Lyman α emitters - from Cosmic Noon to Reionisation

Josephine Kerutt

What we will cover in this lecture:

- What are Lyman α emitters (LAEs)?
- How is the Lyman α emission line produced?
- What can we learn from studying LAEs?
- How do LAEs related to the Epoch of Reionisation?
- What are their properties?

Please interrupt me with questions!

September 28$^{\text{th}}$ 2023

Structure of the Lecture

1. Introduction
2. Lyman α production
3. LAE Observations
4. Radiative Transfer
5. Lyman α as a tracer of Reionisation
6. Summary

Introduction

Short Overview - What you should remember from this lecture

Lyman α emission

- Lyman α is the transition from the first excited state to the ground state of hydrogen
- around 2/3 of recombinations result in Lyman α

Short Overview - What you should remember from this lecture

Lyman α emission

- Lyman α is the transition from the first excited state to the ground state of hydrogen
- around 2/3 of recombinations result in Lyman α

Observability

- Lyman α line at 1215.67 Å shifts into the optical at redshifts $z \sim 3$
- Lyman α can be very strong, easy to observe even for UV faint galaxies

Short Overview - What you should remember from this lecture

Lyman α emission

- Lyman α is the transition from the first excited state to the ground state of hydrogen
- around 2/3 of recombinations result in Lyman α

Observability

- Lyman α line at 1215.67 Å shifts into the optical at redshifts $z \sim 3$
- Lyman α can be very strong, easy to observe even for UV faint galaxies

What we can learn from LAEs

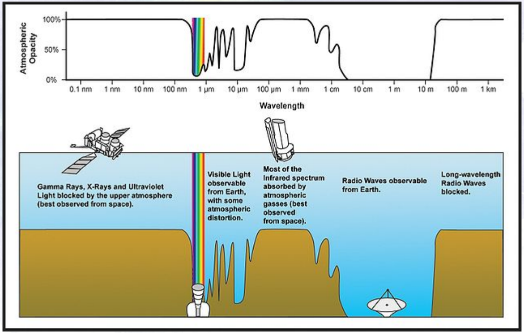
- timing and process of reionisation
- properties of star-forming galaxies in the early universe

High-z Galaxies are difficult to observe

Problems

- for photometry: galaxies become fainter at larger distances
- for spectroscopy: even worse, but also typical optical lines shift into the infrared

What is "high" redshift?

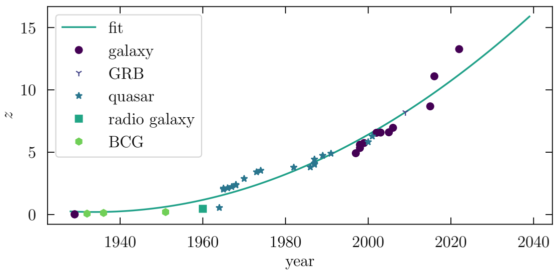


Source: NASA

High-z Galaxies are difficult to observe

Problems

- for photometry: galaxies become fainter at larger distances
- for spectroscopy: even worse, but also typical optical lines shift into the infrared



Source: https://en.wikipedia.org/wiki/List_of_the_most_distant_astronomical_objects

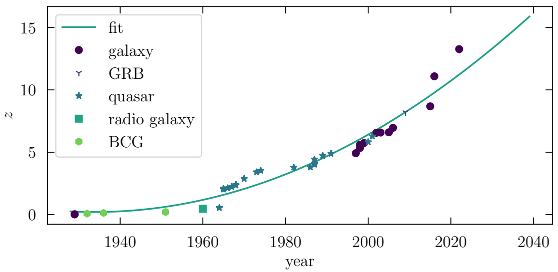
Redshift records

- redshifts beyond 1 have only been observed for around 50 years

High-z Galaxies are difficult to observe

Problems

- for photometry: galaxies become fainter at larger distances
- for spectroscopy: even worse, but also typical optical lines shift into the infrared



Source: https://en.wikipedia.org/wiki/List_of_the_most_distant_astronomical_objects

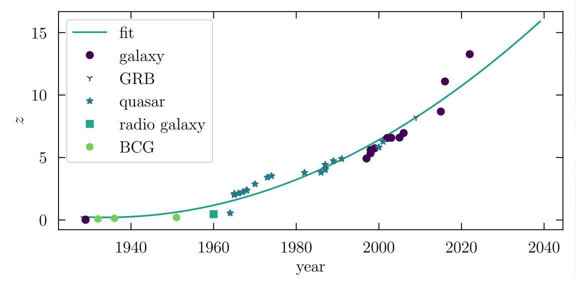
Redshift records

- redshifts beyond 1 have only been observed for around 50 years
- Latest redshift record: galaxy at $z = 13.2$ observed with JWST

High-z Galaxies are difficult to observe

Problems

- for photometry: galaxies become fainter at larger distances
- for spectroscopy: even worse, but also typical optical lines shift into the infrared



Source: https://en.wikipedia.org/wiki/List_of_the_most_distant_astronomical_objects

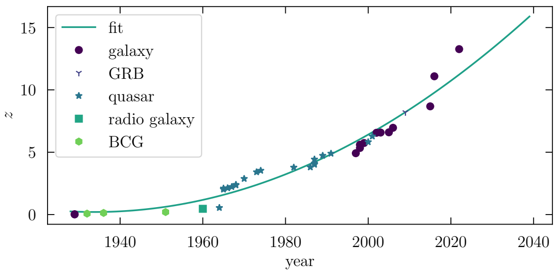
Redshift records

- redshifts beyond 1 have only been observed for around 50 years
- Latest redshift record: galaxy at $z = 13.2$ observed with JWST
- quasars are extremely bright and thus observable to high redshifts

High-z Galaxies are difficult to observe

Problems

- for photometry: galaxies become fainter at larger distances
- for spectroscopy: even worse, but also typical optical lines shift into the infrared



Source: `https://en.wikipedia.org/wiki/List_of_the_most_distant_astronomical_objects`

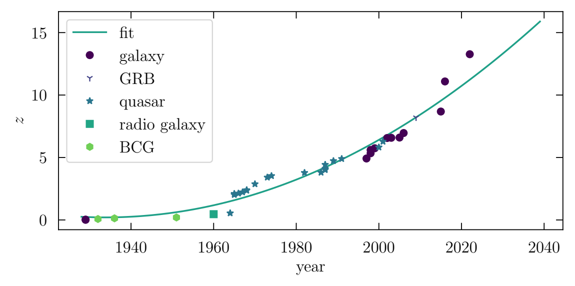
Redshift records

- redshifts beyond 1 have only been observed for around 50 years
- Latest redshift record: galaxy at $z = 13.2$ observed with JWST
- quasars are extremely bright and thus observable to high redshifts
- more recently: galaxies are holding the redshift records

High-z Galaxies are difficult to observe

Problems

- for photometry: galaxies become fainter at larger distances
- for spectroscopy: even worse, but also typical optical lines shift into the infrared



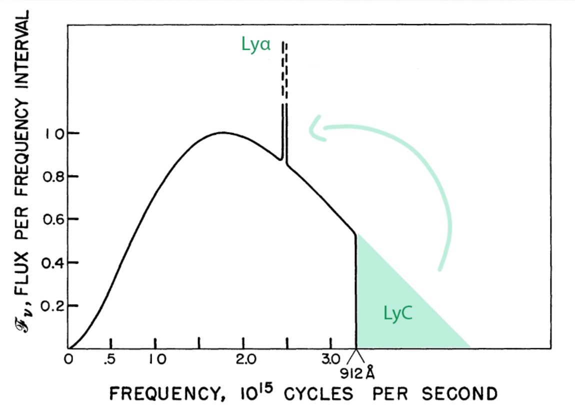
What we needed: strong spectral feature that shifts into the optical wavelength range at high redshifts

$\rightarrow$ **Lyman α emission!**
... among others

Source: https://en.wikipedia.org/wiki/List_of_the_most_distant_astronomical_objects

Lyman α production

Large Part of Galaxy's Emission Transformed to Lyman α



Partridge & Peebles, 1967

Predicted already over 50 years ago by Partridge & Peebles (1967).

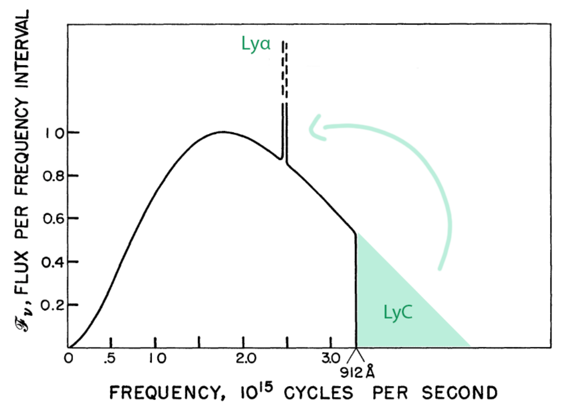
Concept: most of the hydrogen ionising radiation of a galaxy could be transformed into Lyman α photons

↓

Lyman α emitters (LAEs)

Prediction: galaxies at high redshift should be observable through their Lyman α emission

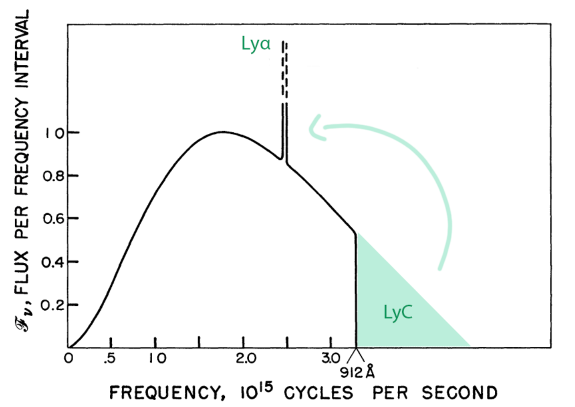
Large Part of Galaxy's Emission Transformed to Lyman α



Partridge & Peebles, 1967

- galaxy spectrum is the sum of spectra of stars

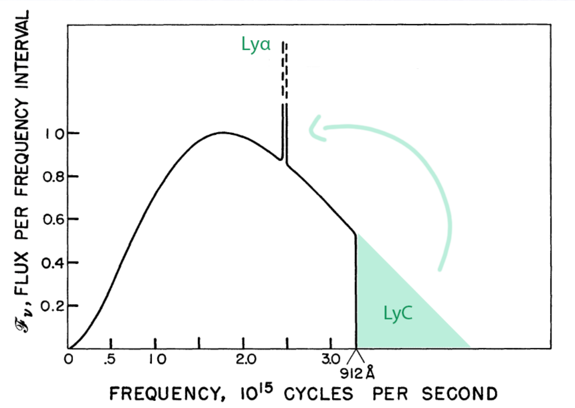
Large Part of Galaxy's Emission Transformed to Lyman α



Partridge & Peebles, 1967

- galaxy spectrum is the sum of spectra of stars
- stars emit black-body radiation

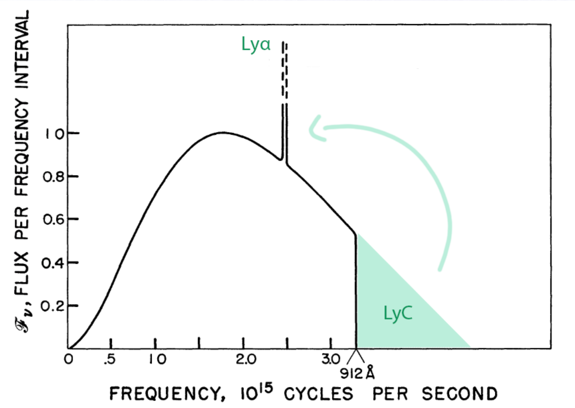
Large Part of Galaxy's Emission Transformed to Lyman α



Partridge & Peebles, 1967

- galaxy spectrum is the sum of spectra of stars
- stars emit black-body radiation
- photons with high energy ionise H I

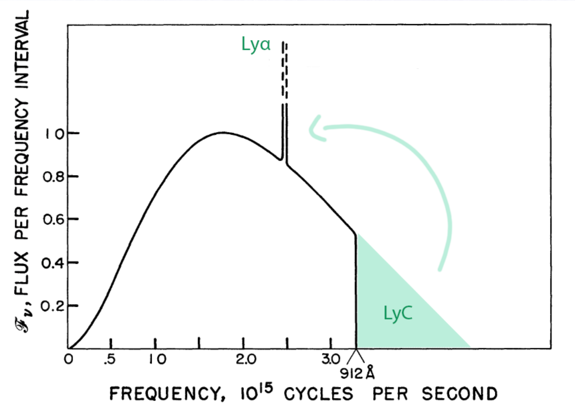
Large Part of Galaxy's Emission Transformed to Lyman α



Partridge & Peebles, 1967

- galaxy spectrum is the sum of spectra of stars
- stars emit black-body radiation
- photons with high energy ionise H I
- Which stars produce high-energy photons?

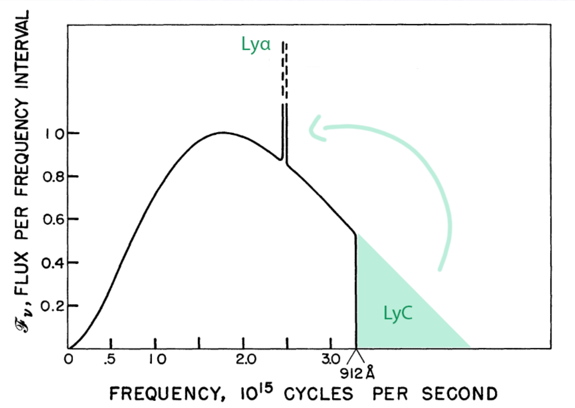
Large Part of Galaxy's Emission Transformed to Lyman α



Partridge & Peebles, 1967

- galaxy spectrum is the sum of spectra of stars
- stars emit black-body radiation
- photons with high energy ionise H I
- Which stars produce high-energy photons?
- $\rightarrow$ stars with highest temperatures

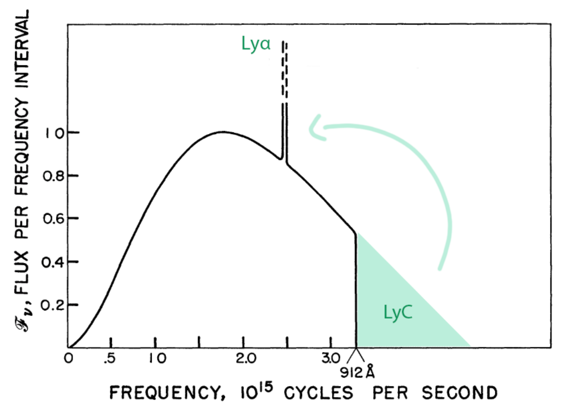
Large Part of Galaxy's Emission Transformed to Lyman α



Partridge & Peebles, 1967

- galaxy spectrum is the sum of spectra of stars
- stars emit black-body radiation
- photons with high energy ionise H I
- Which stars produce high-energy photons?
- $\rightarrow$ stars with highest temperatures
- Which stars have the highest temperatures?

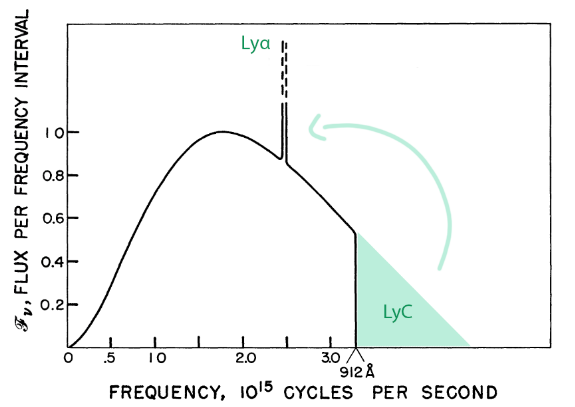
Large Part of Galaxy's Emission Transformed to Lyman α



Partridge & Peebles, 1967

- galaxy spectrum is the sum of spectra of stars
- stars emit black-body radiation
- photons with high energy ionise H I
- Which stars produce high-energy photons?
- $\rightarrow$ stars with highest temperatures
- Which stars have the highest temperatures?
- $\rightarrow$ stars with largest masses

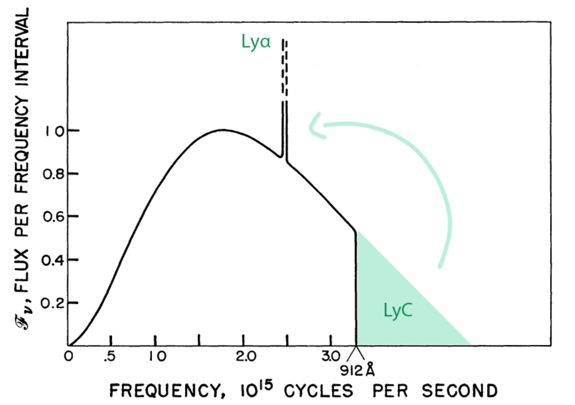
Large Part of Galaxy's Emission Transformed to Lyman α



Partridge & Peebles, 1967

- galaxy spectrum is the sum of spectra of stars
- stars emit black-body radiation
- photons with high energy ionise H I
- Which stars produce high-energy photons?
- → stars with highest temperatures
- Which stars have the highest temperatures?
- → stars with largest masses
- Where do we find high-mass stars in galaxies?

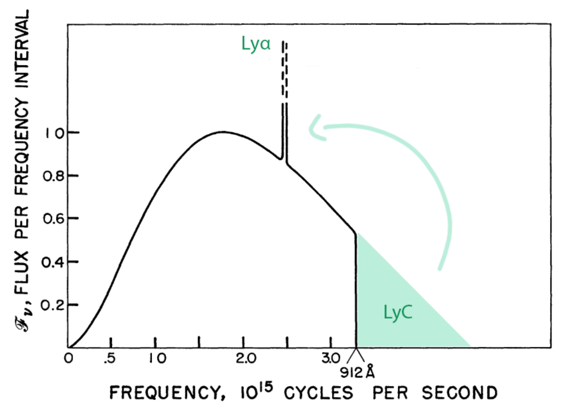
Large Part of Galaxy's Emission Transformed to Lyman α



Partridge & Peebles, 1967

- galaxy spectrum is the sum of spectra of stars
- stars emit black-body radiation
- photons with high energy ionise H I
- Which stars produce high-energy photons?
- → stars with highest temperatures
- Which stars have the highest temperatures?
- → stars with largest masses
- Where do we find high-mass stars in galaxies?
- → in star-forming regions, because massive stars have shorter lives

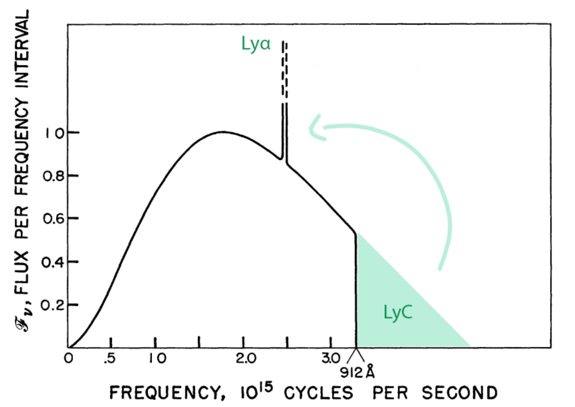
Large Part of Galaxy's Emission Transformed to Lyman α



- Lyman Continuum (LyC): 912 Å

Partridge & Peebles, 1967

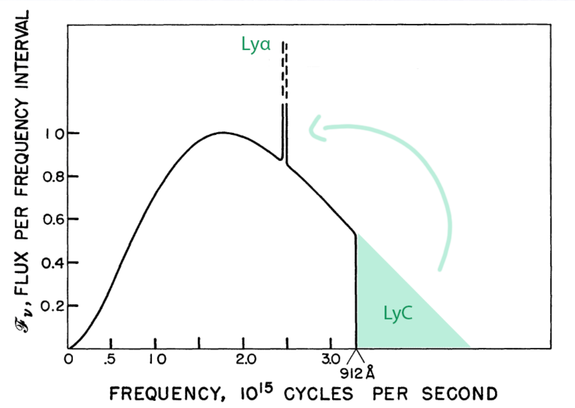
Large Part of Galaxy's Emission Transformed to Lyman α



Partridge & Peebles, 1967

- Lyman Continuum (LyC): 912 Å
- Lyman α (Lyα): 1215.67 Å

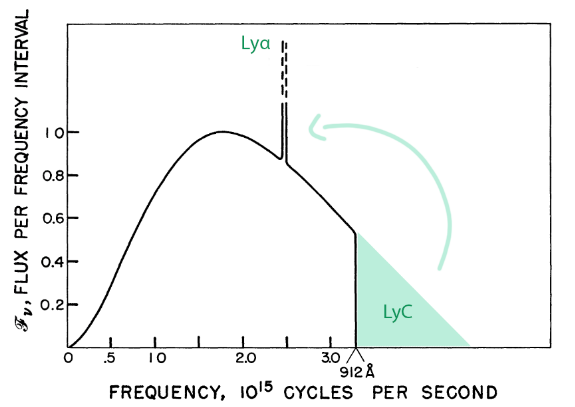
Large Part of Galaxy's Emission Transformed to Lyman α



Partridge & Peebles, 1967

- Lyman Continuum (LyC): 912 Å
- Lyman α (Lyα): 1215.67 Å
- optical wavelength range: $\sim$ 4000 – 9000 Å

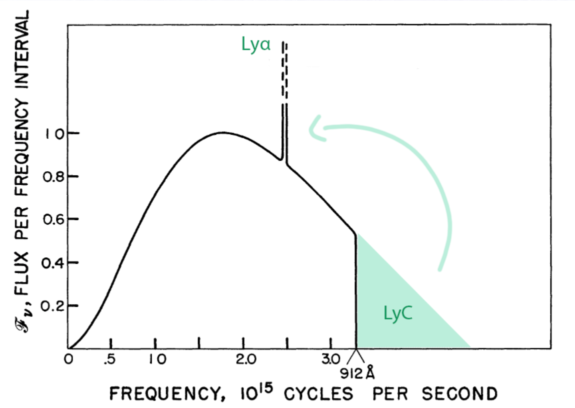
Large Part of Galaxy's Emission Transformed to Lyman α



Partridge & Peebles, 1967

- Lyman Continuum (LyC): 912 Å
- Lyman α (Lyα): 1215.67 Å
- optical wavelength range: $\sim 4000 - 9000$ Å
- At what redshift does Lyman α shift into the optical?

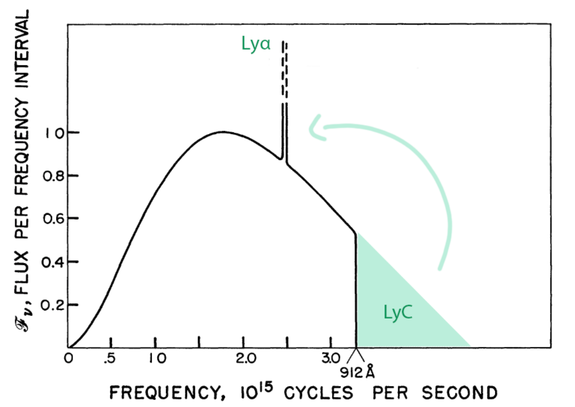
Large Part of Galaxy's Emission Transformed to Lyman α



Partridge & Peebles, 1967

- Lyman Continuum (LyC): 912 Å
- Lyman α (Lyα): 1215.67 Å
- optical wavelength range: $\sim 4000 - 9000$ Å
- At what redshift does Lyman α shift into the optical?
- reminder redshift: $z = \frac{\lambda}{\lambda_0} - 1$

Large Part of Galaxy's Emission Transformed to Lyman α

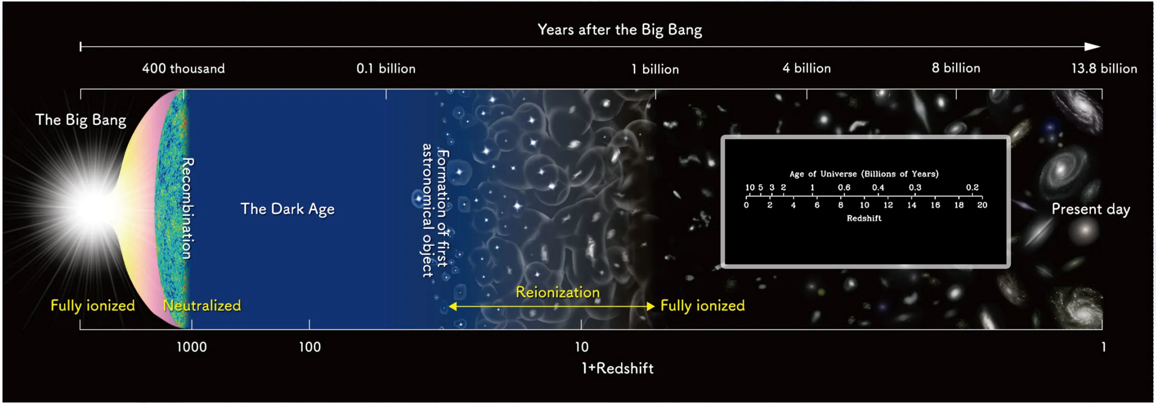


Partridge & Peebles, 1967

- Lyman Continuum (LyC): 912 Å
- Lyman α (Lyα): 1215.67 Å
- optical wavelength range: $\sim 4000 - 9000$ Å
- At what redshift does Lyman α shift into the optical?
- reminder redshift: $z = \frac{\lambda}{\lambda_0} - 1$
- $\rightarrow$ At redshifts between $z \sim 2.3 - 6.4$

What stage of the universe can we observe with Lyman α?

Reminder:



Source: NOAJ

Production Mechanisms of Lyman α

Collisions

- electron excites hydrogen atom by losing kinetic energy $\rightarrow$ cooling
- thermal energy of the electron (and thus the gas) is converted into radiation

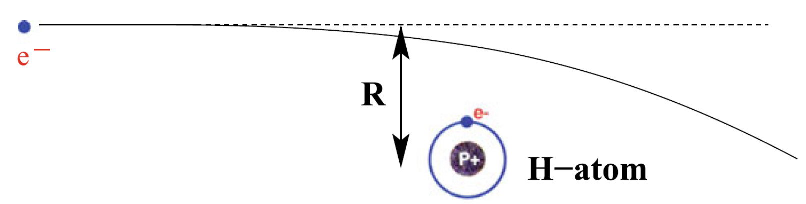
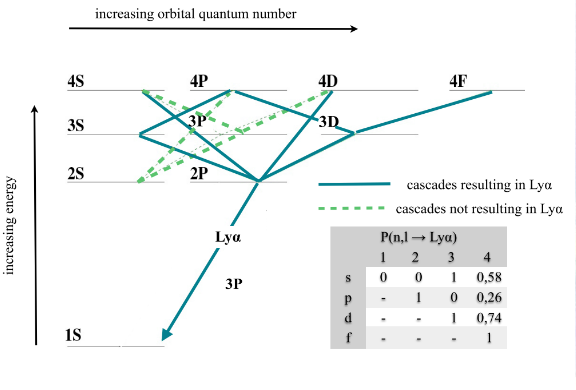


Figure taken from Dijkstra (2014)

Production Mechanisms of Lyman α

Lyman α emission line: transition from first excited state to ground state



P(n,l → Lyα)	1	2	3	4
s	0	0	1	0,58
p	-	1	0	0,26
d	-	-	1	0,74
f	-	-	-	1

Figure taken from Dijkstra (2014)

Recombination

- a free electron and a proton combine to a hydrogen atom
- electron can be in any quantum state (n, l)
- radiative cascade down to ground state - probability for Lyman α can be computed for each initial quantum state
- summing over all states (n, l) gives probability for Lyman α emission

Case A and Case B

Probability depends on gas temperature and case A or B.

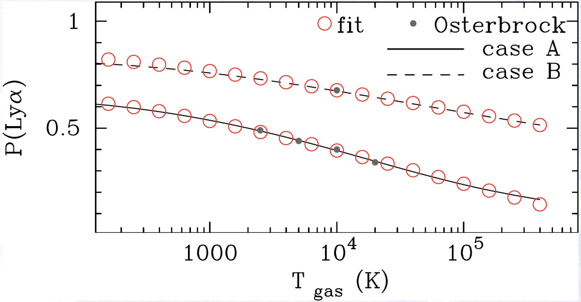


Figure taken from Dijkstra (2014): Probability of Lyman α over gas temperature

Case A

- electron and proton recombine into any state (n, l)
- all (permitted) radiative transitions are allowed
- gas is optically thin to Lyman photons

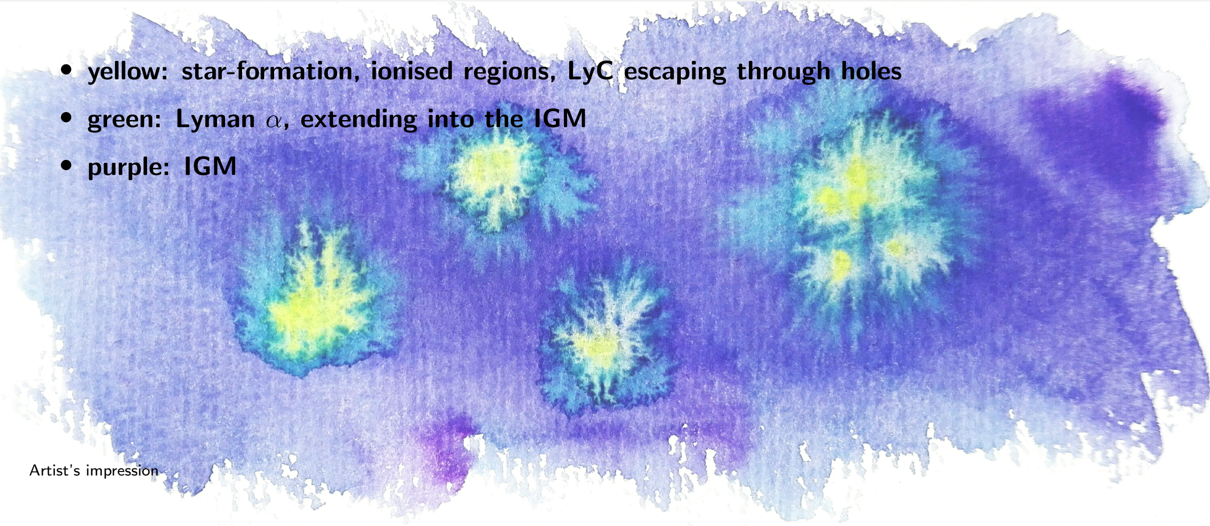
Case B

- no recombinations to the ground state are allowed
- no radiative transitions of higher order Lyman series
- gas is opaque to Lyman series photons

LAE Observations

What do LAEs look like?

- **yellow: star-formation, ionised regions, LyC escaping through holes**
- **green: Lyman α, extending into the IGM**
- **purple: IGM**



Artist's impression

What do LAEs look like?

- after their prediction in the 60s, it took until 1996 to detect the first LAE
- detected through a comparison of two photometric bands, close to a quasar at redshift $z = 4.7$

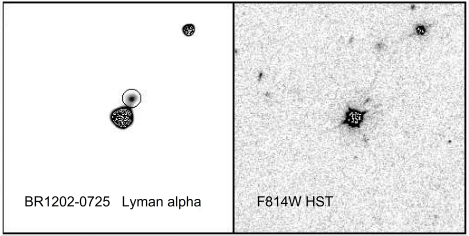
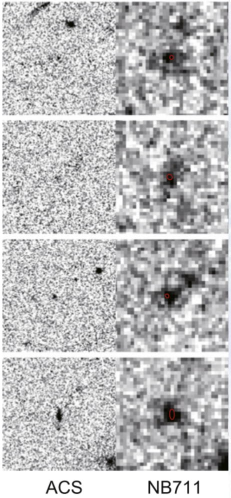


Figure taken from Hu et al. (1996)



- examples of LAEs at $z = 4.86$
- left: UV continuum
- right: Lyman α emission

Figure taken from Kobayashi et al. (2016)

LAEs Observation strategies: Narrowbands

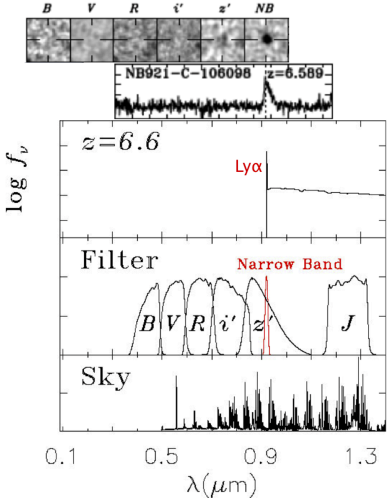


Figure taken from Ouchi et al. (2010)

- Lyα line can be strong because most of the ionising emission of a galaxy can be converted to Lyα
- neutral hydrogen in the IGM absorbs emission bluewards of Lyα
- spectrum expected: weak below Lyα, strong Lyα emission
- strategy: drop-out technique using several narrowbands or a combination of broadband and narrowbands

LAEs Observation strategies: Narrowbands

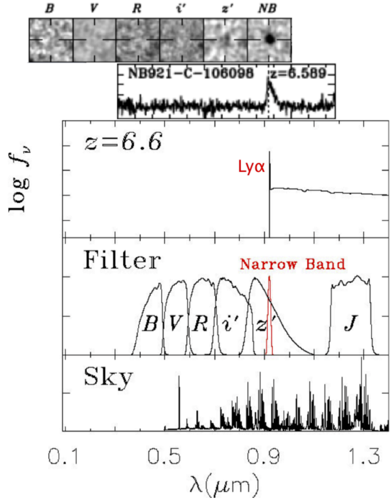


Figure taken from Ouchi et al. (2010)

Problems:

- can be confused with low redshift objects, like brown dwarfs
- needs spectroscopic confirmation to determine if it is really Lyα
- limited to narrow redshift range

Advantages:

- covering large area for surveys
- no pre-selection needed
- HST data can be used

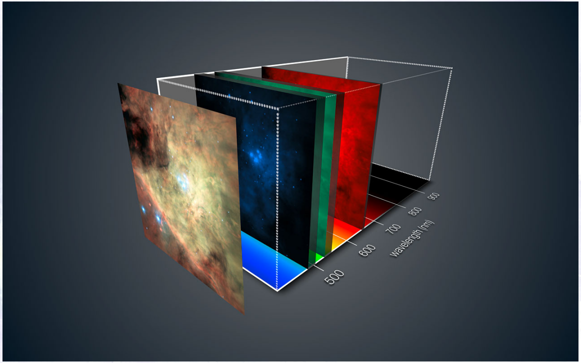
Ideal: Combination of spectroscopy and photometry

Small excursion: MUSE - Multi-Unit Spectroscopic Explorer

- integral field spectrograph
- two spatial, one spectral dimension
- wavelength range:
  4750 - 9350 Å
- field of view: 1x1 arcmin^2

$\rightarrow$ ideal for detecting emission lines, especially Lyman α in redshift range $2.9 < z < 6.7$

advantages: we get a spectrum in each pixel!
No pre-selection needed, wide field of view, good for surveys and blind detections



LAEs Observation strategies: Narrowbands

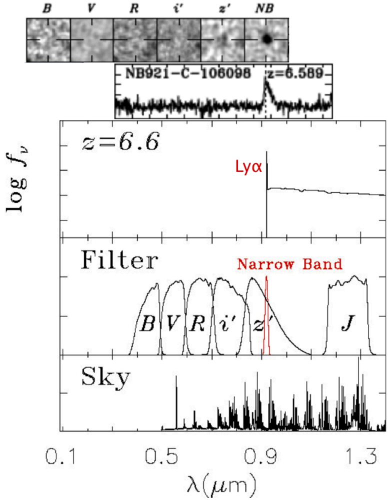


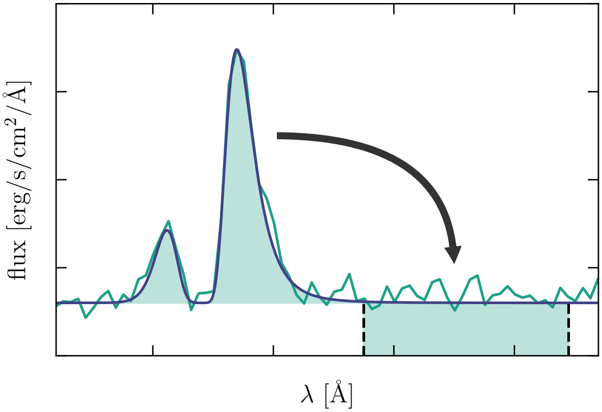
Figure taken from Ouchi et al. (2010)

Definitions

- galaxies can be found with "drop-out technique" using broadbands: drop in the spectrum at Lyman break
- advantage: wide redshift range
- these galaxies are called "Lyman break galaxies" (LBGs)
- they can have Lyman α emission
- definition often depends on how they were detected
- definition: LAEs need to have a Lyman α equivalent width of **EW** $>$ 20 **Å**

Measuring the Line Strength: Lyman α Equivalent Width

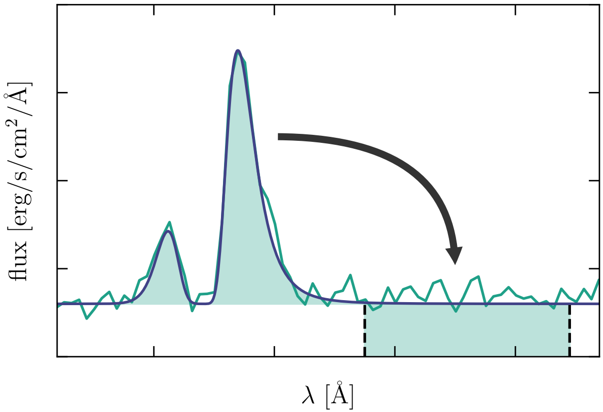
$$\mathrm{EW} = \mathrm{EW}_0(1+z) = \frac{F_{\mathrm{Ly}\alpha}^{\mathrm{line}}}{f_{\mathrm{Ly}\alpha}^{\mathrm{cont}}}$$



Measuring the Line Strength: Lyman α Equivalent Width

$$\mathrm{EW} = \mathrm{EW}_0(1+z) = \frac{F^{\mathrm{line}}_{\mathrm{Ly}\alpha}}{f^{\mathrm{cont}}_{\mathrm{Ly}\alpha}}$$

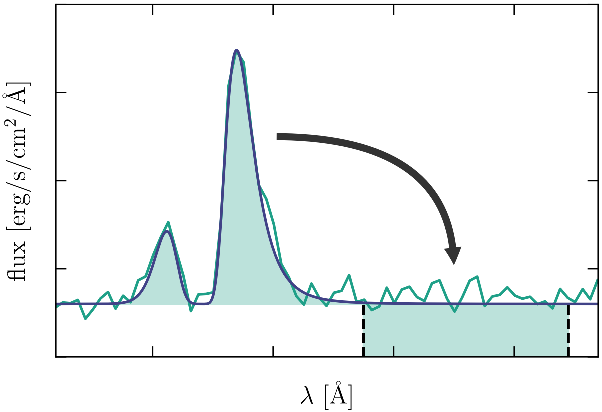
- What do you notice about this line?



Measuring the Line Strength: Lyman α Equivalent Width

$$\mathrm{EW} = \mathrm{EW}_0(1+z) = \frac{F^{\mathrm{line}}_{\mathrm{Ly}\alpha}}{f^{\mathrm{cont}}_{\mathrm{Ly}\alpha}}$$

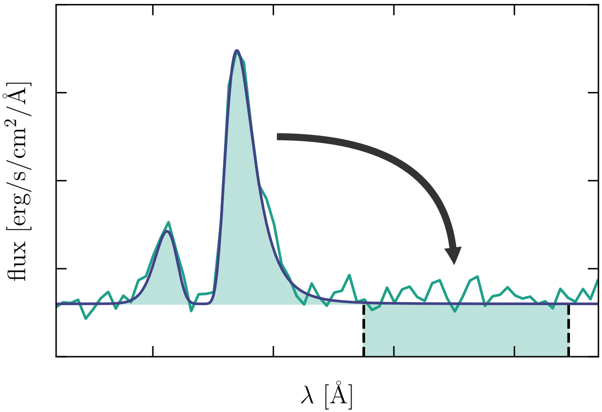
- What do you notice about this line?
- two peaks



Measuring the Line Strength: Lyman α Equivalent Width

$$\mathrm{EW} = \mathrm{EW}_0(1+z) = \frac{F_{\mathrm{Ly}\alpha}^{\mathrm{line}}}{f_{\mathrm{Ly}\alpha}^{\mathrm{cont}}}$$

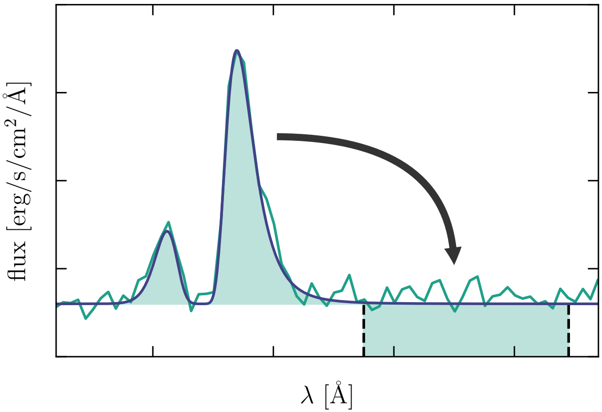
- What do you notice about this line?
- two peaks
- blue peak is smaller



Measuring the Line Strength: Lyman α Equivalent Width

$$\mathrm{EW} = \mathrm{EW}_0(1+z) = \frac{F_{\mathrm{Ly}\alpha}^{\mathrm{line}}}{f_{\mathrm{Ly}\alpha}^{\mathrm{cont}}}$$

- What do you notice about this line?
- two peaks
- blue peak is smaller
- both are asymmetric



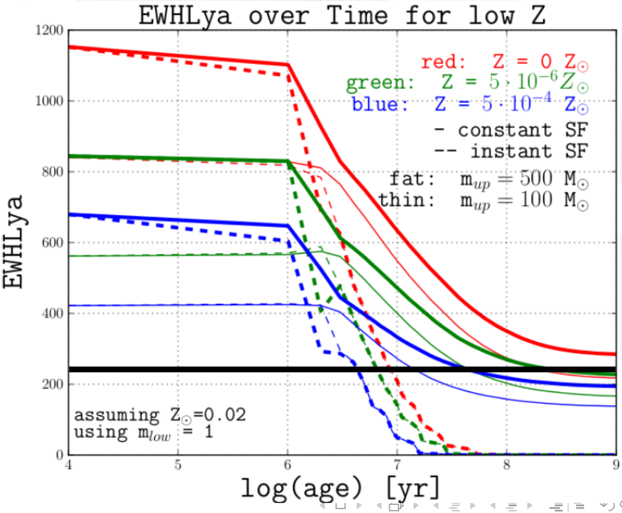
Lyman α EW is Influenced by many Parameters

Using synthetic stellar population models we know:

Rest-frame EW larger for...

- ... younger stellar ages
- ... lower metallicities
- ... initial mass function (IMF)
- ... instant star formation rate (SFR)

e.g. Raiter et al. (2010), Schaerer (2003)

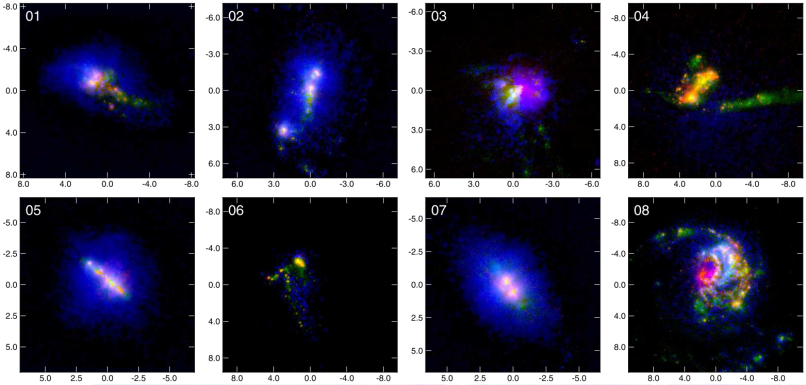


Observing LAEs at low redshift?

Why study low-z LAEs?

- other lines available give more secure redshifts
- higher resolution, more details (both in photometry and spectroscopy)
- we can study connection between Lyman α, Hα and absorption lines

Observing LAEs at low redshifts: Lyman α Reference Sample (LARS)



- low redshift analogues of LAEs
- blue: Lyman α halos
- through resonance scattering
- UV morphology: irregular
- clumpy and irregular galaxy, many star-forming regions

Figure taken from Hayes et al. (2013) showing 8 of the first 14 LARS galaxies

Radiative Transfer

Large Diversity of Lyman α line shapes

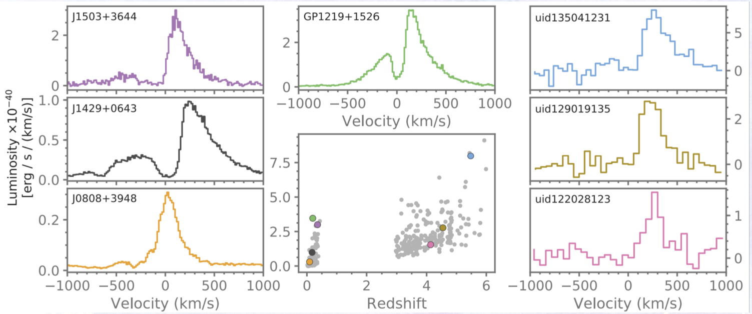


Figure taken from Runnholm et al. (2021)

- left: low-redshift LAEs
- right: high-redshift LAEs
- we find single peaks, double peaks, asymmetric lines, ...

How do we explain the characteristic Lyman α line shape?
$\rightarrow$ Radiative Transfer!

Radiative Transfer Imprints Information on Lyα Line Shape

Lyman α scatters in neutral hydrogen $\rightarrow$ in frequency and in direction

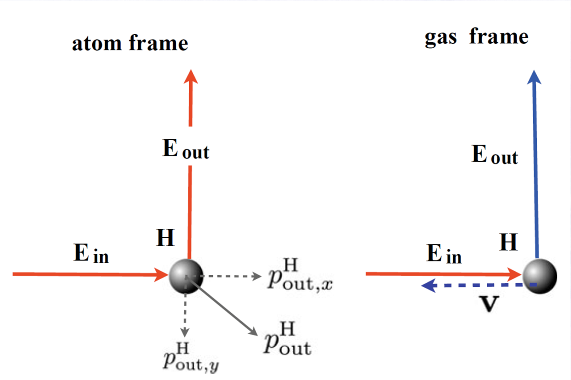
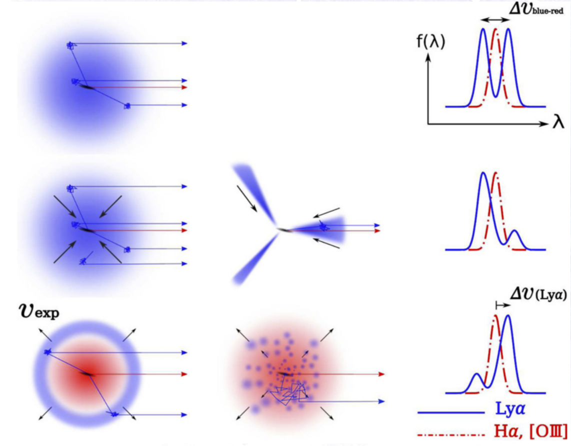


Figure taken from Dijkstra (2017)

- Lyman α scattering is partially coherent
- energy conservation in the atom frame
- gas frame (left): Energy before and after is different
- Doppler shift due to random thermal motion of the atom
- depends on atom velocity and scattering angle

Radiative Transfer Imprints Information on Lyα Line Shape



Influence on line:

- H I column density
- ISM kinematics
- distribution of ISM
- dust absorption
- IGM absorption

Figure taken from Yang et al. (2014)

Radiative Transfer Imprints Information on Lyα Line Shape

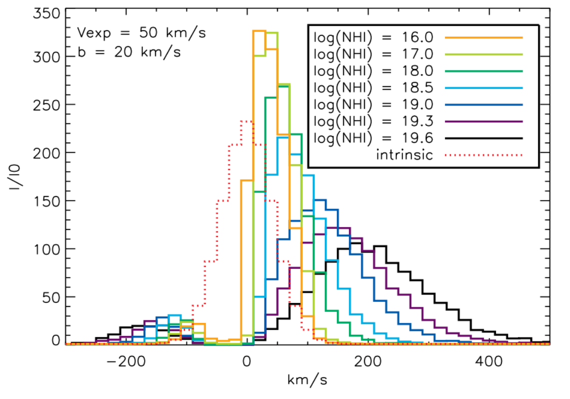
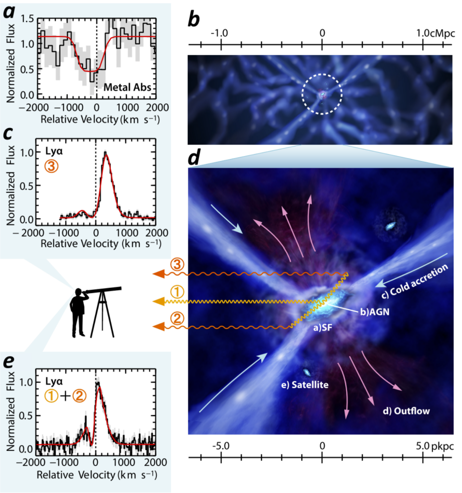


Figure taken from Verhamme et al. (2015)

Influence on line:

- H I column density → broader peak separation and full width at half maximum (FWHM)
- ISM kinematics → ratio of blue and red peak
- distribution of ISM → can boost Lyman α EW
- dust absorption → decreases Lyman α line strength
- IGM absorption → reduces mostly blue peak

Structure of LAEs - the effects of Radiative transfer



- panel b: LAE is at centre of filamentary structure in cosmic web (white dashed circle: virial radius)
- panel d: zoom-in showing cold gas accretion, outflows, satellite galaxies, star formation and a possible AGN at the centre
- red lines (2 and 3) indicate Lyα photons that were resonantly scattered

Illustration taken from Ouchi et al. (2020)

LAEs usually have extended halos!

Observed with MUSE:

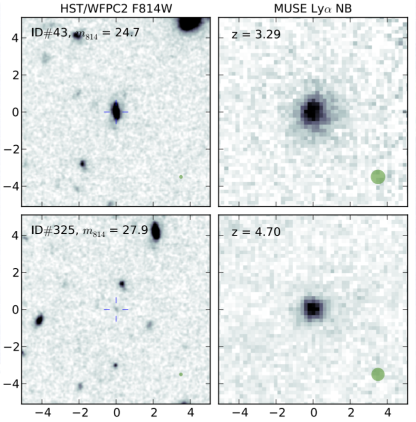


Figure taken from Wisotzki et al. (2016)

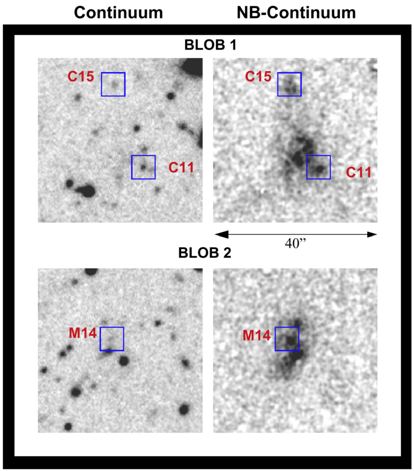


Figure taken from Steidel et al. (1999)

Lyman α Halos - Scattering leads to extended emission

- most LAEs have extended Lyman α halos (10 times larger than UV continuum)
- Lyman α scatters in CGM (circum galactic medium)
- small halo: potentially easier escape of Lyman α and LyC
- line shape properties can vary over halo

$\rightarrow$ The whole sky is covered in Lyman α emission!

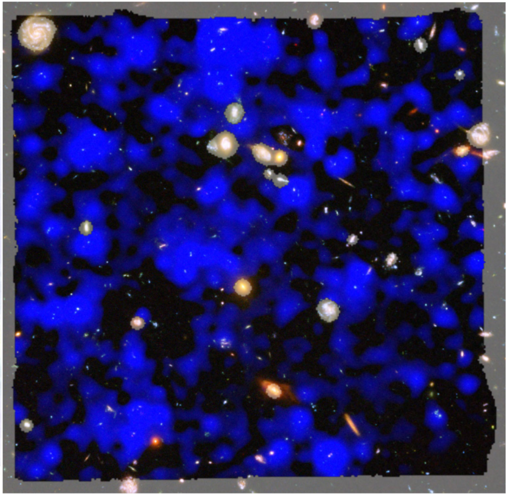


Figure taken from Wisotzki et al. (2018) showing Lyman α emission in blue

LAEs come in different sizes

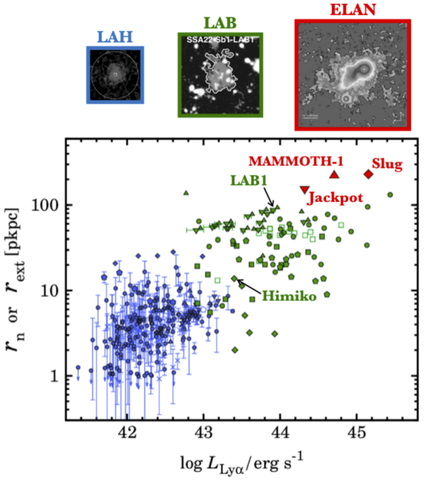


Figure taken from Ouchi et al. (2020), a composite of data from the literature

- LAEs usually have extended Lyα emission around them
- their sizes can vary, giving rise to new classifications
- three classes: Lyα halos (LAH, image from Leclercq et al., 2017), Lyα blob (LAB, image from Matsuda et al., 2011) and enormous Lyα nebulae (ELAN, image from Cantalupo et al., 2014)
- in extended Lyα emission we can see cosmic web filaments

Large scale structures in the Universe

- Reminder: Large scale structure → Cosmic Web
- left: observations, right: simulation

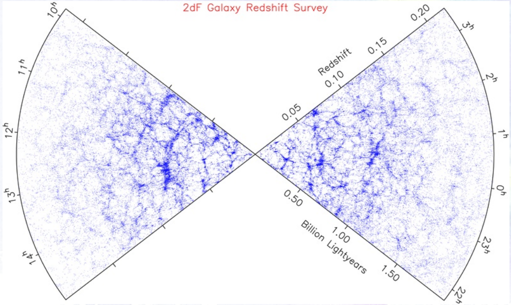


Figure taken from http://www.2dfgrs.net/

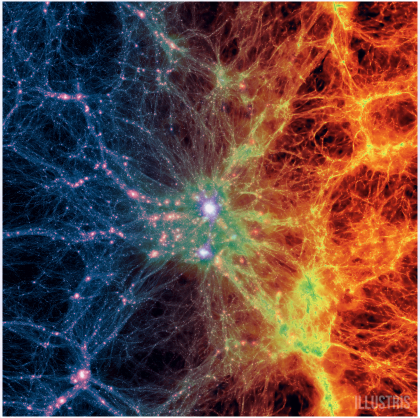


Figure taken from https://www.illustris-project.org/

Lyman α unveils the Cosmic Web

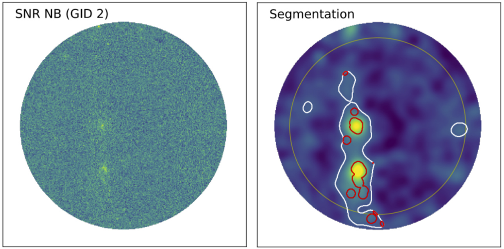


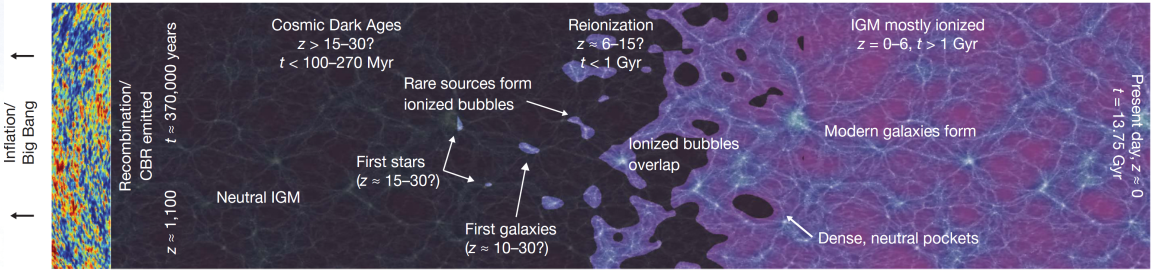
Figure taken from Bacon et al. (2021), showing a filament at a redshift of $z = 3.07$

- first detection of Cosmic Web in Lyman α in filamentary structures with the MUSE instrument (Bacon et al. (2021))
- around 70% of Lyman α luminosity in these filaments from beyond the CGM
- fluorescent emission from UV background can only account for around one third of the emission
- there must be a large population of faint LAEs responsible for the filaments

Lyman α as a tracer of Reionisation

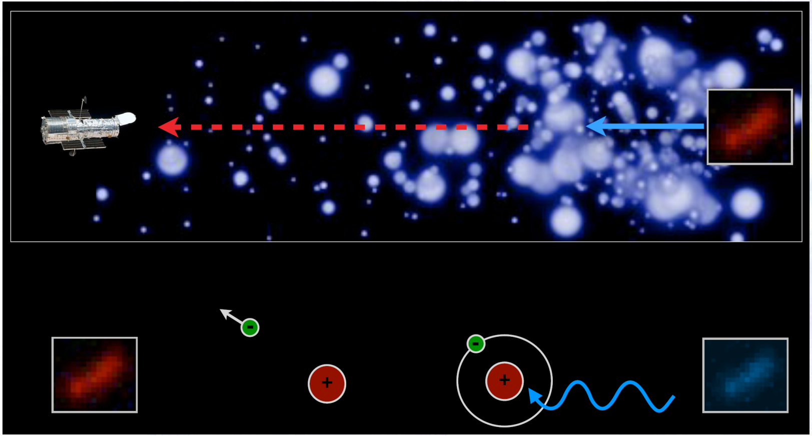
Reminder: Reionisation of the IGM

Questions: Which objects reionised the universe? Candidates: Star-forming galaxies or AGN.
When did reionisation happen? What was the process?



Source: Robertson et al. (2010)

The effect of the IGM on Lyman Continuum and Lyman α emission



- the HI in the IGM absorbs LyC and the blue part of Lyman α
- the sources of reionisation are not directly observable at the epoch of reionisation (EoR)
- LAE fraction can be used to study the end of the EoR

credit: Pascal Oesch

Redshift Evolution of Fraction of LAEs

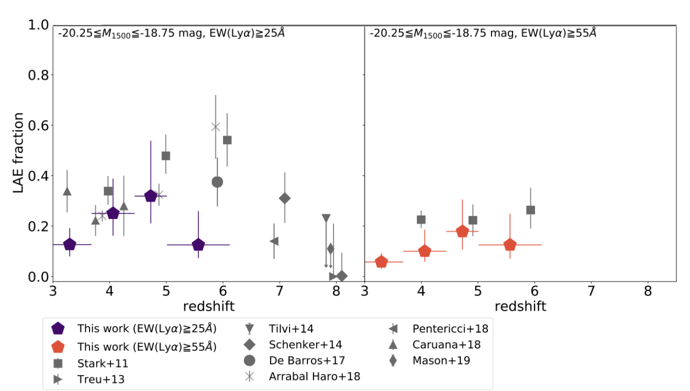


Figure taken from Kusakabe et al. (2020)

- fraction LAEs goes down at $z \sim 6$
- indication of epoch of reionisation

IGM absorption of Lyman Continuum

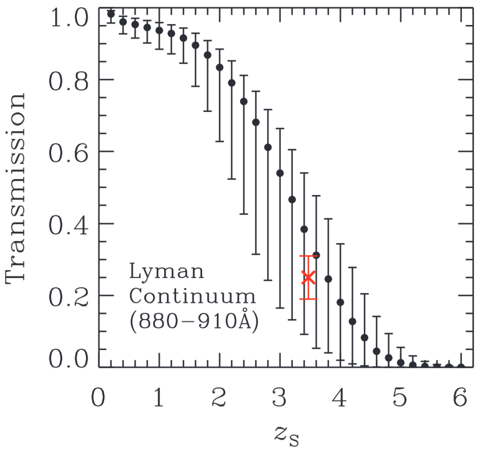


Figure taken from Inoue & Iwata, 2008

Lyman Continuum

- LyC gets absorbed in neutral hydrogen
- therefore not observable at the EoR directly

Possible solutions

- observing ionised bubbles at the EoR directly
- or: Finding indirect tracers that can be observed at the EoR

Connection between f_{esc} and Ionising Photon Rate

Ionising photon rate from star-forming galaxies
(e.g. Ellis, 2014, McCandliss et al., 2019):

$$\dot{n}_{\mathrm{ion}} = \xi_{\mathrm{ion}}\, \rho_{\mathrm{SFR}}\, f_{\mathrm{esc}}$$

- ξ_{ion} ionising photon production efficiency
- ρ_{SFR} star formation rate density
- f_{esc} escape fraction

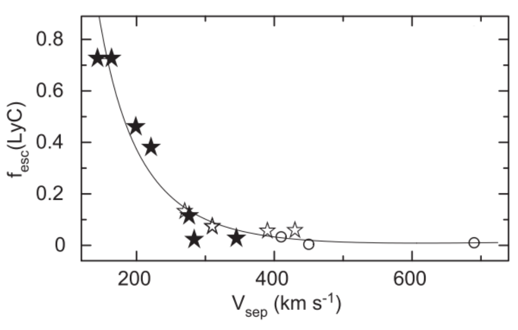
See Steidel et al. (2001):

$$f_{\mathrm{esc}}^{\mathrm{rel}} = \frac{(f_{\mathrm{LyC}}/f_{\mathrm{UV}})_{\mathrm{obs}}}{(L_{\mathrm{LyC}}/L_{\mathrm{UV}})_{\mathrm{int}}} \exp(\tau_{\mathrm{IGM}})$$

- $f_{\mathrm{esc}}^{\mathrm{rel}}$ relative escape fraction
- $(L_{\mathrm{LyC}}/L_{\mathrm{UV}})_{\mathrm{int}}$ intrinsic luminosity ratio between Lyman continuum (LyC) and UV continuum
- $(f_{\mathrm{LyC}}/f_{\mathrm{UV}})_{\mathrm{obs}}$ observed flux ratio
- τ_{IGM} optical depth of the IGM for LyC

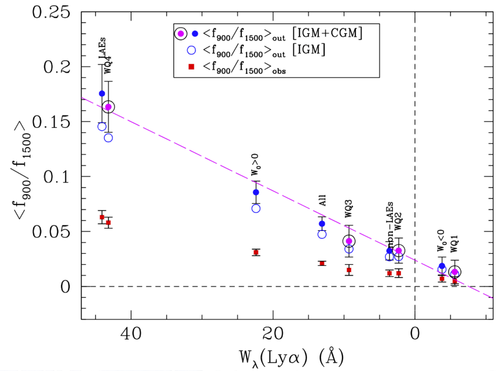
Can we use Lyα to infer LyC escape fractions?

Indeed, LyC emission and Lyα seem to be correlated



Izotov et al. (2018)

For low-redshift LAE analogues



Steidel et al. (2018)

Comparing f_{esc} and Lyα properties

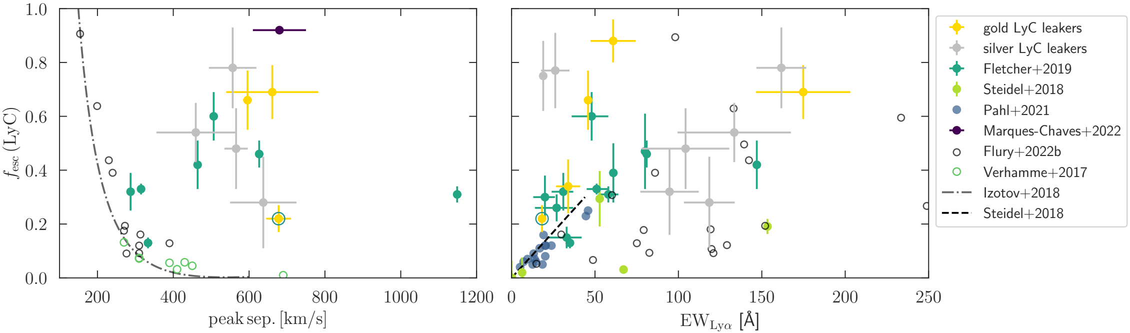


Figure from Kerutt et al. in prep.

- here: surprisingly high peak separations
- Lyα EW seems to work slightly better, but not ideal either
- high Lyα EW has high f_{esc}, but low Lyα EW can have high f_{esc} as well

Observations of High-z double peaks

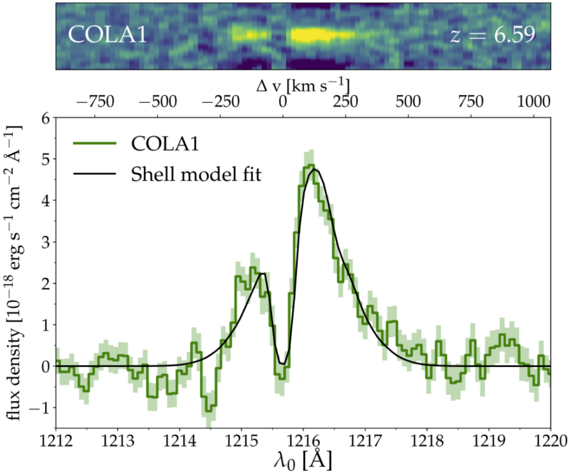
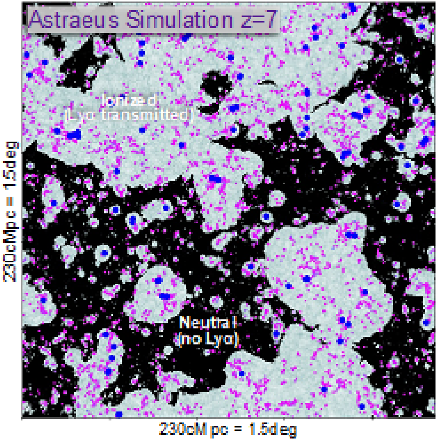


Figure taken from Matthee et al. (2018)

- IGM should absorb blue part of Lyman α at the EoR
- here: observation of "blue bump" at $z = 6.59$
- process of ionisation not homogeneous, happened in ionised bubbles

Analysing ionised Bubbles at high redshifts



- Comparison between observations and simulations to better understand ionised bubbles
- ionised bubbles grow in the EoR
- here: slice through the Astraeus simulation
- simulation at redshift ~ 7
- size of $0.23\,\mathrm{cGpc}^3$

Ucci et al., 2020; Hutter et al., 2021

Simulations of the EoR

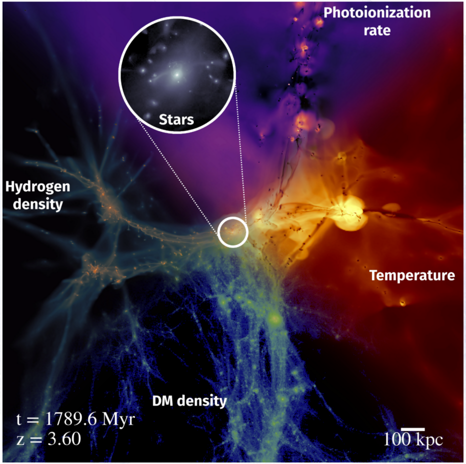


Figure taken from Trebitsch et al. (2021)

Simulations give us insights into processes that are not directly observable, especially at high redshifts.

- snapshot of OBELISK simulation
- left: gas distribution
- bottom: dark matter
- right: gas temperature
- top: photoionisation rate

Simulations of Lyman α lines

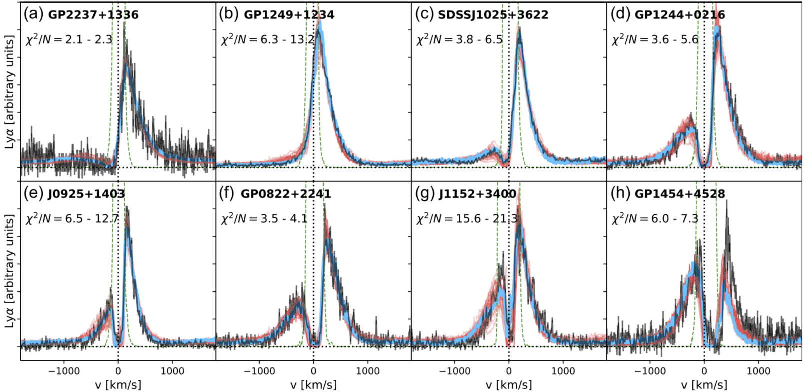


Figure taken from Blaizot et al. (2023)

- black: data of low-redshift LAEs
- blue: best-matching simulated line
- red: other potential simulated lines

Simulations can now reproduce observed Lyman α lines. From them we can learn about the underlying mechanisms and the physical properties of the LAEs.

Summary

Open Questions

Is everything understood? - No!

- Are LAEs at high redshifts different from low-redshift LAEs?
- Do LAEs produce enough hydrogen ionising emission to (re-) ionise the universe?
- For simulations: Can we reproduce very exotic Lyman α line shapes with triple peaks and stronger blue bumps?
- What powers Lyman α halos?

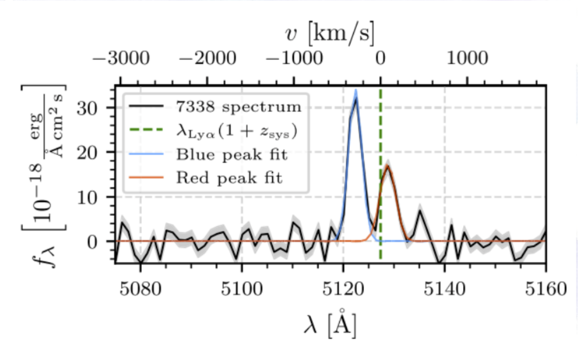


Figure taken from Furtak et al. (2022)

Reminder: What you should remember from this lecture

Lyman α emission

- Lyman α is the transition from the first excited state to the ground state of hydrogen
- around 2/3 of recombinations result in Lyman α

Observability

- Lyman α line at 1215.67 Å shifts into the optical at redshifts $z \sim 3$
- Lyman α can be very strong, easy to observe even for UV faint galaxies

What we can learn from LAEs

- timing and process of reionisation
- properties of star-forming galaxies in the early universe

Thank you for your attention!

References

Bacon, R., Mary, D., Garel, T., et al. 2021, *Astronomy and Astrophysics*, 647, A107

Blaizot, J., Garel, T., Verhamme, A., et al. 2023, *Monthly Notices of the RAS*, 523, 3749

Cantalupo, S., Arrigoni-Battaia, F., Prochaska, J. X., Hennawi, J. F., & Madau, P. 2014, *Nature*, 506, 63

Caruana, J., Bunker, A. J., Wilkins, S. M., et al. 2012, *Monthly Notices of the RAS*, 427, 3055

Dijkstra, M. 2014, *Publications of the Astron. Soc. of Australia*, 31, e040

Dijkstra, M. 2017, arXiv e-prints, arXiv:1704.03416

Ellis, R. S. 2014, arXiv e-prints, arXiv:1411.3330

Fan, X., Carilli, C. L., & Keating, B. 2006, *Annual Review of Astron and Astrophys*, 44, 415

Finkelstein, S. L., Rhoads, J. E., Malhotra, S., Pirzkal, N., & Wang, J. 2007, *Astrophysical Journal*, 660, 1023

Furtak, L. J., Plat, A., Zitrin, A., et al. 2022, *Monthly Notices of the RAS*, 516, 1373

George, E. M., Reichardt, C. L., Aird, K. A., et al. 2015, *Astrophysical Journal*, 799, 177

Giri, S. K., Zackrisson, E., Binggeli, C., Pelckmans, K., & Cubo, R. 2019, arXiv e-prints, arXiv:1903.01483

Gronke, M. & Dijkstra, M. 2014, *Monthly Notices of the RAS*, 444, 1095

Gunn, J. E. & Peterson, B. A. 1965, *Astrophysical Journal*, 142, 1633

7 Appendix

Wavelengths of Emission Lines

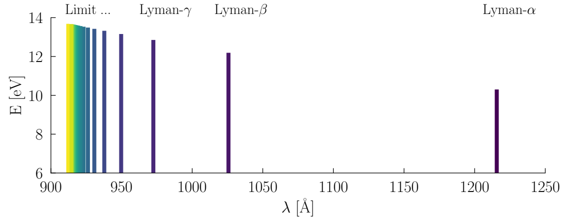
To generate the Lyman series:

$$\frac{1}{\lambda} = R_H \left(1 - \frac{1}{n^2}\right)$$

More general:

$$\frac{1}{\lambda} = R_H \left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right)$$

- R_H: Rydberg constant $\approx \frac{13.6\text{eV}}{\text{hc}}$
- n: principal quantum number



Studying the Epoch of Reionisation

Thomson Scattering

- elastic scattering of photons on electrons
- optical depth through correlation between temperature and polarisation anisotropies in CMB, parameterises column density of free electrons
- best fits with instantaneous reionisation at $z = 7.8 - 8.8$ (Planck Collaboration et al., 2016)

21 cm line

- spin-flip transition of neutral hydrogen
- tomography maps distribution of neutral hydrogen
- even at late stages of EoR there are large neutral islands, see Giri et al. (2019)

Lyman α luminosity function

- number of galaxies per luminosity bin

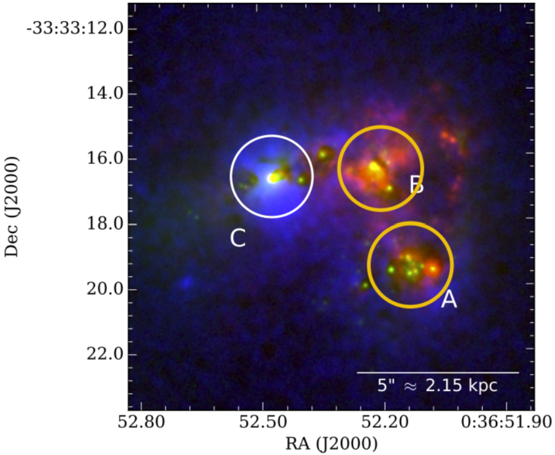
Kinematic Sunyaev Zel'dovic Effect

- Doppler shift of scattered photons due to bulk velocity of electrons relative to CMB
- resulting temperature shift scales with free electron density
- Sunyaev & Zeldovich, 1972
- duration constrained to $\Delta z < 5.4$ (George et al., 2015)

Gunn-Peterson trough

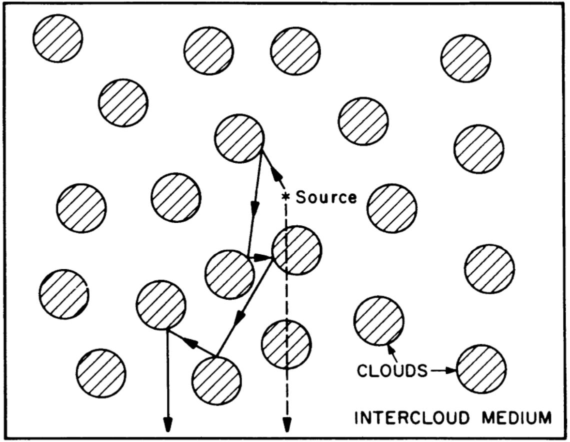
- absorption trough in the spectra of quasars bluewards of Lyman α
- used to infer neutral hydrogen density in IGM (Gunn & Peterson, 1965)
- complete troughs seen at $z > 6$ (e.g. Fan et al., 2006, Fan et al., 2006)

Observing LAEs at low redshifts: Haro 11



- Another example of a low-redshift LAE at $z = 0.02$: Haro 11
- Lyman α in blue, UV continuum ($\lambda \sim 1500$Å) in green, Hα in red
- clumpy and irregular galaxy, many star-forming regions
- Lyman α is extended, but not always at the same place as other emission

Neufeld Scenario Increasing Lyman α EWs?

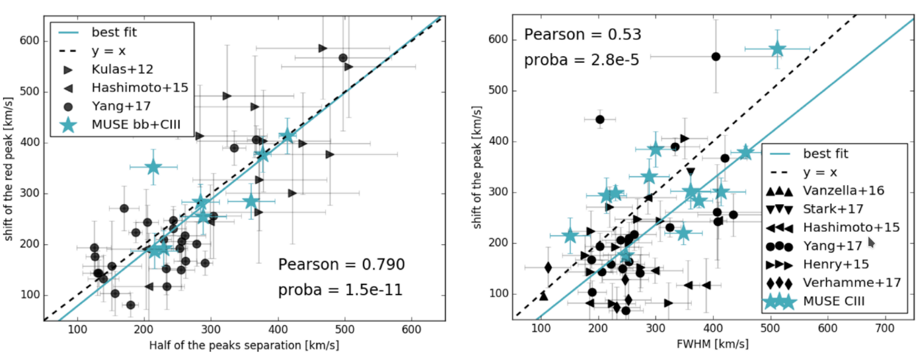


- clumpy ISM could increase EW
- Lyman α scatters off the surface of high density clouds containing dust
- UV continuum would pass through and get absorbed
- might not be realistic Gronke & Dijkstra (2014), Finkelstein et al. (2007)

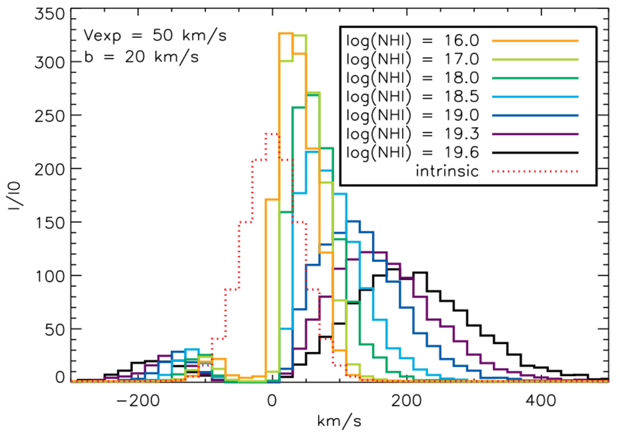
Figure taken from Neufeld (1991)

Correcting the Redshift Using FWHM and Peak Separation

Taken from Verhamme et al., 2018:



Can we use Lyα to infer LyC escape fractions?



Star-forming galaxies emitting LyC emission (probably) ionised the universe.

Theory: Neutral hydrogen column density influences the escape of LyC photons, but also the shape of the Lyα line.

higher neutral hydrogen column density
$\rightarrow$ larger peak separation

Verhamme et al. (2015)

Indirect Tracers of LyC are Needed (Lyman α)

LyC is absorbed in neutral hydrogen

$\downarrow$

not observable at the epoch of reionisation

$\downarrow$

indirect tracers are needed

Indirect Tracers of LyC are Needed (Lyman α)

LyC is absorbed in neutral hydrogen

$\downarrow$

not observable at the epoch of reionisation

$\downarrow$

indirect tracers are needed

Most promising: Lyman α properties

- peak separation
- full width at half maximum (FWHM)
- halo size
- equivalent width

Indirect Tracers of LyC are Needed (Lyman α)

LyC is absorbed in neutral hydrogen

↓

not observable at the epoch of reionisation

↓

indirect tracers are needed

Most promising: Lyman α properties

- peak separation
- full width at half maximum (FWHM)
- halo size
- equivalent width

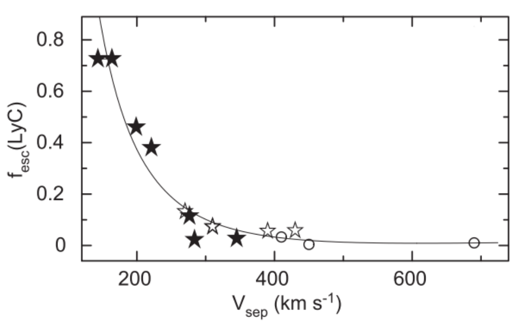
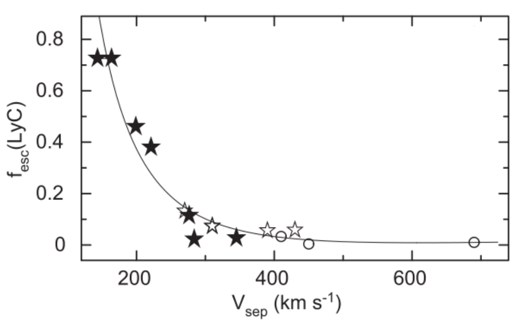


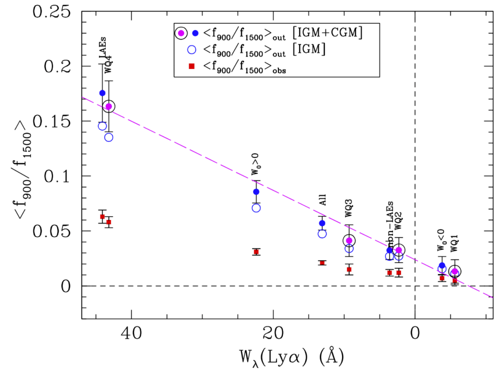
Figure taken from Izotov et al. (2018) showing low-redshift star-forming galaxies

Can we use Lyα to infer LyC escape fractions?

Indeed, LyC emission and Lyα seem to be correlated (at lower redshifts)



Izotov et al. (2018)



Steidel et al. (2018)

Can we find the same trends at $z \sim 3-4$?