Exploring the high redshift Universe with deep spectroscopy in the CANDELS fields

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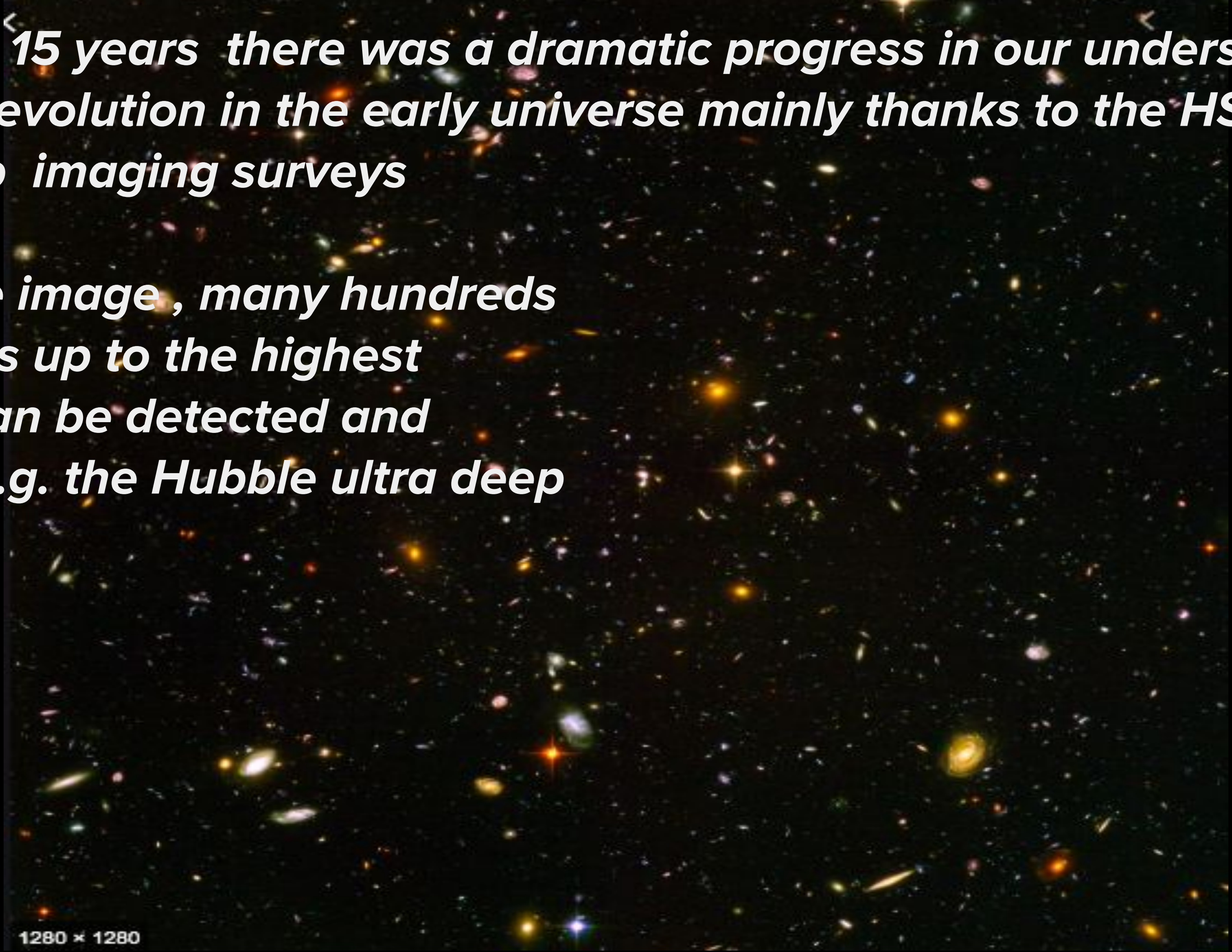
In the last 15 years there was a dramatic progress in our understanding of galaxy evolution in the early universe mainly thanks to the HST ultra-deep imaging surveys

In a single image , many hundreds of galaxies up to the highest redshift can be detected and studied (e.g. the Hubble ultra deep field)



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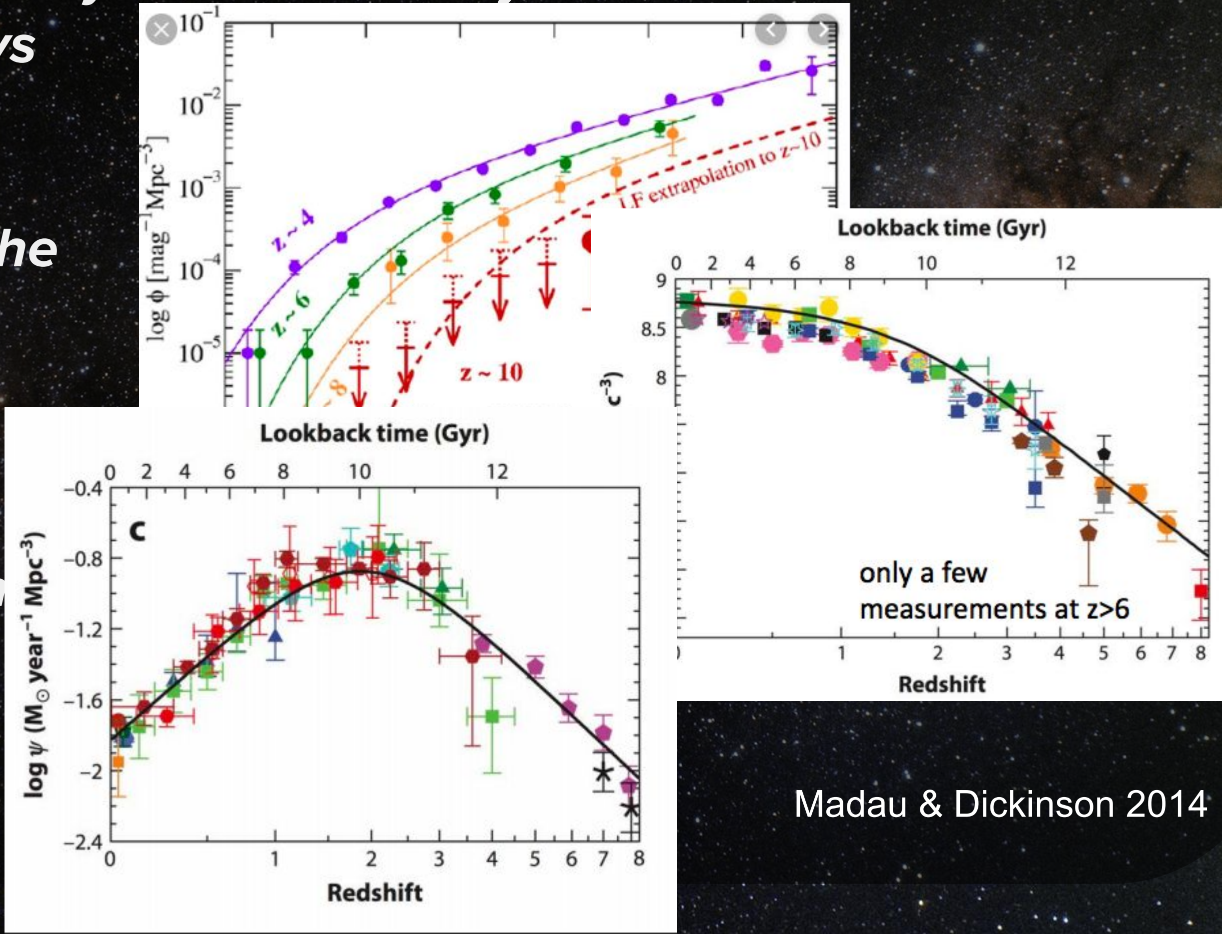
Multi-wavelength surveys have allowed us to study the statistical properties of galaxies through the luminosity function and cosmic star formation density and their evolution in cosmic time



Madau & Dickinson 2014

Progress in our understanding of galaxy evolution at high redshift is not limited by poor statistics (anymore) but rather by the systematic uncertainties in our measurements of crucial physical parameters, caused by the interrelated degeneracies between e.g. age, dust attenuation and metallicity

Systematic spectroscopic follow-up is needed as a key complement to the deep multiwavelength data

Spectroscopy is key to :

- validate redshifts

- validate Luminosity function, Mass Function, SFRD density and their evolution with cosmic time

-Probe ISM , gas and kinematics , chemical enrichment, IGM interaction

- Probe structures and the impact of environment on galaxy evolution

Main spectroscopic surveys carried out in the last few years
(clearly not a complete list, focussed on high redshift surveys)

VUDS -VIMOS Ultra Deep Survey (PI O. LeFevre): optical survey 3 independent fields ~10000 galaxies @$2<z<6$

3D-HST All 5 CANDELS fields - near-IR ~10,000 galaxies @ $1 < z < 3.5$.

MOSDEF COSMOS +AEGIS+GOODS-N near -IR ~1500 galaxies at $1.4 < z < 3.8$

LEGA-C 2000 galaxies @$0.6<z<1$

Also ***DEEP3,zCOSMOSdeep,UCR-DEIMOS, DEIMOS 10K etc etc***

VANDELS ECDFS - UDS optical ultra deep ~2200 galaxies @ $1<z<7$ including a passive sample

CANDELSz7 COSMOS GOODS-S UDS optical ~200 galaxies at $z> 6$ reionization epoch

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VANDELS

A deep VIMOS survey of the CANDELS UDS and CDFS fields

ESO public VIMOS spectroscopy survey of the UDS and CDFS fields

McLure et al. 2018
Pentericci et al. 2018

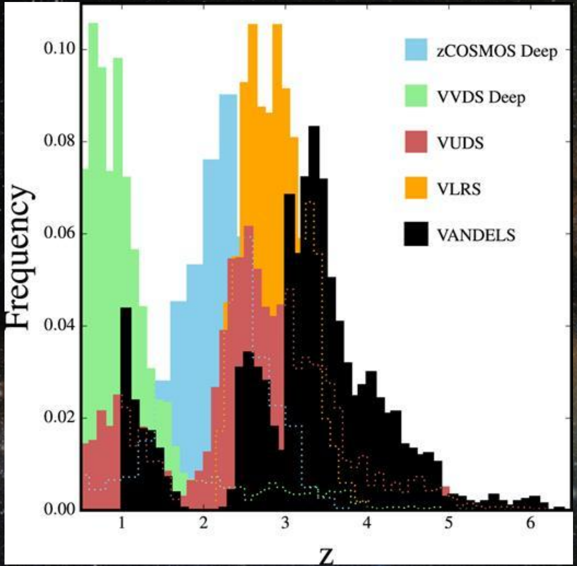
What is it?

- >1000 hours of VIMOS visitor time: 2015-2018 → observation completed!
- spectra between ~4800-9800 Å
- 20-80 hours integration time, focused on z>3 star-forming galaxies
- Medium resolution ~600
- Science goals: ages, masses, stellar metallicities and outflows at high-z
- Raw data immediately public
- Regular releases of reduced data (DR2 available, DR3 available soon)
- Full details can be found at: **vandels.inaf.it**

VANDELS: overview

Proposal was focused on two key aspects:

- Legacy value to astronomy community
- Different science from previous VIMOS surveys (VUDS VVDS zCOSMOS VIPERS which were mainly redshift surveys



Four key elements of VANDELS:

- Small area (0.2 sq. degrees), best available multi-wavelength data
- Ultra-long integrations, minimum 20 hours max 80 hours per source
- Medium resolution spectra (MR grism)
- Pre-selection biased to very high redshift (85% of targets at z>3)

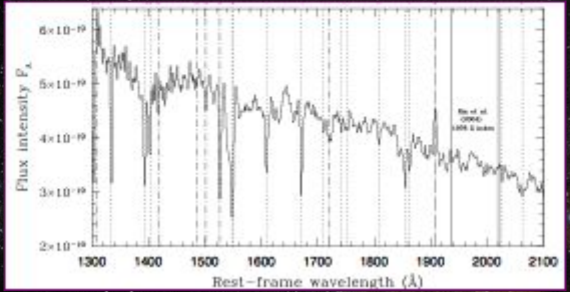
VANDELS motivation

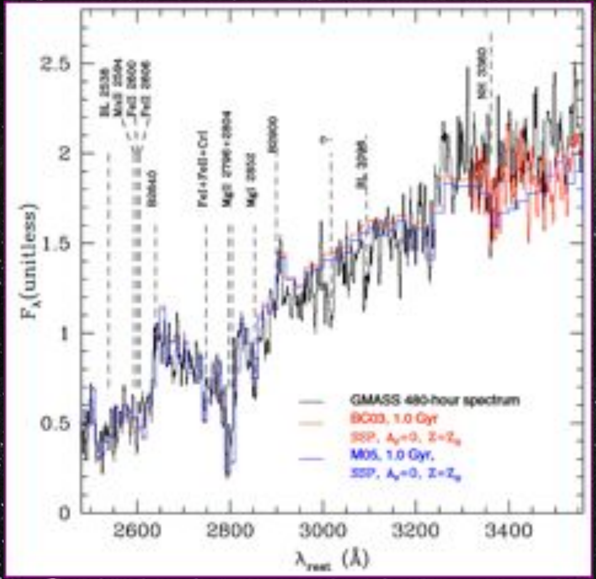
TARGETS

- Star-forming galaxies at $2.4<z<5.5$ ($H_{AB}<24$)
- Passive galaxies at $1.0<z<2.5$ ($H_{AB}<22.5$)
- Lyman-break galaxies at $3.0<z<7.0$ ($H_{AB}<27$)

Combine ultra deep optical spectroscopy with near-IR grirm spectroscopy (3DHST) and 0.3-4.5 micron photometry to measure physical tracers of galaxy evolution: ages mass dust SFR outflows, stellar metallicity

Provide sufficient signal to noise and resolution to measure physical properties in individual objects rather than only in stacks



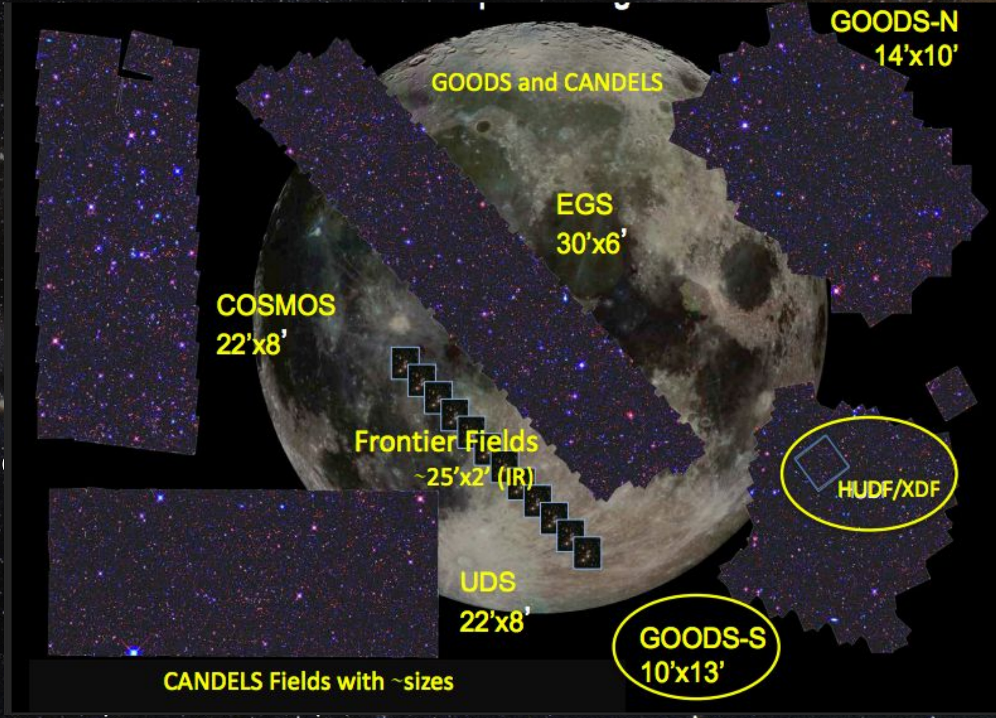


VANDELS fields

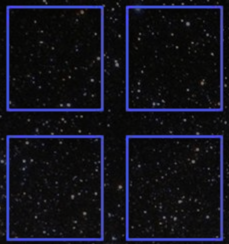
VANDELS is centered on 2 of the premier extragalactic fields ECDFS and UDS (COSMOS was assigned to the LEGA-C survey). The central part of the fields is covedere by ultradeep HST CANDELS data.

In these fields we can combine the ultra deep optical spectroscopy with

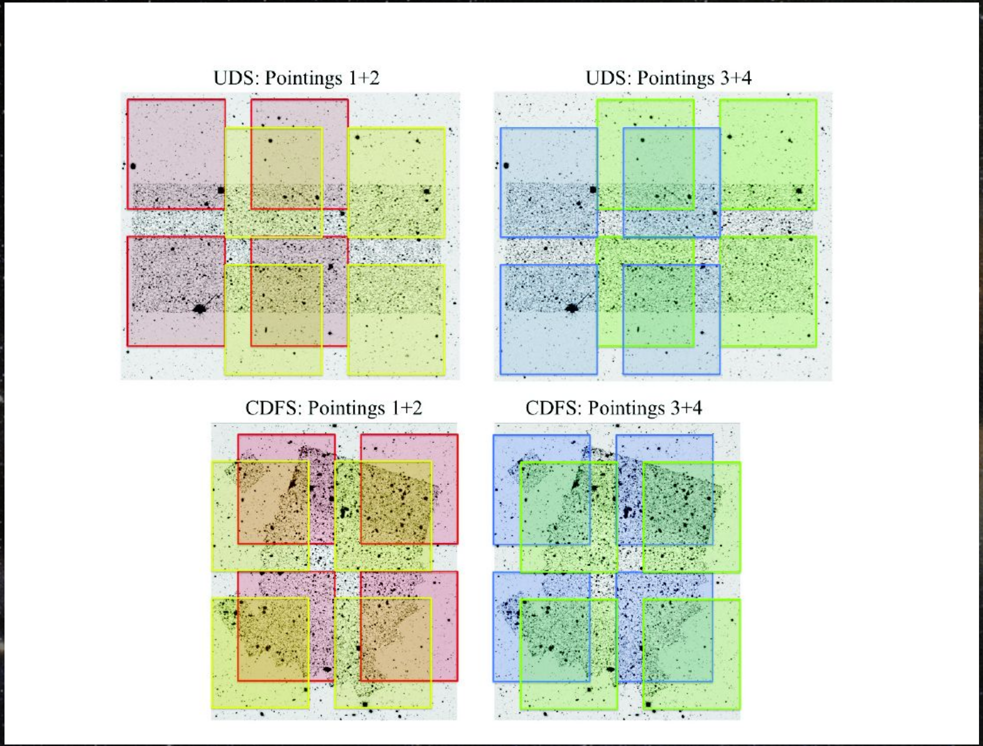
1. near-IR grism spectroscopy (3DHST)
2. exquisite 0.3-4.5 micron photometry (including multiband HST imaging in the central area and deep Spitzer data)
3. Deep multiband imaging with VLT, Subaru, Vista etc
4. Ultra deep (CDFS- 7 Msec) to deep (UDS- 800ks X-ray imaging data.
5. Deep VLA radio observations



VANDELS: observations



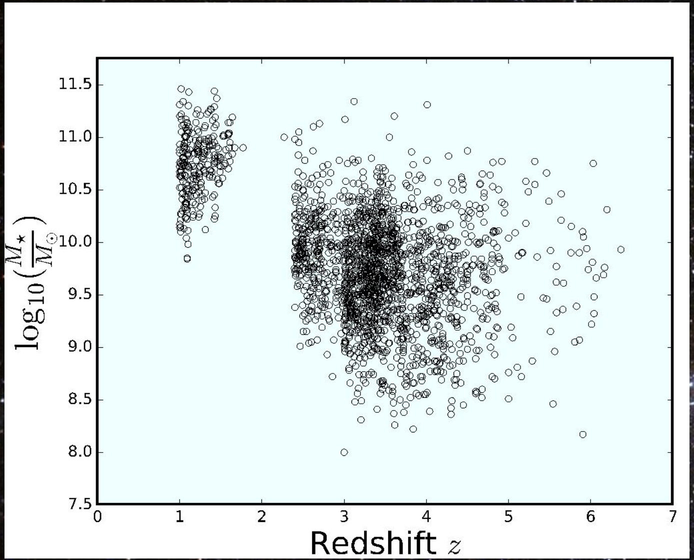
Vimos footprint

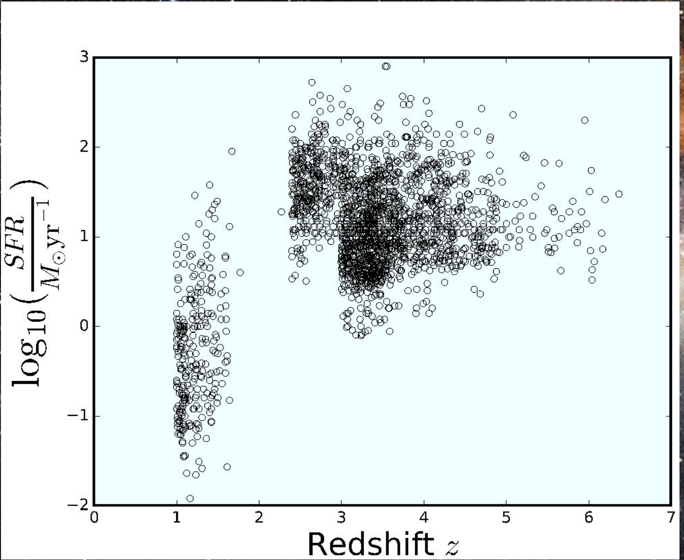


Each pointing is targeted 4 times, for 20 hours each: bright targets get 20 hours integration, faint targets get 80 hours. We aim at a S/N=15-20 per pixel for the brightest and S/N=10 for the faintest (SFG& Passive), S/N=3 on the continuum and line flu limit $2x10^{18}$ erg/s/cm^2 (5σ) for the faintest LBG

VANDELS: science

The full VANDELS sample consists of >2100 targets, designed to sample the star-forming population at $2.5<z<5.5$ and their passive descendants at $1<z<2$.





Final sample will span: 3 dex in stellar mass

4 dex in star formation rate

Provide good sampling of SF "main sequence" at $2.5<z<5.5$

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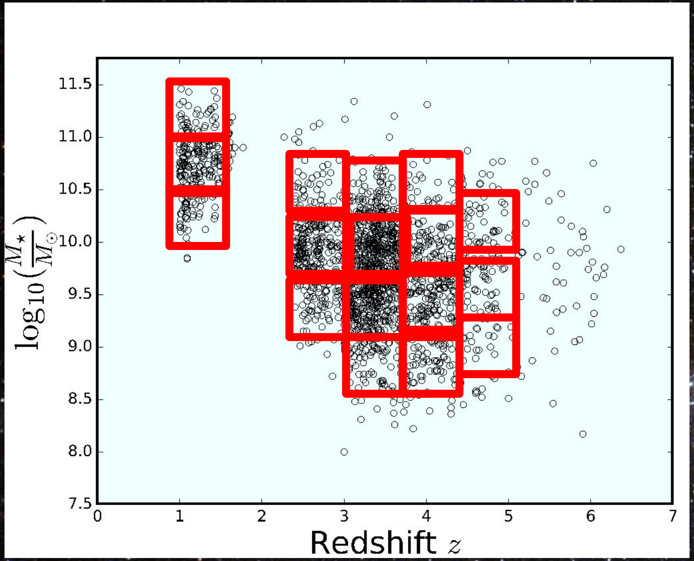
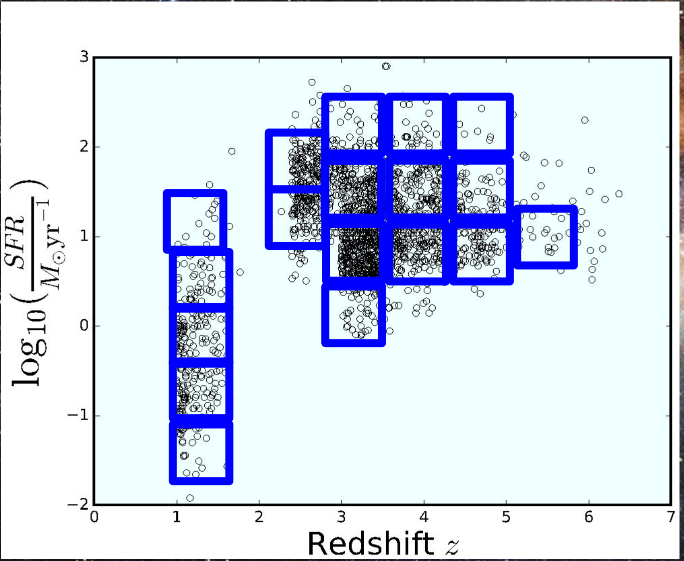
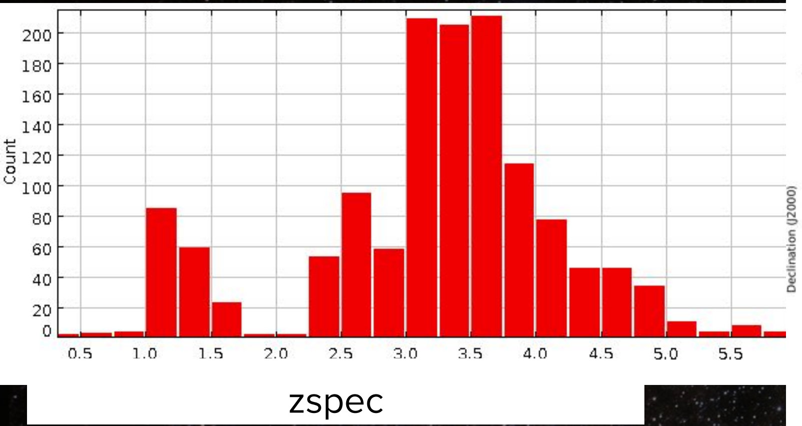
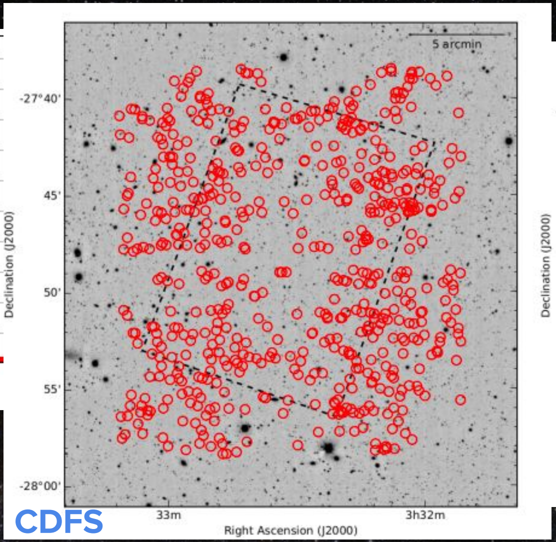


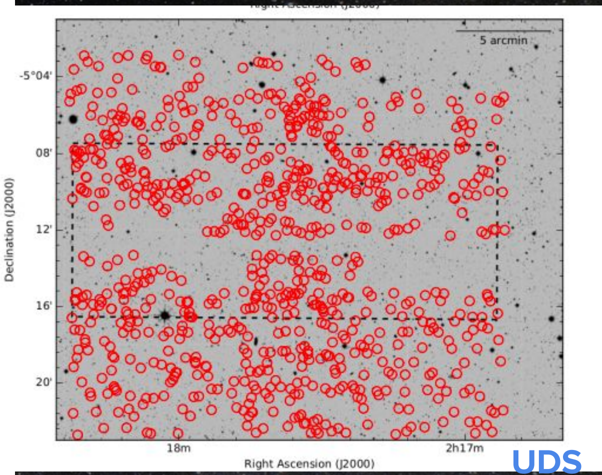


High SNR will allow detailed studies of individual targets, but clearly many opportunities to explore the properties of composite spectra as function of z, mass, metallicity, SFR….

VANDELS data release two (DR2): available from 1st Oct. 2018







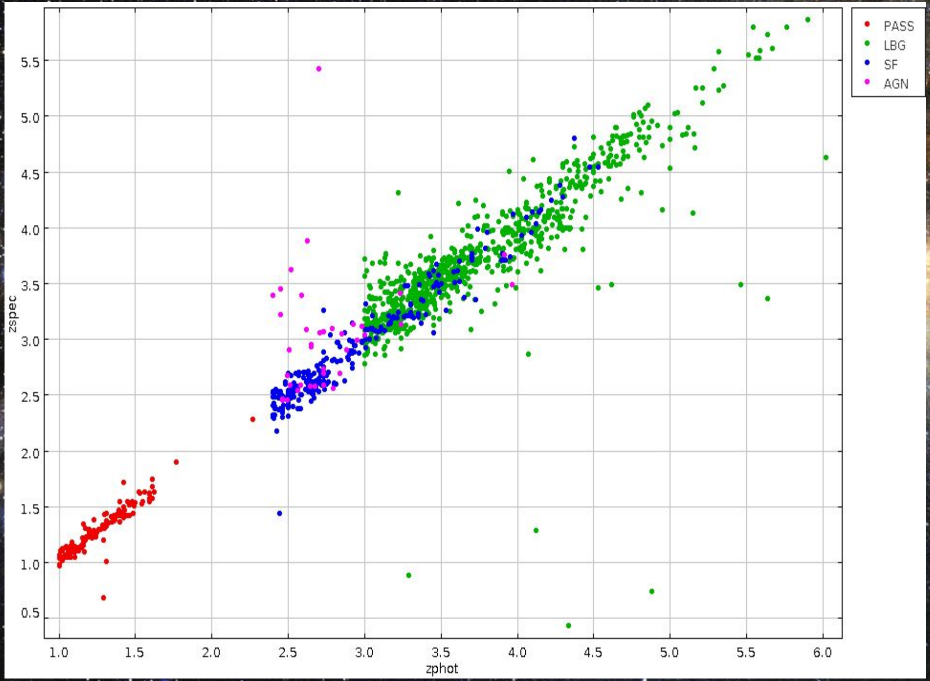
The data release which is now available on the ESO webpages includes the spectra for all galaxies for which the scheduled integration time was completed during season one. and two In addition, it includes the spectra for those galaxies for which the scheduled integration time was 50% complete at the end of season 2.

The total number of spectra released is 1362 (586 in CDFS and 776 in UDS) of which 1132 are completed spectra *including 217 spectra which received 80 hours integration time*

The third data release will be available soon both on the ESO and in the VANDELS database which is open.

Excellent accuracy of the photometric redshifts up to z=6 and minimum number of outliers for all classes of targets (apart from AGN)

Class	bias	σ_o	Nout	%out
SF	-0.007	0.029	1	0.4
LBG 2.5<z<5.5	-0.009	0.038	13	1.5
LBG 5.5<z<7.0	-0.068	0.014	2	18
PASS	0.007	0.019	2	1.2
AGN	0.057	0.050	7	18



Statistics of 1132 completed objects contained in DR2 (217 with 80 hours, 654 with 40 hours , 261 with 20 hours

Credits to the VANDELS team:

Catalogs& zphot: *>15 people including: M. Jarvis, A. Fontana, M. Bolzonella, W. Hartley, S. Finkelstein*
Target maximization: *A. Iovino*
VIMOS mask preparation: *>10 people including L. Guaita, O. Cucciati, A.Bongiorno,A. Carnall*
Observers@Paranal : *> 20 people*
Data reduction, database handling and ESO DRs: *IASF group B. Garilli, P. Franzetti, A. Gargiulo and M. Scodeggio*
Redshift & Flag measurements: *> 20 people including D. Maccagni, M. Talia, F. Cullen, F.Marchi*

Some early results from partial VANDELS dataset

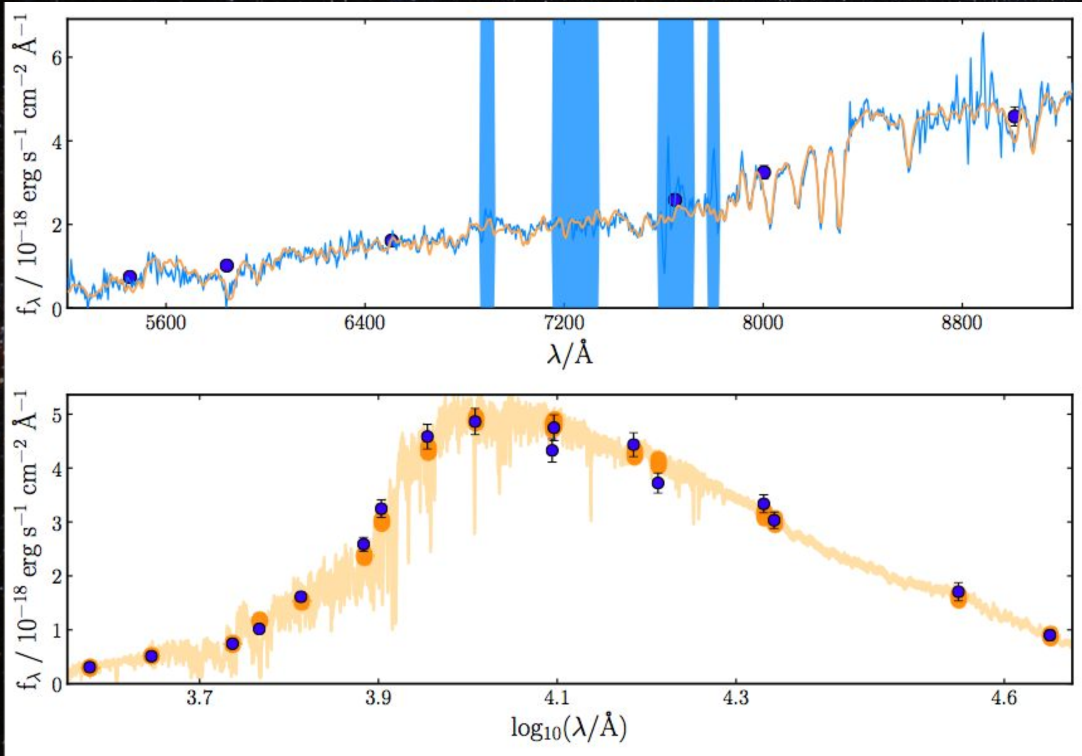
credits : A. Carnall, F.Marchi, F. Cullen, M. Talia et al

The results in particular provide examples of

- the power of combining deep spectra with multi-wavelength photometry
- the detailed ISM studies that can be conducted with the best S/N spectra
- the advantages of combining many hundreds spectra to produce and analyse super-deep stacks
-

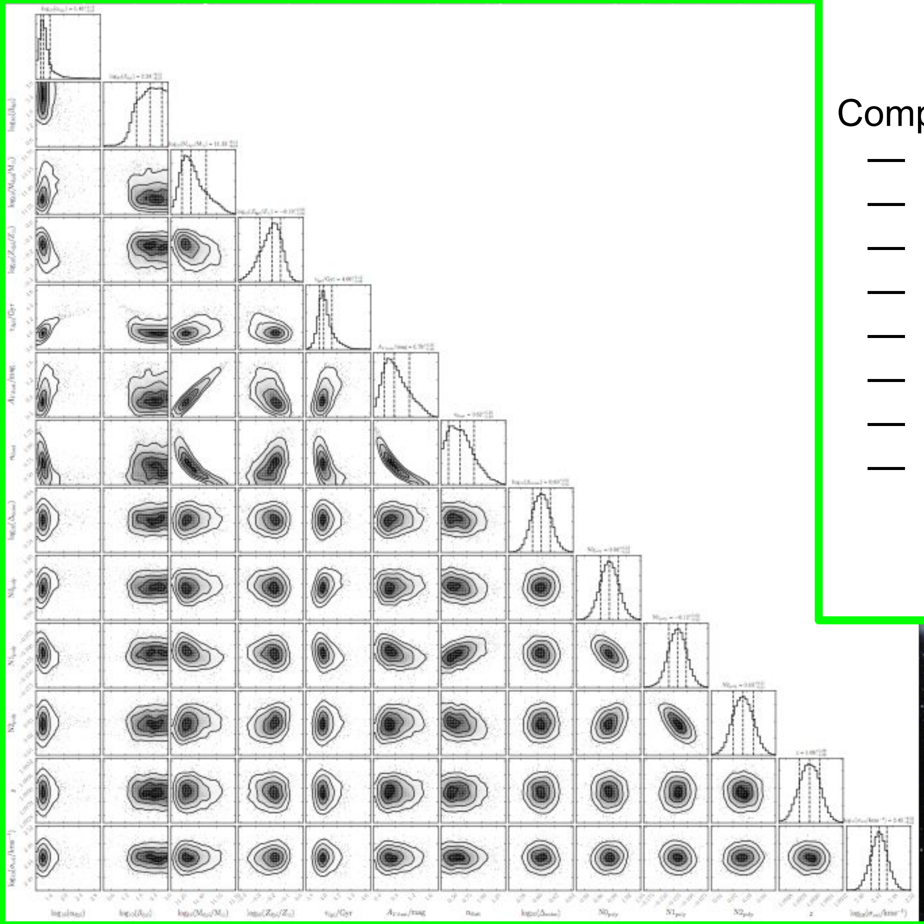
Star formation histories of massive quiescent galaxies at 1.0<z<1.3 (Carnall et al. 2019)

Bayesian Analysis of Galaxies for Physical Inference and Parameter EStimation
BAGPIPES https://bagpipes.readthedocs.io



Bayesian full-spectral-fitting analysis of 75 massive UVJ-selected galaxies at redshifts of 1.0<z<1.3, combining extremely deep rest-frame ultraviolet spectroscopy from VANDELS with multi-wavelength photometry.

SFHs and physical parameters from VANDELS spectra



Complex physical model (13 free parameters)

- — Redshift
- — Stellar mass
- — Metallicity
- — 3 x SFH shape
- — 2 x dust (slope and A_V)
- — Velocity dispersion
- — Noise uncertainty parameter
- — 3 x calibration uncertainty

Carnall et al. 2019

SFHs and physical parameters from VANDELS spectra

When did they quench?

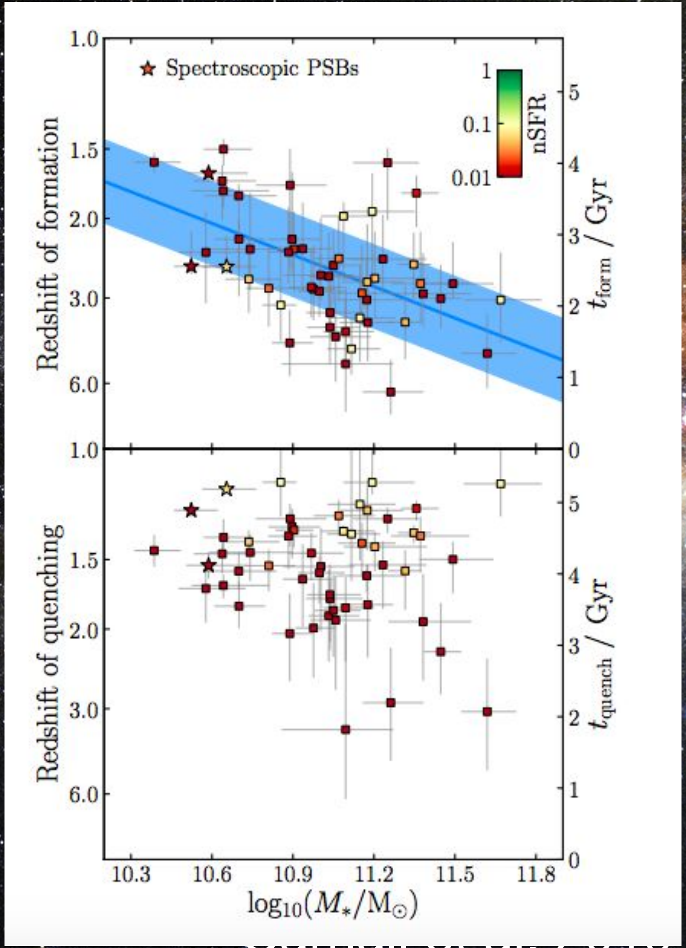
Define t_{quench} as the age of the Universe when nSFR fell below 0.1 (i.e. the SFR fell to <10% of time average)

$$\mathrm{nSFR} = \mathrm{SFR}_{100} \frac{t_{\mathrm{obs}}}{\int_0^{t_{\mathrm{obs}}} \mathrm{SFR}(t)\,\mathrm{d}t}.$$

Most passive galaxies (nSFR<0.1) quenched earliest, clear sequence with mass

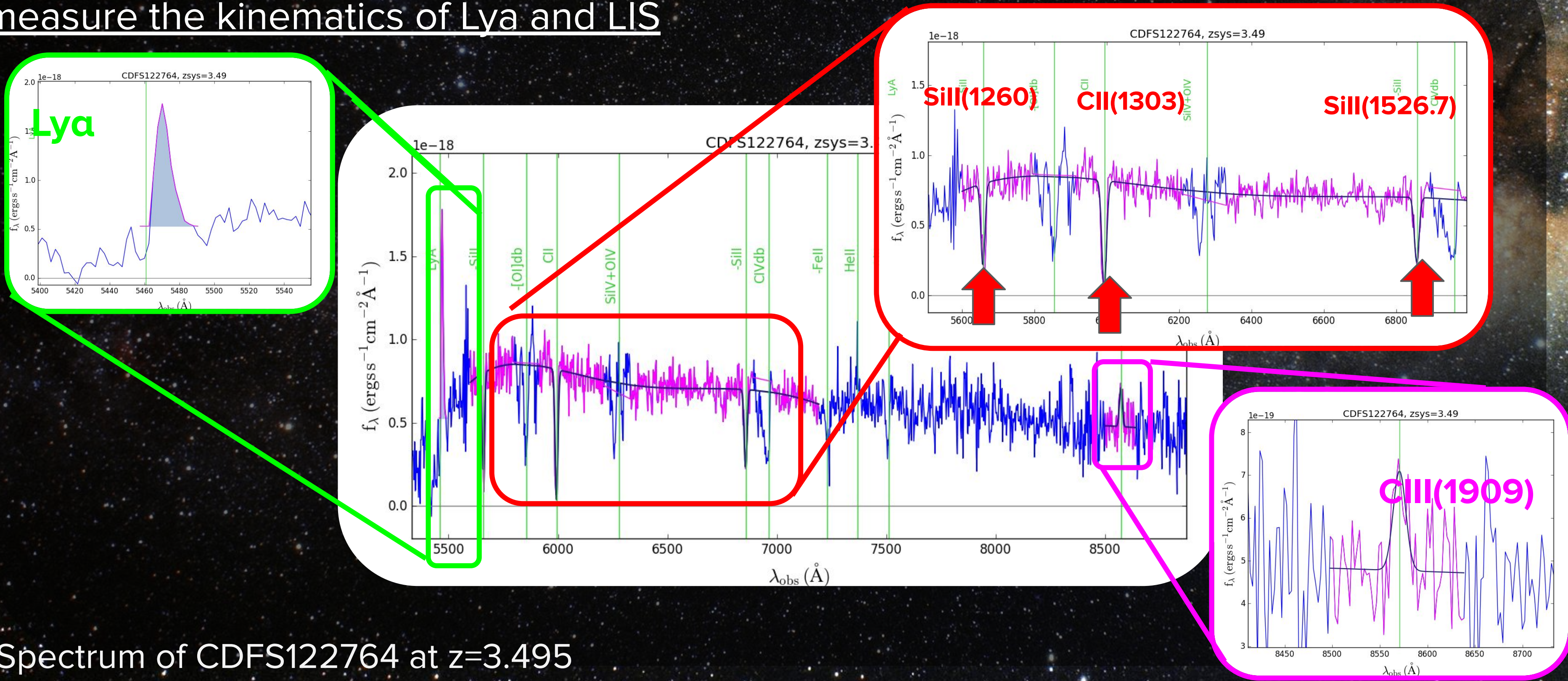
Those forming more stars are younger

OII emission primarily within younger, more star-forming galaxies



What's regulating the escape of Lyα photons in high redshift star-forming galaxies? (Marchi et al. 2019)

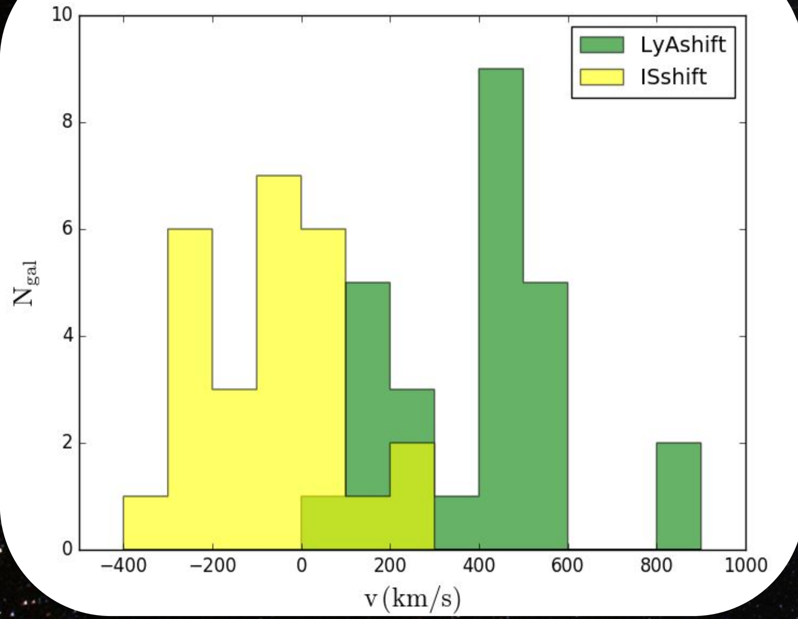
Method- from the **VANDELS spectra** of ~40 star forming galaxies at z=3-4 we measure the kinematics of Lya and LIS

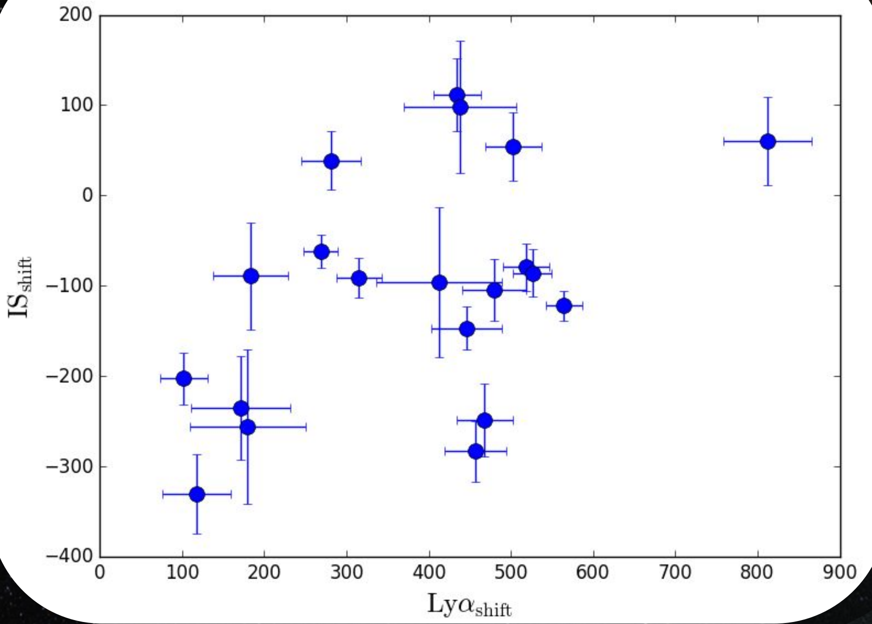


Spectrum of CDFS122764 at z=3.495

What's regulating the escape of Lyα photons in high redshift star-forming galaxies?

We observe a well defined correlation between IS and LyA velocity shifts (both for outflows and inflows)





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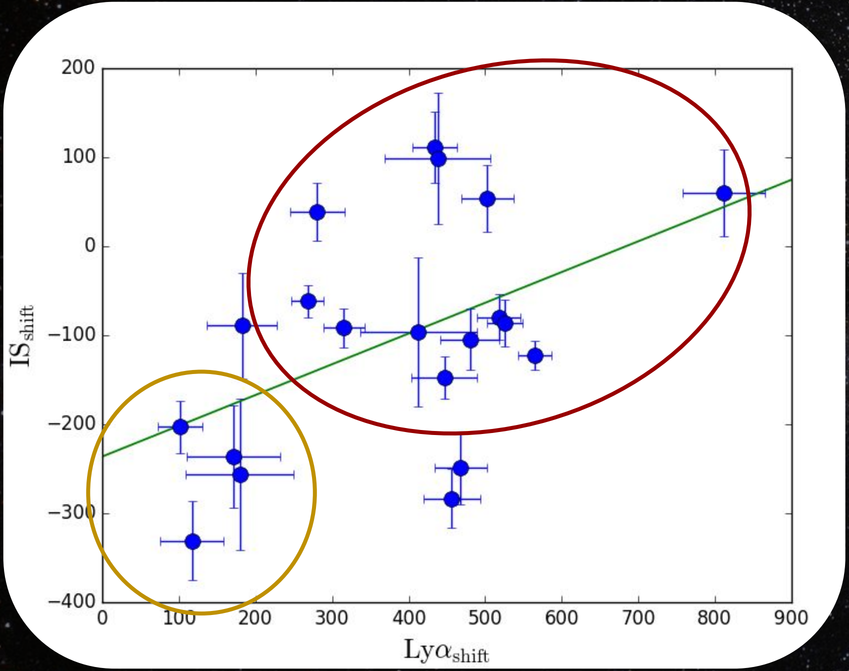


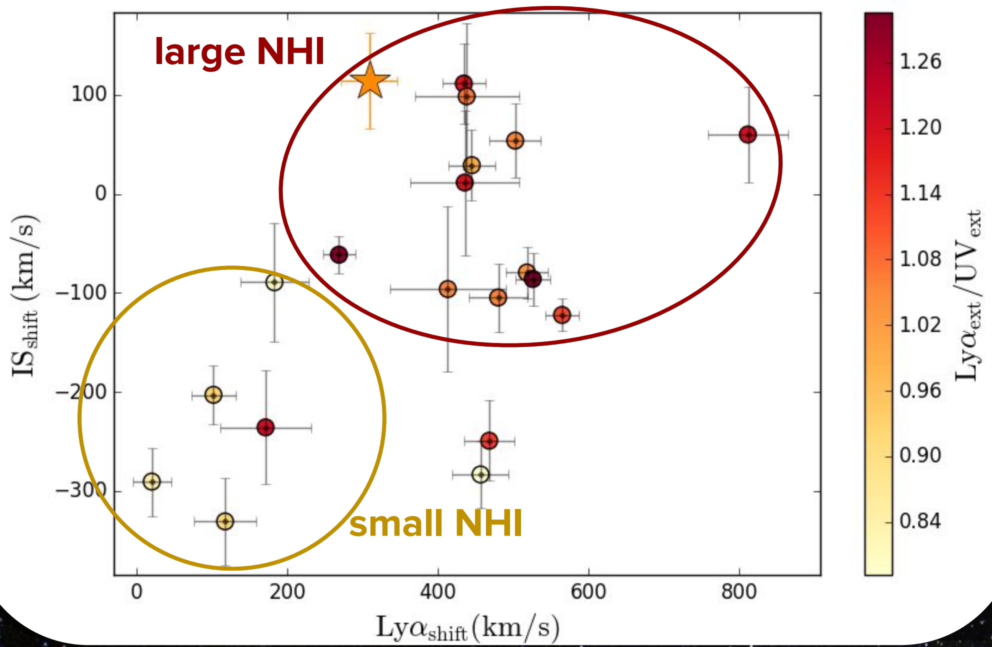
Spearman rank correlation coefficient: 0.35

We can interpret this relation in the context of the **shell model** (e.g., Verhamme et al 2015):

- Small Lyα shifts and large outflow velocities are predicted only for **small HI column densities** (~10^{19} cm^{-2})
- large Lyα shifts but with small or null outflow velocities can be observed in case of **large HI column density** (~10^{20} -10^{21} cm^{-2}) because the Lyα photons must have undergone many scatters before escaping the galaxy

Is this in agreement with the physical properties of the galaxies?

We investigate the relation between NHI and Mass, SFR, sSFR, Σ_{SFR}, dust, EW(Lyα) and **Lyα$_{ext}$/UV$_{ext}$**



- galaxies with larger outflow velocities and smaller Lyα velocity shifts, show smaller Lyα$_{ext}$/UV$_{ext}$ ➔ small NHI
- galaxies with no outflows and larger Lyα shifts show larger Lyα$_{ext}$/UV$_{ext}$ ➔ large NHI

✔ in agreement with the expectations

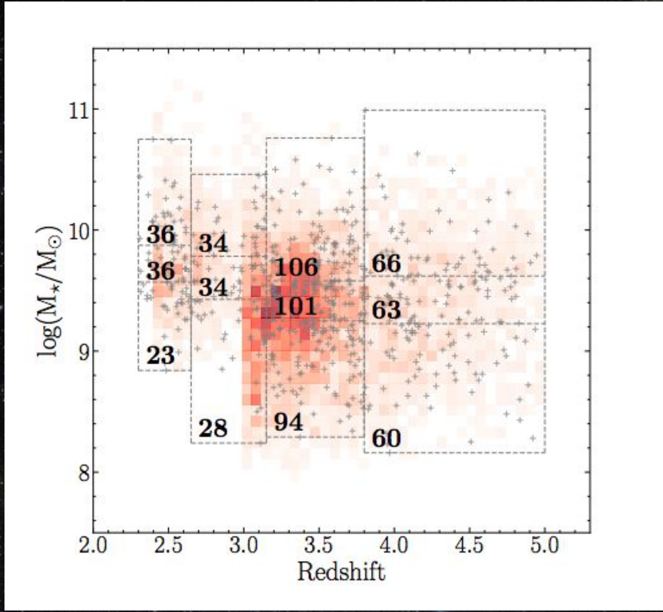
✗ No trend is observed with other physical properties such as Mass SFR and AGE

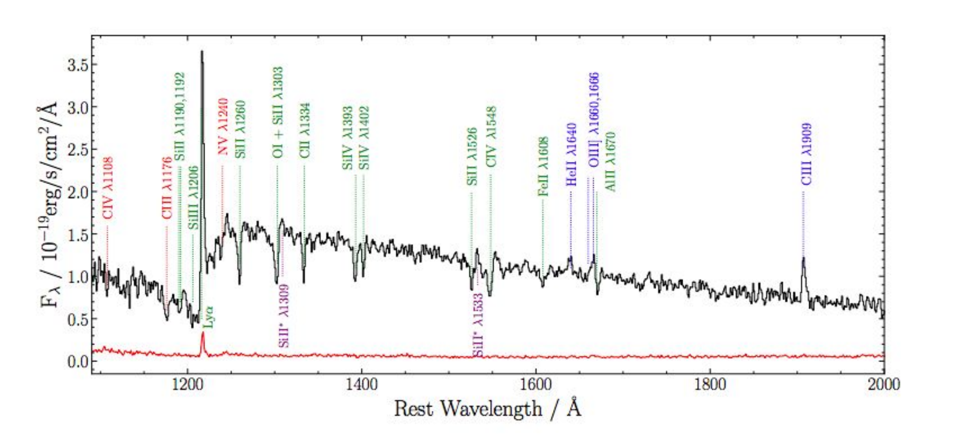
The stellar metallicities of star-forming galaxies at 2.5 < z < 5.0 (Cullen et al. 2019)

681 galaxies at 2.5 < z < 5.0 from VANDELS DR2 (< z > = 3.5)

• At these redshifts, VIMOS cover the rest frame FUV spectrum

• The sample spans 3 dex in stellar mass (10^8 – 10^{11} Mo) drawn from the main sequence of star formation



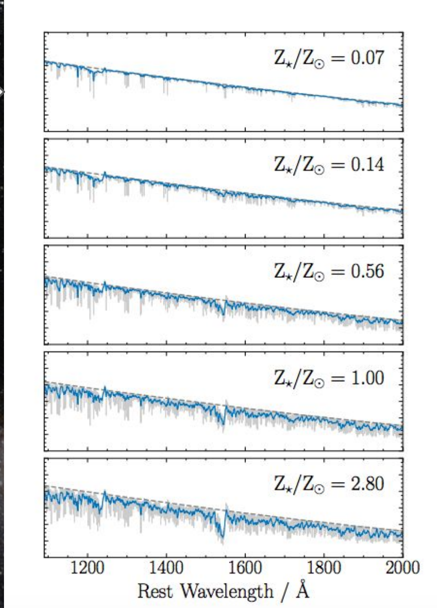


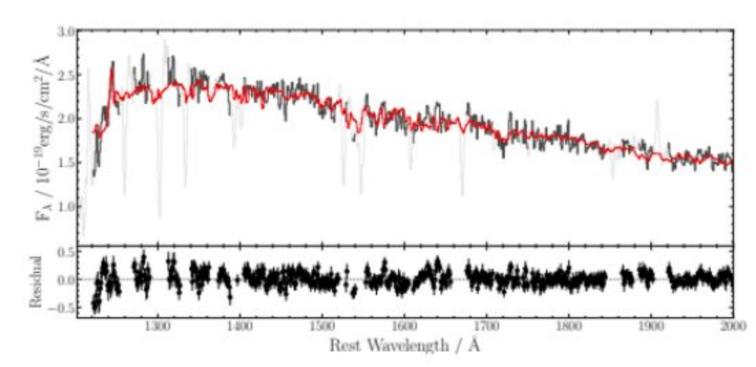
For each mass and redshift bin a stacked high S/N spectrum is produced: we can observe stellar absorption features, Low/High ionization ISM absorption lines, fine structure emission lines and nebular emission lines

The stellar metallicities of star-forming galaxies at 2.5 < z < 5.0 **(Cullen et al. 2019 MNRAS)**

The effect of increasing metallicity is an increasing line-blanketing of the continuum

- Almost all individual stellar absorption lines are blended at the medium resolution VANDELS spectra



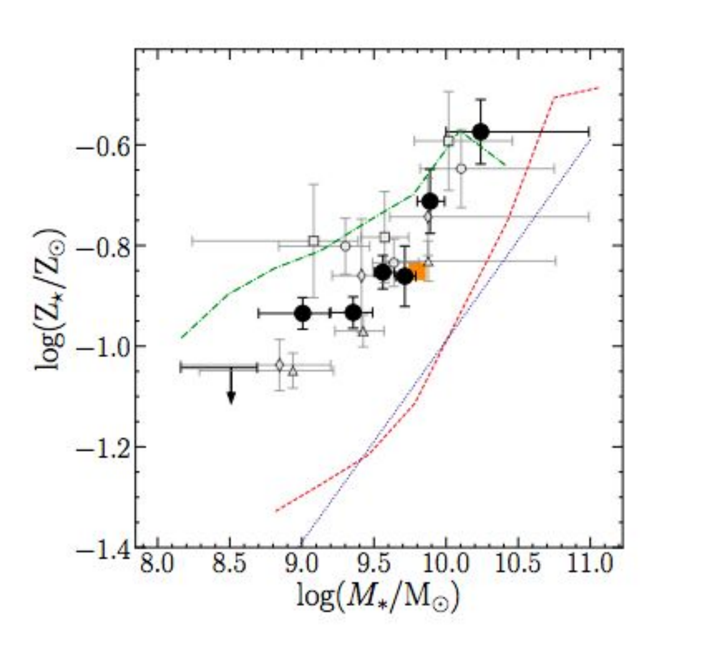


Model fitting is then done using bayesian nested sampling and the metallicity derived for each stack in mass and redshift

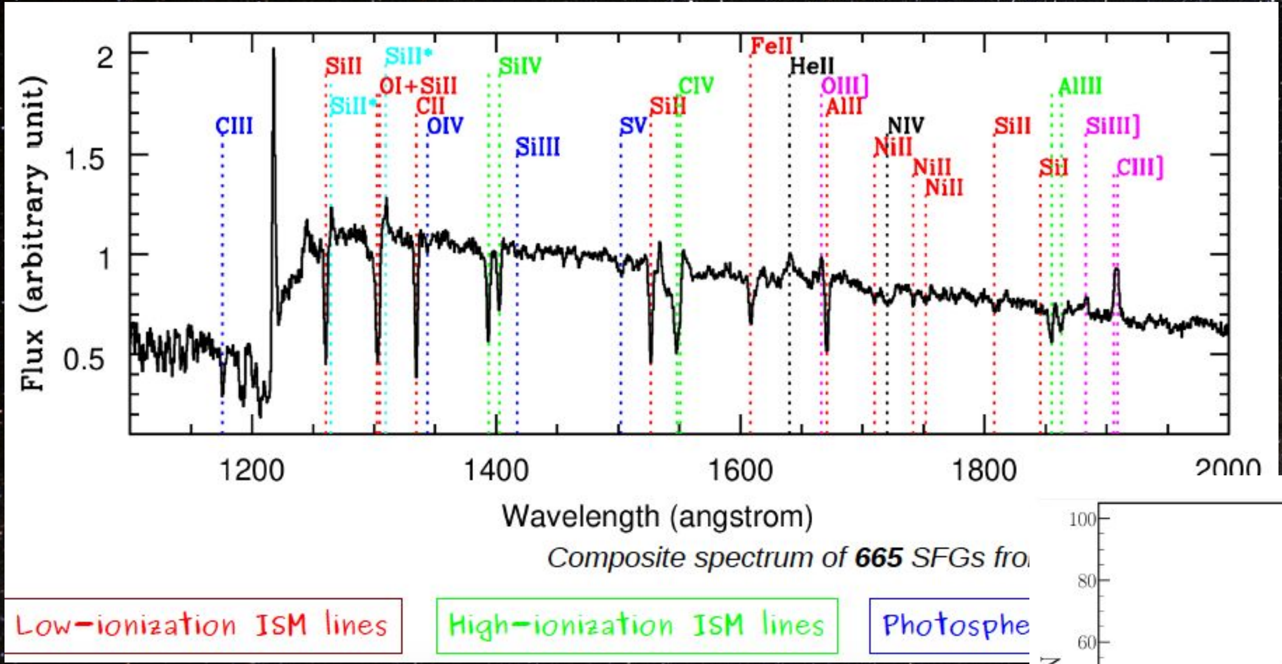
The stellar metallicities of star-forming galaxies at 2.5 < z < 5.0 **(Cullen et al. 2019 MNRAS)**

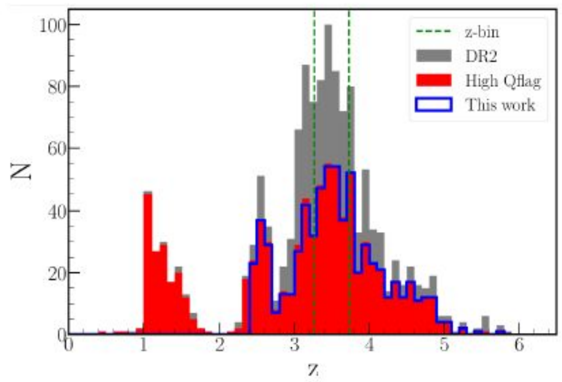
RESULTS

- A clear Mass metalicity relation is observed with a slope consistent with the slope of SDSS galaxies (Zahid+2017) with an offset of -0.6 dex
- No evolution seen within the redshift range of our sample (2.5 < z < 5.0)
- Comparing to simulations, absolute abundances are not consistent, however the slope is generally wellrecovered



ISM properties from VANDELS spectra (Talia et al to be submitted)





3 redshift bins:

Zmed=2.92

Zmed=3.51

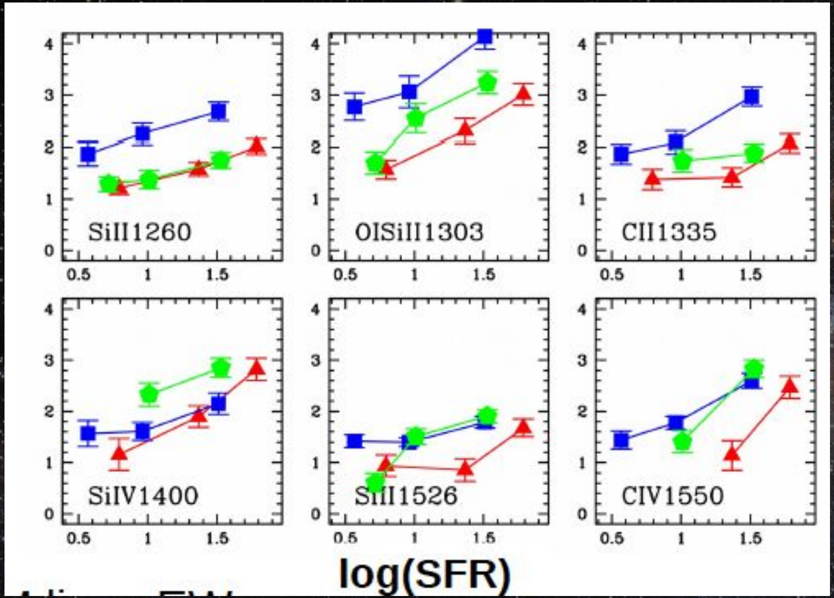
Zmed=4.16

ISM properties from VANDELS spectra (Talia et al to be submitted)

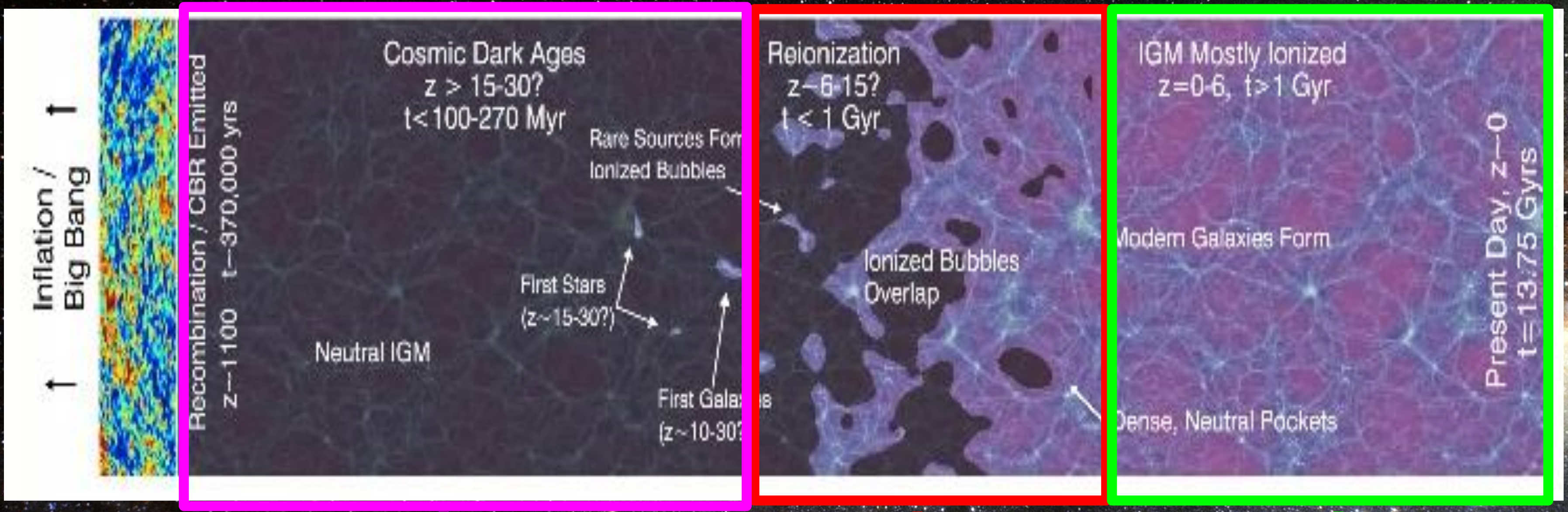
Clear relation between ISM_EW
and SFR at all redshifts in VANDELS

ISM_EW also correlate with metallicity

This implies a tension with the FMR
at high redshift



A synthetic view of cosmic history



<u>Dark Ages</u>: Universe is mostly neutral, very first stars form

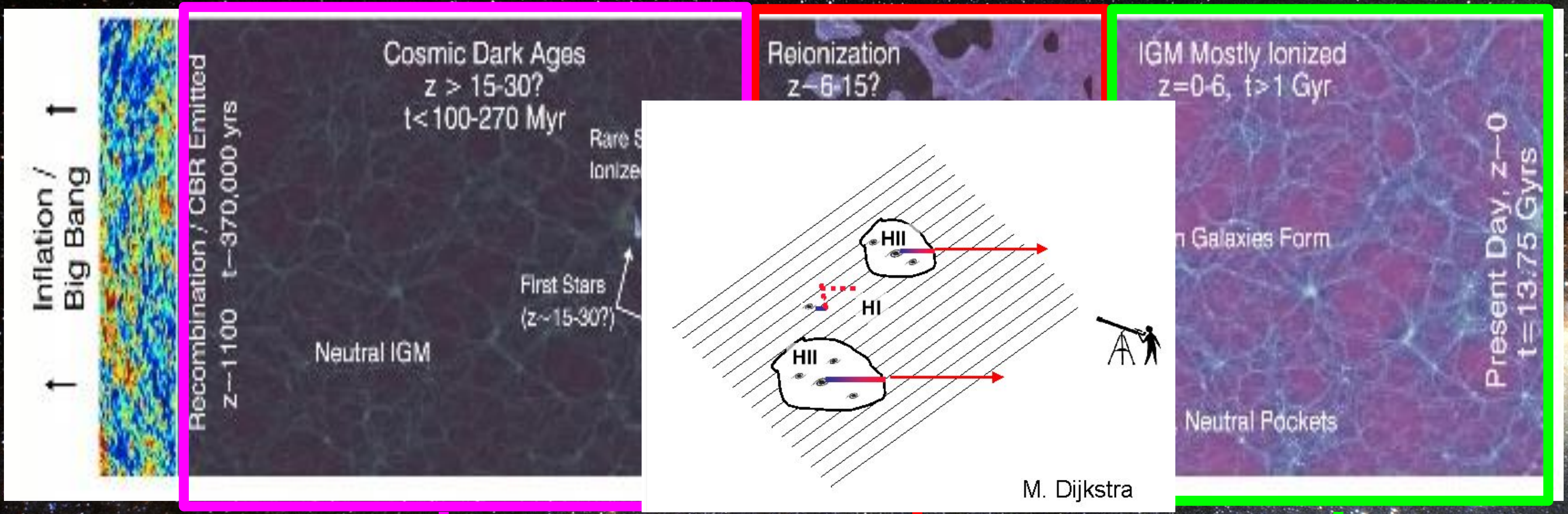
End of dark age: first PopIII dominated galaxies (JWST, EELT)

<u>Reionization</u> Epoch:

Star forming galaxies now observable from ground (VLT, SUBARU) and space (WFC3@HST)

The <u>ionized Universe</u>

A synthetic view of cosmic history



Dark Ages: Universe is mostly neutral, very fi

Reionization Epoch:

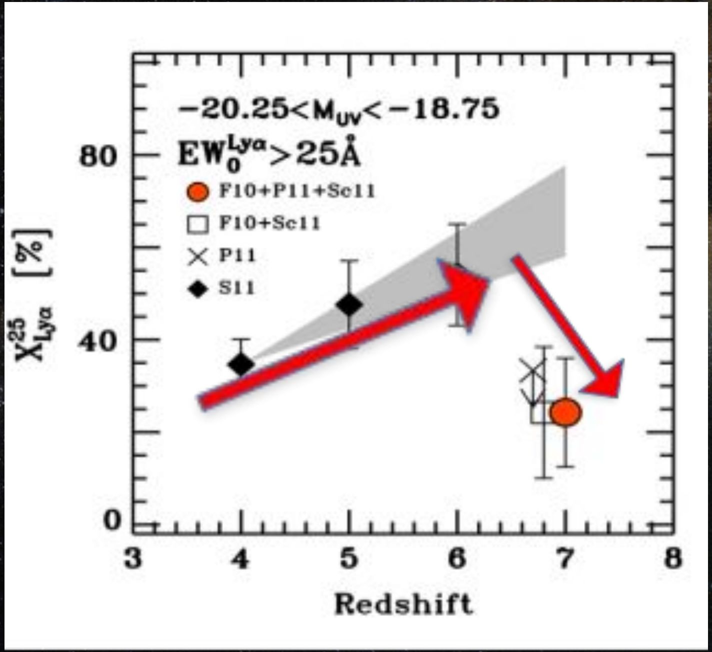
The ionized Universe

End of dark age: fir
(JWST, EELT)

Lyα spectroscopy provides information on reionization timeline and topology

Main motivation: when exactly does the Lyα decline?

Early results by several independent groups indicated that the fraction is rising up to z=6 and then sharply declining (Stark+2010, +2011, +2014,Ono + 2012,Cassata+2012, Treu+2013, Caruana+ 2014 etc etc)



The rise and fall of Lyα is particularly pronounced for the faintest galaxies (but at these magnitudes samples are smaller and observations more difficult)

Field to field variation are large (patchy reionization LP+2014)

CANDELSz7 - probing the reionization epoch with deep spectroscopy (ESO Large Programme)

A deep survey of galaxies at z~6-7 with VLT-FORS2 (LP 190.A-0685, PI L. Pentericci)

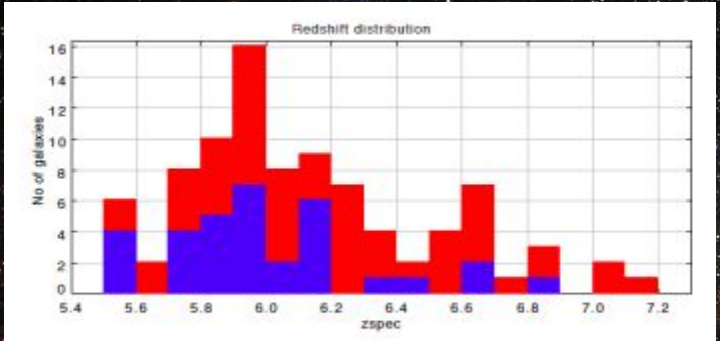
- t_{int}=10-20 hours
- CANDELS fields (GOODS-S COSMOS UDS)
- FORS2 observations cover the Lya visibility in the range $5.8<z<7.3$
- Target selection based on LBG color diagrams and CANDELS photometric redshifts
- Including ancillary programs (PI Fontana, Bunker) we analysed a total of 230 hours of FORS2@VLT observations

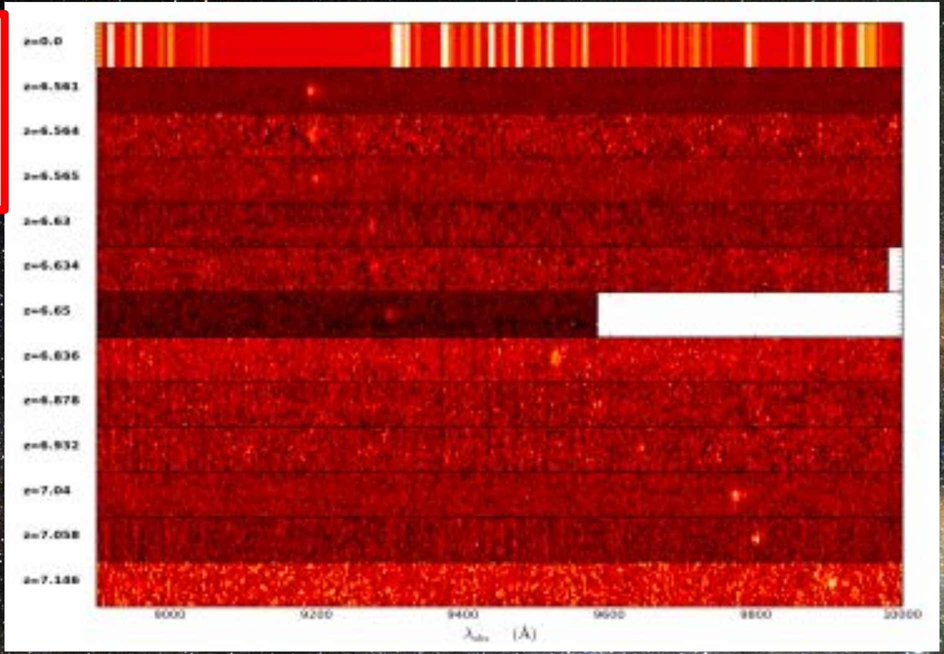
Aims

- Evolutions of the Lyα visibility over the epoch of the reionization -> constrian neutral hydrogen fraction as a function of redshift and luminosity
- Evolution of Lyα properties of galaxies vs other physical parameters
- Provide targets for ALMA

Results can be found in Pentericci et al. 2018, De Barros et al. 2017, Castellano et al. 2017

We have confirmed 17 new galaxies at $6.5 < z < 7.2$ all with Lyα emission, and 48 new $5.5<z<6.5$ galaxies mostly with Lyα emission

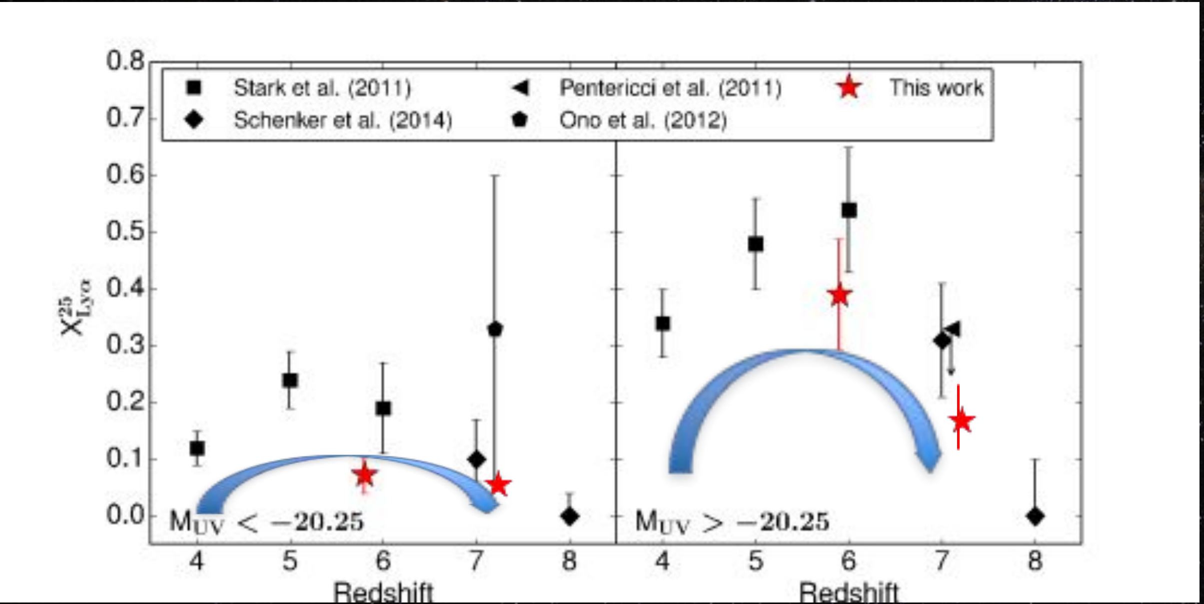




Including the new Large program data + earlier & archival observations (LP+2014,LP+2011,Vanzella+2011,2009, Caruana+2012,2014) we have assembled a sample of >135 z-dropouts & 130 i-dropouts in 8 independent fields (including 4 of the CANDELS fields), mostly observed with the same instrumental set-up and with similar limiting flux. For the undetected objects we set firm limits on the Lyα EW using very accurate simulations (see Vanzella+14, LP+14)

The Lyα decline begins at z<6

Our results indicate that the rise in the fraction of Lyα emitters might actually stop at z > 5 with a flattening (for faint sources) or downturn (for bright sources) already at z=6

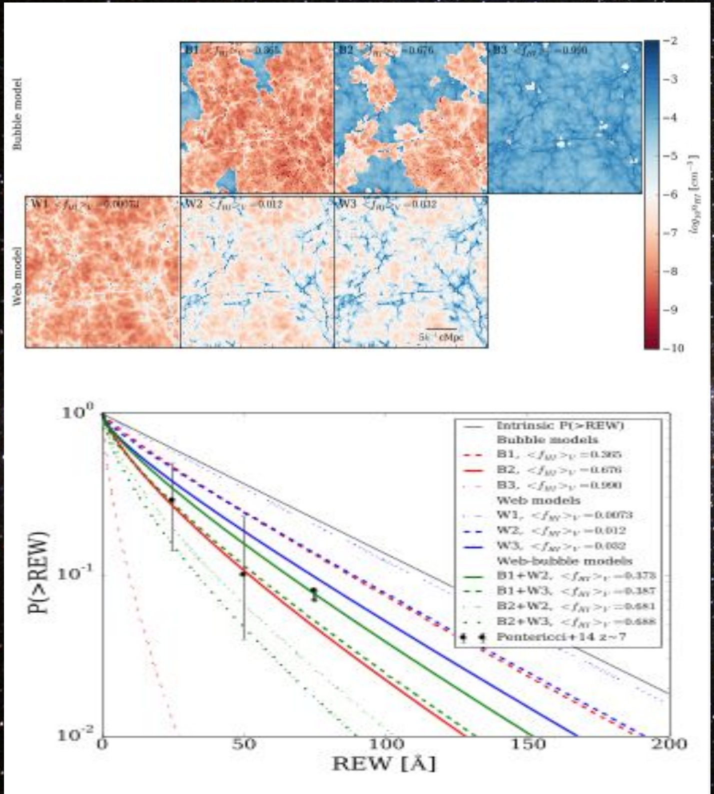


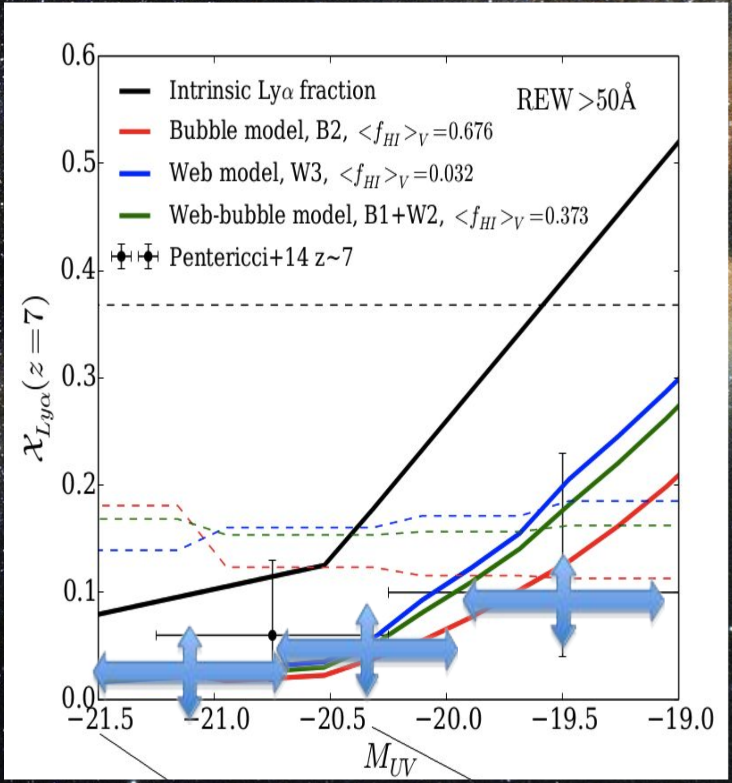
If the visibility of Lyα is only driven by IGM this could indicate a more extended reionization process and a less rapid evolution of the IGM neutral hydrogen fraction

Pentericci+18, deBarros+17

Implications on the neutral hydrogen fraction

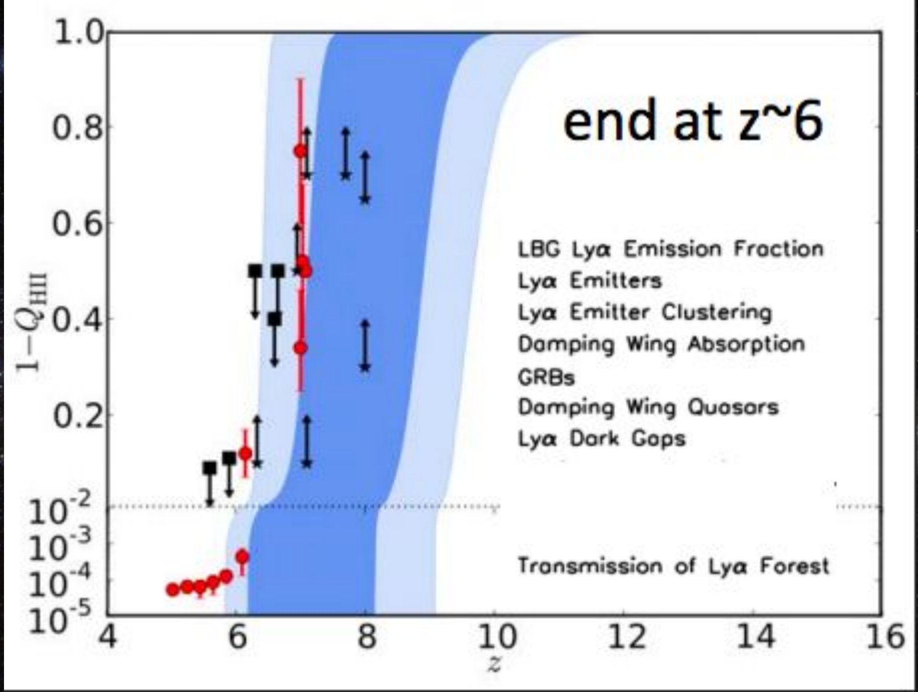
There are intrinsic degeneracies between the effects of small scales HI absorbers and diffuse neutral IGM. Kachiiki+2017 show that a joint anaysis of LAE LF and Lya fraction i LBGs can potentially discriminate between models.





The new z=7 measurements favour slightly a bubble model with XHI=0.67

Implications on the cosmic reionization history



The neutral hydrogen fraction inferred from various observational probes (including Lya fraction, Lya clustering , GP trough in QSOs,QSO damping wings etc etc) compared to what is inferred by PLanck observations: reionization onset at z=10 and ends at z=6

Progress in our understanding of galaxy evolution at high redshift is not limited by poor statistics (anymore) but rather by the systematic uncertainties in our measurements of crucial physical parameters, caused by the interrelated degeneracies between e.g. age, dust attenuation and metallicity

➔ Systematic spectroscopic follow-up is needed as a key complement to the deep multiwavelength data

Validate redshifts (and therefore LF, MF, SFRD and their evolution with cosmic time) ✓
Probe ISM , gas and kinematics , chemical enrichment ✓
Probe IGM evolution -reionization process ✓
Probe structures/overdensities and impact of environement✓