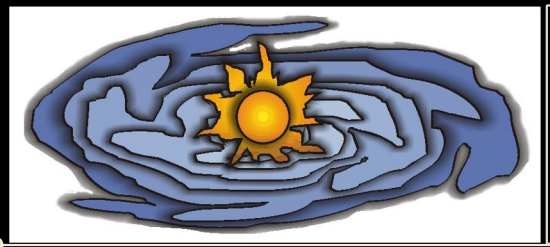
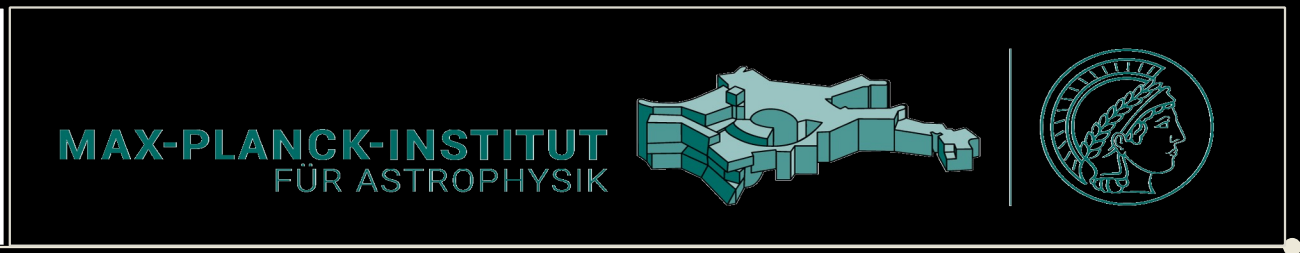
New prospects on HR-pyPopStar evolutionary synthesis models

Iker Millán Irigoyen, Mercedes Mollá, Miguel Cerviño, Marisa García-Vargas





Outline

01 Introduction

02 Synthesis of Stellar Populations

03 Results

04 Conclusions



Introduction

Introduction

- State of the art and future instruments, such as, MUSE, MEGARA, DESI, VLT/MOONS, WEAVE, MOSAIC, JWST,... create huge amounts of data to analyse
- It is necessary to have a fast and accurate way to extract all the information that the spectra can provide us, e.g. , mean age, mean metallicity, chemical enrichment history, Star Formation History,...
- The synthetic spectra of SSPs are vital to use as templates or to plug into a spectral analysis code
- The resolution of the SEDs may change the interpretation of the new data of galaxies.
- This might help to break the age-metallicity degeneracy that evolutionary models with low spectral resolution can not solve
- These synthetic spectra can be used to study the stellar populations of distant galaxies in different environments



Synthesis of stellar populations

SIMPLE STELLAR POPULATION

A Simple Stellar Population (SSP) is a group of stars that are born at the same time from the same cloud, thus having the same age and chemical composition

Evolutionary synthesis models for SSPs needs three basic ingredients:

- An Initial Mass Function (IMF)
- An isochrone that traces the stellar evolution
- Spectra of the stellar atmospheres



Messier 15. Credit: NASA/ESA/HST

SYNTHESIS OF SSPs

- The spectra of a SSP of an age t and metallicity Z is:

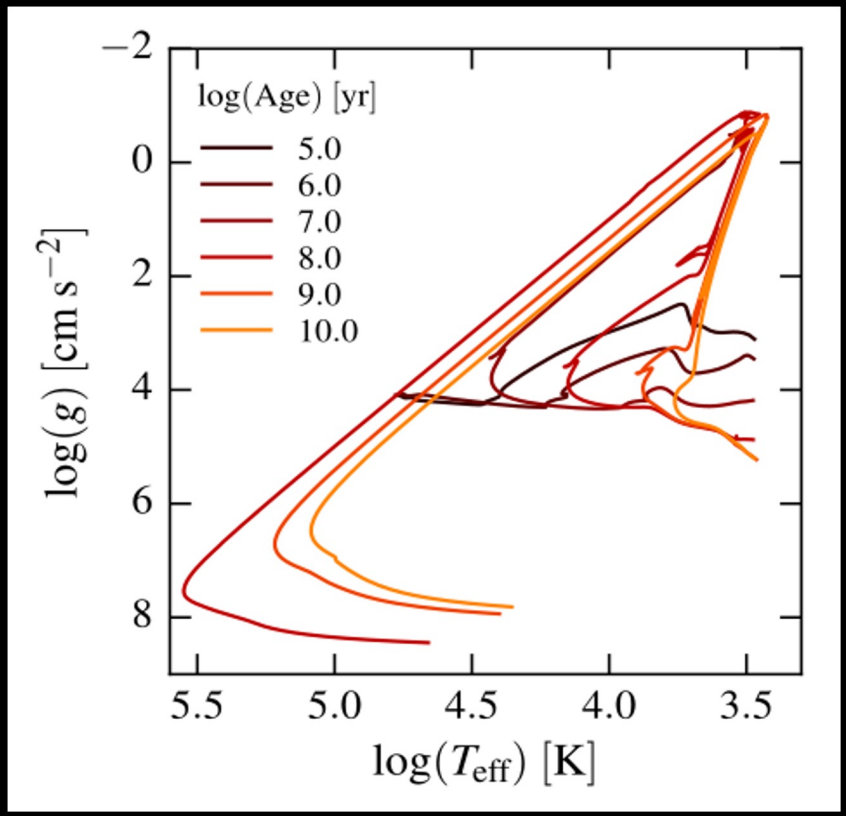
$$F_{\lambda,\mathrm{SSP}}(Z,t) = \int_{\mathrm{m_{low}}}^{m_{\mathrm{lim}}(t)} \phi(m)\, F_{*,\lambda}(m,Z,t)\,\mathrm{d}m$$

- Discretizing the isochrones in a finite number of mass steps:

$$F_{\lambda,\mathrm{SSP}}(Z_i,t_i) = \sum_{j=1}^{\mathrm{N_{tot\ lib}}(Z_i)} w_j(Z_i,t_i) \times F^{\mathrm{lib}}_{\lambda,\,j}(Z_i),$$

ISOCHRONES

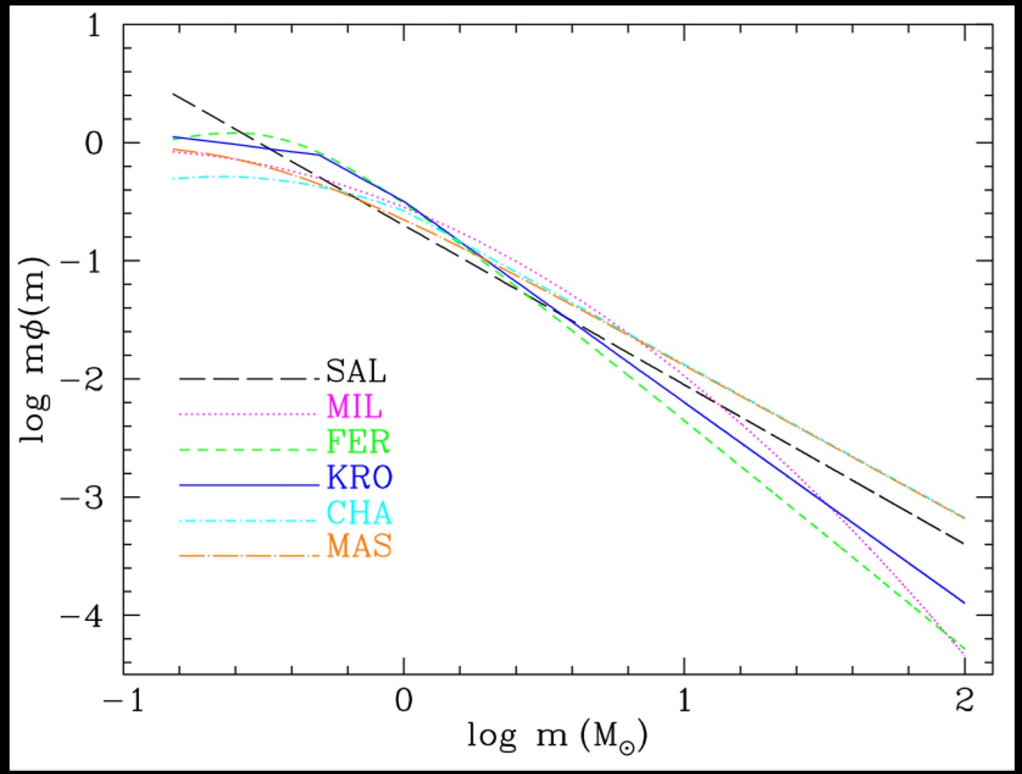
- One vital ingredient for the synthesis of SSP is to know the evolutionary stage of the stars that constitute it
- The stellar evolution can be followed by tracking the location of stars in the Hertzprung-Russell (HR) diagram
- The stellar tracks contain the evolution of each star in the HR diagram
- HR-pyPopStar uses the isochrones of the Padova group: Bressan et al. (1993), Fagotto et al. (1994a,b) & Girardi et al. (1996)



Source: Choi et al. (2016)

INITIAL MASS FUNCTION

- The Initial Mass Function represents how the stars are distributed by mass when the stars are born
- The isochrone is the combination of stellar tracks for a given age and Z
- At each point of the isochrone the number of stars is computed according to the IMF
- HR-pyPopStar uses various IMFs: Salpeter (1955), Ferrini et al (1990), Kroupa (2002) and Chabrier (2003)



SET OF SPECTRA OF STELLAR ATMOSPHERES

- Other vital ingredient is the spectrum of the stellar atmospheres
- The spectra of a star depends heavily on the type of star, its chemical composition, the effective temperature,surface gravity and mass-loss rate
- HR-pyPopStar uses 4 main types of stars:
    - Stars of the spectral type A to M (“cold” stars) Coelho 2014; (low metallicity) Munari et al. (2005)
    - Stars of the spectral type O and B (hot stars) Hainich et al. (2019)
    - Wolf-Rayet stars Sander, Hamann & Todt (2012); Todt et al. (2015)
    - Post-AGB and Planetary Nebulae (PNe) Rauch et al. (2003)

HR-pyPopStar

- We have created HR-pyPopStar, a new python stellar population synthesis modular code based on PopStar Mollá, García-Vargas & Bressan (2009) code that computes high resolution spectra of SSPs

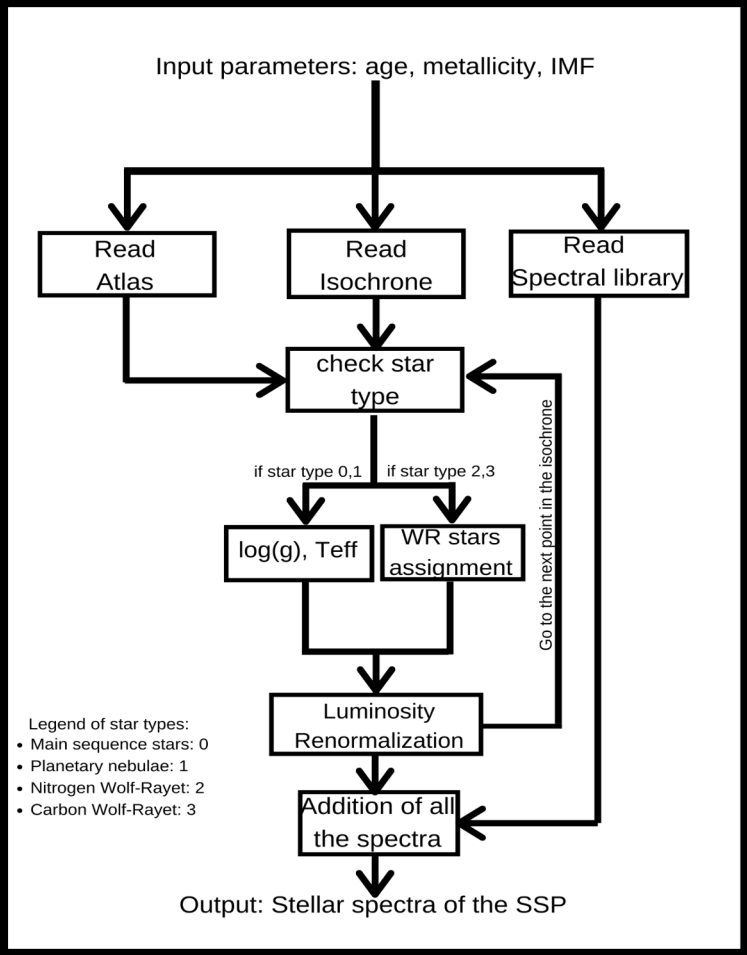
- HR-pyPopStar has a wide range in ages (106 ages), a coverage in metallicity from 0.01 Z to 2 Z (6 metallicities), 4 IMFs and a spectral range from the UltraViolet 91 Å to the Near InfraRed (NIR) 24000 Å
- The computed models are available in https://www.fractal-es.com/PopStar/#hr_py_ingredients

Log(age [yr])	**5.0-10.18**
[M/H]	-1.0 — 0.3
Δλ	0.1 Å
Wavelength coverage	91 — 24000 Å

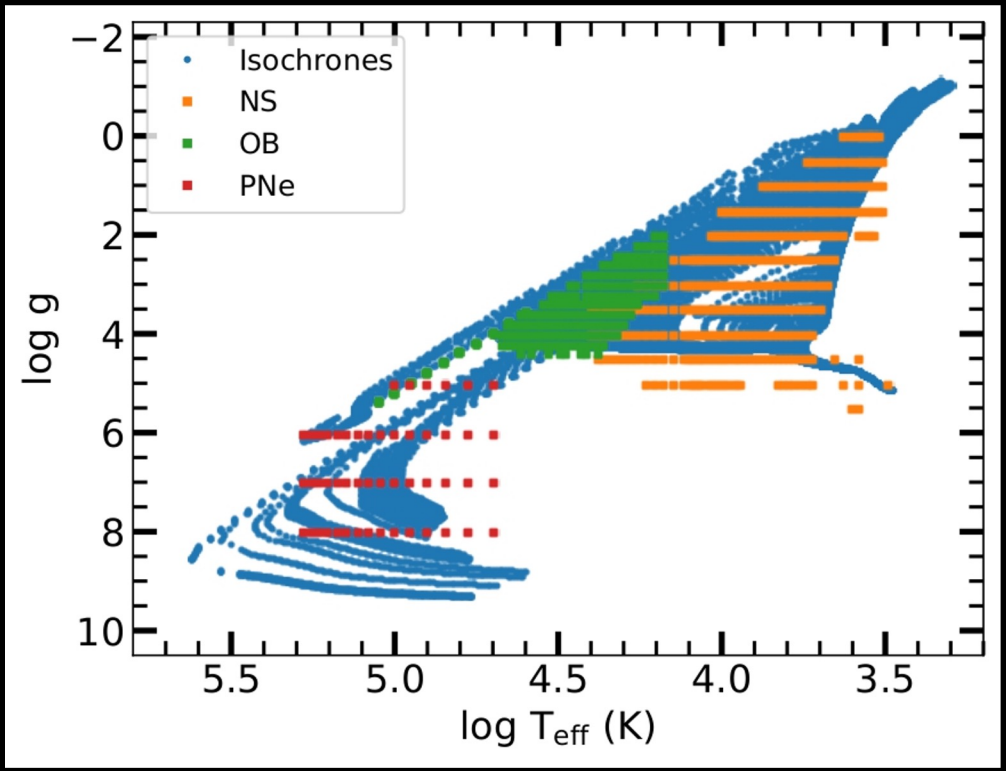
HR-pyPopStar

- We have made a low metallicity extension of the models using the stellar library of Munari et al. (2005) for “cold” stars instead of Coelho (2014)
- These HR-pyPopStar have a wavelength range of 2500-10500 Å
- These models models will be available soon in https://www.fractal-es.com/PopStar/#hr_py_ingredients

DESCRIPTION OF THE CODE



ASSIGNMENT OF STARS



- Main sequence stars and planetary nebulae are assigned using the metallicity, effective temperature and surface gravity

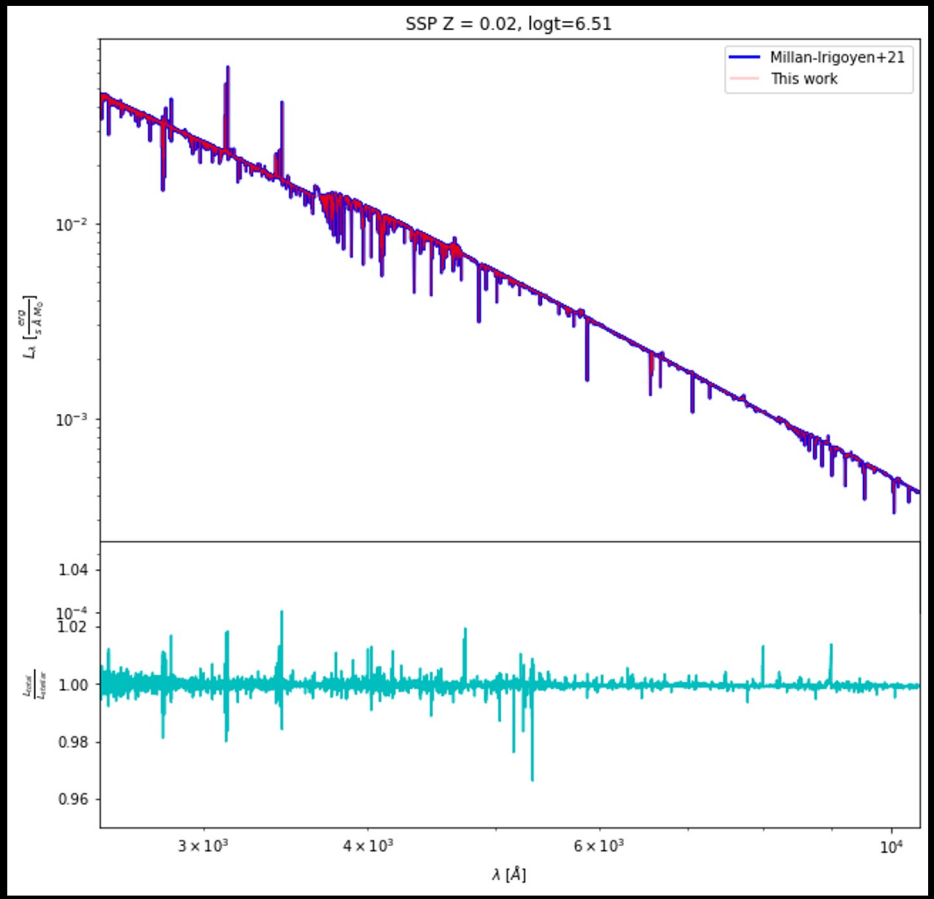
ASSIGNMENT OF WR STARS

- The atmospheres of Wolf-Rayet stars are very violent,with very strong winds
- The effective temperature of the atmospheres of Wolf-Rayet stars is not the same as the hydrostatic equilibrium temperature
- WR stars are assigned by stellar radius, abundance of hydrogen in the surface (Xs) and Mass loss rate ($\dot{M}$)

Results

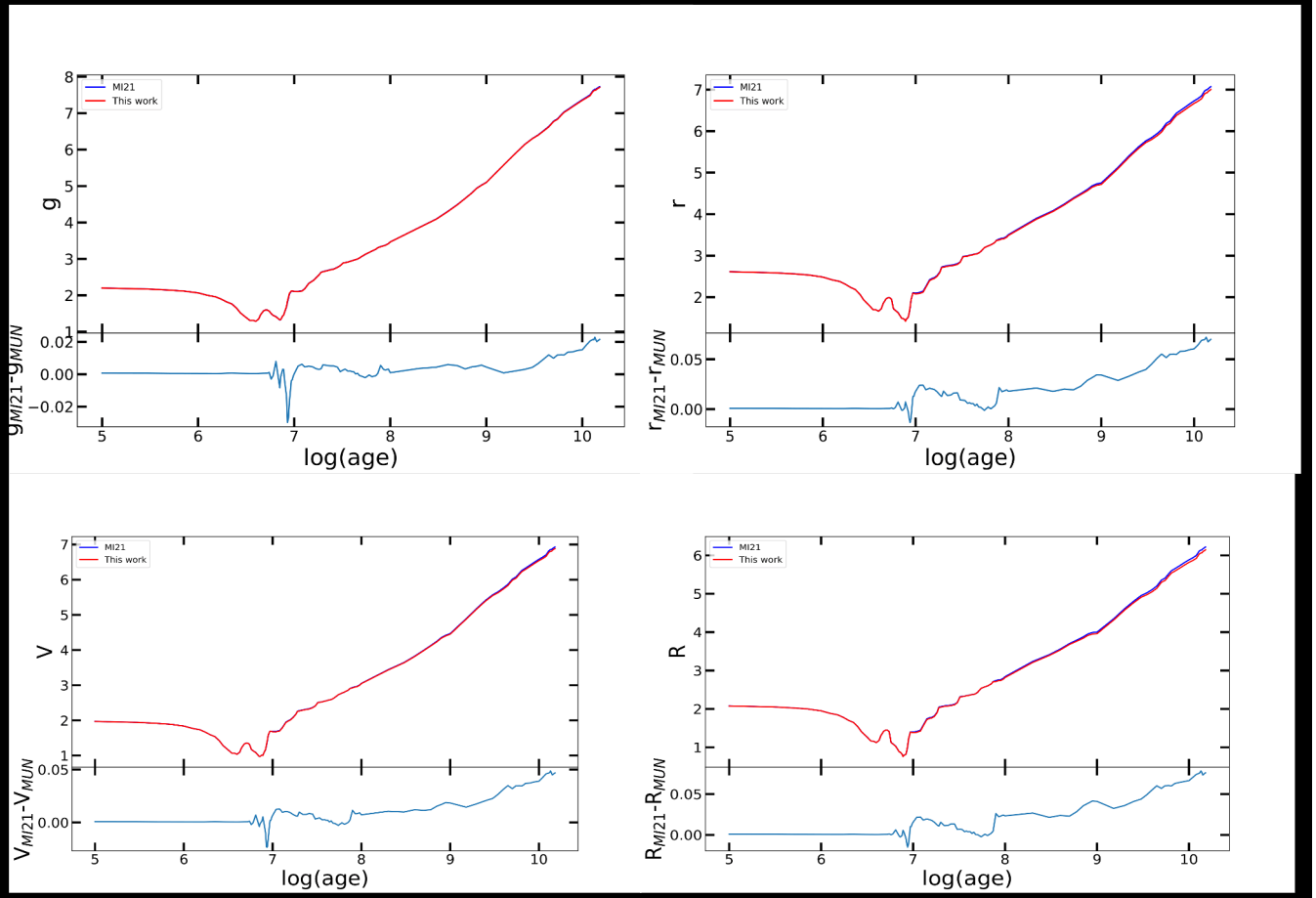
RESULTS:
COMPARISONS WITH HR-pyPopStar

- We have compared our new models to the ones of HR-pyPopStar in the metallicities they coincide
- There are no significant variations with respect to the models of 2021



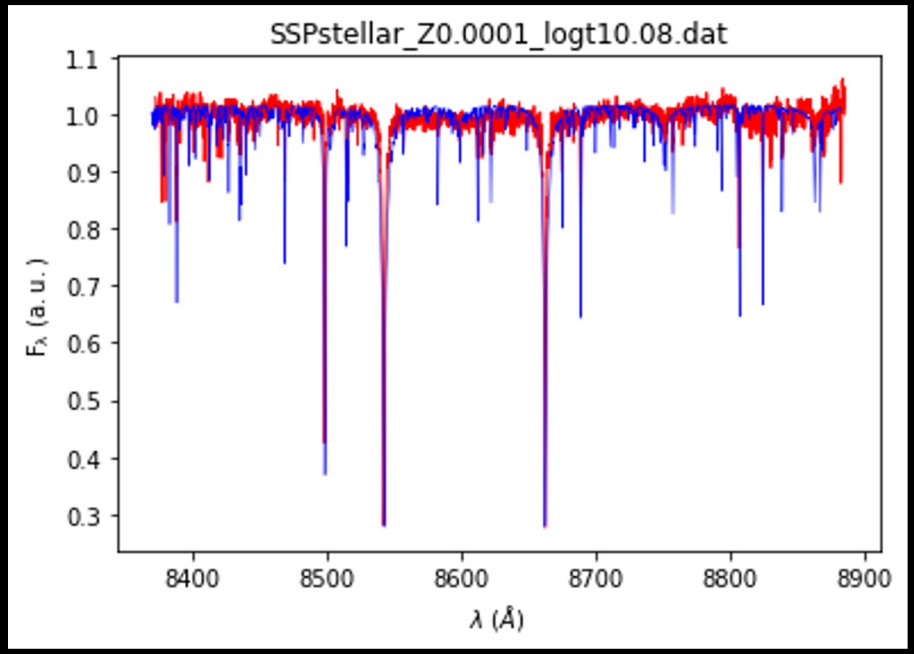
RESULTS:
COMPARISONS WITH HR-pyPopStar

- We have also checked the difference in the magnitudes of the obtained SSPs
- There are no significant differences in the magnitudes
- The maximum difference at the oldest ages is 0.05 dex

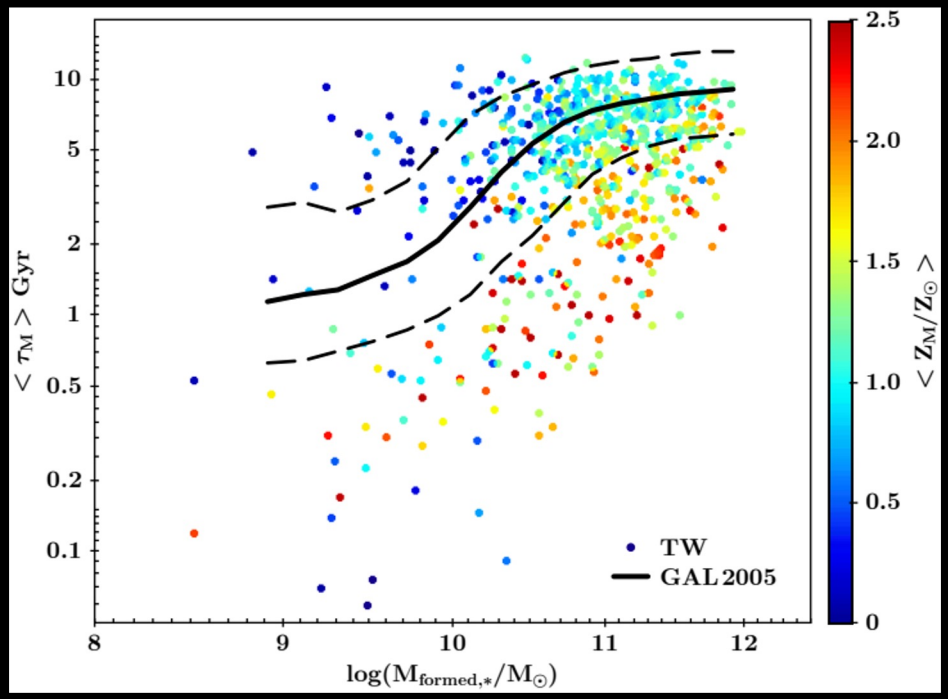


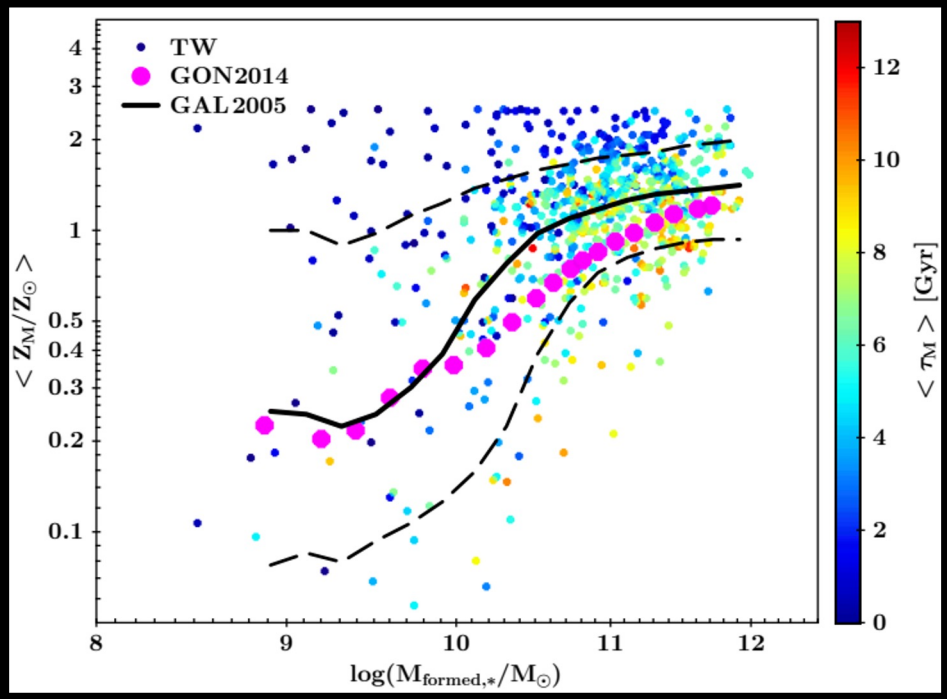
RESULTS: A LOW METALLICITY GLOBULAR CLUSTER M15

- We have used the new low metallicity spectra set to analyse the spectrum of M15 observed with MEGARA
- We have obtained an age of 12 Gyr and Z=0.0001 similar to previous estimates from the literature (12.5 \pm 1.3 Gyr and [Fe/H] = -2.33) O'Malley et al. 2017



RESULTS: ANALYSIS OF THE STELLAR POPULATIONS OF TYPE Ia SN HOST GALAXIES





- These new models have been used to analyse galaxies that host type Ia SN host in the redshift range 0.03 < z < 1.0 using FADO
- Correlations between galaxy parameters of the analyzed galaxies. Our results show younger stellar populations than Gallazzi et al. (2005)
- This difference may be caused by the different SSPs used as templates: Gallazzi et al. (2005) used Bruzual & Charlot (2003)
- We have also compared the mass-metallicity relation with that one obtained by Gonzalez-Delgado et al. (2014)



Future work

New HR-pyPopStar models

- Appart from new low metallicity models we are currently working on new HR-pyPopStar models that are going to use new isochrones using the stellar tracks of MIST, BaSTI, PARSEC+COLIBRI,...
- We are currently working on models using the empirical library of MEGASTAR (see Marisa's talk)
- All these models will be publicly available in the following months
- The code of HR-pyPopStar will be also available in Gitlab/Github

Conclusions

Conclusions

- HR-pyPopStar is a modular and very flexible code that computes state-of-the-art high resolution spectra of SSPs
- We have expanded the models of Millan-Irigoyen et al. 2021 to include low metallicity models
- The high resolution models of HR-pyPopStar are able to distinguish a large number of absorption lines that will be used to make better estimation of the theoretical equivalent widths. Even if these models would need to be broadened to use them with galaxies data, we showed the potential of high-resolution spectra to discern correctly some lines or features
- We have compared our models with high or intermediate resolution spectra obtained with MEGARA of M15, NGC 1659 and NGC 7025
- We have used these models to analyse the stellar populations of galaxies that host type Ia SN
- Concerning mass-metallicity and age-mass relations, we found younger populations than Gallazzi et al. (2005) that can be attributed to the different SSPs used as the basis for the analysis and similar age mass relation to Gonzalez-Delgado et al. (2014)

Thank you!

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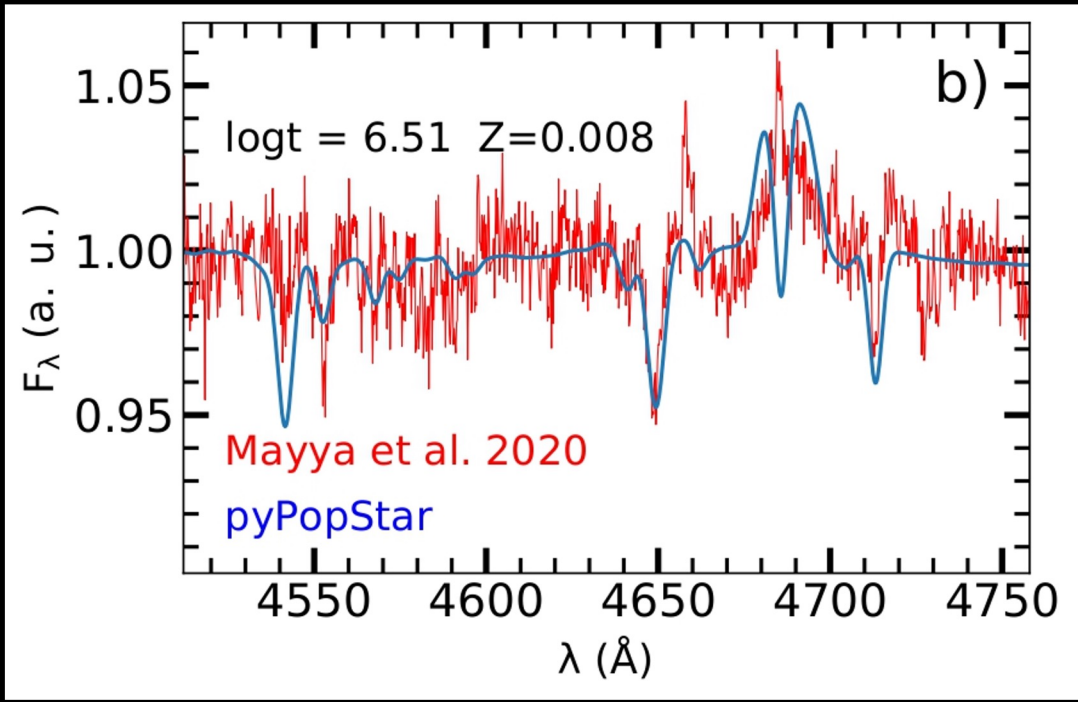
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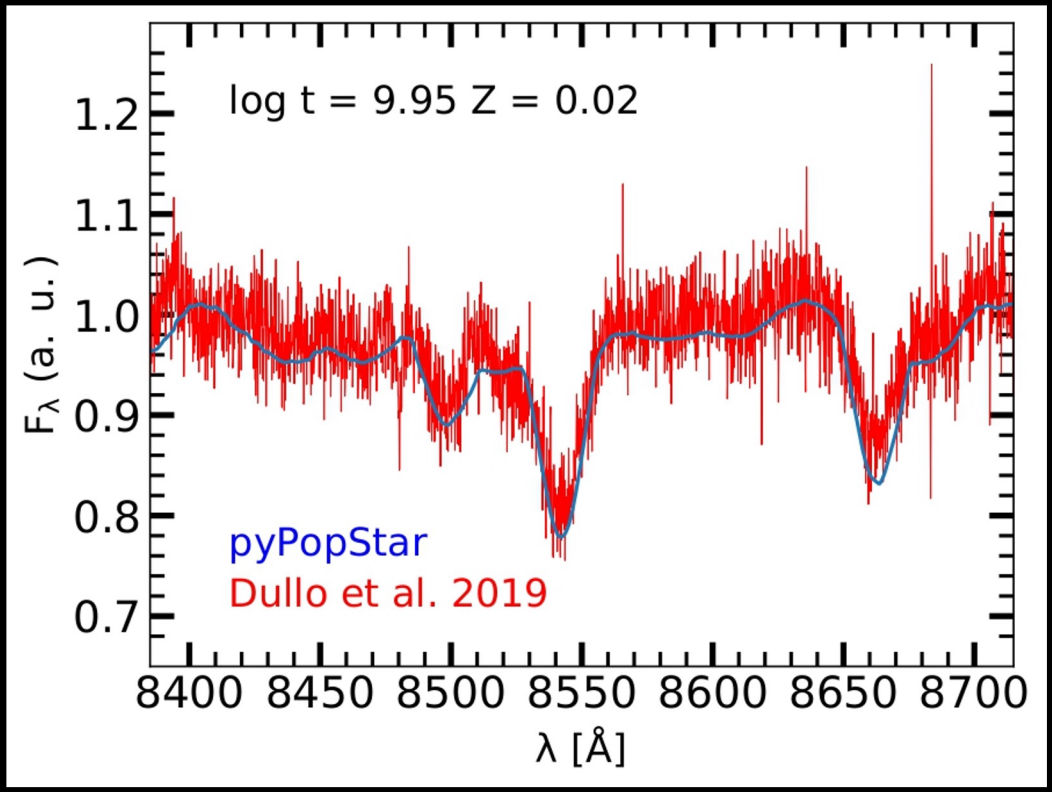
RESULTS: STAR FORMING GALAXY NGC 1569

- We have also used HR-pyPopStar SSPs to characterize a star forming region in NGC 1569 of Mayya et al. (2020)
- We obtain similar ages and metallicities of the population as other authors just using the SSPs
- We reproduce the WR blue bump just using the spectrum where previous models could not

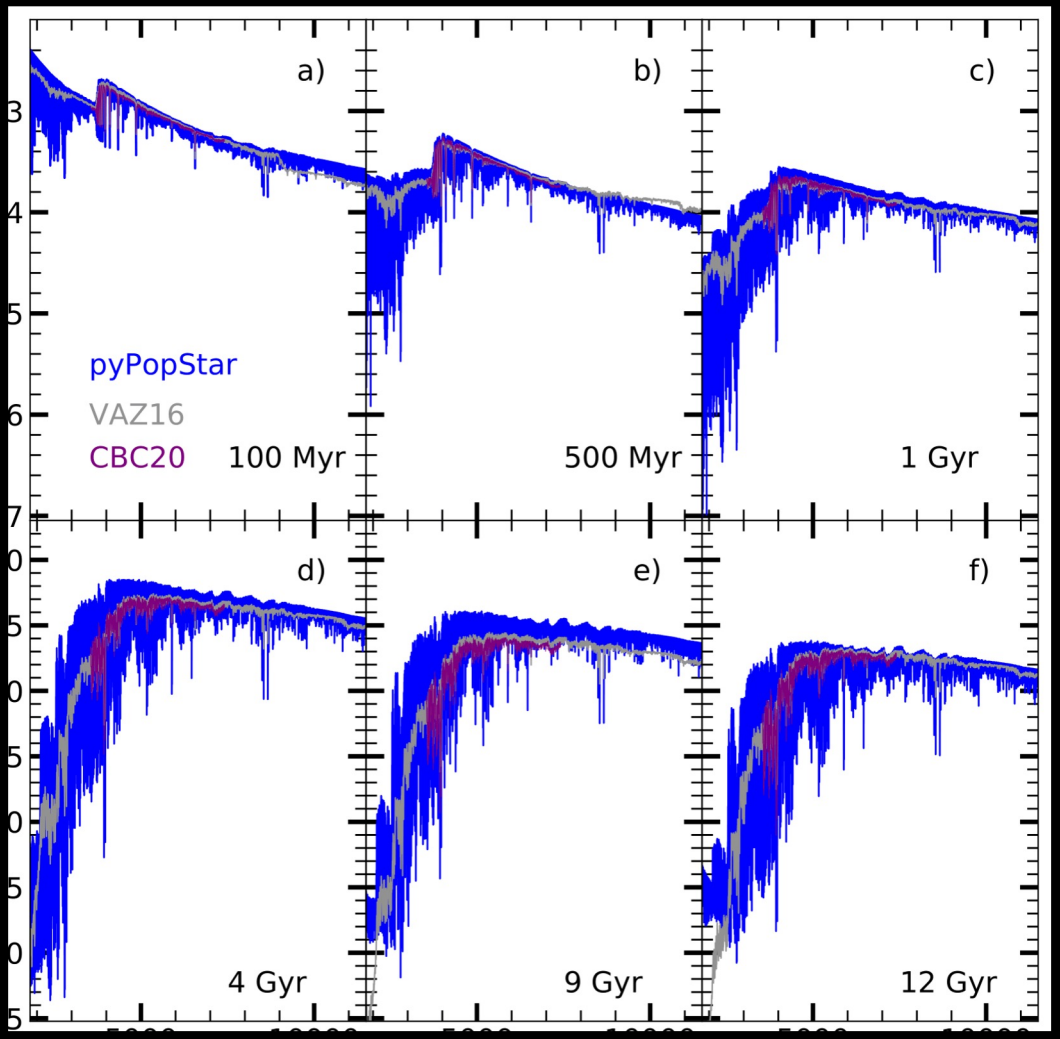


RESULTS: ELLIPTICAL GALAXY NGC 7025

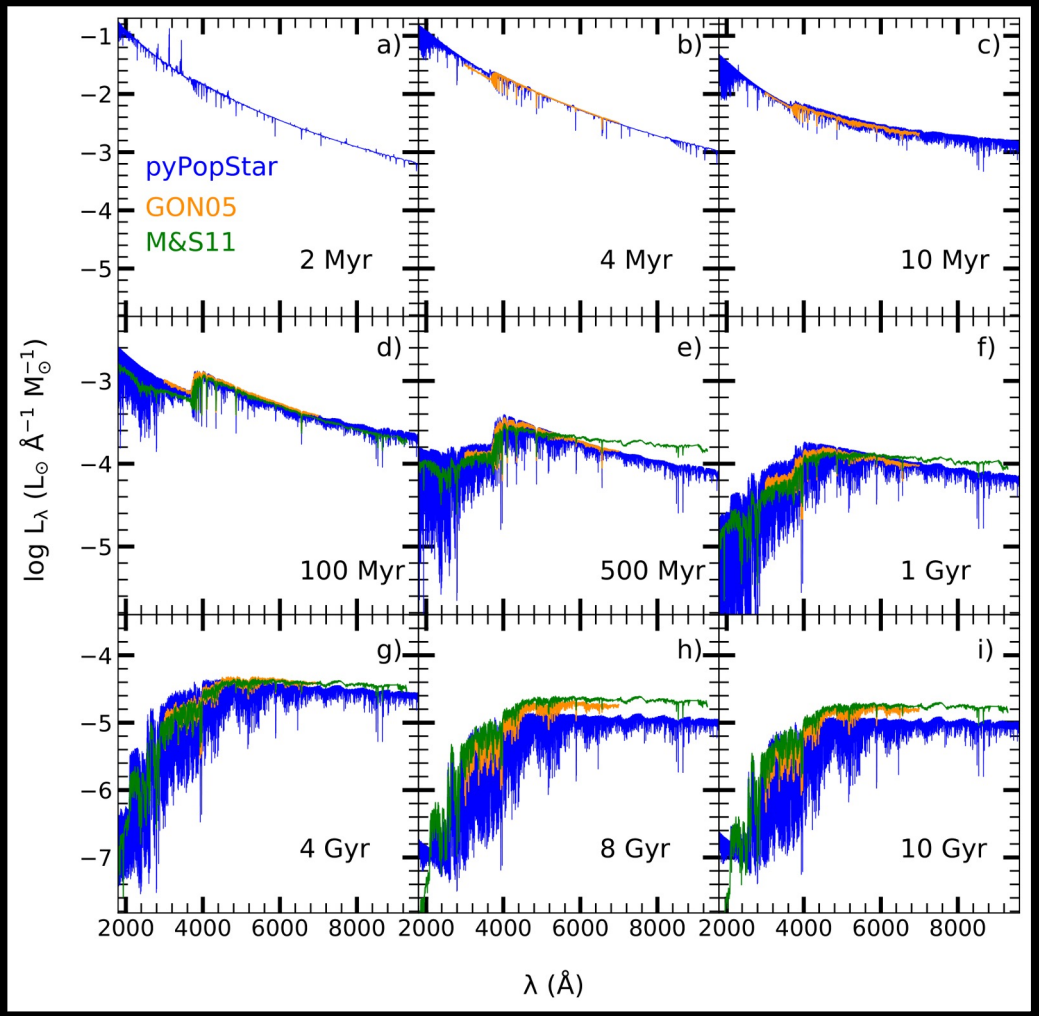
- We also have compared our SSP to an old region of the elliptical galaxy NGC 7025
- We reproduce well this spectrum with an age of 9 Gyr and Z = 0.02 similar to the results from Dullo et al. (2019)



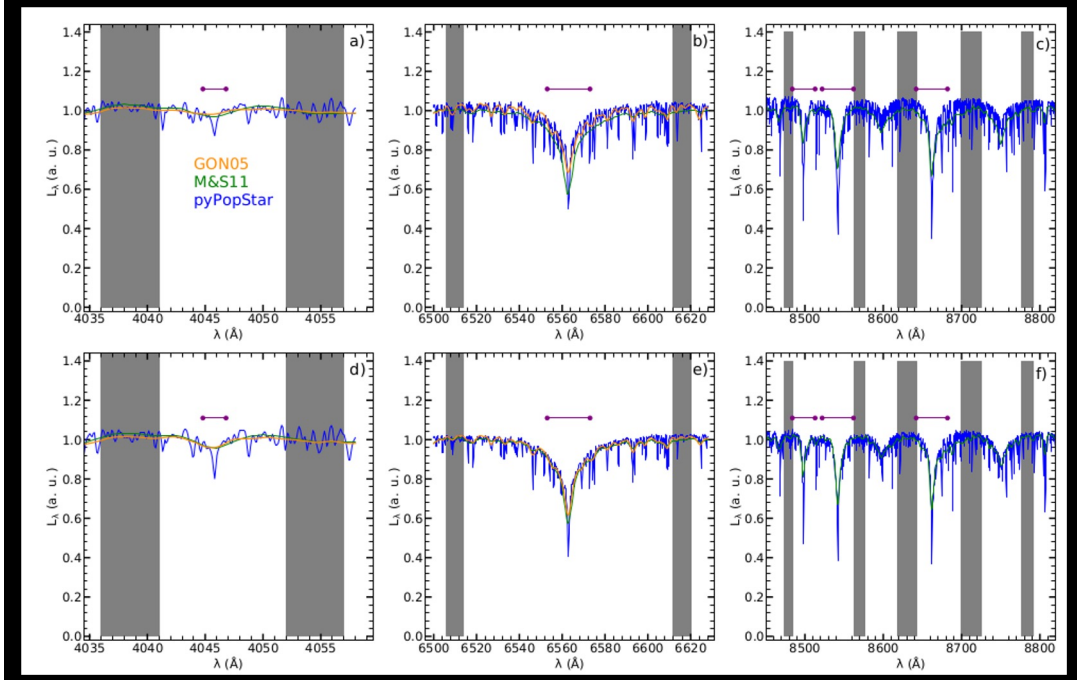
RESULTS: COMPARISONS TO OTHER AUTHORS

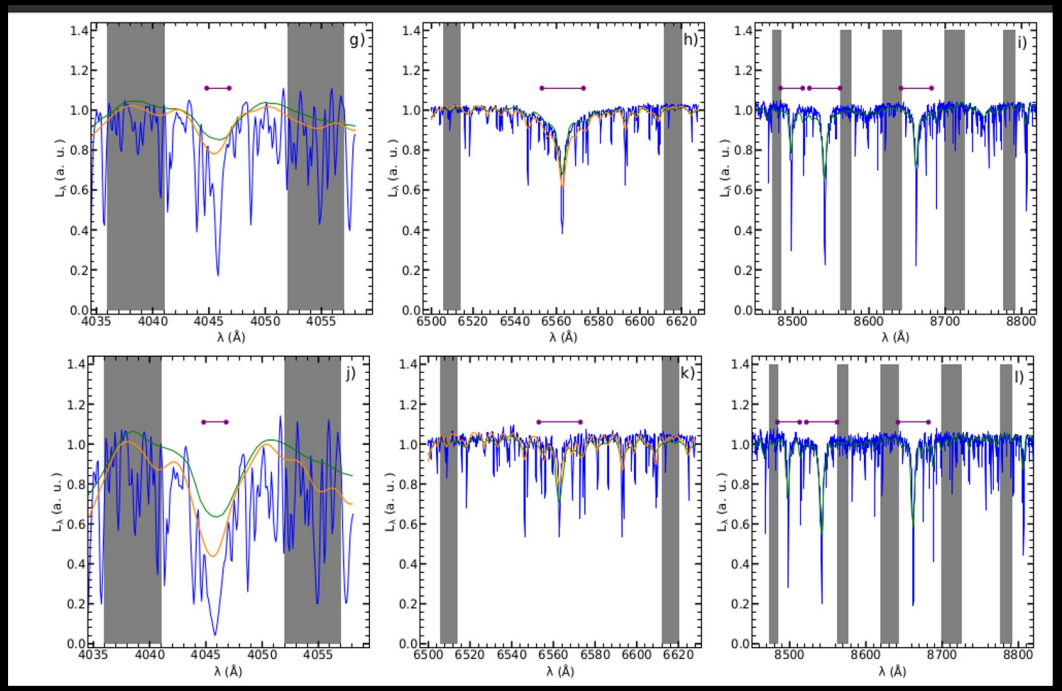


RESULTS: COMPARISONS TO OTHER AUTHORS



RESULTS: STELLAR ABSORPTION LINES



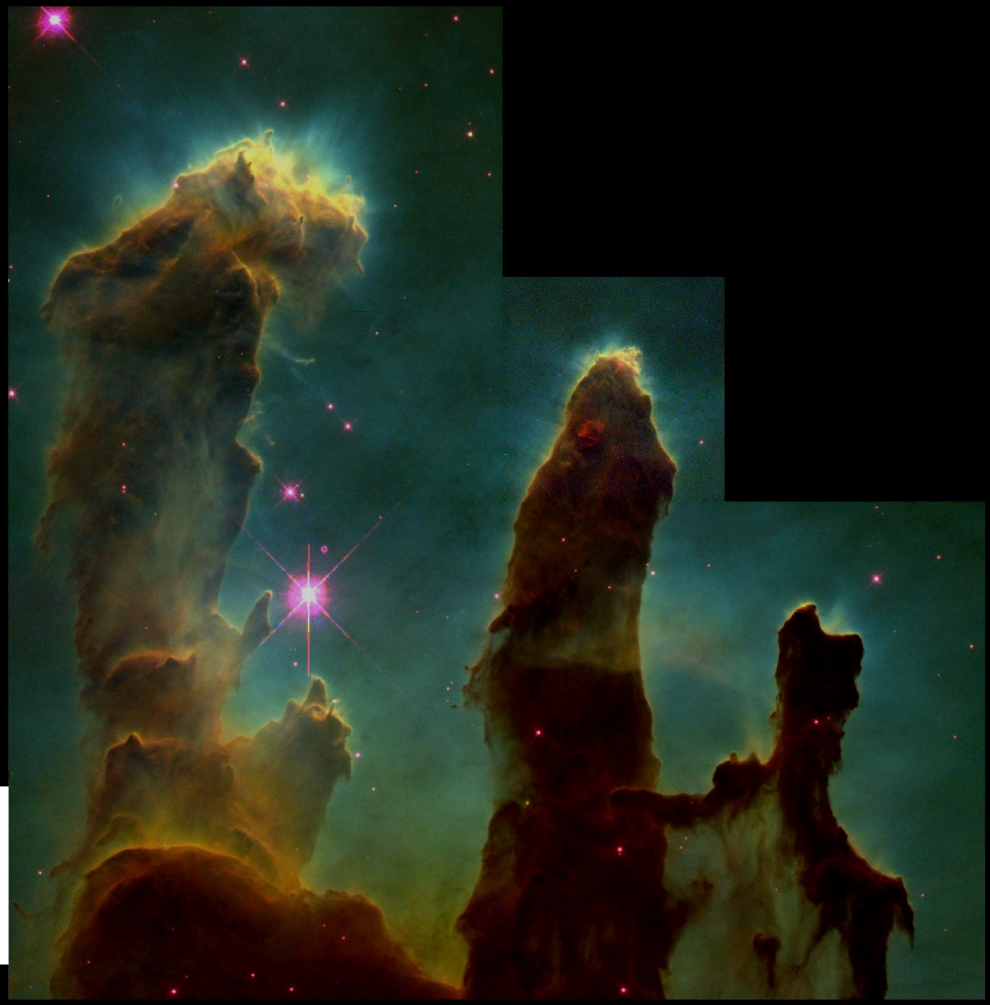


NEBULAR CONTINUUM EMISSION

- Not all the gas in a cloud ends up in stars
- This gas that surrounds the stellar populations can be heated up by the ionizing flux of the stars
- This heated gas emits continuum emission
- The nebular continuum emission is added to the stellar spectra to obtain the total spectra of the SSP

$$L_{\lambda,\mathrm{neb}} = \Gamma \frac{\mathrm{c}\ Q(\mathrm{H\,I})}{\lambda^2\ \alpha_{\mathrm{B}}(\mathrm{H\,I})}$$

$$\Gamma = \Gamma_{\mathrm{H\,I}} + \Gamma_{\mathrm{He\,I}} \frac{N(\mathrm{He\,I})}{N(\mathrm{H})} + \Gamma_{2q}$$



Pillars of Creation. Credit: NASA