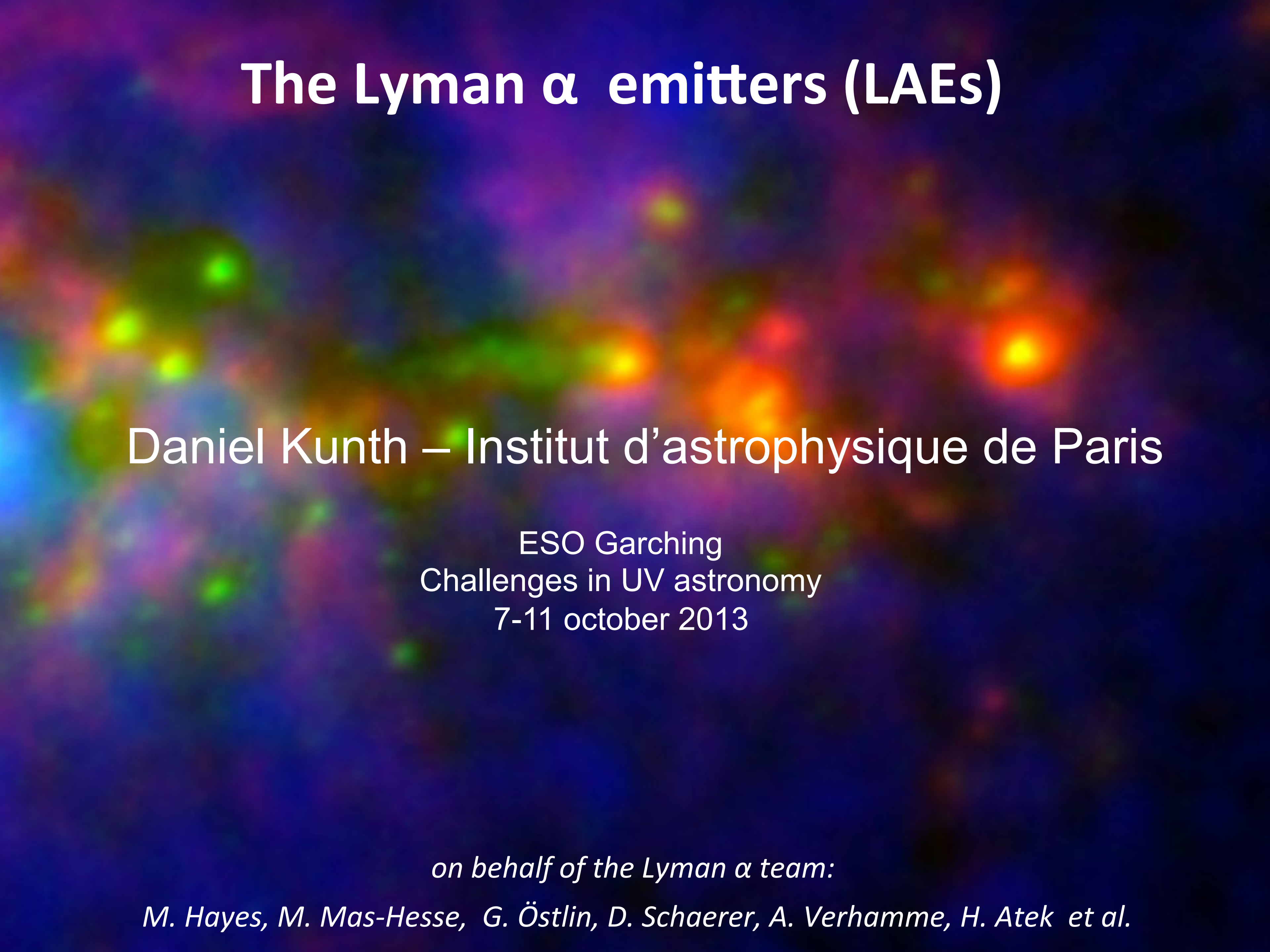


The Lyman α emitters (LAEs)

Daniel Kunth – Institut d'astrophysique de Paris

ESO Garching
Challenges in UV astronomy
7-11 october 2013

on behalf of the Lyman α team:

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


Lyα

Lyα: a cosmic line

The Lyα line reprocesses roughly 40 per cent of the intrinsic ionizing energy ($h\upsilon > 1$ Ryd).
Such a high-contrast feature allows Lyα surveys to probe the most abundant populations of faint low-mass galaxies..

Moreover Lyα is a resonant line, therefore it encodes further information that is unique and exclusive to the n = 1 -> 2 transition.

Specifically it also enables:

- Estimates of kinematic and gaseous properties of the ISM
- Star formation rate SFR(Lyα) and its evolution with z
- Luminosity function LF(Lyα) 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

…. an impressive toolkit for a single monochromatic feature!

Lyα: a cosmic line

Lyman alpha emitters (LAEs)

- A galaxy with SFR = 2 M⊙ / yr. gives:

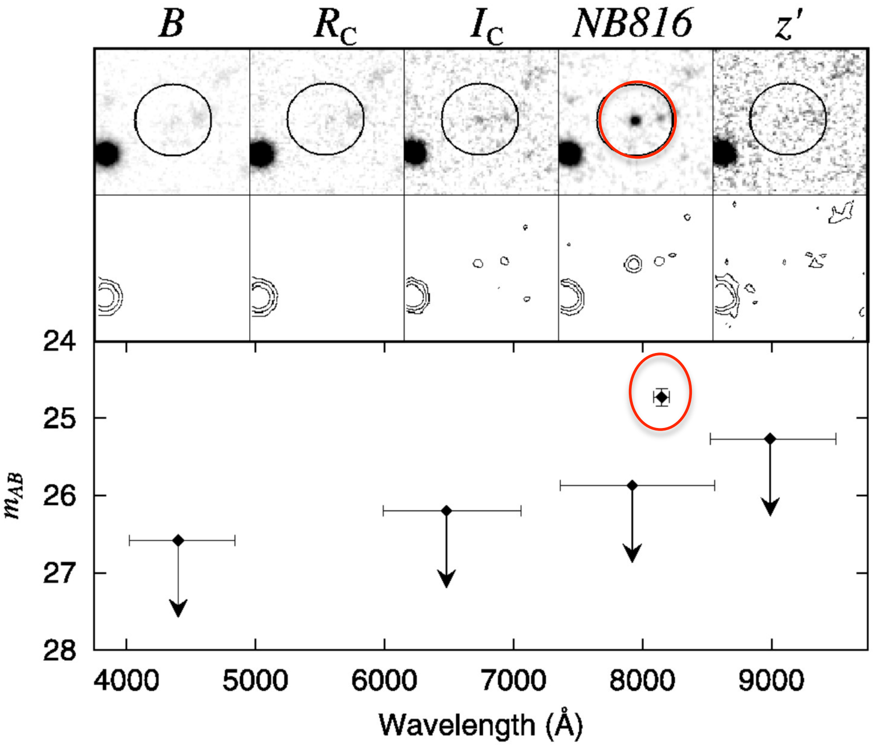
  L(Lyα) = 2.2 x 10^{42} erg/s

  at z=6: f(Lyα) = 5.5 x 10^{-18} erg/s/cm^2

- EW(Lyα) can reach 240 Å or more (Charlot & Fall 1993, Schaerer 2003)

- Imaging surveys: using narrow band filters (in general EW > 20 Å)

- Complement the LBG technique



Taniguchi et al. 2003

Lyα observations of low z galaxies

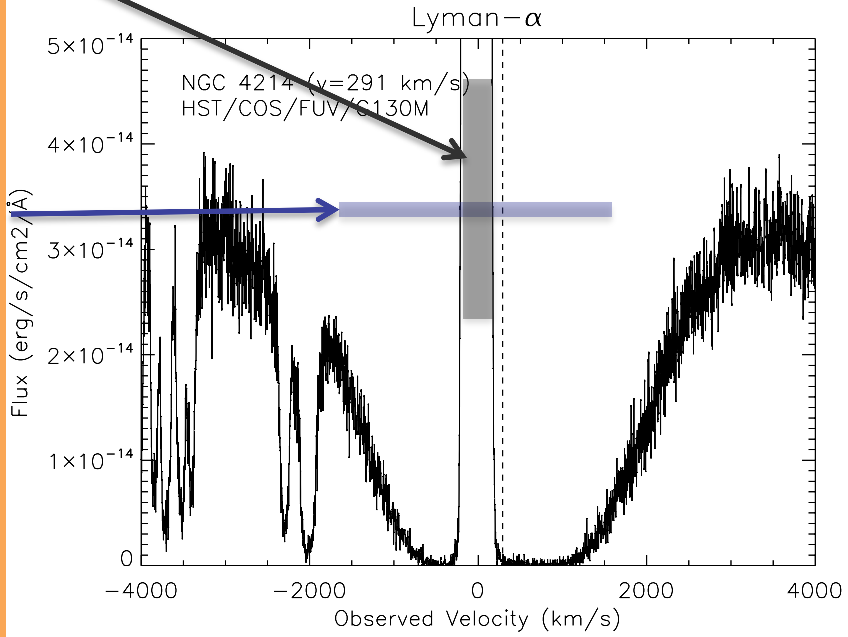
- Best way to understand the physics before going to the astrophysics is to study a local sample.

Why not getting too local?

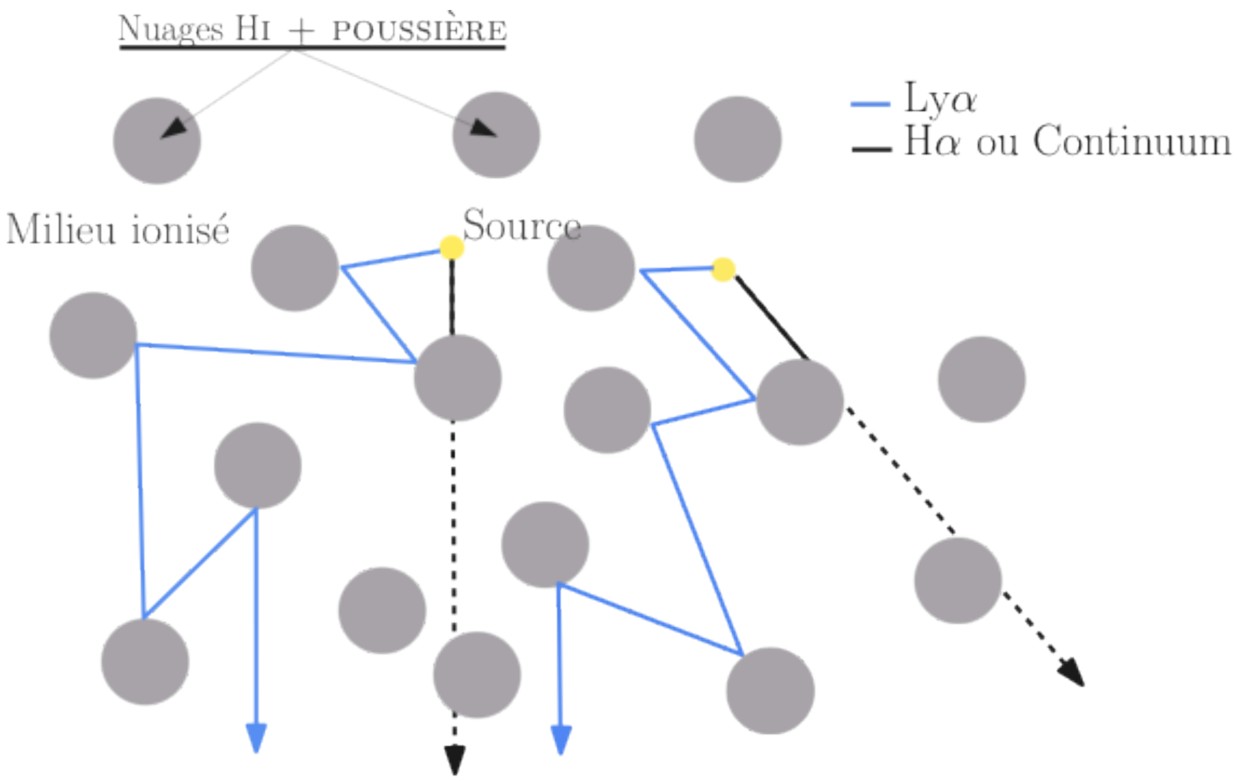
- Intense geocoronal Lyα emission at z=0

- 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.…



key point: Ly α is a resonant line!



The game is to retrieve the true number of Ly α photons emitted at the source! What are the dominant parameters that control the line transfer?

Lyα observations at low z

Observed Lyα line properties depend on:

- Metallicity / dust (IUE)
- Clumpiness of H I gas + dust (GALEX)
- 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(Lyα) and Lyα/Hß do not correlate with extinction or [O/H]. 2) ISM geometry is dominant effect
- ✓ Scarlata+ 2009
  - **Data:** 31 z=0.3 emitters identified by GALEX
  - **Results:** Lyα/Hα & Hα/Hß well reproduced by clumpy dust screen
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  - **Results:** 4 emitters have HI & HII offset by up to 200 km/s
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  - **Data:** I Zw 18 observed with HST/STIS
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- ✓ Mas-Hesse 2003
  - **Data:** 3 galaxies observed with HST/STIS
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  - **Data:** HST WFC3/UVIS+ACS/SBC optical+FUV images
  - **Results:** aperture size and spatial resolution matter

A. Wofford, IAP (2013)

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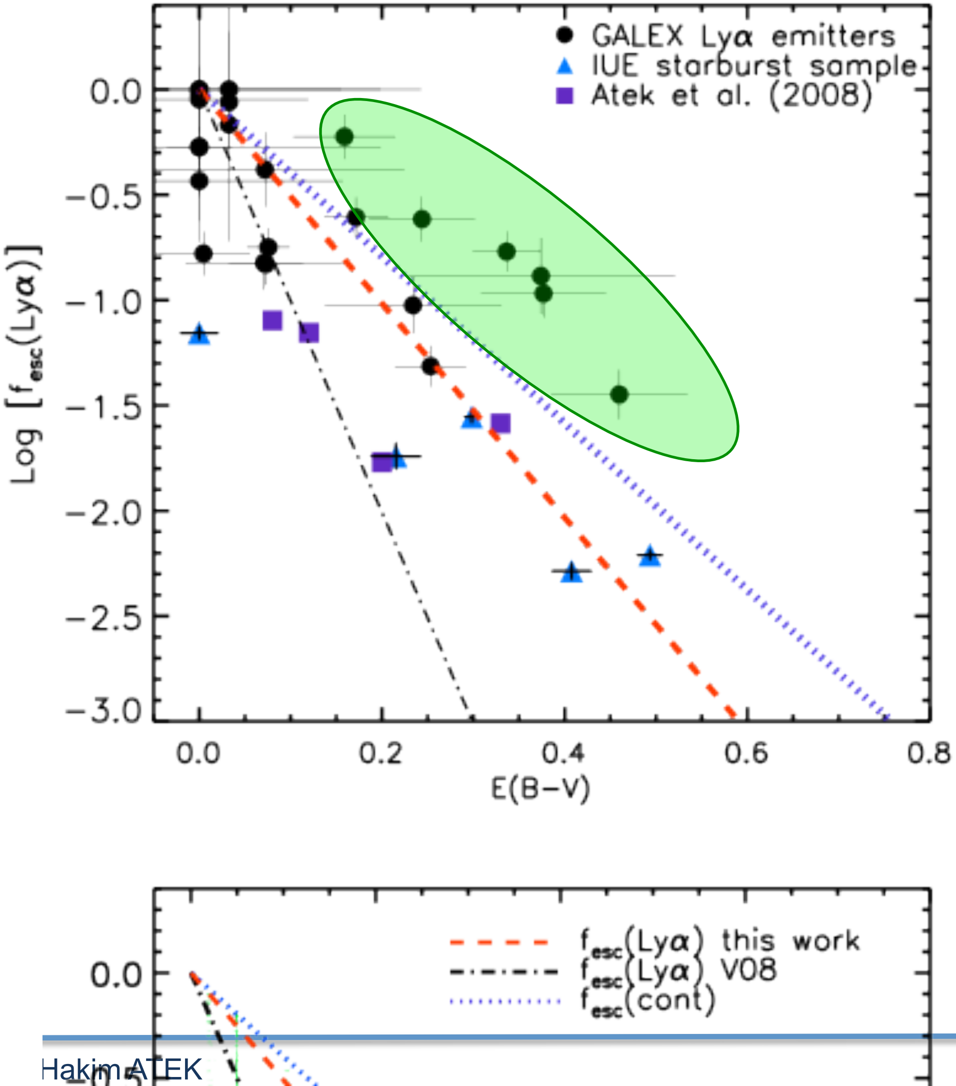
A. Wofford, IAP (2013)

Empirical Estimate of Lyα Escape Fraction

Atek et al. 2009b



fesc(Lyα) = f(Lyα) / 8.7 × f(Hα)cor

- fesc(Lyα) varies from 0.5 to 100 %
- fesc is sensitive to E(B-V)gaz

$$f_{esc}(\mathrm{Ly}\alpha) \;=\; 10^{-0.4\,k(\mathrm{Ly}\alpha)\,E(B-V)}$$

$$k(\mathrm{Ly}\alpha) \sim 12.7 \pm 0.4$$

•Some galaxies have fesc(Lyα) > fesc(cont)

→ Evidence for an inhomogeneous medium ?
Different extinction law ?
(Scarlata et al. 2009)

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- Clumpiness of H I gas + dust (GALEX)
- 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: Lya fainter!!!
  - **Results:** 1) W(Lyα) and Lyα/Hß do not correlate with extinction or [O/H]. 2) ISM geometry is dominant effect
- ✓ Scarlata+ 2009
  - **Data:** 31 z=0.3 emitters identified by GALEX
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  - **Data:** 8 galaxies observed with HST/GHRS
  - **Results:** 4 emitters have HI & HII offset by up to 200 km/s (Kunth et al. 1998). 4 absorbers, no offset.
- ✓ Atek+ 2009
  - **Data:** I 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}.
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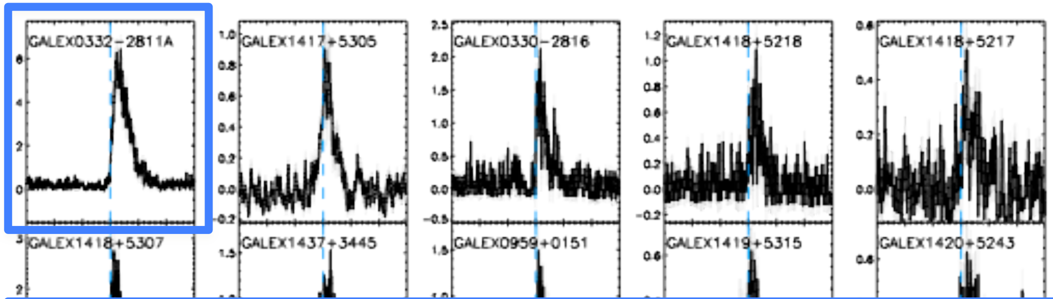
A. Wofford, IAP (2013)

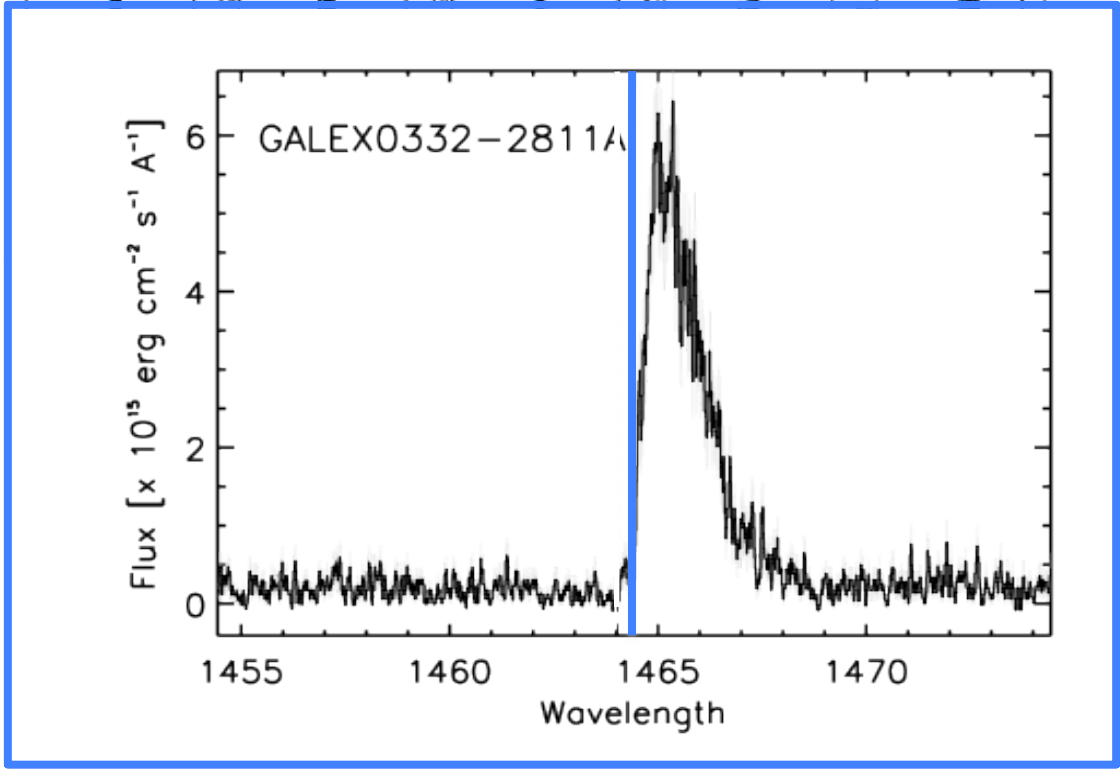
The Lyα Profile

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 Lyα photons can escape easier in the red wing of the profile because they are seen redshifted by the hydrogen atoms.



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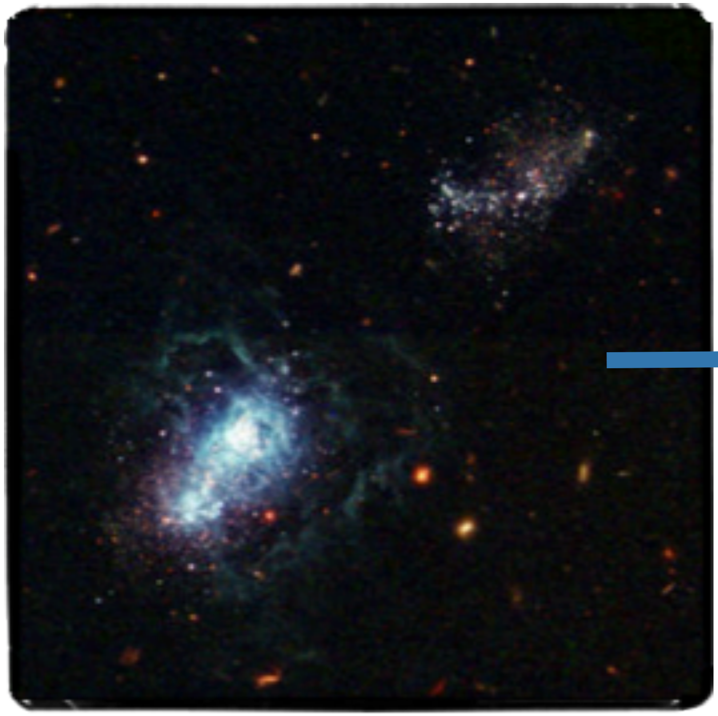
A. Wofford, IAP (2013)

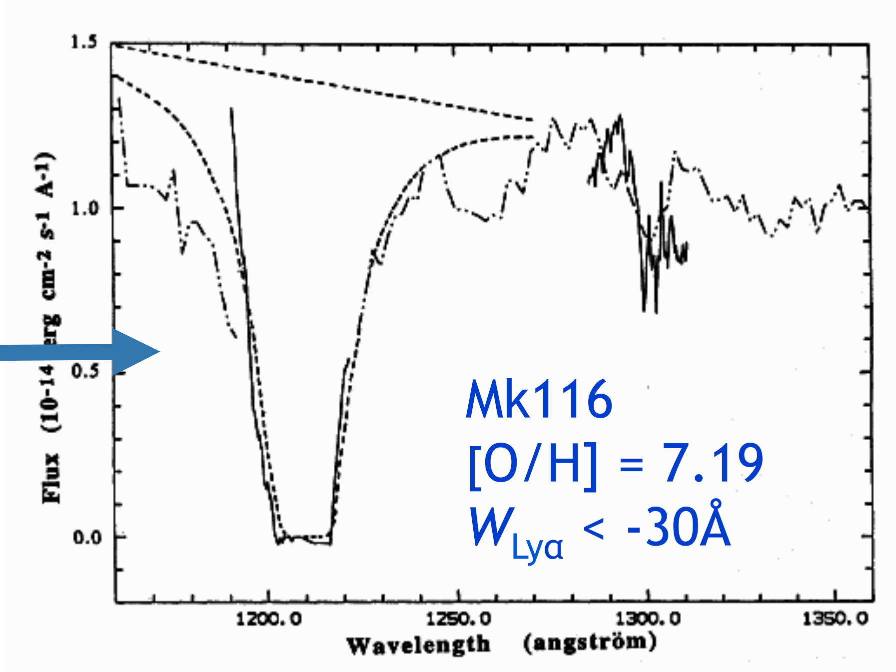
THE OBSERVATIONAL PUZZLE

NEW INSIGHT WITH HST

GHRS results by Kunth et al. (1994) :

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





Mk116
$[O/H] = 7.19$
$W_{Ly\alpha} < -30$Å

modelled by Atek + 2009 !!

Lyα observations at low z

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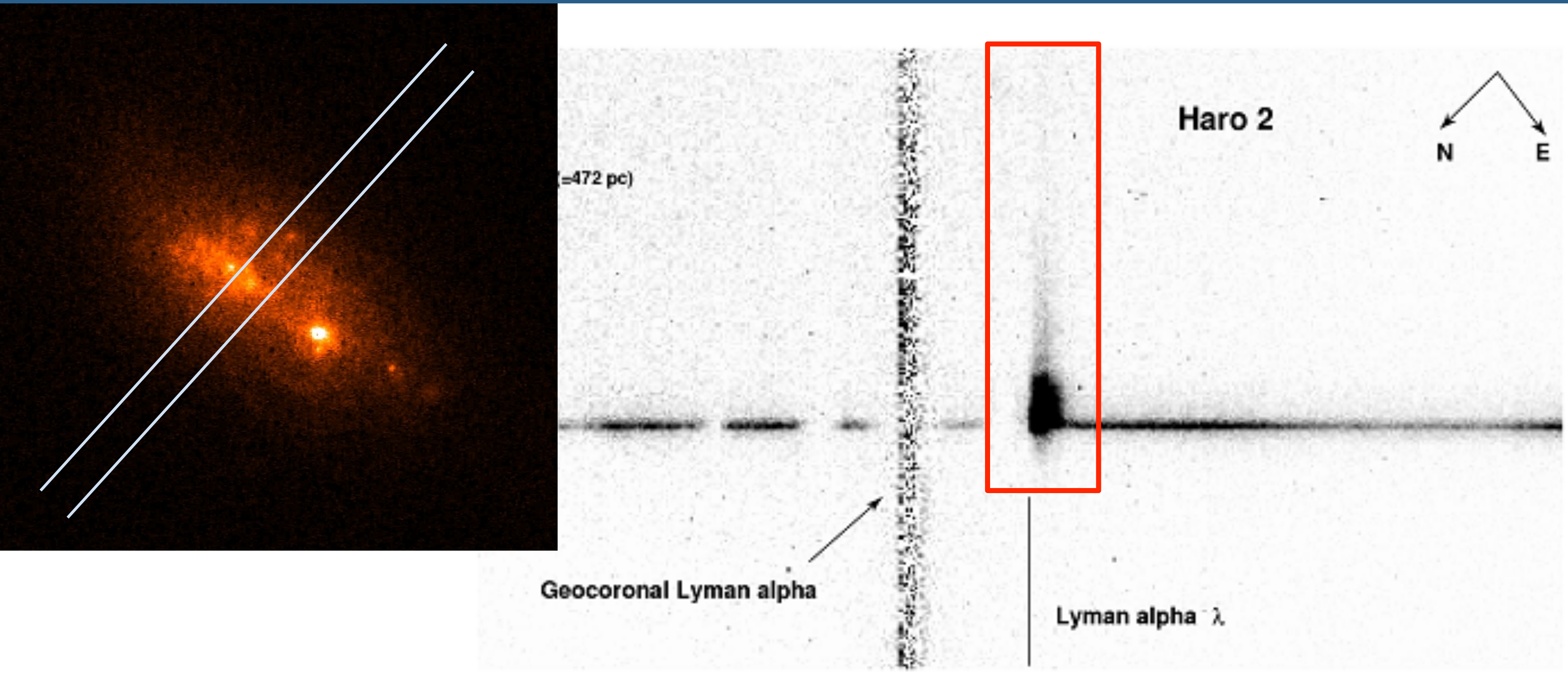
Need for Lyα imaging



Mas-Hesse et al. (2003)

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

→ Imaging needed

Lyα observations at low z

Observed Lyα line properties depend on:

- Metallicity / dust
- Clumpiness of H I gas + dust
- Gas kinematics
- Column density of neutral gas, N_{HI}
- Aperture size & position and spatial resolution
- imaging

Many parameters control the Lyα escape

✓ Giavalisco+ 1996
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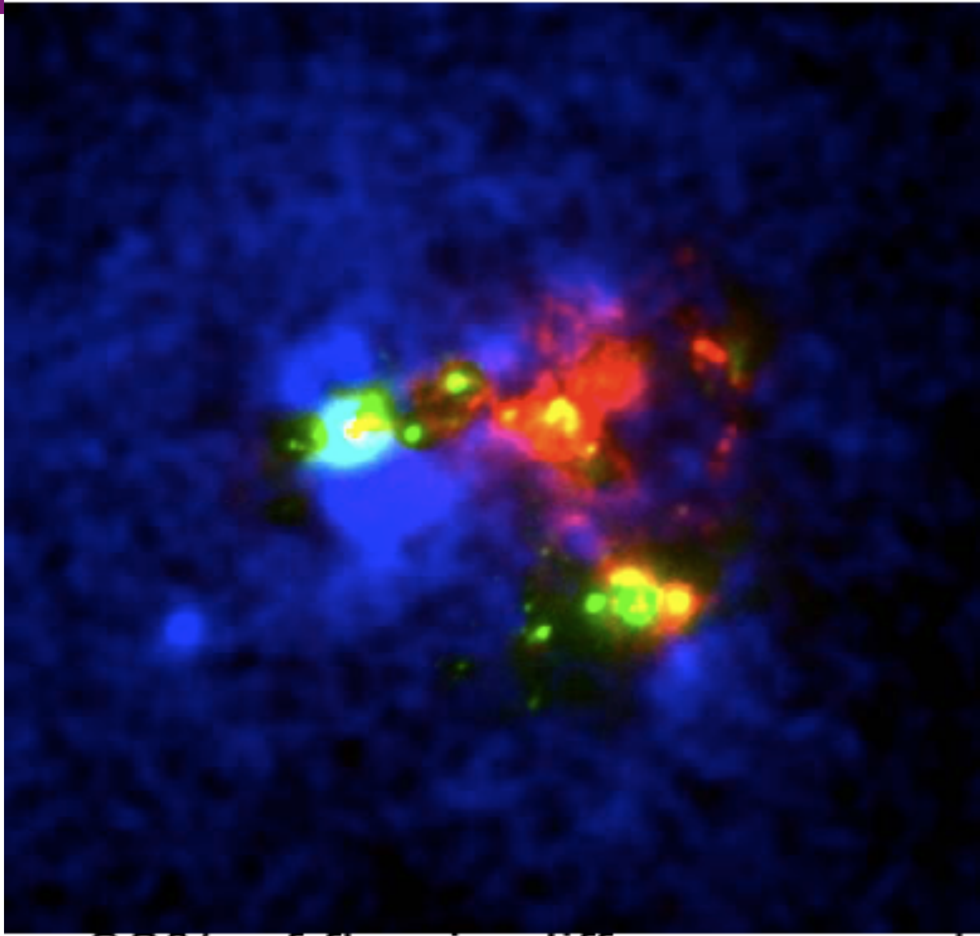
  - **Results:** aperture size and spatial resolution matter

A. Wofford, IAP (2013)

Why Lyman alpha extensive imaging?

Imaging allows to:

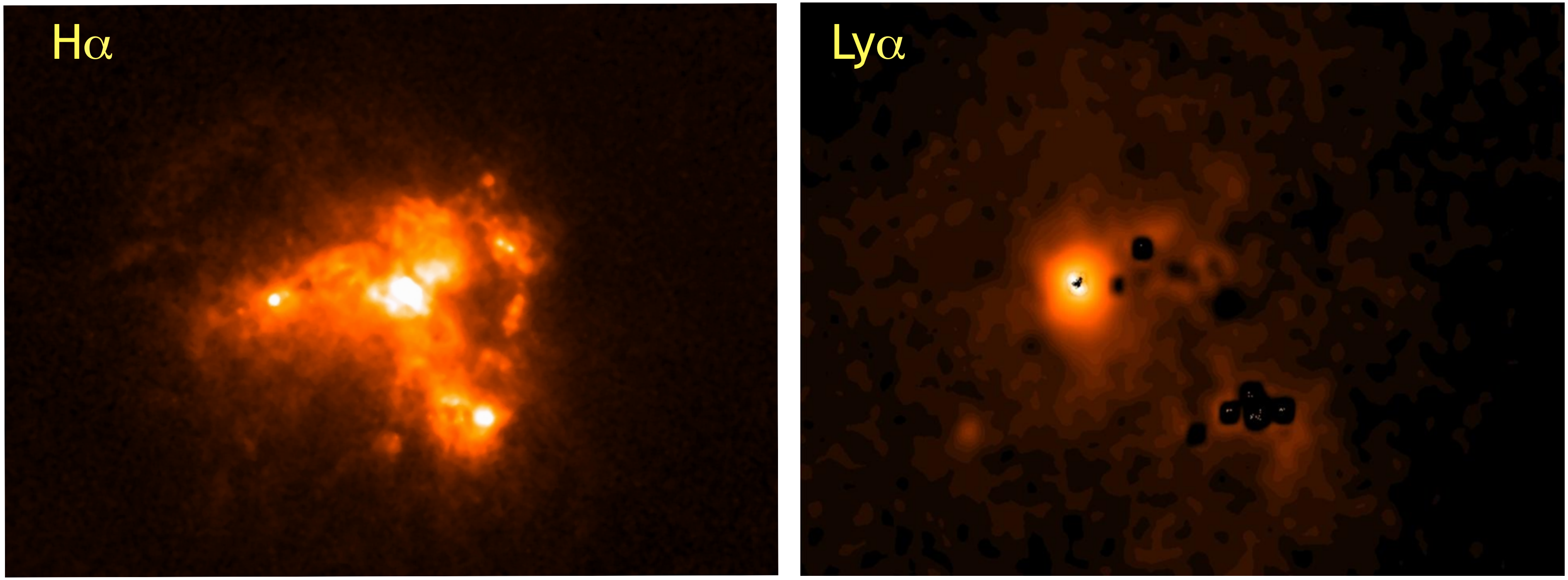
- study the spatial distribution of Lyα
- identify large scale diffuse Lyα emission from resonant scattering
- study porosity, inclination etc…
- study Lyα vs local conditions:
    - ionizing stellar population age
    - Uv continuum luminosity
    - dust, Hα
    - etc



- 90% of flux in diffuse compnt

- *use simulations (P. Laursen, A. Verhamme) to compare model and real galaxies*
- *+ COS and 3D spectroscopy, SED, NIR, radio data etc…*

HST Lyα Imaging



Haro 11

Atek et al. 2008

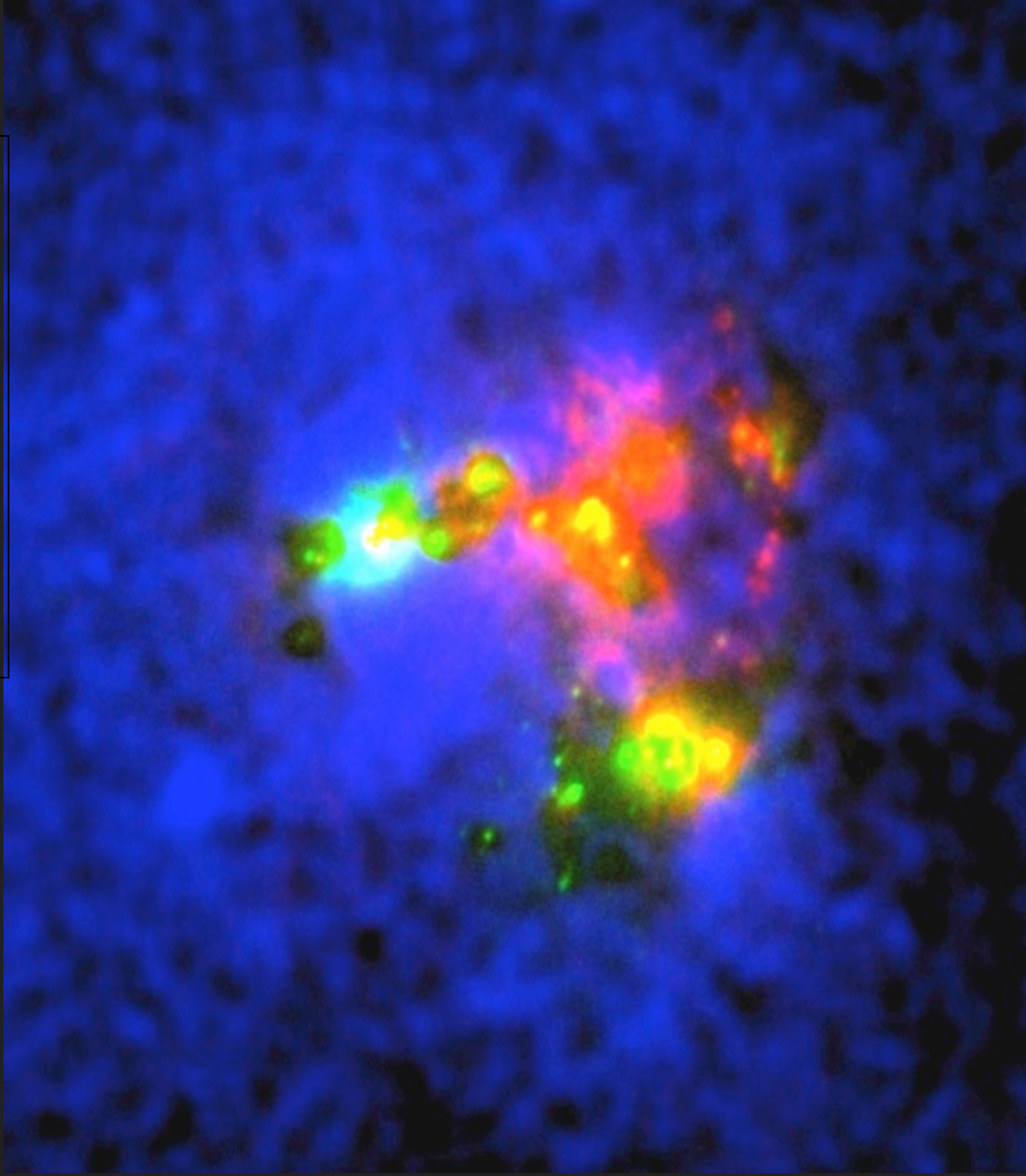
Ostlin et al. 2009

Lyα image does NOT ressemble the Hα image

- Large halo of diffuse Lyα emission with

90% of the total flux!

→ Evidence for the resonant scattering of Lyα photons into the ISM



Haro11: Lyα, Hα, UV, 8x8 kpc

LARS (> 2009) : The Lyα Reference Sample

The driving parameters ?

- Goal: create a reference sample for a complete analysis of Lyα properties (distribution, radiation transfer, effects of dust and neutral gas, kinematics, inclination…)
- Sample selection: GALEX + SDSS

Results: *M. Hayes+ 2013a, ApJ.L, 765, 27*
& M. Hayes + 2013b, ApJ. subm, arXiv:1308.6578

Who is LARS ?

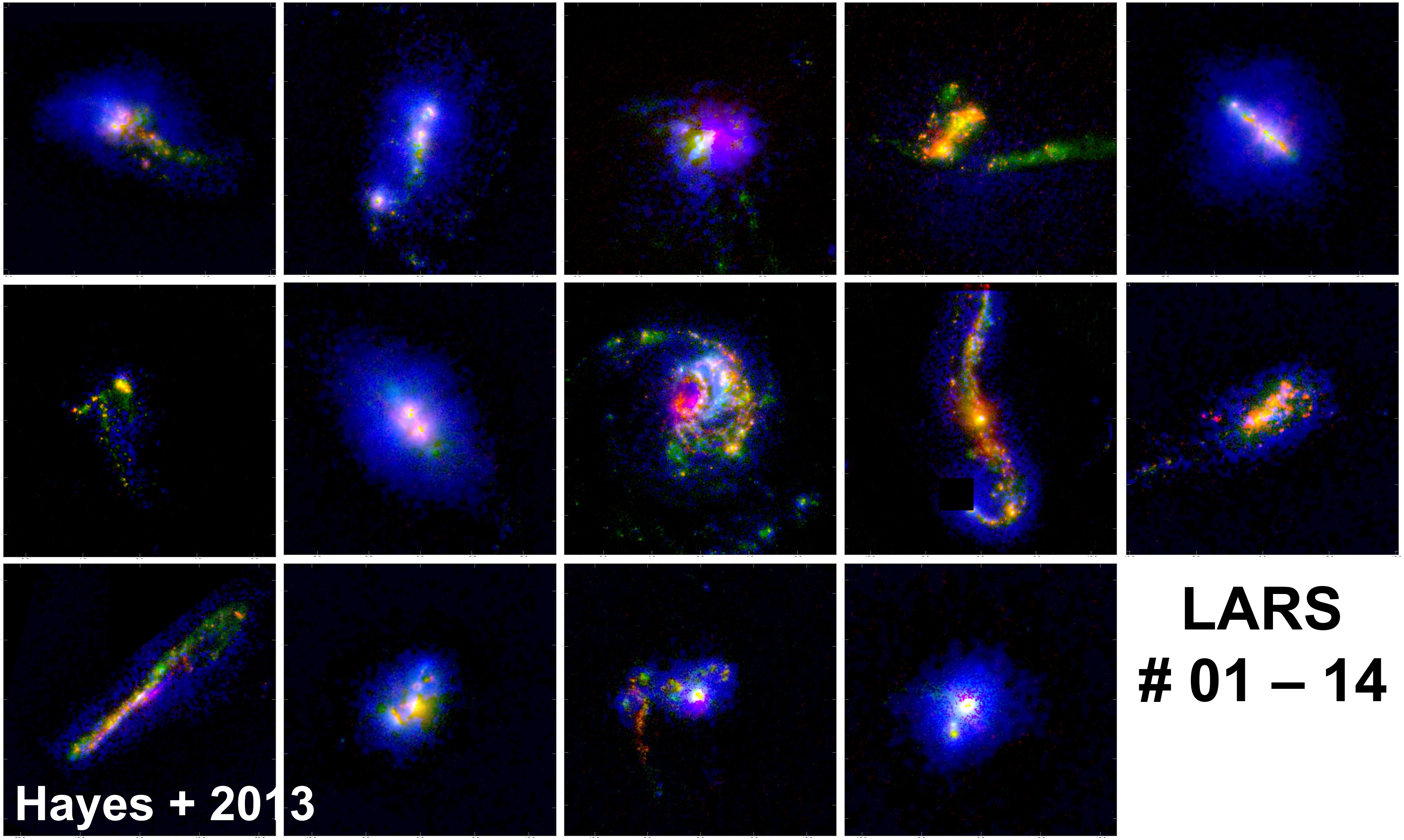
Göran Östlin, Stockholm, PI
Matthew Hayes, Stockholm, PI
Angela Adamo, Heidelberg
Florent Duval, Stockholm
Lucia Guaita, Stockholm
Thomas Marquart, Stockholm
Andreas Sandberg, Stockholm
Hakim Atek, Lausanne
Daniel Kunth, IAP, Paris
Claus Leitherer, STScI
Miguel Mas-Hesse, Madrid
Hector Oti, Unam

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

LARS sample selection

- GALEX + SDSS database
- Z = 0.028 to 0.110 and z = 0.134-0.192
- EW (Hα) > 90 Å (14 emission-line galaxies, strong SFR)
    - 3 ACS/SBC long pass filters
    - WFC3 U(F336W), B(F438W), I(F775W)
    - Hα and Hß from WFC3 or ACS ramp filters

Haloes *(but 6 orbits per targets)*

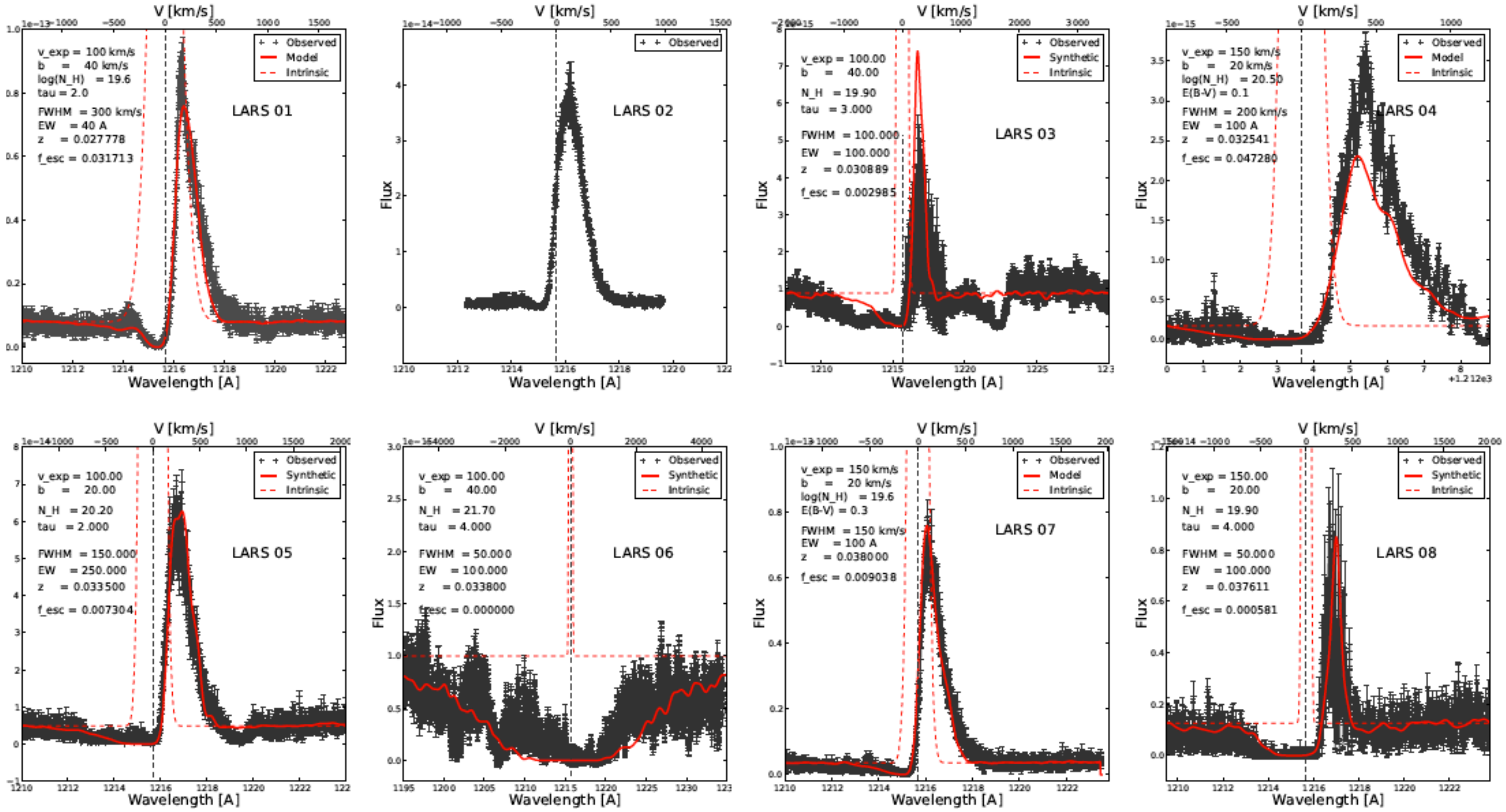


Hayes + 2013

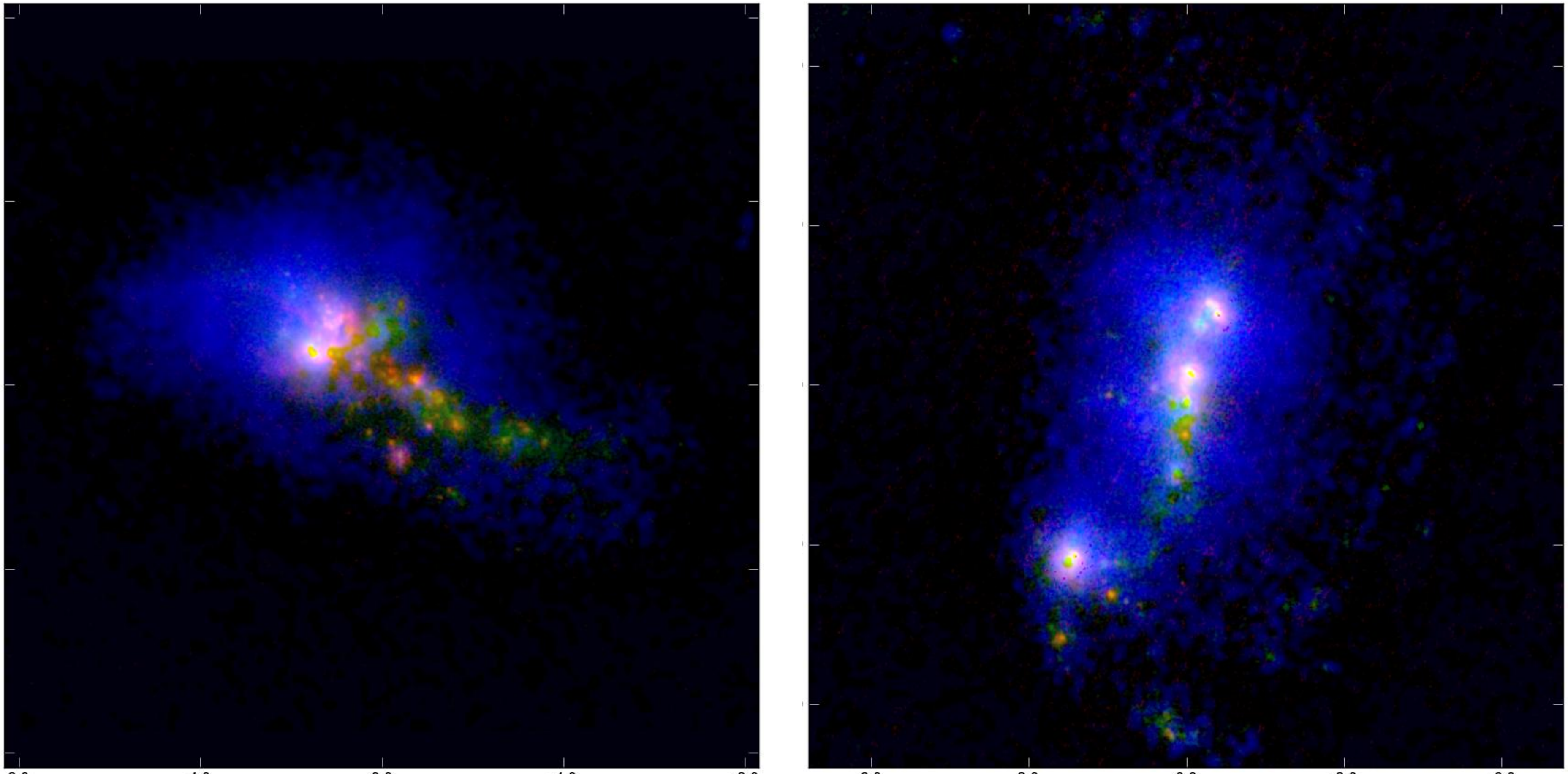
LARS
 # 01 – 14

FUV + Hα + Lyα

COS spectroscopy *(Artipova et al. 2013)*

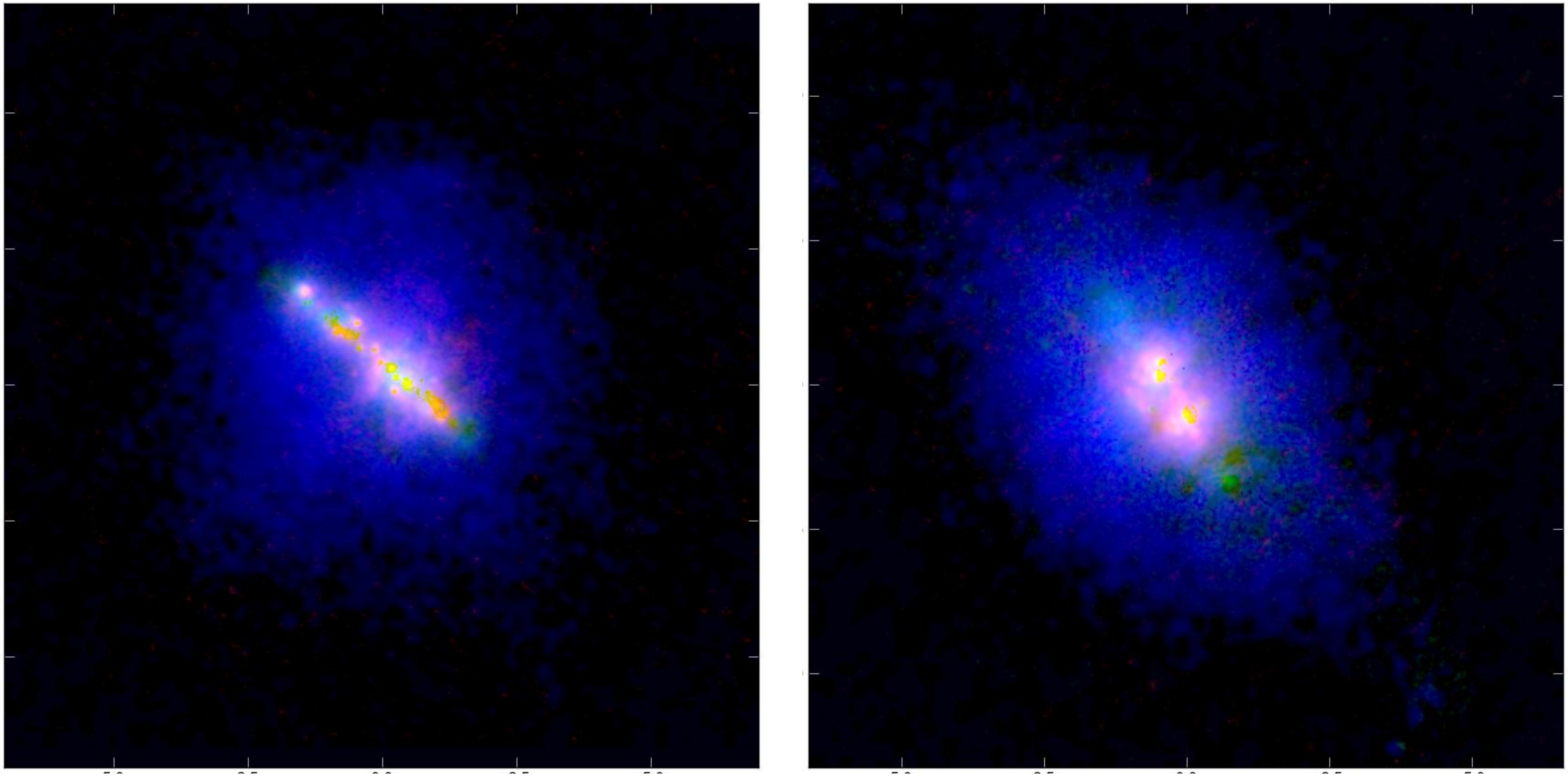


Haloes



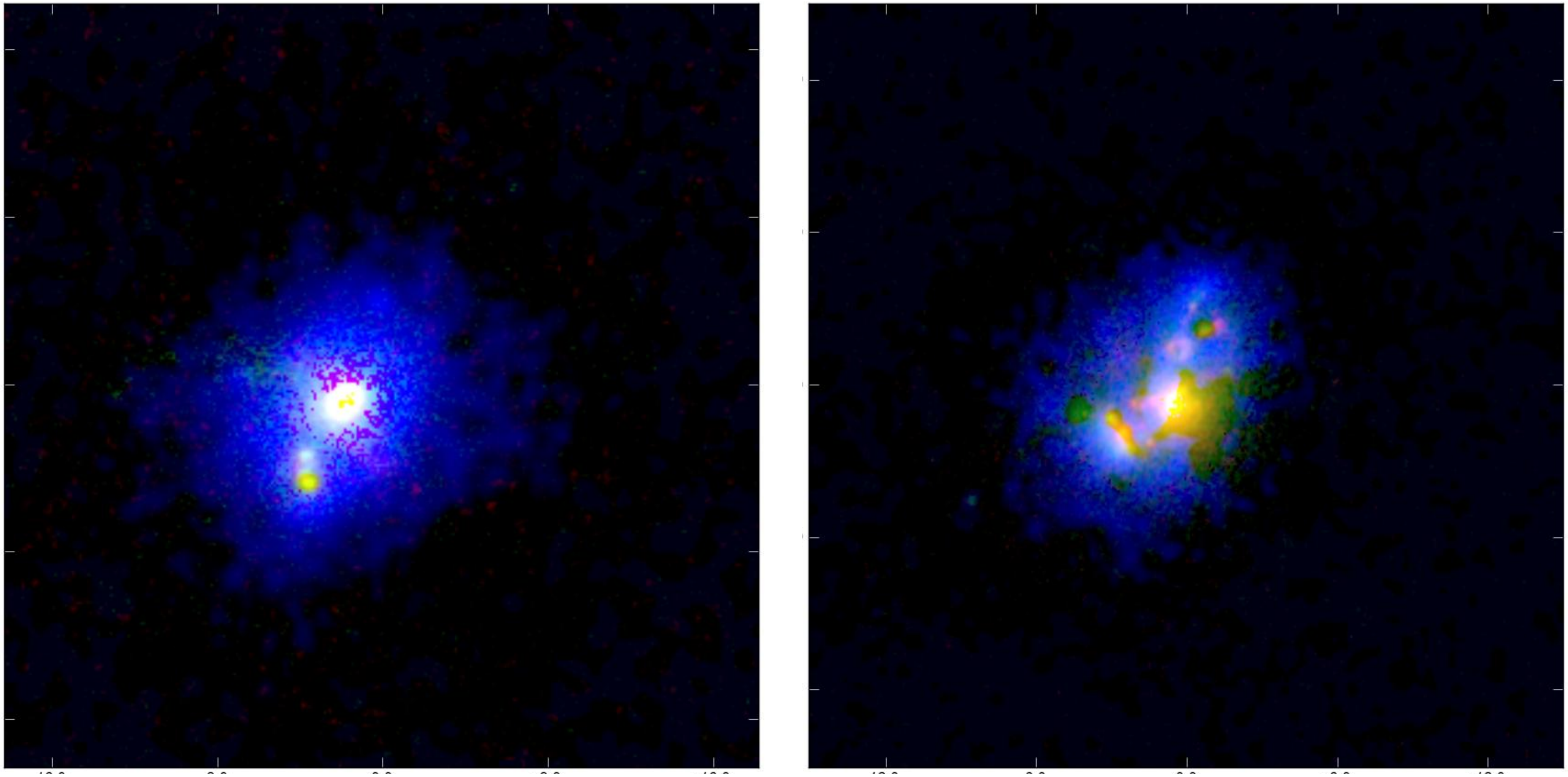
FUV + Hα + Lyα

Haloes



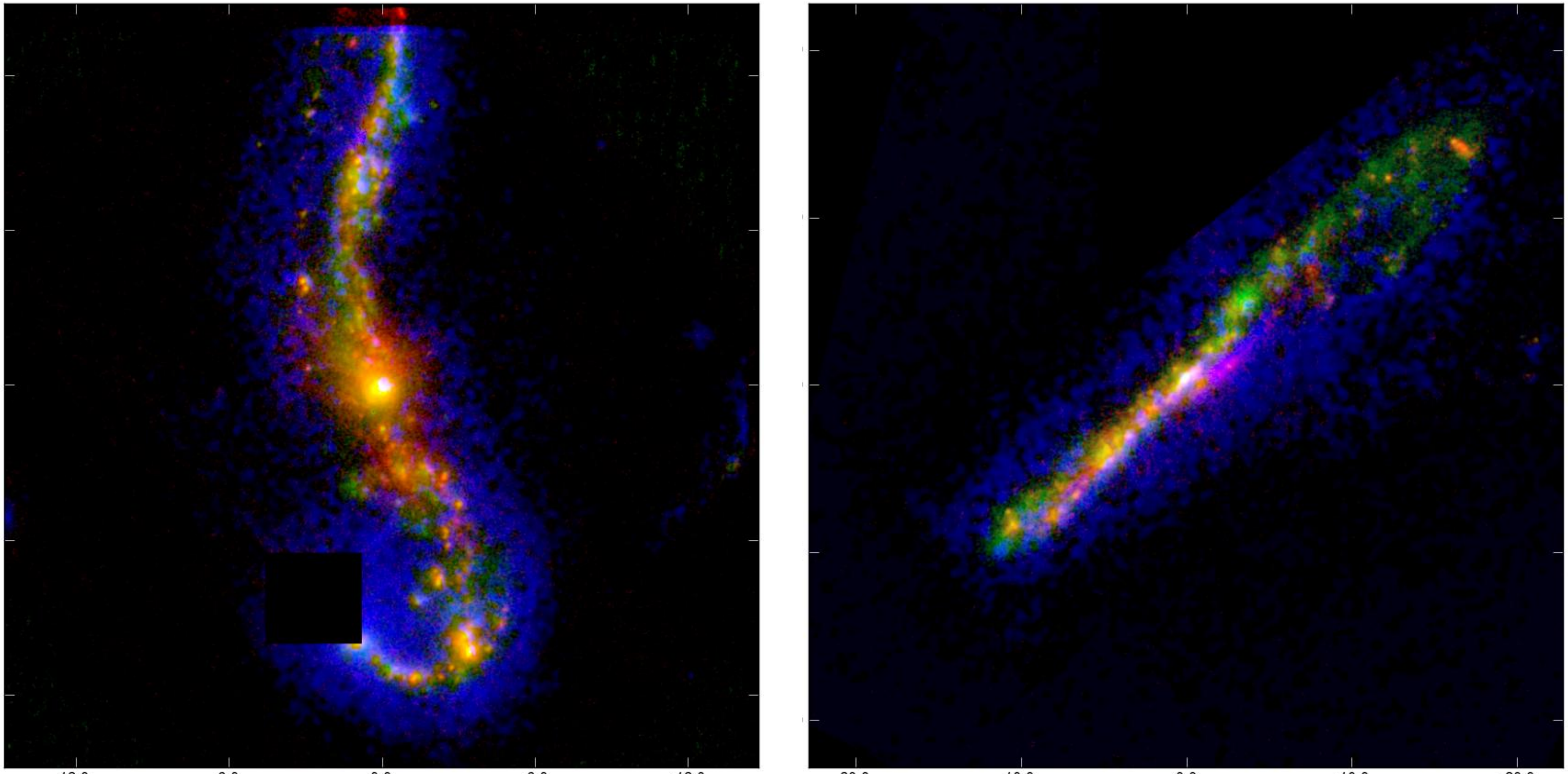
FUV + Hα + Lyα

Haloes



FUV + Hα + Lyα

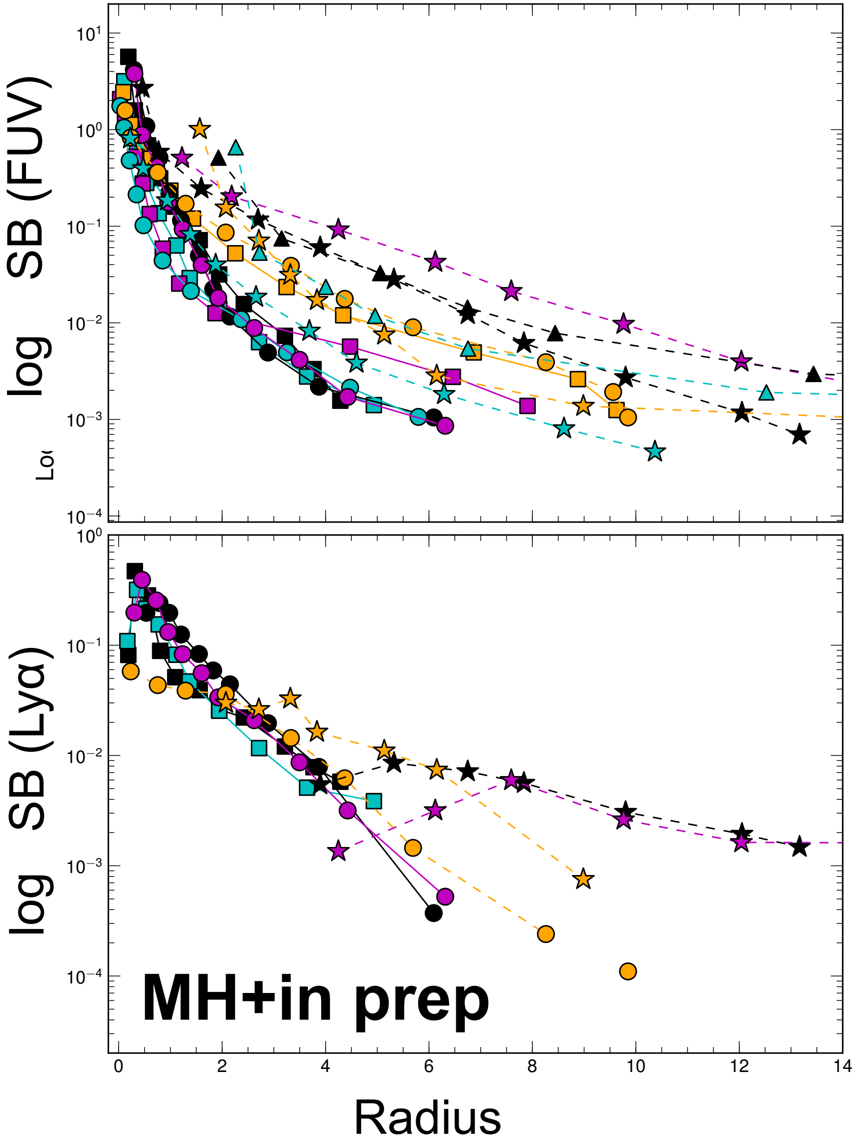
Haloes (mapping HI)



FUV + Hα + Lyα

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

Lyα brightness profiles



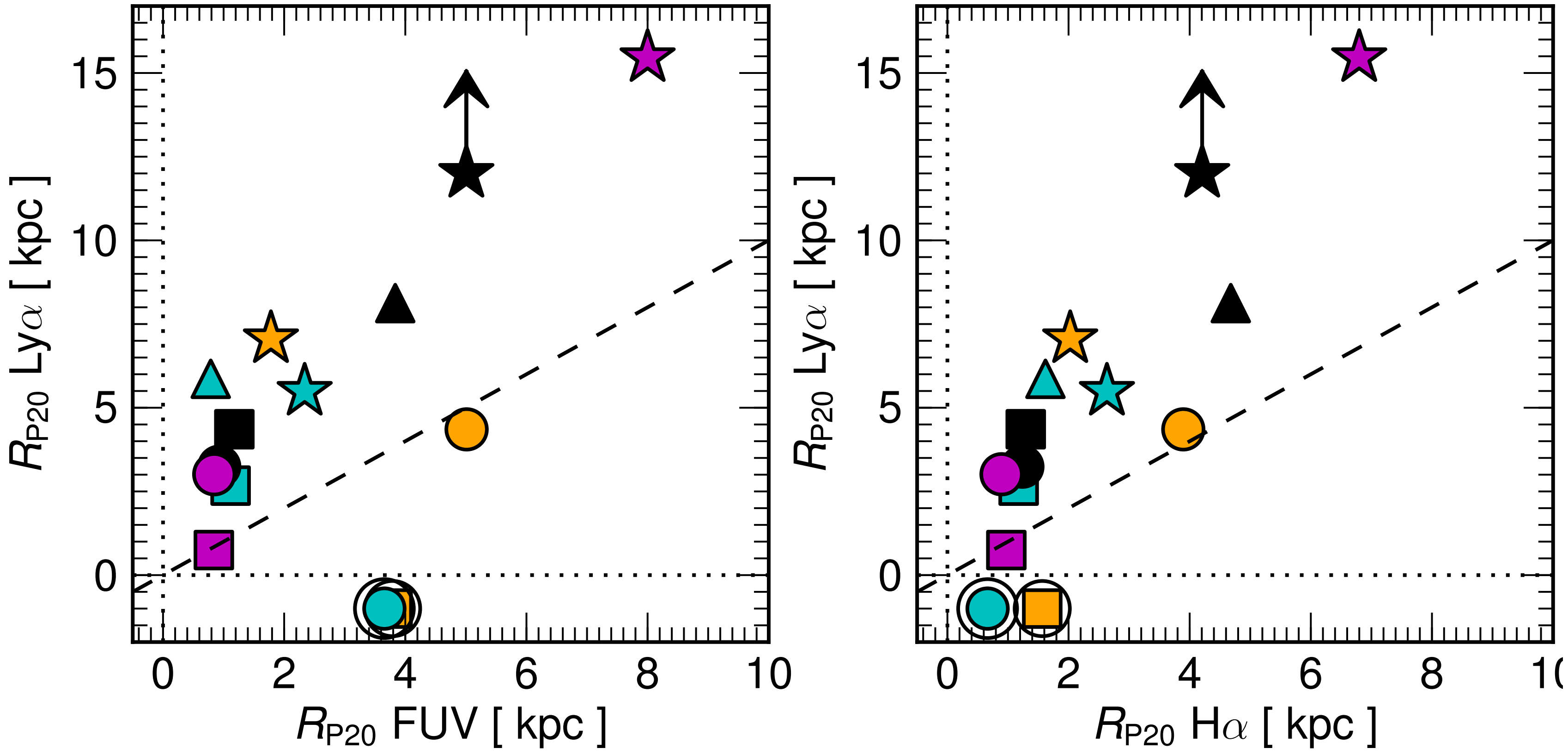
FUV SB close to n=4
As for merger remnants
(e.g. Schweizer+1982)

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

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

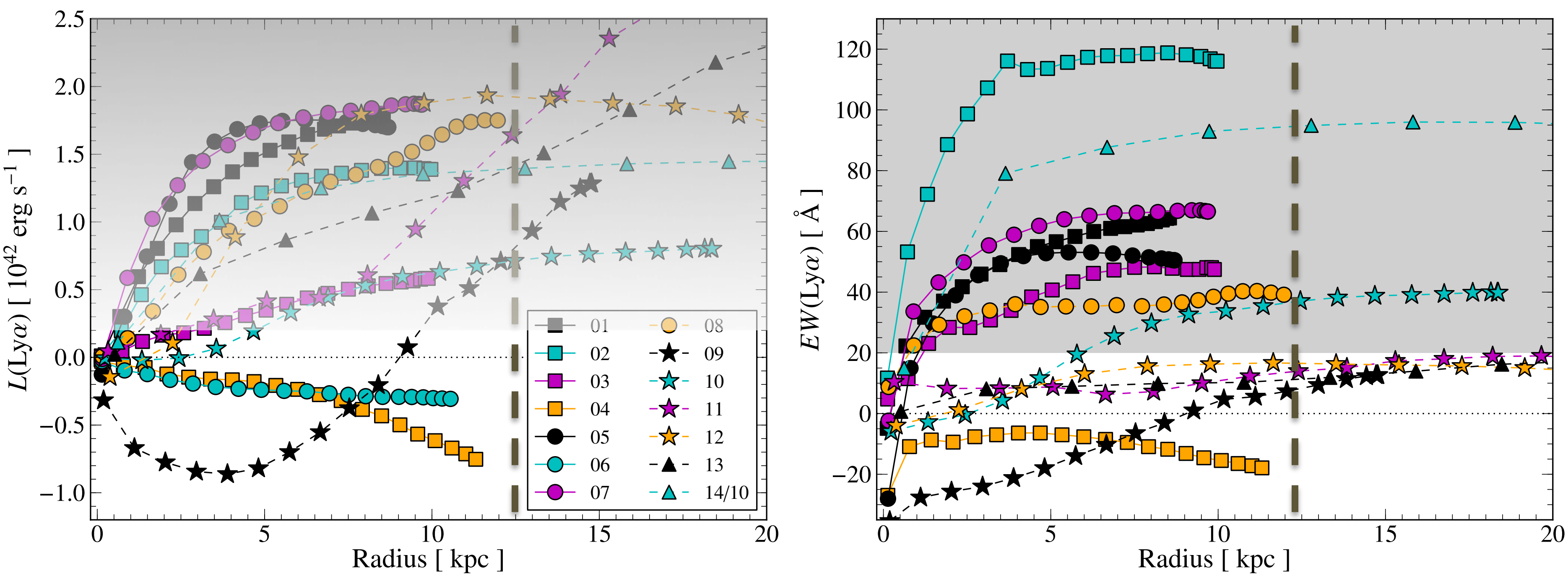
>> does Lyα trace the HI distribution?

Haloes



Lyα characteristic sizes are ~ twice those of UV and Hα

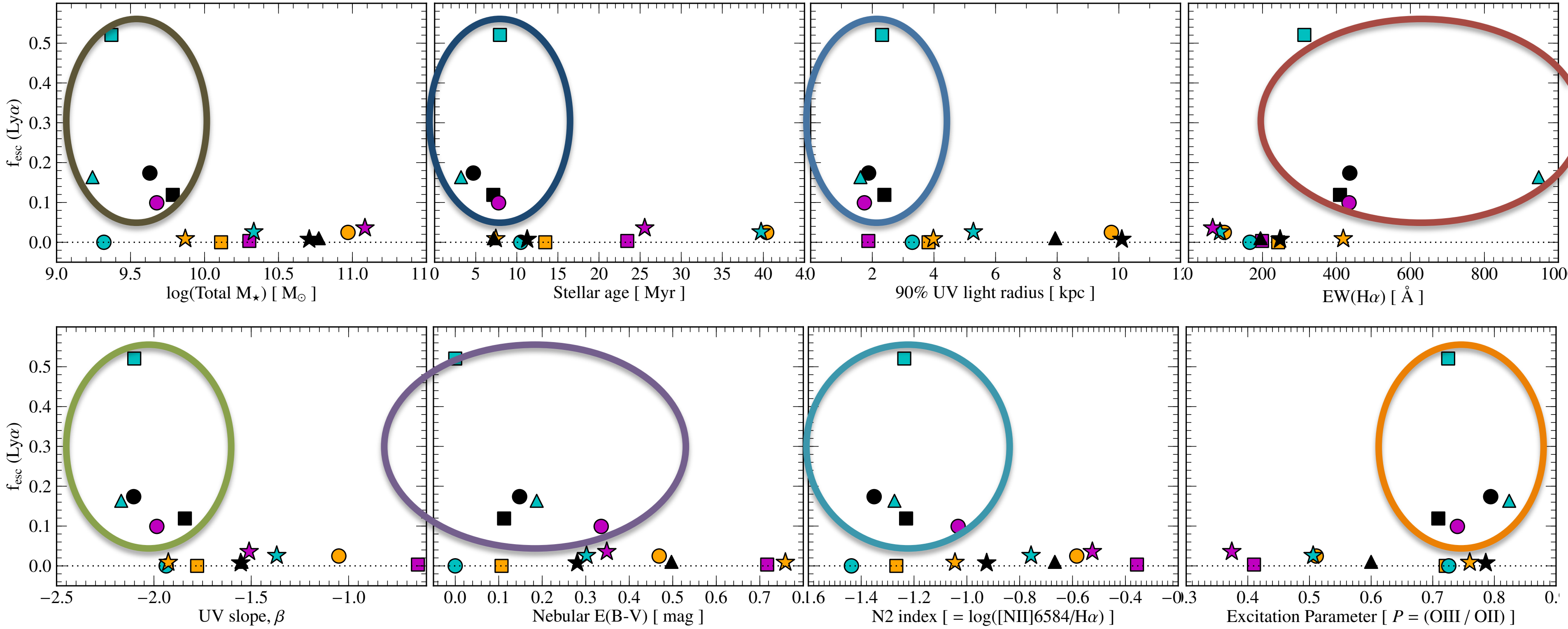
Haloes *: consequences at high z*



Some Lyα radial growth curves flatter, some do not.

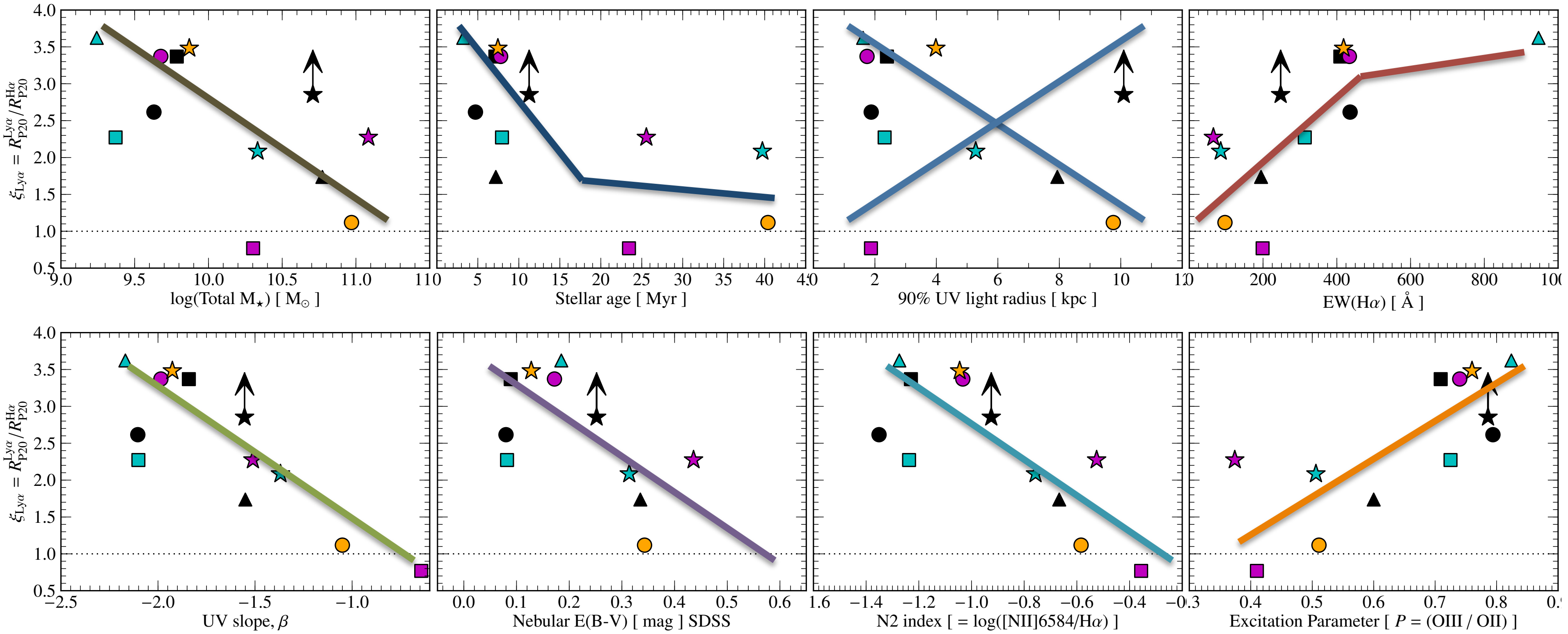
→ Will be flux losses if placed at *z* > 2, but not enormous (1 arc sec slit)

Lyα escape



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

Lyα haloes



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

From (alas!) a too small sample:

1. **Haloes**
   - **a.** Lyα is extended relative to the UV and Hα
   - **b.** higher escape fractions <-> larger haloes
   - **c.** ‘normal’ high-z apertures don’t cause huge flux loss
2. **Global properties**

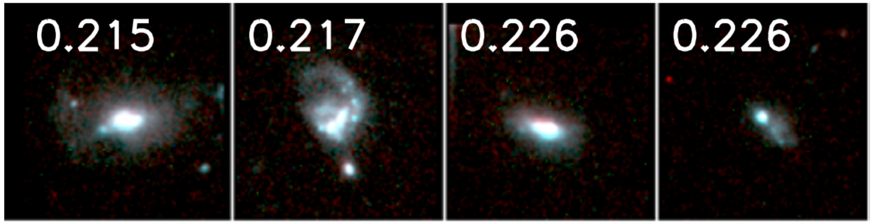
   Lya stronger, and haloes more extended in galaxies with :

   * lower age
   * lower mass
   * smaller sizes
   * fewer metals and less dust
   * higher sSFR
   * harder UV flux
3. **eLARS** will complete a larger (15 more objects) and more representative sample of Lyα physics in local universe star forming galaxies

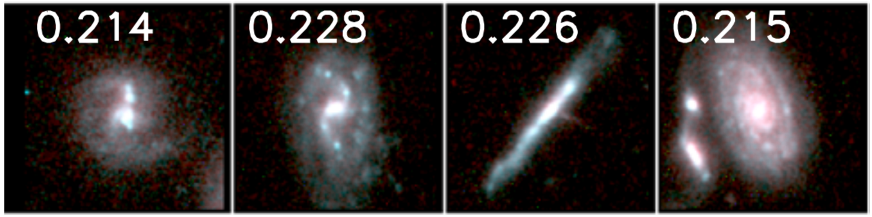
What are z=0.3 LAEs?

1. Compared to a UV continuum selected sample (LBG analogs?) the average LAE at this redshift interval has:
    - lower metallicity
    - bluer colors
    - smaller sizes
    - less extinction

z=0.3 LAE sample



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~1 LAEs and why studying them? ?

- z~1 corresponds to a ~8 billion-year lookback time, i.e.
  when the universe was only 40% of its current age

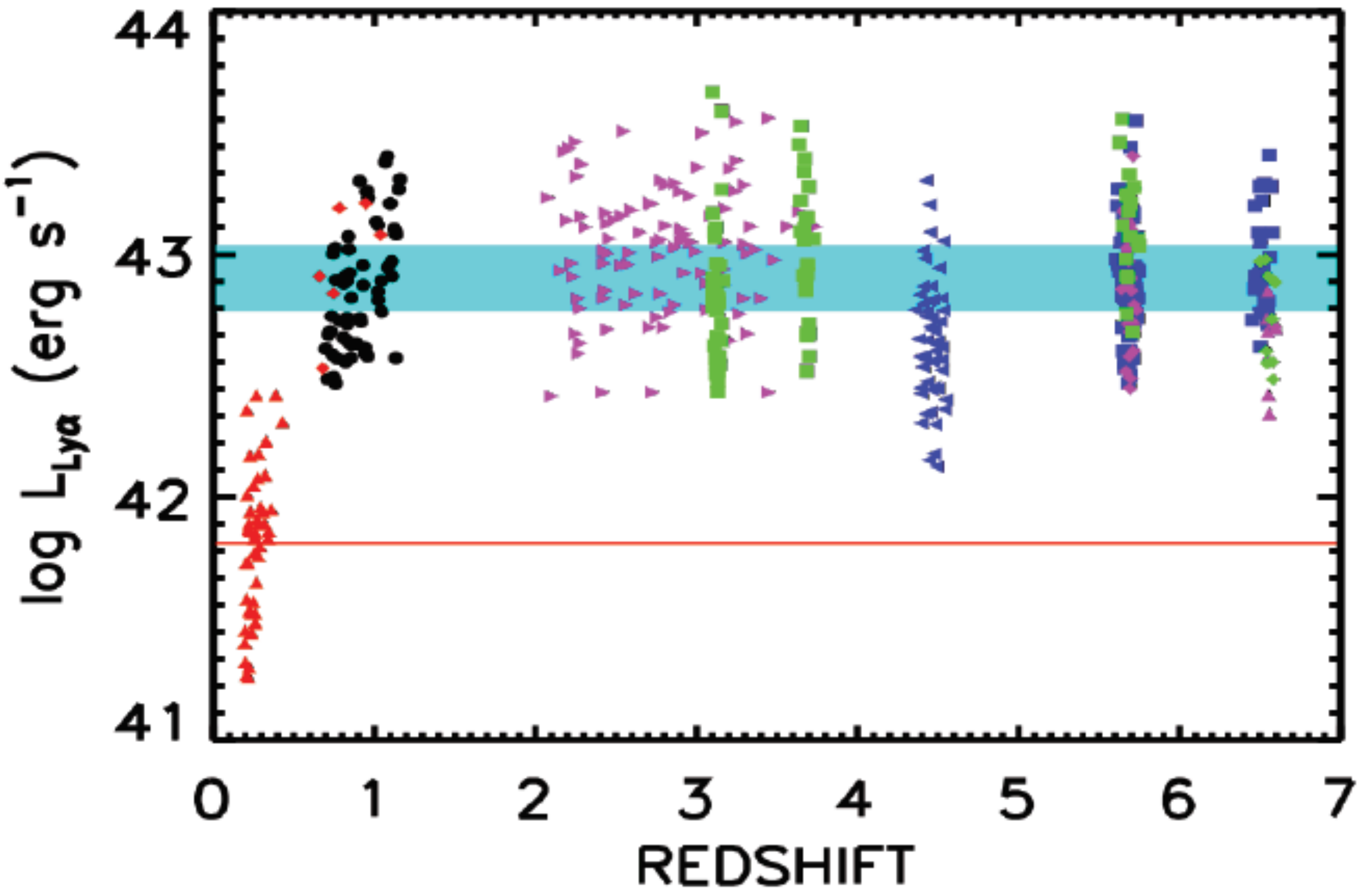
- z~1 marks the start of the end of the era of high star-formation rates.
Lowest redshift where LAEs with luminosities analogous to high-z LAEs can be found.

- z~1 is an era that can only be fully surveyed by space telescopes (i.e. with access to the rest far-UV). At $z \geqq 2$, ground-based telescopes can observe Lyman α (1216 Å) .

- Relatively nearby population allows for detailed multi-wavelength studies to constrain their properties

Slide borrowed from S. Heap and T. Hull

High luminosity Lyα emitters appear at ~ z = 0.8



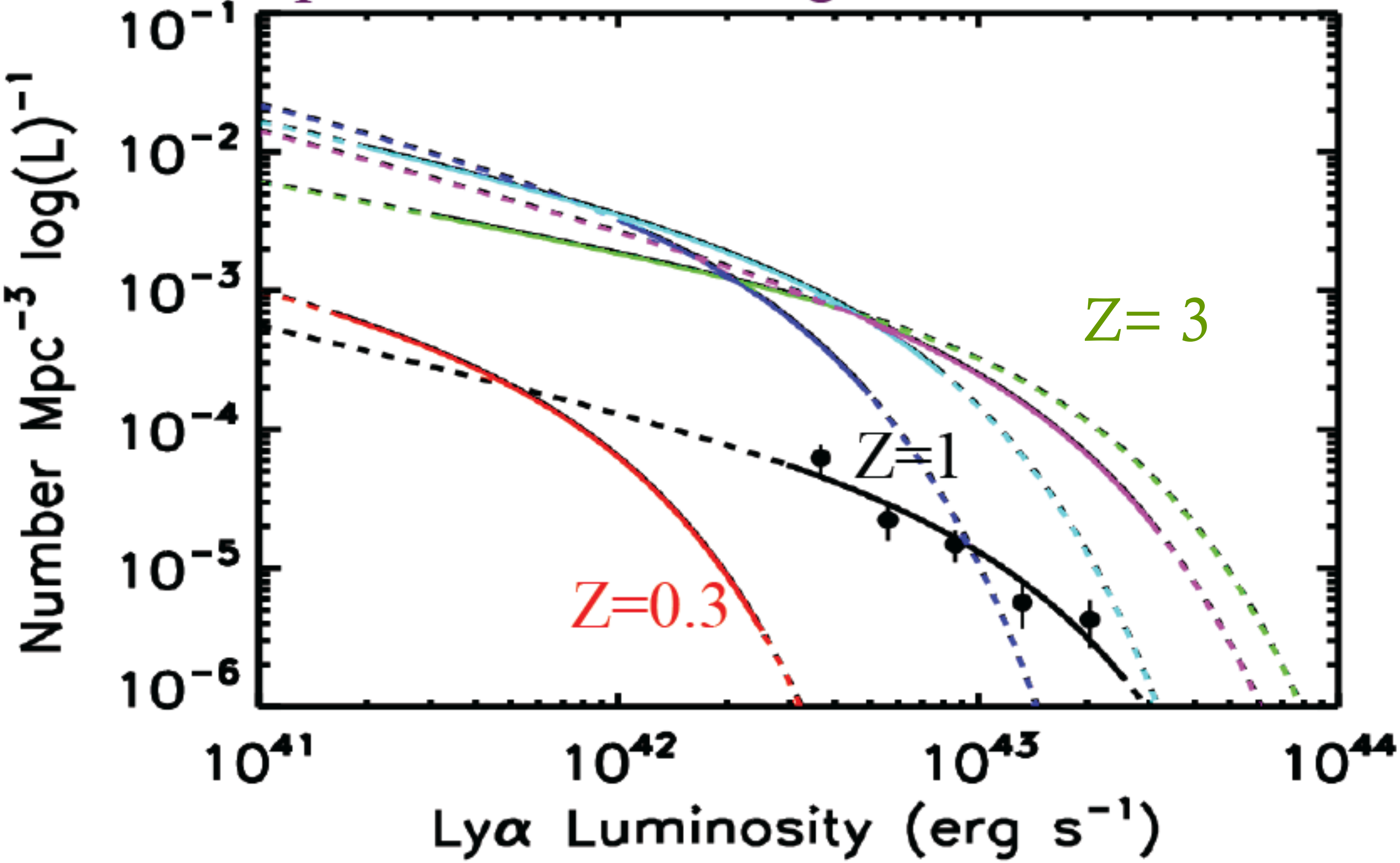
L star
High z

L star
z=0.3

Wold et al 2013

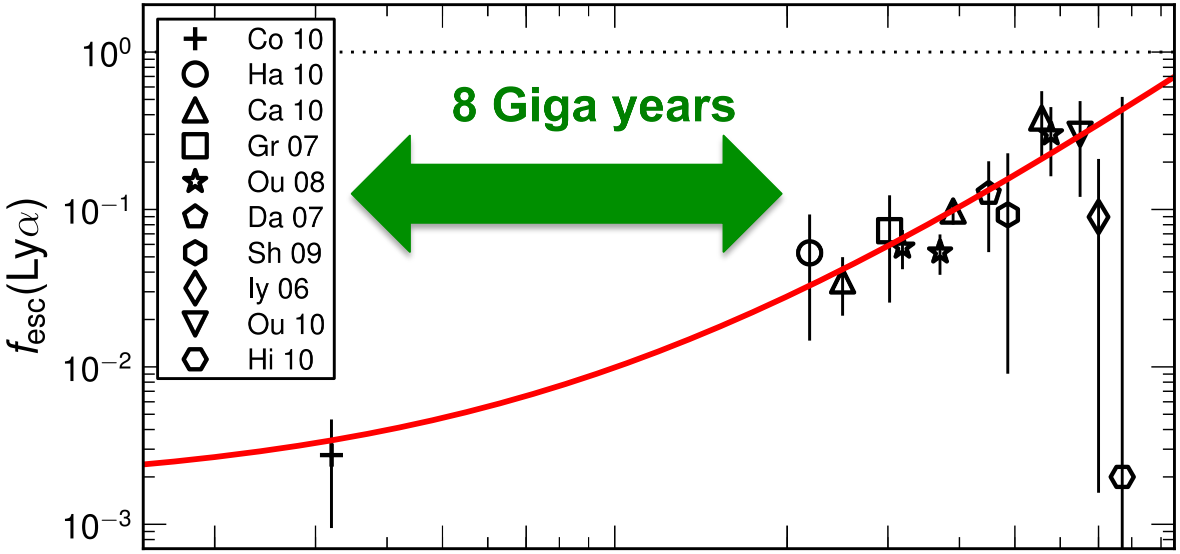
Cowie et al. 2011

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

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



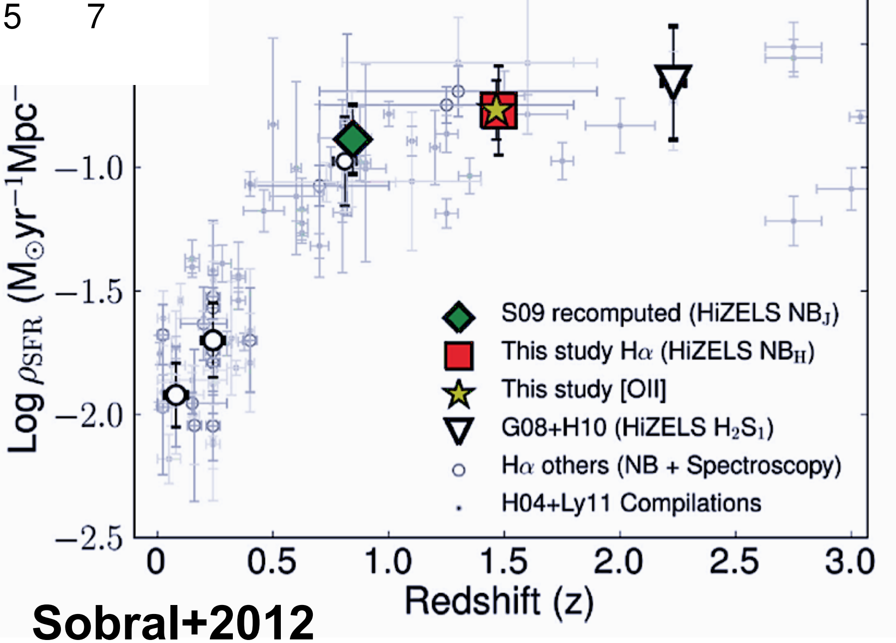
z = 0.25 – 2.1
unexplored

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?



Sobral+2012

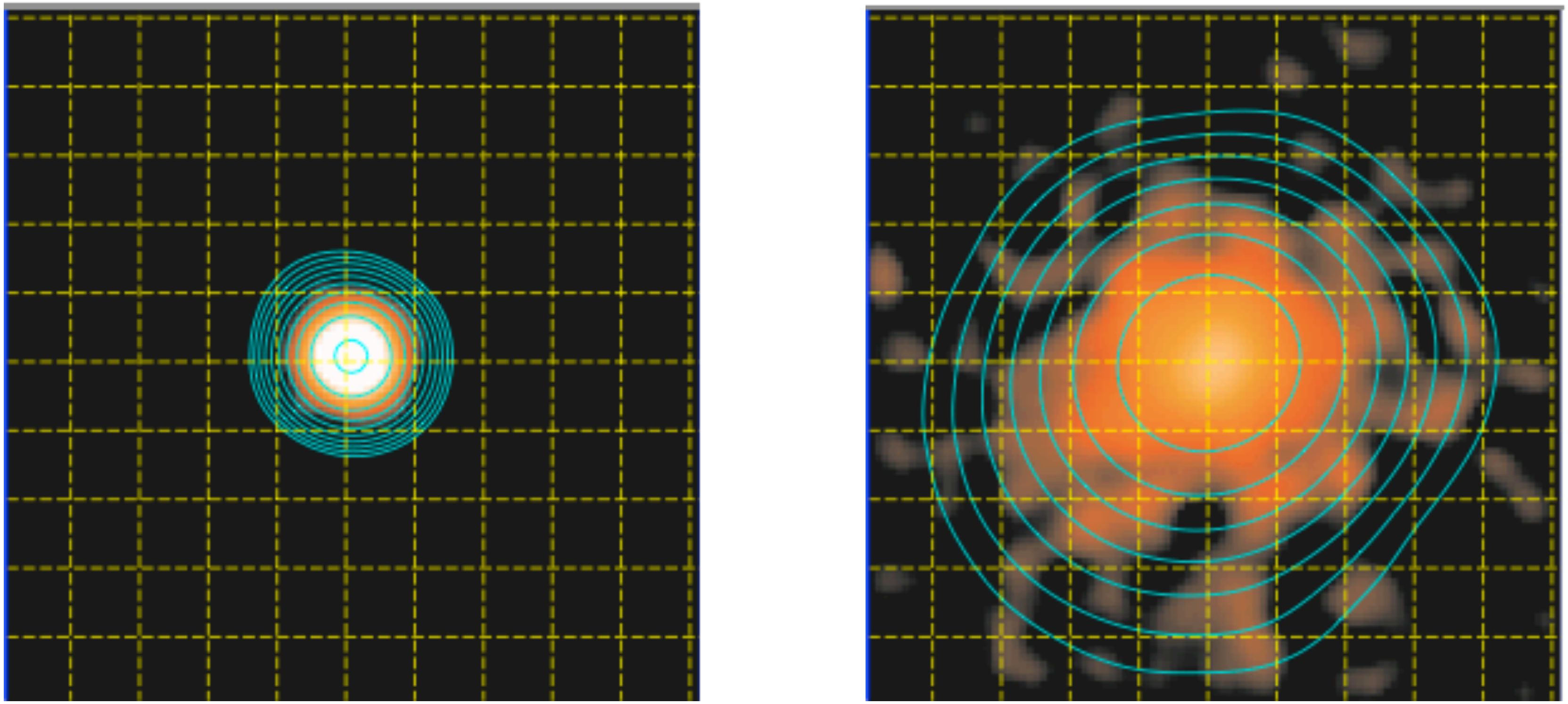
High z LAEs

- Beyond $z \sim 2$ a cosmic zoo is noteworthy. Difficult to anticipate LAE or LBG from visible spectrum.

- Steidel et al.: diffuse Lyα halos: all LBGs would be LAEs if surveys were sensitive to 10 times lower Lyα surface brigthness thresholds; similarly, essentially all LBGs would qualify as LAEs.

EXTENDED HALOES IN HIGH-Z GALAXIES

Steidel et al. 2011

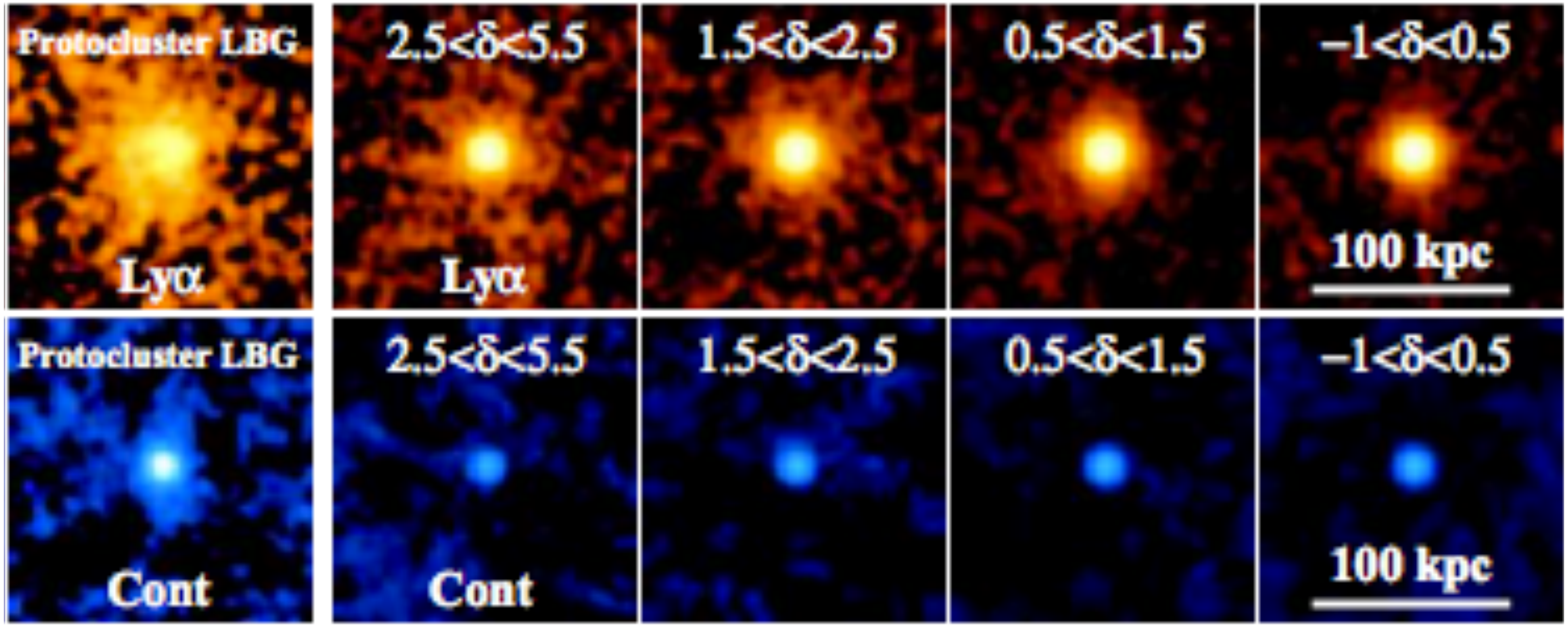


stacking 92 objetcs 900 hours integration at Keck!

Lyα more extended that UV continuum **Aperture effects**

Selection function, EW distribution, Luminosity function, confirmation statistics, could all be ‘broken’

Lyα Haloes at high z



Matsuda+2012

Extension is function of environment

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

High z LAEs

- Beyond z ~ 2 a cosmic zoo is noteworthy. Difficult to anticipate an LAE or LBG from visible spectrum.

- Steidel et al.: diffuse Lyα halos: all LBGs would be LABs if surveys were sensitive to 10 times lower Lyα surface brigthness thresholds; similarly, essentially all LBGs would qualify as LAEs.

- Sources responsible for cosmic reionization remain ellusive. Probably enough low-luminosity galaxies are in place at z ~ 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 < 1 opaque to their LyC (Cowie, Siana, McGreer, Leilet….)

At > 3 they emit a copious amount of LyC (Steidel, Nestor, Iwata..)

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

Ly-alpha future missions

- Why? Lyα being a resonant line its photometry is biased. High – z science MUST calibrate against nearby galaxies.
- Studies at z~ <0.8> will tell us huge amount about cosmic evolution (across ¾ of the Universe age), and provide a remarkable sample for detailed work.
- Reionisation: find out about the link, if any, between Lyα and LyC in intrinsically faint SF galaxies.
- MESSIER, WSO, CUBES …

Lyα future experiments

- Objective of future UV missions and telescopes is to determine unambiguously the rest frame UV and Lyα of the galaxy population *relevant* for high-z astrophysics.

- For Lyα , to z<2 it includes blind imaging surveys using BOTH Lyα and UV continuum selections (∾1000 objects)
  - Measure faint-end slope of the LF
  - Lyα fraction among galaxies
  - How galaxies evolve and why!?

- Implies synergies with ground-based telescopes (ELTs), space-based NIR platforms (EUCLID/WFIRST, JWST) and radio ALMA and SKA

Lyα future experiments

- Detailed observations in UV are necessary such as:

  - Spectroscopy: kinematics in the ISM, gas covering fraction, diagnostics of the massive stellar population:

  - Follow up: Target very faint objects by concentrating on the nearest for detailed studies. From z=0.5 to 0.01 the luminosity distance is reduced by 60, sampling scale by 30, SB dimming by 4….>> to reach faintest limits of the galaxy LF we need to go down to 1216 A .

Basic technical requirements

- Wavelength coverage: (from Lyα to U band : 0.2 to z~<2) hence 1500 – 3000 Å. For high-resolution instruments go down to 1200 Å.
- Observing modes:
  - Surveys: slitless spectroscopy (R 100); NB filters or *pseudo*-combined NB synthetized from long pass filters.
  - Wide field imaging (*eg* MESSIER)
  - Intermediate resolution spectrograph: using similar gratings as for STIS and COS (R> 10 000) (WSO)
  - *Multiplexing with configurable slits, micro shutter arrays or IFU would be revolutionary in the UV.*
  - At z < 0.1 an imager is vital (diffuse light). Spectroscopic aperture never captures diffuse Lyα component

Basic technical requirements

- Sensitivity (to well constrain LF): reach 1/10 $L_{\star}$
  hence: $f = 2\mathrm{x}10^{-16}$ *erg* s^{-1} *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 namely…..

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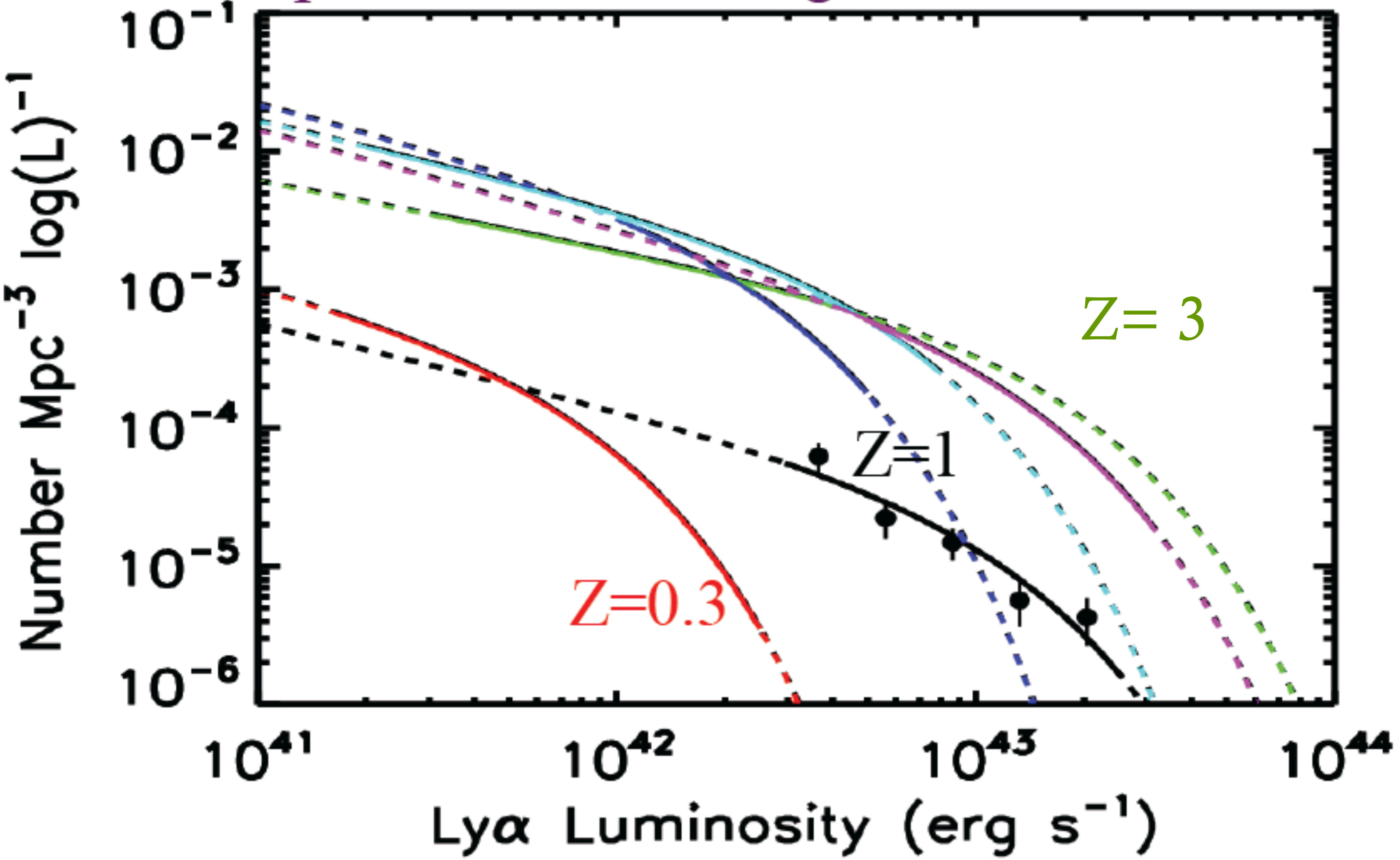

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- Field of view:
  interpolating between z=0.3 and Z= 2 to z = 0.8 we can estimate the density of galaxies:

  volume 600 000 Mpc^{-3} to be explored

  FoV > *WFPC3* but < *GALEX*

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.

Thanks to T. Hull and S. Heap