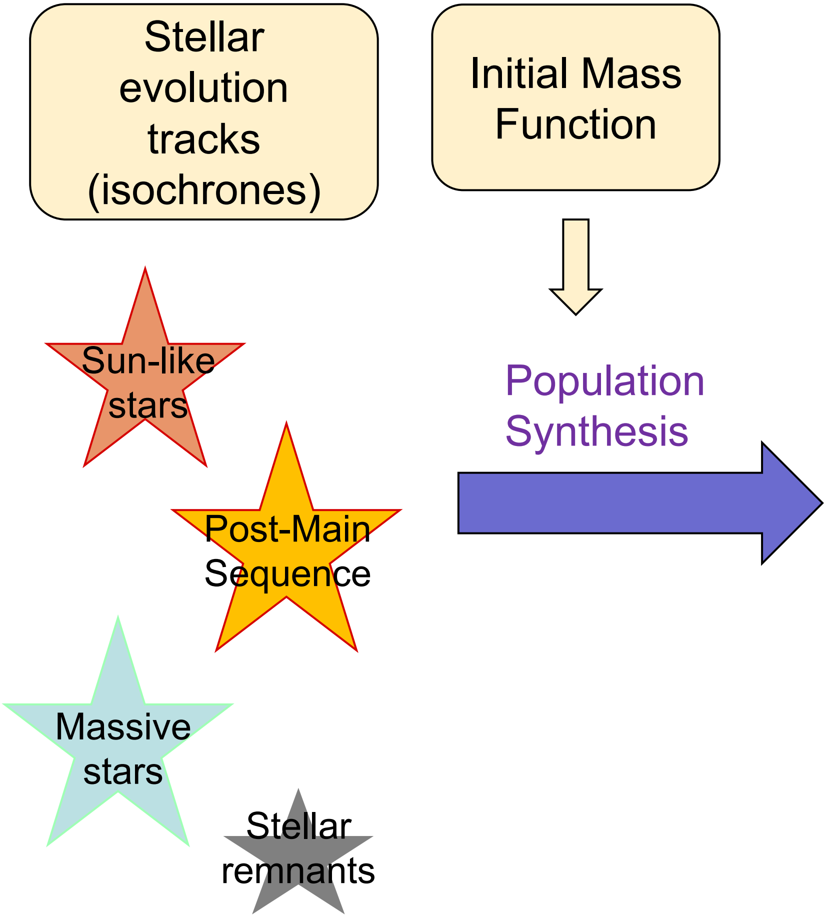
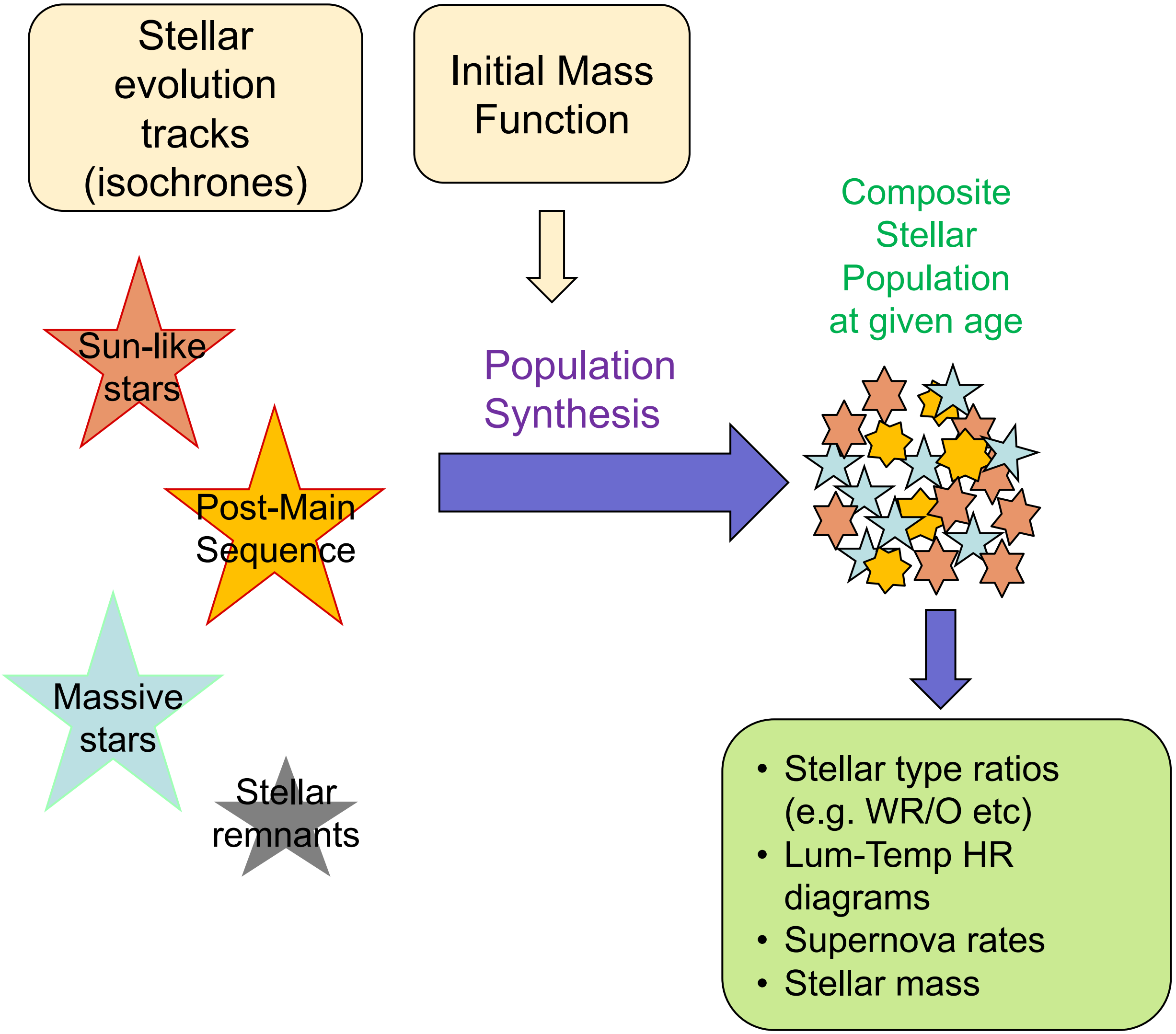


Population & Spectral Synthesis



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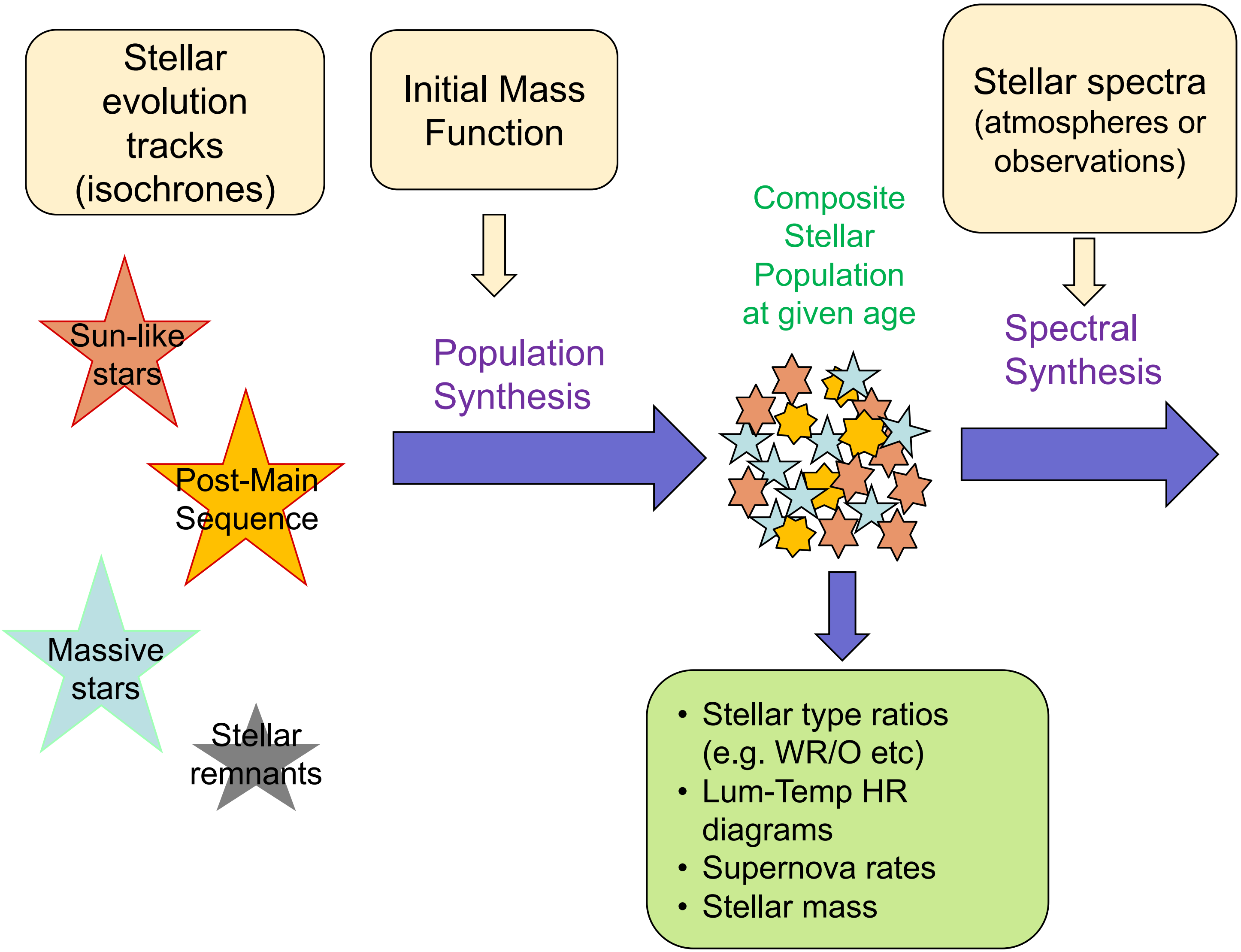
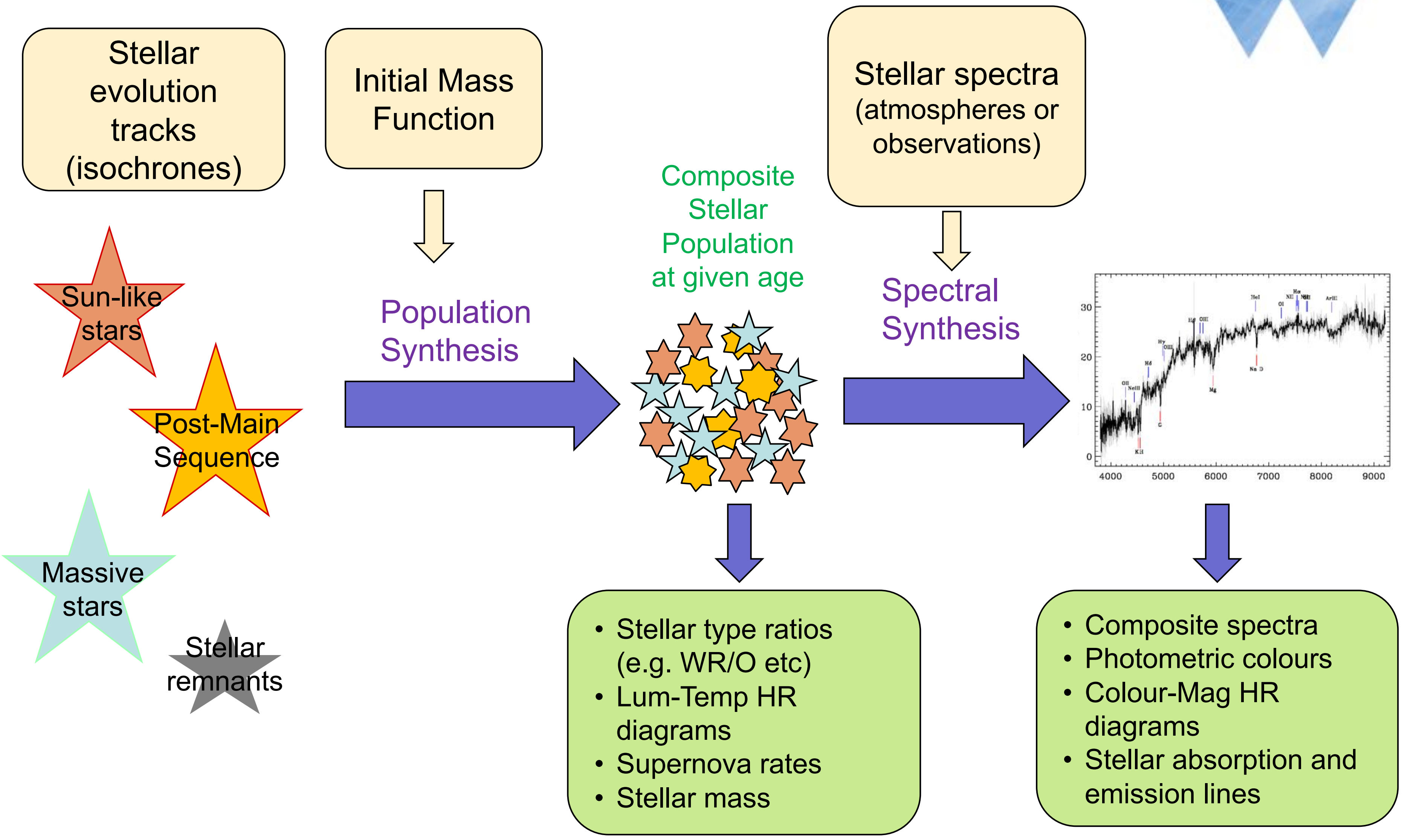


Population & Spectral Synthesis



Population Synthesis

Stellar population synthesis (SPS) codes take a population of co-eval stars, distributed in mass according to an IMF, and either

(i) Build a composite spectrum from empirical observations, or

(ii) Evolve the population according to theoretical models.

Leading evolutionary SPS codes include Bruzual and Charlot (BC03), Starburst99 (Leitherer et al), PEGASE (Fioc & Rocca Volmerange et al), FSPS (Conroy et al) and the Maraston 2005 models.

Population Synthesis

This is not a new idea… e.g.

THE ASTROPHYSICAL JOURNAL, 178:319–336, 1972 December 1

STELLAR EVOLUTION IN ELLIPTICAL GALAXIES

BEATRICE M. TINSLEY
University of Texas at Dallas
Received 1972 May 26

ABSTRACT

Elliptical galaxies are described by models in which the evolution of stars is followed for 12 billion years. Stellar birthrates chosen are mainly power laws in stellar mass, cut off after 10^9 years; effects of these oversimplifications are discussed. Integrated magnitudes, broad-band colors, narrow-band scanner spectral energy distributions, and strengths of spectral features are derived as a function of time.

Tinsley (1972)

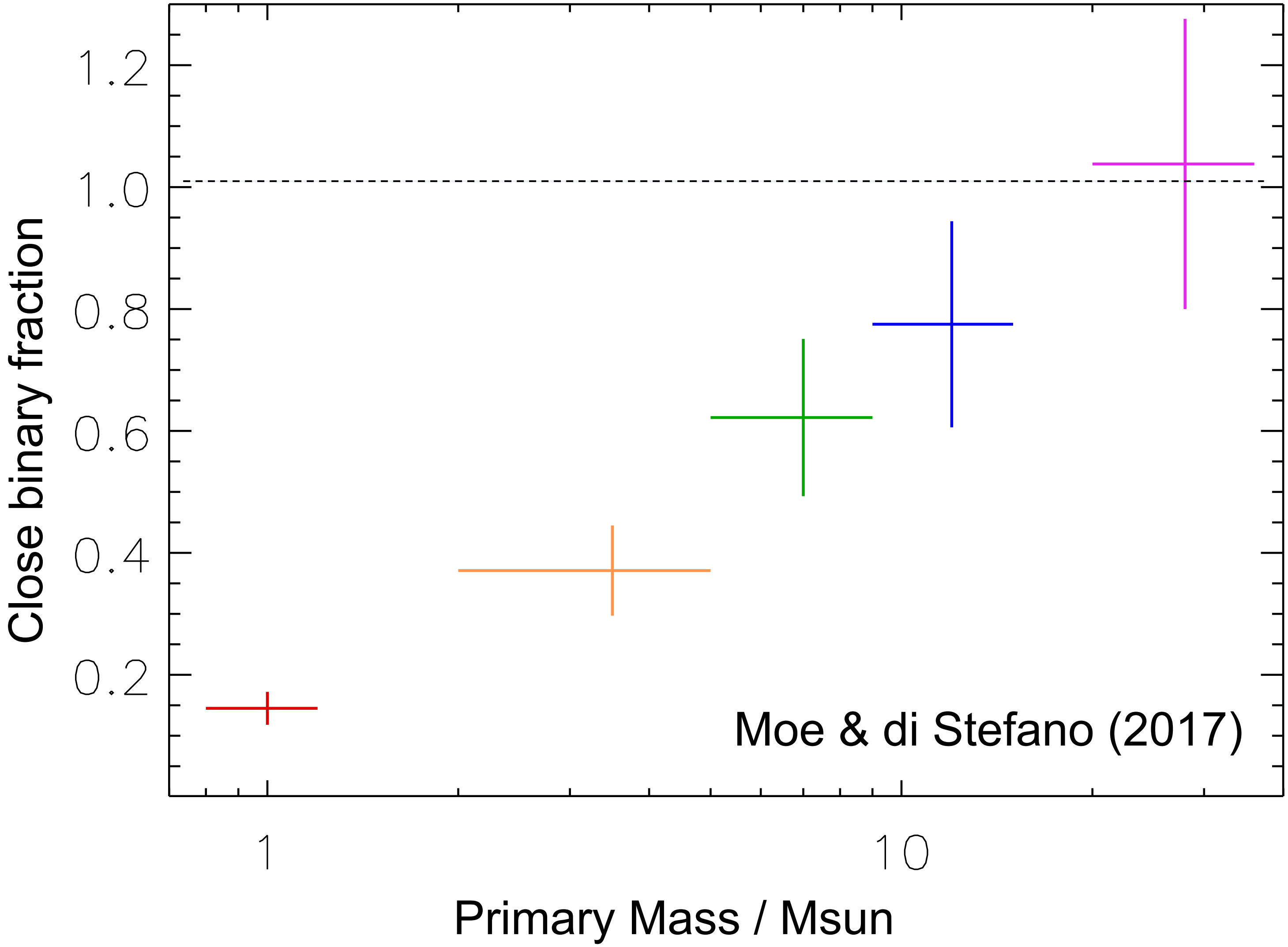
Population Synthesis

But there's one fairly large issue…

All of these synthesis codes use primarily isolated, single star evolution.

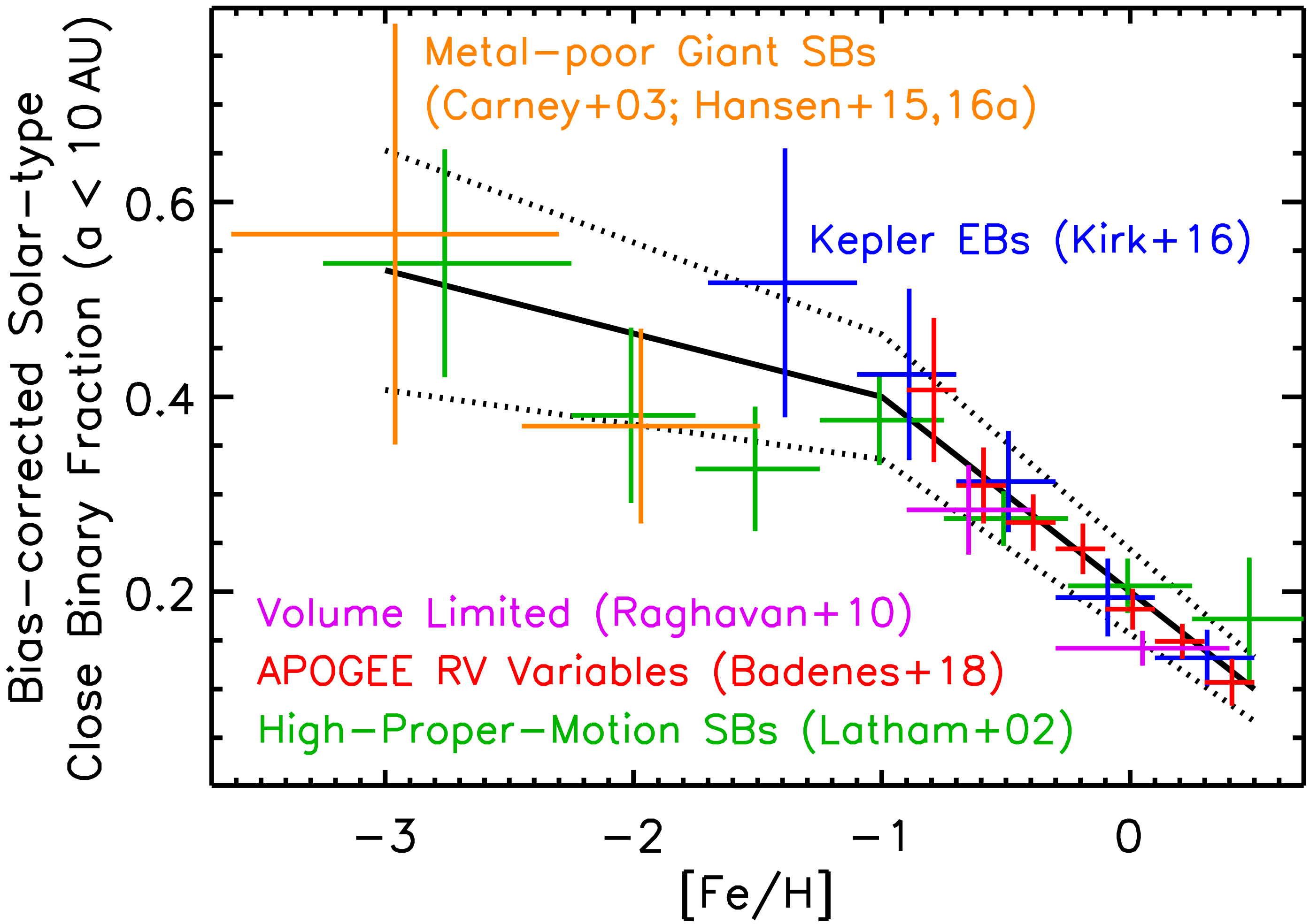
Binary fractions

And most stars are not isolated!



Binary Fractions are even higher at low Z

“The close binary fraction of sun-like stars is strongly anti-correlated with metallicity”, Moe et al, arXiv:1808.02116

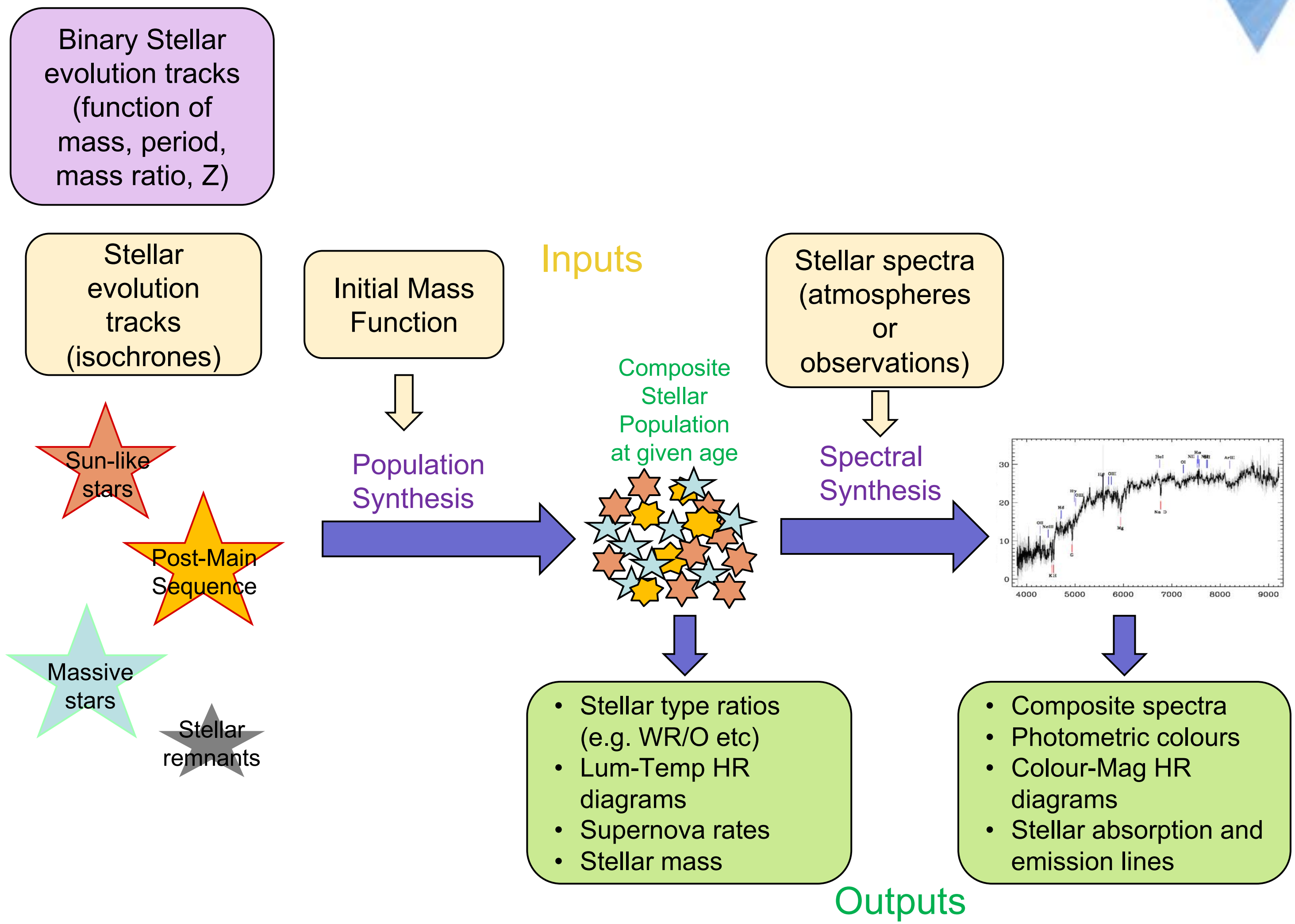


The Need for New Models

- The spectra of young stellar populations are dominated by the most massive stars.
- 70% of massive stars interact with a binary partner in their evolutionary lifetime.
- The effects of these interactions are strongest at low metallicities

=> We cannot ignore binary effects at high z

Population & Spectral Synthesis



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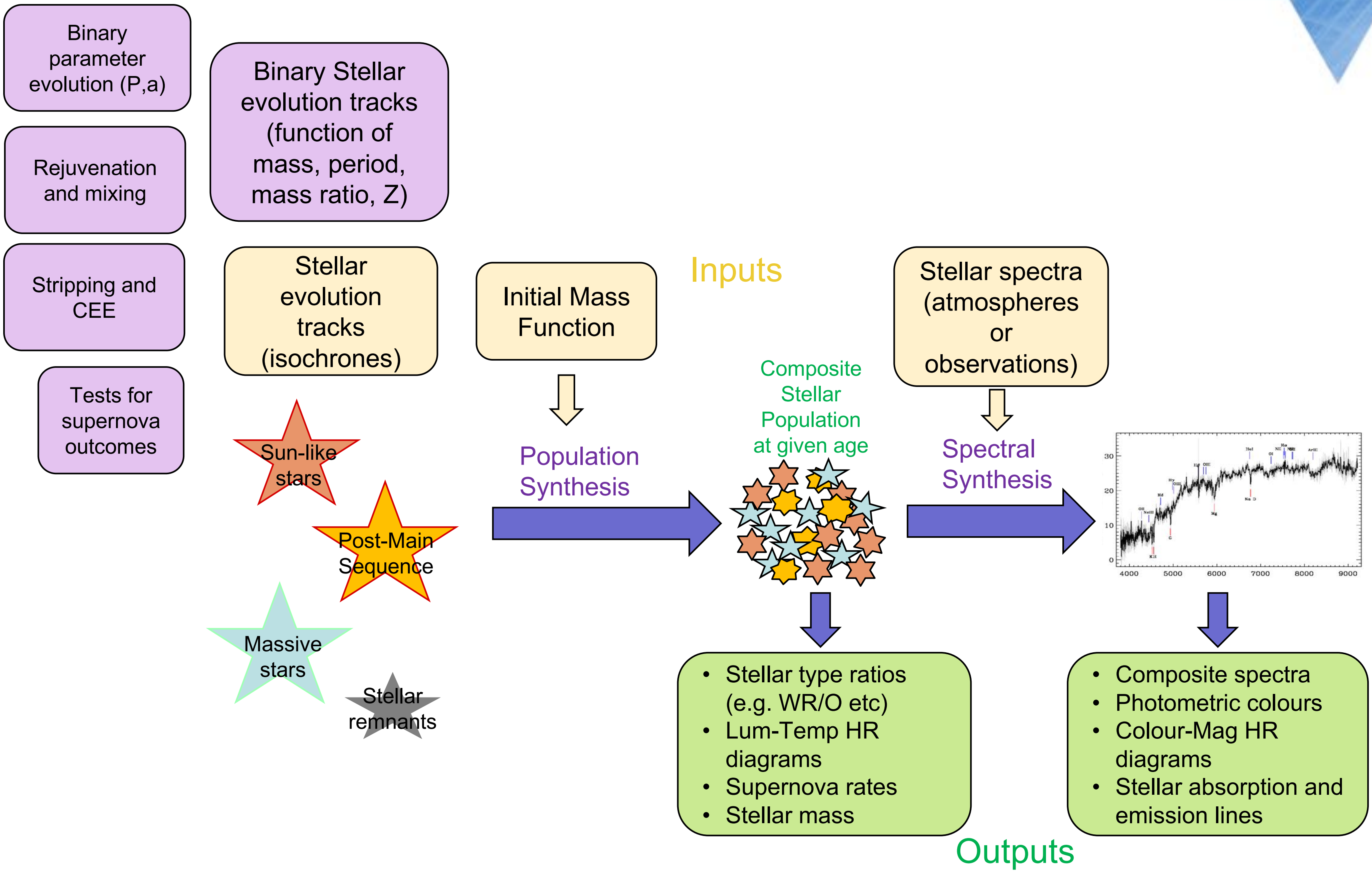

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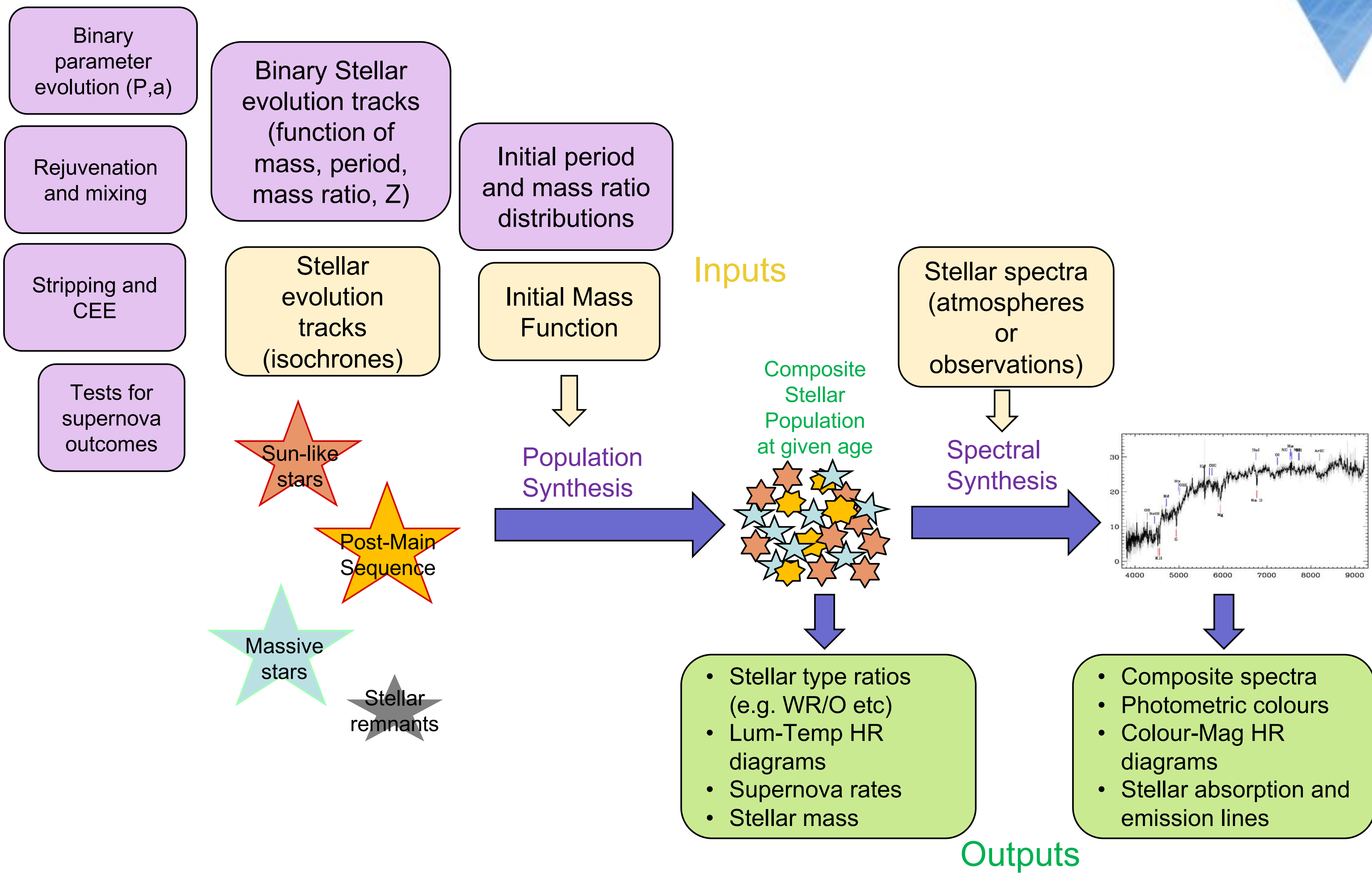


Population & Spectral Synthesis

Tests for supernova outcomes

Rejuvenation and mixing

Stripping and CEE

Binary parameter evolution (P,a)

Binary Stellar evolution tracks (function of mass, period, mass ratio, Z)

Initial period and mass ratio distributions

Stellar evolution tracks (isochrones)

Initial Mass Function

Inputs

Stellar spectra (atmospheres or observations)

Sun-like stars

Post-Main Sequence

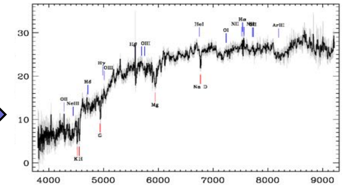
Massive stars

Stellar remnants

Population Synthesis

Composite Stellar Population at given age

Spectral Synthesis



Identify GRBs, accreting compact objects, compact object mergers

- Stellar type ratios (e.g. WR/O etc)
- Lum-Temp HR diagrams
- Supernova rates
- Stellar mass

- Composite spectra
- Photometric colours
- Colour-Mag HR diagrams
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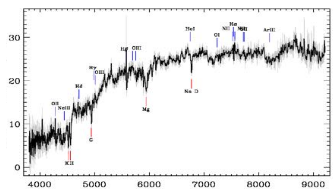

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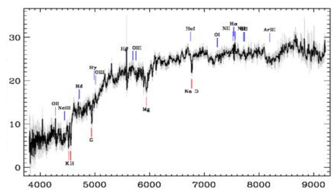

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Binary Population Synthesis

There are two broad approaches:

Rapid Pop Synth (e.g. BSE, Binary_c)

- A semi-analytic approach to evolution and interactions
- Allows parameter space to be explored.

Detailed Pop Synth (e.g. BPASS)

- Uses detailed stellar structure and evolution models
- Much slower, but much more accurate at key evolutionary phases

Hybrid: detailed models for some stars, in a semi-analytic framework (e.g. Amsterdam group, Yunnan group)

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FACULTY OF SCIENCE

- BPASS = Binary Population And Spectral Synthesis
- **~250,000 detailed** stellar evolution models in v2.2.
- A stellar population is generated with a specified IMF, period distribution, binary fraction etc and each star is evolved through detailed modelling, including binary interactions.
- Evolution models are then combined with atmosphere models
- The resultant spectra, HR diagrams and other data are available in our model data release; current version is **v2.2.1**

- **BPASS.AUCKLAND.AC.NZ or WARWICK.AC.UK/BPASS**

(Eldridge & Stanway 2009, 2012; Stanway et al 2016; Eldridge, Stanway et al 2017)

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Publications of the Astronomical Society of Australia (PASA)
doi: 10.1017/pas.2017.xxx.

Binary Population and Spectral Synthesis Version 2.1: construction, observational verification and new results

J.J. Eldridge[1]; E. R. Stanway[2]; L. Xiao[1], L.A.S. McClelland[1], G. Taylor[1], M. Ng[1], S.M.L. Greis[2], J.C. Bray[1]
[1]Department of Physics, University of Auckland, New Zealand
[2]Department of Physics, University of Warwick, Gibbet Hill Road, Coventry, CV4 7AL

Abstract

The Binary Population and Spectral Synthesis (BPASS) suite of binary stellar evolution models and synthetic stellar populations provides a framework for the physically motivated analysis of both the integrated light from distant stellar populations and the detailed properties of those nearby. We present a new version 2.1 data release of these models, detailing the methodology by which BPASS incorporates binary mass transfer and its effect on stellar evolution pathways, as well as the construction of simple stellar populations. We demonstrate key tests of the latest BPASS model suite demonstrating its ability to reproduce the colours and derived properties of resolved stellar populations, including well-constrained eclipsing binaries. We consider observational constraints on the ratio of massive star types and the distribution of stellar remnant masses. We describe the identification of supernova progenitors in our models, and demonstrate a good agreement to the properties of observed progenitors. We also test our models against photometric and spectroscopic observations of unresolved stellar populations, both in the local and distant Universe, finding that binary models provide a self-consistent explanation for observed galaxy properties across a broad redshift range. Finally, we carefully describe the limitations of our models, and areas where we expect to see significant improvement in future versions.

arXiv:1710.02154
PASA, 34, 58 (2017)

See also our new User Manual.

Reevaluating Old Stellar Populations

E. R. Stanway[1★] and J. J. Eldridge[2†]
[1] *Department of Physics, University of Warwick, Gibbet Hill Road, Coventry, CV4 7AL, United Kingdom*
[2] *Department of Physics, Private Bag 92019, University of Auckland, New Zealand*

Accepted 2018 May 17. Received 2018 May 14; in original form 2018 March 27

arXiv:1805.08784

ABSTRACT
Determining the properties of old stellar populations (those with age >1 Gyr) has long involved the comparison of their integrated light, either in the form of photometry or spectroscopic indexes, with empirical or synthetic templates. Here we reevaluate the properties of old stellar populations using a new set of stellar population synthesis models, designed to incorporate the effects of binary stellar evolution pathways as a function of stellar mass and age. We find that single-aged stellar population models incorporating binary stars, as well as new stellar evolution and atmosphere models, can reproduce the colours and spectral indices observed in both globular clusters and quiescent galaxies. The best fitting model populations are often younger than those derived from older spectral synthesis models, and may also lie at slightly higher metallicities.

Key words: methods: numerical – binaries: general – galaxies: stellar content – globular clusters: general

MNRAS (2018)

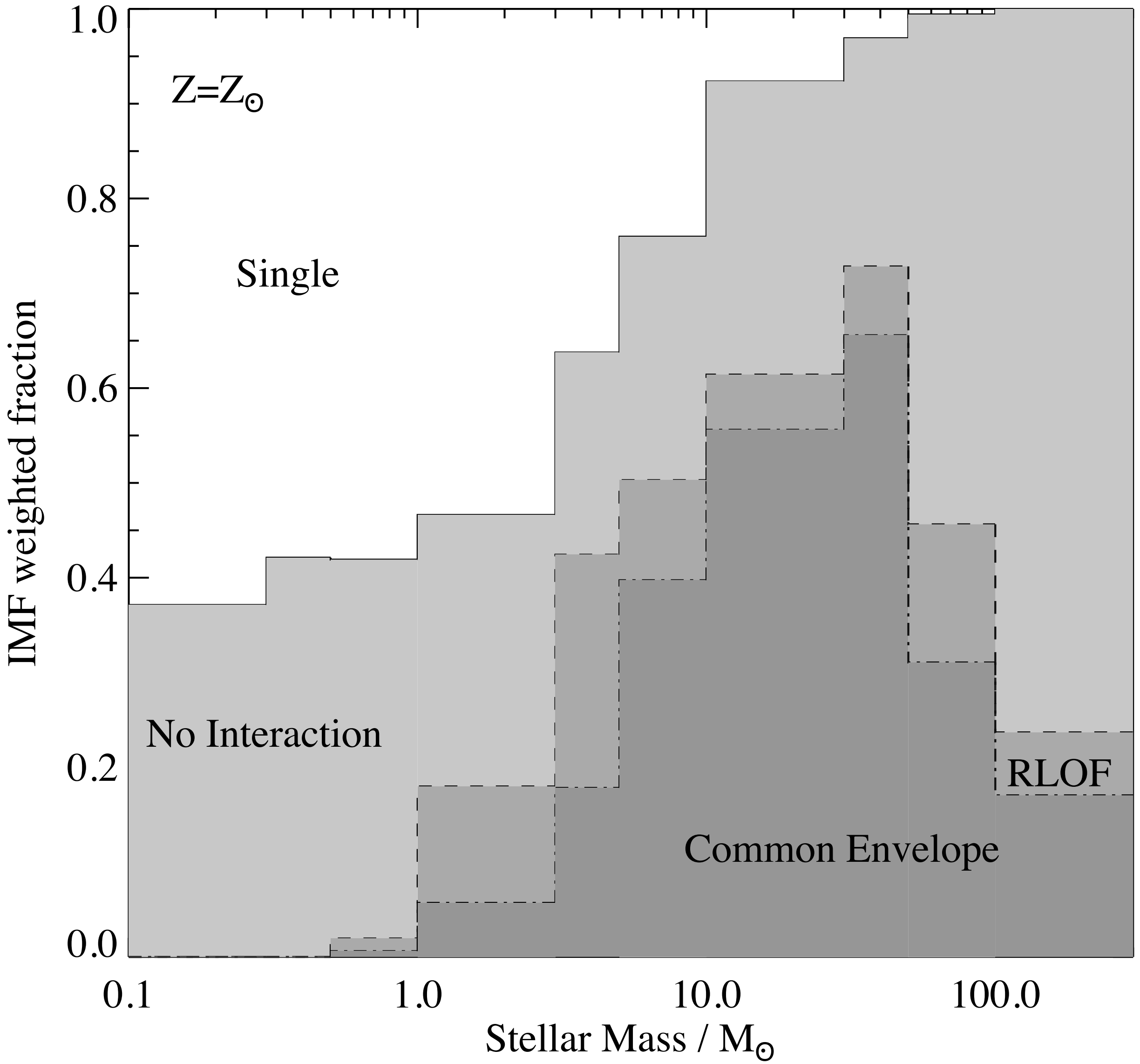
Also an updated User Manual.

- v2.2 (Stanway & Eldridge 2018) deals primarily with old stellar populations – young stellar pops are mostly unchanged
- It includes more low mass models, improved binary parameter distributions, improved rejuvenation and post-main-sequence prescriptions
- Adds Lick indices and mass-to-light ratios to our standard outputs
- Adds the Chabrier IMF (with M_{max}=100 or 300M_{sun}) to our standard outputs
- Paper and data release now out (arXiv:1805.08784)

- **BPASS.AUCKLAND.AC.NZ or WARWICK.AC.UK/BPASS**

(Eldridge & Stanway 2009, 2012; Stanway et al 2016; Eldridge, Stanway et al 2017)

Binary Interaction Fraction



BPASS v2.2
Stanway &
Eldridge (2018)

BPASS

Custom grid of BPASS single and binary stellar evolution models at 13 metallicities

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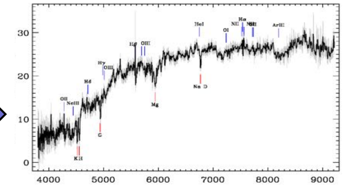

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v2.1: simple functions (7 IMFs)

v2.2: Moe & di Stefano (2017) functions (9 IMFs)

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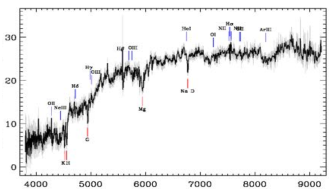

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v2.2: Moe & di Stefano (2017) functions (9 IMFs)

Inputs

v2.1: PoWR + Basel + custom

v2.2: PoWR + Conroy + Levenhagen WDs + custom

evolution (P,a)

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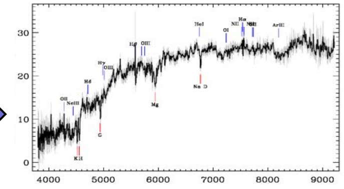

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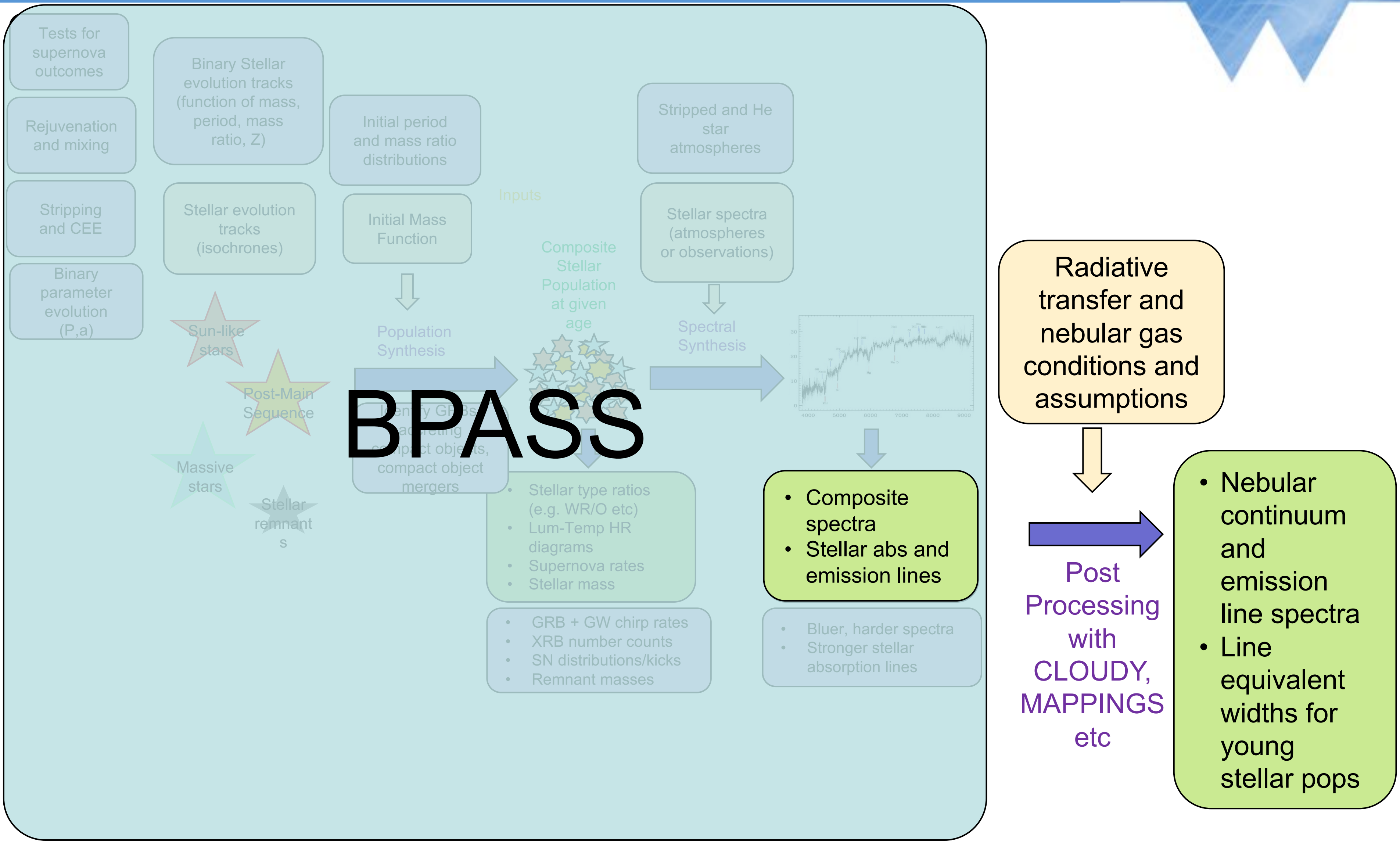
BPASS

The result is a set of output integrated stellar-light spectra at 51 age steps from 1 Myr to 100 Gyr, together with transient rates, stellar number counts, HR diagram information, etc.

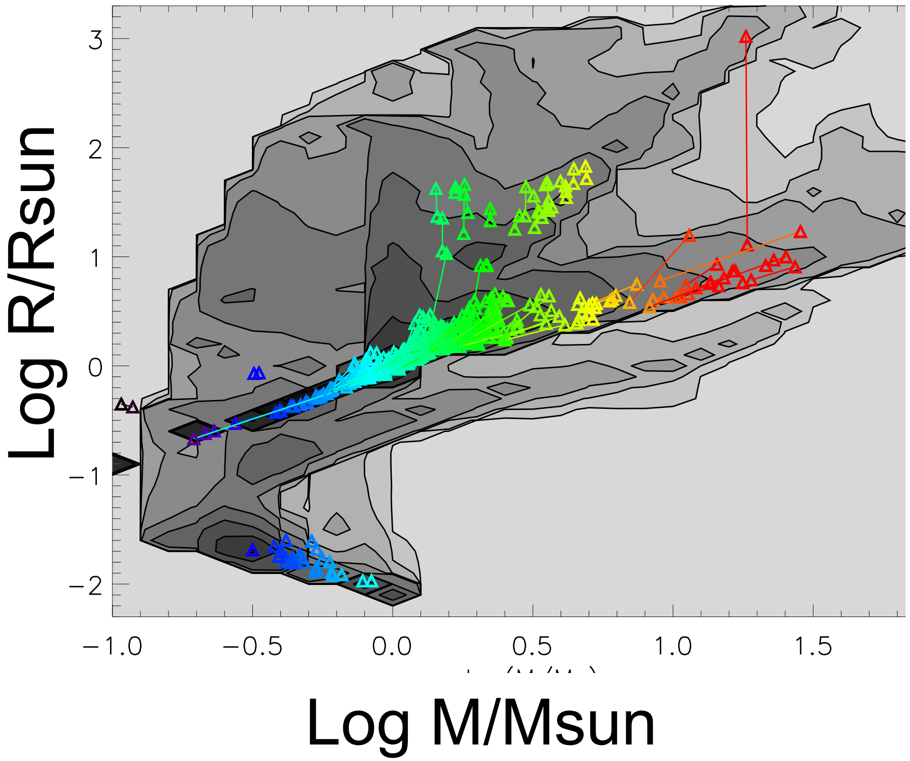
The spectra yield the shape, strength and absorption lines of the Lyman continuum

Further post-processing is then possible to study non-stellar components.

BPASS + post-processing

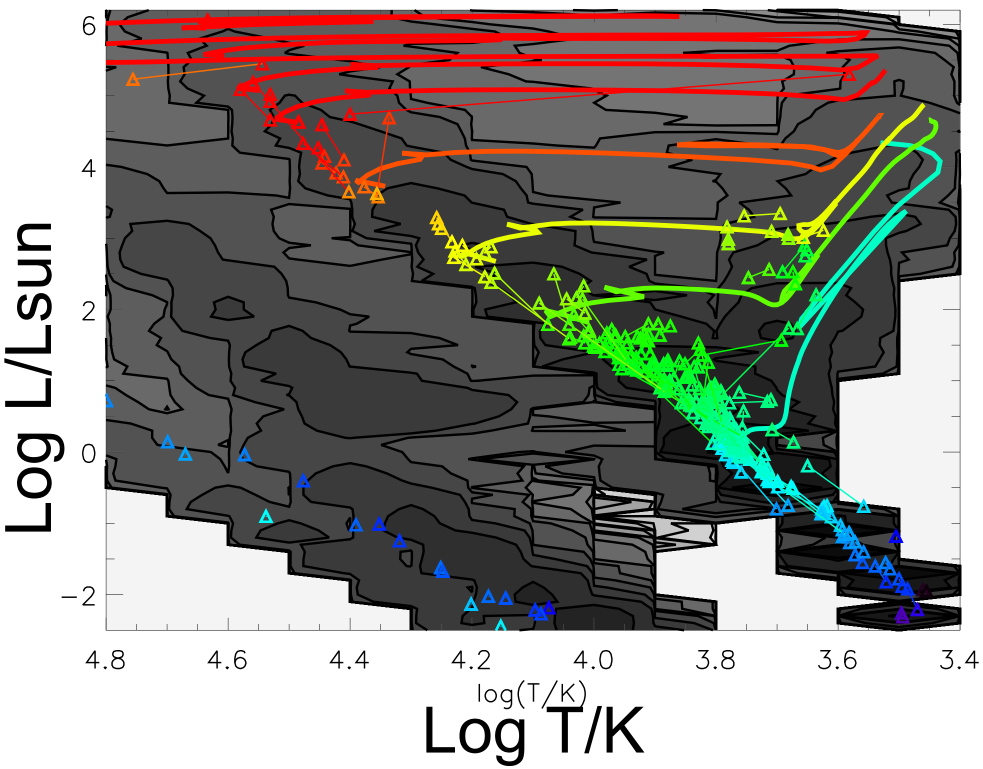


HR Diagram Isocontours



Observed eclipsing binaries and BPASS tracks

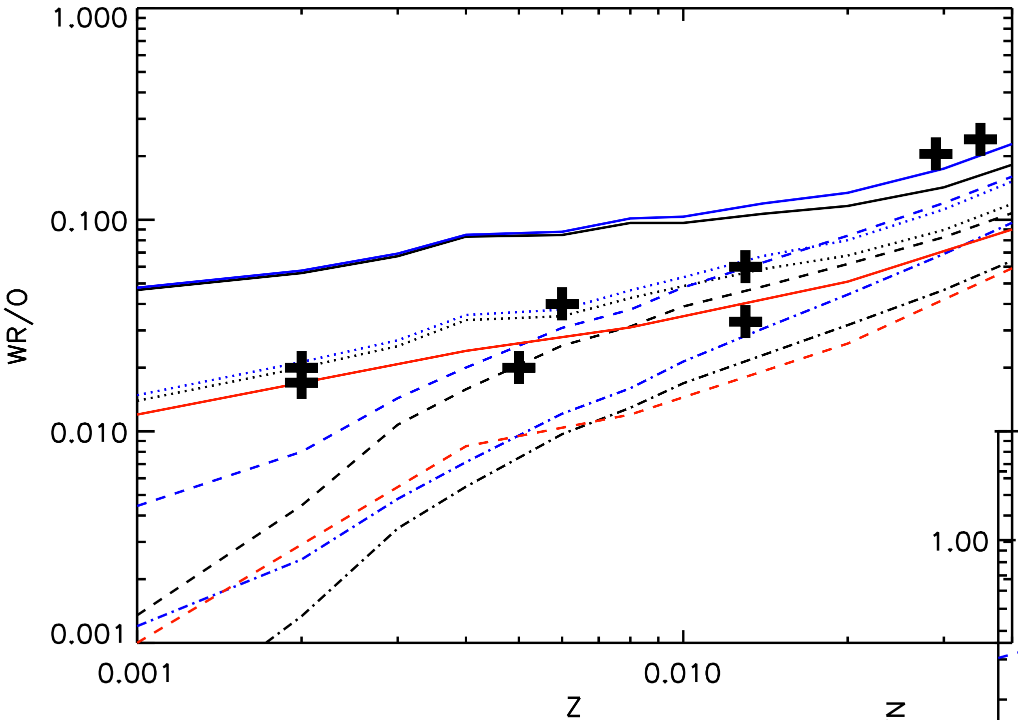
(colour coded by mass)



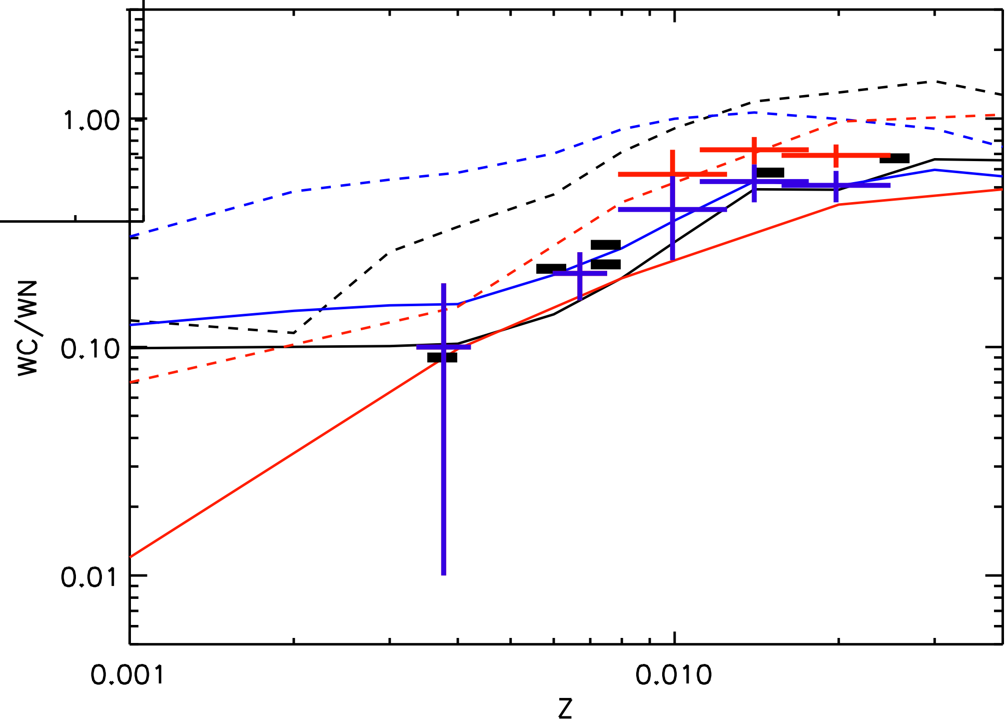
Southworth and Parsons samples of eclipsing binaries shown as triangles

BPASS v2.1, Eldridge, Stanway et al (2017)

Stellar Type Ratios



Wolf-Rayet to O star ratios with metallicity



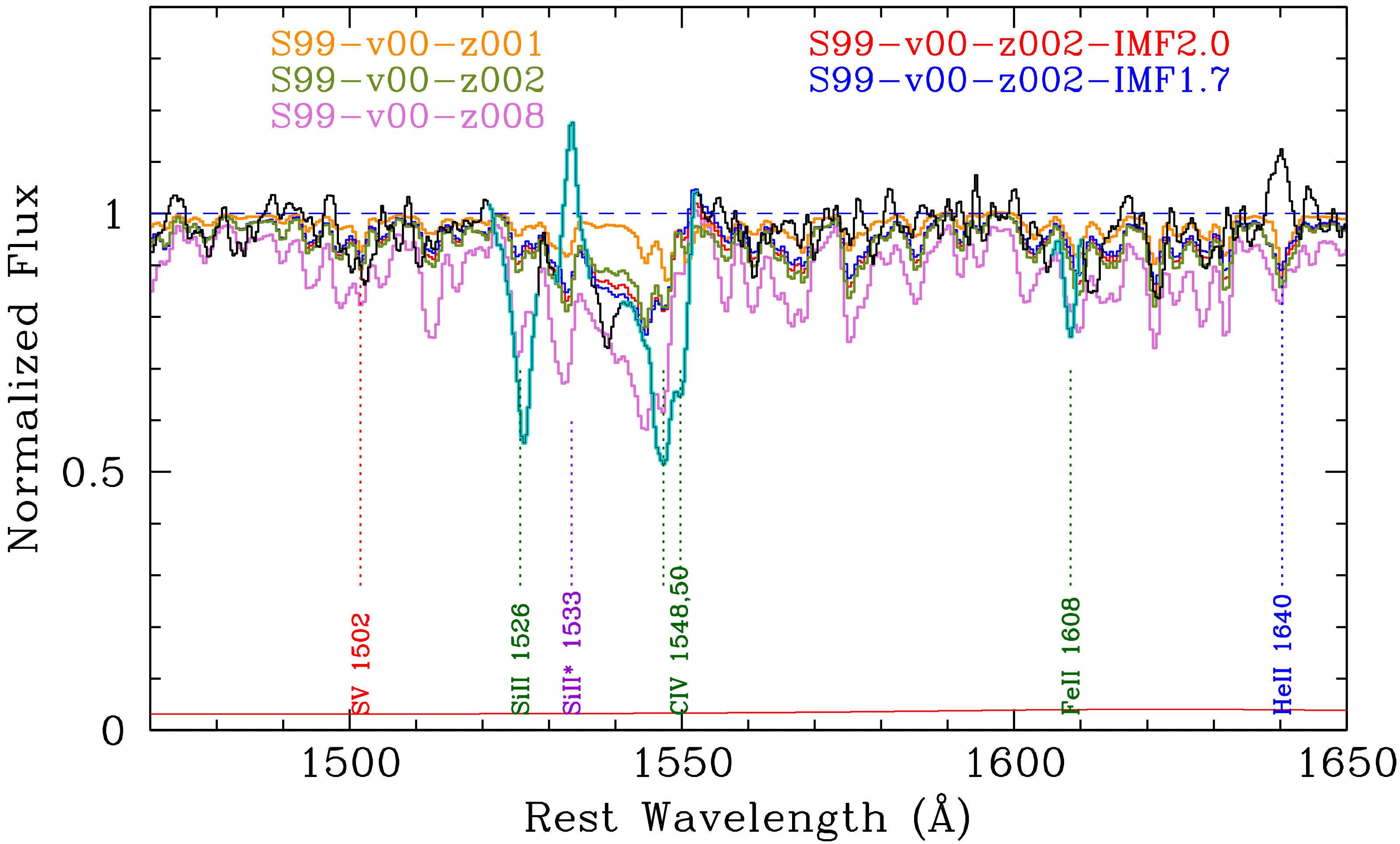
Wolf-Rayet stellar subtype ratios with metallicity

BPASS v2.1, Eldridge, Stanway et al (2017)

So far so good…

… but let's get back to where we started: the observed properties of distant, young, low Z stellar populations

Stellar Lines at z~3



Steidel et al. (2016), see also Eldridge & Stanway (2012)

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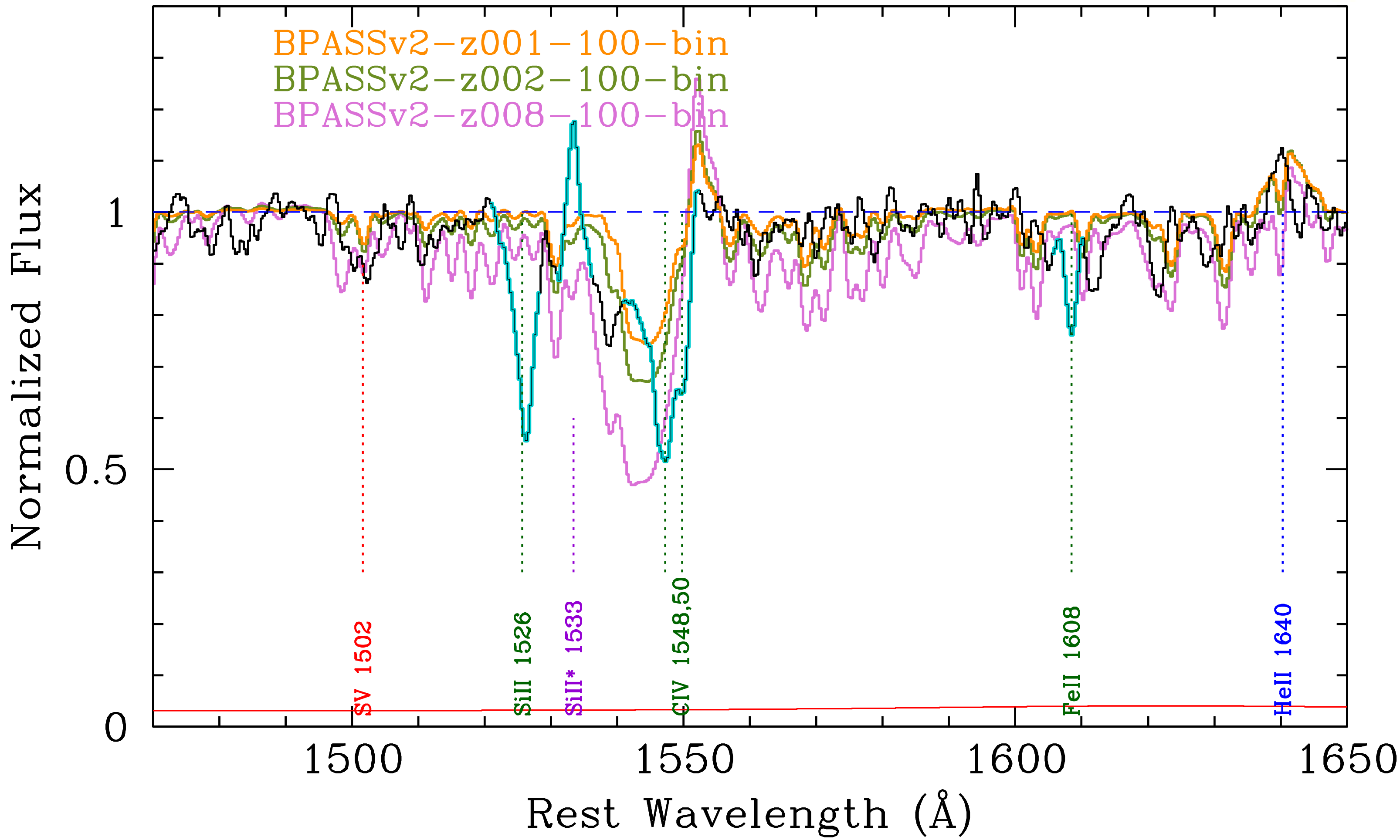

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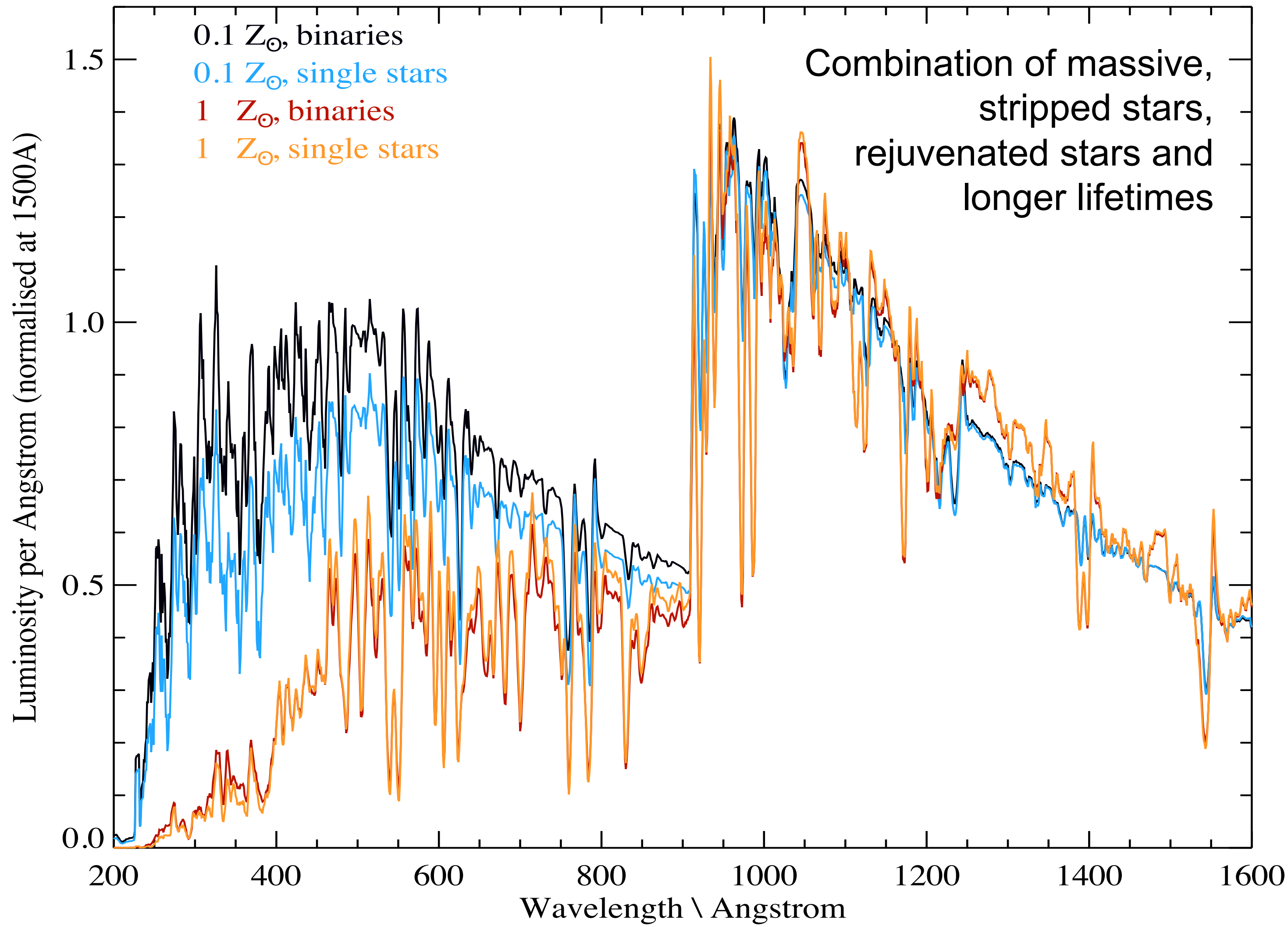
The Effect of Binary Evolution

Binary evolution produces stronger Lyman continuum flux:



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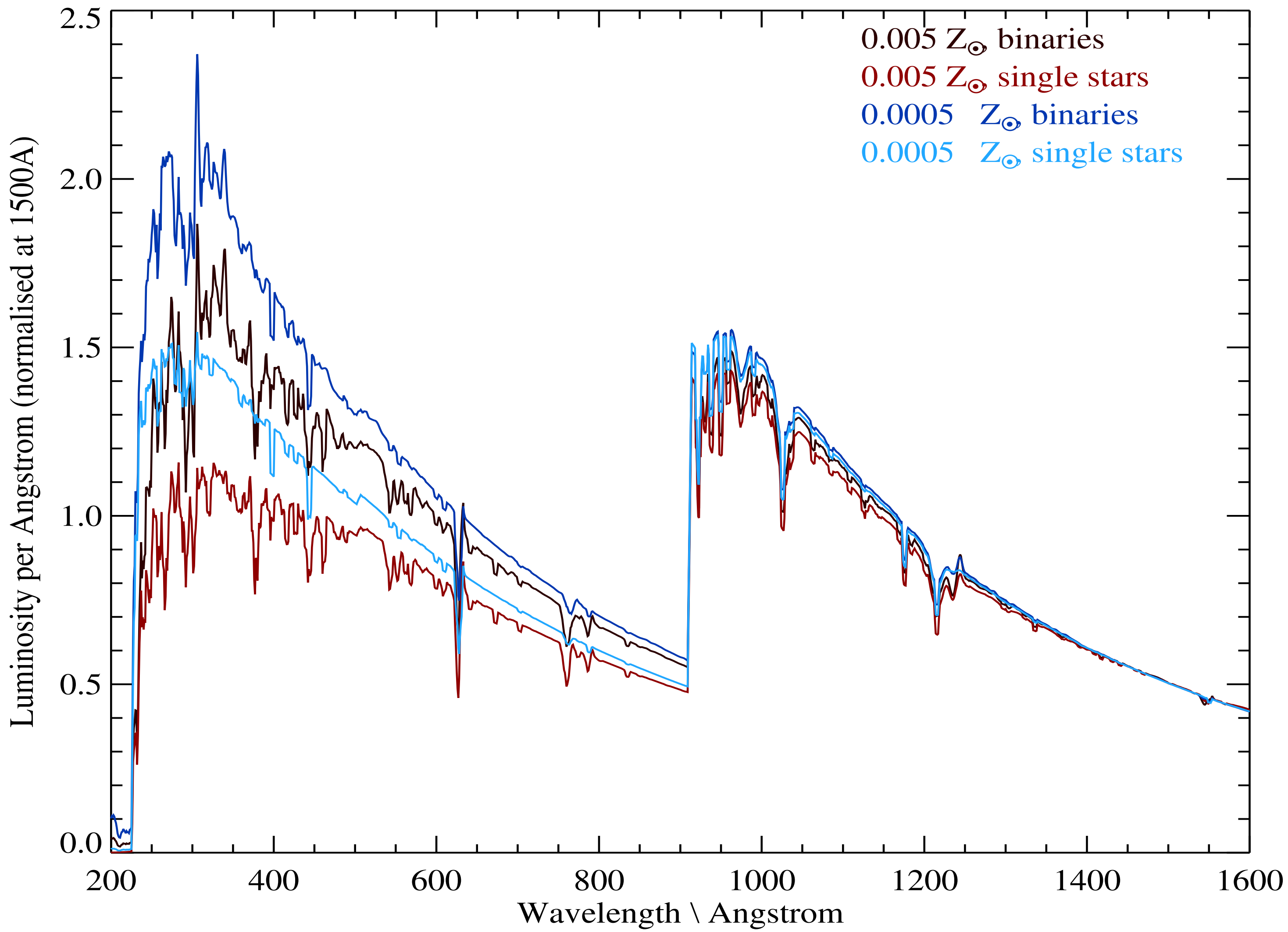
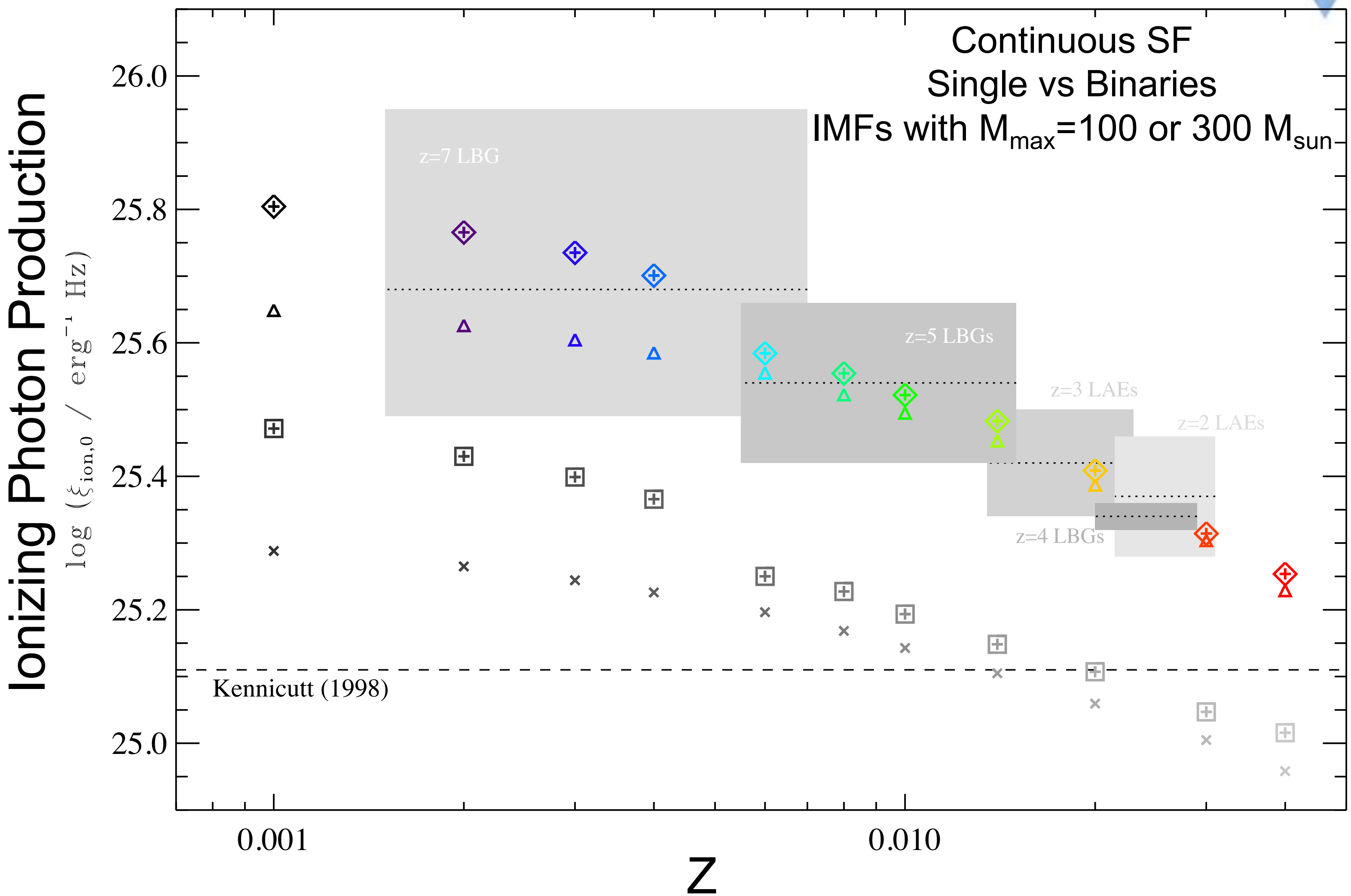


Difference in Ionizing Flux

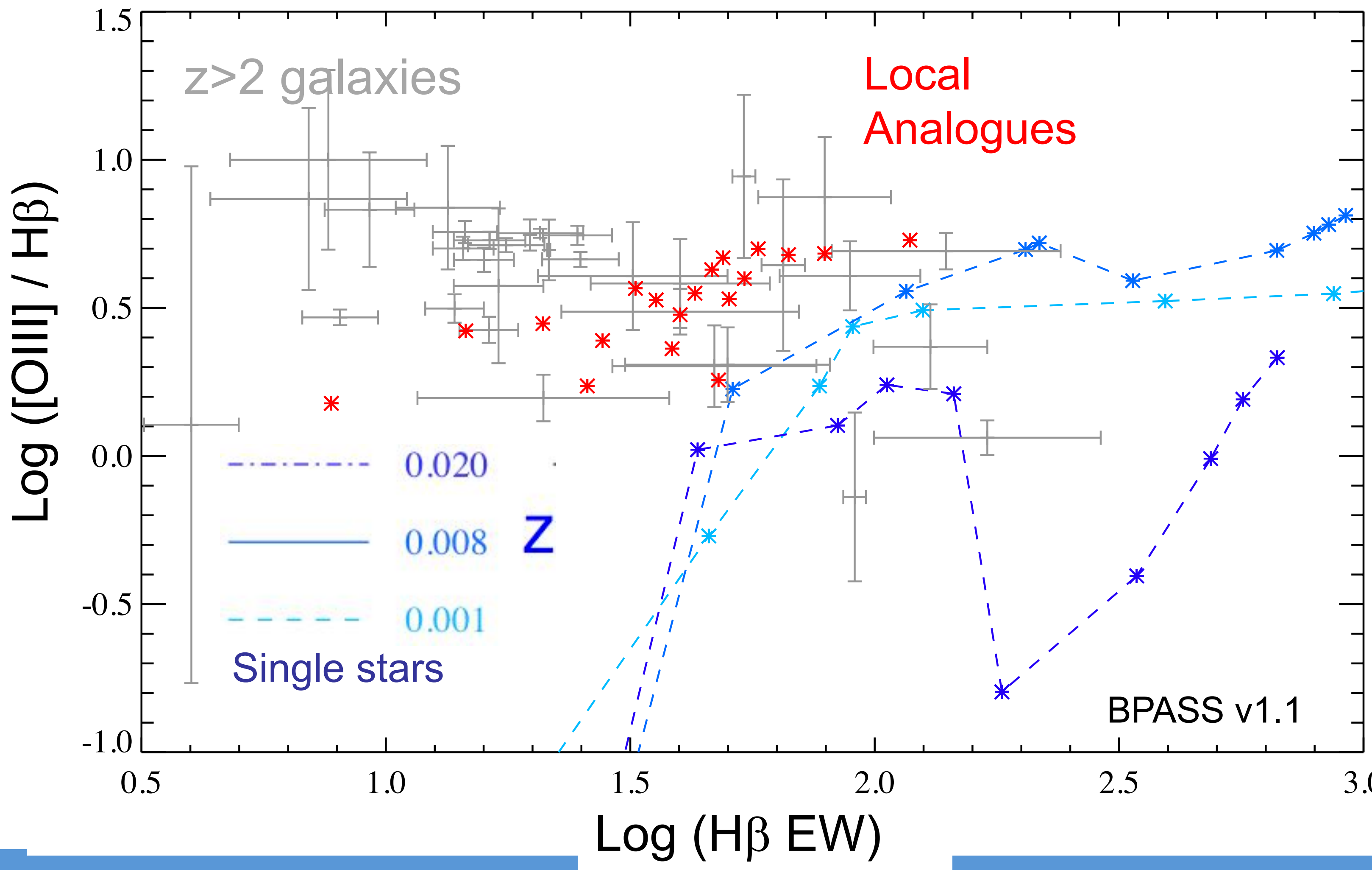


BPASS v2,
Stanway et al (2016,2017), Eldridge et al (2017)

See also Wilkins et al 2016; Ma et al 2016; Steidel et al 2016

Emission Line Diagnostics

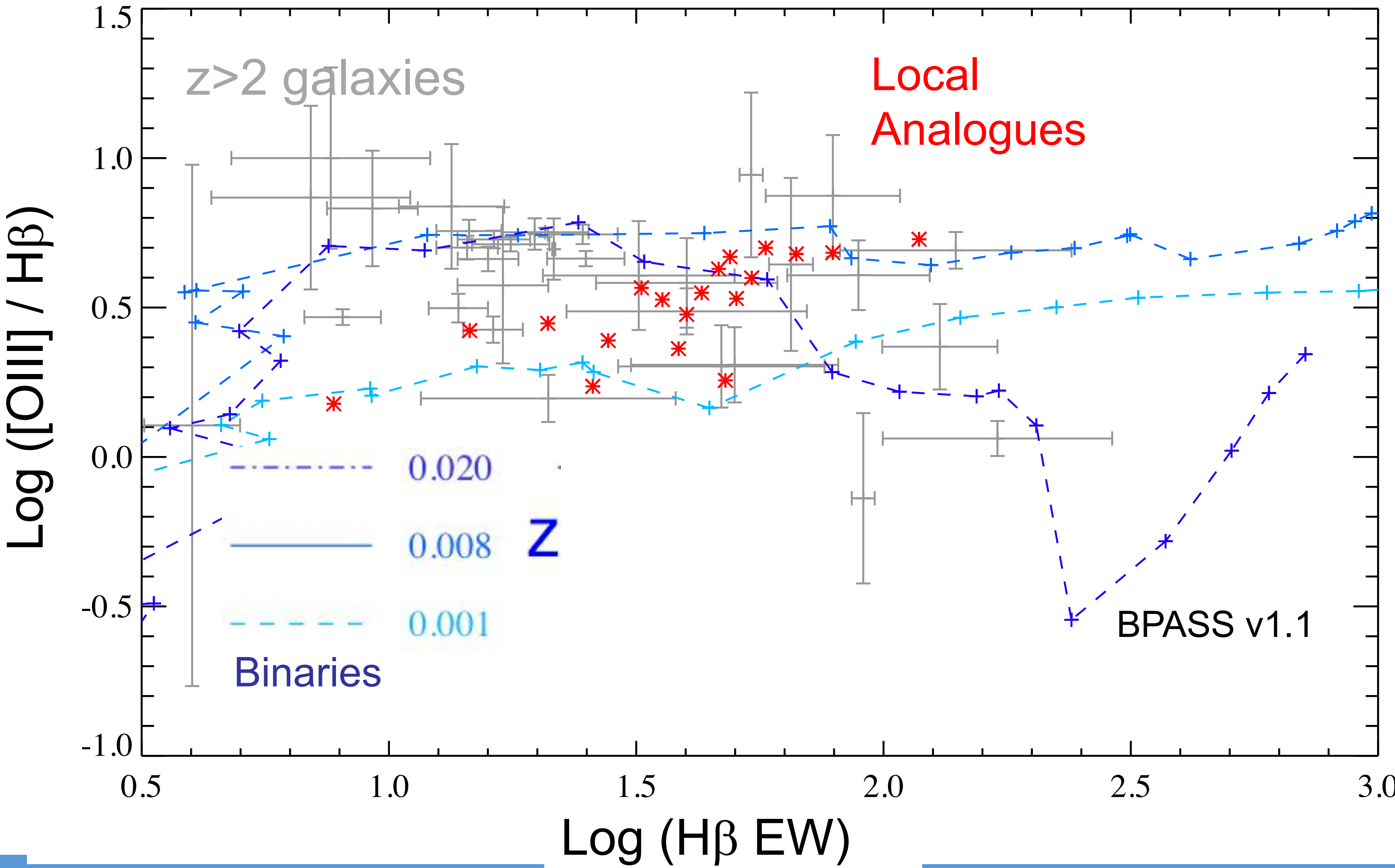
The ratio of optical emission line strengths provides information on the hardness of the ionizing radiation field



Stanway et al, 2014, MNRAS 444 3466
For LBAs see Stanway & Davies 2014; Greis et al 2016

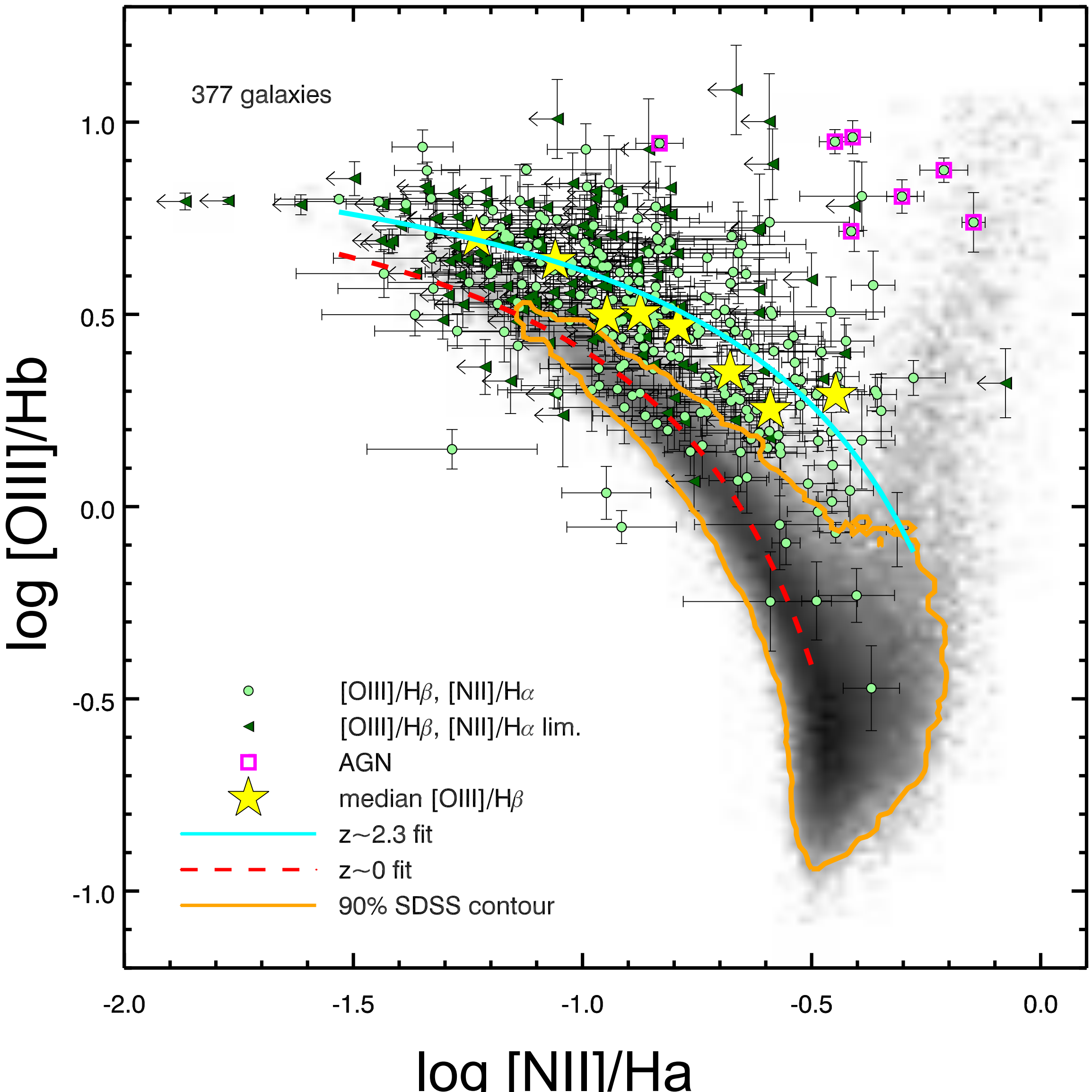
Emission Line Diagnostics

The ratio of optical emission line strengths provides information on the hardness of the ionizing radiation field



Stanway et al, 2014, MNRAS 444 3466

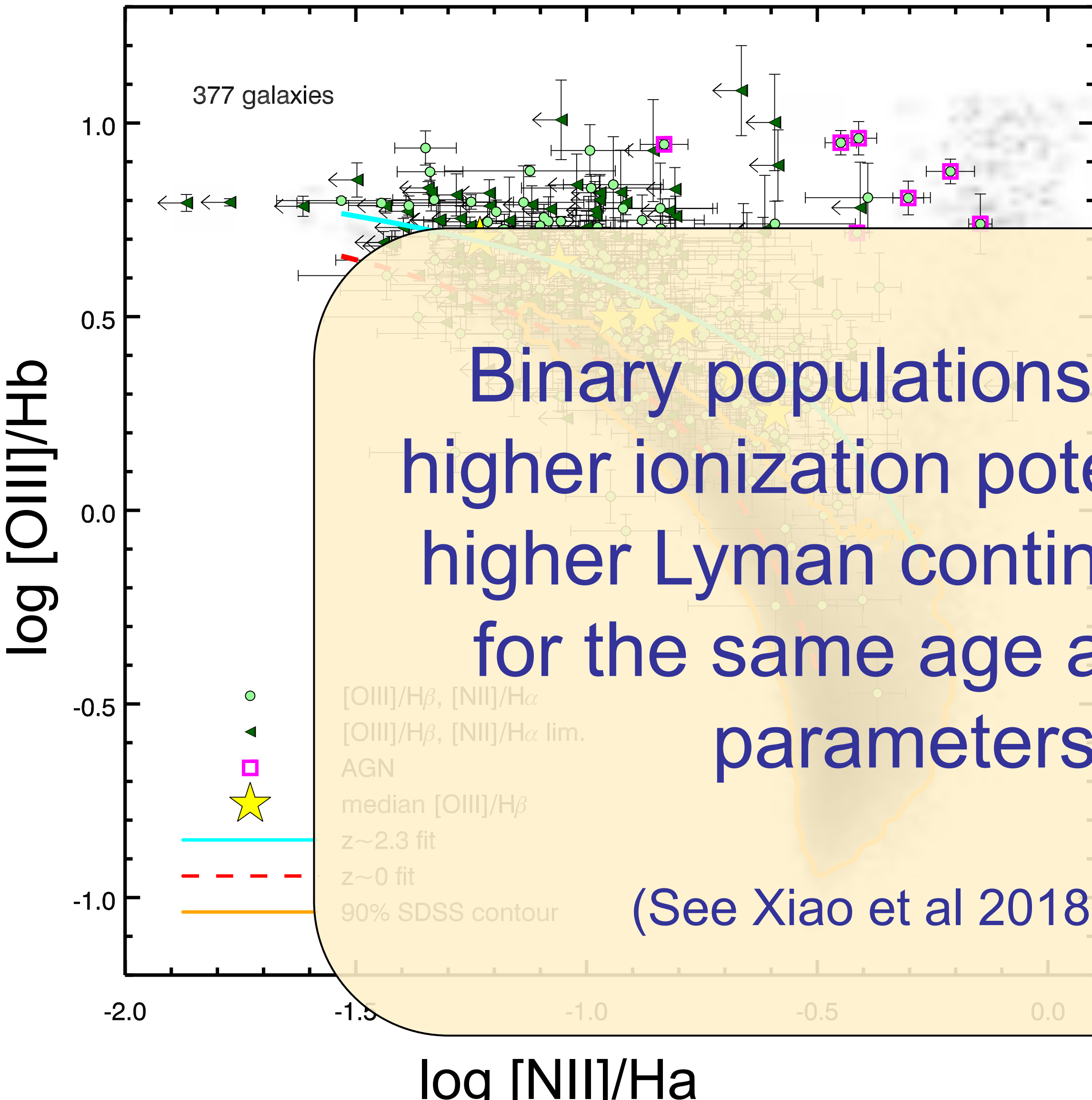
The Ionizing Spectrum at z~3



Multi-object near-IR spectrographs on 8-10m class telescopes (notably MOSFIRE on Keck) are making the high z rest-optical diagnostics accessible for the first time.

(Strom et al 2016, see also Steidel et al 2016, Kriek et al 2016, Reddy et al 2016)

The Ionizing Spectrum at z~3



Binary populations have a higher ionization potential and higher Lyman continuum flux for the same age and gas parameters

(See Xiao et al 2018a,b)

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(Strom et al 2016, see also Steidel et al 2016, Kriek et al 2016, Reddy et al 2016)

BPASS Caveats and Gotchas

He II lines seem to be systematically underestimated

- Stellar Winds at low metallicity
- X-ray binaries, PNe and CVs

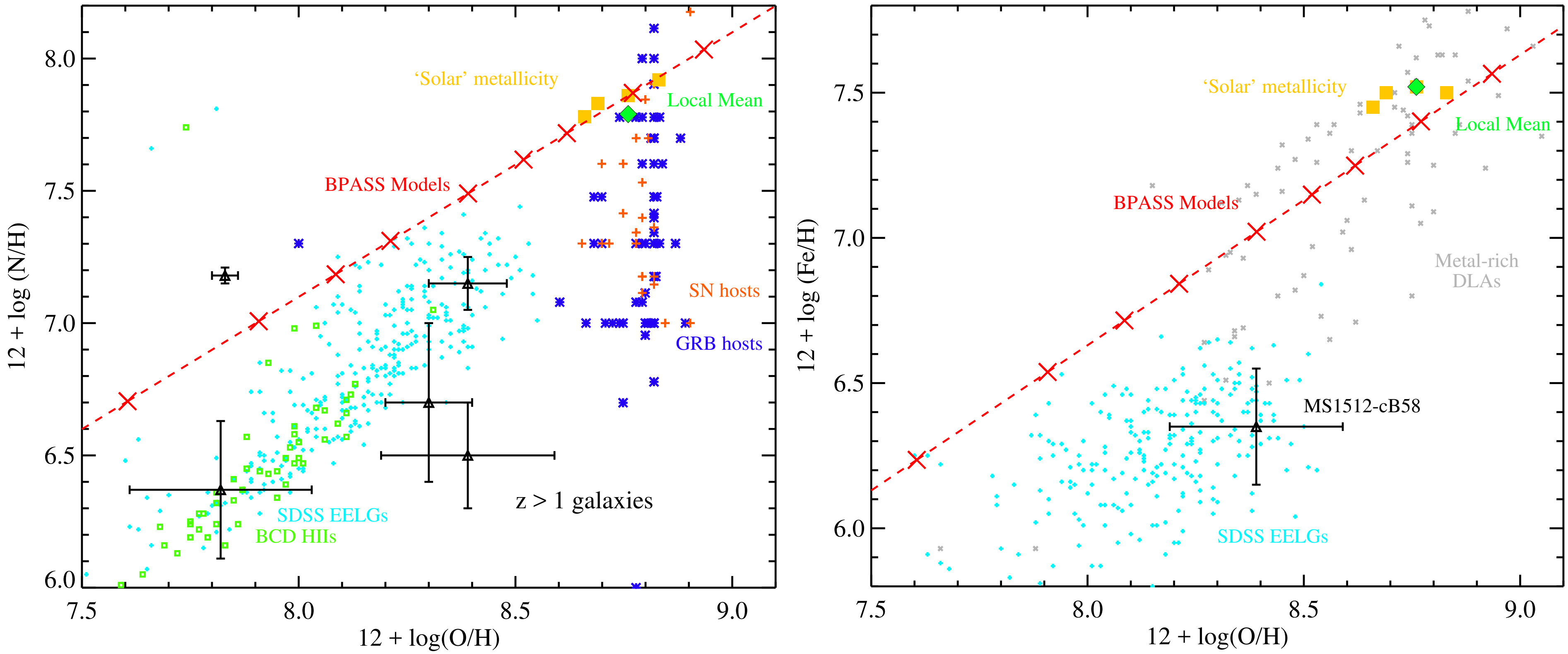
We currently fix the elemental abundance ratios at Solar – this will deviate at low metallicity

- Needs new stellar models
- Needs new atmosphere models

We think we need even higher binary fractions at low metallicity

- Needs new parameterisation

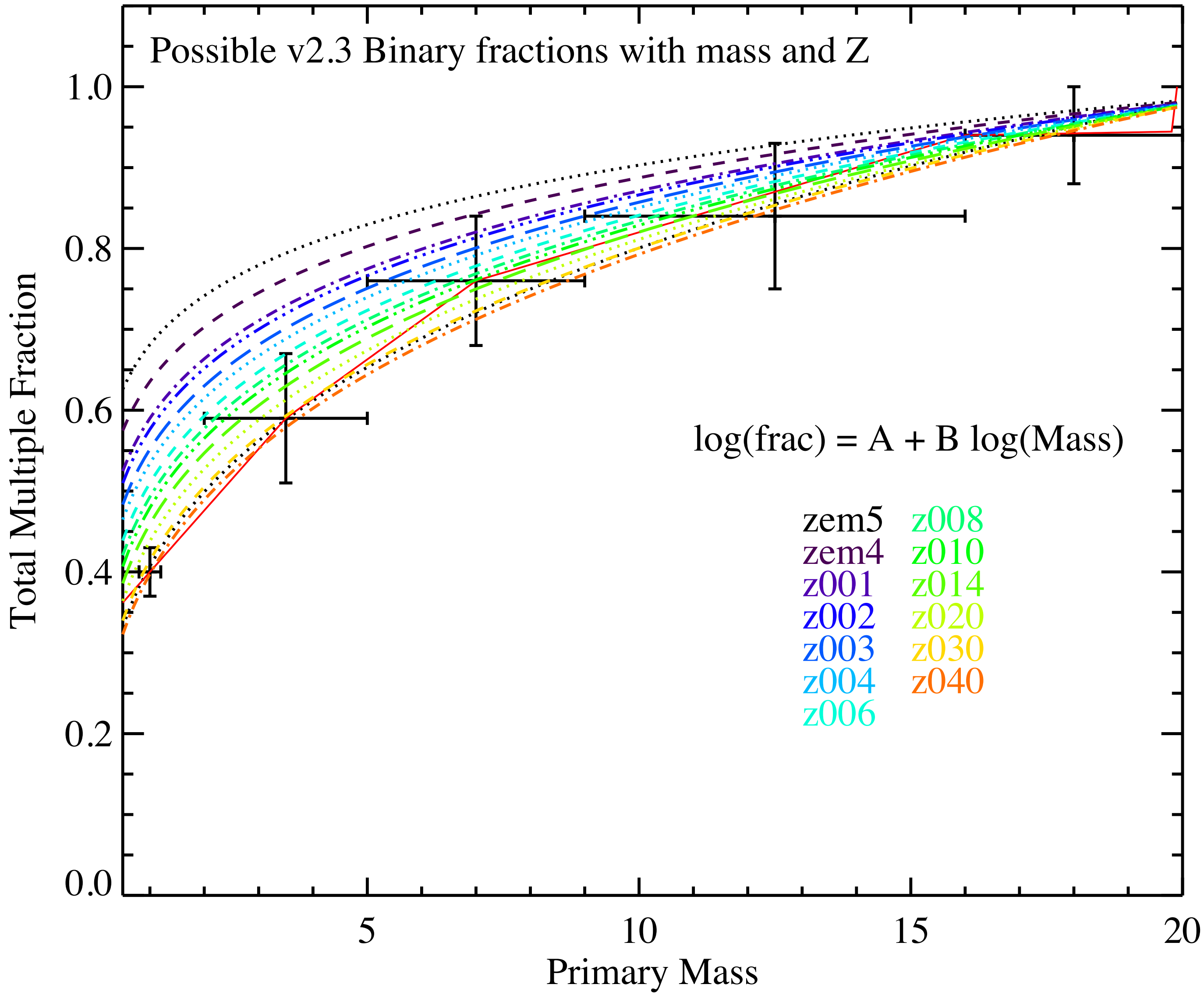
Abundances



But remember:

Stellar metallicity is not necessarily gas phase metallicity.

The evolution of binary fraction with Z



Work in progress!

Conclusions

- Galaxy observations sensitive to the Lyman continuum are finding evidence for intense, highly ionizing stellar populations across a wide redshift range.

- Incorporating binaries in stellar pop synth models is necessary in this regime.

- Our BPASS models include detailed binary models – bpass.auckland.ac.nz.

- Binary evolution modelling is an ongoing effort which needs community input.