On the use of star formation rate tracers in mixed star formation scenarios

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Escape of Lyman radiation from galactic labyrinths

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Introduction

- The Lyman α emission line (luminosity and equivalent width) is our best (only?) tracer of star formation in the primordial Universe.
  - *But it is affected by different processes making the relation Lyα vs. SFR not straightforward.*

- Main goal of this workshop: understanding the factors that determine the escape of Lyman α photons from star formation regions.
  - *The first step is to derive the intrinsic Lyα luminosity.*
    - For this, we have first to evaluate the number of ionizing photons ($\lambda<912$Å) emitted by the young, massive stars.

Introduction

- It is difficult (if not impossible!) to measure directly the intrinsic ionizing continuum
  - *It has to be derived from different proxies which need to be properly calibrated*
- At low redshift, the luminosity of the Balmer lines, properly corrected from extinction, provides a good, direct estimate *(assuming Case B conditions and ionization bounded star forming regions)*:
  - $L(H\alpha) = 1.37\times10^{-12}\ N_{Lyc}\ \text{erg s}^{-1}$ $L(Ly\alpha) \sim 8.7\times L(H\alpha)$

    N_{Lyc}: *number of ionizing photons per second* $(= Q_{ion})$
- But at high redshift, with no $L(H\alpha)$ available, we have to rely only on rest-frame-UV data, strongly affected by the environment:
  - $L(Ly\alpha)$
  - $L_{1200\text{-}1500Å}$

  → $EW(Ly\alpha)$

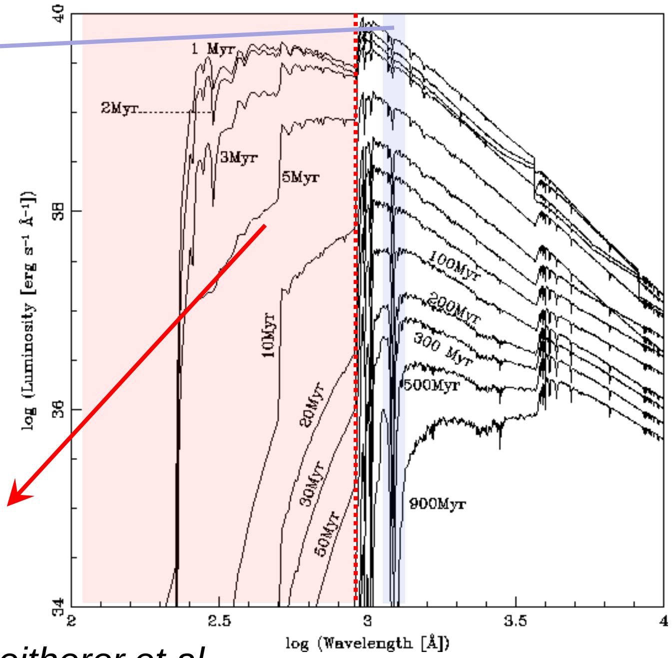
Star formation strength tracers

- Evolutionary population synthesis models, provide an unbiased calibration of star formation strength tracers.

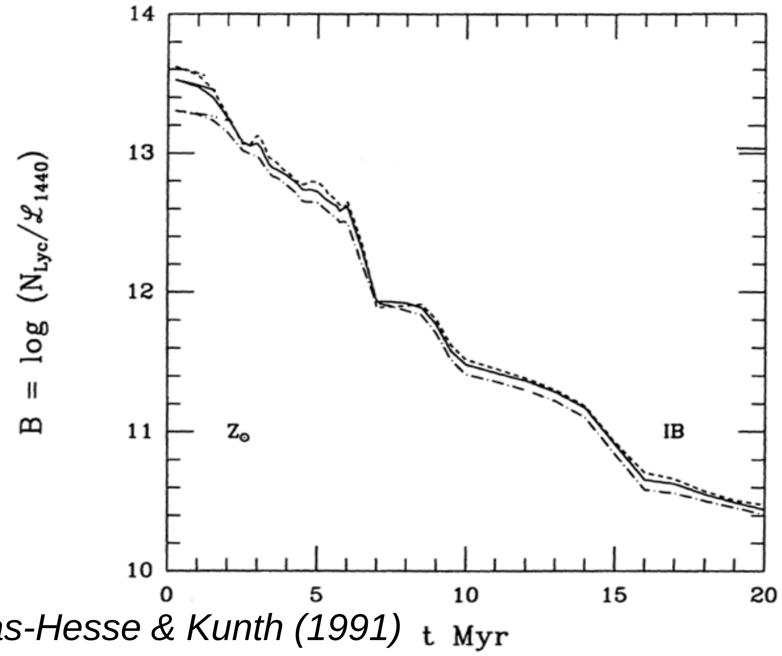
B_{ion} (=ξ_{ion}): the number of ionizing photons per unit UV luminosity

UV continuum

Intrinsic ionizing continuum



Starburst99, C. Leitherer et al.



Mas-Hesse & Kunth (1991)

Star formation strength tracers

- By using state of the art evolutionary synthesis models we can derive self-consistent predictions for different parameters
  - *The physics of stellar evolution implies that all observables have to be correlated, in the form of specific ratios that can be computed for different scenarios*

NLyc	L(Lyα)	L_{1200}	EW(Lyα)	L(Hα)
2.4e53 s^{-1}	2.9e42 $erg\ s^{-1}$	4.5e40 $erg\ s^{-1}$ $Å^{-1}$	64.4 Å	3.3e41 $erg\ s^{-1}$

Example for SFR = 1 $M_{\odot}$/yr, at t=30 Myr, with no extinction and 100% Lyα escape

  - *Observation of any of these parameters necessarily constrains the posible values of the other ones!*

Star formation strength tracers

- …but only if we can constrain a priori the star formation scenario!

	NLyc	L(Lyα)	L_{1200}	EW(Lyα)	L(Hα)
SFR = 1 $M_\odot$/yr, at t=30 Myr	2.4e53	2.9e42	4.5e40	64	3.3e41
SFS = 1e8 $M_\odot$, at t=6 Myr	2.4e53	2.9e42	2.4e41	12	3.3e41
SFS = 3e6 $M_\odot$, at t=2 Myr	2.4e53 *s^{-1}*	2.9e42 *erg s^{-1}*	8.3e39 *erg s^{-1} Å^{-1}*	320 *Å*	3.3e41 *erg s^{-1}*

No extinction and 100% Lyα escape

- This is not always possible and in most cases we can only make an educated guess based on available information!

Star formation scenario

- First we need to define the star formation scenario
  - *Star formation history, statistics (stochasticity), binarity…*
  - *Metallicity*
  - *Environment*

Star formation scenario

- Star formation history
  - Recent burst of massive star formation
    - Population dominated by a coeval cluster of massive stars.

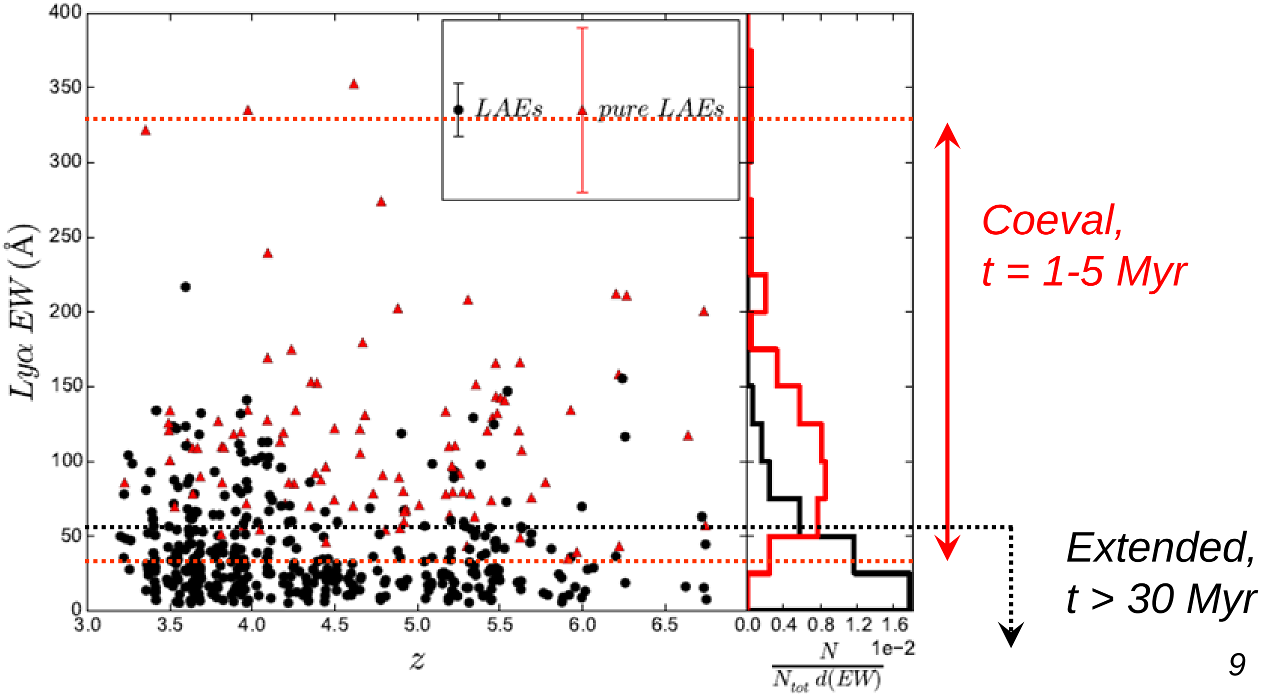
      Parameterized by **Star Formation Strength**:
      SFS → total amount of gas transformed into stars: $M_\odot$

      Note: *stochastic effects for SFS < ~10^6 $M_\odot$*
  - Star formation episode ongoing at a ~constant rate for tens of Myr
    - Intermediate mass, non-ionizing stars provide a significant contribution to the stellar continuum.

      Parameterized by **Star Formation Rate**:
      SFR → amount of gas transformed into stars per year: $M_\odot$/yr
  - Convolution of both regimes
    - Exponentially decaying SFR
    - Sequence of short bursts along the time….

Star formation scenario

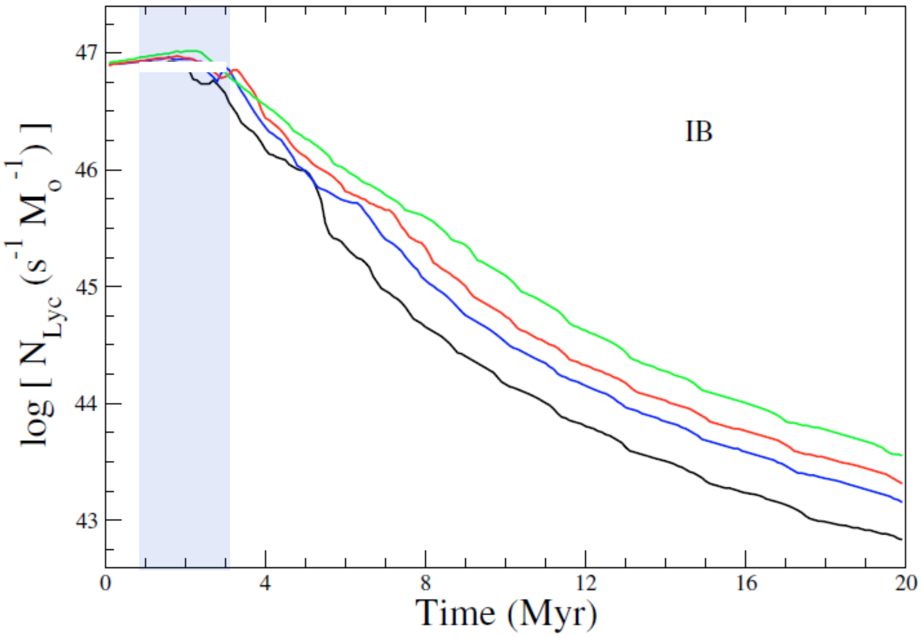
- Star formation history
  - High values of EW(Lyα) are only compatible with short, recent (t~1-3 Myr) bursts of massive star formation

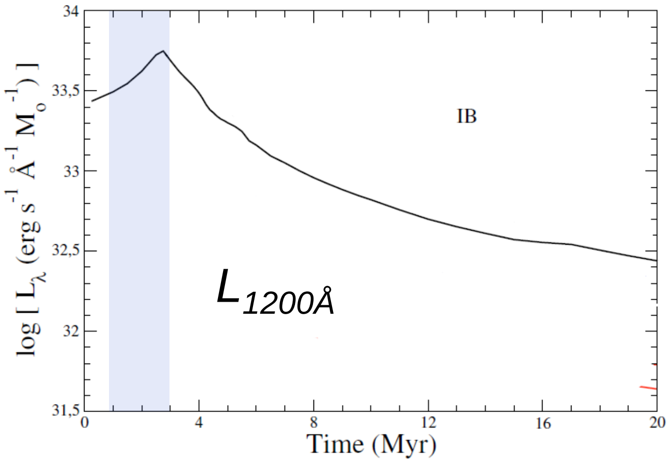


Data from Arrabal et al.(2018)

Star formation scenario

- Star formation history
  - High EW(Lyα) → Young, coeval population: t~1-3 Myr.



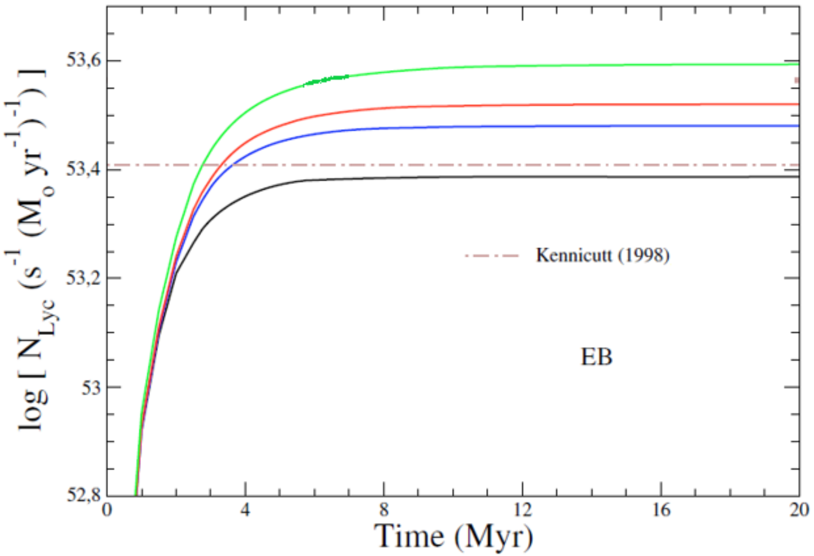


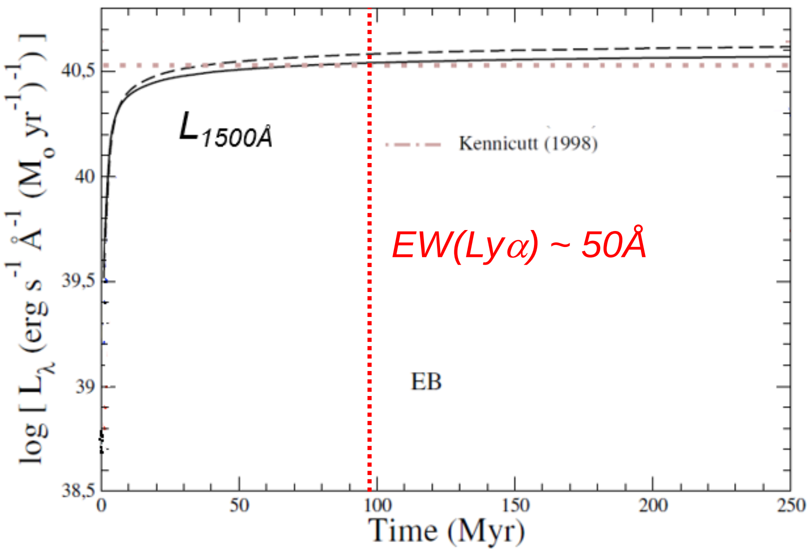
Z = 0.020, 0.008, 0.004, 0.001

Otí-Floranes & Mas-Hesse (2010)

Star formation scenario

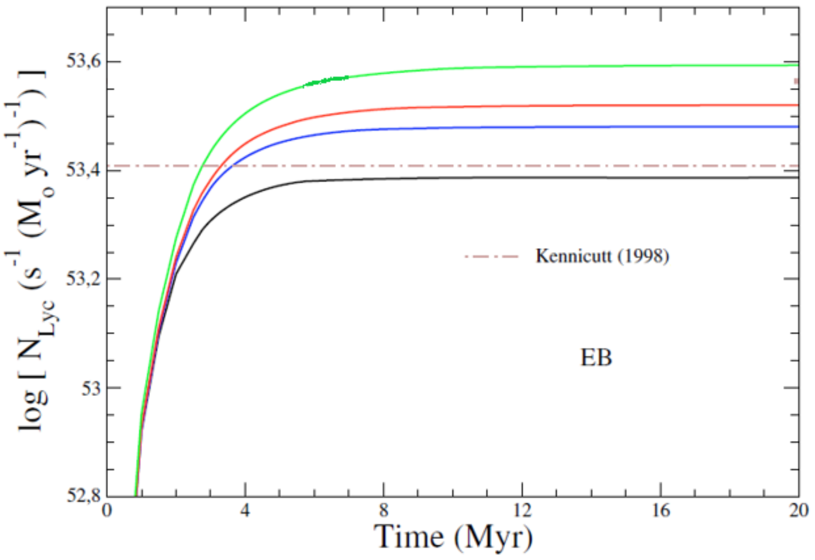
- Star formation history
  - Moderate EW(Lyα) → Extended star formation in equilibrium t>~100 Myr)

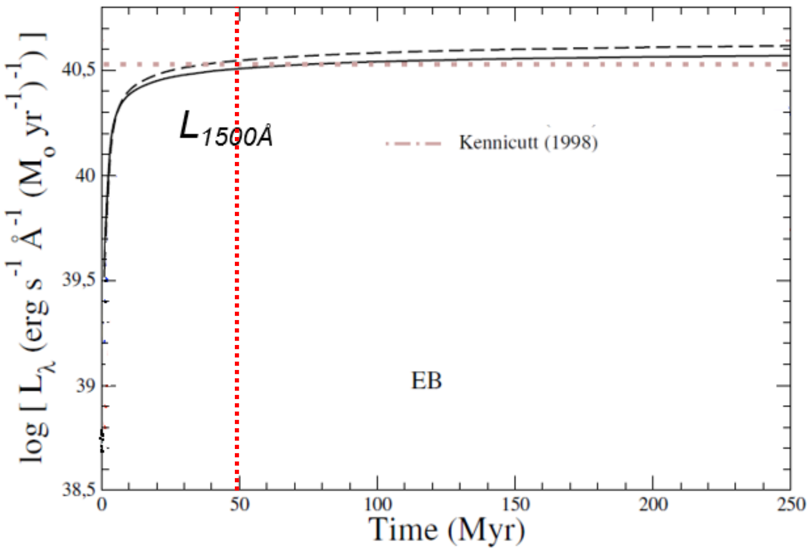




Z = 0.020, 0.008, 0.004, 0.001 *Otí-Floranes & Mas-Hesse (2010)*

Star formation scenario



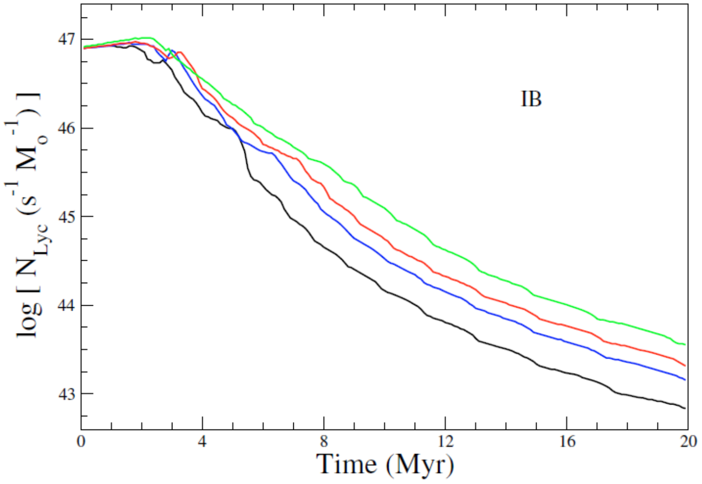


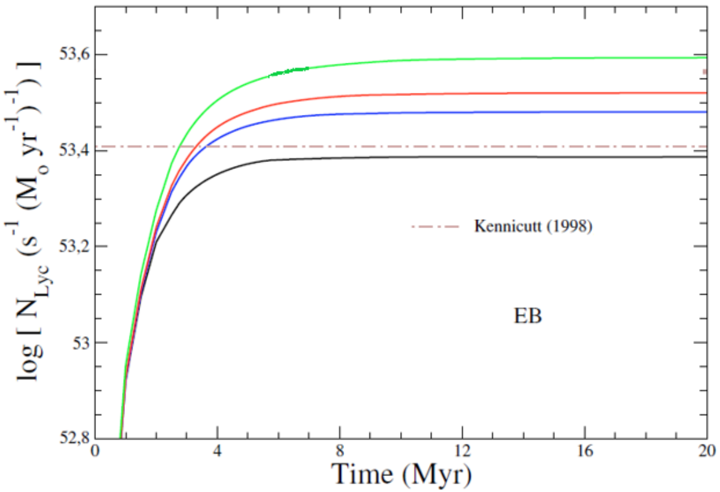
- N_{Lyc} stabilizes after ~6 Myr of evolution with constant SFR
- L_{UV} does not stabilize before t ~ 50 Myr

→ $SFR_{Ly\alpha} \neq SFR_{UV}$ for t < 50 Myr

Star formation scenario

- Metallicity
  - Second order effect (<~50%)





Z = 0.020, 0.008, 0.004, 0.001
Otí-Floranes & Mas-Hesse (2010)

- Environment
  - Absolutely critical!

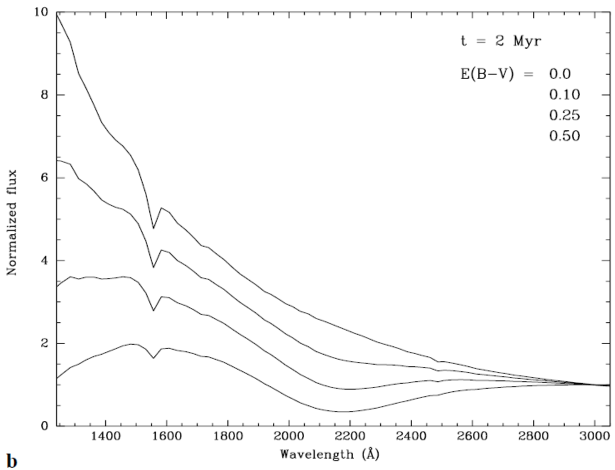
Environmental effects: N_{Lyc} escape fraction

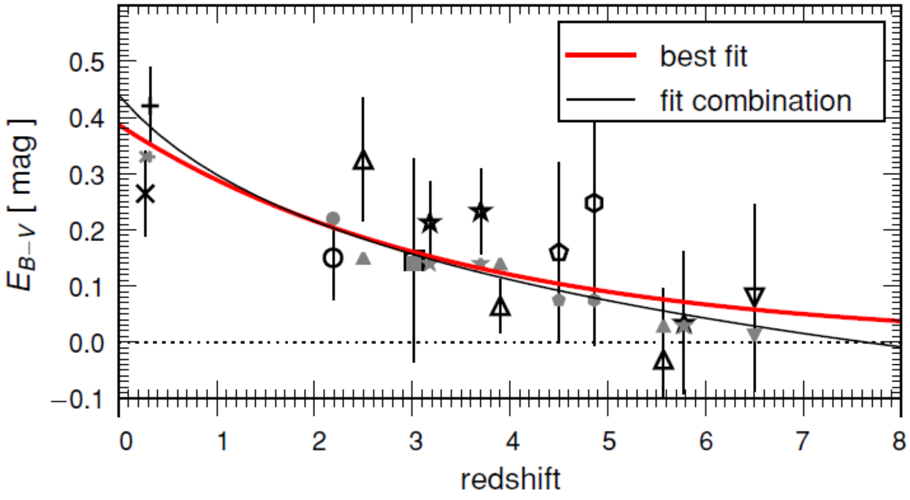
- Ionizing photons leakage
  - *Star forming galaxies can be essentially ionization bounded:*
    - no Lyman continuum photons are leaking
    - Complete ionization → relation emission lines vs. N_{Lyc} valid
  - *Or they can become density bounded and/or show channels through which N_{Lyc} can escape*
    - In average the escape fraction of Lyman continuum photons increases with z
      - Required to re-ionize the Universe at $z>7$
    - Correspondingly increasing decoupling between $L(Ly\alpha)$, $L(H\alpha)$ and the intrinsic N_{Lyc}
      - Increasing divergence between SFR(Lyα) and SFR(L_{UV})

Extreme example: *100% escape of N_{Lyc} would lead to SFR(Hα,Lyα) = 0*

Environmental effects: *dust extinction*

- Not only the amount, but also the distribution of dust define the resulting SED.
  - *Dust extinction becomes more negligible the higher the redshift: E(B-V) → ~0.0*
  - *At medium to low redshift E(B-V) can be estimated from L(Hα)/L(Hβ) or from the UV continuum slope.*





Hayes et al. (2011)

Lyα escape fraction

- To properly compute the Lyα escape fraction everything has to be consistent
  - *Potential N_{Lyc} escape has to be considered*
  - *Dust effects have to be corrected*
  - *All magnitudes observed have to be consistent with the predictions of self-consistent synthesis models for the adequate star formation scenario:*
    - $L(Ly\alpha)$, L_{UV}, L_V, $L(H\alpha)$, EWs, L_{NIR}, L_{FIR}, L_X,….

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Astronomy & Astrophysics

Calibration of star formation rate tracers for short- and long-lived star formation episodes

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Self consistent calibration of SF proxies

http://www.laeff.cab.inta-csic.es/research/sfr/index.php

Star formation rate/strength tracer calibrations

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CONSOLIDER - INGENIO GTC

ESTALLIDOS

Choose the values which best describe your burst and input the value of the magnitude observed in order to obtain the value of the Star Formation Strength (IB models) or of the Star Formation Rate (EB models). Also, the intrinsic values expected for the rest of the magnitudes are output. For more information, read below.

Star formation history and age:	EB (30 Myr) ▼
Initial Mass Function: Salpeter	2-120 ▼
Magnitude observed	L(Lyα) (erg s-1) ▼
Value of the magnitude observed =	2.9e42
Color excess: E(B-V)=	0.0

Calculate

L(Lyα) (erg s-1) ▼

- NLyc (s-1)
- L(Lyα) (erg s-1)
- L(Hα) (erg s-1)
- L1500 (erg s-1 Å-1)
- L2000 (erg s-1 Å-1)
- L3500 (erg s-1 Å-1)
- L4400 (erg s-1 Å-1)
- L5500 (erg s-1 Å-1)
- L22200 (erg s-1 Å-1)
- LFIR(E(B-V)=0.1) (erg s-1)
- LFIR(E(B-V)=0.2) (erg s-1)
- LFIR(E(B-V)=0.3) (erg s-1)
- LFIR(E(B-V)=1) (erg s-1)
- Lrad(at 1.4 GHz) (erg s-1 Hz-1)
- LX(0.4-2.4 keV) (erg s-1)

SFR(L(Lyα))= 1.008e+0 Mo yr^{-1}

The expected values for the different magnitudes are:

N_{Lyc} = 2.458e+53 s^{-1}

L(Hα) = 3.342e+41 erg s^{-1}

L_{1500} = 3.053e+40 erg s^{-1} $Å^{-1}$

L_{2000} = 1.527e+40 erg s^{-1} $Å^{-1}$

L_{3500} = 3.875e+39 erg s^{-1} $Å^{-1}$

L_{4400} = 2.399e+39 erg s^{-1} $Å^{-1}$

L_{5500} = 1.399e+39 erg s^{-1} $Å^{-1}$

L_{22200} = 8.397e+37 erg s^{-1} $Å^{-1}$

L_{FIR}(E(B-V)=0.1) = 3.732e+43 erg s^{-1}

L_{FIR}(E(B-V)=0.2) = 5.038e+43 erg s^{-1}

L_{FIR}(E(B-V)=0.3) = 5.598e+43 erg s^{-1}

L_{FIR}(E(B-V)=1) = 6.718e+43 erg s^{-1}

L_{rad}(at 1.4 GHz) = 2.343e+28 erg s^{-1} Hz^{-1}

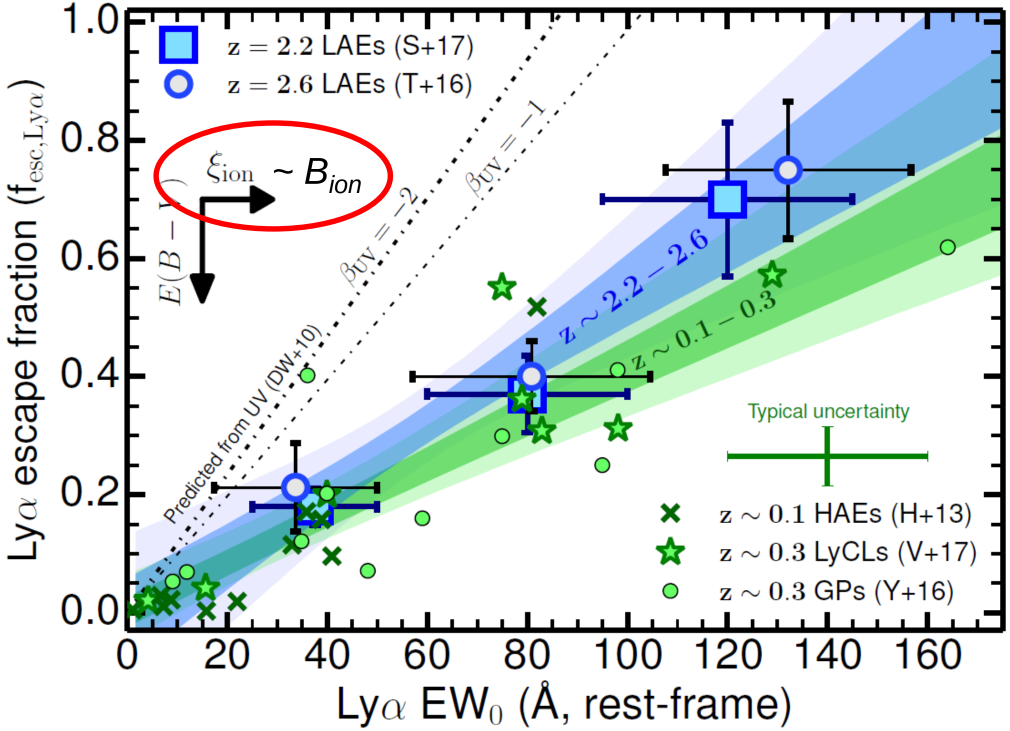
L_X(0.4-2.4 keV) = 5.038e+40 erg s^{-1}

An empirical approach

- There is a nice empirical relation between Lyα escape and rest-frame EW(Lyα)

  - *The correlation requires higher B_{ion} values the higher the EWs*

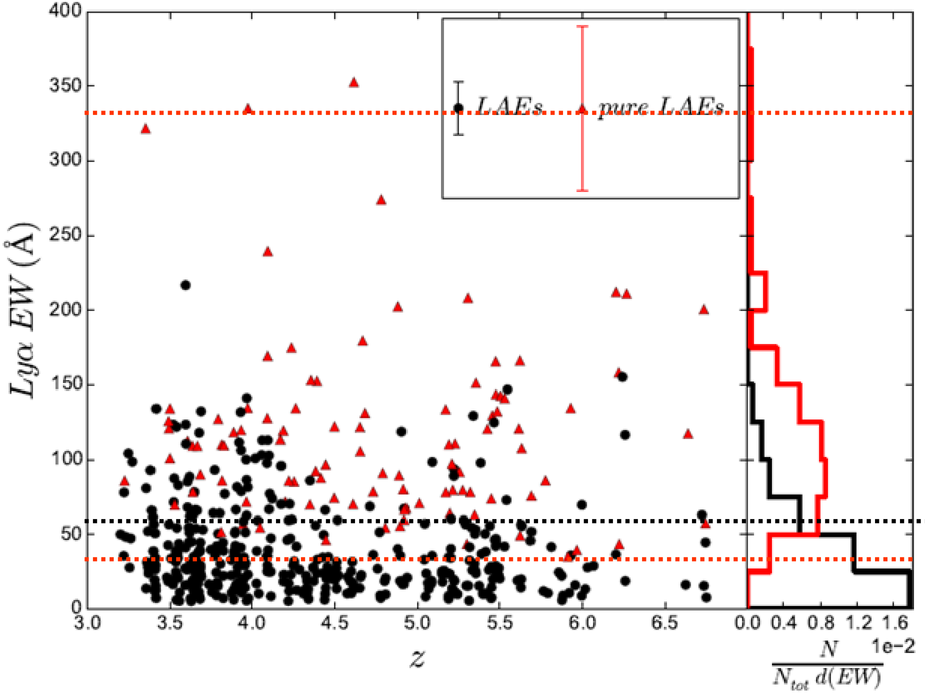
  - *This is exactly as expected for very short, coeval starbursts*



Sobral & Matthee (2018)

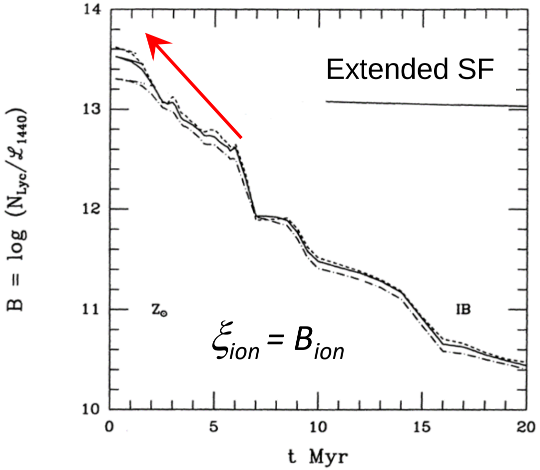
Indeed, it is not expected for extended episodes of star formation!

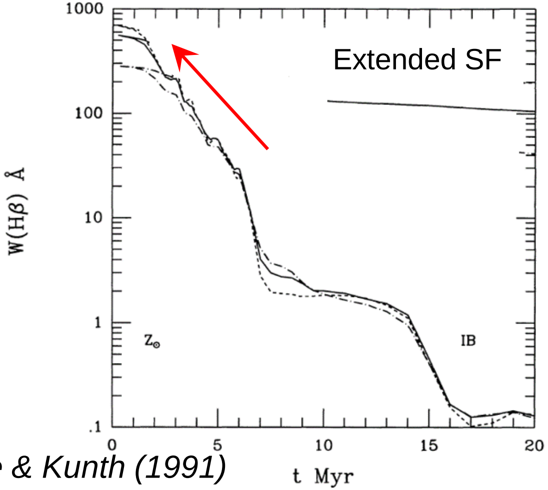
An empirical approach



Coeval,
t = 1-5 Myr

Extended,
t > 30 Myr

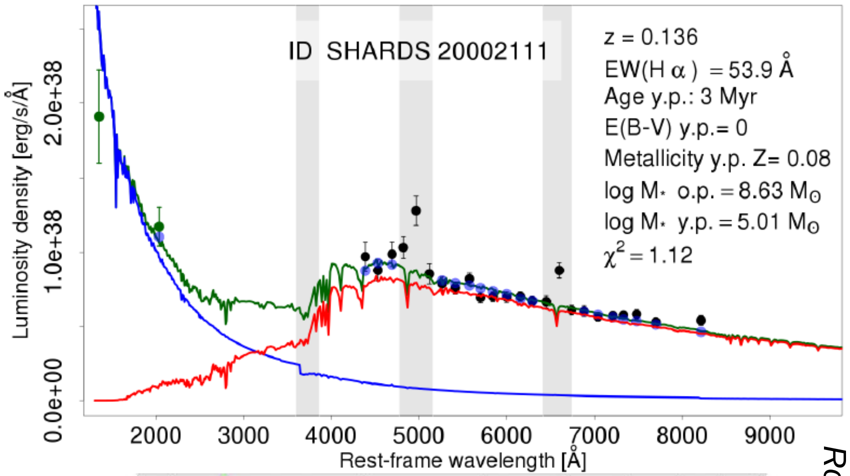




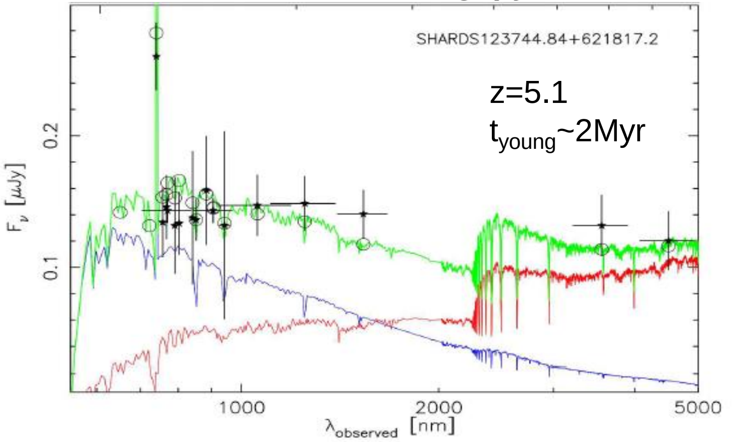
Mas-Hesse & Kunth (1991)

An empirical approach

- When multiwavelength data are available a mixed star formation scenario emerges in most cases:
  - *UV continuum + emission lines dominated by a very young cluster of very massive stars*
    - t < 2 - 4 Myr
  - *Optical-NIR continuum dominated by an older stellar population, accumulated over 100's of Myr*
    - Negligible contribution to ionization (emission lines) and UV continuum
  - *An evolved star formation regime at a ~constant SFR does not fit most of these cases*



Lumbreras-Calle et al (2018)



Rodríguez-Espinosa et al (2014)

Conclusions

- A key problem to understand star formation is to derive the intrinsic ionizing continuum luminosity from available observations.
- It is essential to use a self-consistent calibration of star formation tracers based on evolutionary synthesis models to get unbiased results
  - *The more parameters fitted together, the better*
- The star formation history has to be treated consistently
  - *SFR is meaningless to describe a short starburst episode: has to be used with care!*
- As a first approximation a two-phases scenario allows to characterize the star formation episode
  - *Very young (t<~3Myr), short lived, starburst :*
    - dominates UV + emission
  - *Underlying evolved population accumulated over 100's of Myr:*
    - dominates the optical+NIR continuum (and the total dynamical mass)