The global budget of ionizing photons escaping from local galaxies

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The diffuse intergalactic gas is highly ionized

Haardt Madau 2012

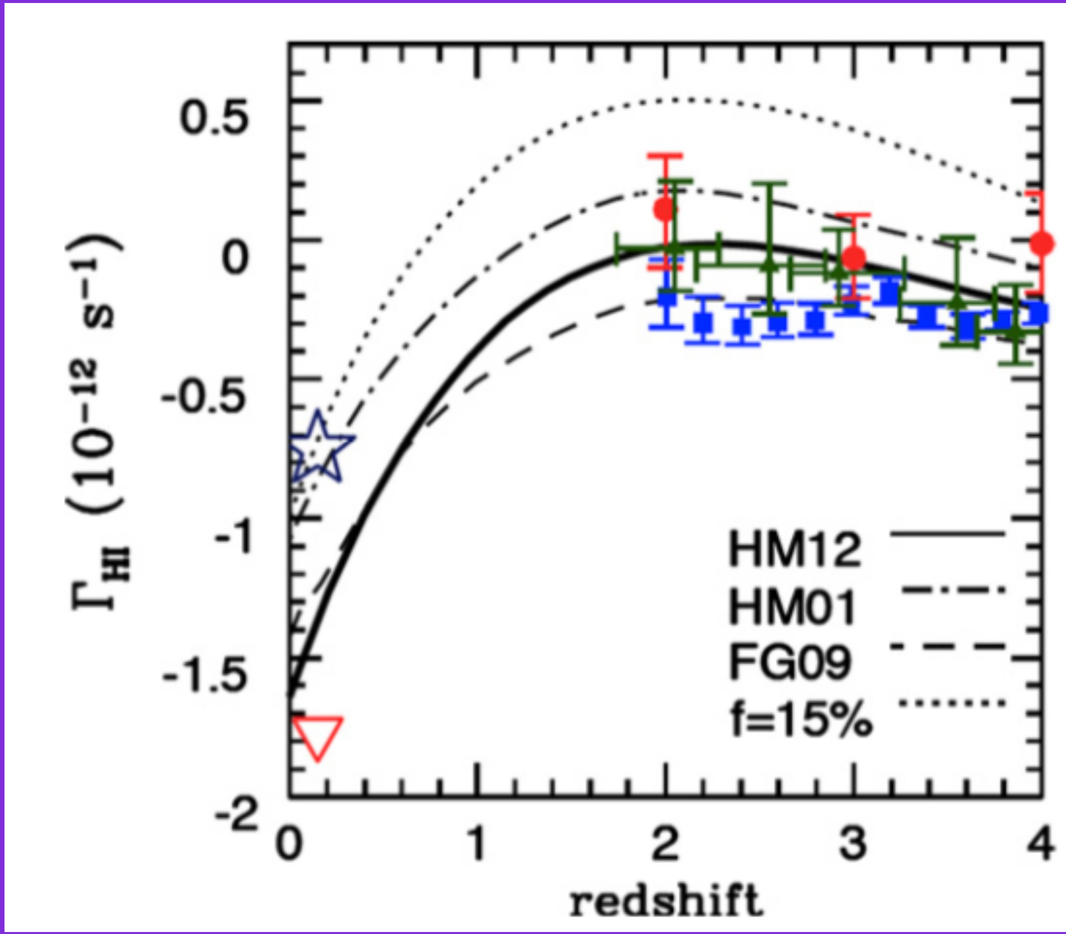
The intensity and spectrum of the cosmic ultraviolet background remain one of the most uncertain yet critically important astrophysical input parameters

for cosmological simulations of the IGM

and for interpreting quasar absorption-line data

and derive information on the distribution of primordial baryons (traced by H i, He i, He ii transitions)

and of the nucleosynthetic products of star formation (C iii, C iv, Si iii, Si iv, O vi, etc.).



Kollmeier et al 2014
H photoionization rates vs z
« observed » and estimated

Some current estimates of Γ_H at z=0

	AGN	OB stars
Shull et al 99	$3.2\ 10^{-14}\ s^{-1}$	$2.7\ 10^{-14}\ s^{-1}$
Faucher Giguere et al 2009	$1.4\ 10^{-14}\ s^{-1}$	$2.6\ 10^{-14}\ s^{-1}$
Haardt Madau 2012	$2.3\ 10^{-14}\ s^{-1}$	~ 0

Shull et al 2015

The primary uncertainties are the

- contribution from massive stars
- and the LyC escape fraction (generally estimated to be of a few %)

stellar

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Estimating the Lyc leakage from galaxies

Direct Detection of Lyman Continuum Escape from Local Starburst Galaxies

Leitherer et al 2016, Izotov et al 2016, Vasei et al 2016

Observationally expensive, can be done on only few objects

Comparison of star-forming galaxies with photoionization models

Jaskot & Oey 2013, Nakajima & Ouchi 2014

Such comparisons often fail to consider all the available constraints (ie [OI]) and lead to incorrect conclusions as shown by Stasińska et al 2015

Use of Ly α to detect galaxies that leak Lyman continuum

Verhamme et al 2015

Difficult to use quantitatively

Determination of ionizing photon budget using emission lines

Oey & Kennicutt 1997, Relaño et al 2002, Zackrisson et al 2013

Easy to implement and apply to large samples

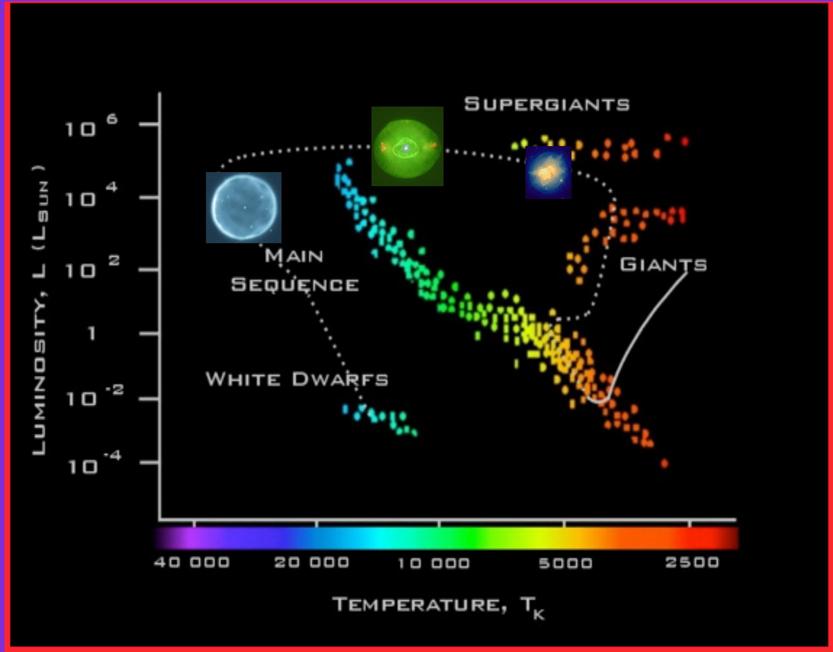
Two populations of ionizing stars in galaxies

Massive stars ($M^* > 20 M_\odot$) **- the only ones considered in Lyc photon leakage estimates**

- Generally located in their birth clouds
- Lyc output: $10^{47} – 10^{50}$ s^{-1} per star, T*~ 40,000K
- leakage may occur through density-bounded zones or if covering factor is <1

Hot low-mass evolved stars: HOLMES ($M^* < 5\text{-}8 M_\odot$)

- Far away from their birth clouds
- Have lost most of their mass through winds in previous stages
- Lyc output: $10^{47} – 10^{48}$ s^{-1} per star, T* > 100,000K
- Only a small fraction of those photons are absorbed by planetary nebulae



nb: the line ratios observed in the DIG of edge-on spiral galaxies indicates that it is ionized by extraplanar HOLMES Flores-Fajardo et al 2011

Ionizing photons from an instantaneous starburst

During the first 10^7 yr:

Ionizing photons are produced by massive stars

They do not escape easily

After 10^8 yr:

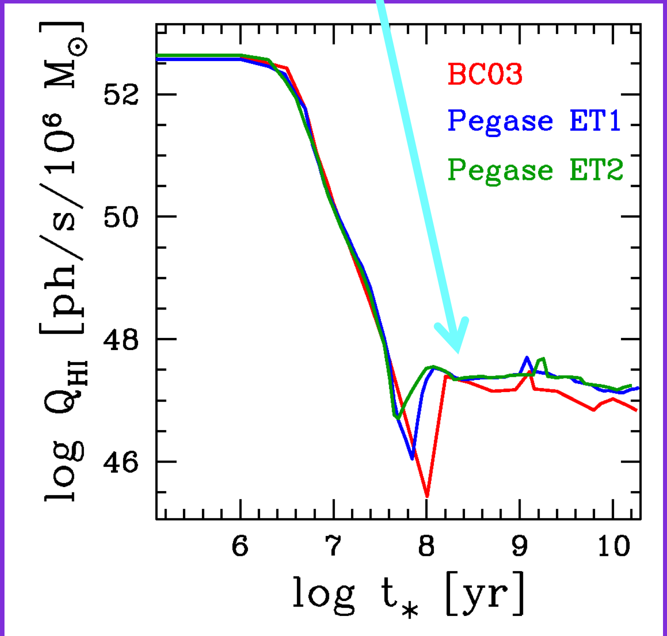
ionizing photons are produced by the HOLMES

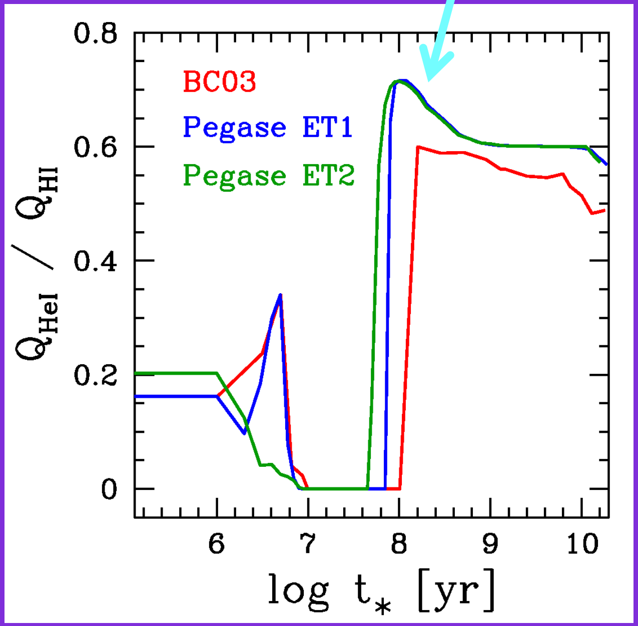
at a much smaller rate

but during a large amount of time

and at much higher energies

They may escape easily from the galaxies





A galaxy is composed of different stellar populations

The stellar populations of various ages and metallicities have different weights

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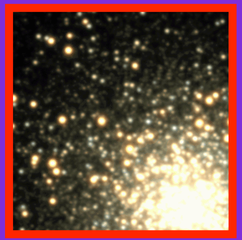

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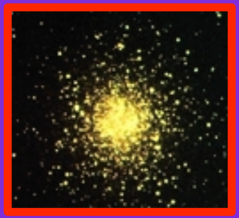

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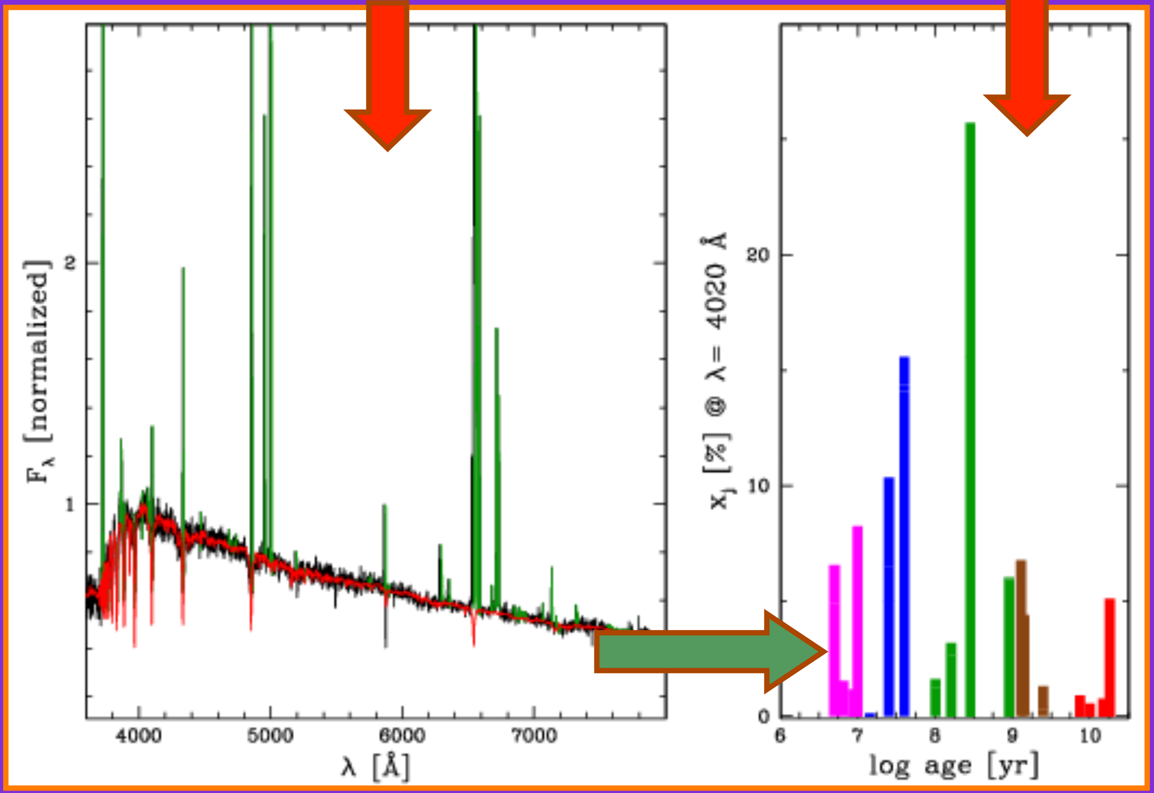
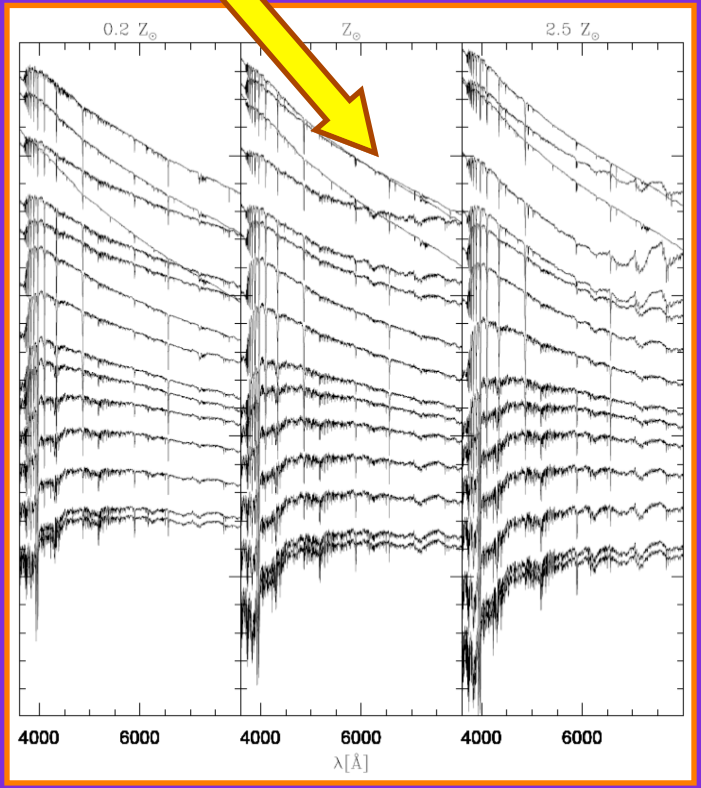
Each population has a specific spectral signature

How to estimate the production of stellar Lyc photons

1- Find the linear combination of simple stellar populations that fits the observed galaxy stellar spectrum (ie excluding the emission lines)

$$L_{\lambda gal} = A(M^*) \sum_{i,j} \left(x(t_i, Z_j) B_{ij\lambda}(t_i, Z_j) \right)$$





2- Compute the corresponding Lyc photon production Q_H

How to estimate the Lyc photon leakage

- From Q_H estimate to total Hα emission expected from the observed stellar populations assuming that all the Lyc photons are absorbed by H and that case B recombination applies

$$L(H\alpha)_{exp} = \varepsilon(H\alpha) / \alpha_B(H)\ Q_H$$

- From the observed Hα luminosity compute the extinction-corrected Hα luminosity

$$L(H\alpha)_{corr} = 10^{0.4\,k(H\alpha)\,A_V}\, L(H\alpha)_{obs}$$

where A_V is the visual extinction computed from the observed Hα/Hβ ratio and $k(H\alpha)$ depends on the adopted extinction law

- Escaping Hα radiation:

$$L(H\alpha)_{esc} = L(H\alpha)_{exp} - L(H\alpha)_{corr}$$

The SEAGal project

Semi
Empirical
Analysis of Sloan Digital Sky Survey
GALaxies

Data: The Sloan Digital Sky Survey DR7

- 3 arcsec fiber spectra of nearly 10^6 galaxies, spectral range 3800-9200 A,
- We use the Main Galaxy sample, which is complete to mr =17.77 mag

Tools: The inverse stellar population synthesis code STARLIGHT

Cid Fernandes et al 2005

Code and results on http://astro.ufsc.br/starlight/

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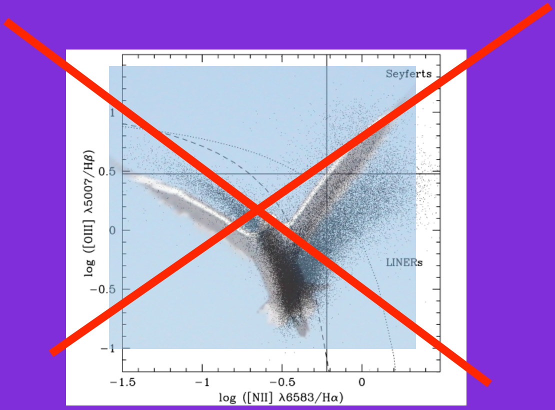
Classification of galaxies

We need a classification

- That separates the dominant stellar populations as well as possible
- That uses as few lines as possible, to be able to classify as many galaxies as possible
- That can take into account the lineless galaxies



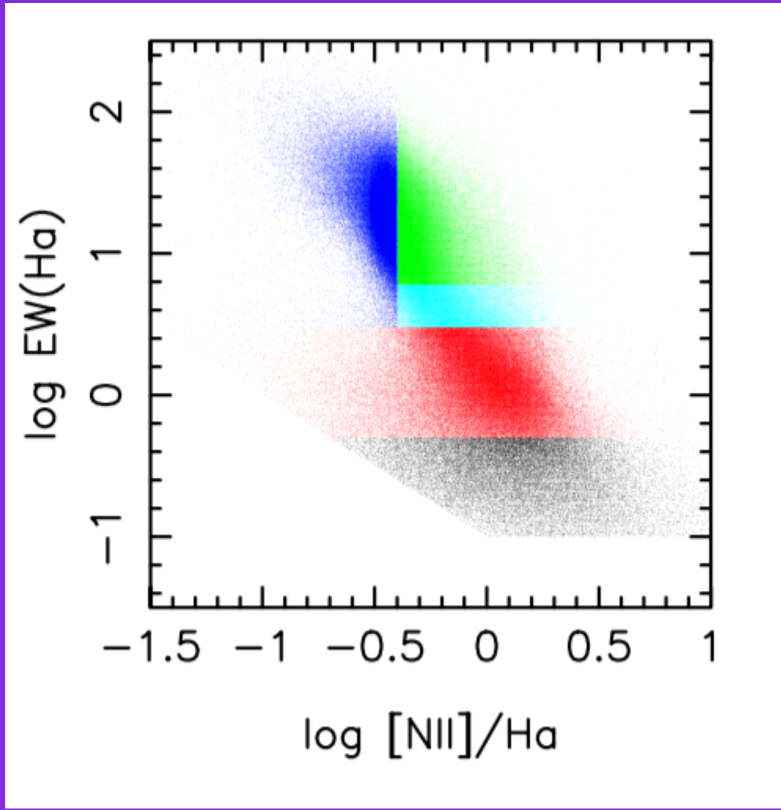
This is not the case of the classical BPT diagram

The WHAN diagram

Cid Fernandes et al 2011

- fulfills our requirements.
- In particular, it separates
  - galaxies with current star formation
  - from retired galaxies, ie galaxies that stopped star formation and are ionized by their old stellar populations (Stasinska et al 2008)

The WHAN classification of galaxies



master sample
defined as

- MGS
- 0.05 < z < 0.2
- no bad pixels in the region of Hα and [N II]

501061 objects

- SF: log [N II] / Hα <− 0. 4 and W(Hα) > 3Å
- Strong AGN: [N II] / Hα >− 0. 4 and W(Hα) > 6Å
- Weak AGN: log [N II] / Hα >− 0. 4 and 3Å < W(Hα) < 6Å
- Retired: W(Hα) < 3Å
- Lineless: W(Hα) and W(NII) < 0.5 Å

Provisional reduction of the MGS sample

Constraints on S/N in the continuum

To derive meaningful quantities with STARLIGHT: S/N > 10

Constraints on emission-lines

To compute a reasonable value of $A_{V:}$ S/N in Hα and Hβ >3

Constraint on A_V

Remove the few objects with very large A_V to avoid unrealistic luminosities: $A_V < 3$

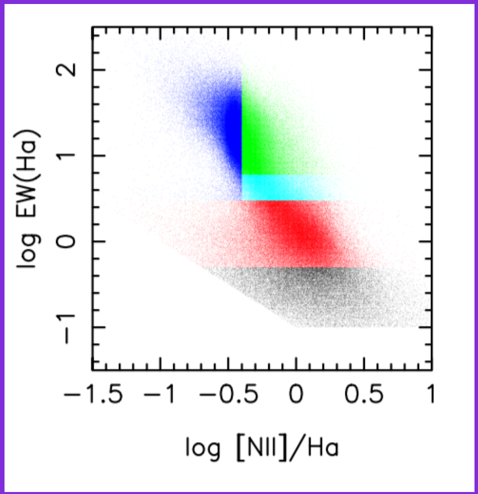
The MGS sample

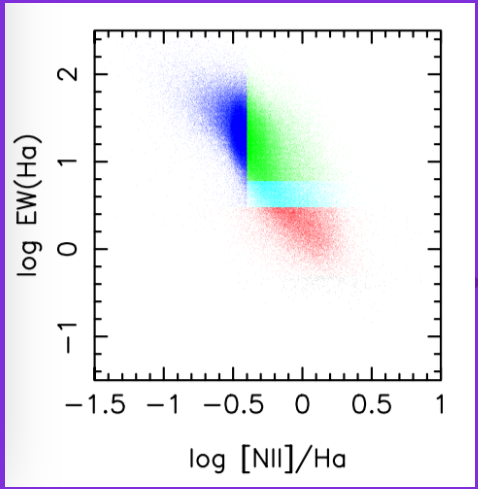
Reduces from 501,063 to 192,922

Lineless galaxies are eliminated,

Many retired galaxies are eliminated,

Faintest SF galaxies are eliminated





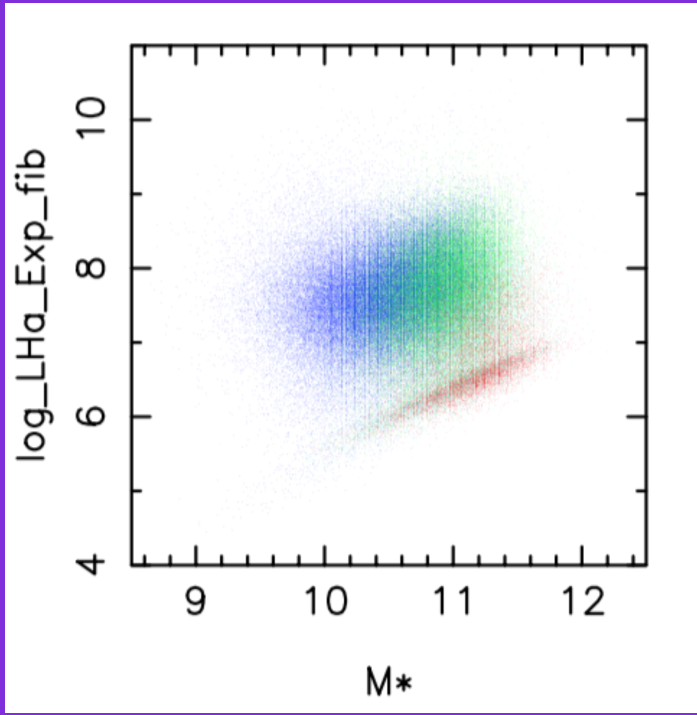
Values of $L(H\alpha)_{exp}$ in the reduced MGS sample

The plot

- $L(H\alpha)_{exp}$ values correspond to the fiber coverage
- They are plotted as a function of the total galaxy mass M* (corrected for aperture)
- $L(H\alpha)_{exp}$ values are obtained from the stellar populations (ie do not contain the contribution of the AGN in AGN galaxies)

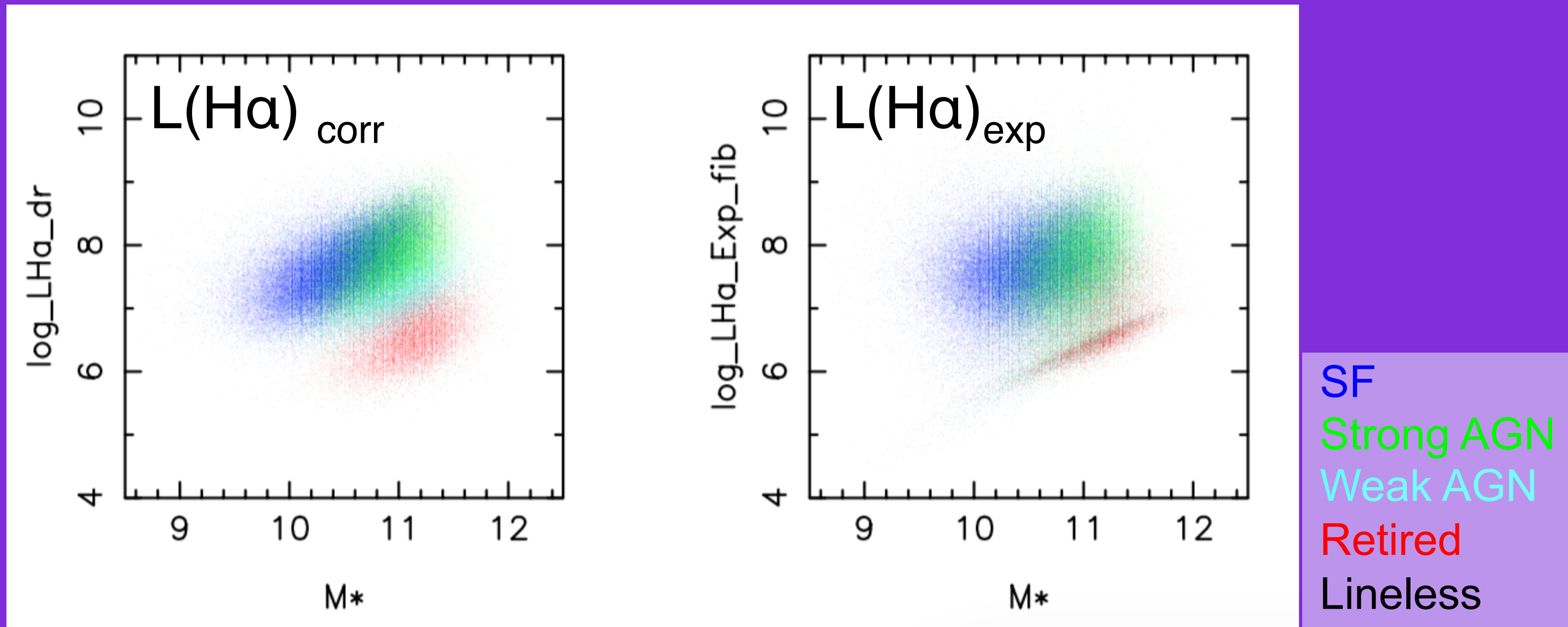
We note

- For each WHAN-type, $L(H\alpha)_{exp}$ increases with M*
- Strong AGN seem to be the prolongation of the SF class
- The sequence of retired galaxies is
  - well below that of galaxies with current star formation
  - very narrow



SF
Strong AGN
Weak AGN
Retired
Lineless

Comparing L(Hα) $_{corr}$ and L(Hα)$_{exp}$ in the reduced sample



- L(Hα)$_{corr}$ increase with M* in each WHAN-category

- The L(Hα)$_{corr}$ sequence is less scattered than the L(Hα)$_{exp}$ one for SFs and AGNs
    - Because L(Hα)$_{exp}$ is inaccurate by several factors for SFs and AGNs

- The L(Hα)$_{corr}$ sequence is more scattered than the L(Hα)$_{exp}$ one for retired galaxies
    - Because of the uncertainty in dereddening

Our procedure to derive Lyc esc

In the reduced MGS sample

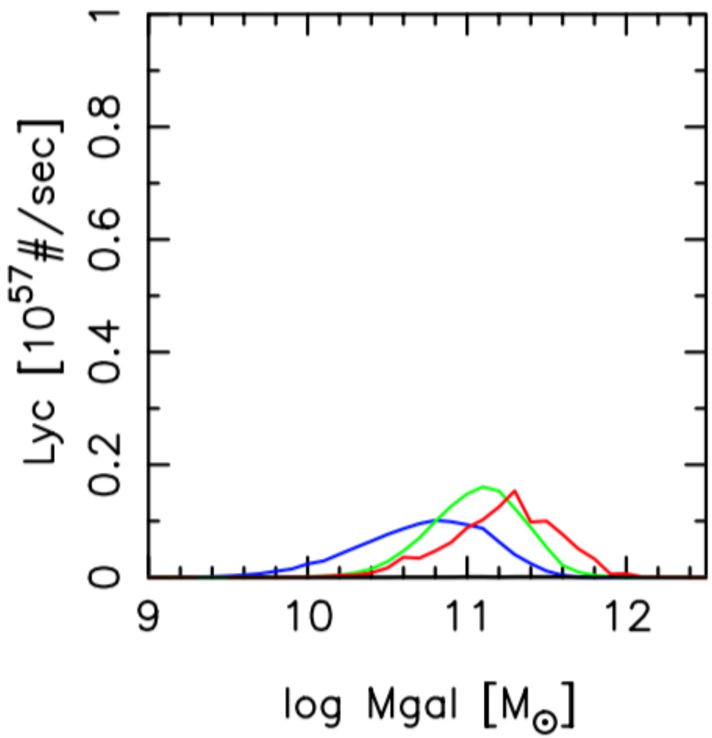
- For SFs and AGNs
  - Since the values of$L(H\alpha)_{exp}$ are so uncertain, use the observed $L(H\alpha)$ corrected for extinction, convert in to a number of ionizing photos, and assume a canonical escape fraction of 5% just to have a point of comparison with retired galaxies
- For retired galaxies
  - compute $L(H\alpha)_{corr}$ - $L(H\alpha)_{exp}$ and convert into a number of ionizing photons

In the total master sample

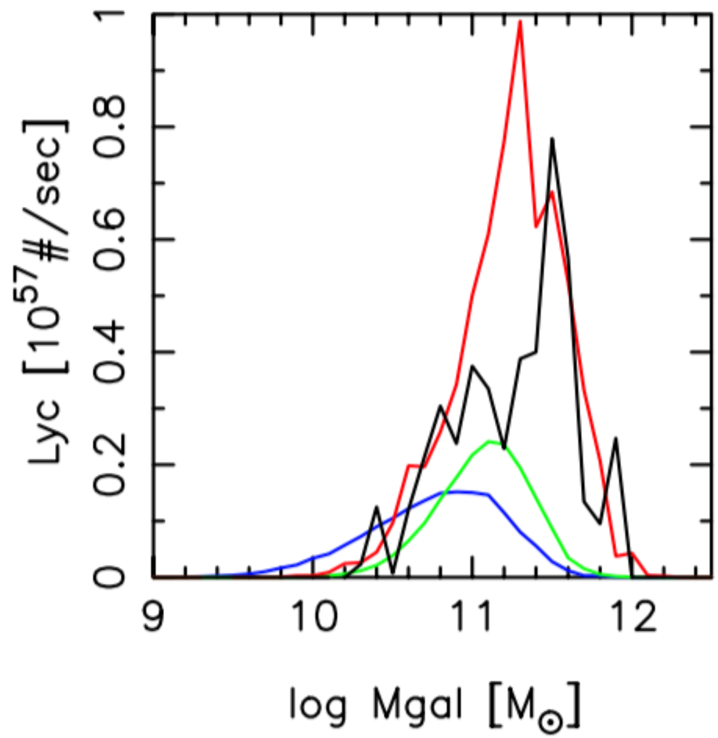
- Divide the results for the reduced MGS sample into bins in galaxy mass and WHAN categories.
- In each bin
  - multiply the result by the number of objects in the master sample
  - and divide it by the number of objects of the reduced sample

Resulting numbers of Lyc Esc as a function of M_{gal}

Reduced MGS sample



Master sample



Total

SF	1.60e57
Strong AGN	1.73e57
Weak AGN	<< 1e57
Retired	6.50e57
Lineless	4.56e57

Next steps

- Find a proper way to estimate Lyesc from SF galaxies
- Estimate the number of escaping photons outside the SDSS fibers
- Take into account that for some galaxies the SDSS spectra correspond to retired bulges of galaxies with a SF disk (Gomes, Papaderos et al 2015…)

Provisional conclusions

Assuming that the Lyc escape fraction in SF galaxies is 5%, we find that

- in a volume corresponding to $z < 0.2$
- the Lyc escape from retired galaxies (with and without emission lines)
- dominates that the SF galaxies by a factor 3.3

The galaxies with stellar masses log M = 10.5 – 11.5 $M_\odot$ contribute most

The prediction of LyC escape for retired galaxies is rather robust since

- The LyC from old stellar populations is not expected to vary with the details of star-formation history
- Dust and gas in retired galaxies is diffuse and

do not absorb much of the produced Lyc photons

In the overall budget of escaping Lyc photons one must add AGNs and perhaps intracluster stars and low surface brightness galaxies but in any case

do not ignore the retired !