Modeling and interpretation of spectral properties of primeval galaxies

RJP – 18 March 2021

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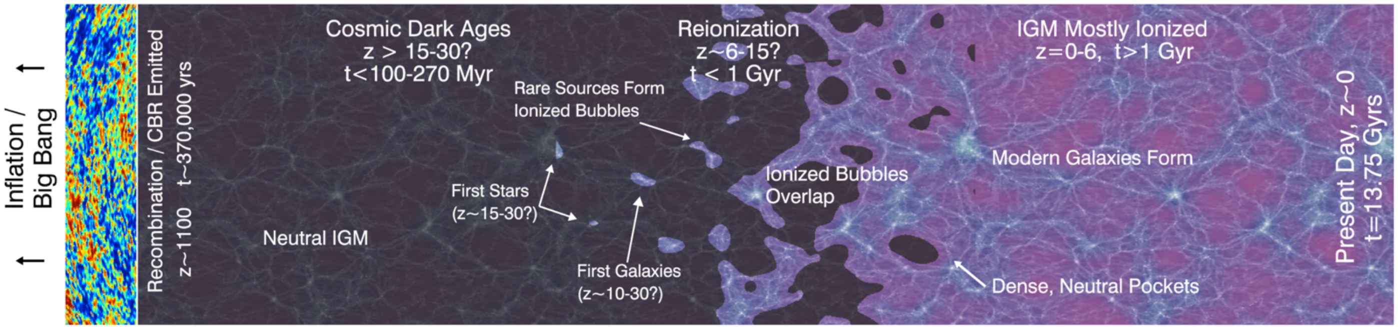
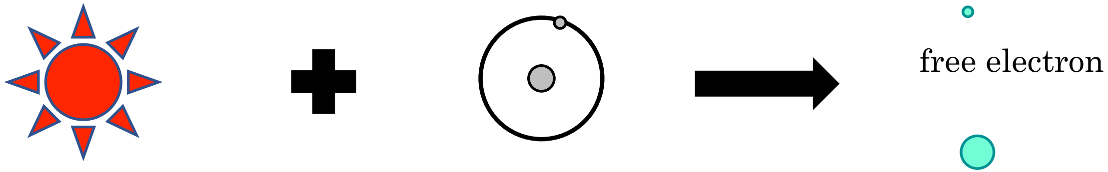
Introduction
The Epoch of Reionization

EoR



Robertson+10

Photoionization of hydrogen



source of H-ionizing photons: $E \geq 13.6$ eV

neutral hydrogen

Lyman continuum photons (LyC)

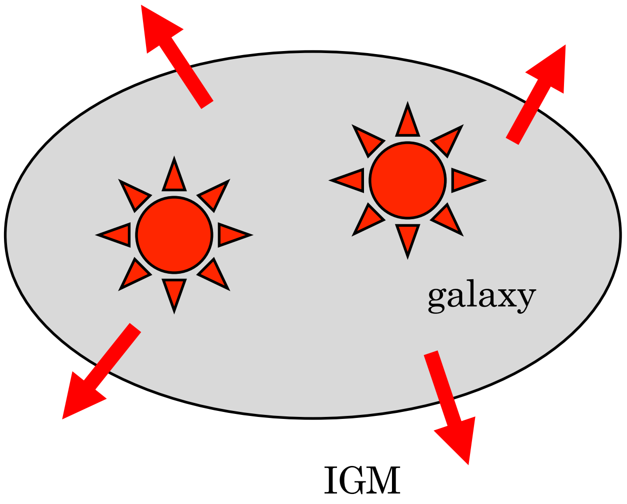
Rate of LyC photons injected into a unit volume of the inter-galactic medium (IGM):

$$\dot{N}_{\rm ion} = \rho_{\rm source} \times \dot{n}_{\rm ion} \times f_{\rm esc}$$

$\rho_{\rm source}$: volume density of the ionizing sources

$\dot{n}_{\rm ion}$: rate of LyC photons produced by a source

$f_{\rm esc}$: fraction of LyC photons escaping into the IGM



❀ 1. What are the main sources of ionizing radiation ?

❀ 2. What fraction of this ionizing radiation escapes from the galaxy ?

Introduction
The Epoch of Reionization

1. Are hot stars in star-forming galaxies the main sources of reionization ?

hot stars

The number density of **faint SF galaxies** rises with redshift.

↓

These might have dominated the production of ionizing radiation during the EoR.

↓

Can be assessed by constraining the rate / escape fraction of LyC photons in EoR galaxies.

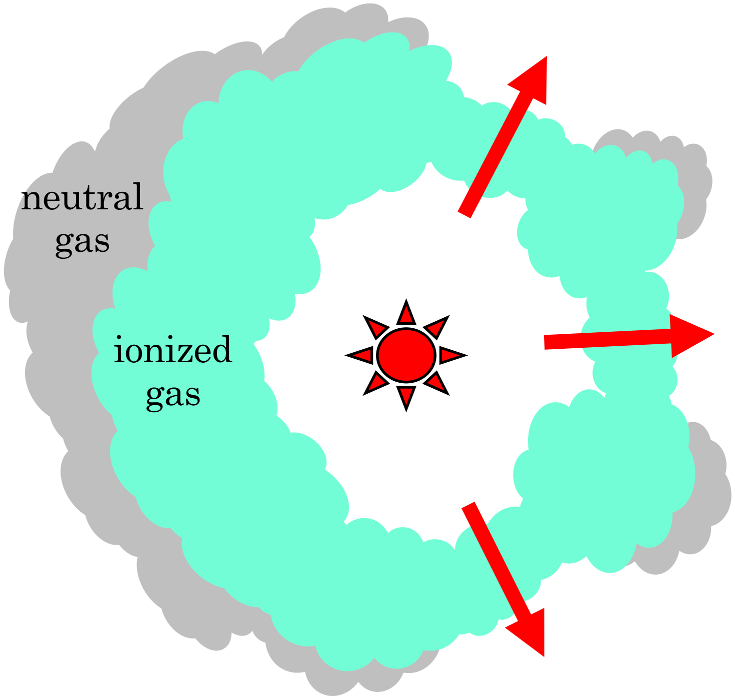
accreting supermassive black hole

Active galactic nuclei (AGN) produce a lot of LyC photons. But the number density of AGN drops with increasing redshift.

↓

Perhaps not the main sources of reionization, but possible significant contribution from faint AGN.

2. What factors allow LyC photons to escape from a galaxy ?



❀ Supernova explosions

❀ Stellar winds

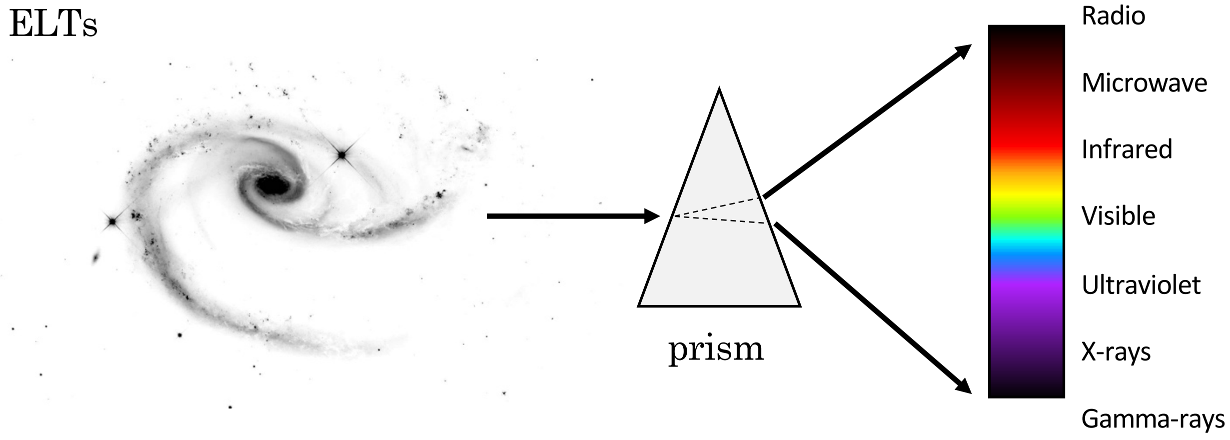
❀ Strong ionizing radiation

LyC photons escape through paths of low hydrogen column density.

Introduction
Constraints on galaxy physical properties from observed spectra

Upcoming observations of rest-frame UV spectra of high-redshift ($z>6$) galaxies.

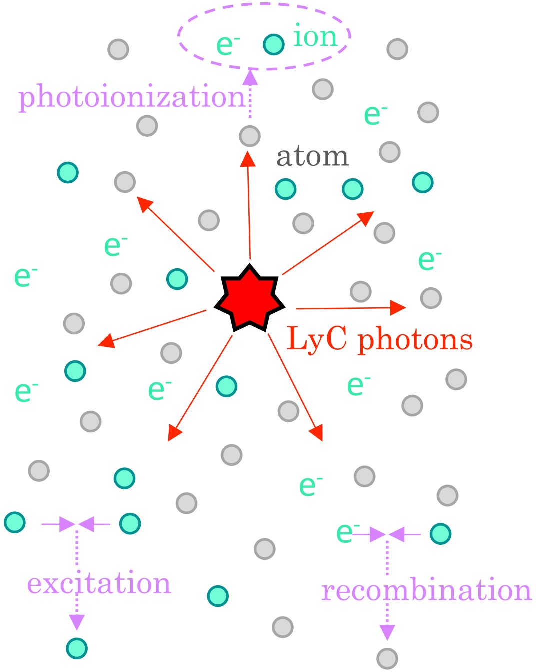
JWST, ELTs

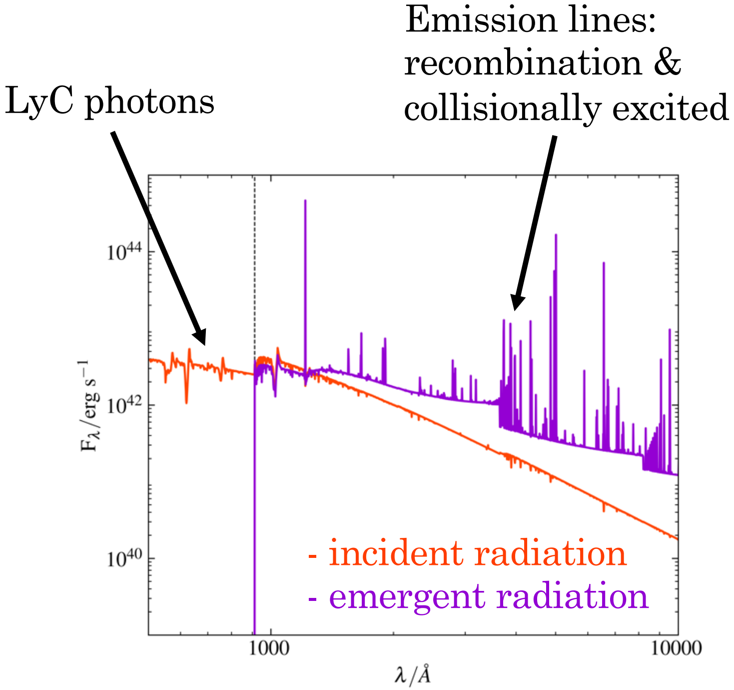


❀ How can we trace the sources of reionization through the spectral analysis of primeval galaxies?

Constraints on galaxy physical properties from observed spectra

Incident radiation transfers through the gas.

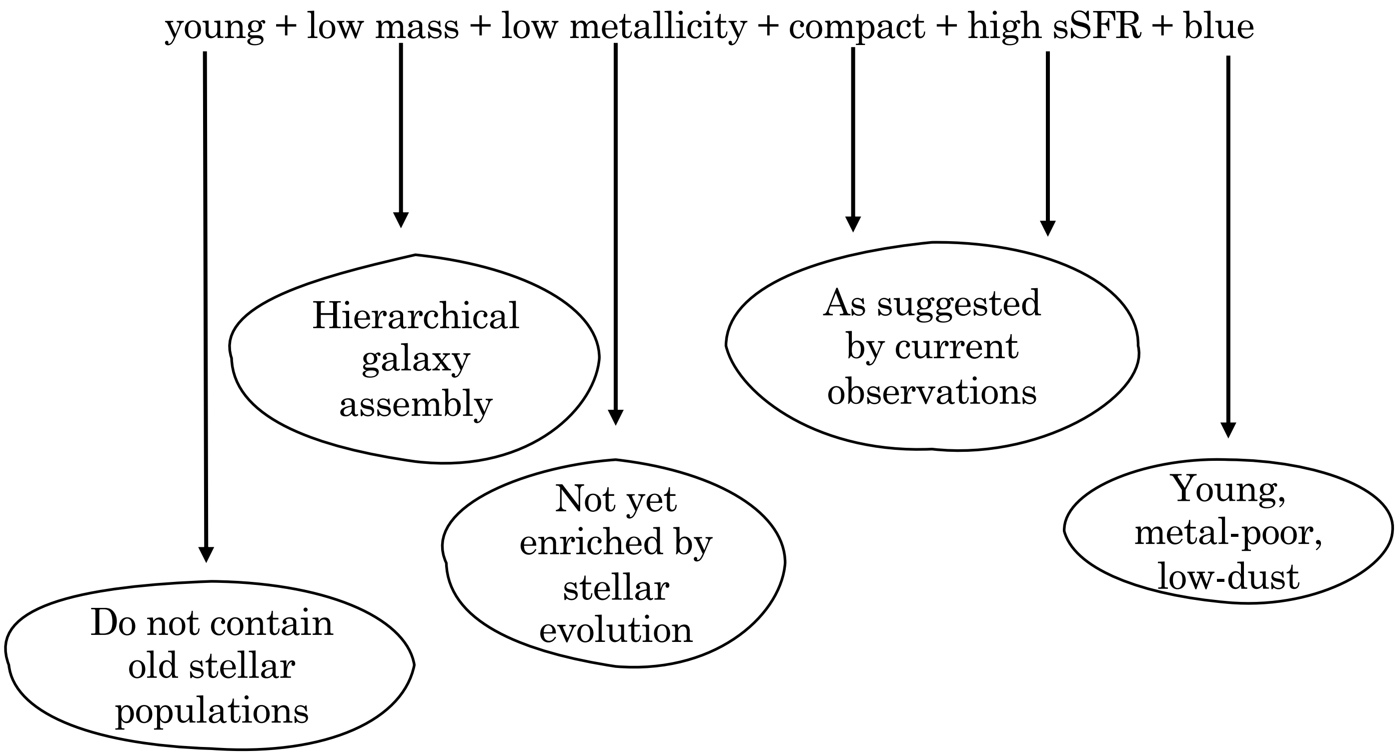




❀ Emission-line diagnostics to characterize ionizing source and gas properties.

Properties of primeval galaxies

Expected properties of primeval galaxies:



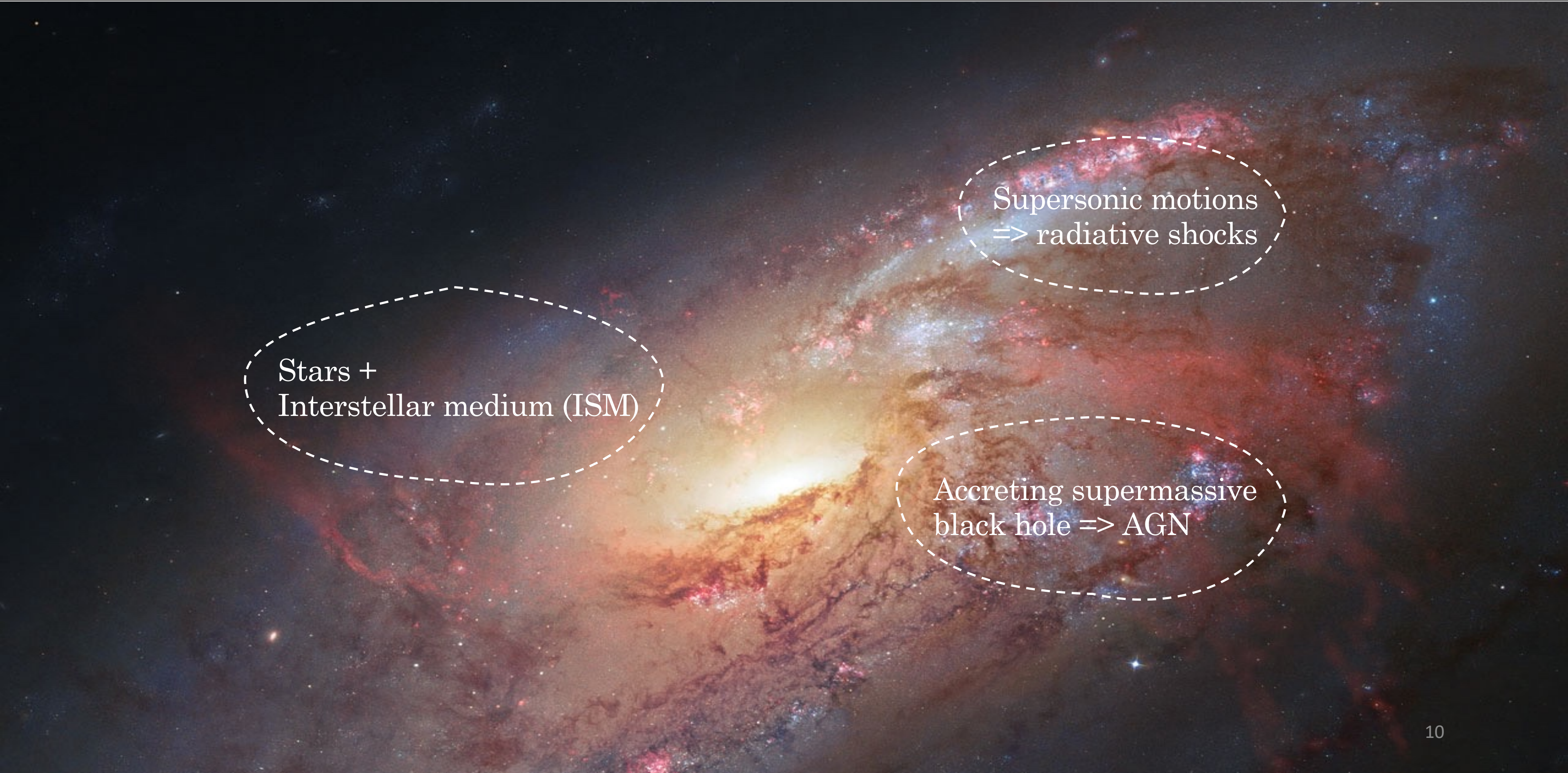
Various existing samples of metal-poor star-forming galaxies and LyC leakers
➽ target galaxies approaching the properties of primeval galaxies (at any z);
➽ typically few lines available per sample;
➽ different samples analyzed independently with different models;

Outcome:

- the galaxies tend to exhibit prominent CIII] (and even CIV) emission;
- strong nebular HeII emission, which tends to increase toward low metallicities, not reproduced by current stellar models;
- combination of CIV, CIII] and HeII can discriminate between star-forming galaxies, AGN and shocks;
- [OII]/[OIII] and HeI lines as potential diagnostics of *fesc*, but degenerate.

❀ Need for a homogeneous investigation of a full set of optical/ultraviolet emission-line diagnostics of metal-poor star-forming galaxies with a wide collection of intercomparable models.

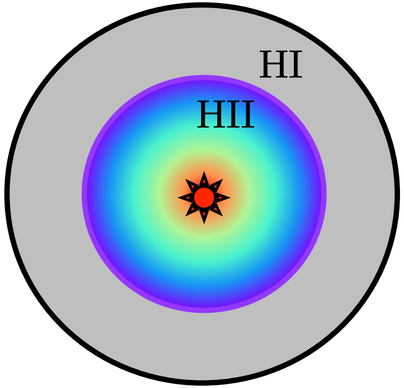
Production and escape of ionizing photons
Modeling approach



Stars with effective temperature $\gtrsim$ 30,000 K ionize the interiors of their birth clouds ➽ **HII regions**

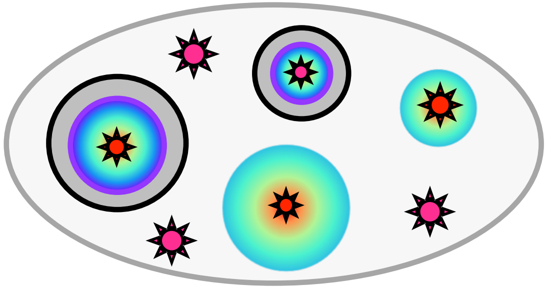
ISM: Mixture of gas and dust composed of H, He and metals.

~70% ~28% ~2% (solar)



Modeling approach

Star-forming galaxy models computed following the approach of Gutkin+16.

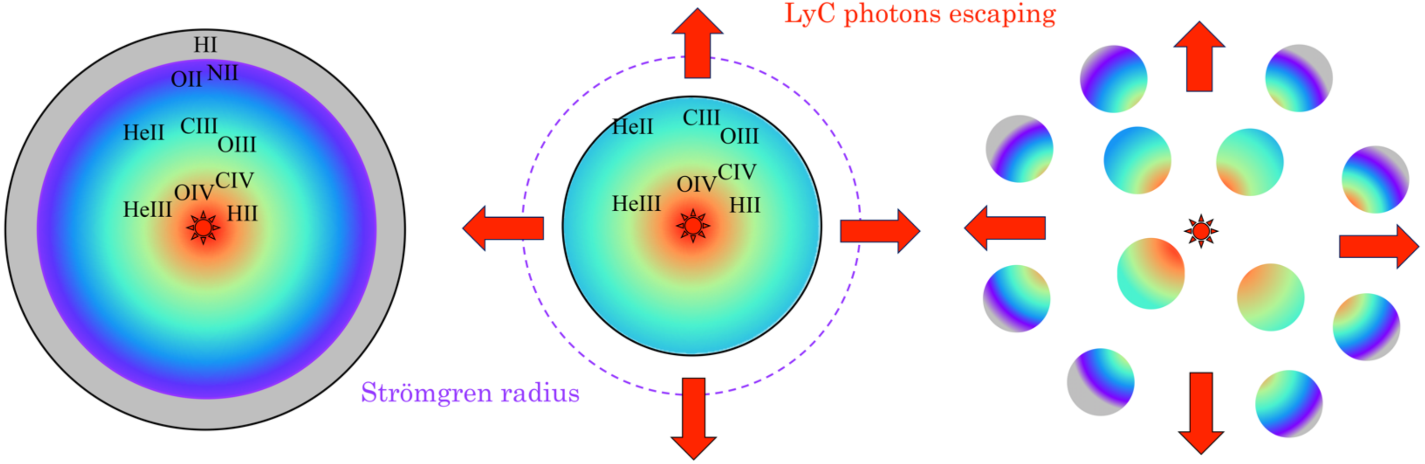


'isochrone-synthesis' technique: star-formation history expanded into a series of simple stellar populations (SSP)

$$L_\lambda(t) = \int_0^t dt' \, \psi(t - t') \, S_\lambda(t', Z) \, T_\lambda(t, t')$$

- $L_\lambda(t)$: Galaxy luminosity at time t
- $\psi(t - t')$: Star-formation rate
- $S_\lambda(t', Z)$: Luminosity of an SSP of age t'
- $T_\lambda(t, t')$: Transmission of the ISM

Escape of ionizing radiation: **density-bounded models**



Ionization-bounded model
optically thick to LyC photons

Density-bounded model
optically thin to LyC photons

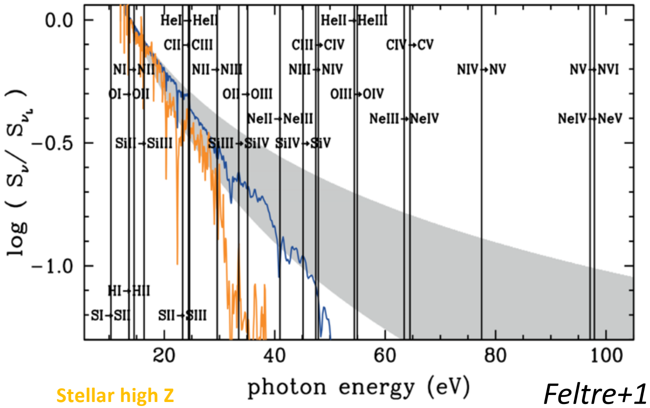
Ionization-bounded with holes

In density-bounded models, peeling off the HII region makes:

- *fesc* larger;
- line EWs decrease (except for lines from high ionization species);
- line ratios of low-to-high ionization species decrease.

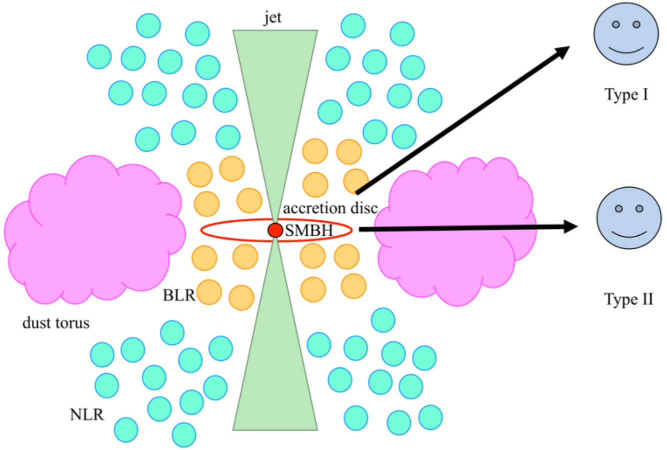
Component of **AGN narrow-line region**: updated version of Feltre+16 models.

Harder ionizing radiation than stars



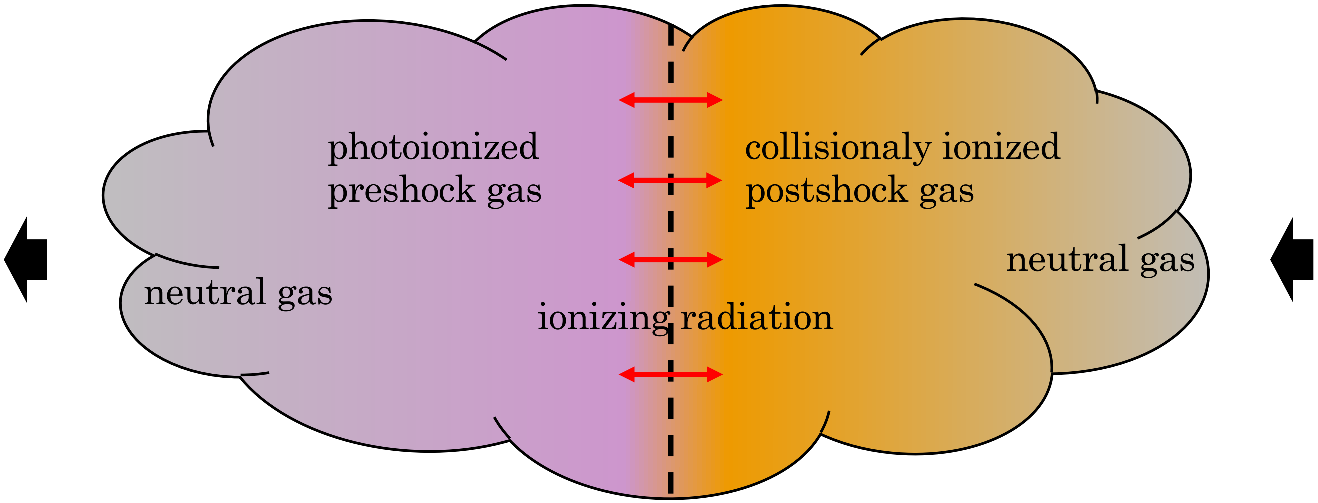
Stellar high Z
Stellar low Z
AGN

Feltre+16

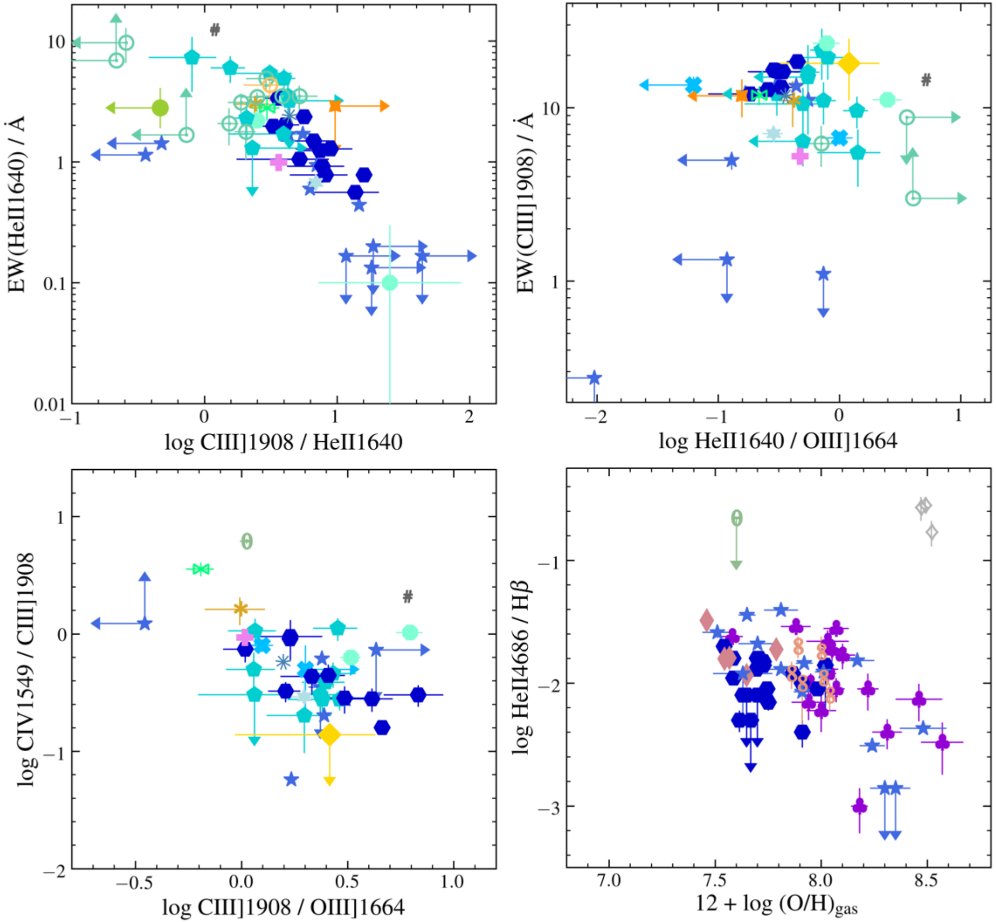


➽ higher fraction of high ionization potential species than in HII region.

Component of **radiative shocks**: models from Alarie&Morisset19.

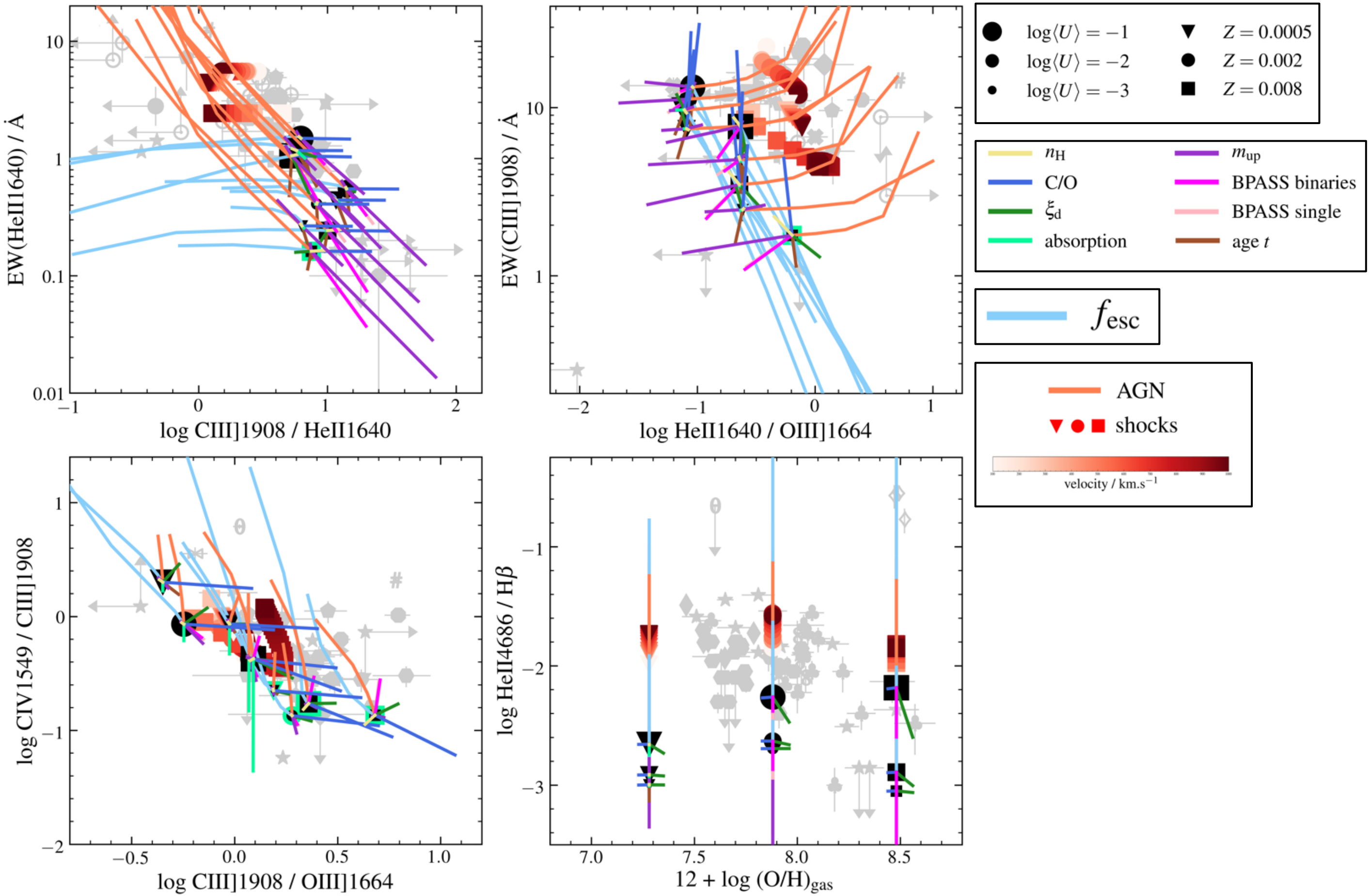


Production and escape of ionizing photons
Observations of metal-poor star-forming galaxies and LyC leakers



- metal poor star forming galaxies
- LyC leakers or candidate
- other star-forming galaxies
- AGN

Production and escape of ionizing photons
Diagnostics of ionizing sources and LyC-photon leakage



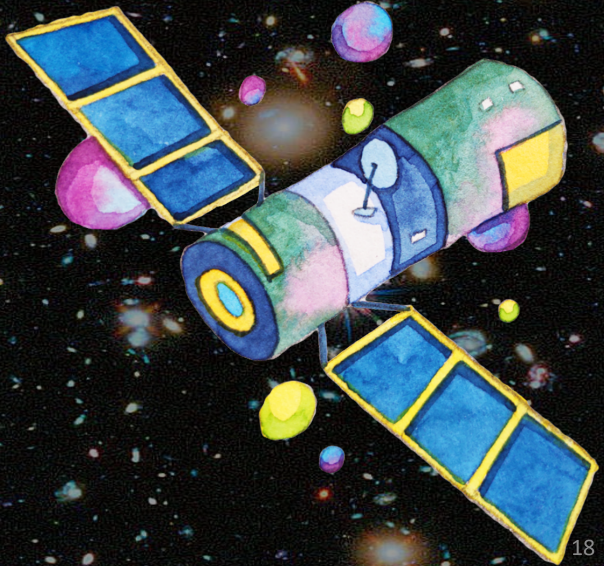
❀ Need a hard ionizing radiation to redroduce the observed line ratios :

➽ more work required to model emission of primeval galaxies.

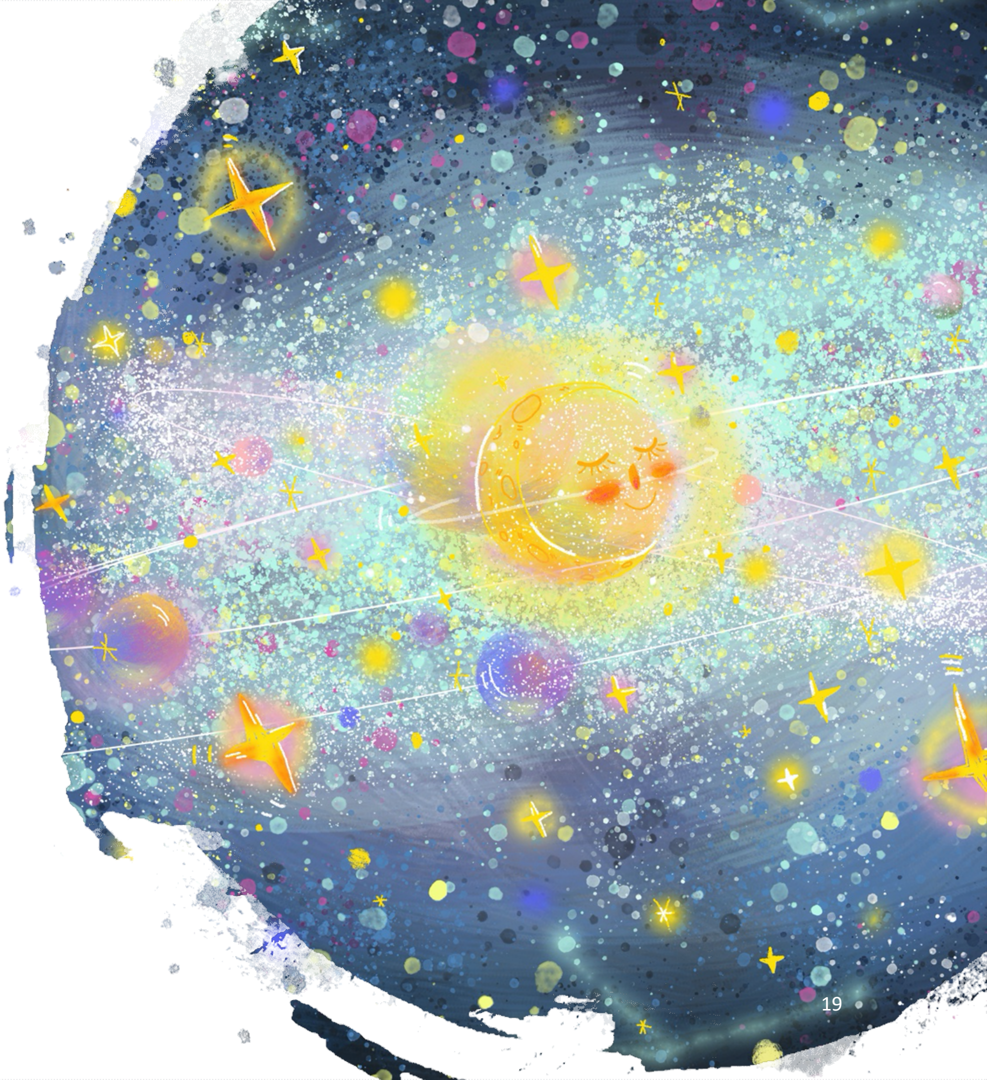
❀ Important degeneracy between the ionizing source and gas parameters :

➽ need to use appropriate statistical tools.

New observations will help us understand the Epoch of Reionization.



Backup slides



Production and escape of ionizing photons

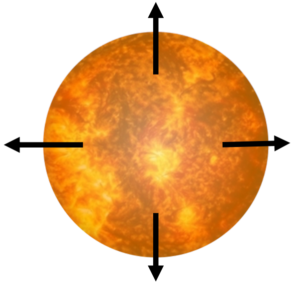
Modeling approach

The production of ionizing radiation by young stellar populations

- Main-sequence OB stars:

Massive stars are hotter than lower-mass ones.
Metals increase atmosphere opacity, resulting in lower T_{eff}.

stellar winds

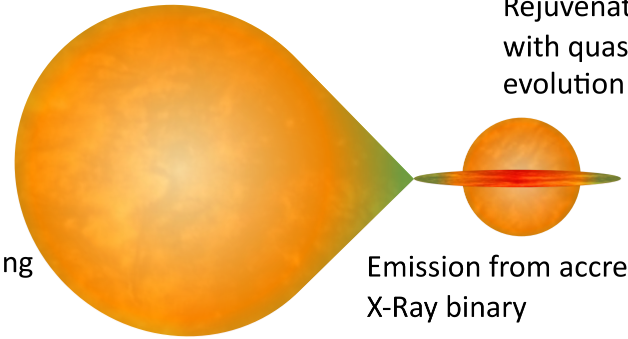


- Wolf-Rayet (WR) stars:

Hot massive stars, which have lost their hydrogen envelopes.
More WR stars at high Z because of higher mass-loss rate caused by line driven winds, but they produce a softer ionizing radiation.

- Binary interactions:

Rejuvenated accreting star,
with quasi chemically homogeneous
evolution at low Z



Stripped star loosing
its envelope

Emission from accretion disc:
X-Ray binary

+ mergers.

Production and escape of ionizing photons

Modeling approach

Emission from an HII region (see Gutkin+16):

❀ Stellar population synthesis codes:

- GALAXEV (Bruzual&Charlot03, 2019 version): single stars
- BPASS (Stanway&Eldridge18, 2019 version): single and binary stars

➽ Stellar parameters :

- metallicity Z = 0.0005, 0.002, 0.008 ($Z_{\odot}$ = 0.01524)
- Chabrier IMF with upper mass cutoff m_{up}= 100, 300 and 600 $M_{\odot}$

❀ Photoionization code CLOUDY (Ferland+17)

➽ Nebular parameters :

- Interstellar (gas- + dust-phase) metallicity: same as that of the stars
- Hydrogen gas density n_H = 100 and 1000 cm^{-3}
- Zero-age volume-averaged ionisation parameter log ⟨U⟩ = −3, −2 and −1
- Dust-to-metal mass ratio ξ_d = 0.1 and 0.3
- Carbon to oxygen abundance ratio C/O = 0.17 and 0.44 (solar)

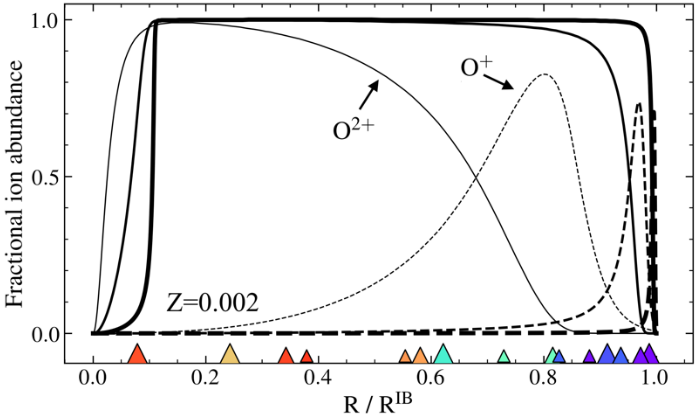
Interstellar-line absorption in stellar birth clouds (HII+HI) using the prescription of Vidal-García+17.

Production and escape of ionizing photons

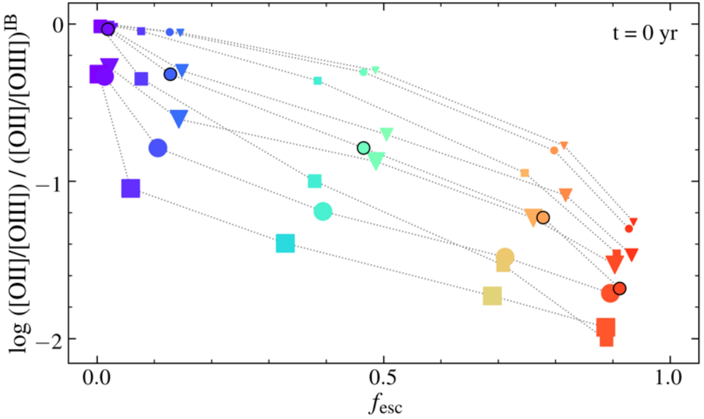
Modeling approach

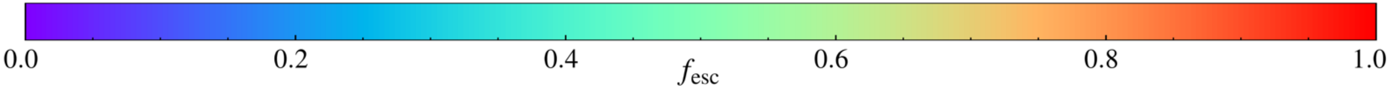
Influence of *fesc* on emission lines:

Ionization structure



[OII]/[OIII] in units IB model





Δ's : sizes of density bounded models

log ⟨U⟩ : increases in order of increasing line thickness / symbol size.

▼ $Z = 0.0005$ ● $Z = 0.002$ ■ $Z = 0.008$

❀ Complex dependence of this (and other) line ratio on *fesc.*

❀ Degeneracy between the signatures of *fesc* and those of other parameters, such as the nature of the ionizing source, *U* and *Z*.