A deep imaging and spectroscopic investigation of a reionized bubble at z~7

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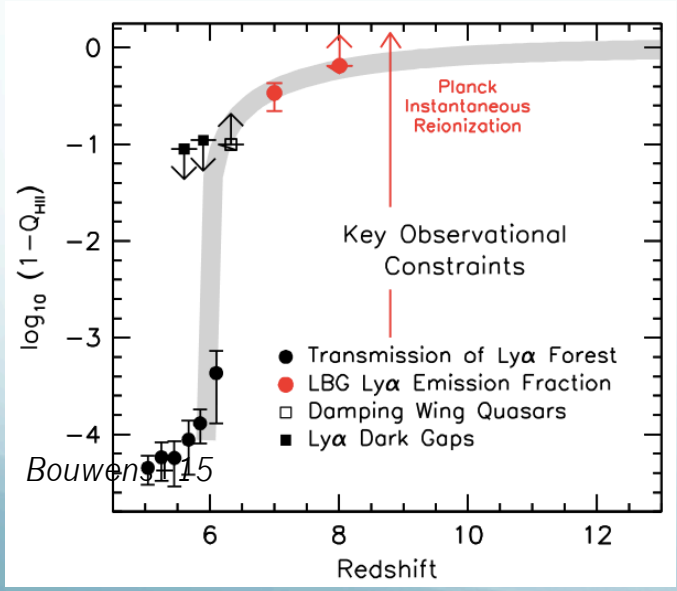
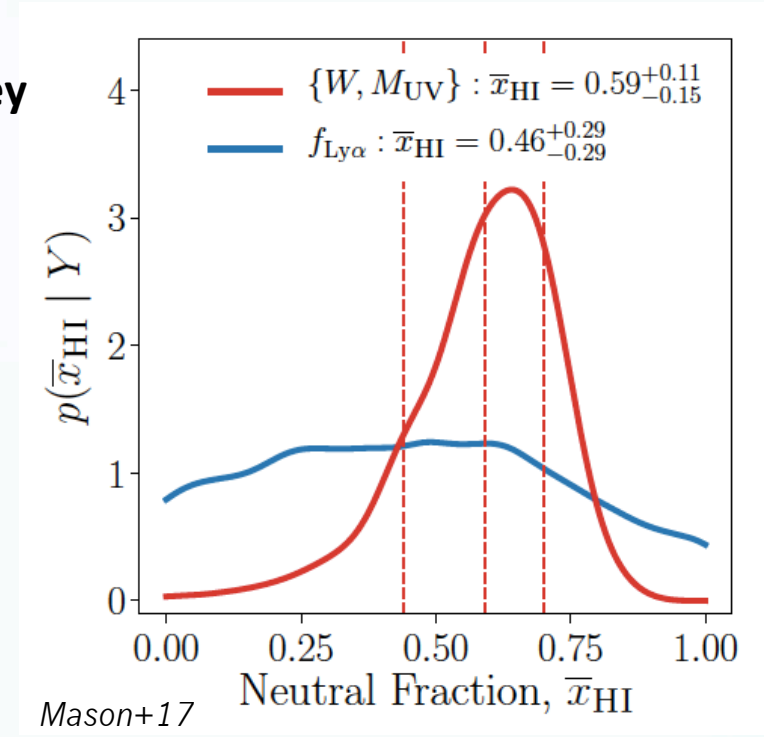
OAR

Timeline and sources of HI Reionization

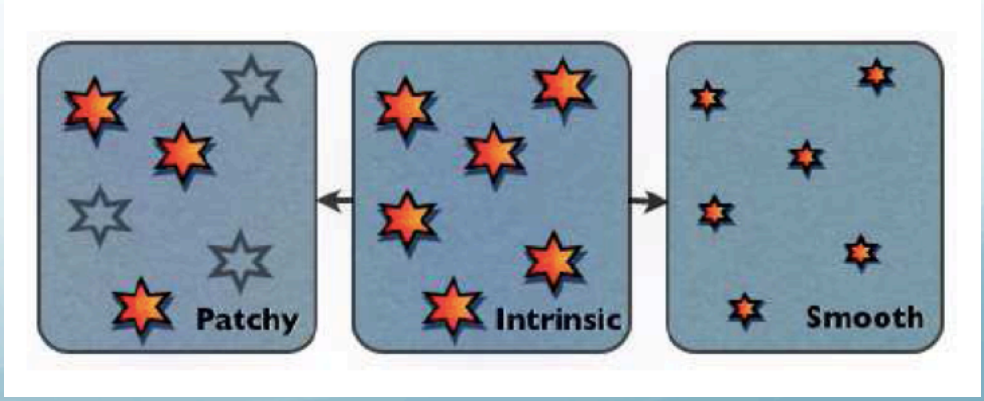
***Decline of Lyα visibility in star-forming galaxies key probe of late reionization** (e.g. Stark+10, Fontana+10, Pentericci+11,+14, Schenker+12)

***Reionization timeline can be explained by the evolution of UV luminosity density** from star-forming galaxies (e.g. Bouwens+15, Robertson+15).





Patchy topology favoured (Treu+12, Pentericci+14)

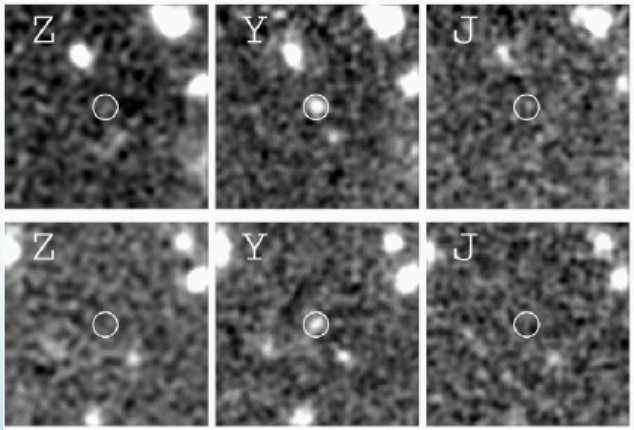


A space oddity at z=7: three close-by strong LAEs

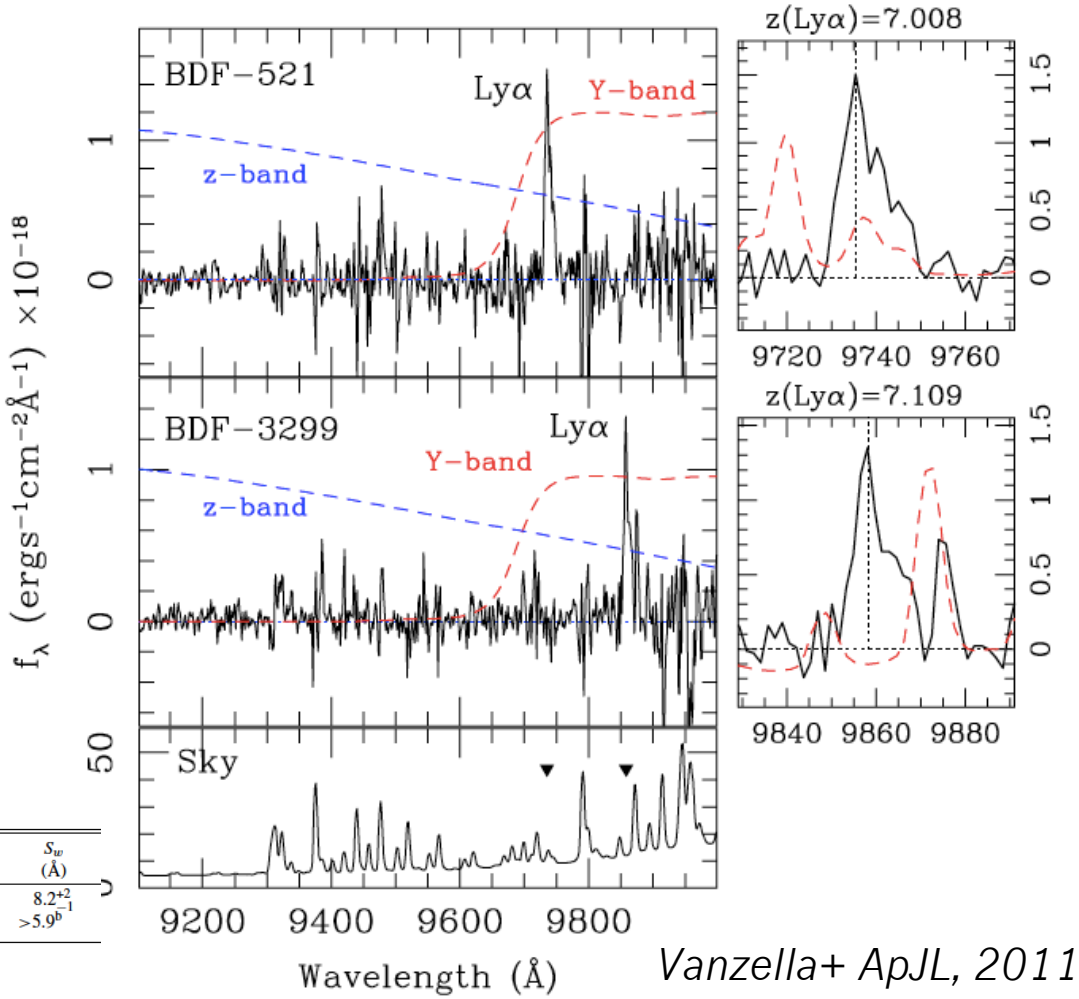
In the overall paucity of Lyα lines: one line of sight with twin bright emitters among the 8 l.o.s. investigated in Pentericci+14 (see also Pentericci +18).

The BDF4 field (Lehnert&Bremer 03) hosts three close-by EW~50-60AA emitters.

Additional sources required to Reionize the region?
(e.g. Dayal+09)



MC+ A&A, 2010b

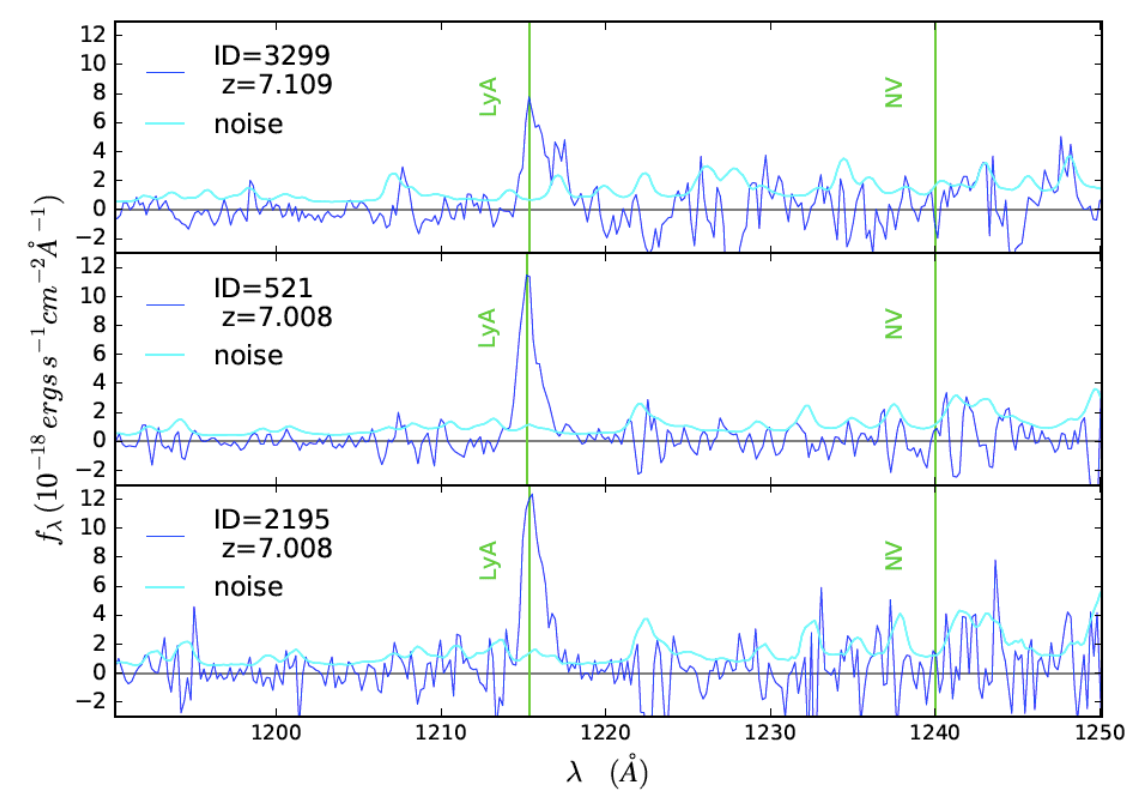


ID	R.A., Decl. J2000	Redshift	f(Lyα)	SFR(Lyα) ($M_\odot$ yr^{-1})	EW$_{rest}$ (Å)	FWHM[a] (km s^{-1})	S_w (Å)
BDF−521	336.9444, −35.1188	7.008 ± 0.002	1.62 ± 0.16	8.5	64	240	8.2^{+2}_{-1}
BDF−3299	337.0511, −35.1665	7.109 ± 0.002	1.21 ± 0.14	6.6	50	200	>5.9[b]

Notes. f(Lyα) in units of 10^{-17} erg s^{-1} cm^{-2} Å^{-1}.

Vanzella+ ApJL, 2011

A space oddity at z=7: three close-by strong LAEs



Z=7.109
EW=50AA
FWHM=200 km/s

Z=7.008
EW=64AA
FWHM=240 km/s

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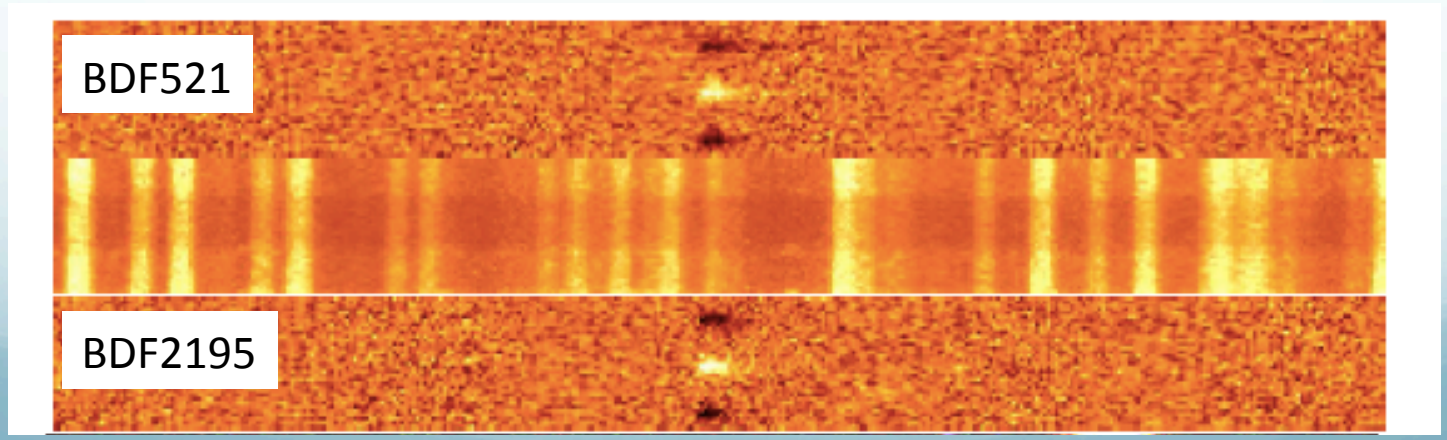
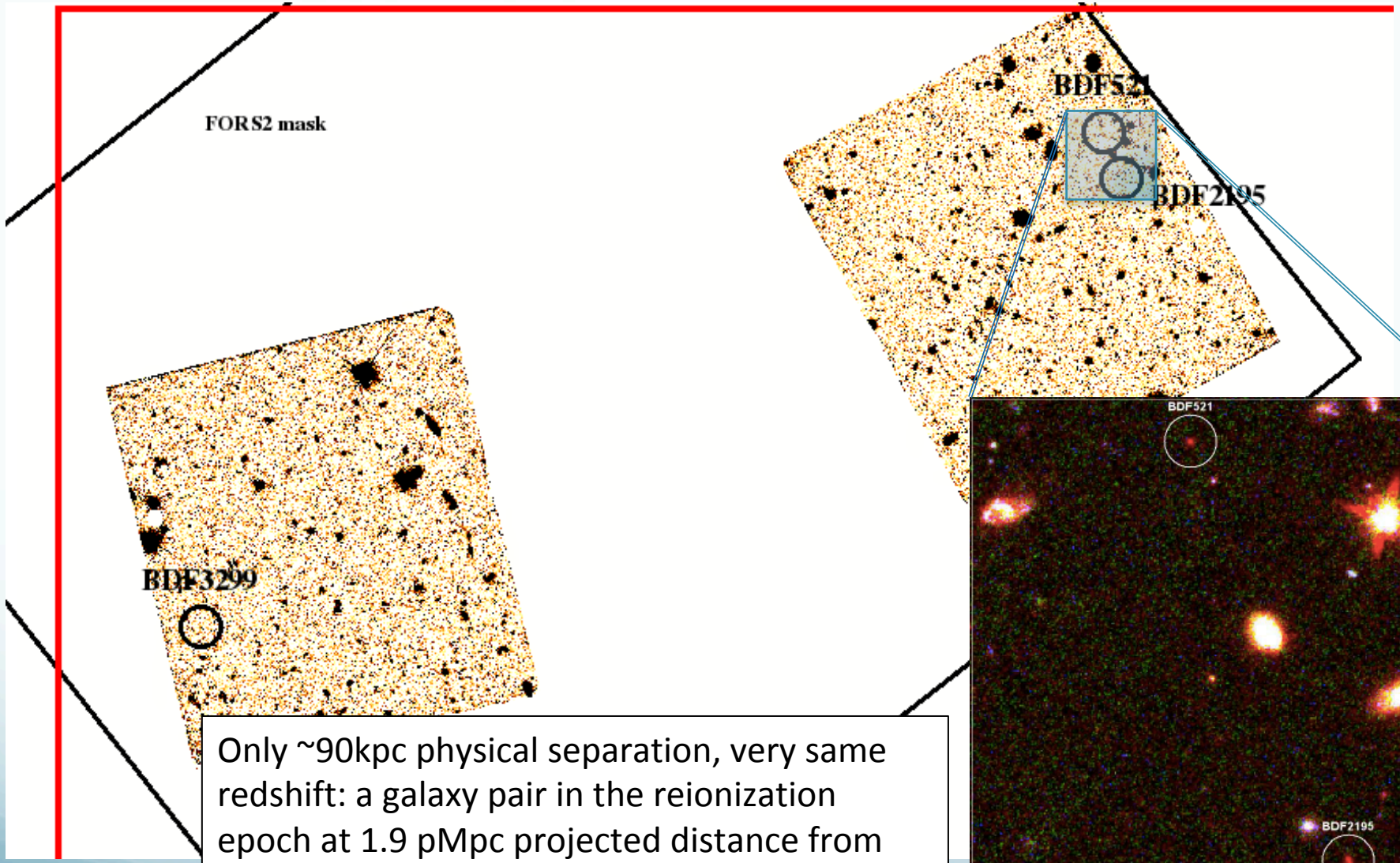
EW=50AA
FWHM=240 km/s



MC+ ApJL, 2018

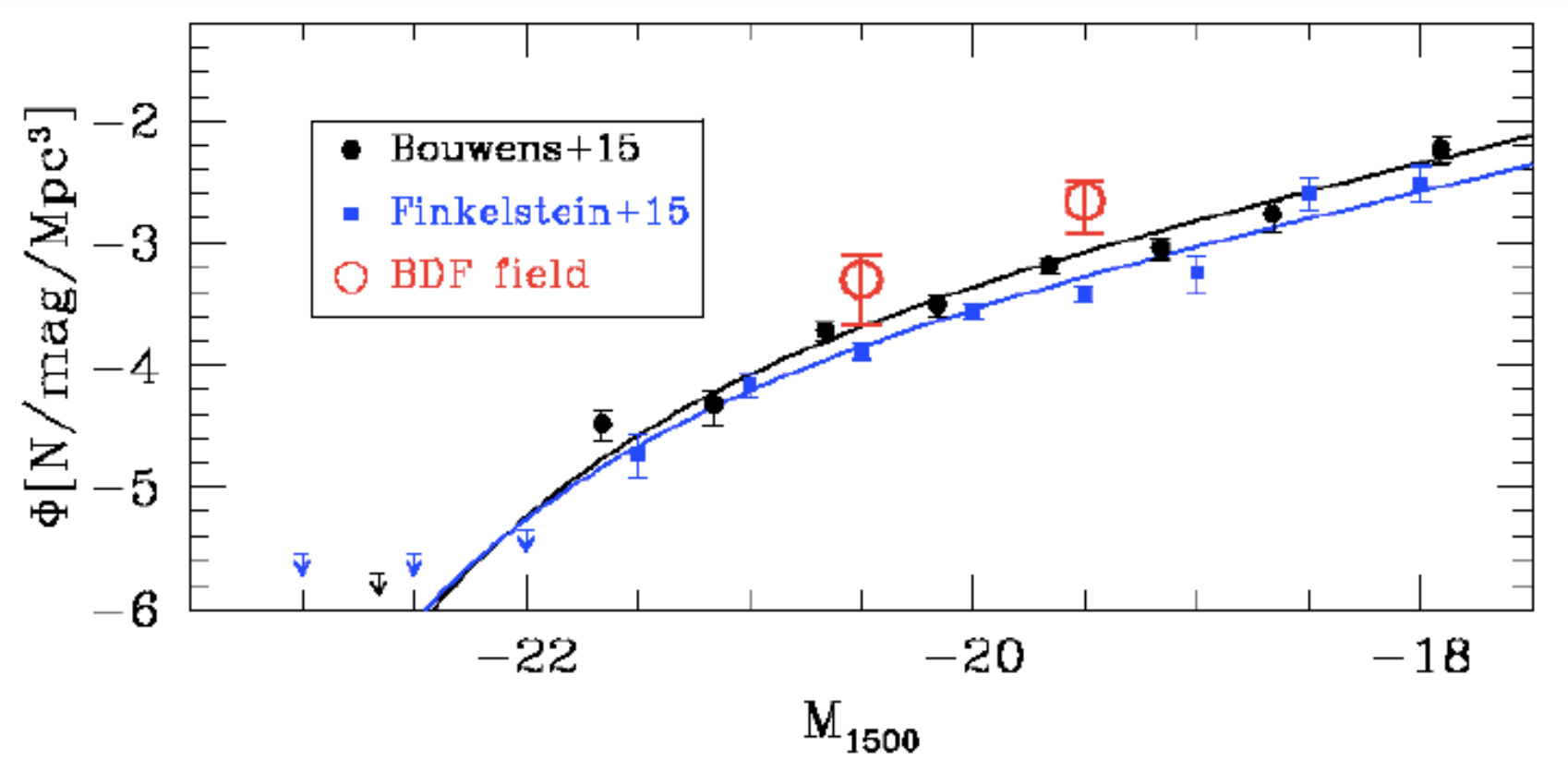
A space oddity at z=7: three close-by strong LAEs



Only ~90kpc physical separation, very same redshift: a galaxy pair in the reionization epoch at 1.9 pMpc projected distance from the other LAE BDF3299

MC+ ApJL, 2018

An overdensity of z~7 LBGs around the three LAEs



Observed= 8 objects in two pointings. Expected N_{exp}~1.8-2.9 objects (cosmic variance: $0.5N_{exp}$).

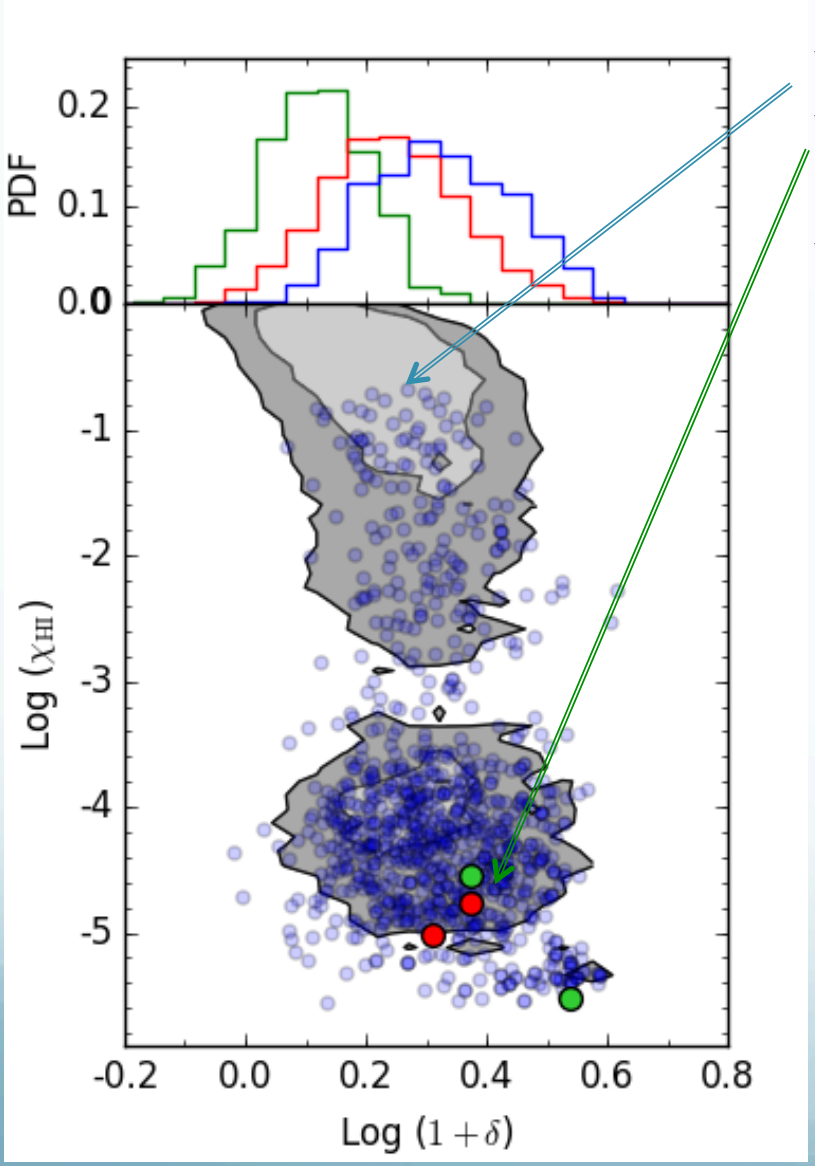
The BDF field is 3-4x overdense wrt average: consistent with a positive relation between line visibility and galaxy density as in ***inside-out reionization scenarios.*** (e.g. McQuinn+ 07, Wyithe&Loeb 07, Dayal+ 09). *No similar clustering around bright z~7 LBGs in CANDELS GS.*

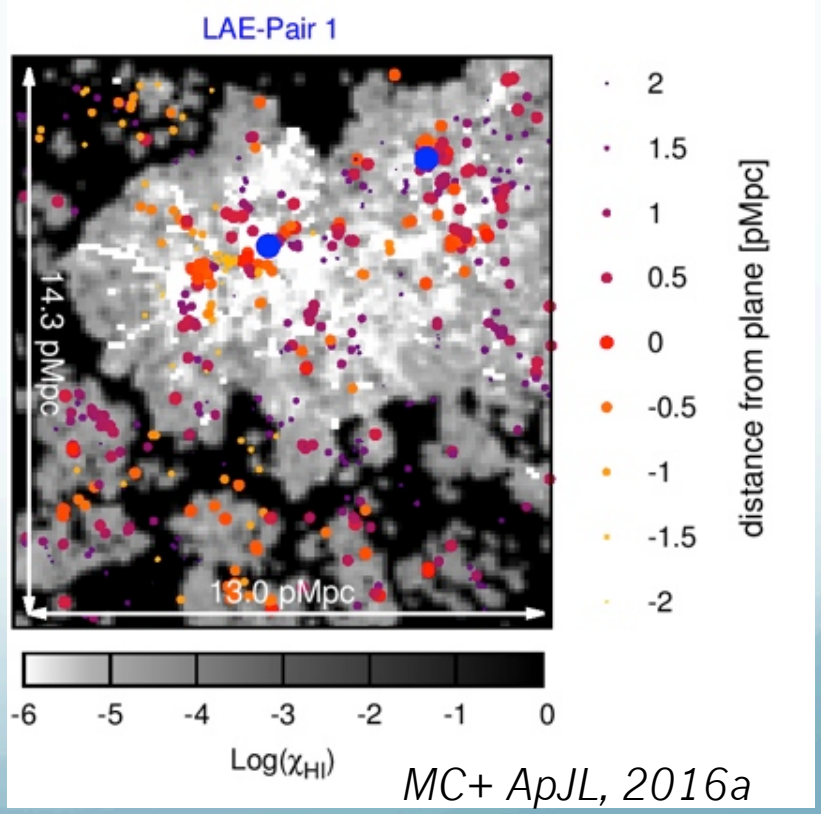
MC+ ApJL, 2016a

Connection between reionization and overdensities

Comparison with SPH model (Hutter+14,+15).

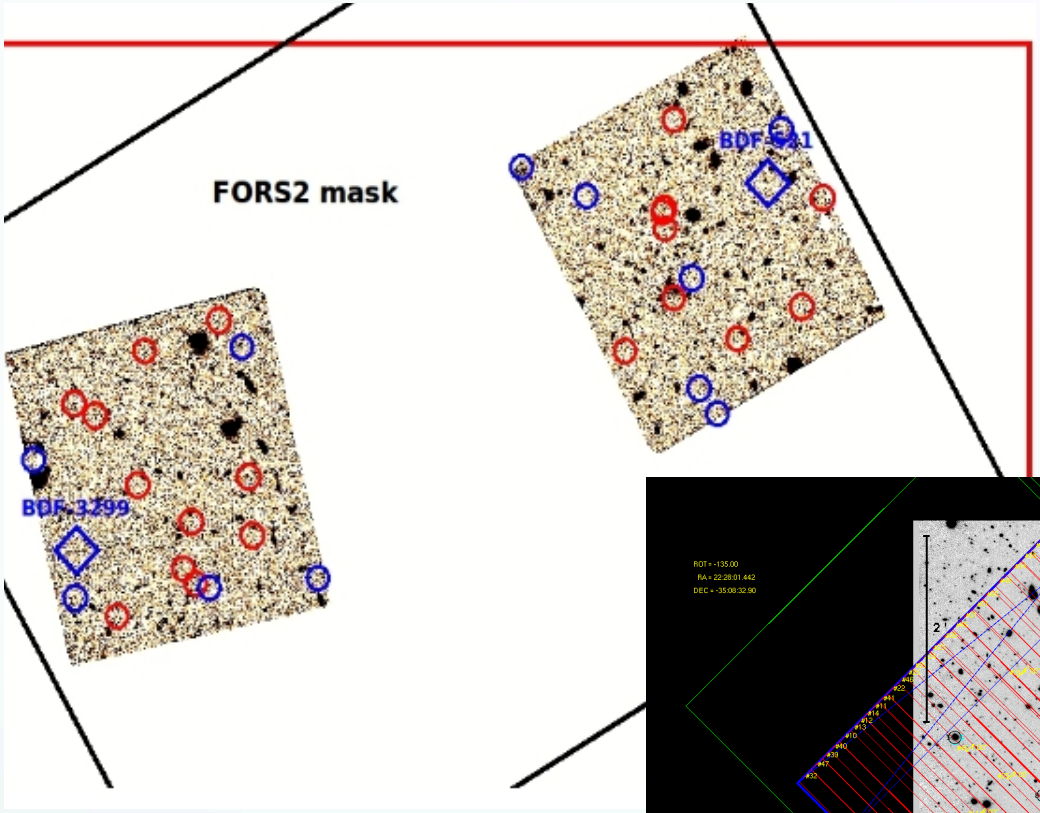
- ✓ Relation between density and HI fraction
- ✓ Clustered LAEs live in overdense regions with low HI
- ✓ BDF analogs are reionized, overdense bubbles





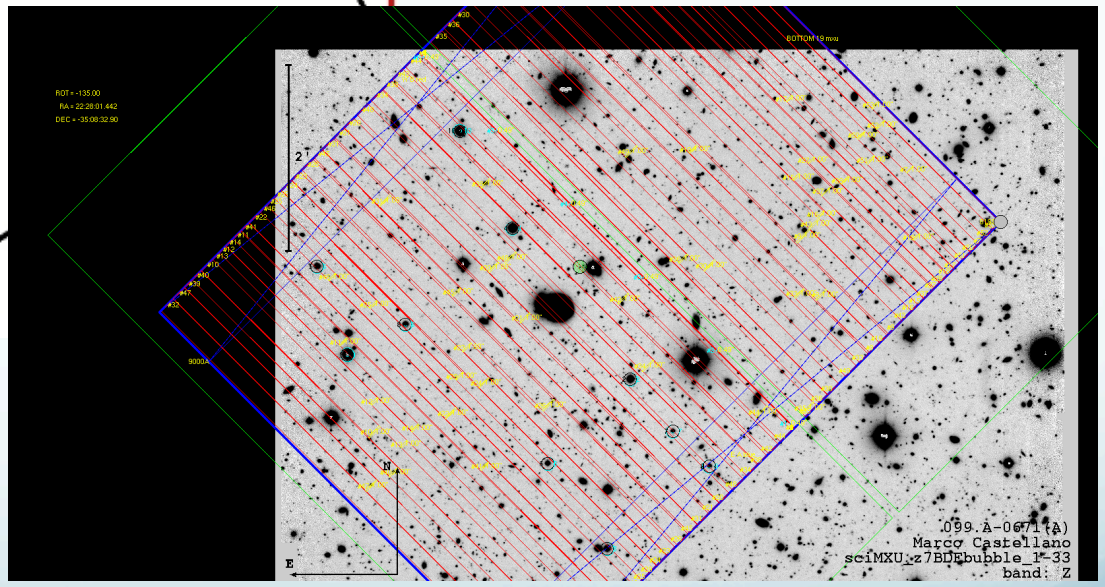
MC+ ApJL, 2016a

Spectroscopic follow-up of the full z~7 sample



33 hrs FORS2@VLT, (program 099.A-0671 P.I. MC)

600z+23(OG590) grism (resolution R=1390), with slits 1” wide and a length in the range 6-12”



Observed 14 robust S/N(Y105)>5 z~7 candidates, plus z~6 fillers and lower quality LBGs

Plus FORS2 data on the two LAEs BDF521 and BDF3299 and another bright HAWK-I-selected candidate from programme 181.A-0717

No Lyα from any of the faint galaxies

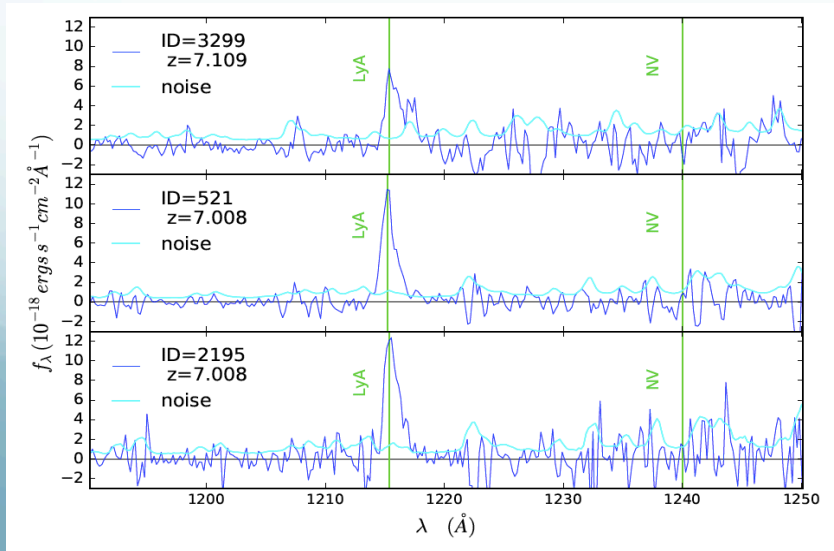
Sample	Total	Bright	Faint
Observed	17	5	12
Detected in Lyα	3	3	0

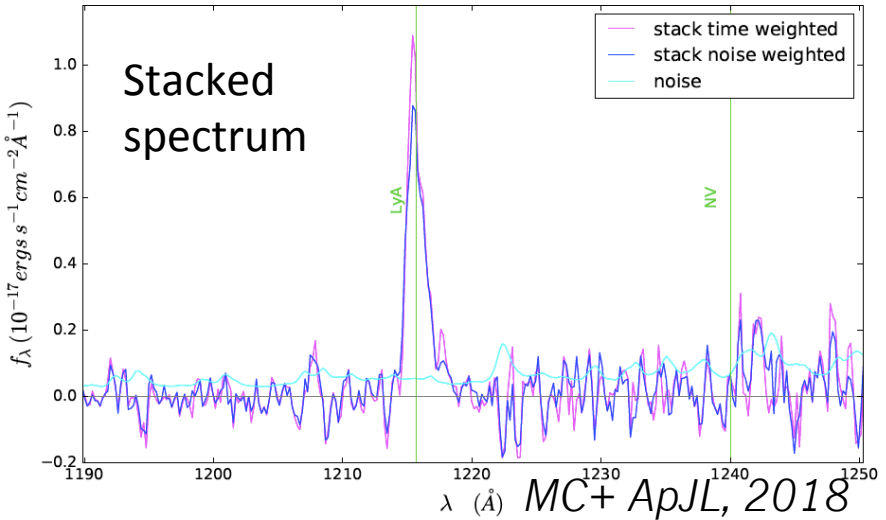
3 out of 5 “bright” LBGs have Lyα

No detections from faint (Y>26.7) sources

PDF(z)	Lyα visibility	Probability $P(tot=3)$	$P(bright=3)$	$P(faint=0)$	Expected Number $< N_{tot} >$	$< N_{bright} >$	$< N_{faint} >$
Flat	z=7	0.21	0.009	0.17	2.1	0.7	1.4
P(z,Y)	z=7	0.18	0.009	0.22	1.9	0.7	1.2
Flat	z=6	0.08	0.035	0.002	5.5	1.2	4.3
P(z,Y)	z=6	0.11	0.036	0.004	5.0	1.2	3.8

Comparing number of detected lines to number of expected detections under different hypothesis:
- peaked (“Flat” at z=7) or wide (“P(z,Y)”) redshift distribution
- z=7 (low) or z=6 (high) line transmission through the IGM





MC+ ApJL, 2018

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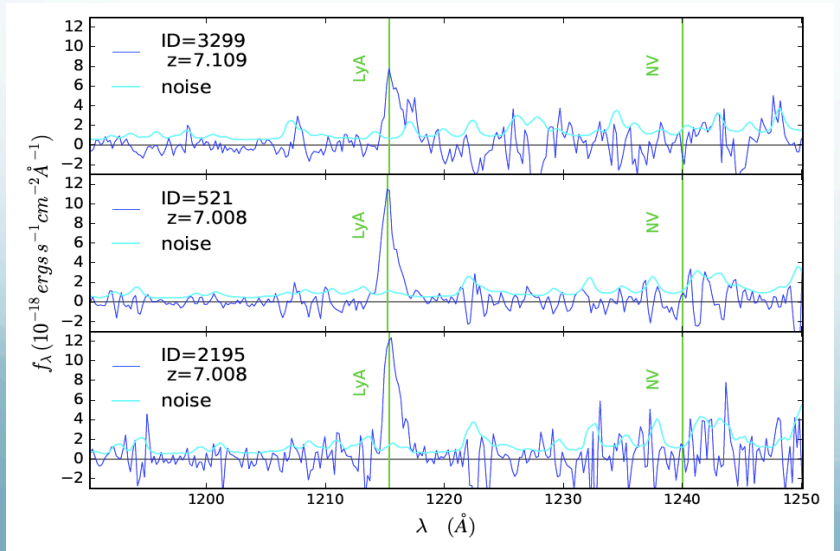
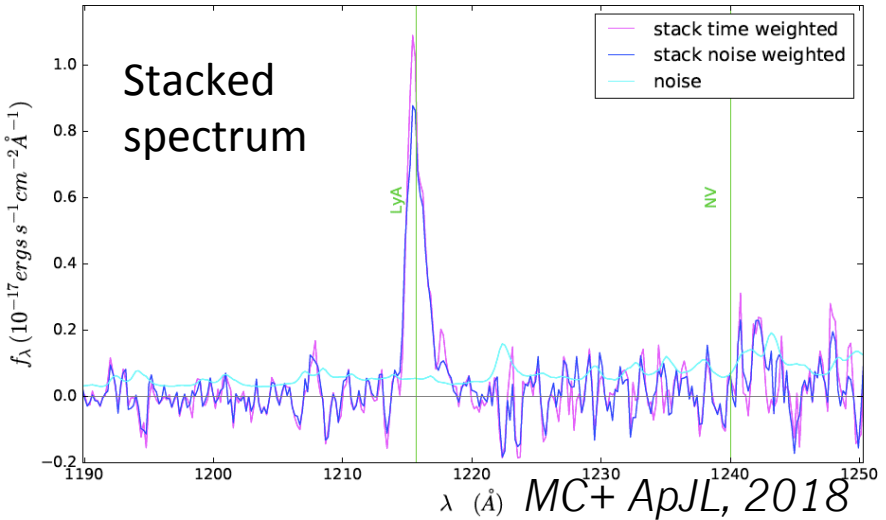
Low prob. of 3 bright (M_UV<-20.25) LAEs (**less** are expected)
→ High visibility, more consistent with a z~6 reionized Universe





MC+ ApJL, 2018

No Lyα from any of the faint galaxies

Sample	Total	Bright	Faint
Observed	17	5	12
Detected in Lyα	3	3	0

3 out of 5 “bright” LBGs have Lyα

No detections from faint (Y>26.7) sources

PDF(z)	Lyα visibility	Probability $P(tot=3)$	Probability $P(bright=3)$	Probability $P(faint=0)$	Expected Number $< N_{tot} >$	Expected Number $< N_{bright} >$	Expected Number $< N_{faint} >$
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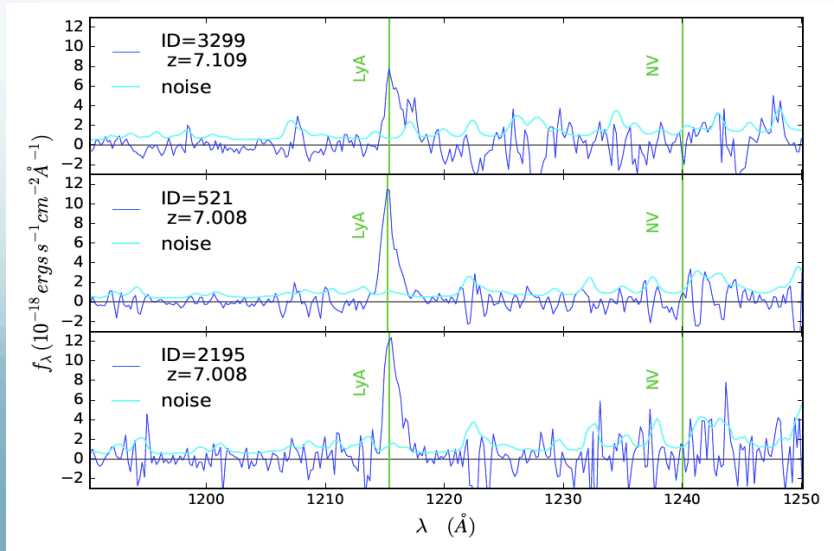
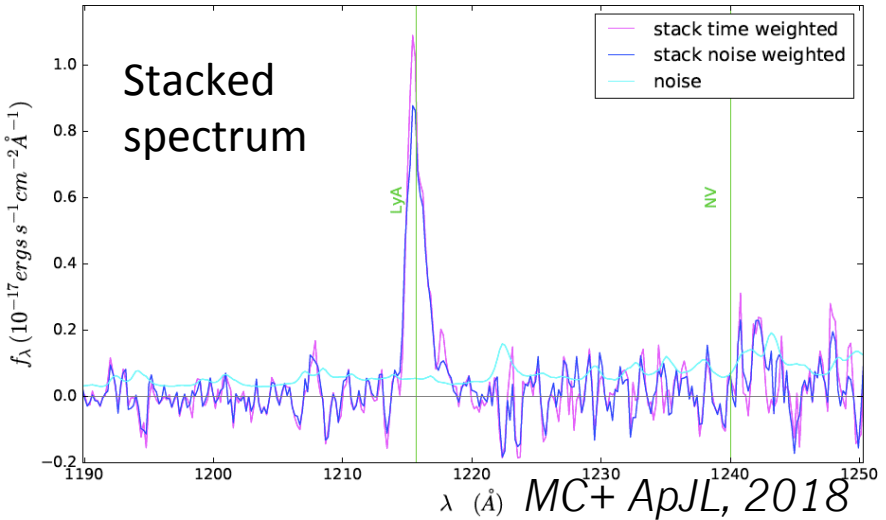
P(z,Y)	z=6	0.11	0.036	0.004	5.0	1.2	3.8

Low prob. of 0 faint (M_UV>-20.25) LAEs (**more** are expected)
→ Low visibility, more consistent with z~7 half-neutral Universe





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Possible scenarios

Sample	Total	Bright	Faint
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Flat	z=6	5.5	1.2	4.3
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- *Bright galaxies are in a reionized "bubble" but faint galaxies are outside*.

→ Bubbles are created by the **bright galaxies alone** (SFR and/or AGN), or **by bright galaxies+ objects beyond the current BDF detection limit** (M_{UV}>-19, e.g. Vanzella+17a,b).
→ Lyα from bright galaxies is boosted by **velocity offsets** and/or enhanced photon production (Mason+2018, Stark+2017).

- *Bright and faint galaxies are all members of the reionized "bubble" but some mechanisms decrease Lyα escape from faint galaxies*.

→ Accelerated evolution of overdensity members: bright galaxies are young with high SFR, **faint LBGs are more evolved and dustier**.
→ Recombination of neutral hydrogen in the regions close to overdensity members, **velocity shifts (higher in massive galaxies) are needed** to make the line visible to us.

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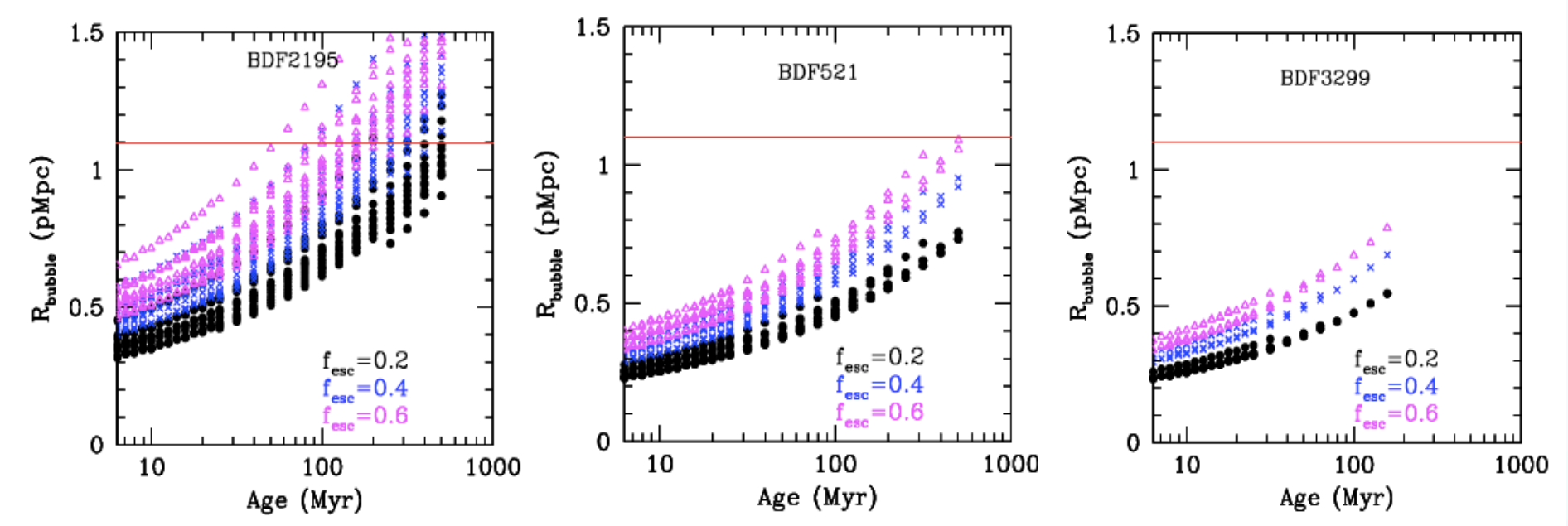
Are bright galaxies enough?



We estimate the **size of the bubble** (e.g. Madau 1999) **created by each galaxy** for all SED-fitting models compatible (68%c.l.) with the observed photometry.

Constant SFR, BPASS V2.0 libraries, Calzetti extinction. *Escape fraction of UV ionizing photons (f_{esc}) varied from 0 to 1.*

Compare to size needed to have Lyα redshifted to us (Loeb et al. 2005)

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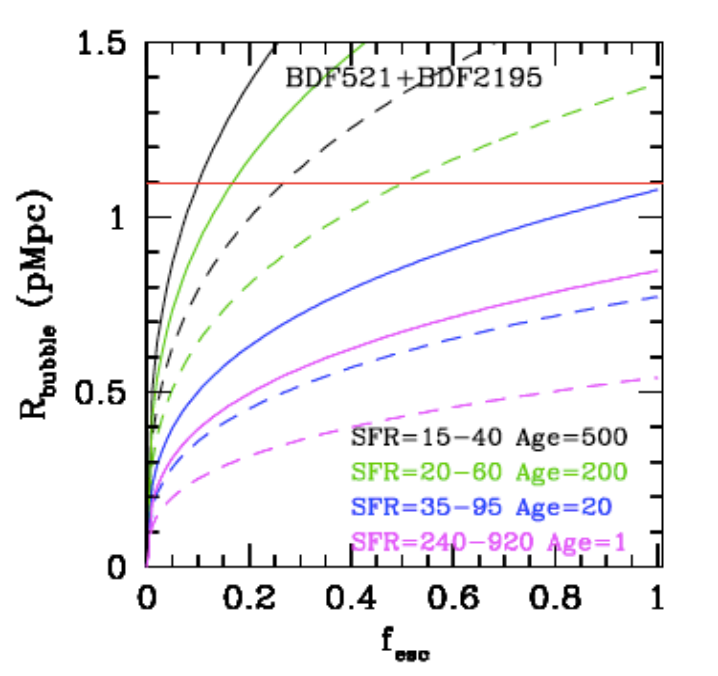
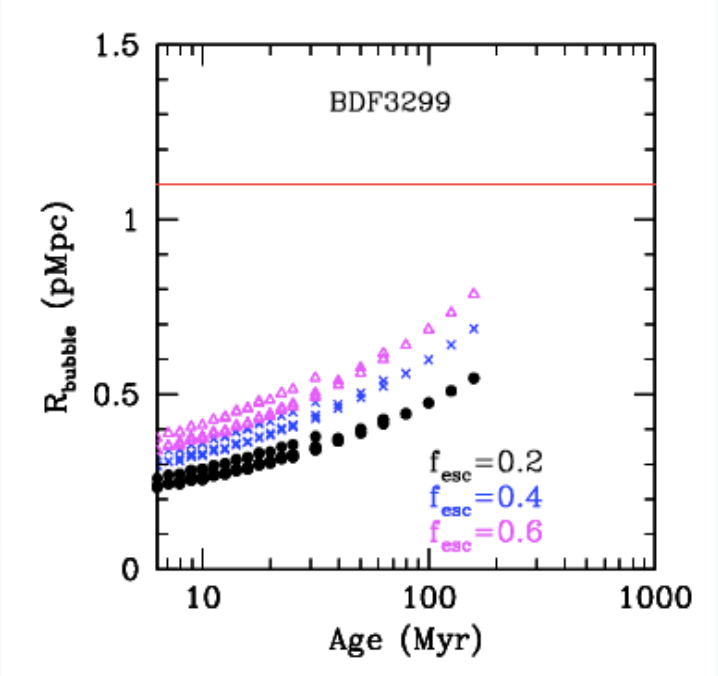
Are bright galaxies enough?





When summing the two contributions the BDF521-BDF2195 pair can create a large enough bubble with f_{esc}>10-15% and moderate SFRs over > 400Myr lifetime.

Adding the contribution of 220 km/s shifts f_{esc} <10% can do the job.

But no way for BDF3299 which is >2 pMpc distance from the pair.

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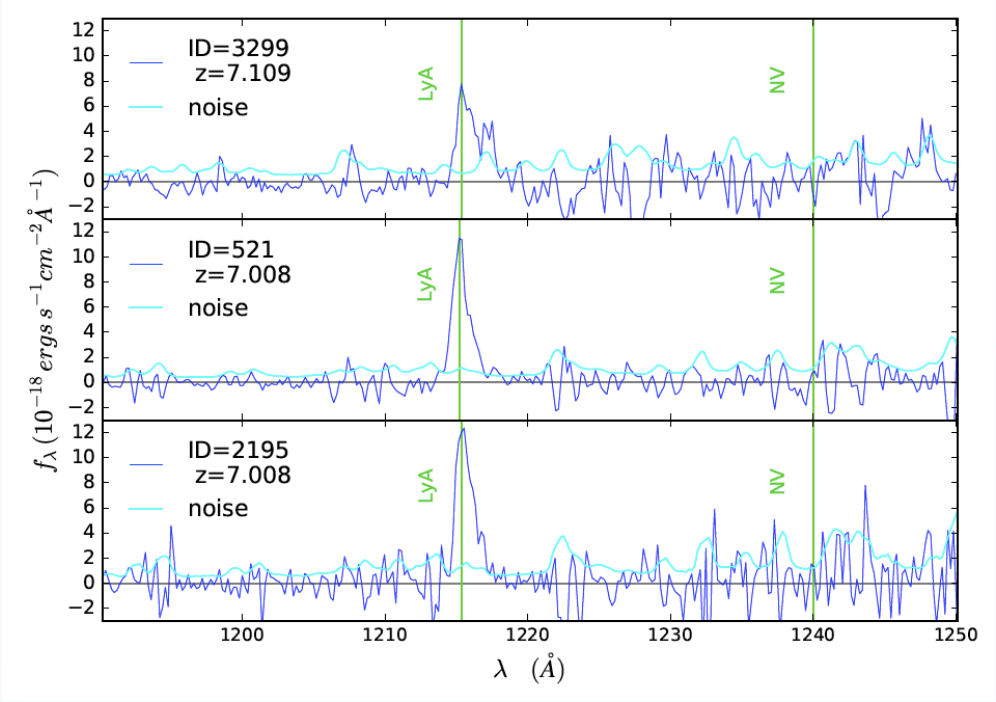
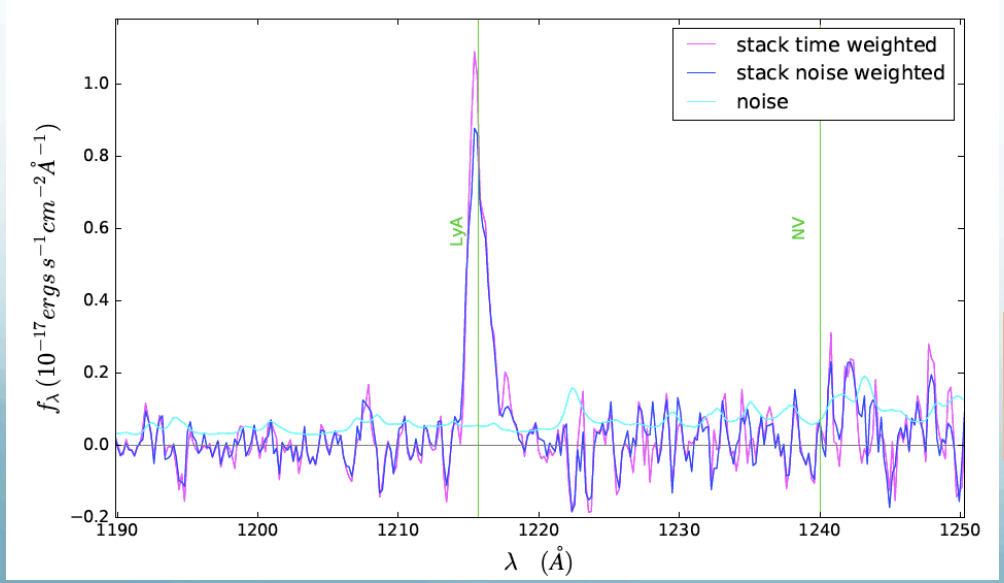
What about AGN?



Lyα/NV>~8-10 on single spectra



Lyα/NV>17 on stacked spectrum

Limits not enough to rule out AGN.
Not to mention past AGN activity…

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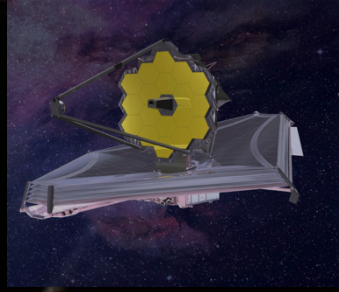
Waiting for JWST



JWST-NIRSPEC can easily detect optical lines, and look for other faint lines in the UV range. We will be able to:

① Assess whether faint candidates are members of the localized overdensity at z~7.0-7.1 as the bright ones.

② Perform accurate measurements of SFR, extinction and age (Hα luminosity, Hα /Hβ and Hα /UV ratios) to constrain re-ionization capabilities.

③ Measure velocity shifts between Lyα and UV/optical lines.

④ Probe signatures of a high escape fraction (e.g. Zackrisson+13, Verhamme+15, de Barros+16, Chisholm+18 etc)

⑤ Probe signatures of AGN or of hard ionizing stellar spectra (e.g. Stark+17, Mainali+17, Senchyna+17, Schaerer+18).

⑥ Confirm a low neutral fraction looking for blue wings in high-resolution Lyα spectra (e.g. Hu+16)

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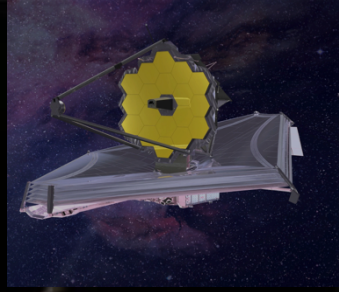

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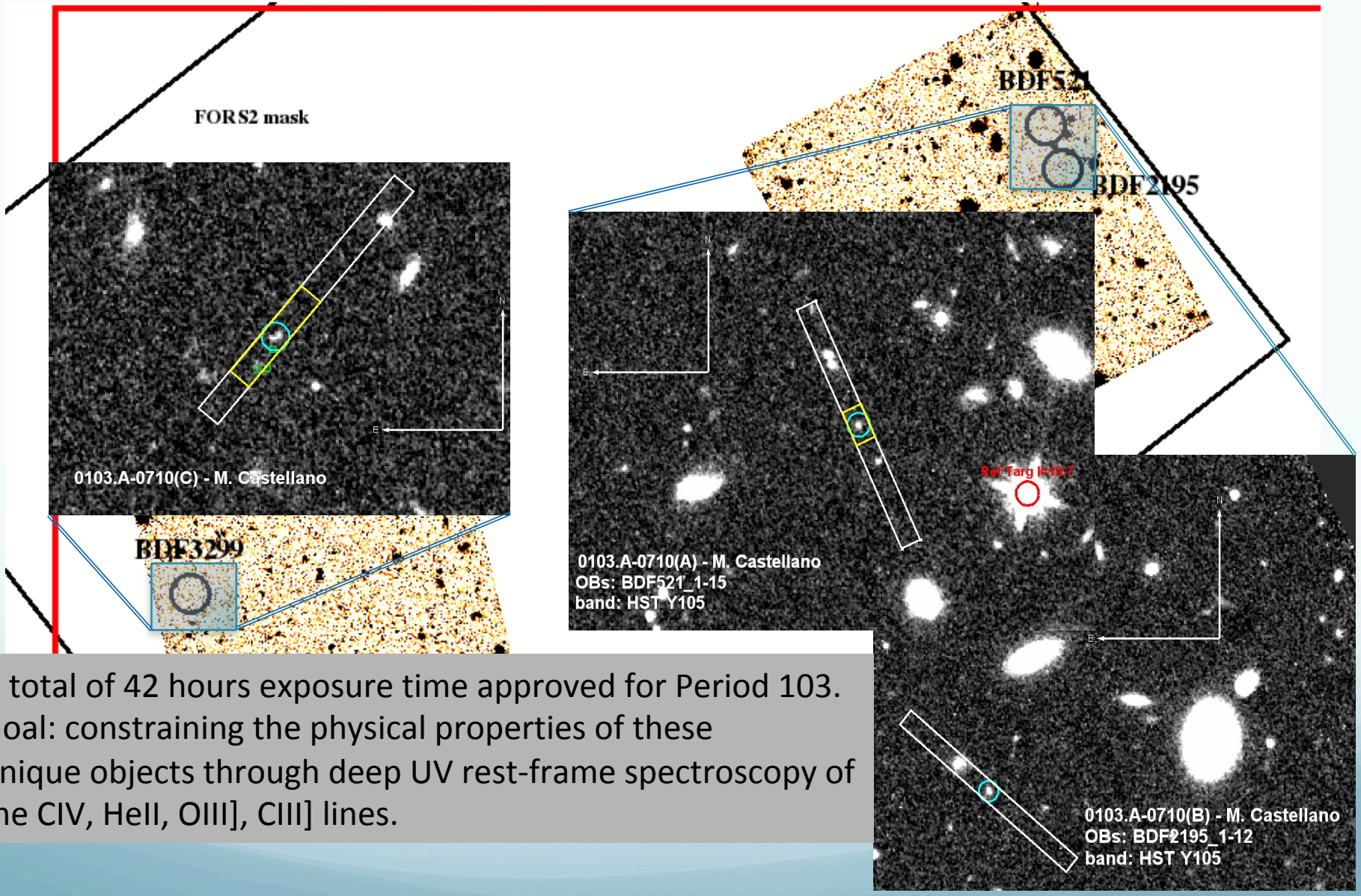
Deep X-SHOOTER observations coming soon!

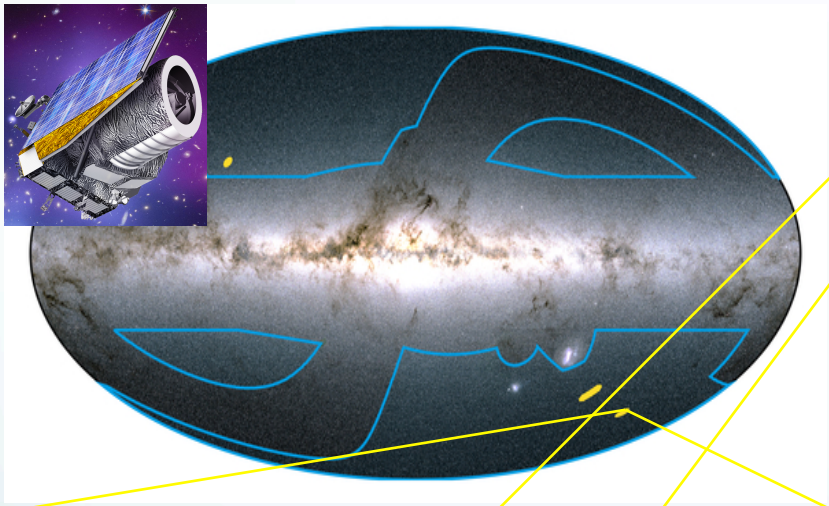


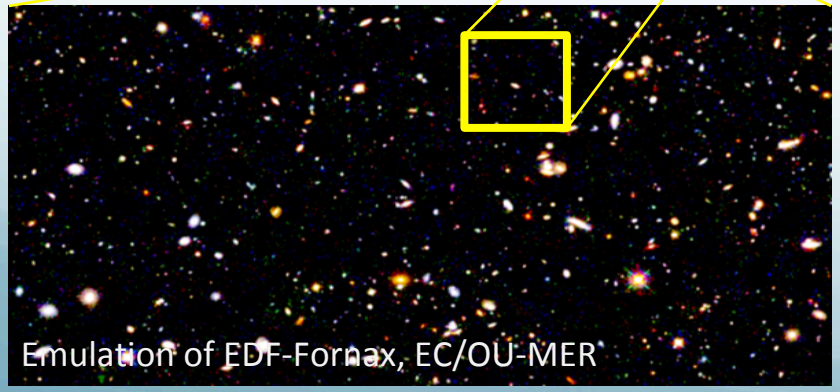
A total of 42 hours exposure time approved for Period 103.
Goal: constraining the physical properties of these unique objects through deep UV rest-frame spectroscopy of the CIV, HeII, OIII], CIII] lines.

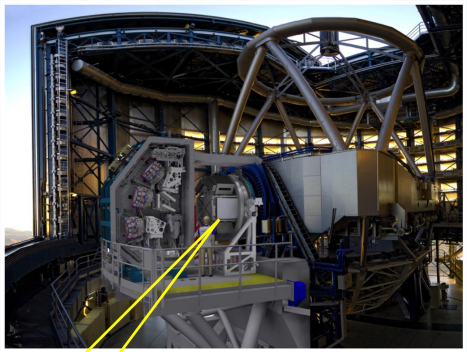
The future: synergies to map early reionized regions

1) **Euclid Deep Fields**: 40 sq. deg. multi-wavelength at CANDELS depth (NIR~26).

Selection, LF and morphology of L~L Lyman Break galaxies in the reionization epoch.*

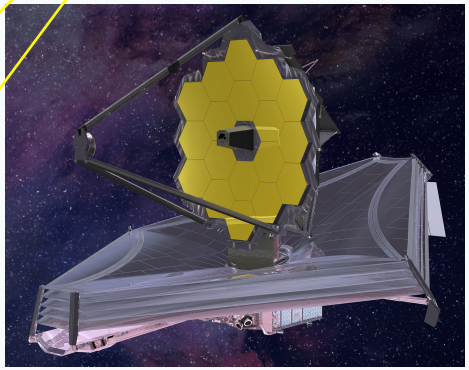






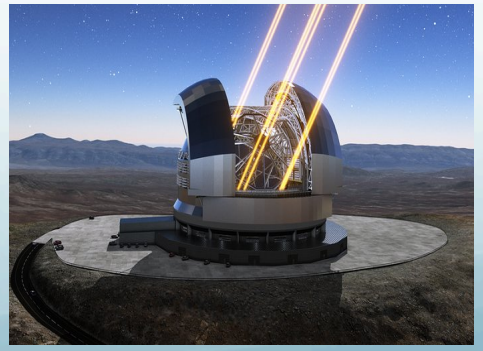
2) **VLT-MOONS**
(500 arcmin^2 FoV, R>4000, λ=0.65-1.8μm)

Spectroscopic follow-up of L~L LBGs, Lyα LF.*



3) **JWST**

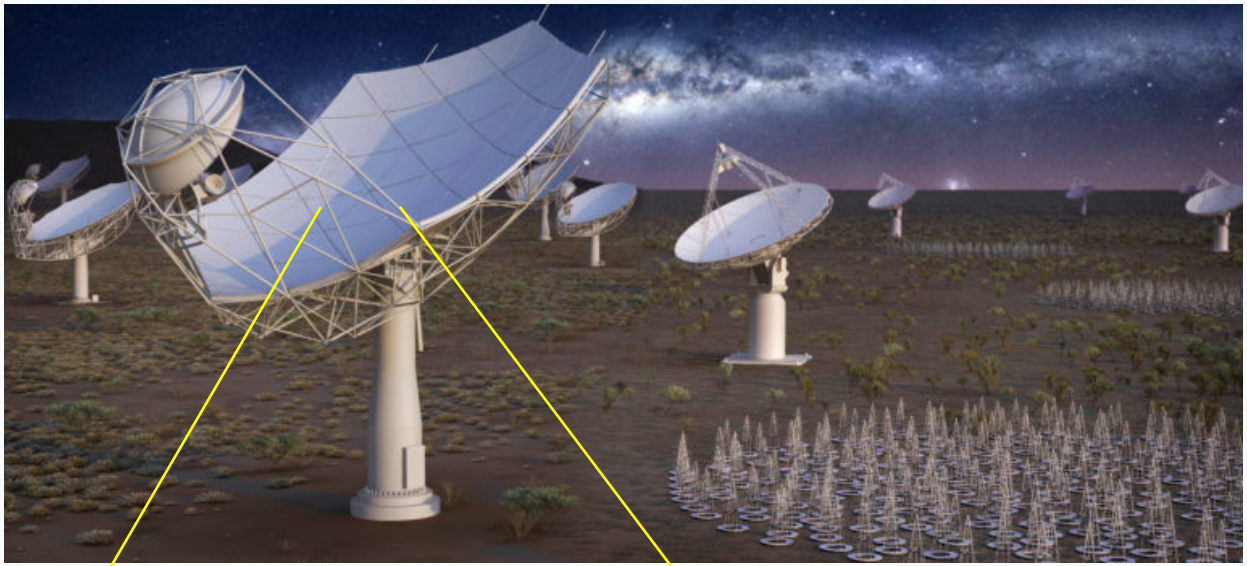
Selection, LF, morphology and spectroscopy of faint LBGs around L LAEs.*



4) **ELT/TMT/GMT**

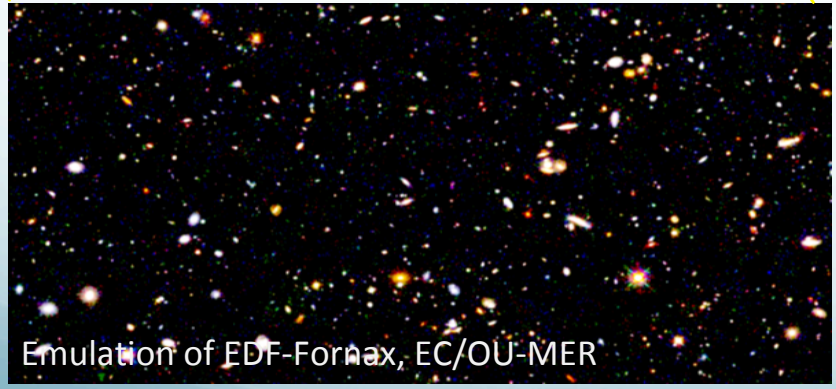
Ultra-deep AO-assisted spectroscopy, morphology and dynamics of faint and bright LBGs and LAEs.

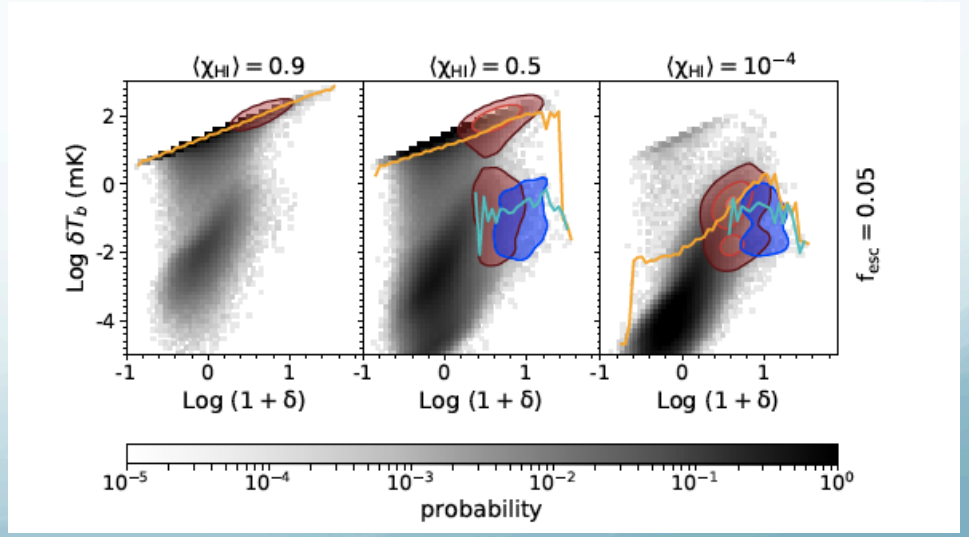
The future: synergies to map early reionized regions



5) **SKA**

Connecting galaxy density field and 21cm signal to map reionization topology (e.g. Hutter+17,+18)





Summary and conclusions

- Three close-by z~7 LAEs in the BDF field embedded in an overdensity of faint LBGs. They are all L~L* galaxies.
- Two LAEs form a pair at ~90 kpc distance.
- Lyα fraction much higher than average at z~7 : patchy scenario (see Pentericci+14) likely due to clustering.
- Consistent with the presence of overlapping reionized "bubbles" of ~5Mpc radius.
- Puzzling lack of Lyα from faint companions: low Lyα escape from faint galaxies?
- The pair BDF521-BDF2195 can reionize their surroundings with "reasonable" f_{esc}~5-20%.
- BDF3299 would require other (ultra-faint?) sources, or AGN (but Lyα/NV>10).
- **Ideal target for JWST to discriminate among various scenarios.**
- ***Hot topic for the future: synergy among future telescopes will allow to select and investigate many regions like the BDF.***