Search for the FIRST GALAXIES

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Outline

1. Looking for the first galaxies

a) Introduction

b) Theoretical considerations

c) Observable properties of the first galaxies

d) Present constraints

(based on observations)

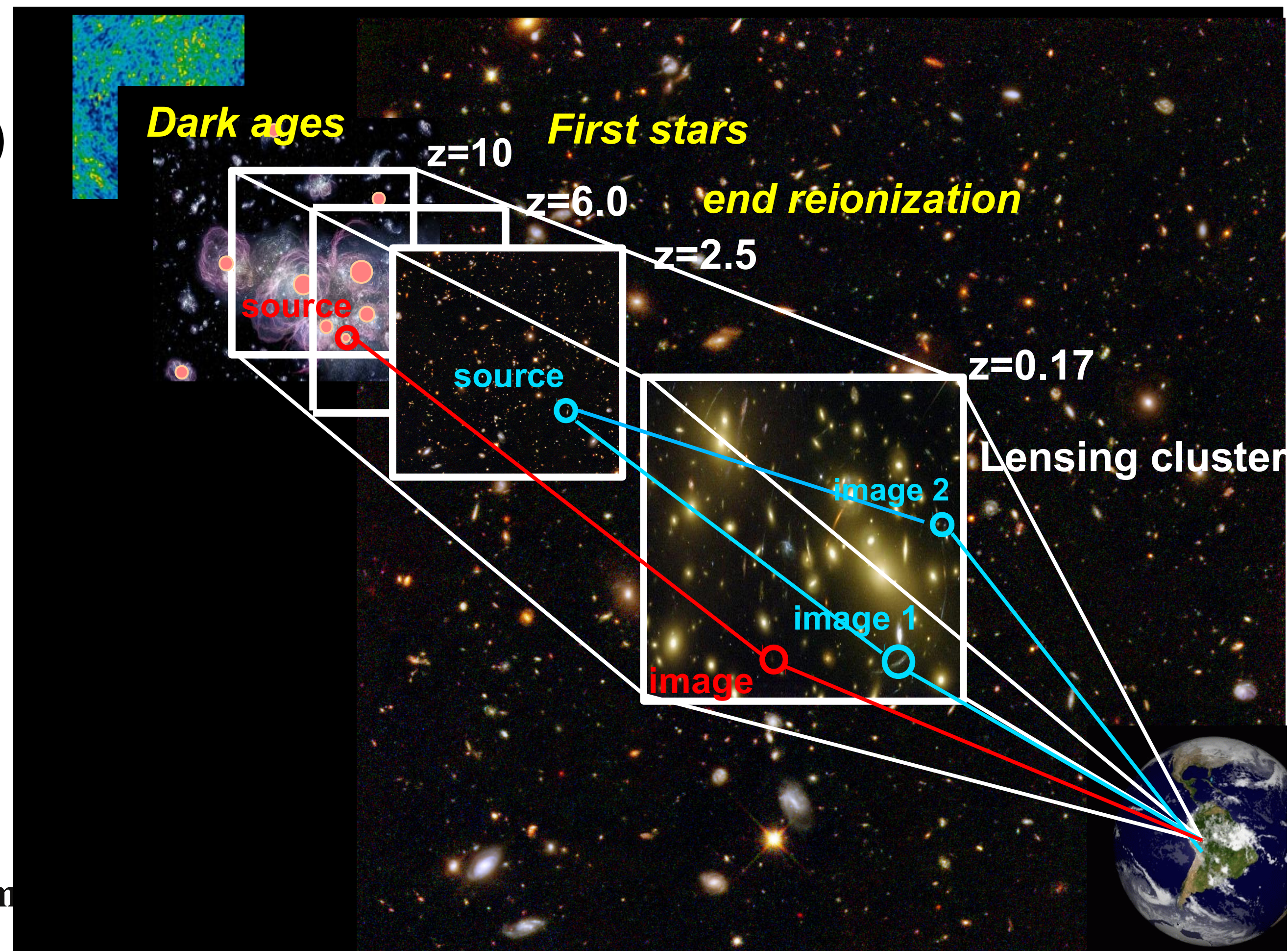
2. First galaxies & gravitational telescopes

a) Historical overview

b) Lensing versus blank fields : a matter of efficiency

c) Current surveys and (expected) results

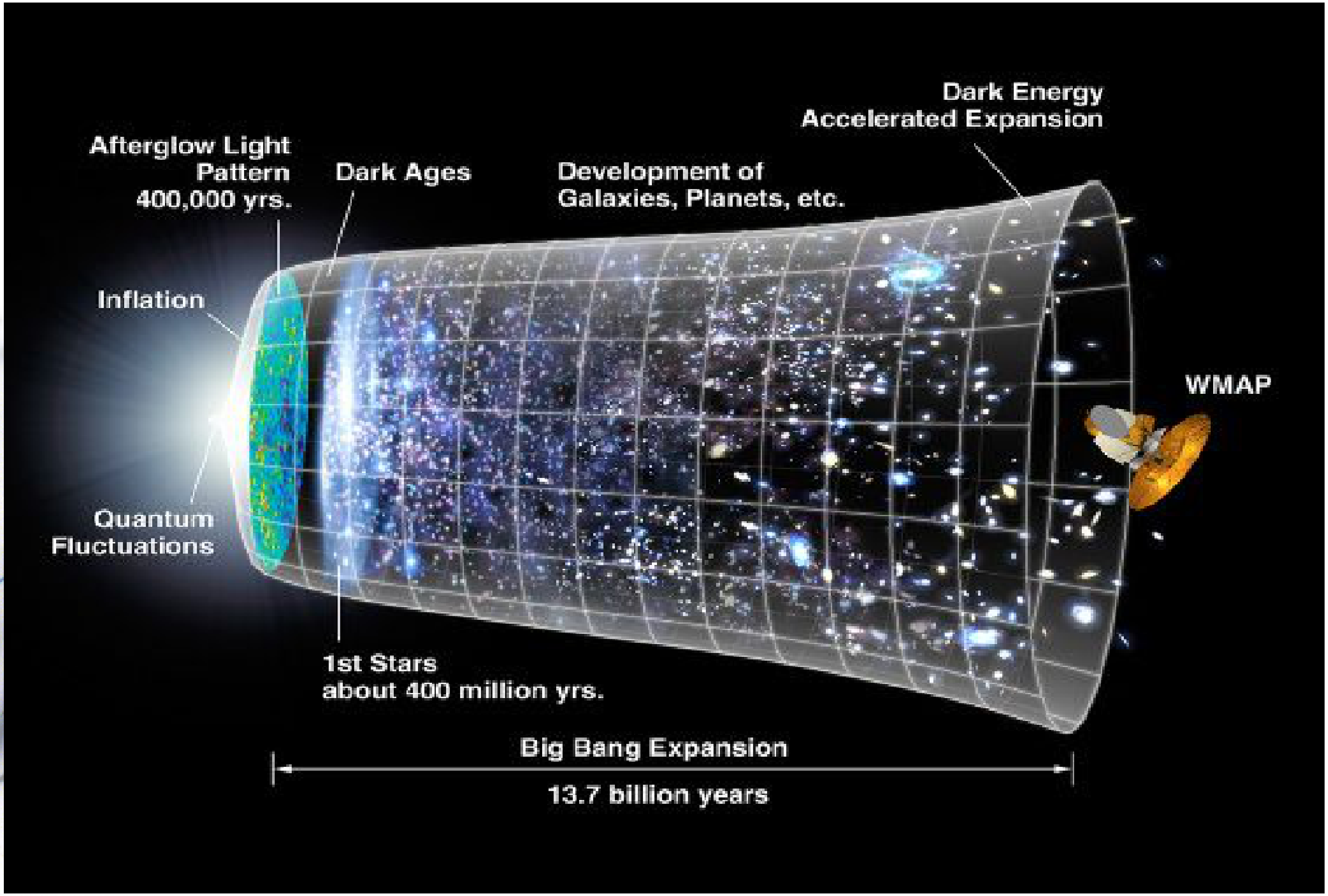
d) Future developments



Lecture 1 : Looking for the first galaxies

Fundamental Questions in Cosmology :

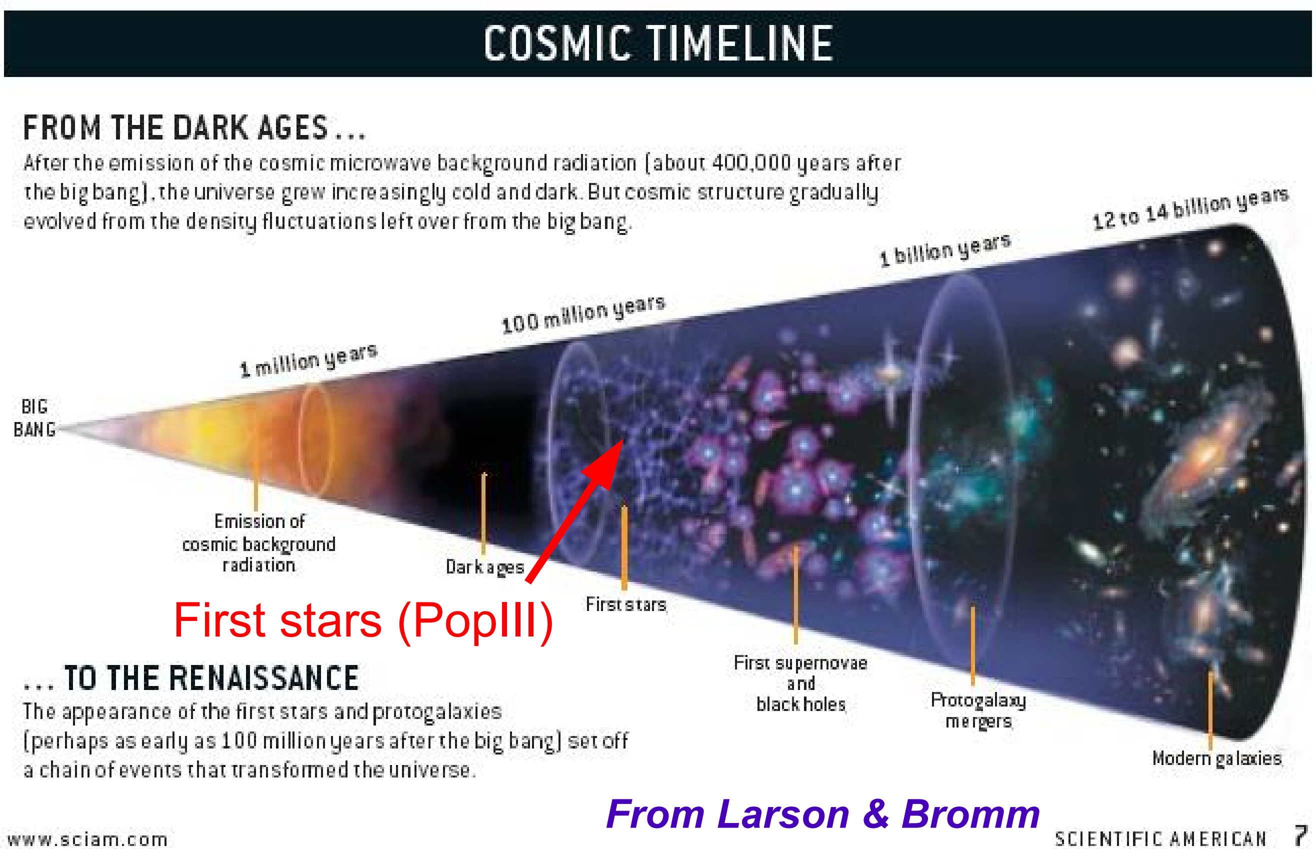
•The nature of dark energy, dark matter, modified gravity...
• **Investigate the birth of the first objects out from the dark ages as well as structure assembly in the universe.**



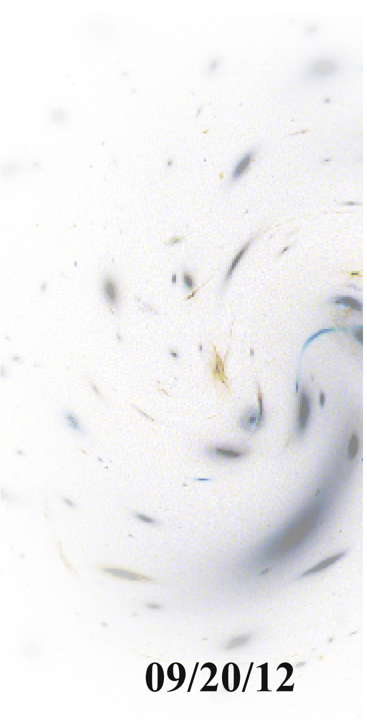
<u>The formation of the first stars & galaxies :</u>

- CBM :
  - 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 <u>bounded objects</u> marks the transition from simplicity to complexity …

→ **Cristiano Porciani's lectures**



From Larson & Bromm

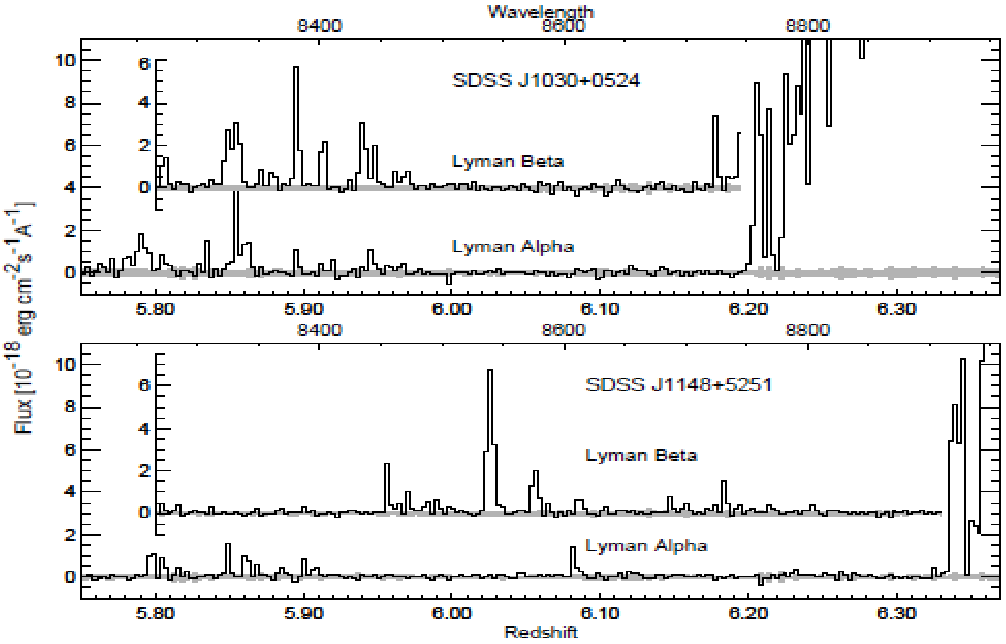


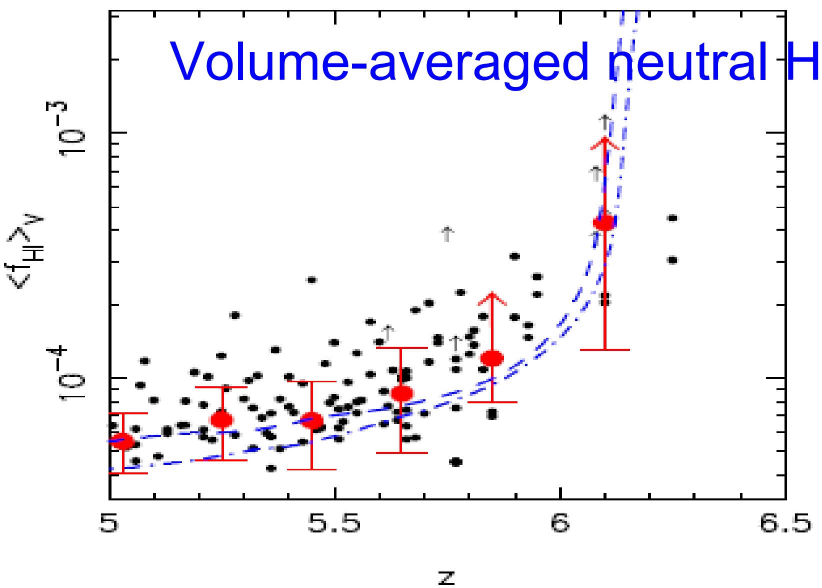
The end of the reionization :

- 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**)
- The optical depth to Lyman alpha photons (Gunn & Peterson 1965) at high-z, for a uniform IGM is :

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

- 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.





Fan et al 2006

The beginning of the reionization probed by WMAP :

- Foreground electron scattering of CMB photons with an optical depth corresponding to z(reionization). Observed since year-1 (2003) at 4 sigma level.
- z(reionization)=11+/-1.4 (Dunkley et al. 2009). Large uncertainties remain. The actual value depends on the reionization process (instantaneous or more complex scenarios). **==> more with Planck**

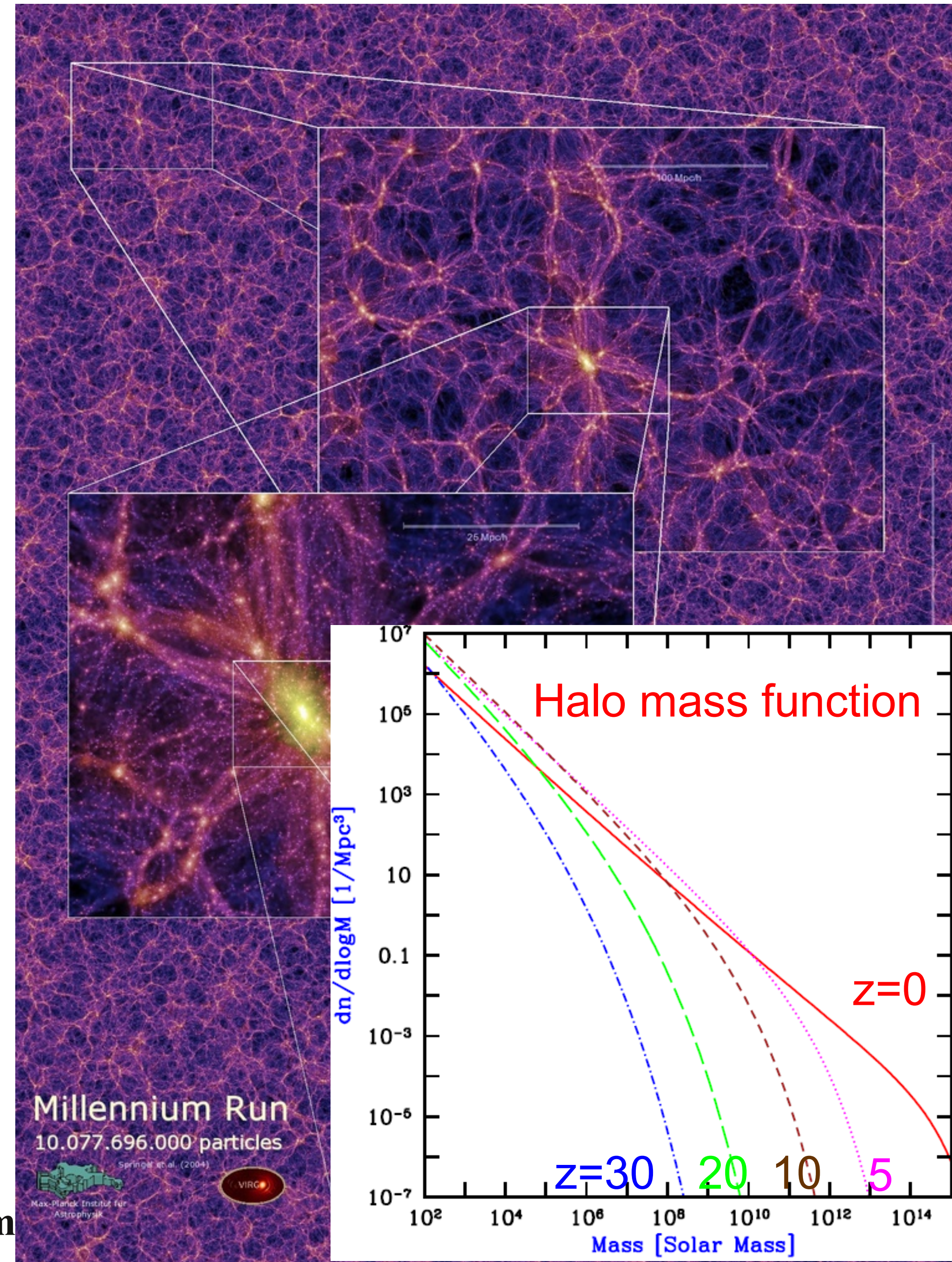
Some important questions remain:

- What were the **sources responsible for the reionization?** Galaxies & AGNs? GRB contribution?
- When and how reionization occurred? A gradual process? Multiple phases?

Theoretical considerations (I)

Hierarchical formation and abundance of CDM halos

- Linear growth of small spatial fluctuations in the energy density and gravitational potential generated in the early universe ($\delta \sim 10^{-5}$) due to gravitational instability.
- Formation of non-linear objects. Halos reach virial equilibrium by violent relaxation. A halo of mass M collapsing at z has r_{vir}, circular velocity and T_{vir}
- Number density of halos :
  - numerical simulations (e.g. the Virgo Consortium & Millenium Simulation)
  - analytic models providing physical understanding (see e.g. review by Barkana & Loeb, 2001)



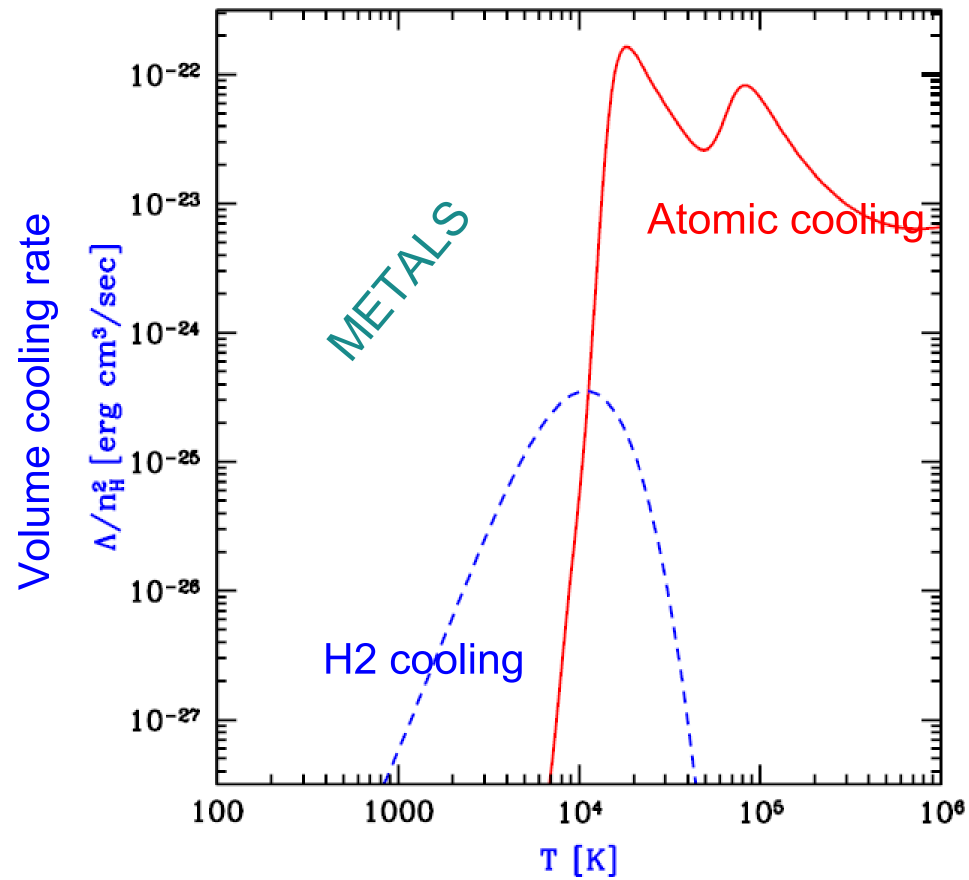
This part is relatively well understood...

Theoretical considerations (II)

Galaxy formation models

- Model baryonic processes:
  - Semi-analytic models ==> simple spherical symmetry, analytic recipes
  - Hydrodynamical simulations ==> hydro equations solved numerically
- Gas infall & cooling in DM halos
  - **DM dominates gravity**
  - **The baryonic mass that can accrete 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 :
    - **Formed in mini-halos (10^6 solar masses)**
    - **T_{vir} ~ a few 10^3 K**
    - **Cooling : molecular H (H_2 ; see Abel & Haiman 2000)**
  - First galaxies :
    - **Formed in larger halos (~10^8 solar masses)**
    - **T_{vir} ≥ 10^4 K**
    - **Cooling : atomic hydrogen**

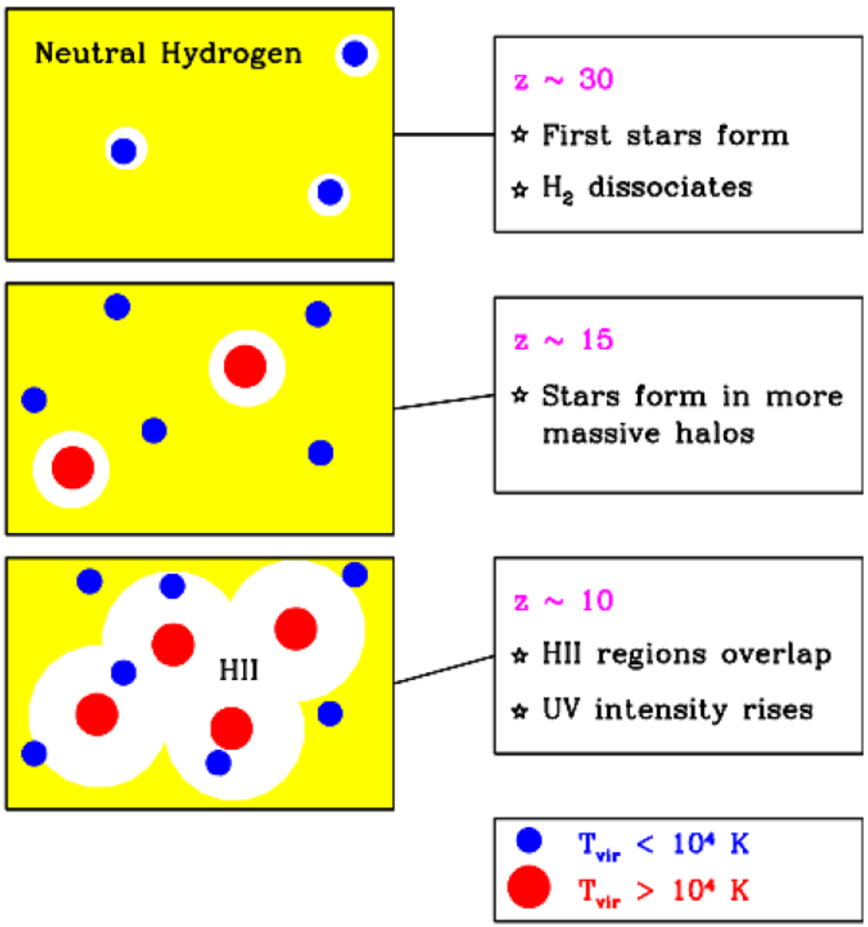
Barkana & Loeb (2001)



Virial temperature (PopIII)

Galaxy formation models

Barkana & Loeb (2001)

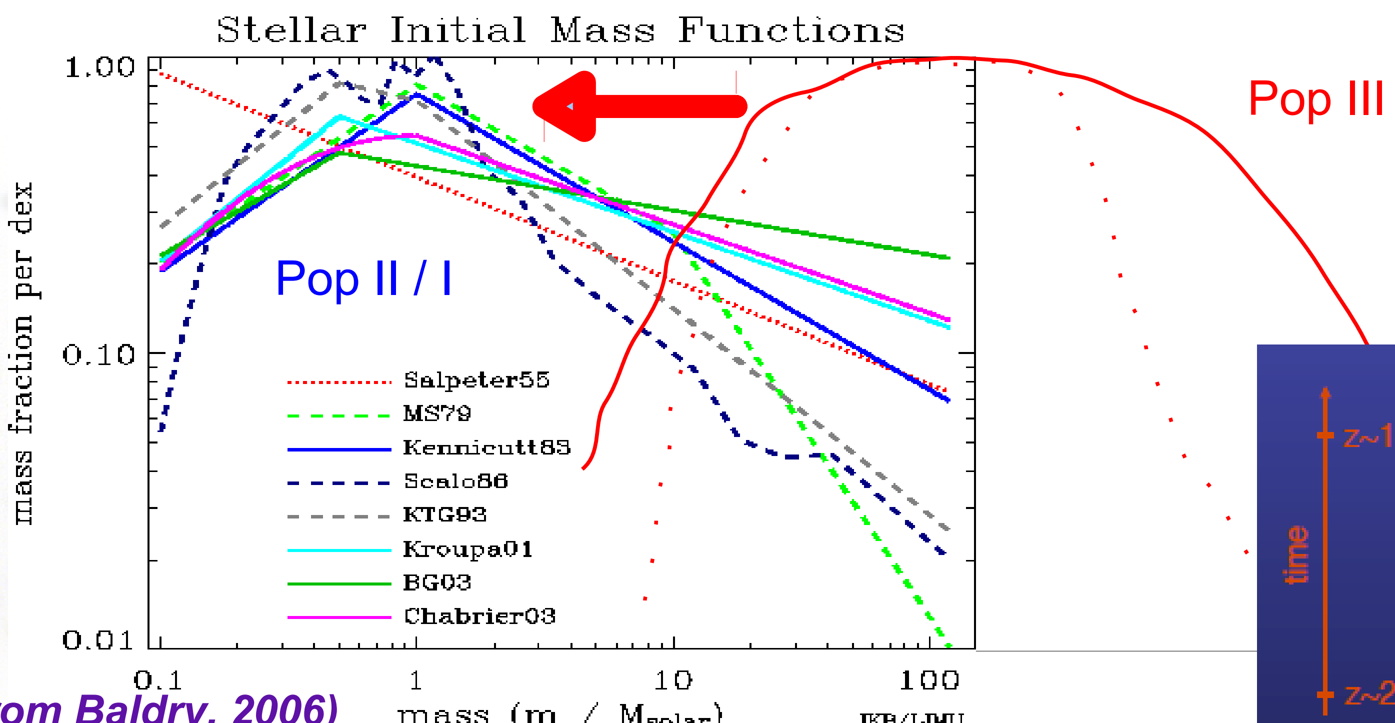


- H2 is easily photo-dissociated by UV photons.
- The UV flux needed to photo-dissociate H2 is ~2 orders of magnitude lower than the minimum to ionize the universe ==> as soon as the first stars form, the H2 cooling is suppressed
- New stars form in larger halos ($T_{vir} \geq 10^4$ K) through atomic-line cooling ==> M(total) > 10^8 x $[(1+z)/10]^{-3/2}$ solar masses

Theoretical considerations (IV)

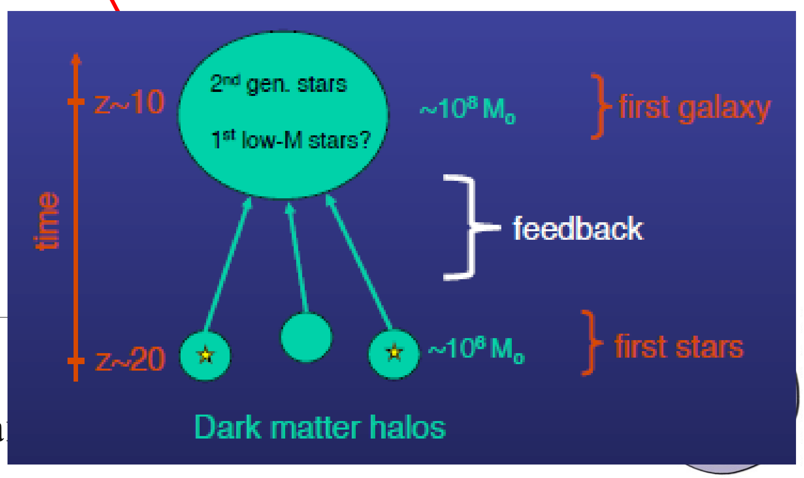
The first stars (PopIII)

- Numerical simulations : Bromm et al. (1999, 2002), Abel et al. (2000, 2002), Nakamura & Umemura (2001, 2002), Yoshida et al. (2006, 2008), Gao et al. (2007),...
- Main results :
  - The first stars in the universe were “massive” (~10-300 solar masses)
  - Top-heavy Initial Mass Function (IMF)
  - Formed in isolation (~1 star formed / 10^6 solar mass dark matter halo ~ size of simulation)
  - Live time ~ 10^6 years ==> rapid metal enrichment, strong impact on subsequent SF in the universe (UV radiation, ...)



(from Baldry, 2006)

Bromm & Yoshida 2011

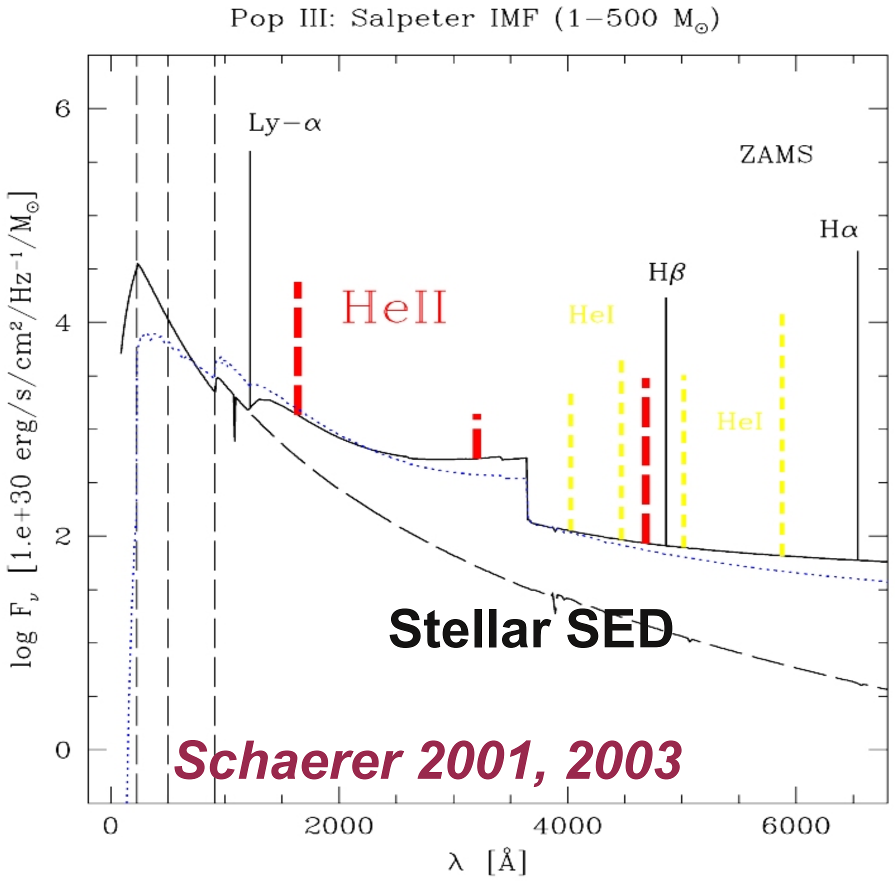


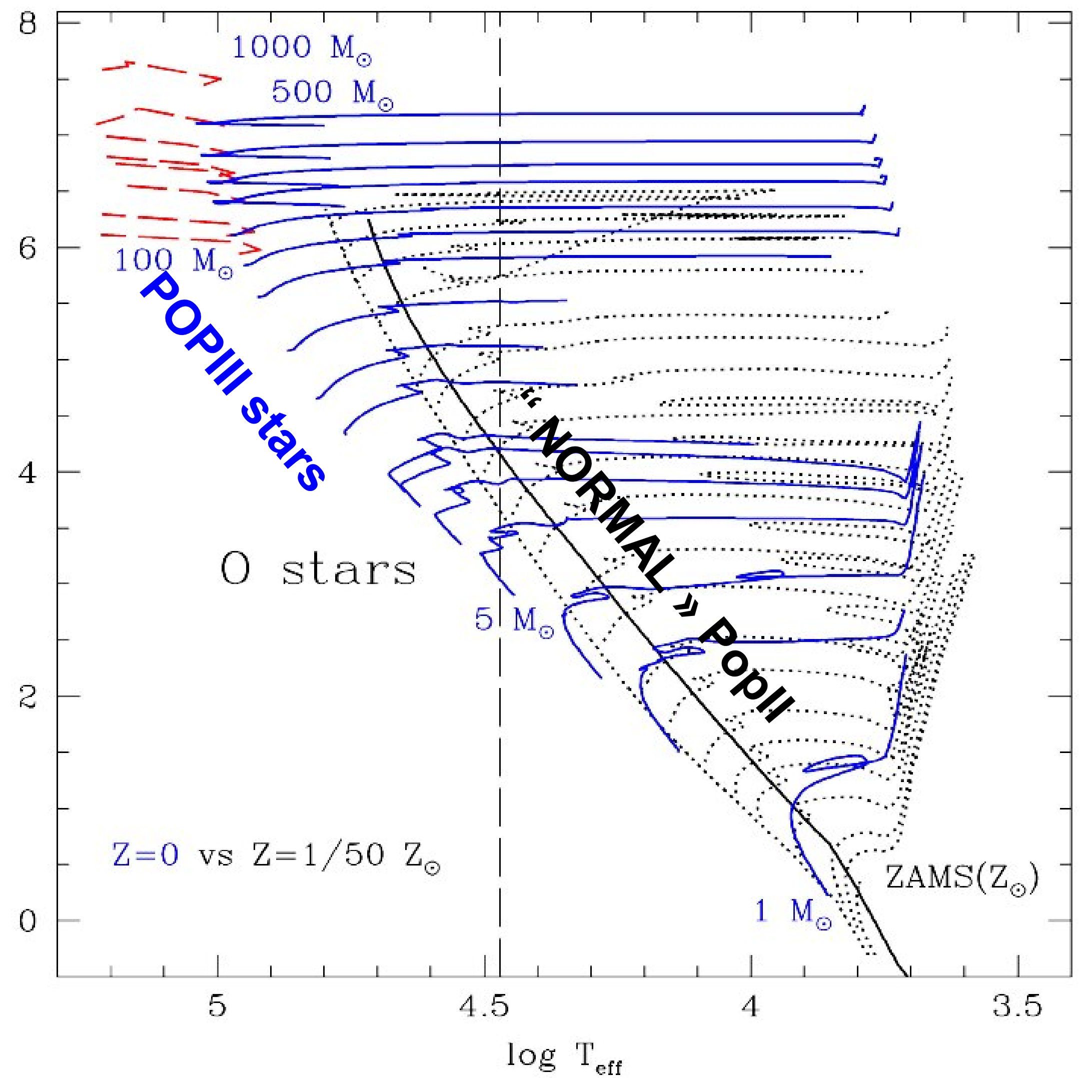
Theoretical considerations (V)

The first stars (PopIII)

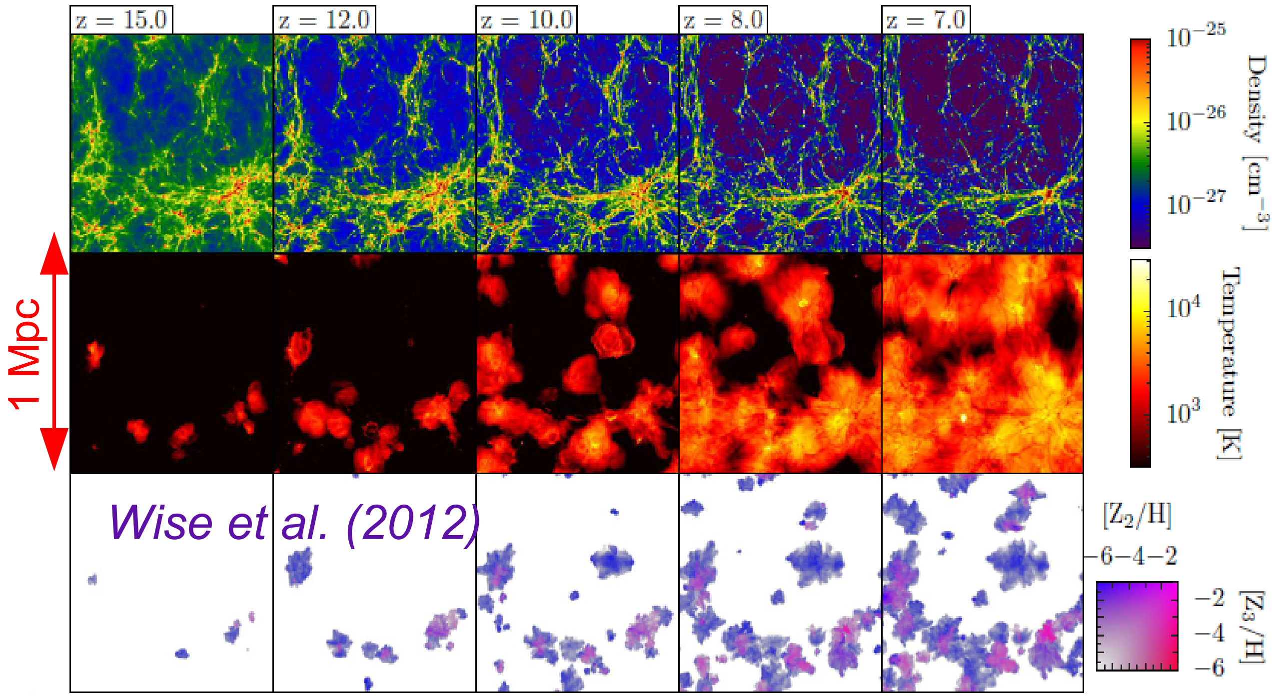
- “Hot” stars as compared to PopII ==> strong impact on ISM
- Nebular continuum dominates at lambda >1400A
- Strong e-lines expected : H-lines,

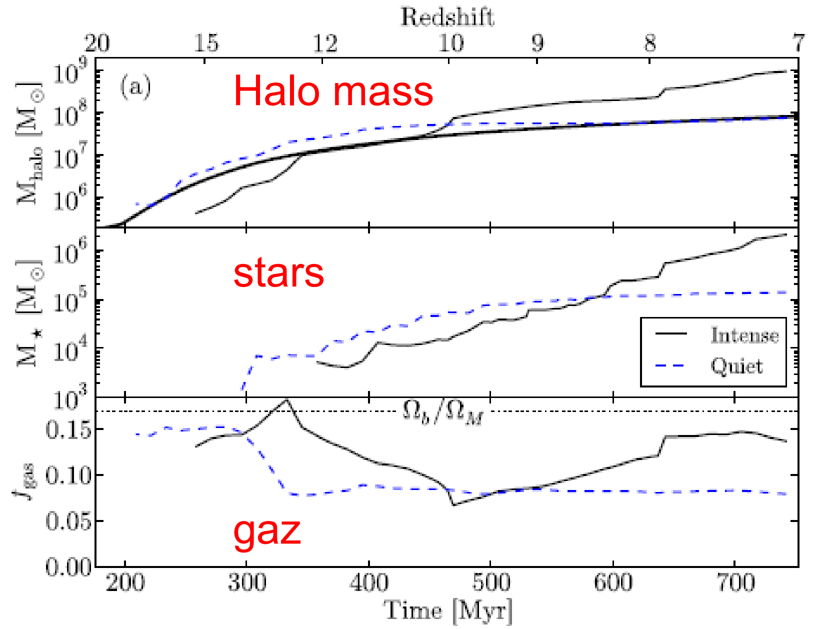
but also HeII λ1640, HeII λ3203, ...





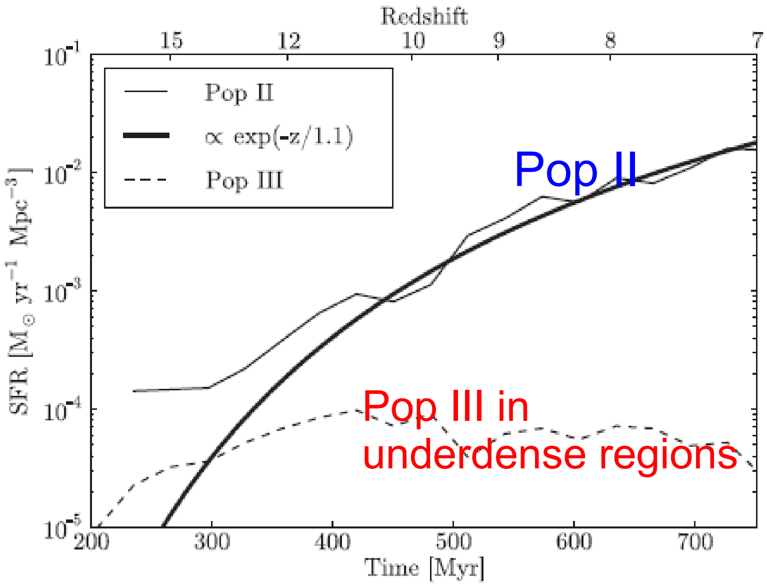
Theoretical considerations (VI)





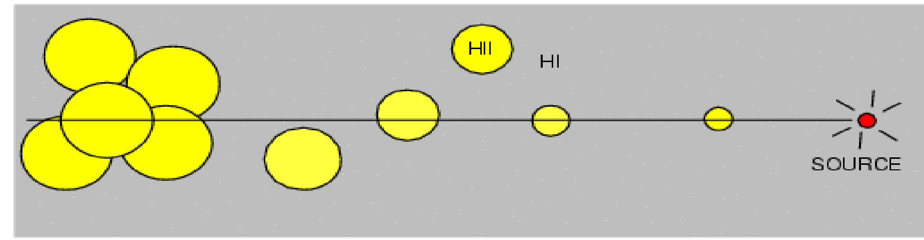
The first galaxies

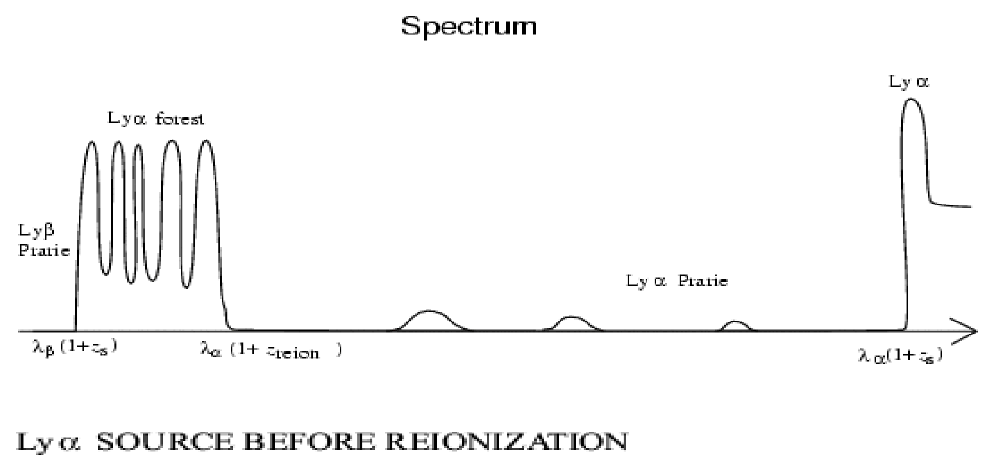
- Pop II formed when Z > 10^{-6} – $10^{-3.5}$ Z(solar)
- Numerical simulations : e.g. Wise et al. (2012),...
- Main results :
  - Efficient enrichment by Pop(III) stars : A single pair-instability supernova is enough to enrich the host halos to Z~10^{-3} Z(solar). Transition Pop(III) → Pop(II)

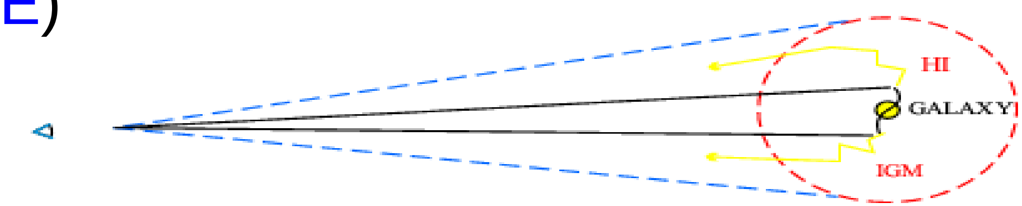


Observable properties of the first galaxies (I)

- Looking for star-forming galaxies at (extremely) high-z
- Two main signatures susceptible to be used for detection in lensing fields :
    - Lyman break signature (LBGs) : “drop-out” due to interstellar & intergalactic scattering by neutral hydrogen
    - Lyman alpha emission (LAE)
- Others :
    - Gamma-Ray Bursts
    - 21 cm tomography





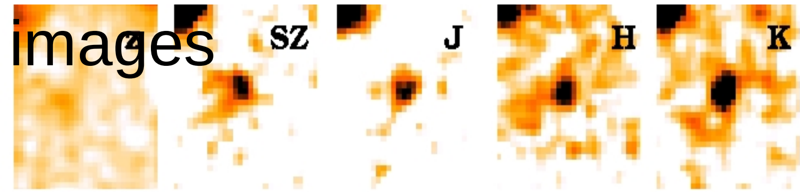


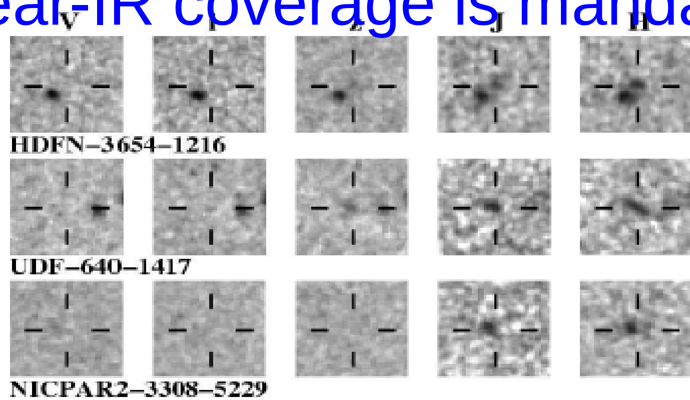
Barkana & Loeb 2001

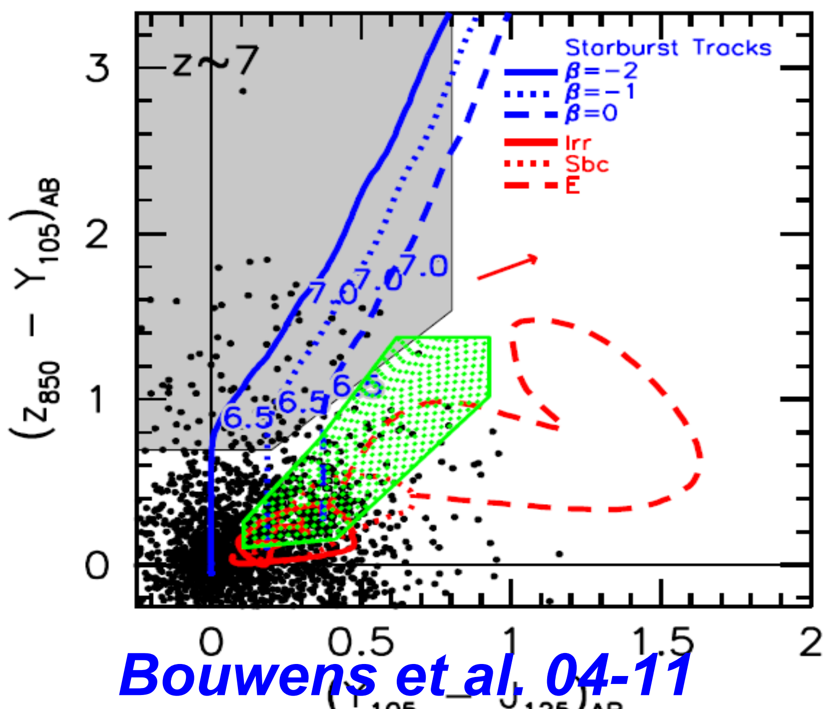
Observable properties of the first galaxies (II)

Identification of Lyman Break Galaxies (LBGs)

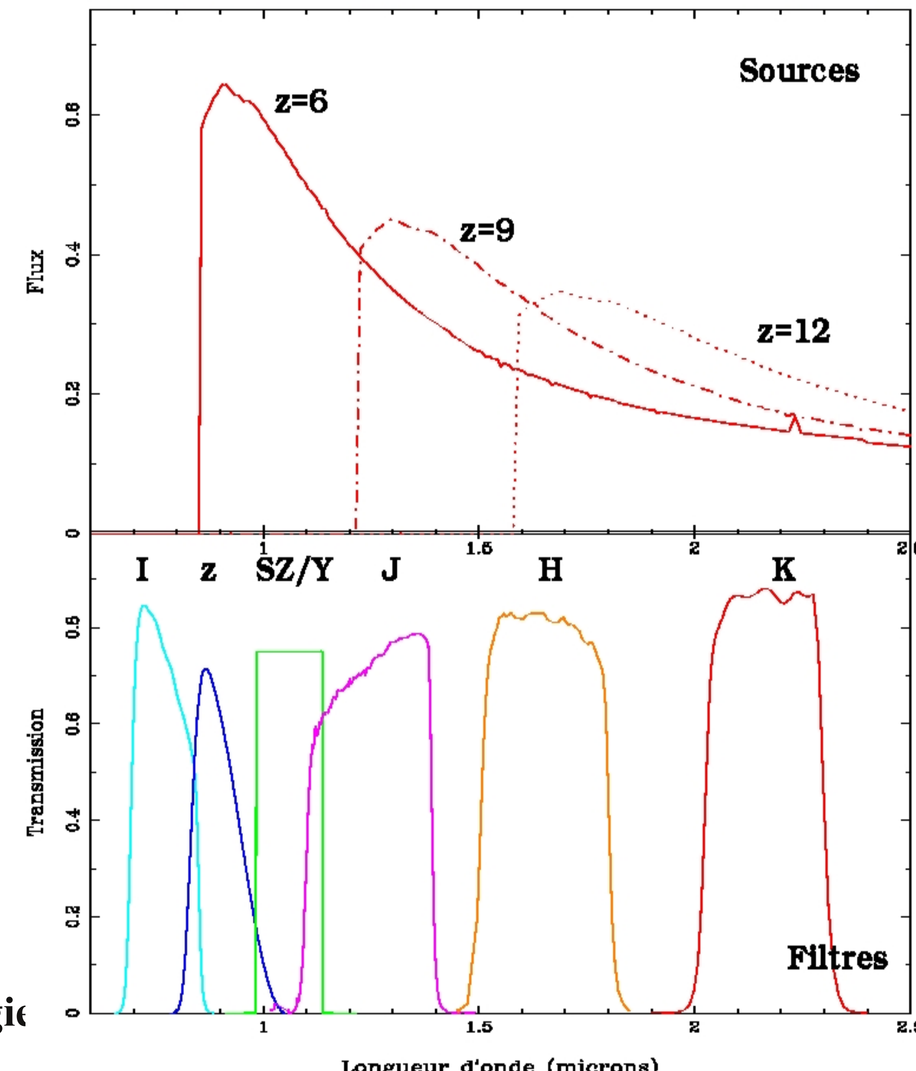
- Ultra-deep space (HST) or ground-based images
- Near-IR coverage is mandatory







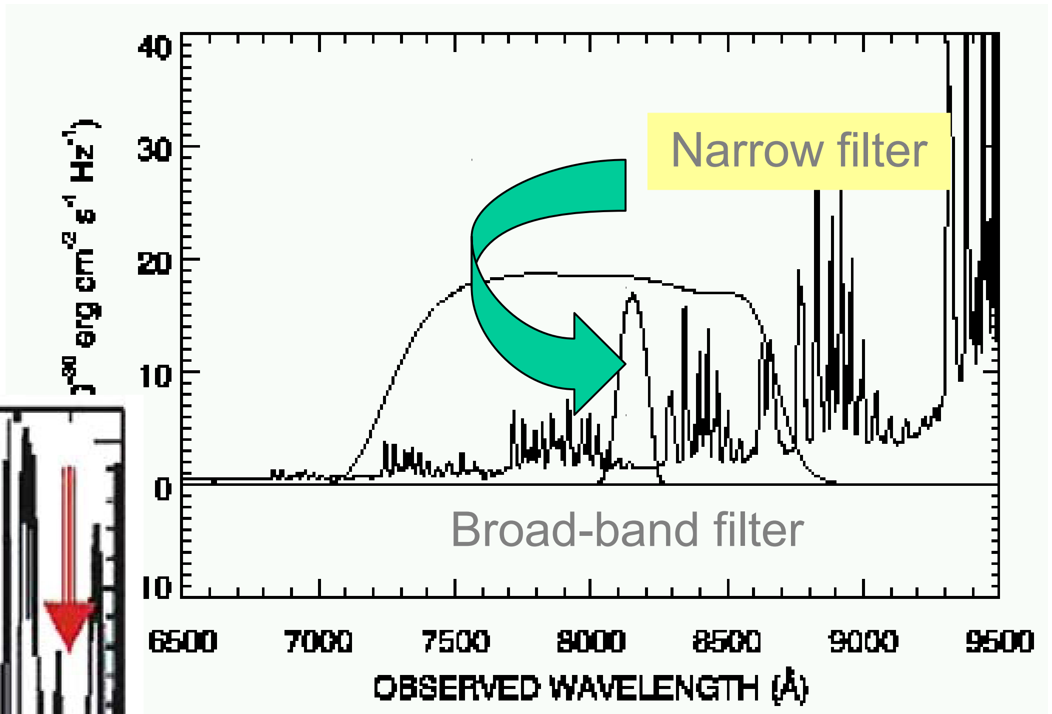
Bouwens et al. 04-11

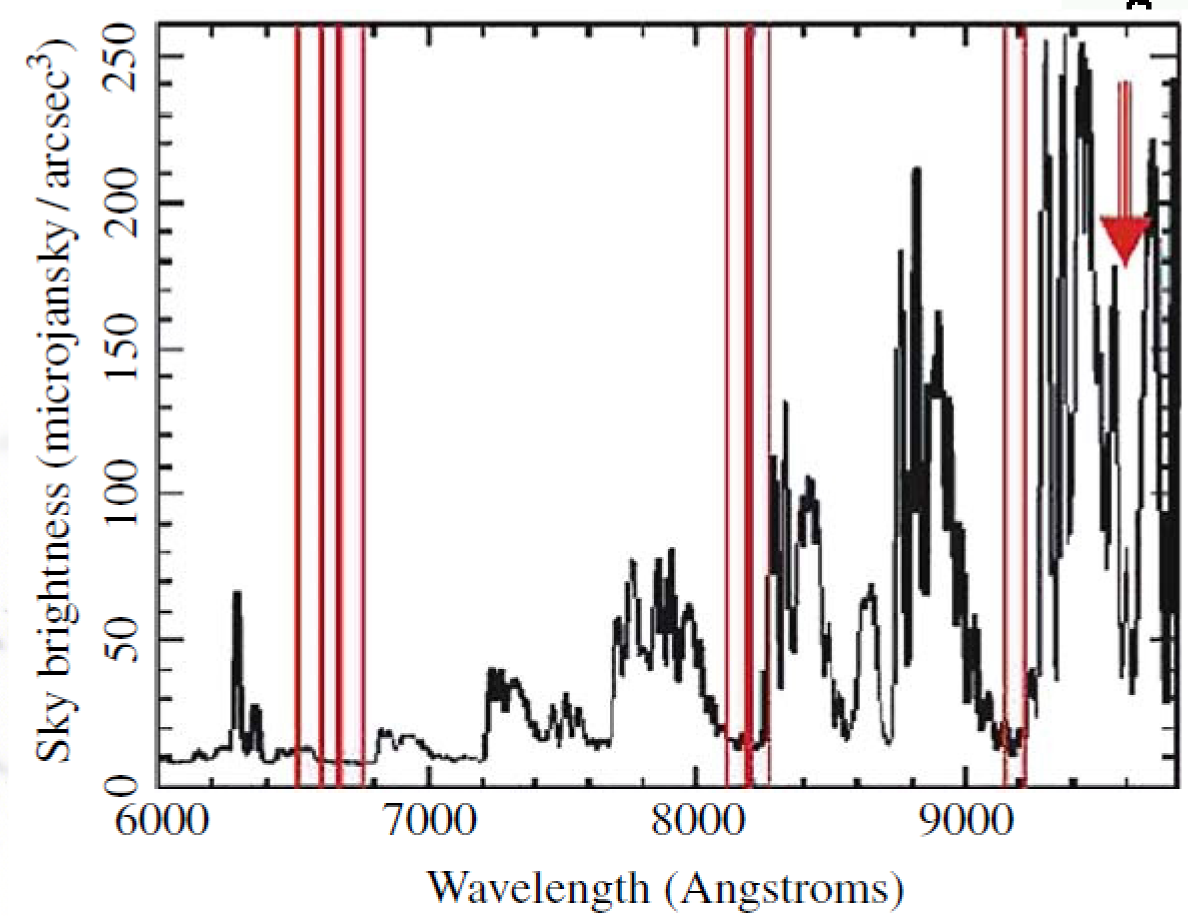


Observable properties of the first galaxies (III)

Narrow-band Surveys (LAEs)

- Candidates selected from contrast between NB and a broader-band filter





$z(L\alpha) = 4.7$ 5.7 6.6 6.9

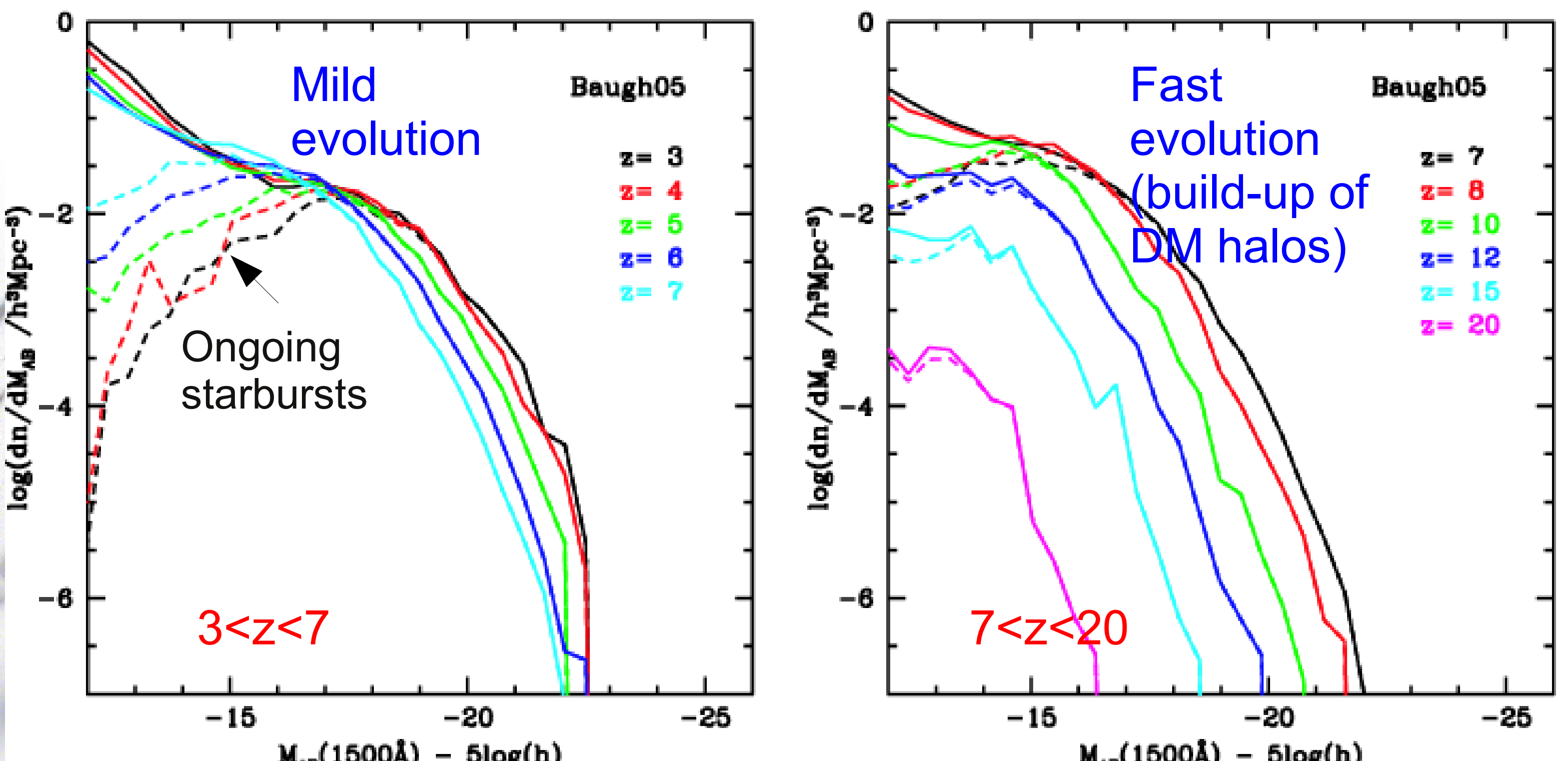
- Wide field surveys (small Δz)
- Contamination by other e-lines
- Subsequent spectroscopic follow up is mandatory

Observable properties of the first galaxies (IV)

Evolution of LBGs in the ΛCDM model

- Evolution of the LBG Luminosity Function (LF) based on semi-analytical models (tuned to fit z~0 to z~2-3 observed properties at all wavelength...).
  - Starbursts dominate the bright end and at high-z
  - Quiescent galaxies dominate the faint end
  - Detailed predictions depend on (technical) modeling details & physical parameters

LF
Including
Dust
extinction

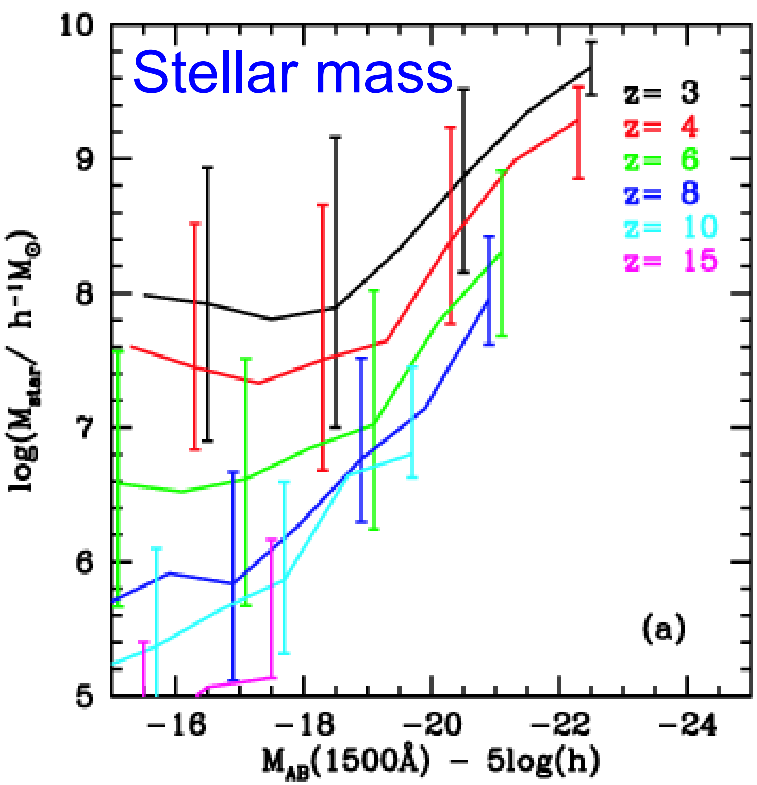


GALFORM Lacey et al. 2011

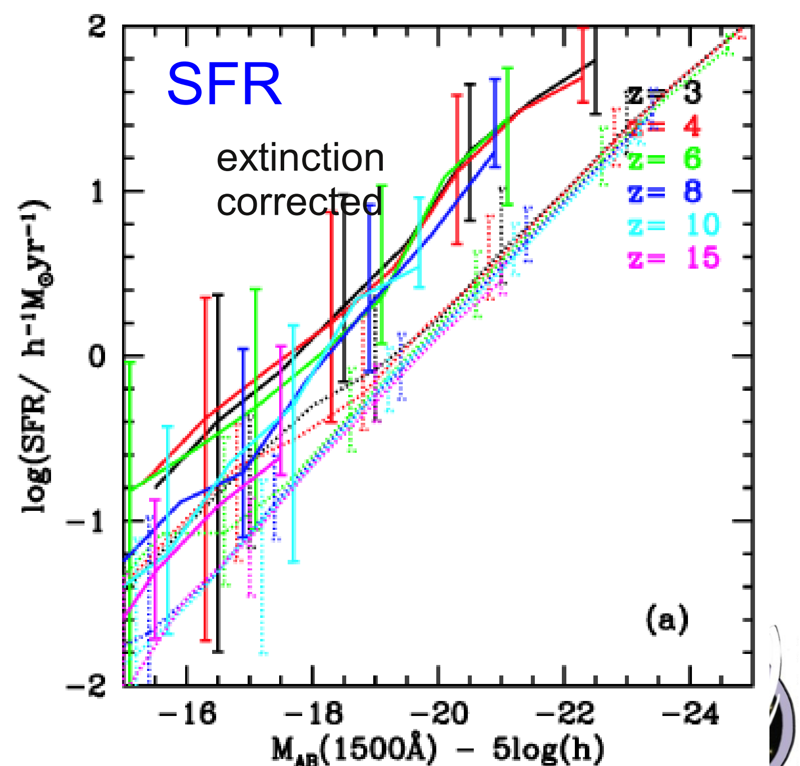
Observable properties of the first galaxies (V)

Evolution of LBGs in the ΛCDM model

- LBG have typical SFR ~ 1-10 solar masses/yr for a L* galaxy at z~8
- Stellar masses & SFRs currently measured are often larger... (sensitivity to fit parameters, such as IMF...)
- LBG stellar masses are typically M*~ few 10^{7}- 10^{8} solar masses for L* at z~8



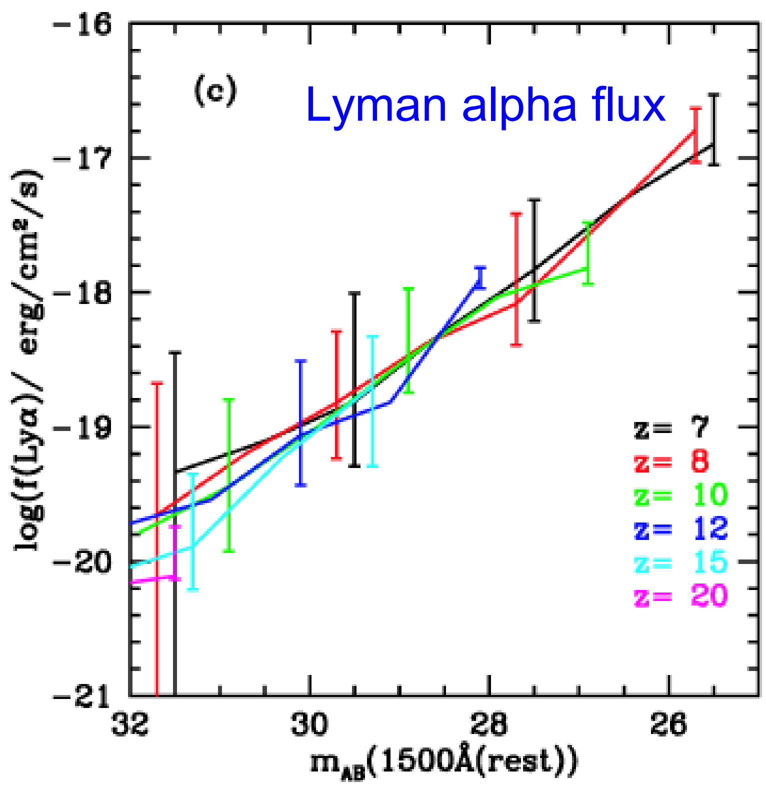
GALFORM
Lacey et al. 2011

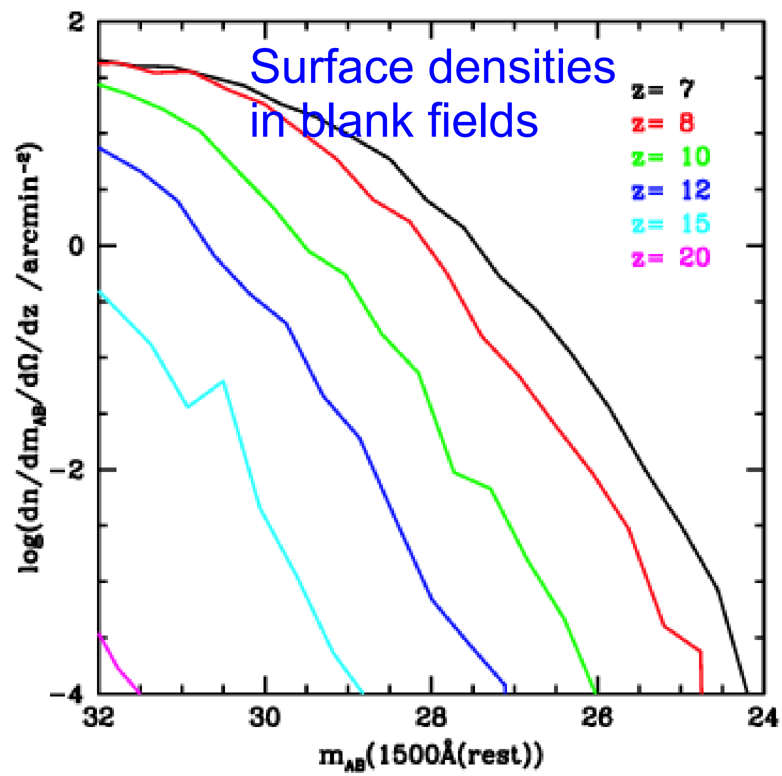


Observable properties of the first galaxies (VI)

Expected evolution of LBGs observed properties in the ΛCDM model (based on semi-analytical models)

- Surface density (in blank fields) : a few z~15 LBGs expected with m~30 in “wide field surveys” (~100 arcmin2, within the reach of JWST)
- Ly alpha flux (assuming escape fraction 2%) ~ a few 10^{-18}- 10^{-19} erg/cm2/sec for LBGs with m~28-30 (within the reach of E-ELT)



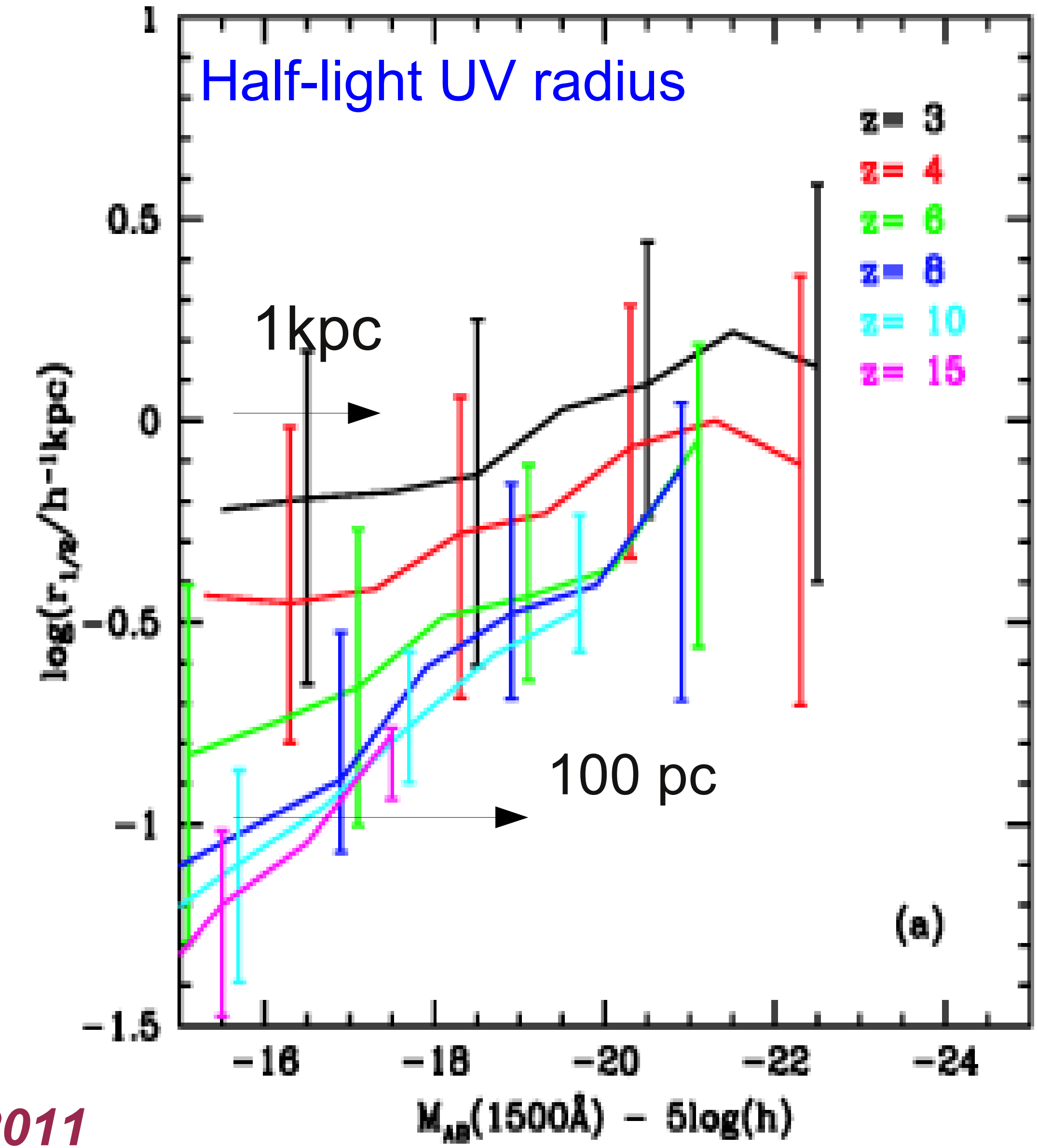


GALFORM Lacey et al. 2011

Observable properties of the first galaxies (VII)

Evolution of LBGs in the ΛCDM model

- Evolution of the LBG sizes (LF) based on semi-analytical models.
- Dust-corrected models
- Half-light (UV) radius between ~100 pc and 1kpc

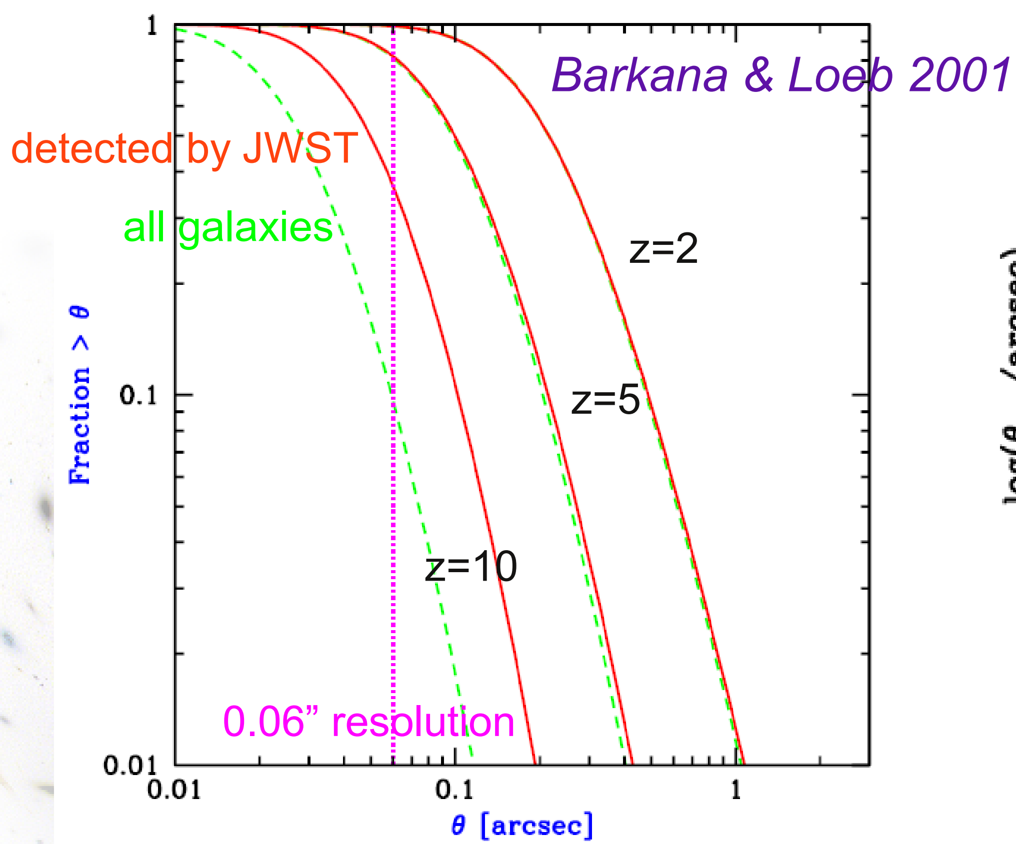


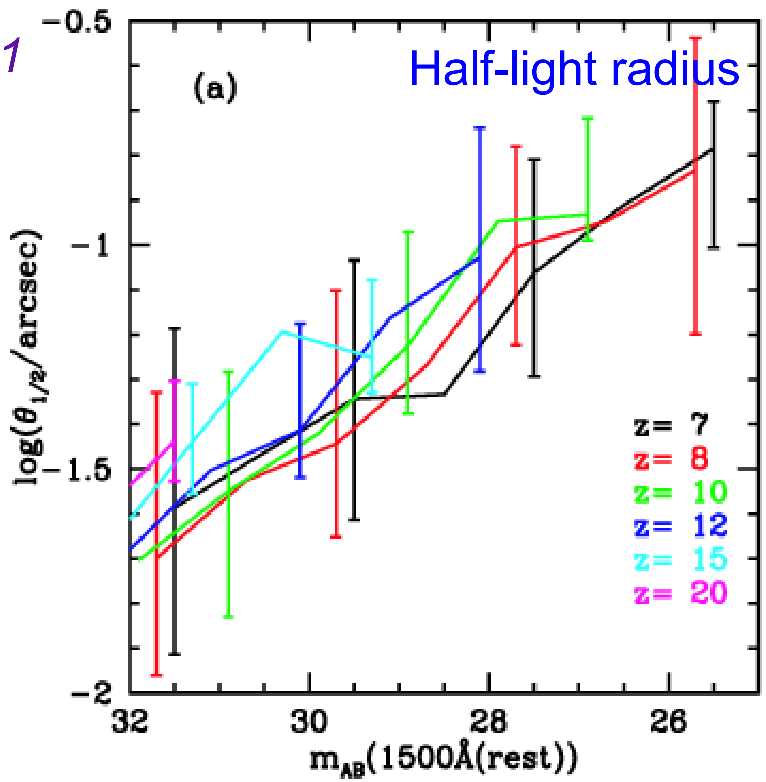
GALFORM
Lacey et al. 2011

Observable properties of the first galaxies (VIII)

Expected evolution of LBGs observed properties in the ΛCDM model (based on semi-analytical models)

- Angular Half-light observed radius (UV, dust corrected) : LBGs are "small", within the reach of JWST, but a large fraction of m>30 galaxies will remain unresolved … (at least in blank fields!)



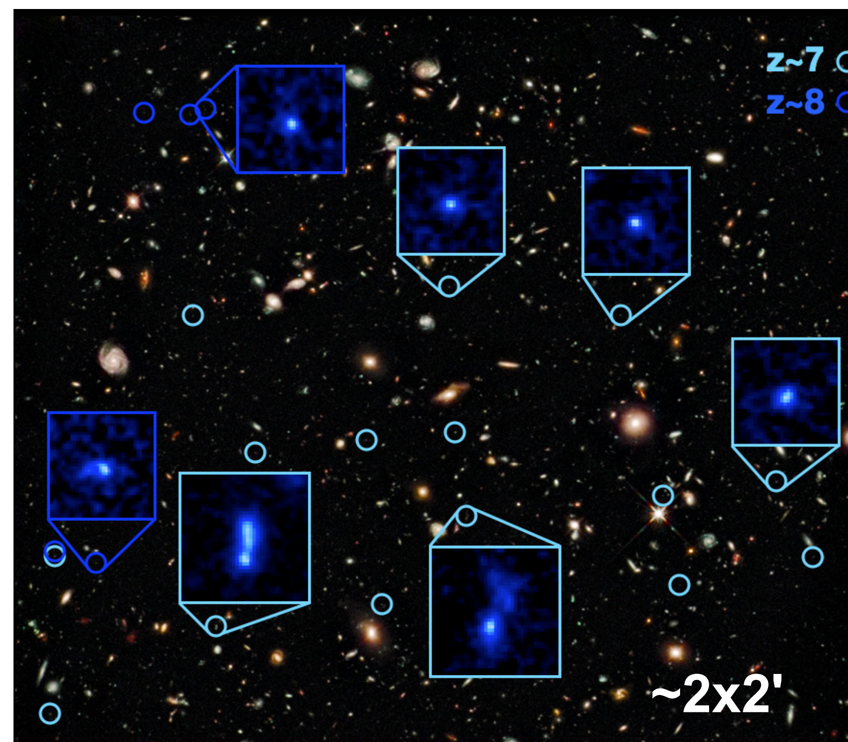


GALFORM Lacey et al. 2011

Present constraints based on observations (I)

- 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,...)
- Samples are "faint", typically m~28-29 at z~7-8
- Spectroscopic follow up is difficult, but the situation is rapidly evolving...

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



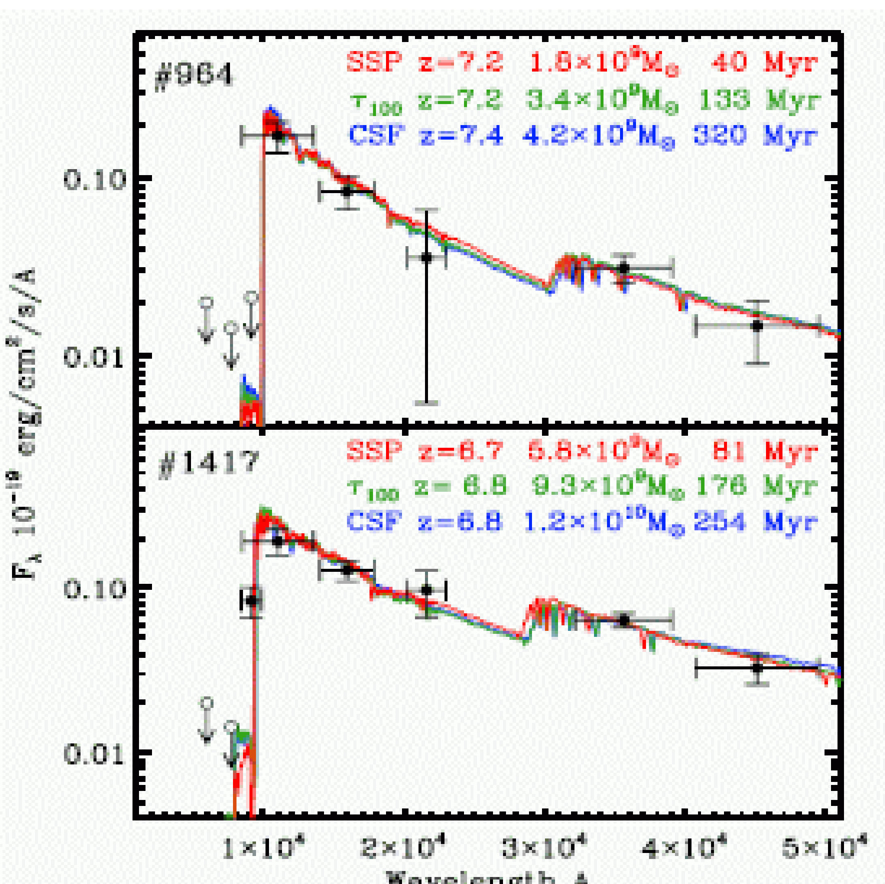
HUDF09 WFC3/IR Image with z~7 and z~8 Galaxies

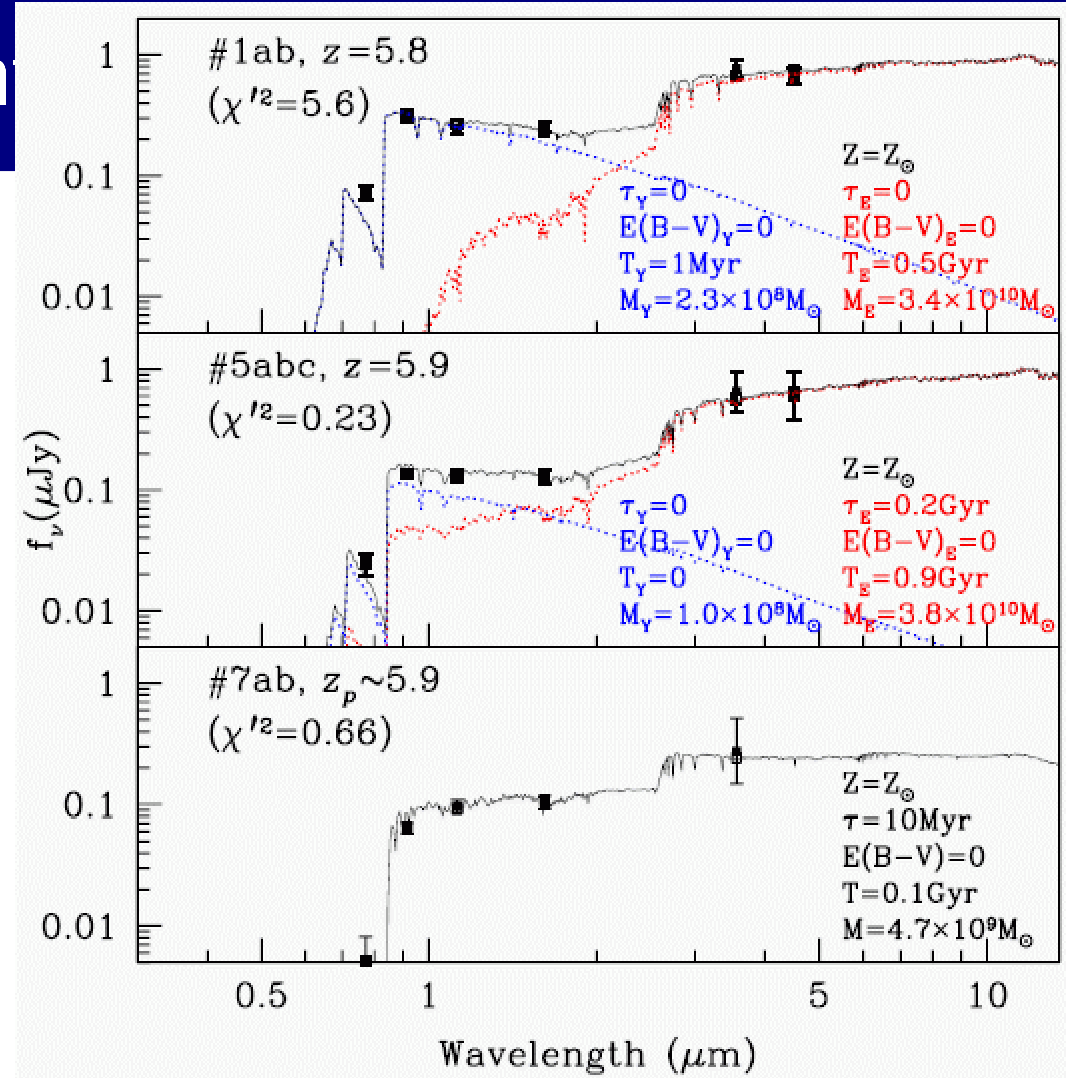
Credit: NASA, ESA, G. Illingworth, R. Bouwens (University of California, Santa Cruz), and the HUDF09 Team.

Present constraint

Observation of "massive" objects at z~5-6. (see e.g. Mobasher et al. 05; Yan et al. 05, 06; McLure et al. 06; Labbé et al. 06)

==> early star formation at z > 7-10 ?





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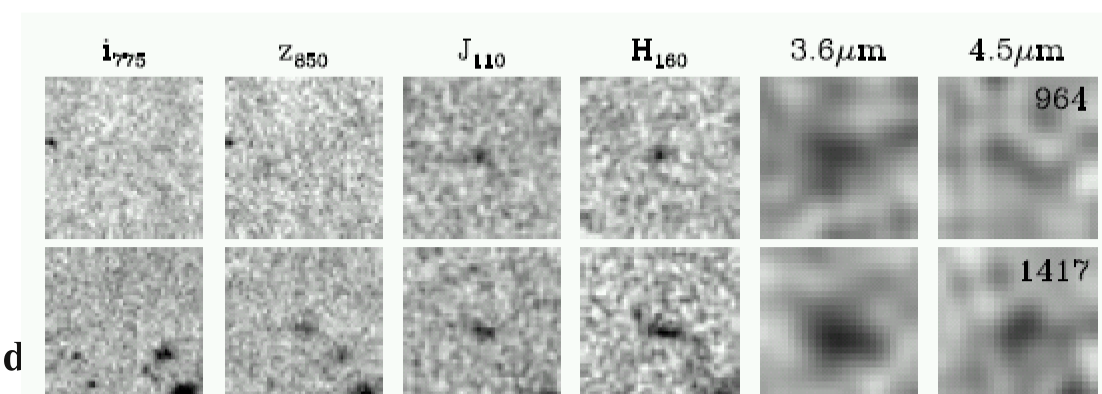
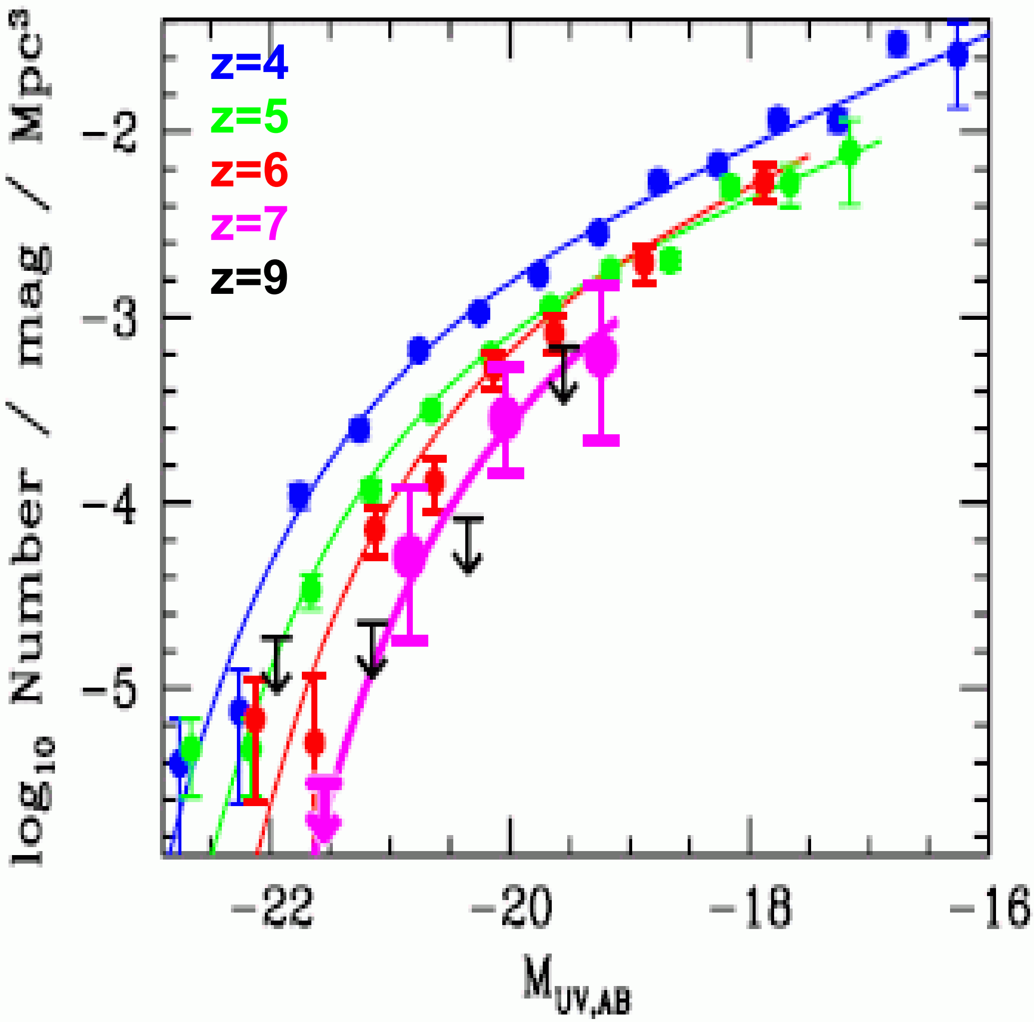
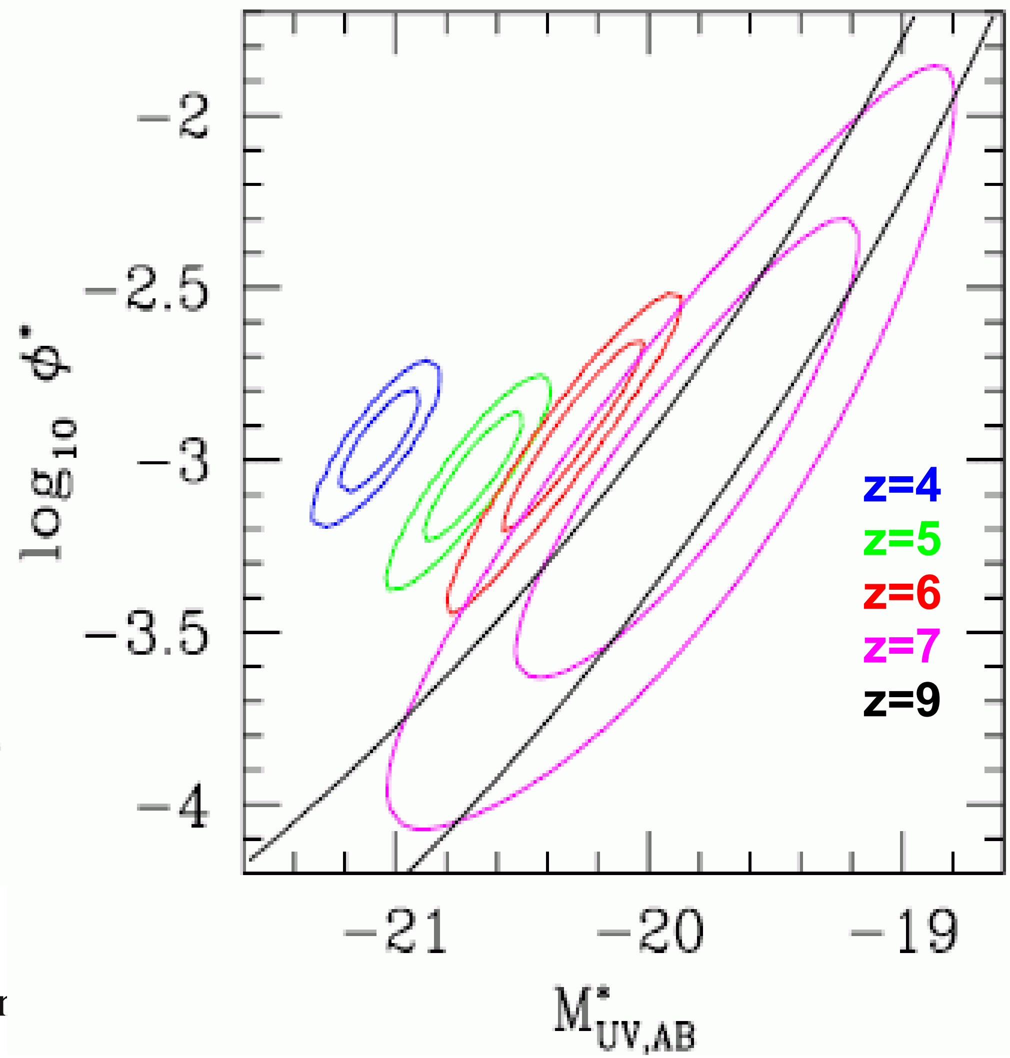
GOODS z~7 galaxies



Present constraints based on observations (III)

Blank-field LBG Surveys



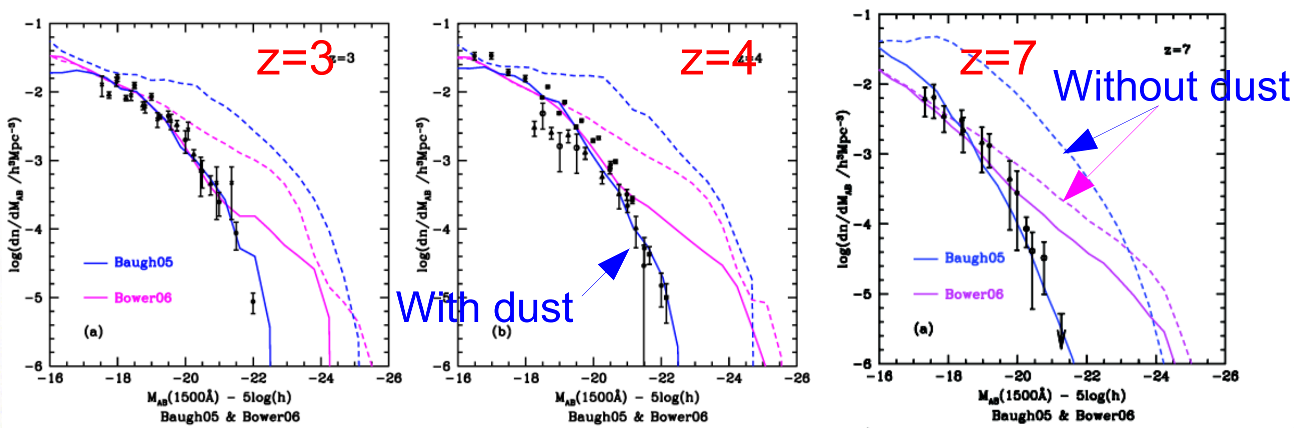


Bouwens et al. 2008 to 2011

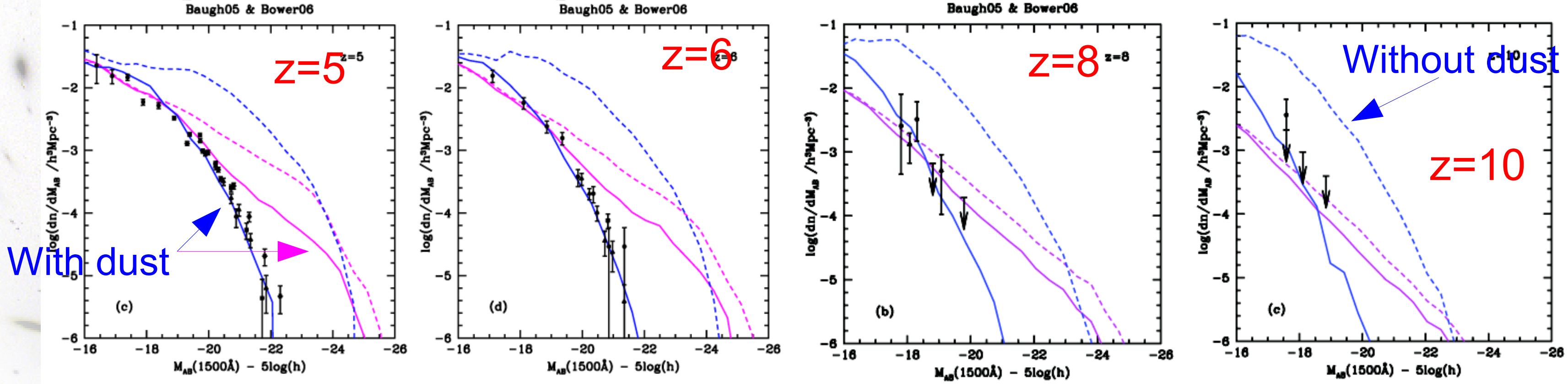
Present constraints based on observations (IV)

Expected versus observed evolution in the UV LF

- Predictions are very sensitive to modeling assumptions & parameters regarding :
  - **dust extinction**
  - Photoionization & supernova feedback
  - IMF
  - Burst time-scale & duration

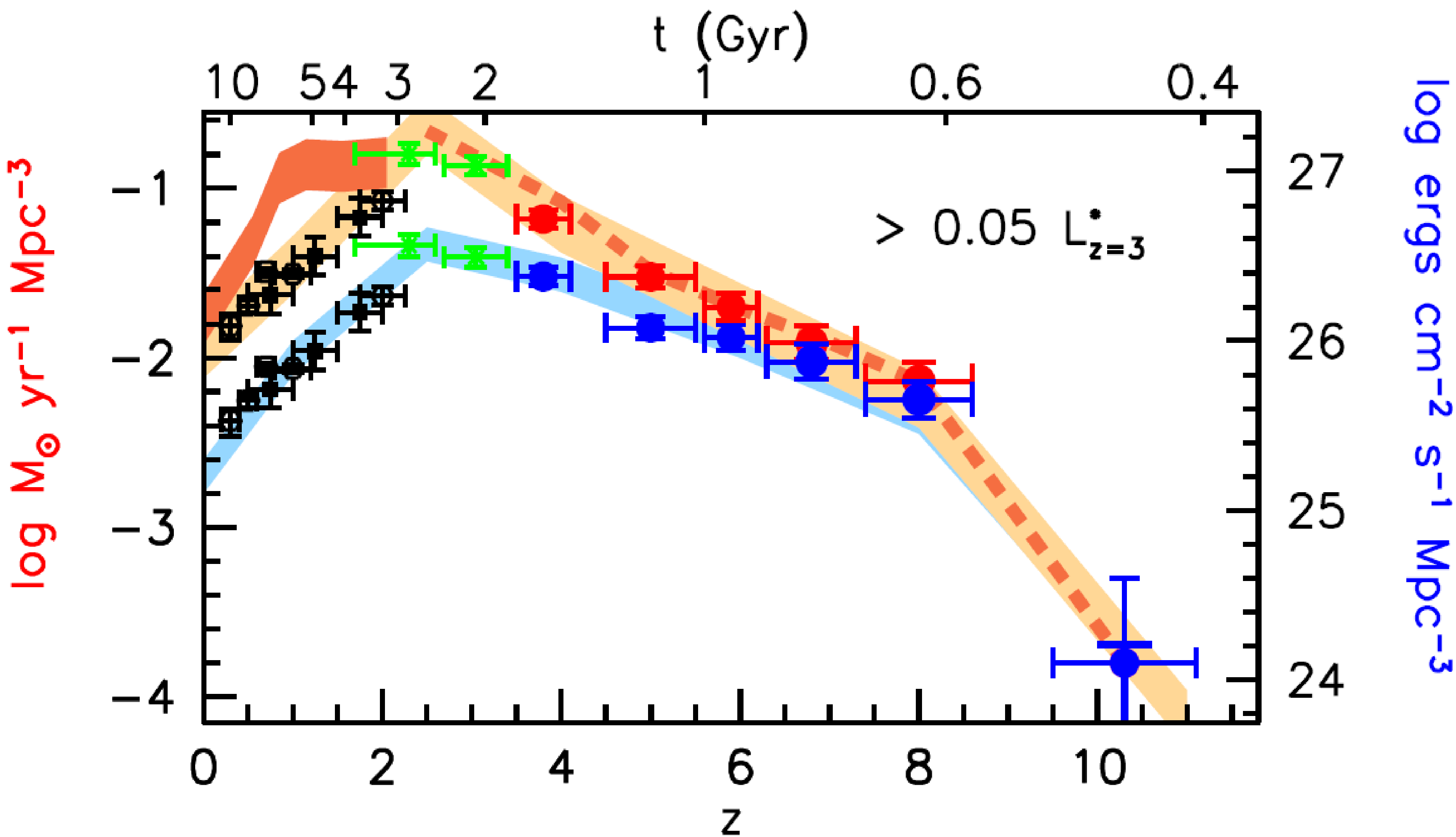


- Consistent up to z~10
- Large extinction at the bright end (~1.5–2.5 mags)
- High metallicity expected with top-heavy IMF + metal enrichment in bursts



GALFORM
Lacey et al. 2011

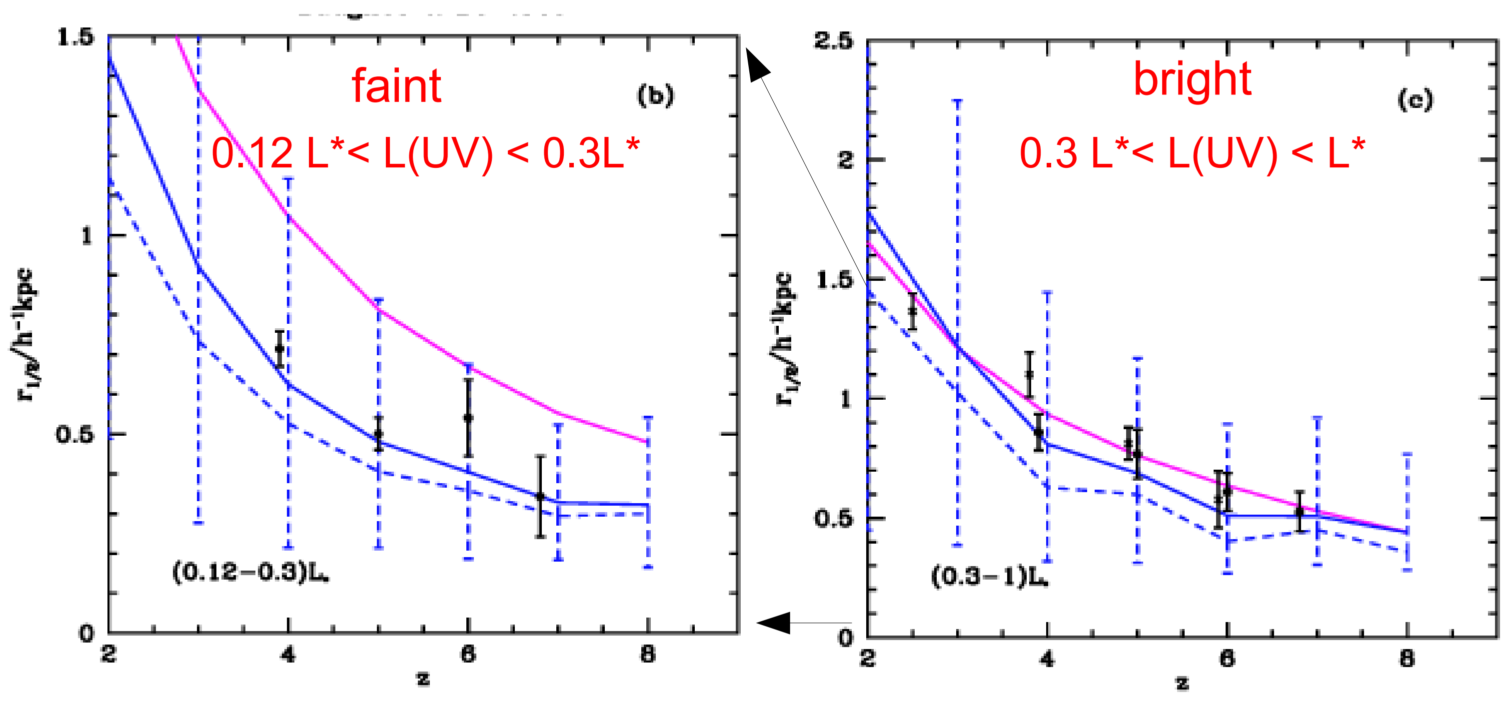
Present constraints based on observations (V)



Bouwens et al. 2008 to 2011

Expected versus observed evolution of LBGs sizes in the ΛCDM model

- Global evolution observed in redshift and luminosity in reasonable agreement with expectations...
- Large dispersion in simulations (lack of sensitivity on models parameters...)

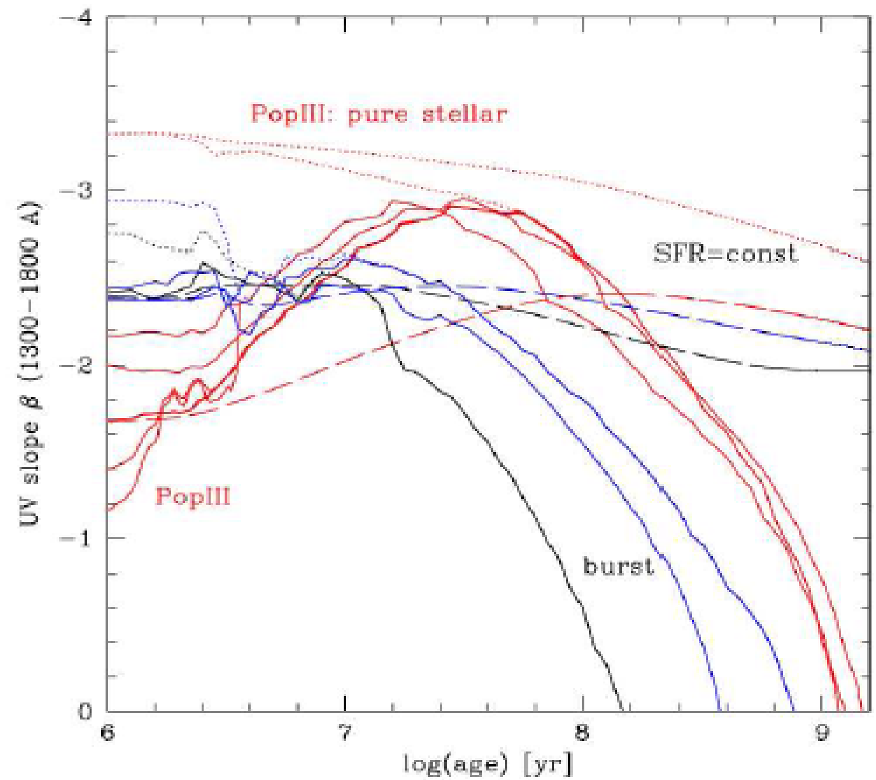


GALFORM Lacey et al. 2011

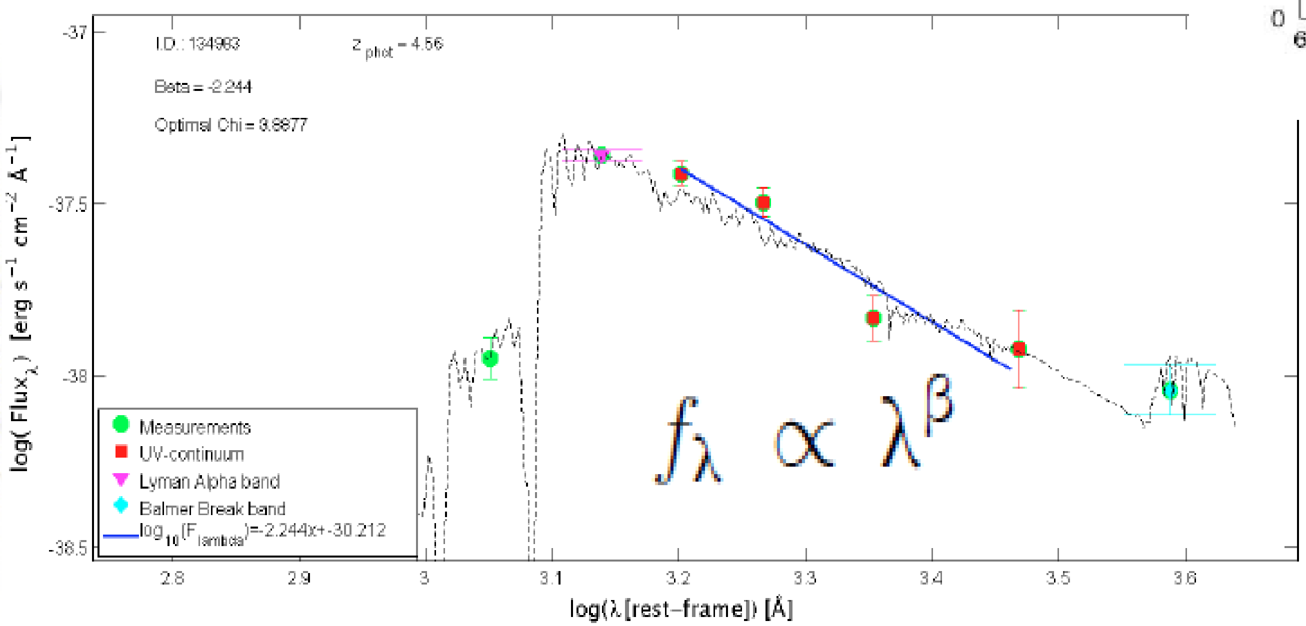
Present constraints based on observations (VII)

Evolution of the UV slope

- UV-continuum slope β is correlated with SF history, metallicity, dust content, IMF, ag of the stellar population (at leas
- Difficult to measure due to photometric uncertainties...



Schaerer & Pello 2005

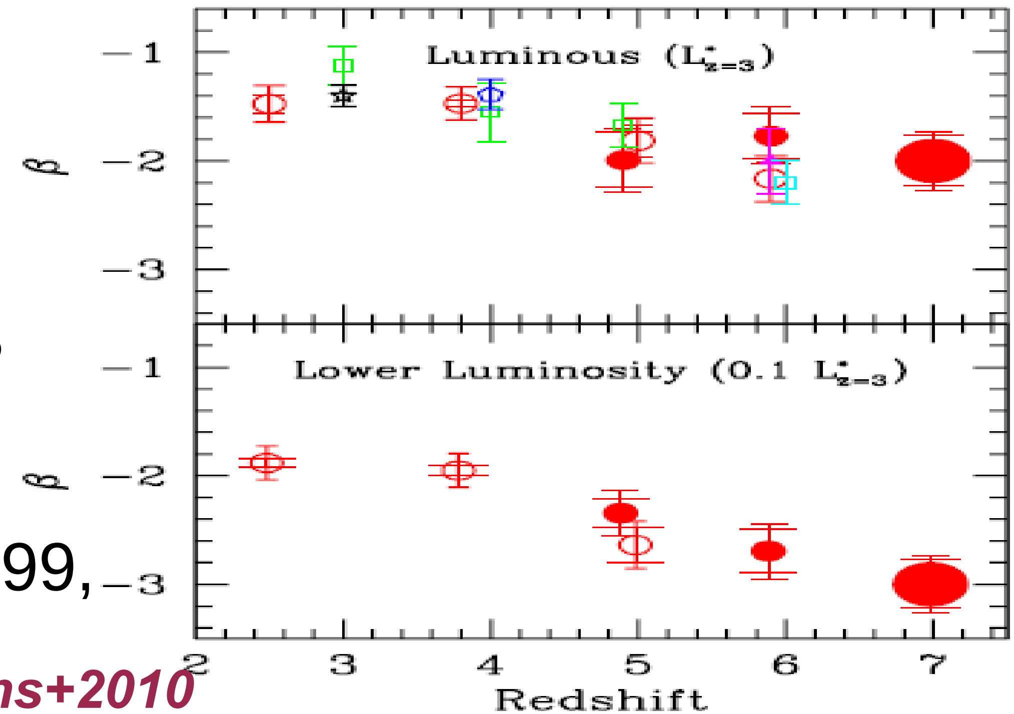


èse 2012

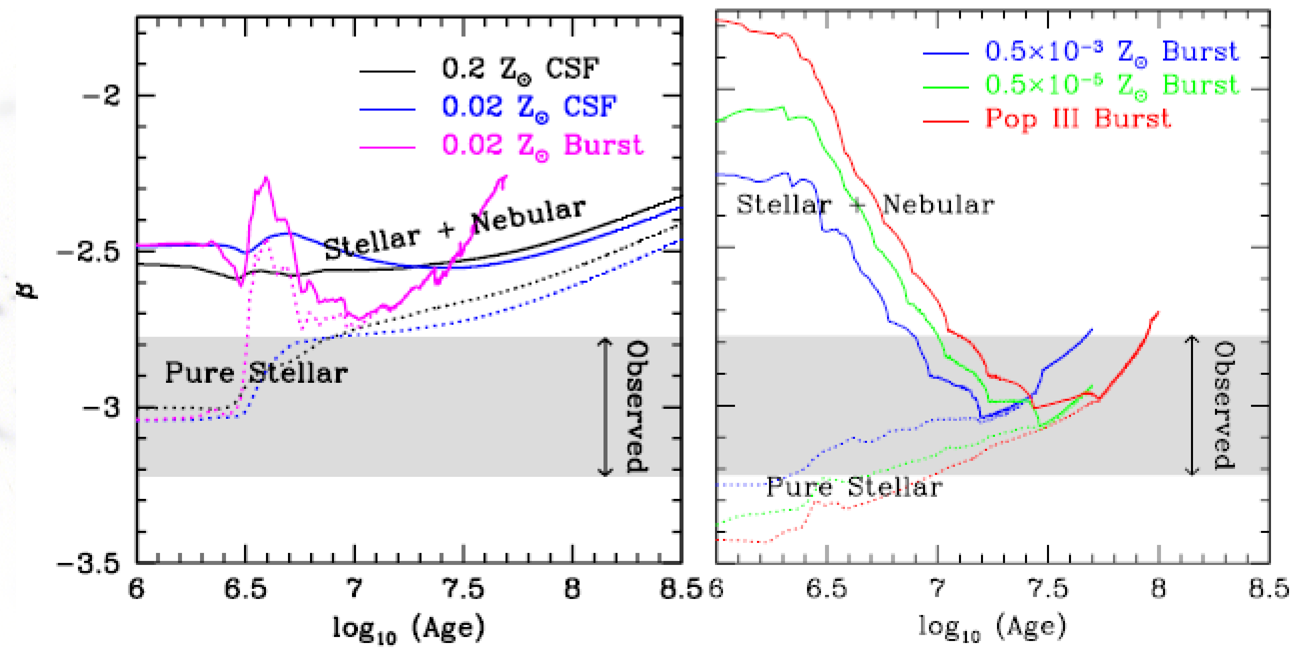
Present constraints based on observations (VIII)

Evolution of the UV slope (observations)

- β becomes bluer (steeper) with increasing redshift between z~3 and 7 (e.g. Stanway+ 2005, Bouwens+ 2010), and towards fainter luminosities (Meurer+ 1999, Bouwens+ 2010).



Bouwens+2010

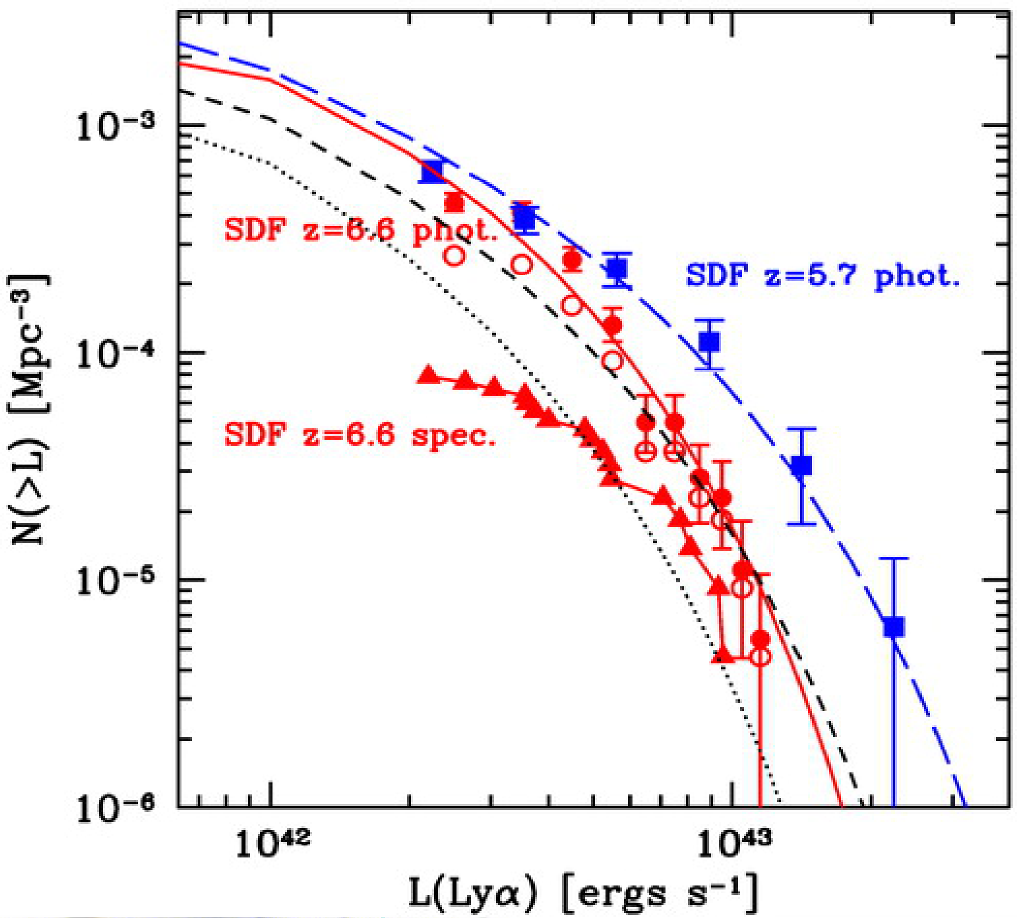


Interpretation : correlation with a decrease in the overall dust content at high redshifts &/or a metallicity effect

Results & interpretation are still subject to debate

Present constraints based on observations (IX)

Kashikawa et al. 2006



LAE from NB Surveys

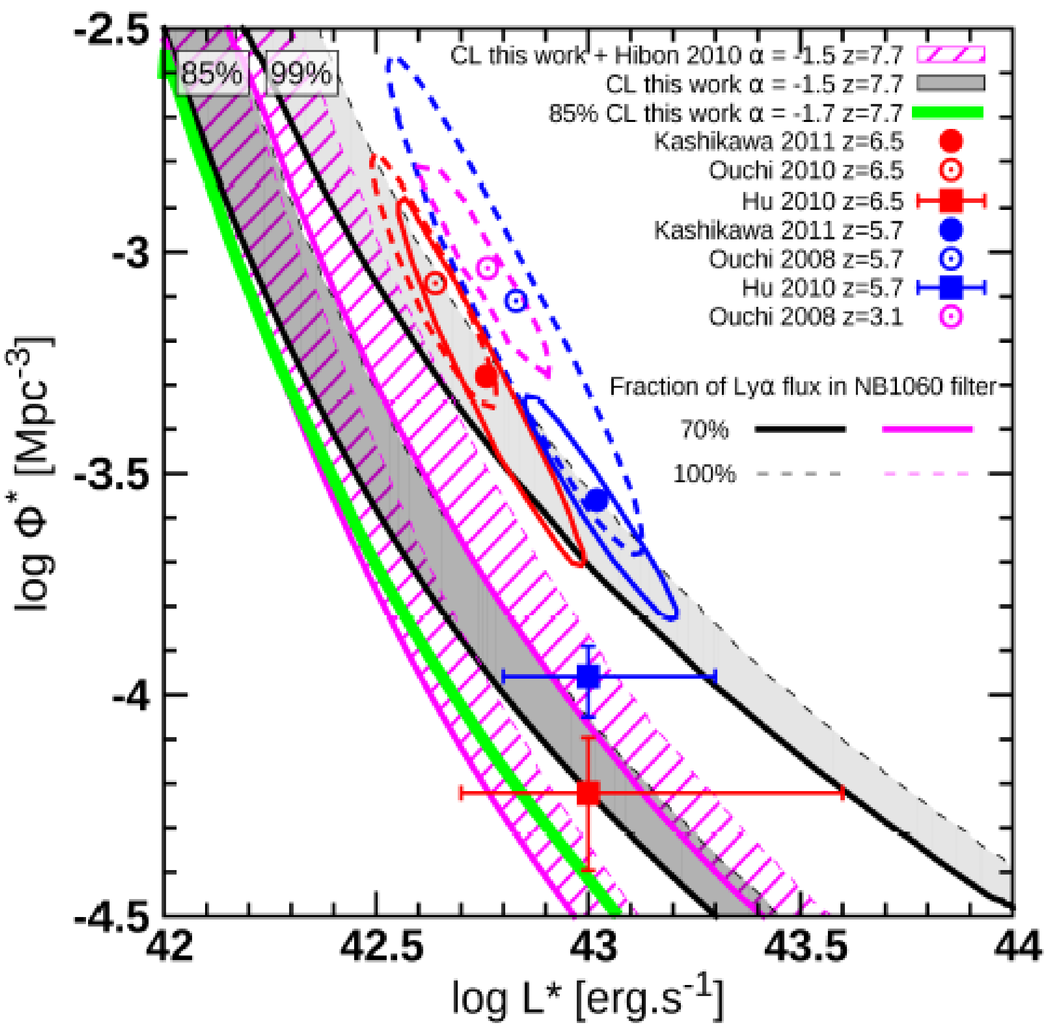
- LF based on NB surveys shows a strong decline between z~5.7 and 7

==> increase in the neutral fraction?

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

Present constraints based on observations (X)

Clément et al. 2012



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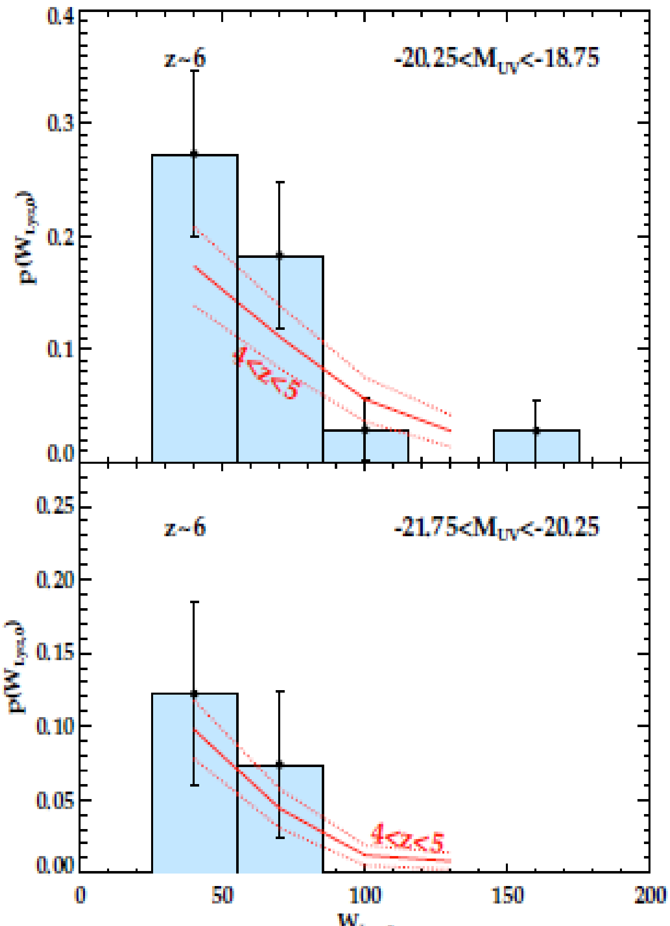
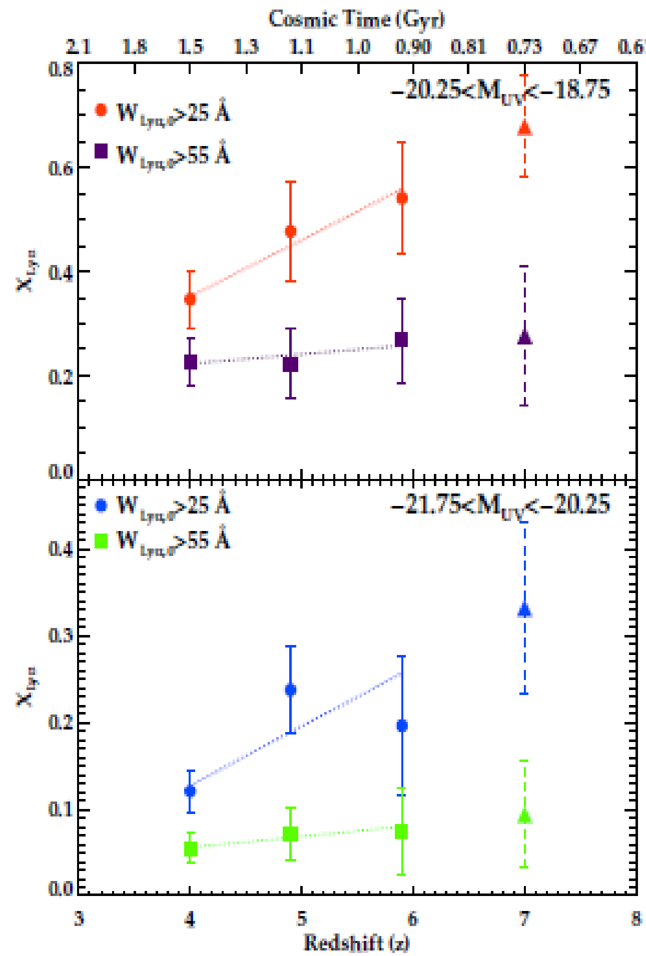
Present constraints based on observations (XI)

Stark et al. 2011

LAE vs LBGs

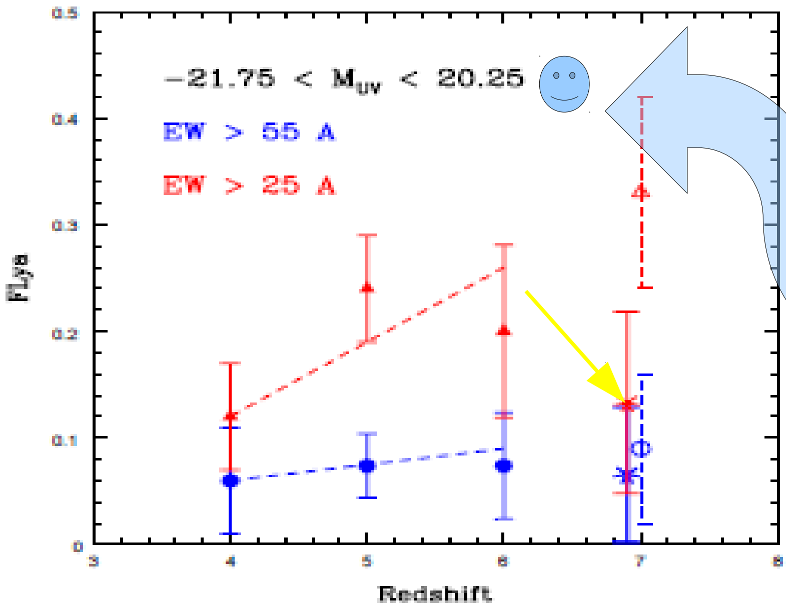


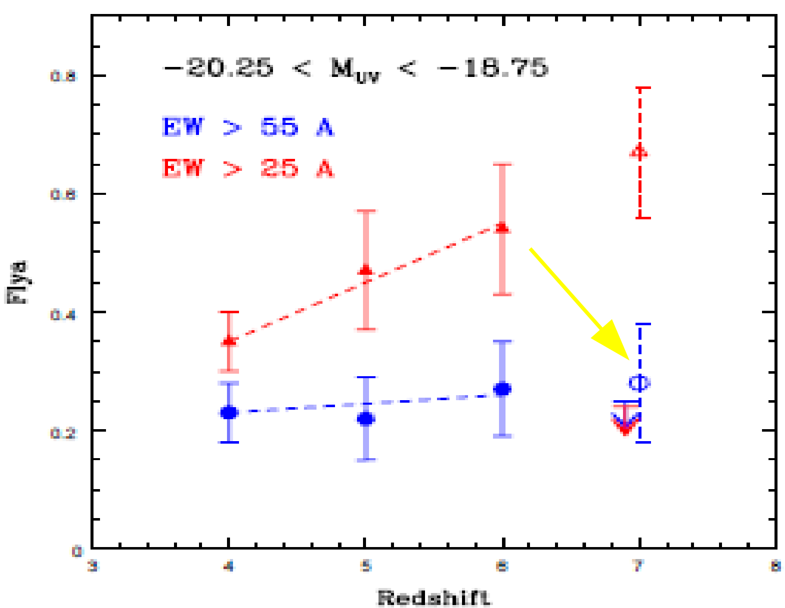


- Systematic trend for
  - An increasing fraction of Lya emitters among LBGs between z~3 and 6,
  - increasing with decreasing L.

Present constraints based on observations (XII)

Pentericci et al. 2011

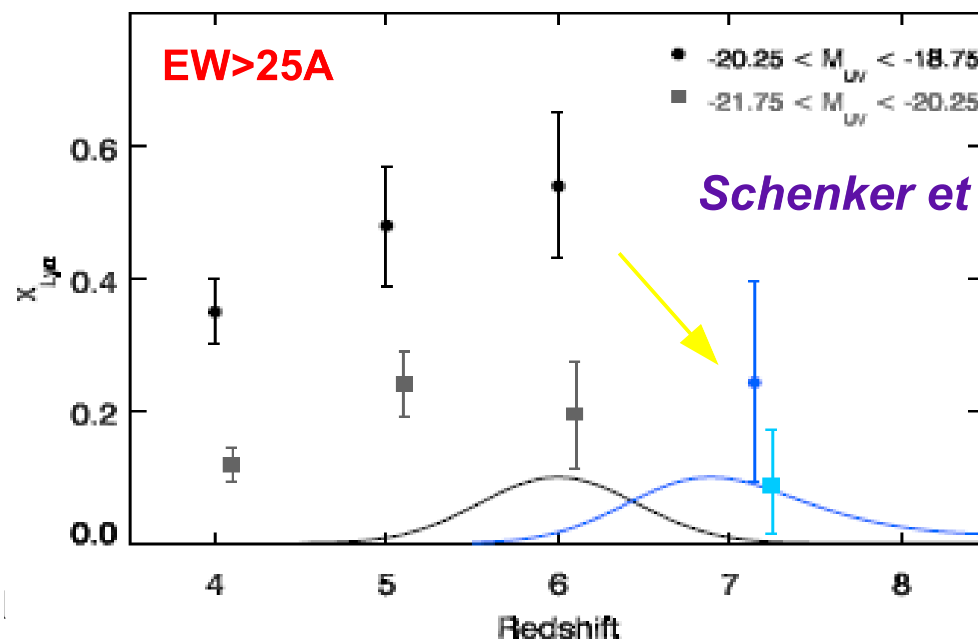




LAE vs LBGs

Possible decrease beyond z~6 → 7, still tbc.
==> Evidence for increase in the neutral fraction?

Results based on small samples, still not well understood... e.g. the remarkably high fraction (~45%) of strong Ly a emitters amongst luminous (L>2L*) 6 < z < 6.5 LBGs in the UKIDSS Ultra-Deep Survey (Curtis-Lake et al. 2011)



Schenker et al. 2011

Summary & Conclusions (1rst part)

- Linear growth of small density fluctuations in the primeval universe, formation of halos in non-linear regime, deriving the expected number of halos as a function of DM halo mass & redshift is relatively well understood (numerical experiments & physically-meaning analytical models)
- Star & Galaxy formation processes involving (complex) baryon physics and feedback are much more problematic... Rapid evolution is expected in this field.
- The first stars formed in the universe were "massive" (top-heavy IMF) ==> strong impact on early star-formation & radiation field. Rapid evolution of metal enrichment. Burst dominate at high-z, and also the bright part of the LF all the way to z~3.
- Typical values for L* galaxies at z>8 : M*~ few 10^{7}- 10^{8} solar masses, sizes (~100 pc to 1 kpc), SFR (1-10 solar masses/yr), Lyman alpha fluxes (~ a few 10^{-18}- 10^{-19} erg/cm2/sec), … **==> lensing fields are susceptible to make a major contribution!**
- A rapid evolution in the global properties of galaxies is expected at z~>8, and this trend is indeed observed (LF of LBGs & LAEs).
- Predictions are very sensitive to physical parameters in simulations, in particular dust extinction, feedback, IMF, and SF regime (burst duration & strength). Degenerate solutions when only photometric "global" samples are used. Spectroscopy is needed to make progress **==> strongly-lensed sources are a unique oportunity**


Thanks!