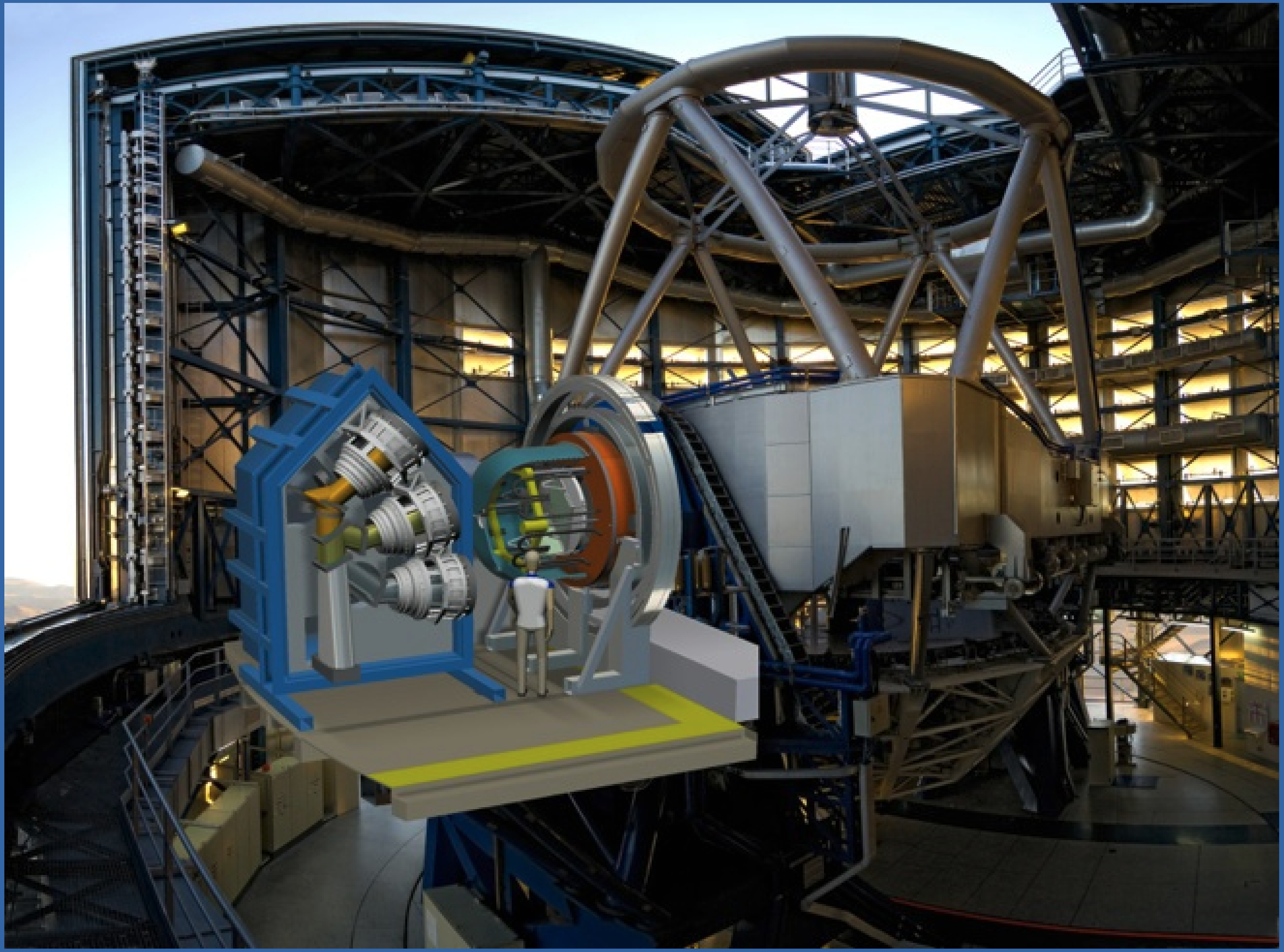
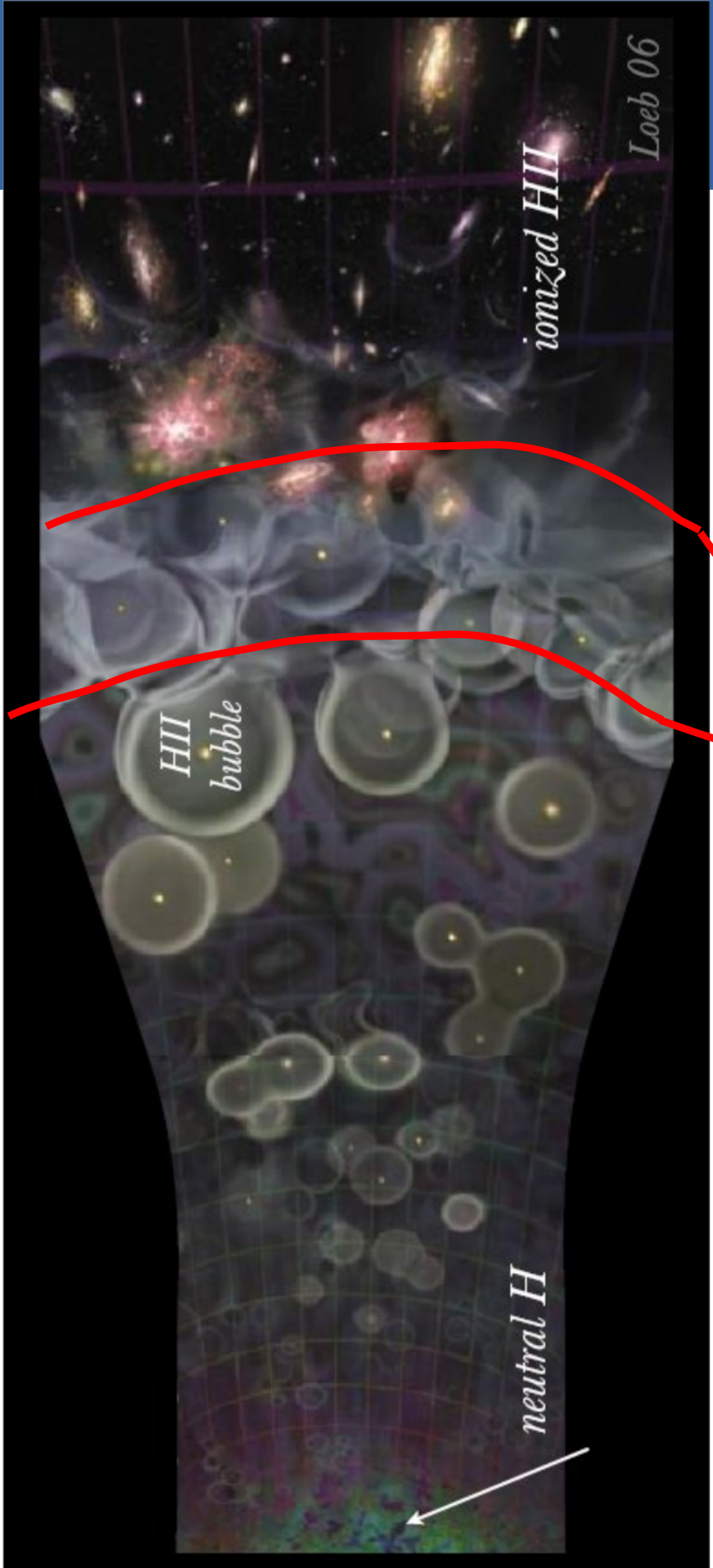
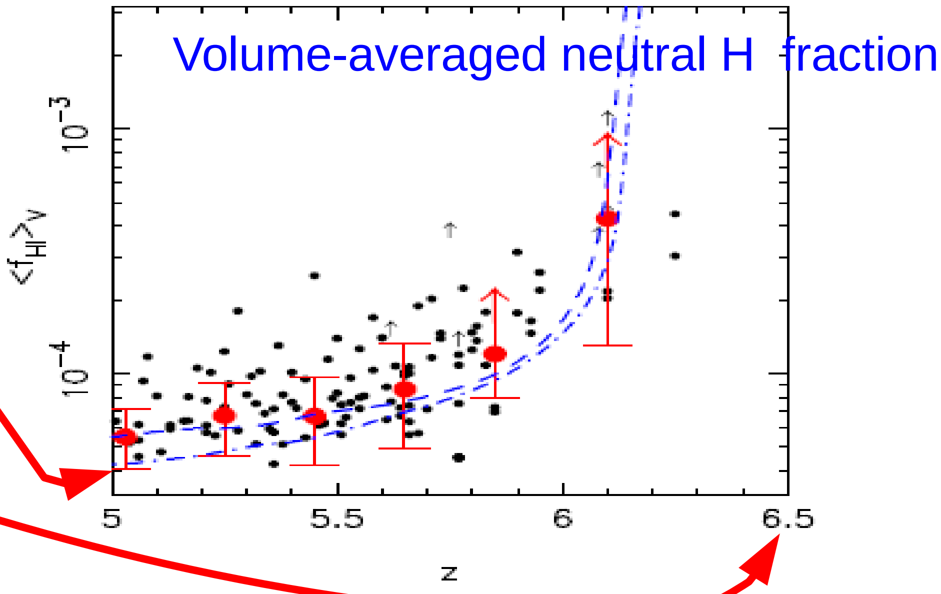


MOOONS: Constraints on the reionization

R. Pelló (IRAP / GAHEC Group)

The end of the reionization

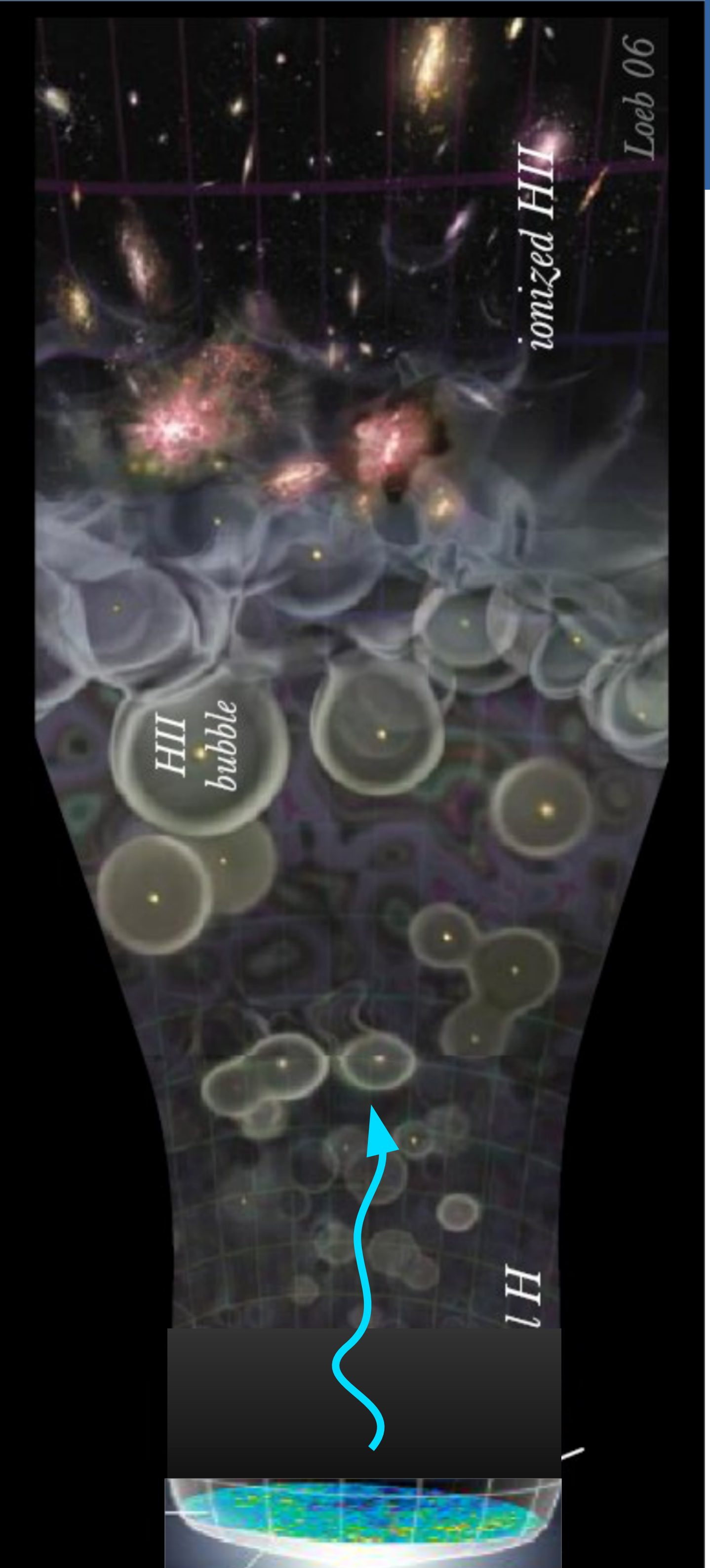




Fan et al 2006

$$\tau_{GP}(z) = 4.9 \times 10^5 \left(\frac{\Omega_m h^2}{0.13}\right)^{-1/2} \left(\frac{\Omega_b h^2}{0.02}\right) \left(\frac{1+z}{7}\right)^{3/2} \left(\frac{n_{HI}}{n_H}\right)$$

- Evolution of **optical depth of Lya photons.** GP effect
- Complete absorption even for a tiny neutral H fraction (~10^{-4}) >> present value (~10^{-5}) ==> this test is only sensitive when the IGM is “almost” ionized, and saturates for higher neutral fractions.

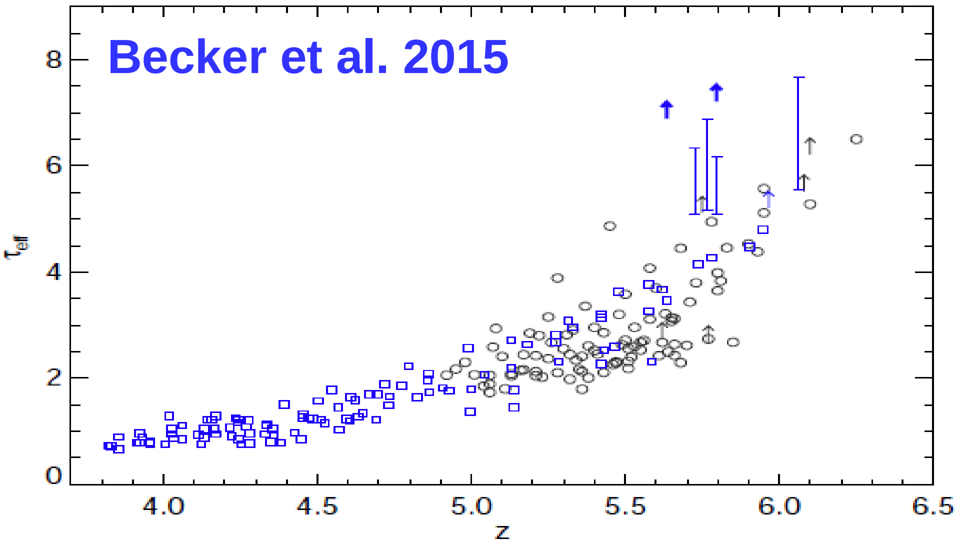


The beginning of the reionization

- Foreground **electron scattering of CMB photons** with an optical depth corresponding to z(reionization). Observed since WMAP year-1 (2003) at 4 sigma level.
- **z(reionization)**=
  - 11+/-1.2 (Komatsu et al. 2011) WMAP
  - 11.4 [+4.0/-2.8] (Planck col. 2014) PLANCK
  - 7.8 – 8.8 (model dependent) PLANCK 2016

    < 10% ionization at z > 10
- Uncertainties remain... The actual value depends on the reionization process (“instantaneous” versus more complex scenarios).

Sources of the reionization and actual process

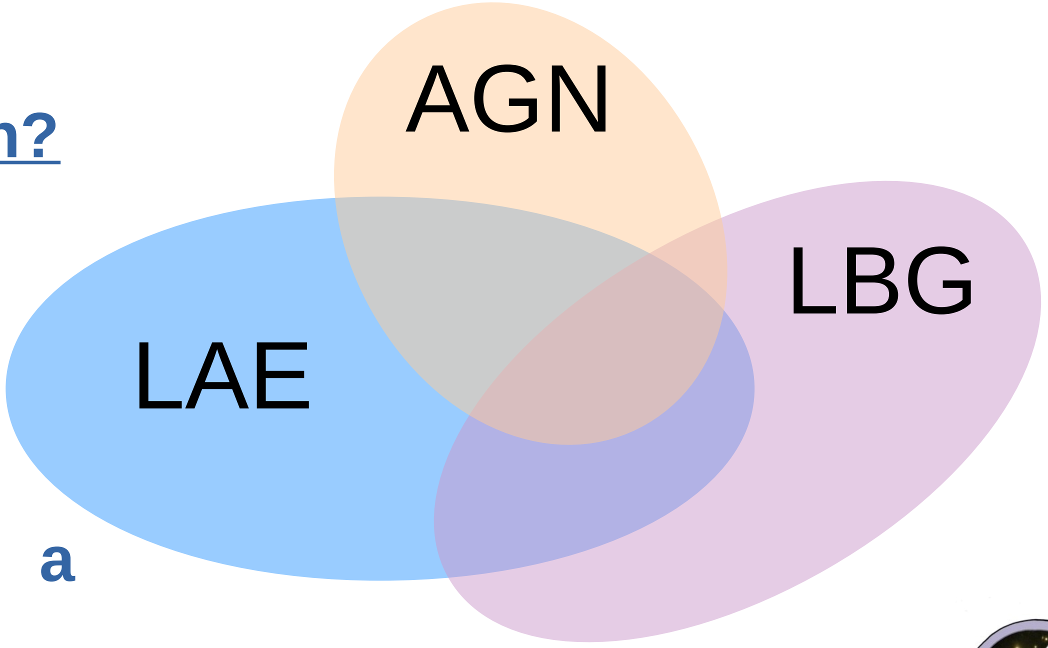


- Large line of sight variance is also observed!
- Evidences for a “patchy” H reionization (inhomogeneous at ~100 Mpc scale; see Becker et al. 2015)
- A gradual process? Multiple phases?

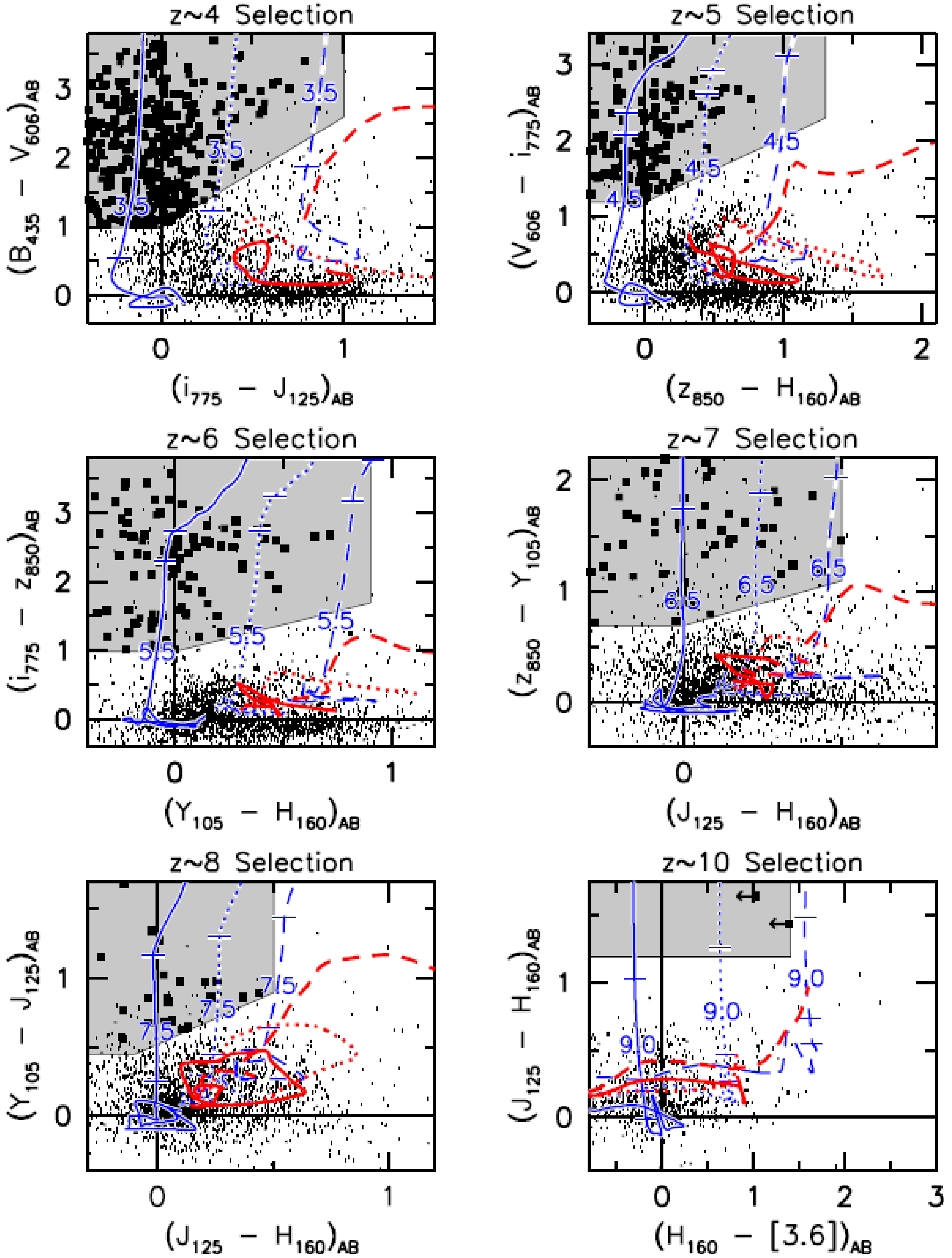
What were the **sources responsible for the reionization?**

- Galaxies
- AGNs
- GRB contribution?

Observational selection has a huge impact !



LBG Surveys : UV Luminosity Function



- HST Legacy surveys :
  - ➔ CANDELS,
  - ➔ HUDF09,
  - ➔ HUDF12,
  - ➔ ERS
  - ➔ BORG/HIPPIES

Total FOV: ~1000 arcmin^2

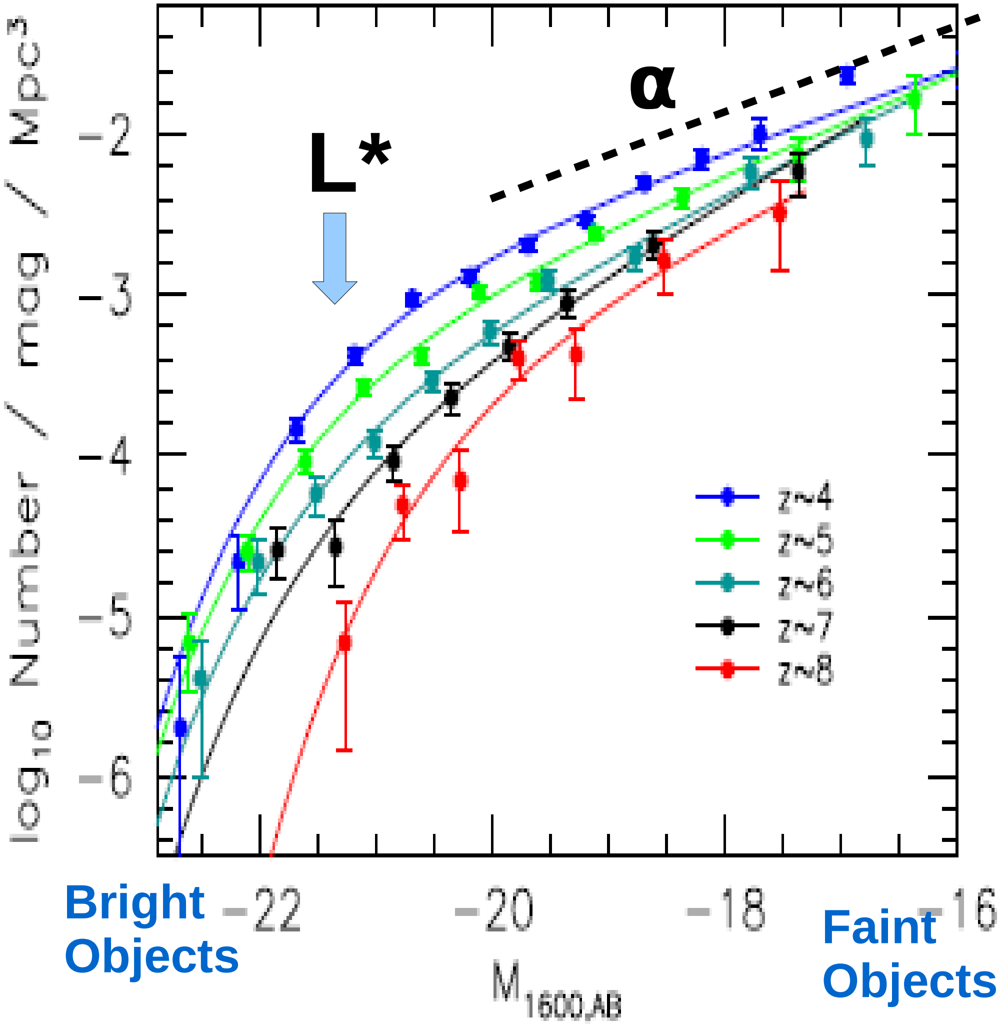
Bouwens et al. 2015

PARIS

LBG Surveys: Luminosity Function

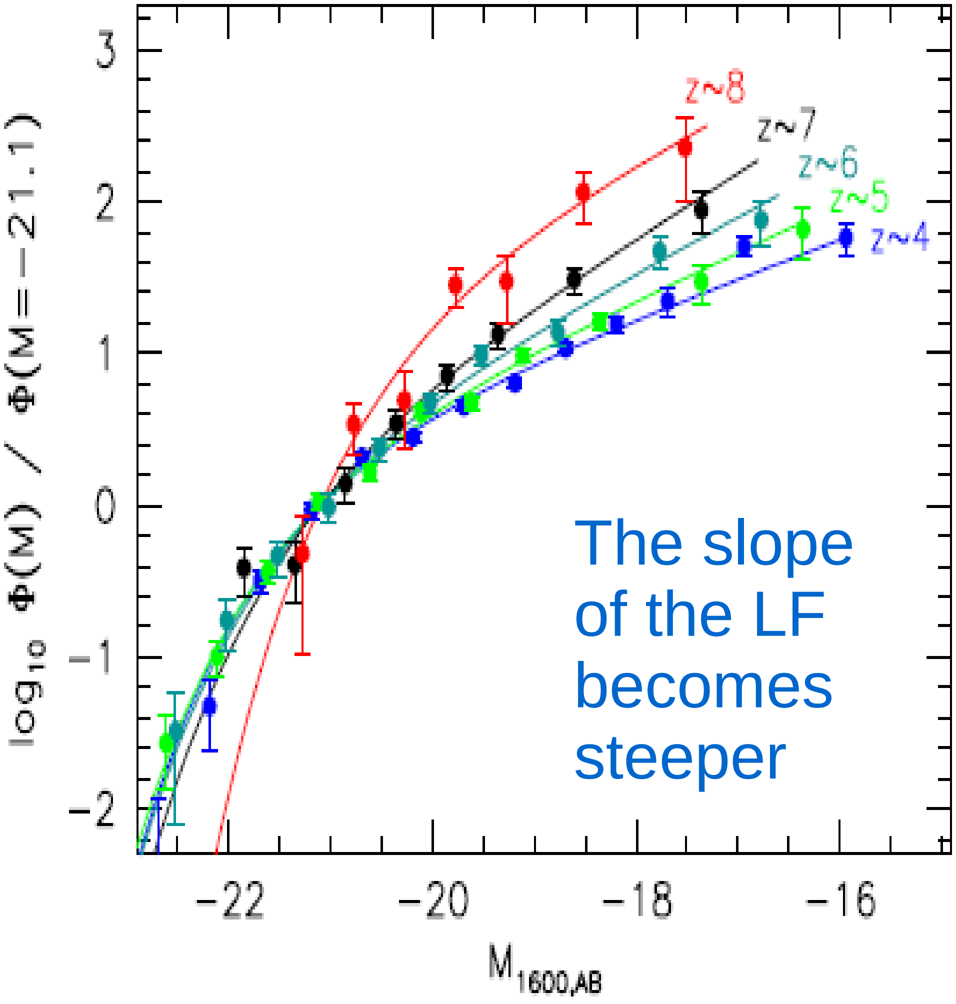
$$\Phi(L)\,dL = n_* \left(\frac{L}{L_*}\right)^{\alpha} exp\left(-\frac{L}{L_*}\right) d\left(\frac{L}{L_*}\right)$$

Bouwens et al. 2015



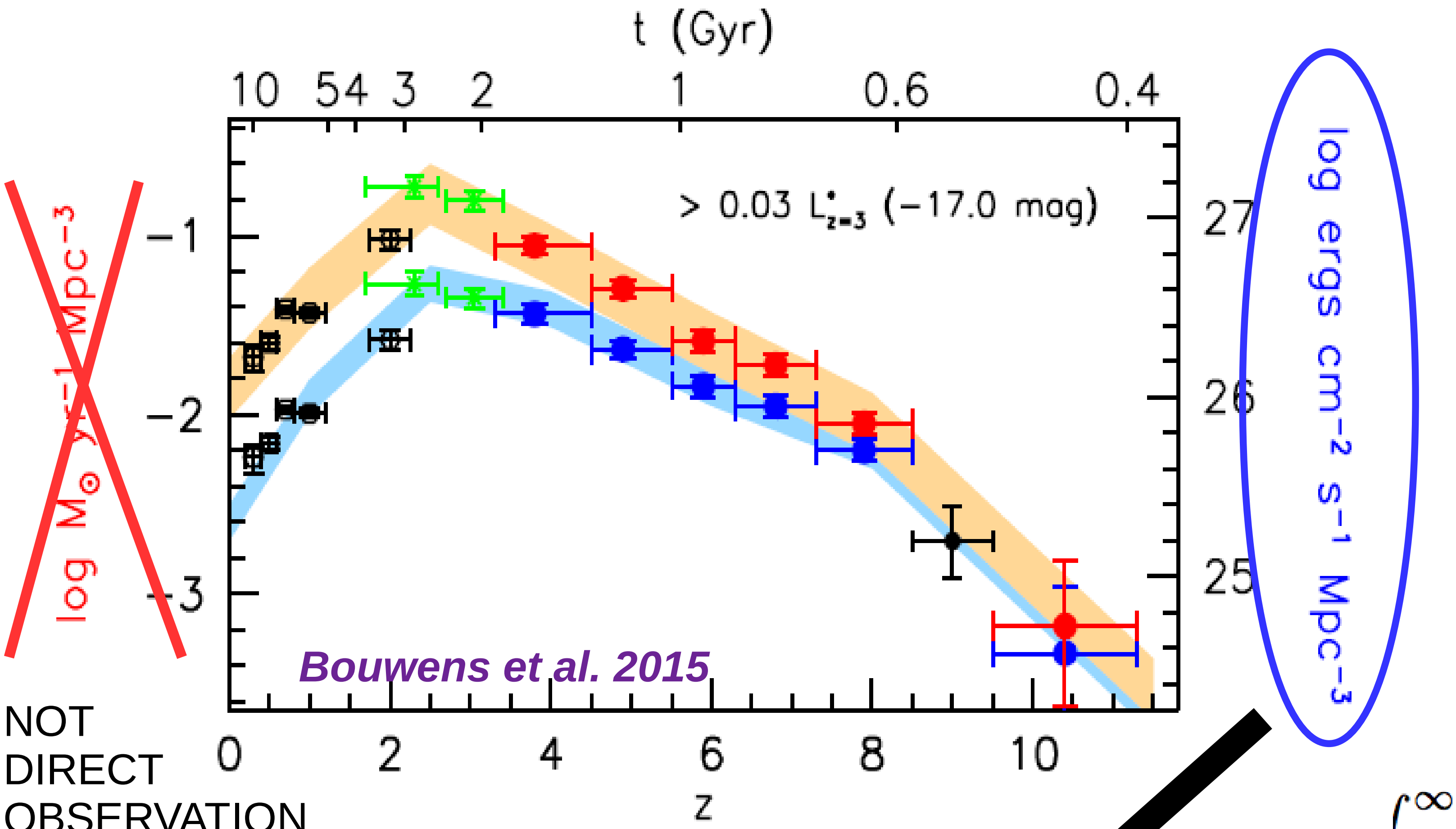
Bright Objects

Faint Objects



The slope of the LF becomes steeper

Cosmic SF History



Bouwens et al. 2015

Evolution on the density of UV photons

NOT DIRECT OBSERVATION

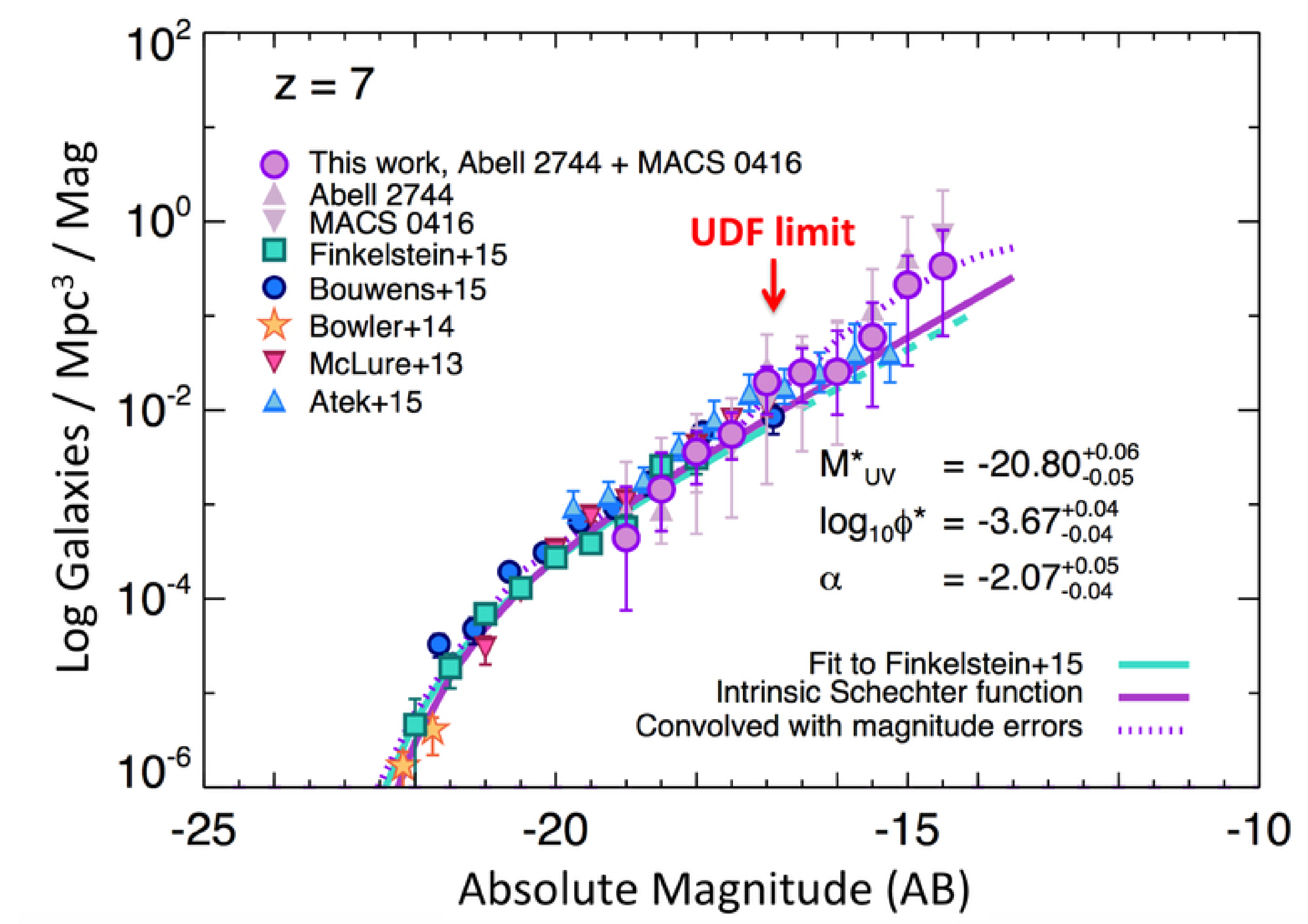
Physics of Star-forming galaxies

$$\rho_{UV} = \int_{L_{lim}}^{\infty} \Phi(L_{1500}) dL_{1500}$$

EVOLUTION OF THE COSMIC IONIZING EMISSIVITY

LBG Surveys (Lensing fields)

Coe+ 2016
Hubble FF



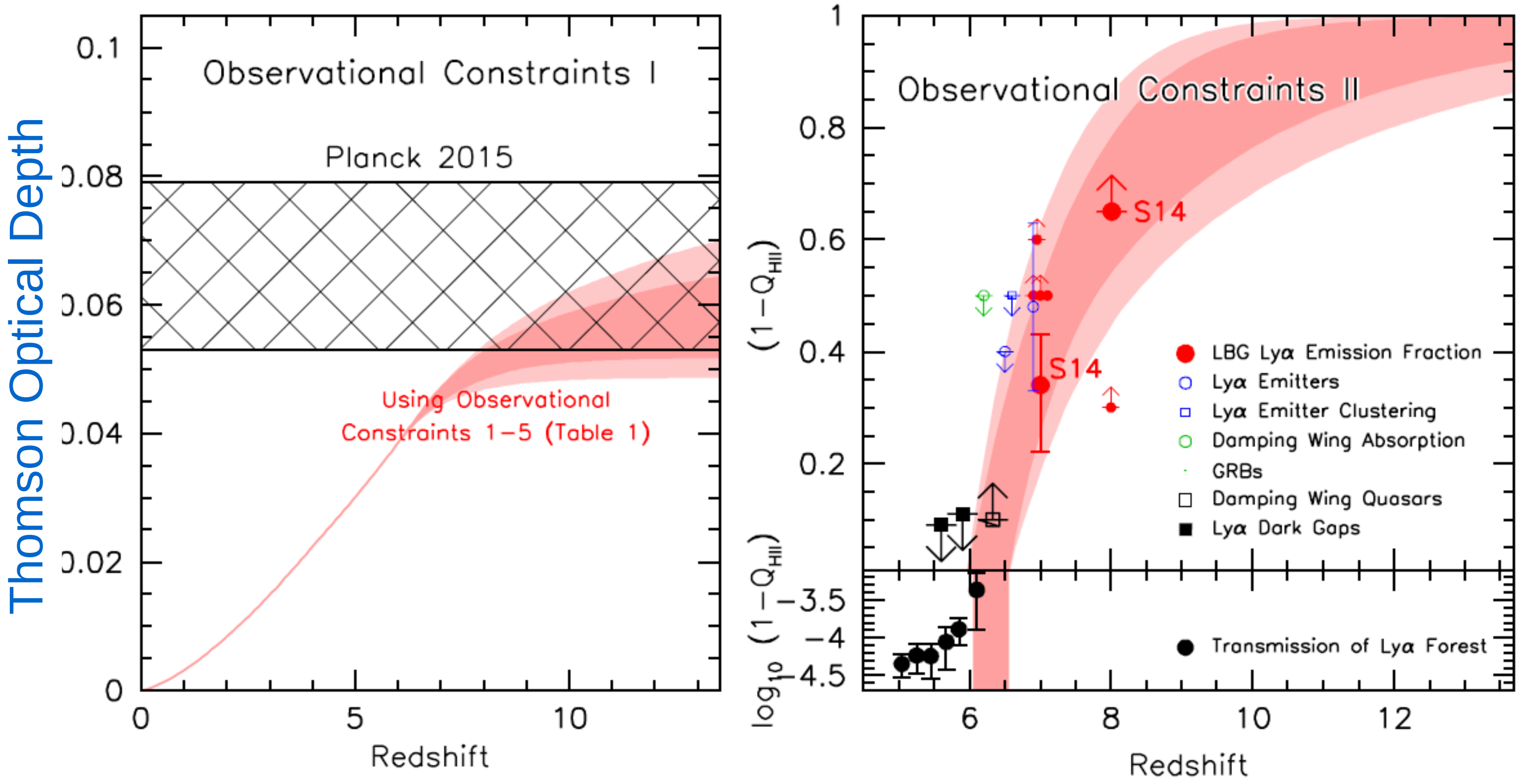
See also
Laporte+ 2014,
Atek+ 2014,
Infante+ 2015,
Laporte+ 2016

Empirical evolution of the cosmic ionizing emissivity

Bouwens et al. 2015

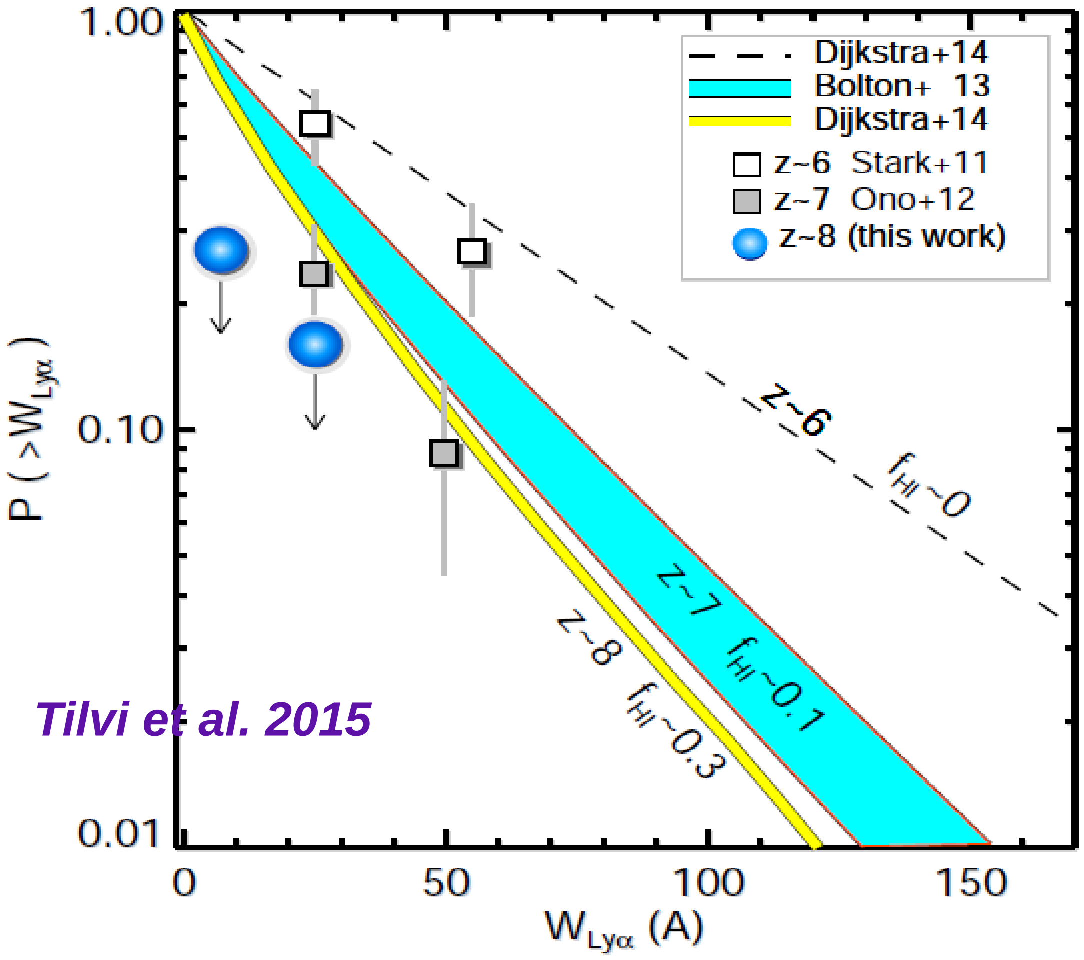
Q(HII) : filling factor of ionized H

- Conversion UV luminosity density ⬌ ionizing emissivity is consistent with plausible values of f(esc) and clumping factor C(HII)... provided that the LF is extended up to the faintest limits M(inf)~ -13



- The UV luminosity density at z~7 seem sufficient to keep the universe reionized assuming “standard” conditions (see also Atek+2015).
- Uncertainties at z>~8 : The faint end of the UV LF is not constrained enough. LAE studies seem to show that the reionization is in progress at z~8 (see Tilvi+2015).
- The reionization seems to be dominated by faint star-forming galaxies, presently beyond the reach of current facilities … in blank fields!

LAE and HI fraction



Tilvi et al. 2015

- Example from Tilvi+2015 : Cumulative Lyman-α probability distribution for their faint sample (M(UV) > −20.25 mag), compared to model predictions.

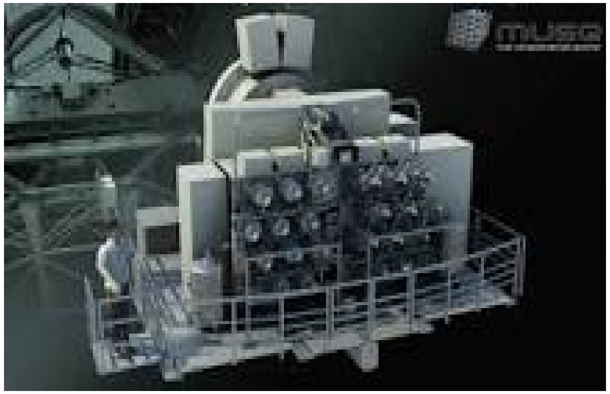
- Usual assumption: On average, the prevalence of Lya emission in galaxies beyond the reionization is a simple extrapolation of observations below the reionization (z<6). Departures from this general trend are interpreted as an increasing fraction of neutral H.
- Based on this approach, the “filling factor" of ionized hydrogen is supposed to evolve from 66% at z~7 to <35% at z~8, with large uncertainties (Pentericci et al. 2014; Tilvi et al. 2014; Schenker et al. 2014).

=> reionization in progress at z~8

MOONS / VLT :

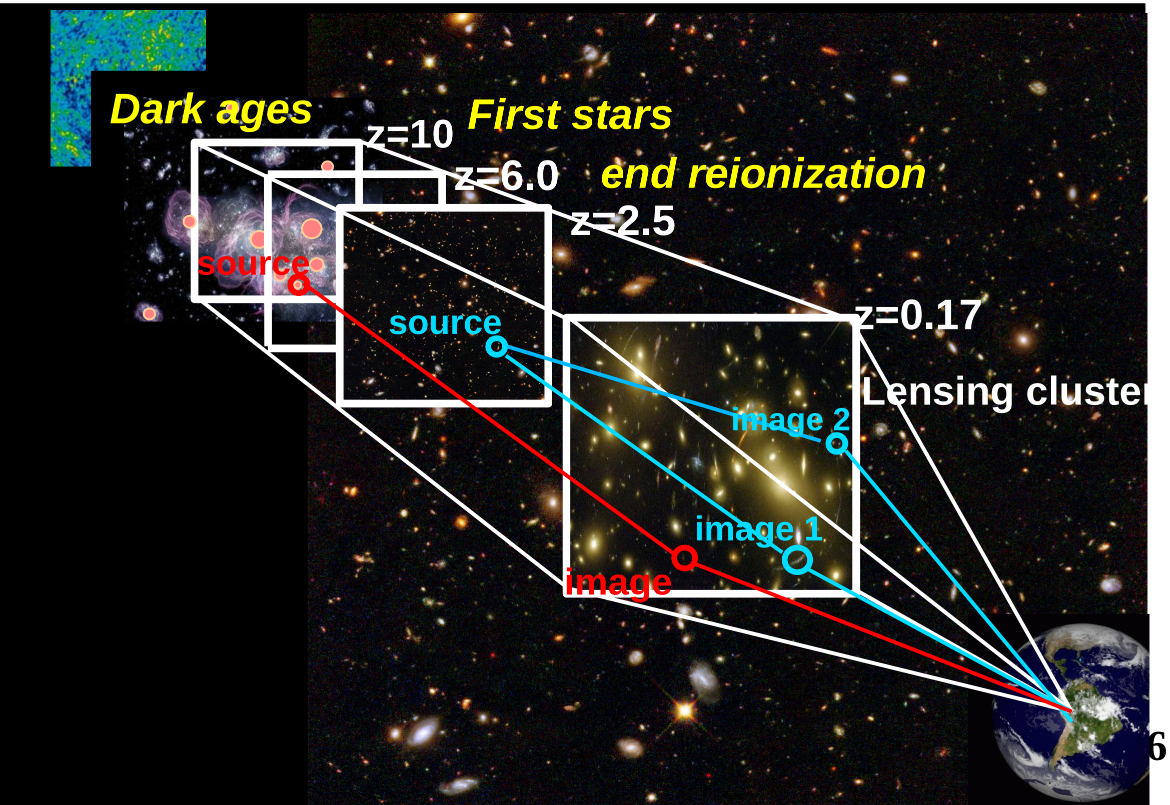
- The identification of galaxies at 6<z< 12 requires an homogeneous and deep coverage of the near-IR domain in combination with (ultra-deep) optical data.
- Lensing clusters are more efficient to conduct detailed (spectroscopic) studies in the sensitive redshift domain, and also to explore the faint-end of the LF, whereas observations in wide blank fields are needed and fully complementary to set reliable constraints on the “bright" end of the LF
- All photometrically-selected samples, either LBG or LAE, need a spectroscopic follow up to confirm both the redshift and the nature of these candidates.
- 2 complementary approaches for a MOONS survey targeting the sources of cosmic reionization:
  - **“Pointed” survey** up to H~24 (maximum ~25) of photometrically selected LBGs
  - **“Blind” survey** looking for serendipitous detections of LAEs within the “sky” fibers.

Blind census of LAE behind lensing clusters with MUSE



MUSE

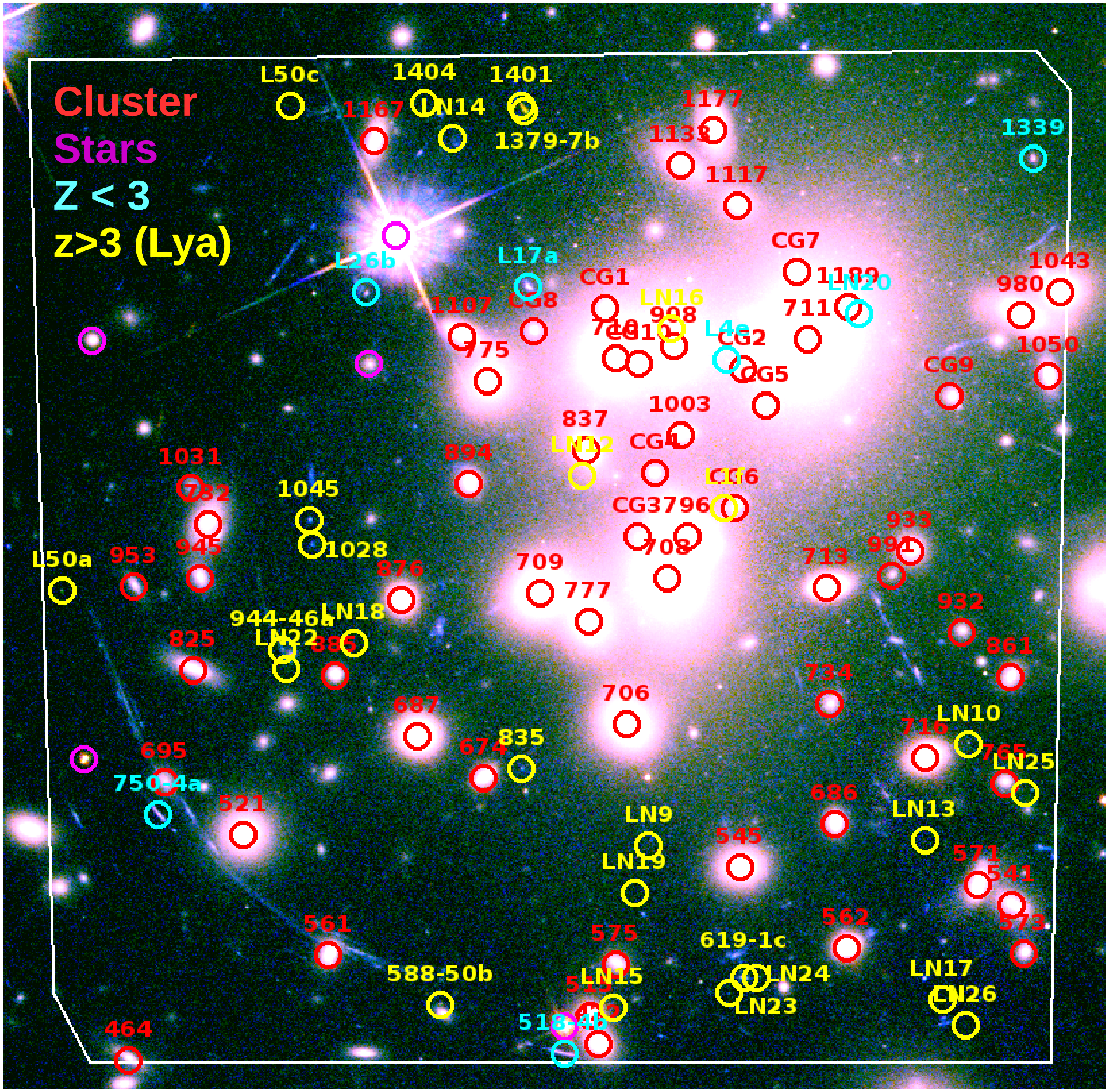
- GTO project (work in progress)
- **Final Goal:** A first complete census of star-forming galaxies/ ionizing sources. Determining the contribution of (faint) LAEs to the re-ionization
- **Why MUSE?** MUSE is ideally suited in terms of FOV. No preselection of sources.
- **Why lensing fields?** (See e.g. Maizy et al. 2010): Magnification => reducing the bias towards the brightest sources.



Results on LAE Lensing Program :

A1689 (z=0.18),
A2390 (z=0.23),
A2667 (z=0.23),
A2744 (z=0.308)
...

A1689



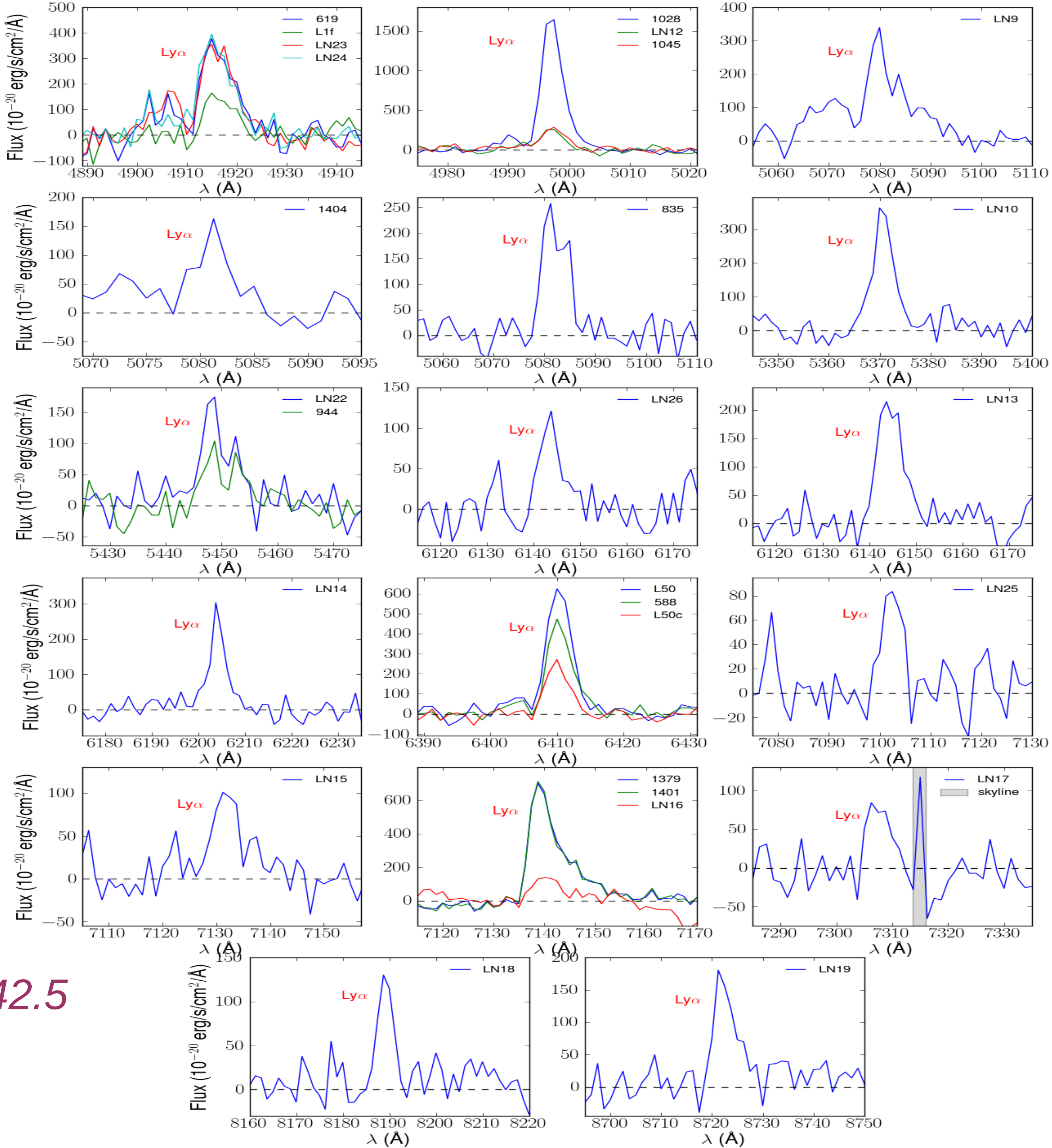
- A1689 (z=0.1847, Teague et al. 1990)
- FOV : ~185x185 kpc
- MUSE observation : ~1.8h = 1100 sec x 6 exposures
- Seeing ~0.6” at 7300A
- Source Extraction + z measurements :
  ➔Manual/guided
  ➔**LSD-CAT, MUSELET & CubEx**
- 21 e-line background galaxies: 7 known + 14 new galaxies
- 17 LAE at z>3
- All these sources are multiple-image systems

Bina, RP et al. 2016

- $z>3$ LAE :
  - 17 galaxies
  - 7 of them are NOT detected in the continuum ($m(AB)>28$)
  - $3.0 < z < 6.2$
  - Magnification :

    $\mu = 4.4 – 75$!
  - Typical $\mu \sim 6 - 10$

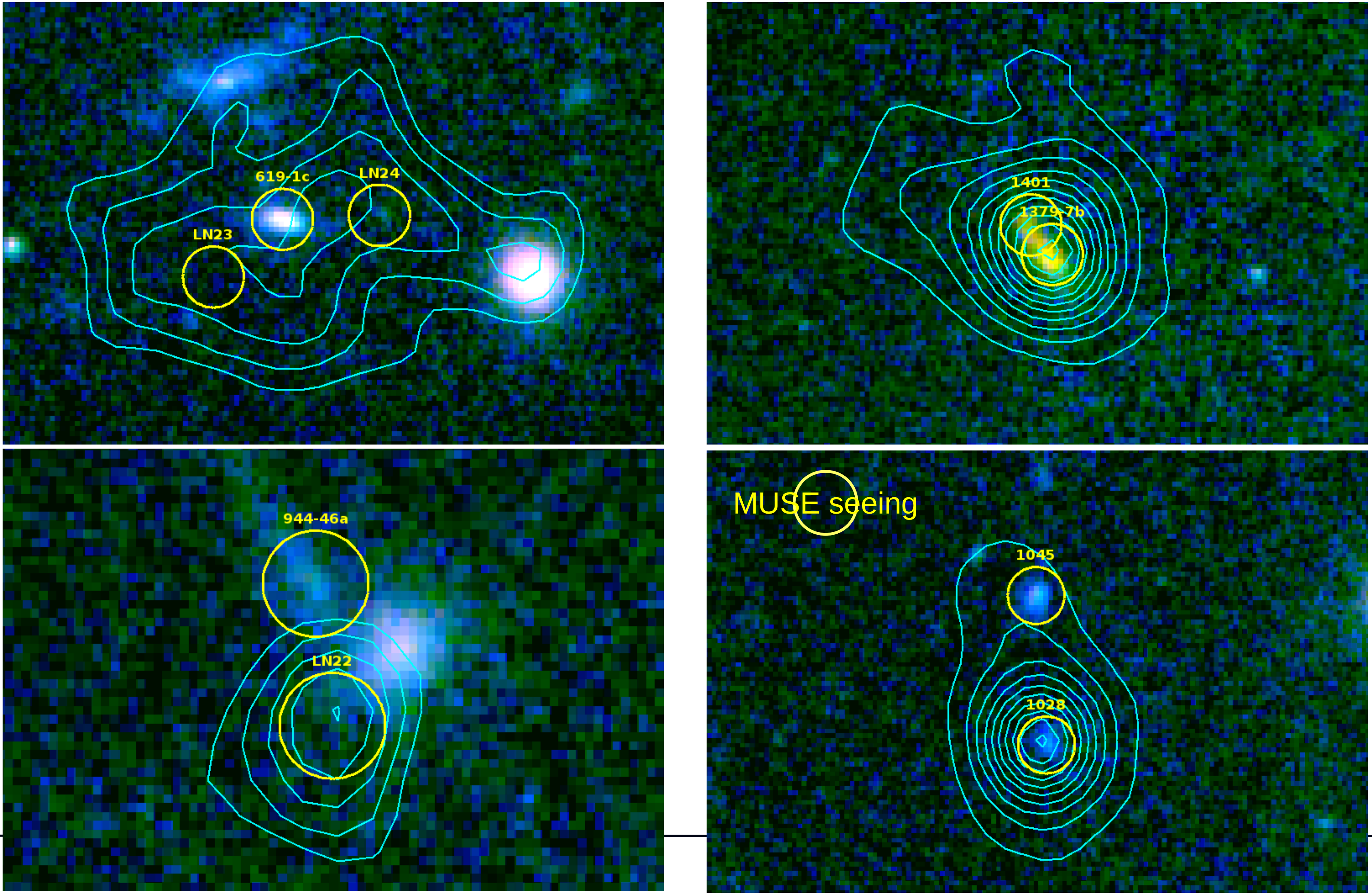
$40.5 < \mathrm{Log(Lyman)} < 42.5$



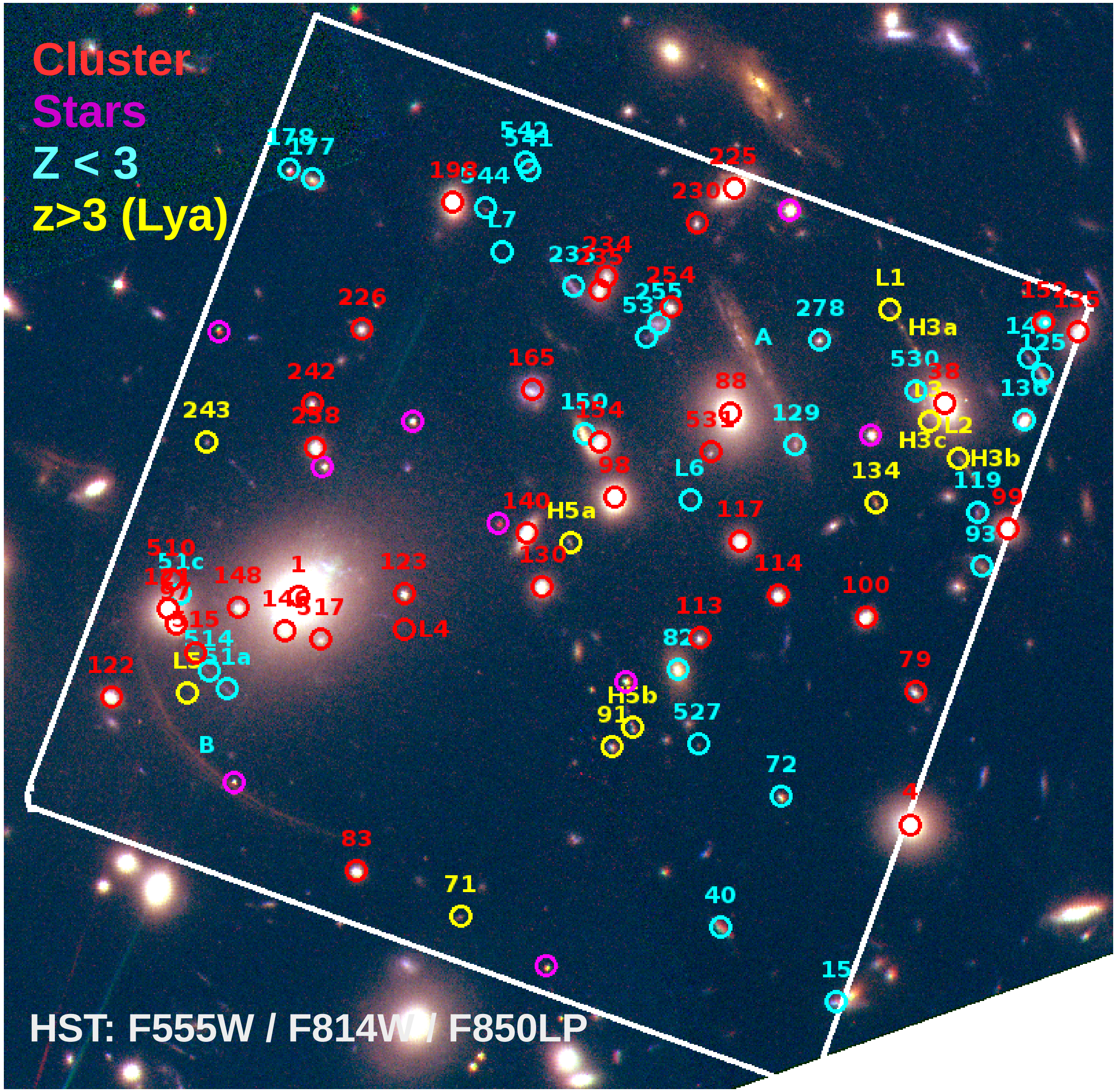
A1689: extended Lya emission

Bina, RP et al. 2016

- Extended Lya emission seen in 4 cases :



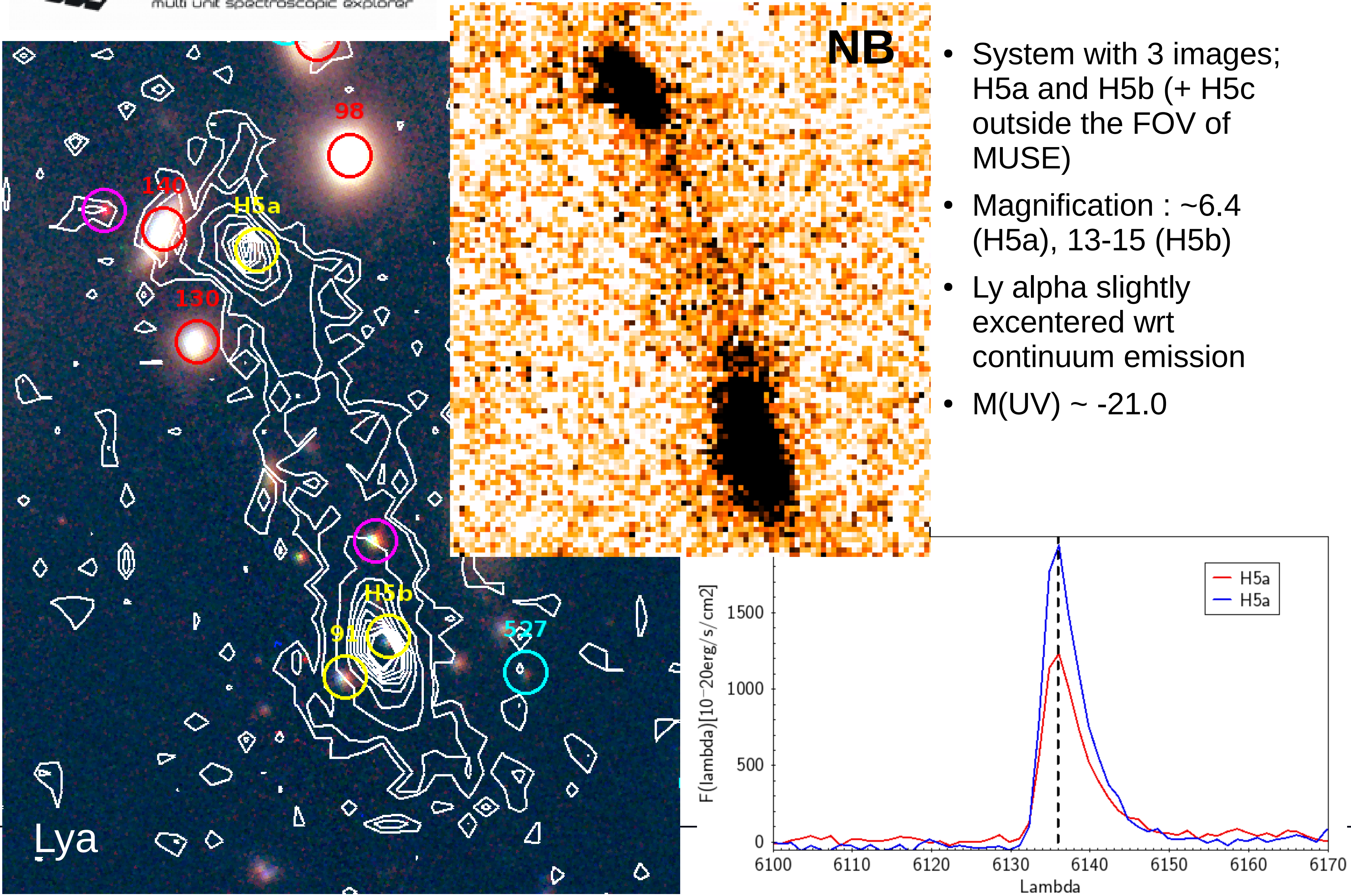
A2390



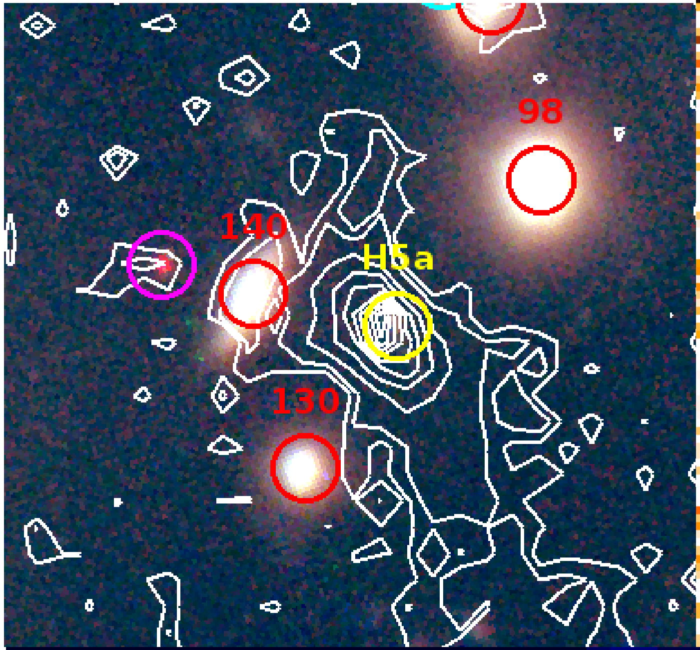
- **A2390** (z=0.23, Le Borgne et al. 1991; Yee et al. 1996)
- 3.698 kpc/", FOV ~220x220 kpc
- MUSE observations: 2h (4x1800 sec)
- Seeing ~ 0.75” (FWHM, white light)
- Same procedure as for A1689 (Bina+16):
  - Guided extraction of sources detected on HST/F814W image (continuum selected)
  - Automated extraction of line-emitters with MUSELET
- Source extraction + z measurement:
  - 38 cluster galaxies / 9 stars
  - **42** images of **31 background sources**
  - **9 multiple images / 5 are NEW**
  - **5 sources at z≳4**

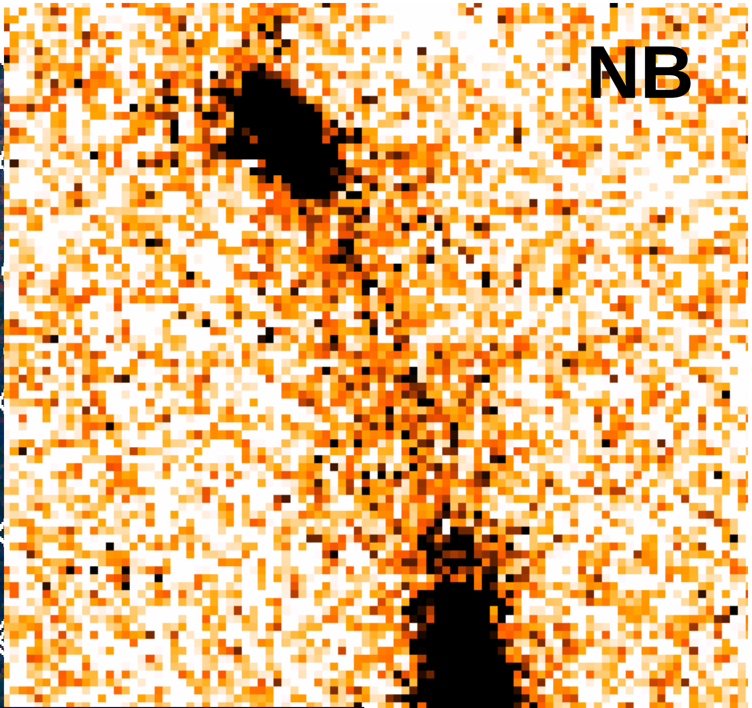
A2390 – H5

- System with 3 images; H5a and H5b (+ H5c outside the FOV of MUSE)
- Magnification : ~6.4 (H5a), 13-15 (H5b)
- Ly alpha slightly excentered wrt continuum emission
- M(UV) ~ -21.0



A2390 – H5





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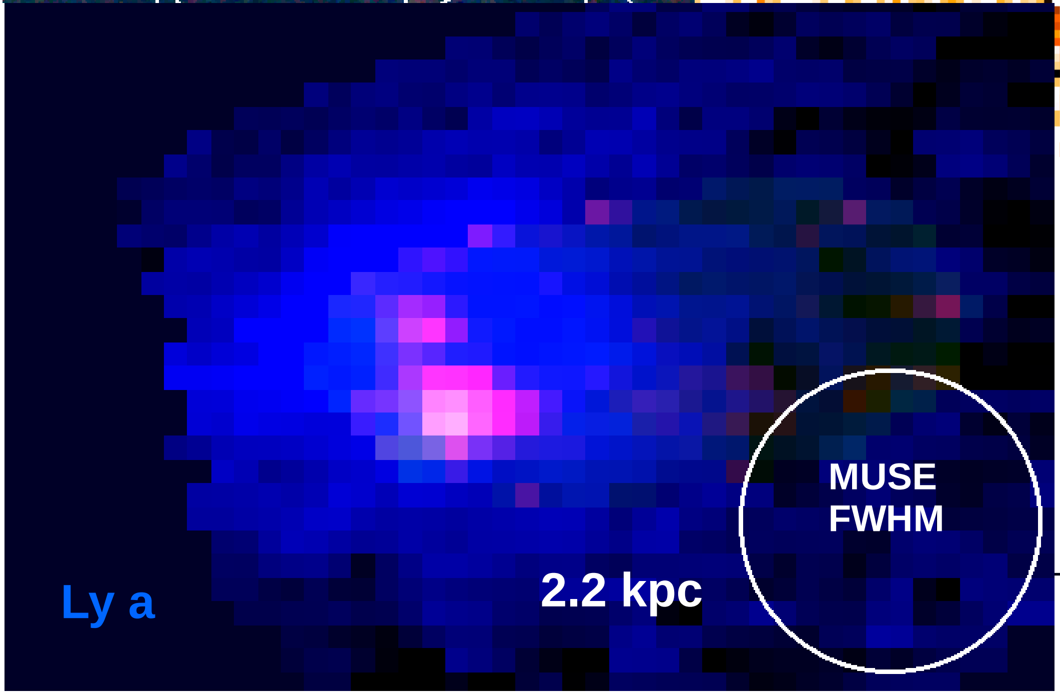
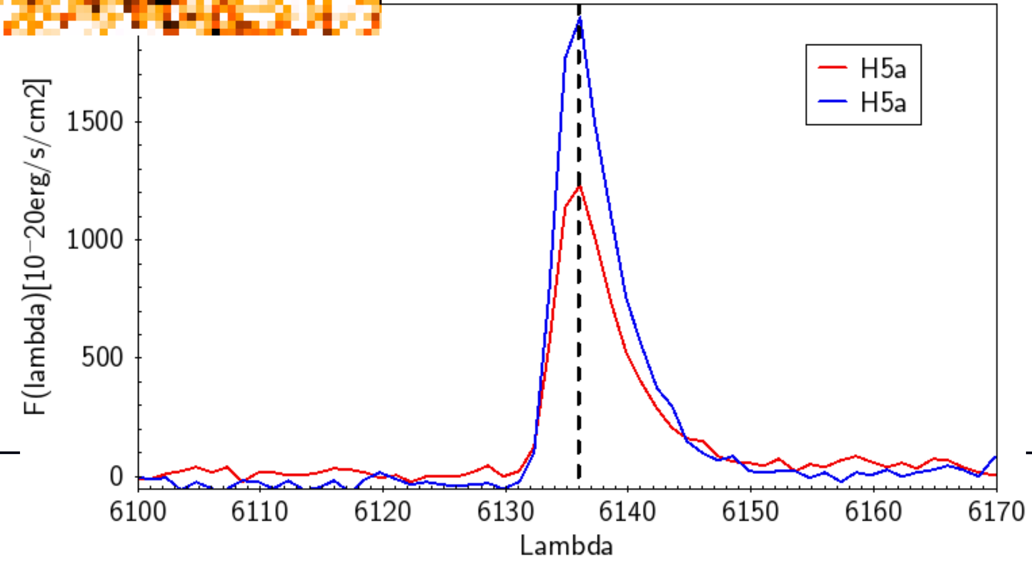
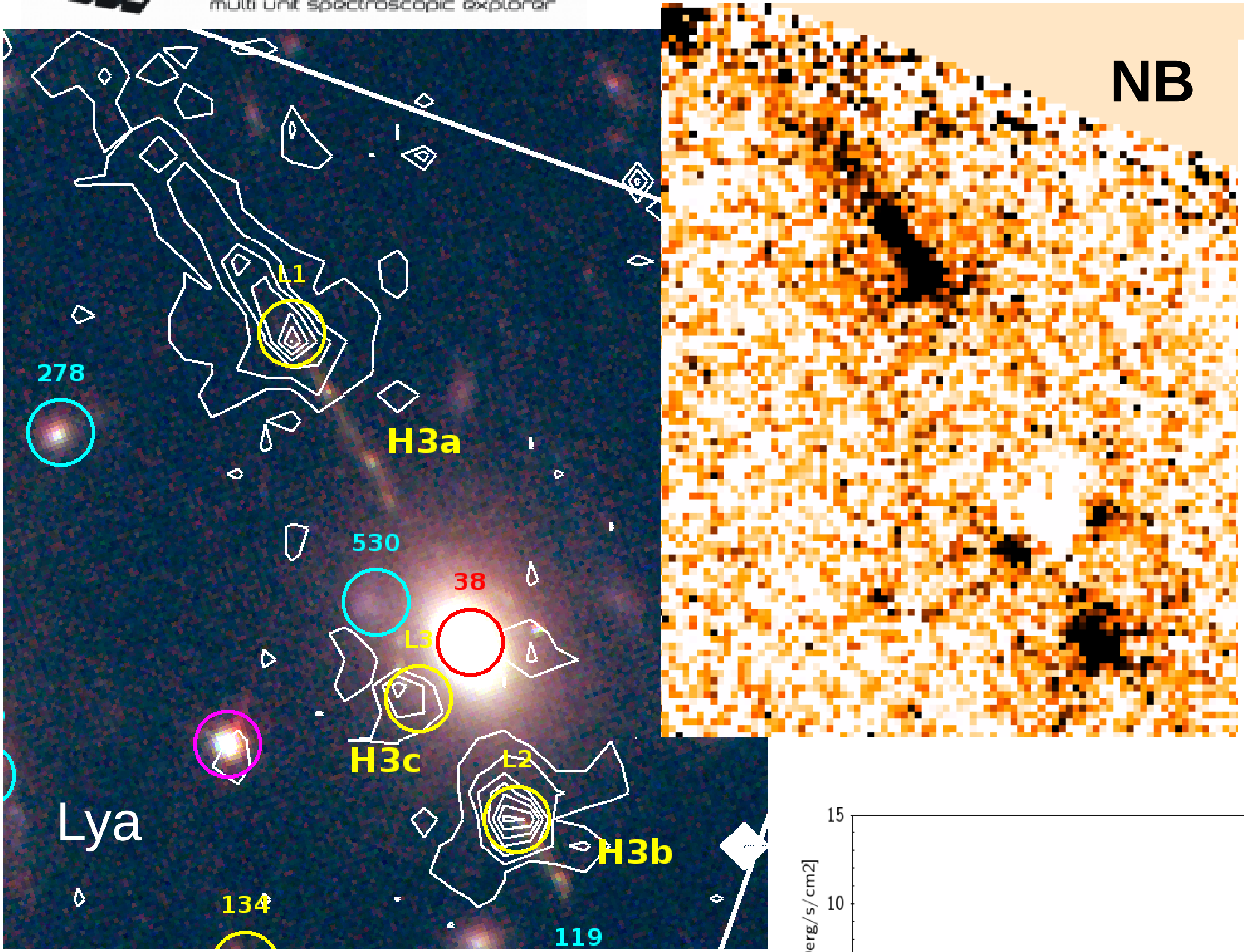
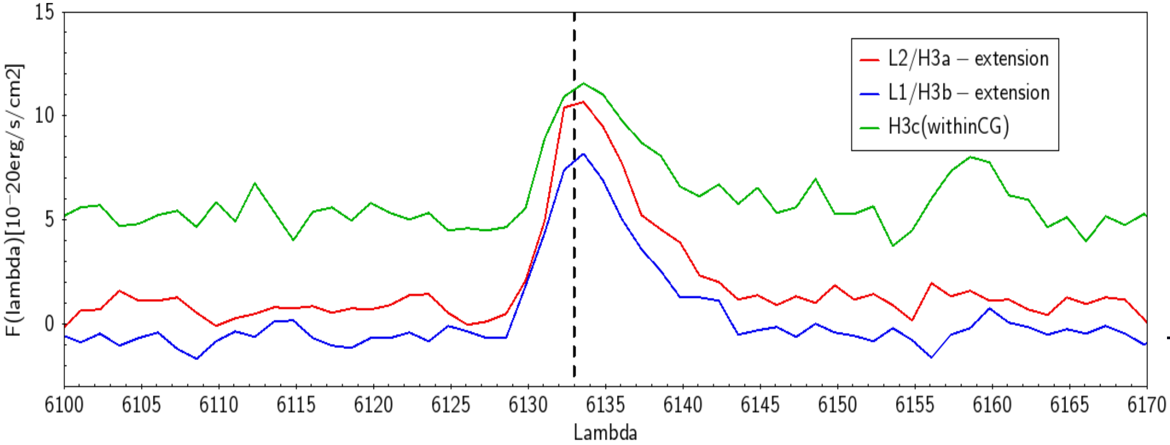




A2390 – H3

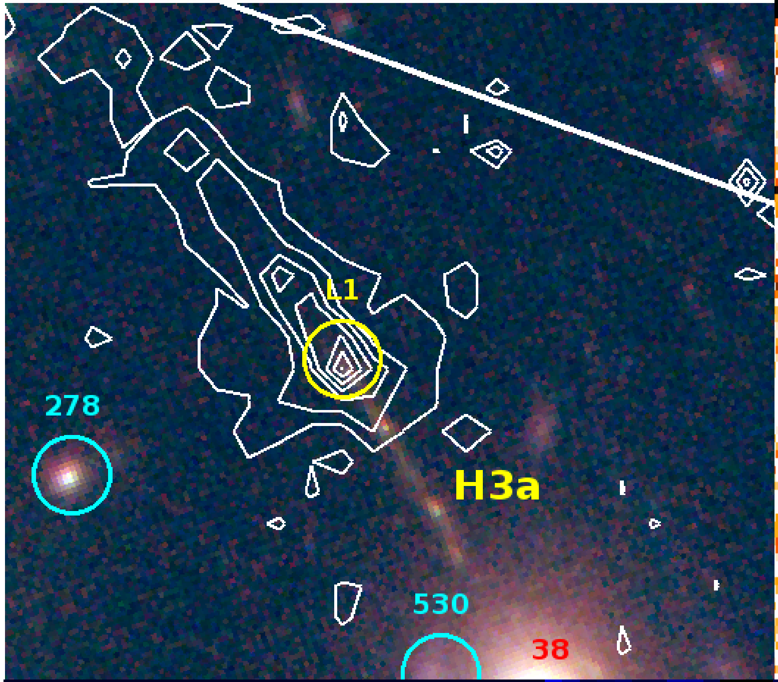


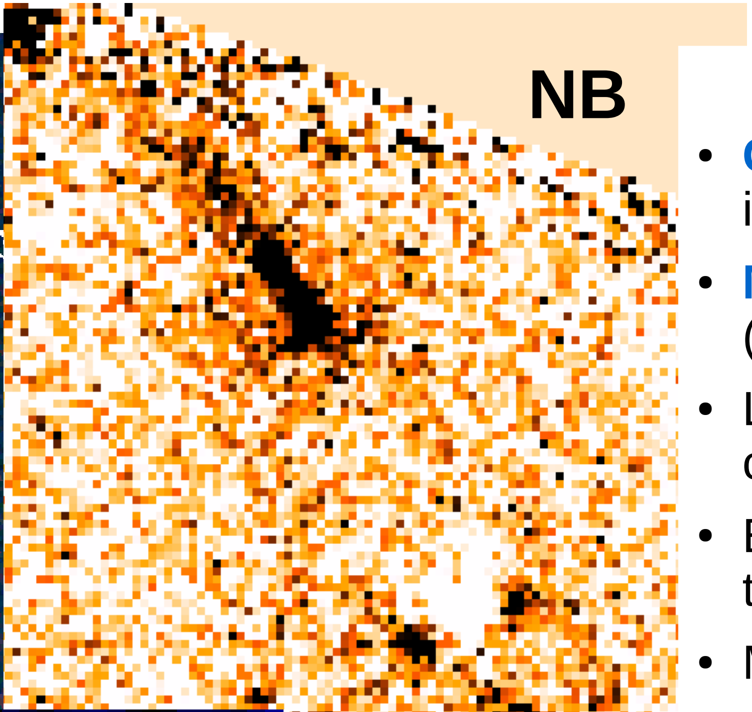
- **Complex system :** 4-5 images
- **Magnification :** ~16 (Ha), 13 (Hb), 6 (Hc)
- Ly alpha decoupled from continuum emission
- EW(Lya) varies across the system
- M(UV) ~ -21.3

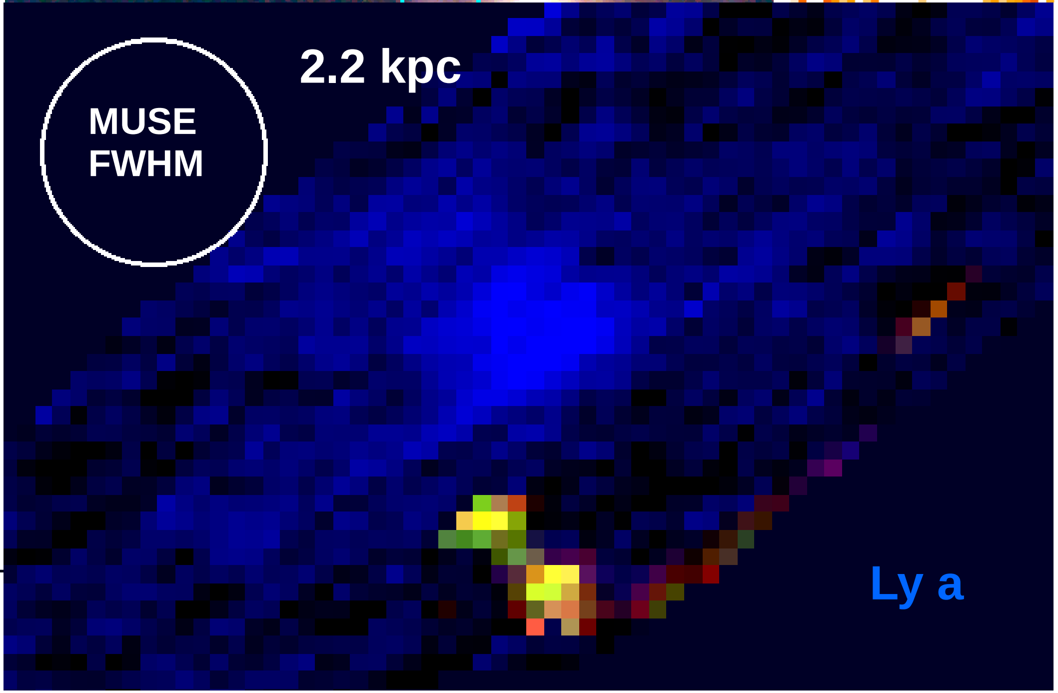


muse
multi unit spectroscopic explorer

A2390 – H3







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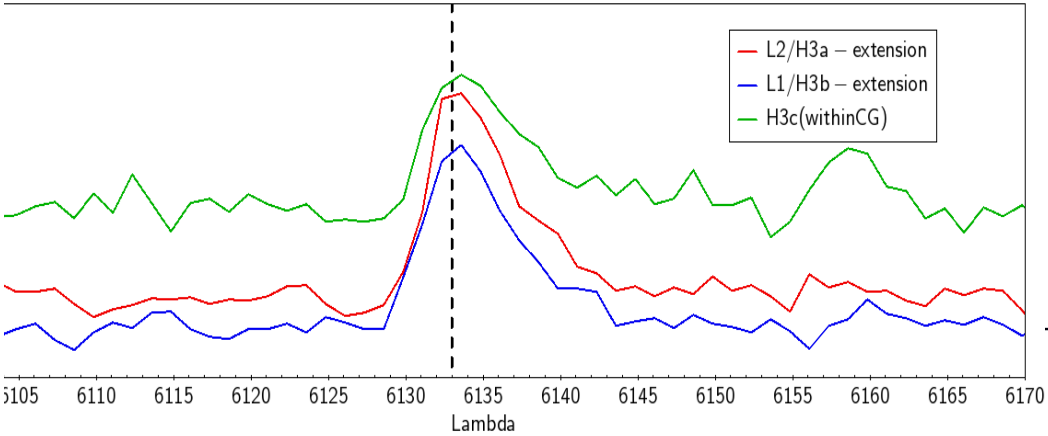
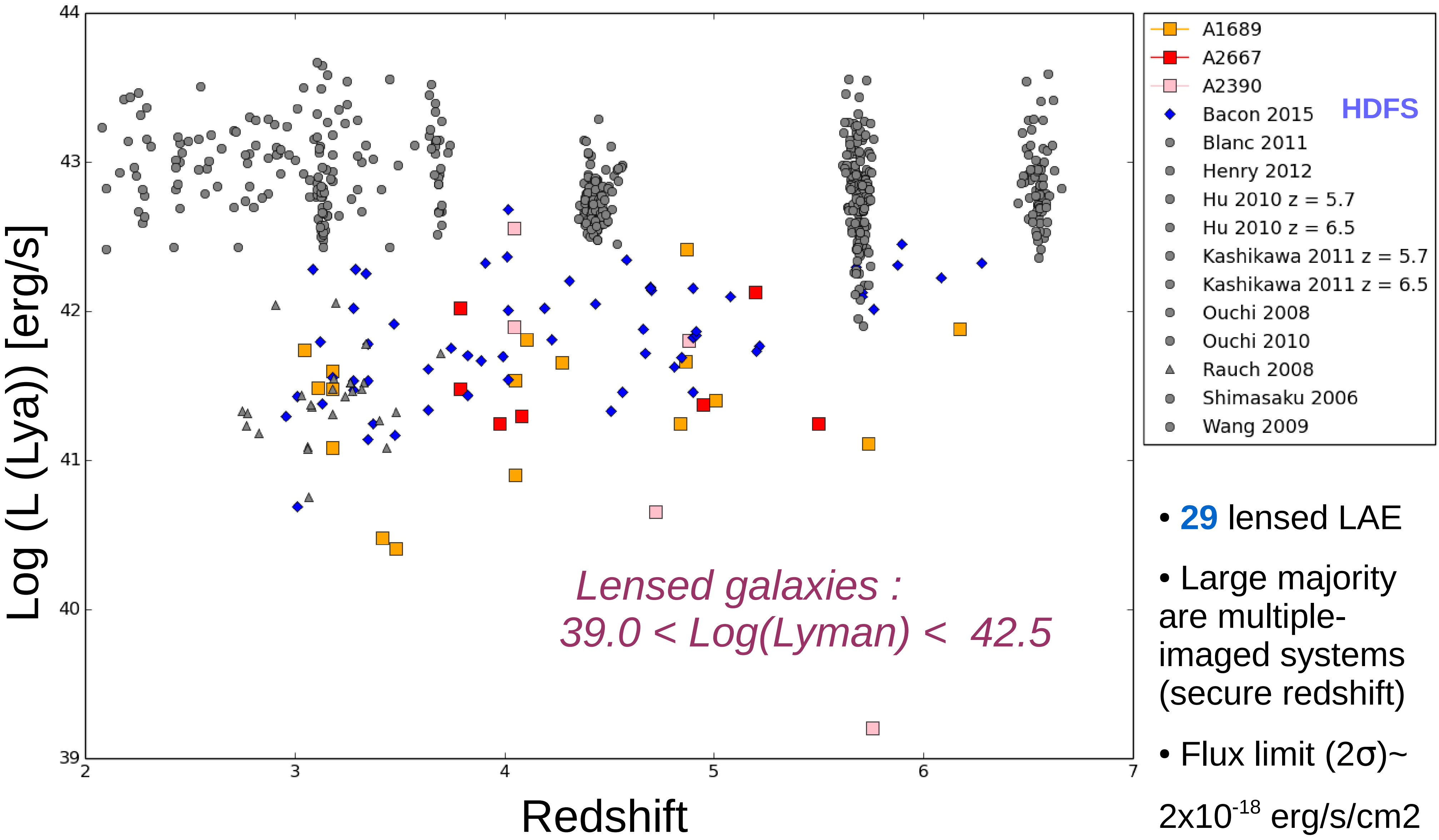


LAE in A1689 + 2390 + A2667



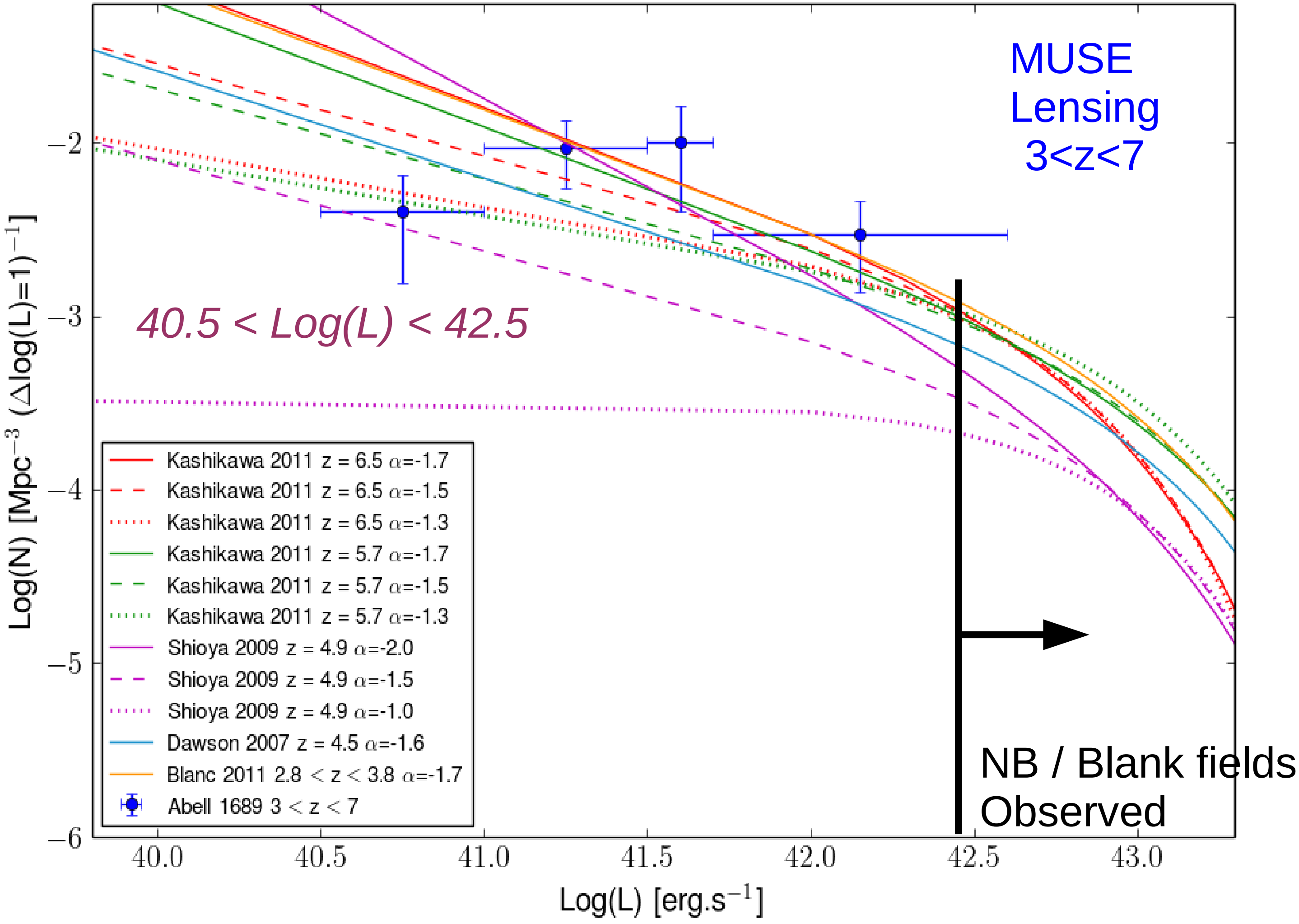
Lensed galaxies :
39.0 < Log(Lyman) < 42.5

- **29** lensed LAE
- Large majority are multiple-imaged systems (secure redshift)
- Flux limit (2σ)~ 2×10^{-18} erg/s/cm2

LF in the field of A1689:

Bina, RP et al. 2016

$\Phi(L)dL = \Phi^*(L/L^*)^{\alpha} \exp(-L/L^*)dL/L^*$



MUSE Lensing 3<z<7

40.5 < Log(L) < 42.5

NB / Blank fields Observed

- MUSE data probe the faint-end region
- Error bars: Poisson + FTF variance
- Poisson statistics dominates the error budget...
- LF sensitive to α
- Good complementary with blank-field surveys.
- Results in A1689 are consistent with a steep slope α < -1.5 (TBC)

Some lessons learned

- Our survey of LAEs at $z \gtrsim 3$ behind lensing clusters with MUSE is sensitive to luminosities ranging between $39.0 < \log(L) < 42.5$ after correction for magnification.
- Some of these systems display extended and/or ex-centered Lya emission wrt the continuum emission. Accounting for this, between ~1/3 and 50% LAE could be not detected in the continuum up to $m \gtrsim 28$
- Given the intrinsically-low luminosities, this sample is particularly sensitive to the slope of the LF towards the faintest-end. The density of sources obtained in this survey is roughly consistent with a steep value of $\alpha < -1.5$ (evolving towards $\alpha < -2$ between z~4 and 7) (see also Drake+16, Bina+ in preparation).

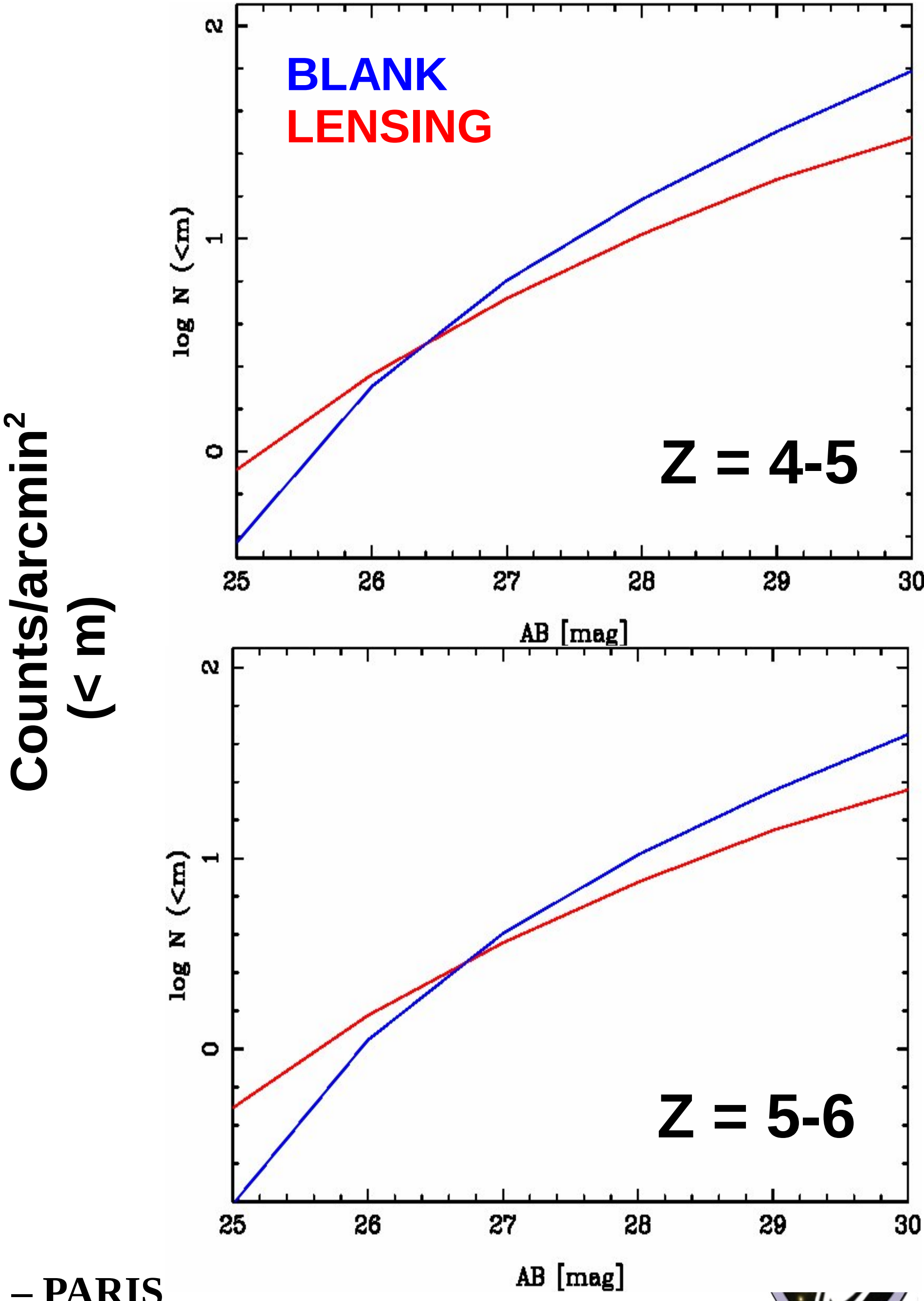
… TO BE CONTINUED !

“BLIND”/”POINTED” Surveys with MOONS / VLT :

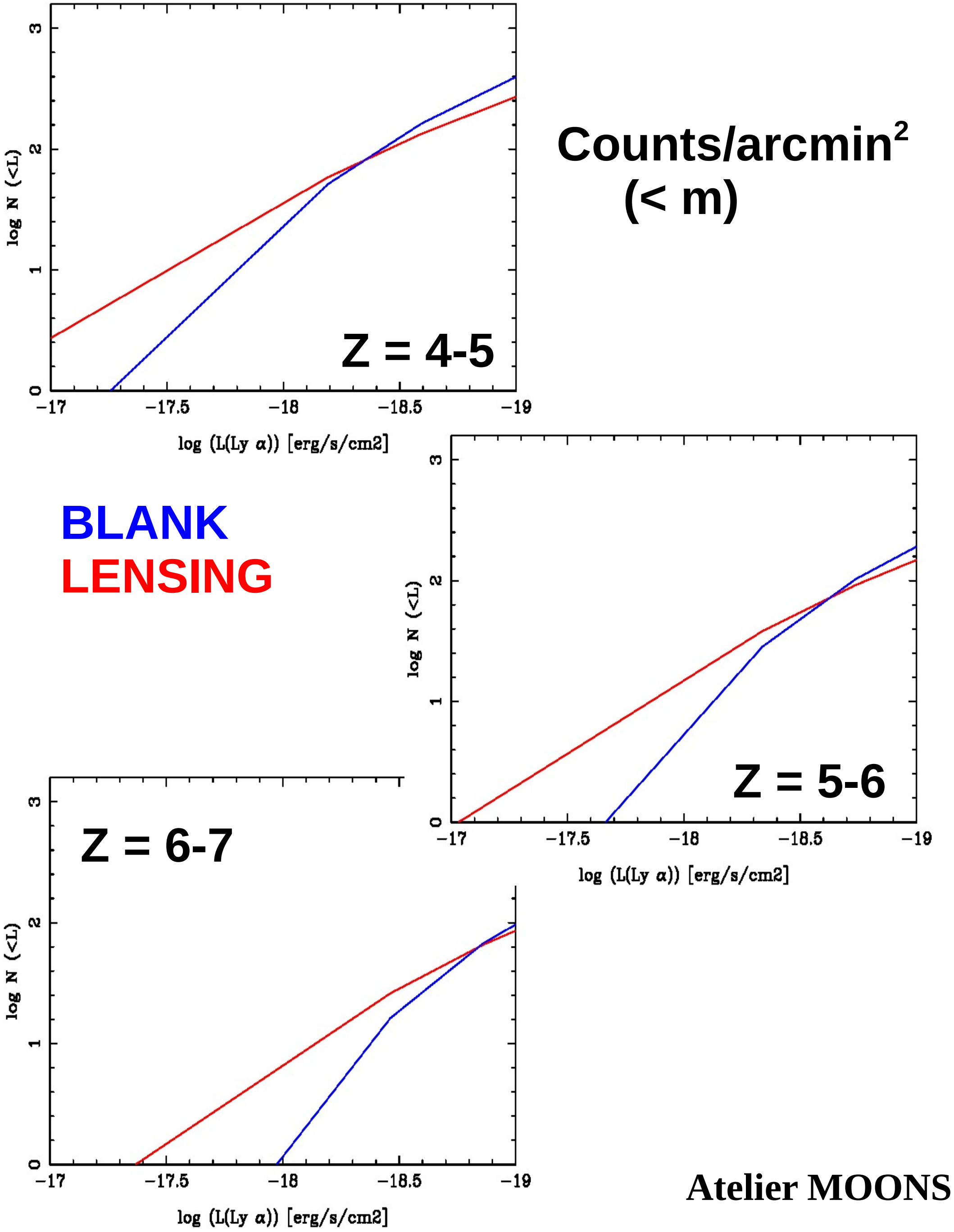
- **“Pointed” survey** up to H~24 (maximum ~25) of photometrically selected LBGs
- Counts expected with H(AB)<25 & 26, MOONS FOV = 500arcmin^2

Z	N / deg^2	MOONS FOV	
6.5-7.5	6 - 16	~2	H~25
7.5-8.5	2 - 11	<~1	
8.5-9.5	<~1	<~1	
6.5-7.5	117 - 153	16-21	H~26
7.5-8.5	36 - 88	5 - 12	
8.5-9.5	0 - 5	<~1	

- Photometric selection based on “deep” photometry (H>26) is needed !



“BLIND”/”POINTED” Surveys with MOONS / VLT :



- **“Blind” survey** looking for serendipitous detections of LAEs within the “sky” fibers (stable!)
- 0.6µm-1.8µm => Lya between z~4-12
- ~500 “sky” fibers <=> a “long-slit” equivalent of 1.05” x 8.8 arcmin / exposure (~0.154 arcmin^2 / exposure => 1 arcmin^2 in 7 exp.)
- Expected / 1 “long” exposure:

z	Mpc^3/exp	MOONS	Ref. *
3 - 6.7	**1600**	**9**	**Drake+16** *
6.5-7.5	**336**	**>0.04?**	**Kashikawa+11**
7.5-8.5	**303**	**?**	
8.5-9.5	**274**	**?**	

* F ~ 5x10^{-18} to 10^{-17} erg/s/cm2

Thanks!