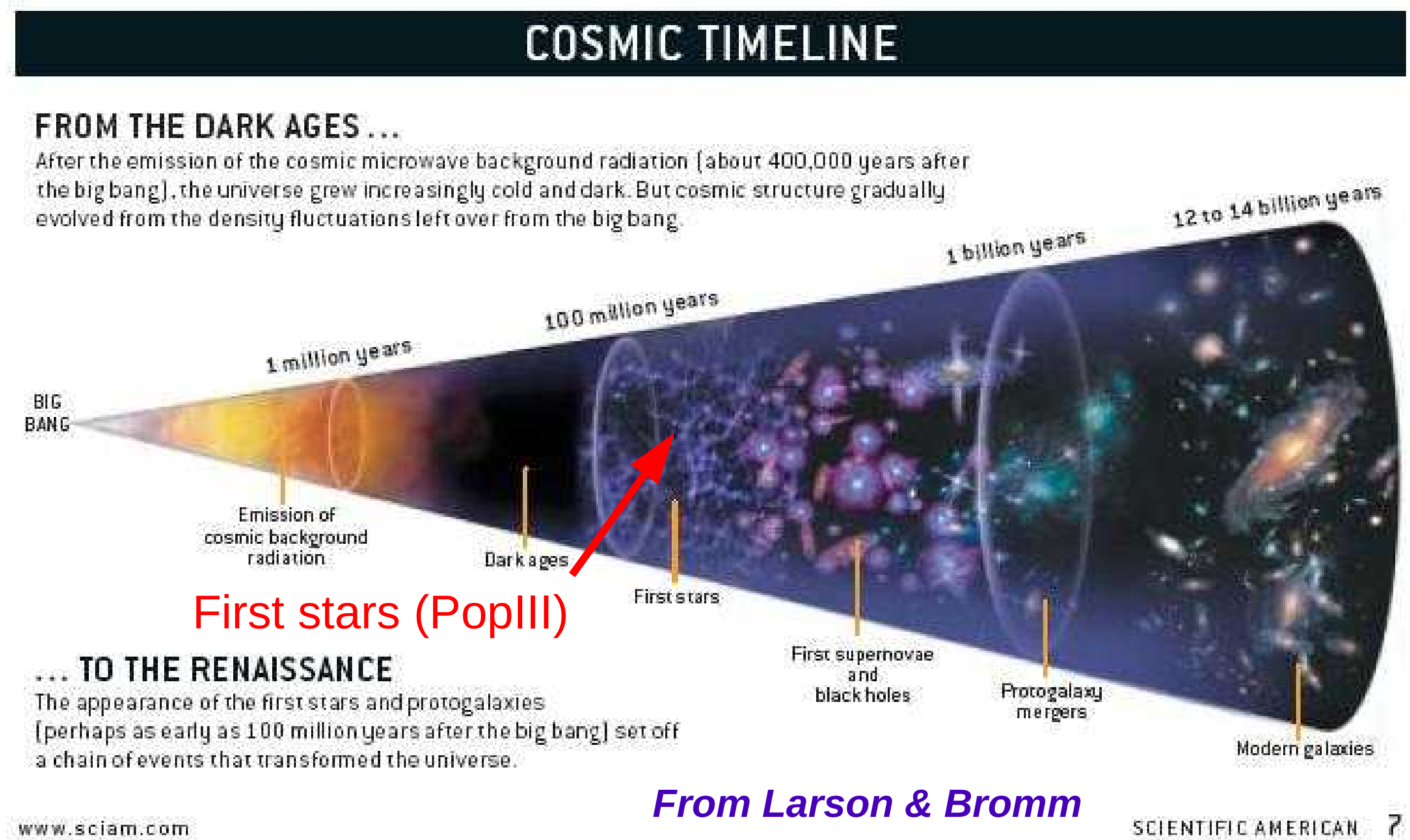
High-z Galaxies & Reionization

R. Pelló (IRAP / GAHEC Group)

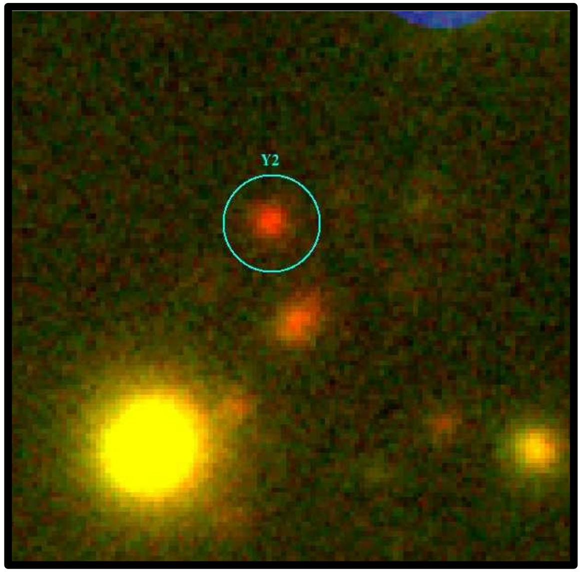
The formation of the first stars & galaxies :

- CMB :
  - the universe started out simple, homogeneous and isotropic
  - small fluctuations described by linear perturbation analysis
- Present-day universe : clumpy & complicated
- The formation of the first bounded objects marks the transition from simplicity to complexity …



From Larson & Bromm

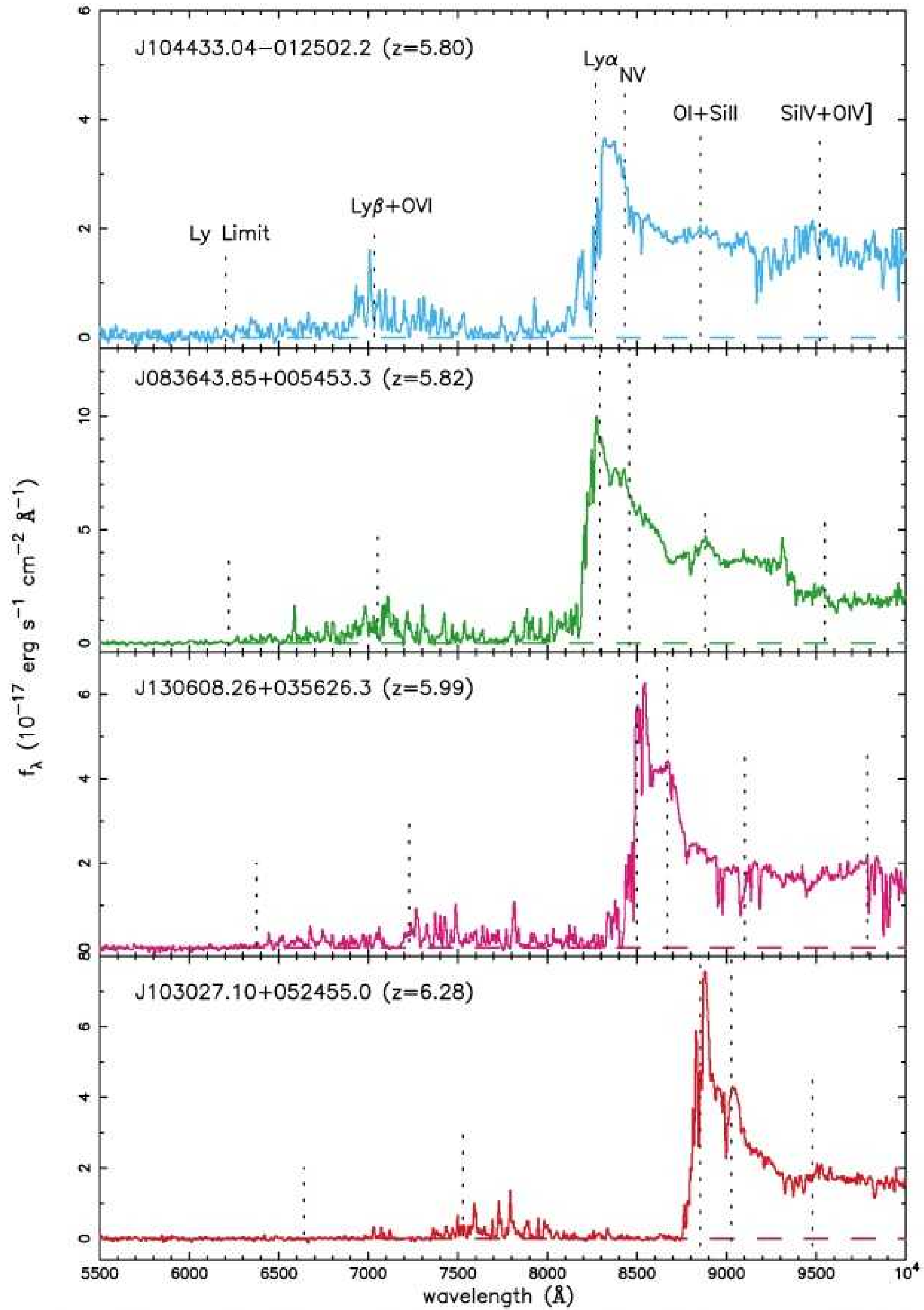
High-z galaxies & Reionization



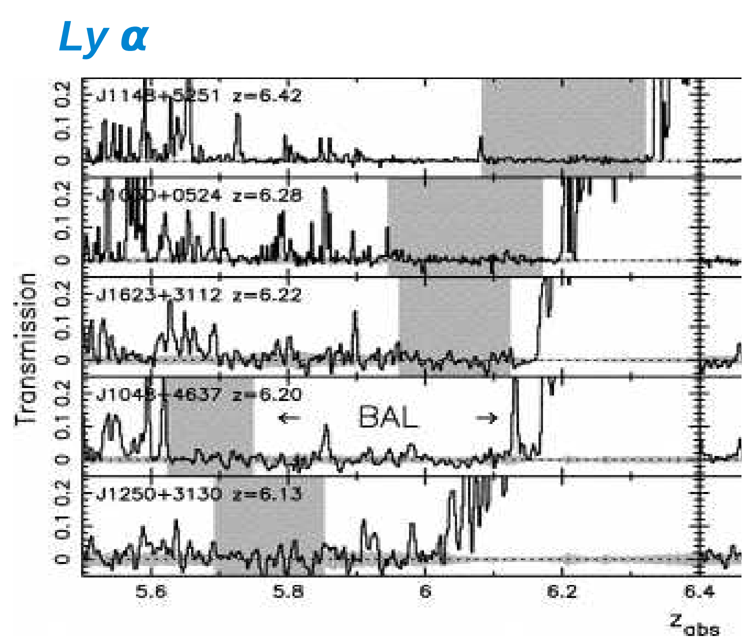
- Present constrains on the Reionization epoch & galaxy formation scenarios
- Observational approaches : identification and characterization of the galaxies
- Present results … and open issues
- Discussion. Perspectives

The end of the reionization

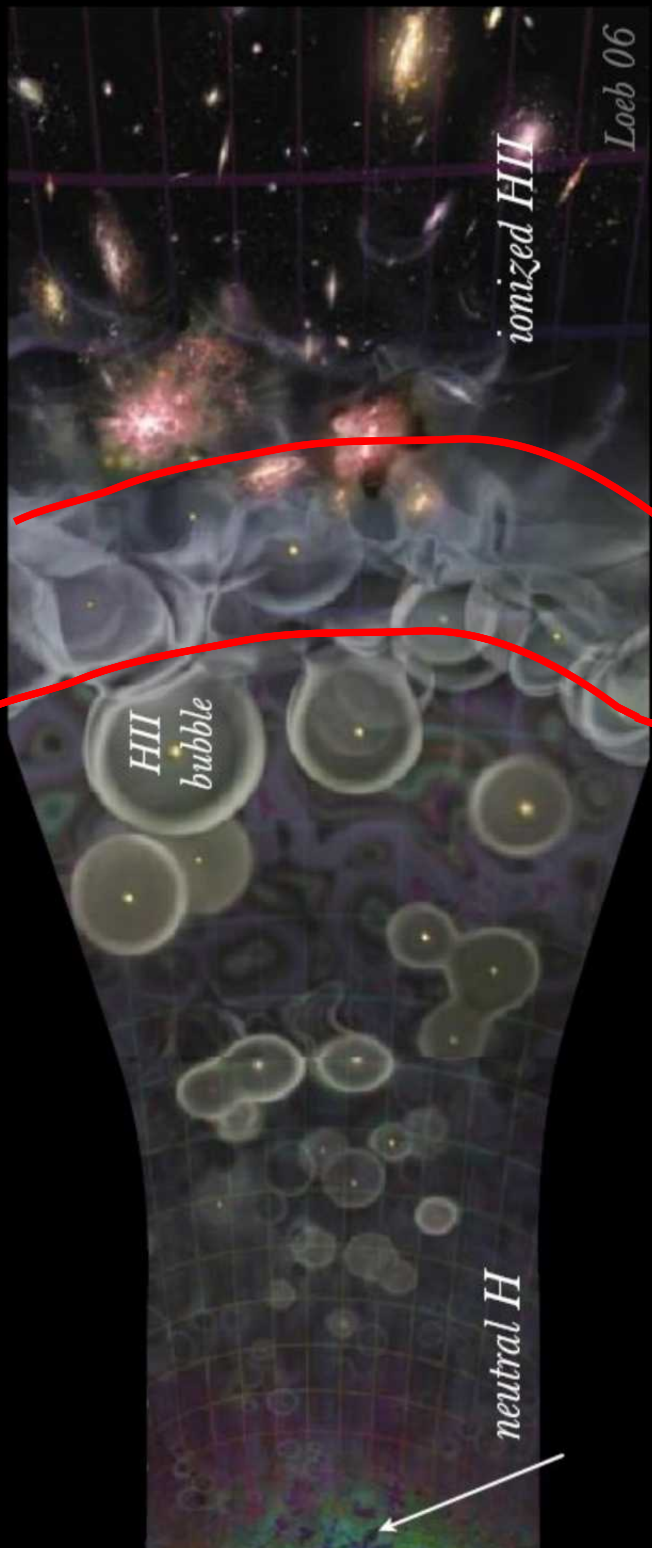
- Evolution in the optical depth of Lyman absorption series observed in high-z quasars tells us about the end of the reionization (e.g. **Fan et al. 2000 to 2006**)
- Increase in the optical depth to Lyman alpha photons (Gunn & Peterson 1965) at high-z



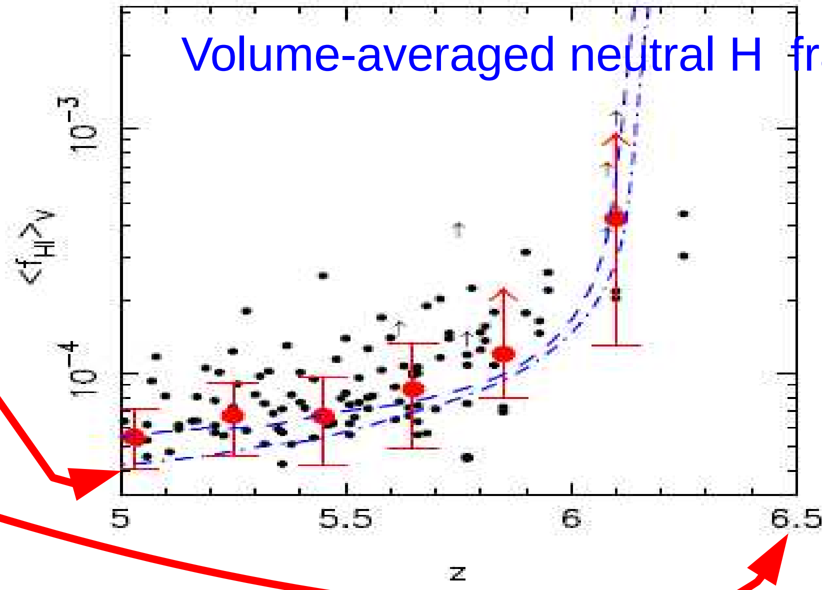
ptical spectra of $z \gtrsim 5.8$ quasars observed with Keck/ESI in the observed frame. The spectra have been smoothed to 4 Å p
the observed z-band flux. The spectrum of SDSS 1044−0125 has been taken from Fan et al. (2000). In each spectrum, the
mission lines, as well as the Lyman limit, are indicated by the dashed lines.



Fan et al 2006



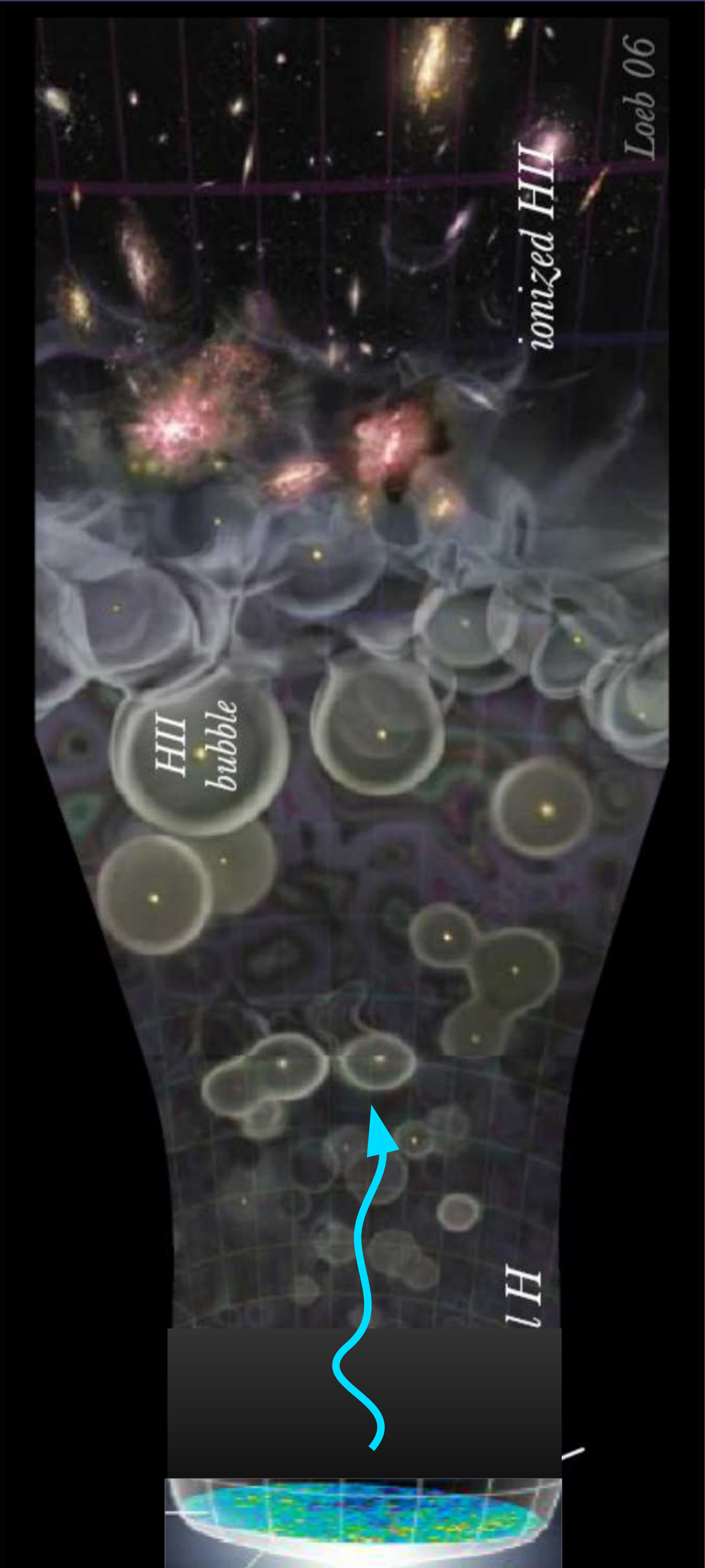
The end of the reionization



Fan et al 2006

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

- Complete absorption even for a tiny neutral fraction (~10^{-4}, whereas the present value is ~10^{-5}) ==> this test is only sensitive when the IGM is “almost” ionized, and saturates for higher neutral fractions. Large line of sight variance is also observed!



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

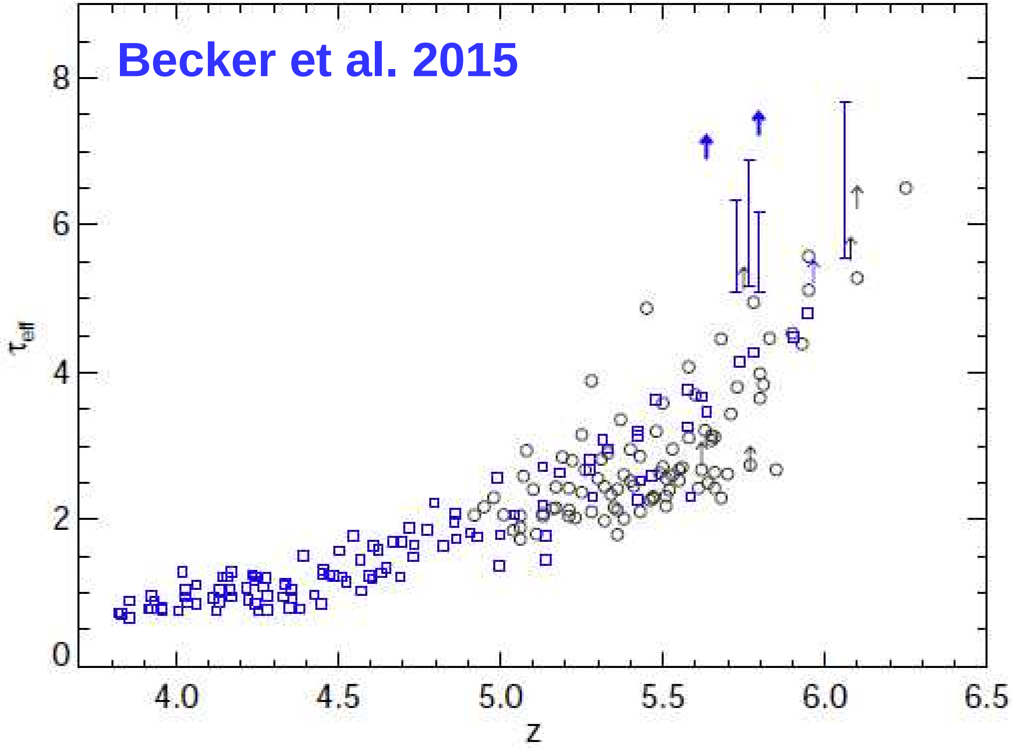
- Uncertainties remain... The actual value depends on the reionization process ("instantaneous" versus more complex scenarios).

(see talk by M. Langer & M. Douspis)

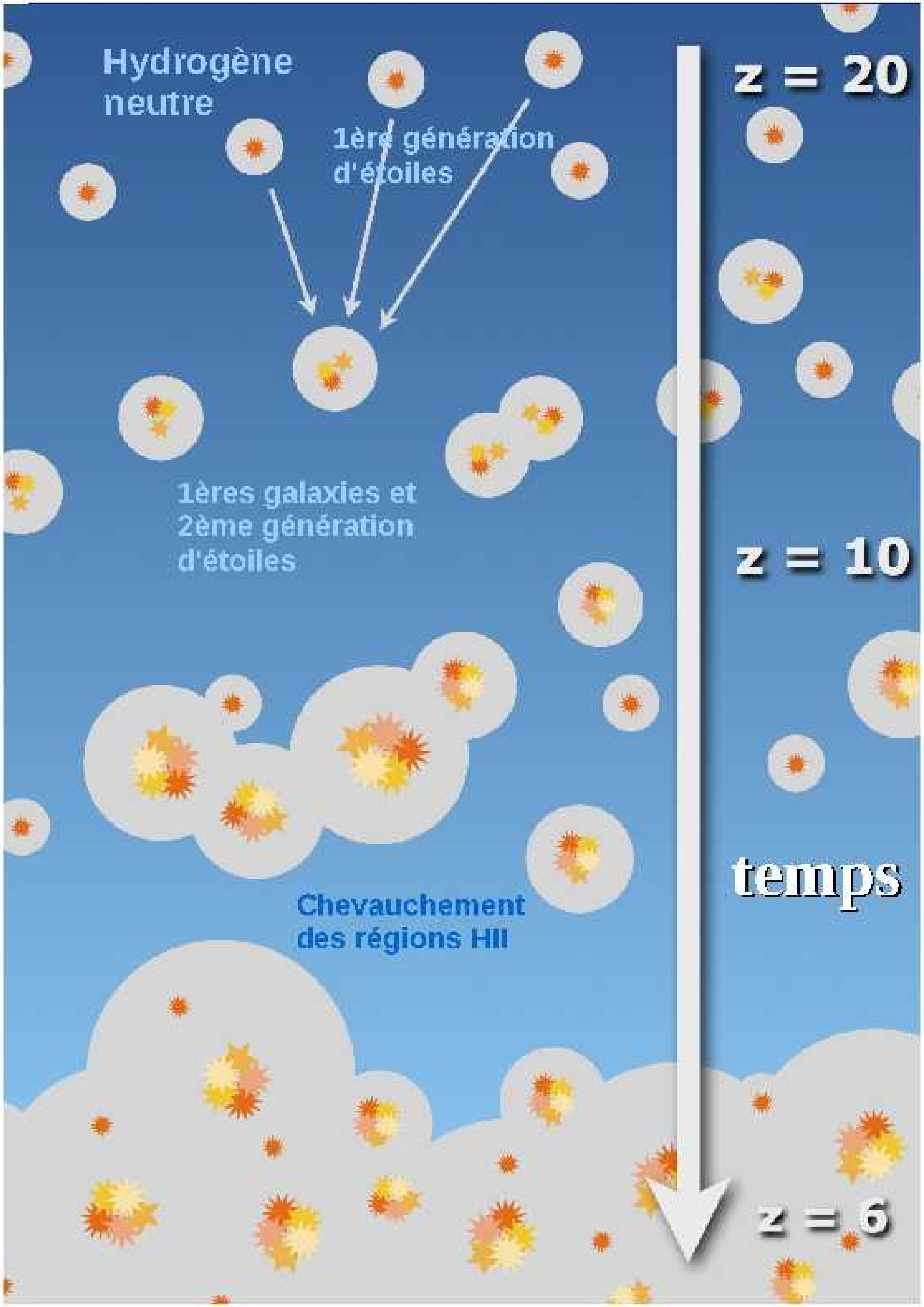
Sources of the reionization and actual process

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

- Galaxies
- AGNs
- GRB contribution?



- When and how reionization occurred?
- Evidences for a “patchy” H reionization (inhomogeneous at ~100 Mpc scale; see Becker et al. 2015)
- A gradual process? Multiple phases?



First stars / galaxies

Gas infall & cooling in DM halos

- **DM dominates gravity**
- **The baryonic mass accreted into a final DM potential well is ~ the Jeans mass**
- **Two independent mass thresholds for SF : the Jeans mass (accretion) and the cooling mass (fragmentation into stars) => lower limit M ~10^4 solar masses at z~20**

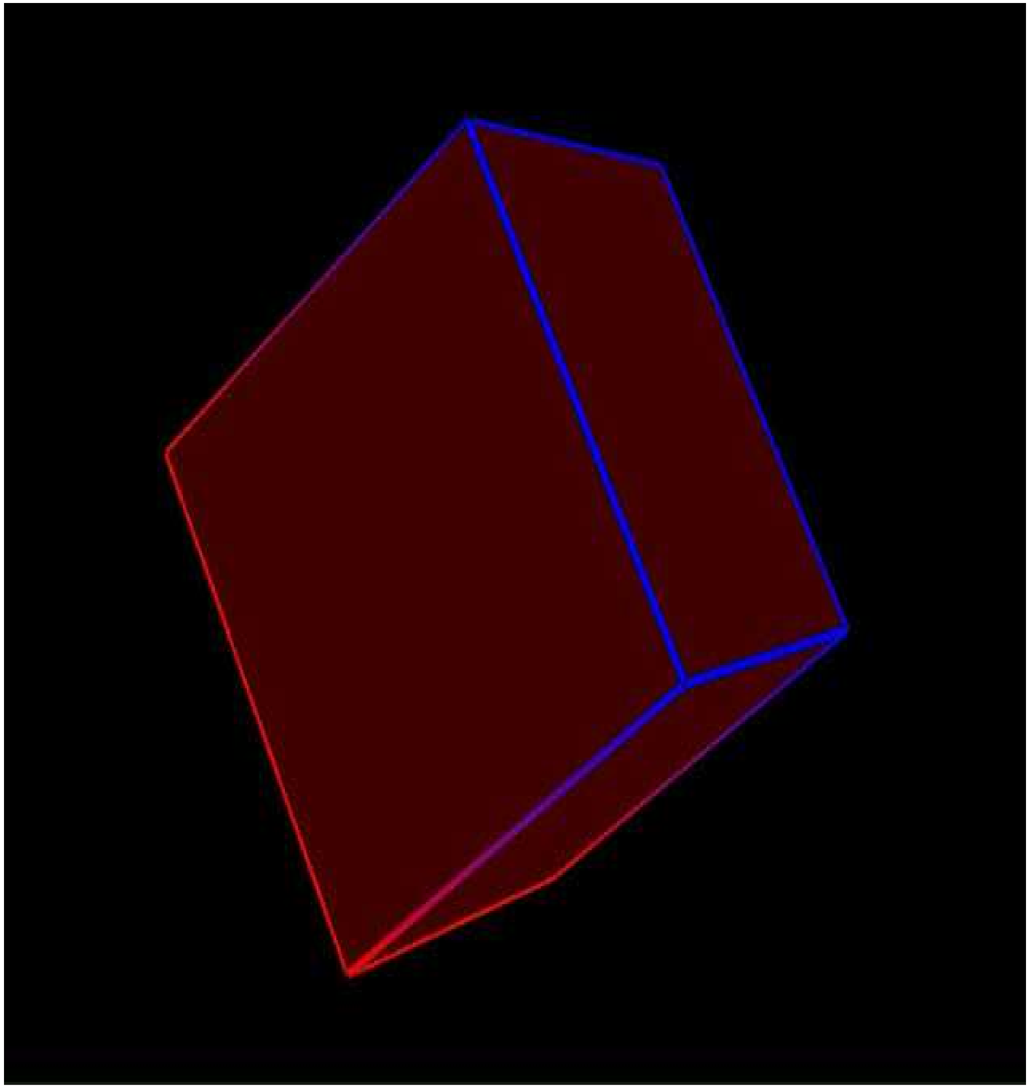
First stars : z~20

- **Formed in mini-halos (10^6 solar masses DM). Cooling : molecular H (H_2)**

First galaxies : z~10

- **Formed in larger halos (~10^8 solar masses). Cooling : atomic hydrogen**

First stars / galaxies / Reionization



Simulations by N. Gnedin

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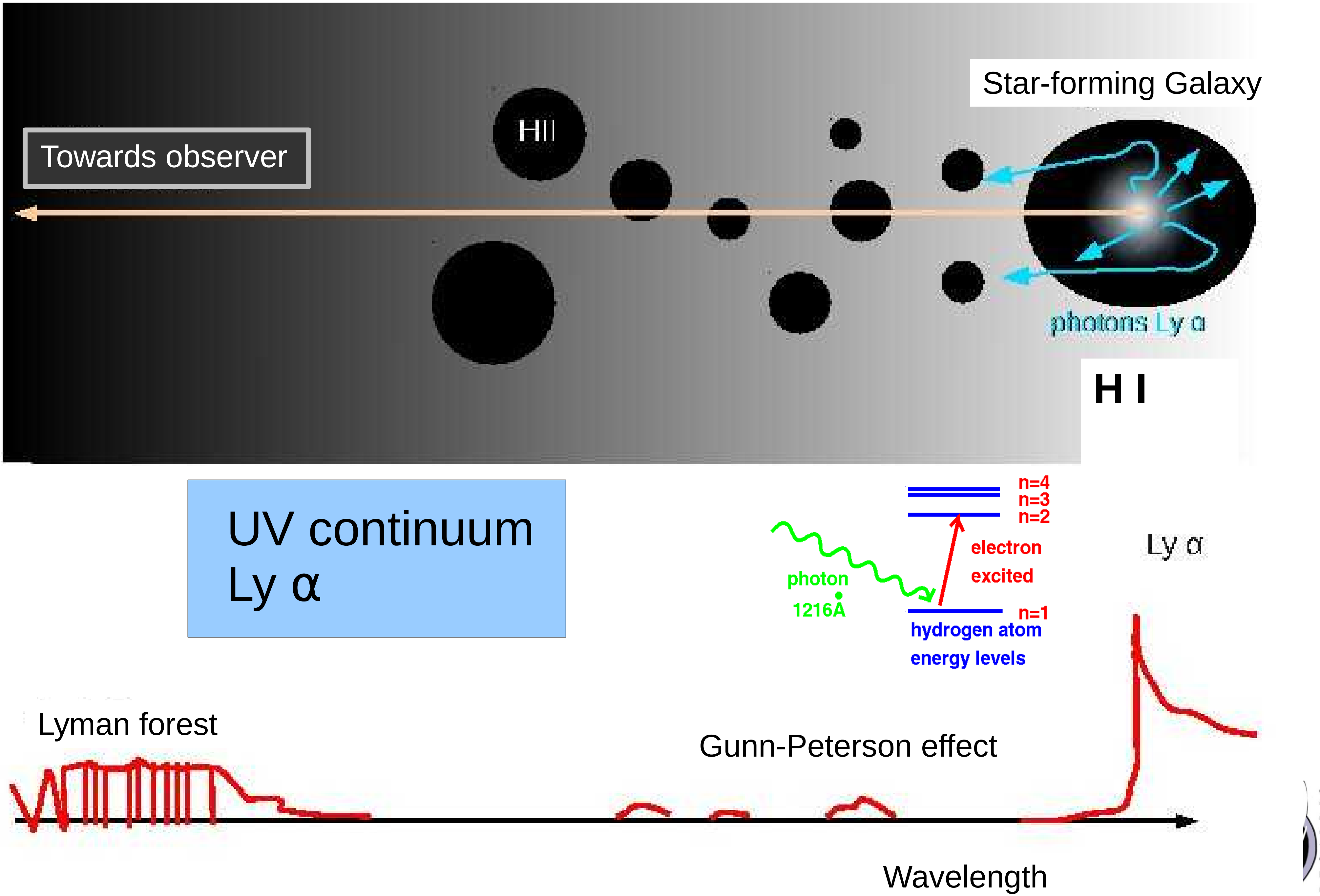
Observable properties of the "first" galaxies



Observable properties of the “first” galaxies

- Two main signatures susceptible to be used for the detection of star-forming galaxies et (extremely) high-z:

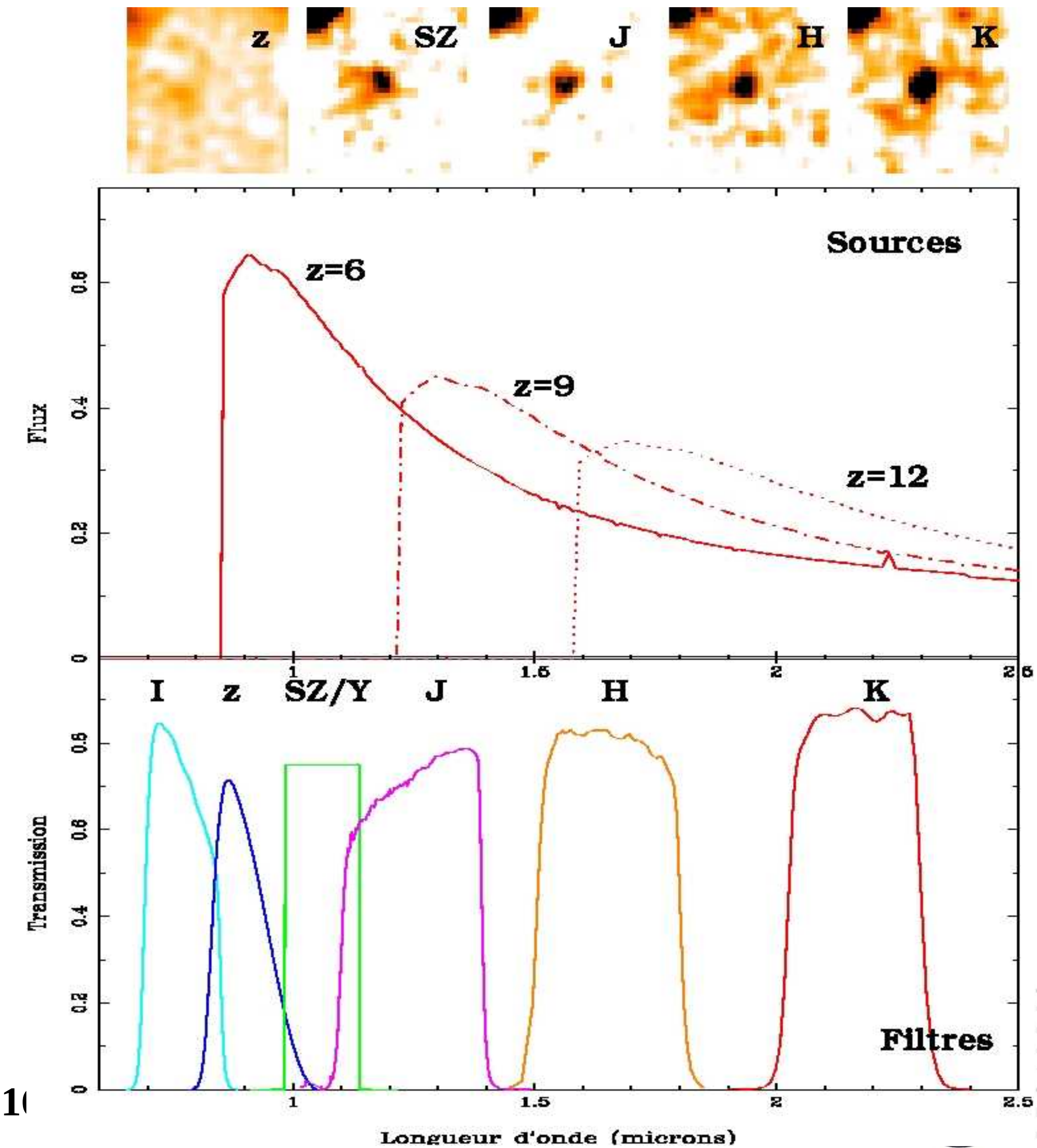
➔ Lyman break signature (LBG) : “drop-out” due to interstellar & intergalactic scattering by neutral hydrogen

- ✓ Color-color diagrams or photometric redshifts
- ✓ Near-IR coverage is needed

➔ Lyman alpha emission (LAE)

- ✓ Either wide-field coverage (NB filters) or efficient IFU facilities are needed.

Spectroscopy is mandatory !



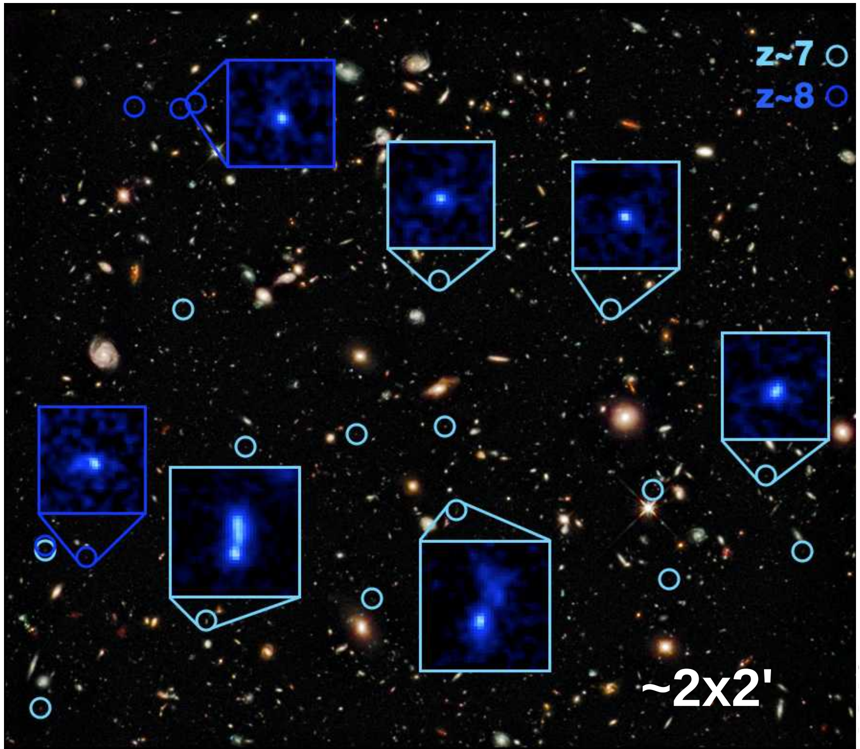
Present Surveys

- **Extremely deep Surveys** combining optical+near-IR data : HUDF09, UKIDSS Ultra Deep Survey, GOODS, CANDELS, Extended Groth Strip, Chandra Deep Field, …
- Multi-wavelength data (HST, Spitzer,...)
- High-z samples are "faint", typically m~28-29 at z~7-8

Bouwens et al. 2010,
Oesch et al. 2010
See also HUDF09 web site

+ cluster lenses (e.g. CLASH SURVEY & Frontier Fields)

- Spectroscopic follow up is difficult with 8-10m class telescopes! The situation is rapidly evolving with the arrival of multi-object NIR facilities (e.g. KMOS/VLT or EMIR/GTC) … for the brightest candidates !

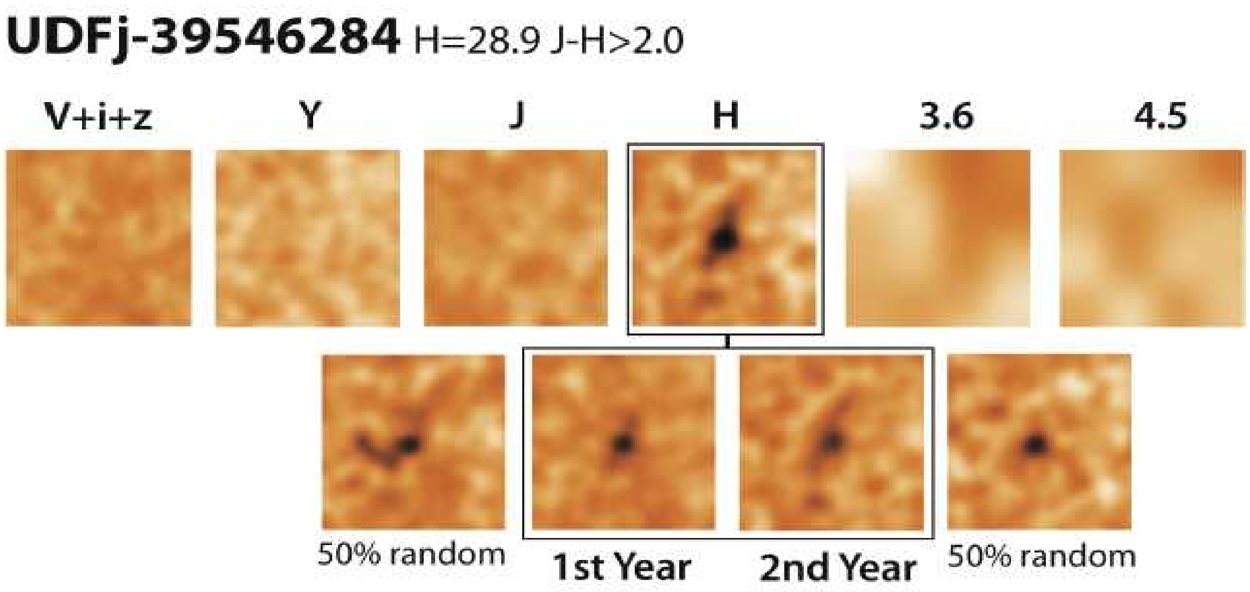


HUDF09 WFC3/IR Image with z~7 and z~8 Galaxies

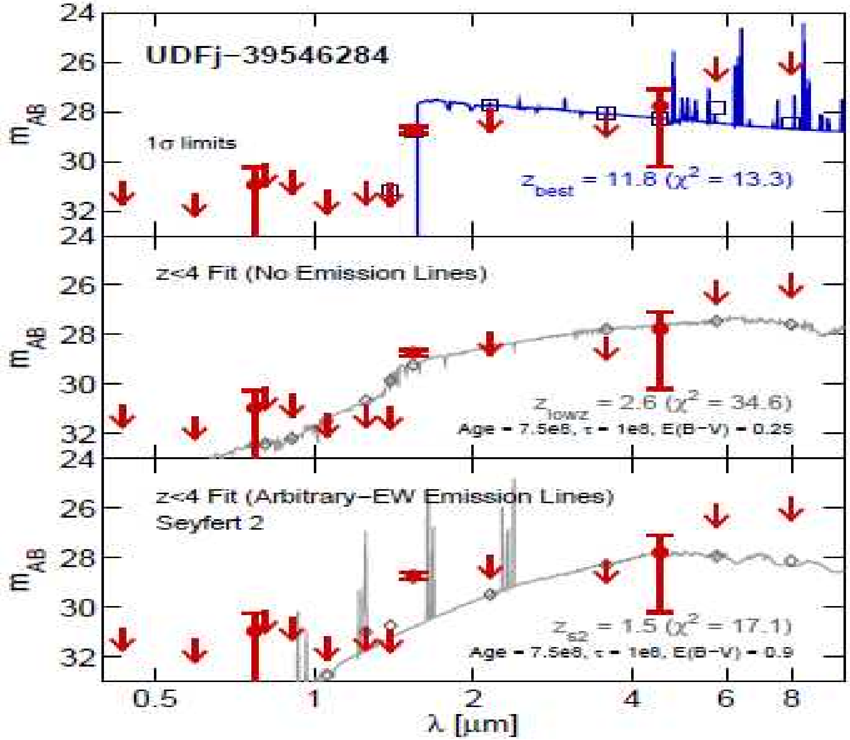
Credit: NASA, ESA, G. Illingworth, R. Bouwens (University of California, Santa Cruz), and the HUDF09 Team.

Photometric candidates

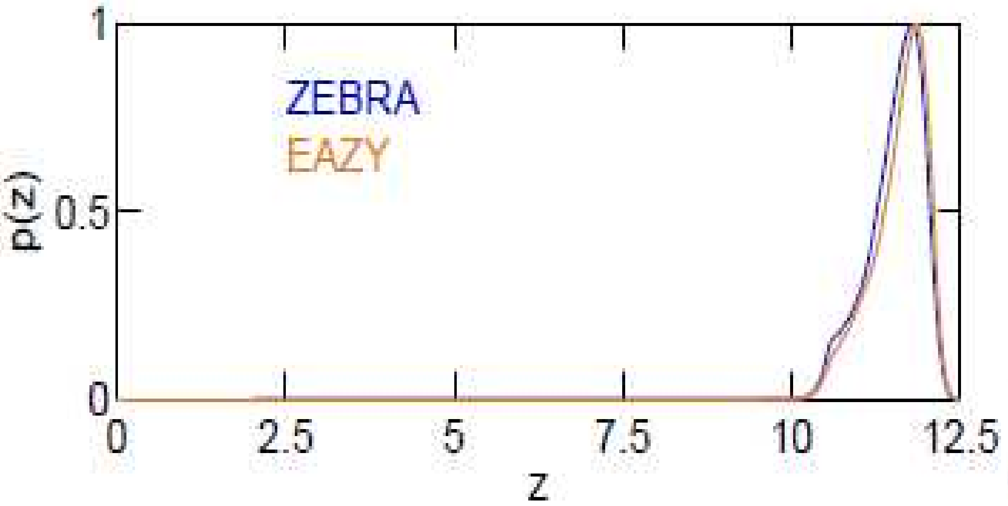
Bouwens et al. 2011



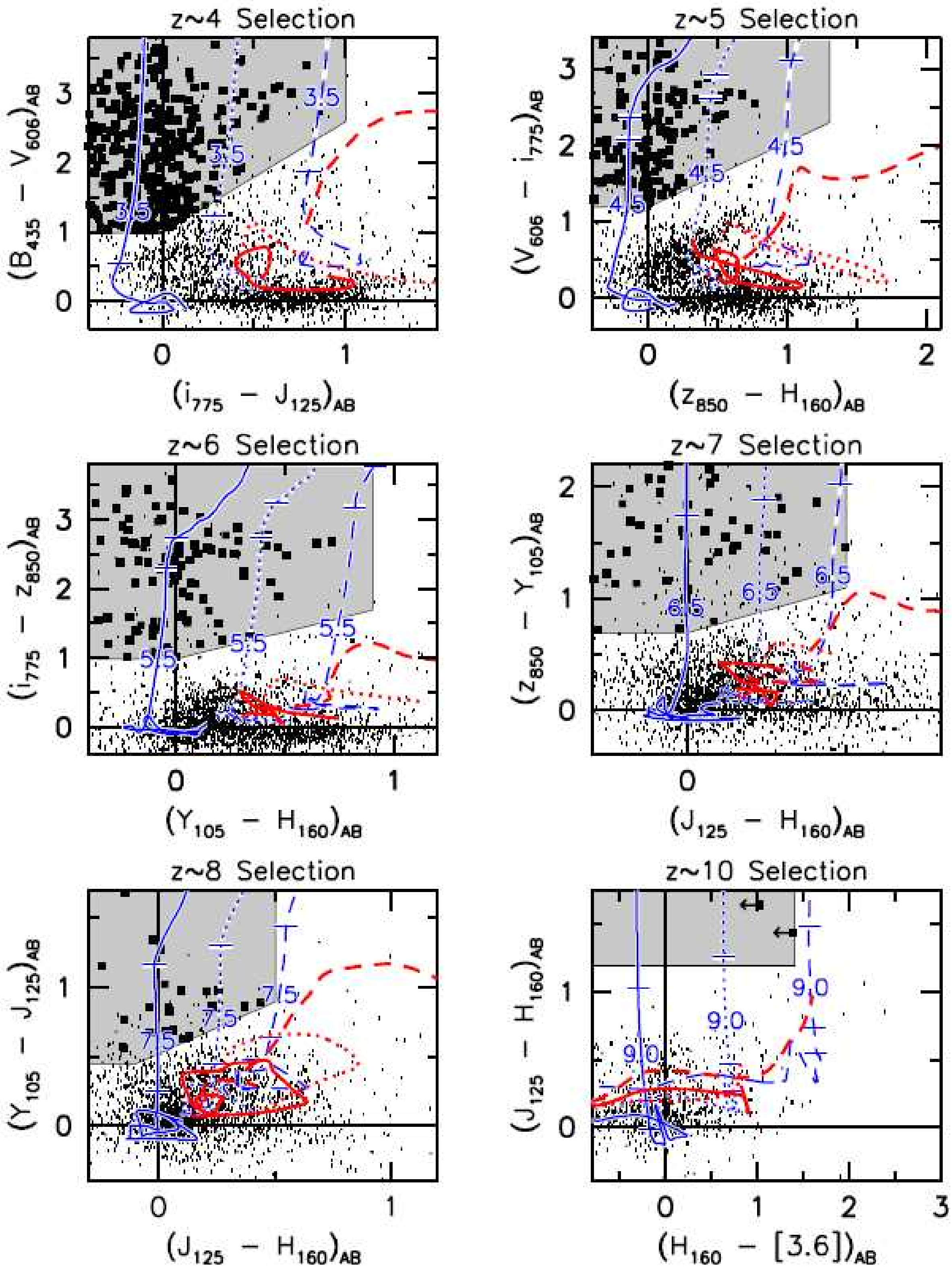
Z~10 candidate in the HUDF09



Bouwens et al. 2013 (revisited)
+ Brammer et al. 2013 (tentative redshift)



LBG Surveys : UV Luminosity Function

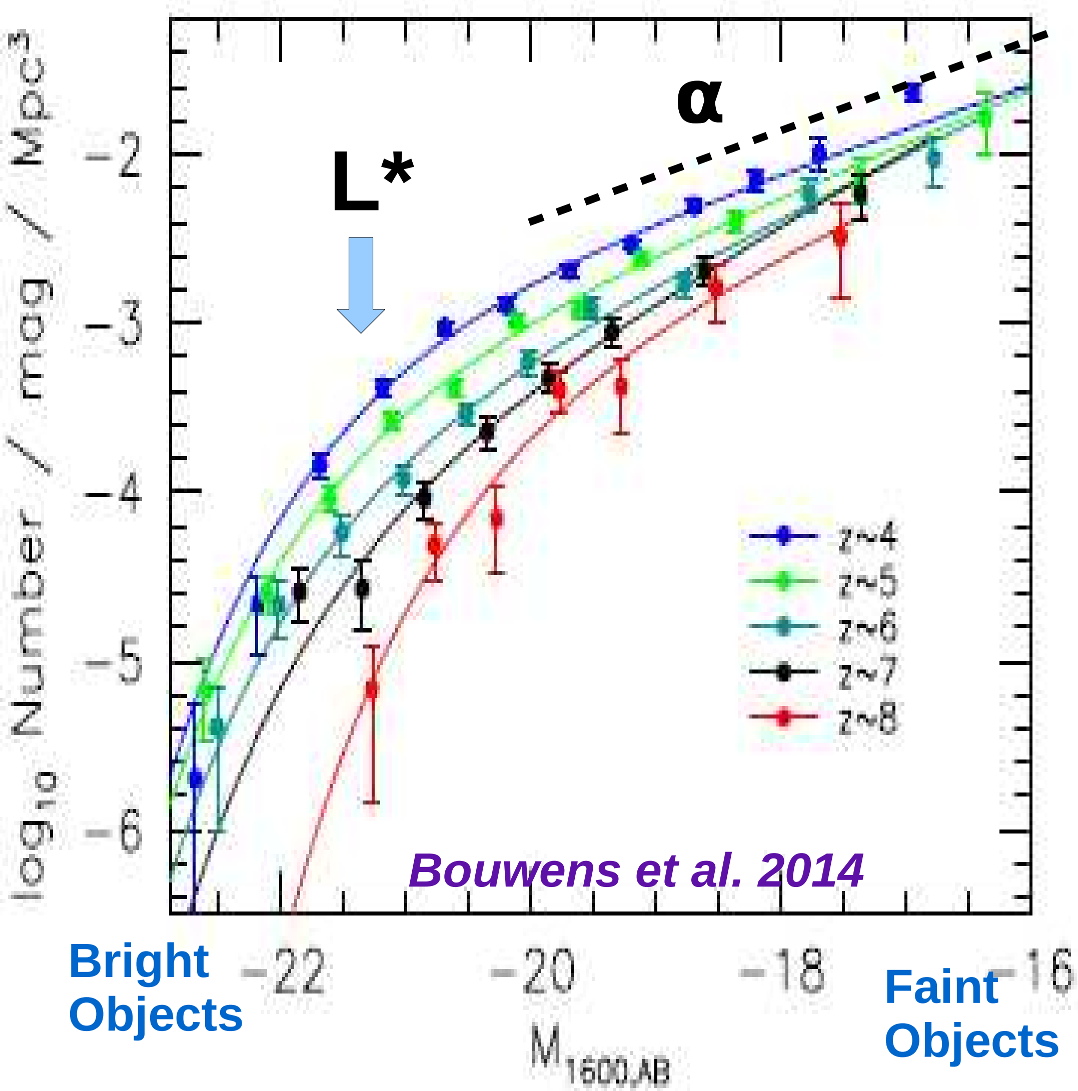


- HST Legacy surveys :
  - ➔ CANDELS,
  - ➔ HUDF09,
  - ➔ HUDF12,
  - ➔ ERS
  - ➔ BORG/HIPPIES
- ~100 arcmin2

Bouwens et al. 2014

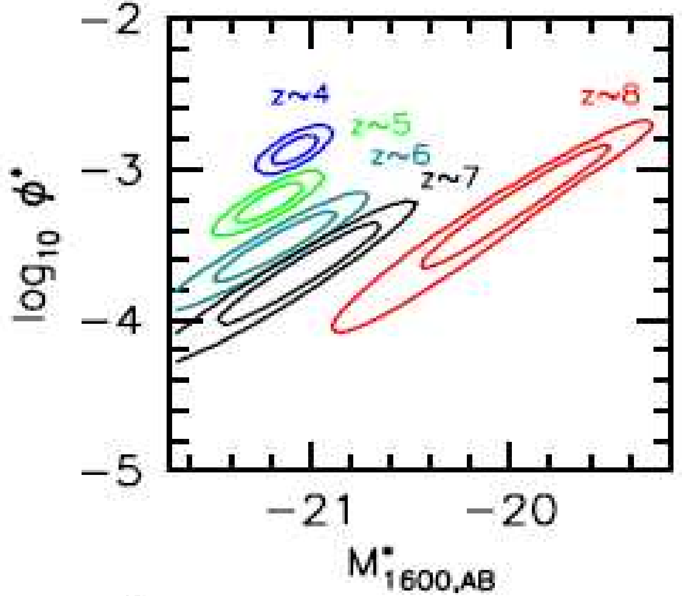
LBG Surveys: Luminosity Function

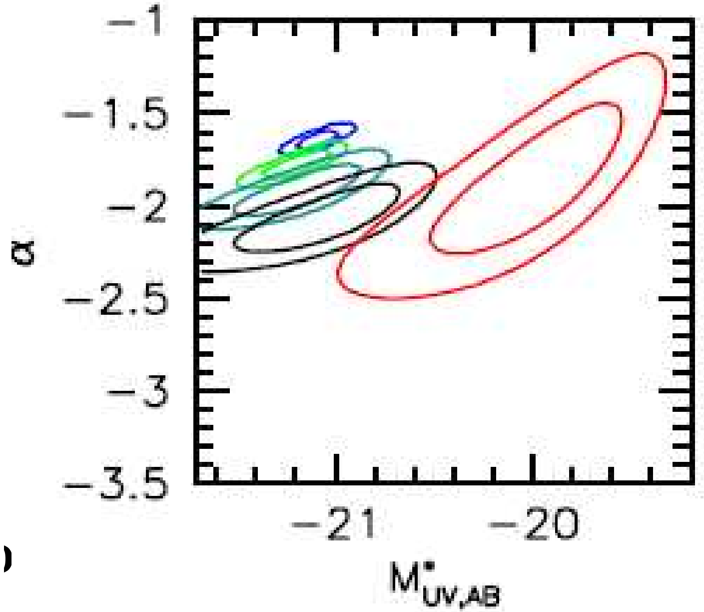
$$\Phi(L)\,dL = n_*\left(\frac{L}{L_*}\right)^{\alpha} exp\left(-\frac{L}{L_*}\right)\,d\left(\frac{L}{L_*}\right)$$



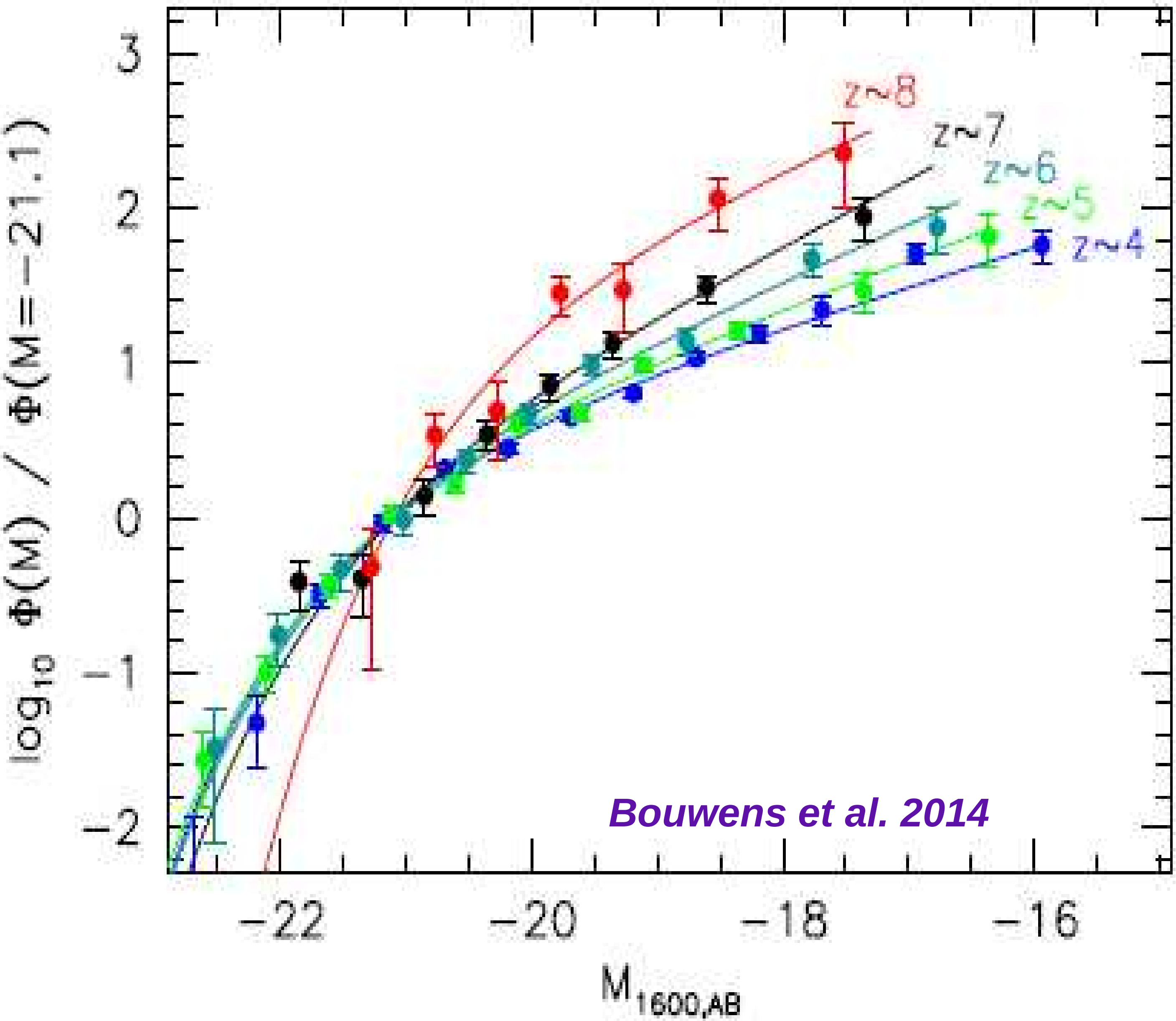
Bright Objects

Faint Objects

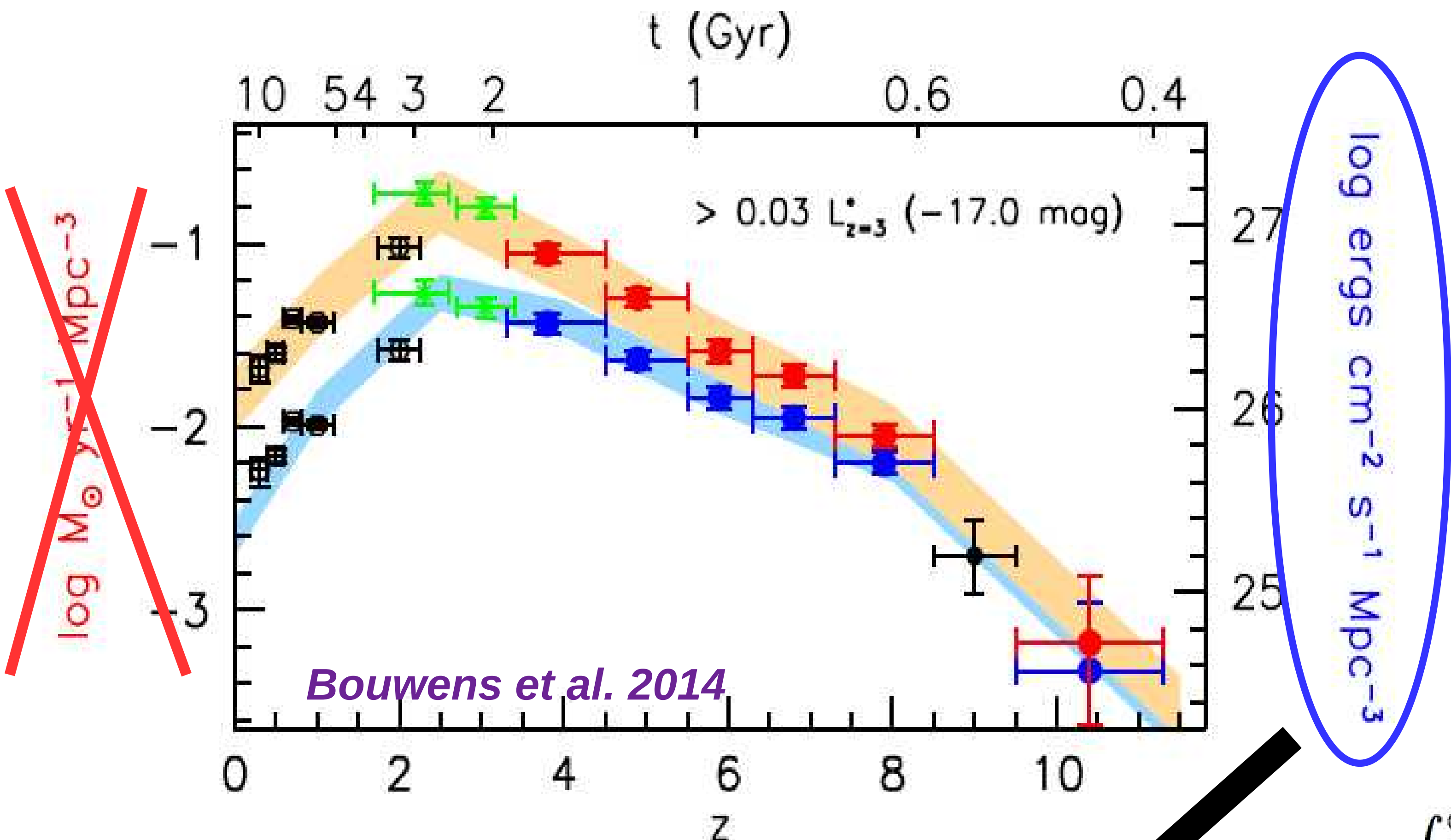




LBG Surveys: Luminosity Function



The slope of the LF becomes steeper



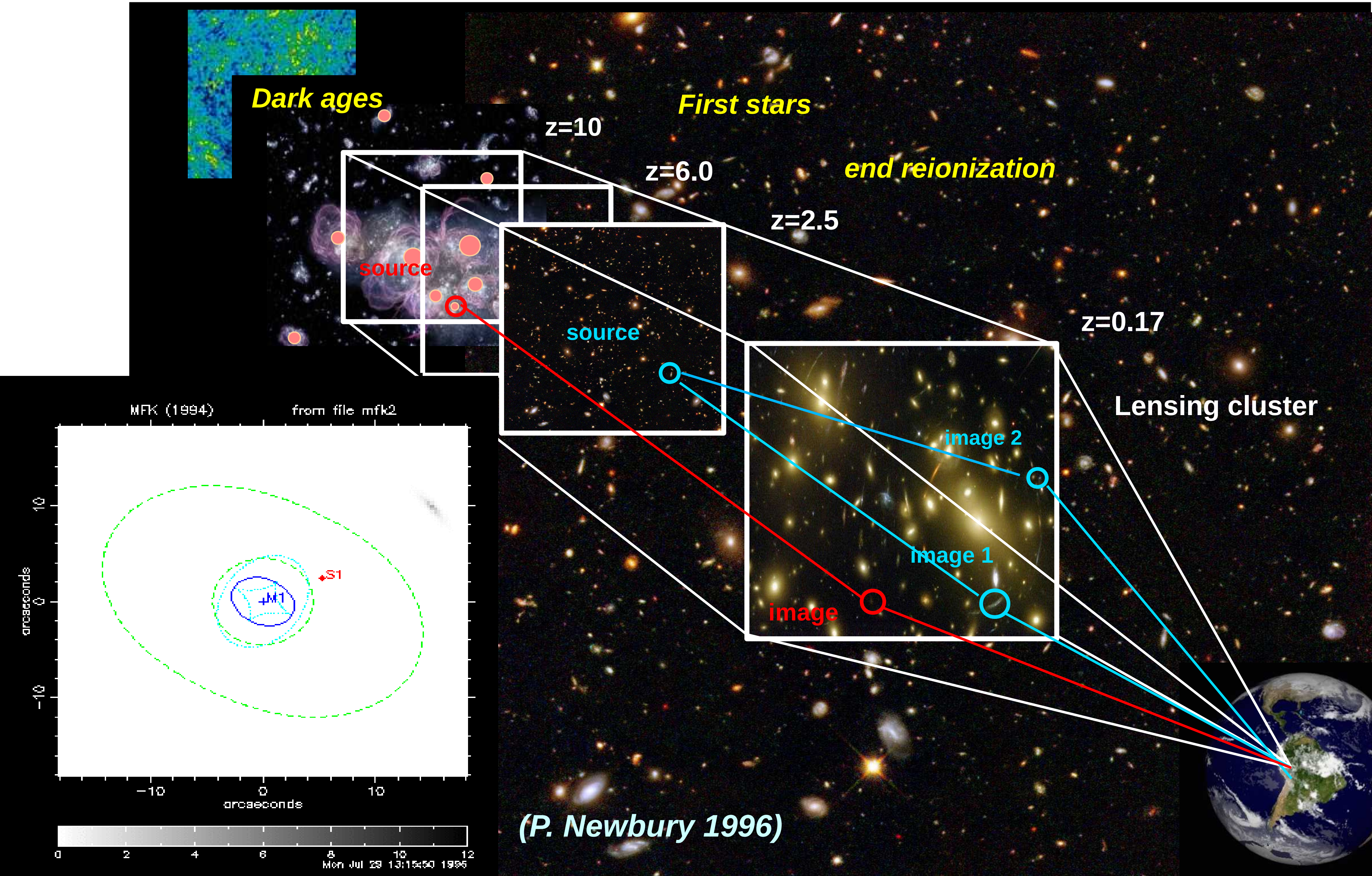
Evolution on the density of UV photons

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

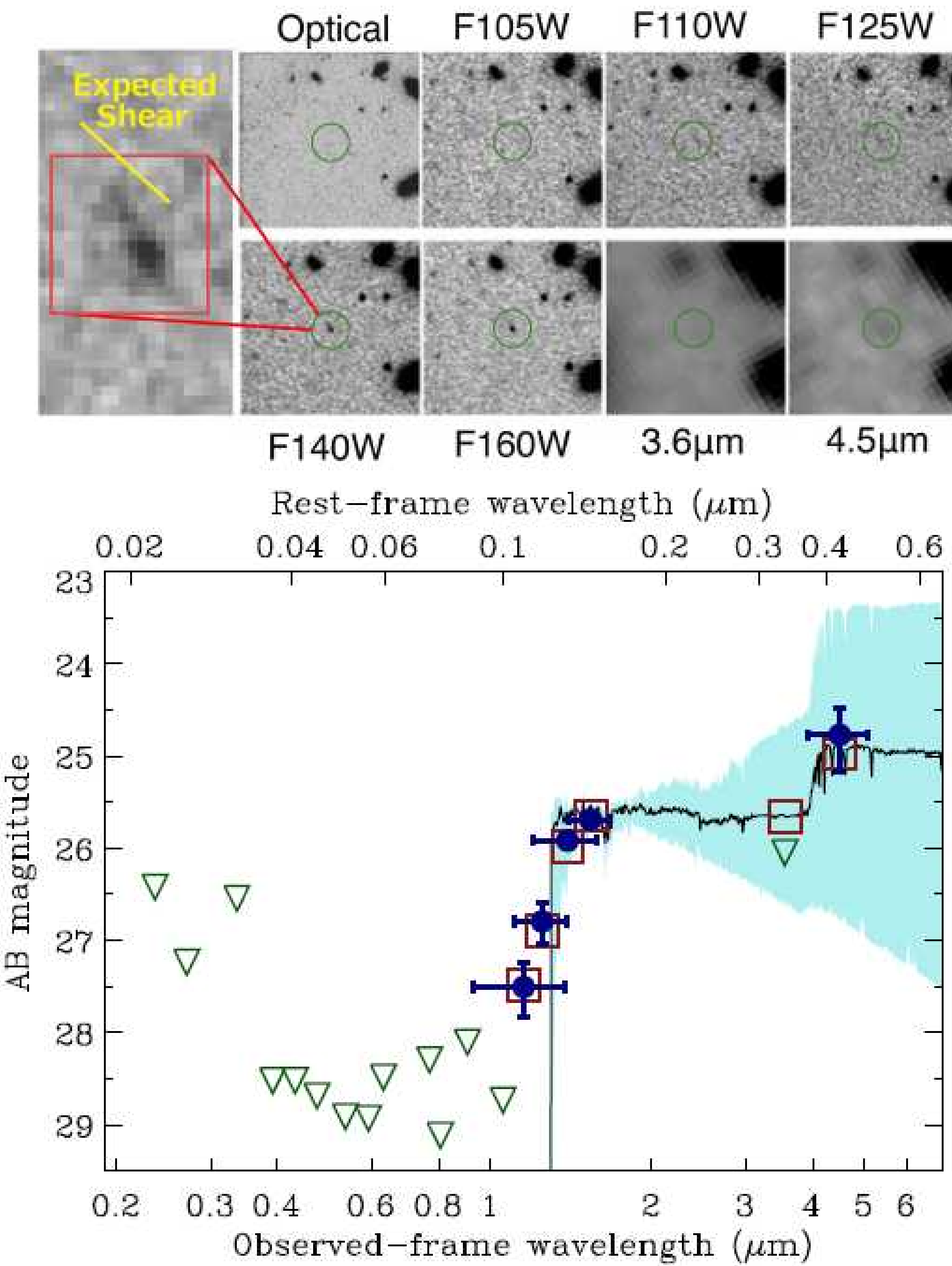
Physics of Star-forming galaxies

EVOLUTION OF THE COSMIC IONIZING EMISSIVITY

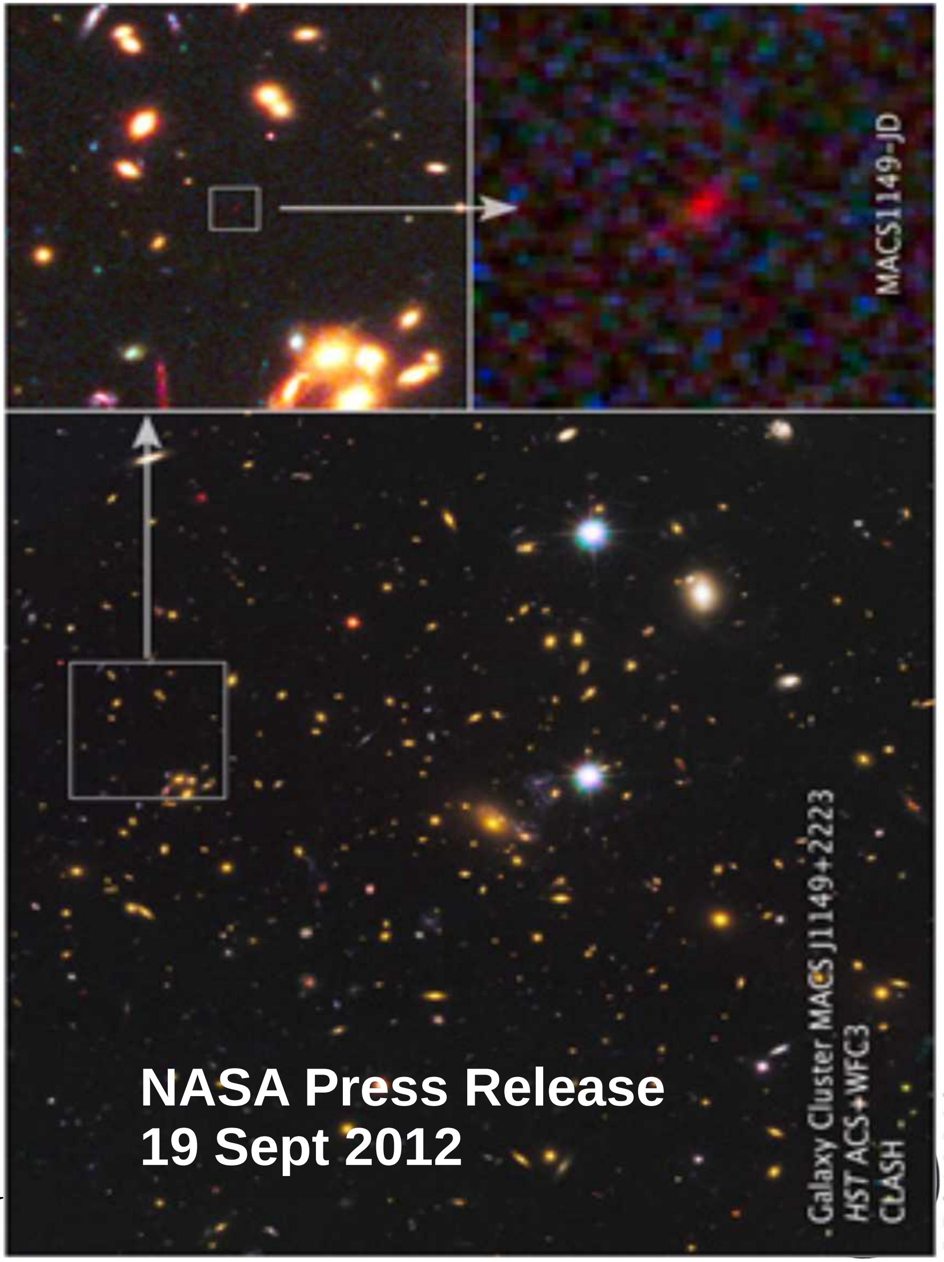
Lensing clusters used as gravitational telescopes



Z~9.6 candidate behind MACSJ1149.6+22



Zheng et al. 2012

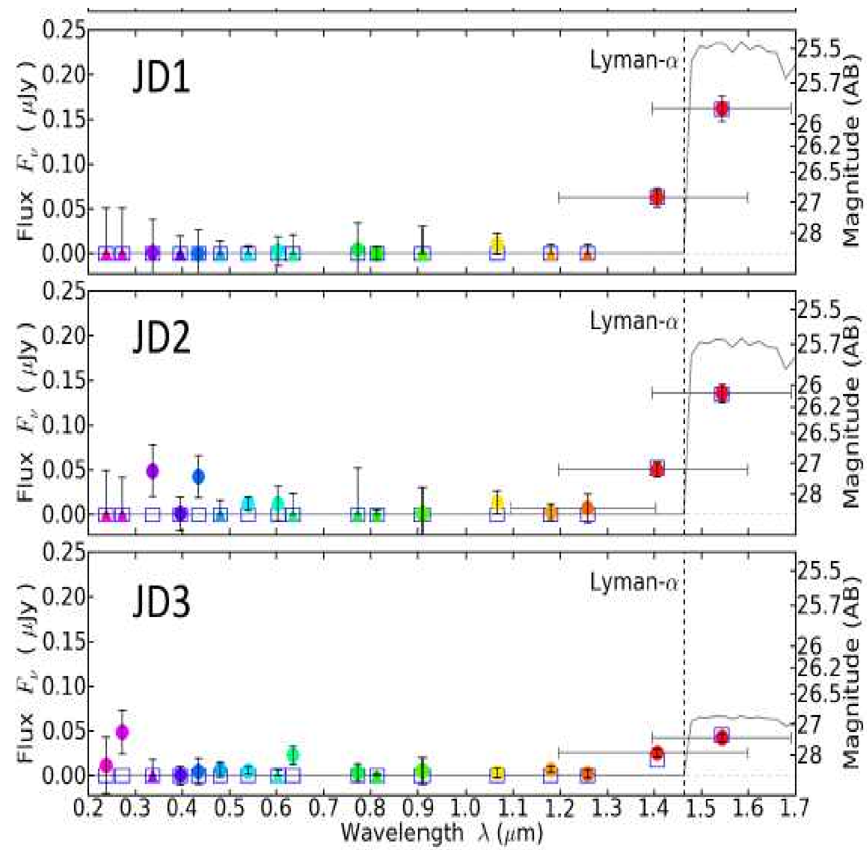


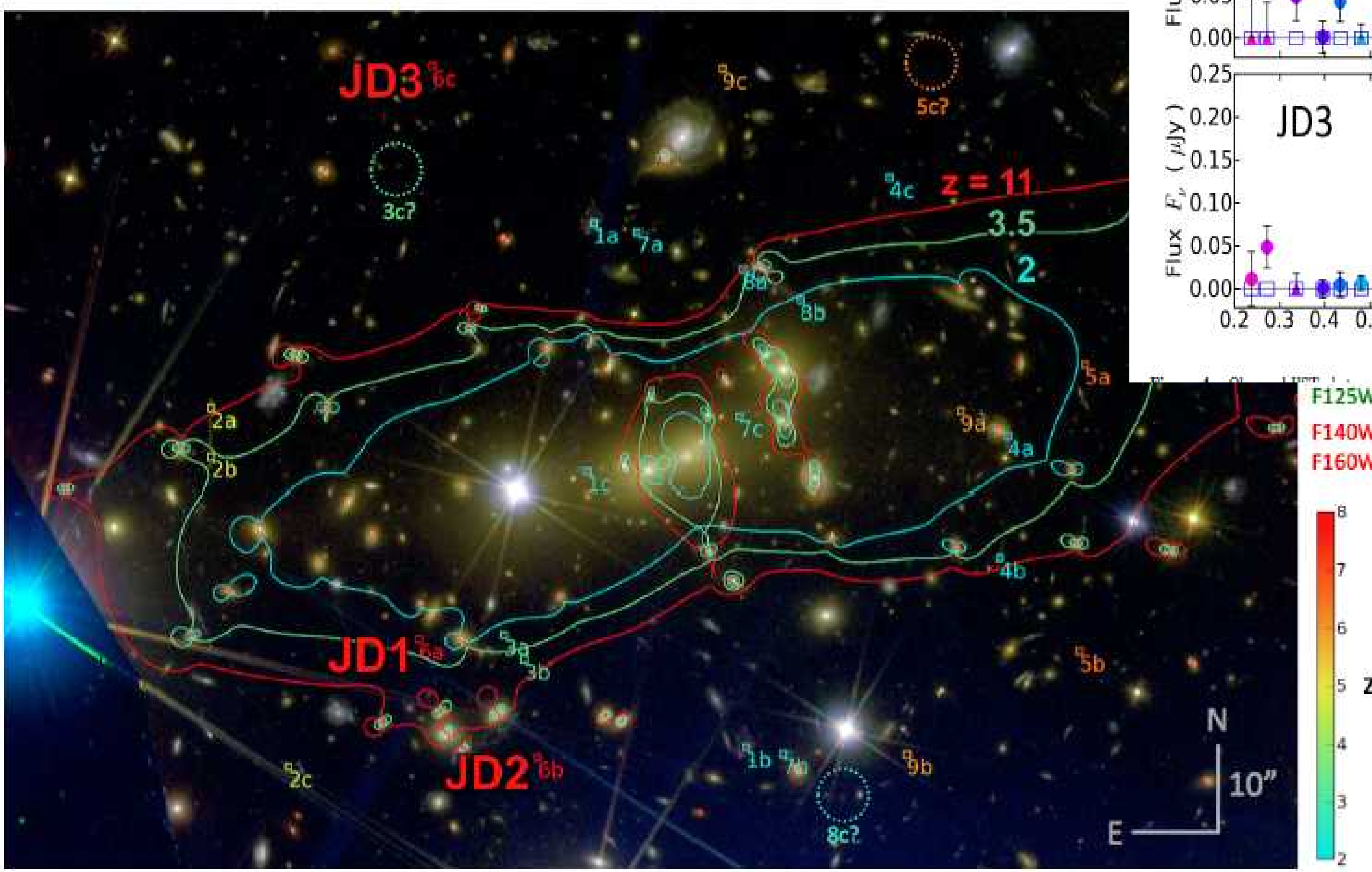
– LY

Z~11 candidate in CLASH MACSJ0647.7

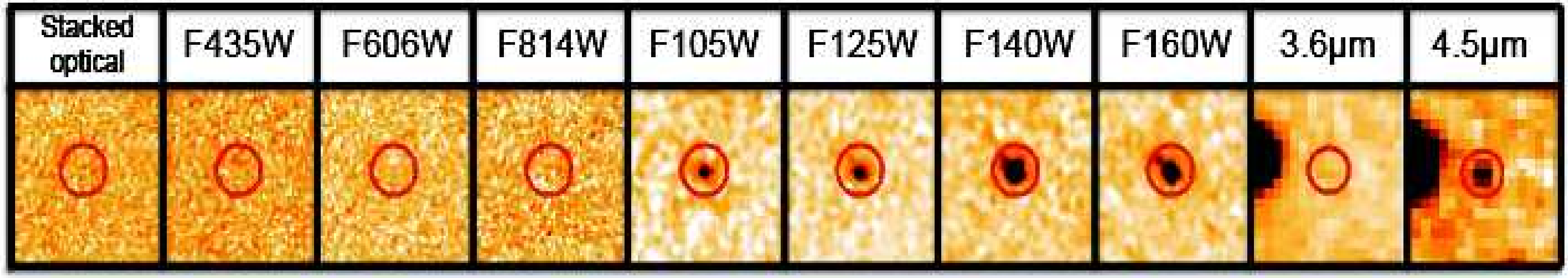
Coe et al. 2013

3 images of the same source

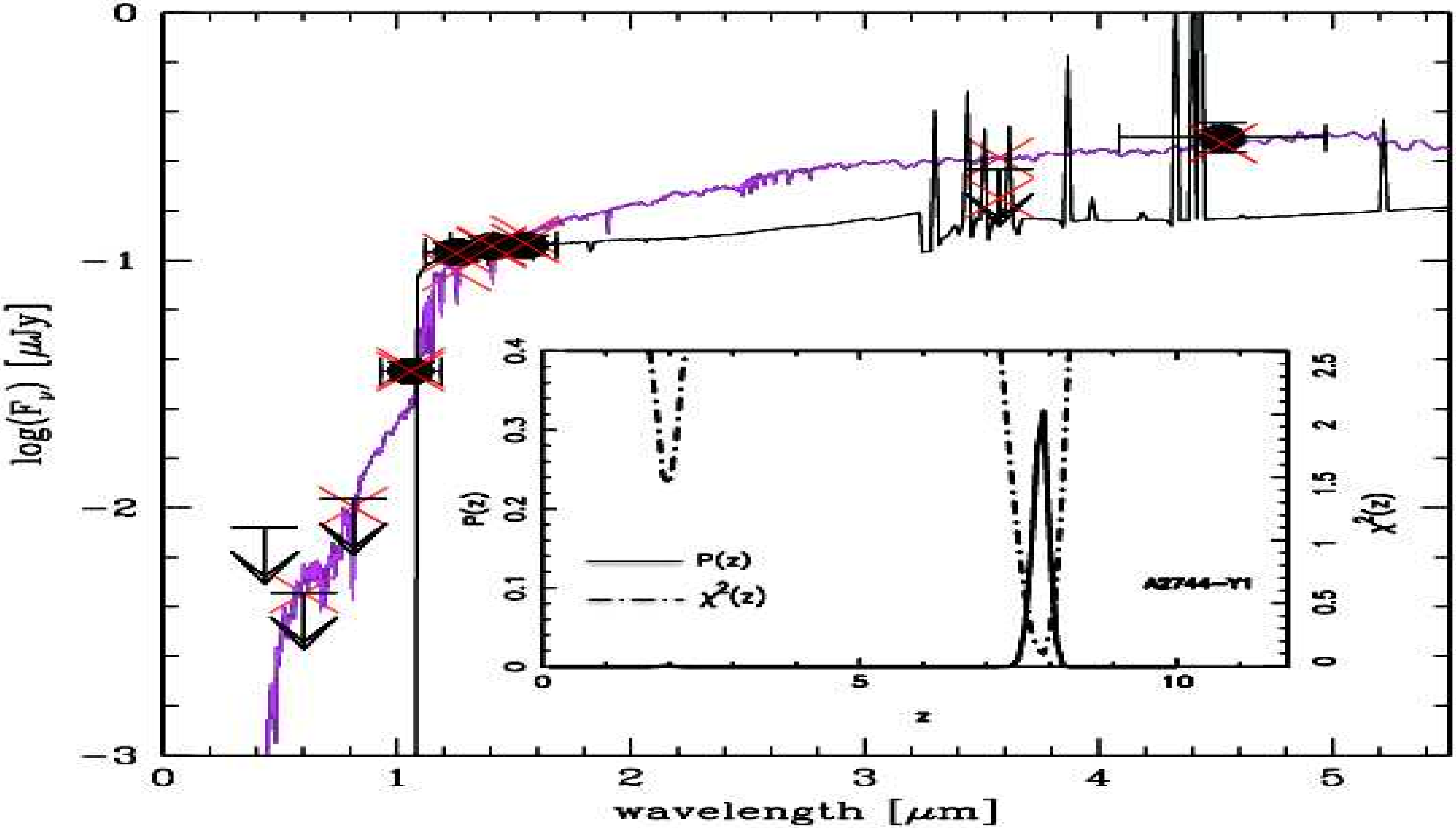




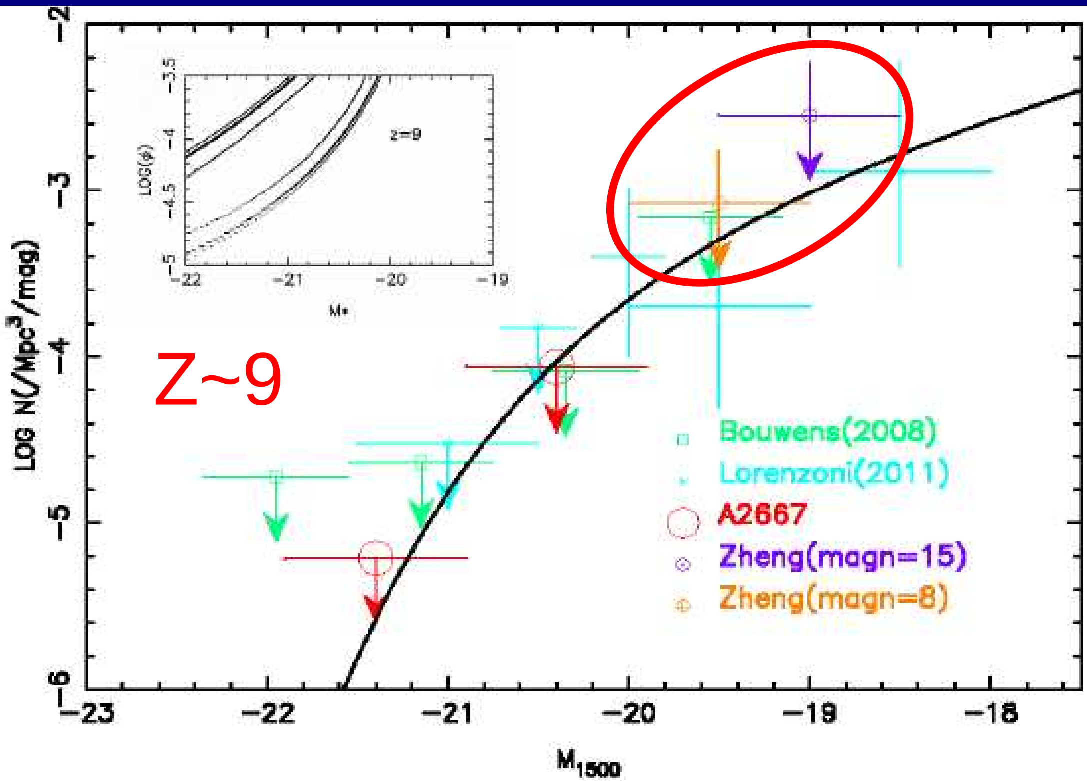
Z~8 candidate behind A2744



Laporte et al. 2014



LBG Surveys (Lensing fields)

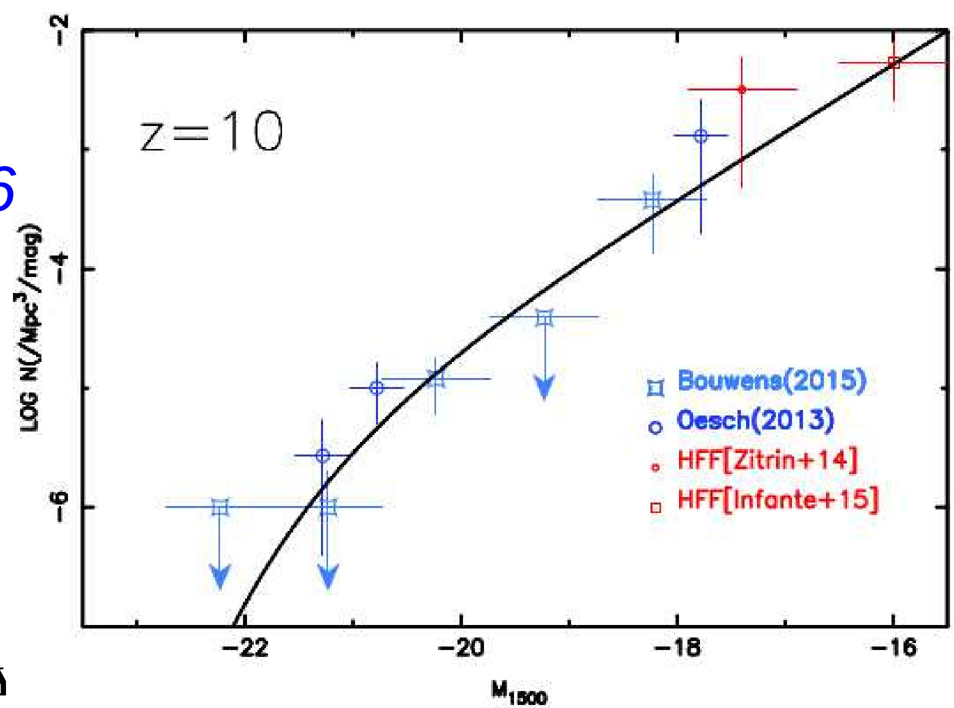


Laporte et al. 2012

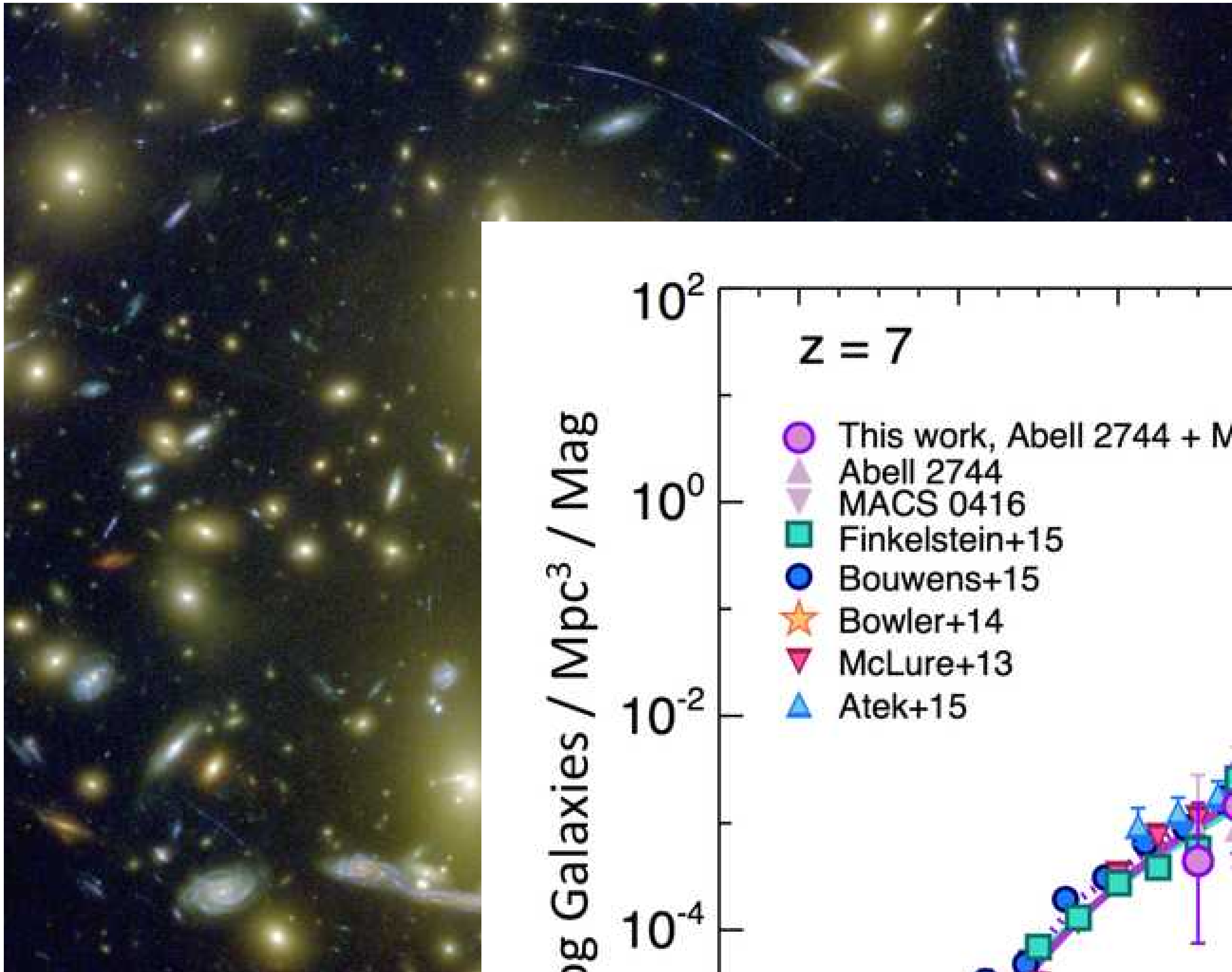
See also Atek+ 2015

Laporte et al. 2016

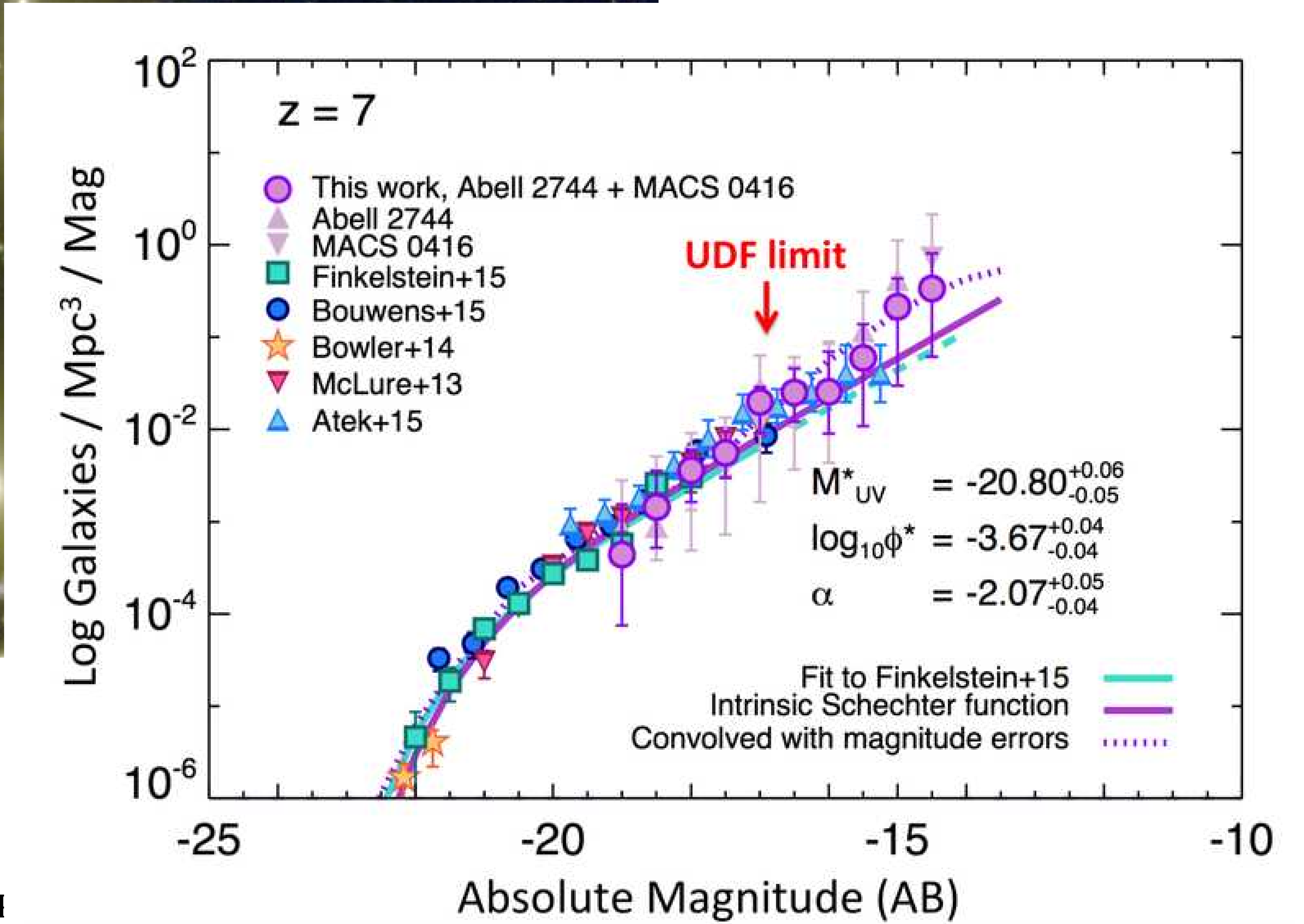
(see talk by N. Laporte)



LBG Surveys (Lensing fields)

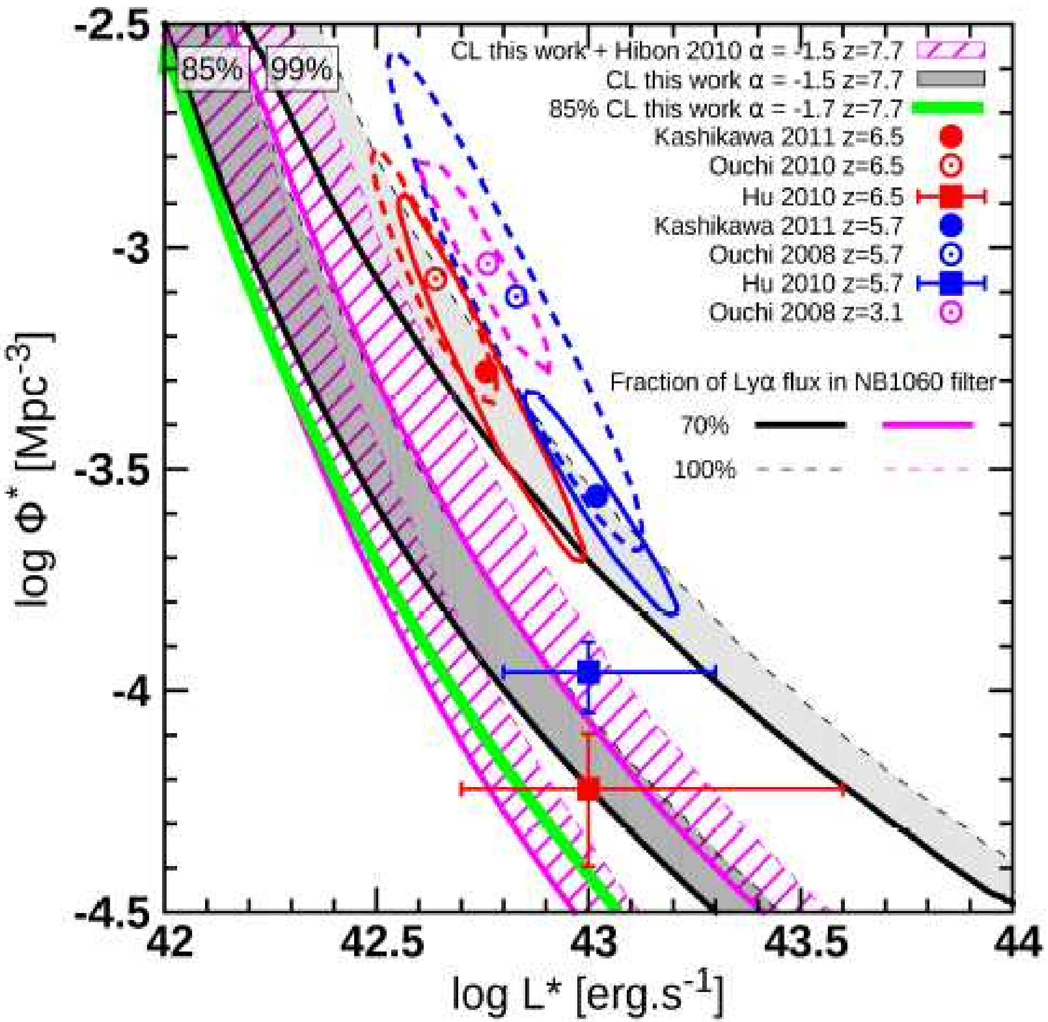


Coe+ 2016
Hubble FF



Evolution of LF for LAE

Clément et al. 2012



LAE from NB Surveys

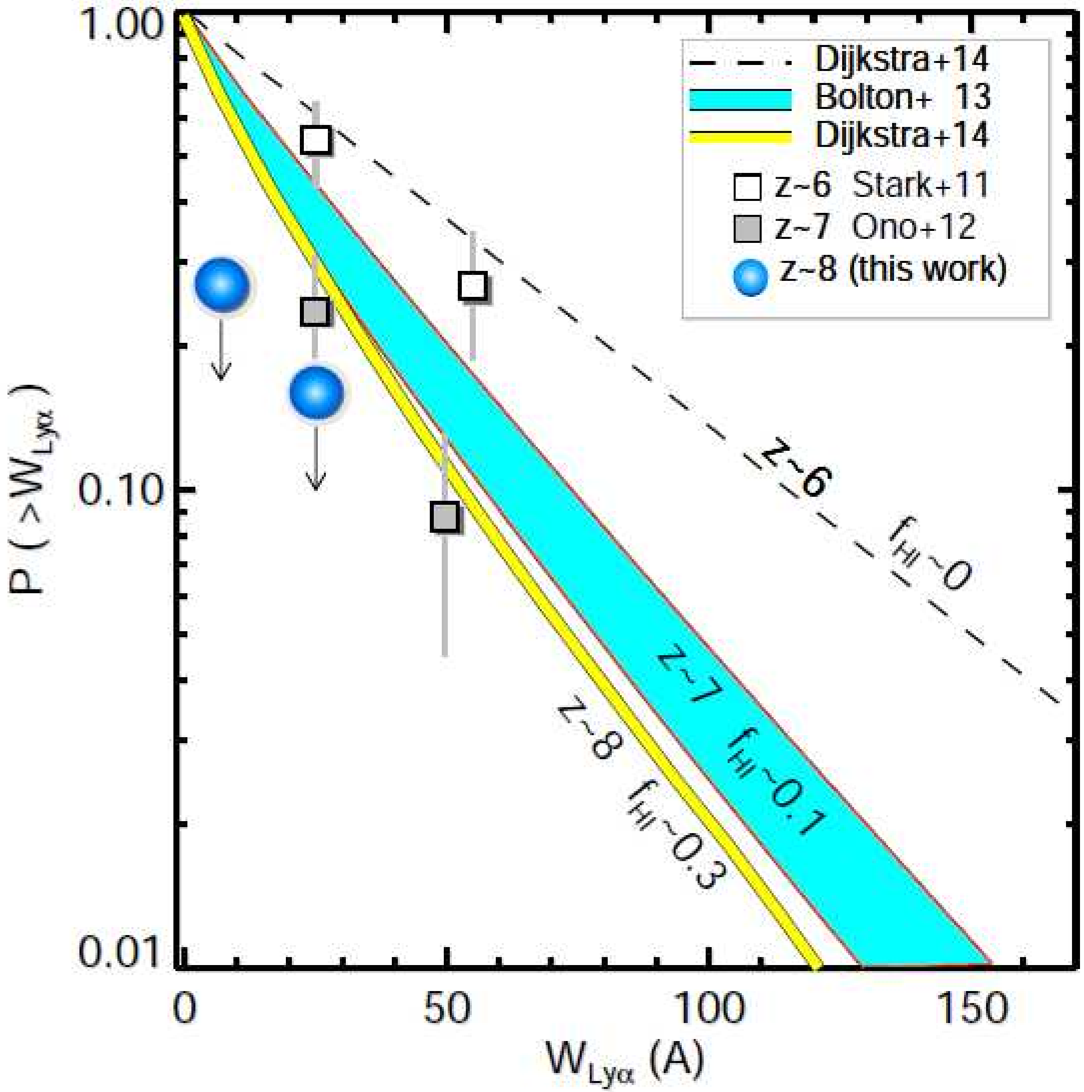
- LF based on NB surveys shows a strong decline between z~5.7 and 7

==> increase in the neutral fraction?

- Other factors could be important: variations in the host-galaxy number densities, properties of interstellar gas, kinematics, dust, etc...

LAE and HI fraction

Tilvi et al. 2015

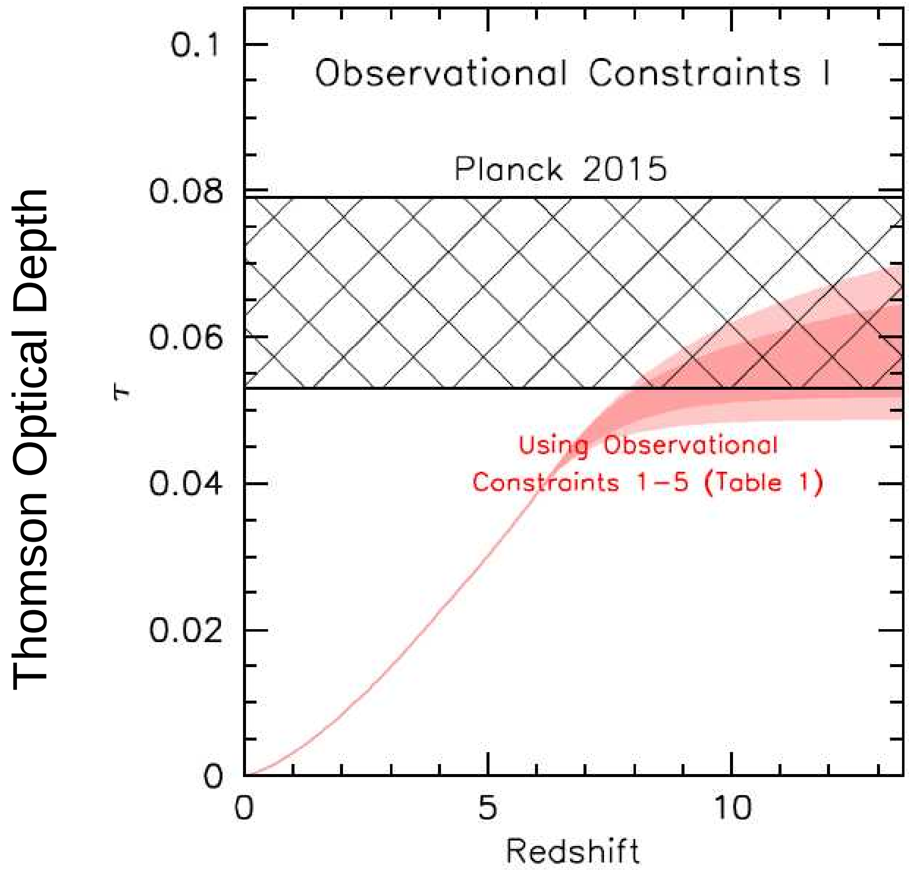


- Cumulative Lyman-α probability distribution for their faint sample (M(UV) > −20.25 mag), compared to model predictions
- The volume-averaged neutral hydrogen fraction at z~8 is at least f(HI) >~ 0.3

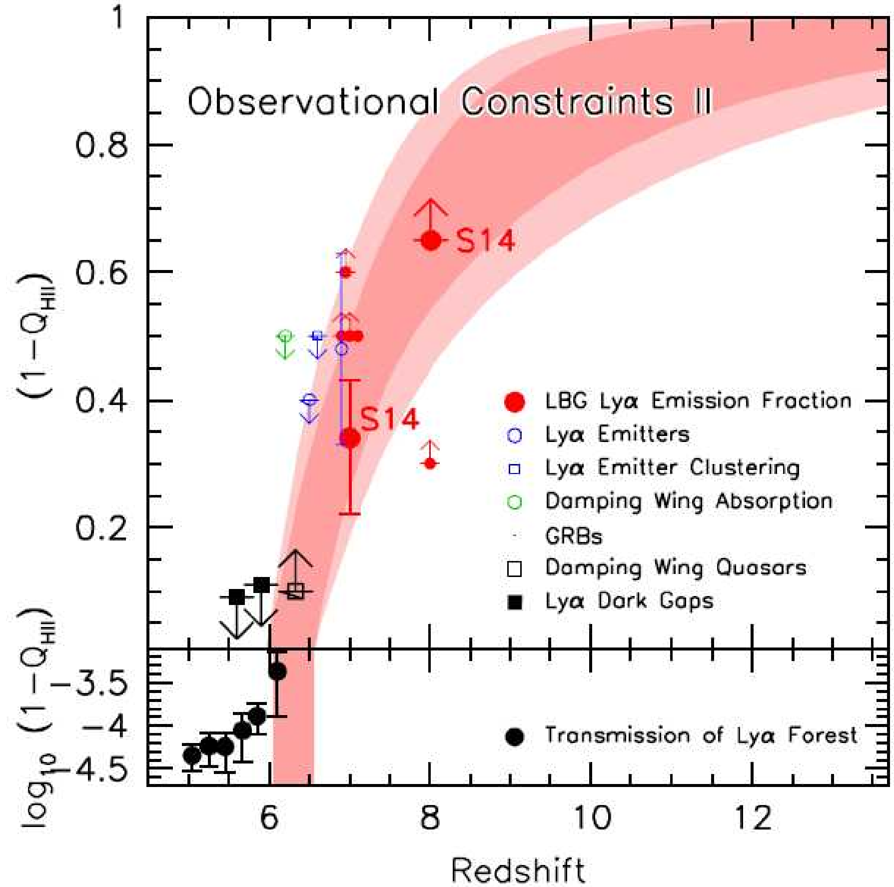
=> reionization in progress at z~8

Empirical evolution of the cosmic ionizing emissivity

Bouwens et al. 2015



Q(HII) : filling factor of ionized H

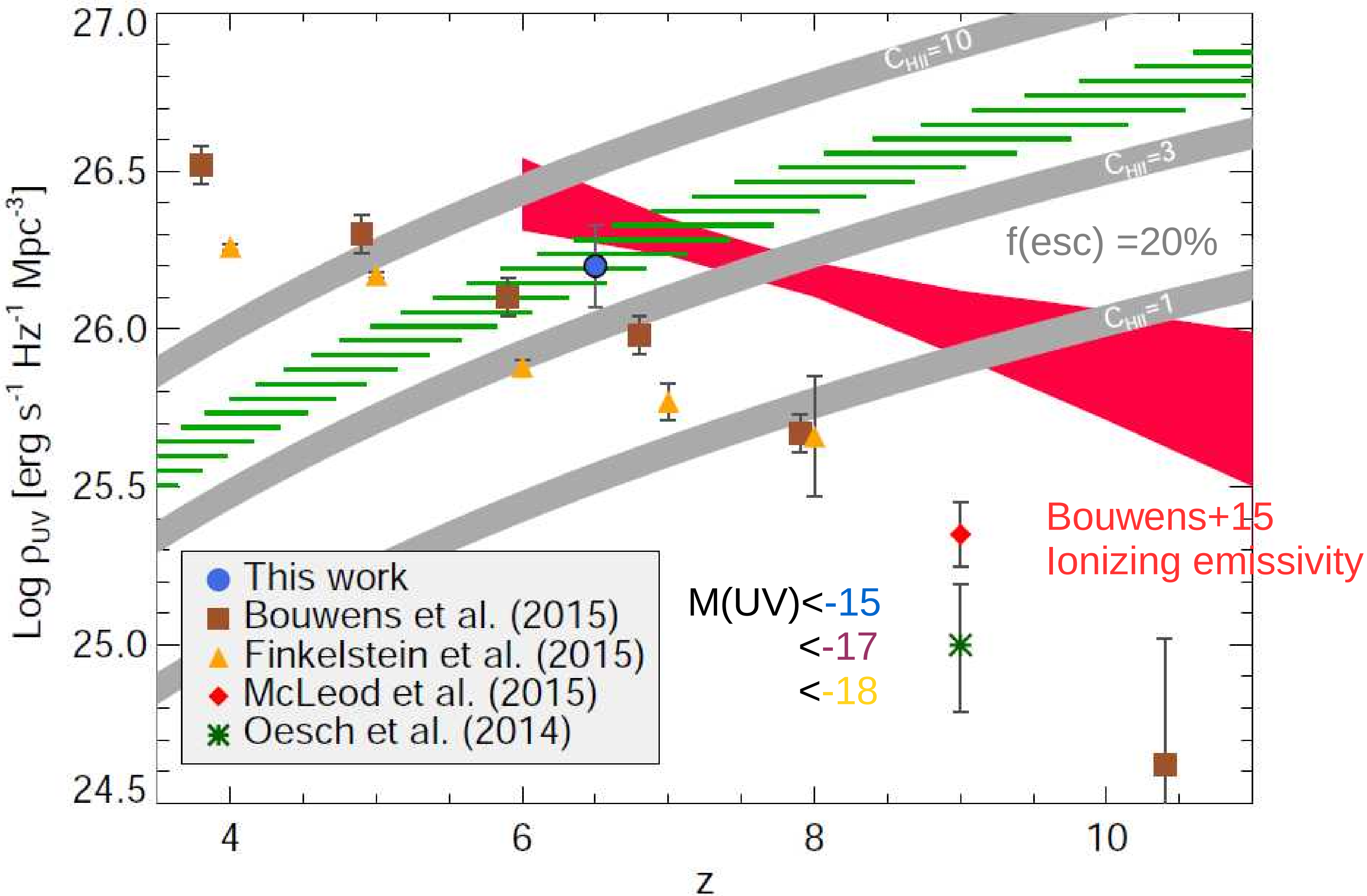


- The conversion factor between UV luminosity density to ionizing emissivity is consistent with plausible physical values of f(esc) and clumping factor C(HII)... for a faint limit of the UV LF M(inf) ~ -13
- The reionization seems to be dominated by faint star-forming galaxies, presently beyond the reach of current facilities … in blank fields!

Evolution of the UV luminosity density

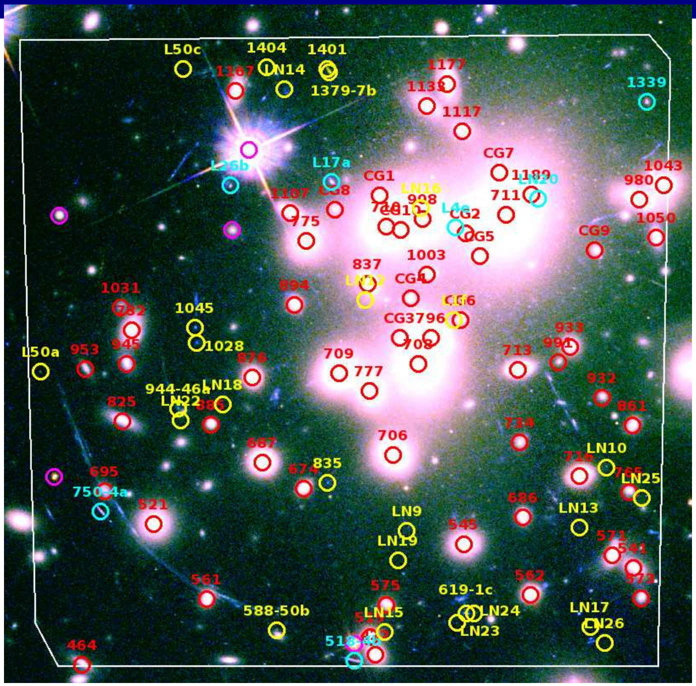
Atek et al. 2015

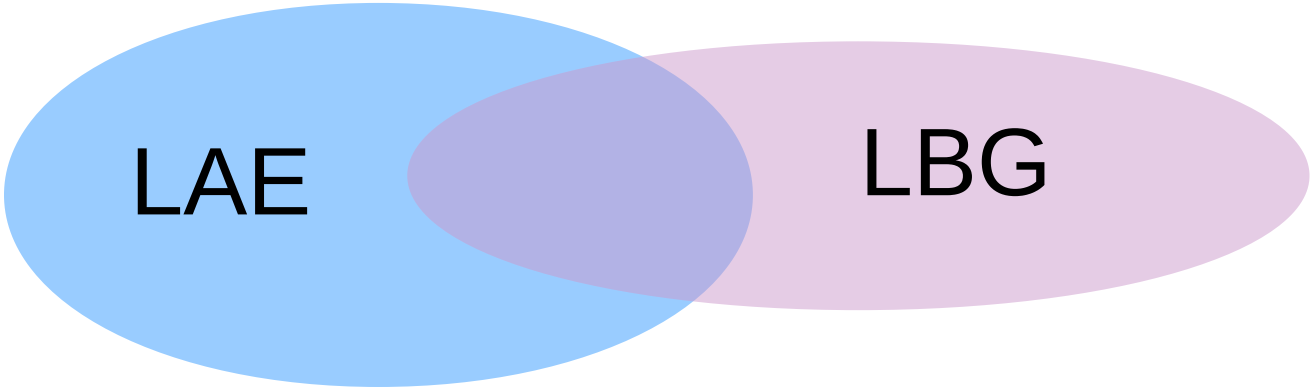
f(esc)=10-15%
C(HII)=3



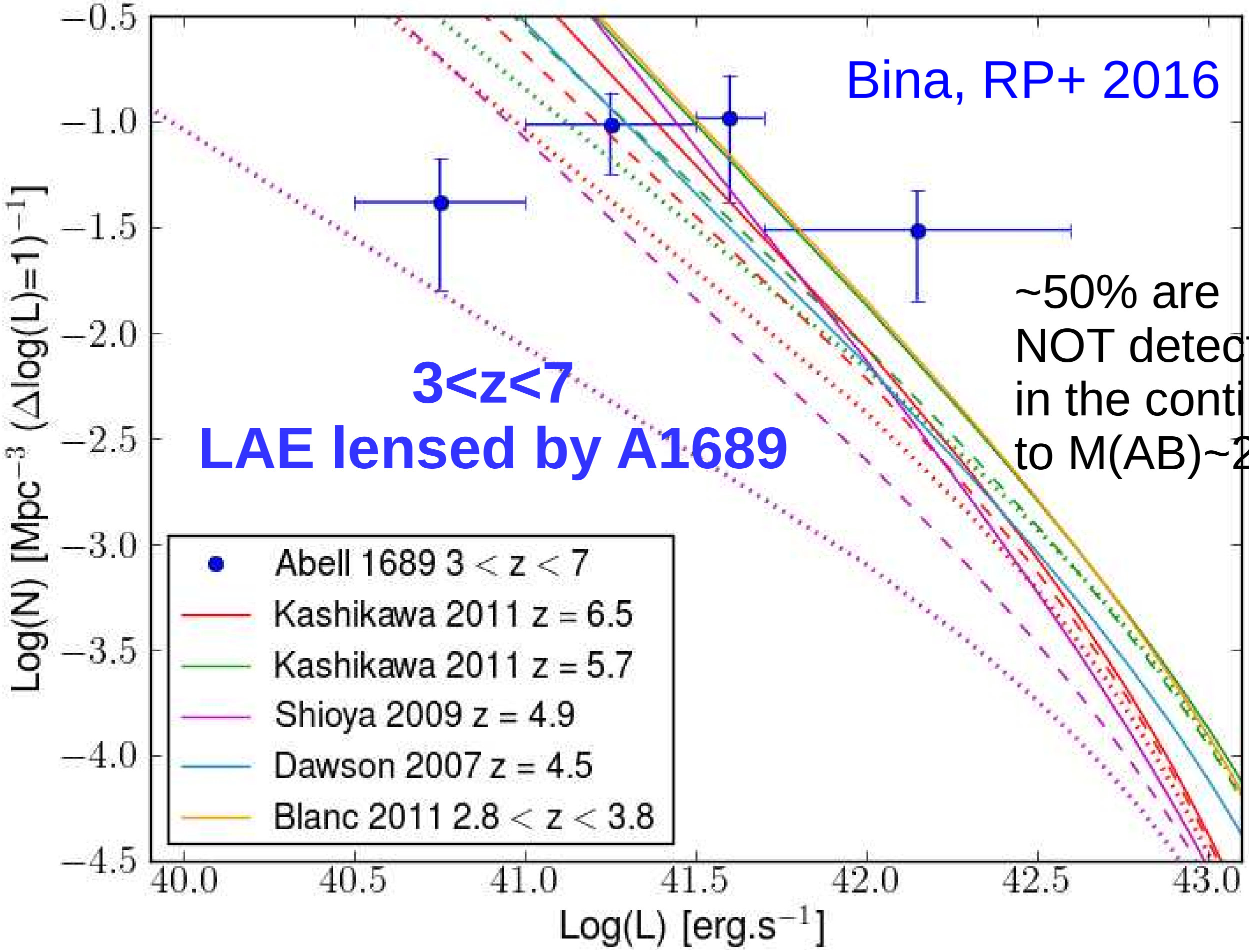
- UV luminosity density at z~7 is sufficient to keep the universe reionized assuming “standard” conditions
- At z>~8, the faint end of the UV LF is not enough constrained to determine the contribution to the ionization budget

A complete census of ionizing sources...





- **MUSE** observations of LAEs lensed by A1689
- MUSE data probe the faint-end region of the LF
- Error bars: Poisson + FTF variance
- LF sensitive to α
- Results in A1689 are consistent with a steep slope α < -1.5 (TBC)

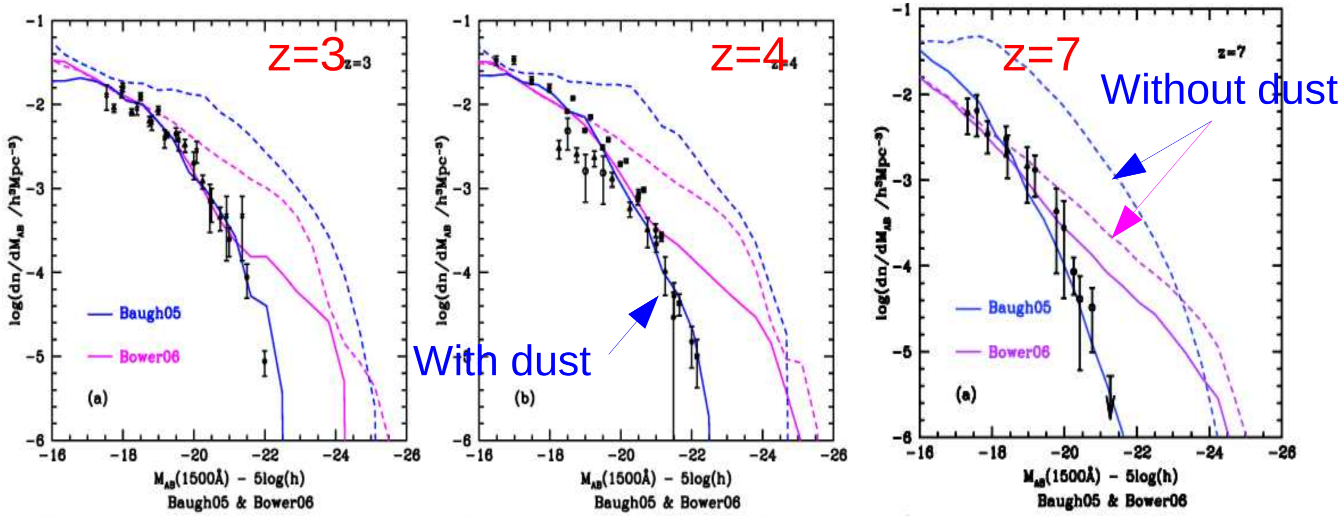


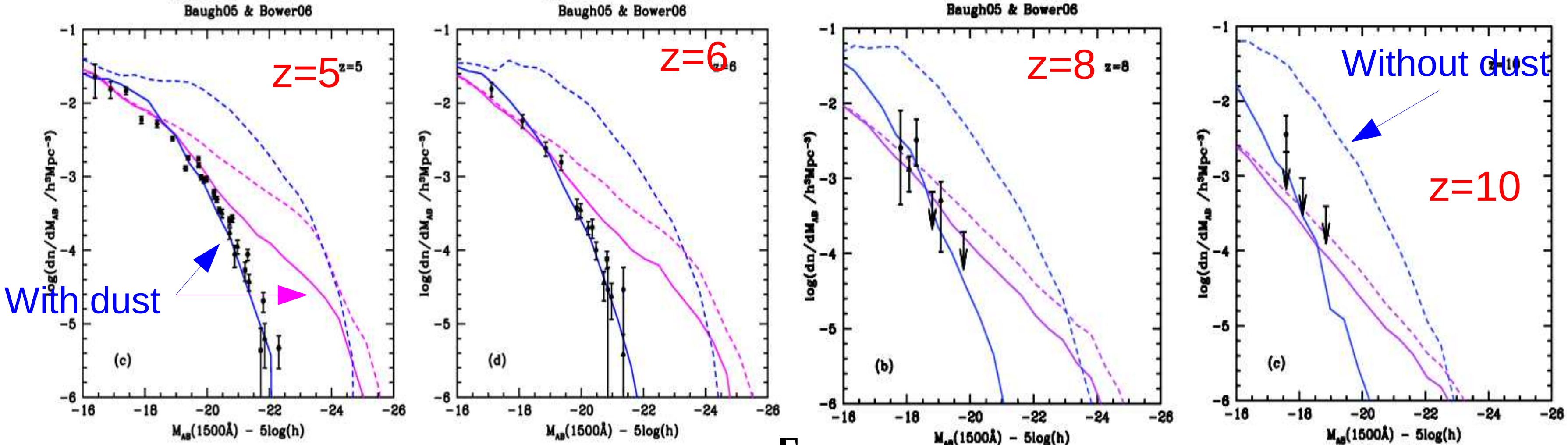
~50% are NOT detected in the continuum to M(AB)~28!

Evolution of the UV LF : models versus observations

- Predictions are very sensitive to modeling assumptions & parameters regarding :
  - [dust extinction]
  - Photoionization & supernova feedback

- Consistent scenario up to z~10
- Large extinction at the bright end (~1.5–2.5 mags)... in tension with the "steep" UV slope (!)
- High metallicity expected with top-heavy IMF + metal enrichment in bursts





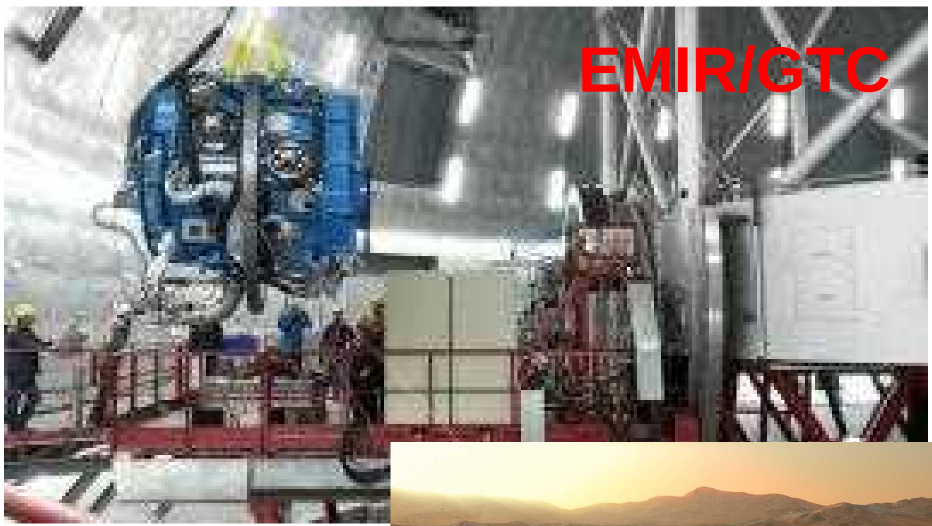
GALFORM Lacey et al. 2011

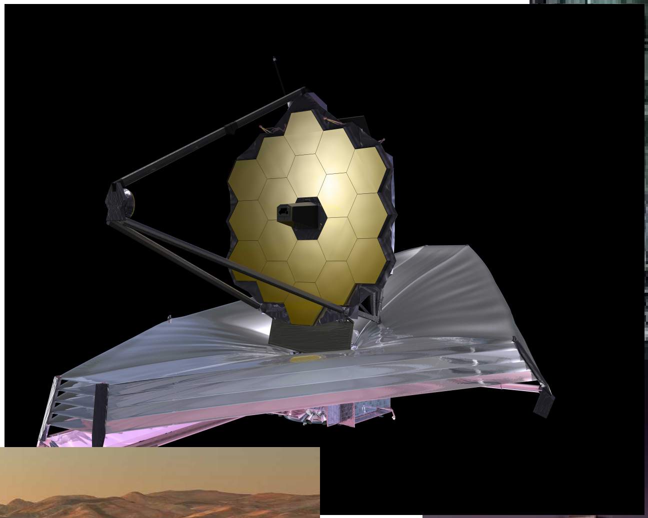
Discussion : Other issues...

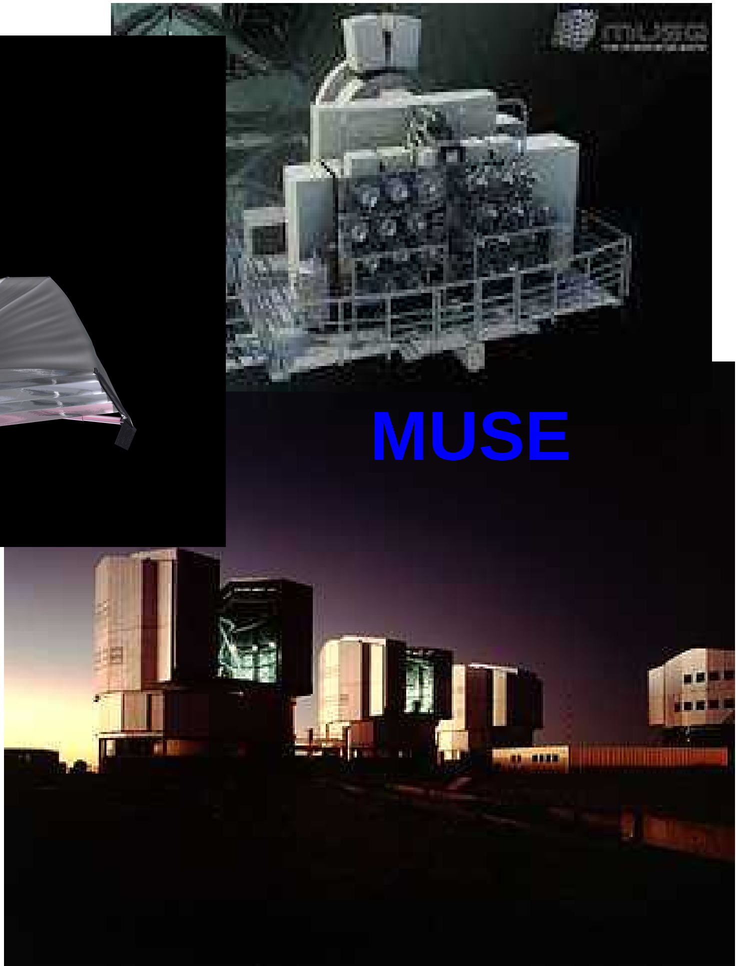
- Reionization scenarios discussed before, requiring appreciable star formation in small halos (*e.g.* M(vir)~ 10^8 solar masses at z ~ 8) seem to be in serious tension with galaxy counts in the Local Group (Boylan-Kolchin et al. 2014).
- Implication : Star-formation became inefficient in halos smaller than log(M)~9 at early epochs ==> the LF must break at M(UV) brighter than -14 (as usually assumed), and star formation efficiency must increase to keep the universe reionized.
- Ionizing emissivity depends on the physical parameters of star-forming galaxies (*e.g.* star-formation history, …), and is is (still) poorly constrained.
- Detailed multi-wavelength / spectroscopic studies at the depth of JWST or HST Frontier Fields (lensing) is needed to conclude... (m(AB) ~ 32)

Perspectives

- **Spectroscopy :**
  - <u>**Redshift**</u> mesurements (based on Ly alpha + other strong e-lines). Determination of the <u>**nature**</u> of high-z galaxies
  - 3D spectroscopy : <u>**Complete census of LBG/LAE in the sensitive** </u>range z~5 -12, e.g. in blank AND lensing fields







Thanks!