

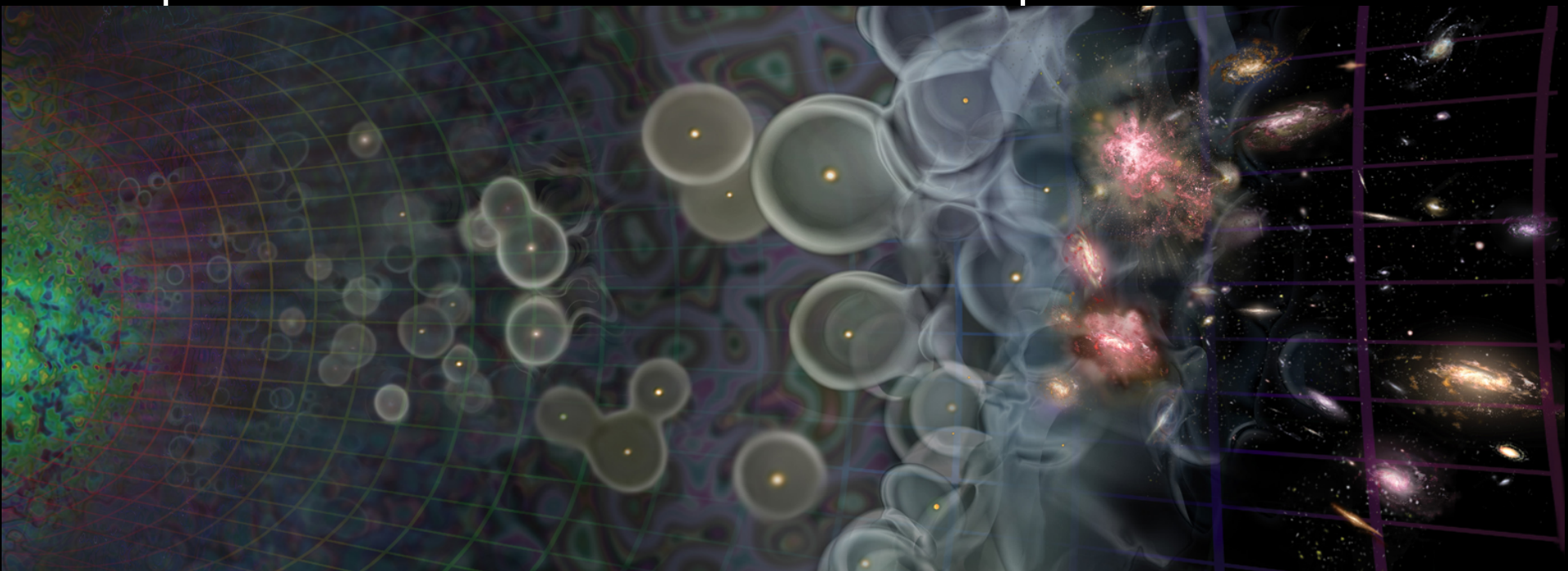
The Lyman α emitters (LAEs)

Daniel Kunth – Institut d'astrophysique de Paris

February 14th, 2014

on behalf of the Lyman α team:

M. Hayes, M. Mas-Hesse, G. Östlin, D. Schaerer, A. Verhamme, H. Atek et al.



$z=1100$

$z\sim 30$

$z=10$

$z=6$

$z=2$

$z=0$

Age = 0.3Myr

100 Myr

500 Myr

1 Gyr

5Gyr

13.7Gyr

CMB

Dark Ages

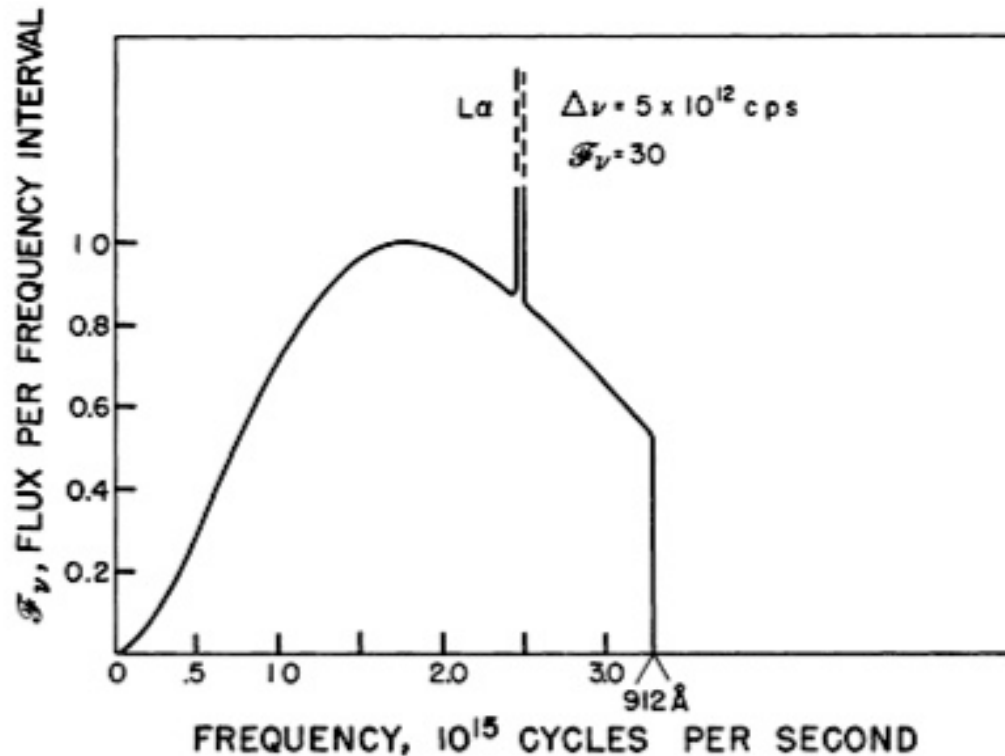
Epoch of Reionization

Peak of Star Formation

Ly α : a cosmic line

Soon after the discovery of QSOs (1965) it had been conjectured that primeval galaxies could be found from Ly α :

up to $\sim 10\%$ of L_{bol} emitted in Ly α !



(Partridge & Peebles 1967)

FIG. 3.—This curve represents semi-quantitatively the expected spectra of young galaxies in the extreme case that all photons of ionizing radiation have been converted to Lyman photons (§ IIc). The expected Lyman- α flux is calculated with $\Delta\nu = 0.002 \nu$ for the line.

Introduction -- distant galaxies using continuum surveys

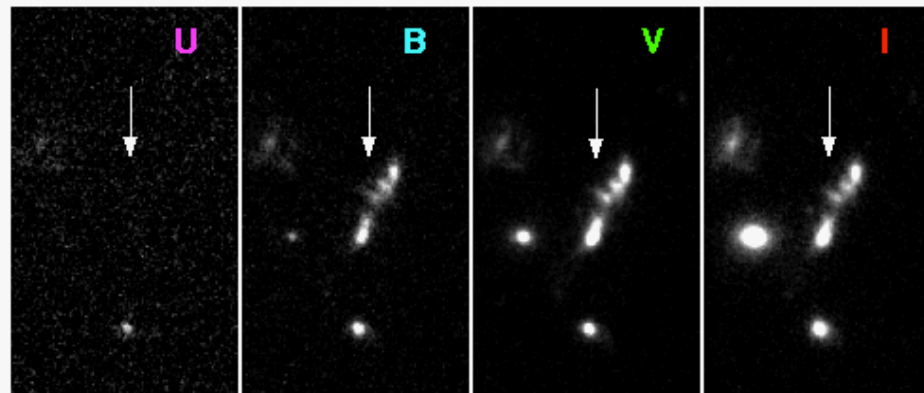
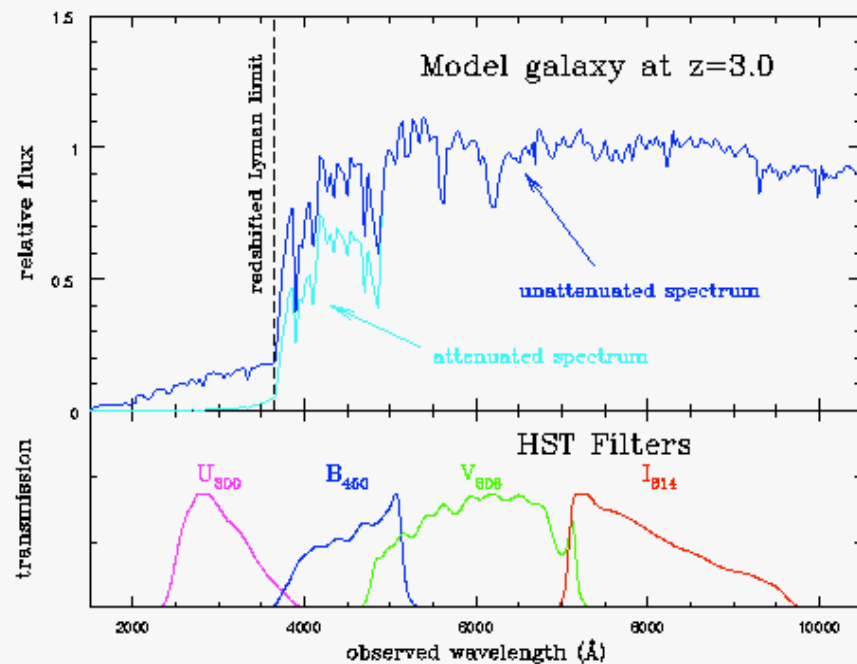
... by direct images, color techniques

Lyman break galaxies : LBGs

➤ strong absorption by HI at $\lambda < 912 \text{ \AA}$ (ionisation threshold)

- explore the **continuum** using wide band filters to detect the Lyman discontinuity

➤ High detectivity and high rate of confirmation $\sim 90\%$ at $z = 3$



(Giavalisco 2001)



Ly α : a cosmic line

Lyman alpha emitters (LAEs)

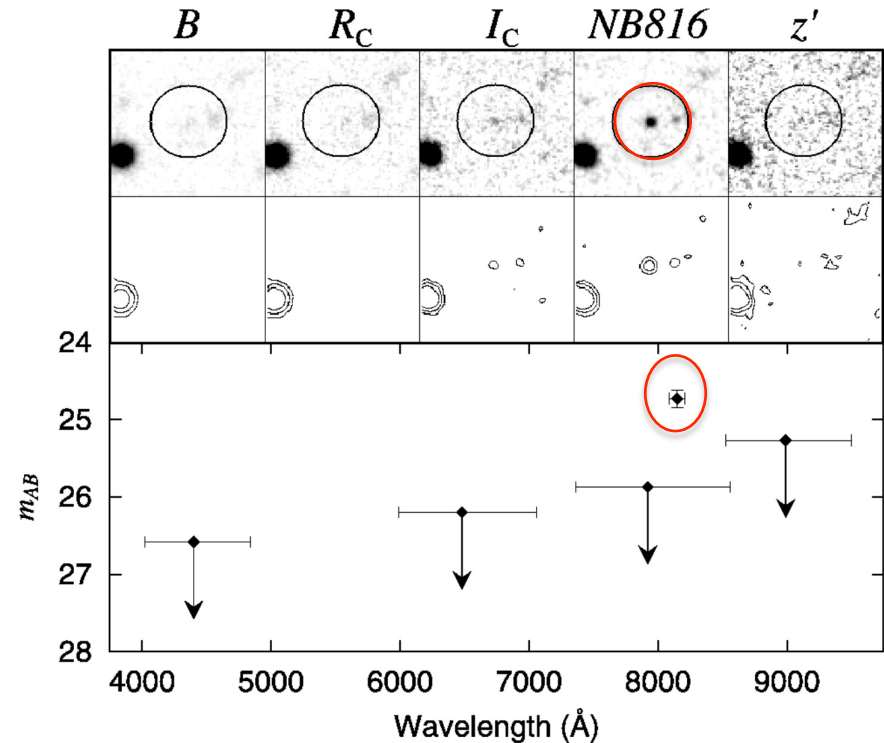
- A galaxy with $\text{SFR} = 2 \text{ M}_{\odot} / \text{yr.}$
gives:

$$L(\text{Ly}\alpha) = 2.2 \times 10^{42} \text{ erg/s}$$

at $z=6$: $f(\text{Ly}\alpha) = 5.5 \times 10^{-18}$
 erg/s/cm^2

- $\text{EW}(\text{Ly}\alpha)$ can reach 240 Å or more
Charlot & Fall 1993, Schaerer 2003
Hence predicted to be a dominant
spectral signature in young galaxies

-
- Imaging surveys: using narrow band filters (in general $\text{EW} > 20 \text{ Å}$)
 - Complement the LBG technique (another population?)

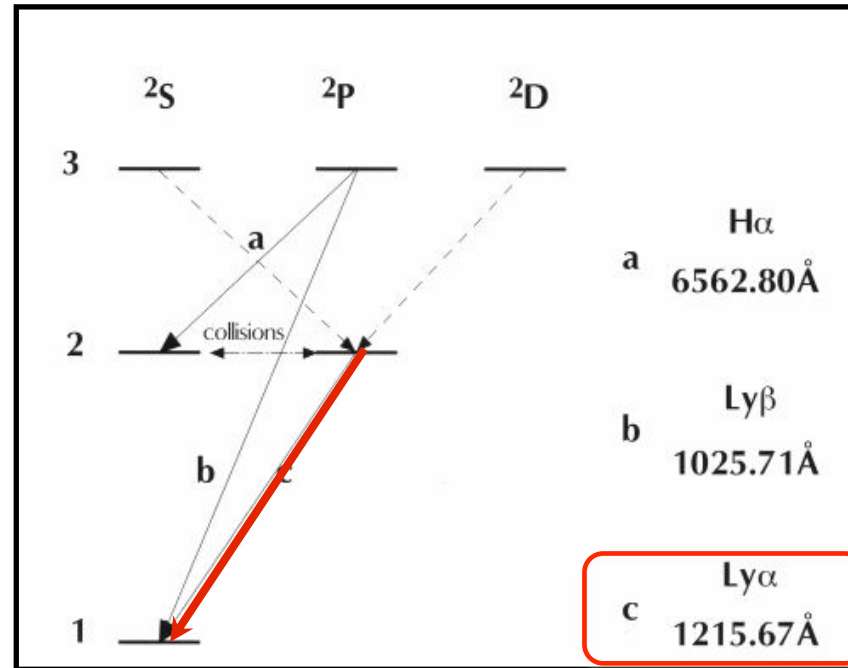


Taniguchi et al. 2003

$2 < z < 7$
from ground based telescopes

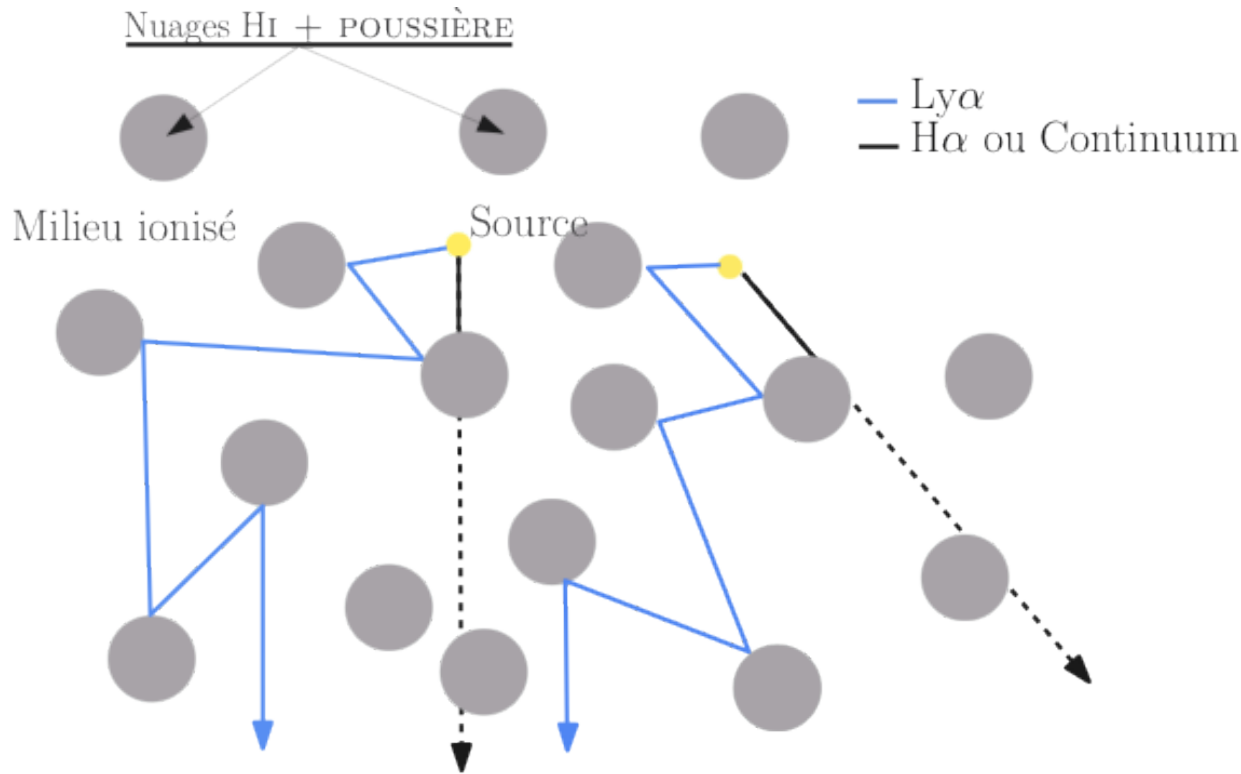
Ly α : potentially a powerful cosmic line

H grotian diagram



a resonant line: therefore it also **encodes** further information of the ISM and the IGM that is unique and exclusive to the $n = 2 > 1$ transition.

key point: Ly α is a resonant line!



One of the tasks is to retrieve the true number of Ly α photons emitted at the source: $f_{\text{esc}(\text{Ly } \alpha)}$ is the escape fraction to be determined

>>> What **are** the dominant parameters **s** that control the line transfer?

Ly α : a cosmic line

1 - Such a high-contrast feature allows Ly α surveys to probe the most abundant populations of faint low-mass galaxies..

2 – a resonant line

Specifically it enables:

- Estimates of kinematic and gaseous properties of the ISM (dust, geometry,..)
- Star formation rate SFR(Ly α) and its evolution with z
- Luminosity function LF(Ly α) of the LAEs
- A test of population III star-formation
- A probe of the cosmic web large structures
- A diagnostic of circumgalactic gas via its polarisation
- Studies of the cosmic reionization of the Universe: sharp drop in the number density as the ionisation state of the IGM changes or change in the line profile itself
- Poses the pb to linking this population to LBGs

.... an impressive toolkit for a single monochromatic feature!

EARLY INVESTIGATIONS

Many surveys were initiated during the 80's and 90's to detect Ly α emitters:

Koo & Kron 1980
Meier & Terlevich 1981
Hartmann et al. 1984
Deharveng et al. 1985
Pritchett & Hartwick 1987
Hartmann et al. 1988
Smith et al. 1989
Lowenthal et al. 1990
Thompson et al. 1992
Djorgovski & Thompson 1992
de Propris et al. 1993
Djorgovski et al. 1993
Moller & Warren 1993
...



quasi-systematic failure

most of these programs yielded ...
0 detection

For the very few detections Ly α
was still well below the predictions

- 1- Detectability
- 2- Ly α line strength below recombination values (as we'll see)

2 problems to solve:

- Insufficient number of Ly α galaxies
- Very faint Ly α emission (or even in absorption)

Ly α observations of low z galaxies

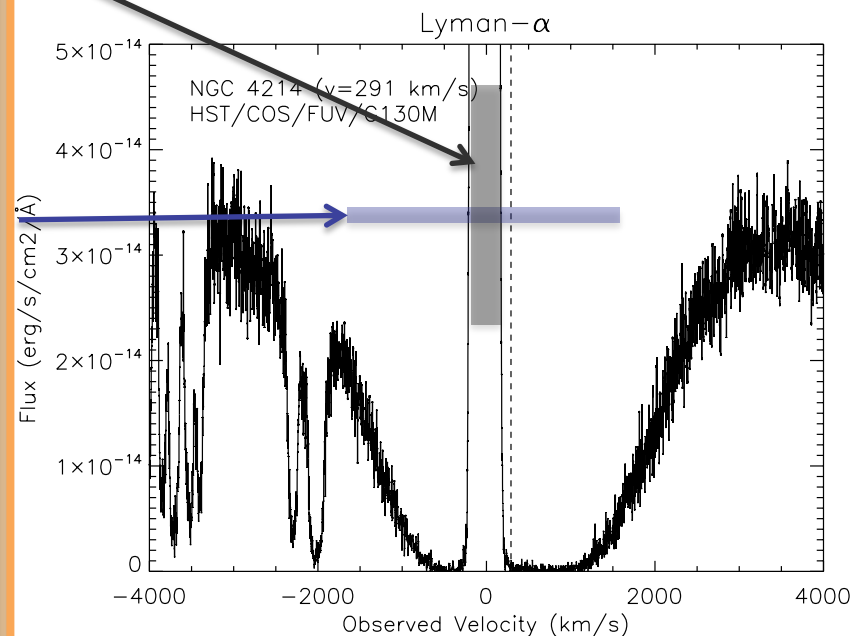
WHY?

- In the ISM, resonant scattering leads to a complicated radiative transport of Ly α : the visibility of the line is influenced by a variety of factors, including **metallicity, dust content, dust geometry, neutral gas content and kinematics, and gas geometry.**
- These issues, and the fact that to date **no clear order of precedence** has been established implies that the total escape fraction of Ly α photons be predicted from knowledge of any of these quantities. **Absorption or emission?**
- Thus, photometric measurements of Ly α will reflect the underlying properties of galaxies only in the very broadest statistical sense.
- Still the best way to explore the **physics** before going to the **astrophysics** is to study a local sample with « exquisite » spatial details

Why not getting too local?

- Intense geocoronal Ly α emission at $z=0$
- Interstellar HI in our Galaxy produces a damped absorption which hides the potential emission of star-forming galaxies with redshifts below several hundreds of km/s along many sightlines

forget 30 Dor, NGC 604 etc....



Ly α observations at low z

Observed Ly α line properties depend on:

- Metallicity / dust (IUE)
- Gas kinematics (HST)
- Column density of neutral gas, N_{HI}
- Aperture size & position and spatial resolution
- imaging

- ✓ Giavalisco+ 1996
 - **Data:** 21 galaxies observed by IUE
 - **Results:** 1) $W(\text{Ly}\alpha)$ and $\text{Ly}\alpha/\text{H}\beta$ do not correlate with extinction or $[\text{O}/\text{H}]$. 2) ISM geometry is dominant effect
- ✓
 - Kunth+ 1998
 - **Data:** 8 galaxies observed with HST/GHRS
 - **Results:** 4 emitters have HI & HII offset by up to 200 km/s
 - ✓
 - Atek+ 2009
 - **Data:** 1 Zw 18 observed with HST/STIS
 - **Results:** 1) If outflows present, f_{esc} determined by N_{HI} and t_a . 2) Otherwise, absorption possible in static/low- v case with a high N_{HI} .
 - ✓
 - Mas-Hesse 2003
 - **Data:** 3 galaxies observed with HST/STIS
 - **Results:** spatial variations of Ly α
 - ✓
 - Ostlin+ 2009
 - **Data:** HST WFC3/UVIS+ACS/SBC optical+FUV images
 - **Results:** aperture size and spatial resolution matter

Ly α observations at low z

Observed Ly α line properties depend on:

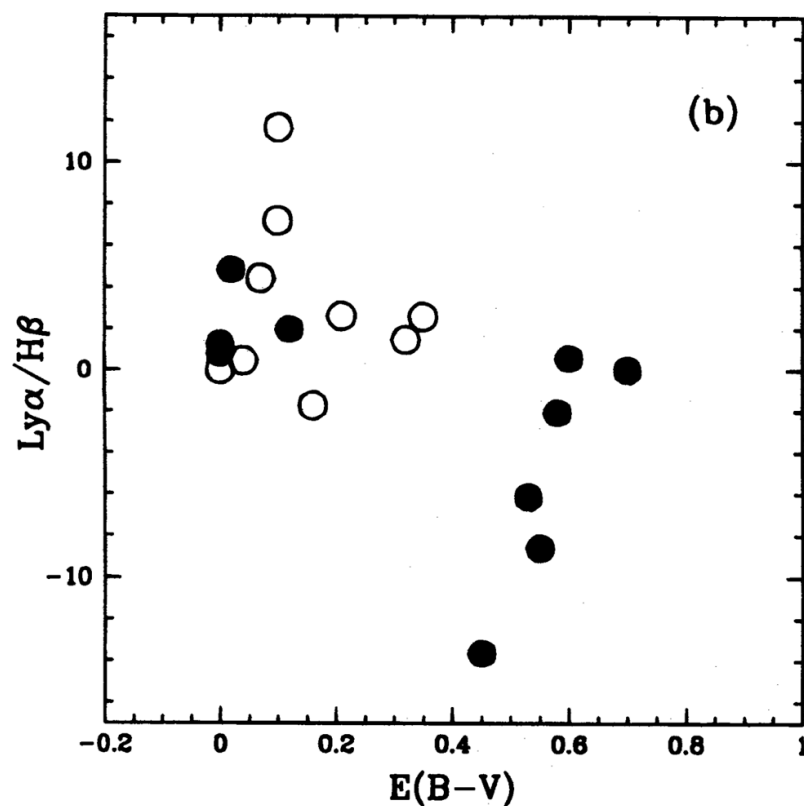
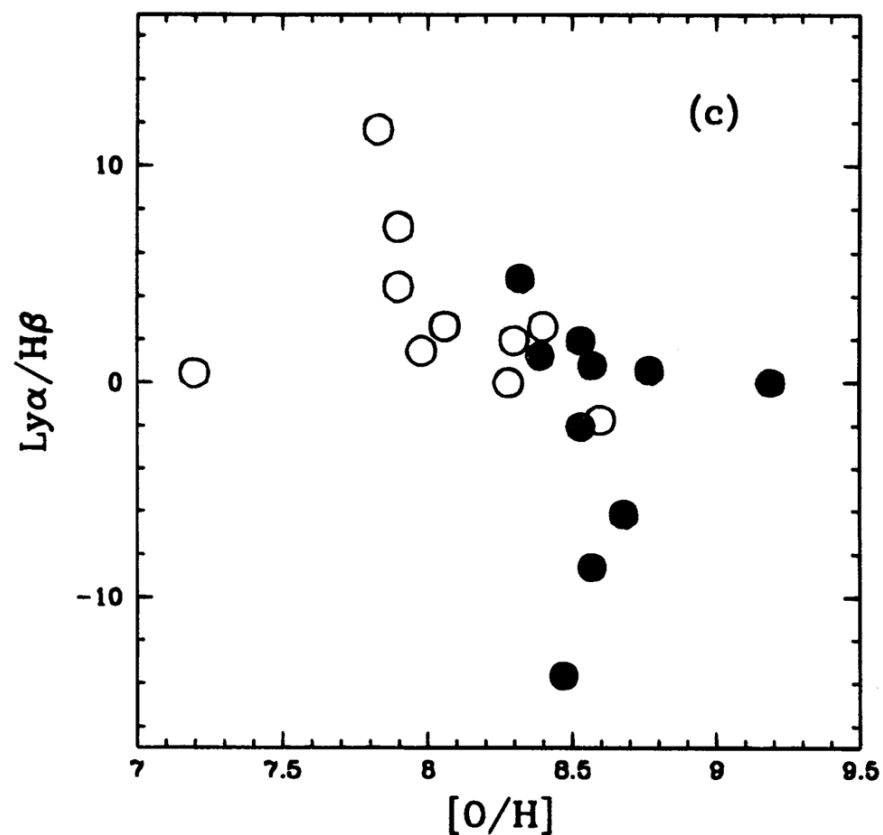
- Metallicity / dust (IUE)
- Gas kinematics (HST)
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- imaging

THE OBSERVATIONAL PUZZLE

First insights with the IUE satellite (International Ultraviolet Explorer) and the HST

Dust attenuation of Ly α emission and the detectability of high- z galaxies:
But no clear correlation between Ly α and metallicity or dust extinction

Giavalisco et al. (1996)

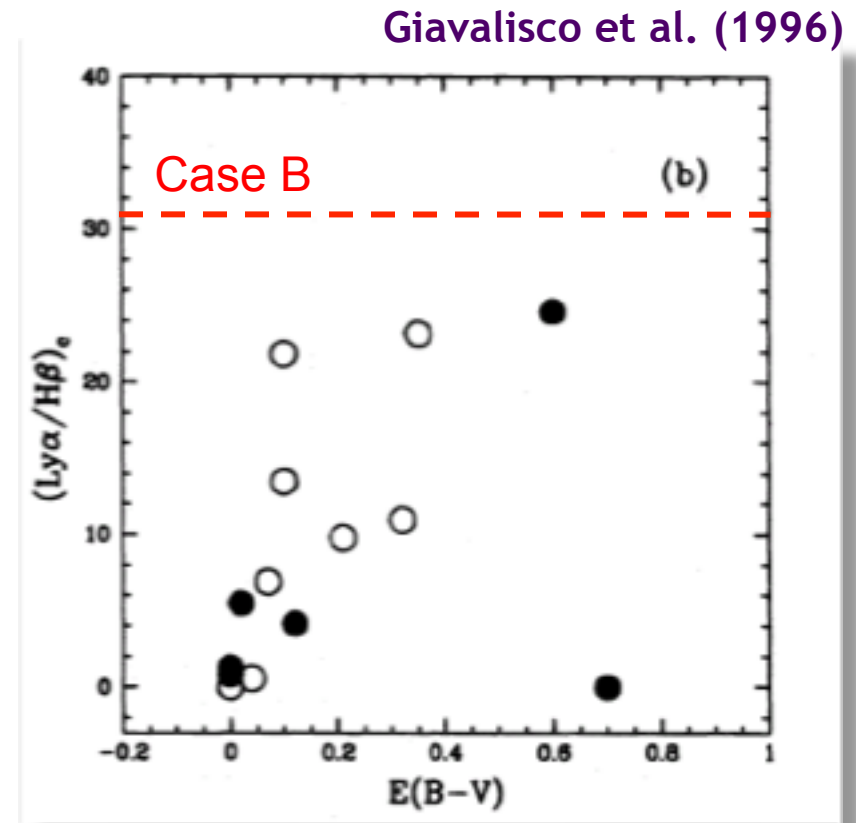
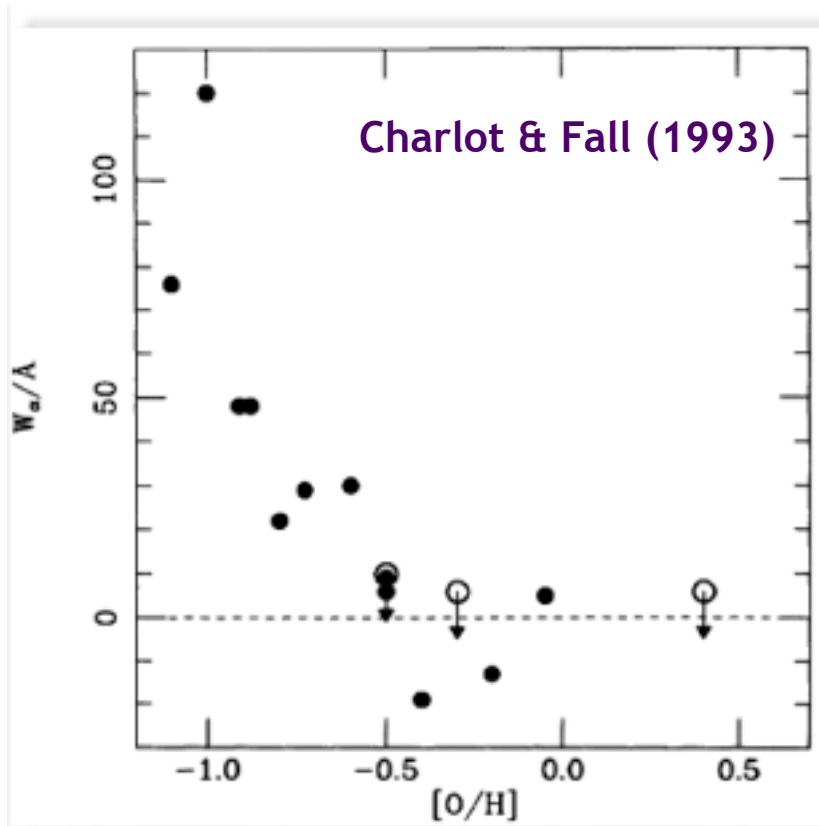


OBSERVATIONAL PUZZLE: AT LOW Z

After early IUE observations + HSTs

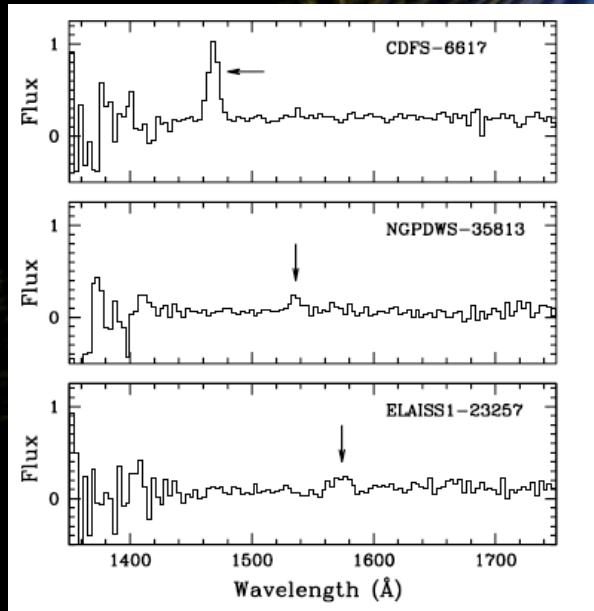
- ✓ **Dust attenuation :**
→ A way to detect high-z galaxies ?

No obvious correlation between $\text{Ly}\alpha$ and extinction $\text{Ly}\alpha$ is still well **below the Case B** recombination level



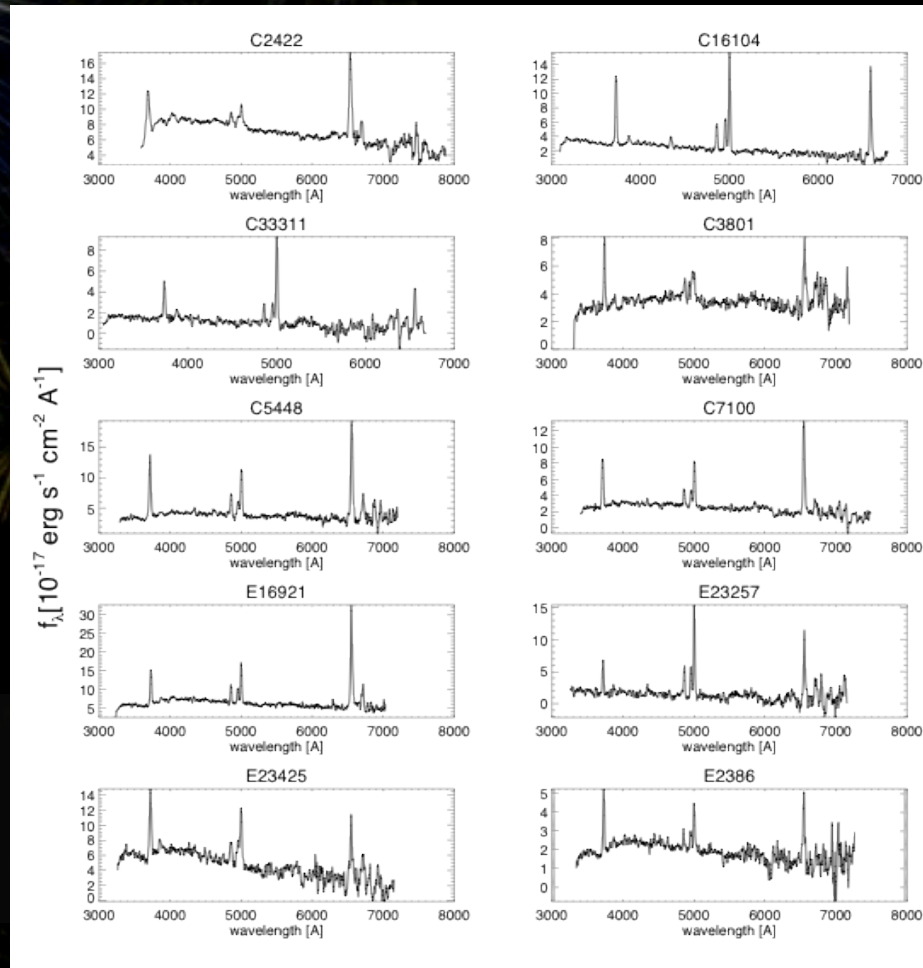
The GALEX sample

Deharveng et al. 2008



96 Ly α emitters detected by GALEX satellite
at a redshift of $0.2 \leq z \leq 0.35$
GRISM FUV (1350 - 1750 Å)
Ly α emission line selection ($EW \geq 10$ Å)

Spectroscopic follow-up of 24 objets with the NTT
Spectro and spectrophotometric configuration
Optical spectral range 3690 - 9320 Å

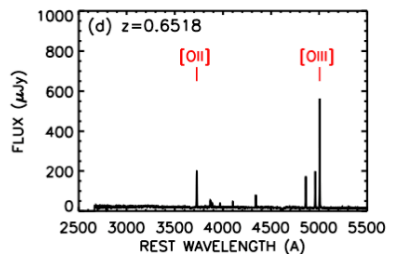
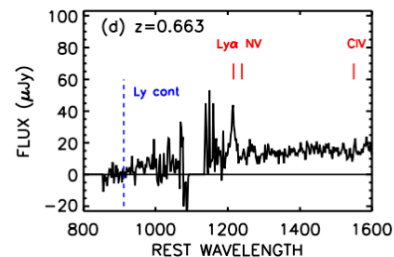
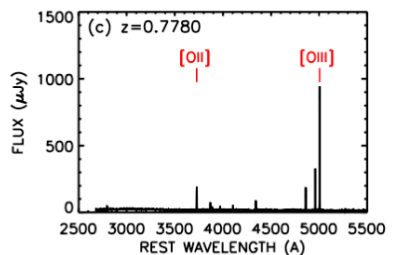
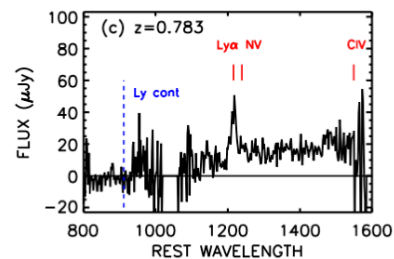
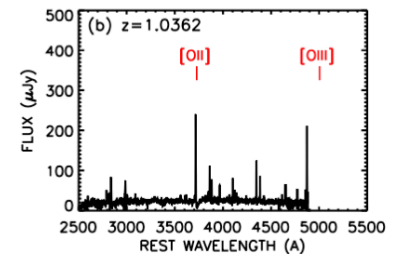
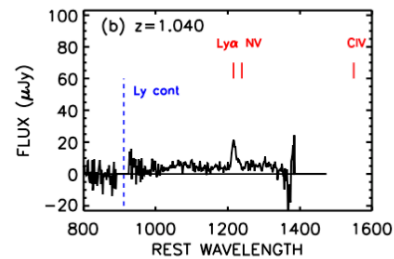
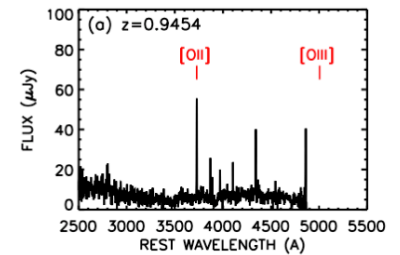
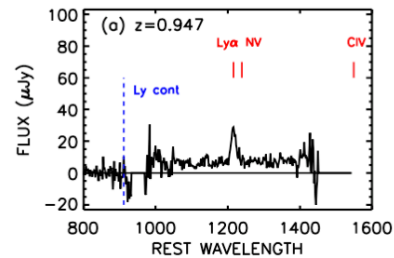
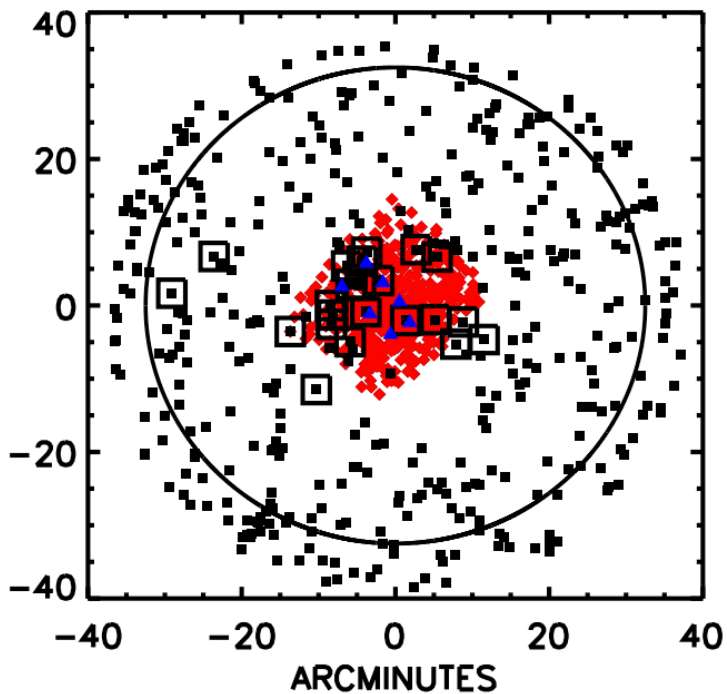


The GALEX sample

2 additional samples of comparable size
from GALEX Spectroscopic selection:

NUV GRISM 2300 Ang

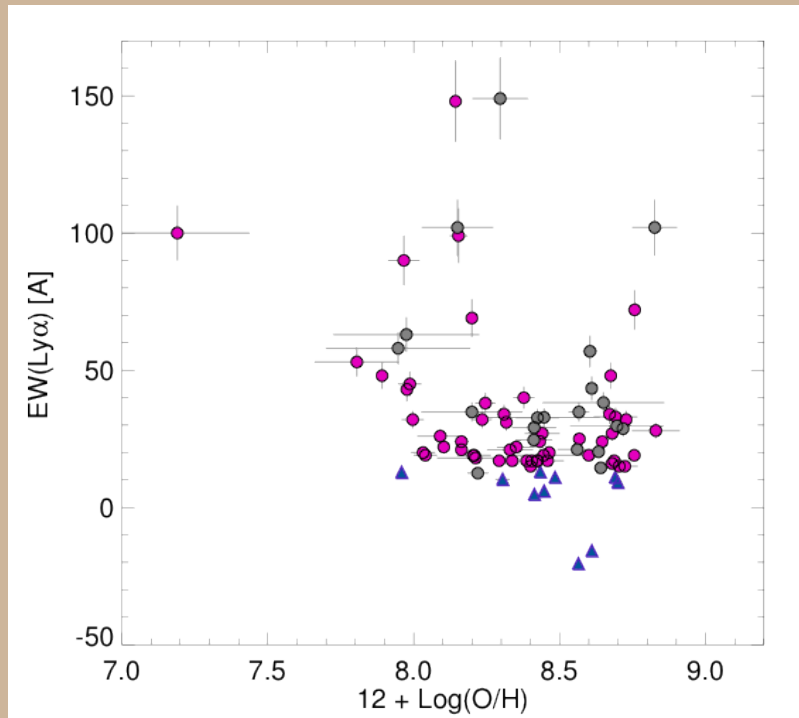
Scarlata et al. (2009), Cowie et al. (2011).



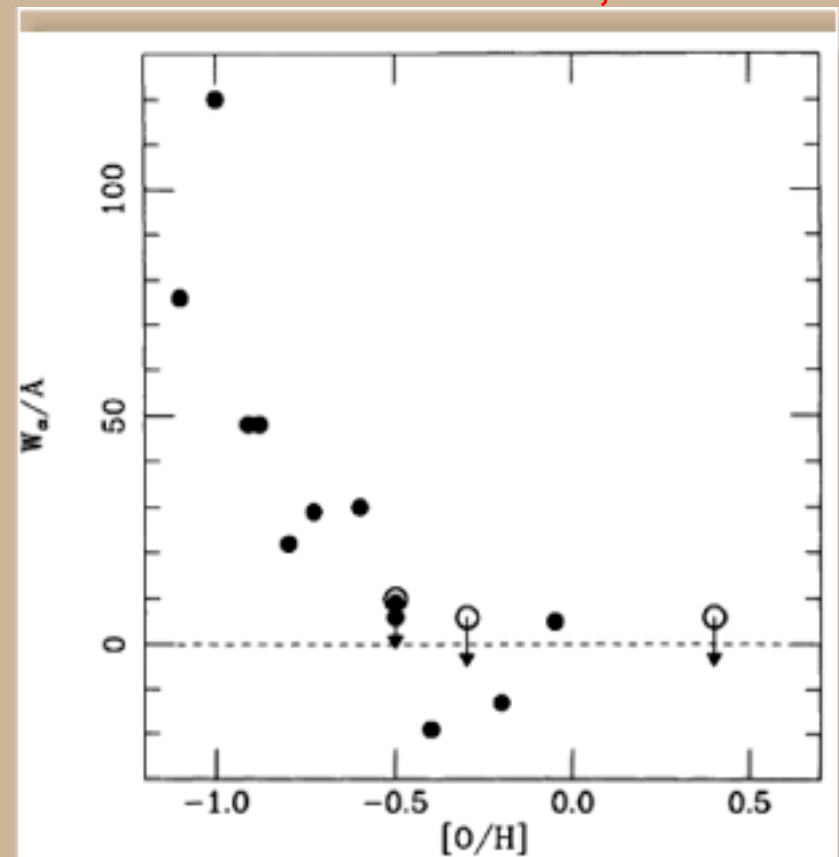
THE $\text{Ly}\alpha$ STRENGTH AT LOW- AND HIGH-Z

The influence of metallicity on $\text{Ly}\alpha$ visibility:
are LAEs systematically metal poor ?

Atek et al. (2013)



Charlot & Fall, 1993



THE $\text{Ly}\alpha$ STRENGTH AT LOW- AND HIGH- z

The visibility of $\text{Ly}\alpha$ photons results from a multi-parameter process

- ✦ intrinsic $\text{EW}(\text{Ly}\alpha)$ (age, mass ...)
- ✦ Doppler broadening

- ✦ Static HI coverage: $\text{Ly}\alpha$ strongly attenuated by dust
- ✦ Expanding HI gas: optical depth reduced
- ✦ ISM Geometry: can favor $\text{Ly}\alpha$ escape

INTRINSIC
EMISSION



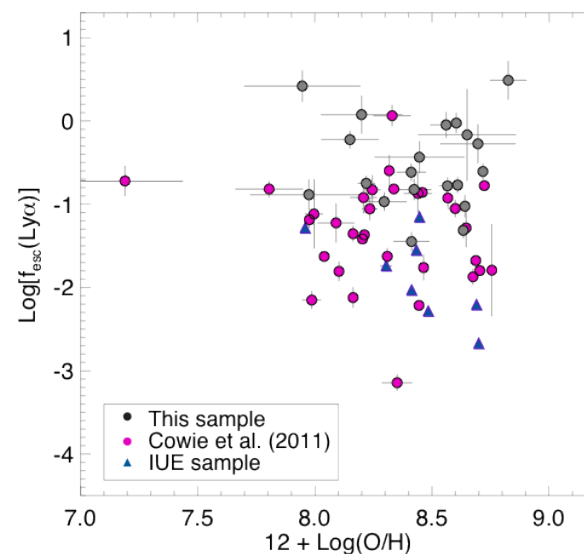
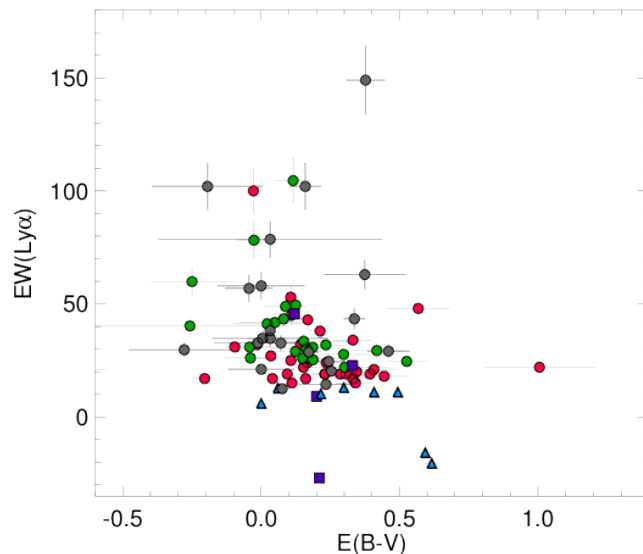
RADIATION
TRANSFER



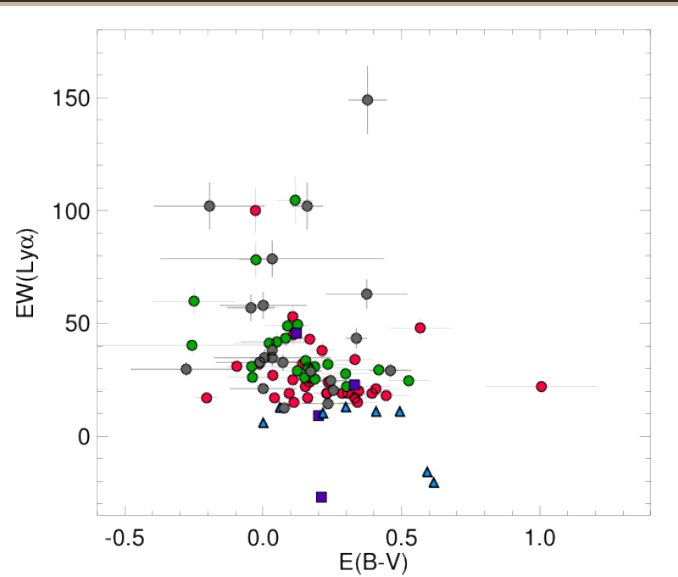
A dependence on the metallicity is not seen.

Nor for the dust attenuation

Contrary to what is reported at high z

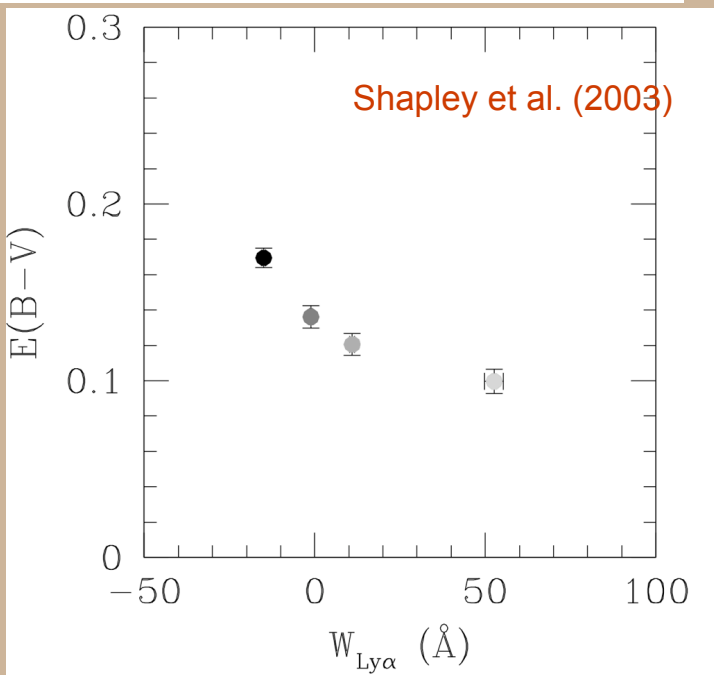


THE $\text{Ly}\alpha$ STRENGTH AT HIGH-Z

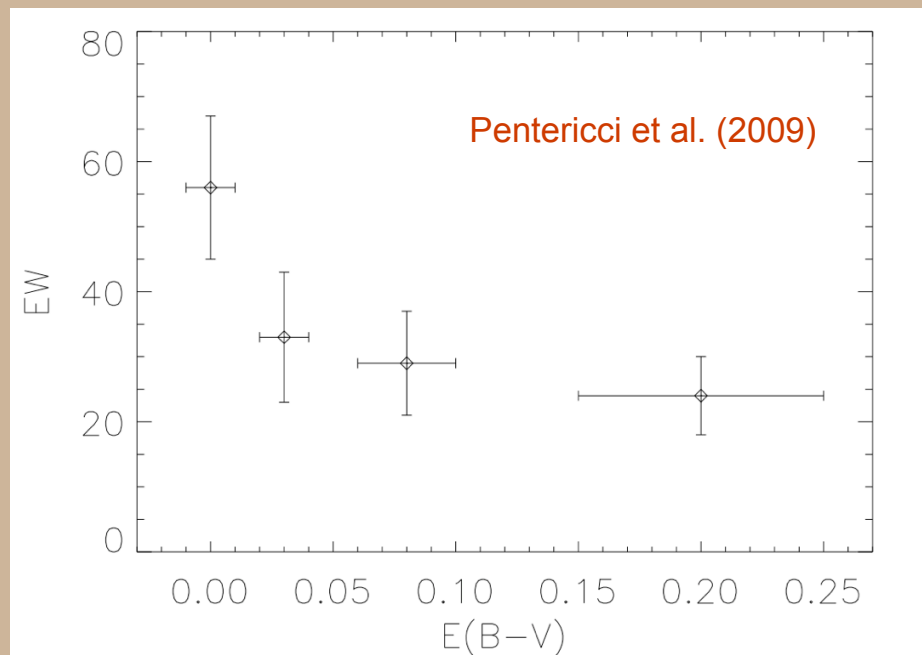


Atek et al; 2014

The anti-correlation seen at high redshift between EW(Ly α) and dust extinction

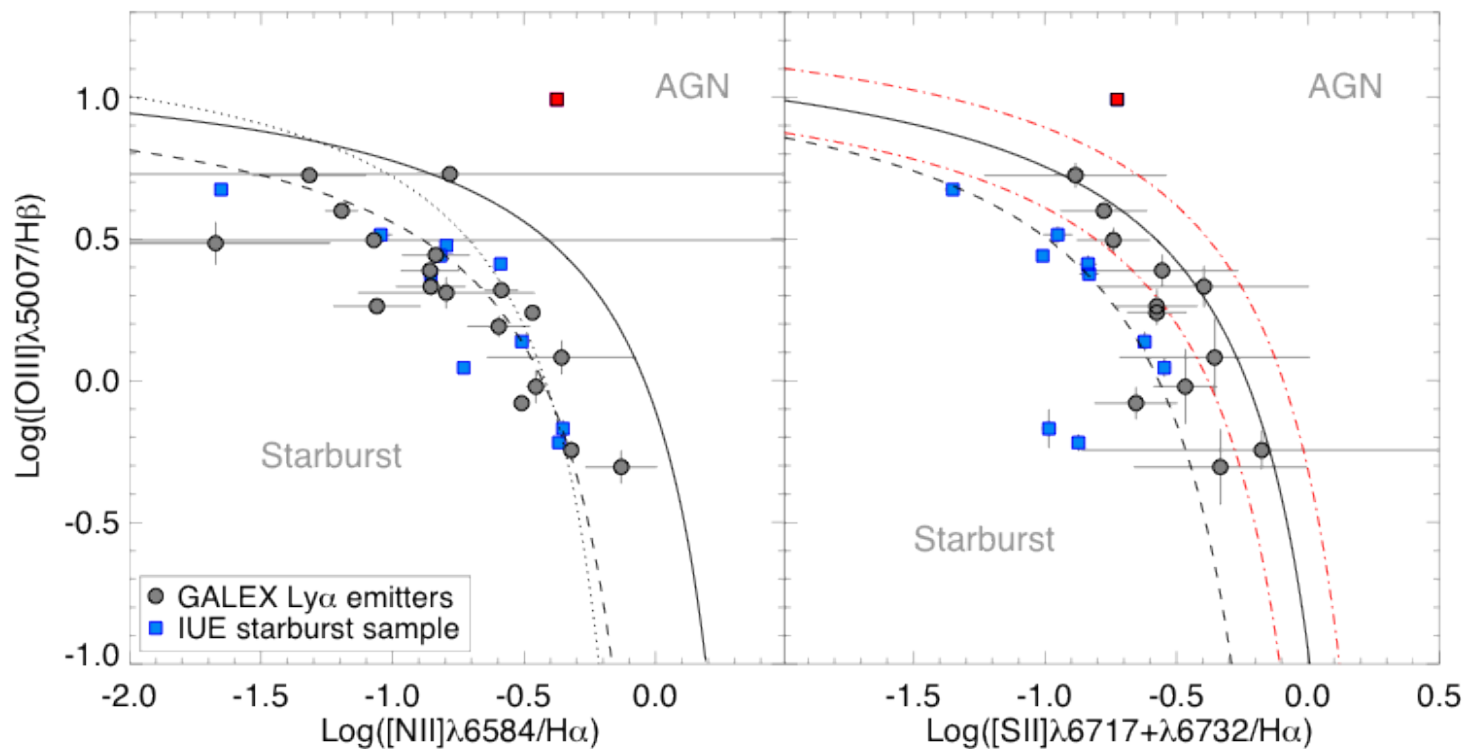


Shapley et al. (2003)



Pentericci et al. (2009)

AGN Contamination

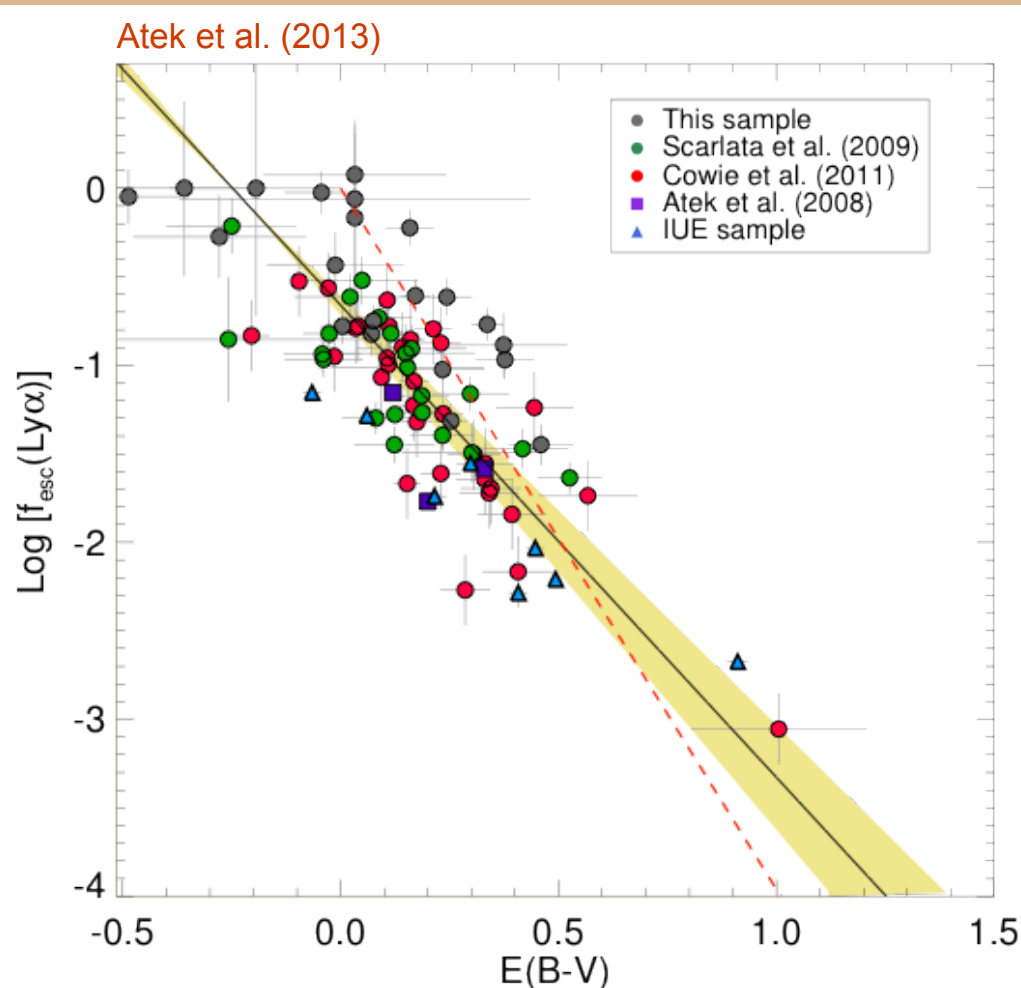


BPT diagram: 12% of Galaxies classified as AGNs

- Scarlata et al. (2009) ~ 10%
- Cowie et al. (2011) ~ 17%
- Finkelstein et al. (2009) up to 45%

WHAT AFFECTS $\text{Ly}\alpha$ ESCAPE FRACTION?

The total escape fraction of $\text{Ly}\alpha$ photons is defined as the ratio of the observed to intrinsic $\text{Ly}\alpha$ luminosity



$$f_{\text{esc}}(\text{Ly}\alpha) = f(\text{Ly}\alpha) / 8.7 \times f(\text{H}\alpha)_{\text{cor}}$$

$$f(\text{H}\alpha)_{\text{cor}} = f(\text{H}\alpha) \times 10^{(1.048 \times E(B-V))}$$

◆ Clear correlation of $f_{\text{esc}}(\text{Ly}\alpha)$ with dust extinction

$$f_{\text{esc}}(\text{Ly}\alpha) = C_{\text{Ly}\alpha} \times 10^{-0.4 E(B-V) k_{\text{Ly}\alpha}}$$

$$k_{\text{Ly}\alpha} \sim 6.67 \pm 0.52$$

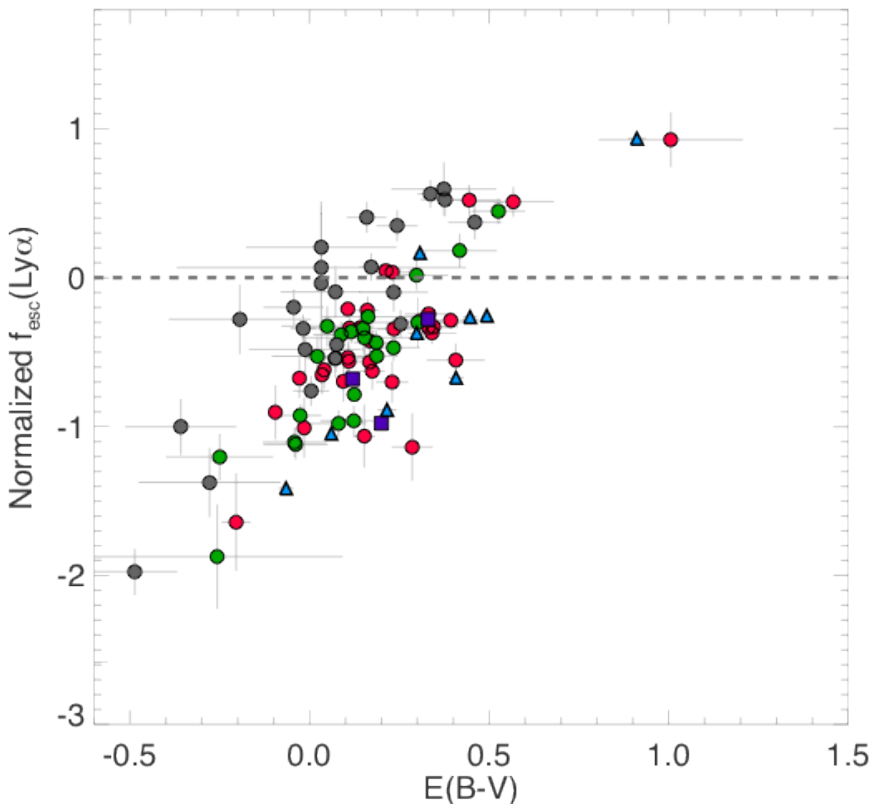
$$C_{\text{Ly}\alpha} = 0.22 \pm 0.03$$

- Some galaxies have $f_{\text{esc}}(\text{Ly}\alpha) > f_{\text{esc}}(\text{cont})$
- The ISM Geometry can explain such observations

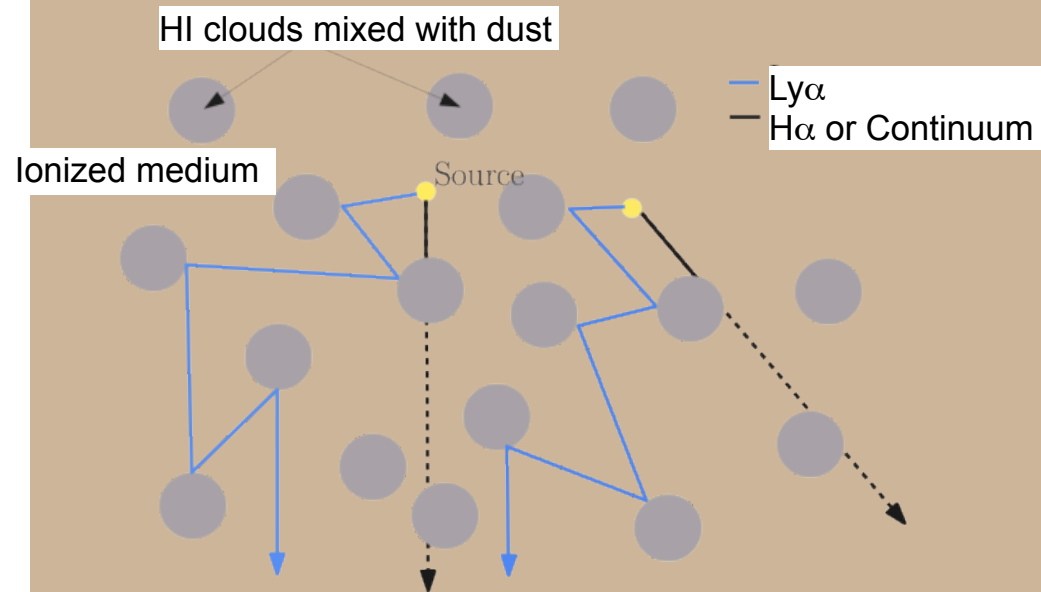
Atek et al. 2014

THE ENHANCEMENT PROCESS OF $\text{Ly}\alpha$

deviation of $f_{\text{esc}}(\text{Ly}\alpha)$ from $f_{\text{esc}}(\text{cont})$
as a function of extinction

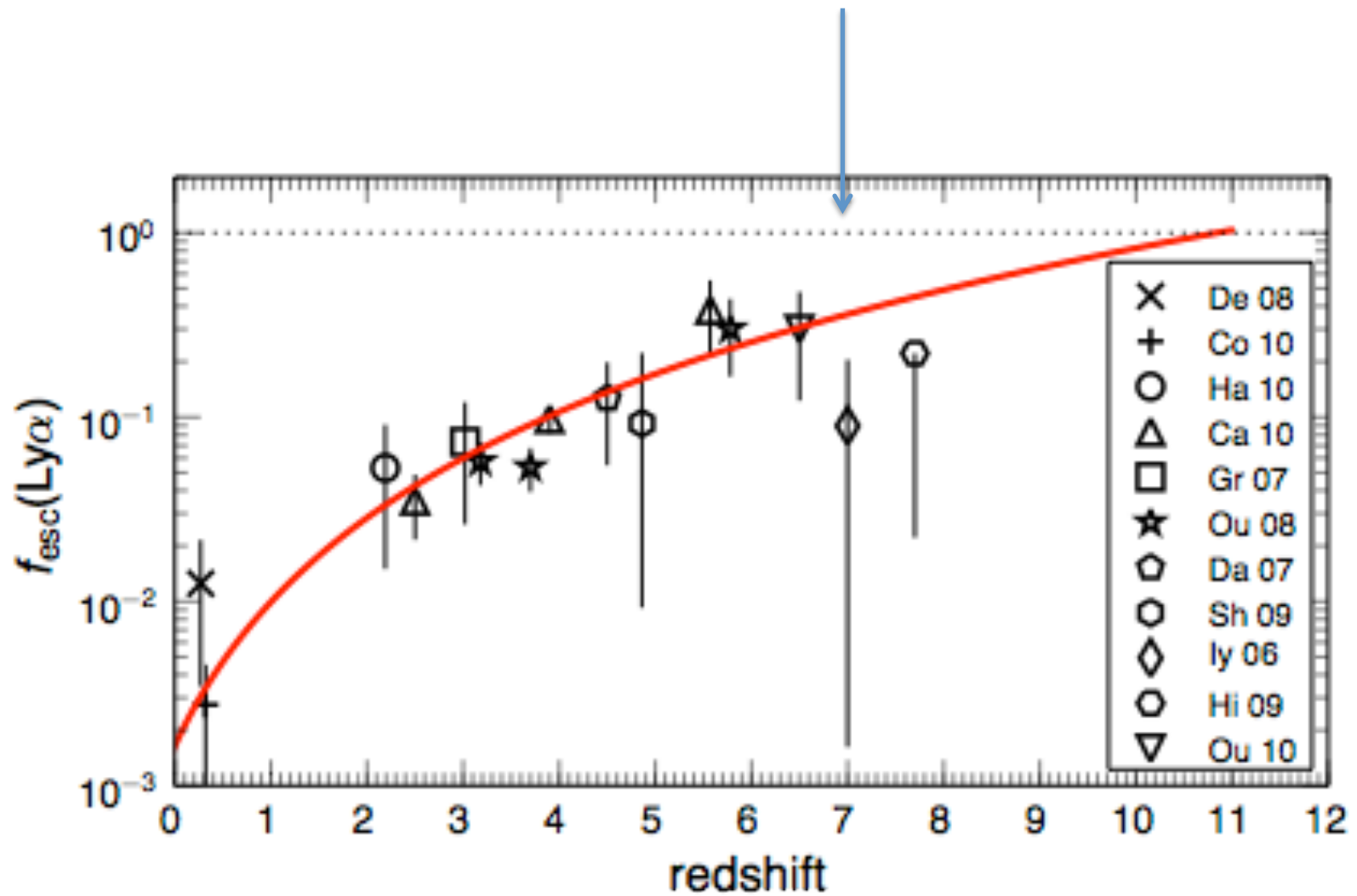


cf. Duval et al. (2013), Scarlata et al. (2009), Oti-Floranes et al. (2013), Verhamme et al. (2012)



$E(B-V)$	0.1	0.2	0.3	0.5	1
Cardelli et al. (1989)	0.37	0.14	0.05	7×10^{-3}	5×10^{-5}
Prevot et al. (1984)	0.19	0.04	7×10^{-3}	2×10^{-4}	6×10^{-8}

The Redshift-Evolution of $f_{\text{esc}}(\text{Ly}\alpha)$



Hayes et al. 2010 a,b

LY α IN HIGH-Z STUDIES

Probe the epoch of cosmic reionization

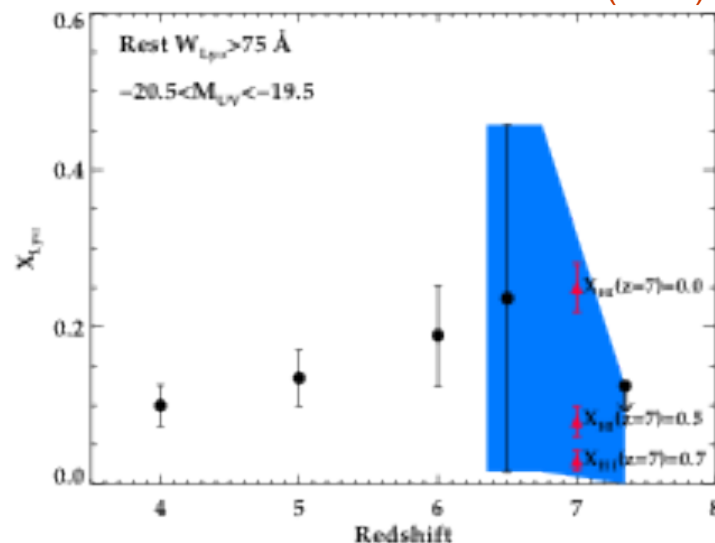
Spectroscopic observations of LBGs at $3 < z < 6$:
Redshift-evolution of the fraction of Ly α emitters
a decline @ $z \sim 6.5$?

- HI covering factor
- ISM kinematics
- Evolution of dust content
- Regulation of Ly α escape fraction

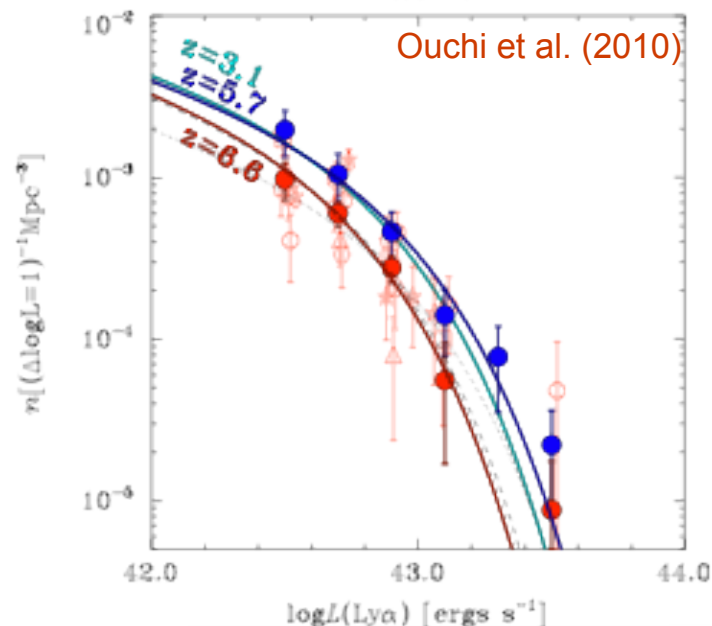
Evolution of the Ly α luminosity function around the reionization epoch at $z \sim 6-7$

- Ly α radiation transfer in galaxies
- redshift-evolution of the physical properties

Stark et al. (2010)

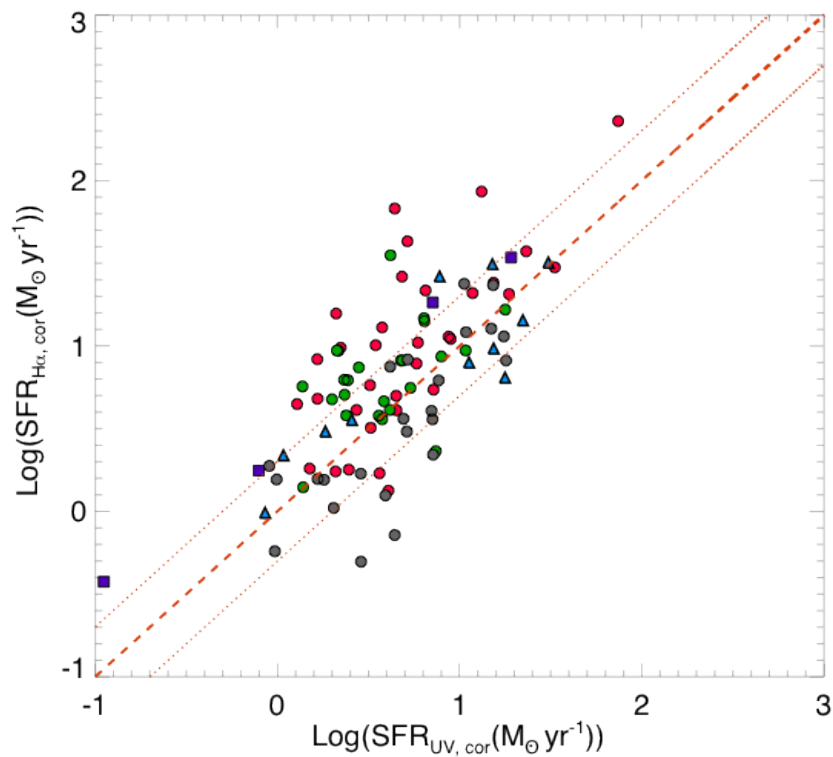


Ouchi et al. (2010)

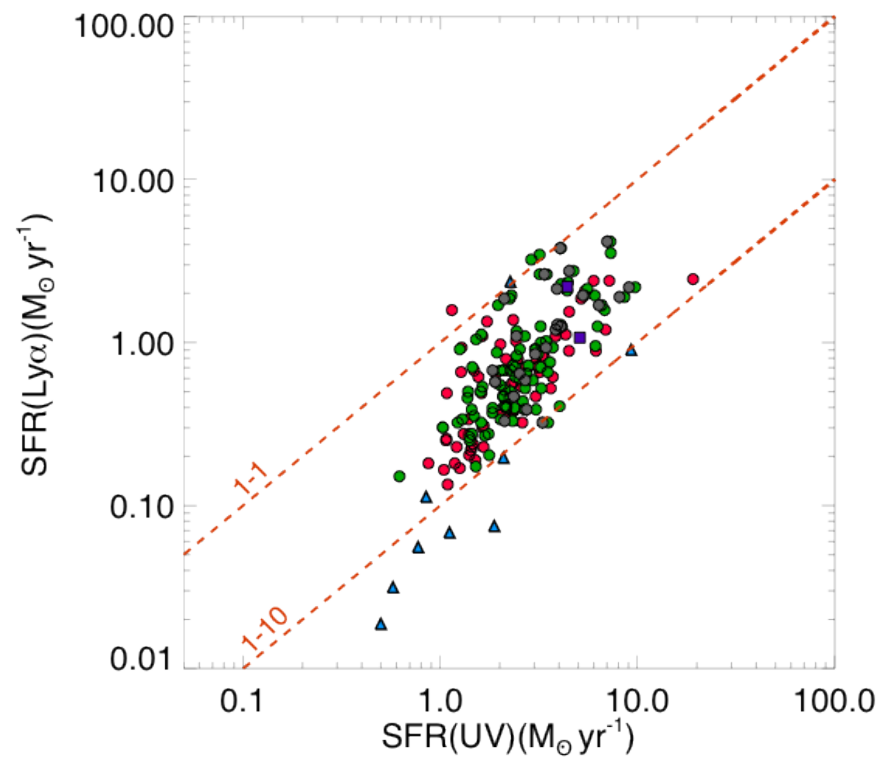


LY α AS AN SFR INDICATOR

general agreement between SFR(H α)
and SFR(UV) (extinction-corrected)



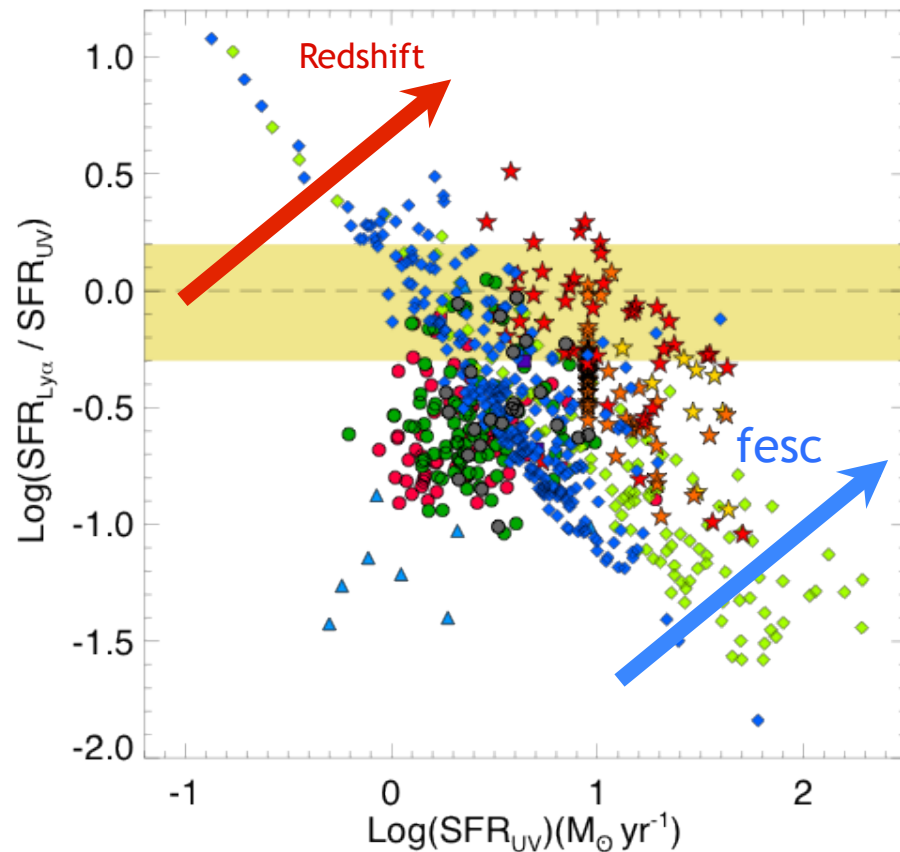
deviation of SFR(Ly α) from the true SFR



LY α AS AN SFR INDICATOR

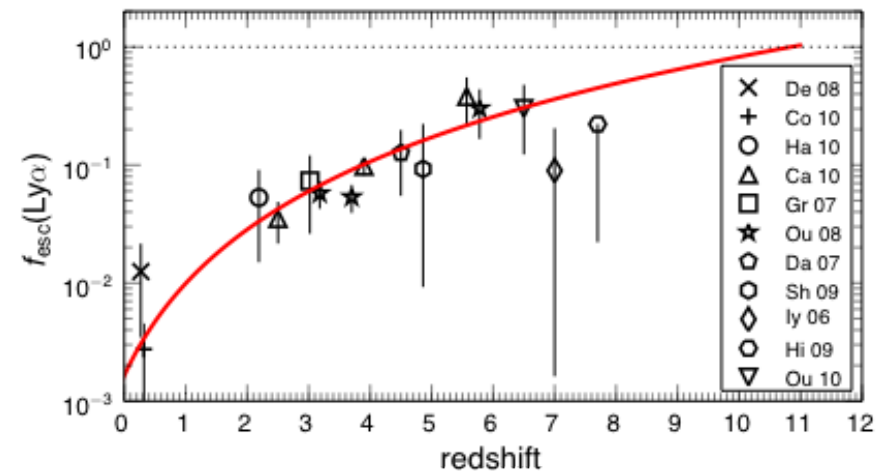
Atek et al. 2014

SFR(Ly α) deviation is a function of SFR(UV)



SFR(Ly α)/SFR(UV) ratio is redshift-dependent
consequence of the f_{esc}(Ly α) redshift-evolution

Hayes et al. (2011)



Ly α observations at low z

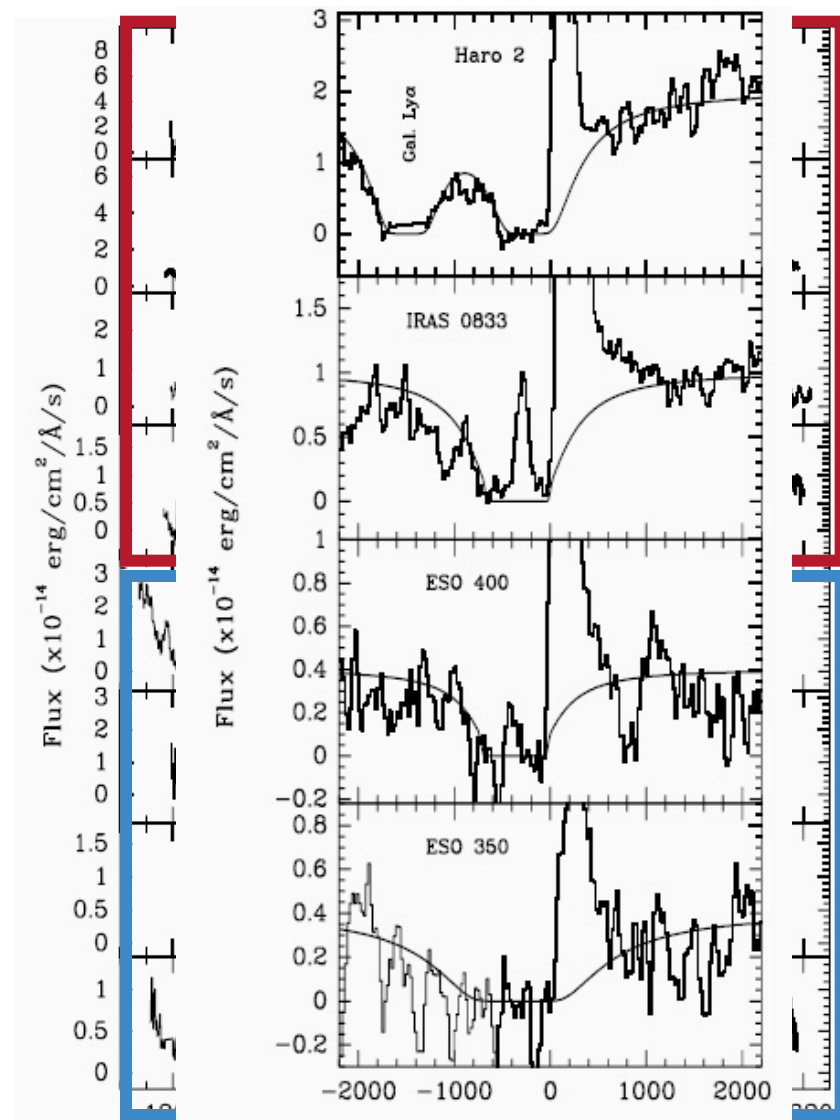
Observed Ly α line properties depend on:

- Metallicity / dust (IUE)
- Gas kinematics (HST)
- Column density of neutral gas, N_{HI}
- Aperture size & position and spatial resolution
- imaging

LY α : THE ROLE OF ISM KINEMATICS

➤ 8 local BCGs : 4 Ly α emitters, 4 absorbers

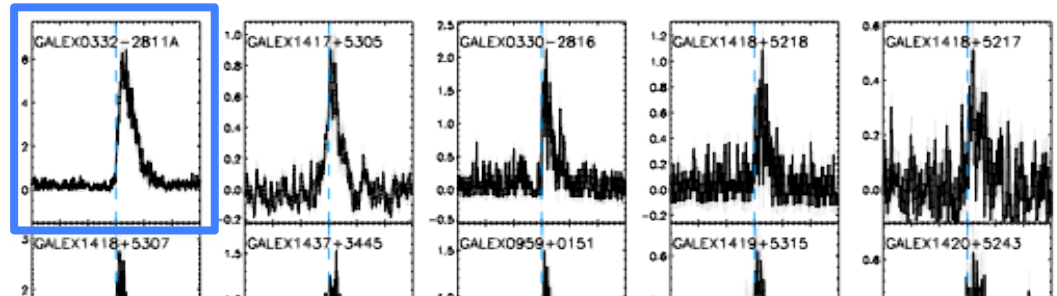
- In all Ly α emitters, the interstellar absorption lines were blue-shifted by 100 to 400 km/s.
- Galaxies with Ly α absorption profiles had ISM absorption lines at the systemic velocity of the galaxy
- When Ly α is in emission it shows a P Cygni profile characteristic of an outflowing ISM
- + Profiles are well fitted using the measured expansion velocity



Kunth et al. 1998

The Ly α Profile

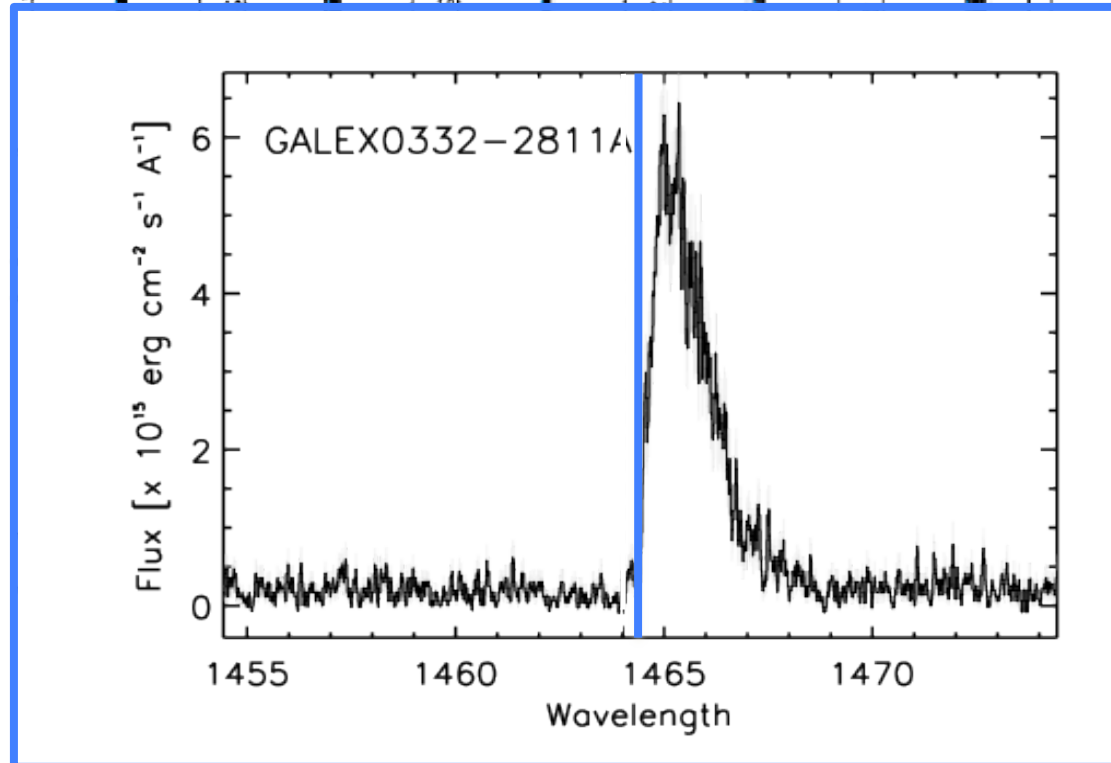
From GALEX' targets



asymmetric line profiles
(5/22 ~23%)

characterized by a sharp drop on the blue side, and a pronounced red wing.

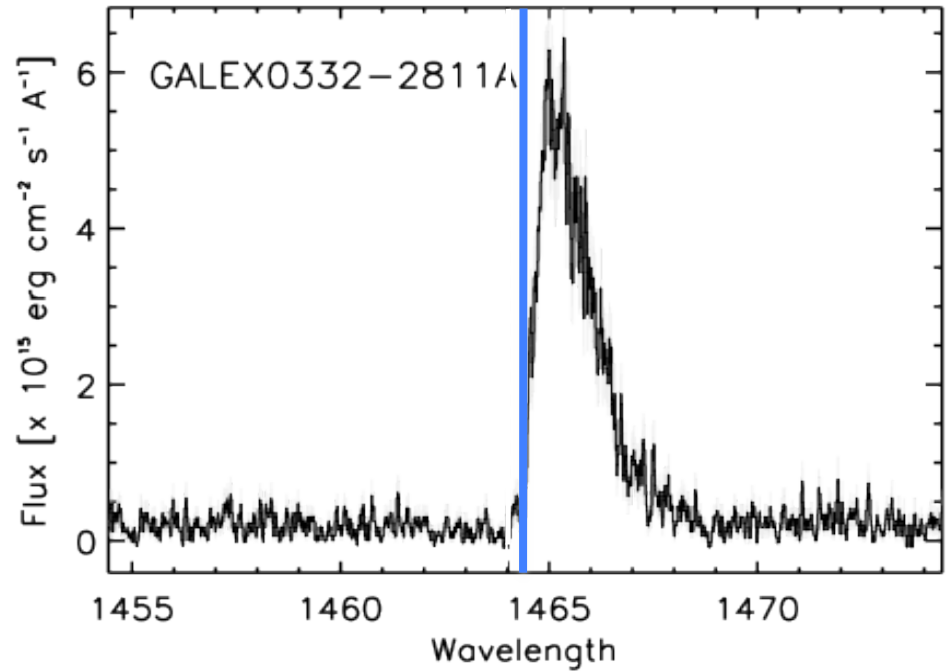
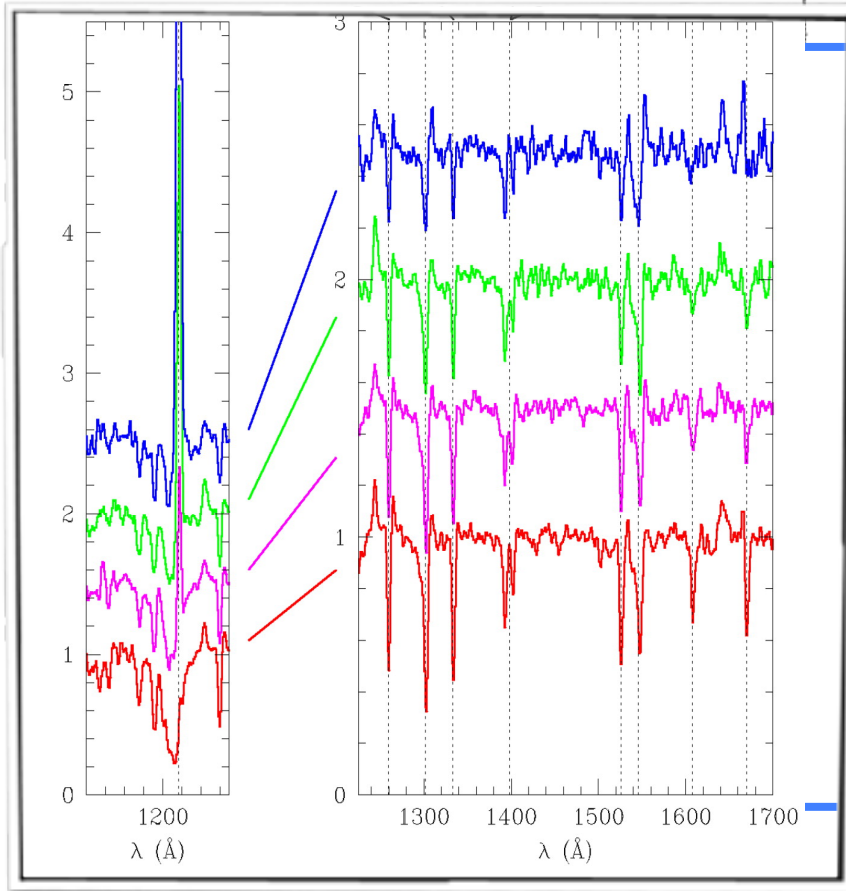
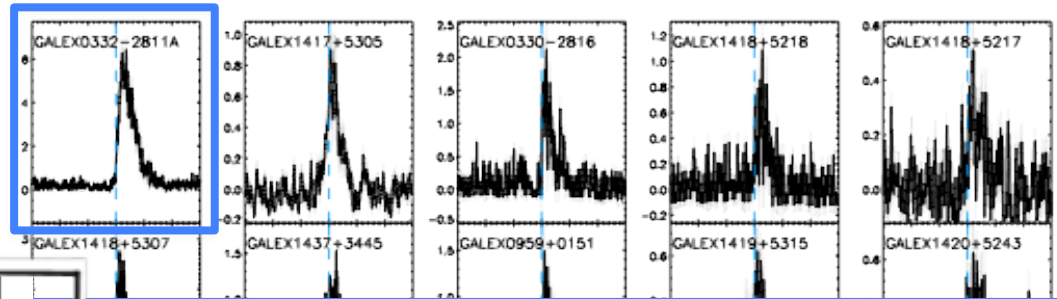
This is indicative of an expanding neutral gas where the Ly α photons can escape easier in the red wing of the profile because they are seen redshifted by the hydrogen atoms.



Also true in distant LAEs (Shapley et al. 2003)

The Ly α Profile

From $z = 2$ targets



Ly α observations at low z

Observed Ly α line properties depend on:

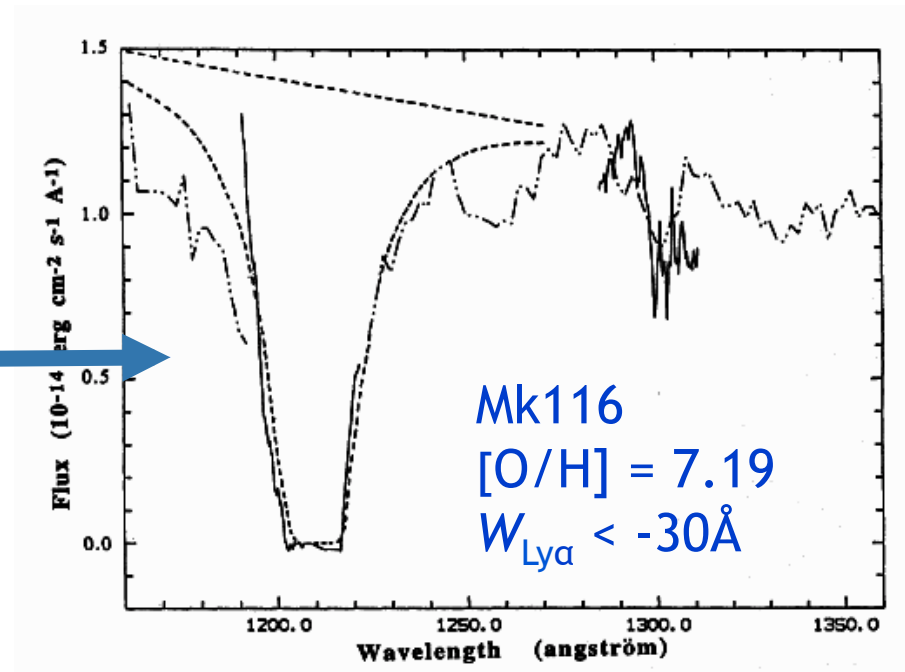
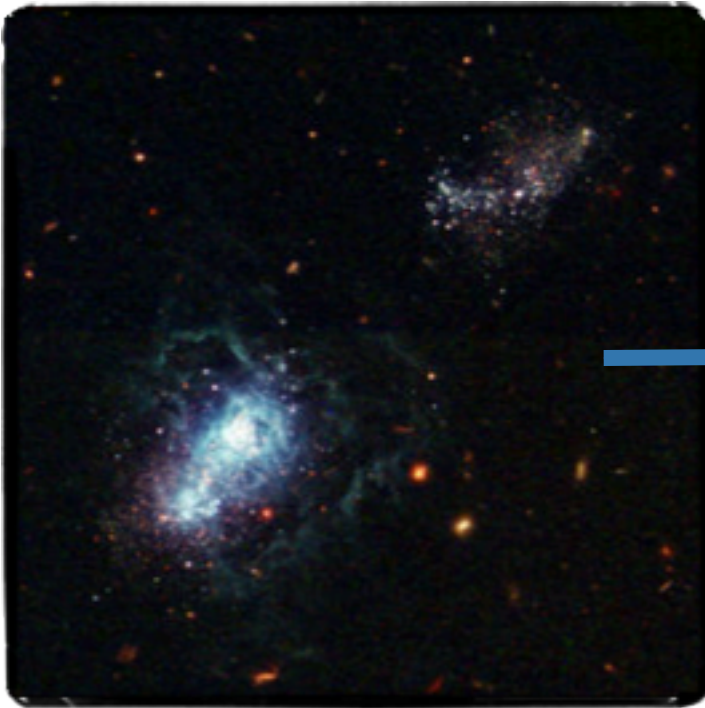
- Metallicity / dust (IUE)
- Gas kinematics (HST)
- Column density of neutral gas, N_{HI}
- Aperture size & position and spatial resolution
- imaging

SOME OBSERVATIONAL PUZZLE

how to transform strong emission
into absorption without dust ?

GHRs results by Kunth et al. (1994) :

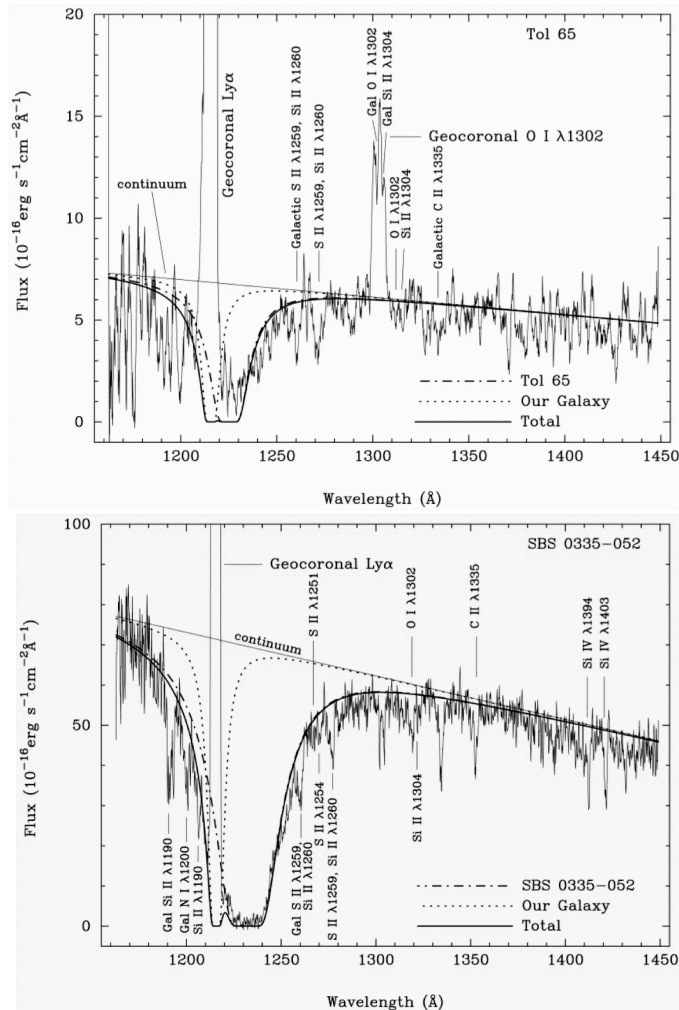
Targeting the very **metal-poor and dust-free** galaxy Mk116: a damped Ly α absorption.



modelled by Atek + 2009 !!

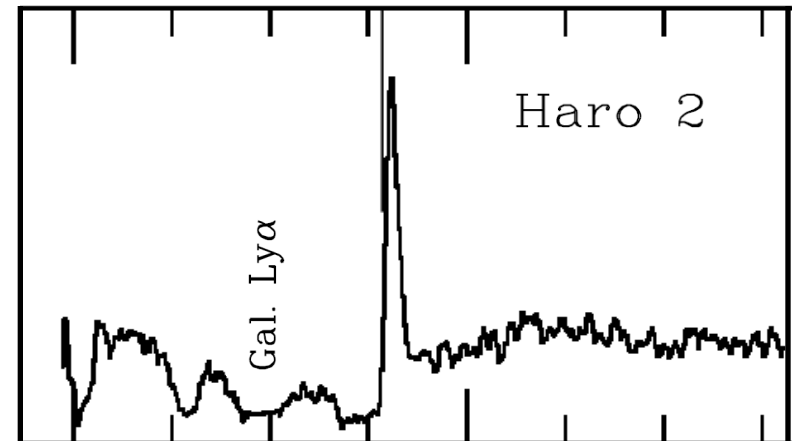
THE OBSERVATIONAL PUZZLE

Similar results were found by [Thuan and Izotov \(1997\)](#) :
Low metallicity galaxies SBS 0335-052 & Tololo 65



A prominent Ly α emission line is observed in the spectrum of Haro 2, an order of magnitude dustier and metal-rich galaxy

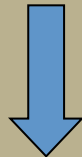
[Lequeux et al. 1995](#)



simple dust extinction alone cannot explain the Ly α attenuation

Superbubble Evolution

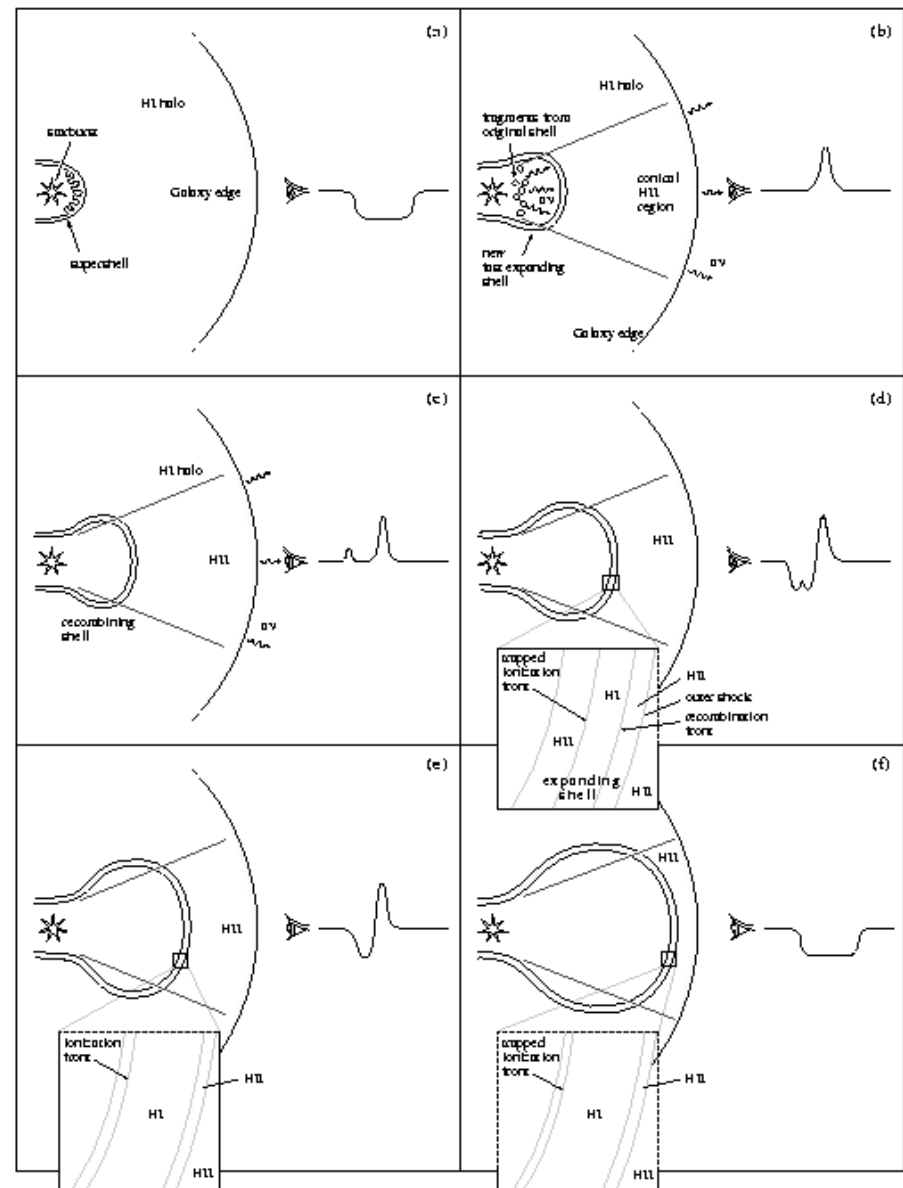
Tenorio-Tagle et al (2000)



As a starburst evolves SNe expell the gas, creating a superbubble evolving in a low density spherical halo:disperse and mix

Silich & T-T, 1999
Mc Low & Ferrara, 1999
de Avellez et al. 2002

Kunth

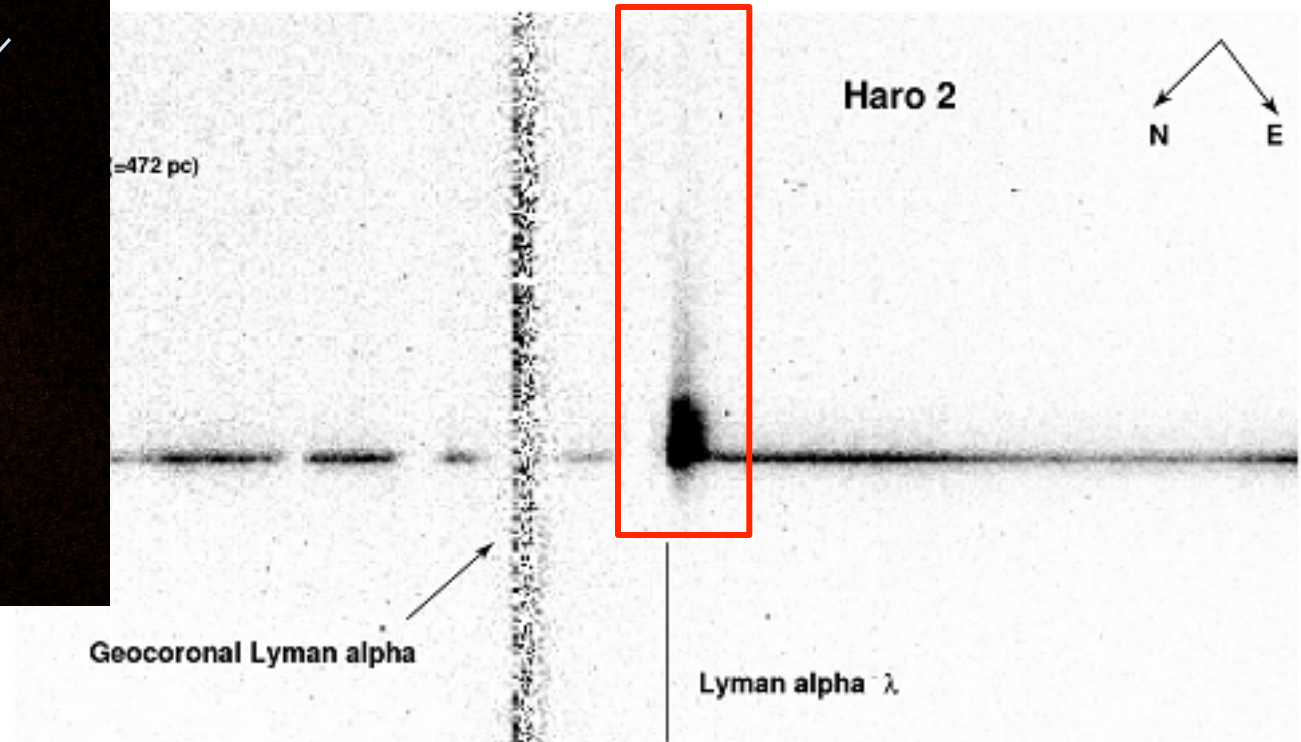
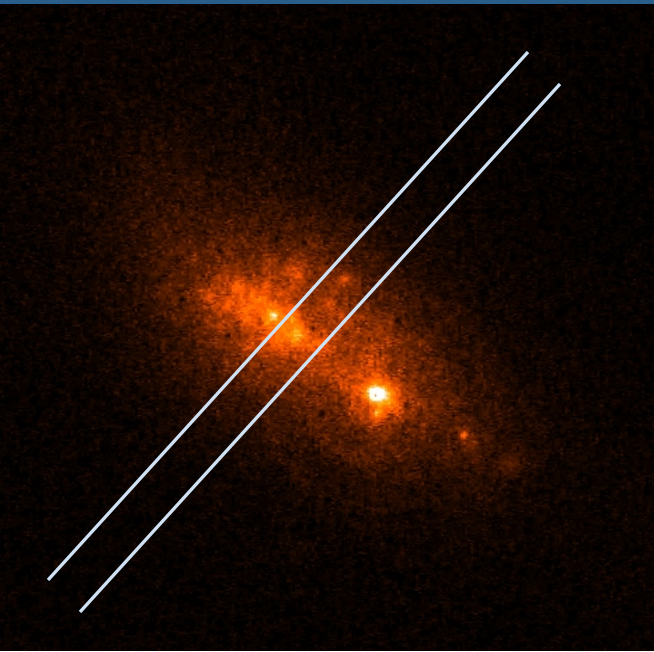


Ly α observations at low z

Observed Ly α line properties depend on:

- Metallicity / dust (IUE)
- Gas kinematics (HST)
- Column density of neutral gas, N_{HI}
- Aperture size & position and spatial resolution
- imaging

Need for Ly α imaging



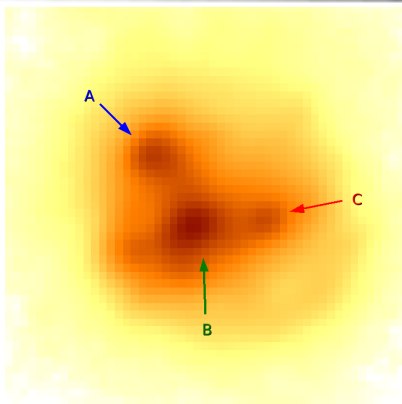
Mas-Hesse et al. (2003)

Spectroscopy can miss a large part of the diffuse Ly α component
(UV not coeval with Ly α)

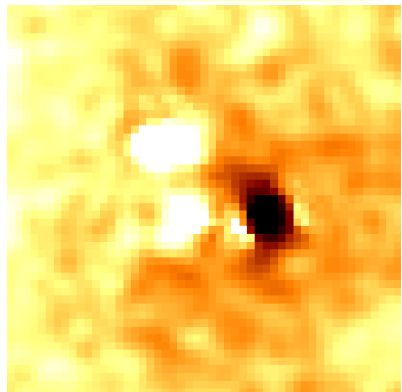
→ Imaging

PILOT STUDY

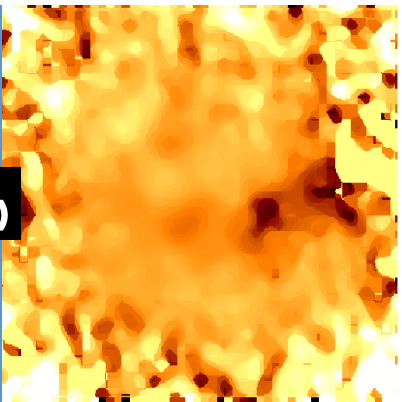
H α



Ly α



E(B-V)



Ly α vs dust distribution

ESO/NTT observations of Balmer lines
--> H α /H β decrement + HST image

✦ Three H α emission knots, only one in Ly α

✦ Here, Ly α seems to emerge from the dusty regions!

Atek et al. 2008

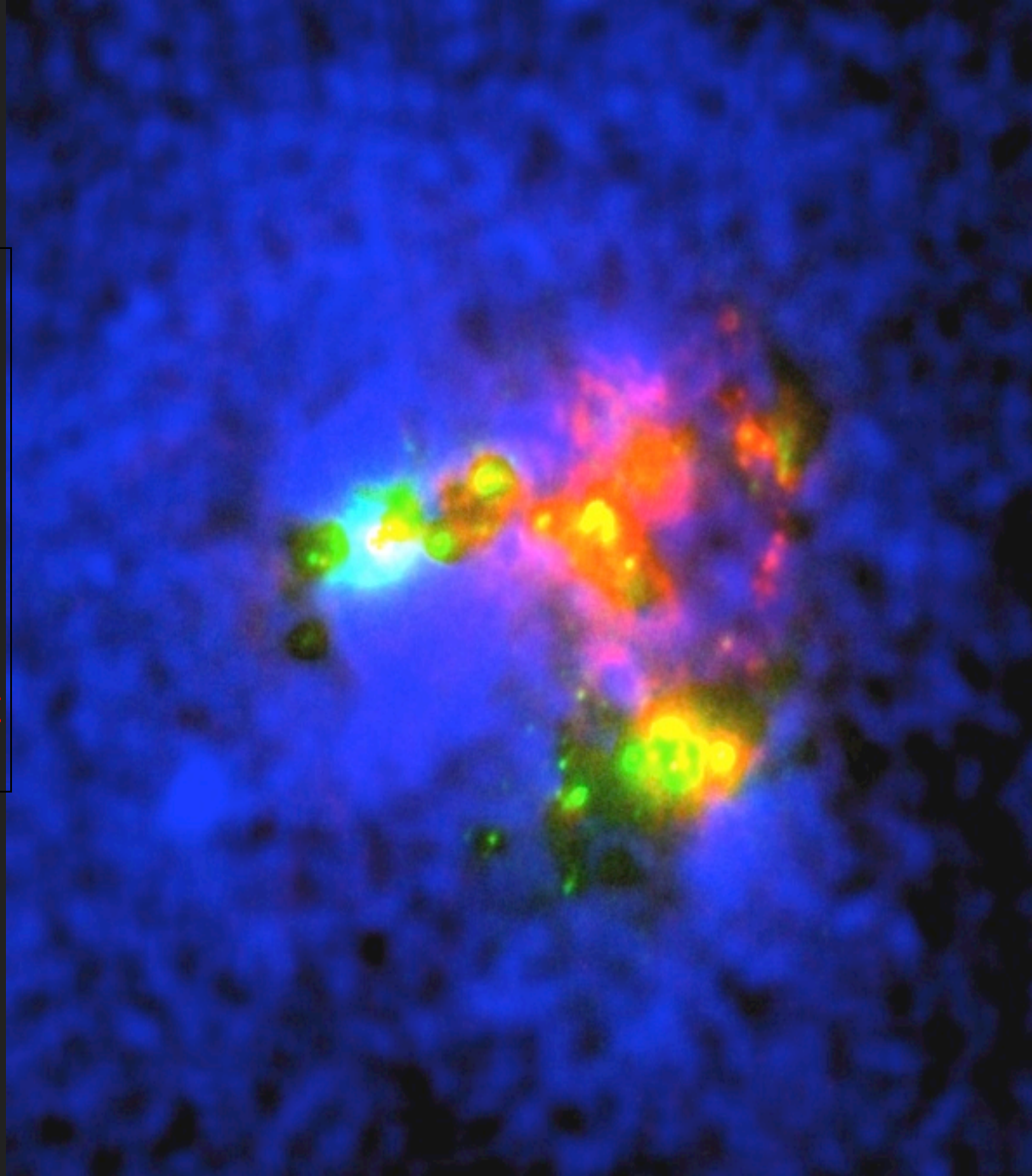
PILOT STUDY

- Large halo of diffuse Ly α emission with

90% of the total flux!

→ Evidence for the resonant scattering of Ly α photons into the ISM

Haro11: Ly α ,
H α , UV, 8x8 kpc
In 20'x20'



LARS (>2009) : the Lyman alpha reference sample

- **Goal:** create the HST reference sample for a complete analysis of Ly α properties versus the local conditions (UV luminosity and distribution, stellar age, radiation transfer, effects of dust and neutral gas density, gas kinematics, porosity, inclination... etc...) and **determine the MOST important parameters at play.**
- *develop quantitative simulations (P. Laursen, A. Verhamme) to compare models and real galaxies*
- **+++ additional :** *COS and 3D spectroscopy, SED, NIR (Grantecan), radio data (GBT, LMT, VLA) etc...*

Who is LARS ?

Göran Östlin, Stockholm, PI
Matthew Hayes, Stockholm, PI
Angela Adamo, Heidelberg
Florent Duval, Stockholm
Lucia Guaita, Stockholm
Thomas Marquart, Stockholm
Andreas Sandberg, Stockholm
Hakim Atek, Lausanne
Daniel Kunth, IAP, Paris
Claus Leitherer, STScI
Miguel Mas-Hesse, Madrid
Hector Oti, Unam

Daniel Schaerer, Geneva
Anne Verhamme, Geneva
Peter Laursen, Copenhagen
John Cannon, Macalester
Stephen Pardy, Macalester
Jens Melinder, Stockholm
Thøger Thorsen, Stockholm
Ivana Stoslakova, Geneva
Emily Freeland, Stockholm
Pieter Gruyters, Uppsala
Christian Herenz, Potsdam
Martin Roth, Potsdam

LARS sample selection

- GALEX + SDSS database
- $Z = 0.028$ to 0.110 and $z = 0.134$ - 0.192
- $\text{EW}(\text{H}\alpha) > 90 \text{ \AA}$ (14 emission-line galaxies, strong SFR)

Results: *M. Hayes+ 2013a, ApJ.L, 765, 27*
& *M. Hayes + 2013 and 2014*

Additional observations include

- **HST/COS spectroscopy** of **Ly α** and **FUV abs. lines**
- Green Bank Telescope **21 cm** giving **HI masses**
- Very Large Array **21 cm** maps giving **HI distributions**
- Herschel/PACS at **70, 110, 160, [OI]63 and [CII]158 μm**
- GTC tuneable NB in **H α , [NII]6584 Å, (later [OII], [OIII])**
- Calar Alto PM**AS 3D** spectroscopy in **H α + other lines**
- **CFHT NIR imaging** in **Y, J, H, K**
- (Archival Chandra, XMM, Spitzer, ...)

The LARS project is receiving attention

(www.spacetelescope.org →)



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Light and dust in a nearby starburst galaxy



[Click to Enlarge](#)

Visible as a small, sparkling hook in the dark sky, this beautiful object is known as J082354.96+280621.6, or J082354.96 for short. It is a starburst galaxy, so named because of the incredibly (and unusually) high rate of star formation occurring within it.

One way in which astronomers probe the nature and structure of galaxies like this is by observing the behaviour of their dust and gas components; in particular, the [Lyman-alpha emission](#). This occurs when electrons within a hydrogen atom fall from a higher energy level to a lower one, emitting light as they do so. This emission is interesting because this light leaves its host galaxy only after extensive scattering in the nearby gas — meaning that this light can be used as a pretty direct probe of what a galaxy is made up of.

The study of this Lyman-alpha emission is common in very distant galaxies, but now a study named [LARS \(Lyman Alpha Reference Sample\)](#) [1] is investigating the same effect in galaxies that are closer by. Astronomers chose fourteen galaxies, including this one, and used spectroscopy and imaging to see what was happening within them. They found that these Lyman-alpha photons can travel much further if a galaxy has less dust — meaning that we can use this emission to infer how dusty the source galaxy is.

The LARS study relies heavily on the high resolving power of Hubble. When Hubble is decommissioned, no telescope will be able to make observations like this in the far ultraviolet part of the spectrum — meaning that small, glittering galaxies imaged and probed by studies like LARS may give us some of the most detailed data we have to work with for some time to come.

Credit: ESA/Hubble & NASA, M. Hayes

Notes

[1] Hayes, Östlin et al., [The Lyman Alpha Reference Sample: extended Lyman alpha halos produced at low dust content](#), The Astrophysical Journal, 2013.

Credit: ESA/Hubble & NASA, M. Hayes

[Go](#)

[Gilla](#) [Du, Matthew Hayes och 410 gillar detta.](#)

About the Image

Id: potw1313a
Type: Observation
Release date: 1 April 2013, 10:00
Size: 2010 x 2009 px

About the Object

Name: [SDSS J082354.96+280621.6](#)
Type: • Local Universe : Galaxy :
Activity : Starburst
• X - Galaxies Images/Videos
Distance: z=0.047 (redshift)

Colours & filters

Band	Wavelength	Telescope
Ultraviolet	336 nm	Hubble Space Telescope WFC3
Optical	438 nm	Hubble Space Telescope WFC3
Infrared	775 nm	Hubble Space Telescope WFC3

Images

- [Fullsize Original](#) 9.6 MB
- [Large JPEG](#) 2.4 MB
- [Publication JPEG](#) 7.6 MB
- [Screensize JPEG](#) 328.9 KB

Zoomable

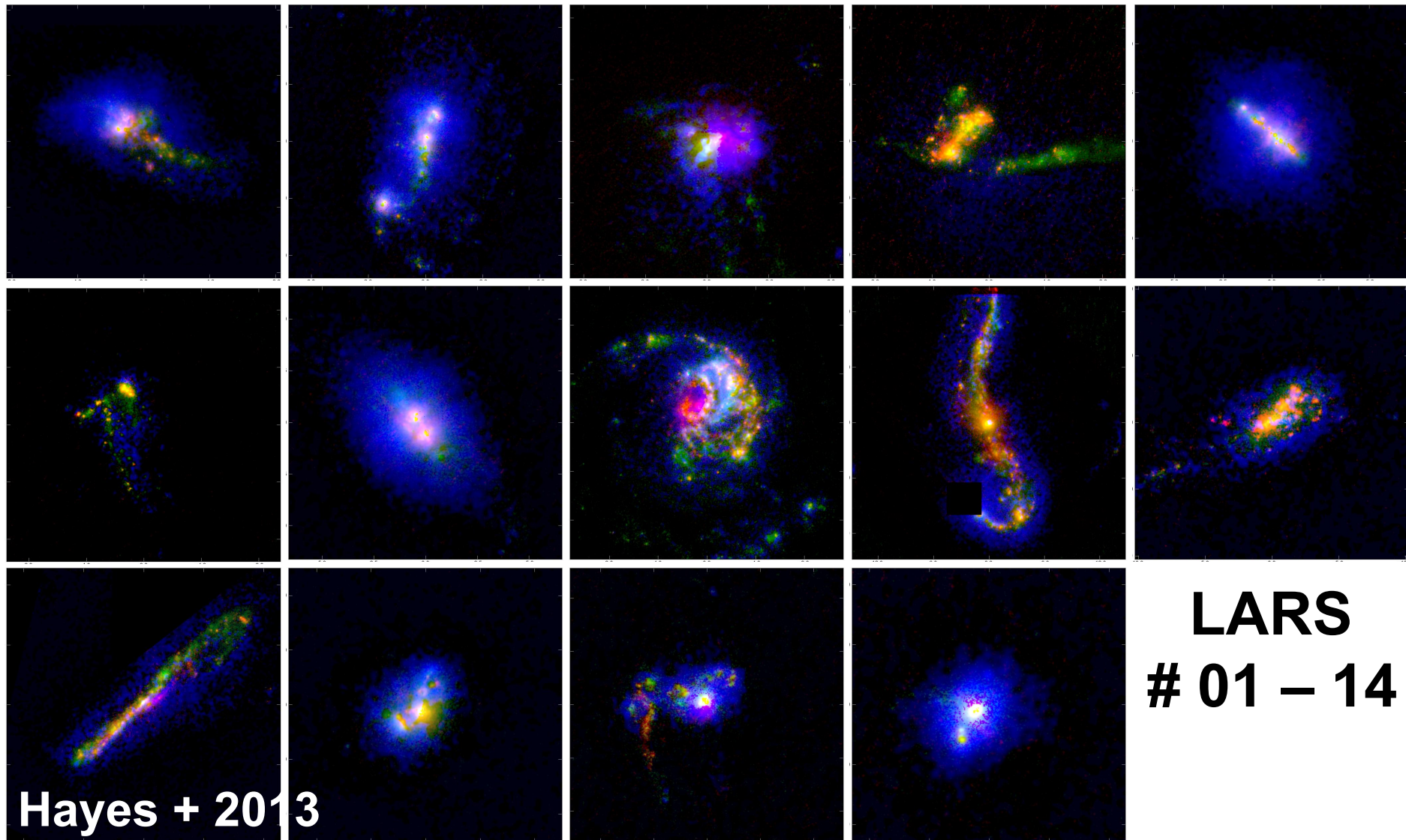
[Zoomable](#)

Wallpapers

	1024x768	385.9 KB
	1280x1024	700.8 KB
	1600x1200	1.1 MB
	1920x1200	1.4 MB
	2048x1536	1.9 MB

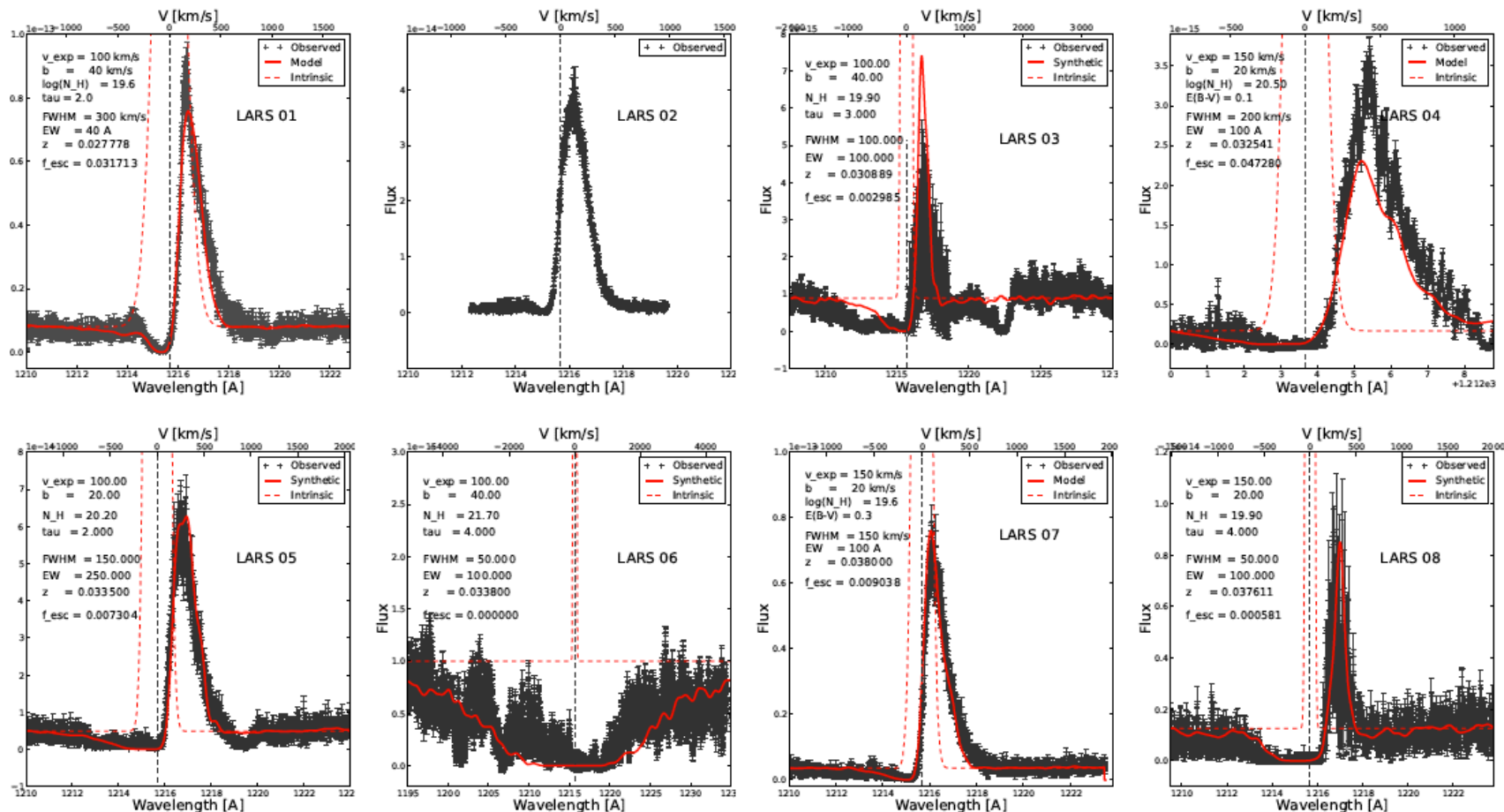
Halo

(but 6 orbits per targets)



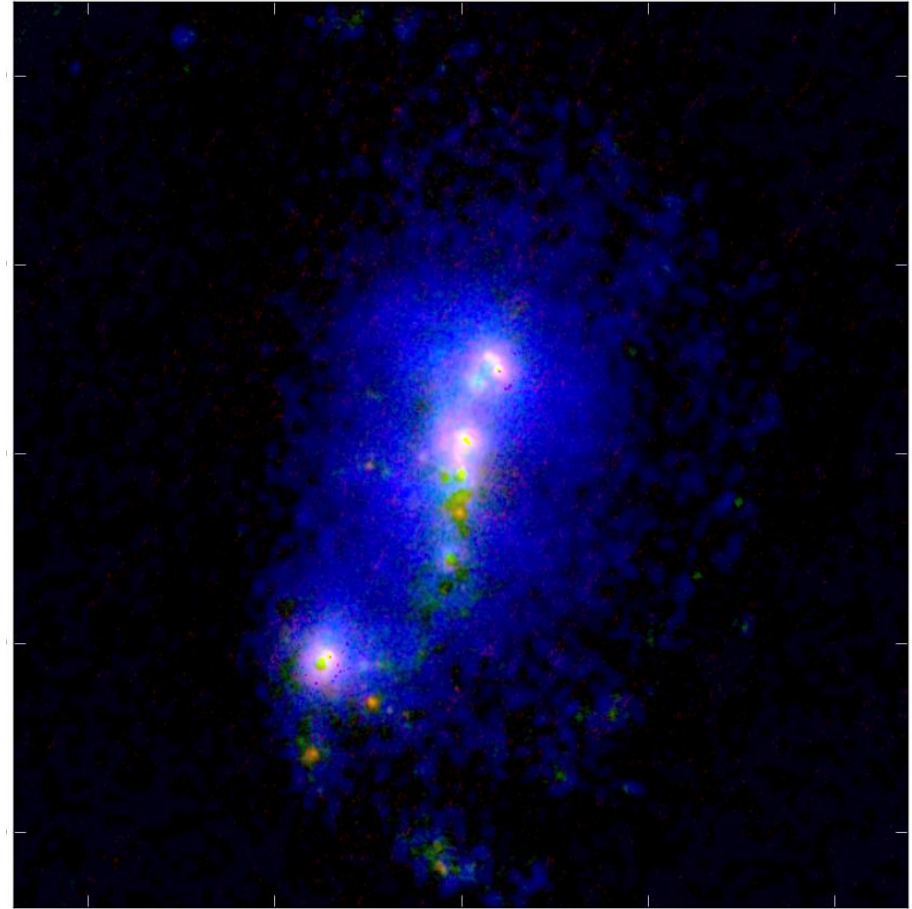
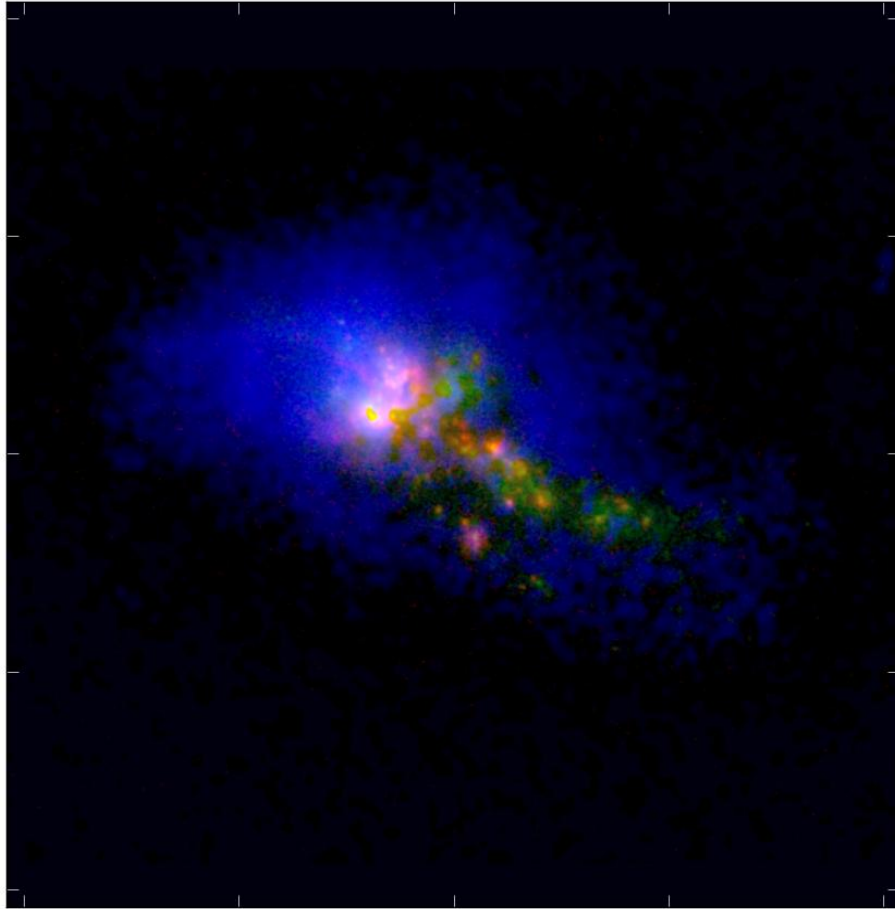
FUV + H α + Ly α

COS spectroscopy (Artipova et al. 2013)



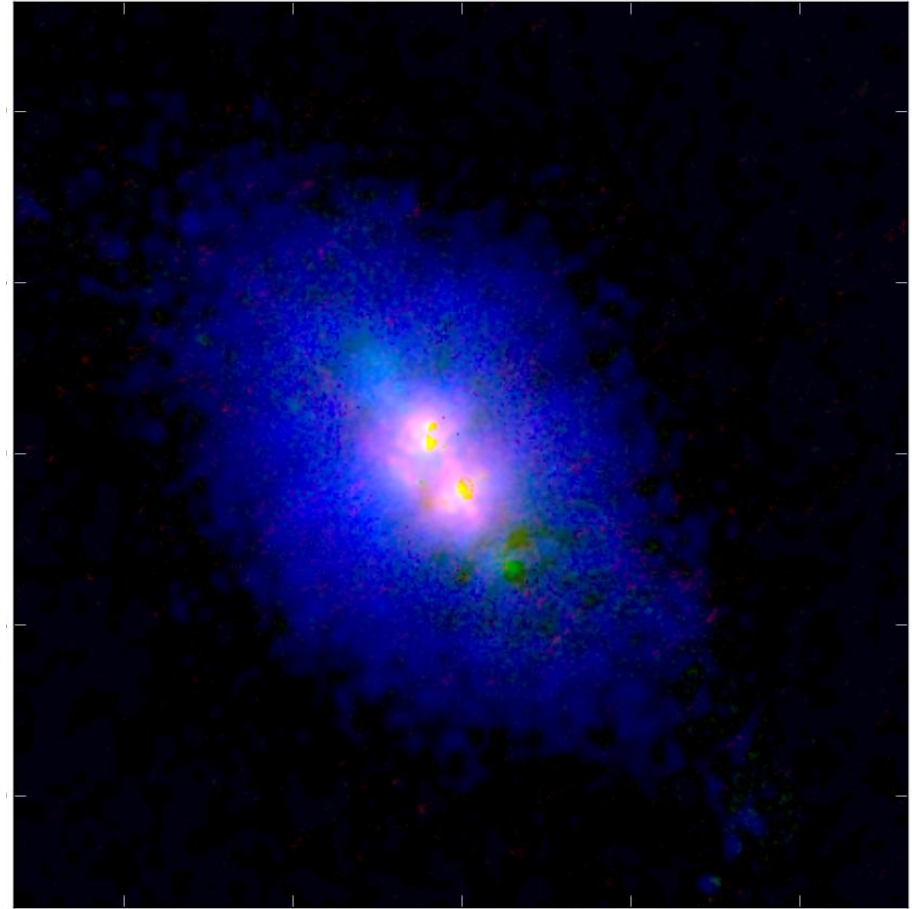
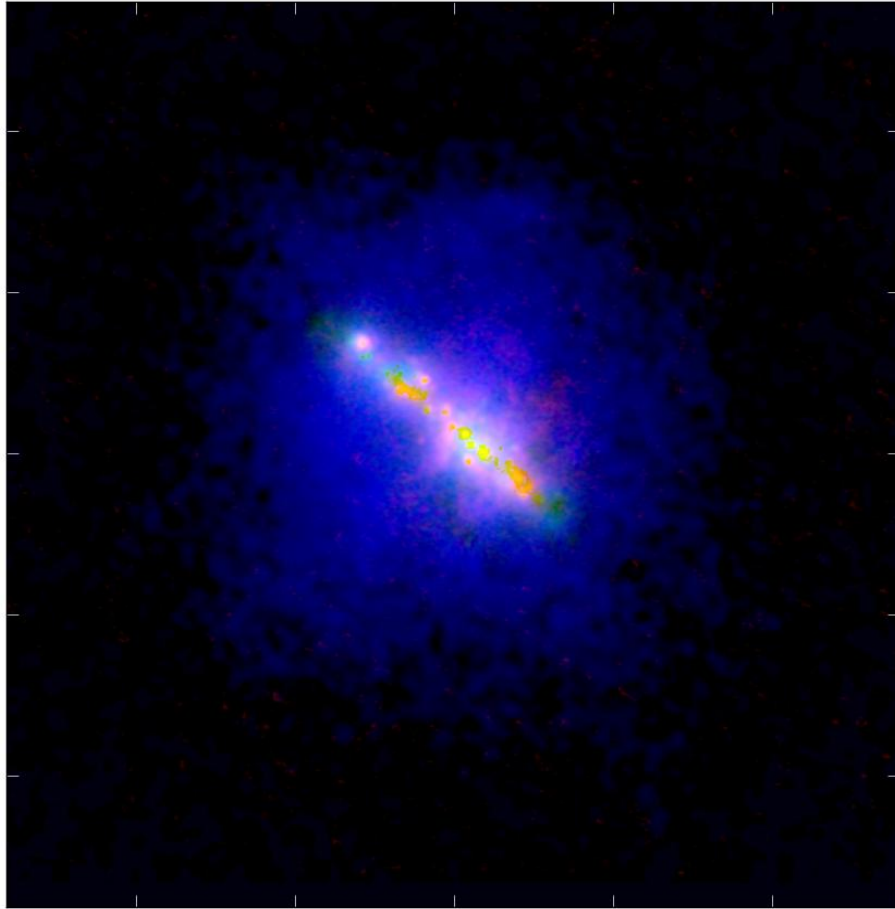
Profiles fit by models of A. Verhamme, D. Schaerer etc...from the LARS team

Halo



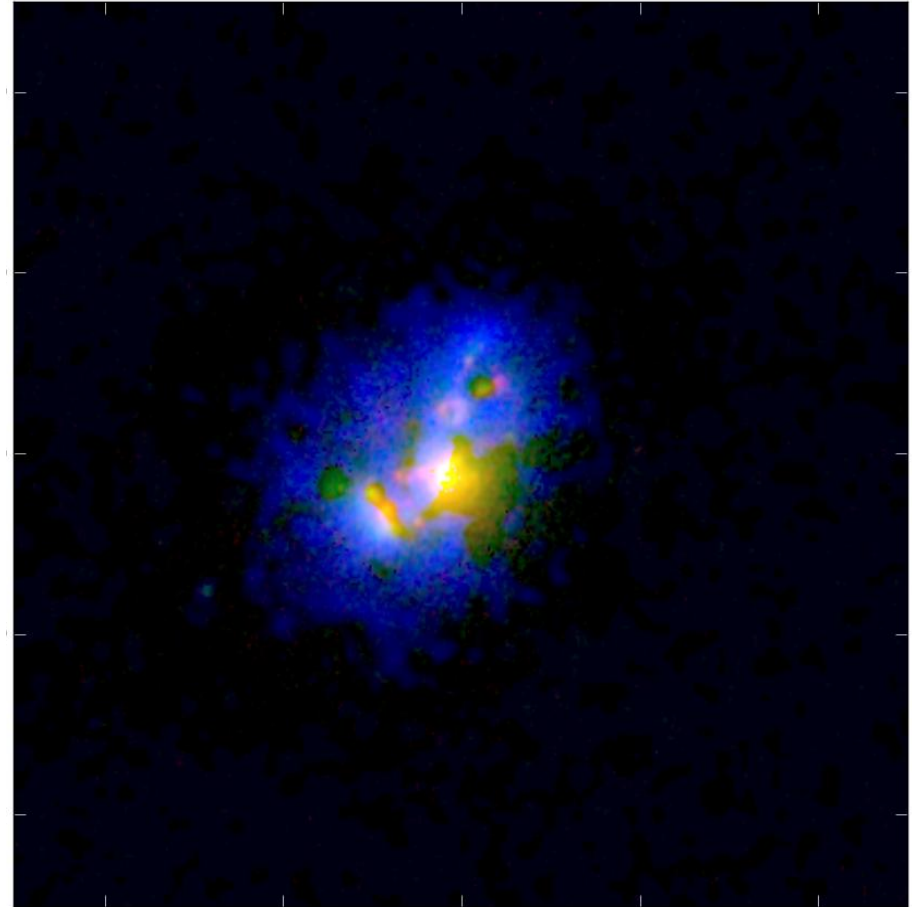
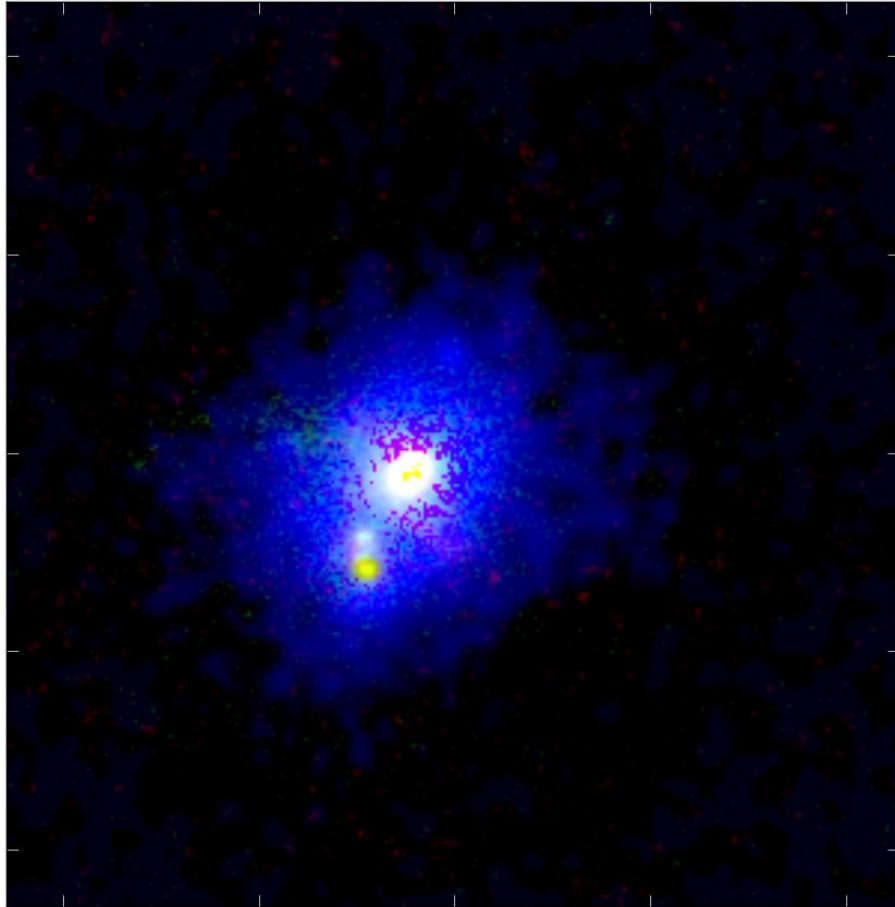
FUV + **H α** + **Ly α**

Halo



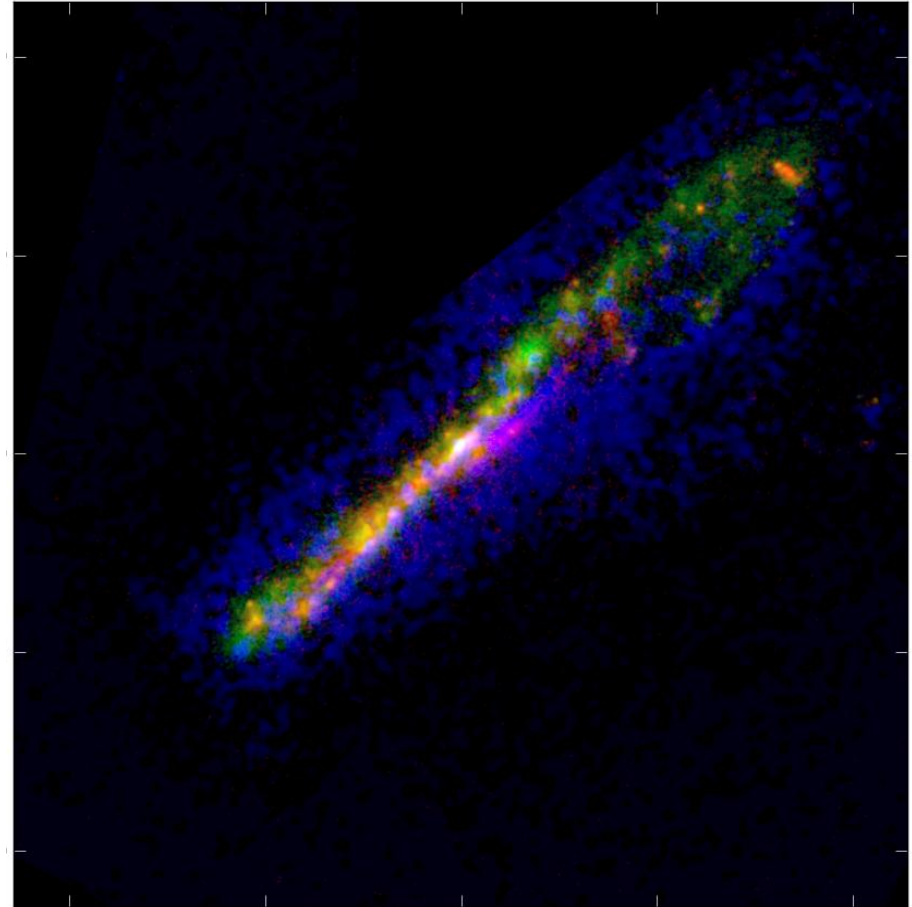
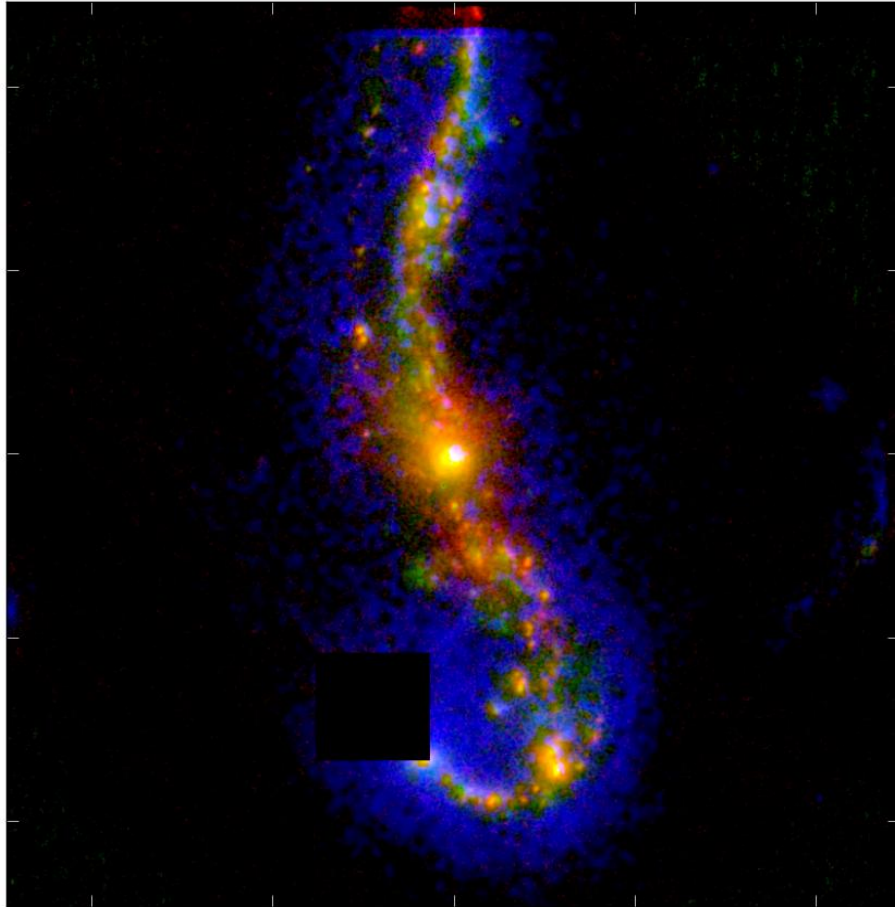
FUV + H α + Ly α

Halo



FUV + H α + Ly α

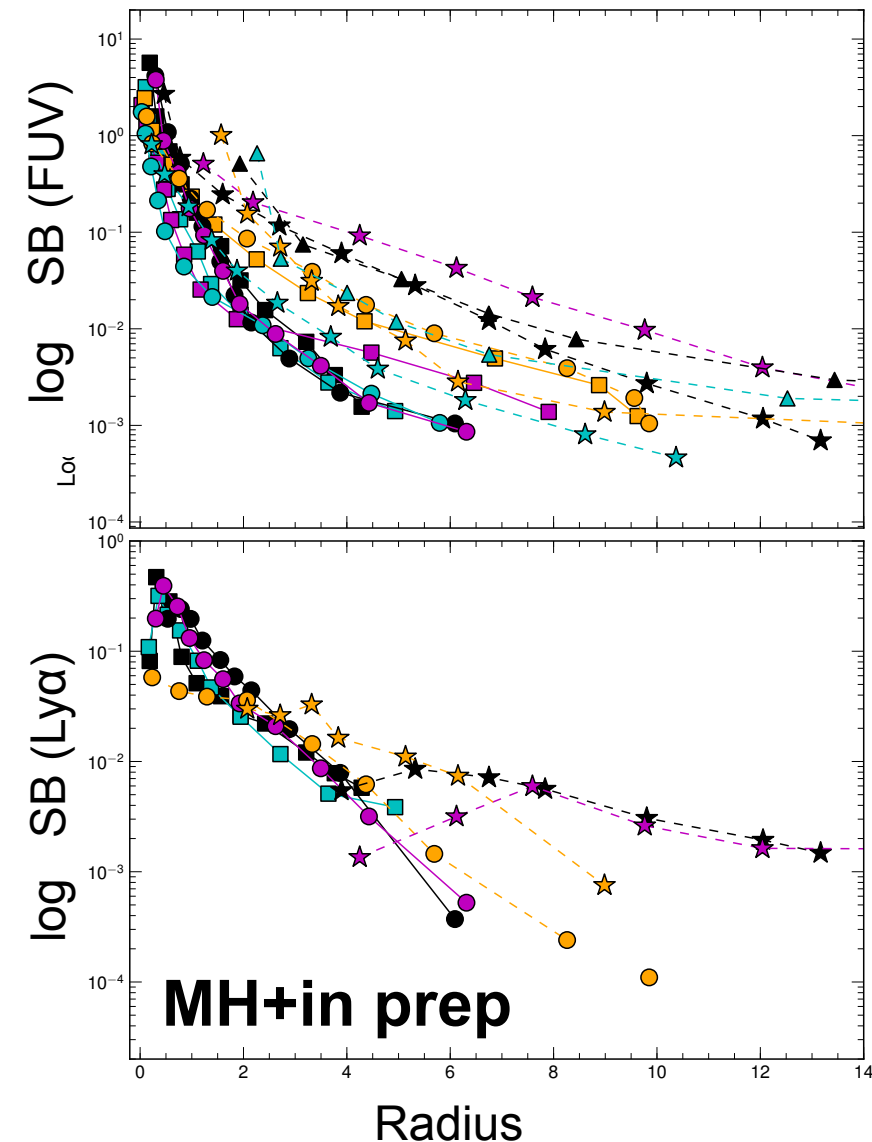
Halo (mapping HI?)



FUV + H α + Ly α

Ly α profiles consistent in shape with those of HI envelopes (Bigiel & Blitz 2012)

Ly α brightness profiles



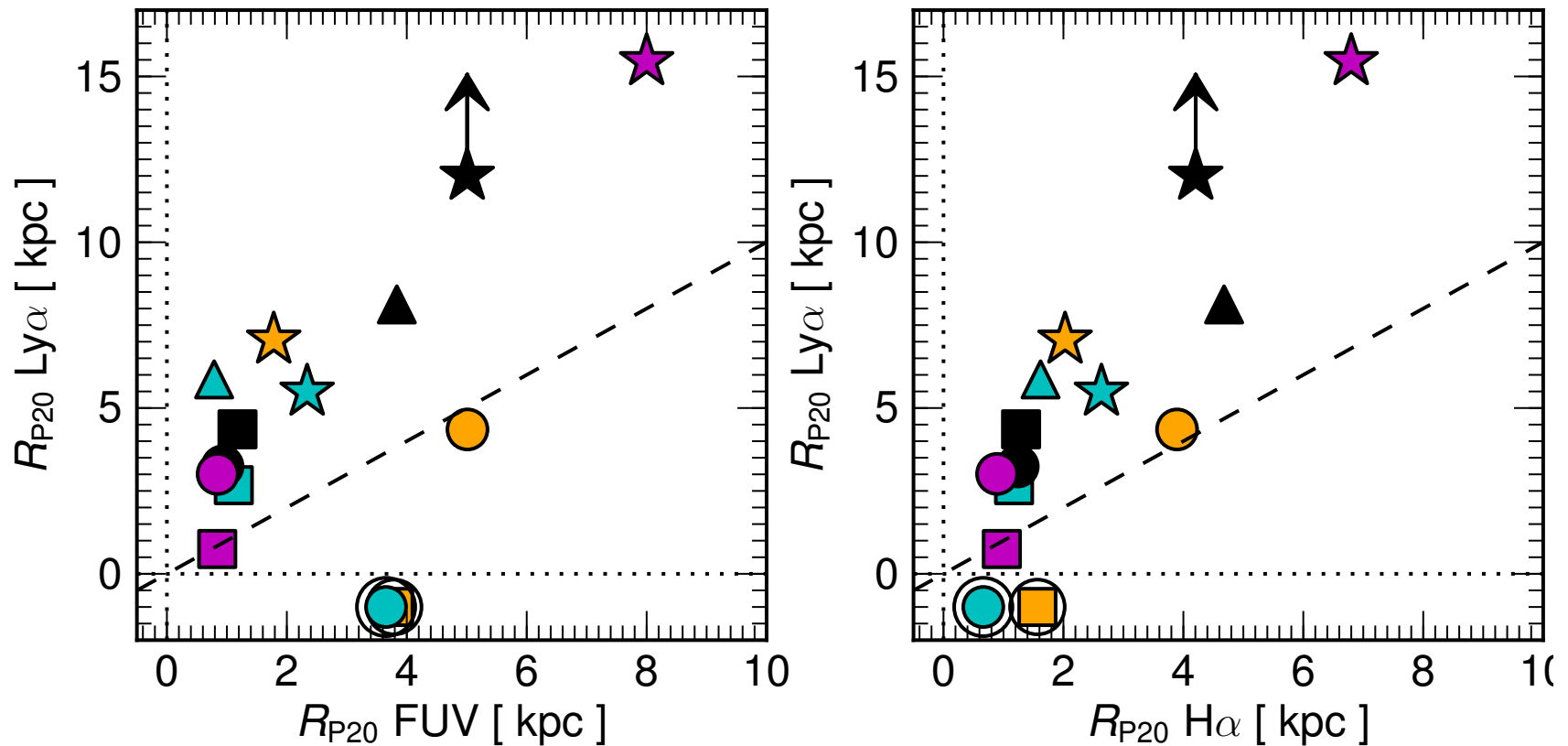
FUV SB close to $n=4$
As for merger remnants
(e.g. Schweizer+1982)

Ly α SB close to $n=1$
a much shallower exponential
profile. As for Ly α of Steidel+2011

but also as for HI (Bigiel & Blitz
+2012)

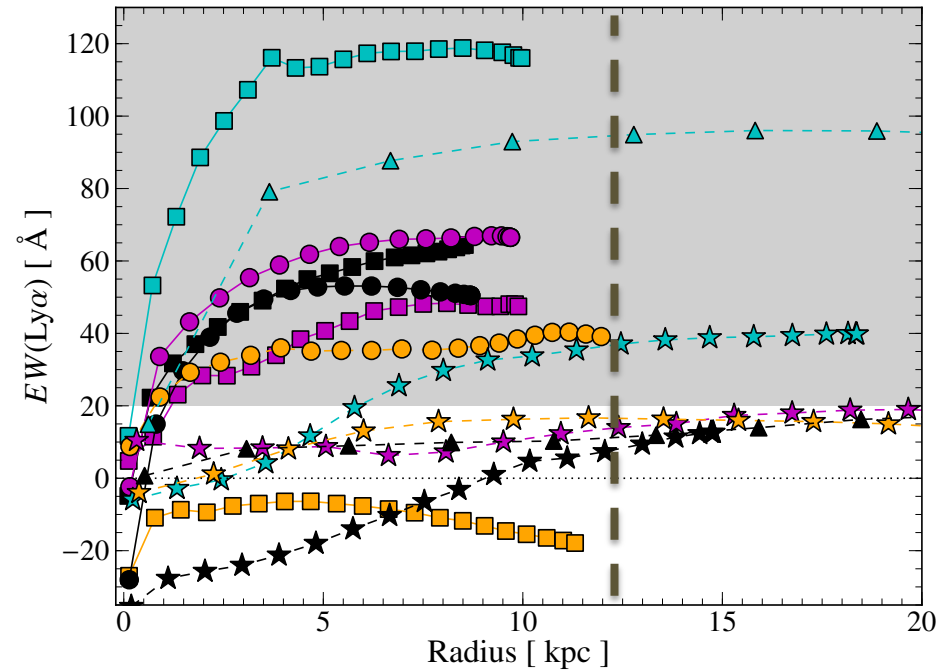
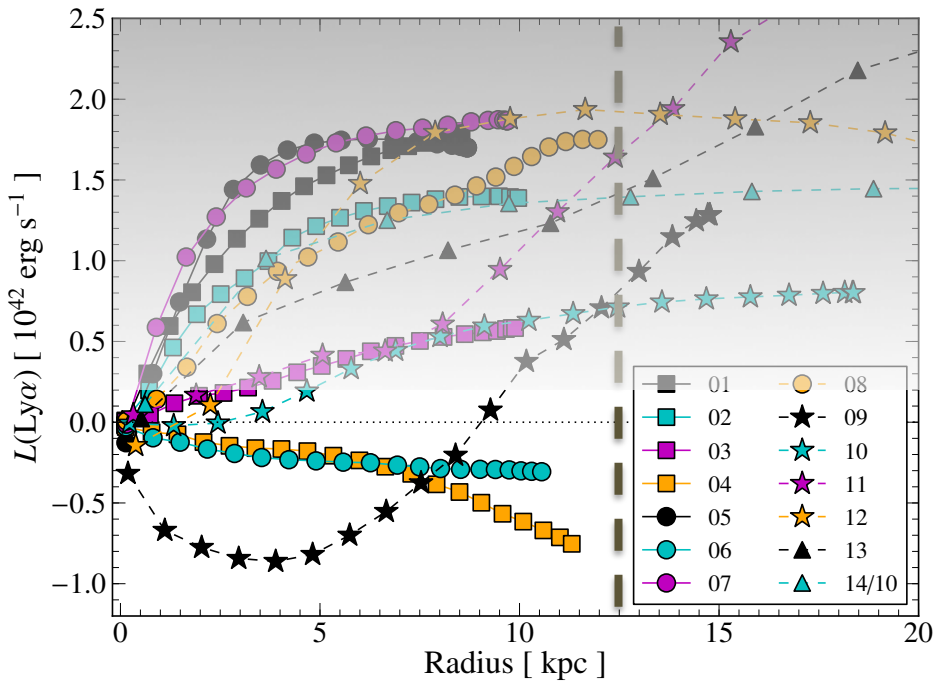
>> does Ly α trace the HI
distribution?

Halo



$\text{Ly}\alpha$ characteristic sizes are $\sim$ twice those of UV and $\text{H}\alpha$

Halo : *consequences at high z*

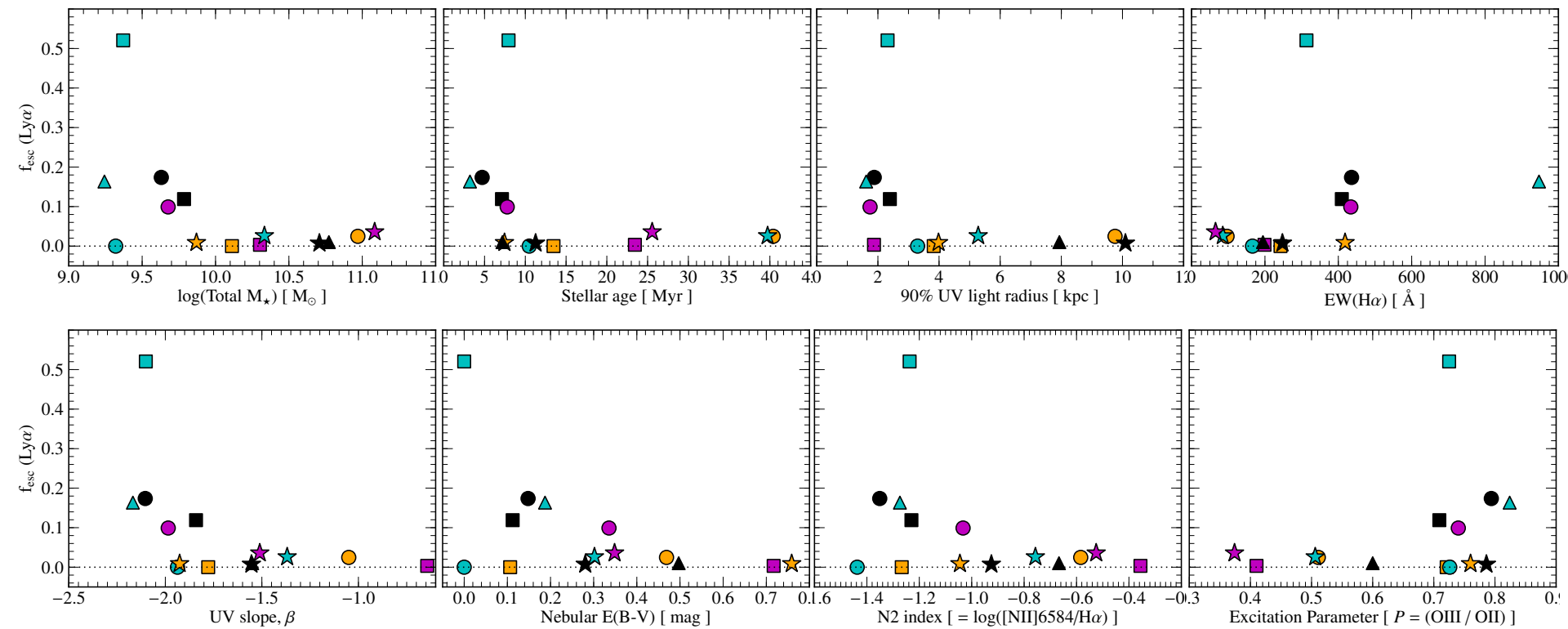


Some **Ly α radial growth curves flatter**, some do not.

→ Will be flux losses if placed at $z > 2$, but not enormous (1 arc sec slit)

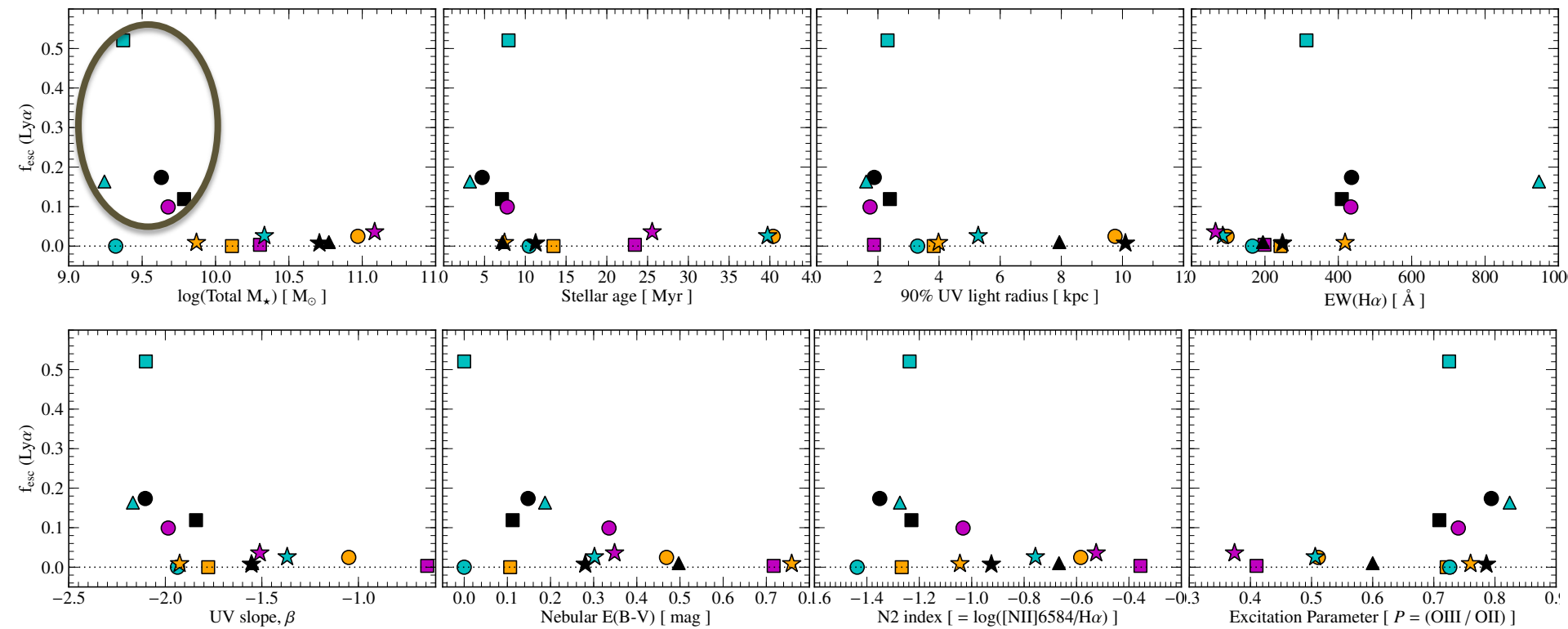
Ly α escape

$$f_{\text{esc}}(\text{Ly}\alpha) = f(\text{Ly}\alpha) / 8.7 \times f(\text{H}\alpha)_{\text{dust corrected}}$$



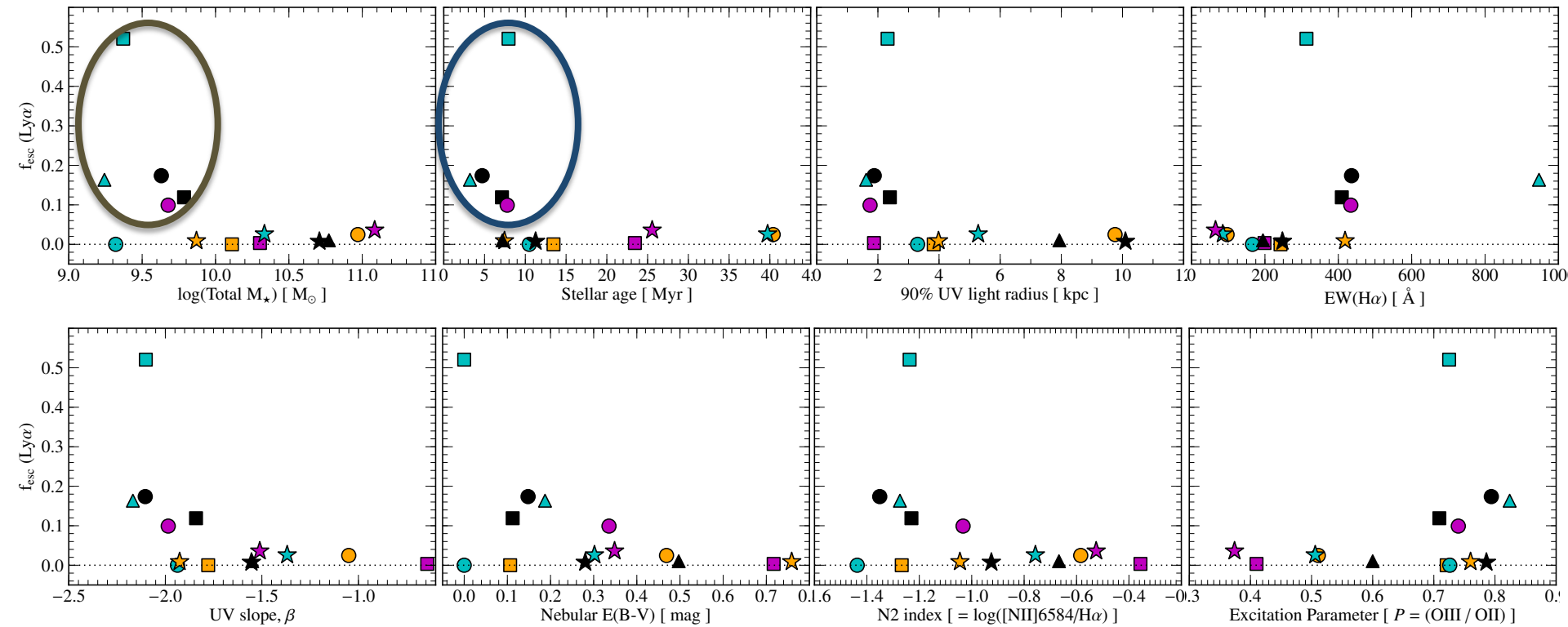
Lyman alpha emitting galaxies are :

Ly α escape



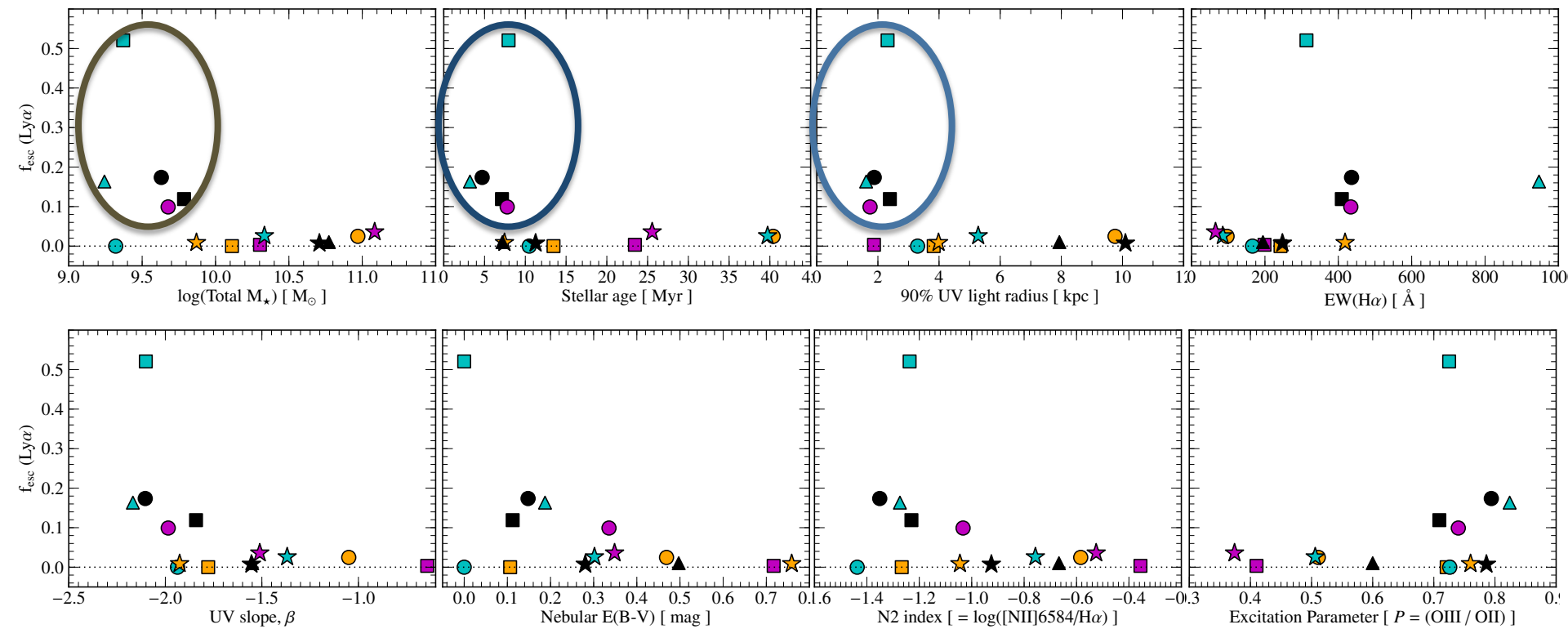
Lyman alpha emitting galaxies are : **lower mass**

Ly α escape



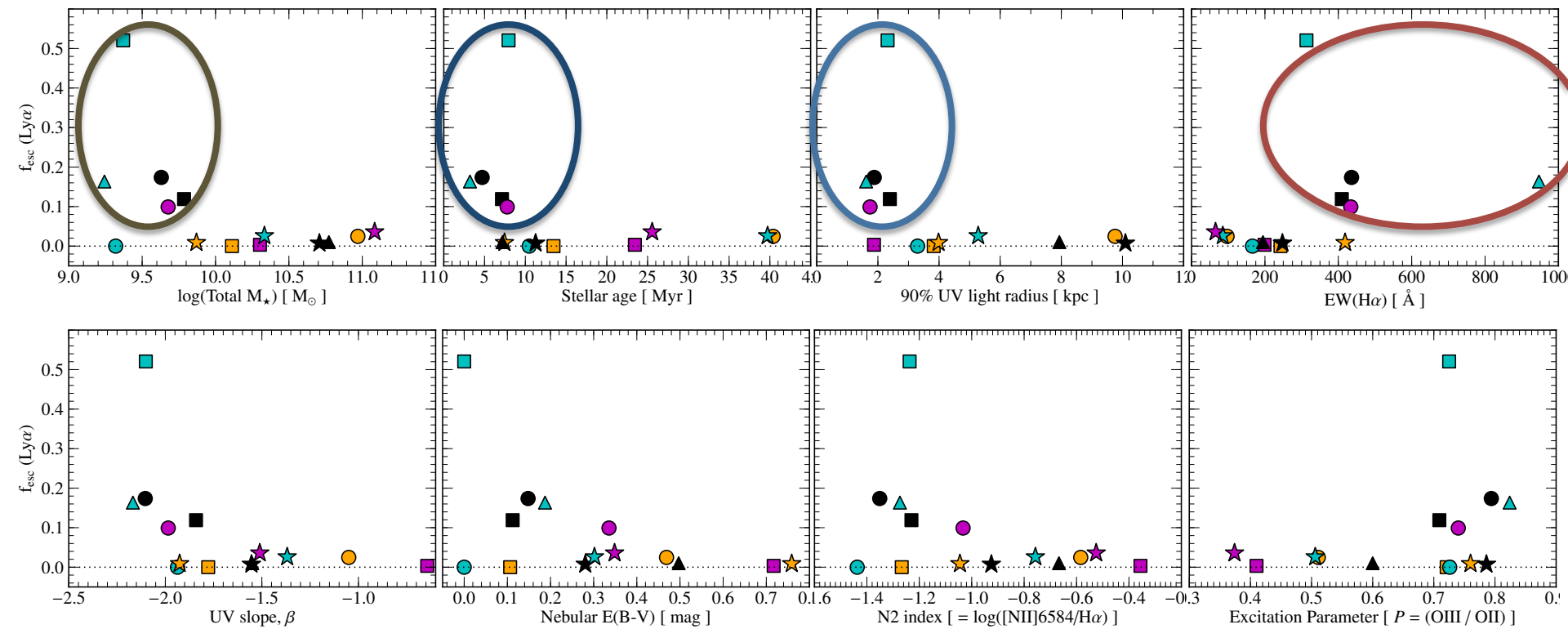
Lyman alpha emitting galaxies are : **lower mass**, **younger**

Ly α escape



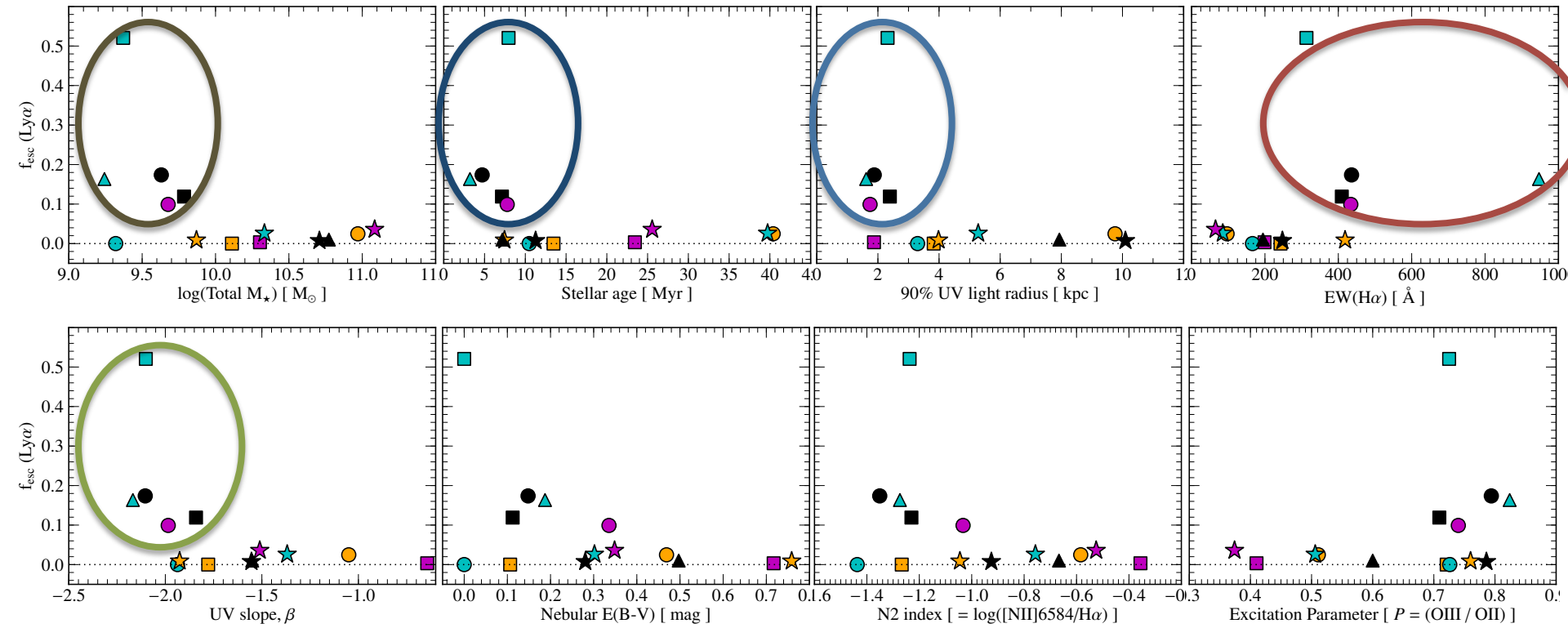
Lyman alpha emitting galaxies are : **lower mass**, **younger**, **more compact**

Ly α escape



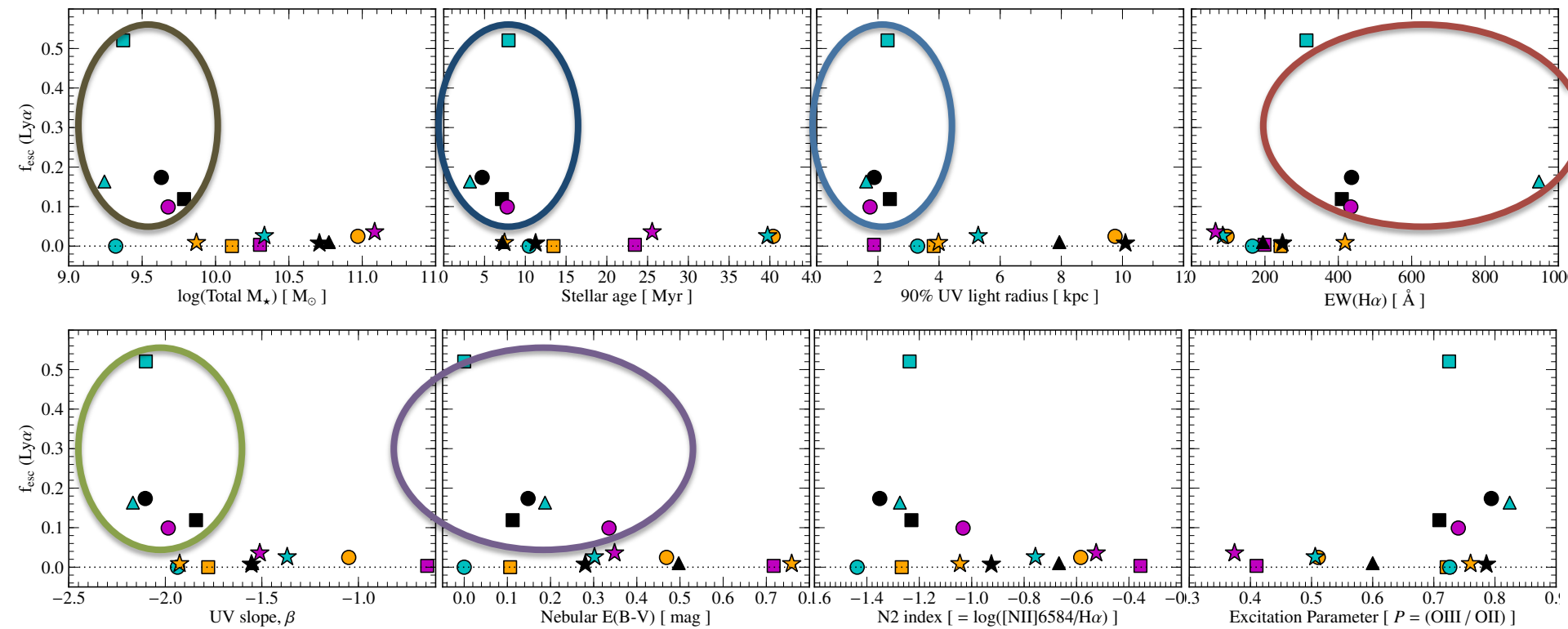
Lyman alpha emitting galaxies are : **lower mass**, **younger**,
more compact, **higher sSFR**

Ly α escape



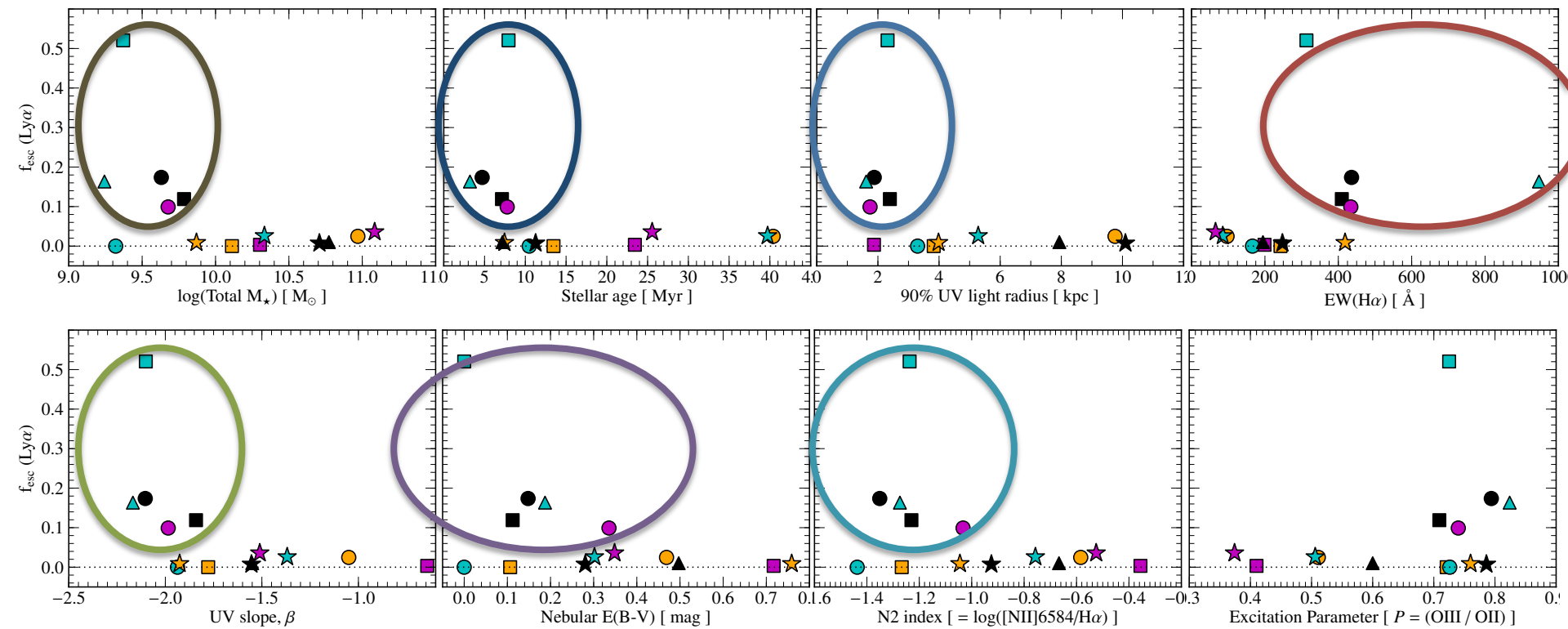
Lyman alpha emitting galaxies are : **lower mass**, **younger**,
more compact, **higher sSFR**, **bluer**

Ly α escape



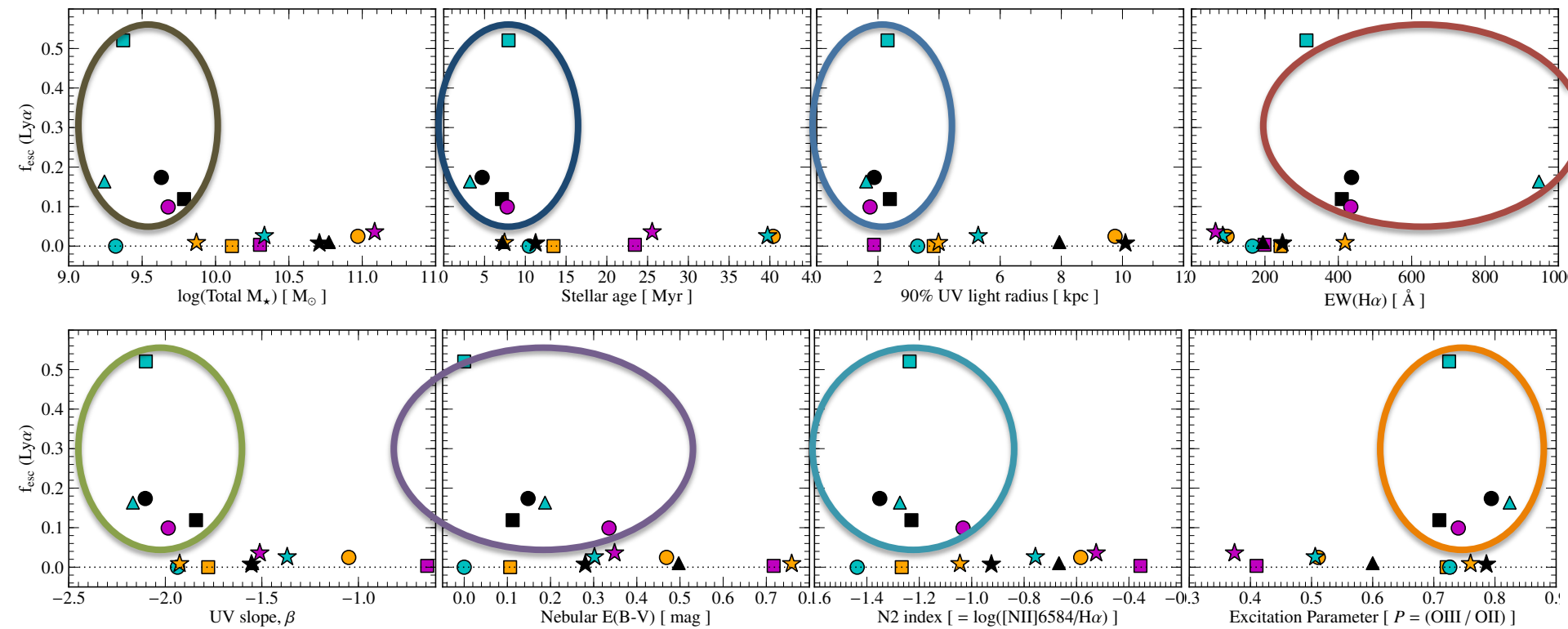
Lyman alpha emitting galaxies are : **lower mass**, **younger**,
more compact, **higher sSFR**, **bluer**, **less dusty**

Ly α escape



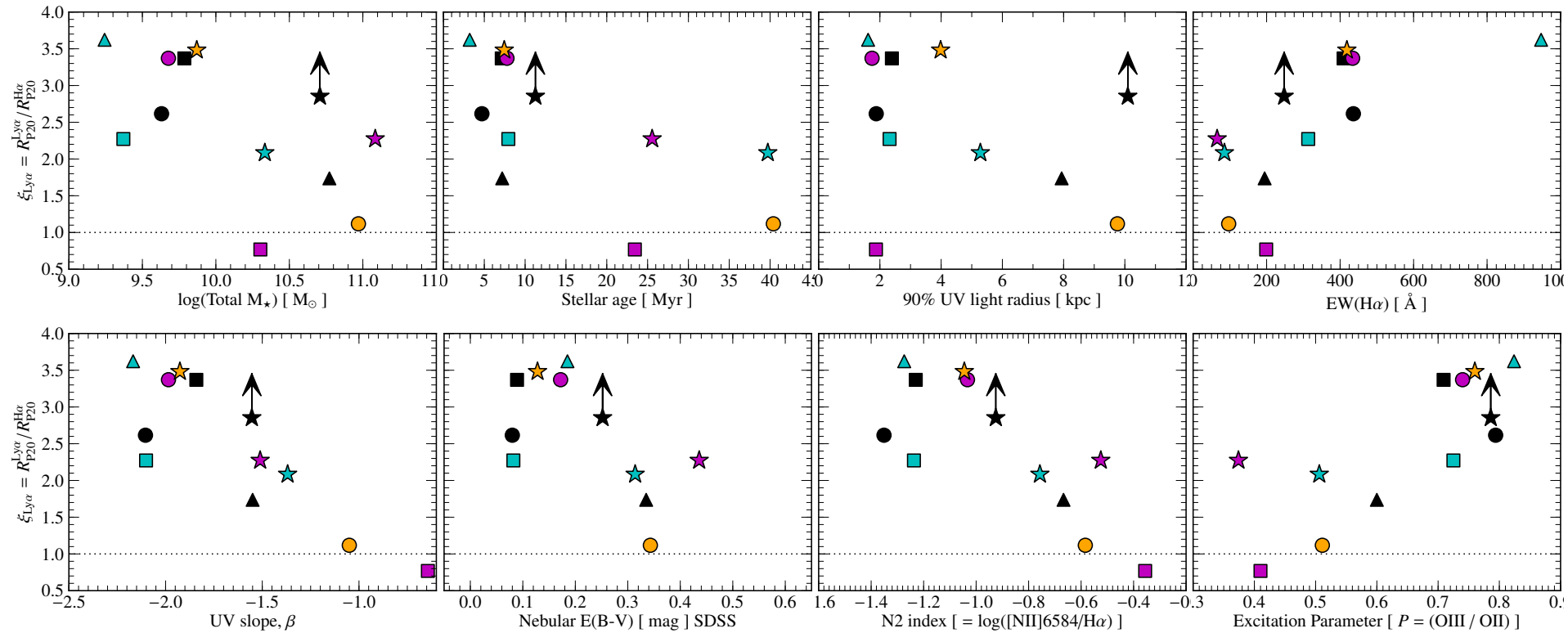
Lyman alpha emitting galaxies are : **lower mass**, **younger**, **more compact**, **higher sSFR**, **bluer**, **less dusty**, **lower metallicity**

Ly α escape



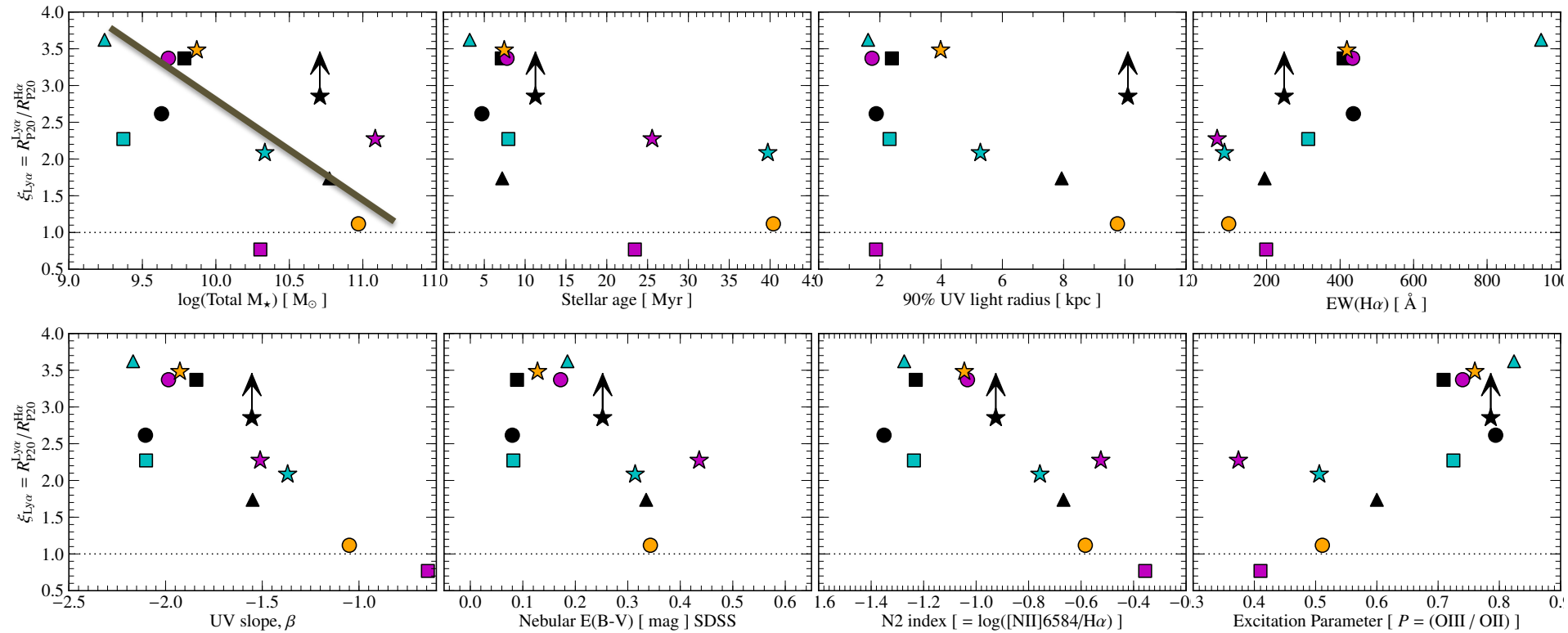
Lyman alpha emitting galaxies are : **lower mass**, **younger**, **more compact**, **higher sSFR**, **bluer**, **less dusty**, **lower metallicity**, and **more strongly ionizing** than non Ly α emitting galaxies.

Ly α haloes



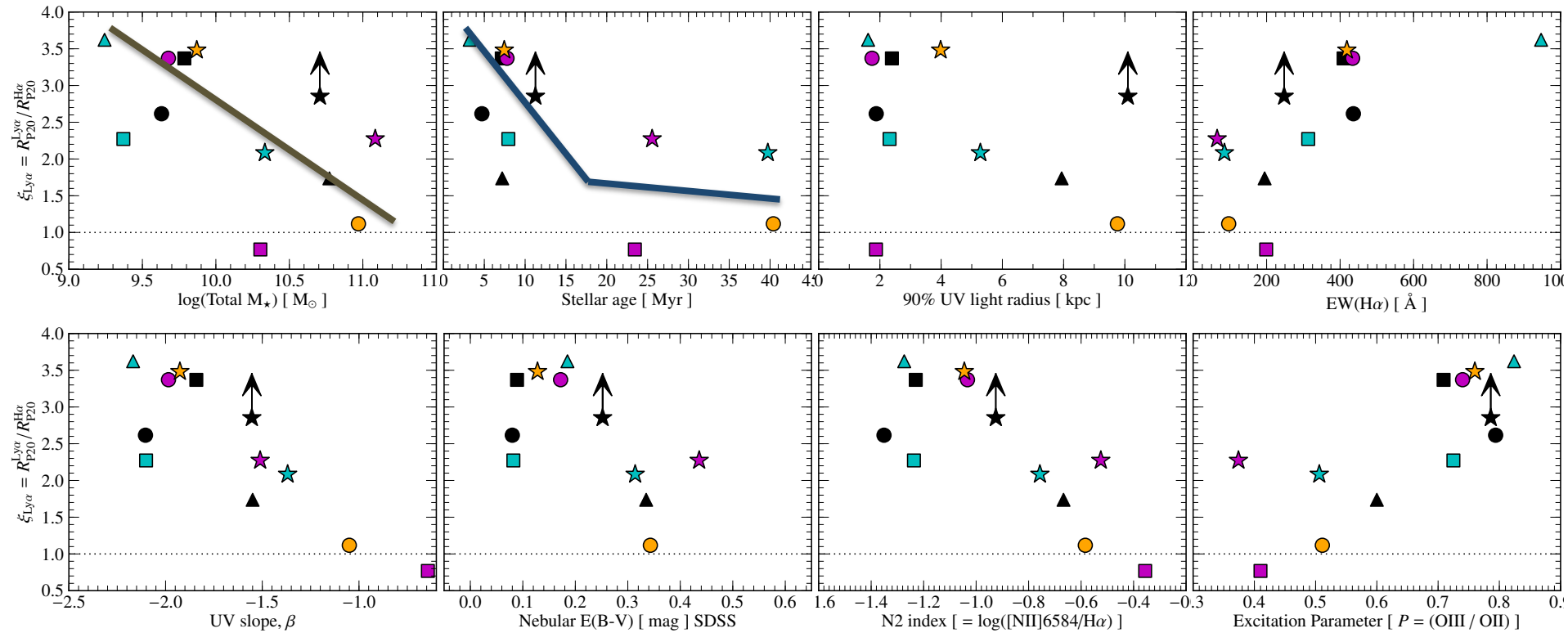
Large Ly α haloes occur in :

Ly α haloes



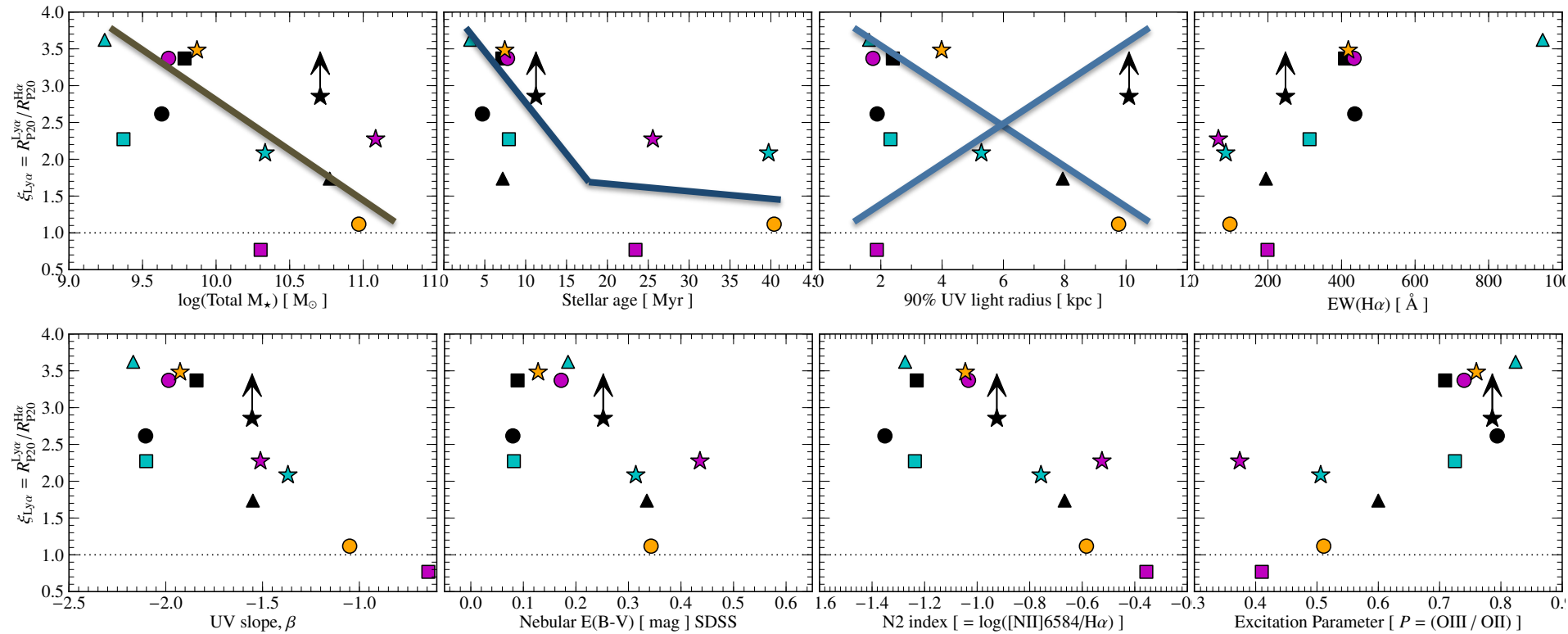
Large Ly α haloes occur in : **lower mass**

$\text{Ly}\alpha$ haloes



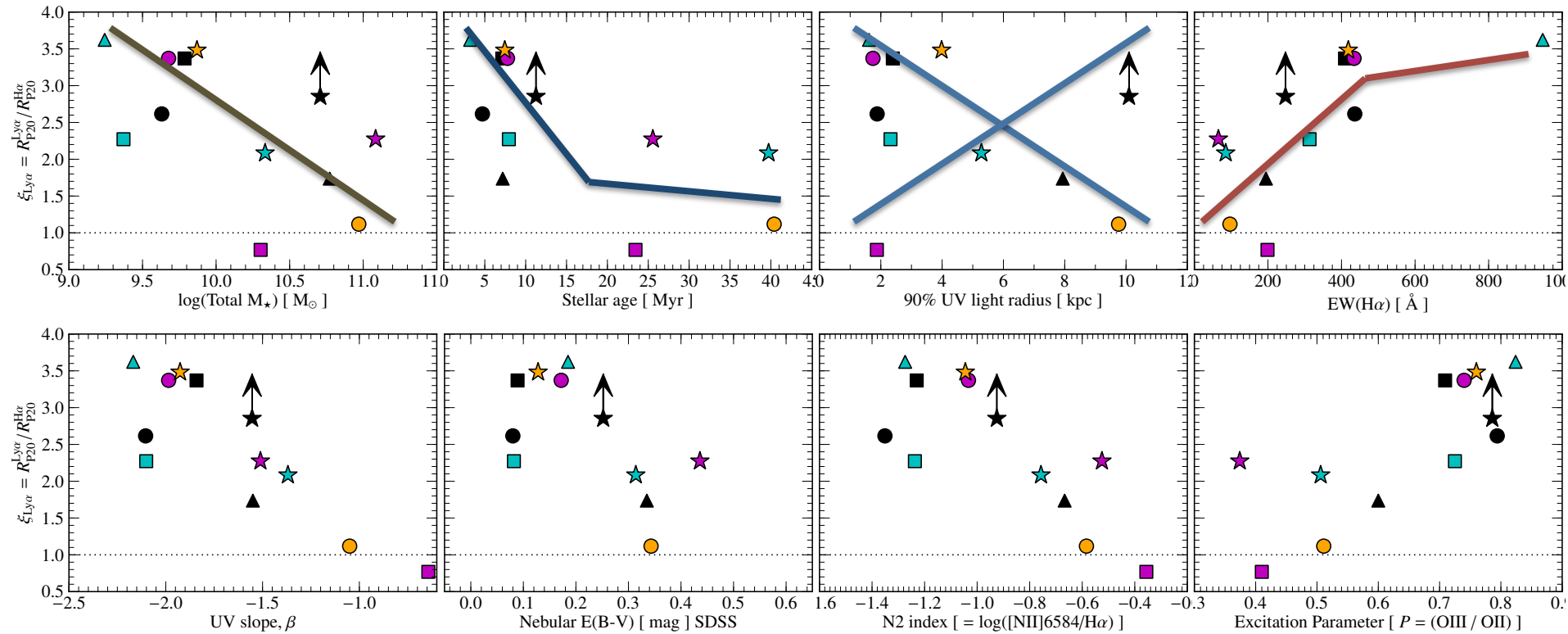
Large Ly α haloes occur in : **lower mass**, **younger**

Ly α haloes



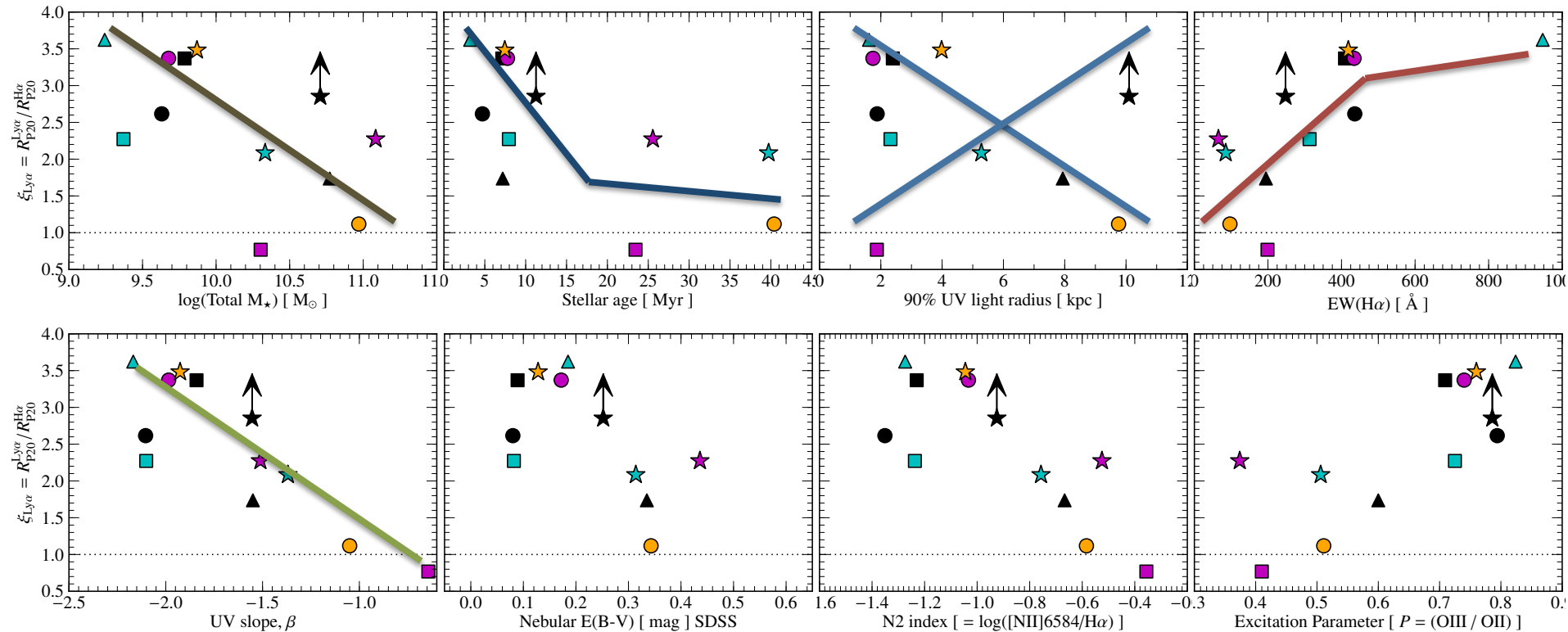
Large Ly α haloes occur in : **lower mass**, **younger**, **more compact**

Ly α haloes



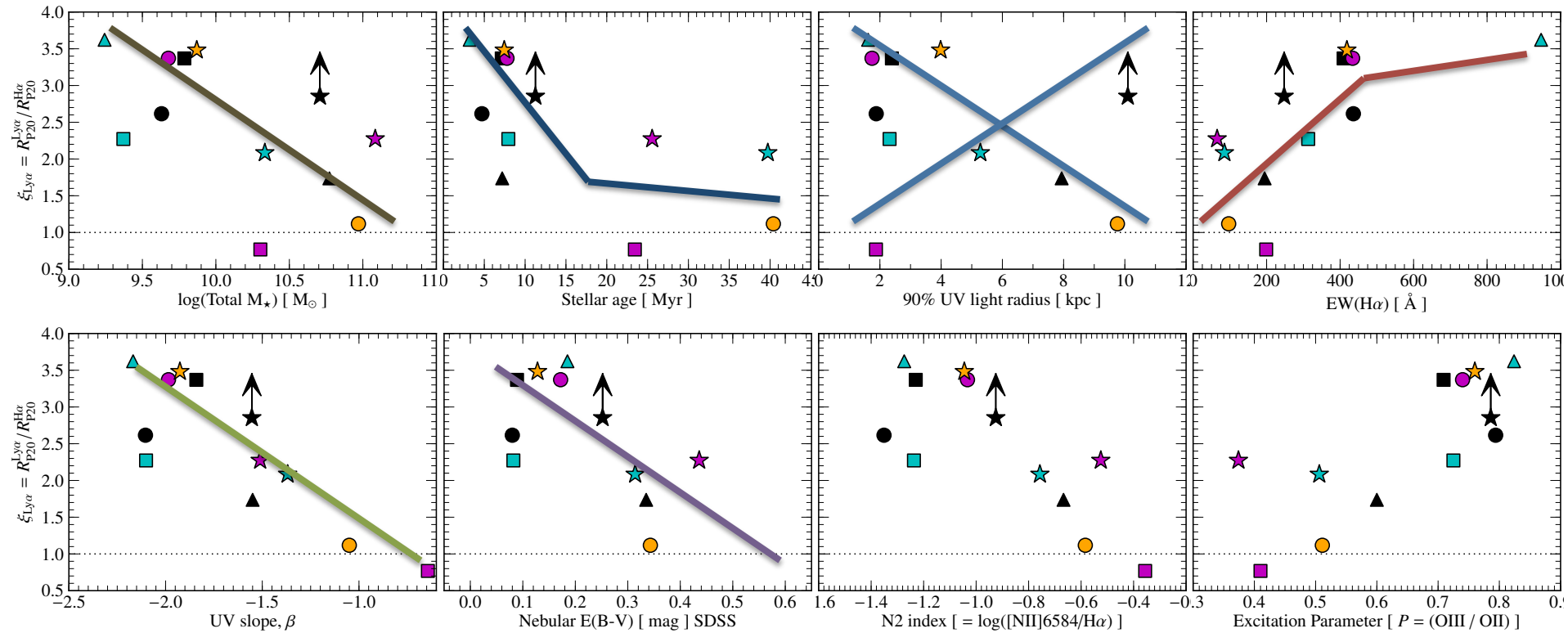
Large Ly α haloes occur in : **lower mass**, **younger**, **more compact**, **higher sSFR**

Ly α haloes



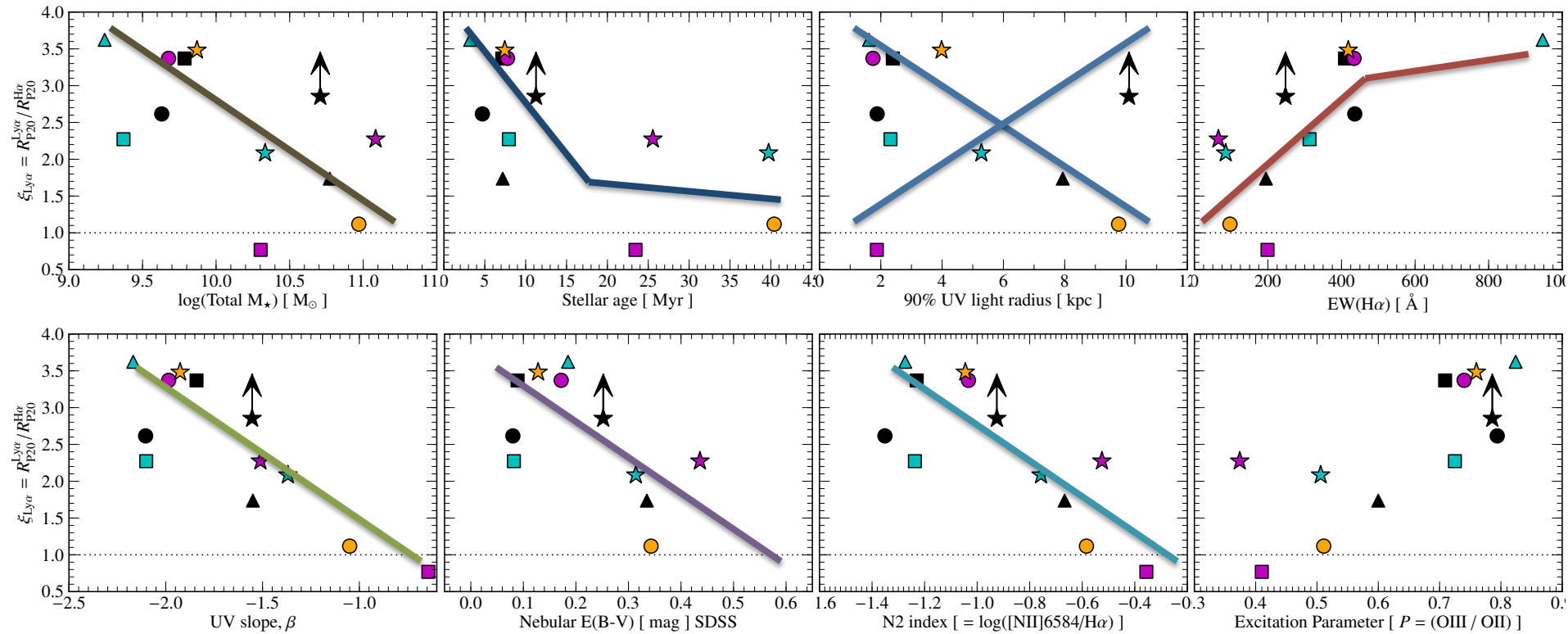
Large Ly α haloes occur in : **lower mass**, **younger**, **more compact**, **higher sSFR**, **bluer**

Ly α haloes



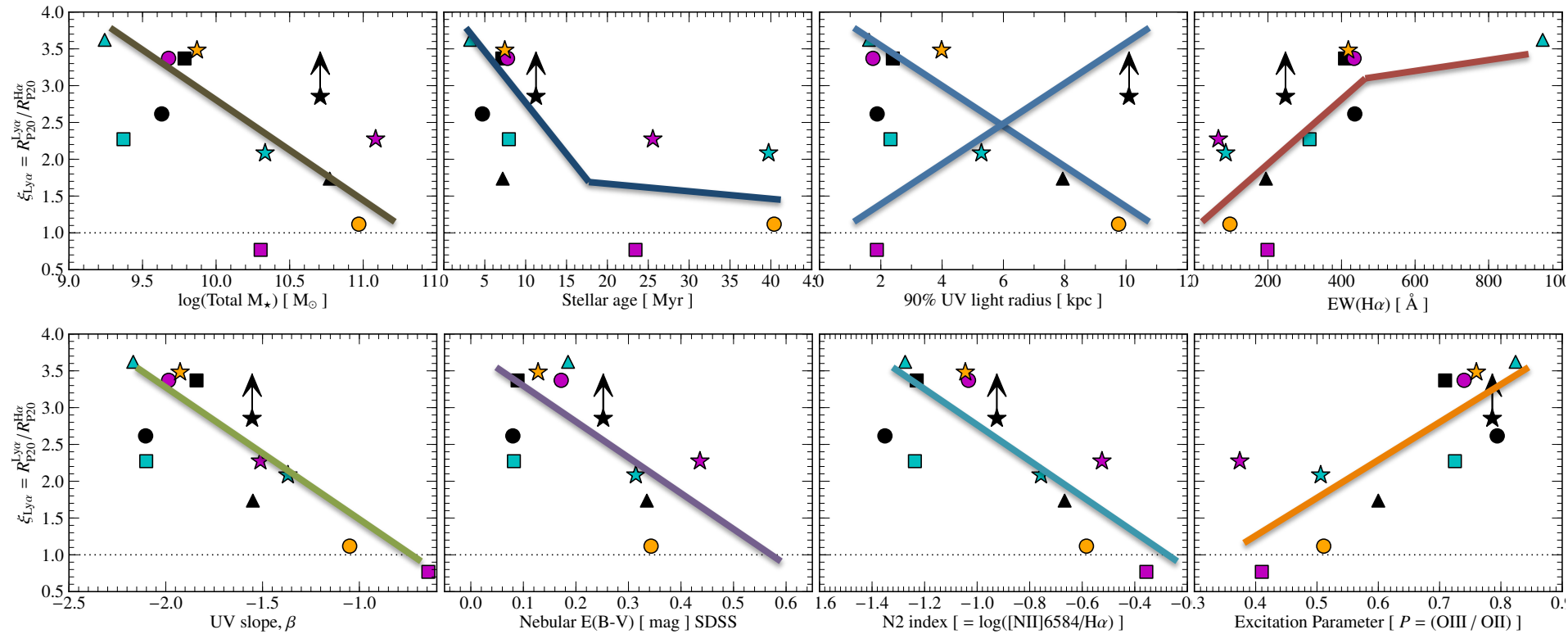
Large Ly α haloes occur in : **lower mass**, **younger**, **more compact**, **higher sSFR**, **bluer**, **less dusty**

Ly α haloes



Large Ly α haloes occur in : **lower mass**, **younger**, **more compact**, **higher sSFR**, **bluer**, **less dusty**, **lower metallicity**

Ly α haloes



Large Ly α haloes occur in : **lower mass**, **younger**, **more compact**, **higher sSFR**, **bluer**, **less dusty**, **lower metallicity**, and **more strongly ionizing** than non Ly α emitting galaxies.

From (alas!) yet a too small sample:

1. Haloes in MOST > resonance

- a. Ly α is extended relative to the UV and H α
- b. higher escape fractions $\leftrightarrow$ larger haloes
- c. 'normal' high-z apertures don't cause huge flux loss

2. Global properties

Ly α stronger, and haloes more extended in galaxies with :

- * lower age
- * lower mass
- * smaller sizes
- * fewer metals and less dust
- * higher sSFR
- * harder UV flux

3. **COMING NOW (cycle 21): eLARS** will complete a larger (28 more objects) and more representative sample of Ly α physics in local universe star forming galaxies.

Status of LARS and eLARS

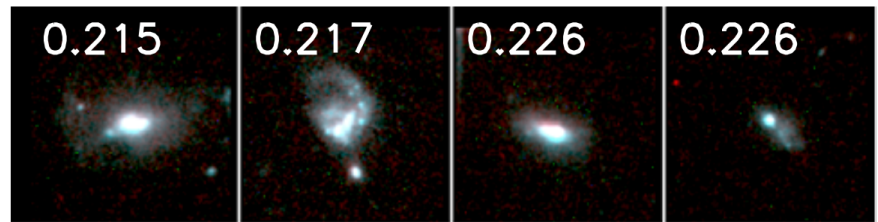
- LARS is the first local universe Ly α imaging + spectroscopy sample with a well defined selection function
- LARS allows Ly α laboratory astrophysics at spatial resolution of ≈ 30 pc
- While sources not necessarily fully analogous to high z objects, the goal is to understand the Ly α physics – how it couples to global and local properties
- LARS sample still small (14) and dominated by starbursts and mergers
- eLARS will provide a larger and more representative sample of Ly α physics in local universe star forming galaxies

What are $z=0.3$ LAEs?

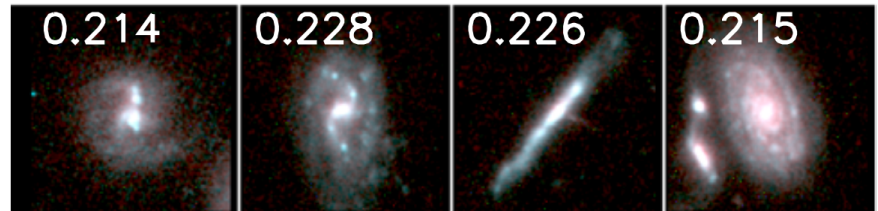
1. Compared to a UV continuum selected sample (LBG analogs?) the average LAE at this redshift interval has:

$z=0.3$ LAE sample

- lower metallicity
- bluer colors
- smaller sizes
- less extinction



$z=0.3$ UV continuum sample



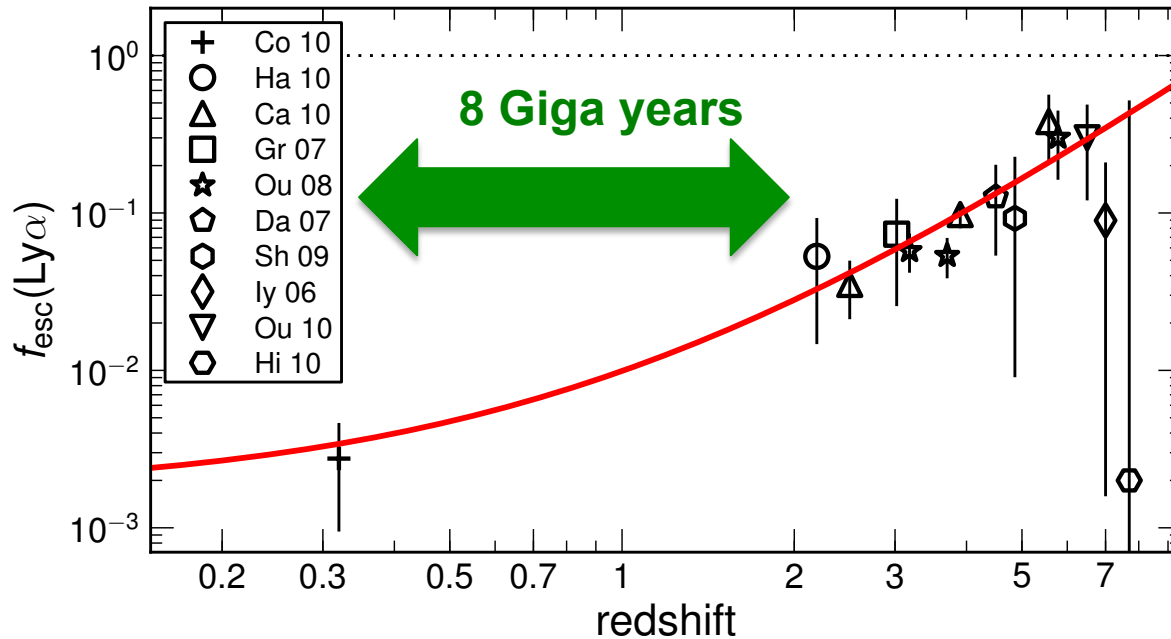
2. Evidence that LAEs at $z=0.3$ are in an **early stage** in a star-burst when the star-forming gas is still relatively metal poor and the star-forming region is small

Cowie et al. 2011

What are $z \sim 1$ LAEs and why studying them?

- $z \sim 1$ corresponds to a ~ 8 billion-year lookback time, i.e. when the universe was only 40% of its current age
- $z \sim 1$ marks the **start of the end** of the era of high star-formation rates. Lowest redshift where LAEs with luminosities analogous to high- z LAEs can be found.
- $z \sim 1$ is an era that can only be fully surveyed by space telescopes (i.e. with access to the rest far-UV). At $z \geq 2$, ground-based telescopes can observe Lyman α (1216 Å) .
- Relatively nearby population allows for detailed multi-wavelength studies to constrain their properties
- these LAEs will allow a follow up for LyC (from space)

$f_{\text{esc}}(\alpha)$ evolution with z



$z = 0.25 - 2.1$
unexplored

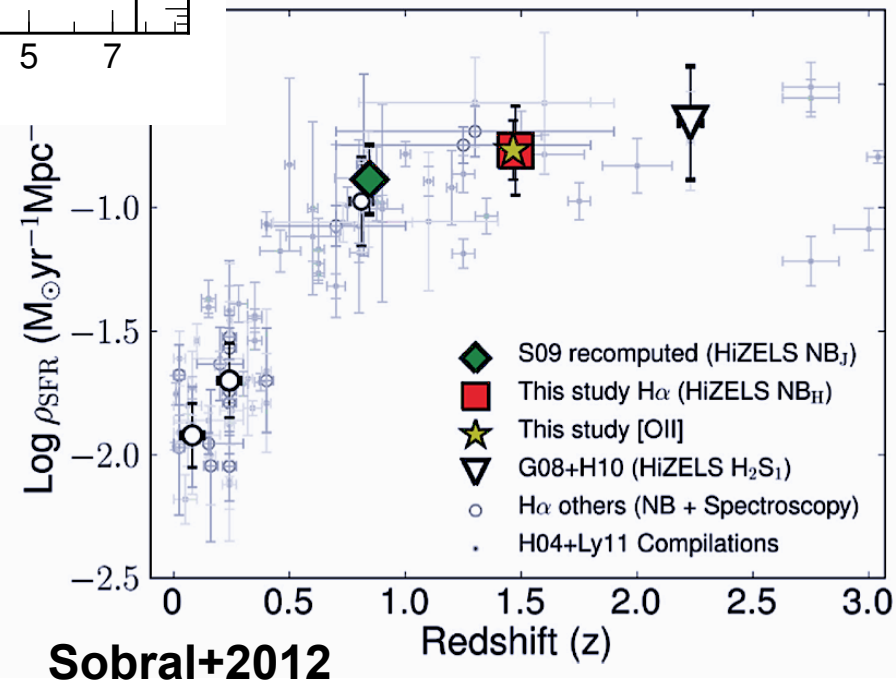
70% of cosmic history

M. Hayes + 2011

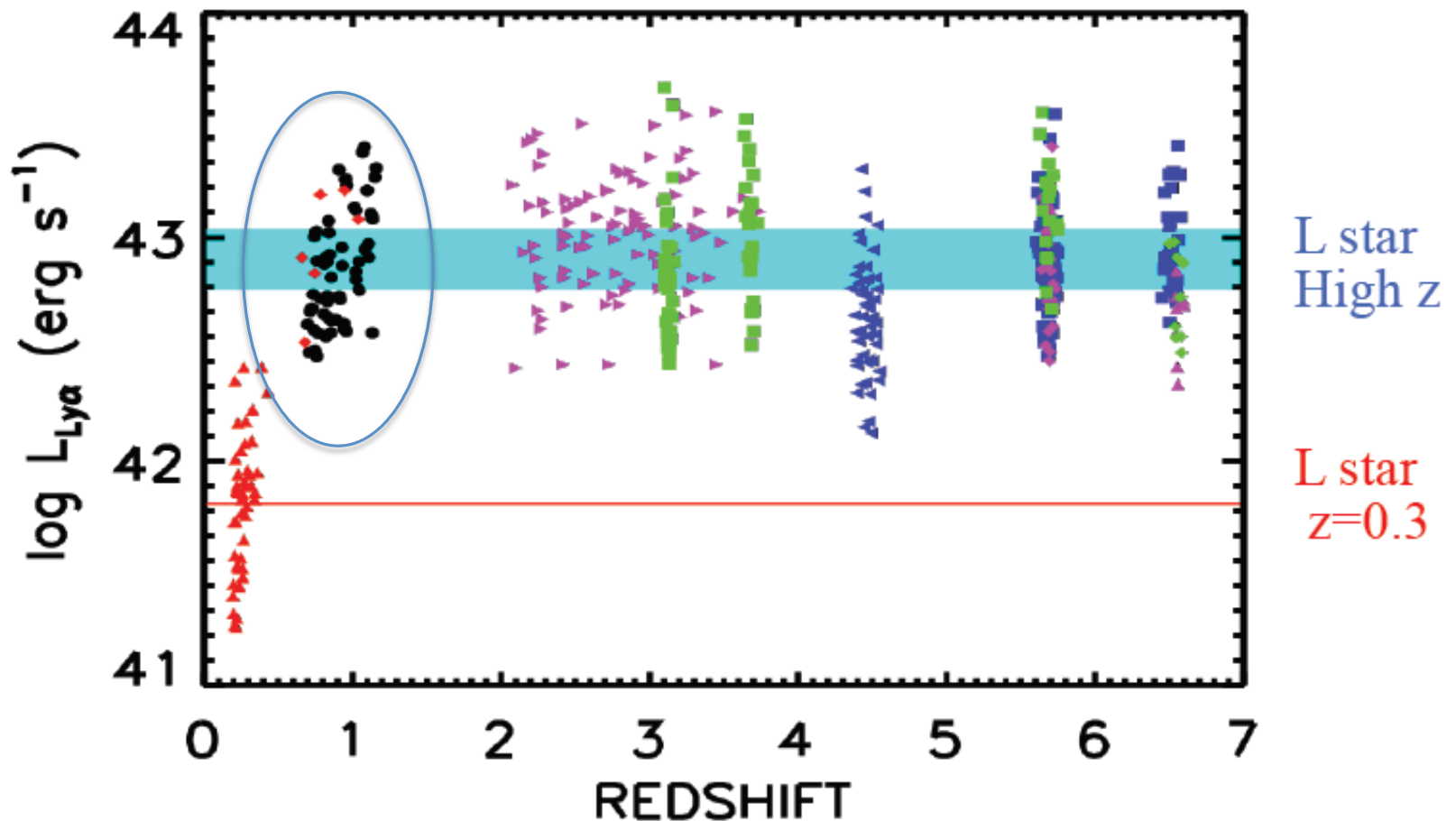
That dz just happens to be the point at which cosmic SFRD changes most rapidly

What is evolving?

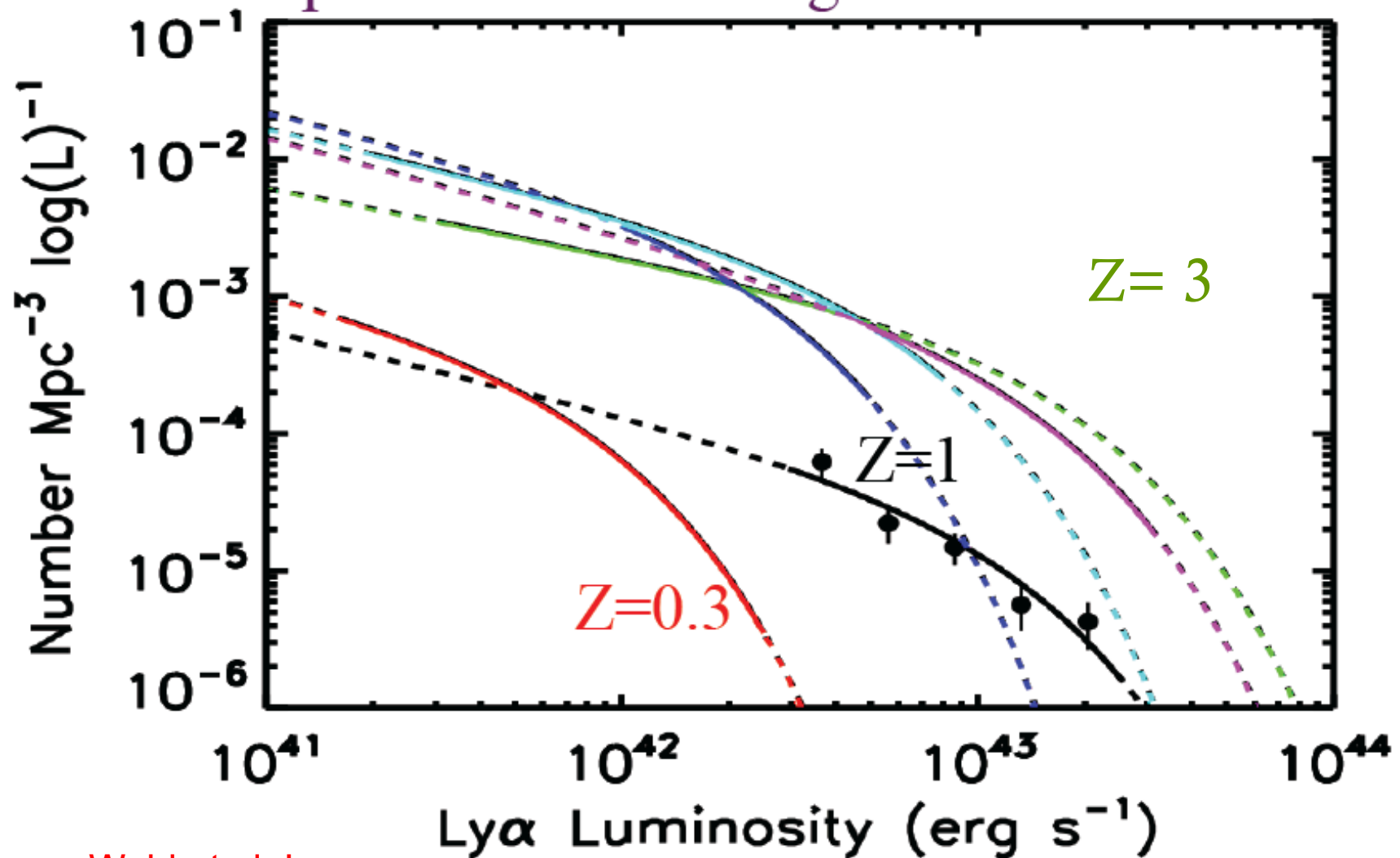
Dust? HI clumpiness?



High luminosity Ly α emitters appear at $\sim z = 0.8$



$z=0$ to z above 2 seems a key range in the LAE evolution:
Ideally we would like to have large cleanly selected
statistical samples of LAEs through this redshift interval



Wold et al. In prep

High z LAEs

- Beyond $z \sim 2$ a cosmic zoo is noteworthy. Difficult to anticipate LAE UV properties from « visible » spectrum.
- Ly alpha emission is larger in galaxies with small SFR, less massive (Ouchi, Stark...)
- Steidel et al.: diffuse Ly α halos: all LBGs would be LAEs if surveys were sensitive to 10 times lower Ly α surface brightness thresholds; similarly, essentially all LBGs would qualify as LAEs. (??)

High z LAEs

- Most LAEs at high z are of low mass, very blue and compact.
- Sources responsible for cosmic reionization remain elusive. Probably enough low-luminosity galaxies are in place at $z \sim 8$ (Bouwens et al 2013). But what is their ionizing output?

>> Testing the ionizing emissivity of mid and low- z galaxies is a pressing concern.

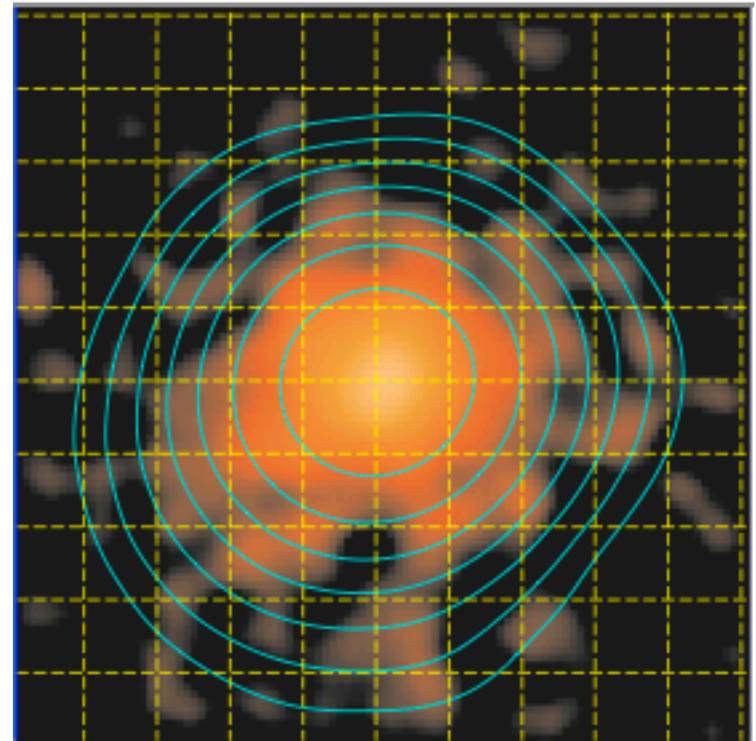
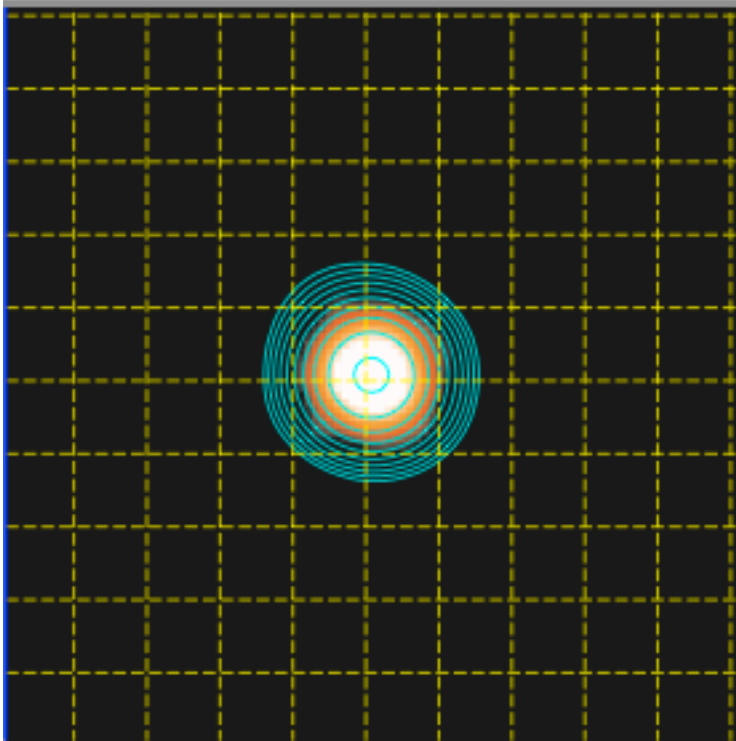
At $z < 1$ opaque to their LyCont (Cowie, Siana, McGreer, Leilet....)

At $z > 3$ emit a copious amount of LyCont (Steidel, Nestor, Iwata..)

- *(At very high $z > sky$ lines!!! wait for JWST for detecting Ly α in LBGs candidates unless we know the z and use the right NB filter).*

EXTENDED HALOES IN HIGH-Z GALAXIES

Steidel et al. 2011

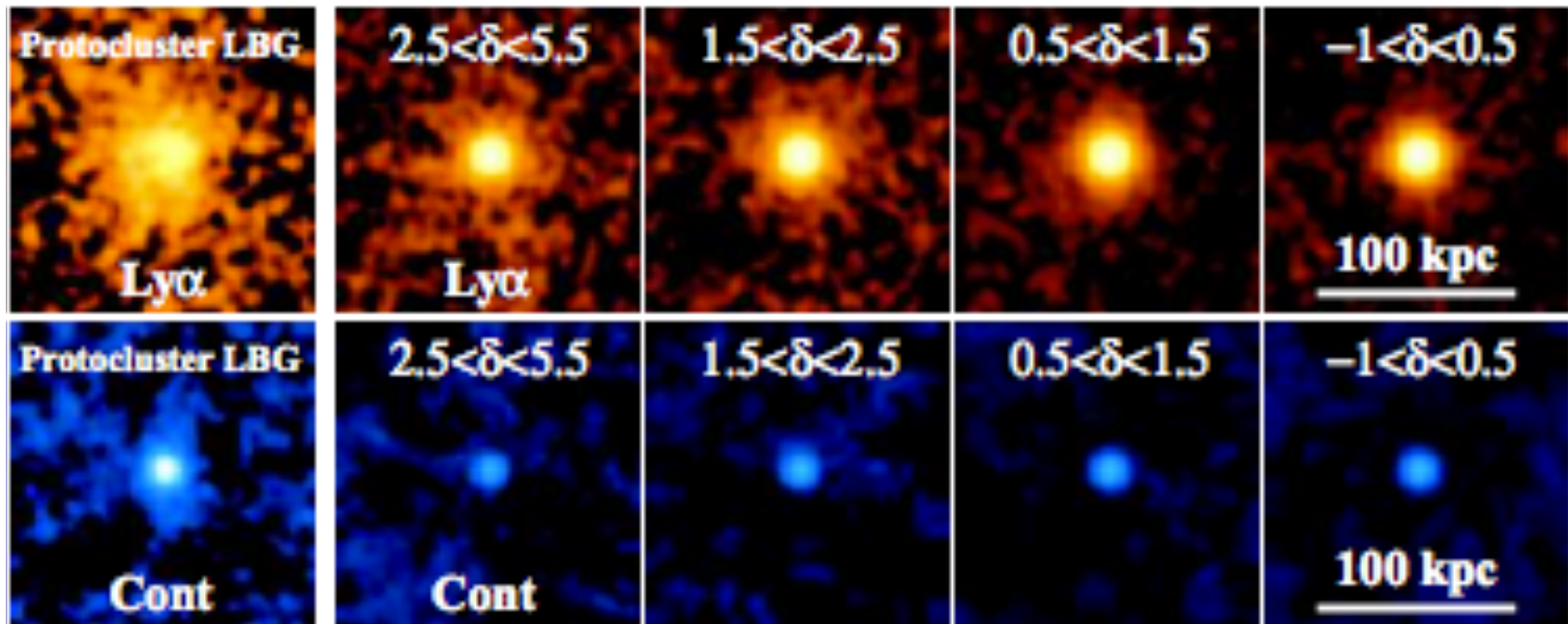


stacking 92 objects 900 hours integration at Keck!

Ly α more extended than UV continuum

At $z=2$ MUSE will do better

Ly α Haloes at high z



Matsuda+2012

Extension is also function of environment

Extended Ly-alpha, as well as galaxy statistics trace out gas distribution in circumgalactic regions

Ly-alpha: future space missions

- Why? $\text{Ly}\alpha$ being a resonant line its photometry is biased. High – z science MUST calibrate against nearby galaxies.
- Need to explore the ionizing spectra of SF dwarf galaxies (re-ionization problem)
- Surveys at $z \sim <0.8>$ will tell about cosmic evolution (across $\frac{3}{4}$ of the Universe age), and provide a remarkable sample for further work.
- Reionisation: find out about the link, if any, between $\text{Ly}\alpha$ and LyC in intrinsically faint SF galaxies. Search and study faint low metallicity $\text{Ly}\alpha$ emitters.
- MESSIER, WSO, CUBES ...

Ly α : future projects

- For Ly α , to $z < 2$ it includes **blind imaging surveys** using **BOTH** Ly α and UV continuum selections (~ 1000 objects)
 - Measure faint-end slope of the LF
 - Ly α fraction among galaxies
 - How galaxies evolve and why!?
- Implies synergies with ground-based telescopes (MUSE ELTs), space-based NIR platforms (EUCLID/WFIRST, JWST) and radio antennae (ALMA and SKA)

Basic technical requirements

- **Sensitivity (to well constrain LF):** reach $1/10 L_{\star}$

hence: $f = 2 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$

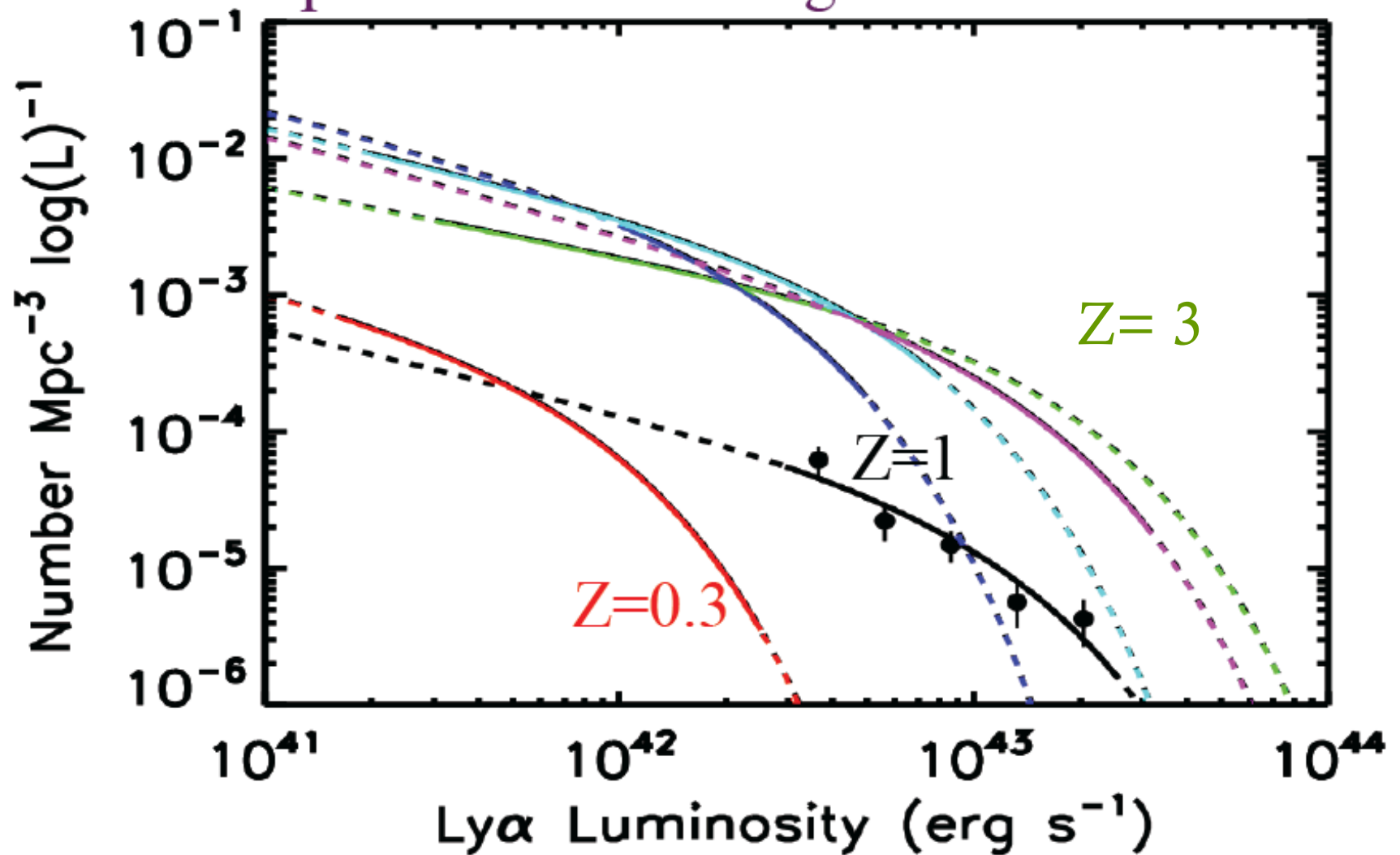
(22 hours at the HST with ACS/SBC for a S/N of 5 if point source)

➤ need a large UV-optimized mirror or high QE detectors

- **Field of view:**

interpolating between $z=0.3$ and $Z=2$ to $z=0.8$ we can estimate the density of galaxies:

$z=0$ to z above 2 seems a key range in the LAE evolution: Ideally we would like to have large cleanly selected statistical samples of LAEs through this redshift interval



A. Wold et al. In prep

Basic technical requirements

- **Sensitivity (to well constrain LF):** reach $1/10 L_{\star}$
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- **Field of view:**

interpolating between $z=0.3$ and $Z=2$ to $z=0.8$ we can estimate the density of galaxies: to get around 1000 or 100/bin

volume 600 000 Mpc^3 to be explored

FoV > WFPC3 but < GALEX

Final note:

Observations of Ly α emitters in the Local Universe will remain possible only as long as ACS, STIS and COS remain operational on the HST.

The post-HST era will be a *dark age* for local Universe UV astronomy, unless some ongoing projects mature and become a reality.