Modeling the ultraviolet emission from young galaxies at high redshift

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Outline

- Introduction
- Calibration of models for simple stellar populations
  - Importance of IMF sampling
- Modeling the interstellar medium
  - Approach
  - Results: revealing the cleanest tracers of the properties of the stars, emitting and absorbing gas
- Conclusions

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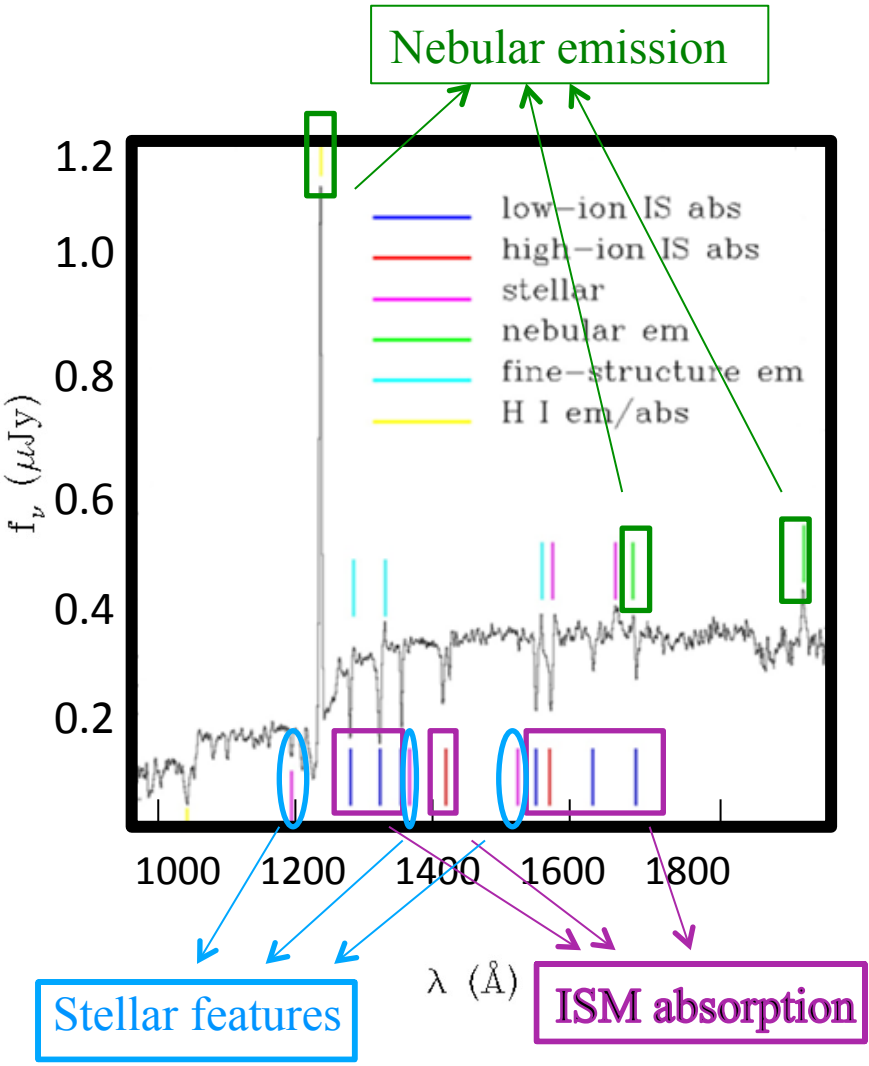
Introduction:
Example of spectrum of high-z galaxy

- Future telescopes (JWST, EELT, …) will observe rest-frame **ultraviolet** and **optical** spectra of large samples of **distant galaxies**
- High-z galaxies ➡ rest-frame UV redshifted to the optical and IR
- FUV spectrum exhibits several **absorption** and **emission** features:

  Photospheric and wind absorption → properties of stellar populations

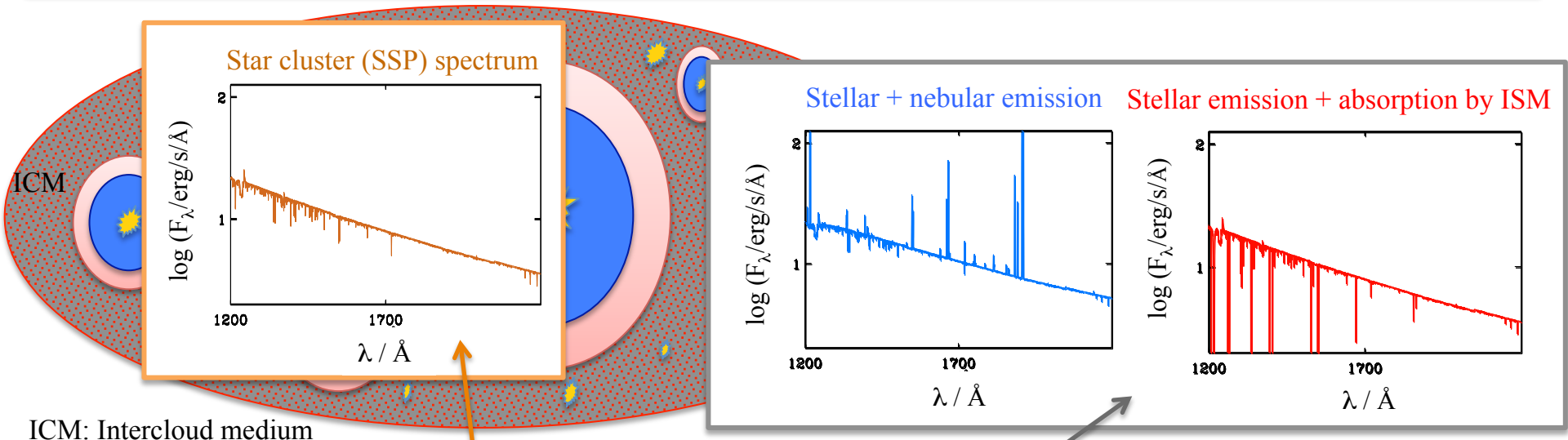
  Nebular emission → properties of ionized gas

  Interstellar absorption → properties of ionized and neutral gas



Stacked spectrum of z~3 star-forming galaxies (Shapley et al. 2003)

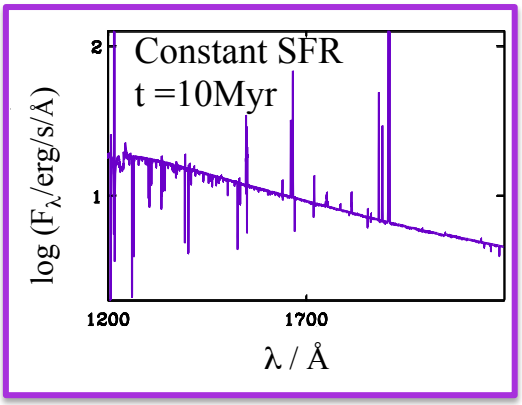
Introduction:
Modeling of different components of a galaxy



ICM: Intercloud medium

The luminosity emitted by a galaxy at wavelength λ at time t can be expressed as:

$$L_\lambda = \int_0^t S_\lambda[t', Z(t-t')]\, T_\lambda^{ISM}(t,t')\, SFR(t-t')\, dt'$$



Flux(λ) emitted per unit mass by a single stellar generation of age *t-t'* and metallicity Z(*t-t'*)

Transmission function of the ISM: emission and absorption

Star-formation rate at time *t-t'*

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Calibration of SSP models: Approach

- To calibrate the new stellar models, use observations of nearby star clusters

Star clusters ≈ SSPs

The Large Magellanic Cloud
Credit: NOAO/AURA/NSF

- We can use ultraviolet observations of young star clusters in the Large Magellanic Cloud and compare the observed strengths of **stellar absorption** features with those predicted by the models

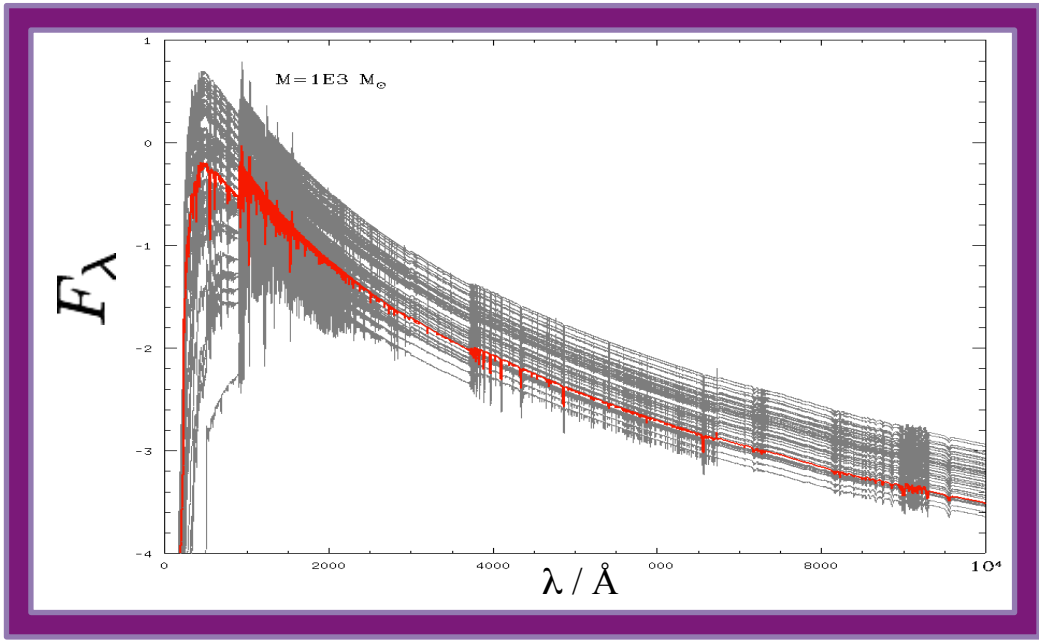
→ 19 UV **absorption-line indices** (Fanelli et al. 1992)

Calibration of SSP models: Importance of IMF sampling

- Mass range of young clusters: 10^3-10^6 $M_\odot$ ⟶ number of massive stars fluctuates around a few

- Particularly important in the UV (where single massive star can dominate cluster emission)

- For clusters of few ×1000 $M_\odot$: populate **IMF stochastically**

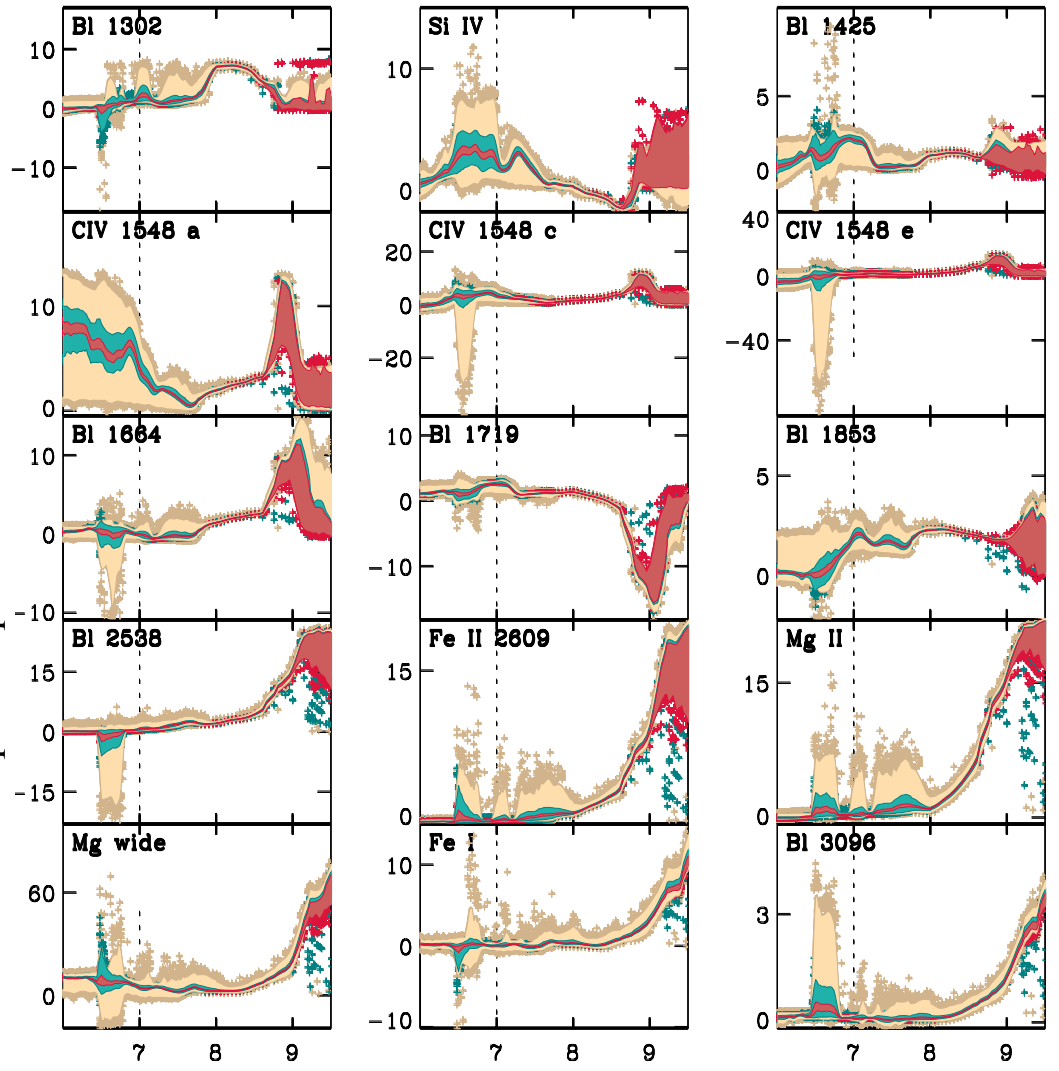


$10^3 M_\odot$,1Myr, Salpeter IMF

Smoothy sampled IMF

Stochastically sampled IMF

Calibration of SSP models:
Importance of stochastic IMF sampling: ultraviolet spectral indices



(1292 - 3106 Å)

Star cluster models with masses:

- 500 $M_\odot$
- 10^4 $M_\odot$
- $2*10^5$ $M_\odot$

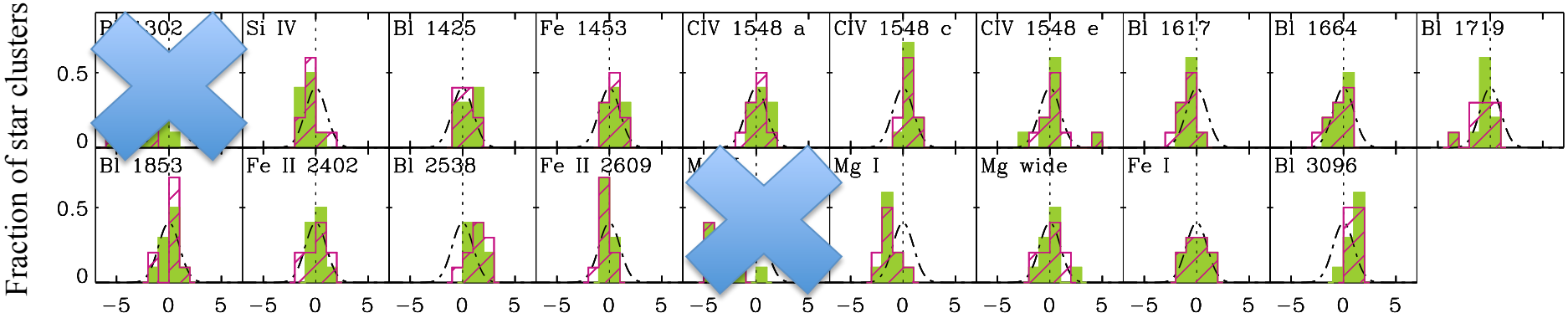
➡ Dispersion in index strength increases with decreasing mass

➡ Dispersion least important between ~10-500Myr

(Vidal-García+ 2017)

Calibration of SSP models: Comparison of the prediction of best-fit model and data

Difference between best-fit stochastic model and observed strengths (corrected for Milky Way absorption) for 19 UV absorption lines (in units of σ^{data})



Stochastic
Smooth

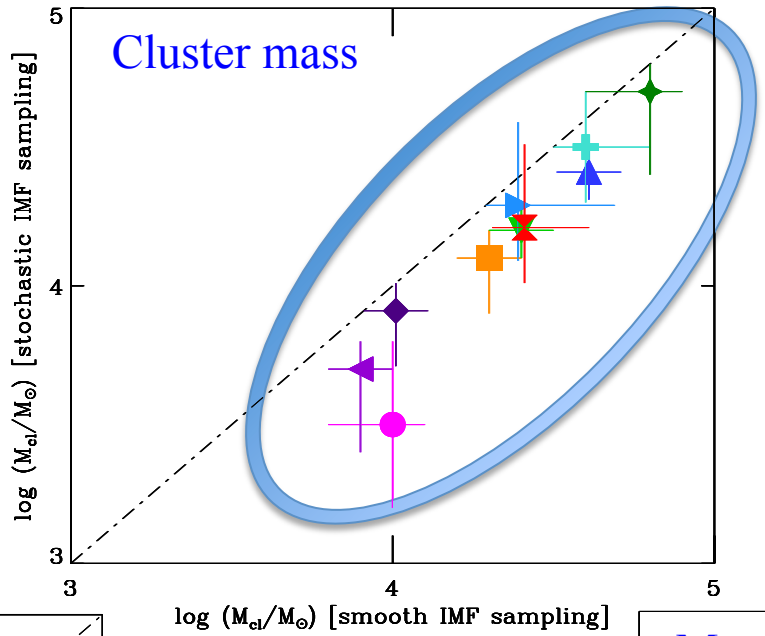
$(EW^{mod}-EW^{data})/\sigma$

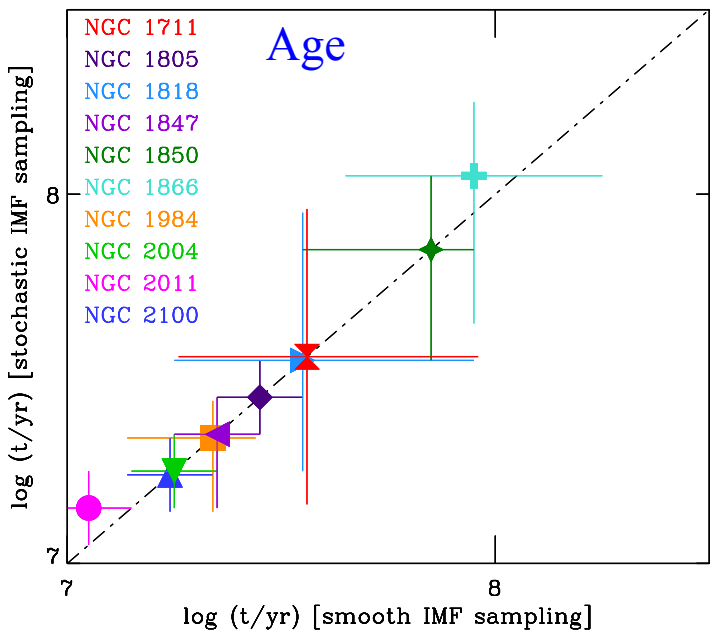
(Vidal-García+ 2017)

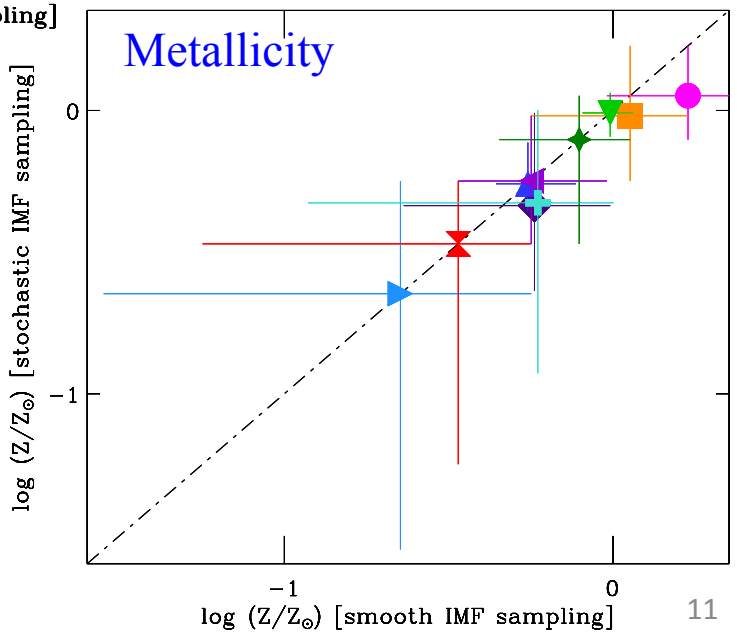
→Best-fit model extracted from comprehensive library of SSPs encompassing full ranges of age, metallicity and mass

→Compare indices of large library of models (uniform sampling of age, metallicity and mass) with those of each observed cluster to derive Bayesian estimates of different parameters

Calibration of SSP models: Parameter estimates using stochastic vs. smooth IMF sampling







(Vidal-García+ 2017)

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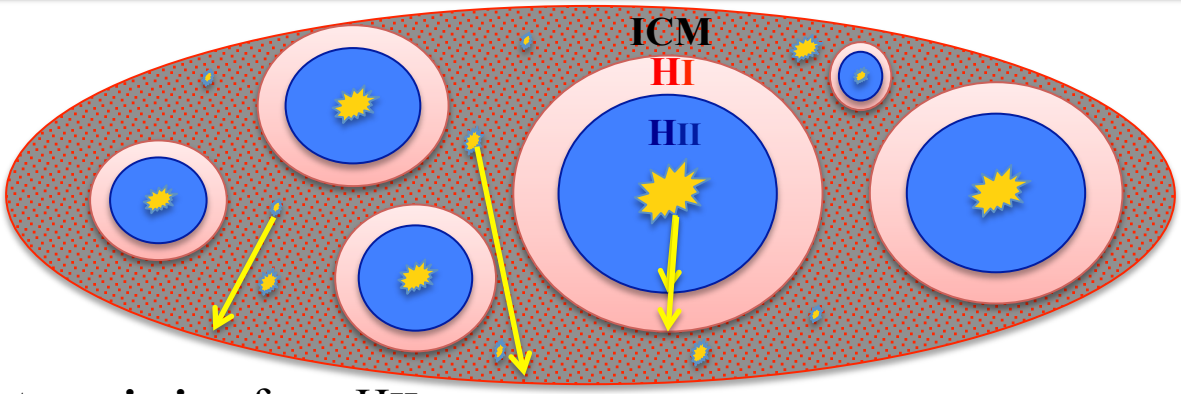
ISM modeling: Approach



Gutkin+2016: compute **emission** from HII regions with photoionization code *Cloudy*:

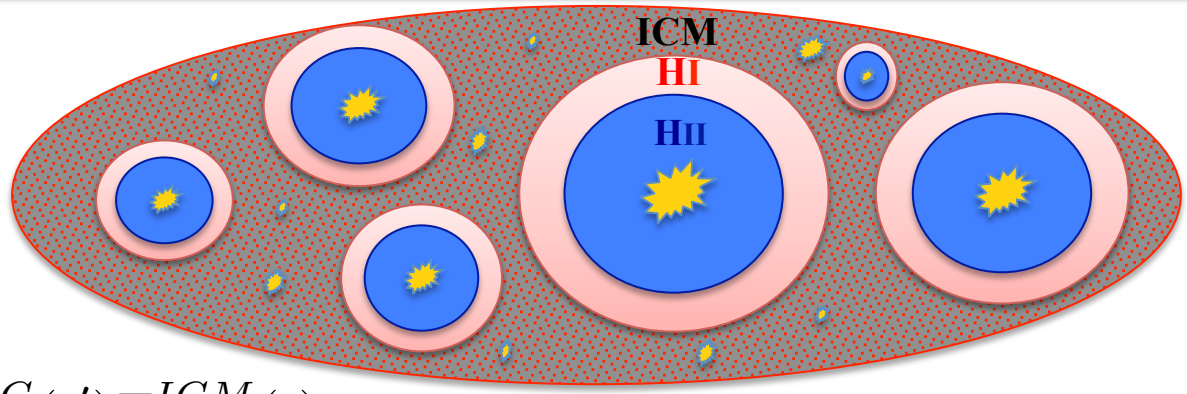
- Parametrize photoionized gas in terms of $S_\lambda(t')$, n_H, U_S, Z_{ISM}, ξ_d and C/O
- Two component dust model (Silva+1998, Charlot&Fall2000)

Stellar birth clouds	
n_H	Hydrogen number density
U_S	Zero-age ionization parameter[b]
Z_{ISM}	Interstellar metallicity [$Z_{ISM} = Z(t)$ by default][c]
ξ_d	Dust-to-metal mass ratio
C/O	Carbon-to-oxygen abundance ratio

Here: compute **emission + absorption** from ISM with code *Cloudspec* (photoionization code *Cloudy* + general spectrum synthesis code *Synspec*):

- Extend previous calculations to include contribution by HI envelopes of stellar birth (giant molecular) clouds (BC)
- Expand parametrization of photoionized gas (Charlot&Longhetti2001, Gutkin+2016)
- Include contribution by intercloud medium (ICM)

ISM modeling: Approach



$$T_\lambda(t,t') = T_\lambda^{BC}(t')T_\lambda^{ICM}(t)$$

BCs dissipate on timescale ~10Myr (Murray+2010; Murray+2011):

$$T_\lambda^{BC}(t') = \begin{cases} T_\lambda^{HII}(t')\,T_\lambda^{HI}(t') & \text{for } t' \le 10\,\mathrm{Myr} \\ 1 & \text{for } t' > 10\,\mathrm{Myr} \end{cases}$$

Cloudspec to compute transmission through ICM:

- Emitting sources (BC+stars older than 10Myr) distributed throughout the galaxy: radiation diluted
- Not parametrized in terms of ionizing factor
  - Energy density at 1500Å scales linearly with SFR
  - Energy density of ICM at 1500Å = that observed in Milky Way

$$u_{1500}(t) = 3\times10^{-16}[\psi(t)/1\,\mathrm{M_\odot\,yr^{-1}}]\,\mathrm{erg\,cm^{-3}\,Å^{-1}}$$

Diffuse intercloud medium

$n_{\rm H}^{\rm ICM}$	Hydrogen number density
$N_{\rm HI}^{\rm ICM}$	HI column density
$\sigma_v^{\rm ICM}$	Velocity dispersion of the gas
	scopic velocity field of the gas

$$L_\lambda(t) = T_\lambda^{ICM}(t)[L_\lambda^{BC} + L_{\lambda,*}^{ICM}(t)]$$

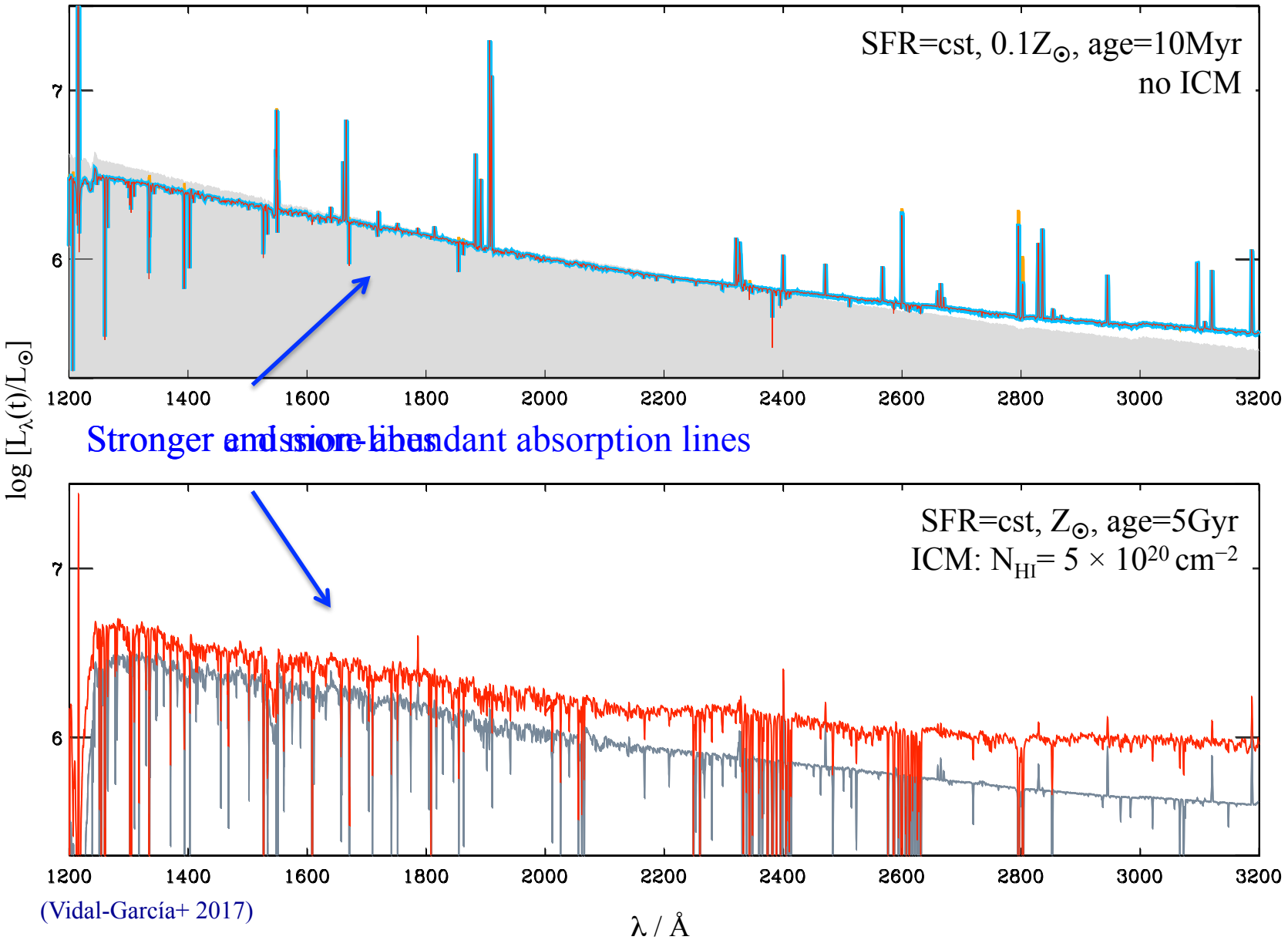
Luminosity emerging from BCs

$$L_\lambda^{BC} = \int_0^{10\,\mathrm{Myr}} dt'\,\psi(t-t')\,S_\lambda[t', Z(t-t')]\,T_\lambda^{BC}(t')$$

Luminosity of stars older than 10Myr

$$L_{\lambda,*}^{ICM}(t) = \int_{10\,\mathrm{Myr}}^{t} dt'\,\psi(t-t')\,S_\lambda[t', Z(t-t')]$$

ISM modeling:
Examples: young metal-poor and old metal-rich galaxy

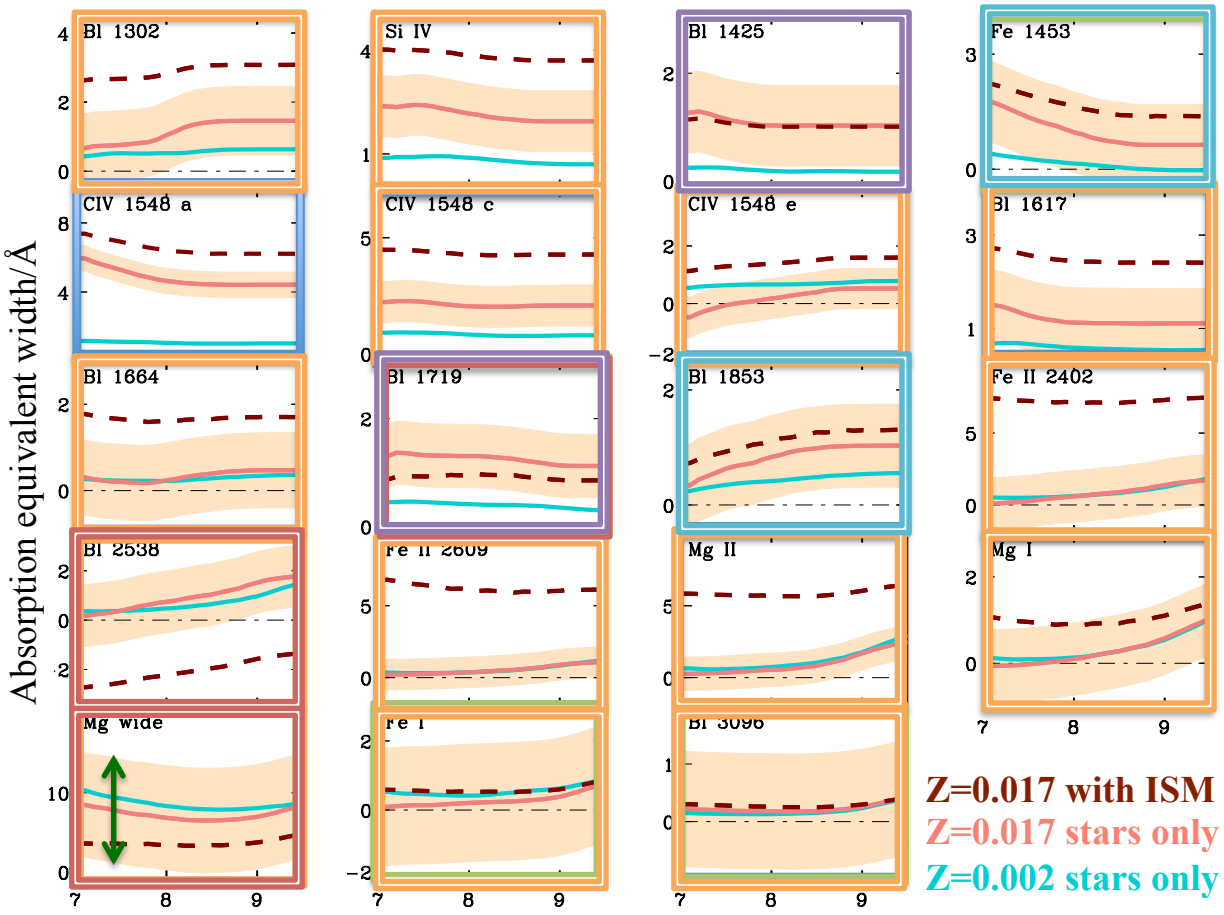


Stronger and more abundant absorption lines

(Vidal-García+ 2017)

ISM modeling:
Features tracing young stars

Strengths of 19 Fanelli et al. indices measured in the spectrum of mature-galaxy model:



Median of uncertainty for the 10 LMC star clusters

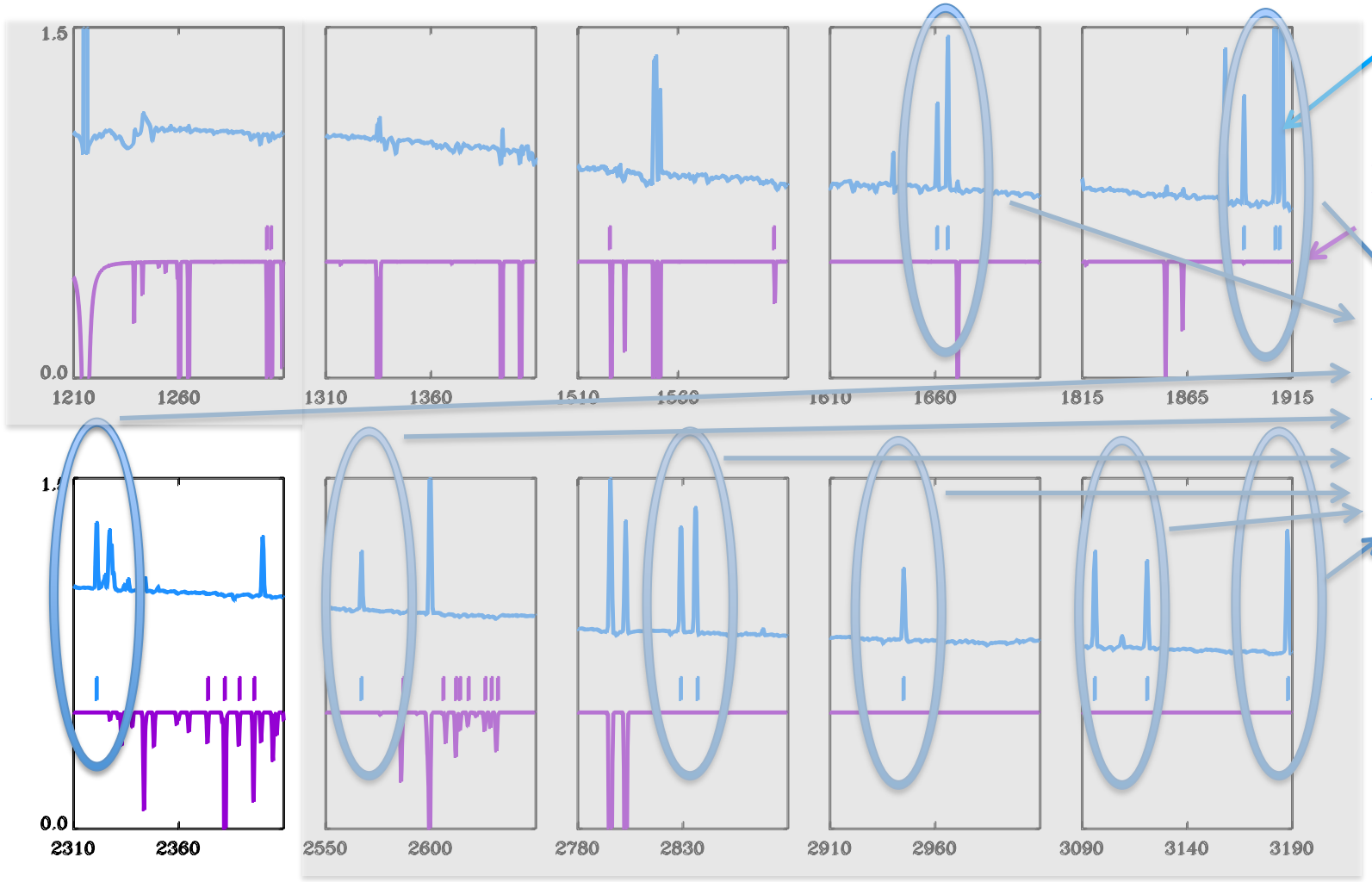
(Vidal-García+ 2017)

- For most indices, inclusion of interstellar absorption deepens stellar features
- Indices least affected by ISM contamination
- For most indices, ISM contamination can affect index strength more than change in Z
- Otherwise, change in index strength induced by change in Z is smaller than typical observational error
- Among least ISM-sensitive, effect of metallicity is measurable and stronger than that of ISM contamination only for **Bl 1425** and **Bl 1719**

↓

Most useful to trace stellar population properties

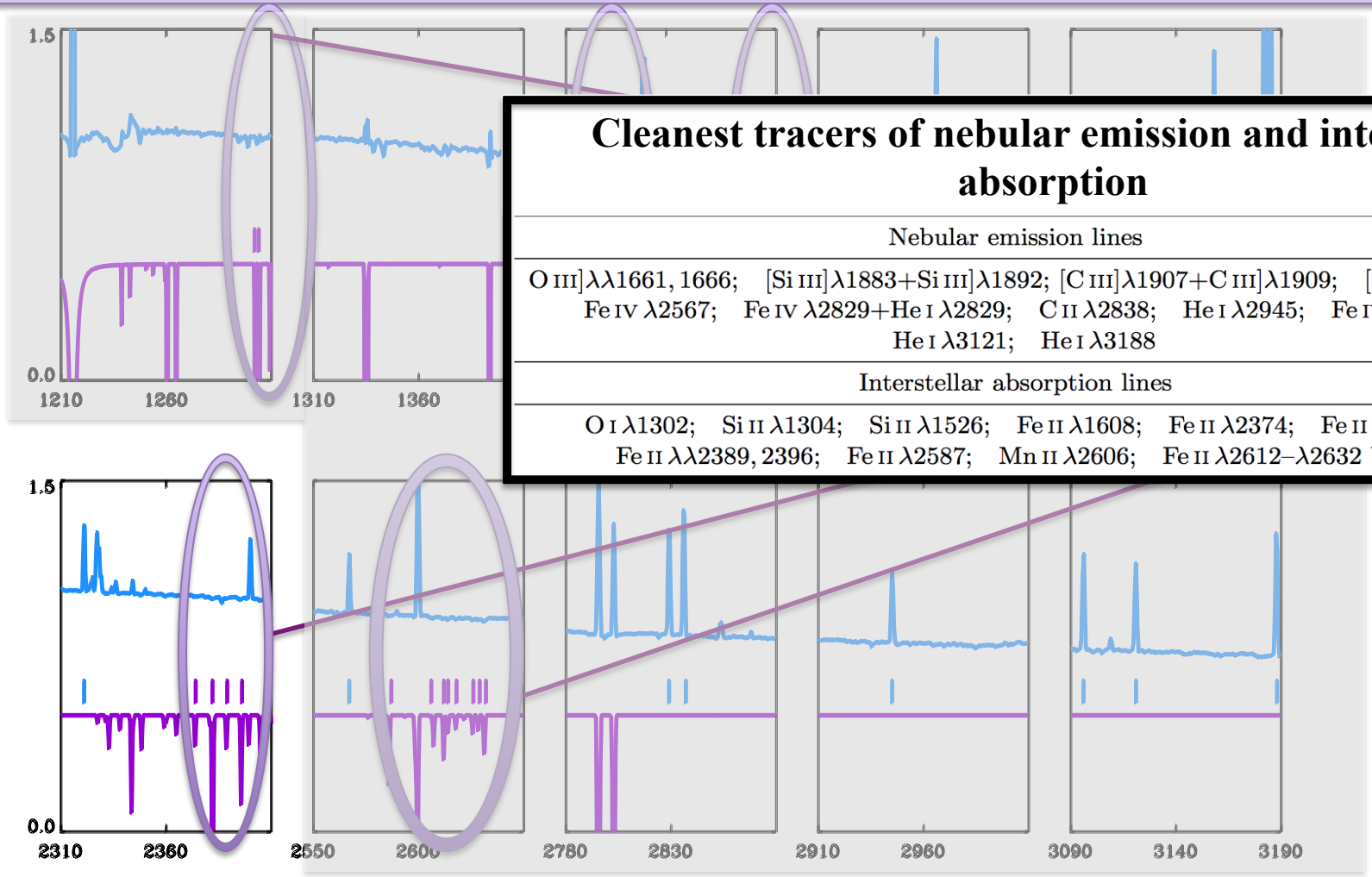
ISM modeling:
Features tracing nebular emission (young metal poor galaxy model)



(Vidal-García+ 2017)

Emission component of young galaxy model
Transmission function of the ISM for metal-poor galaxy model

ISM modeling:
Applications: features tracing interstellar absorption



(Vidal-García+ 2017)

Cleanest tracers of nebular emission and interstellar absorption

Nebular emission lines
O III]λλ1661, 1666; [Si III]λ1883+Si III]λ1892; [C III]λ1907+C III]λ1909; [O III]λ2321; Fe IV λ2567; Fe IV λ2829+He I λ2829; C II λ2838; He I λ2945; Fe IV λ3096; He I λ3121; He I λ3188
Interstellar absorption lines
O I λ1302; Si II λ1304; Si II λ1526; Fe II λ1608; Fe II λ2374; Fe II λ2383; Fe II λλ2389, 2396; Fe II λ2587; Mn II λ2606; Fe II λ2612–λ2632 blend

Emission component of young galaxy model
Transmission function of the ISM for metal-poor galaxy model

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Conclusions

In this work, I use a combination of state-of-the-art models for the production of stellar radiation and its transfer through ISM to investigate ultraviolet-line diagnostics of stars, ionized and neutral ISM in star-forming galaxies:

1) Assessed ability of new stellar population synthesis models to reproduce pure **stellar absorption features** in ultraviolet spectra of star clusters in the LMC

2) Developed **new approach** to model in a physically consistent way combined influence of nebular emission and interstellar absorption on ultraviolet spectra of star-forming galaxies

3) Used this approach to explore competing effects of **stellar absorption, nebular emission** and **interstellar absorption** in ultraviolet spectra of star-forming galaxies